Petrological investigation of the sheeted dike zone of the Troodos ophiolite, Cyprus

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INTRODUCTION

The Troodos Ophiolite is one of the best exposed ophiolite complexes in the world, and it provides a unique opportunity to study a nearly complete piece of oceanic crust. Included in this sequence is a fully developed sheeted dike complex. Sheeted dikes were the key part of the puzzle which initially identified ophiolites as spreading structures (Gass, 1968); they represent the mechanism which accommodates magmatic extension at spreading centers. In the stratigraphy of an ophiolite, the sheeted dikes are the conduits which connect underlying isotropic and mafic cumulates and the extrusive pillow series above. Therefore, by studying the sheeted dikes we can hope to learn about the magma chambers below and the processes which affect them.

The goal of this project is to gain insights into the evolution of the magma chambers that fed the sheeted dikes through careful field mapping combined with petrographical and chemical analysis of a section of sheeted dikes

FIELD RELATIONS

The sheeted dikes that are the focus of this study are exposed on a road cut along the main road from Nicosia to Paliachori just north of Paliachori approximately 600 meters from the location of the CY-4 drillhole (Malpas, 1987). This road cut was chosen because the rocks showed a small degree of weathering and the strike of the dikes was nearly perpendicular to the length of the outcrop. Intrusive relationships of dikes and screens were mapped in detail for the 120 meter-long outcrop. A total of 70 dikes and 15 screens were identified, and several more minor screens were mapped without giving them a designation.

After mapping of the outcrop was complete, an attempt was made to classify the dikes into different rock types in the hope of coming up with preliminary suites which might be related temporally. Rock classifications were based on grain size, rock color, and whether or not samples were phyric. This proved to be very difficult since all grain sizes were fine to aphanitic, making mineral identification nearly impossible, and colors ranged in a continuum from blue-gray to green-gray.

Of the six field suites that were designated only two of them, the phyric suite and the coarse-grained blue suite, showed any temporal bias. The phyric suite seemed to be the oldest suite; it was cut by other dikes nine times but only cut other dikes three times. The coarse blue-gray suite showed strong evidence for being the youngest group; it cut other dikes five times and was never cut by younger dikes. Even though these field groupings did not turn out to be significant, sampling was based on them. Twenty-nine dikes, selected to represent each suite proportionally, and one screen were taken back for chemical and petrographic analysis.

PETROGRAPHY

The petrography of the sheeted dikes in this study is nearly identical to the petrography described by Baragar (1990). The dikes consist of a mix of primary igneous minerals and secondary metamorphic minerals (chlorite, actinolite, and epidote) consistent with greenschist facies. The dikes are all fine-grained and most are phyric to some degree with the more evolved samples tending to be glomeroporphyritic. Phenocrysts are invariably plagioclase, clinopyroxene, and an opaque phase, but the pyroxene has been pervasively altered to actinolite. Groundmass assemblages contain the same minerals with quartz frequently occurring as a late stage interstitial phase. In the groundmasses of relatively finer grained samples many plagioclase laths are radially arranged and relict clinopyroxene is acicular. These textures are characteristic of very fast cooling.

The main mafic phase is actinolite, as would be expected in the greenschist facies, but there is abundant evidence, in the form of relict crystal shapes, that the original mineral was clinopyroxene. Indeed, one dike, 61, is unusually fresh with small bits of the original clinopyroxene remaining. Plagioclase is for the most part fresh, and ranges from An_{40} to An_{70}, although some alteration to albite and epidote occurred since sodium was mobile during alteration.

Trace minerals are also present in the dike samples. Titanite is often found near or on opaque phases, suggesting that the opaque mineral is titanomagnitite or ilmenite. In most cases chlorite is a trace constituent, but it may be as high as 10% modally. Like actinolite, it is often found replacing clinopyroxene. Epidote is important because it is the main phase in tiny veins which cut through some sections. This epidote does probably not affect the whole rock chemistry much because the veins are so small and infrequent. Hematite is also present in very small quantities in some samples.

The most problematic phase present in the samples is quartz. In many rocks the quartz is a late stage interstitial phase. In some samples, however, quartz appears to be a secondary mineral filling miarolitic cavities. Often, this secondary quartz is easy to pick out. Some samples have large, circular shaped amygdules rimmed with quartz and filled in the interior by actinolite, chlorite, and sometimes epidote. Most of the time, however, the difference between primary magmatic quartz and secondary hydrothermally deposited quartz is hard to tell, and in fact may not be possible. The size of the quartz regions is often a clue to whether or not it is primary or secondary.

GEOCHEMISTRY

Although we typically think of the rocks at mid-ocean ridges as being basaltic, the rocks from this section of sheeted dikes are by no means limited to basaltic compositions. Percent SiO_2 ranges from 50.1 % to 72.9% by weight (Table 1), while basalt should only range from 45% to 52% (Philpotts, 1989). The plagiogranite screens have silica weight percents in the upper part of this range, with the maximum silica reaching 70.7%. Potassium is low in all samples, with all alkali trends being sketchy at best.

The geochemical data gives us a good chance to look at the processes which are taking place in the magma chamber. A plot of MgO vs. Cr (Figure 1) shows a tight fractionation trend. Chromium is a highly compatible element in clinopyroxene (Cox, et al, 1979), a phase which crystallizes early. So, as magnesium decreases with magma evolution, so does nickel. The same trend can be seen with other compatible elements, especially chromium. Another way to test the fractionation trend is to plot compatible elements against each other. Compatible-compatible plots should be straight lines if fractionation is indeed happening. We see this in Figure 2.

One of the original hopes in this project was to see if chemical data would give us any indication of how we might group the dikes into different suites, just as we tried in the field with the hand samples. The opportunity presented itself after looking at the Zr-MgO (Figure 3) and Y-MgO plots. Both of these elements (Zr and Y) are incompatible and, like Cr and Ni, show good fractionation trends. Both plots, however, show a break which separates the rocks into the suites shown in Figure 3. These two groups of rocks cannot be related by one episode of fractionation.

DISCUSSION AND CONCLUSIONS

Separately, field relations, petrography, and geochemistry are interesting, but together they provide a much more complete story. One of the initial hopes of the project, as mentioned earlier, was to try and find a temporal relationship between dike suites in the outcrop. When the two suites of Figure 3 are plotted on the field map a remarkable relationship is shown. Every dike represented by a solid circle cuts dikes represented by open circles and open circle dike *never* cut closed circle dikes. From this comparison of geochemical and field data, it is easily seen that rocks in the upper group are younger than those in the lower group. One way this could happen is by fractionation and periodic replenishment of the magma chamber (O'Hara and Matthews, 1981). As fractionation continues, zirconium, being incompatible, will increase in abundance in the liquid. Then, at a certain point, a new primitive magma replenishes the magma. This new liquid has not undergone fractionation and still has a relatively low zirconium concentration. The new magma dilutes the zirconium from the old liquid, but the total zirconium is left at some intermediate level. Fractionation then continues, but this time the zirconium begins at a higher level. This younger episode of fractionation is seen in the upper trend in Figure 3.

If we look at any of the chemical plots, we see that the plagiogranite compositions lie right in the middle of all the dike trends. This seems to suggest that the injection of dikes continues well into the fractionation process, so much that the dike compositions approach and may evolve farther than the composition of the plagiogranites, which are thought to be the late stage differentiates of the gabbroic magma chambers (Xenophontos and Malpas, 1987).

The idea that dike injection continues late into fractionation and that younger dikes may be more silicic is contradicted by other field evidence. When dikes within the same suite cut each other, evolved dikes are usually cut by more primitive dikes. How can this fit with the information in the previous paragraph if the fractionation is continuing? One way of doing this would be to make the magma chamber heterogeneous. If the magma chamber is compositionaly stratified, with lighter, more silicic magmas near the top and heavier, more mafic magmas near the base, it is entirely possible that later dikes could tap layers farther down in the chamber to get more and more mafic melts. Such stratification could develop by multiple replenishments of mafic magma into a silicic chamber (Sparks and Hubbert, 1984)). The chamber would be emptied from the top down, with successive injections coming from lower levels.

The data suggests that all dikes could have been produced from a single compositionaly stratified , periodically replenished magma chamber. For this suite of data there is no need to have multiple magma chambers at depth or laterally spaced magma chambers inject dikes horizontally as suggested by Baragar (1990) to explain other sections of sheeted dikes. In fact there is evidence to suggest that all of these dikes came from a source directly below the dikes and not from a lateral locality. Huskey (1996, pers. comm.) has shown through paleomagnetic analysis that the intrusive directions of the dikes from this outcrop are all nearly vertical.

We believe that the dikes in the this outcrop were injected from a continuously fractionating, periodically replenished source directly below. This source was probably receiving periodic replenishments from a parental source at greater depth. Further petrographical work regarding liquidus phases and distribution coefficients as well as geochemical modeling should shed more light on the exact nature of the magma chamber processes.

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Table 1. Major element compositions for selected samples. Compositions are anhydrous and normalized to 100%.

Dike #	**26**	**3**	**46**	**29**	**53**	**50**	**62**	**S11**
SiO2	50.06	53.92	56.87	59.23	63.44	65.85	72.50	70.71
TiO2	0.57	1.04	0.40	1.19	1.05	0.73	0.36	0.61
Al2O3	18.19	15.31	13.84	14.82	14.04	13.64	12.63	13.49
Fe2O3	12.46	11.46	8.30	11.22	10.42	9.38	6.55	5.57
MnO	0.18	0.18	0.13	0.14	0.09	0.07	0.03	0.08
MgO	8.20	6.44	8.49	3.37	2.49	1.76	0.42	1.08
CaO	6.34	9.20	9.50	6.20	5.87	3.68	2.95	4.68
Na2O	3.19	2.11	2.22	3.40	1.42	4.56	4.38	3.43
K2O	0.79	0.26	0.22	0.31	0.84	0.25	0.05	0.24
P2O5	0.03	0.08	0.04	0.11	0.35	0.08	0.12	0.11

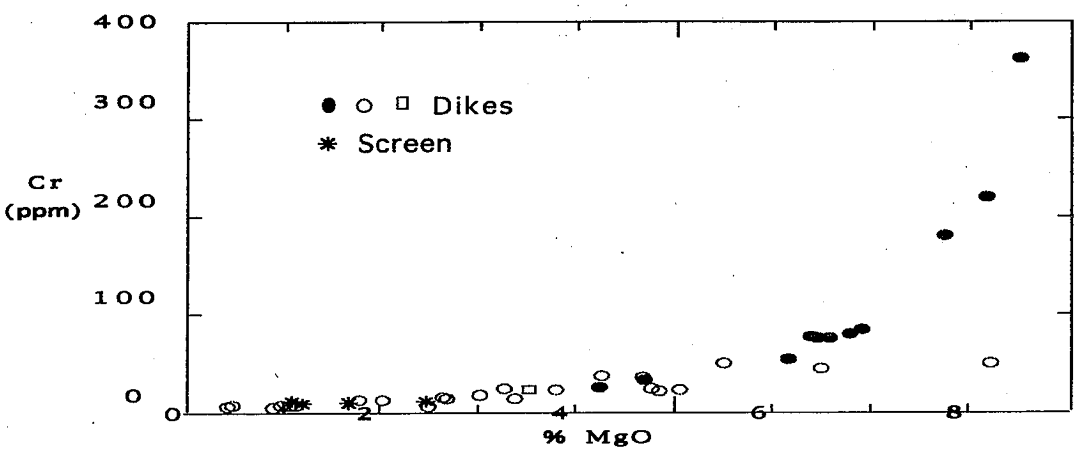

Figure 1. Plot of Cr-MgO. Curve is characteristic of fractionation trend.

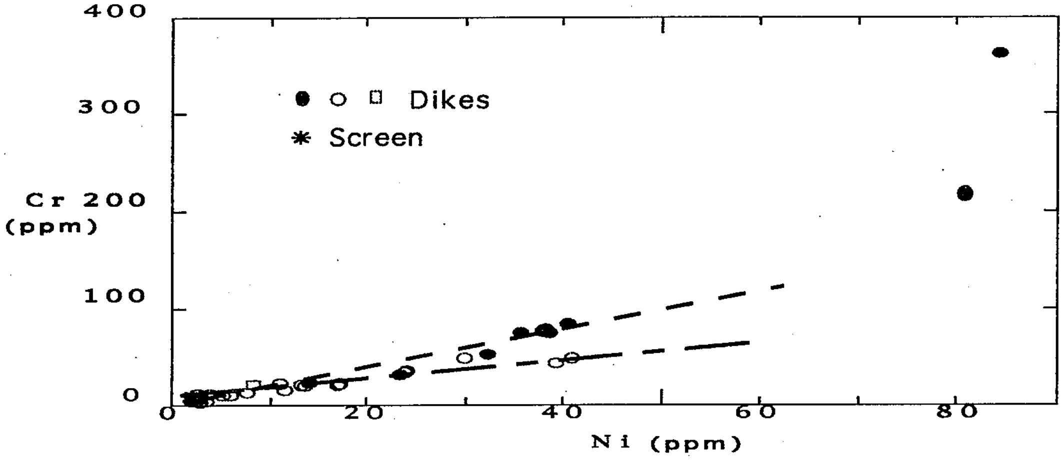

Figure 2. Cr-Ni plot. Straight lines within each suite show fractionation.

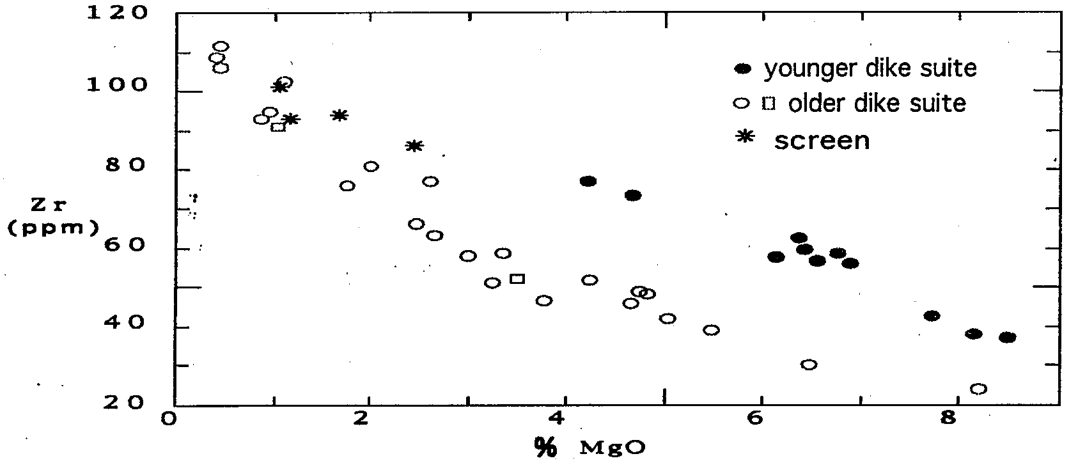

Figure 3. Zr-MgO plot showing separation into two suites. The upper, full circle suite is younger and the lower, open circle suite is older.