Origin of plagiogranite in the Troodos ophiolite, Cyprus

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INTRODUCTION

In most ophiolite sequences observed around the world, there are small bodies of intrusive felsic rocks. These rocks are collectively called plagiogranites, but include plagiogranite as well as tonalite and quartz diorites. Several petrogenetic models have been proposed for the formation of these rocks. Coleman and Peterman (1975) suggested that plagiogranite forms by fractional crystallization of tholeiitic basalt. Spulber and Rutherford (1979) proposed that it forms as a result of liquid immiscibility. Gerlach et al. (1981) and later Pederson and Malpas (1984) suggested that plagiogranite forms by partial melting of mafic rocks under water-rich conditions.

Plagiogranite in the Troodos ophiolite, Cyprus, is a well-exposed unit located on the western side of Mt. Troodos. The rocks have previously been described (Wilson, 1959), but their petrogenesis has not been addressed in much detail. The goals of this project are to geochemically characterize these rocks and to test the possibility of a genetic relationship between the Troodos plagiogranites and associated mafic rocks, specifically, by partial melting and fractional crystallization processes.

FIELD RELATIONS

Diabase dikes are located at the bottom of the studied sequence. They are overlain by a massive body of plagiogranite, which is overlain by tonalite and gabbro. Structural doming at the center of the ophiolite has caused the stratigraphic sequence to be tilted. Contacts between gabbro and plagiogranite are often hard to identify in the field, and occasionally intermingling relationships are observed. Diabase dikes usually intrude plagiogranite, however, some contacts between diabase and plagiogranite are "soft"; such contacts are crenulate, indicating coeval intrusion. Quantitative volumetric estimates were not conducted, but exposures show the plagiogranite body to be volumetrically minor relative to mafic rocks in the ophiolite.

The plagiogranites and diabase dikes are visibly altered throughout the studied exposures. In general, dikes show more alteration than plagiogranite. The gabbros show no alteration. Samples were selected for petrographic and geochemical analysis on the basis of least visible alteration. Most are plagiogranites, but tonalites and gabbros were also collected.

PETROGRAPHY

Twenty thin sections of plagiogranites and gabbros from the ophiolite were examined. The felsic rocks are generally fine to medium-grained and have granophyric textures. As previously noted, these rocks are highly altered, making quantitative estimates of their modal mineralogy difficult. Rocks identified in the field as plagiogranites were subdivided into two groups based on primary quartz content estimated by thin section analysis. Primary quartz was used as the classification criterion because it is relatively unaltered and can be easily distinguished from secondary silica. "True" *plagiogranites* contain 50-55% primary quartz, in addition to plagioclase and amphibole; secondary minerals include quartz, chlorite, epidote, and opaques. None have total alteration minerals greater than 12% by volume. The second group includes *tonalites*, which have similar textures as the plagiogranites, but contain 25-35% primary quartz, plus plagioclase and amphibole. They are altered to a lesser degree with the same secondary mineralogy as the plagiogranites. Mafic rocks include unaltered gabbros which are medium to coarse-grained and contain plagioclase, amphibole, and pyroxene.

GEOCHEMISTRY

Major and trace element geochemical data were obtained for all twenty samples by inductively coupled plasma emission spectrometry at Texas Tech University. Selected samples were submitted for x-ray fluorescence and neutron activation analysis at Washington University and Oregon State University, respectively.

Major element geochemistry. Plagiogranites have higher silica content relative to tonalites reflecting their higher modal quartz. Fe_2O_3 and MgO decrease from gabbro to plagiogranite. Low overall K_2O and variable and overlapping Na_2O abundances are observed in plagiogranites and tonalites. Other workers have noted that K_2O

depletion and Na_2O enrichment can be caused by interaction with seawater (e.g. Brown et al., 1979). In addition, CaO contents are high in the siliceous rocks relative to typical granitic rocks probably due to crystallization of epidote (Fig. 1).

Trace element geochemistry. In an attempt to overcome difficulties associated with hydrothermal alteration, geochemical analysis focused on trace elements generally thought to be immobile during alteration (Pearce, 1983). These elements include Zr, Hf, Nb, Ta, Y, and the rare earth elements (La, Ce, Sm, Eu, Tb, Yb, and Lu).

Pearce et al. (1984) provide a single plagiogranite analysis from Troodos. They noted its overall trace element depletion compared to plagiogranites in other ophiolites (ORG) and its similarity to some volcanic arc plagiogranites, such as those found in Oman (Fig. 2a).

Plagiogranites and tonalites analyzed in this study (cf. Fig 2a) either overlap with or are depleted compared to the Troodos and Oman plagiogranite analyses of Pearce et al. (1984). In contrast to Pearce et al.'s Troodos sample, the samples here exhibit Nb depletions similar to those observed in Oman plagiogranites. Gabbros have the lowest trace element contents of the Troodos suite, with especially large depletions in the light REE (Fig. 2). In fact, several elements (Ce, Nd, Nb, Ta) could not be determined because they are below detection limits. The gabbros are notably depleted compared to typical mid-ocean ridge basalts (MORB; Fig. 2b).

TRACE ELEMENT MODELS

Spreadsheet templates were created to numerically model trace element variations during partial melting and fractional crystallization processes. Fractional crystallization models used the Rayleigh equation: $C_l/C_o=F^\wedge(D-1)$. Bulk partition coefficients (D) given in Pearce et al. (1984) were used, and crystallization ranged from 60-75% (F=0.40-0.25). Plagiogranites and tonalites are assumed to represent derived liquids, and their compositions (C_l) were used to calculate the parental magma composition (C_o). These calculated parental compositions are shown in Fig. 3a along with analyses of Troodos gabbros (this study) and diabase dikes (Veit, this volume).

Partial melting models used the equation for batch partial melting: $C_l/C_o=1/[D+F(1-D)]$. Based on experimental studies of mafic rocks that yield plagiogranitic melts (e.g., Spulber and Rutherford, 1983), the models assumed degrees of melting ranging from 10-30% (F=0.10-0.30). The same D values used in the fractional crystallization models were employed, and plagiogranite and tonalite compositions were used to calculate the source rock composition, C_o. The results are shown in Fig. 3b.

Fig. 3 and results of modeling Zr, Hf, Nb, and Y contents (not shown) indicate that some mafic rocks in the Troodos ophiolite could be related to the plagiogranites by either fractional crystallization or partial melting processes. A more effective means of distinguishing between fractional crystallization and partial melting processes involves examination of a strongly incompatible element (e.g., La) and a compatible element (e.g., Sc). Fig. 4 shows fractional crystallization and partial melting models based on La and Sc. Most plagiogranites and tonalites lie between partial melting trends involving mafic source rocks with compositions represented by Troodos gabbros and diabases. Reasonable degrees of crystallization (60-80%) of assumed parental magma result in depletions that are too large to represent plagiogranite and tonalite compositions. In the calculations a conservatively low bulk partition coefficient for Sc (D_{Sc}=4.0) was used; higher values would result in even greater depletions.

CONCLUSIONS

The mafic rocks of the Troodos ophiolite sequence are depleted in trace elements relative to MORB (Fig. 2b). This depletion is consistent with a supra-subduction zone tectonic setting as discussed by Pearce et al. (1984). Plagiogranites and tonalites of this sequence have strongly depleted trace element signatures relative to other plagiogranites. Contents of many trace elements in the plagiogranites and tonalites are consistent with fractional crystallization and partial melting petrogenetic models. However, Sc variations favor partial melting of Troodos mafic rocks as a more viable hypothesis.

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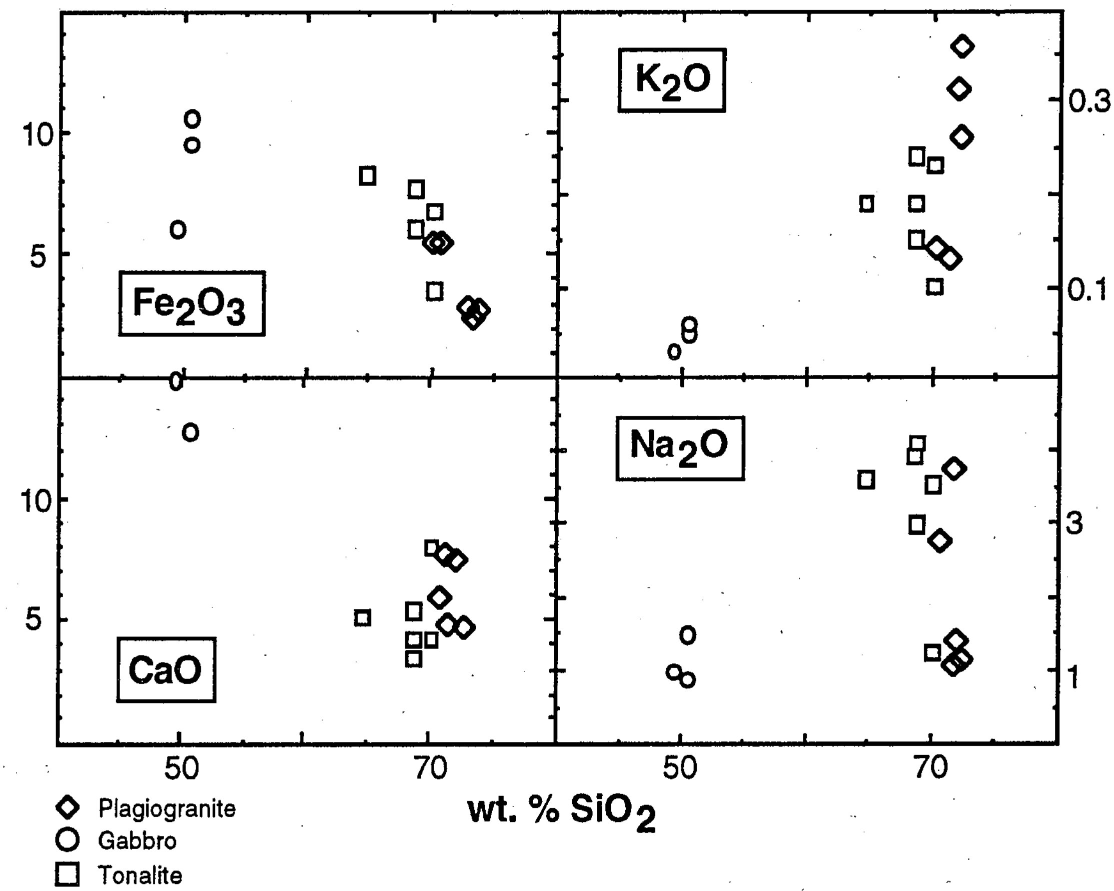

Figure 1. Major element variation diagrams.

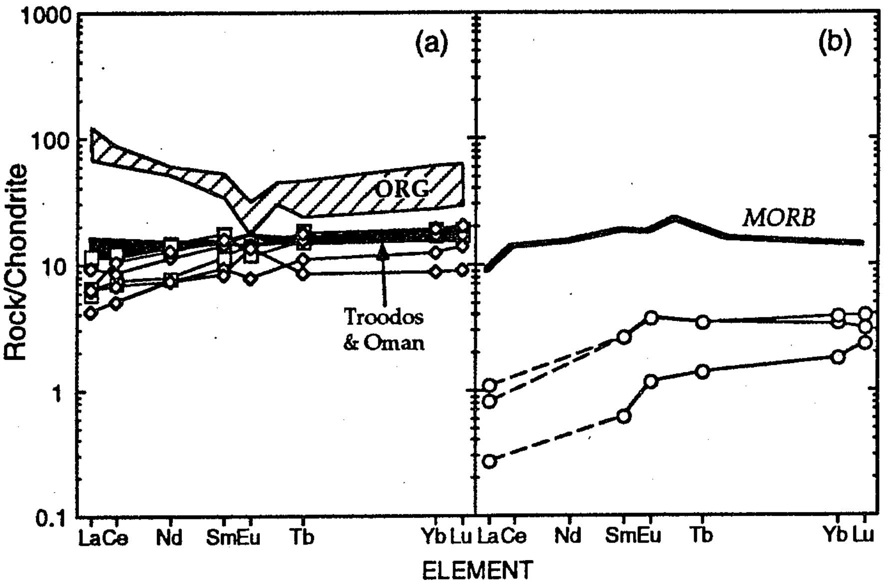

Figure 2. (a) REE profiles for plagiogranites and tonalites (symbols as in Fig. 1); also shown are Pearce et al.'s (1984) data for typical oceanic ridge granites (ORG; ruled field) and plagiogranites from Troodos and Oman (black field). (b) REE profiles for gabbros (this study; open circles) and typical MORB (Humphris et al., 1985).

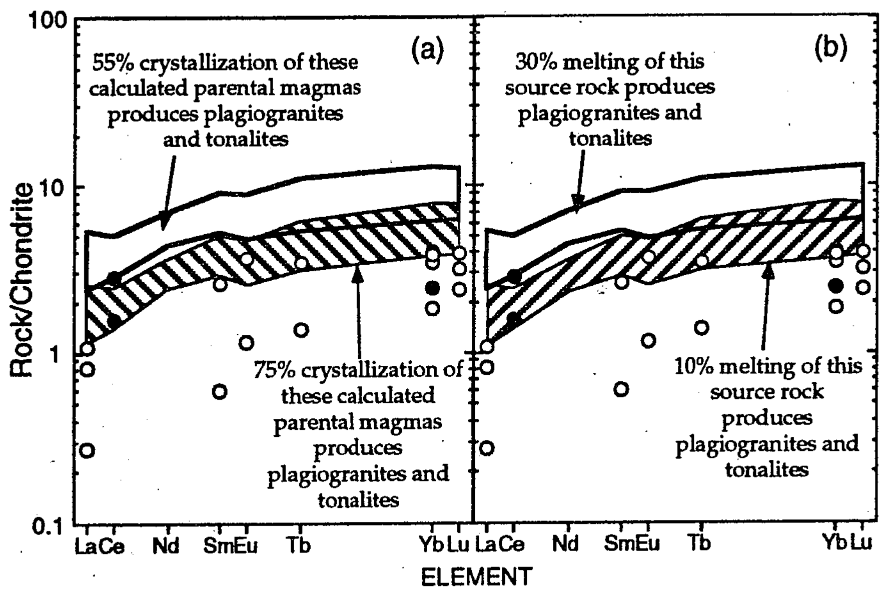

Figure 3. REE profiles for calculated (a) parental magma and (b) source rock compositions; model parameters discussed in text. Also shown are data for Troodos gabbros (this study; open circles) and diabase dikes (Veit, this volume; filled circles).

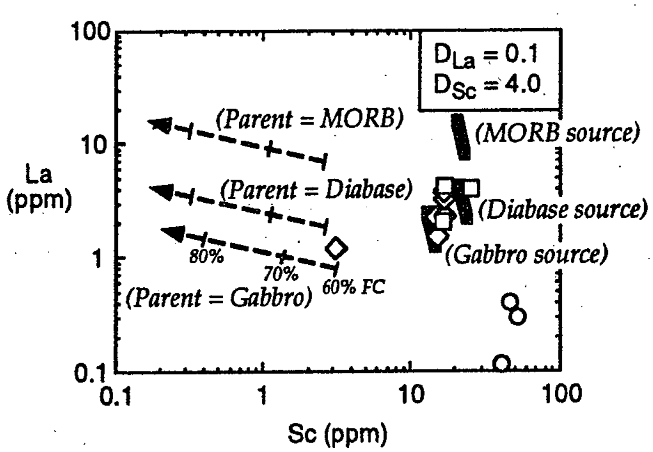

Figure 4. Log-log plot of La and Sc variations in Troodos rocks (symbols as in Fig. 1). Dashed vectors show variations in liquids produced by different degrees (60 to 80%) of crystallization of several assumed parental magmas, including Troodos gabbro and diabase and MORB. Heavy black bars represent liquids produced by 10 to 30% partial melting of source rocks similar to Troodos gabbro and diabase and MORB.