Penrose Conference Report

Ophiolites and Oceanic Crust: New Insights from Field Studies and Ocean Drilling Program

Conveners
***Yildirim Dilek**, Department of Geology, Miami University, Oxford, OH 45056, dileky@muohio.edu*
***Eldridge M. Moores**, Department of Geology, University of California, Davis, CA 95616, moores@topaz.ucdavis.edu*
***Don Elthon**, National Science Foundation, Arlington, VA 22230, delthon@nsf.gov*
***Adolphe Nicolas**, Université Montpellier II—CNRS, 34095 Montpellier, France, tectono@dstu.univ-montp2.fr*

Ophiolites have been of particular importance in the reconstruction of ancient plate boundaries ever since their recognition as on-land fragments of oceanic lithosphere. The internal architecture of well-preserved ophiolite complexes shows that ophiolites are good structural analogues for oceanic crust, providing three-dimensional exposures and age relations to study the nature of extensional tectonics and magmatic construction in oceanic spreading environments. Thus, ophiolites complement significantly our knowledge of the architecture and generation of oceanic crust that is derived mainly from seismic images and drill holes at mid-ocean ridges. However, the geodynamic setting of many ophiolites remains controversial, as a result of petrological and geochemical observations that imply magmatic affinities to subduction zone settings, rather than mid-ocean ridge environments. Recent multidisciplinary studies of intact ophiolites and drilled core samples of modern oceanic crust from various mid-ocean ridge and subduction zone settings have provided significant information on the mantle heterogeneity, magma chamber processes, melt migration, and geochemical evolution of magma in these modern tectonic settings and in ancient spreading environments, thus leading toward a better understanding of oceanic crust formation and toward resolving the structural-geochemical conundrum. Within this context, we organized a Geological Society of America Penrose Conference to bring together a multidisciplinary group of geoscientists from the communities of ophiolite geology and marine geology and geophysics to reevaluate the existing models on oceanic crust generation, ophiolite formation, and ophiolite-ocean crust analogy; to explore the possibility of reaching a new consensus on the architecture of oceanic lithosphere; and to discuss the significance of ophiolites and oceanic crust for the present plate tectonic processes and for processes in the geological past. The timing of this meeting nearly coincided with the 25th anniversary of the first Penrose Field Conference on ophiolites, during which the definition of an ophiolite was developed.

The conference, "Ophiolites and Oceanic Crust: New Insights from Field Studies and Ocean Drilling Program" was convened in Marshall, California, September 13–17, 1998. It brought together 86 earth scientists, with backgrounds ranging from structural geology, tectonics, and geophysics to petrology and geochemistry. Participants, of whom 12 were students, came from 12 countries.

PRESENTATIONS AND PANEL DISCUSSIONS

The conference was organized into five major sessions: 1—Structural and magmatic processes at oceanic spreading centers; 2—Ophiolite–ocean crust analogy and field observations; 3—Petrology and geochemistry of oceanic crust and ophiolites; 4—Hydrothermal alteration and mineralization of oceanic crust and ophiolites; 5—Active margin tectonics, orogeny, and emplacement mechanisms of ophiolites. The invited talks introduced an overview of current ideas, observations, and interpretations on various themes and case studies related to these topics. In addition, the two evening sessions on Ophiolites and the Sedimentary Record (Robert Coleman and Emile Pessagno, Jr.) and Current Thoughts on the California Coast Ranges (John Shervais, Ray Ingersoll, and Clifford Hopson) highlighted some of the unresolved questions and outstanding controversies on the geological evolution of the Jurassic ophiolites and the Mesozoic active margin tectonics of the western United States, and provided a stimulus for the field trip to the California Coast Ranges on the third day of the meeting. Another informal evening session gave us an opportunity to learn about the geology of oceanic crust exposed on Macquarie Island (Australia) through Rick Varne's (University of Tasmania) slide presentation. A daily panel discussion facilitated exchange among the diverse participants. This format was most effective in providing a forum that promoted active participation of all attendees and cross-pollination of ideas from investigators in both oceanic and continental terranes and diverse approaches of field geology, geochemistry, and geophysics.

In the first session, Ken Macdonald presented the evidence and significance of off-axis volcanic activity for melt distribution beneath mid-ocean ridges and for the evolution of oceanic crust. He noted that the highly asymmetric zone of primary melting at the East Pacific Rise near 17°S, as deduced from the MELT (Mantle Electromagnetic and Tomography) experiment, mimics the asymmetric distribution of seamount chains and the asymmetry in seafloor subsidence in the area. He concluded that processes occurring as deep as 200 km beneath the oceanic crust may have an imprint on the seafloor that can be mapped. Jeff Karson emphasized the complexity and the heterogeneity of the internal structure of both modern oceanic crust and ophiolite. This complex structure is an artifact of highly asymmetric magmatic and tectonic processes operating at mid-ocean ridges which create "tectonic windows," major faulted escarpments on the seafloor, where crustal and mantle structures can be investigated in three dimensions. Henry Dick presented a comparison of structural and magmatic processes at spreading centers, as seen from in situ lower oceanic crust and shallow mantle. He discussed the occurrence of large variations in the stratigraphy of the ocean crust at slow-spreading ridges, reflecting along-axis transport of melt in the lower crust from a central intrusive center, and the significance of synmagmatic deformation in melt transport and igneous differentiation. These observations indicate that the evolution of slow-spreading oceanic crust deviates significantly from the Penrose ophiolite paradigm. Peter Kelemen addressed the topics of magmatic processes and melt transport in the mantle and the nature of crust-mantle transition. He discussed the probability of porous flow processes controlling the first-order geometry of melt-transport networks beneath ridges and producing trace element enrichments.

In the second session, Eldridge Moores discussed the significance of the scale and distribution of mantle heterogeneity for the generation of ophiolitic magmas. The composition of magmas at spreading centers may depend upon a complex tectonic history lasting for millions of years. Moores stated that geochemical indicators must be used integrally in concert with geological information to obtain the most robust tectonic interpretation of a given ophiolite. Tjerk Peters presented the geology of the Masirah ophiolite on the southeast Arabian continental margin and discussed its evolution at a ridge-transform intersection in the proto–Indian Ocean. The unusually thin (~500 m) plutonic sequence in the Masirah ophiolite might have been related to a weak magma supply as a result of the "cold-edge effect" of the bounding continental blocks, rather than tectonic thinning. Jean Bédard described syntectic assimilation processes and magmatic differentiation patterns in the plutonic sequence of the Bay of Islands (Newfoundland) ophiolite and discussed their significance in development of melt evolution and crustal heterogeneity at all scales. This discussion suggests that the assumption of fractional crystallization being the only process controlling melt evolution may generate incorrect calculations of parental melts, leading to erroneous conclusions about mantle sources and processes. Hans Schouten compared the structure of the volcanic stratigraphy drilled in Ocean Drilling Program (ODP) Hole 504B at the Costa Rica Rift and in Hole CY-1/1A in the Troodos ophiolite, Cyprus, and suggested that the contrasting kinematic histories and deformation in the lavas and sheeted dikes in 504B and near CY-1/1A may reflect their contrasting mechanical response to lava burial, rather than faulting.

Julian Pearce began the third session by summarizing new and published methods, each of which yields a geochemical fingerprint that can be related to present tectonic settings empirically and/or using petrogenetic reasoning. He discussed several modern analogues for oceanic crust formation in suprasubduction-zone environments and the processes affecting arc magma composition in these settings. Elisabetta Rampone presented an overview of the petrogenesis of the Ligurian ophiolites in the Apennines of Italy and discussed the occurrence of the Jurassic MORB-type oceanic crust in the Internal Liguride belt and variably old subcontinental lithospheric mantle in the External Liguride belt. The data thus suggest that the Ligurian ophiolites do not represent the remnants of mature oceanic lithosphere, but rather an early stage of ocean crust formation in the Ligurian Tethys. Stephen Edwards addressed melt migration and reaction in conductive mantle lithosphere with a specific reference to the Bay of Islands ophiolite and discussed the potential of these processes to cause significant chemical modification of melt and mantle at shallow depth. Paul Robinson reviewed the structure, stratigraphy, and petrology of lower oceanic crust, formed at the Southwest Indian Ridge, that has been drilled in ODP Hole 735 B, and compared its characteristics to those of well-known ophiolites. He concluded that the cored section from the Southwest Indian Ridge is unlike typical "Penrose-type ophiolites" and that ophiolites representing an ultra-slow-spreading ridge environment might not have been preserved in the rock record.

In the fourth session, Jeff Alt discussed the mechanism and effects of hydrothermal alteration in seafloor spreading environments as recorded in young oceanic crust and ophiolites. He reviewed the main differences between hydrothermal effects in oceanic and ophiolitic crust. Many ophiolites have a higher grade of metamorphism of volcanic rocks and more continuous geothermal and metamorphic gradients than are seen in oceanic crust. The primary volatile contents of the rocks, the abundances of mafic phases and glassy groundmass, styles of faulting and fracturing, and multiple phases of intrusion and eruption may contribute to these differences. Rachel Haymon discussed the importance of shallow crustal magma supply and delivery configuration to ridge-crest hydrothermal systems, on the basis of observations from the East Pacific Rise and the Semail ophiolite. She concluded that the distribution and geochemical character of hydrothermal alteration on ridge crests are fundamentally different in magma-rich, dike-dominated segments (fast-spreading), compared to magma-starved, fault-dominated segments (slow-spreading). Debbie Kelley discussed the geochemical, isotopic, and thermal history of fluids circulating in the oceanic crust from magmatic to hydrothermal vent conditions and the role of these fluids in crustal development and microbial processes. Her discussion suggests that lower oceanic crust is a potentially major reservoir for abiogenic methane in submarine hydrothermal systems, and that carbon-bearing fluids in gabbros may provide a critical energy source for diverse microbial populations in the sub-seafloor. Susan Humphris presented thermal and geochemical mass balances for the TAG active hydrothermal mound and discussed their implications for the time of formation, the size of reaction zone, and the heat source of a seafloor large massive sulfide deposit. Her calculations suggest that there is an insufficient amount of new material intruded at the ridge axis each year at steady state to provide the heat necessary to drive a large hydrothermal system (1000 MW), and therefore heat must be extracted either from individual magma bodies or from heat stored at depth in the crust. She then utilized this discussion to constrain the growth of large ophiolite-based massive sulfide deposits.

In the final session, Nicola Godfrey presented generalized crustal-scale cross sections of the Great Valley in California at different latitudes which are based on seismic-reflection, bore hole, gravity, and aeromagnetic data, and discussed the 600-km-long, 70-km-wide ophiolitic slab beneath the Great Valley forearc basin. The existence of such an extensive ophiolitic slab beneath the Great Valley basin has strong implications for the tectonics of the coeval ophiolites in the Sierra Nevada foothills on the east and the Coast Ranges on the west, and for the Mesozoic active-margin tectonics of the western United States. Bradley Hacker reviewed the recent data on the thermochronology and thermobarometry of the metamorphic sole of the Semail ophiolite which imply extremely rapid subduction (~200 km/m.y.) beneath a very young oceanic crust. The key questions still remaining are the magnitude, style, and age of extension of the Semail ophiolite, and the timing of high-pressure metamorphic events. Adolphe Nicolas presented a comparative study of the inferred microplate tectonics of the Semail ophiolite, the Easter Island microplate, and the Magellan Plateau, and discussed the kinematics of rapid rotation at spreading centers and rotation-related compressional deformation at the tip of propagating ridges. Ophiolites that display evidence for large rotations (i.e., Troodos, Semail) soon after their igneous accretion might have originated as a result of microplate tectonics. Alan Smith reviewed the current models on ophiolite emplace-

Ophiolites *continued on p. 32*

Penrose Conference Participants

Jeffrey Alt
Neil Banerjee
Jean Bédard
Donna Blackman
Françoise Boudier
Roger Buck
John Chen
James Cochran
Robert Coleman
Henry Dick
Arjan Dijkstra
Grenville Draper
Stephen Edwards
Andrew Fisher
Martin Fisk
Gretchen Frueh-Green
Patricia Fryer
Harald Furnes
Jennifer Georgen
A. Mohamad Ghazi
Kathryn Gillis
Nicola Godfrey
David Goldberg
Robert Gregory
Bradley Hacker
Gregory Harper
Ron Harris
Rachel Haymon
Ben Holtzman
Clifford Hopson
Susan Humphris
Steve Hurst
Ray Ingersoll
Tenuaki Ishii
Barbara John
Jeffrey Karson
Peter Kelemen
Deborah Kelley
Martin Kleinrock
Astri Jaeger Kvassnes
Jian Lin
Ken Macdonald
Bruce Malfait
Craig Manning
Rodney Metcalf
Jay Miller
Thomas Moore
Pierre Nehlig
Julie Newman
Yujiro Ogawa
Julian Pearce
Emile Pessagno, Jr.
Tjerk Peters
Philippe Pezard
Stephen Phipps
Victor Ramos
Elisabetta Rampone
Paul Robinson
Sarah Roeske
Daniel Kent Ross
Jane Scarrow
Hans Schouten
Anjana Shah
John Shervais
Alan Smith
Jonathan Snow
Rachel Sours-Page
Piera Spadea
Debra Stakes
Marnie Sturm
Guenter Suhr
Damon Teagle
Craig Thomas
Ricardo Tribuzio
Brian Tucholke
Rick Varne
Scott Veirs
John Wakabayashi
Timothy Wallin
Scott White
Aaron Yoshinobu
Rovert Zierenberg

Ophiolites *continued from p. 31*

ment mechanisms and discussed the involvement of two distinct subduction phases during the terminal obliteration of ocean floor. The origin of the forces that lead to the relative velocities appropriate for ophiolite emplacement is likely large-scale changes in the geometry and relative velocities at plate margins.

The poster sessions provided an opportunity for participants to present case studies and their results on different aspects of the topics of the five major sessions, and an effective way of initiating and stimulating discussions. The content varied from the geophysics of oceanic core complexes, thermal effect of a melt lens at Moho, estimations of strain rates in the uppermost mantle, and processes of shear-zone development in oceanic lithosphere, to the nature of magma—hydrothermal transition in ophiolites and oceanic crust, textural and chemical evidence for microbial alteration of the upper oceanic crust, PGE and Os isotope systematics of the oceanic mantle, isotope evidence for recent contamination of the mantle beneath the Southern Chile Ridge, evidence for delivery of unpooled fractional melts to the oceanic crust as recorded in gabbros, and significance of serpentine and blueschist mud volcanism in convergent margins.

The first panel discussion addressed some overarching questions, such as how melt is focused beneath spreading segments and how it is diffused into the crust; how melt is translated into lower crustal structure; the mode and nature of brittle and ductile behavior of lower crust and upper mantle and associated hydrothermalism; causes and consequences of episodicity; diagnostic features to distinguish the tectonic setting of ophiolites and to determine the spreading rate and magma budget in paleo–spreading environments; and differentiating spreading-related structures from emplacement-related structures in ophiolites. The second panel discussion focused on melt transport mechanisms in the mantle and crust; constraints on the age of ophiolite generation and emplacement; what controls serpentinization and the depth of seawater penetration into the upper mantle; what the reaction zone is and how a sufficient volume of fluid moves through it; what makes large ore deposits in oceanic crust and ophiolites; how mantle temperatures, viscosity, and flow in suprasubduction zone settings differ from those at mid-ocean ridges; what we know about the architecture of suprasubduction zone settings; and how distinct the compositions of suprasubduction zone magmas are from those of mid-ocean ridges. The final panel discussion started with a short reminiscence by each panel member, who had participated in the first Penrose field conference on ophiolites in 1972; they also gave a short account of the progress made in ophiolite and ocean crust studies since then. These discussions and the statements by other participants confirmed that the original Penrose definition of *ophiolite* has been very useful and remains effective in ophiolite–ocean crust comparisons, as long as the term is used independently of its origin and/or tectonic significance. The Penrose definition needs to be expanded, however, to include more information about the geological context of individual complexes as revealed in the underlying and overlying rock units.

FIELD EXCURSION

The third day of the conference was devoted to field examination of the Coast Range ophiolite and ophiolitic rocks within the Franciscan Complex. The Coast Range ophiolite is a good example of the "ophiolite conundrum," as abundantly demonstrated by the presentations of Shervais, Ingersoll, and Hopson during the conference. Proposed emplacement mechanisms (as well as the general regional geological setting) for the Coast Range ophiolite differ from those of typical "Tethyan-type" ophiolites. The Coast Range ophiolite structurally overlies the Franciscan subduction complex, rather than the continental margin. The Great Valley ophiolite, on the other hand, appears to overlie the continental margin (Godfrey). The structural complexity of the ophiolitic–subduction complex contact, as well as the present-day geometry of the contact, is a product of a series of complex tectonic interactions, including its major reactivation during the late Cenozoic transform regime.

Following an introductory presentation on the regional and local geology of the California Coast Ranges by Moores and John Wakabayashi, participants had an opportunity to examine one of the rare occurrences of a sheeted dike complex in the Coast Range ophiolite in Mt. Diablo, as well as a depositional contact of the basal Great Valley Group sedimentary rocks on volcanic rocks of the Coast Range ophiolite in the Oakland Hills. At Tiburon, participants observed the mantle base of the Coast Range ophiolite in which serpentinized peridotites are present at the structurally highest horizon in the Franciscan subduction complex. Blocks of eclogite, amphibolite, and blueschist occur as tectonic inclusions in the serpentinite. At the Nicasio Reservoir, a >1-km-thick pillow basalt section and an underlying gabbro possibly represent part of a seamount that was incorporated into the Franciscan complex in late Mesozoic–early Cenozoic time.

SUMMARY

Participants collectively agreed that more integrated and interdisciplinary studies of modern oceanic crust and ophiolites are needed to foster collaboration between the members of the marine geology and geophysics community and ophiolite geologists in order to address the questions that arose during the panel discussions. Systematic and detailed structural, kinematic, petrological, and geophysical process-oriented studies both in ophiolites and modern oceanic crust are important for modeling oceanic systems. Of particular significance for future studies are establishing objective criteria for structural reference frames (paleohorizontal and younging direction) in oceanic rocks, finding ways to constrain pressure-temperature-time paths for oceanic mafic and ultramafic rocks, and better defining the geological significance of the geophysical models for oceanic crust structure.

Scientific drilling in the oceans has been instrumental in advancing our knowledge of the oceanic lithosphere. The priorities of future deep-earth sampling in the marine environment include drilling an intact section of modern oceanic crust, preferably 3 km into the basement, drilling the plutonic foundation of oceanic crust, and drilling into the complete crust and crust-mantle boundary (goals of the "Mohole" project), and finally a comprehensive program aimed at a fuller understanding of the structural and compositional variations in modern and ancient oceanic crust in relation to ophiolites.

ACKNOWLEDGMENTS

We thank the Geological Society of America for sponsoring the conference and providing funds to enable student participation, and the Joint Oceanographic Institutions/USSAC and the Marine Geology and Geophysics Program of the National Science Foundation for provision of grants to support travel by participants and for field trip preparation. We thank Lois Elms (Western Experience, Inc.) and the staff of the Marconi Conference Center (California State Parks) for effective and efficient logistics throughout the meeting. John Wakabayashi kindly helped us organize and run an informative and stimulating field trip in the California Coast Ranges. We thank RMC Lonestar Company for help in arranging a stop on the field trip at the Clayton Quarry in Mt. Diablo to examine a well-exposed sheeted dike complex. We are grateful for the support and input provided to us by the participants before, during, and after the conference. We thank them all for the synergy and excitement they brought to the meeting and for sharing their knowledge and observations with the community. ■