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Litho-structural Interconnections and Deformation histories of the Tullu Dimtu Neoproterozoic Basements, Western Ethiopia

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Abstract:- The Lithostructural setting of Tullu Dimtu Neoproterozoic metamorphic rocks of western Ethiopia were comprised tectonically interleaved components of East African Orogen (EAO). Systematic field observations combined with petrographic investigations comprises variably polydeformed and metamorphosed metavolcano-sedimentary, mafic-ultramafics, and granitoids units. The interconnections and cross-cutting relationships of slightly foliated gneissosity, fold axial surfaces, ductile shear zones, and strike-slip faults manifests four phases of deformations in the area. The weekly foliated lenses of ferromagnesian rocks due to extensive shortening (D1) as a relict with in eastern high grade rocks were north northeast-trending and dipping subhorizontal to east. The variably dipping of axial surfaces and crenulation cleavage, and easterly plunging mineral stretching manifests the crustal thickening due to thrusting and folding (D2) causes for the migmatization of biotite-hornblende gneiss. The major north northeast- and north-south- trending lithological stretching and thinning of the uplifted basement rocks in the area were parallel to extensive ductile shearing (D3) with dextral sense and minor of sinistral sense of movements. The northwest striking Fault to the west and semibrittle shearing to the east (D4) characterized by steep foliations, sub-horizontal lineations and steeply plunging minor asymmetric folds was observed as sinistral sense of movements along strike-slip fault. These lithostructural associations are provided new evidences for reconstructed deformation sequences, sense and direction of movements, exhumation mechanisms, and metamorphisms along each deformation event. The litho-structural position, preferred grain orientations and their contact nature, grain shape and arrangements, pressure solutions, and asymmetric folds observed in outcrops and thin-sections shows the deformations was happened in case of east-west shortening, northwest-southeast compression, and later activated by escape tectonics which is the last phase during EAO evolution.

***Keywords**:- Mafic-Ultramafic; Migmatitic Gneiss; Escape Tectonics; Shear Zone; Tullu Dimtu.*

I. INTRODUCTION

The Neoproterozoic metamorphic rocks of western Ethiopia is comprised of both Mozambique Belt (MB) (Holmes, 1951) to the south, and east, and Arabian Nubian Shield (ANS) to the north which together constitute what is known as East African orogen (EAO) (Stern, 1994). Regionally the belt comprises of rock assemblages which were developed in response to plate tectonic processes that encompasses complete Wilson cycle (Abdelsalam and Stern, 1996). The two components of EAO were characterized by units of high grade metamorphic rocks in MB (Holmes, 1951), and low grade volcano-sedimentary rocks with associated metamafic-ultramafic and granitic intrusive rocks of varied composition and emplacement age in the ANS to the north (Camp, 1984; Gass, 1977; Kroner, 1985; Patchett and Chase, 2002; Stern et al., 2004; Vail, 1983, 1985). The Tulu Dimtu Neoproterozoic rocks the focus of current study was global interesting as it comprises the complete setup of EAO which is not characterized well yet and rises a contradicts among the researchers (Alemu and Abebe, 2007; Allen and Tadesse, 2003, 2005; Kazmin et al., 1979; Kebede et al., 1999, 2001, 2007). Moreover, as it is widely located including the rocks of MB and ANS, this paper forwards a clue to understand the litho-structural interconnections linked to different deformation events to the north-east part of EAO.

This Orogen amalgamation was achieved during distinct phases of orogeny between ~850 and 550 Ma and with the northern part of the orogen, the Arabian–Nubian Shield, is predominantly juvenile Neoproterozoic crust that formed in and adjacent to the Mozambique Ocean (Abdelsalam and Stern, 1996; Berhe, 1990; Gass, 1981; Meert, 2003; Tadesse, 1996; Fritz et al., 2013). On the other hand to the southern continuation the EAO is comprised of high metamorphic grade, migmatites, para- and ortho-gneiss and schists together with folded calc-silicates, marble and lenses of granulite facies rocks (Kroner, 1985; Shacklaton, 1996; Stern, 1994, 2002). The juvenile ANS in the north which is dominated by low-grade volcano-sedimentary rocks in association with disconnected intrusives and ophiolitic remnants, and the tract of older remobilized crust Mozambique Belt (MB) to the south interleave widely within western Ethiopia, and hence makes the Precambrian geology of Ethiopia scientifically interesting to study the kinship between the two distinct, but geographically continuous belts in eastern Africa (Allen and Tadese, 2003; Berhe, 1990; Kazmin, 1979; Kusky, 2003; Stern, 1994). Abdelsalam and Stern (1996) stated the deformational belt or high strained zone within ANS were related to the structures of (1) sutures, arc-arc and arc-continent, and (2) post-accretionary structures, and linked the ophiolite in the ANS is related with arc-arc suture.

The microstructures which refers to grain shape, arrangement of grains, preferred orientation of grains, grain boundary configuration, and internal features of grains in the rocks (Hobbs et al, 1976) in the deformed area provides information regarding the environmental conditions of deformation and deformation history (Schmid 1982; Passchier and Trouw, 1995).

The Precambrian rocks of Ethiopia is situated at the critical location of the EAO, and contains a wide variety of metamorphosed degree from protolith of sedimentary, volcanic and intrusive rocks, with granitoids and gneisses predominate at south and western part and low grade metamorphic rocks at northern and western parts of Ethiopia (Kazmin et al., 1973, 1975, 1979; Ayalew and Peccerillo, 1998; Ayalew and Johnson, 2002).

The deformational sequences, the kinships of the lithotectonic units and their uplifting processes, sequence of deformation and with respect to metamorphism and the stratigraphic implications of the area was not well stated yet. Eventhougth, the area is of global scientific interest, the previous research works did not focus on detail of lithological and structural interconnections to reconstruct the deformational histories.

This article was conducted by using structural geology approaches to establish deformation sequences of the area. During different phases of field works conducted the investigations of lithological assemblage, structural features, deformation episodes, and appropriate oriented samples across the Tullu Dimtu Shear Zone are compiled in the form of maps, and representative figures.

II. GENERAL GEOLOGY OF THE AREA

The present investigations were incorporated the data of extensive field observations supported by petrographic analysis comprises the variably polydeformed and metamorphosed metavolcano-sedimentary, mafic-ultramafic, and granitoids units hosting mostly NE-,N-trending structural grains at west, central and east, respectively.

➢ *Migmatitic biotite-hornblende gneiss*

It is part of eastern high grade gneisses and migmatites exposed along Didesa River (Fig.2). It is characterized by coarse-grained, dark brown color and dull surface, composed mainly of brown and black amphibole minerals (hornblende) and thin lenses of quartzo-feldspathic layers. It is the segregate of mafic and felsic minerals which shows weekly foliated gneissosity. There is weekly foliated medium grain and dominated with pyroxene and plagioclase are observed as a relict in this unit (Fig. 3A).

The mineral assemblages of this rock was comprises biotite (10%), quartz (15%), plagioclase (20%), hornblende (30%), K-feldspar (5%), muscovite (10%) and Cordierite (5%). The mineral associations was indicates the rock is characterized by polydeformed nature of grains and dominantly striking N- and NNE- direction, and later deformation sinistral sense movements with striking NW direction of the main faulting. The pre-existing extensive shortening, and thrusting and folding was observed from the relict of weekly foliated very high grade ferromagnesian rocks, and the preserved axial surfaces and mineral stretching directions respectively. This outcrop were continuously exposed in the west of Didesa river along the road cut with variable concentration of major minerals such like hornblende, biotite, muscovite, cordierite, plagioclase, quartz and feldspar.

➢ *Hornblende-biotite gneiss*

It is exposed west of Suqii Waggaa granite in the eastern high grade gneisses and migmatite, and mostly composed of pale-white feldspar and quartz, together with dark minerals, of which the most abundant is the biotite with hornblende. The dark minerals are arranged in a streaky banding, giving the rock a gneissic texture. The thin lenses of light color quartzofeldspathic layers are folded with the main foliations and asymmatric folds with vertical hinge axis and axial plane. The folded fabrics are later affected by slightly east-west aligned ductile shearing, and structurally located at the top of the eastern amphibolite rocks at Aba Sena ridge and migmatitic biotite-hornblende gneiss along Didesa River at contact by huge magmatic emplacement of syn-sheared Suqi Waggaa granite.

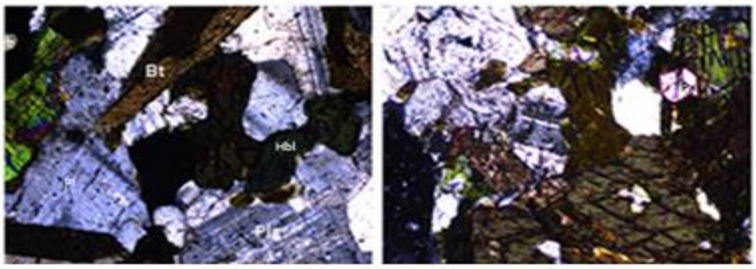

Fig 1:- Photomicrographs of Hornblende-biotite Gneiss at east of Gaba Sanbata locality. It is the mineral assemblage of biotite (Bt), hornblende (Hbl), plagioclase (plg) and Pyroxene (px). The folded hornblende grain in B manifests the dextral sense of movements.

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➢ *Microcline-hornblende-quartzofeldspathic Gneiss*

It is exposed to east of Melka hola hill, and west of slightly migmatized hornblende-biotite gneiss at quarries with light to dark brown color (Fig. 3E). It is coarse grain and shows segregated of mafic-felsic mineral compositions. It is composed of pyroxene, plagioclase, muscovite, biotite, microcline, quartz, and hornblende minerals. Microcline is colorless and has low relief in plane light, and well-developed cross-hatch twinning. Adjacent to this rock at west and southwest part there is undeformed and massive circular gabbro was exposed at high elevations. The rock is affected by four phases of deformations in which the third shear zone affects the first and second northeast aligned superposed fabrics, and the NW displaced materials shows the sinistral shear sense movements.

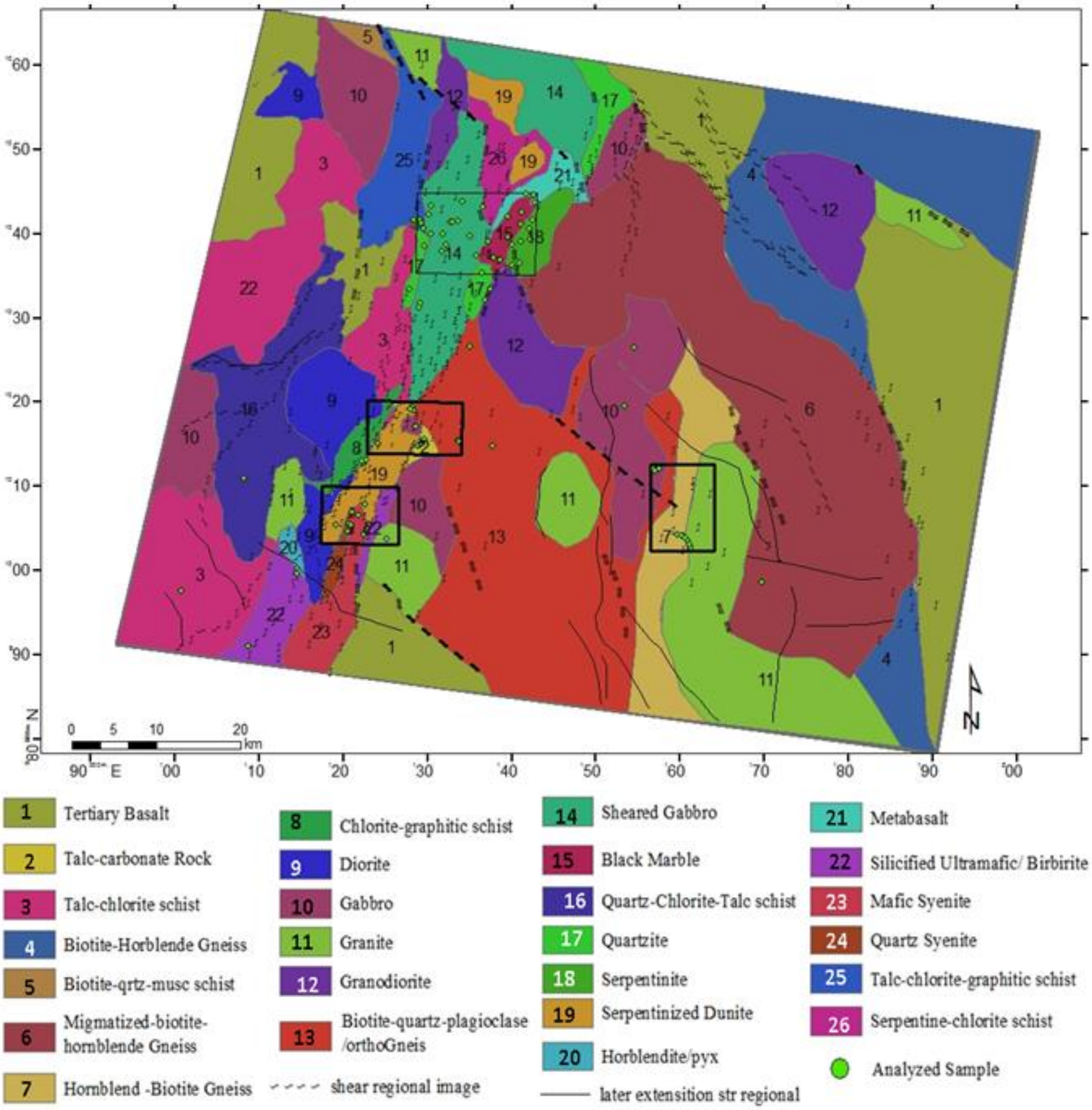


Fig 2:- Geological map of the total selected area. (Inlier rectangles are detail selected area).

➢ *Biotite-quartzofeldspathic Gneiss*

As traversing to the west of Gimbi town at Inango quarry (near Inango town) this units was structural overlain the other eastern high grades and at a contact with metamafic-ultramafic rocks of Dalati area. It is dominantly composed of biotite, epidote, pyroxene, quartz and k-feldspar minerals. It is dark and light gray color, characterized as mafic and felsic minerals respectively. The black mineral constituents are biotite, and pyroxene. It is medium to coarse grain and moderately banded dark and light minerals. This rock was moderately migmatized which shows partially melted and mixed with the host rocks. The Plagioclase and quartz were developed along the main foliation after pre-existing fabric of axial surfaces, and later retrograded to biotite with quartz and plagioclase. With continuous retrograde process/alteration both muscovite and epidote minerals was existed with biotite, plagioclase, and quartz. At the contact to the west talc carbonation rock and mafic-ultramafic rocks are extensively sheared during their exhumation processes. The Plagioclase and quartz were developed along the main foliation after pre-existing fabric, and later retrograded to biotite with quartz and plagioclase. With continuous retrograde process/alteration both muscovite and epidote minerals were existed with biotite, plagioclase, and quartz related to extensive shearing. The eastern high grade rocks with different concentrations of major minerals (pyroxene, hornblende, biotite, muscovite, and feldspars) are a shear contacts with the central greenschist facies of mafic-ultramafic rocks.

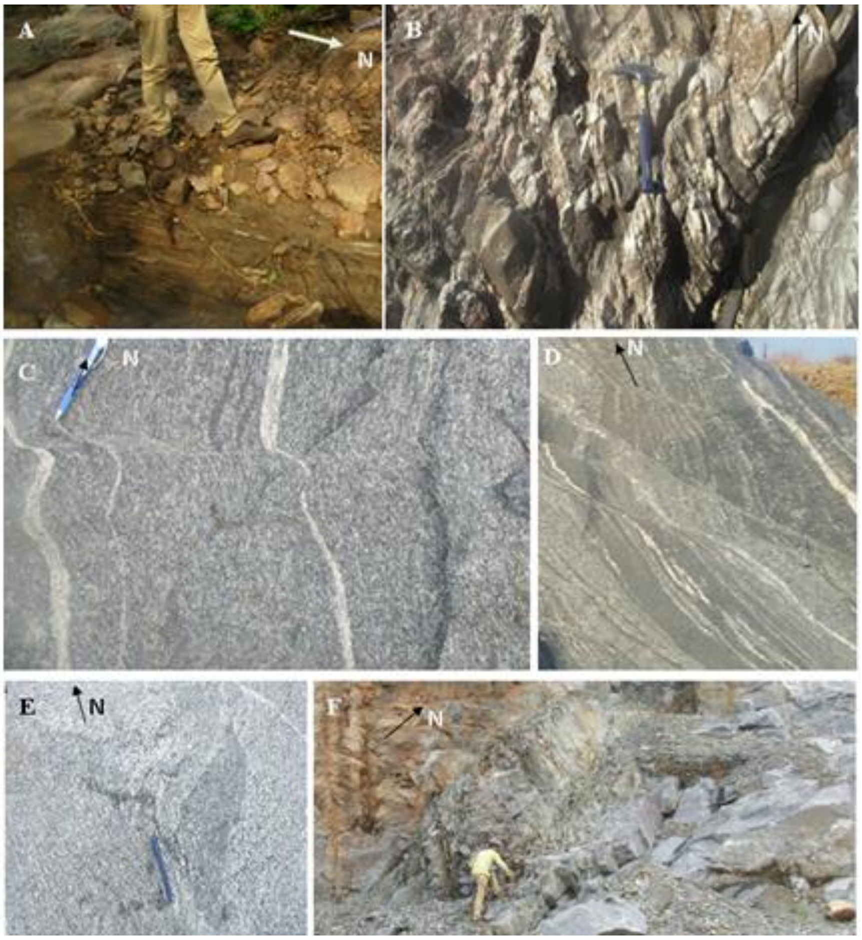


Fig 3:- The eastern high grade gneisses outcrop photos. (A) Represents the relict of weekly foliated pyroxene gneiss along the Didesa River. (B) High strained zone in migmatitic biotite-hornblende gneiss along Didesa River. (C and D) Hornblende-biotite gneiss with sheared quartzofeldspathic layers exposed at Gaba Sanbata locality. (E) The plagioclase and quartz rich light to dark brown color with rotated pre-existing relicts at Melka hola Quarry west of Gaba Sanbata displays hornblende-plagioclase-quartz gneiss. (F) hornblende-biotite-quartzofeldspathic gneiss at Inango quarry and near the contact with metamorphosed mafic-ultramafic rocks exposed to the west.

➢ *Serpentinite*

It is altered and metamorphosed ultramafic rock exposed at different localities of Dalati area (serpentinized Dunite) (Fig. 5) and along the hill side and quarry at Dimtu area (Serpentinite) (Fig. 8) north part. This outcrop comprises serpentine, magnetite, chromite, asbestos, and clinopyroxene (cpx) minerals. Serpentine is pale to dark color, greasy looking and slippery feeling textures. The heavy and black color of elongated and spot like grain is described as magnetite and pale surface of that chromite. Olivine is rarely observed as greenish color and fibrous textures and pale brown color grain is described as asbestos. All the grains were highly strained parallel to the regional shear zone. The thin-sections of Dalati serpentinized dunite consists major concentrations of serpentine and magnesite. The microphotograph of the Dimtu outcrop is comprises different stages of mineral assemblages corresponding to involved deformations. It comprises mineral assemblages of serpentine (55%), magnetite (10%), cpx (5%), actinolite (15%) and magnesite (10%). It is bounded by black marble to the west, talc schist/soap stone to the opposite direction and metabasalt to the north. This unit forms cliff with vertical and sub-vertical dipping to east at the slope along the road and quarries. It is affected by N-S shearing and folding deformation and NNE aligned shortening and extensional shearing were the asymmetric augen structures, broken and displaced pebbles and grains shows dominantly dextral sense of movements.

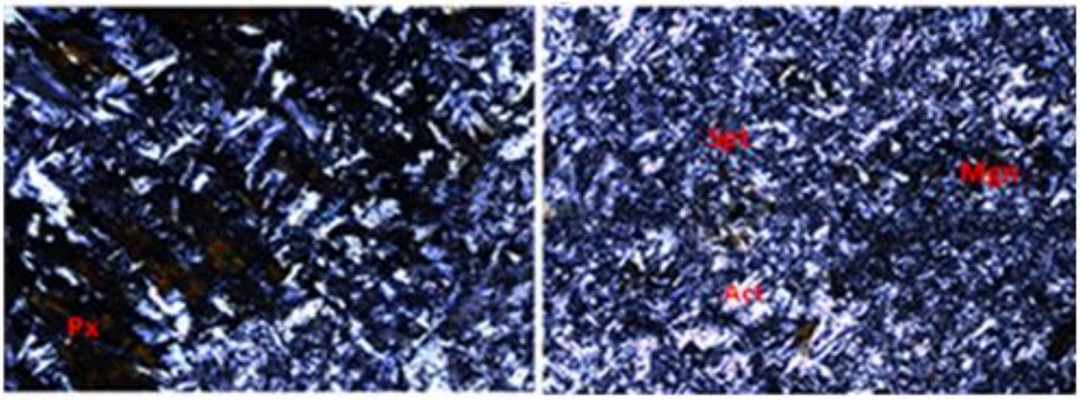
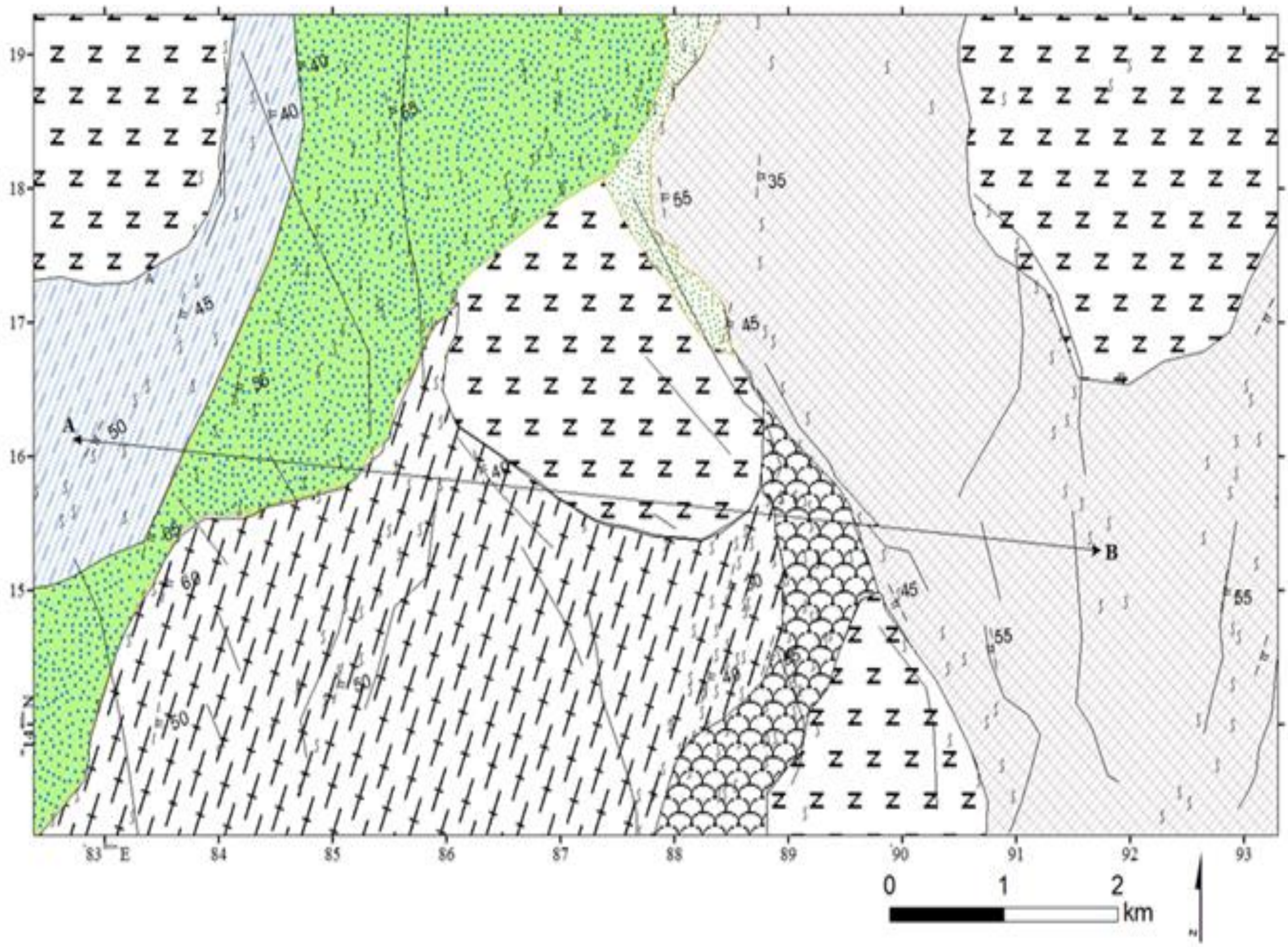


Fig 4:- Photomicrographs of Serpentinite from Dimtu quarry to the north part. It consists serpentine (Spt), pyroxene (Px), actinolite (Act) and magnesite (Mgn).

- *Talc-Carbonate Rock*

It is exposed at the bottom of Serpentinite of Dimtu hill towards southeast part to the north and at the contact of serpentinized dunite of Dalati area and biotite-quartzofeldspathic gneiss of Inango quarry (Fig. 5). It is characterized with soapy surface and slightly foliated texture. Its color is pale brown to dark greenish and comprises mineral contents of talc, epidote, magnetite. This outcrop aligned along the major extensive shearing striking N-S direction.



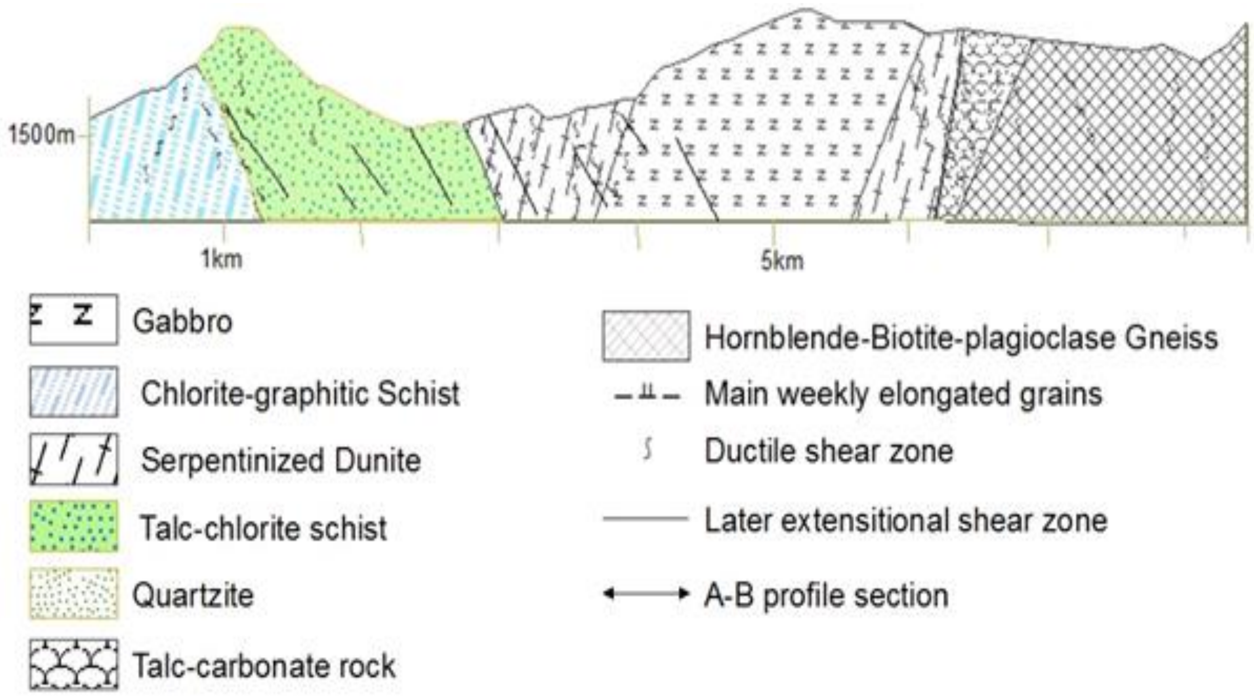


Fig 5:- Geological Map of Dalati area.

➢ *Sheared Gabbro*

This outcrop widely exposed at northwest of kidano king quartzite, and weekly foliated and sheared of medium to coarse grain mineral alignments. It is black and dark green color with folded of sub-vertically NNW plunging fold axis and transposed foliation or mineral alignments (hornblende, plagioclase, chlorite, and muscovite) are observed. As it is exposed along the high strained zone the shear stress was promotes the elongated grains and rotations, which supports the idea of syn-sheared metamorphism rather than significant directed pressure. The sheared gabbros at different localities are characterized with variable degree of metamorphism from the concentrations of minerals. It comprises mineral assemblages of plagioclase, hornblende, quartz, chlorite, muscovite and ilmenite.

➢ *Quartzite*

It is exposed at different localities in the area and elongated grains of quartzite rock were exposed narrowly in between hornblende-biotite-quartzofeldspathic gneiss and metamafic rocks exposed at the northwest part of Dalati quarry (Fig. 5). It is pink and gray color composed of interlocked quartz crystal. Mostly fresh, interlocked elongated grain and with developed granoblastic texture of quartzite also exposed at kidano king area (Fig. 8), south and southwest of Dimtu hill with the sheared contacts adjacent to gabbro and talc-chlorite schist.

The oriented sample is collected parallel to the main fabric aligned NNW direction and it shows rotated and sutured grain of quartz. This deformed quartzite in which elongated quartz crystals along the extensive shearing, and recrystallization and the broad and rounded suturing due to compression and shearing.

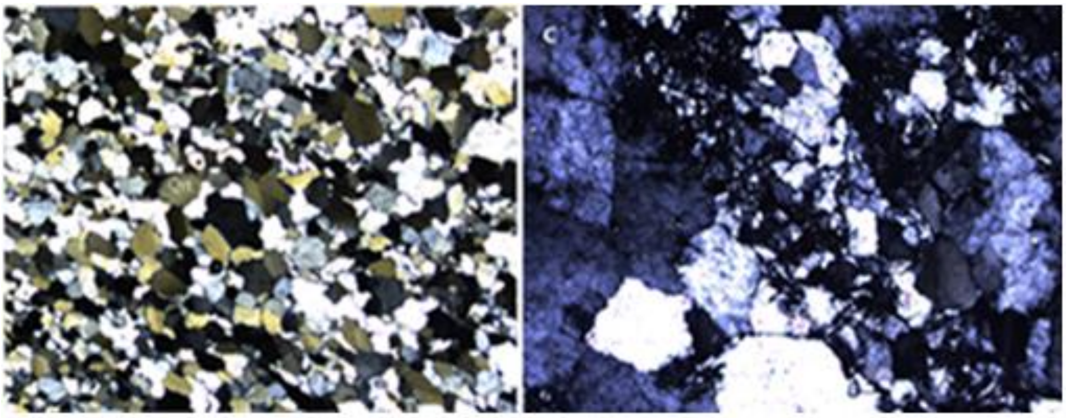


Fig 6:- Photomicrographs of Quartzite. (A & B) from western contact north of Bila, and (C & D) were sampled from Kidanoking hill. Interlocked grains manifests grain boundary migration.

➢ *Marble*

Marble exposed at western slope of Dimtu area adjacent to Serpentinite unit is dark gray color and slightly krastified (Fig. 8 and Fig. 10D). It consists of long and gradual contacts with talc-chlorite schist to the west, north and southwest parts and with Serpentinite unit towards east and southeast part. Petrographically comprises calcite, dolomite tremolite and other impurities.

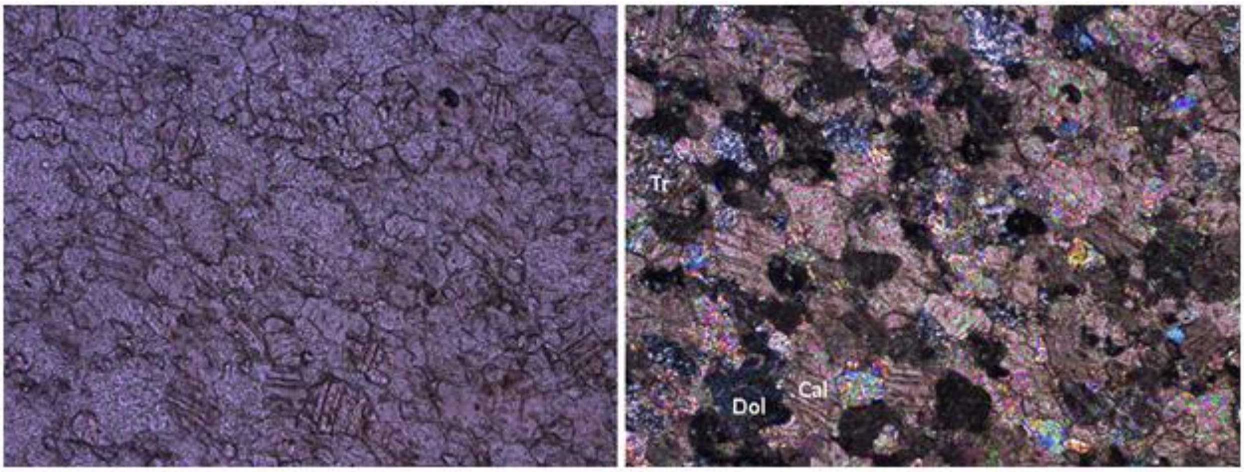
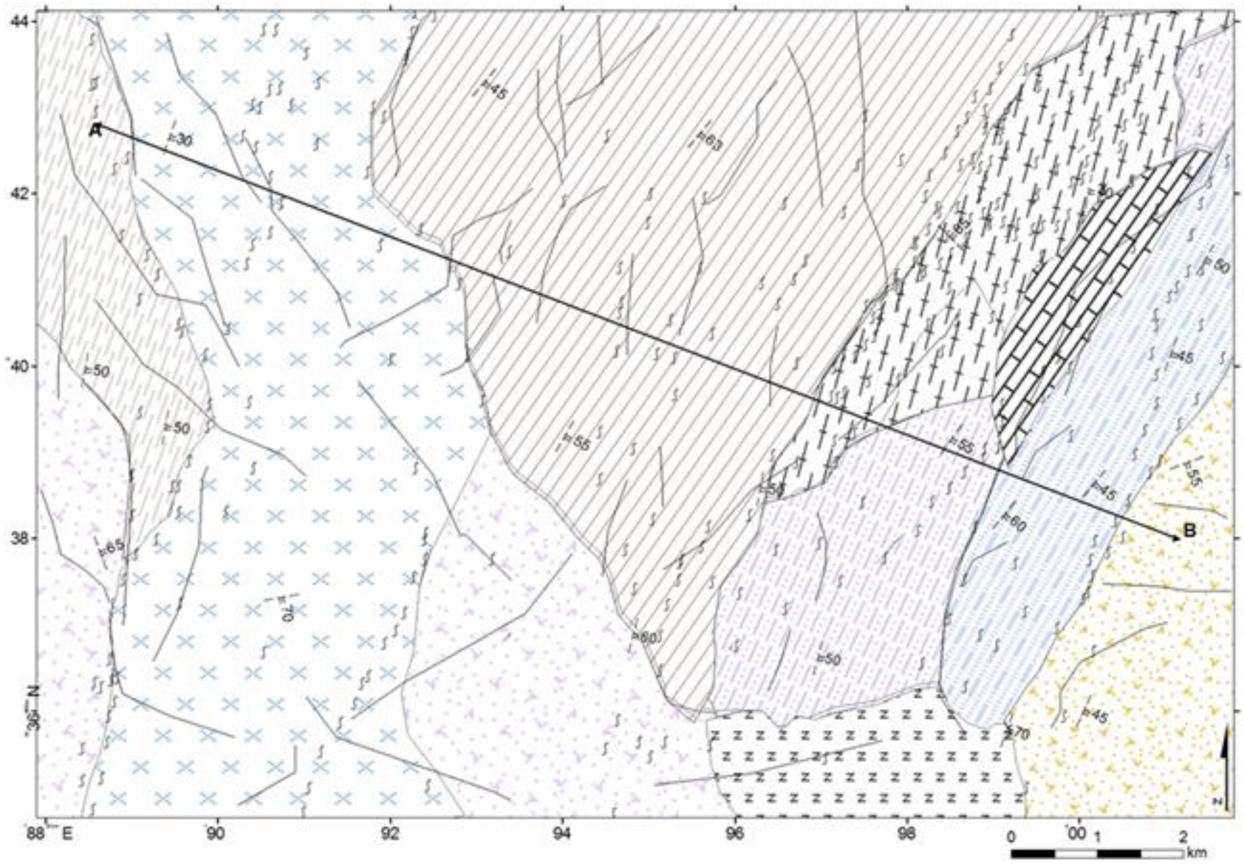


Fig 7:- Photomicrographs of black marble. It is made of calcite (Cal), dolomite (Dol) and tremolite (Tr) mineral assemblage. The twin lamellae in calcite are parallel to the long diagonal and in dolomite it is parallel to the short diagonal.



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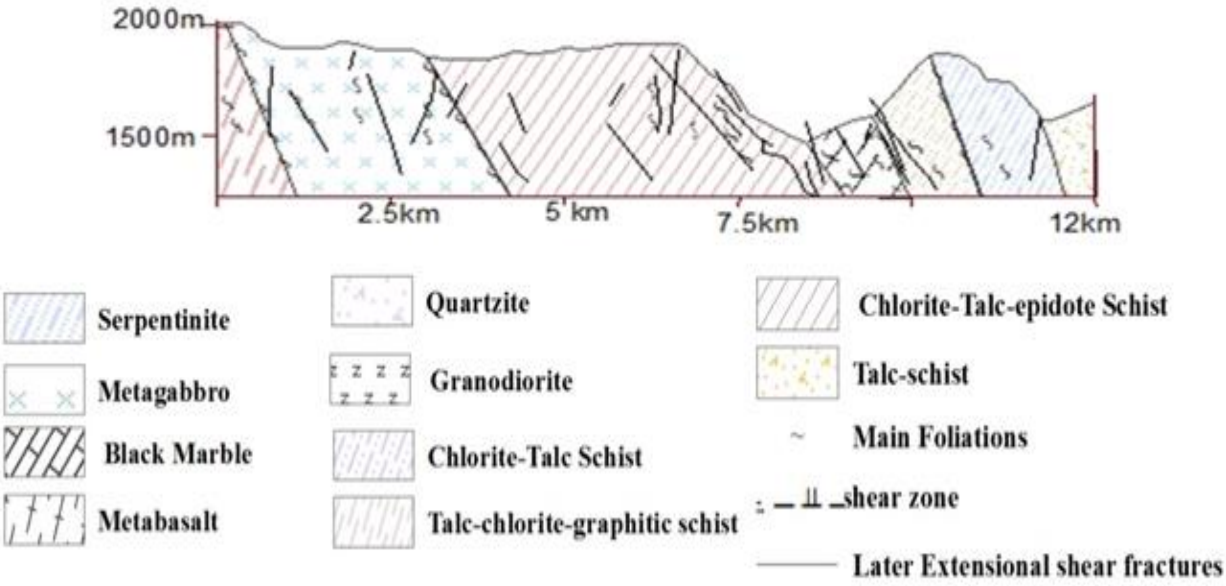

Fig 8:- Geological map of Dimtu/Horfa area.

➢ *Metabasalt*

Petrographically, it comprises pyroxene, epidote, actinolite and with opaque mineral of magnetite. This unit is black to dark brown color and shows closely spaced displaced fabrics which is supports the rock is foliated parallel to the extensive shearing. It is slightly foliated fine to medium grain size exposed along Horfa River striking northeast to SW towards north and northwest of Dimtu Serpentinite quarry (Fig. 8). Later it is deformed by brittle deformation striking northwest to southeast and northeast-dipping directions, continuously sub-vertical fractures filled by displaced light color of felsic grains. It is at a contact with quartzite to the northeast and north parts; talc-chlorite schist to the west, and talc schists to the east and southeast parts. Metabasalt of this area was intruded by narrow veins which is deformed and manifests different deformation phases from its crosscutting relationships.

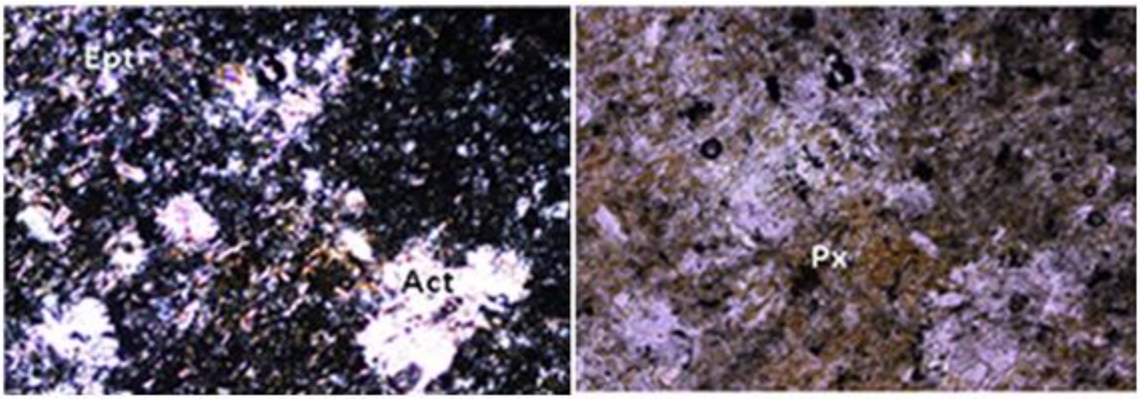

Fig 9:- Photomicrographs of metabasalt exposed along Horfa River. Fine grained mineral assemblages of pyroxene (Px), epidote (Ept), actinolite (Act) and with opaque magnetite (Mgt).

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Fig 10:- Field outcrops of the metamorphosed mafic-ultramafic rocks. (A) Sheared gabbro at west of Dimtu hill. (B) Quartzite at kidanoking hill. (C) Metabasalt along Horfa River. (D) Gray marble at the contact with serpentinite of Dimtu hill. (E) Serpentinite at Dimtu hill. (F) silicified ultramafic/birbirite rock at east of Tullu Kappi. (G) serpentinized Dunite exposed at Dalati. All these outcrops are partiall exposed in the mapped area.

➢ *Chlorite-Talc Schist*

It is exposed to west of the Dimtu outcrops were exposed along the River and Hill side, and strongly develop schistosity aligned to NE direction (Fig. 8). It composed of chlorite, talc and muscovite minerals. This outcrop is intruded with folded and sheared quartz vein along the main foliation and indicates sinistral sense of movements (verging to NW). Also after NW aligned shearing the outcrop were affected by E-W aligned fault zone.

This unit was exposed at the foothill of Dimtu Hill which is outcrop of Serpentinite and at the contact with others such like marble, metabasalt, talc-schist sheared gabbro and quartzite. Most of the contact was labeled as shear zone and randomly thrusting of different a mafic-ultramafic units which manifests the ophiolitic assemblages. To the south dark greenish to brown color soapy surface foliated schist intruded with quartz vein along the main foliations exposed at east of Tullu Kappi site.

➢ *Magnetite-Chlorite Carbonate Schist*

This unit was exposed at the west of the silicified ultramafic rocks and with talc-chlorite schist having sheared contacts. It is composed of chlorite, talc, and opaque mineral of magnetite and other carbonate minerals. It is dark greenish to brown green color and north-south striking and easterly dipping foliation.

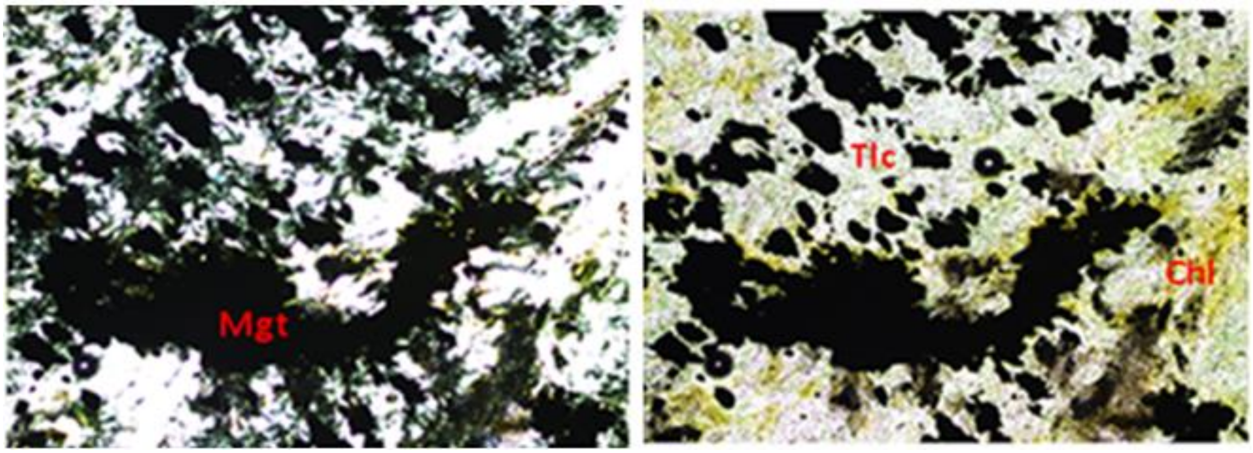


Fig 11:- Photomicrographs of magnetite-chlorite-carbonate schist found at the bottom of silicified ultramafic rocks east of Tullu Kappi. This microphotograph shows the mineral assemblages of talc (Tlc), chlorite (Chl), and intergrowth with opaque magnetite (Mgt).

➢ *Silicified Ultramafic Rocks*

It is exposed to the south of the area (Fig. 13) manifests shearing structures at the contact with magnetite-chlorite carbonate Schist to the west and Ganji granite to the east. The exposed unit is light gray to pinkish color with recrystallized quartz vein, sillimanite and garnet. The secondary silicified gray quartz grains were appears due to hydrothermal mineralization.

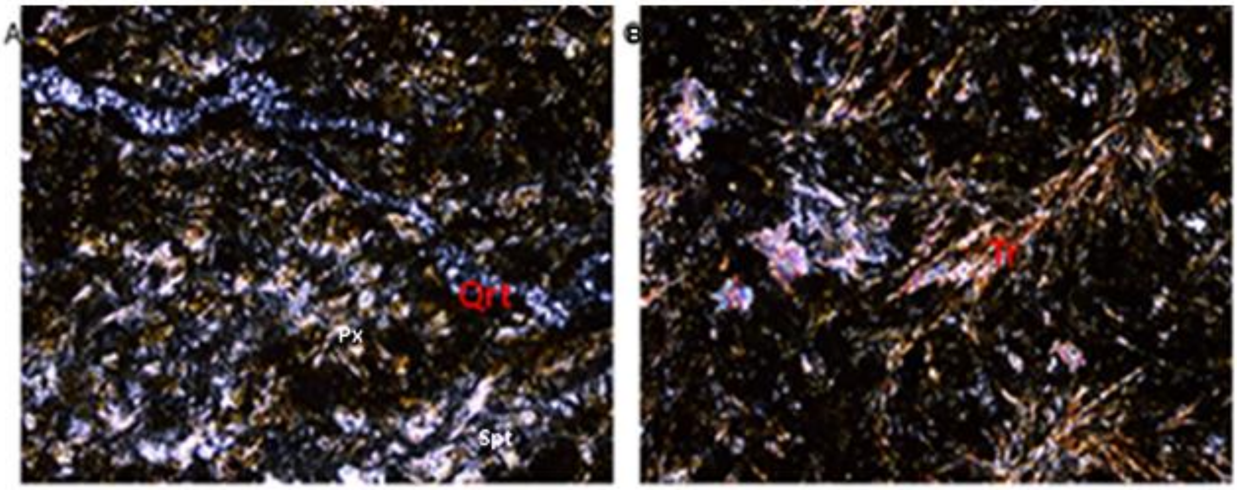
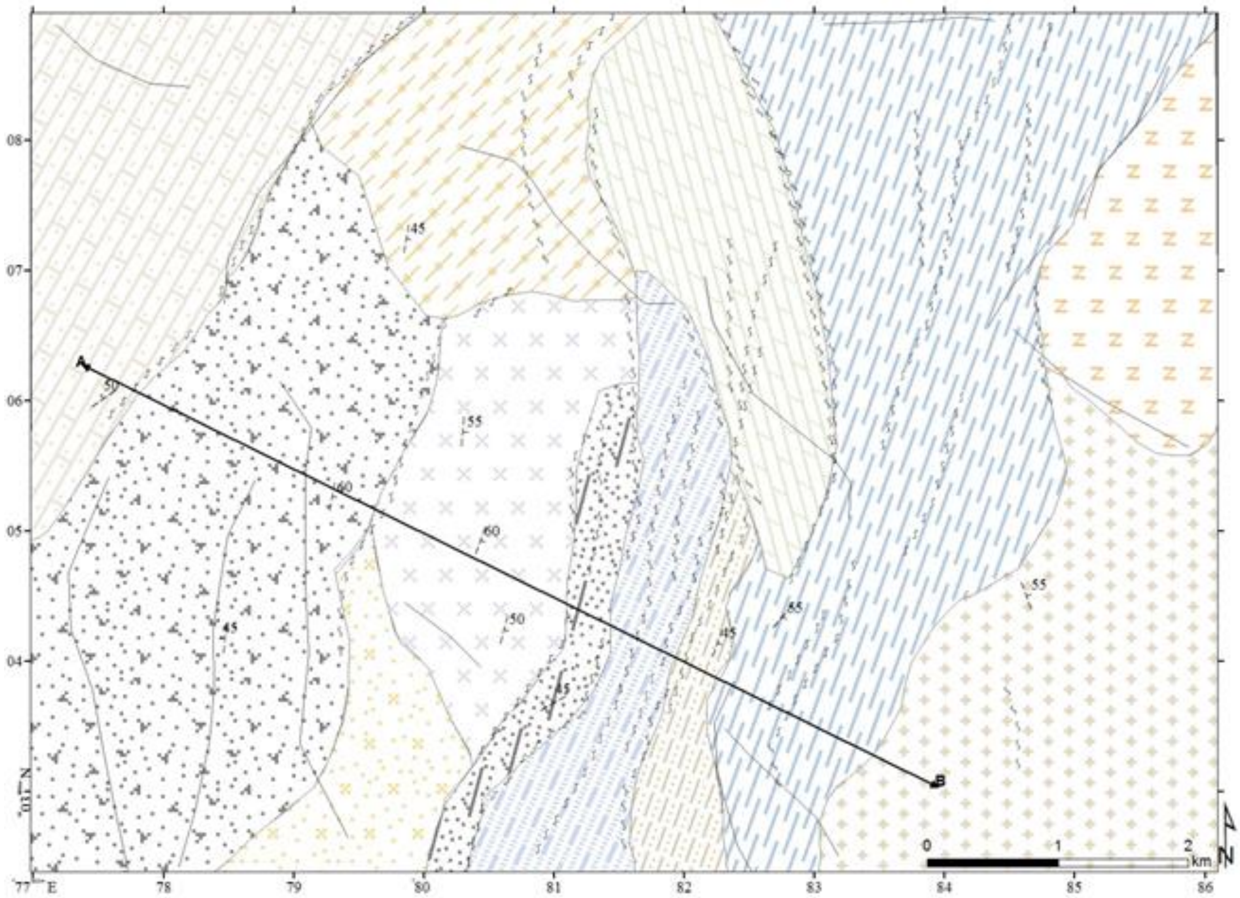


Fig 12:- Photomicrographs of silicified ultramafic rocks from eastern Tullu Kappi. It comprises recrystallized quartz (Qrt), altered pyroxene (Px), radiated patterns of tremolite (Tr) and with magnesite (Mgn).

➢ *Graphitic-Chlorite-Talc-Schist*

This unit was exposed to the central and north part of the area, to the west and northwest of metabasalt exposed along Horfa River. Its outcrop color is pale greenish to yellowish green with fresh color and gray to yellow of weathered color. It consists fine grain size and foliated texture, and mineral constents of talc, chlorite, epidote, serpentine, and other black opaque minerals.



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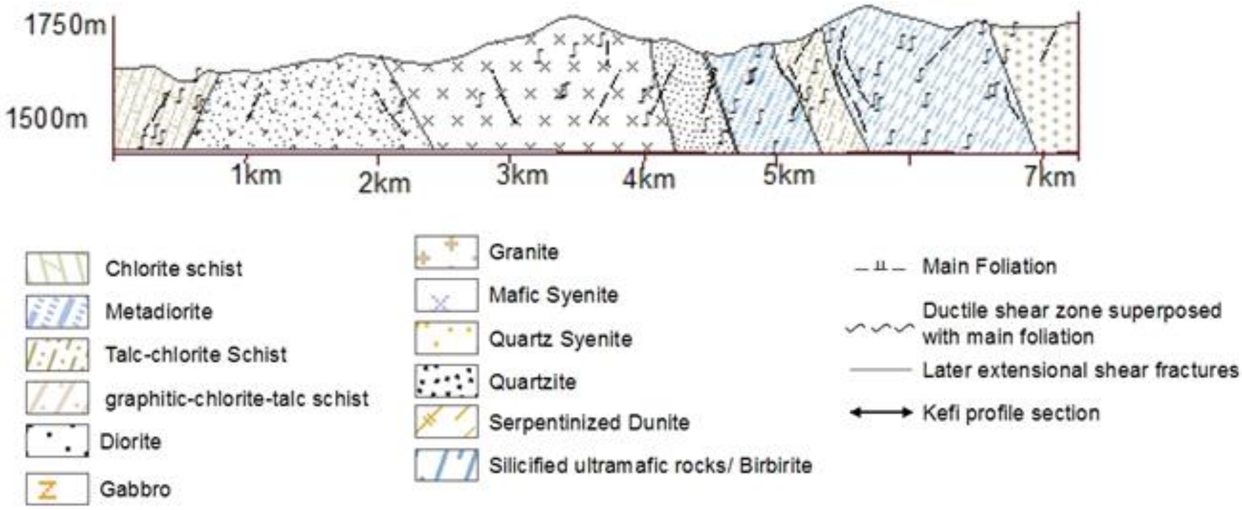

Fig 13:- Geological map of Tullu Kappi area.

➢ *Quartz-Chlorite-Graphitic-Talc Schist*

This lithotype of low grade metavolcanosedimentary rocks exposed to the west of the current study area and it comprises the lithological assemblages of quartz-chlorite-graphitic-talc schist, talc-chlorite schist, and chlorite-talc schist named based on their mineral dominance.

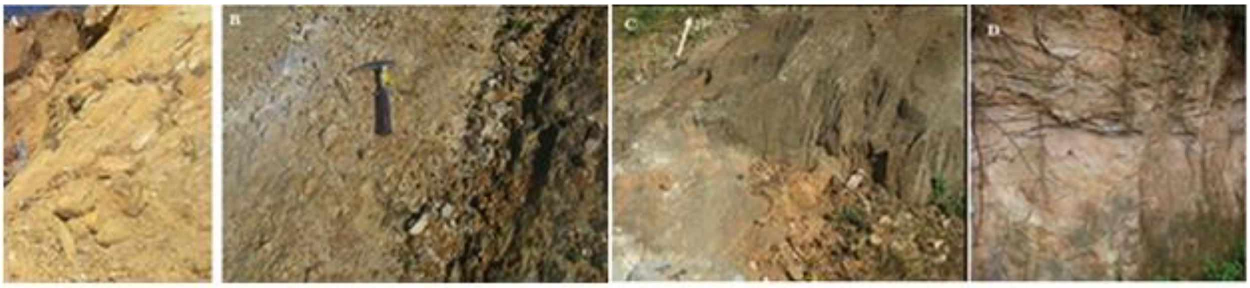

Fig 14:- These outcrop photo were taken from the third domain of low grade metavolcano-sedimentary rocks to the west. (A) Talc-chlorite schist. (B and C) Quartz-chlorite-graphitic-talc Schist. (D) Chlorite-Talc schist.

This outcrop is NNE-SSW striking and easterly dipping foliated dark brown color exposed western margin of the selected area. It is fine grained and deeply altered foliation that affected by later northwest verging tectonic transports. It composed of epidote, chlorite, graphite and talc at the field observations and they differently named based on the dominance of each minerals. This unit was bounded by serpentinized dunite to the east and graphite schist to the west, with diorite intrusions to the northwest.

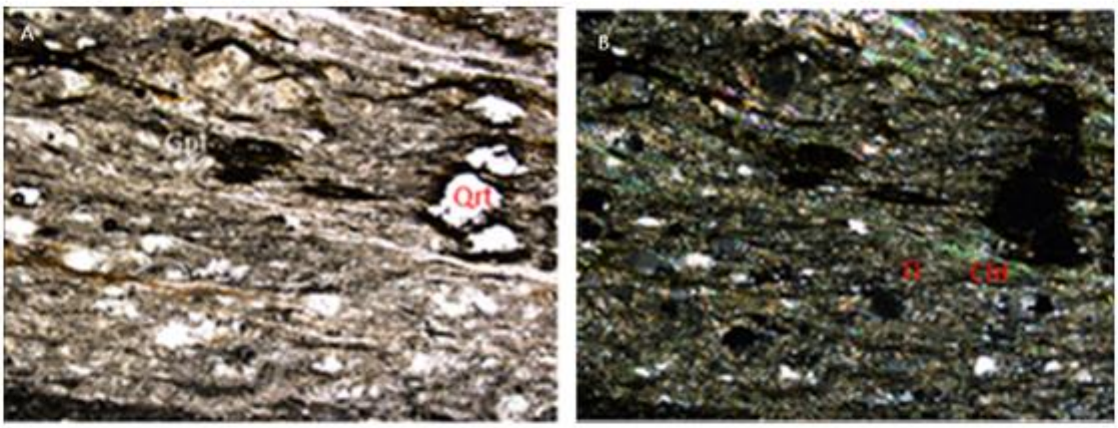

Fig 15:- Photomicrographs of chlorite- graphitic-talc schist exposed at west of Dalati. Syn-sheared garnet (Grt) with rotated quartz (Qrt) porphyroblasts along the extensive shearing (D3) with the assemblages of talc (Tlc), graphite (Gpt), chlorite (Chl), feldspar and Qrt. The pressure solutions, rotated grains and S-C fabric developed during extensive shearing shows top-to-right sense of tectonic transports.

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➢ *Talc schist*

It is exposed at the bottom of Serpentinite of Dimtu hill towards southeast part and it is characterized with soapy surface and slightly foliated texture. Its color is pale brown to dark greenish and comprises mineral contents of talc, epidote, magnetite. This unit was similarly deformed with adjacent rocks with exposed extensive shearing and later strike slip fault with N-S and NW-SE direction, respectively.

➢ *Plutonic Rocks*

The plutonic rocks (granite, granodiorite, syenite and gabbro) exposed within each major Neoproterozoic rocks are manifests different signature of deformation sequences. The textural variations from central to the eastern margin of this plutonic rock were closely very coarse grains with different among each grain. The observed fabrics in the most of deformed plutonic rocks are similar with that of extensive shearing stated as third phase of deformation.

➢ *Granite*

It is medium to coarse grain, light to pinkish brown color, composed of K-feldspar, quartz, plagioclase, fine biotite at different localities and phases of magmatism. It exposed at different localities such like: Suqii Waggaa, Ujuka Katta, Guliso-Kurfessa, Ganji, Homa, and other with different compositions and phases of tectonic activities. At these localities it forms elevated topography which followed by folding and fracturing at the hinge zone and mostly interpreted previously as within plate granitoid setting. The surrounding rocks of these intrusions seems like vertical to sub-vertical inclinations with opposite directions in both sides and exposure continuity observed parallel to the axial surface of regional deformation. This outcrop was very coarse grain to the eastern margin and becomes medium to fine grain near the stated ophiolitic assemblages.

As observed along Didesa River and Suqi Waggaa granite outcrop there is very coarse grain pegmatitic granite with light to pink color, composed of feldspars, quartz, muscovite and biotite within high grade gneiss and granitic intrusions. This intrusion mostly aligned with the main foliations of the host rock.

Fig 16:- Field outcrop of (A) pegmatitic granite at Gaba sanbata. (B) granodiorite at Dongoro. (C) Granite at Ganji. (D) Gabbro at north of Dalati. (E) Mafic Syenite at Tullu Kappi. (F) Quartz Syenite at south of Tullu Kappi.

➢ *Granodiorite*

It is medium to coarse grain size, black to brown color, composed of more plagioclase, biotite and quartz, hornblende and biotite exposed at Dongoro Katta and to the south at Tullu Kappi localities. This outcrop was vertically exposed along the main shear zone affected by shallow weathering and by the latter NW- trending semibrittle deformation.

➢ *Gabbro*

Medium to coarse grain, dark to greenish color, contains pyroxene, plagioclase, hornblende and olivine exposed at different localities of the area. In the most part of the area there are two phases of gabbro exposed as sheared and free of deformation, with the dominance of hornblende at mafic-ultramafic outcrops, and olivine at eastern high grade gneisses. The circular and coarse grain gabbro of olivine rich within eastern high grade gneisses are massive, and variably metamorphosed sheared gabbro manifests two events of magmatism during shearing and after.

- *Syenite*

It is a coarse-grained plutonic rock which is composed mainly of alkali feldspar and various ferromagnesian minerals. Compositionally variable types of syenite where identified towards the south and south west of the area as mafic syenite, quartz syenite, and altered and sheared albitized syenite rocks. Typically dark light colored of mafic minerals with pink orthoclase being the most obvious mineral. In the south of Tullu Kappi after mafic syenite were identified as quartz syenite with considering previous findings and the quartz content is high as compared to mafic syenite (Fig. 13). The mafic mineral dominantly amphibole is slightly elongated parallel to the main trend of NNE-SSW shear zone. It is deformed by the later brittle shearing striking northwest to southeast.

III. STRUCTURAL EVOLUTIONS AND DEFORMATION EPISODES

The lithostratigraphic units of Tullu Dimtu Neoproterozoic Precambrian rocks are affected by four deformation events. The deformation and structural features was recognized by considering the geometric distributions of main foliations and lineations, overprinting and cross-cutting kinships between each fabric, folding of planar and linear structures that have been produced by earlier deformation, superposition of later fabrics on earlier fabrics (cleavages or schistosity or gneissosity), vergence and overall physiography of the area. In case of this article the area was deformed by four phases of deformations in which the first two events are recognized from the preserved lenses of mafic rock, northwest verging of thrusting and folding, identified at field and petrographic analysis, although deformed by the latest extensive shearing and magmatism. These lithostructural associations are provided new evidences for reconstructed deformation sequences, sense and direction of movements, exhumation mechanisms, and metamorphisms along each deformation event. The litho-structural position, preferred grain orientations and their contact nature, grain shape and arrangements, pressure solutions, and asymmetric folds observed in outcrops and thin-sections shows the area were variably polydeformed and metamorphosed across the Tullu Dimtu shear zone. The interconnections and cross-cutting relationships of slightly foliated gneissosity, fold axial surfaces, ductile shear zones, and strike-slip faults manifests four phases of deformations in the area.

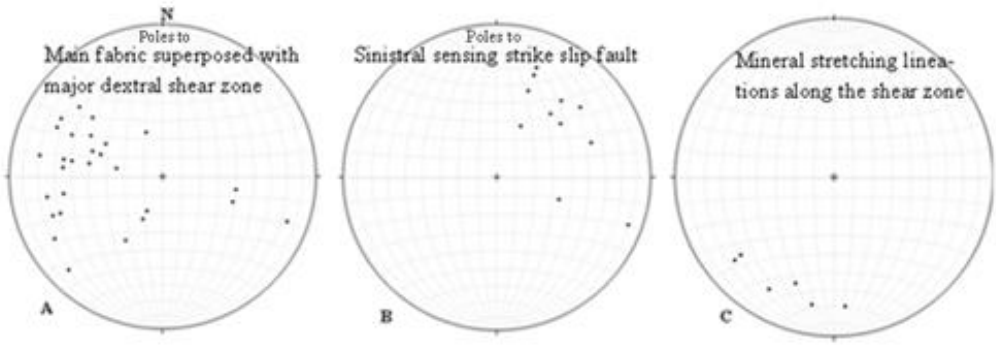

Fig 17:- A. Main fabrics along the extensive ductile shearing. B. the later semibrittle faulting NW- striking and slightly SW-dipping direction. C. Major SW-plunging mineral stretching and elongation lineations along the shear zone.

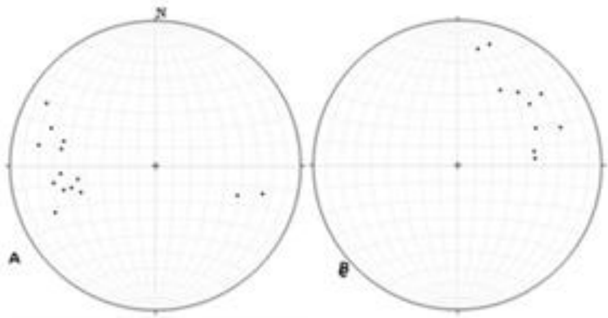

Fig 18:- **A**. SE-dipping shear zone and moderately foliated schistosity. B. NW-striking main faults at the Dimtu polydeformed mafic-ultramafic rocks.

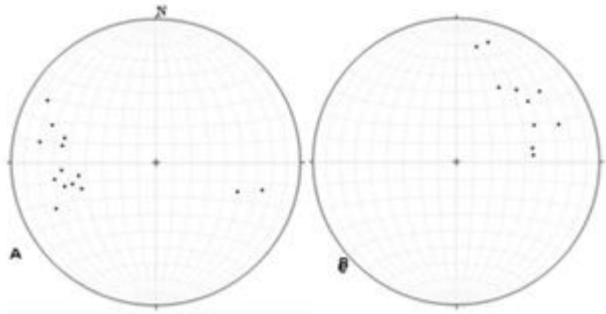

Fig 19:- Lower hemisphere equal area stereonet plot of A. N-, and NNE- oriented elongated grains along the sheared axial surface, and B. later the brittle deformation NW-striking main fault at Tullu Kappi localities.

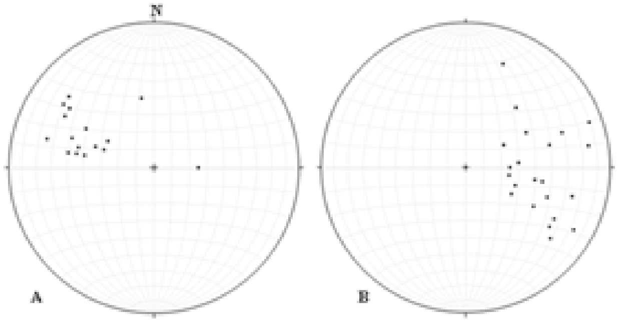

Fig 20:- A. NNE- and N-striking and SE-dipping shear zone structures and elongated grains. B. W-dipping and N- and NW-striking strike-slip fault collected from Dalati outcrops.

- *The First Phase of Deformation*

The evidence for this event was observed along the Didesa River preserved within migmatized biotite-hornblende gneiss as thin lenses of dominated dark minerals (pyroxene) and segregated plagioclase within the relict of granulite facies (Fig. 23A). It is dominantly aligned to N-S directions probably affected by NW-SE directed field of stress. Both mafic and felsic minerals was elongated perpendicular to the field of stress early to migmatization which affects the whole part of eastern high grade gneisses. The current field observation tell us there is pre-existed deformation episode reasonable for the preserved gneissosity mostly transposed with the migmatized and achieved greater grade of metamorphism.

- *The Second Phase of Deformation*

It is extensive shortening promotes folding and thrusting striking north-south to NNE direction (Fig. 19A) and becomes steep axial surface as traversing from east to west. As compared to the field situations in case of grade of metamorphisms most of the migmatized gneisses are structurally at the bottom and manifests the thickened continents from thrusting and later upright folding (Fig. 22 and Fig. 24). The degree of metamorphisms was varies from the bottom structures that of relict fabrics and those observed after the second phase of deformation which promotes the thickened continents. Near the emplaced granitoids mostly the structures are closely steeped. There is extensive shearing that affects the pre-existed lithostratigraphic units with increasing degree of deformation from eastern margin to the west ward. Most of the intruded veins including pegmatitic granite and quartz vein are preserves the shearing fabric and exposed along the axial surface of this phase of deformation. Most of the thrusting and folding manifestation of this phase of deformation was affected by extensive shearing of the dextral sense of movements. The ascending of metamorphic grade from top structural level to bottom structural level and huge emplacement of magmatism was observed as the result of crustal thickening by progressive thrusting and folding of this event from field and petrographic studies.

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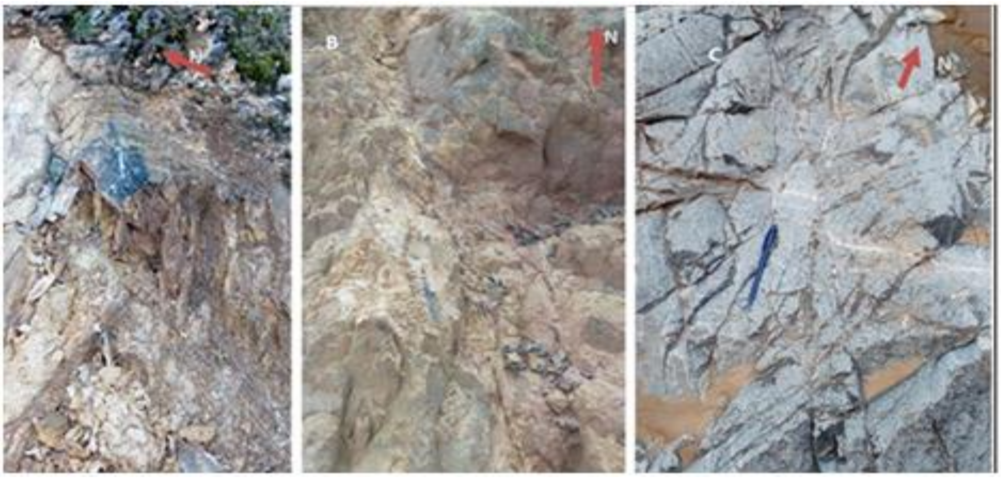

Fig 21:- (A and B) NNE striking and SE dipping axial surface of folded layer and later sheared of exposed talc-chlorite schist. (C) deformed metabasalt along Horfa River.

➢ *The Third Phase of Deformation*

This event was characterized by closely spaced elongated grains and stretched minerals, displaced axial plane, pressure solutions, and asymmetric folds identified from field and thin-section analysis with vertical to steeply east-dipping axial surfaces. It is extensive shearing striking N-S, NNW- and NNE-trending sub-vertically to east dipping high strain fabrics. This event was recognized from S-C fabrics, rotated porphyroblastic grains, asymmetric folds and dominantly shows dextral sense of movements and sinistral local movements. This phase of deformation was mostly a major way of N-S stretching and thinning of the crust and causes the uplifted basement rocks in the area. There are high strained zone with steep angle formed at this phase of progressive deformation which forms extensive shearing and forms Tullu Dimtu Shear Zone. Most of the folds are asymmetric folds and northeast tectonic movements. This subsequent deformation was mostly similar with the axial surface of the pre-existing steep folding.

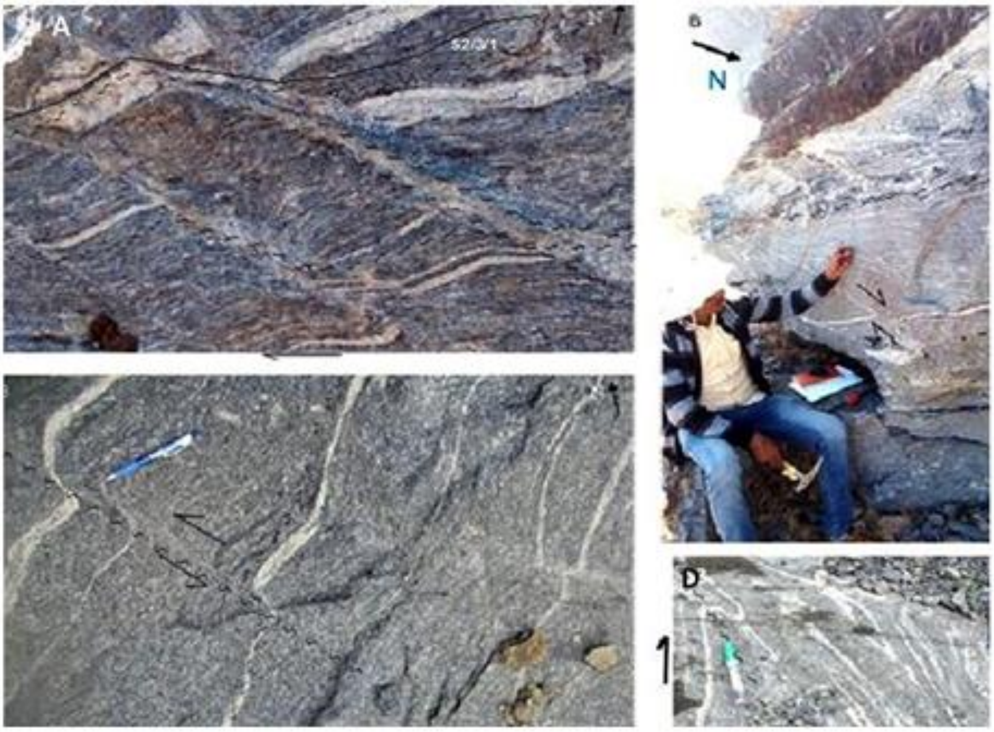

Fig 22:- (A) Top- to- right shearing deformations events (D3). (B and C) semibrittle shearing (D4). (D) asymmetric folds along the extensive shearing manifests dextral sense of movements in migmatitic-hornblende-biotite gneiss, at Kabbaa Quarry east of Gimbi, Gaba Sanbata locality.

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➢ *The Fourth Phase of Deformation*

The steep foliations, sub-horizontal lineations and steeply plunging asymmetric folds were characterizes the strike-slip faulting (D4) with sinistral sense of movements. This deformation was recognized from NW-SE striking strike-slip fault (Fig. 22 and Fig. 23) and developed riddle shear structures identified at Didesa River, deformed Suqii waggaa granite and Kabba quarry, and within hornblende-biotite-quartzo-feldspathic gneisses at Inango quarry site. The deformed intrusive rocks (Suqi Waggaa granite and Ganji granite preserved third phase deformation fabric (shear structures) and others like Ujuka granite and massive gabbro at dongoro Katta and melka hola manifests only brittle fractures.

IV. DISCUSSIONS

The systematic field observations and petrographic analysis data were supports the lithological and structural interconnections for the deformation history of the Neoproterozoic Metamorphic Rocks of Tullu Dimtu area. This article was investigated lithological variations, structural features and four deformational events to understand the degree of deformations. The weekly foliated fabric along Didesa River was displaced by the effect of E-W extensive shortening that represents the first deformation episode.

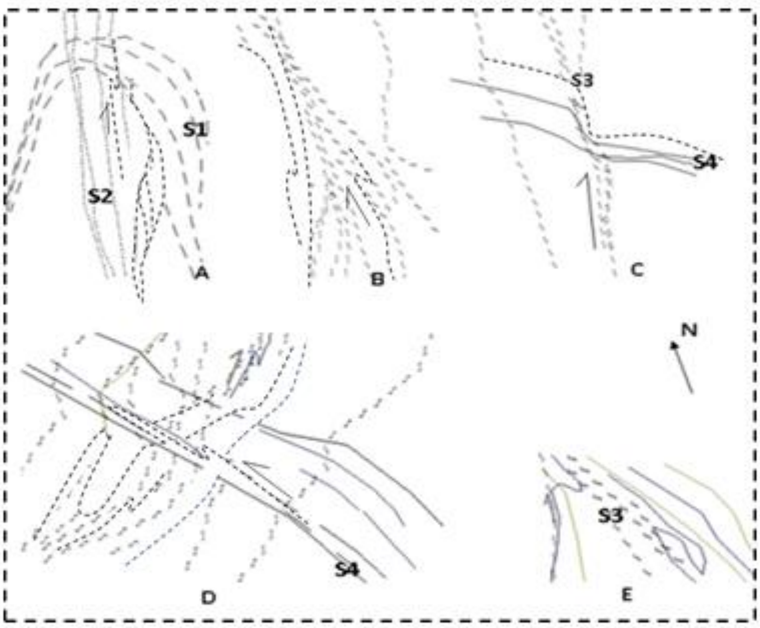

Fig 23:- (A) steeply east dipping axial surface during pre-existing folded surface and relict of weekly foliated granulite fabric. (B, C and E) extensive shearing transposed with pre-existing axial surfaces. (C and D) semibrittle shearing/strike slip fault observed at Gaba Sanbata, Dimtu and Dalati localities.

To the east the high grade granulite facies was preserved at bottom structural level along the Didesa River within the migmatized biotite-hornblende gneiss. The grade of metamorphism was identified as ascending from the bottom to top structural level to the west and becomes steep sheared axial surface along the numerous plutonic emplacement observed and variably sheared. Followed extensive shortening the SE- plunging mineral stretching and sub-vertically E-dipping axial surface shows the crustal thickening happed due to thrusting and folding. The different shear indicators observed at field and thin section were manifests extensive shearing striking NNW-, N- and NNE- directions and dextral sense of movements with minor sinistral sense of movements along which the orientations of mineral stretching and elongated grains, steeply plunging asymmetric folds, quartz veins and gently E-dipping foliations are governed. During the current investigations the eastern migmatized high grade gneisses are correlated with the southern continuation of EAO that is MB, and to the west there is low grade metavolcano-sedimentary rocks and variably altered mafic-ultramafic rocks as correlated with the ANS of northern continuation. At the shear contact with hornblende-biotite-quartzofeldspathic gneiss northwest of Dalati quarry the k-feldspar was altered to sericite/fine muscovite and epidote, and it is altered to mica schist possibly where hydration available at low to moderate temperatures. In this area along the quartz grain boundaries the mica grains are parallel and show a foliation along elongated quartz. The metamorphism accompanied by hydration during uplifting converts feldspar to sericite or muscovite at low to medium grades. The dominated alterations along the high-strained zone of sheared mafic-ultramafic rocks are serpentinization, chloritization, epidotization, silicification and etc. the development of serpentine, chlorite and epidote minerals were demonstrates the greenschist facies are achieved for the metamorphosed or altered mafic-ultramafic rocks and low grade metavolcano sedimentary rocks to the west. Stratigraphically, the grade of metamorphisms was characterized by preserved of relict granulite facies at structural bottom with migmatized biotite-hornblende gneiss of amphibolite facies, as traversed structural top to the west the dominated hornblende is replaced by biotite in the case of eastern high grade gneisses. Further to the west the alterations happened by extensive ductile shearing to the later brittle structures. The compositional banding of different fabrics, crenulation cleavage, high strained zone and later semibrittle transcurrent faults are recognized and manifests the area was polydeformed (Fig. 17-23). These associated structures to the specific deformation events are happened as a result of different field of stresses. From the relict of asymmetric folds (Fig. 23) the pre-existing events are happened from northwest oblique compression and causes extensive shortening and thrusting, then folding. The third deformational events considered as ductile shearing with N-S, NNW-SSE, and NNE-SSW orientations with variably east-dipping transposed shear zone and main foliations (Fig. 23). The NW verging of folding and thrusting, dextral sense of movements along ductile shear zone, and later sinistral sense of movements along strike slip fault are existed during the continental collision and escape tectonics as well as post-accretionary deformation, as coincided with the interpretations of Abdelsalam and Stern (1996) and Stern (1994).

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