Geochemistry of Metavolcanics and Granitic Intrusive from Western Margin of Northern Afar Depression, Dallol, Northern Ethiopia

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ABSTRACT
The western margin of northern Afar Depression constitutes various rock units of Neoproterozoic basement complex. Major oxide data of metavolcanic and granitoid rock samples from basement complex indicate significant variation in the concentration of major oxides (e.g. Fe_2O_3, TiO_2, CaO, MgO). Metavolcanic rocks of Dallol demonstrate heterogeneous nature of magma source. The mafic metavolcanics indicate two distinct groups, (i) CaO-enriched and (ii) tholeiitic composition. Another group of magmatic series, the felsic metavolcanic group, shows a co-genetic relationship with the tholeiitic metavolcanics. Granitoids on the other hand have a wider range of SiO_2 (61.5 – 76.65 wt %) and are peraluminous to metaluminous in nature.

Keywords: Geochemistry, Metavolcanics, Granitioids, Dallol, Northern Afar Depression, Ethiopia.

1. INTRODUCTION

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 are 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 et al., 1998). Generally, the fabric and nature of deformation of the metamorphic rocks at northern Afar is similar to the 850 Ma Tsaliet and 800-735 Ma Tambien Group rocks of Tigray region (Beyth, 1972; Teklay, 1997; Alene et al., 2006).

1.2. The Western Margin of Dallol Area

Dallol area is always considered as hostile environment. Many people named the area as, awful, hot, and barren desert region. However, the physiographic feature of Dallol area is 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. The plateaus are built on 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 1400 m thick encrusted evaporite deposits. It is thought as one of the deepest and hottest spots in Africa with an average daily temperature of ~37°C; during summer (June- August) the temperatures reaches above 52°C on its floor.

1.2.1. Geology of the 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 and others) 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 complexes and sedimentary successions of the marginal areas of Dallol Depression.

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

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

1.2.1.1. Pre-rift complexes

These complexes consist of the Neoproterozoic crystalline basement rocks (Arabian-Nubian Shield), 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 1). The Arabian–Nubian Shield (ANS) also called the ‘low-grade basement complex’ covers a wide zone to the western and central parts of the marginal areas. 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 has 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).

1.2.1.2. Syn-rift volcano-sedimentary successions

Following the southward propagation of the Red Sea rift to the Nubian plate, Series of syn-rift volcano-sedimentary sequences are deposited along the newly developing basins (Fig 1). Because of the unique physiographic feature, the western margin of northern Afar Depression hosts lacustrine deposits of Quaternary - Miocene volcano-sedimentary rocks. Significant shallow water sedimentary rocks were 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 m thick cover the Dallol Depression in the north (Varet and Gasse, 1978).

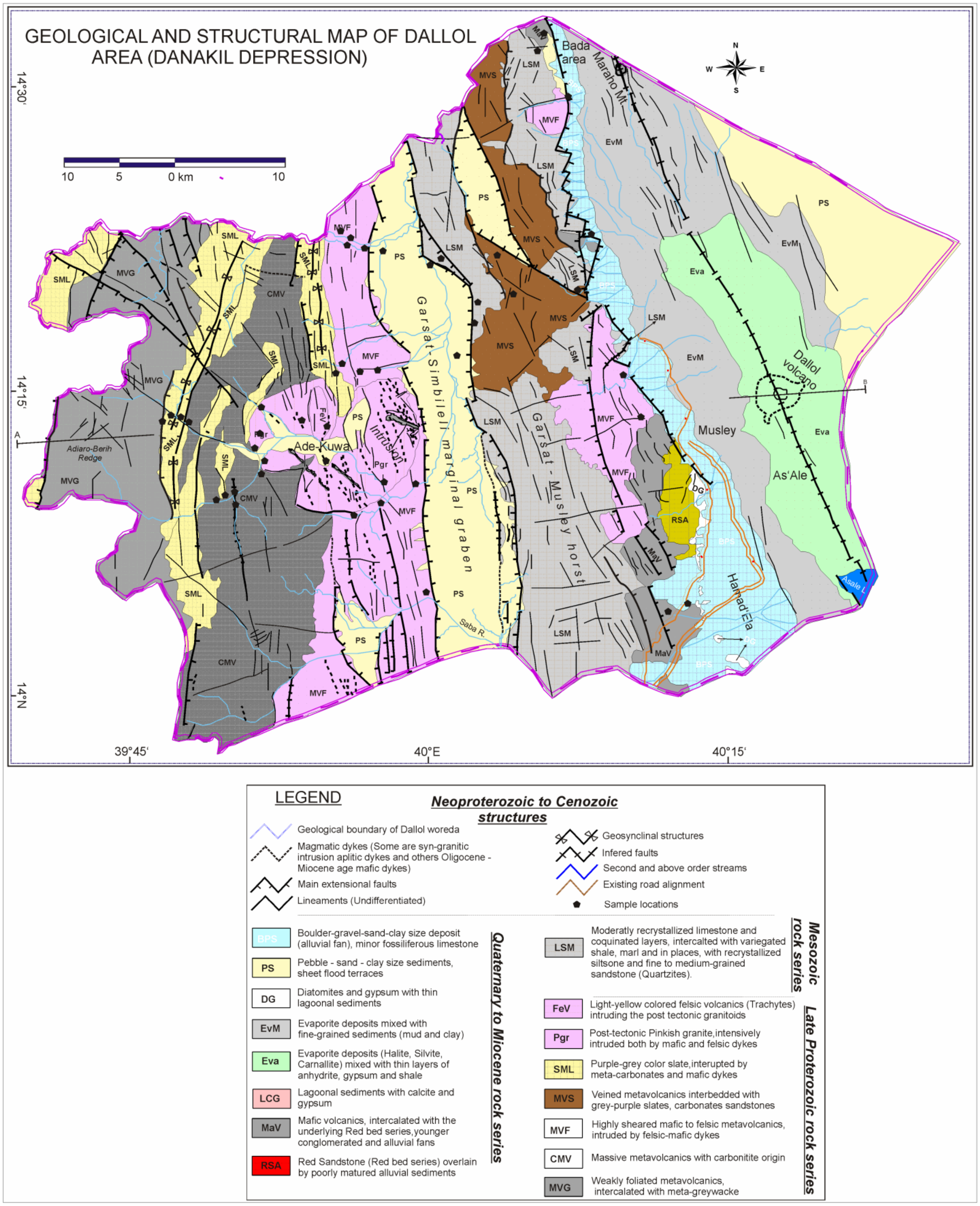

Figure 1. Detailed geological, structural and rock sample location map of Dallol area. Rock samples are indicated by the solid circles (After Hagos et al., 2016).

2. METHODOLGY

Out of 45 rock samples were collected from metavolcanics, metavolcaniclasts, phyllites, slates, laterites, basalts, and rhyolites, 32 from metavolcanics, volcanics and granite were selected for the study and geochemical analysis. Among the 32 samples, 15 belong to metavolcanics, 6 from younger volcanics, and 11 samples from the granitic plutons. Rock samples were crushed and milled at the Department of Earth Sciences, Mekelle University, to produce fine powders for the purpose of geochemical analysis. 32 rock powders, each weighing about 50 gm, were sent to Johannesburg University, South Africa, for major and minor oxide analysis (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, MgO, CaO, Na_2O, K_2O, and P_2O_5) using wavelength-dispersive X-Ray Fluorescence (XRF) Spectrometer (Philips PW 2400). All the sample powders were calcined/ heated and borate fused. 1.2 g of powdered rock was mixed with 6 g of lithium tetra-borate to prepare fused pellets for the major oxides analyses. Internationally certified rock reference materials of different compositions (i.e., Serpentine UB-N, Granite GSR-1, Andesite GSR-2, Basalt GSR-3, Sandstone GSR-4, Shale GSR-5, Limestone GSR-6) were used as control samples. The geochemical data is presented in table 1.

3. RESULTS AND DISCUSSION

3.1. Geochemistry of Metavolcanics and Granitoids

The general characteristics of the Dallol metavolcanic and granitoids are illustrated in the total alkali-silica (TAS) classifications of Le Bas et al. (1986) and Cox et al. (1979) (Fig 2). In this classification, the rocks with the exception of few samples are sub-alkaline in nature. All the analyzed rocks have SiO_2 contents ranging from 36.9 to 76.65 wt% and also show a wide range in concentrations of other major and minor element oxides. Some of the Dallol mafic metavolcanics have exceptionally very high CaO (4.79 to 19.92 wt%) and low TiO_2, MgO and Fe_2O_3 contents (Fig 3).

The Dallol granitoides on the other hand are subalkaline in nature and plotted on the granite and granodiorite fields (Fig 2b). They all display a bulk medium to high-K calc alkaline trend and strong affinity towards the metaluminous and to some extent peraluminous character with SiO_2 contents ranging from 61.5 – 76.65 wt% (Fig 4a &b, Table 1). They show mild Fe-enrichment, similar to calc-alkaline volcanic rocks. As Asrat (2003) indicated, most of the northern Ethiopian granitoids are characterized by highly peraluminous with some affinity towards metaluminous

Table 1. Major element contents of the volcanic, metavolcanic and felsic intrusives from the western margin of Dallol area, Northern Ethiopia.

Sample no	**Rock type**	**Latitude (N)**	**Longitude (E)**	**SiO_2**	**TiO_2**	**Al_2O_3**	**$(Fe_2O_3)^T$**	**MnO**	**MgO**	**CaO**	**Na_2O**	**K_2O**	**P_2O_5**	**LOI**	**SUM**
Metavolcanic rocks															
DL-01a	Felsic MV	14°13’00”	39°48’6”	65.34	0.65	17.21	3.22	-	1.15	2.98	5.61	1.81	0.21	2.23	100.41
DL-02	Int. MV	14°12’58”	39°46’45”	54.78	0.97	15.83	6.83	0.10	4.21	5.66	5.47	0.68	0.20	5.92	100.65
DL-03a	Mafic MV	14°13’7”	39°46’52”	48.17	1.01	16.84	9.09	0.16	8.14	4.79	5.56	0.08	0.17	6.78	100.79
DL-04a	Tuff	14°13’10”	39°46’56”	65.18	0.63	14.41	5.77	0.05	1.66	3.28	1.19	3.15	0.13	4.99	100.43
DL-09	Tuff	14°13’14”	39°47’17”	61.37	0.71	18.12	4.49	-	2.35	0.87	1.91	7.25	0.37	3.06	100.49
DL-11	Carb. MV	14°09’34”	39°50’15”	38.62	0.63	16.00	7.98	0.16	2.03	19.92	2.49	0.48	0.15	11.84	100.29
DL-13	Mafic MV	14°09’11”	39°49’26”	52.76	1.02	17.84	8.86	0.17	3.53	7.78	5.52	0.61	0.37	1.66	100.13
DL-15	Mafic MV	14°10’49”	39°51’49”	48.97	0.70	20.45	9.74	0.17	3.69	12.21	2.55	0.54	0.32	0.89	100.23
DL-19d	Mafic MV	14°12’45”	39°55’6”	49.45	0.70	13.78	9.31	0.36	5.59	17.23	2.01	0.53	0.20	2.18	101.35
DL-20	Felsic MV	14°04’38”	39°59’59”	61.98	0.52	17.11	6.32	0.12	2.06	5.14	3.80	1.04	0.11	2.28	100.48
DL-31b	Carb. MV	14°15’34”	39°56’57”	36.90	0.50	12.53	7.98	0.22	3.63	19.76	2.63	0.29	0.13	14.60	99.15
DL-33	Mafic MV	14°15’44”	39°55’32”	48.61	0.59	12.76	9.26	0.15	8.42	12.77	3.10	0.31	0.22	3.08	99.28
DL-35b	Int. MV	14°22’4”	39°56’16”	59.74	0.60	15.26	6.40	0.15	2.26	4.96	3.41	1.21	0.14	5.76	99.88
DL-39	Felsic MV	14°18’55”	40°03’01”	74.08	0.35	12.28	2.68	0.13	2.17	1.17	4.01	2.40	0.08	1.02	100.36
DL-40a	Mafic MV	14°19’18”	40°07’39”	47.01	1.18	14.11	8.83	0.17	3.96	10.88	1.98	0.81	0.21	11.61	100.75
Mafic sill-dyke															
DL-07	Mafic sill	14°13’13”	39°47’6”	52.09	2.25	14.20	13.61	0.21	4.84	8.39	3.00	0.54	0.37	1.09	100.60
DL-10	Basalt	14°12’48”	39°48’13”	48.41	3.70	14.10	16.03	0.24	5.71	9.53	2.98	0.58	0.53	0.08	101.88
DL-19a	Mafic Dyke	14°12’45”	39°55’6”	50.49	2.98	12.91	14.74	0.22	4.65	7.87	3.67	0.68	0.36	1.90	100.47
DL-22	Mafic Dyke	14°10’5”	39°59’43”	46.74	3.55	12.73	18.06	0.23	5.21	8.96	2.71	0.89	0.34	1.24	100.65
DL-45	Mafic Dyke	14°13’6”	40°10’52”	44.26	3.10	14.14	12.58	0.15	4.27	10.79	1.71	0.15	0.44	8.10	99.70
DL-46	Mafic Dyke	14°04’1”	40°13’10”	48.99	1.97	14.93	15.34	0.24	5.56	10.58	2.67	0.35	0.27	0.26	101.16
Granitoids															
DL-16	Fine Granite	14°11’5”	39°51’45”	69.87	0.30	17.02	1.96	-	0.57	1.73	3.17	4.18	0.14	1.44	100.37
DL-17	Coarse Granite	14°11’23”	39°51’50”	66.84	0.62	15.66	3.56	0.05	1.38	2.84	4.08	4.19	0.21	0.54	99.96
DL-19b	Apilitic Dyke	14°12’45”	39°55’6”	76.65	-	14.35	0.49	-	0.06	0.71	7.02	0.88	-	0.33	100.48
DL-19c	Granodiorite	14°12’45”	39°55’6”	63.61	0.89	15.41	4.75	0.04	2.30	3.73	4.10	3.21	0.43	0.69	99.17
DL-23	Apilitic Dyke	14°09’56”	39°59’28”	73.24	0.14	14.21	1.65	-	0.17	1.09	5.15	3.49	-	0.90	100.03
DL-24a	Coarse Granite	14°10’4”	39°57’55”	68.34	0.43	16.36	2.53	-	0.83	2.58	4.60	3.93	0.12	0.59	100.31
DL-24b	Granodiorite	14°10’4”	39°57’55”	64.26	0.91	15.65	4.21		1.92	3.66	4.19	3.50	0.32	0.88	99.48
DL-25	Fine Granite	14°11’6”	39°55’2”	70.81	0.32	12.50	3.67	0.10	0.17	1.46	3.29	5.03	-	1.79	99.14
DL-26	Granodiorite	14°12’25”	39°51’37”	61.47	1.08	15.46	5.65	0.08	2.89	4.41	4.01	2.93	0.54	0.60	99.12
DL-27a	Fine Granite	14°13’44”	39°51’43”	70.04	0.35	15.24	2.06	-	0.54	1.70	4.37	4.06	0.10	0.95	99.42
DL-28	Coarse Granite	14°13’41”	39°51’46”	68.61	0.47	15.15	2.91	-	0.94	2.23	4.12	4.20	0.19	0.44	99.26

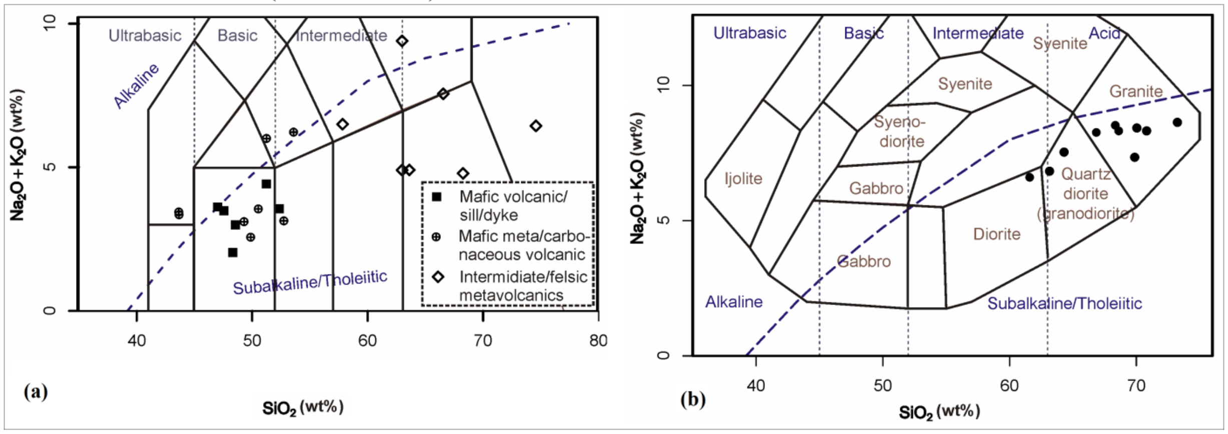

Figure 2. Total alkalis ($Na_2O + K_2O$) versus silica (SiO_2) variations in the western margin of Danakil Depression. Oxides are recalculated (LOI-free) using the SINCLAS program of Verma et al. (2002) for obtaining the TAS names. (a) Volcanic and metavolcanic rocks; (b) Dallol granitoids. The dashed lines distinguishes alkaline from subalkaline basalts (after Le Bas et al., 1986 and Cox et al., 1979).

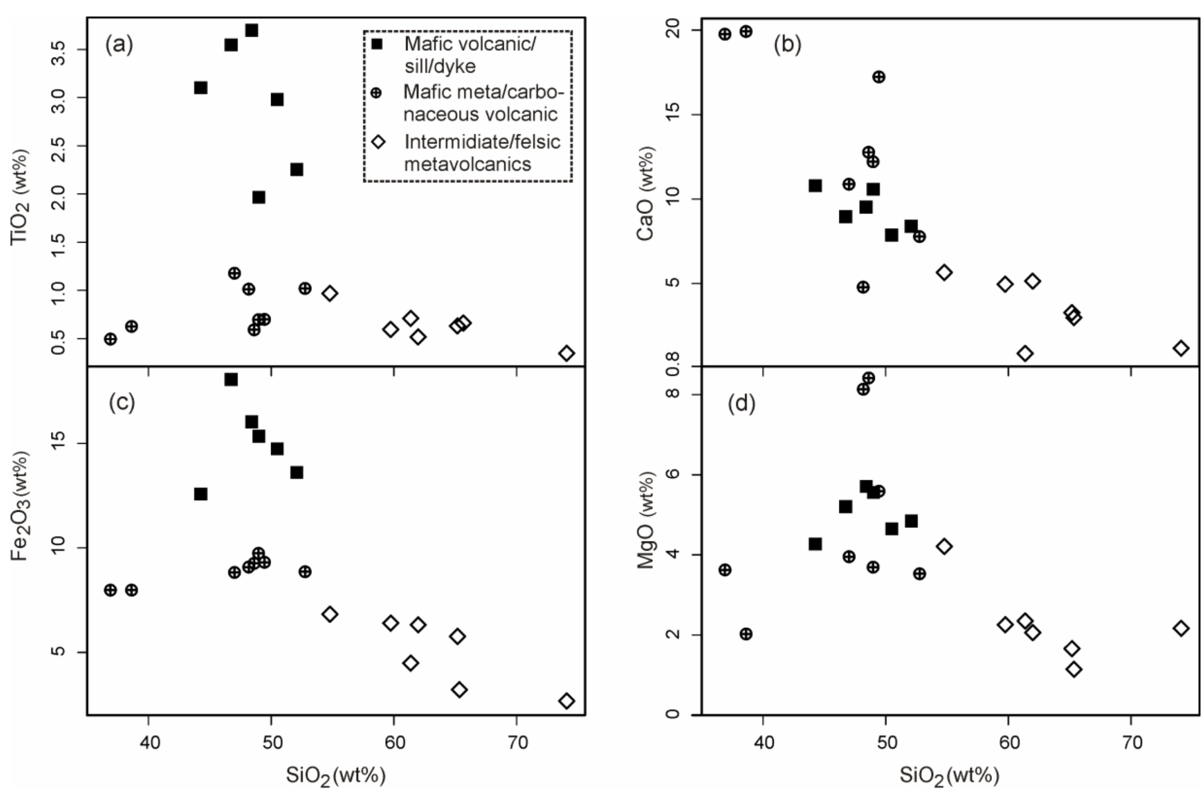

Figure 3. Harker variation diagrams for the volcanic metavolcanic rocks of Dallol area. All the major oxides are characterized by their own pattern as SiO_2 progress from 35–75 wt%.

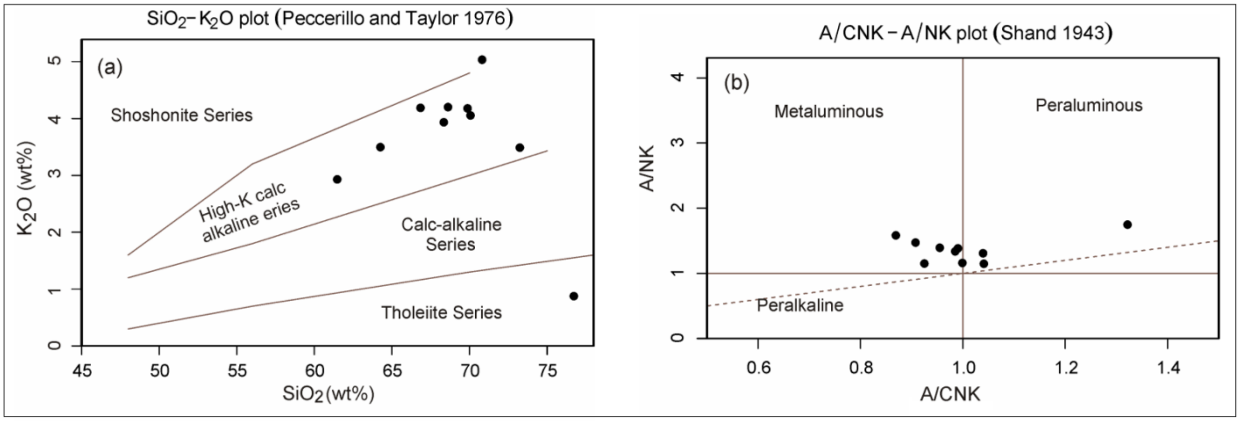

Figure 4. (a) K_2O vs. SiO_2 diagram illustrating the character of the Dallol granitoids; (b) Classic A/CNK vs A/NK plot for discriminating metaluminous, peraluminous and peralkaline compositions. (A/CNK vs A/NK → $Al_2O_3/CaO+Na_2O+K_2O$ vs. Al_2O_3/Na_2O+K_2O).

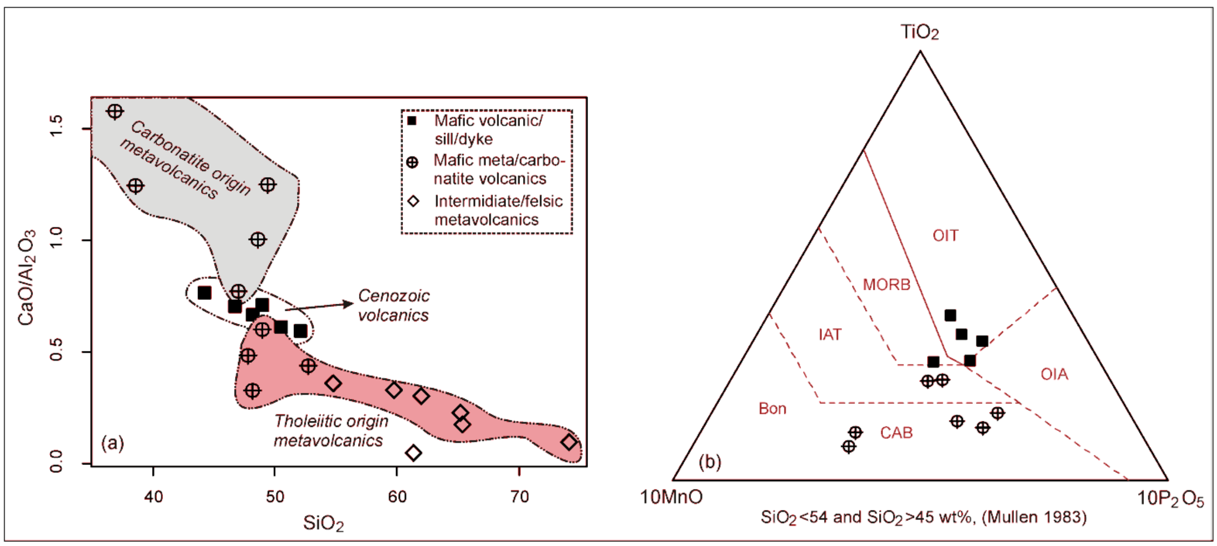

Figure 5. (a) Plot of CaO/Al_2O_3 ratio against SiO_2 (Hagos et al., 2010), showing the two apparent evolution trends for the metavolcanic rocks of Dallol area. Most of the mafic/ultramafic metavolcanics plot at higher ratios and some of the mafic/ultramafic and all the felsic metavolcanics plot at lower ratios; (b) MnO—TiO_2—P_2O_5 discriminant plot (after Mullen, 1983) for non-boninitic Lushs Bight Group lavas and dykes (A—lavas, B—dykes). OIT—ocean-island tholeiites; OIA—ocean-island basalts; MORB—mid-ocean ridge tholeiites; IAT—island-arc tholeiites; CAB—calc-alkalic basalts. (Note: Plots were screened for samples with silica content between 45 and 54 percent).

nature, but the granitoids of western margin of northern Afar Depression are highly metaluminous in nature (Fig 4b). The Dallol area mafic volcanic rocks commonly exist as dykes and sills within the basement rocks and as lava flows along the Dallol rift floor are tholeiitic in nature and are indistinguishable with the Stratoid and axial volcanics of the Erta'Ale range (Hagos, 2011). These volcanic/hypabyssal rocks have similar petrological and geochemical characteristics. They are enriched by TiO_2 and Fe_2O_3 and depleted in MgO showing early fractionation of olivine from the magma (Figs 3a, c & d).

Though, many studies have already been conducted on ANS with integrated approaches of radiometric, isotopic and geochemical investigations, the nature and genesis of the juvenile crust of northeastern Africa is not still well constrained. Based on the geochemical results of samples collected from the western margin of northern Afar, two distinct magma series exist within the metavolcanic rocks of the area. The distinct geochemical and geotectonic signatures for the samples from Dallol area indicate that the petrogenetic processes of the provenance that formed these rock types were different (Fig 5). One of the major element binary plots that can show differences in the petrogenetic processes is the CaO/Al_2O_3 vs. SiO_2 (Hagos et al., 2010).

5. CONCLUSIONS

In this study some genetic variations on the metavolcanic rocks of the western margin have been roughly constrained. Two well-defined metavolcanic rocks exist. The first group of metavolcanics have tendencies of mildly alkaline to tholeiitic nature and comprise differentiated rocks of mafic – felsic compositions; whereas, the second group of metavolcanics have extremely higher contents of CaO and consequently higher values of loss-on-ignition (LOI) indicating the presence of carbonatitic lava as provenance. The presence of metaluminous-peraluminous granite in the area indicated that the granitic magma producing these rocks might come from the melt of the volcano-sedimentary assemblages of volcanic arc terrains.

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