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Microstructure and Mineralogic Evidences of Fractional Differentiation: The Yeşilova Ophiolite Example

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Abstract: The Yesilova ophiolite located in the Alpine zone. This work deals with differentiation mechanism of ultramafic cumulate in ophiolite. Generally, the sequence consists of gabbro and plagiogranite. The petrographic and petrolgichal properties of it show that the layering in gabbros are products of a differentiation by fractional crystallization insitu. Because it has ferrous compounds (magnetite, hematite) by means of volatiles (H_2O, CO_2) that evidence magma at high temperatures (>700 °C). Ferrous liquids are compatible with fractional crystallization through olivine, plagioclase, clinopyroxene removal; whereas the evolved gabbros represent clinopyroxene, plagioclase cumulates from ferrous liquids with little amounts of trapped melt. Furthermore, cathodo luminesans image of zircons shows chemichal characteristic of oceanic plagiogranit (such as Fe_2O_3/MgO, Rb, Sr, Zr,TiO_2) that these characters can be explained by fractional crystallization processes in the late stage of magma generation. Furthermore, all plagiogranites have small positive Eu anomalies indicating the significant role of plagioclase in the fractional crystallization. So, the Yeşilova ophiolite ultramafic cumulates are the most probably related to crystal-liquid fractionation process of the oceanic crust of the Alpine belt. The plagiogranite is differentiation products of crystal-liquid insitu of a mafic magma in the magma chamber.

Key words: Crystal-liquid fractionation, SW-Turkey, plagiogranite, gabbros.

1. Inroduction

The process of magmatic differentiation is effective physical separation of phases that one is liquid and the others are crystalline. Gravitational segregation of crystals was long thought to be the main way of achieving this. The other mechanisms may be diffusion-driven fractionation that under conditions of slow cooling, fractionation may be achieved by chemical diffusion across a front of advancing crystallization [1], compaction-driven fractionation mechanism is mainly a function of the rate of solidification and thickness of the zone of crystallization [2], convection-driven fractionation processes have been proposed as means of enhancing crystallization and displacing evolving liquids from an advancing zone of crystallization [3, 4]. The sediment-like structure is enough to show why crystal settling has seemed such an obvious mechanism of differentiation. A variety of mechanisms are involving nucleation and growth of crystal in gradient of temperature and composition [1, 5]. The sediment like structure is a form in crystal mushes along the roof and margins of magma chambers during cooling [6]. By faulting in the magma chamber or tectonically emplacement of ophiolite there are observable dunitic bodies [7]. The key factor in all mechanism is regional stress, influencing magmatic transport, crystallisation and cooling prosess [8].

The cumulative layering models have applied to be understanding of layered mafic magmatic complexes [1, 9, 10]. Geologic structure observations, mineralogic and chemical data show that mafic magma has low viscosities inhibit low crystal settling [11]. The cumulative layering is characteristic for some ophiolite complex (Oman ophiolite, Skaergaard intrusion). This structure is displayed at some ophiolite series in Turkey and it is not enough to be investigated. The ophiolitic series have emplaced in five different zones in Turkey; these are, from south to

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North; Pontide ophiolites, Anatolide ophiolitic belt, Tauride ophiolite belt, Southeast Anatolian ophiolites, Peri-Arabian ophiolites (Fig. 1). All of these ophiolites are the products of subduction zone [12-14]. It consists of ultrabasic extrusive rocks and associated sediment rocks belong to the Alpine folds of the country. Rock successions are strongly related to the development of the Alpine orogenic belt on their particular information on the deep mechanics of the Alpine orogeny.

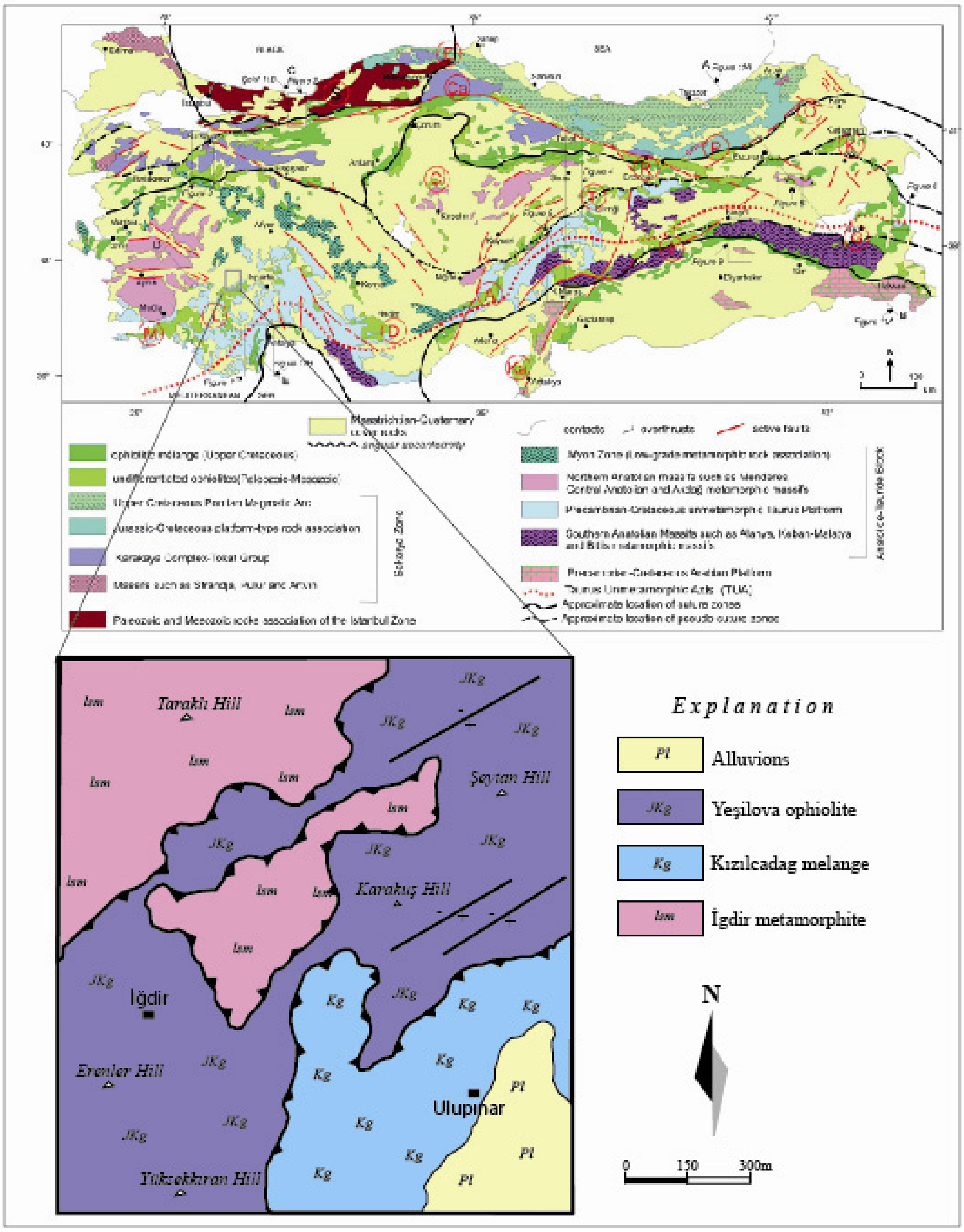

Fig. 1 Ophiolites, ophiolitic mélanges and metamorphic massifs of Turkey (Yılmaz & Yılmaz, 2013) and Geologic map of investigated area (Kılıç, 1996).

The Yesilova ophiolite is one of the most important tectonic units representing the western part of the ophiolite belts of the Anatolide-Tauride block, SW Turkey. The present paper is discussing cumulative layering processes in cumulates of ophiolite. The properties is same as microstructure, mineralogy is revealing for the Yeşilova ophioite.

2. Analytical Methods

Examples have been taken from all the rocks in the examination area for petrographical and geochemical examination and thin sections have been prepared in the geology laboratories of Pamukkale University. Total amount of major oxides and minor elements have been found by the method of ICP-MS (Inductively Paired Plasma Mass Spectrometry), and lithium metaborate/tetraborate ($LiBO_2$) fusion and dilute nitric acid digestion methods are used in the examples of 0.2 g and made in ACTLAB (Canada).

An Cathodoluminescence analyzer (CL) was used for CL-images of zircons. Zircons are seperated from plagiogranite via heavy fluids that their size varies from a few milimeters to centimeter with colors of gray-gray or sometimes dark brown. Cathodoluminescence images of the zircons were taken before in-situ LA-ICPMS dating in Geological Department of the Hacettepe University (Ankara) to characterize zircons to be dated. An ICPMS analysis was used for quantitative analysis of major elements and trace element concentrations in the samples and maked in Canada-ACTLAB.

The CL images were produced by a Zeiss Evo-50 SEM equipped with cathodeluminescence and EDS detectors in METU physics laboratories. For mineral pre-separation, rock samples pulverized from zircon rich plagiogranite are first separated into 2 samples with sieve diameters of 63-125 mm and 125-250 mm; they are enriched first on a wet shaking table and afterwards with tetrabromethane and diodemethane and magnetic heavy minerals were removed via a magnetic separator. In the last stage, the sample was passed through Clerici solution, separated into 5 dimensional fractions and hand separated under a binocular until 100% purity is obtained.

3. Results and Discussion

3.1 Geological Setting, Petrography and CL-İmages

The Yesilova ophiolite located in the Alpine zone (Western Taurus) (Fig. 1). It was formed at the southern branch of Neo-Tethys, and was abducted over the southern edge of the Menderes Massif during the Cenonian during Laramian orogenesis [15]. The Yeşilova ophiolite tectonite is consisting of harzburgites, dunite and chromite pods. The sequence continues with cumulates overlie tectonites and it includes dunite, wehrlite, clinopyroxenite, layered and nonlayered gabbro. The tectonite and cumulate sequences have been cut by isolated gabbro and diabase dikes. The dikes which have various thicknesses and display chilled zones in various directions are suggested to have been formed by fractional crystallization processes in an island arc geotectonic setting [16]. it is defined as a dismembered ophiolite. Rodingites show in serpantinized gabbros belong to cumulates and around the margins of diabase dykes in the Yeşilova ophiolite which is emplaced (Jurassic-Upper Creatase) in western Lycia naps and is between Burdur and Acıgöl lakes in the Southwest Anatolia. Rodingites in the serpentinized ultramafics occur as lenses [17].

The ultramafic cumulates which have gradual contact with tectonites are represented by dunites with banded or disseminated chromites, wehrlite, clinopyroxenes and plagiogranite. A thick layered gabbro level takes place on isotrope gabbros (Fig. 2).

Layering in gabbros is defined by the change of rate of olivine, plagioclase and pyroxene in layered gabbros. In microscopic investigation of gabbro samples show holochristaline and subophitic texture. They are comprised of clinopyroxene (30-38%), olivine (32%), plagioclase (42-47%), zircon and oxide

Fig. 2 Layered gabbro on isotrop gabbro and pyroxene-plagioclase alteration.

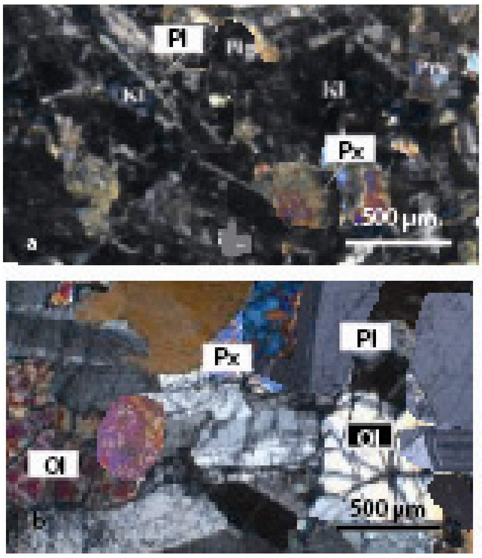

Fig. 3 Microscopic image of plagiogranite (a) and gabbro (b) Pl: plagioclase, Ol: olivine, Px: pyroxene, Kl: klorite, Zr: zircon.

minerals (Fig. 3a). The anorthite content of plagioclases is found as 10%. The anorthite rate of plagioclase is displayed being layered gabbro [18]. The isotrope gabbro (iron-rich gabbros) consists of plagioclase, pyroxene, amphibole, Fe-Ti oxides (ilmenite, magnetit), titanite, sphene, magnesite (Fig. 3b). There are products of a differentiation by fractional crystallization in situ. It is furthermore proposed that the ore might be formed by repulse of Fe and Ti from the pyroxene lattice at a late magmatic stage. The ferrous compounds such as magnetite or hematite by means of volatiles (H_2O, CO_2) present in rock magmas at high temperatures (> 700 °C) are inconsistent with thermochemical considerations [19]. The fractionation of Fe-Ti oxide rich rocks initiates the marked SiO_2 enrichment of the magma.

Plagiogranites are located in isotrope gabbros. These light colored acidic rocks can easily be observed in gabbros in macroscopic scale. These rocks which display poikilitic texture have a modal mineralogical composition of plagioclase (An20-25), amphibole, and quartz, and minor to trace amounts of Fe-Ti oxide, biotite, potassium feldspar, titanite, zircon. The crystallization is thought to have taken place while static conditions existed in the magma. This is supported by poikilitic texture so commonly developed in these rocks and the general absence of igneous layering. Zoning is observed subeuhedral plagioclases in plagiogranites [20] (Fig. 3b). These rocks are commonly overprinted by extensive subsolidus hydrothermal alteration of magmatic plagioclase and amphibole to secondary plagioclase, tremolite/actinolite, chlorite, and smectite [12, 21].

In catholuminescent image of zircons in plagiogranite display clear, colorless grains with oscillatory and sector CL zoning. Textures are distinctly porous, opaque, and faintly colored. The porous arise from inclusions (enriched in Y, Th, and U). The porous zircons are not abundant. The luminescent rims in zircons can arise from high Ti-values. The light or high luminescent area of CL images is higher inclusions enriched such as U, Th, and Y. Dark region on CL image represents low inclusion contents (Fig. 4).

3.2 Geochemistry

Main oxides and trace elements analyses of cumulate rocks (gabbros and plagiogranite) of Yeşilova ophiolites were conducted in ACME Analytic Laboratories in Canada. Total amount of major oxide and minor elements were analysed by ICP-MS method and by acid digestion and lithium metaborate/tetraborate fusion method on 0.2 gr samples. The results are shown in Table 1.

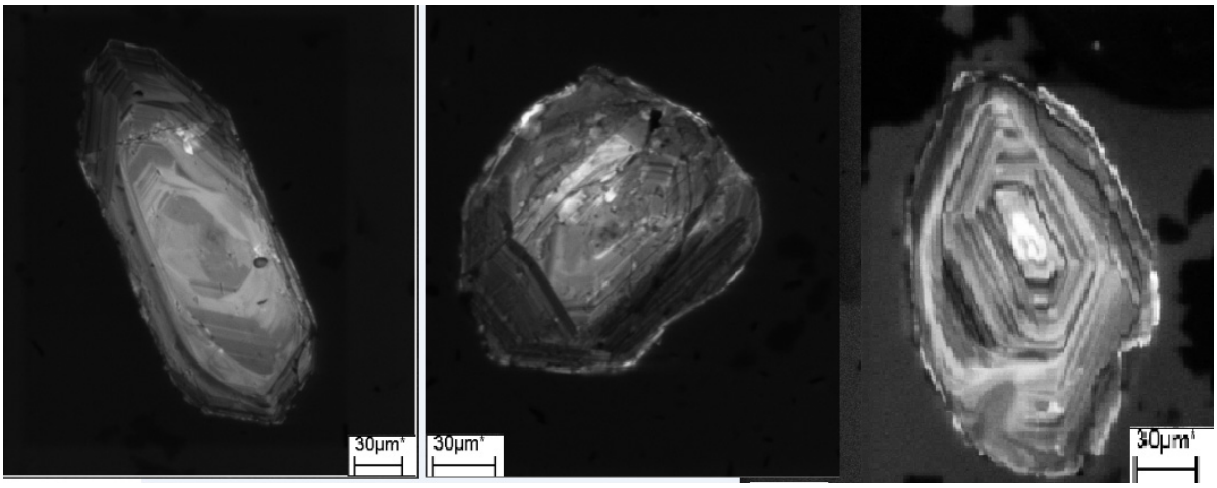

Fig. 4 Representative cathodoluminescence (CL) zoning patterns on zircons of plagiogranite.

Table 1 Analysed results of major oxides-trace elements of gabbros and plagiogranites.

Elements (wt%)	Gabbros								Plagiogranite	
	YG1	YG2	YG3	YG4	YG5	YG6	YG7	YG8	Pl2	Pl4
SiO_2	45.53	45.58	47.03	44.05	46.80	47.12	41.44	45.69	63.11	67.10
Al_2O_3	15.10	12.60	11.11	14.85	12.23	12.56	15.11	11.08	12.32	13.25
MgO	6.99	7.17	7.35	7.36	7.37	7.33	7.25	6.56	2.42	1.35
CaO	11.12	6.60	10.22	9.70	11.18	10.42	10.01	10.23	3.27	5.09
Na_2O	3.30	3.41	3.45	3.52	3.21	3.27	3.29	3.04	5.21	3.58
TiO_2	0.70	1.37	1.05	0.66	0.60	1.51	1.47	1.54	0.68	0.34
P_2O_5	0.12	0.12	0.13	0.13	0.13	0.15	0.15	0.13	0.07	0.08
Fe_2O_3	13.76	9.92	8.42	8.98	12.76	8.24	15.09	9.21	6.17	3.41
MnO	0.21	0.15	0.12	0.14	0.14	0.13	0.21	0.12	0.07	0.08
K_2O	0.06	0.04	0.66	0.20	0.04	0.05	0.03	0.05	0.23	0.31
LOI	3.01	1.0	2.8	4.1	2.0	4.01	2.14	1.7	1.0	2.4
Total	99.90	87.96	92.34	93.69	96.46	94.83	96.19	90.15	94.56	96.99
Rb	3.2	3.8	3.4	2.9	3.6	4.1	3.7	3.6	2.5	1.8
Sr	151.2	168.4	166	173	184	158	181	169	170	178
Nb	0.6	2.1	1.3	0.4	1.1	1.3	1.5	1.7	1.9	2.7
Zr	57	43	52	56	49	59	53	55	38	47
Y	23.1	18.4	26.1	21	20.8	24.3	22.6	21.9	23	29
Ba	17	22	54	33	41	35	46	52	65	77
Ta	1.0	1.6	1.0	1.0	1.3	1.0	1.0	1.0	0.2	0.1
Hf	3.6	3.2	2.6	1.5	2.4	1.7	1.9	2.5	1.6	1.4
Th	1.2	0.3	0.2	0.7	0.4	0.7	0.9	1.1	0.2	0.5
La	2.3	2.5	2.2	2.6	2.1	2.1	1.8	2.0	3.44	2.70
Yb	0.06	0.11	0.13	0.44	1.0	0.56	2.01	0.62	1.62	1.53

Gabbros have been affected from this alteration even if less and in mafic element chemistry this effect is observed. Due to alteration the Na_2O+K_2O value is average 3.45%. K_2O rate is less than that of Na_2O and enrichment of Na can be due to spilitization of mafic rocks as a result of low gade hydrothermal metamorphism. The $\%Na_2O+K_2O$ and $\%SiO_2$ represent sub-alkaline magma (Fig. 5a).

In AFM diagrams it is observed that some gabbros fall into an III area (Fig. 5b). This indicates the formation of the primary fraction of solutions in depleted mantle which typicaly occurs at the floor of the magma chamber of mafic cumulate gabbros. The REE values of the gabbro show positive Eu anomaly ($Eu/Eu^* = 1.08$), positive LREE $(La/Sm)_N = 0.6$ is caused by the resence of clinopyroxene and amphibole [22].

Plagiogranites are accepted as a product of a later differentiation of magma [20]. The elements such as Zr, Y, Nb and TiO_2 used determine petrologic characters and sources are durable opposite to alteration, metamorphism and metasomatism. In Zr-TiO_2 diyagram, plagiogranites is mafic-ultramafic rock area (Fig. 5c).

Whole rock geochemical plagiogranites are different from high SiO_2 (63.11-67.10%) with remarkably low K_2O (0.23-0.31%), higher MgO (1.35-2.42%), CaO (3.27-5.09%) than the continental granite. Moreover, they have slightly high amount of Fe_2O_3/MgO ratio, Rb, Sr, Zr and TiO_2 values to oceanic plagiogranite composition. These characters can be explained by fractional crystallization processes in the late stage of magma generation. Plagiogranite samples display enrichment in REE according to normal values. They exhibit slightly depletion in LREE ($(La/Sm)_N$ = 1.44-2.55) relative to HREE ($(Sm/Lu)_N$ = 0.41-0.88). Furthermore, all the samples of the plagiogranites have small positive Eu anomalies ($(Eu/Eu^*)_N$ = 1.04-1.08), indicating the significant role of plagioclase in the fractional crystallization [20]. The positive Eu anomaly decreases with decreasing Mg# of the gabbros. It is

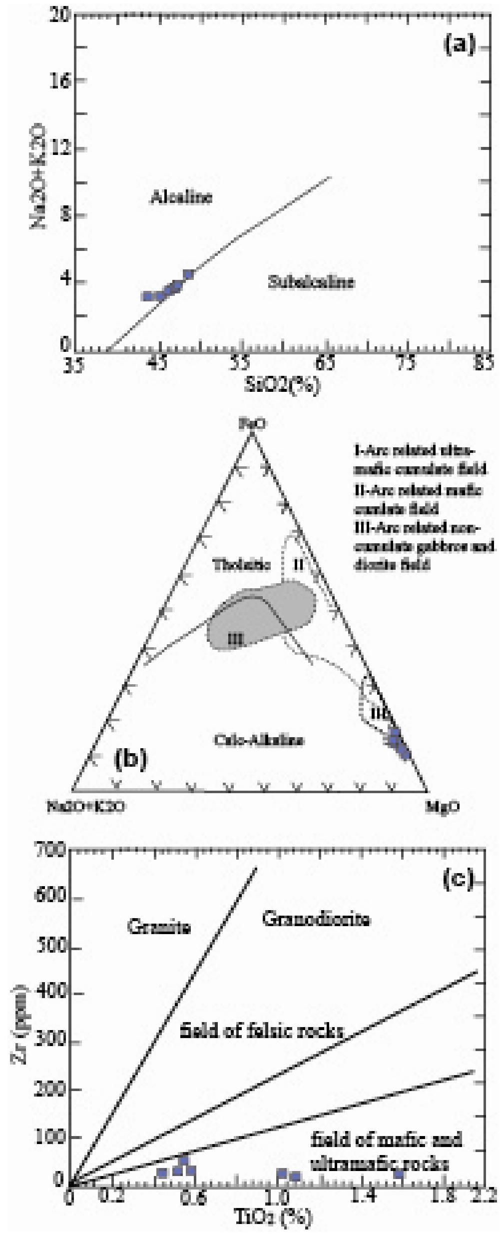

Fig. 5 (a) $\%Na_2O+K_2O$ and $\%SiO_2$ diagram, (b) AFM diagram, (c) Zr -TiO_2 diyagram of gabbros, I, II, III after [27].

changed by portions of cumulus plagioclase. The gabbro exhibits evidence for crystal-liquid fractionation. The Mg#(100Mg/Mg+Fe) of 33-48 for the gabbro precludes equilibration with a mantle source olivin or pyroxene [23]. Fractionation of amphibole can explain low Mg# and low Ti concentrations of the evolved gabbro. The early crystallization of amphibole suggests that the source was hydrous [24].

Crystallization of new phases in subsolidus leads to significant redistribution of major and trace elements during cooling. Because gabbros are slowly cooled it is no zoning in major, minor and trace elements. The Rb/Sr rate is defined as 0.01. This ratio is used by Ref. [25] for the plagiogranites formed by fractional crystallization. In all plagiogranites which were assumed to have formed by differentiation of basic magma the Rb/Sr is less than 0.1 [26]. The petrographic and geochemical results suggest that plagiogranites of the Yeşilova ophiolite are the most probably related to crystal-liquid fractionation process of the oceanic crust of the Alpine belt. The mechanism of crystal-liquid fractionation has three basic mechanisms: diffusive exchange, compaction, convective exchange. The essential requirement of any process of differentiation is an effective physical separation of phases, normally one liquid and the others crystalline [1].

4. Conclusions

The Yesilova ophiolite is one of the most important tectonic units located in the Alpin zone and it is a major part of the Lycian nappes of SW Turkey. The Yeşilova ophiolite consists of tectonites, cumulate, diabase dike. The tectonite and cumulate sequences have been cut by isolated gabbro by plagiogranite and diabase dikes and have rodingites lenses.

The cumulate consists of layering gabbro, isotrop gabro and plagiogranite. The layering in gabbros is defined by the change of rate of olivine, plagioclase and pyroxene in layered gabbros. In microscopic investigation of gabbro samples shows holochristaline and subophitic texture. It shows clinopyroxene, olivine, plagioclase, zircon and oxide minerals. The contrast between two gabbros are anorthite rate of plagioclase and opac minerals. The layering in gabbros is product of a differentiation by fractional crystallization in situ. It is furthermore proposed that the ore might be formed by repulse of Fe and Ti from the pyroxene lattice at a late magmatic stage. The ferrous compounds such as magnetite or hematite by means of volatiles (H_2O, CO_2) present in gabbros that these magma at high temperatures (>700 °C) are inconsistent with thermochemical considerations [19]. Plagiogranites locating on isotrope gabbros display hypidiomorphic granular texture and have a modal mineralogical composition of plagioclase, amphibole, and quartz, and minor to trace amounts of Fe-Ti oxide, biotite, potassium feldspar, titanite, zircon.

In chemical analyses of cumulate rocks and CL-image of zircon in plagiogranite show that plagiogranites have higher value from the oceanic plagiogranite composition (such as Fe_2O_3/MgO, Rb, Sr, Zr,TiO_2, etc.). These characters can be explained by fractional crystallization processes in the late stage of magma generation. Moreover, all plagiogranites have positive Eu anomalies, indicating the significant role of plagioclase in the fractional crystallization. As for gabbros that have been affected from this alteration even if less and in mafic element chemistry this effect is observed. The K_2O rate is less than that of Na_2O and enrichment of Na can be due to spilitization of mafic rocks as a result of low gade hydrothermal metamorphism and is character of sub-alkaline magma. The gabbros are related to cumulate gabbro that indicated the formation of the primary fraction of solutions in depleted mantle which typicaly occurs at the floor of the magma chamber of mafic cumulate gabbros. The REE values of the gabbro show positive Eu anomaly ($Eu/Eu^* = 1.08$), positive LREE $(La/Sm)_N = 0.6$ is caused by the resence of mafic minerals. In catholuminescent image of zircons in plagiogranite display clear, colorless grains with oscillatory. Textures are distinctly porous, opaque, and faintly colored. The porous arise from inclusions (enriched in Y, Th, and U). Moreover, the luminescent rims in zircons can arise from high Ti-values. All samples are high titanium oxides (ilmenite, titanite). The titanium is a common lithophile metallic element. During magmatic processes, Ti follows Fe in magmatic crystallisation.

Ti^{4+} is predominantly partitioned into Fe-Ti or Fe oxides such as ilmenite and magnetite. The compatibility displayed by Ti during the early stages of fractionation results in enrichment in mafic (> 1% TiO_2) and ultramafic (> 2% TiO_2) rocks relative to felsic igneous lithologies (0.2% TiO_2). Therefore elevated Ti values are indicative of mafic and ultramafic rocks (http://www.weppi.gtk.fi/publ/foregsatlas). Titanium oxides value of analysed samples displays mafic rocks. The petrographic and geochemical results suggest that cumulate rocks of the Yeşilova ophiolite are most probably related to crystal-liquid fractionation process of the oceanic crust of the Alpine belt.

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