Petrochemistry of Mafic and Ultramafic Rocks of CY-4 Drill-Hole, Cyprus Crustal Study Project

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ABSTRACT. This paper is a result of study and investigation of 45 samples collected, at 50 meter intervals, from CY-4 drill hole of the Cyprus Crustal Study Project, to confirm, on basis of petrographic studies and chemical analysis, the classification of the Troodos Ophiolite suite and the terminology of the rock units.

Troodos complex comprises a Cretaceous ideal ophiolite suite. Drill hole CY-4, located in the southeastern part of the complex, penetrates through sheeted dikes, gabbroic rocks, and ultramafic cumulates. The rock sequence of the drill hole could be broadly classified into:

1) a diabasic zone representing the sheeted dikes, (9.85m-483.50m),
2) a zone of mixture of sheeted dikes and gabbros, (483.50m-837.45m),
3) massive gabbro zone, (837.45m-1346.80m),
4) cumulate gabbro zone, (1346.80m-1754.10m), and
5) ultramafic zone consisting essentially of clinopyroxenite, websterite and dunite, (1754.10m-2263m).

The studied samples can be divided chemically into mafic and ultramafic groups which correspond closely to the petrographic classification. Mafic magmatic rocks are generally oversaturated tholeiites. Trace element contents are similar to those expected from such rock suites. Chemical characteristics of the ultramafic rocks indicate a cumulate origin consistent with previous investigations.

Introduction

The Troodos complex (Fig. 1) covers an area of about 3000 km² in southern Cyprus (Gass 1960). This complex comprises mainly Cretaceous intermediate, mafic and ultramafic, volcanic and plutonic rocks (Gass 1980, Robinson et al. 1983; Schmincke et al. 1983). These rocks, locally overlain by marine sediments (Fig. 1), form an ideal ophiolite sequence ranging from pillow lavas through sheeted dikes, cumulate gabbro and peridotites to dunite and tectonized harzburgite (Gass 1980).

Many workers studied the petrology of the Troodos ophiolite (e.g. Ingham 1959, Greenbaum 1972 & 1977, Malpas and Langdon 1984, Cameron 1985). The following is a summary of these studies:

Generally, the extrusive rocks form a continuous belt around the plutonic rocks of the ophiolite complex (Fig. 1). They are divided into two members: Lower pillow
laves (LPL), which are andesites to dacitic andesite comprising mainly plagioclase (An$_{50-30}$), orthopyroxene, clinopyroxene and opaques, and Upper pillow lavas (UPL) which are mainly basaltic andesite containing plagioclase, low-Ca pyroxene, and amphibole with olivine and diopside as phenocrysts.

The sheeted dike swarms have a general N-S trend and according to Moore and Vine (1971) they indicate an extension of more than 100 km. These rocks are generally diabasic consisting of plagioclase (An$_{50-30}$), orthopyroxene, clinopyroxene and opaques.

The cumulate rocks are underlain by mantle tectonized harzburgite. They comprise dunite, websterite, pyroxenite and gabbro cumulates with the phase layering: olivine, olivine + diopside, olivine + diopside + enstatite, olivine + diopside + enstatite + plagioclase, diopside + enstatite + plagioclase (Greenbaum 1972, Allen 1975, Thy et al. 1986).

The mantle sequence of the Troodos complex is composed mainly of tectonized harzburgite containing olivine (Fo$_{90-80}$), enstatite, and diopside. Dunite and plagioclass lherzolite pods are common. The harzburgite, which is considered to represent the residue of plagioclase lherzolite partial melting, is assumed to form the parent units of pillow lavas, sheeted dikes, and cumulate rocks (Stewing et al. 1975, Wood 1979).
Drill hole CY-4, which is a part of the Cyprus Crustal Study Project, is located in the southeastern part of the Troodos massif (Fig. 1) at 34°53'50"N Latitude and 33°05'38"E Longitude. This drill hole penetrates 2263m of the ophiolite sequence starting from sheathed dikes passing through the gabbroic zone and ends in the ultramafic zone.

A total of 45 samples from this drill hole was selected for petrographic studies and chemical analysis, in order to understand the petrochemical characteristics of the ophiolite sequence. Table 1 shows the petrographic classification and the results of chemical analysis of the studied rocks.

**Petrography**

The rock sequence observed in drill hole CY-4 may be broadly classified into the following zones:

1. A diabasic zone (9.85-48.3.50m) representing the sheathed dikes,
2. A mixture of sheeted dike and gabbro (40.50m-837.45m),
3. Massive gabbro (837.45m-1346m),
4. Cumulate gabbro (1346.50m-1754.10m), and
5. Ultramafic zone (1754.10m-2263m).

The position of the contacts are not known because of the 50 meter intervals between sample. The exact thickness of different zones can be obtained from the hole CY-4 core descriptions (Horne and Robinson 1984).

### 1. Sheeted Dike Zone

The thickness of this zone is about 470m. The upper part of the sequence consists of fine-grained ophiitic, altered rock consisting mainly of plagioclase (An42-54), tremolite, chlorite and opaque minerals. Zeolite veinlets and amygdalae were observed in some sections, especially in the upper most parts. Relicts of clinopyroxene are seen frequently and epitaxiation of plagioclase is common. This fine-grained rocks represent narrow dikes or chilled margins of thicker dikes.

The lower part of the dike sequence consists of medium-grained diabases and composed mainly of plagioclase (An45-55), altered pyroxene and opaque minerals. Chlorite, tremolite and actinolite are the main alteration products of pyroxene. Zeolite veinlets are less common than in the upper dikes.

### 2. Sheeted Dike/Gabbro Zone

This zone, which is a mixture of a diabasic and gabbroic rocks, is about 730m thick. The diabases are petrographically similar to those of the overlying sheeted dike complex.

The gabbroic rocks are generally coarse-grained with some cumulate textures and they consist mainly of calcic plagioclase (An45-55), clinopyroxene (augite-diopside), tremolite and opaque minerals. Epitaxiation and albitization of plagioclase are frequently present. One sample (Sample N 18 - Table 1) is a leucocratic with more than 60% sheared plagioclase.
In general, low-grade metamorphism is common, especially in the felsic basics of the sheeted dikes. It includes zoelite facies in the upper part of the sequence grading to lower green schist facies. This type of metamorphism is indicated by occurrence of zoetite, altered plagioclase and appearance of such minerals as tremolite and chlorite.

3. Massive Gabbro Zone

The gabbroic rocks may be divided broadly into a massive gabbro zone about 509m thick and a cumulate gabbro zone about 408m thick.
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The massive gabbros are generally coarse-grained and characterized by a uniform texture. The main minerals are plagioclase (An80-85), diopside, augite, tremolite, and opaque minerals. Plagioclase sometimes shows igneous-lawsonite (e.g. sample N 17).

**4. Cumulate Gabbro Zone**

Dyke hole CV-4 penetrates gabbro and ultramafic cumulates (Zone 4 and 5) down to the clinopyroxenite and websterite. Opx and Cpx occur throughout the core and plagioclase decreases sharply as a cumulus phase below 1693.4 meters depth. Olivine...
appears as a cumulus phase below approximately 1418.3 meters depth. Major petrographic and/or chemical breaks occur approximately at 483.5, 837.5, 1346.8, 1692.4 and 2224.3 meter depth.

The cumulate gabbro zone consists essentially of gabbro and gabbronite cumulates. A websterite zone was encountered at a depth of 1496.70 meters (sample N. 25).

The cumulate rocks consist mainly plagioclase, clinopyroxene, orthopyroxene and tremolite-actinolite. Plagioclase representing 50%-80% of the rock, exists as both cumulus and intercumulus phases. It is characterized by its calcic nature (An90). Clinopyroxene is diopsidic in composition and orthopyroxene is magnesian. They may occur as cumulus or intercumulus phases. Epidotization and serpentinization are the most common types of alteration.

5. Ultramafic Zone

The ultramafic zone of the sequence consists essentially of clinopyroxenite, websterine and dunite. These rocks are characterized by the sudden decrease in their plagioclase content, compared to the gabbroic zones and by the relative increase in pyroxene and olivine contents. Clinopyroxene (40%), orthopyroxene (40%), and olivine occur mainly as cumulus minerals while plagioclase represents intercumulus material. The bottom 100 meters of the drill hole are of dunite composition, where olivine makes up to 90% of the rock. Serpentinization is widespread obscuring the textures. However, these rocks are interpreted as cumulate dunites.

Chemistry

All the samples were chemically analysed in the laboratories of the Faculty of Earth Sciences, King Abdulaziz University, using XRF for the major oxides and atomic absorption and plasma (DCP) for the trace elements (Table 1). Fourteen samples are sheeted dikes (N1-N14), eight are massive gabbro (N15-N22), six are layered gabbro (N23-N28), and seventeen are ultramafic rocks (N29-N45). Normalized oxides values were used for norm calculations (Table 2).

Based on chemical composition, the rock series may be divided into two major groups: Mafics and ultramafics.

a) Mafic Group

Sample N1 to N28, except N18, represent sheeted dikes, massive gabbro and a layered gabbro (Table 1). Due to similarity in chemical composition, these samples will be discussed as one group unless it is otherwise mentioned, in spite the fact that the sheeted dikes and the massive gabbro are genetically different than the cumulates. Few samples (N1, N7, N8, N10, N11 and N20) show an intermediate chemical composition. Moores and Vite (1971) and Desmet et al. (1980) indicated the dacitic andesite or basaltic andesite chemical composition of some of these rocks.
Most samples are oversaturated in silica as indicated by their normative quartz averaging 5.28% and reaching up to 17.05%. Normative orthopyroxene is generally high. The wide variation in chemical composition in some elements is probably due to the variations in the relative proportions of the major mineral components.

The chemistry of the cumulus phase of drill hole CY-4 (below 1346 meters) are characterized by some variations which are probably due to variations in mineral chemistry. Tby (1986) mentioned the extensive variation in mineral chemistry with olivine ranging from FOg to FO60, plagioclase from An80 to An60, diopside from En88Fs10Wo10 to En55Fs35Wo10 and enstatite from En15Fs85Wo10 to En55Fs35Wo10.

Mg (3.06%-10.36%) and CaO (7.29%-16.84%) are normal and generally show an increase with depth. The sudden increase in MgO content between N25 and N29 distinguishes the mafic and the intermediate rocks from the ultramafic rocks. Total FeO content is generally constant a features characteristic of most basalts which belong to ophiolites (Coleman 1977). TiO2 content is within the range of such rocks. Total alkalis are relatively high probably due to mobilization of K2O and Na2O. The increase in total alkalis, especially in the sheeted dikes, may be attributed to the presence of realities. The relatively high SiO2, alkali and H2O contents and low CaO, MgO and FeO contents of some of the sheeted dikes is possibly caused through sea water lava interaction (Gaus and Smewing 1973, Serri 1979).

Trace elements such as Sr, Zr, Nb, Rb and Sr are comparable to those observed in other ophiolite masses (Coleman 1977). Ni content is relatively low, probably due to lack of olivine. In the sheeted dikes, Ni content varies between 33-94 ppm which may

![Fig. 2. AFM diagram of mafic and ultramafic rocks of drill hole CY-4, Tristan da Cunha.](image-url)
| Sample No. | Ni | N2 | N3 | N4 | N5 | N6 | N7 | N8 | N9 | N11 | N12 | N13 | N14 | N15 | N16 | N17 | N18 | N19 | N20 | N21 | N22 |
|-----------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Adj. (ppm) | 12.0 | 1.25 | 1.32 | 1.48 | 1.67 | 1.80 | 1.87 | 1.07 | 1.10 | 1.17 | 1.22 | 1.29 | 1.41 | 1.53 | 1.65 | 1.77 | 1.89 | 2.01 | 2.13 | 2.25 |
| N2O | 1.04 | 1.03 | 1.04 | 1.05 | 1.06 | 1.07 | 1.08 | 1.09 | 1.10 | 1.11 | 1.12 | 1.13 | 1.14 | 1.15 | 1.16 | 1.17 | 1.18 | 1.19 | 1.20 | 1.21 |
| N2O2 | 1.49 | 1.50 | 1.51 | 1.52 | 1.53 | 1.54 | 1.55 | 1.56 | 1.57 | 1.58 | 1.59 | 1.60 | 1.61 | 1.62 | 1.63 | 1.64 | 1.65 | 1.66 | 1.67 | 1.68 |
| N2O3 | 1.66 | 1.67 | 1.68 | 1.69 | 1.70 | 1.71 | 1.72 | 1.73 | 1.74 | 1.75 | 1.76 | 1.77 | 1.78 | 1.79 | 1.80 | 1.81 | 1.82 | 1.83 | 1.84 | 1.85 |
| N2O4 | 1.81 | 1.82 | 1.83 | 1.84 | 1.85 | 1.86 | 1.87 | 1.88 | 1.89 | 1.90 | 1.91 | 1.92 | 1.93 | 1.94 | 1.95 | 1.96 | 1.97 | 1.98 | 1.99 | 2.00 |

**Table 2: Adjusted Data (ppm), High Crust and Normalized Meteorite Data for CV-5 Chondrite Group—Inperms**

**Normalized Meteorite Data**

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represent more than one magma. Also a consistent relation is observed between the Ni and TiO2 content in these rocks, where Ni increases with the decrease in TiO2.
| Sample No. | N2S | N2O | N2F | N2P | N2R | N2S | N2O | N2F | N2P | N2R | N2S | N2O | N2F | N2P | N2R | N2S | N2O | N2F | N2P | N2R | N2S | N2O | N2F | N2P | N2R | N2S | N2O | N2F | N2P | N2R |
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| Synergies |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |     |
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**Note:** The table represents data from a study on the petrochemistry of Mafic and Ultramafic Rocks. The table includes various elements and their concentrations, which are essential for understanding the composition and origin of these rock types. The data is crucial for geologists and researchers studying the Earth's crust and its evolution.
Fig. 3. \( \text{SiO}_2 \)-FeO/MgO diagram (Miyashiro 1975) showing composition of sheeted dikes and dike/gabbro mixture of CY-4 drill hole, Toudous Complex.

Fig. 4. \( \text{MgO}-\text{Al}_2\text{O}_3-\text{CaO} \) diagram (Coleman 1977) of mafic and ultramafic rocks of CY-4 drill hole, Toudous olivine.
b) Ultramafic Group

The ultramafic rocks have cumulate textures and are interpreted as crystal cumulates. MgO content ranges from 15.13 to 28.69% and total iron content ranges from 4.56 to 9.26%. The last two samples (Nk & Nk4) are characterized by their exceptionally high MgO contents (34.11 & 36.29%, respectively) and their high total iron contents reaching up to 13.3% indicating olivine enrichment. The NiO & Cr₂O₃ ratios were used for discrimination between mantle and cumulates rocks (Malpas 1976, Irvine and Findlay 1972, and Price 1984) for the East African Ophiolite suites. By using the same design, all the Troodos ultramafics lie within the field of cumulates. The depletion in Ni may be due to less abundance of olivine. These rocks show clear similarity both in their composition and on variation diagrams, to those reported from other ophiolite suites. The high SiO₂ content in some of the ultramafites may be due to secondary SiO₂ enrichment.

The high CaO contents may be due to the high Ca-rich pyroxene content. K₂O, P₂O₅, and Al₂O₃ are less than those encountered in the mafic group. Zr, Y, Rb are very low or even below detection limit reflecting the depleted nature of oceanic tholeiites, affecting the crystal accumulation.

On the Al₂O₃-CaO-MgO diagram (Fig. 4) and a FeO₉₀-Al₂O₃-MgO diagram (Fig. 5) most of the analysed samples cluster within the field of the ultramafic rocks (Coleman 1977).
Conclusions

Petrographic and geochemical studies of 45 samples from CY-4 drill hole (CCSP) show that the rock sequence of this bore hole can be classified into (1) sheeted dike zone of diabasic composition, (2) zone of mixed dikes and gabbros, (3) massive gab- bro, (4) cumulative gabbro, and (5) ultramafic cumulates and undifferentiated diu- tole.

The mafic rocks are generally tholeiite in composition with some SiO₂ enrichment. The chemical composition is variable due to variation in major mineral components. The sudden increase in MgO differentiates the mafics from the ultramafics. Trace elements are comparable to those observed in other ophiolite masses.

The ultramafics are crystal cumulates. Olivine enrichment is reflected by the relatively high MgO content. The last 1000 m could represent the lowermost part of ultramafic cumulates. Very low Zr, Y and Rb contents reflects the depleted nature of the oceanic tholeiite effecting the crystal accumulation.

References


بتروكيميائية الصخور المائية وفوق المأهله للفرارة التقليدية قرص 4 مشروع
دراسة القشرة الفجرية

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نعتبر وقفة تحت هذه العصالة إلقاء محم وآرئي عبير شعيب على مساقط 50
متر من جرعة تقلي غير قرص 4 الفيما لدراسة القشرة الأرضية وذلك
للقياس مجموعة أمثلة وردية من أساس الدراسات الجغرافية والتحليل الكيميائي
وتشمل محققة توزيع جميع أمثلة مائية من الحمر الماشية حيث
نزيف القشرة 4 (C4) في الجزء الغربي الشرقي من النقد شرفة صحو
القشرة، وصخور الغاز والبراكين فوق المائية.

ويمكن قائمة مجموعة المائية منThanOrة القشرة بصورة عامة إلى:
- - منطقة صخور القشرة (صخور مرتبة) في العلم من 0.900 إلى 0.983
- - خليط من صخور القشرة ويصخور الجام في العلم من 0.983 إلى 0.958
- - ماحر طيني في العلم من 0.958 إلى 0.939
- - - ماحر تراكي في العلم من 0.939 إلى 0.919
- - - صخور فوق مائية وتشكل أساساً فو كلينياً ومستقيمة
وشيئاً في العلم من 0.919 إلى 0.873.
يمكن تقسيم العناصر إلى مجموعات كيميائية فوق مائية وفقاً للأعمال في هذا التصنيف تتوافق مع التصنيف الصخري (الكروي). 

قبل هذه الصور، عُموا إلى التركيب التكويني فوق النشط، كان العناصر الأثرية أيضاً مكونة من مركبات تنشئها من الصخور التكوينية وكذلك الصخور الكيميائية. 

الصخور فوق النشط تؤكد تركيبة هذه الصخور، عندما مع ما أجري من دراسات سابقة.