

THE DIVERSITY OF OPHIOLITES¹

R. G. COLEMAN²

ABSTRACT

Coleman, R. G. 1984 The diversity of ophiolites. In: H. J. Zwart, P. Hartman & A. C. Tobi (eds): *Ophiolites and ultramafic rocks – a tribute to Emile den Tex – Geol. Mijnbouw* 63: 141-150.

Present studies reveal that ophiolites from the Alpine and Cordilleran orogenic belts may not represent deep abyssal oceanic crust but seem to have formed mainly in interarc or small ocean basin spreading centres. Abundant petrologic data on basalts from mid-ocean spreading centres (MORB) reveal a uniform and characteristic chemical nature. Current petrologic studies have shown an apparent scarcity of MORB within lavas of ophiolites from Phanerozoic orogenic belts. Peridotites from ophiolites reveal a complicated history of sub-solidus deformation and partial melting resulting from their diapiric rise into spreading centres and final incorporation into the oceanic crust. Structural studies reveal that ophiolites are emplaced either across passive continental margins or as basement fragments in accreted terranes. Attenuation of continental crust along passive margins in the formation of small ocean basin characterizes the tectonic setting for Tethyan ophiolites, whereas the ophiolites of Western North America are usually the oldest units in allochthonous tectonostratigraphic terranes and have formed in interarc spreading centres along the continental margins. Terraine accretion of these arc complexes preceded the continuous subduction of the Pacific and Farallon plates consisting of abyssal oceanic crust (MORB). Thus, ophiolite associations are mainly products of continental break-up or interarc spreading. Abyssal oceanic crust has been mainly consumed by subduction and only in extremely rare instances has it become accreted into continental crust.

INTRODUCTION

Ophiolites are now an acceptable part of the plate tectonic orthodoxy and have become the focus of an extraordinary amount of study by petrologists and tectonists concerned with the development of mountain belts and the origin of oceanic crust. In 1972, a Geological Society of America Penrose Conference was convened in the western United States and Professor den Tex was one of the participants who contributed to a consensus definition for ophiolites (ANONYMOUS, 1973)³. As one might suspect this definition has been criticized for a number of shortcomings but surprisingly it is still generally accepted by geologists in all parts of the world. It therefore seems appropriate as part of this volume dedicated to Professor den Tex to discuss some of the current problems related to the concept of ophiolites. This paper is not to be considered a comprehensive review of the problem and for more detailed summaries the recent papers by MOORES (1982)

and GASS (1982) or the Symposium volumes of PANAYIOTOU (1980) and SHELTON (1983) provide more details.

The concept that oceanic crust of the present day oceans is formed by igneous processes similar to those revealed within ophiolites has stimulated great interest in those scientists now undertaking large scale projects in the deep oceans (EAST PACIFIC RISE STUDY GROUP, 1981). Through the impetus of the Deep Sea Drilling Program (DSDP), U.S. National Science Foundation, thousands of chemical analyses have been made on drill core samples from nearly all the major oceans (MELSON ET AL., 1976, and individual reports from each leg). Most of these samples represent pillow lavas less than 1/2 km below the ocean crust surface. Therefore, the actual petro-

³ Ophiolites refer to a distinctive assemblage of mafic to ultramafic rocks. A completely developed ophiolite shows the following sequence from bottom to top: 1. an ultramafic complex, consisting of variable proportions of harzburgite, lherzolite and dunite, usually with a metamorphic tectonite fabric; 2. a gabbroic complex, ordinarily with cumulus textures, commonly containing cumulus peridotites and pyroxenites and usually less deformed than the ultramafic complex; 3. a mafic sheeted dyke complex; 4. a mafic volcanic complex, commonly pillowed.

¹ Manuscript received: 1983-09- - .

Revised manuscript accepted: 1984-05-01.

² Geology Department, Stanford University, Stanford, Cal. U.S.A.

logic nature of the crust has been inferred from geophysical measurements and scattered dredge hauls in comparison with intact on-land ophiolite sequences (COLEMAN, 1977; GASS, 1982; LEWIS, 1983). The geophysicists have understandably dominated the discussion regarding the nature of the oceanic crust and its origin. Thus, the definition of oceanic crust is given in seismological terms and with the apparent assumption that all oceanic crust has been formed by uniform igneous processes at spreading centres throughout Phanerozoic time (SPUDICH & ORCUTT, 1980; LEWIS, 1983). Most of the definitive studies on the geophysical structure of oceanic crust have been carried out by oceanographers within the Atlantic (FOWLER & KEEN, 1979) or Pacific Oceans (LEWIS & SNYDSMAN, 1979). Models for spreading centres are necessarily restricted to the still active Mid-Atlantic Ridge (TALWANI ET AL., 1970) or East Pacific Rise (ORCUTT ET AL., 1976) for instance, and rely mainly on seismic, gravity, magnetic and heat flow measurements combined with shallow DSDP holes, dredging, and deep submersible dives. Apparently the oceanic crust has a distinct and fairly uniform seismic structure with a supposed continuous horizontal layering that has been divided into three major units based on seismic velocities (CHRISTENSEN & SALISBURY, 1975). Layer 1 consists mainly of a thin layer of time-transgressive sediments whose thickness averages 0.3 km in the deep oceans and has a V_p seismic velocity that varies from 1.5 to 3.4 km/s. DSDP drilling in Layer 1 within the deep oceans reveals mainly pelagic carbonate or claystone with lenticular cherts, but ribbon radiolarites (cherts) are not present in the ocean basins of today (JENKYN & WINTERER, 1982). Layer 2 shows steep velocity gradients with depth and fine lateral variations in structure beyond the resolution of present seismic techniques. This layer has an average thickness of 1.4 km and an average V_p velocity of about 5 km/s and has recently been penetrated by DSDP drilling in the Costa Rica Rift revealing a sheeted dike complex at 1,055 m BSF in hole 504B (ANDERSON ET AL., 1982). Layer 3 (oceanic layer, ~ 5 km) exhibits a weak seismic velocity gradient with increasing depth and is much more homogenous ($V_p = \sim 6.7$ km/s) than Layer 2 even though low velocity zones are present and a high velocity layer at its base may be widespread. The transition from the oceanic layer to the upper mantle (Moho) is usually marked by a sharp increase of velocity to $V_p = 7$ or 8 km/s at depths below the ocean floor from 8 to 11 km.

The concept of layering in the ocean crust is apparently an artifice of geophysicists (refraction seismologists). The wave length of introduced seismic energy ranges from about 100 m to about 2 km and therefore restricts the resolution of velocity variations in the oceanic crust (SPUDICH & ORCUTT, 1980). For a geologist, the degree of resolution a refraction seismologist can reach would be unacceptable at almost any reasonable scale (at best 100 m for shallow, high frequency experiments). For instance, important basal ultramafic layers found in the Bushveld or Stillwater layered ultramafic intrusions would be undetected using such seismic techniques. Therefore, the

controversial high velocity layer ($V_p = 7.2$ - 7.8 km/s) at the base of the oceanic layer could be a mafic cumulate as well as it could be a partially serpentinized peridotite. It is not now possible to resolve such seismic velocity variations unless other finer scale measurements can be made or direct sampling by drilling is attempted.

Because of such geophysical dilemmas, the comparison of oceanic crust to on-land sections of ophiolites provided an attractive analogue. Careful studies of the vertical variations in the physical properties of ophiolites could then establish the rheology of the ocean crust that was beyond the reach of the oceanographers drill or dredge. Perhaps the most successful research along these lines was the actual determination of seismic velocities of the layered sequences in ophiolites. Pioneering work by CHRISTENSEN & SALISBURY (1975) led to the exciting discovery that rock velocities measured on slugs drilled from the Bay Islands ophiolite sequence could be integrated into a depth velocity structure that matched velocity profiles from the average oceanic crust (CHRISTENSEN & SALISBURY, 1979). The comparison of velocity profiles produced non petrologic evidence that ophiolites could be used as an analogue for oceanic crust, although there remained the problem of scale as these measured slugs represented only a few centimetres of rock. It is difficult to take cracks, alteration, and porosity gradients into account and in-situ velocity measurements of ophiolites have proved elusive. Notwithstanding these limitations, the ophiolite analogue has grown in acceptance since both the Bay of Islands and Samail ophiolites have seismic profiles that integrate into a startling similarity to oceanic crust (CHRISTENSEN & SMEWING, 1981; KEMPNER & GETTRUST, 1982). Comparisons between ophiolites and ocean crust have led the petrologists into less satisfactory analogues and the structural geologists are learning that many ophiolites could not have been formed in deep ocean basins. The following section will illustrate that ophiolites may form in many different tectonic settings most of which are not in deep ocean basins.

WHERE DO OPHIOLITES FORM?

One of the most important aspects of ophiolites is trying to establish the particular plate tectonic setting in which they have formed. The presence of ophiolites in sutures or as part of orogenic belts requires that some kind of oceanic crust has been incorporated during the tectonic event that led to mountain building (DEWEY, 1976; DEWEY & BIRD, 1971; MOORES, 1982). Ophiolites are now thought to form in a variety of tectonic settings all of which are based on actualistic situations: 1. mid-ocean ridge, 2. backarc basin, 3. forearc basin, 4. island arc, 5. passive margin or small ocean basin. Geologic and structural observations regarding the tectonic setting of presently exposed onland ophiolites bring out the fact that most occurrences can be placed in two broad geologic settings (MOORES, 1982): 1. Passive margins related to the

Tethyan or Iapetus Oceans where the ophiolite slab (often intact) overlies marine sedimentary sequences above Hercynian or Precambrian continental crust. In these situations, the ophiolites are obviously allochthonous and the oceans in which they apparently formed have now disappeared by subduction. These ophiolites are collectively referred to as Tethyan (MOORES, 1982). 2. Western North America and Circum Pacific accretionary terranes. These so called Cordilleran ophiolite associations (MOORES, 1982) are often incomplete, metamorphosed, or dismembered and are invariably the basement rock for individual terranes. It is rare for Cordilleran ophiolites to be emplaced onto the older crystalline basement of North America or Asia. Up to now none of these ophiolites can be considered as ever having been part of the Pacific or Farallon plates.

This two-fold tectonic classification provides a new basis for establishing the place of ophiolite origin. As shown by SMITH & WOODCOCK (1982) the Tethyan ophiolites formed in small ocean basins that were surrounded by continental crust overlain by Permo-Triassic sediments. Using a rigid plate kinematic synthesis they reconstructed the movements between Africa and Eurasia since the Jurassic. In that reconstruction, they assumed fixed boundaries with conservation of the continental mass. Therefore, the open spaces between continents shown for the post-Jurassic movements must represent oceanic crust formed at spreading centres with no apparent relationship to subduction and island arc activity (BIJU-DUVAL ET AL., 1979). However, if we assume that the Tethyan continental margins underwent stretching during the opening phase, as has been documented for Atlantic ocean margins (VAN DER LINDEN, 1975; ROYDEN & KEEN, 1980), then large areas of transitional crust would be formed and it would then not be possible to assume total conservation of the continental mass. The transitional crust must have existed along areas of active stretching and may have been tens to hundreds of kilometres wide within the Tethyan Sea as has been shown for the Atlantic margins (BOTT, 1982; COURTILOTT, 1982).

In some instances, such as in the longitude of present day Gibraltar the attenuation between Eurasia and Africa was not enough to actually allow ocean crust to form (BIJU-DUVAL ET AL., 1979). The development of the North Sea Basin apparently followed the same contemporaneous stretching pattern but failed to produce new oceanic crust (WOOD & BARTON, 1983). In other areas of the Tethyan ocean, transitional crust with extensive screens of new basaltic igneous crust would develop in a way similar to that described for the early stages of the Red Sea depression (COLEMAN, in press). Partial melting of the attenuated crust underlying the Tethyan Sea could produce silicic volcanics in association with basalts rising through the stretched crust and account for the bi-modal volcanics described in the Tethyan realm (ROCCI ET AL., 1980). The rise of asthenosphere within areas of continental extension would provide a mechanism of bringing deep mantle rocks near the surface as the Tethyan ocean develop-

ed. Formation of new oceanic crust would only form where the stretched continental crust began to rift in narrow elongate zones (COURTILOTT, 1982). Within these narrow rifts, change in plate motion could provide ample opportunity for disruption of spreading centres by transform faults or by closing and overlapping of oceanic plates. The chance for changing the magma compositions in these small rifted basins seems unlimited considering the possibility of juxtaposing stretched continental crust with active magma systems. The closing of the Tethyan ocean apparently began in the Jurassic and extended through the late Cretaceous and so the Tethyan ocean crust was apparently never completely removed from the influence of its attenuated margins and large transcurrent displacements (SMITH & WOODCOCK, 1982). The petrologic implications of continental attenuation and its effect on the composition of oceanic crust forming in small ocean basins will be considered later.

In contrast to the small ocean basins and attenuated continental crust of the Tethyan realm, the Cordilleran reconstructions provide a distinctly different picture as to where these ophiolites form (IRWIN, 1979). As pointed out by MOORES (1982) nearly all of the western North American ophiolites are often the oldest rocks in tectono-stratigraphic sequences that are marked by both pelagic sediments and flysch-type sandstones often intercalated with andesitic pyroclastics and volcanic flows. Usually there is no evidence of sedimentary material being derived from the North American craton. Reconstruction of the plate movements between the North American continent and the adjacent oceanic plates (Farallon and Pacific) over the last 150 Ma shows complete consumption of the oceanic plates by subduction (ENGBRETSON, 1982). CONEY ET AL. (1980) have produced a remarkable map of accreted terranes that have formed outboard of the Palaeozoic passive margin (miogeocline) of North America. All of the major ophiolites of western North America are incorporated into these terranes, and they often mark the boundary between these terranes (MONGER, 1977; IRWIN, 1979). The radiometric ages on many of these ophiolite bodies indicate ages much older than any of the ocean crust of the present Pacific Ocean basin (180 Ma) and some ophiolites may represent remnants of the Panthalassic Ocean. Accretion and subduction along the North American continent since the Palaeozoic is marked by intermittent island arc volcanism and the amalgamation of upper Palaeozoic to middle Mesozoic arcs (CONEY ET AL., 1980). Reconstruction of possible tectonic settings of the Cordilleran ophiolites within these accreted terranes almost invariably leads to the supposition that the ophiolites have formed in some sort of inter-arc setting rather than representing fragments of abyssal oceanic crust (SALEEBY, 1982; EVART, 1977; MOORES, 1982). Up to the time of writing this paper no unequivocal fragments of the Pacific, Farallon, or Panthalassic plates have been identified in the North American accretionary terranes. Petrologic arguments related to this general statement will be considered later.

The two-fold separation of ophiolites into Tethyan and

Cordilleran provides a much needed tectonic basis to consider analogies with present day deep oceanic crust. Because the accreted terranes of North America contain ophiolite fragments that either represent the Panthalassic ocean or interarc oceanic crust, any comparison with Pacific Ocean crust (0-200 Ma) would be suspect. Macquarie Island, Papua-New Guinea, or other Western Pacific island may contain fragments of Cainozoic to Mesozoic Pacific abyssal crust and may provide the only direct comparison (GRIFFITHS & VARNE, 1972; DAVIES, 1980). In considering the Atlantic Ocean crust, which is all less than 170 Ma old, there are no on-land exposures of this crust as there has been more or less continuous spreading since Jurassic times. The best analogue for the Atlantic crust are the Tethyan ophiolites because they are nearly the same age and have formed along passive continental margins. The troublesome aspect of the Tethyan ophiolites is their obvious association with attenuated continental crust in actively deforming small ocean basins.

The assumption that magmatic and tectonic processes leading to the formation of ocean crust are uniform at all spreading centres during the Phanerozoic is terribly oversimplified (CANN, 1974). Perhaps the general mechanics of ocean crust formation at spreading centres can be formulated into a single model but the magmatic processes in the mantle and differentiation during magma transport must produce many chemical variations that may be virtually impossible to ascribe to a single tectonic setting. The section that follows will attempt to highlight the variety of magmas found in ophiolites.

OPHIOLITES AND THEIR PARENT MAGMAS

The first attempts at comparing ophiolites and ocean crust were hampered by sparse chemical and petrologic data from the ophiolites and their widespread alteration by hydrothermal fluids as well as being affected by regional metamorphism. The paucity of good chemical data however did not deter petrologists in their quest of trying to establish the tectonic settings of ophiolites as a function of their petrology and chemical variation related to evolution of oceanic crust (MOORES & VINE, 1971; NICOLAS & JACKSON, 1972; MIYASHIRO, 1975). None of these comparisons were derived from a quantitative approach. Because of this, volcanic rocks were since collected from present day mid-ocean spreading centres, back arc basins, island arcs and other likely areas considered as possible sites of magma generation for ophiolites so that actualistic petrologic parameters could be established. Careful analytical work on these samples produced a series of discriminate diagrams that could be used as a guide to establishing the petrotectonic setting of ophiolites in ancient orogenic belts (PEARCE & CANN, 1973; UPADHYAY & NEALE, 1979). By using these discriminate diagrams combined with judicious geological observations it is possible to classify many ophiolite lavas into a possible petrotectonic setting. These

studies when applied to some ophiolites brought out considerable discussion because the geologic evidence often contradicted the tectonic setting determined by discriminant diagrams (MIYASHIRO, 1973; GASS ET AL., 1975; COLEMAN, 1977, p. 94). As more and more petrologic and chemical data accumulated from the DSDP drilling of the mid-ocean basalt (MORB) near and around active spreading centres it has become slowly evident that most ophiolites have element distribution and petrographic characteristics distinct from the MORB basalts that make up the large ocean basins and formed over the past 200 Ma (MELSON ET AL., 1976; CAMERON ET AL., 1980). Comparison of the chemistry and petrography of the Phanerozoic ophiolites with these various petrotectonic settings indicates a general possibility that most of these ophiolites formed in fore-arc, back-arc, island-arc, or small ocean basin settings rather than being fragments of MORB (MOORES, 1982; ROCCI ET AL., 1980; SCHMINCKE ET AL., 1983). Some petrologists have resisted this claim and show that ribbon cherts, geologic setting, and radiometric age require formation at mid-ocean spreading centres (HOPSON ET AL., 1981; COLEMAN, 1981). The puzzling enigma of having some ophiolites exhibit geologic features that seemed to indicate formation in a mid-ocean ridge setting whereas the petrologic nature indicated formation in an island arc setting forced some geologists into proposing ophiolite generation in awkward plate tectonic situations. The petrologic and chemical nature of MORB now seems well established and quite distinctive (MELSON ET AL., 1976). All of the MORB rocks have formed at accretionary ridges that are either still active or can be related to ocean crust that is no older than 180 MA. The MORB rocks are subalkaline and contain phenocrysts of plagioclase, olivine, and occasionally clinopyroxene. Some petrologists consider that the parent magmas for MORBs are picrites that have fractionated olivine and chromite, plagioclase, and clinopyroxene in that order (O'HARA, 1968; 1982; ELTHON, 1979). The fractionation is thought to take place in shallow magma chambers under spreading ridges. According to experimental work by STOLPER (1980) the MORB glasses are not primary melts derived directly from partial melting of the mantle but represent evolved picrite melts that first formed by partial melting of a lherzolite at 15-20 kbar which later fractionated to form the MORB compositions. Other petrologists consider that MORB represents a primary magma formed in the mantle at moderate pressures 8-10 kbar (PRESNALL, 1980). Whatever the way the MORB basalts form, they have a unique chemical composition that shows less than 52% SiO₂, TiO₂ contents greater than 0.8%, with rare earth elements nearly the same as chondrites. An important consideration here is that almost all of the analytical data on MORB basalts represent samples taken from in or around present day active spreading centres. Very little is known about petrologic variations in Atlantic, Pacific, or Indian ocean crust of early Mesozoic age, but it is assumed that all this abyssal oceanic crust is similar.

The search for abundant MORB type basalts from ophiolite

ites has not been successful and as brought out earlier, the geological and petrological comparisons all point to tectonic settings in inter-arc, island arc, or small ocean basins. The discovery of boninites in the forearc region of the Mariana Islands and its presence within the pillow lavas of Cyprus has produced considerable interest in the magmas that form ophiolites (SHARASKIN ET AL., 1980; CAMERON ET AL., 1979; ROBINSON ET AL., 1983). As more analytical data become available on ophiolites it is apparent that perhaps only a few rare instances of MORB have been incorporated into the world's continental margins (SAUNDERS ET AL., 1980). This is a startling observation when we consider that the presently exposed Phanerozoic ophiolites represent probably less than 0.001% of the ocean crust (COLEMAN, 1977). This ratio of exposed ophiolites to oceanic crust would be even much less if it was possible to estimate the volume of the consumed Iapetus, Panthalassic, and Tethyan Oceans! Does this mean that our structural and petrologic comparisons between ophiolites and ocean crust formed in large ocean basins may not be valid? Perhaps not, since the spreading process of forming new oceanic crust is visualized in a kinematic way and should have gross similarities for various tectonic settings depending on spreading rates. However, the variety of magmatic products generated at a spreading ridge is the result of accretion behind island arcs, in front of island arcs, within plates and in small ocean basins along attenuated continental crust. In each tectonic situation outlined above, the degree of partial melting of the mantle, fractionation and metasomatism, magma mixing, or contamination will have a profound effect on the igneous products that form new oceanic crust. Our present knowledge of magmatic processes derived from petrologic studies of ophiolites adequately bears out the contention that establishing the nature of parent magmas by the study of ophiolite lavas alone can lead to erroneous conclusions (PRESNALL, 1982). The dilemma facing petrologists studying MORB genesis is that they are restricted to surface lavas and scattered dredge hauls and the implementation of the ophiolite analogy has proved misleading since ophiolites forming along continental margins or arc systems are petrologically distinct from ocean crust formed in deep ocean basins such as the Pacific or Atlantic.

Penetration into Layer 2 by DSDP into oceanic crust only 6 Ma old near the Costa Rica rift has established the presence of sheeted dikes in hole 504B (ANDERSON ET AL., 1982). This is the first time DSDP drilling has penetrated into a sheeted dike sequence and so at least part of the ophiolite analogy has been substantiated in the east Pacific Ocean. The exact nature of the magmatic processes that form MORB can not be established until the ocean drilling penetrates Layer 3 and beyond into the mantle. The prospects of such penetration happening within the next few years are not bright and so the petrologists must rely on dredge hauls and petrologic reasoning with ophiolites as a quasi-model.

WHAT DO OPHIOLITE PERIDOTITES TELL US ABOUT THE FORMATION OF OCEANIC CRUST?

In many ophiolites, peridotites are the predominant rock or the only rock exposed. Naturally this has led to a situation where there are much more data on ophiolite peridotites than on the associated gabbros, dikes, and volcanics. In certain geologic occurrences it is difficult to establish if the peridotites did indeed originally exist with other mafic igneous rocks (LONEY ET AL., 1971; WRIGHT ET AL., 1982). There are very few areas in the deep ocean basins where peridotites have been sampled by dredging and up to the present time DSDP drilling has not penetrated into the upper mantle. As before, the conclusions concerning the oceanic mantle have been strongly biased towards the studies on ophiolite peridotites. An active group at the University of Nantes in France is now undertaking studies of a number of ophiolite peridotites from the standpoint of their internal structures and deformation (NICOLAS ET AL., 1980; NICOLAS & LE PICHON, 1980; NICOLAS & PRINZHOFFER, 1983; NICOLAS & VIOLETTE, 1982). One of the most significant properties of the ophiolite peridotites is the fact that they invariably exhibit crystal fabrics that indicate sub-solidus recrystallization (NICOLAS, 1976). The recrystallization of olivine has been studied carefully in the laboratory and it is now possible to establish conditions of recrystallization by twinning style, glide planes, and fabric orientation within peridotites (NICOLAS ET AL., 1980). These studies have convincingly shown that most ophiolite peridotites have undergone plastic deformation prior to their emplacement. In some instances, this deformation can be related to diapiric uprise and mantle flow developed under spreading centres. Lineation of grains in these tectonized peridotites mark the trace of ductile flow directions. From careful fabric studies in selected ophiolite peridotites it is possible to show that there has been a nearly horizontal flow of the asthenosphere underlying the ocean crust and that this flow is usually normal to the spreading ridge (NICOLAS & VIOLETTE, 1982). In certain cases the mantle flow may be subvertical and it appears to be a vestige of vertical diapiric uprise of the asthenosphere near a spreading centre (NICOLAS & VIOLETTE, 1982; HIMMELBERG & LONEY, 1980). Deformation of the overlying cumulates observed in some areas indicates that the lower part of the oceanic crust can be affected by this upper mantle flow beneath spreading centres (GEORGE, 1978; HIMMELBERG & LONEY, 1980).

Harzburgite, the main rock found in ophiolite peridotites, is considered by many to be a residue of partial melting (COLEMAN, 1977; MOORES, 1982). It is rare to find lherzolites or plagioclase-bearing peridotites within the ophiolite peridotites. The occurrence of discordant and concordant dunite, websterite, and gabbroic bodies within these harzburgites provides evidence of magmatic activity in the harzburgite before and after sub-solidus deformation (BOUDIER & COLEMAN, 1981). Studies of these discrete bodies within the harzburgites and their relationship to magmatic processes has

just started, but the large dunite bodies and dikes have been interpreted as fractionated residues of olivine and chromite that formed as primary picritic magmas that passed through the upper mantle (BOUDIER & COLEMAN, 1981; GREGORY, 1982). Other features of these discrete bodies suggest that at least some wall rock reaction between ascending picrite melts and surrounding harzburgite may have produced some of the dunite by zone refining (QUICK, 1981a; b).

Bulk compositions of the websterite and gabbro dikes in ophiolite peridotites indicate that they also represent crystal fractionation products of other distinct magma types as they passed through the depleted harzburgite (GREGORY, 1982). In certain situations these dikes are folded and boudinaged as a result of the asthenosphere plastic flow under the spreading ridge and in other cases they represent undeformed dikes invading brittle fractures formed away from the spreading centre (BOUDIER & COLEMAN, 1981).

Sparse dredge hauls from the deep oceans produce peridotites with similar deformational fabrics as seen in the ophiolite peridotites (NICOLAS ET AL., 1980). Geometrical relationships and the spreading rheology can not be established, but anisotropy detected by seismic studies of deep oceanic crust indicates that the mantle underlying the crust could have undergone sub-solidus deformation as the asthenosphere rose and moved away from the spreading ridge (CHRISTENSEN & SALISBURY, 1979; NICOLAS ET AL., 1980).

Petrologically the ophiolite peridotites record an extremely complicated history of sub-solidus deformation, reaction with migrating melts, and the discordant and concordant bodies reveal evidence that diverse magmas have migrated within the mantle. The common association of chromite bodies in large dunites masses as part of the mantle supports the idea that picrite magmas crystallize olivine and chromite just before they enter magma chambers under some spreading centres. Future studies of ophiolite peridotites could provide a controlled model for the relationships between partial melting, deformation, and metasomatism within the mantle as related to the variation of basaltic magma compositions. Realizing that all these documented mantle processes act upon magmas as they move through the upper mantle on their way to spreading ridge magma chambers should convince geochemists that basalt glasses are a product of a complicated magmatic history and that the incompatible elements and major elements can not uniquely characterize such processes.

EMPLACEMENT OF OPHIOLITES

Because ophiolites are present within or along sutures that mark continental collision or accretion their age and origin can provide important clues as to the nature of orogenic zones (DEWEY, 1976). JONES ET AL. (1982) have pointed out that North America has grown by more than 25 percent as a result of accretion since early Jurassic, approximately the same age

as the oldest Pacific basin abyssal oceanic crust. They make a startling statement that the accreted terranes represent rocks formed in the oceanic realm rather than from erosion of the older North American craton. Yet when estimates are made on the actual amount of exposed oceanic crust within these terranes it is obvious that oceanic crust or ophiolite makes up less than about 1 percent of the total rock volume. Even accounting for submerged portions that could be projected to depth it is clear that if these exotic terranes once rested on Pacific Basin abyssal oceanic crust they have become completely detached. If we return to the idea that exposed ophiolites of Western North America are interarc fragments then it is unlikely that any of these ophiolites had their origins on or within deep oceanic crust similar to the Pacific of Farallon Plates. The sedimentary sequences of the exotic terranes mainly show island arc or interarc affinities with very little clastic material typical of the North American miogeocline sequences (CONEY ET AL., 1980). Furthermore, the petrologic nature of the ophiolites or kindred mafic igneous rocks at the base of these terranes seems to point to island arc or interarc affinities (J. H. NATLAND, 1983, pers. comm.). If the ophiolites are not parts of deep oceanic plates (MORB) then it seems apparent that these terranes were never transported as part of the Pacific, Farallon, or Panthalassic plates but rather may have been part of arc systems. Their transport perhaps being related to large oceanic plateaus moving in concert with surrounding oceanic crust as has been suggested by NUR & BEN-AVRAHAM (1982). Intra-plate volcanism often produces large seamounts whose petrologic signatures are distinct and such small areas are present within the North American accretionary terranes that there is little evidence that the 'oceanic basement' for most terranes can be related to seamounts.

A detailed look at the Klamath Mountains gives us some insight into the emplacement of ophiolites and the amalgamation of terranes. The so-called ophiolites of the Klamath Mountains form an arcuate series of belts that are younger towards the west (IRWIN, 1979). In southwest Oregon, serpentinite melanges imbricated with Campanian flysch and blueschist knockers apparently mark a period of west-directed thrusting of older dismembered ophiolites over younger sediments (COLEMAN, 1972; ROURE & BLANCHET, 1983). Further inboard, the Josephine ophiolite (~ 150 Ma) is the oceanic basement for the Galice Formation of Late Jurassic age which consists of andesitic volcanic rocks and distal flysch deposits (SALEEBY ET AL., 1982). This group of rocks is thrust westward over the Dothan graywackes of early Cretaceous age. Further inboard older Triassic and Palaeozoic terranes (Hayfork and Rattlesnake Creek) are also thrust westward over the Galice Formation. Late Tertiary doming of these same terranes exposed a basal sequence of tectonically melanged and metamorphosed ophiolites and interarc basin sediments thrust over a sequence of interarc basin sediments metamorphosed to greenschist-blueschist facies. The easternmost ophiolite belt consists of the Trinity

peridotite of early Palaeozoic age overlain by a sequence of Devonian bi-modal volcanics and interarc sediments. The Trinity oceanic basement is thrust westward over a sequence of amphibolites and blueschists derived from interarc volcanics and sediments.

All of these Klamath Mountain ophiolites have geologic and petrologic affinities to interarc or island arc situations; volcanics with MORB affinities have not yet been documented. The predominate west-directed thrusts are perhaps a secondary manifestation of continuous deep-seated subduction of abyssal oceanic lithosphere under the continental margin. The intermittent accretion of arc or interarc slabs is brought about by deep faults that penetrate towards the continent and imbricate evolving interarc and arc sequences (WRIGHT, 1982). Northward translations of the younger outboard terranes in the Klamaths is marked by prominent strike slip faults and the juxtaposition of distinct tectonostratigraphic terranes whose oceanic basement now consists mainly of tectonic serpentinite melanges.

Gravity and seismic observations indicate that the Klamath Mountain accretionary terranes have a crustal thickness of less than 30 km (JACKENS, 1983, pers. comm.). Isostatic adjustment at the present time suggests that, with this configuration, most of the continental crust consists of sediments understuffed beneath thin wedges of 'oceanic basement' decoupled during the subduction of the Pacific and Farallon plates during the Mesozoic and Tertiary. A recent model developed for forearc basins portrays a mechanism whereby rupture of forearc oceanic crust accompanied by understuffing of marginal basin sediments can effectively trap small slabs of ocean crust and thicken the continental margin by these underthrust sediments (SEELY, 1979). Variations of this model could explain those Cordilleran ophiolites considered 'oceanic basement' to be successively older detached terranes that accrete by flat oceanward thrusts forming above forearc subduction zones.

The Tethyan ophiolites, on the other hand, require a tectonic regime that relates to the formation of passive continental margins and small ocean basins (SMITH & WOODCOCK, 1982; BIJU-DUVAL ET AL., 1979). The occurrence of bi-modal volcanics and the presence of boninites in some pillow sequences suggests a special tectonic situation (ROBINSON ET AL., 1983). Recent reviews on ophiolites in the Mediterranean area provide new facts towards an understanding of the problem (ROCCI ET AL., 1980; DIETRICH, 1979). The sedimentary history of the area is complex with a Permian-Triassic seaway forming marginal basin sequences as Africa and Eurasia began to separate. Numerous areas of bi-modal volcanics consisting of alkali basalts with dacites and rhyolites are present along the margins (SMITH & WOODCOCK, 1982). In the western Mediterranean, in Corsica and the Alps small areas of Jurassic oceanic crust formed while in the eastern Mediterranean extension ceased or declined to an extremely slow rate (ROCCI ET AL., 1980). During late Cretaceous small amounts of ocean crust formed in the eastern

Mediterranean at Cyprus, Antalya, Bear-Basit, perhaps not more than several hundred kilometres according to ROBERTSON & WOODCOCK (1980). Within these narrow and deep (?) small ocean basins ribbon cherts were abundant. Ribbon cherts have ordinarily been considered to indicate abyssal depths characteristic of large oceans, but drilling experience on the DSDP has failed to find similar cherts. JENKYN & WINTERER (1982) have suggested that ribbon cherts could form more readily in small ocean basins because carbonate compensation levels may be much shallower in these small basins and thus favour silica-rich sediments that derive from abundant silica produced by the nearby bimodal volcanism. SUGISAKI ET AL. (1982) presented evidence that Triassic ribbon cherts in Japan may also have formed in a marginal sea environment. Emplacement of the eastern Mediterranean ophiolites is now considered to be the result of the collision between Africa and Eurasia and the disappearance of the Tethyan Ocean (SMITH & WOODCOCK, 1982). One important aspect of this collision is that there have been found only Jurassic age ophiolites in the western Mediterranean orogenic zones and only Late Cretaceous ophiolites in the eastern Mediterranean (ROCCI ET AL., 1980). Thus it appears that Tethyan ophiolites were emplaced as young hot crust and that spreading centres were destroyed by closing the Tethyan. The concomitant overlap of oceanic crust and attenuated continental crust gave rise to the possibility of unique magmatic events developing as spreading ceased and the magmatic systems were modified by compressional or transform movements. It is known that passive margins may stretch to 1/4 of their original thickness and that the asthenosphere ascended and emplaced at a spreading centre would probably require more than 10 Ma. to cool (ROYDEN & KEEN, 1980; TAPPONNIER & FRANCHETEAU, 1978). It seems likely that at least some of the compositional variations found in Tethyan ophiolites could have resulted from magma changes during the collision and translation of newly-formed oceanic crust where water or xenoliths of altered continental crust could be easily introduced into magma chambers in the terminal stage of magmatic activity. The striking lack of large-scale subduction related island arc volcanics in the Tethyan during closing of this sea provides indirect evidence that the ocean basins were small and the strange shoshonites of the Kyrenia range (BAROZ, 1980) in Cyprus could be explained by involvement of continental crust in the collision of Africa and Eurasia over the still active late Cretaceous spreading centres.

Another characteristic of these eastern Tethyan ophiolites is the common development of a narrow zone of high grade metamorphic rocks along the detachment base of the ophiolites (PARROT & WHITECHURCH, 1978; WOODCOCK & ROBERTSON, 1977). As has been documented in Oman, the detachment metamorphic aureoles from before emplacement of the ophiolite but only 5 Ma after the igneous formation of the oceanic crust. These detachment metamorphic aureoles are considered to have developed by overriding of still hot oceanic lithosphere onto basalts and sediments as the Arabian

plate moved towards Eurasia (GHENT & STOUT, 1981). Basalt dikes cutting these metamorphic aureoles at the base of the Samail ophiolite are evidence of still active magma chambers existing in the zone of detachment. These same observations have been recorded by JUTEAU ET AL., (1977) in other eastern Mediterranean ophiolites. An analogy between the small Tethyan ocean basins and the present Red Sea seems likely and leads to the possibility that the Tethyan ophiolites represent the collapse of an embryonic spreading centre with still hot detached slabs of oceanic crust being emplaced on to their own passive continental margins. Involvement of attenuated continental crust in magmas still active but sealed by compression could lead to volcanics similar to calc-alkaline island arcs but formed in a quite different tectonic setting.

IMPLICATIONS OF OPHIOLITE DIVERSITY

The interesting changes in concepts brought about by detailed studies of ophiolites over the past ten years has been amazing and shows once again that the simple plate tectonics models were only a beginning. If all the abyssal oceanic crust is subducted and virtually none is accreted onto continents what effect does this have on the evolution of the mantle? Does the lack of abyssal oceanic crust (MORB) in exotic terranes indicate that these terranes moved as island arc complexes or as oceanic plateaus? These are just two questions one might ask of the author regarding the new problems brought out by this discussion. Obviously the question of abyssal oceanic crust formation is not resolved and its comparison with ophiolites should be viewed with some skepticism. It is apparent that the ophiolite assemblage as defined by the Penrose Conference (ANONYMOUS, 1977) can form in a multitude of tectonic settings and that the process of accreting new ocean crust in spreading centres can develop a great variety of magma types.

REFERENCES

- Anderson, R. N. and others 1982 DSDP hole 504B, the first reference section over 1 km through Layer 2 of the oceanic crust – *Nature* 300: 589-594.
- Anonymous 1973 Penrose field conference on ophiolites – *Geotimes* 17: 24-25.
- Baroz, F. 1980 Volcanism and continent-island arc collision in the Pentadaktylos range, Cyprus – In: Panayiotou, A. (ed.): *Ophiolites – Geol. Surv. (Cyprus): 73-85.*
- Biju-Duval, B., J. Letouzey & L. Montadert 1979 Variety of margins and deep basins in the Mediterranean – In: Watkins, J. S. et al. (eds) *Geological and geophysical investigations of continental margins*, Am. Assoc. Pet. Geol. Mem. 29: 293-318.
- Bott, M. H. P. 1982 The mechanism of continental splitting – *Tectonophysics* 81: 301-309.
- Boudier, F. & R. G. Coleman 1981 Cross section through the peridotite in the Samail ophiolite, southeastern Oman mountains – *J. Geophys. Res.* 86: 2573-2592.
- Cameron, W. E., V. G. Nisbet & V. J. Dietrich 1979 Boninites, komatiites and ophiolites – *Nature* 280: 550-553.
- 1980 Petrographic dissimilarities between ophiolitic and ocean-floor basalts. In: Panayiotou, A. (ed.): *Ophiolites – Geol. Surv. (Cyprus): 182-192.*
- Cann, J. R. 1974 A model for oceanic crustal structure developed – *Geophys. J.R. Astr. Soc.* 39: 169-187.
- Christensen, N. J. & M. H. Salisbury 1975 Structure and constitution of the lower oceanic crust – *Rev. Geophys. Space Phys.* 13: 57-86.
- 1979 Seismic anisotropy of the oceanic upper mantle: Evidence from the Bay of Islands ophiolite complex – *J. Geophys. Res.* 84: 4001-4610.
- Christensen, N. I. & X. Smewing 1981 Geology and seismic structure of the northern section of the Oman ophiolite – *J. Geophys. Res.* 86: 2699-2708.
- Coleman, R. G. 1977 *Ophiolites – Ancient oceanic lithosphere?* Springer (Berlin, New York): 229 pp.
- 1981 Tectonic setting for ophiolite obduction in Oman – *J. Geophys. Res.* 86: 2497-2508.
- in press The Tihama-Asir igneous complex, a passive margin ophiolite 27th Int. Geol. Cong. Moscow.
- Coney, P. J., D. L. Jones & J. W. H. Monger 1980 – Cordilleran suspect terranes – *Nature* 288: 329-333.
- Courtillot, V. 1982 Propagating rifts and continental break-up – *Tectonics* 1: 239-250.
- Davies, H. L. 1980 Crustal structure and emplacement of ophiolite in southeastern Papua New Guinea. In: Allegre, C. (ed.) *Association mafiques ultra-mafiques dans les orogens-Colloques Int. CRNS* 272: 17-33.
- Dewey, J. F. 1976 Ophiolite obduction – *Tectonophysics* 31: 93-120.
- Dewey, J. F., & J. M. Bird 1971 Origin and emplacement of the ophiolite suite: Appalachian ophiolites in New Foundland – *J. Geophys. Res.* 76: 3179-3206.
- Dietrich, V. J. 1979 Ophiolitic belts of the central Mediterranean – *Geol. Soc. Am. Map and Chart Ser. M.C.* 33 sheet 2.
- East Pacific Rise Study Group 1981 Crustal processes of the mid-ocean ridge – *Science* 213: 31-40.
- Elthon, D. 1979 High magnesia liquids as the parental magma for ocean floor basalts – *Nature* 278: 514-518.
- Engelbreton, D. C. 1982 Relative motions between oceanic and continental plates of the Pacific Basin – Ph.D. Thesis, Stanford University: 211 pp.
- Evárts, R. C. 1977 The geology and petrology of the Del Puerto ophiolite, Diablo Range, central California Coast Ranges – In: Coleman, R. G. & W. P. Irwin (eds): *North American Ophiolites – Oreg. Dep. Geol. Min. Ind.* 95: 121-140.
- Fowler, C. M. R. & C. E. Keen 1979 Oceanic crustal structure – Mid-Atlantic Ridge at 45°N – *Geophys. J. Res. Abstr. Soc.* 56: 219-226.
- Gass, I. 1982 Ophiolites – *Sci. Am.*, 247 (2), 122-131.
- Gass, I. and others, 1975 Comments on 'The Troodos ophiolitic complex was probably formed in an island arc', by A. Miyashiro and subsequent correspondence by A. Hynes and A. Miyashiro – *Earth. Planet. Sci. Lett.* 25: 236-238.
- George, R. P. 1978 Structural petrology of the Olympus ultramafic complex in the Troodos ophiolite, Cyprus – *Geol. Soc. Am. Bull.* 89: 845-865.
- Ghent, E. D. & M. Z. Stout 1981 Metamorphism at the base of the Samail ophiolite, Southeastern Oman Mountains – *J. Geophys. Res.* 86: 2557-2571.
- Gregory, R. T. 1982 Melt percolation beneath a spreading ridge: Evidence from the Samail peridotite, Oman – *Geol. Soc. Lond. meeting: Ophiolites and oceanic lithosphere*, London.
- Griffiths, J. R. & R. Varne 1972 Evolution of the Tasman Sea Macquarie ridge and Alpine fault – *Nature; Phys. Sci.* 235: 83-86.
- Himmelberg, G. R. & R. A. Loney 1980 Petrology of ultramafic and

- gabbroic rocks of the Canyon Mountain ophiolite, Oregon – *Am. J. Sci.* 280-A: 232-268.
- Hopson, C. A., J. M. Mattinson & E. A. Pessagno Jr. 1981 Coast Range ophiolite western California – In: Ernst, W. G. (ed.): *The geotectonic development of California – Rubey I*, Prentice-Hall (New Jersey): 418-510.
- Irwin, W. P. 1979 Ophiolitic terranes of part of the western United States – In: *International Atlas of Ophiolites – Geol. Soc. Am., Map and Chart Ser.*, MC-33.
- Jones, D. L., A. Cox, P. Coney & M. Beck 1982 The growth of western North America – *Sci. Am.* 247 (5): 70-84.
- Jenkyns, H. C. & E. L. Winterer 1982 Paleooceanography of Mesozoic ribbon radiolarites – *Earth Planet. Sci. Lett.* 60: 351-375.
- Juteau, T., A. Nicolas, J. Dubessy, J. C. Fruchard & J. L. Bouchez 1977 Structural relationships in the Antalya ophiolite Complex, Turkey: Possible model for an ocean ridge – *Geol. Soc. Am. Bull.* 88: 1740-1748.
- Kempner, W. C. & J. F. Gettrust 1982 Ophiolites, synthetic seismograms, and oceanic crustal structure. 2. A comparison of synthetic seismograms of the Samail ophiolite, Oman, and the ROSE refraction data from the East Pacific Rise – *J. Geophys. Res.* 87: 8463-8476.
- Lewis, B. T. R. 1983 The process of formation of ocean crust – *Science*, 220 (4593), 151-157.
- Lewis, B. T. R. & W. E. Snodman 1979 Fine structure of the lower oceanic crust on the Cocos plate – *Tectonophysics* 55: 87-105.
- Loney, R. A., G. R. Himmelberg & R. G. Coleman 1971 Structure and petrology of the alpine-type peridotite Buno Mountain, California, USA – *J. Petrol.* 12: 245-309.
- Melson, W. G., G. R. Byerly, J. A. Nelen, T. O'Hearn, T. L. Wright & T. Vallier 1976 A catalog of the major element chemistry of abyssal volcanic glass – In: Mason, B. (ed.): *Smithsonian Contrib. Earth Sci.* 19: (Washington D.C.) – (Smithsonian Inst. Press): 31-60.
- Miyashiro, A. 1973 The Troodos ophiolite Complex was probably formed in an island arc – *Earth Planet. Sci. Lett.* 19: 218-224.
- 1975 Classification, characteristics, and origin of ophiolites, – *J. Geol.* 83: 249-281.
- Monger, J. W. H. 1977 Ophiolitic assemblages in the Canadian Cordillera. In: Coleman, R. G. & W. P. Irwin (eds): *North American ophiolites – Oreg. Dep. Geol. Min. Ind.* 95: 59-65.
- Moore, E. M. & F. J. Vine 1971 The Troodos Massif, Cyprus, and other ophiolites as ocean crust: Evaluation and implications – *R. Soc. Lond. Philos. Trans. A* 268: 443-466.
- 1982 Origin and emplacement of ophiolites – *Rev. Geophys. Space Phys.* 20: 735-760.
- Natland, J. H. 1983 California coast range ophiolite remnants: Fragments of an island arc crustal segment – *Journal*, Vx: xxx-xxx.
- Nicolas, A. 1976 Flow in upper-mantle rocks: Some geophysical and geodynamic consequences – *Tectonophysics* 32: 93-106.
- Nicolas, A., F. Boudier & J. L. Bouchez 1980 Interpretation of peridotite structures from ophiolitic and oceanic environments – *Am. J. Sci.*, 286-A: 192-210.
- Nicolas, A. & E. D. Jackson 1972 Repartition en deux provinces des péridotites des chaînes alpines longeant la Méditerranée: implications géotectoniques – *Bull. Suis. Min. Petr.* 52: 479-495.
- Nicolas, A. & Le Pichon X. 1980 Thrusting of young lithosphere in subduction zones with special reference to structures in ophiolitic peridotites – *Earth Planet. Sci. Lett.* 46: 397-406.
- Nicolas, A. & A. Prinzhofer 1983 Cumulative or residual origin for the transition zone in ophiolites: structural evidence – *J. Petrol.* 24: 188-206.
- Nicolas, A. & J. F. Violette 1982 Mantle flow of oceanic spreading centers: Models derived from ophiolites – *Tectonophysics* 81: 319-339.
- Nur, A. & Z. Ben-Avraham 1982 Oceanic plateaus; the fragmentation of continents, and mountain building – *J. Geophys. Res.* 87: 3644-3662.
- O'Hara, M. J. 1968 Are ocean floor basalts primary magma? – *Nature* 220: 683-686.
- Orcutt, J. A., B. L. N. Kennett & L. M. Dorman 1976 Structure of the East Pacific Rise from an ocean bottom seismometer survey – *Geophys. J. Res. Abstr. Soc.* 45: 305-320.
- Panayiotou, A. 1980 Ophiolites – *Proceedings International Ophiolite Symposium Cyprus, 1979 – Geol. Surv. Dept. Ministry of Agriculture and Natural Resources, (Nicosia):* 781 pp.
- Parrot, J. F. & X. Whitechurch 1978 Subductions antérieures au charriage nord-sud de la croûte Téthysienne: Facteur de Métamorphisme de séries sédimentaires et volcaniques liées aux assemblages ophiolitiques Syro-Turcs, en schist verts et amphibolites – *Rev. Geog. Phys. Geol. Dyn.* 20: 153-170.
- Pearce, J. A. & J. R. Cann 1973 Tectonic setting of basic volcanic rocks determined using trace element analyses – *Earth Planet. Sci. Lett.* 19: 290-300.
- Presnall, D. C., 1980 A double partial melt zone in the mantle beneath mid-ocean ridges – *Phys. Earth Planet. Int.* 23: 103-111.
- 1982 Comments on 'MORB-A Mohole misbegotten?' by M. J. O'Hara – *EOS. Am. Geophys. Union Trans.* 63: 1210.
- Quick, J. E., 1981a The origin and significance of large, tabular dunite bodies in the Trinity peridotite, northern California – *Contrib. Mineral. Petrol.* 78: 413-422.
- 1981b Petrology and petrogenesis of the Trinity peridotite, an upper mantle diapir in the eastern Klamath Mountains, Northern California – *J. Geophys. Res.* 86: 11 837-11 863.
- Robertson, A. H. F. & N. H. Woodcock 1980 Tectonic setting of the Troodos massif in the east Mediterranean – In: Panayiotou, A. (ed.): *Ophiolites, Geol. Survey (Cyprus):* 36-49.
- Robinson, P. T., W. G. Melson, T. O'Hearn & H. U. Schmincke 1983 Volcanic glass compositions of the Troodos ophiolite, Cyprus – *Geology* 11: 400-404.
- Rocci, G. and others 1980 The Mediterranean ophiolites and their related Mesozoic volcanic-sedimentary sequences – In: Panayiotou, A. (ed.): *Ophiolites – Geol. Surv. (Cyprus):* 273-286.
- Roure, F. & R. Blanchet 1983 A geological transect between the Klamath Mountains and the Pacific ocean (Southwestern Oregon): A model for paleosubductions – *Tectonophysics* 91: 53-72.
- Royden, L. & C. E. Keen 1980 Rifting processes and thermal evolution of the continental margin of eastern Canada determined from subsidence curves – *Earth Planet. Sci. Lett.* 51: 343-361.
- Saleeby, J. B. and others 1982 Time relations and structural-stratigraphic patterns in ophiolite accretion, westcentral Klamath Mountains, California – *J. Geophys. Res.* 87: 3831-3848.
- Saunders, A. D., J. Tarney, N. G. Morsh & D. A. Wood 1980 Ophiolites as ocean crust or marginal basin crust; A geochemical approach – In: Panayiotou, A. (ed.): *Ophiolites – Geol. Surv. (Cyprus):* 193-204.
- Schmincke, H. U., M. Rautenschlein, P. T. Robinson & J. M. Mehegan 1983 Troodos extrusive series of Cyprus: A comparison with oceanic crust – *Geology* 11: 405-409.
- Seely, D. R. 1979 The evolution of structural highs bordering major forearc basins – In: Watkins, J. S., L. Montadert & P. W. Dickerson (eds): *Geological and geophysical investigations of continental margins – Am. Assoc. Pet. Geol. Mem.* 29: 245-260.

- Sharaskin, A. Y., N. L. Dobretsov & N. V. Sobolev 1980 Marianites: The clinostatite bearing pillow-lavas associated with the ophiolite assemblage of Mariana Trench – In: Panayiotou (ed.): *Ophiolites – Geol. Sur. (Cyprus)*: 473-479.
- Shelton, A. 1983 *Ophiolites and Oceanic Lithosphere – Geol. Soc. Lond., Spec. Publ.*
- Smith, A. G. & N. H. Woodcock, 1982 Tectonic syntheses of the Alpine – Mediterranean region: A review – In: Berckhemer, H. & K. Hsü (eds): *Alpine – Mediterranean geodynamics – Am. Geophys. Union Geodyn. Ser. 7*: 15-38.
- Spudich, P. & J. Orcutt 1980 A new look at the seismic velocity structure of the oceanic crust – *Rev. Geophys. Space Phys.* 18: 627-645.
- Stolper, E. 1980 A phase diagram for mid-ocean ridge basalts: Preliminary results and implications for petrogenesis – *Contrib. Mineral. Petrol.* 74: 13-27.
- Sugisaki, R., K. Yamamoto & M. Adachi 1982 Triassic bedded cherts in central Japan are not pelagic – *Nature* 298: 644-647.
- Talwani, M., C. Windisch & M. Langseth 1970 Reykjanes ridge crest: A detailed geophysical study – *J. Geophys. Res.* 75: 5093-5111.
- Tapponnier, P. & J. Francheteau 1978 Necking of the lithosphere and the mechanics of slowly accreting plate boundaries – *J. Geophys. Res.* 83: 3955-3970.
- Upadhyay, H. D. & E. R. W. Neale 1979 On tectonic regimes of ophiolite genesis – *Earth Planet. Sci. Lett.* 43: 93-102.
- Van der Linden, W. J. M. 1975 Crustal attenuation and sea-floor spreading in the Labrador Sea – *Earth Planet. Sci. Lett.* 27: 409-423.
- Wood, R. & P. Barton 1983 Crustal thinning and subsidence in the North Sea – *Nature* 302: 134-136.
- Woodcock, N. H. & A. H. F. Robertson 1977 Origins of some ophiolite-related metamorphic rocks of the 'Tethyan' belt – *Geology* 5: 373-376.
- Wright, J. E. 1982 Permo-Triassic accretionary subduction complex, southwestern Klamath Mountains, Northern California – *J. Geophys. Res.* 87: 3805-3818.
- Wright, R. L., J. Nagel & K. C. McTaggart 1982 – Alpine rocks of southwestern British Columbia – *Can. J. Earth Sci.* 19: 1156-1173.