A preliminary Geological and Generalized Stratigraphy of Western Margin of Northern Afar Depression, Dallol Area, Northern Ethiopia

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ABSTRACT

The western margin of northern Afar Depression constitutes various rock units of Neoproterozoic basement complex, Paleozoic to Mesozoic sedimentary successions and the Oligocene to present volcano-sedimentary sequences. As part of a reconnaissance survey for mineral resources in selected districts of Afar region, a geological and structural map of Dallol area has been produced with the help of the Landsat Thematic Mapper Plus imagery at a scale of 1:100,000 and a simplified stratigraphy is constructed for the western rift margin, Dallol area.

Keywords: Geology, Stratigraphy, Western Rift Margin, Dallol, Northern Afar Depression, Ethiopia.

1. INTRODUCTION

The tectonically and seismically active continental rift segment in northern Ethiopia is one of the few regions in the world where one can easily recognize the complete evolution of ocean basin (Hagos, 2010). It is the northern and matured arm of the Afar Triple Junction where the Red Sea, Gulf of Aden, and Main Ethiopian rifts are superimposed (Fig 1). Its evolution has been directly linked with the on land propagation of the southern Red Sea to the eastern Nubian plate (Abbate et al., 1995). The central and southern parts of the Afar Depression have been the focus for many tectonic- related research activities. However, the marginal areas of northern Afar Depression have been given little attention in the study of the tectonic evolution of the region.

Details of lithological formation and structural interplay of the northwestern margin of Afar Depression in this paper and also tried to establish a lithostratigraphic framework for the western marginal area of Dallol Depression by (1) logging stratigraphic sequences of the wide geologic spectrum (i.e. Proterozoic–Recent); and (2) using remote sensing imagery to map stratigraphic units and structures throughout the northern Afar margin. To do this, field and remote sensing studies were undertaken in the deeply incised basement-sedimentary sequences lying at the highly matured western rift margin of the Danakil Depression.

1.1. Tectonic Setting

The northern Afar tectonic domain is a well-defined asymmetrical depression, bordered in the west by the Nubian Plate and east by the Danakil Block (Fig lb). The elevation drops radically from the rift bounding Ethiopian plateau that stands well above 3000 meters above sea level (e.g. Atsbi horst) to the lowest point in northern Afar Depression at ~146 meters below sea level (e.g. Dallol Depression; Tesfaye et al., 2003).

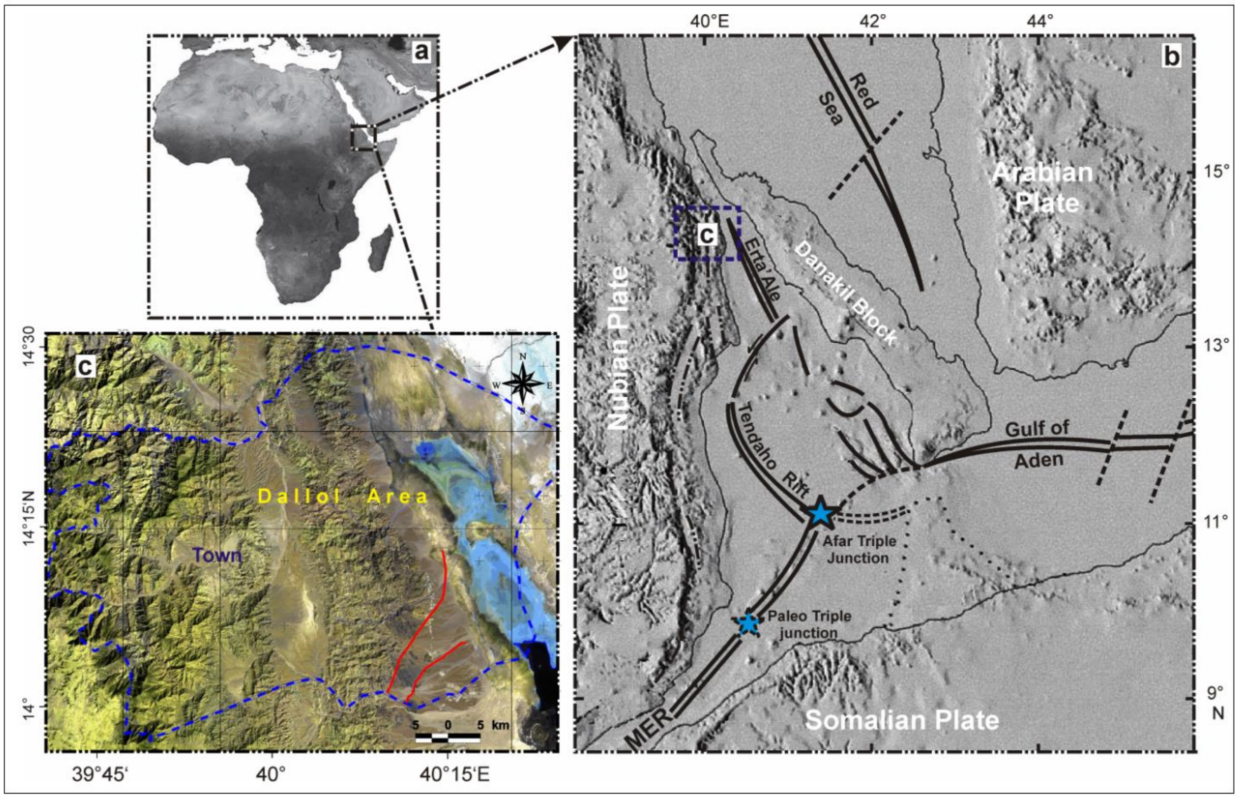


Figure 1. (a) Simplified map showing the Afro-Arabian landmass; (B) Location map of the Afar Triple Junction, the two young oceanic ridges (Gulf of Aden and Red Sea), and the main Ethiopian rift; (C) Location map of the northern western Danakil Depression/Dallol area based on interpretation of Landsat-5 ETM.

The deepest part of the depression is filled with more than one-km-thick Pliocene- to- recent lacustrine sediments, evaporite beds and at places injected by basaltic dykes and sills. The northern Afar Depression as a whole is characterized by an attenuated continental crust (thickness <15 km; Barberi et al., 1980) and intense tectonic activity, analogous to the continental crust of the Red Sea before 4 Ma (Hagos, 2011). The main volcano-tectonic features are intermittent axial volcanic edifices and fissure basalts, open extensional fractures and vertical step-faulting. The volcanic activity in this region has been important since the Pliocene, and is today mostly restricted to the axial zone forming three spectacular shield volcanoes: the Erta'Ale, Alyata and Tat'Ali (Barrat et al., 1998).

The northern tip of Afar Depression, Dallol area is interestingly comprised of the Neoproterozoic basement complex, Mesozoic sedimentary succession and thick Miocene to Quaternary evaporite deposits (Redfield et al., 2003). The Afar Stratoid and Aden series basalts though are absent in the area, present in the form of dykes and sills (Pagli et al., 2012). The Neoproterozoic basement, which represents part of the Arabian-Nubian Shield, is prevalent on the periphery of the Afar Depression. The Arabian-Nubian Shield covers vast terrain to the north and northwest of the Afar Depression and in eastern Eritrea (Beyene and Abdelsalam, 2005 and references therein). The nearly N-S or NNE-SSW strike direction of the regional penetrative foliation suggests that it was formed during D1 deformation by E-W compression (Alene, 1998). Generally, the fabric and nature of deformation of the metamorphic rocks at northern Afar is similar to the Tsaliet Group (850 Ma) and Tambien Group (800-735 Ma) rocks of Tigray region (Beyth, 1972; Teklay, 1997; Alene et al., 2006).

1.2. The Western Margin of Dallol Area

Dallol area is generally considered to have a hostile environment and it is considered by many as an awful, hot, and barren desert region. However, the physiographic features of Dallol area represent one of the world's unique terrains consisting of highlands standing well beyond 2500m above sea level and deep water-free basin subsiding to ~146 m below sea level (Fig 2). The plateaus are comprised of the Neoproterozoic basement complexes with daily temperature ranging from 20-35°C, and average annual rainfall of ~500 mm/year. This environment is a home of many wild animals and birds. On the other hand, the lowland area is filled with more than 1400m thick encrusted evaporite deposits. It is considered as one of the deepest and hottest spots in Africa with an average daily temperature of ~37°C. But, during summer (June- August) the temperature reaches above 52°C on the floor.

The physiography varies drastically from the eastern Atsbi horst/ plateau to the lowest point in the Dallol Depression within 50 km aerial distance. Five physiographic modifiers have been identified across the entire western margin of the Dallol area. These are: (a) deep-cut fault canyon commonly called 'boundary faults'; (b) circular granitic intrusions; (c) marginal graben; (d) flexural slip structures, and (e) central graben (Fig 2). The boundary faults have produced the biggest fault scarp in the margin and cut cross large area. Both east and west dipping fault scarps constitute the rugged terrain of the margin. The granitic intrusions form the lower part of the western margin abruptly piercing the north-south running elevated areas. The Dallol marginal graben is one of the deepest and well bounded graben in the western Afar margin separating the Neoproterozoic basement rock to the west and the Mesozoic sedimentary succession to the east. The flexural-slip structures constitute the lower part of the western Dallol margin. The rocks making up the lower part of the margin are mainly the carbonate and clastic Mesozoic rocks. They are highly inclined to the east and west and their interface is very weak leading to flexural slip movements (Fig 2c). These five physiographic features accumulate a total dropdown of about 3000 meters.

1.3. Geology of Dallol Area

Although, the northern Afar Depression has been one of few places on earth that imprint a complete record of the volcano-tectonic evolution of a young ocean basin. It, however, lacks extensive geological investigations due to extremely difficult field conditions that have prevented access to the region. Despite the difficulties, few authors (e.g. Abbate et al., 1995; Barberi and Varet, 1970, 1975, 1977; Barberi et al., 1972a&b, 1975, 1980; Beyene and Abdeselam, 2005; Hagos, 2011) have tried to constrain the volcano-tectonic evolution of northern Afar and to lesser extent the geochemical and isotopic signatures of the rift volcanics. But surprisingly, none of the authors addressed the nature of the basement complex and sedimentary successions of the marginal areas of Dallol Depression.

Most of the geological makeup of northern Ethiopia is represented from old to young by the Neoproterozoic low-grade metavolcano-sedimentary sequences, Paleo-Mesozoic sedimentary successions and Cenozoic volcano-sedimentary sequences. However, these rocks are found spatially distributed/isolated throughout the region. It is only in the western Afar margin where most of these successions found together one overlying the other. Geology of the western Afar margin is of great interest because it may represent the complete sequence of the rocks spanning from the Late Proterozoic to the present (Hagos, 2011). The 3000m-thick fault scarps constitute the three genetically distinct rock types. The upper part of the scarp constitutes the basement rocks; the lower part is covered by the Mesozoic sedimentary rocks and at places by the older basement rocks.

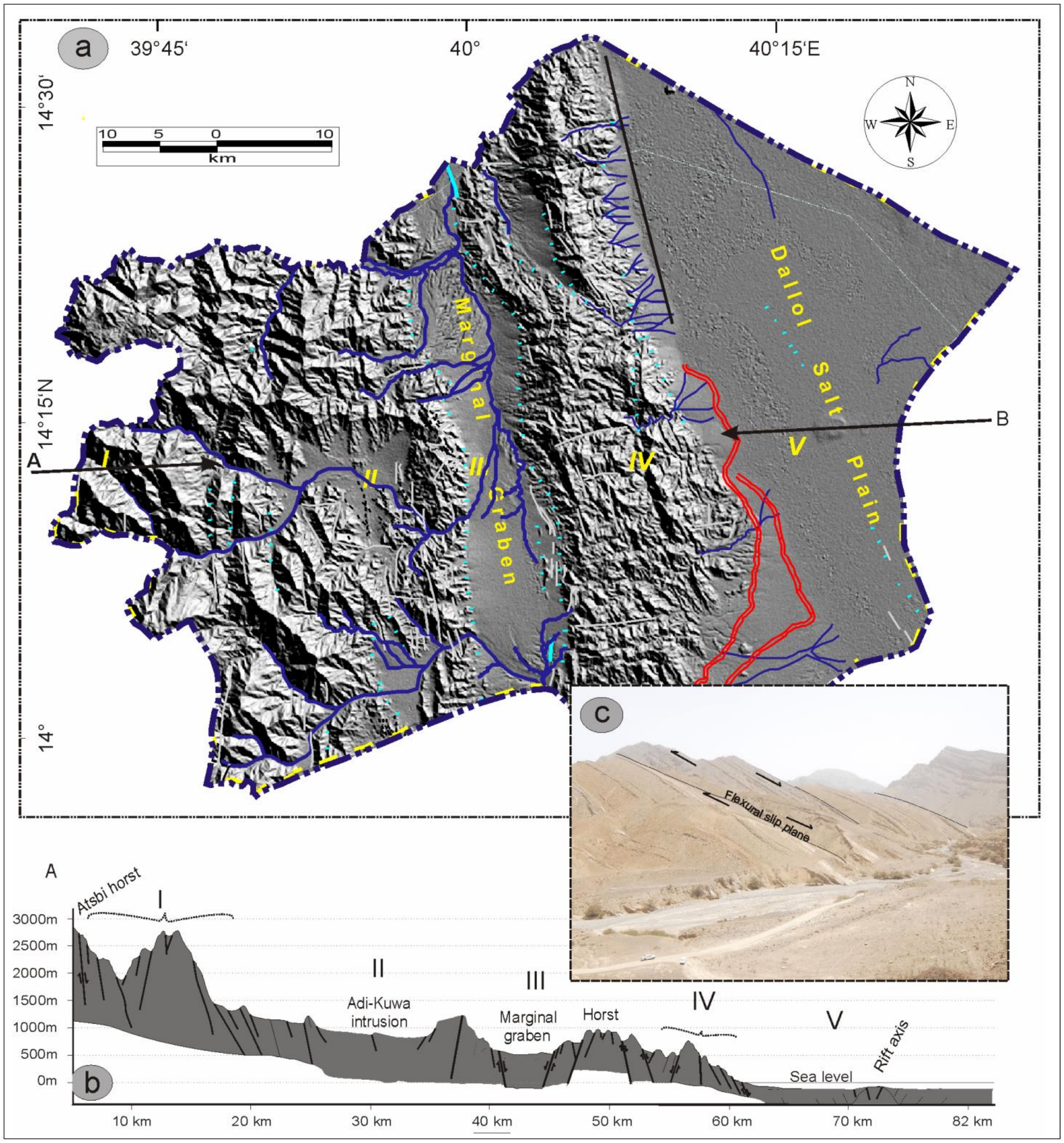


Figure 2. (a) Shaded Relief Thematic Map of the western margin of northern Danakil Depression (Dallol area), (b) profile section along the A-B line, (c) Field photograph showing flexural silp movement. (I) boundary faults representing the major physiographic change in the area; (II) the Ade-Kuwa granitic intrusions, the overlying basement rocks is eroded; (III) The Garsat-Simbileli marginal graben; (IV) faults developed by flexural slip displacement; (V) the lowest part of the Danakil Depression.

The geological formations of the western Afar margin and surrounding plateaus, therefore, can be, divided into two broad divisions (Barberi et al., 1972b): (1) Pre-rift complexes; and (2) Syn-rift volcano-sedimentary rocks.

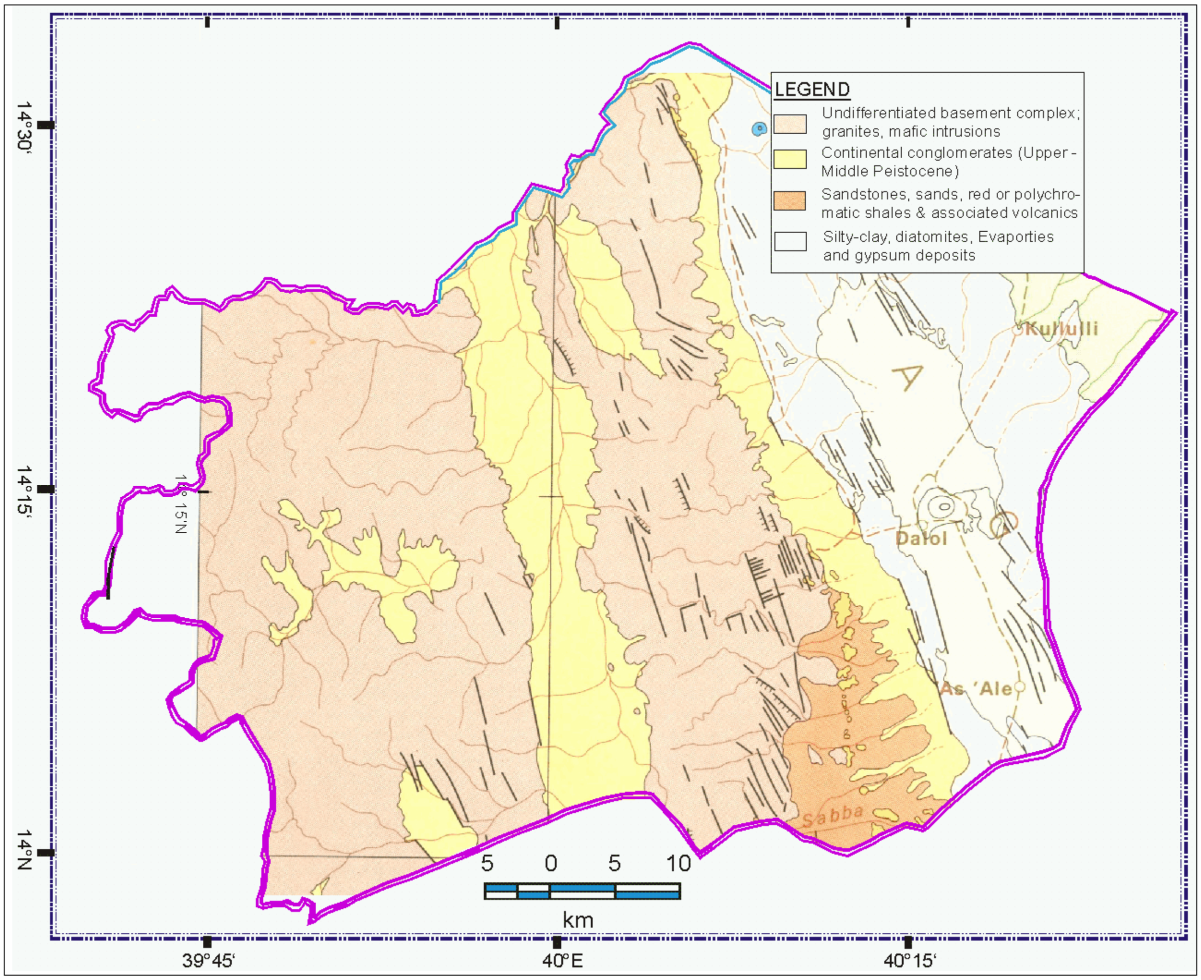


Figure 3. Existing geological map of the Dallol area, cropped from the regional geological map of Danakil Depression, northern Ethiopia (after Barberi et al., 1972b).

1.3.1. Pre-rift complexes

These complexes consist of the Neoproterozoic crystalline basement rocks (Arabian-Nubian Shield (ANS)), and the Paleozoic–Mesozoic sedimentary sequences, which are exposed along the peripheries and plateaus surrounding the northern Afar Depression (Kazmin et al., 1978; Vail, 1985) (Fig 3). The Arabian–Nubian Shield is a 'low-grade basement complex' which covers a wide region to the western and central parts of the marginal areas of Afar Depression. The ANS are overlain by thick successions of Mesozoic and in some places by Paleozoic sedimentary rocks and Tertiary volcanic rocks. The oldest clastic sediments (Lower Sandstone) are generally early Triassic or possibly Permian, overlying the basement complexes, with younger formations (Upper Sandstone) extending into the early Cretaceous (Bosworth et al., 2005). These Mesozoic sedimentary successions correspond to a major transgressive–regressive cycle, which have been assigned to the Adigrat–Amba-Aradom formations. The Mesozoic sedimentary rocks of the western (Ethiopian) Plateau comprise Early Jurassic Adigrat Sandstone, Middle–Late Jurassic Antalo Supersequence and Agulae Shale, and Early–Middle Cretaceous Amba-Aradom Formation (Varet and Gasse, 1978; Tefera et al., 1996; Bosellini et al., 1997).

1.3.2. Syn-rift volcano-sedimentary successions

Following the southward propagation of the Red Sea rift towards the Nubian plate, series of syn-rift, volcano-sedimentary sequences are deposited along the newly developing basins. Because of the unique physiographic feature, the western margin of northern Afar Depression hosts a variety of lacustrine deposits of Miocene - Quaternary volcano-sedimentary rocks. Further, shallow water sedimentary rocks were also deposited along the newly developed grabens (i.e., Dallol Depression) between ~12 and 1 Ma (Beyene and Abdelsalam, 2005 and references therein). Evaporites and lacustrine sedimentary rocks of several hundred meters thick cover the Dallol Depression in the north (Varet and Gasse, 1978).

3. METHODOLGY

Fieldwork was conducted in 2014 in selected Woredas namely Dallol, Megale, Erebti, Yalo, and Gulina of Afar region as part of a reconnaissance survey for mineral resources. The first phase of fieldwork was conducted in Dallol area in March 2014. The area was covered by many pre-planned traverses stationing at different Kebeles namely Ade-Kuwa, Garsat-Simbileli, Badda, Musely, Hamad'Ela and Berahle. Lithological variations and their structural patterns were recorded accordingly. A generalized geological map at 1:100,000 scale is prepared based on the Landsat-ETM+ image and field data (Fig 4A). A cross section along profile A-B in figure 4A is extracted using Global mapper (Fig 4B) and a complete stratigraphy of western margin is presented in figure 8.

3.1. Digital Image Processing Technique

The main inputs for this processing technique were partially from the processed Landsat-TM and ETM images. All Landsat data are obtained from the archives of Mekelle University-Inter

University Cooperation (MU-IUC) project. The Enhanced Thematic Mapper plus (ETM+) sensors are highly advanced, multi-channel scanning devices designed to acquire high resolution image, improved geometric fidelity, sharper spectral separation, and greater radiometric resolution than the older Multi Spectral Scanner (MSS) sensors (Muzein, 2006). The ETM+ sensors with their six compatible multispectral bands and one thermal infrared band (having a spectral resolution of 60 m) are capable of providing more spectral information.

3.2. Radiometric and Atmospheric Correction

These properties are the basic entities of all objects that have to be properly documented and processed during image processing techniques. To reduce the atmospheric interaction, different methods are now used for correction, but the one applied in this work is the dark object subtraction method. The dark object subtraction method works based on the assumption that in every scene (full image) there should be at least a small area completely made of dark pixels (i.e., with 0% reflectance. This characteristic is used in empirically computing the haze component. The minimum digital number (DN) value recorded in the pixels of dark objects is taken as noise and is subtracted from all other pixel values in the entire image.

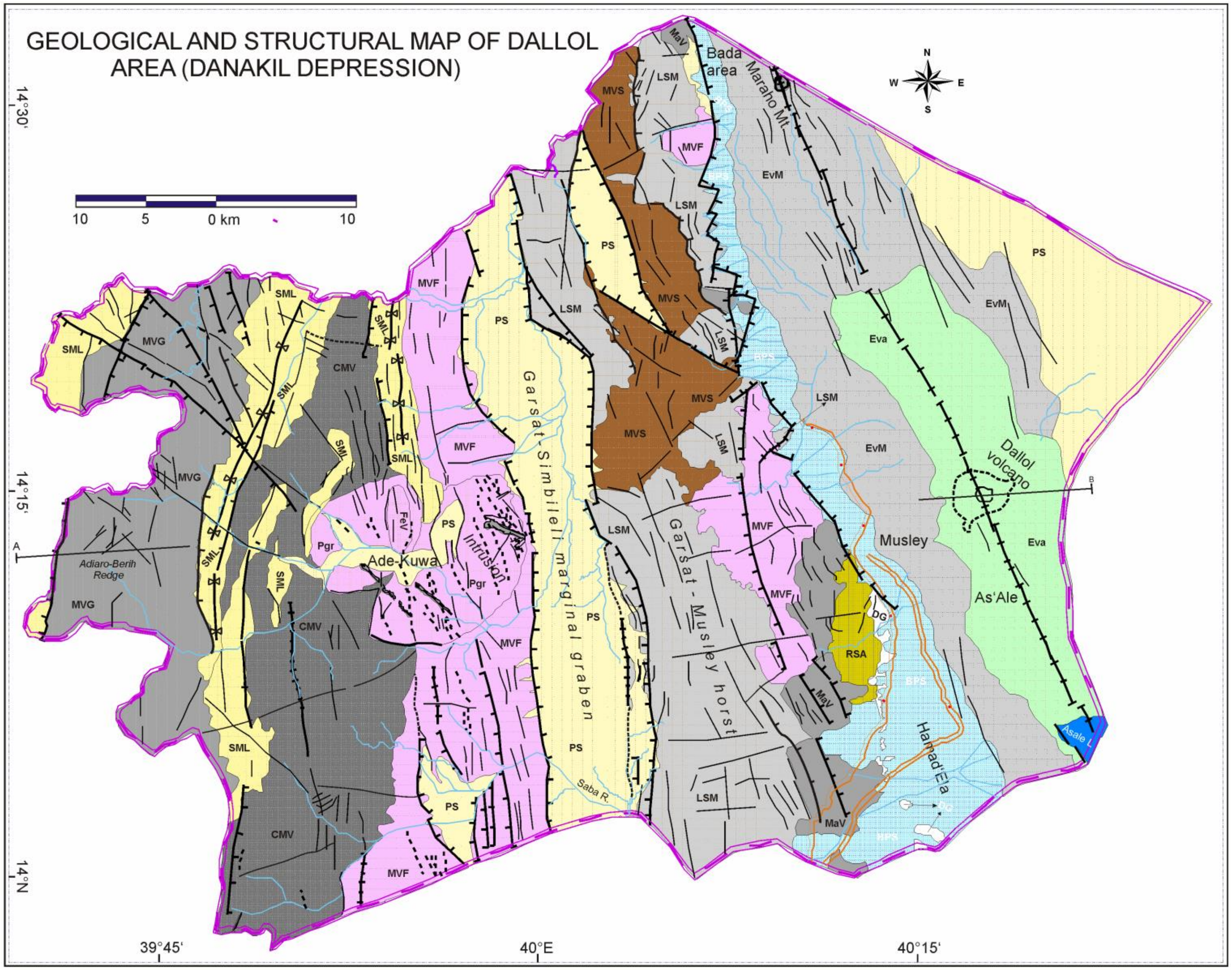
3.3. Image Filtering

The purpose of image filtering is to make the digital images more understandable and interpretable by enhancing information of interest (i.e., area of interest should become better discernible). This technique is carried out by using kernels, also called boxes or filter weight matrices. In order to compute the new DN values of an image, it is expected that the kernel is superimposed over the old image-data array. The original DN values are weighted by the overlying coefficients in the kernel and the resulting total DN value is ascribed to the central pixel in the new image.

4. RESULTS AND DISCUSSION

4.1. Geology and Stratigraphic Succession of Western Margin of Dallol area

Based on the field data and information obtained from satellite imagery, the map of Barberi et al. (1972b) is modified to a great extent and produced a new geological map (Fig 4A) and



(Figure 4A. See the legend and caption in the next page).

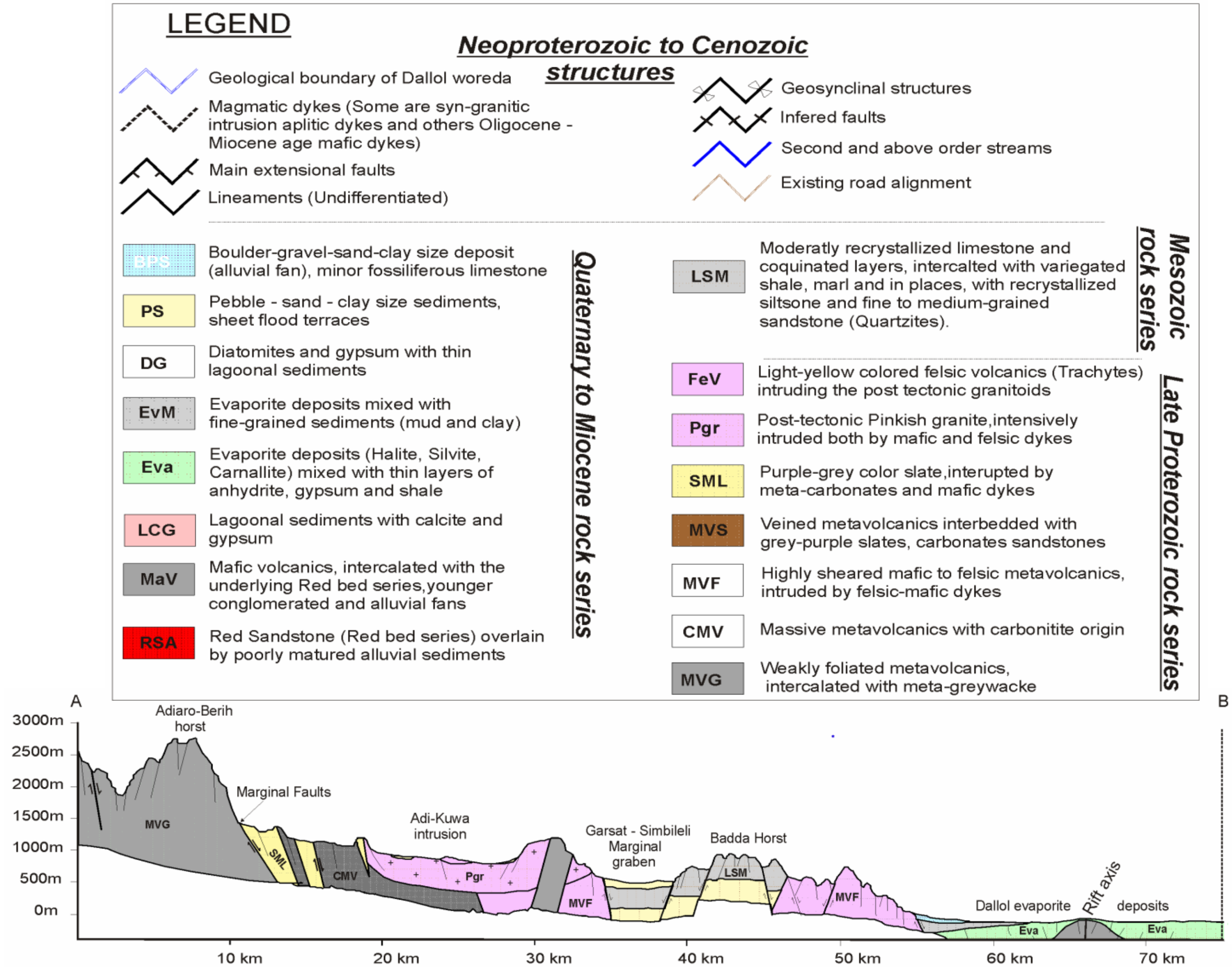


Figure 4(A). Detailed geological and structural map of the Dallol area. The spatial variations of rocks, lithologic contacts and the structures were extracted from 1:50,000 scale Landsat ETM+ 2002, and SRTM. Color composite images of Landsat band 7, 5 and 2 are commonly used to differentiate between the late Proterozoic basement complex, Mesozoic sedimentary rocks, and the Miocene-Quaternary sediments; (B) The structural and profile map of the cross-section is extracted from SRTM map and the geologic contacts from the geological map.

a geological cross section (Fig 4B). The northern end of the Danakil Depression, Dallol area, is a matured rift valley bounded and floored mainly by the late Proterozoic basement complexes, Mesozoic sedimentary successions, and Miocene – Quaternary sediments, where rift related volcanic inputs are found in very restricted areas. The geology of the Dallol area is, therefore, of great interest because it may represent the complete sequence of rocks spanning from the Late Proterozoic to the present.

The geological formations of the Dallol Depression and its marginal areas can be divided into four broad divisions (Fig 4A): (1) Neoproterozoic basement complex; (2) Mesozoic clastic-carbonate successions; (3) Miocene-Pliocene volcano-sedimentary sequences; and (4) Evaporites and young sedimentary deposits.

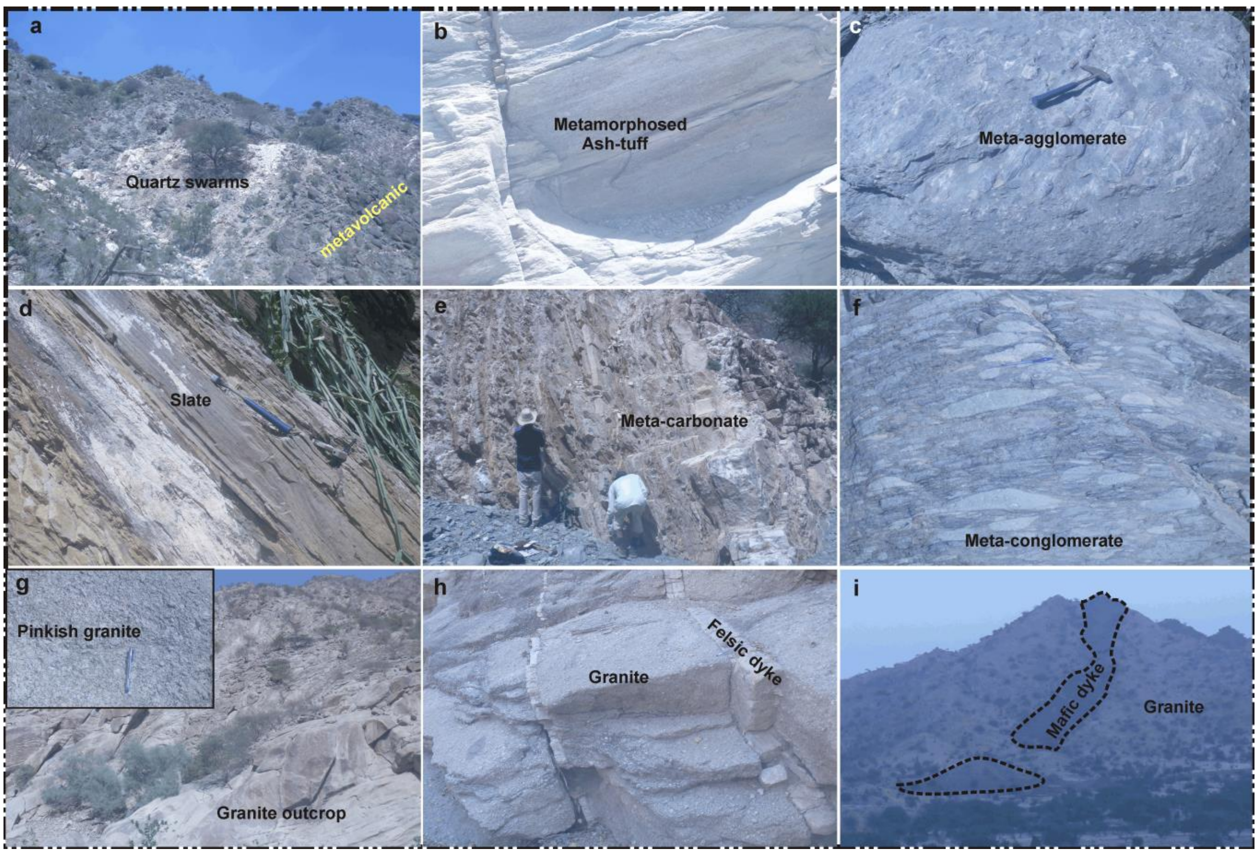


Figure 5. Representative outcrops of the basement complex of Dallol area: (a) Quartz swarms enriched mafic metavolcanics; (b) Meta-agglomerates; (c) Metapyroclastics (ash-tuff); (d) Slates/Phyllites; (e) Metacarbonates interbedded with thin layers of slate; (f) overturned and east-verging fold in the slate-carbonate units; (g-i) Granitoids intruded by felsic and mafic dykes.

4.1.1. The Neoproterozoic Basement Complexes

The entire upper part of the Dallol western margin and partly the lower margin is covered by the metavolcano-sedimentary successions and post-tectonic granitoid intrusions. They form part of the northern Ethiopian ANS and represent the northern extension of the Negash-Atsbi basement complexes. The mafic-felsic metavolcanics and metavolcaniclastics form rugged terrain of the upper western escarpment (Fig 4A&B). The metasedimentary sequences on the other hand are found sandwiched within the metavolcanics. Generally, they are divided into: metavolcanic/metavolcaniclastic rocks, metasedimentary successions and post-tectonic granitoids.

4.1.1.1. Metavolcanic and Metavolcaniclastic Rocks

Fine-to medium-grained metavolcanic rocks of the Tsaliet Group are exposed in the western part of the study area adjoining the Atsbi horst. Their color varies from greenish to light-brown. At places, rounded to angular, 1-5 cm size clasts (Fig 5a&b) of mafic to felsic composition are found within the metavolcanic rocks. But, their thickness does not exceed more than few meters. In some outcrops, the primary structures such as vesicles and layering are not completely destroyed indicating their low degree of metamorphism. Predominantly, they are weakly foliated, but intensely fractured and some of them are veined by quartz swarms (Fig 5a). The general foliation orientation is not well defined but ranges from N10°W to N15°E. Most of the metavolcanic outcrops are differentially deformed and producing an anastomosing type structures. Some of the outcrops show no indication of major deformation and they show similarity with the parent rock.

4.1.1.2. Ash-lapilli tuff

Throughout the Atsbi tectonic domain, fine clastic origin metamorphosed outcrops found along the contact between the metavolcanics, metavolcaniclastic and metasedimentary rocks. Between the upper part of the metavolcanic rocks and lower boundary of metacarbonates, there is a finely laminated, moderate to highly foliated tuffaceous material is present (Fig 5c). Though, these pyroclastic materials are slightly down wrapped by the border faults, they are supposed to be the northern extension of the Atsbi series. Except, the foliation development and some transverse fractures, the outcrops do not show any form of alteration and secondary mineral development. Moreover, they are only deposited between metavolcanics and metasedimentary rocks. The orthogonal thickness of the outcrop is estimated to be ~20 m. The foliation and fracture orientation is oblique to each other with foliation orientation striking N05°-20°E/46°-55°E and the fractures are oriented to S70°-75°E/~74°S. From the stratigraphy and nature of magmatism, these outcrops are related to the island arc volcanism within the ANS indicating the last phase of eruption in the area.

4.1.1.3. Metacarbonates

These are distinct metasedimentary lithologies and constitute the central part of the basement complex. The Dallol metacarbonate sequence includes dolomite and interbedded dolomite-slate intercalations, which in turn grades upward into non-calcareous slate. They are fine to medium grained, moderately recrystallized and consisting of over 70% dolomite with calcite and detrital quartz. It is strongly foliated and showing progressive increase in thickness towards the upper sequences. At places, this unit displays tight overturned fold and refolded structures as well as stromatolitic laminations (Fig 5d&f). This forms a sub-vertical NNE trending, layered Carbonates. In most case, this unit resembles that of the Negash metacarbonate with the exception that the Dallol metacarbonates is repeatedly intercalated the slate and also consists of grayish limestone.

4.1.1.4. Slates and Phyllites

An alternating slate and phyllite sequences are exposed in the central part of the Dallol marginal areas (Fig 4A). The slate is strongly foliated, light-brown in color and develops both compressional and extensional structures. The basal contact with the underlying metacarbonate is gradational with no major discontinuity between the two groups. Greenish grey slate and greywacke layers occur at both sides of the boundary, and there is no marked deformational or metamorphic contrast across the contact. It contains 1–2m thick beds of spotty purple slate, well-laminated bands, thin graphitic layers, conglomerates and metagraywacke. The slates exhibit sign of sulfide mineralization and at places injected by thin layers of mafic sills and dykes (Fig 5e).

4.1.1.5. The Dallol Granitoids

The Dallol area contains the largest granitoid intrusion in northern Ethiopia. It is a merger of two texturally and mineralogical distinct granite bodies (Fig 4a). Both are elliptical in profile with an average diameter of ~15 kms. These granitic intrusions intrude mainly the metavolcanics /metavolcaniclastic in the area and have roughly alkaline-subalkaline in composition. They form part of the town Adi-Kuwa. The bigger intrusion, which is more of alkaline in nature, is intensively dissected both by mafic and felsic dykes (Fig 5h & i). The smaller and lensoidal-shape granitic body is sub-alkaline in composition but zoned. This intrusion is not injected by late-coming felsic as well as mafic dykes. Its main lithology is granite but also contains zones of granodiorite. The time of emplacement of both intrusions is not well constrained, but from the structural point of view, they post-date the time of major collision of the east African orogeny; because, their entire bodies do not show any indication of deformation except the late coming felsic and mafic dykes dissecting the bigger intrusion. The nature of the dykes is different. Some are fine-grained/aplitic and others coarse-grained. Some of the mafic dykes are mappable at a scale of 1:100,000 (Fig 4A). Mineralogically, both the granitic bodies are alkaline to sub-alkaline in composition with minor amounts of dark colored minerals such as biotite and hornblende. The Dallol granitoid is post-tectonic as it free from any form of Neoproterozoic related deformation. Grains are randomly aligned and no developments of quartz-porphyroblasts.

4.1.2. The Mesozoic Sedimentary Successions

Unlike the other segments of the Ethiopian rift, part of the western margin of the Afar Depression is covered by a full succession of the Mesozoic sedimentary sequences. Part of the Mesozoic succession found in the Mekelle outlier is down through by about 2000 m to the Afar Depression. This succession is mainly exposed on the central part of the Dallol area antithetically and synthetically dipping along the lower marginal areas. In general, the entire succession is tilted to ~45° towards west, east and in places to the south. In this area, lower clastic sediments commonly called the Adigrat sandstone, the carbonate rocks or Antalo limestone and the shale units are well exposed.

4.1.2.1. The lower sandstone "Adigrat Sandstone"

The lower sandstone of Dallol is exposed along the base of the eastern Garsat horst and western Musley-Badda plain. The sandstone is light to red in color, fine to medium-grained, well sorted and very mature (e.g., quartz-arenite) clastic sediment. Even though most of the layers appear massive as a result of recrystallization, cross-bedding structures are quite common and lateritization in the upper sequences. Unlike the other sandstone units of the Mekelle outlier, the sandstone in the Dallol area is highly recrystallized and at places particularly near the Badda area, it has been changed to quartzite (Fig 6a). The quartzites are highly fractured or brecciated and show no sign of layering. The formation of the sandstone is supposed to be of fluvial origin, as shown by the occurrence of point-bar sequence and the abundant laterite beds (Bosellini et al., 1997).

4.1.2.2. The Limestone-Marl-Shale intercalation

Limestone

As the area is highly dissected by marginal faults, the limestone unit does not show a direct stratigraphic way-up with the underlying sandstone unit. The limestone is commonly miss-placed and intermingled with the nearby units. Mostly, this unit is found on both flanks of the Garsat-Musley horst, a horst bounded by the Garsat marginal basin in the west and the Musley-Badda plain in the east (Fig 4B). It has light grey to light pink in color and the structures that are found in this unit are systematic joints, faults and some stylolites (Fig 6b). This unit is dipping to the west and east controlled by the geometry of the horst bounding faults, but in places, it shows variation in bedding orientation due to the effect of local faults.

It is micritic in texture, but following some structures, well developed secondary re-precipitates of calcite minerals exist (i.e., growth of rhombohedral shape calcite minerals along bedding and fracture surfaces). The thickness of each limestone bed ranges from delicate lamination to ~2m, but the aggregate thickness of this unit is ~300-400 m.

Marl

This sub-unit is mostly found as intercalation with the limestone and shale units. It has yellowish color when fresh and light-grey color when weathered. It is in most cases unconsolidated but massive layers as hard as the adjacent limestone beds also occur. Some of the flexural slip related faults are developed along the marl surfaces.

Shale

It is a common characteristic that when there is carbonate unit in the northern part of Ethiopia (Mekelle outlier) including the western Afar margin, it is associated predominantly with marl and then shale. The shale-dominated carbonate outcrops are found near the base of the Afar margin. It has grey – purple color with friable nature, highly affected by weathering and erosion. This subunit is underlain by marl and overlain in some part by gypsum deposits. The shale is most fissile, laminated, and loosely consolidated portion of the Limestone-Marl-Shale super sequence. This group is comprised of mainly shale and mudstone with minor thinly bedded layers of marl and limestone. At the lower part of this unit, patches of lagoonal sediments, like evaporite layers, are deposited.

Gypsum Deposit

This is found almost as patches intercalated with the end member of the carbonate unit. The presence of this deposit indicates that the area was once lagoonal environment. It has completely different physical properties: well crystallized light-brown to white color. Its thickness varies from place to place, but gypsum layers as thick as 50 m are found in the Dallol area (Fig 6c).

4.1.3. The Miocene-Pliocene Volcano-sedimentary Sequences

4.1.3.1. Red-Bed Series Sandstones

In northern Afar Depression, since the development of series of marginal basins, Lower Miocene to Lower Pliocene syn-rift Red-Bed Series sandstones and shales were deposited in Danakil Depression (Redfield et al., 2003). Stratigraphically, the red color Red-Bed Series sandstones are commonly overlain by the Pliocene volcanic rocks "Afar Stratoid Series" and underlain by the Mesozoic sedimentary successions. In areas that were not covered by the Stratoid Series, the Red Bed Series sandstones are directly overlain by immature alluvial deposits (Fig 6d). Crustal stretching and block-rotation made the entire series to be tilted to the west. The Red-Bed Series sandstones are immature in texture and are intensely intruded by mafic sills/dykes and form angular unconformity with the overlying deposits (Fig 6.d).

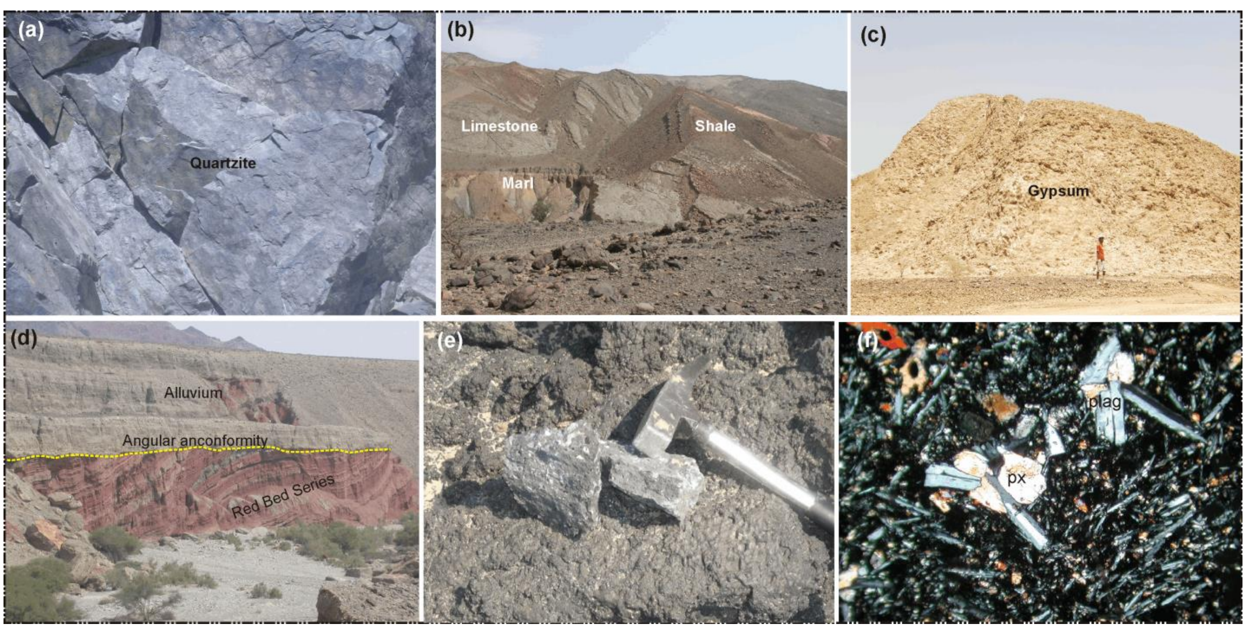


Figure 6. Representative outcrops of the Mesozoic – Cenozoic deposits of Dallol area: (a) Highly silicified sandstone, quartzite; (b) Tilted limestone-marl-shale intercalations; (c) Dome-forming gypsum outcrop; (d) Angular unconformity between the Red-Bed Series and overlying conglomerates; (e) Outcrop of the younger volcanic rocks; (f) Representative microphotographs of the volcanics rocks: px-pyroxene, plag-plagioclase.

4.1.3.2. Younger Volcanics

Though, these are not the major unit in the Dallol area, the lower part of the western escarpment constitutes highly fractured and mostly vesiculated and fresh volcanic rocks (Fig 6e). It is composed largely of basaltic and rarely picritic lavas with sparse pyroclastic materials. Very recent extensional fractures parallel to major axis of the Erta'Ale Range cut the volcanic series. Petrographic analyses were done on samples taken from these volcanoes. The minerals from the samples were inequigranular with finely crystallized to moderately porphyritic plagioclase-lath (Fig 6f). The phenocrysts are dominated by randomly aligned plagioclase and constitute about 9% by volume. To lesser extent, subhedral to skeletal pyroxene phenocrysts (0.3–3mm) exist.

4.1.4. Evaporites and Younger Sedimentary Deposits

Large part of the well-developed basin of the northern Afar Depression is refilled by younger sedimentary strata. Crustal stretching, subsidence, sedimentation; and volcanism characterize the basin formation of the Dallol Depression. This basin constitutes the following formations.

4.1.4.1. Diatomite and Gypsum

The chalky-stone formed from fossilized skeletons of diatoms is exposed around western to southwestern part of the study area. This is characterized by white in color, soft in hardness, light in weight, showing horizontal to sub-horizontal layering. On top of the diatomites are the columnar structure gypsum outcrops. The diatomite is found as patches aligned in NW-SE direction (Fig 4A).

4.1.4.2. Evaporite deposits

The evaporite deposits of Dallol Depression constitute various lithologic and structural set up. In most parts, it's horizontally to sub-horizontally bedded white, red and in places yellow strata (inset in Fig 7d). However, near active hot springs, the nature of the deposits is mushroom shaped white to yellow and red color salt outcrops (Fig 7a&b). At the center of the depression, a circular caldera-type outcrop of red and highly crystalline salt deposit occurs (Fig 7c). The white-colored rock salt, commonly called 'halite', covers the major part of the depression and it is mainly exposed along the Dallol rift axis. It is well layered with layer thickness of 10 to 20 cms (Fig 7d).

At Dallol mount, the nature of the evaporite is different. It is characterized by a volcano emanating very acidic hot springs with pH values of 0.3 - 3 and temperature exceeding 109°C. Pure sulfur minerals also found precipitated directly from the volcanic eruption or reprecipitation during the hydrothermal activities. There are also remnants of small volcanic mouths and water dissolution resistant structures which look like beautiful and orderly arranged seats (Mushroom structures) including bigger size salt travertine cone shape deposits. The flat part of the salt plain is also characterized by series of ponds formed by weak hot springs coming out of the surface along fissures and conduits.

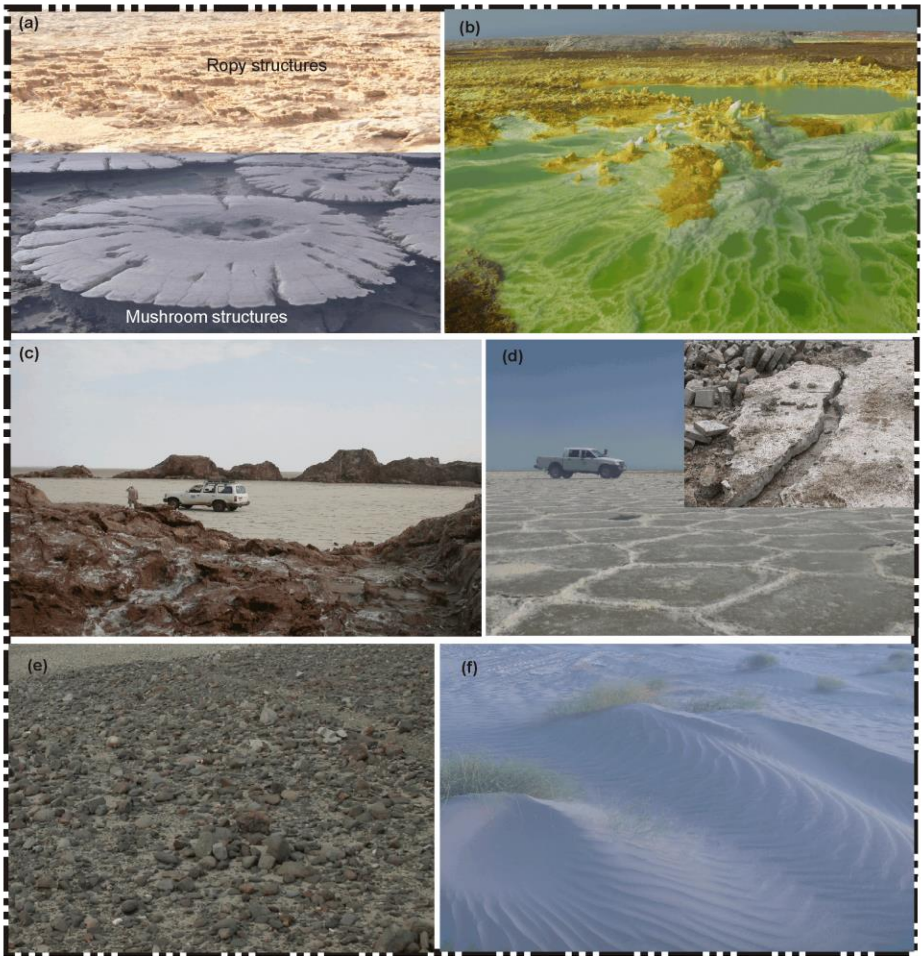


Figure 7. Representative field photograghs showing the different colors and compositions of the evaporite and alluvial deposits: (a) mushroom and ropy structures salt crust (b) Salt-iron-sulfur mixtures at the top of Dallol mount (c) reddish and massive salt rocks at the center of the salt plain forming a circular outcrop, collaps structures; (d) encrusted salt plain, (e) Conglomerate-size alluvial deposits; (f) sand dunes along the lower flank of the margin.

4.1.5. Alluvial fan

The higher elevation difference caused the deposition of Miocene to Quaternary alluvial fan sediments at the base of the highlands. These mostly unconsolidated sediments inter-finger and overlay the Pleistocene and Holocene sediments of the Dallol Depression.

The alluvial deposit covers the western to southwestern part of the depression and this alluvial deposit is aligned NNW-SSE direction; this is at the lower base of the Dallol Depression. This alluvial deposit is composed of clay, silt, sand, gravel and boulders. They are deposited in a fining downward manner from the base of the fault scarp to the center of the depression. The boulders are characterized by shiny and black color as a result of sun-burn effect (Fig 7 e).

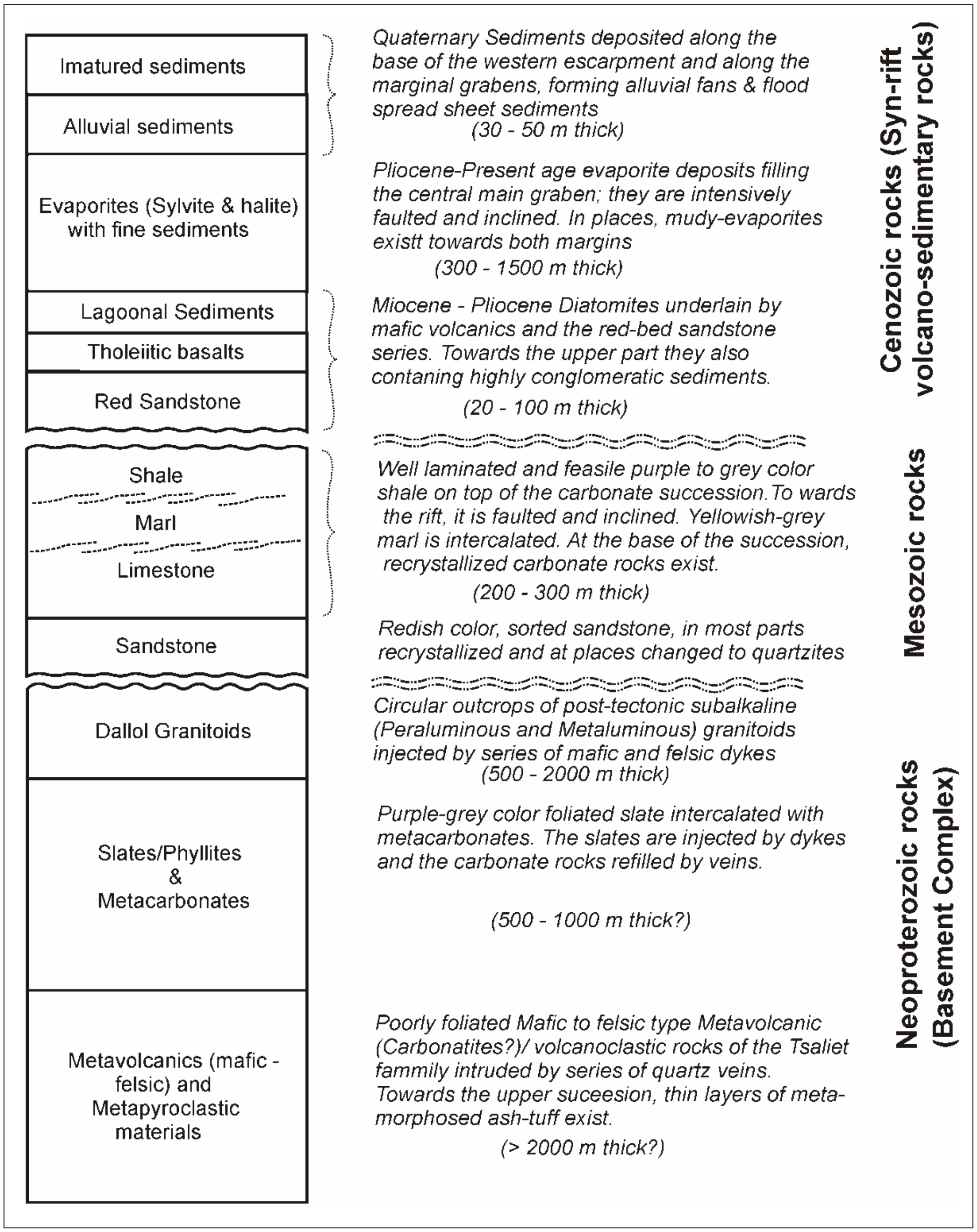


Figure 8. Simplified sketch for the entire stratigraphic succession of the western margin of northern Afar Depression.

The sand dune is another form of alluvial deposit found at eastern part of the Dallol Depression, which has been transported by wind. It forms a hill topography of crescent-shaped loose and fine sand (Fig 7f), which has been characterized by multidirectional wind blow direction mostly along the east-west. This movement and accumulation of sand grains of all dunes are asymmetric in cross-section. The side facing the wind is always longer and less steep than the side opposite. The lithologic diversity of the Dallol area is presented here above from the older to the young formation. Based on the field observation, stratigraphic and structural way-up nature, the sequential order of lithologies is constructed and presented in figure 8.

5. CONCLUSIONS

The western margin of northern Afar Depression comprises a complete sequence of the Neoproterozoic – Cenozoic rock complexes and structures. The geological and structural map produced from Landsat ETM+ image, field survey supported by major geochemical analysis show that the western Afar margin constitutes most of the Neoproterozoic – Quaternary rock formations with the exceptions of the Ambaradom and overlying flood basalts sequences. The absence of these two major units show that the development of the western Afar margin is much after the removal of the flood basalts and underlying sandstone by erosion.

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