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Chapter

Mineral Chemistry of Chalki Basalts in Northern Iraq and Their Petrological Significance

Mohsin M. Ghazal, Ali I. Al-Juboury and Sabhan M. Jalal

Abstract

Chalki basalts as a small body of volcanic rocks have green to grayish green color due to their nearly complete alteration to chlorite. The essential minerals of Chalki basalt to andesitic basalts are plagioclase (labradorite, $An_{51–61}$; andesine, An_{35} to An_{42}; and oligoclase, An_{22}). Moreover, there is sodic plagioclase (albite, $An_{0.1}$ to An_{04}) whose coexistence with the other more calcic plagioclase means that albitization had occurred. The other essential mineral is pyroxene (endiopside, $en_{66–68}$ $wo_{27–28}$ $fs_{05–06}$; and subcalcic augite, en_{72} wo_{14} fs_{14}). Olivine ($Fo_{80–81}$) is also present. According to the NiO content (0.11–0.12 wt%) in olivine grains, they are interpreted to be originated tectonically. The prevalent chlorite in all the samples is mainly diabantite and penninite, indicating chloritization after the ferromagnesian olivine and pyroxene. Serpentine (type lizardite and chrysotile) is also recorded as lesser alteration product after the forsteritic olivine. Rare secondary hornblende (type magnesiohornblende) is also found. The spinel group as accessory minerals is defined as magnetite, chromian magnetite, and chromian spinel giving the imprints of their metamorphic origin due to low temperature sub-sea metamorphism and also of alpine type.

Keywords: petrography, mineral chemistry, electron microprobe, Chalki basalts, Iraq

1. Introduction

The Paleozoic Chalki volcanic rocks crop out in a restricted part of the northern Thrust Zone of Iraq close to Iraqi-Turkish border and are considered as integral part of the upper part of Pirispiki Red Beds (late Devonian) Formation [1–3]. Chalki Formation was defined by Wetzel (unpublished report, 1952 in [1]) (which has no synonyms) who named it after the Chalki village (**Figure 1**).

Lithologically, they represent dull green and grayish green, red- and white-speckled, altered olivine-rich basaltic rocks (flow or intrusions) alternating with intercalations of bright red, ash-containing soft siltstones and shale.

They are undated and their origin is uncertain. Outcrop is typically not diagnostic. They are considered to be extrusive by [4] based on their identification of ash layers (not observed in this study). Petrographically, the bulk of the material consists of olivine basalts or fine-grained dolerites, with hematite-magnetite-rimmed

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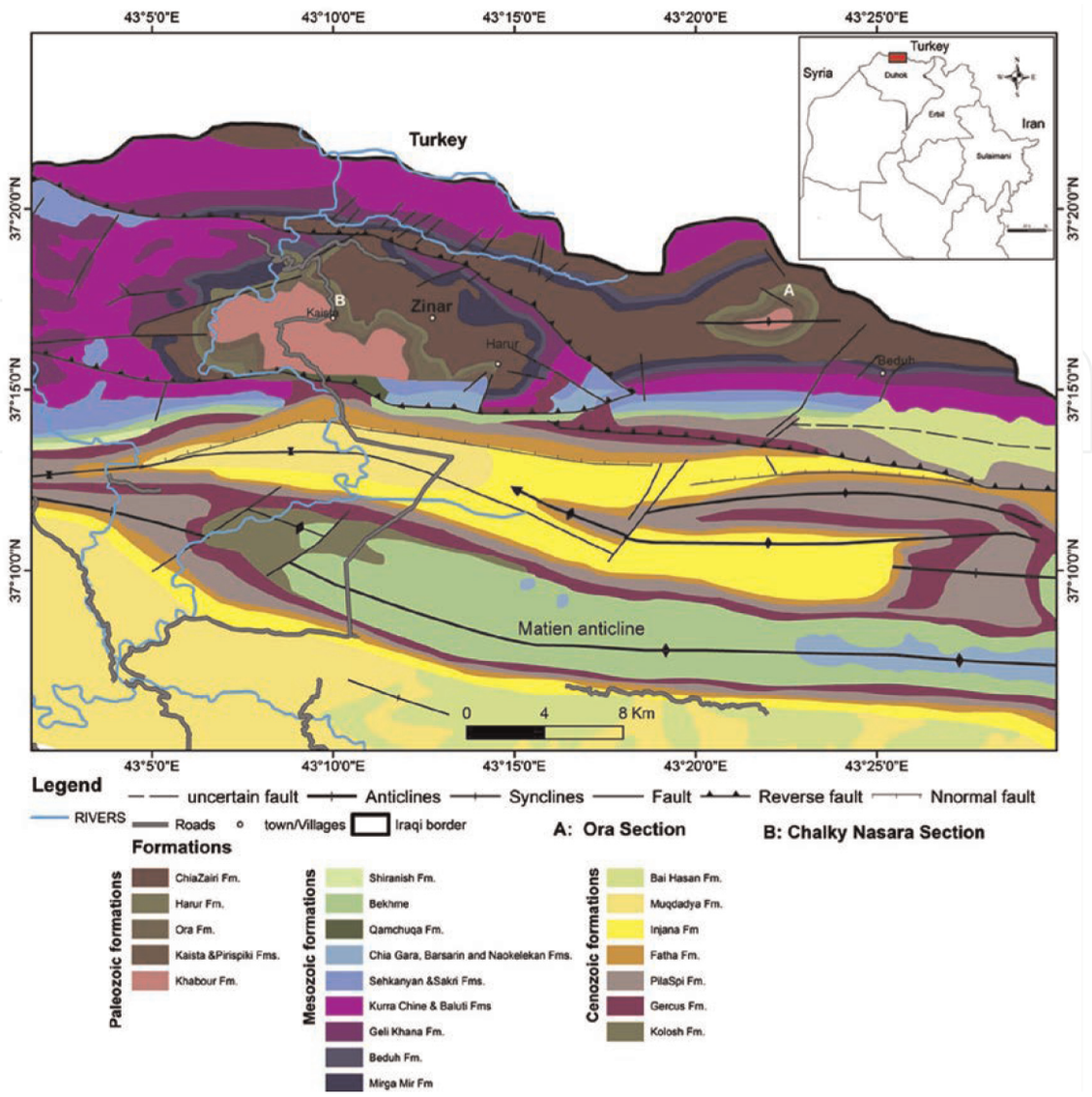


Figure 1.
Geological map of northern Iraq showing the Paleozoic succession including Chalki volcanics within Pirispiki formation in Ora section (A) and the studied section (Chalki Nasara, section B) (modified after [8]).

pseudomorphs, in chlorite, replacing the olivine. There are albitized plagioclase laths and considerable amounts of chlorite and ankeritic carbonates in the groundmass. Locally the basalts are crossed by numerous veins of white ankerite with fibrous chalcedony.

The Chalki volcanic rocks probably had suffered severe sub-sea alterations. Therefore, this work aims to study mineral chemistry using electron probe microanalyzer (EPMA) in order to distinguish the various phases of minerals resulted from the alteration on basaltic rocks of the Chalki volcanics and interpret their petrologic significance.

2. Geologic setting

The Chalki volcanics located near Kaista (Khabour valley, Amadia district, N. Iraq) occur as basalt intercalations, of 2–5 m in thickness within the Pirispiki Formation. The type section lies at Chalki village (**Figure 1**) in which the basaltic beds are associated with ash-containing shales and siltstones occupying most of the uppermost 20 m of the section. The type section is 16 m thick in aggregate [4].

Sharland et al. [5] interpreted the Chalki volcanics to represent back-arc rift volcanics associated with the initiation of subduction along the Tethyan margin of the Arabian Plate. They interpreted the initiation of subduction to have caused the so-called Hercynian orogeny in the late Devonian times. The age of the "Hercynian orogeny" in the Arabian Plate has been reported to range from pre-Late Devonian to middle Carboniferous [6].

Subduction along the southern margin of the Palaeo-Tethys is supported by the occurrence of Devonian-Carboniferous volcanic and metamorphic rocks found in the Kuh-Sefid area of the Sanandaj-Sirjan Zone [7]. However, the central part of the Arabian plate was probably not significantly affected by this subduction.

3. Materials and methodology

The petrography of 15 samples collected from Chalki volcanics section at Chalki Nasara section (**Figure 1**) was determined using petrographic microscope at the Earth Science Department of Mosul University, Iraq. A Swift Polarized microscope is used in the petrographic description.

Electron microprobe analyses of minerals were performed using a Cameca SX-50 in the Department of Geology and Geophysics at the University of Utah, USA. Analyses were conducted using PC1, TAP, PET, and LiF crystals on four wavelength-dispersive spectrometers, with an accelerating voltage of 15 keV, a beam current of 30 nA, and a spot size of 10 mm. Peak intensities were measured for 20 s and background intensities for 10 s on both sides of the analytical peaks. Na was measured first, and analytical times were reduced by half in order to minimize sodium loss under the electron beam. The analytical routine for feldspars included Si, Al, Fe, Ca, Sr, Ba, Na, and K, and a separate analytical routine for mafic and other minerals added Ti, Cr, Mn, Ni, Zn, Mg, F, and Cl (K, Sr and Ba excluded). Mineral standards include fluorite (F-Kα), tugtupite (Cl-Kα), sanidine (Si-Kα, Al-Kα, K-Kα), albite (Na-Kα), plagioclase (Ca-Kα), barite (Ba-Lα), celestite (Sr-Lα), chrome diopside (Mg-Kα), hematite (Fe-Kα), rutile (Ti-Kα), rhodonite (Mn-Kα), chromite (Cr-Kα), nickel silicide (Ni-Kα), and zinc sulfide (Zn-Kβ). Rounds of standard analyses were performed prior to and after the suite of thin sections. Concentrations are calculated using the PAP matrix correction factors. Correction for "excess" F by interference of the Fe-Lα peak with F-Kα peak was accomplished by measuring an F-free Fe-bearing standard (hematite) and calculating a correction factor of 0.029.

4. Results

4.1 Petrography

The volcanic rocks are olivine-basalt, sometimes doleritic, or even andesitic-basalt. They are of greenish to greenish gray color due to high chloritization after olivine. They are associated with little phyllites and pyroclasts of volcano-sedimentary rocks. They contain also veins of carbonate minerals and quartz.

Texturally, the rocks of Chalki volcanics are porphyritic basaltic in general, cut by microscopic veins of carbonate minerals (calcite) in addition to minute quartz veins.

Mineralogically, the pseudomorphs after olivine phenocrysts are identified microscopically, such as chlorite, iddingsite, and iron oxides (**Figure 2**). Another essential mineral is plagioclase (sometimes albitized), which sometimes slightly altered to sericite and kaolinite. No individual pyroxene grains have been identified, but they probably present as fine grains in the groundmass.

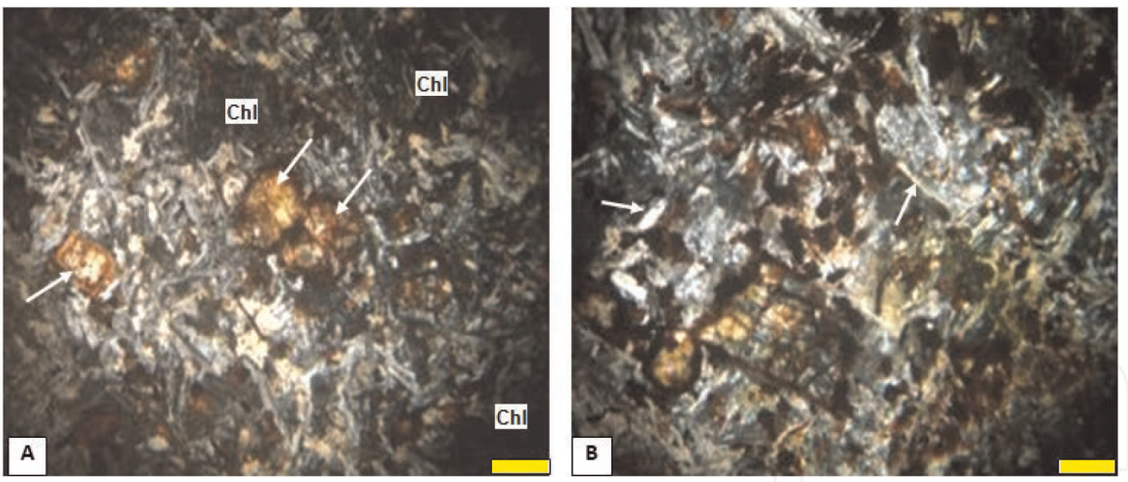


Figure 2.
Representative photomicrograph for Chalki basalt showing (A) dumpy prismatic olivine with rim alteration to black iron oxide and reddish brown iddingsite (arrows), chlorite (Chl), and white fine laths of plagioclase. (B) Plagioclase laths (arrows), altered olivine to iddingsite, iron oxide. Under-crossed nicols. Scale bar is 0.2 mm.

4.2 Mineral chemistry

4.2.1 Plagioclase

The calcic plagioclase (labradorite, An_{51} to An_{61}) is the essential mineral of Chalki basalt resembling the basaltic type. Some grains are less calcic (andesine, An_{35} to An_{42}). Moreover, there is sodic plagioclase (albite, $An_{0.1}$ to An_{04}) as a result of albitization process (**Table 1** and **Figure 3**).

CV-32								
Wt%	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
SiO_2	54.59	56.20	57.15	66.91	65.28	67.76	58.82	55.16
Al_2O_3	27.44	26.06	26.25	19.41	20.81	19.65	25.04	27.56
FeO*	0.59	0.92	0.87	0.91	0.56	0.92	0.77	0.77
CaO	10.32	8.56	8.49	0.34	0.88	0.15	7.25	10.15
SrO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03
BaO	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Na_2O	5.33	6.24	6.07	10.70	10.20	11.23	6.63	5.16
K_2O	0.35	0.24	0.50	0.10	0.91	0.13	0.58	0.27
Total	98.6	98.2	99.3	98.4	98.6	99.8	99.1	99.1
apfu								
Si	2.501	2.575	2.587	2.979	2.914	2.976	2.657	2.511
Al	1.481	1.407	1.400	1.018	1.095	1.017	1.333	1.478
Fe^{2+}	0.023	0.035	0.033	0.034	0.021	0.034	0.029	0.029
Ca	0.507	0.420	0.412	0.016	0.042	0.007	0.351	0.495
Sr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ba	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.473	0.554	0.533	0.924	0.883	0.956	0.580	0.456
K	0.021	0.014	0.029	0.006	0.052	0.007	0.034	0.016

CV-32								
Wt%	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Ab	47.30	56.07	54.75	97.67	90.34	98.52	60.16	47.17
An	50.63	42.48	42.31	1.73	4.33	0.71	36.35	51.21
Or	2.07	1.45	2.94	0.60	5.33	0.77	3.49	1.61
	Labradorite	Andesine	Andesine	Albite	Albite	Albite	Andesine	Labradorite

CV-25						
Wt%	**1**	**2**	**3**	**4**	**5**	**6**
SiO_2	57.80	53.20	52.54	62.32	52.91	57.66
Al_2O_3	25.46	28.77	29.17	22.97	29.20	26.26
FeO*	1.20	0.68	0.86	0.71	0.67	0.55
CaO	7.52	11.68	12.08	4.71	11.64	8.36
SrO	0.00	0.02	0.00	0.06	0.00	0.00
BaO	0.00	0.00	0.00	0.05	0.01	0.03
Na_2O	6.60	4.61	4.15	8.64	4.29	6.32
K_2O	0.56	0.19	0.33	0.63	0.52	0.52
Total	99.1	99.1	99.1	100.1	99.2	99.7
apfu						
Si	2.621	2.433	2.408	2.774	2.419	2.597
Al	1.361	1.551	1.576	1.205	1.573	1.394
Fe^{2+}	0.046	0.026	0.033	0.026	0.026	0.021
Ca	0.365	0.572	0.593	0.225	0.570	0.404
Sr	0.000	0.000	0.000	0.000	0.000	0.000
Ba	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.580	0.408	0.369	0.745	0.380	0.552
K	0.032	0.011	0.019	0.036	0.030	0.030
Ab	59.35	41.18	37.58	74.12	38.76	56.01
An	37.35	57.72	60.45	22.34	58.13	40.94
Or	3.30	1.10	1.97	3.54	3.11	3.05
	Andesine	Labradorite	Labradorite	Oligoclase	Labradorite	Andesine

CV-37					
Wt%	**1**	**2**	**3**	**4**	**5**
SiO_2	57.32	54.96	58.70	56.93	55.49
Al_2O_3	25.85	27.08	24.96	24.40	27.90
FeO*	1.00	1.19	0.87	1.65	0.98
CaO	8.10	9.94	7.05	6.76	10.06
SrO	0.00	0.00	0.00	0.00	0.00
BaO	0.00	0.00	0.03	0.02	0.01
Na_2O	6.13	5.28	6.79	6.25	5.46
K_2O	0.48	0.27	0.61	0.61	0.39
Total	98.9	98.7	99.0	96.6	100.3

CV-37					
Wt%	**1**	**2**	**3**	**4**	**5**
apfu					
Si	2.604	2.516	2.656	2.647	2.502
Al	1.384	1.461	1.331	1.337	1.482
Fe^{2+}	0.038	0.046	0.033	0.064	0.037
Ca	0.394	0.487	0.342	0.337	0.486
Sr	0.000	0.000	0.000	0.000	0.000
Ba	0.000	0.000	0.000	0.000	0.000
Na	0.540	0.469	0.595	0.563	0.477
K	0.028	0.016	0.035	0.036	0.022
Ab	56.14	48.23	61.26	60.16	48.43
An	40.99	50.14	35.14	35.98	49.31
Or	2.87	1.64	3.61	3.86	2.26
	Andesine	Labradorite	Andesine	Andesine	Labradorite

CV-41									
Wt%	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
SiO_2	68.13	67.84	68.02	67.77	68.20	66.15	67.24	67.39	67.87
Al_2O_3	19.45	19.34	19.25	19.59	19.56	20.09	19.51	19.46	19.59
FeO*	0.47	0.56	0.77	0.95	0.54	1.55	0.77	0.71	0.63
CaO	0.04	0.04	0.03	0.10	0.07	0.41	0.32	0.08	0.12
SrO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BaO	0.00	0.01	0.00	0.00	0.00	0.37	0.00	0.00	0.00
Na_2O	11.16	11.13	11.24	11.18	11.43	10.42	11.04	11.09	11.14
K_2O	0.03	0.04	0.02	0.07	0.05	0.29	0.07	0.17	0.09
Total	99.3	99.0	99.3	99.7	99.9	99.3	98.9	98.9	99.4
apfu									
Si	2.996	2.995	2.996	2.980	2.988	2.940	2.977	2.983	2.985
Al	1.008	1.006	0.999	1.015	1.010	1.053	1.018	1.015	1.016
Fe^{2+}	0.017	0.021	0.028	0.035	0.020	0.058	0.028	0.026	0.023
Ca	0.002	0.002	0.001	0.005	0.003	0.020	0.015	0.004	0.006
Sr	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ba	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
Na	0.951	0.953	0.959	0.953	0.971	0.898	0.948	0.952	0.950
K	0.002	0.002	0.001	0.004	0.003	0.016	0.004	0.010	0.005
Ab	99.59	99.59	99.72	99.11	99.39	96.15	98.03	98.61	98.90
An	0.21	0.19	0.14	0.50	0.32	2.10	1.59	0.37	0.60
Or	0.21	0.22	0.13	0.39	0.30	1.75	0.39	1.02	0.51
	Albite	Albite	Albite	Albite	Albite	Albite	Albite	Albite	Albite

Table 1.
Chemical composition (wt%) and atom per formula unit (apfu) of plagioclase on the basis of 8 O (samples CV-32, CV-25, CV-37, CV-41).

4.2.2 Olivine

Chalki olivine is forsteritic (Fo_{80} to Fo_{81}) and consequently high Mg# (80–81) (**Table 2**). It contains NiO (0.11–0.12 wt%), which is plotted against (Fo%) revealing its tectonic origin (**Figure 4**).

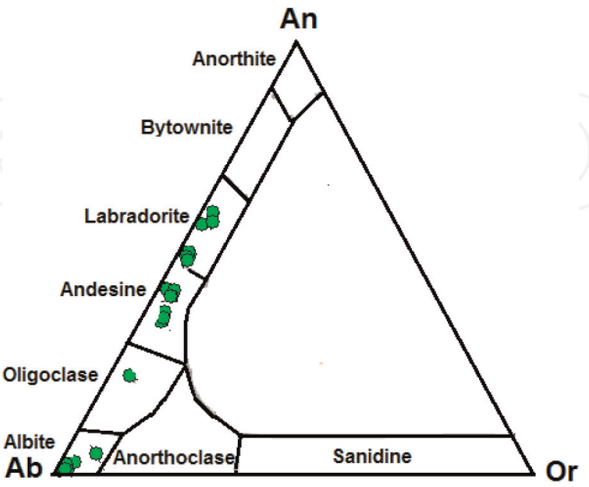


Figure 3.
An-Ab-Or plot for Chalki basalt plagioclase showing the composition variation from labradorite, andesine, oligoclase, to albite (modified from [9]).

Wt%	**1**	**2**	**3**	**4**
SiO_2	39.29	40.01	38.52	39.34
TiO_2	0.02	0.04	0.02	0.04
Al_2O_3	0.19	0.24	0.19	0.24
Cr_2O_3	0.02	0.06	0.02	0.06
FeO*	17.20	18.01	16.86	17.71
MnO	0.37	0.48	0.36	0.47
NiO	0.12	0.12	0.12	0.11
ZnO	0.54	0.00	0.53	0.00
MgO	43.03	41.35	42.19	40.66
CaO	0.01	0.64	0.01	0.63
Na_2O	0.04	0.01	0.04	0.01
F	0.05	0.07	0.05	0.07
Cl	0.00	0.00	0.00	0.00
Total	100.88	101.03	98.90	99.34
apfu				
Si	0.992	1.010	0.992	1.010
Al	0.006	0.007	0.006	0.007
Ti	0.000	0.001	0.000	0.001
Cr	0.000	0.001	0.000	0.001
Fe	0.363	0.380	0.363	0.380
Mn	0.008	0.010	0.008	0.010

Wt%	1	2	3	4
Mg	1.620	1.556	1.620	1.556
Ca	0.000	0.017	0.000	0.017
Na	0.002	0.001	0.002	0.001
K	0.000	0.000	0.000	0.000
Ni	0.001	0.001	0.001	0.001
Zn	0.004	0.000	0.004	0.000
Fo	81.361	79.946	81.361	79.946
Fa	18.639	20.054	18.639	20.054
Mg#	81.686	80.367	81.686	80.367

Table 2.
Chemical composition (wt%) and atom per formula unit (apfu) of olivine on the basis of 4 O (sample CV-67).

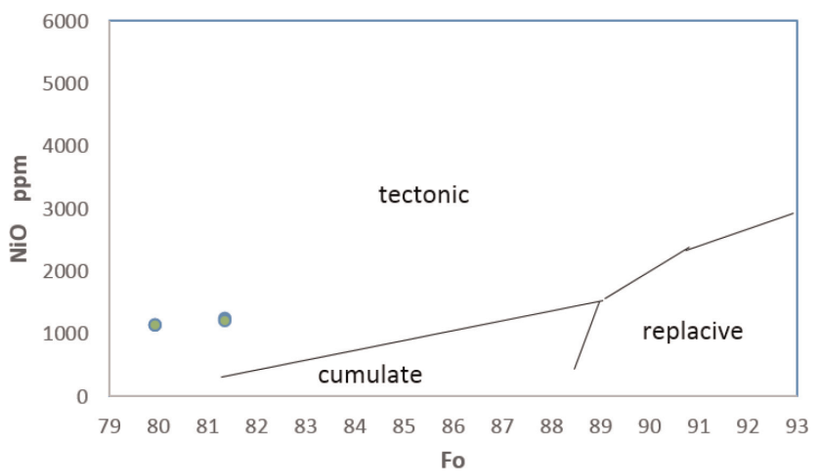


Figure 4.
Fo vs. NiO for Chalki basalt olivines shown as type tectonic (adapted from [10]).

4.2.3 Pyroxene

The pyroxene of Chalki basalt is endiopside to subcalcic augite as shown in **Table 3** and **Figure 5**.

The chemical formula of pyroxene is XYZ_2O_6 [11].

4.2.4 Hornblende

The rare mineral in Chalki basalt is hornblende, whose composition resembles the magnnesiohornblende as shown in **Figure 6** after representation of its chemical composition given in **Table 4**.

The general formula of amphiboles is $W_{(0-1)}X_2Y_5Z_8O_{22}(OH,F)_2$ [11].

4.2.5 Chlorite

The chlorite of Chalki basalt is the predominant secondary mineral in all samples giving the greenish color of the hand specimen samples. The huge number of

Wt%	**1**	**2**	**3**	**4**	**5**
SiO_2	56.54	56.43	56.53	57.31	50.47
TiO_2	0.08	0.07	0.03	0.06	0.05
Al_2O_3	1.92	2.05	1.58	1.11	0.88
Cr_2O_3	0.09	0.12	0.19	0.08	0.11
FeO*	3.28	3.22	3.12	3.39	9.99
MnO	0.13	0.03	0.08	0.09	0.21
NiO	0.05	0.05	0.03	0.02	0.04
ZnO	0.21	0.00	0.00	0.00	0.02
MgO	22.27	22.33	22.91	22.75	29.19
CaO	13.17	13.03	12.79	12.75	8.18
Na_2O	0.23	0.29	0.19	0.10	0.12
F	0.01	0.00	0.00	0.00	0.05
Cl	0.00	0.01	0.01	0.01	0.01
Total	98.0	97.6	97.5	97.7	99.3
apfu					
Si	2.028	2.027	2.033	2.055	1.850
Al^{iv}	−0.028	−0.027	−0.033	−0.055	0.150
Al^{vi}	0.109	0.114	0.100	0.101	−0.112
Ti	0.002	0.002	0.001	0.001	0.001
Cr	0.002	0.003	0.006	0.002	0.003
Fe^{2+}	−0.314	−0.316	−0.335	−0.324	−0.495
Mn	0.004	0.001	0.000	0.003	0.006
Mg	1.191	1.196	1.229	1.216	1.595
Ni	0.002	0.002	0.001	0.000	0.001
Zn	0.006	0.000	0.000	0.000	0.001
Fe^{2+}	0.412	0.413	0.429	0.426	0.801
Ca	0.506	0.502	0.493	0.490	0.321
Na	0.016	0.020	0.014	0.007	0.008
K	0.000	0.000	0.000	0.000	0.000
Z	2.000	2.000	2.000	2.000	2.000
Y	1.002	1.002	1.001	1.000	1.001
X	0.934	0.935	0.936	0.923	1.131
Xmg	0.924	0.925	0.929	0.923	0.839
fs	5.478	5.386	5.177	5.626	13.776
en	66.322	66.659	67.675	67.277	71.777
wo	28.199	27.955	27.148	27.097	14.447

Table 3.
Chemical composition (wt%) and atom per formula unit (apfu) of pyroxene on the basis of 6 O (sample CV-67).

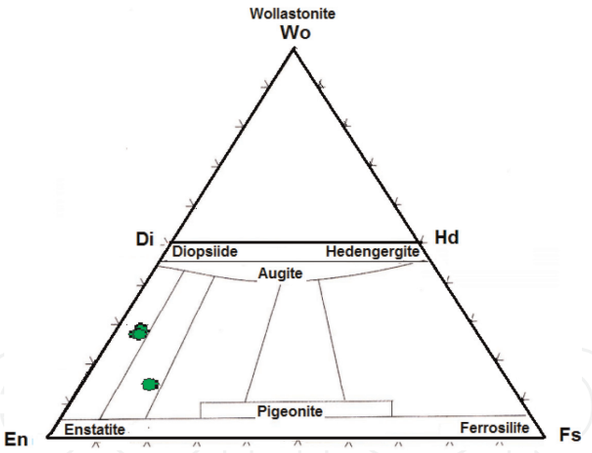


Figure 5.
En-Fs-Wo triangular diagram for Chalki basalt pyroxene shown as endiopside and subcalcic augite (after [11]).

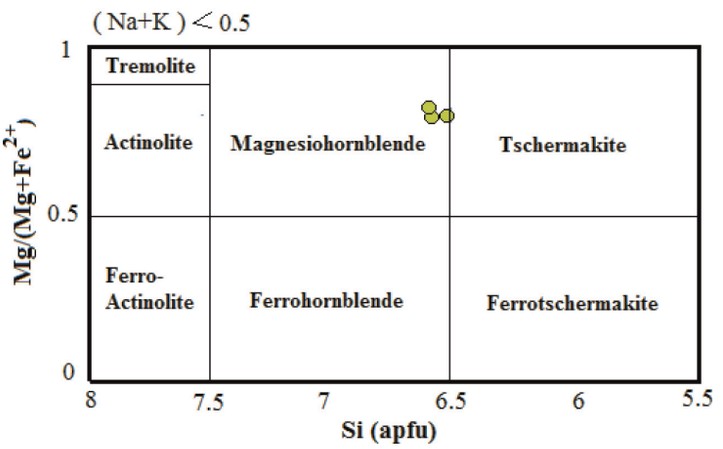


Figure 6.
Si vs. Mg/(Mg + Fe^{2+}) diagram for Chalki basalt amphiboles shown as magnesiohornblende (after [12]).

Wt%	**1**	**2**	**3**
SiO_2	45.77	44.9	45.8
Al_2O_3	11.09	11.45	11.45
TiO_2	0.91	1.1	0.77
Cr_2O_3	1.08	0.96	0.67
FeO*	7.03	7.99	8.02
MnO	0.06	0.03	0.01
MgO	17.04	16.55	16.87
CaO	12.14	12.4	12.66
Na_2O	1.45	0.88	0.6
Total	96.6	96.3	96.9
(apfu)			
Si	6.600	6.522	6.592
Al^{iv}	1.400	1.478	1.408
Al^{vi}	0.483	0.482	0.534

Wt%	**1**	**2**	**3**
Ti	0.099	0.120	0.083
Cr	0.123	0.110	0.076
Fe^{2+}	0.627	0.701	0.685
Mn	0.007	0.004	0.001
Mg	3.662	3.584	3.620
Fe^{2+}	0.221	0.270	0.280
Ca	1.874	1.930	1.952
Na	−0.095	−0.199	−0.232
K	0	0	0
Z	8	8	8
Y	5	5	5
X	2	2	2
W	0	0	0
Mg#	0.812	0.787	0.789

Table 4.
Chemical composition (wt%) and atom per formula unit (apfu) of hornblende on the basis of 23 O (sample CV-67).

CV-32							**CV-67**	
Wt%	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**
SiO_2	32.02	32.76	33.26	34.05	34.88	35.47	32.24	30.38
TiO_2	0.09	0.00	0.04	0.05	0.00	0.02	0.02	0.03
Al_2O_3	13.58	14.80	13.44	13.81	13.75	13.32	13.90	18.68
Cr_2O_3	0.03	0.01	0.04	0.01	0.03	0.00	1.14	0.16
FeO*	17.25	14.75	16.25	14.52	13.18	13.46	7.17	6.04
MnO	0.11	0.06	0.05	0.02	0.03	0.03	0.03	0.06
NiO	0.08	0.09	0.09	0.07	0.09	0.07	0.05	0.10
ZnO	0.00	0.23	0.07	0.37	0.24	0.11	0.06	0.00
MgO	21.66	21.64	22.48	22.76	23.76	23.54	31.03	30.76
CaO	0.48	0.47	0.38	0.39	0.31	0.32	0.26	0.03
Na_2O	0.02	0.05	0.06	0.04	0.07	0.12	0.01	0.05
F	0.07	0.04	0.06	0.04	0.08	0.10	0.08	0.03
Cl	0.01	0.00	0.01	0.00	0.01	0.03	0.02	0.01
Total	85.4	84.9	86.2	86.1	86.4	86.6	86.0	86.3
Apfu								
Si	6.611	6.689	6.742	6.836	6.916	7.020	6.309	5.861
Al^{iv}	1.389	1.311	1.258	1.164	1.084	0.980	1.691	2.139
Al^{vi}	1.914	2.251	1.954	2.103	2.128	2.126	1.513	2.108
Ti	0.013	0.000	0.007	0.008	0.000	0.003	0.003	0.005
Cr	0.004	0.002	0.006	0.002	0.004	0.000	0.177	0.024

CV-32							**CV-67**	
Wt%	**1**	**2**	**3**	**4**	**5**	**6**	**1**	**2**
Fe	2.979	2.518	2.755	2.437	2.184	2.227	1.174	0.974
Mn	0.020	0.010	0.008	0.004	0.006	0.004	0.006	0.010
Ni	0.013	0.015	0.015	0.012	0.015	0.012	0.007	0.016
Zn	0.000	0.035	0.010	0.054	0.035	0.017	0.008	0.000
Mg	6.667	6.587	6.794	6.811	7.024	6.945	9.054	8.848
Ca	0.107	0.103	0.084	0.083	0.066	0.068	0.054	0.005
Na	0.008	0.018	0.022	0.015	0.026	0.046	0.003	0.019
CV-25								
Wt%	**1**	**2**	**3**	**4**	**5**	**6**	**7**	
SiO_2	23.44	25.96	27.76	31.42	33.24	36.69	37.34	
TiO_2	0.72	0.24	0.33	0.19	0.05	0.00	0.04	
Al_2O_3	11.42	13.15	13.84	15.31	16.19	19.58	21.16	
Cr_2O_3	0.01	0.11	0.04	0.01	0.00	0.03	0.08	
FeO*	34.69	30.38	26.27	17.29	14.32	12.79	11.40	
MnO	0.03	0.04	0.04	0.07	0.09	0.01	0.00	
NiO	0.08	0.08	0.10	0.11	0.09	0.08	0.06	
ZnO	0.12	0.00	0.10	0.11	0.00	0.34	0.33	
MgO	17.16	18.73	19.86	22.71	23.52	20.32	18.84	
CaO	0.11	0.13	0.12	0.11	0.24	0.27	0.26	
Na_2O	0.04	0.02	0.04	0.01	0.04	0.07	0.06	
F	0.02	0.04	0.07	0.11	0.11	0.10	0.10	
Cl	0.02	0.02	0.01	0.02	0.01	0.01	0.01	
Total	87.9	88.9	88.6	87.5	87.9	90.3	89.7	
apfu								
Si	5.332	5.624	5.868	6.334	6.524	6.862	6.947	
Al^{iv}	2.668	2.376	2.132	1.666	1.476	1.138	1.053	
Al^{vi}	0.394	0.981	1.315	1.972	2.269	3.179	3.587	
Ti	0.124	0.039	0.053	0.029	0.007	0.000	0.005	
Cr	0.002	0.018	0.007	0.002	0.001	0.005	0.012	
Fe	6.598	5.504	4.642	2.914	2.350	2.000	1.773	
Mn	0.005	0.007	0.007	0.013	0.014	0.002	0.000	
Ni	0.014	0.014	0.017	0.018	0.013	0.011	0.009	
Zn	0.020	0.000	0.016	0.017	0.000	0.048	0.046	
Mg	5.818	6.050	6.260	6.826	6.883	5.666	5.226	
Ca	0.027	0.030	0.027	0.025	0.049	0.053	0.051	
Na	0.018	0.010	0.017	0.005	0.017	0.026	0.023	
CV-37								
Wt%	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
SiO_2	32.18	32.68	32.69	32.85	32.87	32.95	32.96	33.09

CV-37								
Wt%	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
TiO_2	0.02	0.04	0.00	0.05	0.09	0.01	0.06	0.00
Al_2O_3	15.68	15.55	15.56	15.66	13.92	15.62	15.48	15.16
Cr_2O_3	0.13	0.18	0.09	0.08	0.00	0.15	0.02	0.04
FeO*	14.75	14.29	14.47	14.77	17.19	14.96	15.08	14.87
MnO	0.01	0.03	0.04	0.03	0.09	0.04	0.04	0.04
NiO	0.05	0.11	0.06	0.11	0.07	0.06	0.06	0.12
ZnO	0.00	0.18	0.00	0.00	0.43	0.39	0.26	0.18
MgO	23.81	24.67	24.61	24.21	22.20	24.20	23.55	23.70
CaO	0.12	0.20	0.12	0.15	0.39	0.16	0.18	0.20
Na_2O	0.04	0.02	0.03	0.01	0.01	0.03	0.05	0.03
F	0.06	0.10	0.04	0.11	0.05	0.09	0.12	0.10
Cl	0.01	0.01	0.01	0.01	0.00	0.01	0.01	0.01
Total	86.9	88.1	87.7	88.0	87.3	88.7	87.9	87.5
apfu								
Si	6.421	6.429	6.429	6.465	6.629	6.459	6.516	6.558
Al^{iv}	1.579	1.571	1.571	1.535	1.371	1.541	1.484	1.442
Al^{vi}	2.110	2.033	2.033	2.097	1.938	2.067	2.123	2.098
Ti	0.003	0.006	0.006	0.008	0.013	0.001	0.008	0.000
Cr	0.020	0.029	0.029	0.013	0.000	0.023	0.003	0.007
Fe	2.462	2.351	2.351	2.430	2.898	2.451	2.493	2.464
Mn	0.001	0.005	0.005	0.005	0.015	0.006	0.007	0.006
Ni	0.008	0.018	0.018	0.017	0.011	0.010	0.010	0.019
Zn	0.000	0.027	0.027	0.000	0.065	0.056	0.039	0.027
Mg	7.084	7.235	7.235	7.102	6.675	7.070	6.941	7.000
Ca	0.026	0.042	0.042	0.032	0.085	0.033	0.037	0.043
Na	0.016	0.006	0.006	0.004	0.005	0.012	0.018	0.010
CV-41								
Wt%	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
SiO_2	33.06	32.54	32.39	32.62	32.58	32.06	31.82	33.02
TiO_2	0.05	0.04	0.04	0.04	0.01	0.01	0.00	0.00
Al_2O_3	14.98	15.00	15.02	15.04	15.26	15.40	15.44	15.45
Cr_2O_3	0.09	0.21	0.20	0.08	0.08	0.03	0.02	0.05
FeO*	16.38	16.66	16.62	16.96	15.84	16.38	17.11	16.05
MnO	0.02	0.06	0.01	0.02	0.05	0.09	0.11	0.06
NiO	0.02	0.03	0.05	0.11	0.09	0.11	0.06	0.10
ZnO	0.00	0.00	0.06	0.17	0.37	0.02	0.05	0.61
MgO	22.77	22.67	22.57	22.45	22.46	22.28	21.63	22.80
CaO	0.20	0.19	0.20	0.21	0.22	0.29	0.61	0.19
Na_2O	0.03	0.02	0.03	0.03	0.05	0.02	0.00	0.01

CV-41								
Wt%	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
F	0.06	0.07	0.09	0.07	0.00	0.09	0.09	0.06
Cl	0.01	0.02	0.02	0.01	0.00	0.01	0.02	0.00
Total	87.7	87.5	87.3	87.8	87.0	86.8	87.0	88.4
apfu								
Si	6.579	6.512	6.501	6.519	6.532	6.465	6.440	6.529
Al^{iv}	1.421	1.488	1.499	1.481	1.468	1.535	1.560	1.471
Al^{vi}	2.092	2.049	2.052	2.061	2.139	2.126	2.122	2.130
Ti	0.007	0.006	0.006	0.006	0.002	0.001	0.000	0.000
Cr	0.014	0.033	0.032	0.012	0.013	0.005	0.004	0.008
Fe	2.726	2.787	2.789	2.834	2.655	2.763	2.894	2.653
Mn	0.004	0.011	0.002	0.003	0.008	0.016	0.020	0.010
Ni	0.002	0.004	0.009	0.018	0.014	0.018	0.010	0.016
Zn	0.000	0.000	0.008	0.025	0.054	0.003	0.007	0.088
Mg	6.755	6.763	6.754	6.688	6.713	6.701	6.527	6.719
Ca	0.042	0.040	0.043	0.044	0.047	0.063	0.132	0.041
Na	0.010	0.007	0.012	0.013	0.020	0.009	0.001	0.005
CV-41								
Wt%	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
SiO_2	32.62	31.97	32.53	31.62	31.35	34.42	32.19	30.87
TiO_2	1.22	0.08	0.00	0.04	0.01	0.05	0.01	0.01
Al_2O_3	15.50	15.56	16.13	16.15	16.31	16.46	16.71	17.19
Cr_2O_3	0.14	0.13	0.11	0.12	0.15	0.10	0.17	0.18
FeO*	15.25	16.67	14.47	14.18	14.59	13.95	14.87	14.53
MnO	0.04	0.05	0.04	0.04	0.02	0.03	0.03	0.07
NiO	0.05	0.11	0.19	0.09	0.11	0.11	0.11	0.06
ZnO	0.25	0.01	0.10	0.00	0.14	0.02	0.28	0.32
MgO	23.17	21.61	24.06	21.94	22.74	20.25	23.35	22.42
CaO	0.17	0.40	0.11	0.21	0.13	0.60	0.13	0.12
Na_2O	0.01	0.02	0.05	0.01	0.03	0.93	0.05	0.04
F	0.07	0.11	0.10	0.00	0.08	0.08	0.08	0.01
Cl	0.02	0.01	0.00	0.02	0.00	0.01	0.02	0.01
Total	88.5	86.7	87.9	84.4	85.7	87.0	88.0	85.8
apfu								
Si	6.414	6.467	6.410	6.469	6.352	6.803	6.353	6.243
Al^{iv}	1.586	1.533	1.590	1.531	1.648	1.197	1.647	1.757
Al^{vi}	2.006	2.175	2.156	2.362	2.246	2.637	2.239	2.342
Ti	0.181	0.012	0.000	0.006	0.001	0.008	0.002	0.001
Cr	0.021	0.020	0.017	0.019	0.023	0.016	0.026	0.029

CV-41								
Wt%	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Fe	2.508	2.819	2.384	2.425	2.471	2.306	2.454	2.458
Mn	0.007	0.008	0.007	0.006	0.004	0.004	0.004	0.012
Ni	0.008	0.017	0.030	0.014	0.018	0.018	0.018	0.010
Zn	0.036	0.002	0.015	0.000	0.021	0.003	0.040	0.048
Mg	6.792	6.514	7.067	6.689	6.870	5.967	6.869	6.761
Ca	0.036	0.086	0.024	0.045	0.029	0.126	0.027	0.025
Na	0.005	0.008	0.018	0.004	0.013	0.357	0.019	0.015

Table 5.
Chemical composition (wt%) and atom per formula unit (apfu) of chlorite on the basis of 28 O (samples CV-32, CV-67, CV-25, CV-37, CV-41).

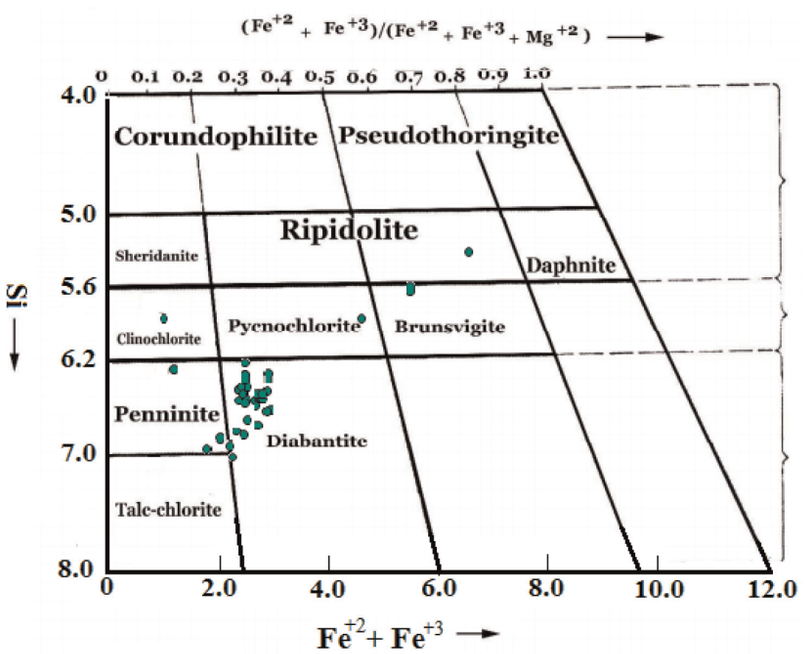


Figure 7.
Chalki basalt chlorite shown as mainly diabantite and less penninite (after [13]).

analysis for many samples as given in **Table 5** reveals the prevalence of diabantite with less abundant penninite, in addition to few grains of clinochlorite, pyenochlorite, and ripidolite (**Figure 7**).

4.2.6 Spinel group

The chemical data (**Table 6**) and their representation (**Figure 8**) for the few measured points of spinel group display that they are magnetite, chromian magnetite, and chromian spinel. Moreover, the plot of their Cr# against Mg# (**Figure 9**) gives an important and clear sign for their metamorphic origin as a result of low-grade metamorphism and of alpine type.

S 25				S 41	S 67	
Wt%	**1**	**2**	**3**	**1**	**1**	**2**
SiO_2	0.25	0.08	1.08	0.12	0.11	0.19
TiO_2	10.93	0.61	1.72	0.50	0.81	0.97
Al_2O_3	4.19	36.74	20.12	41.11	0.42	0.26
Cr_2O_3	21.07	22.96	30.26	23.03	2.03	2.50
FeO*	55.68	28.02	36.84	17.66	89.91	89.06
MnO	0.01	0.00	0.00	0.00	0.09	0.08
NiO	0.10	0.13	0.08	0.20	0.19	0.17
ZnO	1.81	0.00	0.29	0.03	0.44	0.35
MgO	0.17	10.87	5.49	15.45	0.43	0.38
CaO	0.02	0.00	0.02	0.52	0.02	0.01
Na_2O	0.03	0.03	0.00	0.02	0.01	0.00
F	0.00	0.02	0.00	0.10	0.00	0.00
Cl	0.00	0.00	0.01	0.01	0.00	0.00
Total	94.3	99.5	95.9	98.8	94.5	94.0
apfu						
Si	0.0101	0.0024	0.0374	0.0035	0.0053	0.0095
Al	0.2022	1.3019	0.8213	1.3889	0.0242	0.0154
Ti	0.3367	0.0138	0.0448	0.0108	0.0301	0.0362
Cr	0.6827	0.5457	0.8287	0.5219	0.0793	0.0978
∑	*1.2317*	*1.8639*	*1.7321*	*1.9250*	*0.1388*	*0.1590*
Fe	1.9083	0.7045	1.0670	0.4233	3.7136	3.6864
Mn	0.0004	0.0000	0.0000	0.0000	0.0037	0.0035
Ni	0.0034	0.0031	0.0022	0.0047	0.0075	0.0069
Zn	0.0547	0.0000	0.0074	0.0007	0.0160	0.0127
Mg	0.0106	0.4875	0.2834	0.6601	0.0315	0.0284
Ca	0.0007	0.0001	0.0008	0.0160	0.0013	0.0007
Na	0.0020	0.0017	0.0000	0.0010	0.0012	0.0000
∑	*1.9801*	*1.1969*	*1.3607*	*1.1058*	*3.7747*	*3.7387*
Fe^{2+*}	0.6361	0.2348	0.3557	0.1411	1.2379	1.2288
Fe^{3+*}	1.4121	0.5213	0.7896	0.3132	2.7481	2.7279
Cr#	0.771	0.295	0.502	0.273	0.766	0.864
Mg#	0.017	0.675	0.443	0.824	0.025	0.0226
	Cr-magnetite	Cr-spinel	Cr-spinel	Cr-spinel	magnetite	magnetite

**Calculated stoichometrically.*

Table 6.
Chemical composition (wt%) and atom per formula unit (apfu) of spinel group on the basis of 4 O (samples CV-25, CV-41, CV-67).

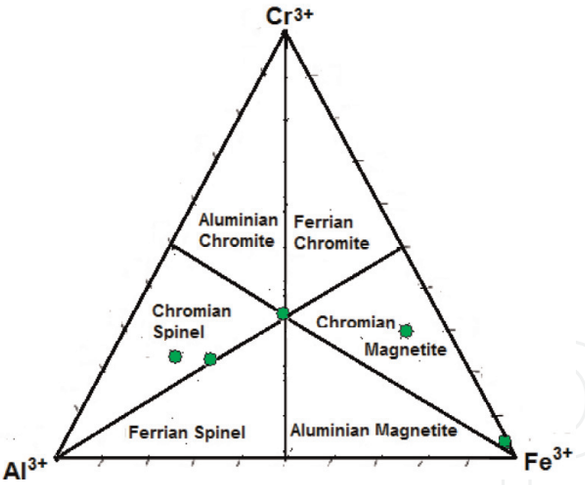


Figure 8.
Cr-Al-Fe plot of Chalki basalt spinels shown as magnetite, chromian magnetite, and chromian spinel (after [14]).

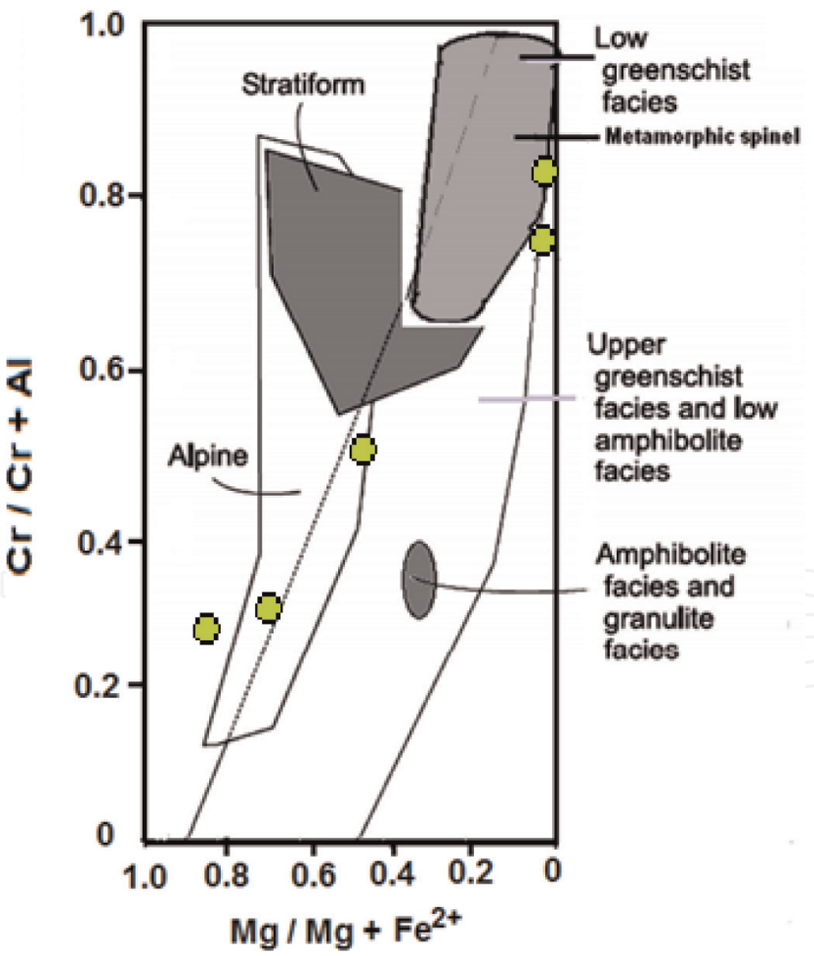


Figure 9.
Cr# vs. Mg# of Chalki basalt spinels indicating their metamorphic origin as a result of low-grade greenschist metamorphism and alpine type (after [15]).

Wt%	1	2	3	4	5	6	7
SiO_2	47.36	46.75	40.64	41.80	41.84	42.52	41.36
TiO_2	0.03	0.00	0.00	0.00	0.06	0.00	0.03
Al_2O_3	0.48	0.63	0.17	0.35	0.86	0.60	0.38
Cr_2O_3	0.01	0.00	0.01	0.02	0.01	0.03	0.00
FeO*	9.88	11.22	10.50	15.14	13.84	13.71	11.09
MnO	0.20	0.10	0.19	0.21	0.25	0.18	0.26
NiO	0.27	0.13	0.23	0.14	0.10	0.19	0.01
ZnO	0.14	0.24	0.58	0.21	0.27	0.00	0.30
MgO	33.21	30.50	36.36	28.77	29.53	29.35	31.96
CaO	0.27	0.42	0.11	0.98	0.32	0.37	0.14
Na_2O	0.07	0.05	0.03	0.03	0.04	0.00	0.03
F	0.01	0.09	0.09	0.09	0.05	0.09	0.09
Cl	0.02	0.02	0.02	0.02	0.02	0.01	0.00
Total	92.0	90.2	88.9	87.8	87.2	87.1	85.6
apfu							
Si	4.298	4.354	3.911	4.141	4.132	4.190	4.107
Ti	0.002	0.000	0.000	0.000	0.004	0.000	0.002
Al	0.052	0.069	0.019	0.041	0.100	0.070	0.044
Cr	0.001	0.000	0.001	0.001	0.001	0.002	0.000
Fe	0.750	0.874	0.845	1.255	1.143	1.130	0.921
Mn	0.016	0.008	0.015	0.018	0.021	0.015	0.022
Ni	0.020	0.010	0.018	0.011	0.008	0.015	0.001
Zn	0.009	0.017	0.041	0.015	0.019	0.000	0.022
Mg	4.493	4.234	5.216	4.249	4.347	4.312	4.732
Ca	0.027	0.042	0.011	0.104	0.034	0.039	0.015
Na	0.012	0.009	0.006	0.005	0.007	0.000	0.005
∑	*9.679*	*9.616*	*10.082*	*9.840*	*9.817*	*9.774*	*9.871*

Table 7.
Chemical composition (wt%) and atom per formula unit (apfu) of serpentines on the basis of 14 O (CV-67).

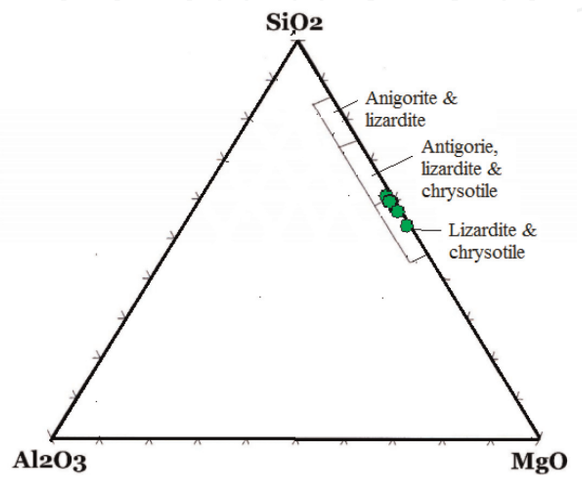


Figure 10.
Chalki basalt serpentines shown as type lizardite and chrysotile (after [16]).

4.2.7 Serpentine

Another less abundant secondary mineral after olivine in Chalki basalt is the serpentine. Their chemistry (**Table 7**) and plot (**Figure 10**) reveal clearly that they are mostly of lizardite and chrysotile types.

5. Petrological significance

1. Olivine alteration to chlorite, serpentine, iddingsite, amphibole, and iron oxide as shown petrographically is a good evidence to low-grade metamorphism.

2. The variation of the plagioclase in Chalki basalt from labradorite ($An_{51–61}$) to andesine ($An_{35–41}$) to andesine (An_{22}) reflects the andesitic variety of these volcanic rocks in addition to basalt, while the coexisting albite composition ($An_{0.1-04}$) indicates clearly that the rocks had suffered albitization due to low-grade sub-sea metamorphism.

3. The NiO content (0.11–0.12 wt%) in the Chalki forsteritic olivine ($Fo_{80–81}$) reflects the tectonic origin of this extrusion.

4. The enrichment of Chalki pyroxene in MgO causes its shifting from diopside-augite trend of the layered igneous rocks to endiopside ($en_{66–68}$ $wo_{27–28}$ $fs_{05–06}$) and subcalcic augite (en_{72} wo_{14} fs_{14}).

5. The prevalent chlorite (mainly type diabantite and penninite) in all the Chalki samples represents its suffering from chloritization process after the ferromagnesian olivine and pyroxene.

6. Serpentine (type lizardite and chrysotile) is recorded as an alteration product after the forsteritic olivine, in addition to another rare amphibole secondary mineral of type magnesiohornblende.

7. The spinel group as accessory minerals in Chalki basalt is classified as magnetite, chromian magnetite, and chromian spinel confirming the metamorphic origin (low-temperature sub-sea metamorphism and also of alpine type).

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