Petrology and geochemistry of sheeted dikes in the Troodos Ophiolite, Peristrona Canyon, Cyprus

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INTRODUCTION

The sequence of rocks in the Troodos Ophiolite represents one of the best examples of exposed oceanic crust in the world. This exposure provides opportunities to study suites of rocks that solidified during different stages of spreading center processes. Within the ophiolitic suite, the sheeted dike complex represents samples of solidified magmas that passed from magma chambers below to lavas at the surface via conduits. Petrologic and geochemical studies of the sheeted dikes may thus result in models for magma chamber processes. The goals of this project are to use field relationships, petrographic analyses, and geochemical data to characterize a suite of Troodos dikes and to evaluate the petrogenesis of the dike magmas.

FIELD RELATIONS

The sheeted dikes studied here are located relatively high in the ophiolite complex, ~1.5 km stratigraphically below the contact with the pillow lavas. They are exposed in Peristrona Canyon, ~8.8 km southwest of the town of Mitsero. Outcrops were selected on the basis of accessibility, a relatively low degree of alteration, and well exposed cross-cutting relationships between dikes. Most dikes strike ~N20E and dip ~50SE, with a second set of cross-cutting dikes striking ~N20W and dipping ~70NW. The steep canyon walls provide good exposures of early and late cross-cutting dikes. Three sections were measured and sketched in detail. The first measures 47 m in length, the second measures 14 m in length, and the third measures 19 m in length. The sections provide evidence for the relative timing of intrusions by cross-cutting relationships and chilled margins. Within the individual sections, relative ages can be well constrained, but age relations among the three sections could not be determined.

A total of 54 dikes were mapped. An attempt was made to categorize the dikes on the basis of color and texture, but proved impossible since all dikes are aphanitic and appear greenish-gray. Samples were instead taken in conjunction with a paleomagnetic study (Rance, this volume). Twenty-nine samples were taken in all, fifteen from dikes drilled for cores, and the remaining fourteen from nearby dikes with interesting temporal relationships and low degrees of alteration.

PETROGRAPHY

All twenty-nine dikes were examined in thin section. Although it was originally hoped that the twenty-nine sampled dikes could be sorted into groups based on petrographic analyses, the alteration of the rocks masks any distinguishable characteristics. The dikes are all very fine-grained, e.g. (< 0.1 mm), with relict igneous textures. Plagioclase occurs as subhedral to euhedral laths. Rare clinopyroxene persists in a few sections. But similar to Troodos dikes described by Baragar (1990), these dikes are dominated by secondary metamorphic minerals. Chlorite is the major secondary phase and relict plagioclase is presumed to be albitic. Quartz and opaque minerals each range up to 20% in some dikes. Accessory actinolite, calcite, pyrite, and epidote variably occur in the dikes. Epidote occurs in some thin sections concentrated along veins and as amygdule fillings. Quartz appears in two varieties; one seems to be interstitial while the second is associated with amygdules and veins. The secondary mineral assemblage and textures indicate that greenschist facies metamorphism affected these rocks.

GEOCHEMISTRY

Major and trace element geochemical data were obtained for twenty-four samples by inductively coupled plasma emission spectrometry at the University of Houston. In addition, samples from the fifteen drilled dikes were submitted for neutron activation analysis at Oregon State University.

Major element geochemistry. The concentrations of SiO_2 range from 53.0 to 62.7 wt%, indicating a basaltic andesite composition. Magnesium numbers (molar $MgO/(MgO + FeO^T)*100$) range from 36-52. However, there are no clear differentiation trends within the suite. For example, MgO and the alkalis show considerable scatter among the dikes. The low-grade metamophic processes may have affected most major elements and hence the major element data may not represent magmatic compositions.

Trace element geochemistry. The large ion lithophile elements Sr, Ba, and Rb are widely known to be strongly affected by hydrothermal and metamorphic processes (Rollinson, 1993). Sr exhibits wide scatter in these rocks, and Ba exhibits depletion compared to dikes lower in the section (Aboussi, this volume). Thus, these stratigraphically higher dikes may have been subjected to higher degrees of alteration compared to the lower dikes. A presumably immobile element, Zr, also exhibits variable abundance in these dikes, but recent work indicates it may have behaved in a mobile fashion (see Chutas, this volume). Thus, Hf, Ta, and the REE are the focus of this study based on their presumed immobility under hydrothermal, low grade metamorphic conditions (Pearce, 1983). The dikes have generally flat REE patterns, with LREE depletions similar to normal mid-ocean ridge basalts. Hf-Ta contents range from 2.07 to 3.09 ppm and 0.08 to 0.23 ppm respectively, and Hf/Ta ratios vary from 10 to 40 (Figure 1). Within this suite of dikes, there are no apparent temporal trends in either Hf, Ta, or REE concentrations or ratios between these elements. For example, in one cross-section, the last dike emplaced has the highest REE concentrations and Hf/Ta ratio compared to earlier dikes. In another cross-section, the last dike has the lowest Hf/Ta ratios but similar REE concentrations compared to earlier dikes.

PETROGENETIC MODELING

Modeling focused on trace elements thought to be immobile during hydrothermal alteration, i.e., Hf, Ta, and the rare earth elements. Variations in these elements resulting from magma chamber processes (fractional crystallization, magma mixing) were calculated with spreadsheet templates.

For fractional crystallization, the Rayleigh equation (C_l/C_o=F^(D-1)) was employed using the least evolved dikes (i.e. those with the lowest REE concentrations) as parental magmas (C_o). Using mineral/melt partition coefficients for basaltic and basaltic andesite liquids (Table 4.1 in Rollinson, 1993), bulk distribution coefficients (D) were calculated for various mineral assemblages. The rare earth element data for a selected group of dikes with well constrained age relationships are shown in Figure 2 along with examples of calculated concentrations (C_l) for evolved liquids (F=0.9 to 0.6, i.e., 10 to 40% crystallization). The modeling results show that fractional crystallization can produce the observed variations in REE, although it appears that fairly high percentages of crystallization (up to 30 to 40%) are required to obtain fits for some samples.

However, Hf-Ta systematics (Figure 3) indicate that another process other than fractional crystallization may be important. The Ta and Hf/Ta data for these dikes broadly define a curve. Magma mixing processes will produce such a curve since Hf and Ta are both incompatible elements (Rollinson, 1993). Therefore, magma mixing equations from Langmuir et al. (1977) were used to calculate trends that would result from the mixing of two endmember magmas. The calculated magma mixing trends broadly match the observed trends, whereas fractional crystallization vectors do not produce the observed trends (Figure 3). To further test the magma mixing model, the same procedure was used for a La/Yb vs. Yb plot (Figure 4). The observed variations are compatible with magma mixing processes, although fractional crystallization models also fit the La-Yb trends.

CONCLUSIONS

Sheeted dikes in the Peristrona Canyon were subjected to greenschist facies metamorphism, causing mineralogical and geochemical changes. Assuming Hf, Ta, and the REE remained immobile during the alteration, fractional crystallization processes may have affected dike magmas to some extent but could not have produced the entire spectrum of compositions. Geochemical models indicate that magma mixing may have operated since variations in Hf/Ta ratios can be closely reproduced through this process. The variations in Hf, Ta, and REE among the dikes imply source heterogeneity. Whereas a single magma chamber supplied with magma from multiple sources could account for such variations, so could mixing between magmas extracted from multiple magma chambers with separate sources. Rance (this volume) shows evidence that not all the magmas in the sampled dikes were injected vertically, allowing for interaction between magmas from laterally separate chambers prior to solidification. The lack of clear temporal trends suggests that the source heterogeneity persisted throughout the history of dike emplacement in the study area.

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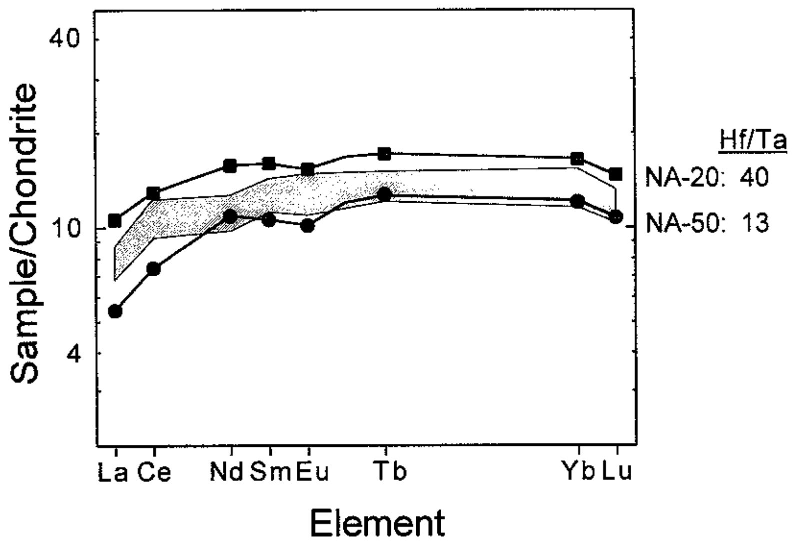

Figure 1. Chondrite-normalized patterns for samples NA-20 (filled square) and NA-50 (filled circle) that represent the high and low ends of the observed compositional spectrum. All other samples plot within the shaded area, demonstrating an overall similarity in REE data, and have Hf/Ta ratios between 10 and 40.

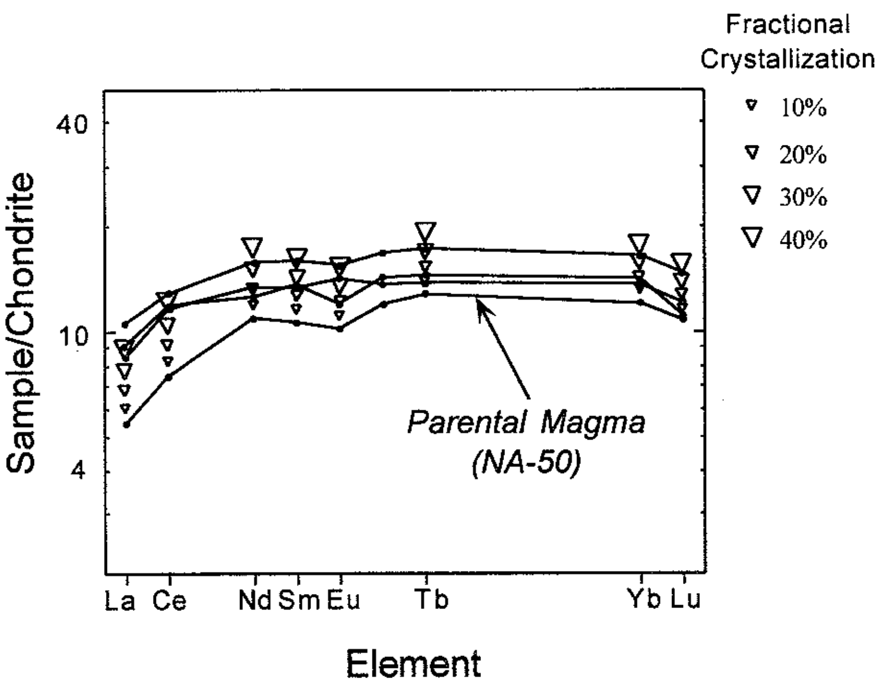

Figure 2. Chondrite-normalized REE patterns for samples NA-48, NA-47, NA-20, and NA-50. Using NA-50 as the parental magma (C_0), REE concentrations were calculated for removal of a mineral assemblage (10% plag + 30% oliv + 30% cpx + 30% opx). Inverted triangles represent increasing percentages of fractional crystallization from 10 to 40%.

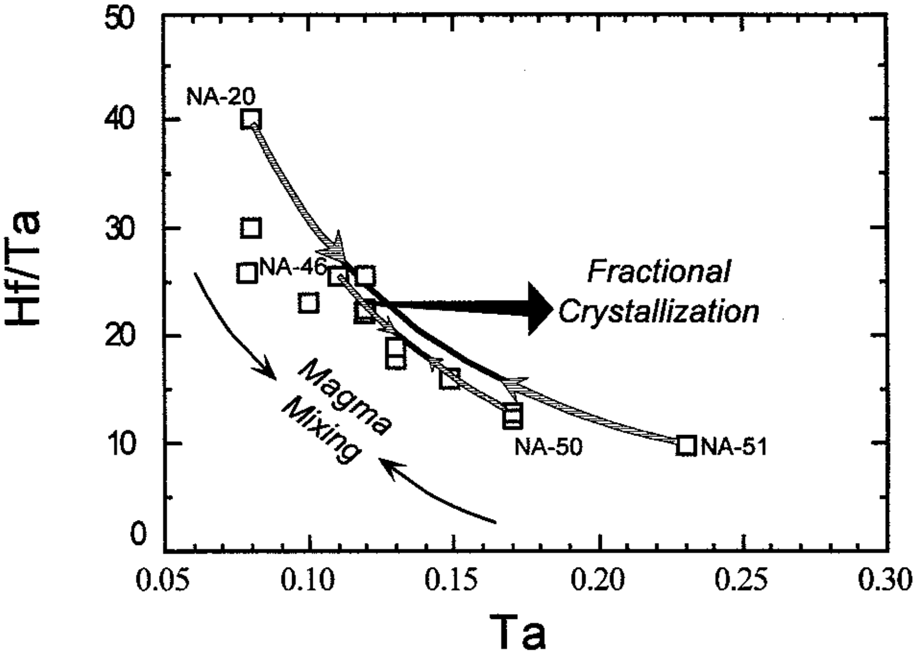

Figure 3. Hf/Ta vs Ta variations in the dikes (open squares). Shaded arrow represents fractional crystallization trends; the length of the arrow represents 20% crystallization. Removal of any combination of plagioclase, clinopyroxene, orthopyroxene, and olivine all produce the same trend. Magma mixing trends using a variety of endmembers appear to fit the observed compositions.

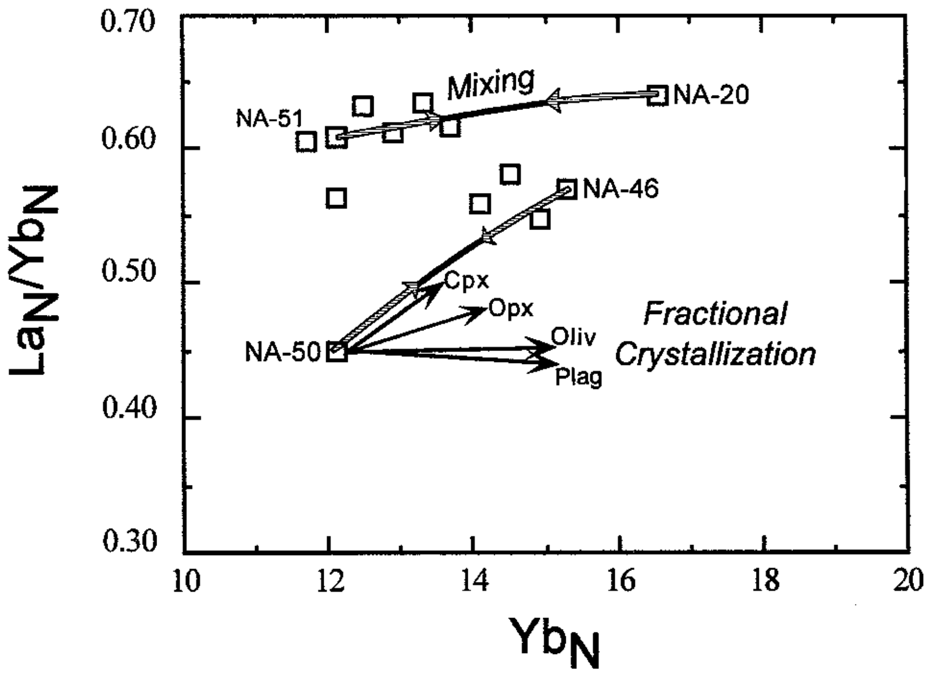

Figure 4. Chondrite-normalized La/Yb and Yb variations in the dikes (open squares). Fractional crystallization vectors representing 20% cystallization of plagioclase, orthopyroxene, clinopyroxene, and olivine are shown, as are magma mixing models.