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

FACULTY

Robert J. Varga, The College of Wooster
Lori Bettison-Varga, The College of Wooster
Mark Wilson, The College of Wooster
H. Allen Curran, Smith College

STUDENTS

Allison L. Dunn, Oberlin College
Christopher Gerbi, Amherst College
Shannon K. Hayes, Beloit College
Elizabeth G. Helstein, The College of Wooster
Jennifer Houghton, The College of Wooster
Amy Huskey, Southeast Missouri State University
Cari Johnson, Carleton College
Cynthia Martínez, Middlebury College
Kim Twining, Trinity University
Kenneth M. Veit, Franklin and Marshall College
Kristin D. Wood, State University of New York at Binghamton

VISITOR

Robert Wiebe, Franklin and Marshall College

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

Robert J. Varga, Lori Bettison-Varga, Mark Wilson
Department of Geology, The College of Wooster, Wooster, OH 44691

H. Allen Curran
Department of Geology, Smith College, Northampton, MA 01603

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 Chris Gerbi (Amherst), Shannon Hayes (Beloit), Kim Twining (Trinity), Ken Veit (Franklin & Marshall), Cari Johnson (Carleton), and Liz Helstein (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 Amy Huskey (SE Missouri State Univ.), Cindy Martinez (Middlebury), Kristin Wood (SUNY Binghamton), and Ali Dunne (Oberlin). In addition, funds from Lori Bettison's NSF-National Young Investigator award were used to cover the participation of Jen Houghton (Wooster). Thus, 11 undergraduate students participated in the 1995 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° 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).

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, four were involved in projects largely involving structural geology and paleomagnetism, four focused on aspects of geochemistry and petrology and three chose projects involving sedimentology and paleontology.

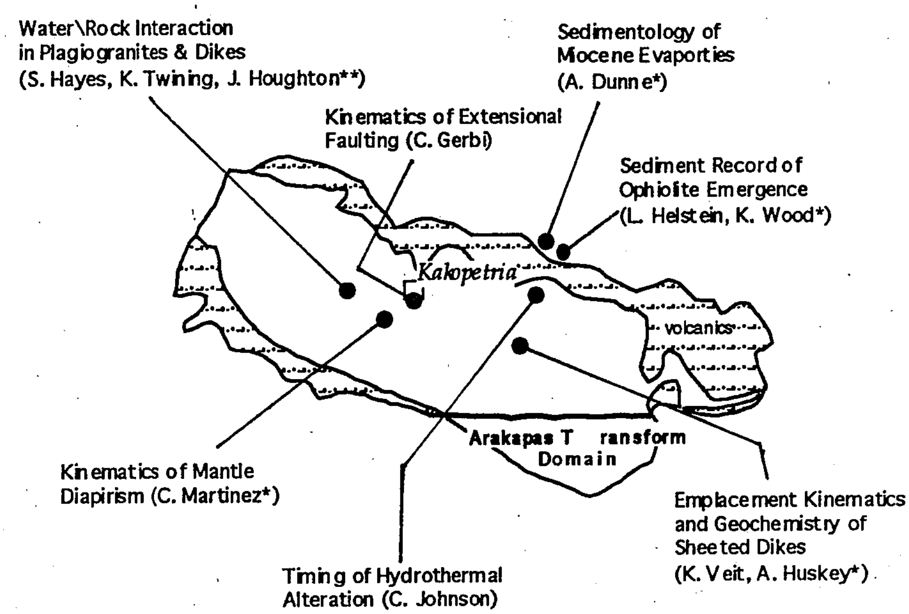

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Figure 1. Map showing locations of student research projects in relation to the Troodos ophiolite.

Projects involving structural geology were directed toward an understanding of the kinematics of intrusions into the sheeted dike complex, the extensional deformation and hydrothermal history of the ophiolite and the dynamics of asthenospheric upwelling at ridge crests. Chris Gerbi is working on the complexities of extensional faulting within the deep levels of the ophiolite and relating this to possible detachment fault geometries. Chris collected hundreds of orientations on fault surfaces in the field and collected critical paleomagnetic samples that he has used to assess structural rotations; Chris analyzed his paleomagnetic samples at the University of Massachusetts. Cari Johnson looked at the relative timing of high-temperature alteration and extensional faulting within sheeted dikes. Like Chris, Cari has combined structural observations with paleomagnetic measurements which she made at University of California at Davis. Cindy Martinez characterized the structure of mantle diapirism on Mt. Olympos by mapping the orientations of high-temperature foliations and lineations within the ultramafic massif and collecting oriented samples. Her subsequent research has involved a kinematic analysis of the peridotite using petrofabric methods. Amy Huskey and Ken Veit mapped in detail a well-exposed section of sheeted dikes near the base of the sheeted dike section. The focus of this study is to characterize the temporal variation in both magma chemistry and source regions. Amy is investigating dike propagation directions using anisotropy of magnetic susceptibility of dike margins which she measured at Scripps Oceanographic Institution. Ken, has characterized the geochemistry of the lower part of the sheeted dikes and has attempted to assess magma source areas and processes. Ken has done extensive geochemical work at Franklin & Marshall.

Shannon Hayes and Kim Twining investigated the origin and alteration of plagiogranites found at the base of the sheeted intrusive complex in the Solea graben. Kim has considered the origin of plagiogranites as late stage differentiates of the magma(s) which generated the sheeted intrusive complex or as melts generated by the re-melting of hydrothermally altered diabase. Kim acquired whole rock analyses, and REE by INAA on a DOE funded proposal to Diane Smith. Shannon characterized the alteration of the plagiogranites with the primary goal of determining the nature of the altering fluid; the extreme epidotization of these rocks could have been formed by modified seawater, magmatic fluid, or a combination of these two. Shannon acquired temperatures of alteration through fluid inclusion analyses at Wooster. Jen Houghton is combining critical field observations with geochemical computer modeling to constrain rock and fluid compositions present during alteration of the plagiogranites. Jen is using the computer programs EQ3\6 and Geochemist's Workbench.

The sediments lying above the ophiolite record translation and rotation of the ophiolite after leaving the ridge crest and the emergence of the massif during emplacement onto the north African margin. Liz Helstein has focused on the origin of reef deposits within Miocene Koronia Limestone. The Koronia and related units record the uplift of fault blocks during emplacement of the ophiolite. Kristin Woods is studying the depositional facies and ecology of the Miocene Pakhna Formation along the northern margin of the ophiolite. Kristin has focused on an excellently preserved assemblage of forams within the Pakhna. Ali Dunne's research has focused on the deposition of evaporitic gypsum deposited during the Miocene. The depositional fabric of these evaporites help to constrain models for the Messinian salinity crises of the Mediterranean Sea.

SUMMER LOGISTICS

Our home base while in Cyprus was the village of Kakopetria ("bad rock" in Greek!), one of the main hill villages on the northern slope of the Troodos massif (see Figure 1). The field program began with a series of field trips designed to introduce students to the geology of the Troodos ophiolite . A circum-Troodos field trip covered two days and covered the basics of the geology of the ophiolite and its sedimentary cover. Follow-up, topical field trips covered the more focused questions of the various disciplines. The four weeks of field time was broken up with several trips including a day excursion to the capital of Cyprus, Nicosia, where students visited the old Venetian walled city and the Cyprus Archeological Museum. In addition, George Constantinou, Director of the Cyprus Geological Survey, led a trip to the historic massive sulfide mines of Cyprus where he treated us to his theories of ancient mining techniques. Certainly the highlight excursion was a two-day trip to visit the extensive and well-preserved archeological sites of southern Cyprus where we were given a private tour of some sites by an archeologist from the Cyprus Antiquities Department.

REFERENCES CITED

Allerton, S. and Vine, F.J., 1987, Spreading structure of the Troodos ophiolite, Cyprus: some paleomagnetic constraints: Geology, v. 15, p. 593-597.

American Geological Institute, 1972, Penrose field conference on ophiolites: Geotimes, v. 17, p. 24-25.

Baragar, W.R.A., Lambert, M.B., Baglow, N. and Gibson, I.L., 1987, Sheeted dikes of the Troodos ophiolite, Cyprus, *in* Halls, H.C. and Fahrig, W.F., eds., Mafic Dyke Swarms: Geological Association of Canada, p. 257-272.

Baragar, W.R.A., Lambert, M.B., Baglow, N. and Gibson, I.L., 1990, The sheeted dike zone in the Troodos ophiolite, *in* Malpas, J.G., Moores, E.M., Panayiotou, A. and Xenophontos, C., eds., Ophiolites and Oceanic Crustal Analogues, Proceedings of the Symposium "Troodos 1987": Nicosia, Geological Survey Department, p. 37-51.

Bettison-Varga, L., Varga, R.J. and Schiffman, P., 1992, Relationship between ore-forming hydrothermal systems and extensional deformation in the Solea graben spreading center, Troodos ophiolite, Cyprus: Geology, v. 20, n. 987-990,

Blome, C.D. and Irwin, W.P., 1985, Equivalent radiolarian ages from ophiolitic terranes of Cyprus and Oman: Geology, v. 13, p. 401-404.

Clube, T.M.M., Creer, K.M. and Robertson, A.H.F., 1985, Paleorotation of the Troodos microplate, Cyprus: Nature, v. 317, p. 522-525.

Constantinou, G. and Grovett, G.J.S., 1973, Geology, geochemistry and genesis of Cyprus sulphide deposits: Economic Geology, v. 68, p. 843-858.

Gass, I.D., 1990, Ophiolites and oceanic lithosphere, *in* Malpas, J.G. and Moores, E.M., eds., Ophiolites and Oceanic Crustal Analogues, Proceedings of the Symposium "Troodos 1987": Nicosia, Geological Survey Department, p. 1-10.

Hurst, S.D., Moores, E.M. and Varga, R.J., 1994, Structural and geophysical expression of the Solea graben, Troodos ophiolite, Cyprus: Tectonics, v. 13, n. 1, p. 139-156.

Livicari, R.F., Geissman, J.W. and Reynolds, S.J., 1993, Palaeomagnetic evidence for large-magnitude, low-angle normal faulting in a metamorphic core complex: Nature, v. 361, p. 56-59.

Miyashiro, A., 1973, The Troodos ophiolite was probably formed in an island arc: Earth and Planetary Science Letters, v. 19, p. 218-224.

Moores, E.M., Varga, R.J., Verosub, K.L. and Ramsden, T., 1990, Regional structure of the Troodos dike complex, *in* Malpas, J.G., Moores, E.M., Panayiotou, A. and Xenophontos, C., eds., Ophiolites and Oceanic Crustal Analogues, Proceedings of the Symposium "Troodos 1987": Nicosia, Geological Survey Department, p. 27-35.

Moores, E.M. and Vine, F.J., 1971, Troodos massif, Cyprus and other ophiolites as ocean crust: evaluations and implications: Philosophical Transactions of the Royal Society of London Serial A., v. 268, p. 443-466.

Mukasa, S. and Ludden, J.N., 1987, Uranium-lead isotopic ages of plagiogranites from the Troodos Ophiolite, Cyprus, and their tectonic significance: Geology, v. 15, p. 825-828.

Mutter, J.C. and Karson, J.A., 1992, Structural processes at slow-spreading ridges: Science, v. 257, p. 627-634.

Nicolas, A., 1988, Structure of Ophiolites and Dynamics of Oceanic Lithosphere: Dordrecht, Kluwer Academic Publishers, 367 pp..

Rautenschlein, M., Jenner, G., Hertogen, J., Hofmann, A.W., Kerrich, J., Schmincke, H.-U. and White, W.E.M., 1985, Isotopic and trace element composition of volcanic glass from the Akaki Canyon, Cyprus: Earth and Planetary Science Letters, v. 75, p. 369-383.

Schiffman, P., Bettison, L.A. and Smith, B.M., 1990, Mineralogy and geochemistry of epidosites from the Solea graben, Troodos ophiolite, Cyprus, *in* Malpas, J.G., Moores, E.M., Panayiotou, A. and Xenophontos, C., eds., Ophiolites and Oceanic Crustal Analogues, Proceedings of the Symposium "Troodos 1987": Nicosia, Geological Survey Depertment, p. 673-683.

Schiffman, P. and Smith, B.M., 1988, Petrology and O-isotope geochemistry of a fossil seawater hydrothermal system within the Solea graben, northern Troodos ophiolite, Cyprus: Journal of Geophysical Research, v. 93, p. 4612-4624.

Schiffman, P., Smith, B.M., Varga, R.J. and Moores, E.M., 1987, Geometry, conditions and timing of off-axis hydrothermal metamorphism and ore deposition in the Solea graben, Troodos ophiolite, Cyprus: Nature, v. 325, p. 423-425.

Sigurdsson, H., 1987, Dyke injection in Iceland: a review, *in* Halls, H.C. and Fahrig, W.F., eds., Mafic dyke swarms: Geological Association of Canada, p. 55-64.

Simonian, D.O. and Gass, I.G., 1978, Arakapas fault belt, Cyprus: a fossil transform fault: Geological Society of America Bulletin, v. 89, p. 1220-1230.

Staudigel, H., Gee, J., Tauxe, L. and Varga, R.J., 1992, Shallow intrusive directions of sheeted dikes in the Troodos ophiolite: Anisotropy of magnetic susceptibility and structural data: Geology, v. 20, p. 841-844.

Varga, R.J., 1991, Modes of extension at oceanic spreading centers: evidence from the Solea graben, Troodos ophiolite, Cyprus: Journal of Structural Geology, v. 13, p. 517-537.

Varga, R.J. and Gee, J., 1995, Paleomagnetic evaluation of the detachment model for crustal extension within the Troodos ophiolite, Cyprus: EOS, Transactions of the American Geophysical Union, v.

Varga, R.J. and Moores, E.M., 1985, Spreading structure of the Troodos ophiolite, Cyprus: Geology, v. 13, n. 12, p. 846-850.

Varga, R.J. and Moores, E.M., 1990, Intermittent magmatic spreading and tectonic extension in the Troodos ophiolite: implications for exploration for black smoker-type ore deposits, *in* Malpas, J.G., Moores, E.M., Panayiotou, A. and Xenophontos, C., eds., Ophiolites and Oceanic Crustal Analogues, Proceedings of the Symposium "Troodos 1987": Nicosia, Geological Survey Department, p. 53-64.

Whitechurch, H., Juteau, T. and Montigny, 1984, Role of the eastern Mediterranean ophiolites (Turkey, Syria, Cyprus) in the history of the Neo-Tethys, *in* Dixon, J.E. and Robertson, A.H.F., eds., The Geological Evolution of the Eastern Mediterranean: Geological Society of London Special Publication, v. 17, p. 301-317.