STRUCTURAL, PETROLOGIC AND SEDIMENTOLOGIC CONSTRAINTS FOR THE GENERATION AND EMPLACEMENT OF THE TROODOS OPHIOLITE, CYPRUS

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Structural, Petrologic and Sedimentologic Constraints for the Generation and Emplacement of the Troodos Ophiolite, Cyprus

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INTRODUCTION

Funding from the Keck Foundation allowed six students from schools of the Keck Geology Consortium to attend the summer field program in Cyprus. These students included Peter Selkin (Amherst), Helen Rance (Whitman), Kalsoum Abbasi (Colorado College), Nancy Adams (Trinity), Steve Dornbos (Wooster), and Brian Hitchens (Wooster). Parallel funding from an Research Experiences for Undergraduates (REU) grant from the National Science Foundation provided for an additional four students from non-Keck schools. The NSF-REU students were Nate Chutas (Mt. Union College), Gail Lipfert (U. Maine), Ellen Avery (Bryn Mawr), and Lorraine Givens (Buffalo State). In addition, funds from Lori Bettison-Varga's NSF-National Young Investigator award were used to cover the participation of Craig Petko (Wooster). Thus, 11 undergraduate students participated in the 1996 summer field program in Cyprus. These students were involved in a series of highly multidisciplinary projects involving structural geology\geophysics, geochemistry\petrology and sedimentology\paleontology.

OVERVIEW OF CYPRUS GEOLOGY

Although no ophiolite is thought to provide a perfect analog for modern ocean crust (e.g. Gass, 1990) the similarity of gross lithospheric/crustal layering (Moores and Vine, 1971), structure (Nicolas, 1988; Varga, 1991) and hydrothermal processes (Bettison-Varga et al., 1992; Constantinou and Grovett, 1973; Schiffman et al., 1990; Schiffman and Smith, 1988; Schiffman et al., 1987) in ophiolites and ocean crust is sufficiently good to deduce that their accretionary processes are quite similar. Indeed, many features documented in ophiolites have proven valuable in the interpretation of observations from ocean ridges. Thus, study of well-exposed and preserved ophiolites, such as Troodos, can provide valuable insights into ocean crustal processes.

The Troodos ophiolite (Fig. 1) constitutes a little disrupted, ideal Penrose (American Geological Institute, 1972) ophiolite which is believed to have formed during the Late Cretaceous (Blome and Irwin, 1985; Mukasa and Ludden, 1987) in a probable "suprasubduction zone" setting (Miyashiro, 1973; Rautenschlein et al., 1985). Although the precise tectonic setting of the Troodos ophiolite is controversial, the areal extent and structure of the sheeted dike complex (Baragar et al., 1987; Baragar et al., 1990; Moores and Vine, 1971; Varga and Moores, 1985) and presence of a transform margin (Moores and Vine, 1971; Simonian and Gass, 1978) suggest formation in an extensional setting broadly similar to mid-ocean ridges. Paleomagnetic data also indicate that the Troodos ophiolite has undergone approximately 90^{0} of counterclockwise rotation since formation and prior to the Early Eocene (Clube et al., 1985; Moores and Vine, 1971). Thus, the present N-S spreading fabric in the ophiolite was formed at an E-W trending spreading center, compatible with the overall spreading structure of the Neo-Tethys (Whitechurch et al., 1984).

The well-exposed and extensive sheeted dike section of the Troodos ophiolite has recently provided new insights into magmatic, structural and hydrothermal processes operating at ridge crests. Combined study of the mesoscopic structural fabric and the anisotropy of magnetic susceptibility fabric of dikes has demonstrated that magmas which fed the sheeted dike complex, as well as the overlying volcanic section, migrated horizontally as well as vertically beneath the spreading center (Staudigel et al., 1992). In some areas, such as the Kionia Peak region of the Troodos ophiolite (Baragar et al., 1987; Baragar et al., 1990), the sheeted dike section comprises geochemically distinct, but contemporaneously injected, dikes which intruded horizontally. These results lend credence to recent models for lateral migration of melts along oceanic ridge crests away from centralized and focused magma chambers (Baragar et al., 1990; Sigurdsson, 1987).

Three major oceanic grabens have been identified within the Troodos ophiolite, based on the distribution of dike attitudes, and are thought to reflect relatively amagmatic extension at ridge crests (Varga, 1991; Varga and Moores, 1985; Varga and Moores, 1990). Paleomagnetic studies of the sheeted dike complex (Allerton and Vine, 1987; Hurst et al., 1994; Moores et al., 1990) have determined that dikes in these regions were steeply dipping when emplaced and have since undergone variable amounts of structural tilting. Much like low-angle detachment faults observed within the Basin and Range of the U.S., the sub-horizontal dike\gabbro contact within the ophiolite is often observed to be a zone of structural discontinuity that was operative during extension (Hurst et al., 1994; Varga, 1991; Varga and Moores, 1985; Varga and Moores, 1990). Recent paleomagnetic studies across this contact (Varga and Gee, 1995) indicate that while some of the detachment segments in the ophiolite were initiated at low angles, others were rotated to low angles following initiation as higher angle faults. Similar results have been obtained in the western U.S. (Livicari et al., 1993).

Metal-bearing sediments rest directly upon the uppermost ophiolite lavas along the edges of the ophiolite and are believed to be analogous to similar deposits produced by black-smoker systems at modern ridge crests (Constantinou and Grovet (1973). Later sedimentation includes reefal and clastic deposits which collectively record the change in environments during movement of the Troodos ophiolite away from the ridge crest as well as its disruption and exhumation during emplacement (Gass, 1990).

STUDENT RESEARCH PROJECTS

Students on the Cyprus project became involved in a wide-variety of research efforts covering a significant areal part of the ophiolite (Figure 1). Of the eleven students, three were involved in projects largely involving structural geology and paleomagnetism, five focused on aspects of geochemistry and petrology and three chose projects involving sedimentology and paleontology.

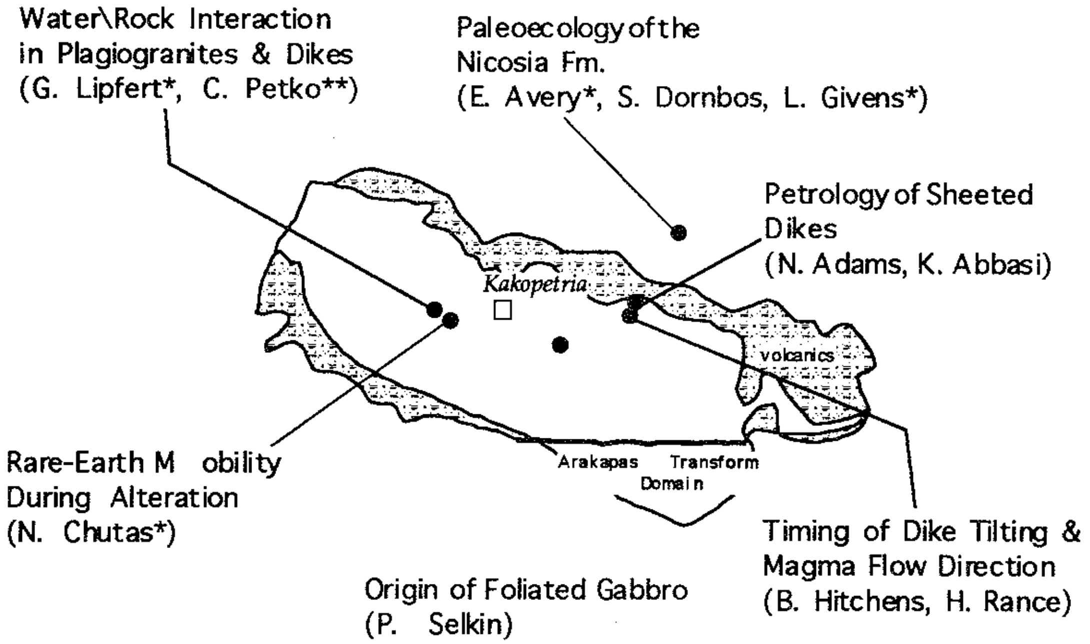

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Figure 1. Map showing locations of student research projects in relation to the Troodos ophiolite.

Projects involving structural geology were directed toward an understanding of the kinematics intrusions into the sheeted dike complex and the extensional deformation and hydrothermal history of the ophiolite. Brian Hitchens and Helen Nance are working on projects designed to determine the Our objective is to test the paradigm of vertical-only flow at spreading centers versus horizontal flow as is seen in many subaerial volcanic centers. Dikes within the ophiolite connect deep magma chambers with ocean floor volcanic rocks. Where possible, Brian and Helen examined various structures on the surface of dikes to determine their flow directions. Where surface structures were not available, they are using a technique for flow determination that employs anisotropy of magnetic susceptibility (AMS). To use this technique, Brian and Helen collected numerous 1" core samples from dikes. They will analyse their samples at Scripps Institution of Oceanography this Fall. Peter Selkin is investigating the origin of the varied foliations that occur within the gabbro section of the Troodos ophiolite. Such foliations have traditionally been ascribed to crystal settling in magma chambers. In the field, Pete identified several sites where foliations in gabbro appear to be deformational fabrics; excellent cross cutting relations at these outcrops provide tight controls on the timing of these structures relative to ridge crest magmatic activity. Peter will be analyzing the structural aspects of his sample using the structural petrographic techniques involving use of the Universal Stage and paleomagnetism.

Three students worked in the Pliocene sediments covering the Mesaoria Plain in the center of Cyprus. They are most interested in the recovery of marine invertebrate faunas following the Messinian (Late Miocene) salinity crisis, during which much or all of the Mediterranean Sea evaporated, leaving thick deposits of gypsum and halite. The Pliocene Nicosia Formation is a thick assemblage of marls, clays and silts laid down on top of the evaporites when sea levels returned to normal. Parts of this formation are extraordinarily fossiliferous, with abundant marine macroinvertebrate and microfossil faunas. Ellen Avery (Bryn Mawr) is studying the gastropods and gastropod-rich assemblages; Steve Dornbos (Wooster) is specializing in the heterodont and taxodont bivalves and a previously unknown fossil coral reef; and Lorraine Givens (Buffalo State) is our expert on oysters and pectenid bivalves. Their hypothesis is that the Pliocene faunas will show major taxonomic differences from the underlying Miocene faunas because the Mediterranean dried up completely, leaving no refuges of normal marine waters where the Miocene fauna survived. The recovery fauna may have had Atlantic and Indo-Pacific origins.

Five Keck and non-Keck students worked on a wide variety of topics concentrating on the petrology and hydrothermal metamorphism of the ophiolite. Kalsoum Abassi and Nancy Adams are working with the structural geology group to develop a model for spreading center magmatism in the Pfterykoudi Canyon area. Kalsoum and Nancy will be using major, trace and rare-earth geochemical data to characterize magma source regions for the sheeted dike complex in that area to test the single vs. multiple magma chamber hypotheses for the Troodos complex. Their work will tie in with the results of flow direction analysis in the same rocks. Craig Petko, Nathan Chutas, and Gail Lipfert (NSF-NYI and NSF-REU students) are investigating various aspects of the hydrothermal metamorphism of the sheeted intrusive complex and plagiogranites. Craig Petko is continuing work begun by Shannon Hayes (Beloit) last year, looking in particular at fluids from which epidote was formed in the plagiogranites. He is specifically trying to determine whether or not epidote can be related to modified seawater reaching the depth of plagiogranites or if the epidote is related to deuteric alteration from fluids coming off the nearby magma chamber during the spreading process. In a related project, Gail Lipfert is characterizing epidote + quartz nodules that formed in both the plagiogranites and sheeted intrusive complex and will evaluate the reactions that progress to form these features. Using microprobe and textural studies, Gail hopes to identify the epidosite-forming reactions. Nathan Chutas is investigating the nature of REE mobility in the hydrothermal system. He sampled across veins, variably altered dikes and plagiogranites and will compare REE contents within these samples to those of glass analyses for the volcanic sequence. His work will be fundamental to determining whether or not REE analyses can be used to model the igneous petrogenesis of the sheeted intrusive complex and at what degree of alteration mobility of specific elements occurs.

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Magma propagation direction and the timing of dike tilting in mid-level sheeted dikes, Troodos Ophiolite, Cyprus

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Introduction

Vertical propagation of magma through the sheeted dike section (seismic layer 3) of the ocean crust has long been the model for magmatism at spreading centers (Gudmundsson, 1990). In recent years however, studies have not been able to locate any large magma reservoirs along slow-spreading ridges, such as the mid-Atlantic ridge (Detrick et al., 1990). Axial magma chambers have, however, been well-documented along fast spreading centers (Macdonald, 1982; Sinton and Detrick, 1992). The lack of magma chambers at slow spreading ridges has been explained by the possibility of ephemeral magma chambers which occasionally pond and supply temporary magmatic events along the ridge (Macdonald, 1982, 1986). In the sheeted dikes of the Troodos ophiolite, Cyprus, looked at in this study, field and paleomagnetic studies show evidence for horizontal propagation of magma along the paleo-ridge axis (Staudigel et. al, 1992; Varga et. al, in review). This opens up the possibility that magma could be supplied from several isolated sources flowing laterally from these points along the length of the ridge. This may change current view points on how spreading zones receive magma without a major axial magma chamber located directly beneath and has implications for study of the mantle souce areas deduced from samples colleceted along spreading centers.

Anisotropy of magnetic susceptibility (AMS) was used to determine flow direction within the sampled dikes. It has been observed that a magnetic field passes most easily through the long direction of magnetite grains or along preferentially aligned groups of grains (Hargraves et. al, 1991). In theory, these grains have been aligned with the flow direction of the magma and thus yield an indirect measure of flow direction (Hargraves et. al, 1991; Staudigel et. al, 1992).

There is controversy surrounding the processes which led to the formation of the grabens that are observed in the Troodos ophiolite. Competing theories suggest that the tilting occurred either while still close to the spreading center, or as a result of obduction (Van-Everdingen and Cawood, 1995). The paleomagnetic remnance of cross cutting dikes were studied in an attempt to constrain the tilting of the dikes to an on or near axis location. In these situations, shallowly dipping dikes were cut by later, more steeply dipping dikes. These dikes were analyzed for distinct paleomagnetic signatures which would indicate that the crosscutting dikes were emplaced diachronously after some sort of rotation and still near a magma source.

Geologic Setting

The field sites were all located within the Mitsero graben of the Troodos ophiolite. After surveying several kilometers of Phterykhoudhi canyon, four sampling sites were chosen in addition to a final site at a roadcut above nearby Peristerona Canyon. All of these sites were constrained to the middle region of the Troodos ophiolite's sheeted dike zone.

Methods

Each core was collected from within 5 cm of the margin of the dike in the hopes of finding an imbricated AMS fabric. An orientation stage was used to accurately record the inclination and declination of the cores as they were drilled. A sun compass was used when possible to correct for possible brunton errors caused by magnetic interference from the dike itself.

Thermal demagnetization was carried out at the Scripps Institute of Oceanographic Research labs in La Jolla Ca with the help of Dr. Jeff Gee. A cryogenic magnetometer was used for the measurement of all of the samples. After initial NRM directions were measured, the samples were heated to 100°C for 45 minutes and remeasured. Temperature steps of 50°C were used up to 500°C. 25° steps were used for the final two steps to a final temperature of 550°C.

The AMS of each core was recorded before magnetic cleaning using a Kappabridge magnetic susceptibility meter. This was done by measuring the magnetic susceptibility of each core in 15 orientations. A three dimensional susceptibility tensor was generated from the maximum, intermediate, and minimum eigenvectors (K_1, K_2, K_3 respectively) of the core sample. The long vector of this ellipsoid is associated with average elongation