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Major, Trace Elements and Sr-Nd Isotopic Characteristics of High-Pressure and Associated Metabasites from the Pan-African Suture Zone of Southern Togo, West Africa

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Abstract
Eclogites and garnet-bearing or garnet-free amphibolites from Lato, Toutouto and Ahito-Meliendo hills in southern Togo, were analyzed for their bulk rock geochemistry and Sr and Nd isotopic compositions. Major and trace element compositions for these rocks indicate that precursor magmas belong to tholeiitic to subalkaline series which may have evolved by fractional crystallisation. However, some intense sheared eclogites from southern Lato hills display secondary LREE-loss patterns not typical of magmatic protoliths. Measured ratios and epsilon values have been recalculated at 800 Ma. $^{87}Sr/^{86}Sr$ initial values for the eclogites and amphibolites range from 0.70215 to 0.70460 and from 0.70126 to 0.70307, respectively. $^{147}Sm/^{144}Nd$ values for both eclogites and amphibolites range from 0.14510 to 0.183320 and are lower than chondritic values of 0.1966. Overall $^{143}Nd/^{144}Nd$ values range from 0.512804 to 0.512862, corresponding to initial $\varepsilon_{Nd}(T)$ from +4.9 to +8.8 that yielded T_{DM} model ages from 1.6 to 0.72 Ga. One eclogite from south Lato hill displays $^{143}Nd/^{144}Nd$ values of 0.512862, corresponding to initial $\varepsilon_{Nd}(T)$ values of +8.83 and T_{DM} model age of 0.72 Ga, that constrains its minimum age. However, eclogites from northern Lato and garnet amphibolites yielded older model ages of 1.65 and 1.43 Ga respectively, suggesting crustal contamination of the surrounding metasedimentary pile.
Key words: Eclogites, Sr-Nd isotopes, Pan-African suture zone, Togo.

1. Introduction

Eclogite facies metamorphic rocks form in the deeper parts of subducted slabs and occur commonly as exhumed and preserved components in orogenic belts (Janak *et al*. 2012; Mpokos *et al.* 2012; Ganade de Araujo *et al.* 2014a and references therein). Eclogites could derive from fragments of oceanic lithosphere that have either been intensely metamorphosed during subduction-obduction-related processes along plate active margins or, alternatively, associated with continental crust and affected by major intracontinental thrusting (Schmädicke *et al.* 1995). They are extremely useful indicators of the geodynamic evolution of plate margins and orogenic belts. The relationship between eclogitic rocks and their country rocks is key to understanding subduction and exhumation processes of UHP-HP metamorphic rocks (Mpokos *et al.* 2012). However, eclogitic rocks commonly experience lower grade overprint during exhumation that obliterates its peak conditions (Wallis and Aoya, 2000; Mouri and Enami, 2008).

The Pan-African Dahomeyides belt in southern Togo is part of the larger West Gondwana Orogen that runs from Algeria to NE-Brazil and contains isotropic, sheared and more or less retrogressed eclogites together with garnet or garnet-free amphibolites (Fig. 1). These metabasites belong to a series of ulbramafic-mafic complexes scattered throughout the Pan-African Dahomeyides belt along the 'so-called' suture zone (Affaton *et al.,* 1980; Ménot, 1980; Bernard-Griffiths *et al.* 1991; Attoh, 1998a; Attoh and Morgan, 2004; Agbossoumondé *et al.* 2004).

Research focus has majorly been paid on the high-pressure rocks from the Pan-African suture zone in Ghana and Togo. In contrast, Sr-Nd isotopic data for the métabasites have been poorly reported, with only Bernard-Griffiths *et al.* (1991) have attempted to present Sr-Nd isotopic studies on eclogitic rocks in southern Togo. In this study, we document Sr-Nd data on four selected eclogite samples from Lato hills and on five garnet-bearing and garnet-free amphibolites samples from the Toutouto and Ahito mountains (Fig. 2) with the objectives of constraining the origin of these rocks and discuss their petrogenesis, protolith of magmatism and eclogite-facies metamorphism during Neoproterozoic times.

2. Geological outline of the Dahomeyide belt

The Dahomeyide belt resulted from collision between the passive continental margin of the West Africa Craton (WAC) and the eastern continental block known as the Benino-Nigerian Shield (Caby, 1987; Castaing *et al.* 1994; Attoh *et al.* 1997; Bessoles and Trompette, 1980; Affaton *et al.* 1991) (Fig. 1). The connection of this shield to the proposed larger Saharan metacraton (Abdelsalam *et al.* 2002) further east is tantalizing, but is yet to be demonstrated. The belt corresponds to the southern segment of the Pan-African TransSaharan orogeny that extends for >2500 km from the Sahara desert to the Gulf of Guinea (Caby, 1987). Prior to the opening of the Atlantic Ocean this large belt was connected to the orogenic areas of northeast and central Brazil running for more than 4000 km in the Neoproterozoic West Gondwana Orogen (Caby, 1989; Trompette, 1994; Cordani *et al.* 2013a,b; Ganade de Araujo *et al.* 2014a).

In Ghana and adjoining parts of Togo and Benin, the Dahomeyide belt has a well-organized orogenic architecture with passive margin-related rocks, belonging to the WAC dominating in the external (westerly) portion of the orogen and active margin-related rocks dominating its internal (easterly) portion, marking the western active margin of the Benino-Nigerian shield (Affaton *et al.* 1991; Agbossoumondé *et al.* 2004; Attoh and Nude, 2008). The classical subdivision of the Dahomeyide belt (Affaton, 1990) includes three main structural units: (i) the western external structural units corresponding to the Buem and Atacora groups; (ii) the eastern internal structural units (Benino-Nigerian shieldbasement) and, (iii) in between the two, the so-called Dahomeyide suture zone is characterized by high-grade mafic–ultramafic massifs (Agbossoumondé *et al.* 2001 ; Agbossoumondé *et al.* 2013 ; Ganade de Araujo *et al.* 2016). The Buem and Atacora structural units correspond to tectonic collages of various lithologies including both metasedimentary rocks from the WAC passive margin and pre-Neoproterozoic gneisses representing the old basement (Affaton *et al.* 1991; Agbossoumondé *et al.* 2004; 2013; Taïrou, 2006; Attoh and Nude, 2008; Attoh *et al.* 2013; Aïdoo *et al.* 2014 ; Ganade de Araujo *et al.* 2016)

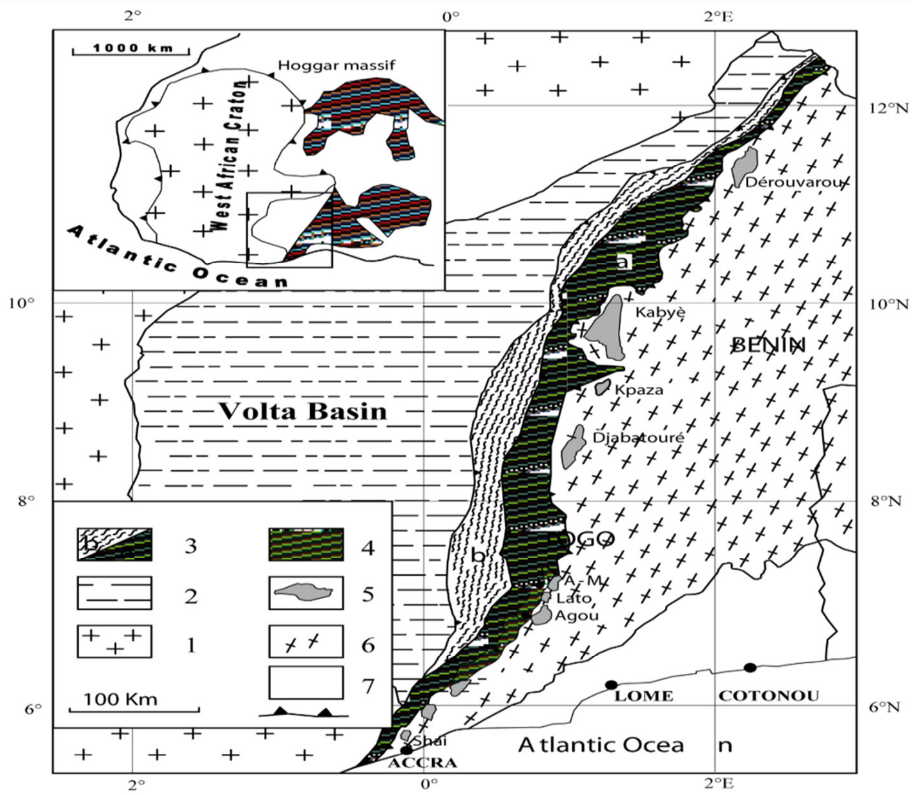


Fig. 1. Geological map with the main structural domains of Pan -African Dahomeyide belt and location of Lato and Ahito-Meliendo massifs in SW Togo. 1. West African Craton, 2. Volta Basin, 3. Buem and Atacora structural units, 4. Palimé-Amlamé Pluton, 5. Ultramafic and mafic complexes, 6. Composite basement of the Benino-Nigerian unit, 7. Coastal sedimentary basin, 8. Thrust. A-M. Ahito-Meliendo massifs

The suture zone is well exposed from southeast Ghana to northwest Benin and corresponds to a narrow and lithologically diverse area marked by striking positive gravity and magnetic anomalies (El-Hadj Tidjani *et al.* 1997). Numerous ultramafic and mafic units are scattered throughout the suture zone and display contrasting lithological and metamorphic features hosting UHP and high pressure (HP) eclogites, HP granulites and amphibolites (Ménot, 1980; Attoh *et al.* 1997; Agbossoumondé *et al.* 2001, 2004; 2013; Duclaux *et al.* 2006; Ganade de Araujo *et al.* 2014a).

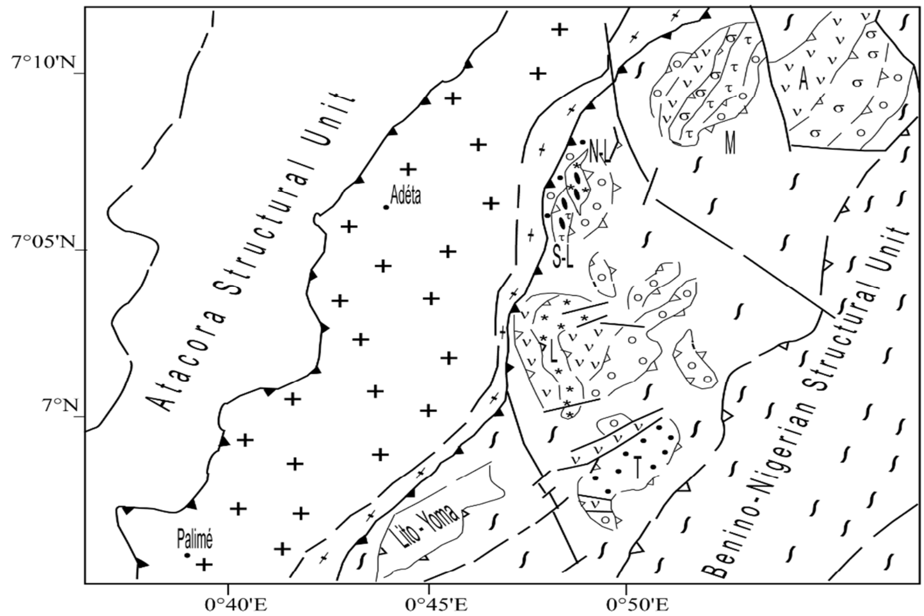
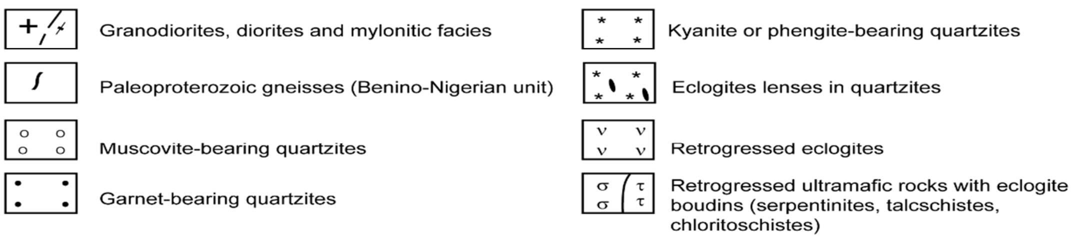


Fig. 2. Structural sketch map of the study area. A : Ahito Hills, L: Lititoé Hills, N-L: northern Lato Hills, S-L: southern Lato Hills, M: Meliendo Hills, T: Toutouto Hills



3. Previous data on eclogites of Lato

In southern Togo, two types of eclogites have been characterized in the Lato hills according to field and textural criteria. These are (a) layers of a few metres thick, intercalated within phengite-bearing quartzites (Fig. 3a) in north Lato hills, (sills and flows "in situ" within detrital sedimentary series) and (b) metric-boudins, as relicts within retrogressed matrix of chlorite and actinolite garnet-bearing schists in south Lato hills (dismembered mafic bodies as tectonic slices within ortho- and paragneisses) (Ménot and Seddoh, 1985; Agbossoumondé *et al.* 2001, Agbossoumondé *et al.* 2016). This paper will focus on these two types of eclogites from the Lato hills and also on garnet bearing amphibolites and garnet-free amphibolites, from the Toutouto and Ahito hills respectively (Fig. 2).

Eclogites from Lato hills were discovered by Kouriatchy (1932) and first described by Ménot and Seddoh (1985). They display two texturally different varieties independently of their location and setting: an isotropic, generally coarse-grained (1-5 mm) facies (samples L2-L4, Figs. 3c and 3d) variety; and a banded and fined grained (0.5 mm) mylonitic type (samples L1, L3, Fig. 3b). Within a single tectonic unit, both isotropic and mylonitic facies exhibit similar mineral assemblages composed of garnet, omphacite, phengite, talc, clinozoisite and quartz. Garnet porphyroblasts contain numerous inclusions of rutile, zircon, allanite and omphacite (Figs. 3c and 3d). This suggests syn-kinematic recrystallisation under eclogite-facies conditions (Gay and Ménot, 1990). Garnet-bearing amphibolites southwards in the Toutouto Hills and garnet-free amphibolites northwards in the Ahito Hills have been recognised as retrogressed eclogites (Agbossoumondé, 1998; Agbossoumondé *et al.* 2001). They outcrop as several metres thick lenses and layers within kyanite- and/or garnet-bearing metaquartzites. Textures vary from massive to finely banded. The mineralogy comprises in decreasing amounts, amphibole, garnet, clinopyroxene, zoisite, plagioclase, quartz, ilmenite, rutile and secondary phases (epidote, actinolite, calcite, titanite). In these rocks, the primary jadeite-rich clinopyroxene was totally transformed to diopside-plagioclase and then to amphibole-plagioclase symplectites (Agbossoumondé *et al.* 2001). According to Ménot and Seddoh (1985), the occurrence of high-pressure (HP) metamorphic rocks, eclogites and eclogitised sediments in the 'suture zone' point out paleosubduction processes. Ocean floor accretion and subsequent continental subduction occur during Neoproterozoic times, as shown by the poorly constrained ages of Bernard-Griffiths *et al.* (1991), from U-Pb zircons ages of 820 ± 100Ma and 638 ± 12Ma of the basaltic protoliths and the high-pressure metamorphism respectively. The HP conditions lasted until 598 ±2Ma (Rb/Sr on phengite).

Agbossoumondé *et al.* (2001) observed in the eclogites and amphibolites a regressive evolution from eclogite- to granulite- to amphibolite- to greenschist-facies conditions. Estimation of the crystallisation of various eclogitic assemblages show that P-T conditions in eclogites intercalated within phengite-bearing quartzites in north Lato hills are 1.9 ± 0.4GPa, 700°±95°C, while the southern Lato eclogites display P-T conditions of 1.3±0.2GPa,, 650±50°C. More recently, Ganade de Araujo *et al.* (2014) indicated that no coesite relics have been found so far in Lato eclogites. However, their calculated P-T conditions plot within the coesite stability field and are in the range of 2.8–3.0GPa (±0.3GPa) and 620–700°C (±65°C) suggesting UHP metamorphism. These authors also obtained the age of crystallization of the basaltic protolith by dating zircon cores at 703.2 ± 8.1 Ma. The age of the UHP metamorphic event is dated at 609±6 Ma from the zircon rims of the Lato eclogites. (Ganade *et al.* 2014) The zircon cores have steep to flat HREE patterns while the zircon rims commonly have lower Th/U (mostly 0.01– 0.09) and no significant Eu anomaly. Depletion of HREE together with the lack of negative Eu anomaly indicates that these zircons have grown in the presence of garnet and in the absence of plagioclase, i.e. in eclogite facies conditions.

Bernard-Griffiths *et al.* (1991) reported major and trace element analyses, as well as Rb-Sr in whole rocks and micas and Sm-Nd (whole rocks) isotopic data for eclogites from northern and southern Lato hills. Eclogites from northern Lato have REE patterns which are comparable both in shape and absolute REE contents to those of oceanic basalts of transitional type from transitional ridge segments and also to those of basalts from extensional settings. However, eclogites from southern Lato hills display unusual REE patterns in the sense that they do not resemble in any way the REE patterns of present-day unmetamorphosed igneous rocks. A whole rock-phengite Rb-Sr pair from northern Lato eclogites gives an age of 598±12 Ma.

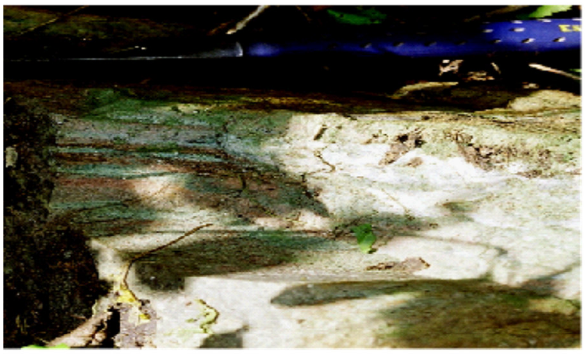


Fig. 3a. Eclogite layer fintercalated within phengite bearing quartzite from northern Lato hills (sample L4)

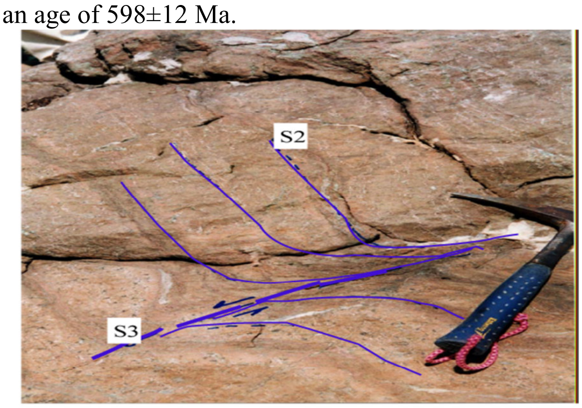


Fig. 3b. Eclogite layer from syn to late-eclogitic shear zone from northern Lato hills (sample L3)

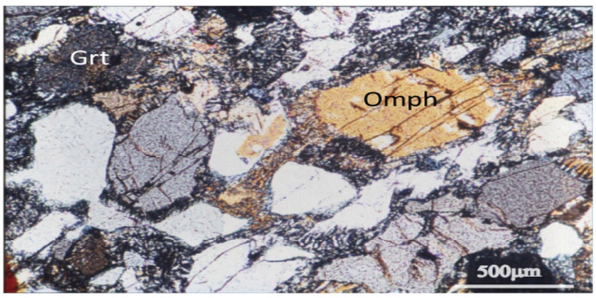


Fig. 3c. Photomicrograph of retrogressed eclogite L2 from the southern Lato Hills

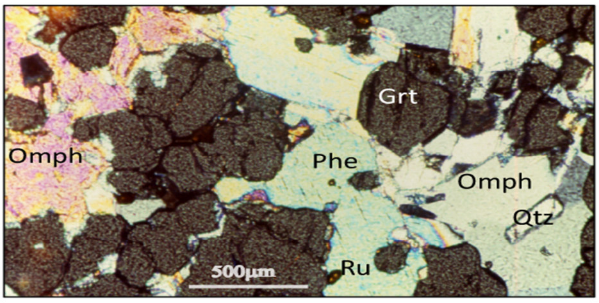


Fig. 3d. Photomicrograph showing the mineral composition of the northern Lato eclogite sample (L3) Omph: omphacite; Grt : garnet; Phe: phengite; Qtz : quartz; Ru : rutile

4. Analytical methods

Major and trace element compositions for four eclogites, two garnet amphibolites and three garnet-free amphibolites were measured at the University of Saint-Etienne (UMR-CNRS 6524 ''Magmas et Volcans''). Chips of whole rocks fresh samples were crushed and ground in an agate mill to ~ 200 mesh. For major element analysis, 0.5 g of the rock powder was mixed with 5 g of $Li_2B_4O_7$, and 3 drops of NH_4Br and the mixture was fused in a furnance to form a glass disk. Major elements were determined on fused glass beads using X-Ray fluorescence operating with a current of 50 mA and voltage of 50 kV. Analytical uncertainties are ( ) from ±1% to ±2% for major elements and ±5% for trace elements. REE analyses were performed using the UMR

CNRS ''Magmas et Volcans'' facilities (ICP-AES) at University Jean Monnet and the School of Mines, Saint Etienne. Prior to the analyses, about 100 mg of crushed whole-rock powder was dissolved using acid (HF + HNO_3, 1:3) in sealed Savillex beakers on a hot plate for 1 week. The method used was able to dissolve zircons and other refractory minerals to avoid trace elements fractionation. The sample was then dried and concentrated HNO_3 was added to the Teflon bomb, which was subsequently put into the jacket again and heated to 150°C for 24h. Separation of the REE was done through a cation-exchange column (AG50WX8, 200–400 mesh). Finally, 0.5g Rh (1 ppm) was added to the solution as an internal standard, and then the solution was diluted by a factor of 500. The solutions were analyzed using ICP-MS, with precisions generally better than 5 %. The analyses were carried out at Ecole des Mines de Saint-Etienne, France. Analytical uncertainties were 1-3% for elements present in concentrations >1 wt%, and about 10% for elements present in concentrations < 1 wt%.

The procedures used for isotopic analyses of Sm and Nd are described elsewhere (McCulloh and Compston, 1981; Li et al., 1994 and Guo et al., 2005). Nd and Sr isotopes were determined on five selected samples (L1, L3, L4, Ag228b and Ym55b) from Lato, Toutouto and Ahito (Togo) at Blaise Pascal University, Clermont-Ferrand (UMR CNRS ''Magmas et Volcans''). Rb, Sr, Sm and Nd concentrations have been measured by the isotope dilution method and the analytical errors of the ratios are estimated to be better than ± 1% (95 % confidence limit). The Sr and Nd compositions were determined on both VG Micromass 54E single-collector mass-spectrometer and Finnigan MAT 262V multicollector mass-spectrometer. For $^{87}Sr/^{86}Sr$ leach analyses, about 200 mg of powder were leached with 6.2 N HCl at 70°C for 60 minutes. The whole-rock powders used to determine element concentrations were not acid-washed and have been split into two aliquots: one for isotope dilution and on for isotopic composition. The $^{87}Sr/^{86}Sr$ ratio was normalised to $^{86}Sr/^{88}Sr$ = 0.1194. Ten determinations of SRM NBS 987 standard yielded an average value of 0.71028 ± 0.00002 (single collector mass-spectrometer). The $^{143}Nd/^{144}Nd$ ratio was normalised to $^{146}Nd/^{14}Nd$ = 0.72190. Results from the La Jolla standard (20 separate units) were in the range 0.511843-0.511852. Blanks for Rb, Sr, Sm and Nd were lower than 2 nanograms. Uncertainties of Rb/Sr and Sm/Nd ratios were less than 2% and 0.5% respectively.

5. Geochemistry

5.1. - Major and trace elements

In this study, two eclogitic samples (L1, L2) from southern Lato hills and also two samples from northern Lato hills (L3, L4) together with two garnet-bearing amphibolites (Ag228a, Ag228b) from Toutouto hills and three garnet-free amphibolites (ym55b, ym68b, Ag327) from Ahito hills were analysed for major and trace elements, including the rare-earth elements (REE). We also used previous analyses of Bernard-Griffiths *et al.* (1991) on the northern (TGL10, TGL13b) and southern (TGL11, TGL12) Lato eclogites (Table 1). All analyses were selected as being representative of basaltic liquids. Both eclogites together with and/or no garnet amphibolites have SiO_2 in the range 45.67-50.04 wt % (volatile free) and MgO from 4.96 wt.% to 10.29wt.% with mg-number of 31-49, and hence can be classified as subalkaline tholeiitic basalt or basaltic andesite (Fig. 4a) whereas the garnet amphibolite (Ag228b) displays more differentiated basaltic compositions with 52.15 wt% SiO_2. Eclogites from northern Lato hills contain higher Al_2O_3 (14.4-15.8 wt.%), TiO_2 (0.93-1.44 wt.%) contents than those from the southern Lato hills (13.6-13.99 wt.%) and (0.52-0.77 wt.%) respectively. Eclogites from southern Lato hills contain relatively higher concentrations in FeOt + MgO (21.62-23.67 wt.%) than the northern ones (17.8-20.6 wt.%), reflecting the primitive nature of the magma. Both display rather high CaO (10.45-13.77 wt.%), and moderate to slightly high Ni (66.9-212 ppm). All the samples have intermediate Na_2O (1.41-2.62 wt.%) and low K_2O (0.01-0.17 wt.%) contents (Table 1). Comparatively, amphibolites show higher TiO_2 (1.14-1.19 wt.%) and Sr (118-127 ppm) than the eclogitic samples (Table 1). This can be explained probably by crustal contamination of the surrounding metasedimentary pile. These samples plotted into the fields of basalt and basaltic andesite (Fig. 4a) exhibit the trend of the tholeiitic series in the AFM diagram (Fig. 4b).Their K_2O contents range from 0.01 wt.% to 0.47 wt.% and can be classified as low-K tholeiitic.

Rocks	Eclogites								Grt-bearing amphibolites		Grt-free amphibolites		
Massif	Southern Lato				Northern Lato				Toutouto		Ahito		
Samples	**L1**	**L2**	**TGL11****	**TGL12****	**L3**	**L4**	**TGL10****	**TGL13b****	**Ag228a**	**Ag228b**	**ym55b**	**Ag327**	**ym68b**
SiO2	47.07	49.5	49.62	48.56	47.94	49.95	50.04	49.87	45.67	52.15	51.21	49.47	49.2
Al2O3	13.99	13.71	13.61	13.7	14.75	15.85	14.4	14.96	13.36	14.5	13.89	14.9	15.57
FeOt	12.53	12.49	12.04	13.6	12.4	10.87	11.72	10.08	16.95	10.73	13.32	11.06	9.54
MgO	10.29	10.01	9.58	10.07	8.58	8.16	6.8	10.15	5.56	4.96	6.34	6.93	7.56
CaO	13.77	11.39	11.1	11.55	11.83	12.41	11.37	10.45	12.52	11.94	9.94	12.58	12.36
Na2O	1.41	1.89	2.19	1.89	2.4	1.83	2.54	1.68	2.9	2.62	2.7	1.5	3.82
K2O	0.04	0.04	0.01	0.01	0.03	0.06	0.01	0.12	0.17	0.06	0.47	0.26	0.22
TiO2	0.775	0.762	0.54	0.52	1.442	1.014	1.38	0.93	1.917	1.136	1.956	1.255	0.956
P2O5	0.01	0.0	0.04	0.07	0.05	0.1	0.31	0.18	0.17	0.09	0.22	0.13	0.14
MnO	0.189	0.181	0.22	0.20	0.196	0.174	0.21	0.17	0.255	0.121	0.194	0.182	0.157
PF	0.0	0.0	0.14	0.03	0.0	0.0	0.10	0.60	0.73	0.58	0.7	0.77	1.1
total	100.06	99.98	99.09	100.2	99.62	100.43	98.88	99.19	100.2	98.88	100.95	99.04	100.62
Mg#	49.14	48.54	48.35	46.55	44.87	46.92	40.56	54.22	24.70	31.61	32.25	42.43	44.21
Ti	4646.12	4568.18	3237.29	3117.39	8644.78	6078.92	8273.09	5575.34	11492.40	6810.31	11726.2	7523.71	5731.21
P	43.64	0	174.56	305.48	218.20	436.41	1352.88	785.54	741.90	392.77	960.1	567.33	610.97
Ni	109.8	151.6	127	150	125.9	132.2	100	212	66.9	87.5	38.3	114.1	98.3
Ga	12.7	15.2	nd	nd	16.5	15.9	nd	nd	15.6	16.3	nd	nd	nd
Rb	1.61	2.4	0.74	0.58	1.47	1.73	0.21	2	<2.0	1.8	25.7	<2.0	<2.0
Sr	30.7	27.6	26	26	56.3	118.1	212	87	118.4	127.0	176.1	118	162.2
Y	32.7	35.2	34	79	30.7	24.1	30	22	39.9	24.6	31.9	21	27.5
Zr	83.9	82.9	63	83	80.8	60.5	90	70	102.1	71.4	116	77.8	61.1
Nb	6.8	7.4	9	12	12.1	9.9	9	9	4.6	7.8	13.8	7.7	15.3
Hf	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	3.6	<3.0	<3.0	<3.0	<3.0
Pb	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0
Th	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0
Sn	3.9	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0	<3.0
Cs	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	<5.0	6	5.1	<5.0	<5.0	<5.0
Ba	16.0	22.7	13	nd	14.7	84.8	nd	128	41.2	27.6	234.3	26.7	56.1
Zr/Y	2.56	2.35	1.85	1.05	2.63	2.51	3	3.18	2.55	2.90	3.64	2.83	2.91
Zr/Nb	12.33	11.20	7	6.91	6.67	6.11	10	7.77	22.19	9.15	8.4	10.1	3.99
Nb/Y	0.20	0.21	0.26	0.15	0.39	0.41	0.30	0.40	0.11	0.31	0.43	0.28	0.73
La	4.86	3.31	0.87	6.01	5.63	5.65	5.97	6.19	5.5	6.02	11.9	5.26	8.93
Ce	13.1	7.55	1.66	15.97	13.9	12.9	14.1	13.79	14.7	14	26	11.9	19.1
Nd	10.1	5.35	1.52	11.89	8.75	7.92	10.58	9.28	15.5	10.8	18.8	8.91	11.7
Sm	2.56	1.86	1	3.80	2.1	2.4	3.32	2.62	4.6	3.18	4.75	2.49	2.69
Eu	0.954	0.992	0.58	1.15	0.819	0.837	1.19	0.9	1.51	0.974	1.49	0.754	0.909
Gd	4.15	4.48	3.49	7.04	3.36	3.08	4.29	3.21	5.38	3.57	5.7	2.68	3.06
Dy	5.65	5.98	5.11	11.2	4.72	3.74	4.99	3.82	6.23	3.9	5.71	3.01	3.26
Y	31.2	33.9	nd	nd	28.9	21.3	nd	nd	38.3	19.4	28.3	17.1	19.1
Er	3.79	3.47	3.52	7.59	3	2.22	3.15	2.44	4.05	2.25	3.17	1.99	2.02
Yb	3.47	3.63	3.51	7.95	2.84	2.27	3.11	2.41	4.05	2.66	3.2	1.69	1.95
Eu/Eu*	0.90	1.06	0.95	0.68	0.95	0.95	0.97	0.95	0.93	0.89	0.87	0.88	0.96
(La/Yb)N	0.93	0.61	0.17	0.50	1.32	1.66	1.28	1.71	0.91	1.51	2.66	2.23	3.28
(Ce/Sm)N	1.20	0.95	0.39	0.99	1.55	1.26	1.0	1.24	0.75	1.03	1.36	1.19	1.77

** samples from Bernard-Griffiths et al., 1991, nd = not determinated

5.2. - REE and incompatible element variations

Figures 5a, 5b, 5c are respectively chondrite-normalized rare earth element (REE) variation diagrams for the eclogites from southern Lato, northern Lato and GBA/GFA from the Toutouto and Ahito-Meliendo Hills. Ta is recalculated according to Rudnick and Fountain, (1995).

Southern eclogites REE patterns normalized spidergrams show that the eclogites from southern Lato display unusual REE patterns (Fig. 5a). Samples L2, L1 and TGL12 have a nearly flat 5-35 chondrite HREE patterns. Their LREE are depleted with respect to their HREE (=10-20 x chondrites), but are not fractionated [$(Ce/Sm)_N$ = 0.95-0.99], except sample L1 whose LREE are slightly enriched [$(Ce/Sm)_N$ = 1.2]. Sample TGL11 presents a markedly flat HREE pattern with extremely fractionated LREE [$(Ce/Sm)_N$ = 0.39]. This sample shows a syn-blastomylonitic fabric developped from sample TGL12 which has a granoblastic heterogranular texture, with large garnet porphyroblasts rich in inclusions (Ménot and Seddoh, 1985). Its LREE are thus not only depleted relative to the HREE, but also relative to the LREE of sample TGL12. Eclogite TGL11 is characterized by a fine-grained texture composed of alternating garnet (free of inclusions) and omphacite-rich bands.

On the contrary, eclogites layers (L4, TGL13b, L3 and TGL10) interbedded with quartzites from northern Lato (Fig. 3a) are characterized by nearly flat HREE normalized patterns (10-15 x chondrites) (Fig. 5b), slightly to moderately enriched LREE [$(Ce/Sm)_N$ = 1.0-1.55] and Eu displays a less pronounced negative anomaly (Eu/Eu* = 0.95-0.97). These eclogites have REE patterns and geochemical characteristics which are comparable both in shape and absolute REE contents to those of oceanic basalts of transitional type (T-type of Schilling, 1975) or E-type MORB from transitional ridge segments, and also to those of basalts from continental extensional settings (Fodor and Vetter, 1984).

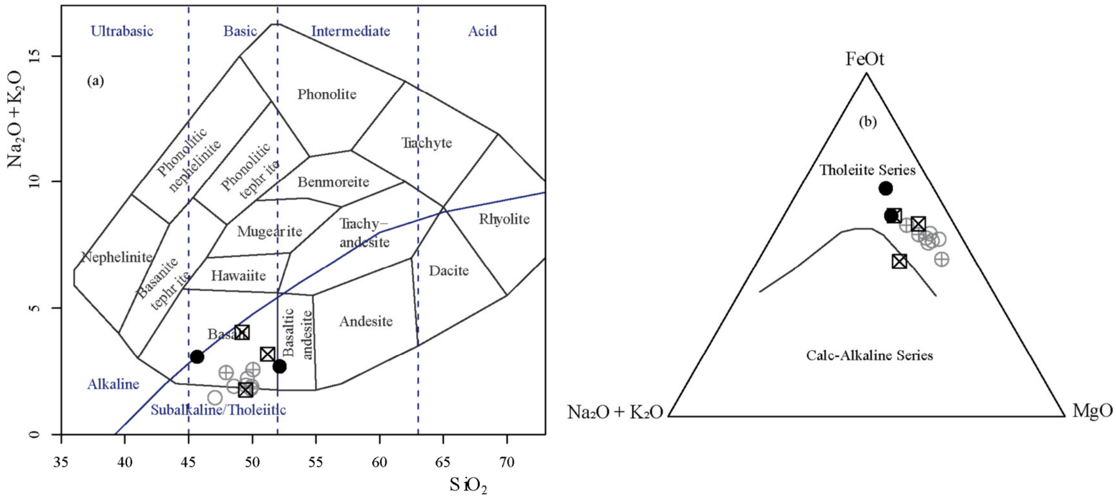


Fig. 4. (a): Na_2O+K_2O vs SiO_2 discrimination diagram after Cox et al., (1979) and (b) : Na_2O+K_2O-FeOt-MgO discrmination diagram after (Irvine and Baragar, 1971)

Legend

○ South Lato eclogites ⊠ Garnet-free amphibolites from Ahito

⊕ North Lato eclogites ● Garnet-bearing amphibolites from Totouto

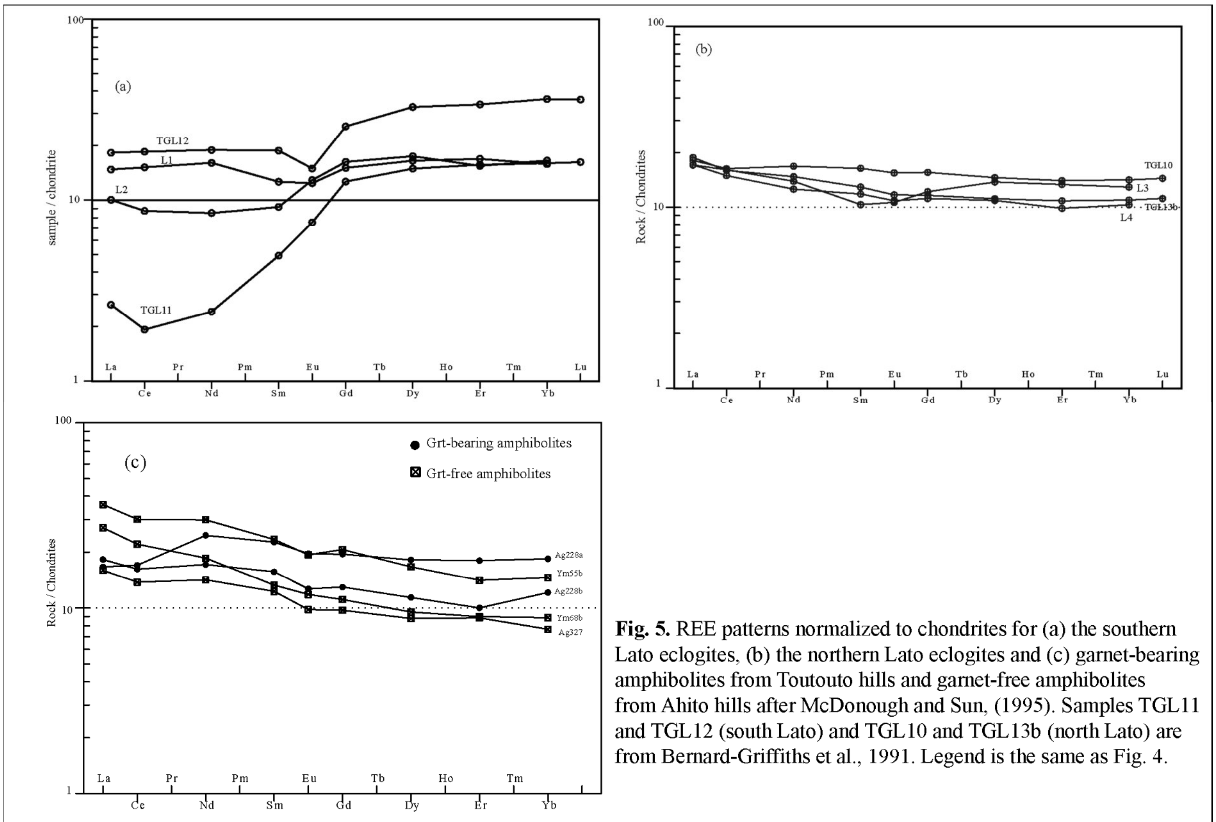


Fig. 5. REE patterns normalized to chondrites for (a) the southern Lato eclogites, (b) the northern Lato eclogites and (c) garnet-bearing amphibolites from Toutouto hills and garnet-free amphibolites from Ahito hills after McDonough and Sun, (1995). Samples TGL11 and TGL12 (south Lato) and TGL10 and TGL13b (north Lato) are from Bernard-Griffiths et al., 1991. Legend is the same as Fig. 4.

Garnet-bearing and garnet-free amphibolites respectively from Toutouto and Ahito have similar REE patterns compared to those of northern Lato (Fig. 5c). Both metabasites are layers interbedded with quartzites or kyanite-bearing quartzites. Chondrite-normalized rare earth element (REE) patterns for the analyzed samples reveal a relatively gradual increase in the concentrations of the LREE from the garnet-bearing to garnet-free amphibolites of Ahito. Garnet-free amphibolites are more fractionated and enriched LREE than the northern Lato eclogites, with a slight slope from LREE to HREE. In contrast, garnet-bearing amphibolites are depleted in LREE and showing significant enrichments in HREE, especially in Yb, characteristics of the presence of garnet. The amphibolite Ag228a displays a humped pattern, with enriched MREE patterns (La_N/Yb_N = 0.91) with a slightly negative Eu anomaly (0.93) which are compatible with presence of amphibole.

5.3. - Isotope data

- Eclogites

Previous U-Pb analyses of zircon from the Pan-African high-pressure rocks gave an age of 603-613 Ma which was interpreted as the time of peak metamorphism (Attoh *et al.* 1991; Hirdes and Davis, 2002; Affaton *et al*. 2000; Attoh and Schmitz, 2005; Attoh *et al.* 2007). According to these authors an age of ~ 800Ma could be attributed to that of the basic protoliths. Therefore, measured ratios and epsilon values have been recalculated in this study at 800Ma for eclogites and amphibolites rocks from the Pan-African suture zone in southern Togo. Sr-Nd isotopes dating result for eclogites and amphibolites are shown in Table 2.

Eclogites from the northern Lato (L3, L4) have fairly constant $^{147}Sm/^{144}Nd$ ratios between 0.14510 and 0.18320 ; $^{143}Nd/^{144}Nd$ ratios between 0.51280 and 0.51281, corresponding to initial $\varepsilon_{Nd}(T)$ values between +4.90 (L4) and +8.53 (L3). $^{87}Sr/^{86}Sr$ ratios of eclogites are higher and range from 0.70215 to 0.70460. Such dispersion of isotopic values for Sr and $\varepsilon_{Nd}(T)$ may be indicative of crustal contamination of a LREE depleted mantle, reflecting either an enrichment of the mantle wedge by fluids derived from subducted metasediments or metamorphic effects during collision

Eclogite L1 from the southern Lato displays similar isotopic features such as eclogite L3. It has constant $^{147}Sm/^{144}Nd$ ratios of 0.15324, $^{143}Nd/^{144}Nd$ ratios of 0.51205 corresponding to initial $\varepsilon_{Nd}(T)$ values of +8.83.

The model ages are consistent with field observations where two types of eclogites were distinguished. Eclogite from the southern Lato (L1) gives a model ages close to 0.72 Ga, similar to the model ages of 0.76 Ga for the eclogite (L3) from the northern Lato, whereas eclogite (L4) from the northern Lato gives and older model ages of 1.65 Ga. Eclogite L4 indicates a maximum age for the basaltic magmatism which gave rise to eclogitic protoliths.Furthermore, this sample is thought to have unaffected or only slightly modified during the metamorphism and mylonitic events than eclogites L1 and L3 which underwent LREE loss during blastomylonitization

- Amphibolites

Garnet-free amphibolite (Ym55b) from Ahito display $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios of 0.15275 and 0.51282 respectively, corresponding to initial $\varepsilon_{Nd}(T)$ value of +8.06 (Table 2). These values are similar to those obtained on eclogites L3 from northern Lato and L1 from the southern Lato. Therefore, amphibolite Ym55b may be considered to have resulted from eclogites L1 and L3 and thought to represent a sample which has been most affected by post-magmatic alteration processes during the cooling of the high-grade metamorphism.

The garnet bearing-amphibolite (Ag228b) from the Toutouto hills displays similar $^{147}Sm/^{144}Nd$ (0.17942) and $^{143}Nd/^{144}Nd$ (0.51282) values corresponding to initial $\varepsilon_{Nd}(T)$ values of +5.46 as eclogite L4 (table 2). It also displays an older model ages of 1.43 Ga very close to 1.65 Ga obtained on eclogites L4. Measured $^{87}Sr/^{86}Sr$ for the amphibolites Ag228b and Ym55b vary from 0.70354 to 0.70608 respectively. The initial strontium isotopic compositions range from 0.70307 to 0.70126 and are slightly lower than those obtained on eclogites, with the exception of sample L3. The slightly high strontium composition of eclogitic samples could be explained either by a heterogeneous mantle source influenced by a crustal component and/or the existence of the metasomatised lithosphere, or by contamination of mantle-derived magma with the continental crust that could have occurred during the emplacement of the basaltic protolith.

6. – Discussion

6.1. - Petrogenesis

Eclogites from the Pan-African suture zone in southern Togo have content of loss on ignition ranging from 0.1 wt.% to 1.1 wt.% (Table 1). The studied samples have linear correlations in the plots of some major oxides vs. SiO_2 (Fig. 6a-f) and the incompatible (e.g., Nd, Y and Nb) elements vs. Zr (Fig. 7a-c). These signatures, together with the consistency of the data set in the REE patterns in figures 5a, b and c (except for the eclogites TGL11, Fig. 5a), suggest an insignificant low-temperature alteration. Eclogites and amphibolites samples have low to moderate mg-number of 31.6 – 54.2 indicating that the magma might have experienced crystallization fractionation of olivine and pyroxene. This is further supported by the decrease of MgO, FeOt and CaO and increase of Al_2O_3 with increasing SiO_2 (Fig. 6a-d), along with the positive correlations between compatible element Ni and MgO (Fig. 7d). According to the variation trends in the plots of La/Sm vs. La and La/Yb vs. Yb diagrams (Fig. 8a-b), it appears that the source heterogeneity is a most likely alternative rather than the crystallization fractionation. It is generally assumed that the REE are reliable geochemical tracers due to their relative insolubility in seawater and their refractory nature (Hajash, 1984). Although cases of REE mobility have certainly been demonstrated (Nyström, 1984), these elements are not strongly affected by eclogite-facies metamorphism (Bernard-Griffiths *et al.* 1991). According to Bernard-Griffiths *et al.* (1991), the REE of eclogite whole-rock samples are not representative of magmatic protoliths.

6.2. - Sr-Nd geochemistry

The Lato hills eclogites and the related retrogressed amphibolites, together with their close association with clastic sediments of continental origin, display distinct geochemical features and represent E and T-MORB tholeiites, typical for extensional environments, continental rift or narrow ocean (Bernard-Griffiths *et al.* 1991; Agbossoumondé *et al.* 2001).

In this study, obtained model ages are consistent with field observations where two types of eclogites were distinguished. Northern Lato eclogite (L4) and garnet bearing-amphibolites Ag228b from Toutouto gave older model ages of 1.43 to 1.65 Ga. Southern eclogite (L1) and garnet-free amphibolite (Ym55b) from Ahito displays model ages of 0.72 and 0.82 Ga, indicating distinctive mantle extraction age. The interpretation of the age data of the eclogites and amphibolites is not quite straight-forward. The petrogenetic affinity of eclogites and amphibolites and their close association in the field must be interpreted as indicating formation during one common Pan-African orogen event. Our present results could be compared to those obtained in the zircon population of carbonatite in the Pan-African suture zone in Ghana (Attoh *et al.* 2007). Nd isotopic analysis of a carbonatite sample, gave $^{143}Nd/^{144}Nd$ = 0.511939 and a model age T_{DM} (Nd) = 0.99Ga. According to Attoh *et al.* (2007), this age sets an upper limit to the time of magmatic emplacement and similar model ages of T_{DM} (Nd) = 0.96 Ga and T_{DM} (Hf) = 0.77 Ga have also been obtained from high-pressure métabasites from the suture zone (Attoh and Schmitz, 2005). Compared to these results from the suture zone in Ghana, our distinctive mantle extraction model ages of 0.72 and 0.82 Ga, indicate that the eclogitic protolith was emplaced magmatically from 800 to 700 Ma and was metamorphosed 200-100 Ma thereafter.

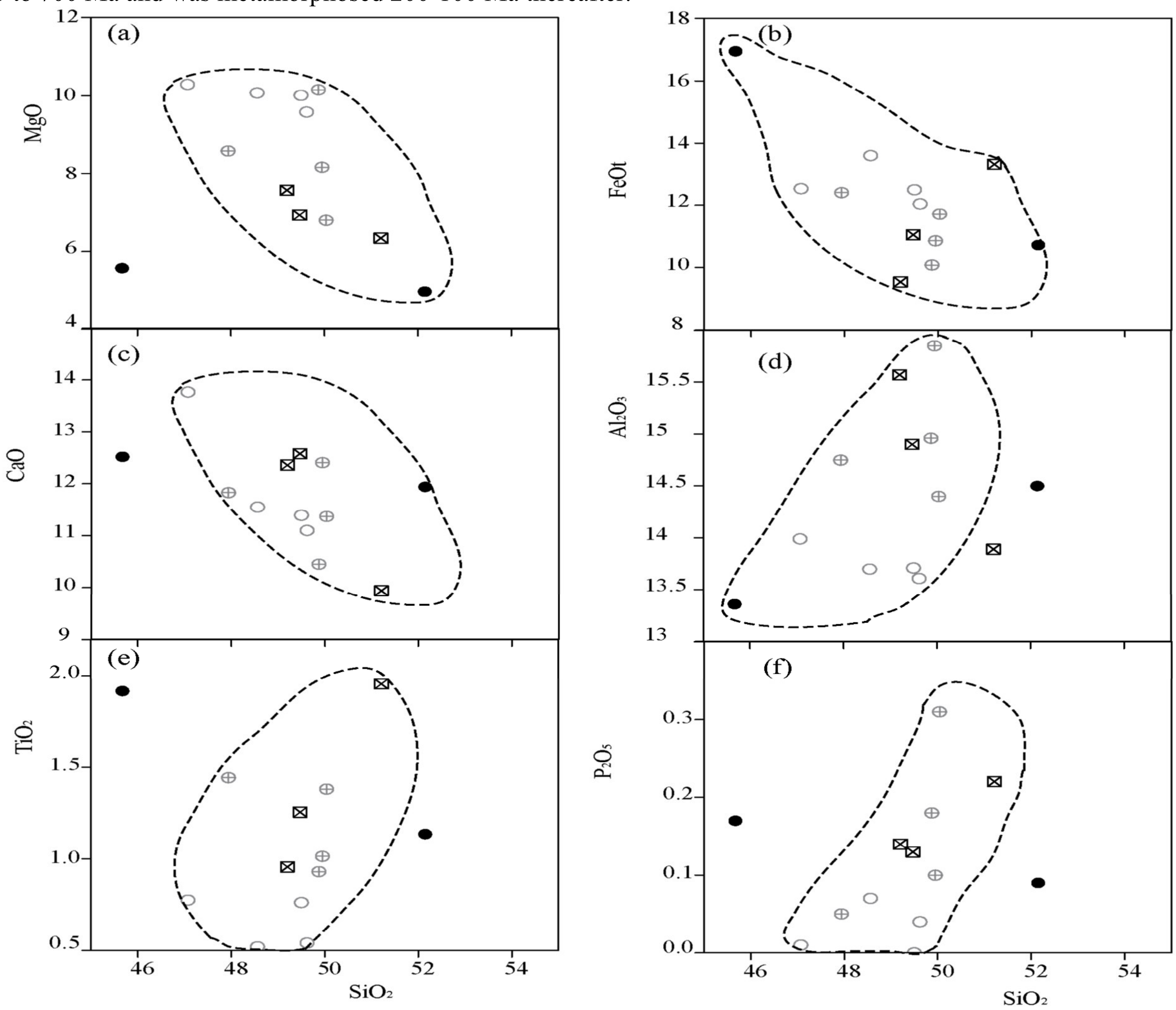


Fig. 6. Plots of (a) MgO, (b) FeOt, (c) CaO, (d) Al_2O_3, (e) TiO_2 and (f) P_2O_5 vs. SiO_2 for the Lato eclogites and Ahito-Toutouto amphibolites from the Pan-African suture zone in southern Togo. Legend is the same as Fig. 4.

Table 2. Sm-Nd and Rb-Sr data of selected eclogites and garnet-bearing or garnet-free amphibolites samples from the Lato, Toutouto and Ahito hills, southern Togo.

	T (Ga)	Sm ppm	Nd ppm	Rb ppm	Sr ppm	$^{143/144}$Nd	$^{87/86}$Sr	^{147}Sm/^{144}Nd	$^{143/144}$Ndi	ε_{Ndi}	^{87}Rb/^{86}Sr	$^{87/86}$Sri	ε_{Sri}	$^{143/144}$CHUR$_i$	T_{DM}(Ga) (Sm-Nd)
samples															
L1	0.8	2.56	10.1	1.61	30.7	0.512862	0.706161	0.153243	0.512058	8.834178	0.151707	0.704427	12.22393	0.511606	0.7261
L3	0.8	2.1	8.75	1.47	56.3	0.512804	0.703016	0.145100	0.512042	8.535432	0.075508	0.702153	-20.10331	0.511606	0.7688
L4	0.8	2.4	7.92	1.73	118.1	0.512818	0.705087	0.183207	0.511856	4.901738	0.042371	0.704602	14.71330	0.511606	1.6527
Ag228b	0.8	4.6	15.5	1.8	127	0.512827	0.703544	0.179425	0.511885	5.465436	0.040989	0.703075	-6.99349	0.511606	1.4319
Ym55b	0.8	4.75	18.8	25.7	176.1	0.512820	0.706087	0.152754	0.512018	8.063340	0.422173	0.701263	-32.74693	0.511606	0.8250

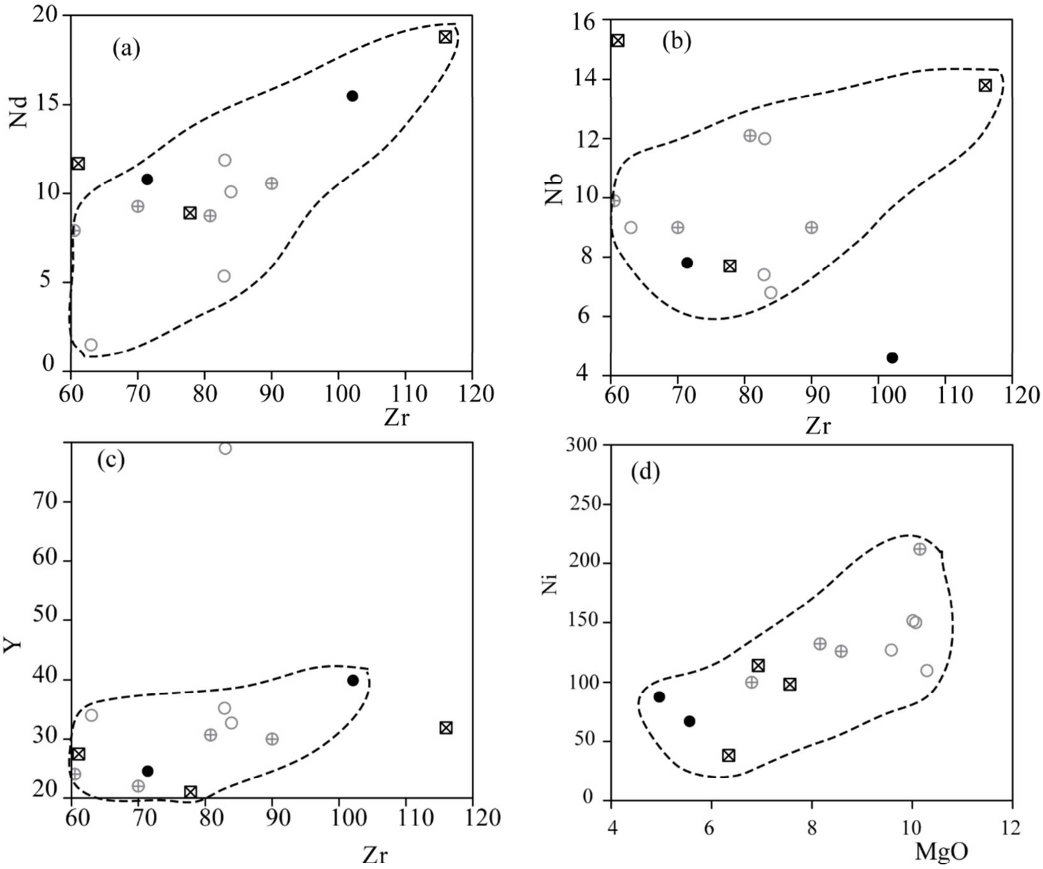


Fig. 7. Plots of (a) Nd, (b) Nb, and (c) Y vs. Zr for the Lato eclogites and Ahito and Toutouto amphibolites from the Pan-African suture zone in southern Togo. Fig. 7d. Plot of Ni vs. MgO

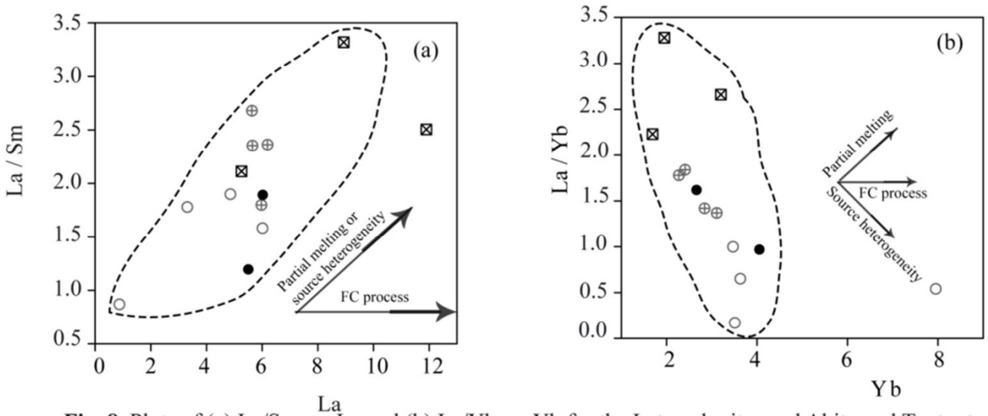


Fig. 8. Plots of (a) La/Sm vs. La and (b) La/Yb vs. Yb for the Lato eclogites and Ahito and Toutouto amphibolites from the Pan-African suture zone in southern Togo. Legend is the same as Fig. 4.

6.3. - Geodynamic implication

In the southern region of Togo, Lato, Toutouto and Ahito hills are massifs mainly consisting respectively of eclogites, retrogressed eclogites with garnet-bearing or garnet-free amphibolites. On the MnO-TiO_2-P_2O_5 plot, these samples fall into the field of island-arc tholéiites and MORB and have low Ti and Zr contents, resembling to arc volcanic (Fig. 9a-b), except eclogites samples from south Lato hills which fall in the island-arc calc-alkaline basalt. This support the petrogenesis observations described above. The studied samples are different from the high-pressure granulites from the Agou Igneous Complex which outcrop southwards of all these eclogitic and garnet amphibolites hills (Agbossoumondé *et al.* 2013). According to their calc-alkaline signature and their metamorphic evolution, the HP-granulites of Agou are derived from deep-seated basic intrusion equilibrated in the lower continental crust (western part of the Benino-Nigerian shield) under MP-HT conditions and never experienced an early eclogite stage (Agbossoumondé *et al*. 2004). This contrasts with the granulites of Toutouto hills which are interpreted to be derived from eclogites, and of Lato hills that are also described in SW Togo. The eclogites from Lato reflect subduction of the passive margin of the West African Craton (Agbossoumondé *et al.* 2001).

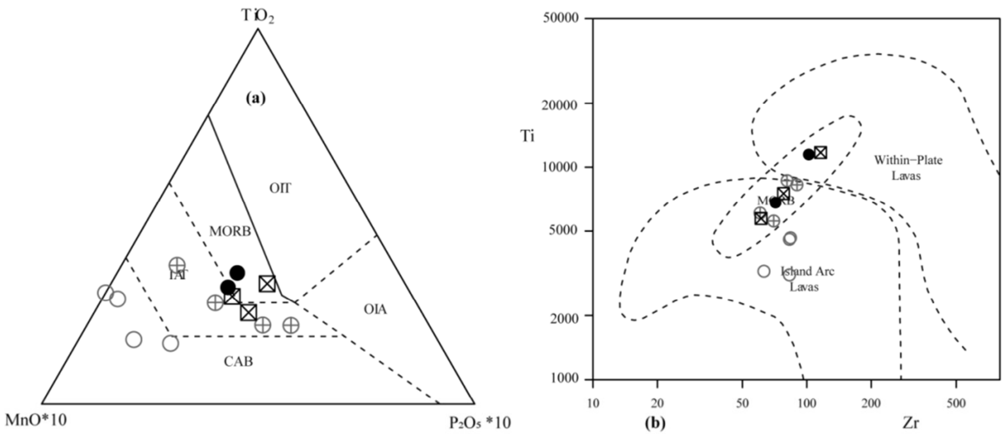


Fig. 9. Discrimination diagrams **(a)** : MnO-TiO2-P2O5 after Mullen, (1983) and **(b)** : Ti vs. Zr (after Pearce and Cann , 1973) for eclogites and amphibolites from the suture panaafrican zone in southern Togo.
OIT: ocean-island tholeiit or seamount tholeiite; OIA: ocean-island alkali basalt; CAB: island -arc calc-alkaline basalt; IAT: island-arc tholeiite; MORB: middle ocean ridge basalt. Legend is the same as Fig. 4.

Eclogites from Lato hills in southern Togo record both subduction and then collision processes (Bernard-Griffiths *et al.* 1991; Castaing *et al.* 1993; Agbossoumondé, 1998; Agbossoumondé *et al.* 2001; Liou *et al*. 2004; Ganade de Araujo *et al.* 2014). According to Ganade de Araujo *et al.* (2014), the decreasing HREE +Y content in zircons from Lato eclogites is consistent with zircon rim growth over a period with increasing garnet modal abundance, as expected during prograde metamorphism. These authors suggest that as Lato eclogites show no age difference within the analytical resolution (c. 12 m.y.) and a rapid tectonic burial rate can be inferred for them.

Even if some paleomagnetic reconstructions do not consider the West African and the Amazone cratons as part of Rodinia, we assume that the Lato and Toutouto Hills eclogites represent meaningful markers of both the break out of Rodinia and the amalgamation of Gondwana. As pointed out by Agbossoumondé *et al.* (2001), the Lato and Toutouto hills mafic complexes display MORB like geochemical signatures and a clockwise metamorphic evolution from eclogitic to granulitic and the retrogression to amphibolitic facies conditions between 610 and 580 Ma. These authors interpreted these bodies as exhumed fragments of the WAC margin previously subducted and metamorphosed under eclogitic facies conditions.

It appears that eclogites, retrogressed eclogites with garnet-bearing or garnet-free amphibolites are all derived from mantle-derived magmas, but the meta-mafic rocks with more evolved Sr-Nd compositions show that these magmas have interacted with older crust. This fits with the presence of the passive margin deposits which correspond to the surrounding metasedimentary pile observed in these hills. The emplacement of these magmas in proximal passive margin, near the continent and thus the evolved isotopic compositions, while the more radiogenic could be related to distal passive margin to frankly oceanic environment.

Considering the dominantly westward verging of the structures along the Dahomeyides suture zone (Affaton, 1990; Attoh *et al.* 1997; Attoh, 1998a, b; Agbossoumondé *et al.* 2004) and the occurrence of eclogitic bodies with WAC affinity, it has been proposed that the initial subduction plane was dipping eastward, beneath the Benino-Nigerian shield (Affaton, 1990; Attoh *et al.* 1997). Recently, the timing of continental collision has been constrained to 608.7±5.8 Ma by the age of UHP metamorphism of eclogites from the passive margin of the

WAC (e.g. Atacora Structural Unit) subducted to mantle depths (Ganade de Araujo *et al.* 2014a). Such scenario is only possible during the proposed east-dipping continental subduction that would carry the flanking passive margin to >90 km and ultimately leading to the continental collision of the WAC (lower plate) and the basement of the Benino-Nigerian Shield which represent the upper plate (Ganade de Araujo *et al.* 2014a).

The eclogitic metamorphic event recorded in these high-grade rocks in southern Togo is Neoproterozoic in age. A poorly T_{DM} age of 1.15 Ga was obtained and the crystallization age of the protolith determined at 822 ± (129/91) Ma (U–Pb zircon; Bernard- Griffiths *et al.* 1991). The eclogite stage was dated at 638 ± (12/53) Ma (U–Pb zircon; Bernard-Griffiths *et al.* 1991) and the age of the secondary post-eclogite granulite event is dated at 610 ± 2Ma (U–Pb zircon; Attoh *et al.* 1991). Amphibolites facies recrystallization event have been dated in Lato massifs at *c.* 580 Ma (598 ± 12 Ma; Rb–Sr: Bernard-Griffiths *et al.* 1991; 587 ± 4 and 582 ± 2 Ma; Ar–Ar: Attoh *et al.* 1997). Zircon U-Pb geochronological data indicate that magmatism related to plate convergence in the active margin of the Dahomeyide belt spanned from ca. 670 to 545 Ma (Kalsbeek *et al.* 2012) and is geographically concentrated in the Benino-Nigerian Shield.

7. - Conclusions

The Dahomeyide belt preserves a well-organized orogenic architecture developed during the Neoproterozoic. Ultramafic and mafic massifs from the Dahomeyide suture zone, witness oceanic closure and amalgamation of Gondwana super-continent during Pan-African time between 640 and 540 Ma. The association of eclogitic and granulitic mafic bodies along a single suture zone reflects a tectonic melange of different high grade rocks coming from both plates acting during subduction.

Petrologic and geochronologic characteristics for the high grade metabasic massifs (Lato eclogites, Toutouto granulites and Ahito amphibolites) strongly suggest that the eclogites from this study were derived from mantle sources and represent a magmatic series related to subducted passive continental margin, whereas both garnet-bearing and garnet-free amphibolites represent retrogressed eclogites related to Pan-African collision events.

This present geochemical study eclogitic rocks from SE Togo provides a new understanding of the Pan-African orogeny, and further constraints on the geochemical characteristics of the mafic granulites in the Pan-Africa belt of West Africa.

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