Canadian Mineralogist
Vol. 17, pp. 871-887 (1979)

SERPENTINITES, SPILITES AND OPHIOLITE METAMORPHISM

JUDITH B. MOODY
Department of Geology, University of North Carolina, Chapel Hill, N.C. 27514, U.S.A.

ABSTRACT

Ophiolite metamorphism occurs before, during or after obduction onto the continental margin. Models of submarine hydrothermal alteration for modern ridge-crests have been developed from heat-flow measurements, seismic data and direct sampling of oceanic crust and mantle from DSDP drilled and dredged samples. The heat-flow data require convective heat-transfer to explain the low measured values, thus requiring the development of a fracture system from thermal contraction of the cooling crust and the tensional environment. The hydrothermal activity will persist if the fracture system remains open to accommodate fluid access as the crust ages. We do not know the distribution and depth of oceanic fracture systems away from the ridge crest and transform faults. Extent of metamorphism of the oceanic crust is strongly dependent on: (1) age, (2) crustal thickness, (3) permeability of sediments and crust, (4) fluid-flow parameters, (5) conductive *vs.* convective heat-flow regime, (6) development of major fault and fracture systems, and (7) spreading rate. Metamorphism of the upper part of a continentally emplaced ophiolite could have occurred within the oceanic environment. The difficulty with determining an oceanic provenance from the whole-rock basalt geochemistry is that (1) significant geochemical variations occur for oceanic basalts from different tectonic environments, and (2) major-element chemistry can be significantly affected by metamorphism. Trace-element data have been more successful in demonstrating the oceanic character of ophiolitic basalts. Seawater involvement in their metamorphism has been demonstrated by Li- and Na-enrichment patterns in the metabasalts and stable isotopic measurements on intrusive and extrusive mafic rocks. The presence of sulfide mineralization in dykes and mafic volcanic rocks at Troodos argues for the ability of an oceanic hydrothermal system to produce sulfide deposits. Metamorphism of the ophiolitic ultramafic layer probably occurs after obduction; heat-flow models do not predict penetration of water to oceanic mantle, and in most ophiolite sequences, metamorphism dies out in the gabbro layer. Therefore, unraveling the metamorphic history of an ophiolite is critical to understanding its tectonic evolution.

SOMMAIRE

Le métamorphisme d'un cortège ophiolitique peut précéder, accompagner ou suivre l'obduction sur la plateforme continentale. Pour les milieux sous-marins, les modèles d'altération hydrothermale aux crêtes océaniques sont construits à partir des mesures du flux de chaleur, des données sismiques et d'un échantillonage direct de la croûte et du manteau (carottes DSDP et échantillons dragués). Le flux calorique observé implique un transfert de chaleur par convection, requérant un système de fractures à la crête, par contraction de la croûte au refroidissement et par tensions tectoniques. L'activité hydrothermale persistera tant que le système de fractures reste ouvert aux fluides au cours du vieillissement de la croûte. On ignore la distribution des cassures océaniques et leur profondeur loin de la crête et des failles transformantes. L'étendue du métamorphisme de la croûte océanique dépend fortement des facteurs suivants: (1) âge et (2) épaisseur de la croûte, (3) perméabilité de la croûte et des sédiments, (4) paramètres du flux des fluides, (5) importance relative de la conduction et de la convection, (6) développement de systèmes importants de failles et de fractures et (7) vitesse de séparation des plaques. Les suites ophiolitiques que l'on trouve sur les plaques continentales peuvent avoir été métamorphisées à leur partie supérieure en milieu océanique, mais il est difficile de le prouver à partir du géochimisme global des roches, vu: (1) la grande variation des basaltes en fonction du milieu tectonique et (2) la mobilité des éléments majeurs pendant le métamorphisme. A cet égard, les éléments traces sont plus utiles pour établir le caractère océanique des basaltes ophiolitiques. Le rôle de l'eau de mer dans leur métamorphisme est démontré par un enrichissement en Li et Na et par les isotopes stables des roches intrusives et extrusives. L'enrichissement en S dans les dykes et les coulées mafiques à Troodos montre que les systèmes hydrothermaux océaniques peuvent donner des gisements de sulfures. Le métamorphisme des niveaux ultramafiques suit probablement l'obduction; les modèles de flux de chaleur ne prévoient pas de pénétration de l'eau jusqu'au manteau. Dans la plupart des cas, le métamorphisme disparait dans le niveau gabbroïque. Pour comprendre les événements tectoniques de l'histoire d'une ophiolite, il faut connaître son évolution métamorphique.

(Traduit par la Rédaction)

Introduction

Ophiolites are stratigraphically connected sequences of igneous and sedimentary rocks (Conference Participants 1972) that are usually considered to be part of the oceanic crust (Fig. 1). These rocks are partly to completely metamorphosed (Table 1) and have been tectonically emplaced onto continental crust.

The purpose of this paper is to examine the metamorphism of individual ophiolite sequences to ascertain the relative timing of metamorphism and to establish criteria for recognizing the metamorphic effects on the primary igneous stratigraphy. In the process of doing this, various models of the oceanic crust will be examined to determine whether metamorphism of the oceanic crust could occur *in situ* prior to tectonic emplacement, or whether metamorphism of the obducted oceanic slab occurs during or after tectonic transport. This work will build on the discussion of ophiolite metamorphism summarized by Coleman (1977).

Oceanic Hydrothermal Models

The degree of metamorphism and alteration of oceanic crust has been a topic of considerable recent interest (Francis 1976, Muehlenbachs & Clayton 1976, Stern *et al.* 1976, Cann 1978, Cann & Moore 1978). Approaches have included: (1) experimental work on basalt–seawater interaction (Hajash 1975, 1977, Mottl 1976, Bischoff & Seyfried 1978, Mottl & Holland 1978) and on peridotite–seawater interaction (Seyfried & Dibble 1978), (2) petrographic studies of oceanic metaigneous rocks (Melson & van Andel 1966, Aumento & Loubat 1971, Aumento *et al.* 1971, Miyashiro *et al.* 1971, Bonatti *et al.* 1975, Bonatti & Honnorez 1976, Prinz *et al.* 1976, Scott & Hajash 1976, Humphris & Thompson 1978a, b), and (3) models of circulation patterns of fluids within the oceanic crust (Ribando *et al.* 1976, Rosendahl 1976, Wolery & Sleep 1976, Lister 1977, 1978, Fehn 1978, Sleep & Rosendahl 1979).

Evidence for the presence of hydrothermal circulation in the oceanic environment is derived from: (1) the presence of metalliferous sediments at oceanic ridges (Bostrom *et al.* 1971, Dymond *et al.* 1973, Piper 1973, Francheteau *et al.* 1979) and in the Red-Sea brines (Bischoff 1969, Shanks & Bischoff 1977), (2) heat-flow measurements at ridge crests and flanks (Williams *et al.* 1974, Wolery & Sleep 1976, Anderson & Langseth 1977, Herman *et al.* 1977, Anderson *et al.* 1979), (3) decay in intensity of magnetic remanence away from a ridge axis (Irving 1970), (4) microearthquake swarms at mid-ocean ridges (Sykes 1971), (5) presence of an active hydrothermal system such as at the Galapagos rift (Corliss *et al.* 1977, 1978, Lonsdale 1977, von Herzen *et al.* 1977) and TAG hydrothermal field (Lowell & Rona 1976). The sediment mounds associated with the Galapagos hydrothermal system are inferred to have formed from slow percolation of hydrothermal fluids circulating through the basaltic crust and overlying sediments (Corliss *et al.* 1978), though direct vertical connection between the mounds and the hydrothermal vents has not been shown to occur (Natland *et al.* 1979). Hydrothermally circulating seawater also has been directly observed from the subaerial geothermal fields at Reykjanes, Iceland (Björnsson *et al.* 1972, Mottl *et al.* 1975). Under the assumption that ophiolites are ancient oceanic crust, arguments have been put forth to use the occurrence of massive sulfides within the ophiolite (Parmentier & Spooner 1978, Rona 1978) and whole-rock isotope geochemistry to infer the presence of a former hydrothermal circulation system (Spooner 1978), ostensibly while at or near an oceanic ridge.

Heat-flow models

In his heat-flow model for oceanic ridges, Sleep (1975) postulated that vertical heat-conduction from the ridge axis is a function of spreading rate. Cooling due to conduction (heat generated from magma accreting at ridge axis) is more rapid near a ridge axis with slow spreading-rates because the heat is conducted almost vertically. However, heat-flow measurements indicate that conduction is not the predominant mode of heat transfer in young oceanic crust.

Vertical heat-transfer at the ridge can be accelerated by hydrothermal circulation systems, as they add a connective term to the total heat-dissipation. Williams *et al.* (1974) and Wolery & Sleep (1976) postulated that hydrothermal circulation is responsible for the anomalously low heat-flow observed at ridges. Wolery & Sleep (1976) estimated the rate of hydrothermal heat advection by computing the difference between a theoretical heat-production associated with sea-floor spreading and the observed heat-flow. This calculation leads to the extremely high calculated flow-rate of seawater through the oceanic hydrothermal system of $1.3 - 9.0 \times 10^{17}$ g/y. Wolery & Sleep (1976) postulated that hydrothermal activity would

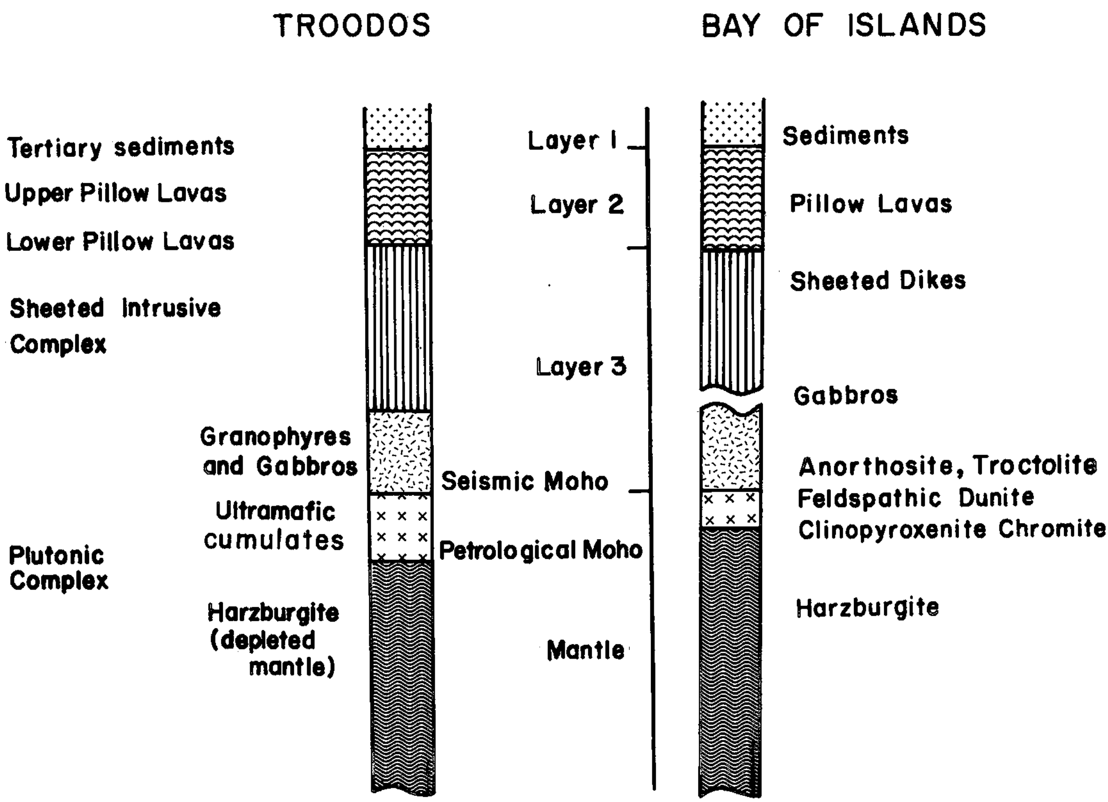

FIG. 1. Stratigraphy of two well-described ophiolite sequences compared to oceanic layer 1, 2, 3 and 4 (mantle).

TABLE 1. ROCKS OF THE CLASSIC OPHIOLITE SEQUENCE

	Unmetamorphosed Rocks	Metamorphic Equivalent
oceanic layer 1	marine sediments	chert
oceanic layer 2	basalt	spilite (keratophyres)**
oceanic layer 3	gabbro*	metagabbro or amphibolite
mantle	ultramafic rock (harzburgite, dunite)	serpentinite (rodingites)**

* sheeted dykes may or may not be present between the intrusive gabbroic layer and the extrusive basalt layer (Fig. 1).
** commonly associated rocks produced during metamorphism.

cease after 15–20 m.y. for fast-spreading ridges and 21–26 m.y. for slow-spreading ridges. These time periods are derived from the convergence of theoretical and observed heat-flow curves; Wolery & Sleep further postulated that after that interval, heat flow should occur purely by conduction. However, Anderson & Langseth (1977) have shown that the transition from predominantly convective to conductive heat-flow in the oceanic crust is highly dependent on the age of the crust and the spreading rate (*e.g.*, 40–60 m.y. for Indian Ocean, 4–6 m.y. for Galapagos spreading-centre, 10–15 m.y. for the East-Pacific rise, 50–70 m.y. on the Mid-Atlantic ridge). This transition is dominated by the development of a certain sediment-thickness ($\geq$ 300 m) and a change in composition from carbonate to siliceous deposition, which effectively decreases the bulk permeability of the sediment cover. Also, hydrothermal flow decreases with time owing to the clogging of fracture systems within the crust by alteration minerals (Sleep & Wolery 1978). Therefore, other physical variables, such as permeability and flow parameters, are also strongly a function of age and spreading rate. By means of very closely spaced heat-flow surveys, Anderson *et al.* (1979) have been able to calculate both the conductive and convective components of heat flow through oceanic crust and sediments (Indian ocean), further substantiating the importance of convective processes in the heat-flow regime of young oceanic crust.

Depth of fluid penetration

Heat-flow models (Lister 1972, 1974, 1977, Ribando *et al.* 1976) have been postulated in which the depth of penetration of water is approximately 5 km, based on the wavelength of the heat-flow variation observed at the Galapagos spreading-centre (Williams *et al.* 1974). Permeability alone limits the access of fluids to about the upper 200–300 m of the oceanic basement (Wolery & Sleep 1976). Therefore, the permeability of the oceanic crust and sediments is not sufficient to explain the heat-flow measurements; most heat-flow models also call upon a fracture system, developed through cooling and static fatigue (Lister 1974), to explain the anomalously low heat-flow values. Widespread porous flow has been shown to be an unlikely mechanism for fluid circulation (Sleep & Wolery 1978).

DSDP drilling results in the Atlantic oceanic crust show a general absence of hydrothermal alteration regardless of crustal age, which led Hall & Robinson (1979) to conclude that the hydrothermal circulation system must occur at depths greater than 600 m and that it is probably irregularly distributed. However, in the Pacific, large fault-scarps about 1 km apart (Williams *et al.* 1974, Rosendahl 1976) dominate the topography and provide zones of high permeability. Also, in DSDP leg 54, Hekinian *et al.* (1977) reported intensely fractured and brecciated oceanic crust on the southern flank of the Galapagos spreading-centre. The development of a fracture system in the oceanic crust is related to the thickness of the basaltic crust, its brittleness (a function of composition) and the spacing of major fault patterns (Rosendahl, pers. comm. 1979).

Fluid penetration obviously determines the depth to which metamorphism can occur. Heat-flow models do not predict penetration to the oceanic mantle. The seismic velocity data (Rosendahl 1976, Fig. 5) and oceanic crustal models generated from those data (Clague & Straley 1977) cannot distinguish between pristine igneous rock in layer 3 and the uppermost mantle (Fig. 1) and metaigneous rocks and

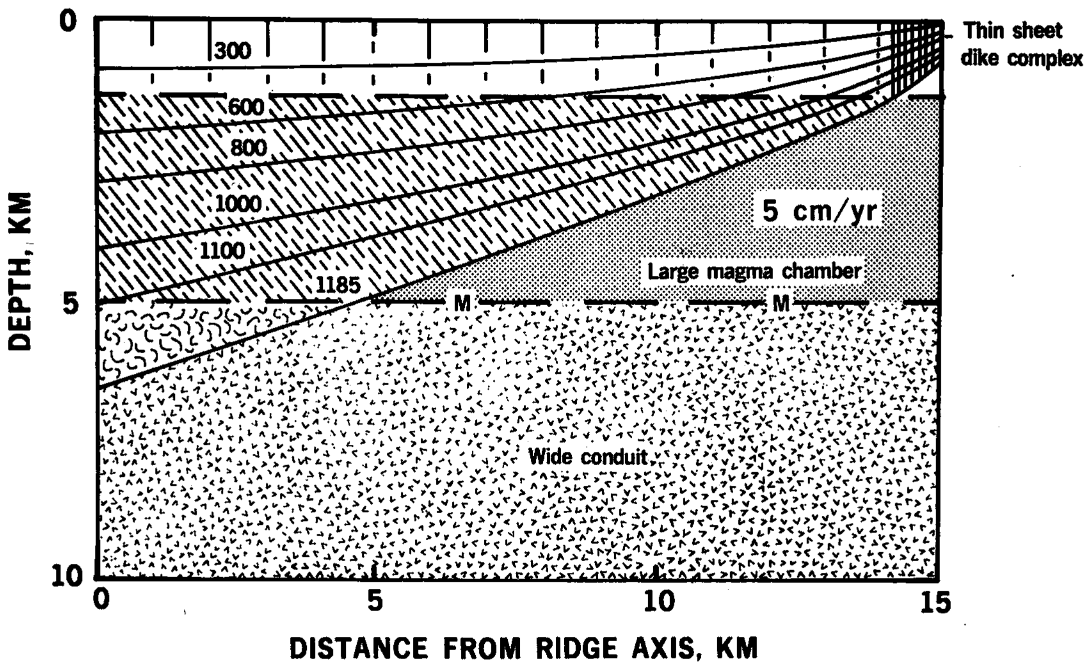

FIG. 2. Ocean-ridge model for a fast-spreading centre from Sleep & Rosendahl (1979). The magma chamber (dots), which is probably filled with cumulate mush, and the conduit of upwelling mantle material (angles) are very wide. The walls of the conduit may consist of cooler material at the sides (half circles) or material segregated from the partial melt. The inner intrusion-zone (dense vertical lines) probably occurs over that part of the magma chamber where melt is usually present. Downwarp of the base of the magma chamber and the density difference between the cooled gabbroic crust (slanted lines) and the magma chamber are possible anomalous masses. The geotherms are calculated assuming conductive heat-transfer only.

serpentinite. Epp & Suyenaga (1978) do not agree with Sleep & Wolery (1978) that hydrothermal precipitation will close the fracture system and stop circulation in the crust older than the heat-flow transition zone (Williams *et al.* 1974). They argued that thermal contraction continues as the crust continues to cool, which allows the fracture system to remain open and to accommodate the volume occupied by the formation of hydrothermal minerals. Thus, fractures would increase in depth with age and therefore would increase the extent of metamorphism with age, perhaps allowing fluid penetration to the mantle. Serpentinites have been dredged from Atlantic oceanic ridges and fracture-zones (Aumento *et al.* 1971, Bonatti & Honnorez 1976). Bonatti & Honnorez (1976), Bonatti (1976), Clague & Straley (1977) and Epp & Suyenaga (1978) proposed diapiric intrusion of serpentinite into fault zones parallel to oceanic ridge-axes, which implicitly assumes that fluid access to the lower crust and mantle occurred through deep fractures produced by the tensional environment at the ridge.

Fast versus slow spreading-rates

The importance of fast *versus* slow spreading has been emphasized not only with respect to heat flow, but also to chemical and stratigraphic differences in the oceanic crust generated (Rosendahl 1976, Lister 1977, Sleep & Rosendahl 1979). Fracture patterns are distinctly different for the two rates of spreading: fast-spreading ridges are marked by axial-block topography and slow-spreading ridges by axial valleys (Rosendahl 1976). The salient structural difference between the two types of oceanic ridge is the presence or absence of deeply penetrating faults; their presence seems to characterize slow-spreading ridges. The difference in the fault patterns between the slow- and fast-spreading ridges can also be inferred from the common occurrence of metaigneous rocks dredged from slow-spreading ridges (Mid-Atlantic ridge) and the absence of metamorphic rocks from fast-spreading ridges (Pacific ocean-basin) (Rosendahl 1976).

Sleep & Rosendahl (1979) presented possible geothermal gradients away from the ridge axis based on evidence that a fast-spreading ridge has a relatively large, wide magma-chamber (Fig. 2), and a slow-spreading ridge has a very narrow magma-chamber (Fig. 3). The slope of the isotherms is much less steep at the fast-

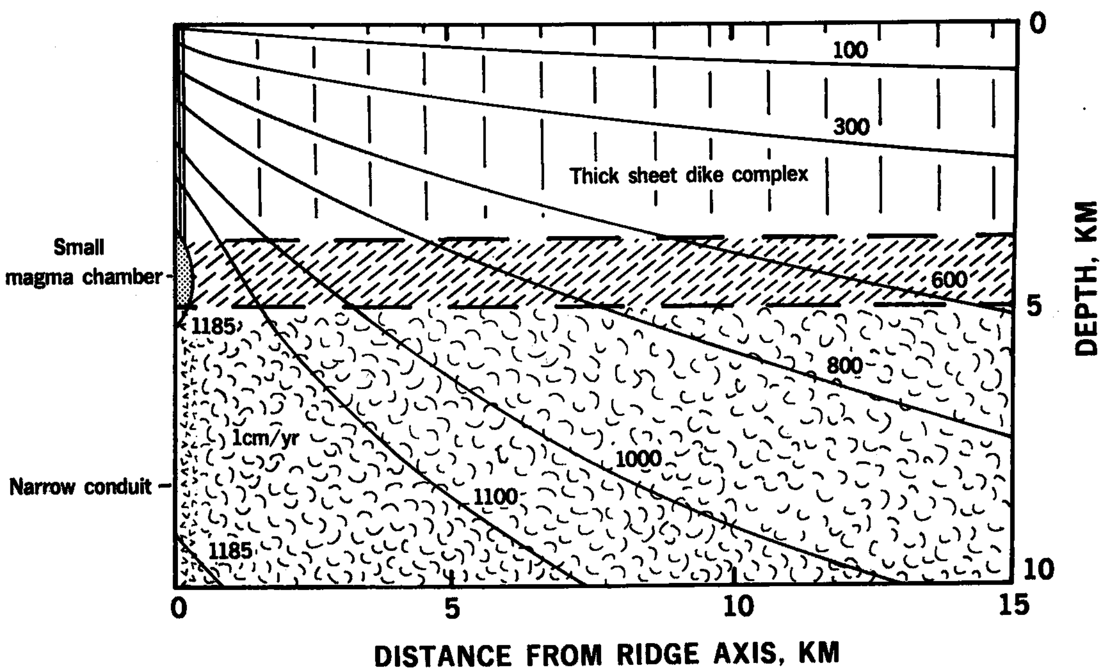

FIG. 3. Ocean-ridge model for slow-spreading centre from Sleep & Rosendahl (1979). Symbols are same as Figure 2. Contrast with fast-spreading centres indicates a very small magma chamber, a thick sheeted-dyke complex, a wide zone of cooler material segregated from melt and a narrower intrusive zone. The geotherms are calculated assuming conductive heat-transfer only.

spreading ridge because of the large magma-chamber and reduced vertical heat-loss by conduction. The Nisbet & Fowler (1978) model for a slow-spreading ridge suggests the absence of a magma chamber and injection of magma by crack propagation. However, the postulated geothermal gradients for both types of spreading centre are high enough to drive a hydrothermal circulation system and to be the cause of metamorphism of the oceanic crust. The presence of a hydrothermal circulation system at the oceanic ridge would significantly alter the geotherms (Figs. 2, 3) as calculated by Sleep & Rosendahl (1979). Parmentier & Spooner (1978) have attempted to model such a convective system, and have demonstrated that the magnitude of the geotherms can decrease significantly as a function of the boundary conditions chosen.

The preceding discussion has shown that oceanic hydrothermal systems exist and that their activity is determined by such factors as: (1) age of oceanic crust, (2) crustal thickness, (3) permeability of sediments and crust, (4) fluid-flow parameters, (5) conductive *versus* convective heat-flow regime, (6) development of major fault- and fracture-systems, and (7) spreading rate. Unfortunately, the extent of oceanic metamorphism, exclusive of fault and fracture zones that allow fluid access, is unknown because of the technical inability to sample deep oceanic crust away from those zones. Therefore, an understanding of oceanic hydrothermal systems is critical to an understanding of the extent of oceanic metamorphism because fluid access to rock determines the extent of metamorphism. Further work is needed on the processes of formation, spacing, depth and frequency of occurrence of fracture systems in the crust, since they are a critical part of the hydrothermal system, both at and away from the oceanic ridge.

TABLE 2. ELEMENTAL MOBILITIES DURING LOW-GRADE METAMORPHISM OF BASALTS

	Experimental[1]	Oceanic Metabasalts[2]	Ophiolitic Metabasalts[3]
SiO_2	-	+ or -	+
TiO_2	-	*	*
Al_2O_3	-	-	* or +
FeO	-	-	-
Fe_2O_3	n.d.	+	+
MnO	-	-	*
MgO	+	+	+, *, -
CaO	-	-	-
Na_2O	+	+	+
K_2O	-	-	+, *
P_2O_5	n.d.	*	+, *, -
H_2O	+	+	+

(-) loss during metamorphism
(+) gain during metamorphism
(*) no change
n.d. not determined

[1]Hajash (1975), Mottl (1976), Mottl & Holland (1978) (low rock/seawater ratios), comparison to unaltered starting-material basalt

[2]Coish (1977), Humphris & Thompson (1978a), comparison to pristine basalts in same petrologic provenance

[3]Coish (1977), Grapes (1976), Menzies et al. (1977), comparison to unaltered basalts in individual ophiolite sequence or an average. for unaltered ophiolitic basalts

OPHIOLITES

The stratigraphic sequence of rocks making up the complete ophiolitic sequence is relatively well defined (Conference Participants 1972). The major problem in correlating ophiolites with oceanic lithosphere is that the oceanic provenance of the ophiolite is uncertain. Various models have been proposed suggesting ophiolites can be correlated with mature oceanic crust and mantle (Gass 1977), marginal-basin type of crust and mantle, or immature oceanic crust, *i.e.*, that from a ridge crest (Rosendahl 1976).

Geochemistry of ophiolitic rocks

Experiments with basalt and seawater (Table 2) show major-element exchange between basalt and fluid. Table 2 also illustrates element changes in oceanic and ophiolitic basalts that have undergone greenschist-facies metamorphism. A good correlation exists between the direction and change of element mobilities between oceanic metabasalts and experimentally derived analogues. The metabasalts of ophiolite suites show the greatest variation in the major-element mobility when compared to the experimentally derived metabasalts and to the oceanic metabasalts.

Experimental work on mineral stabilities and

TABLE 3. COMPARISON OF ELEMENTAL MOBILITIES DURING LOW-GRADE METAMORPHISM OF PERIDOTITE

	Experimental[1]	Oceanic Meta-Peridotite[2]	Ophiolitic Meta-Peridotite[3]
SiO_2	-	*, -	-
TiO_2	n.d.	*, -	*, -
Al_2O_3	n.d.	*, -	-
FeO	n.d.	-	-
Fe_2O_3	n.d.	+	+
FeO_t	-	-	*, -
MnO	-	*	*
MgO	+	+, *	+, *
CaO	+	-	-
Na_2O	-	*, -	*, -
K_2O	*	*	*, -
H_2O^+	+	+	+

(-) loss during metamorphism, (+) gain during metamorphism, (*) no change, n.d. not determined. [1] Seyfried & Dibble (1978); [2] Aumento & Loubat (1971), Prinz et al. (1976); [3] Miyashiro (1966), Moores & Vine (1971), Coleman & Keith (1971), Montigny et al. (1973). Comparison of losses and gains with average peridotite (Nockolds 1954, Green 1967).

TABLE 4. COMPARISON OF DIRECTION OF MAJOR-ELEMENT MOBILITIES FOR METABASALTS AND METAPERIDOTITES FROM DIFFERENT ENVIRONMENTS

	Metabasalts			Metaperidotites		
	Exp/Oc*	Exp/Oph*	Oph/Oc*	Exp/Oc*	Exp/Oph*	Oph/Oc*
SiO_2	d	d	d	d	s	d
TiO_2	d	d	s	nd	nd	s
Al_2O_3	s	d	d	nd	nd	d
FeO	s	s	s	nd	nd	s
Fe_2O_3	nd	nd	s	nd	nd	s
MnO	s	d	d	d	d	s
MgO	s	d	d	d	d	s
CaO	s	s	s	d	d	s
Na_2O	s	s	s	d	d	s
K_2O	s	d	d	s	d	d
H_2O	s	s	s	s	s	s

Exp = experimental results, Oc = oceanic rocks, Oph = Ophiolitic rocks, s = same, d = different, nd = not determined

* from Tables 2 and 3

metamorphism of ultramafic rocks (Chernosky 1975, Moody 1976a, b, Seyfried & Dibble 1978) documents some major compositional changes during serpentinization, involving seawater under greenschist-facies conditions (Table 3). These changes chiefly involve an addition of magnesium and water and a loss in total iron, SiO_2, Al_2O_3 and FeO.

Tables 2 and 3 show the direction of major-element mobilities for metamorphic rocks of the oceanic crust and ophiolite suites. The experimental results presented are for basalt and peridotite reacted with seawater under greenschist-facies conditions. Comparisons of the direction of element mobility for metamorphic rocks from different environments are presented in Table 4. Similar patterns of element mobilities between ophiolitic and oceanic rocks could indicate similar metamorphic conditions (*e.g.*, in ophiolitic and oceanic metaperidotites). A comparison of the rock–seawater experiments and the element-mobility patterns in metamorphic rocks might indicate seawater involvement in metamorphism (*e.g.*, experimental and oceanic metabasalts). However, Table 4 indicates the difficulty in trying to use the major-element geochemistry to determine the time and place of metamorphism, as the correlation between the three different groups, except for the two examples given above, is inconclusive.

The degree of element mobility during metamorphism largely determines the relevance of geochemical studies performed on ophiolitic rocks. Whole-rock chemistry of basalts has been used to demonstrate that ophiolites are related to oceanic crust. For example, Miyashiro (1973, 1975a, b) has used major-element chemistry to suggest that the Troodos ophiolite was formed in an island-arc environment. However, his claim has been refuted by Gass *et al.* (1975), Hynes (1975), Moores (1975) and Church & Coish (1976). Some of the disagreement between Miyashiro (1975a, b) and the other workers results from Miyashiro's (1975c) contention that element mobility during metamorphism is minor. The difficulty in using major-element data to support arguments of tectonic environment is shown in Tables 2 and 3. These tables clearly illustrate significant major-element changes during low-grade metamorphism of both basalts and ultramafic rocks in ophiolite sequences; thus, care must be exercised in an extrapolation from major-element chemistry to the tectonic setting of the igneous rocks. The weight of evidence for the Troodos would favor an oceanic origin of the basalts, but not chiefly on the basis of the whole-rock chemistry. Therefore, Miyashiro's arguments based on major-element chemistry of the basalt are not very convincing evidence of an island-arc origin for the Troodos complex.

Miyashiro (1975a) has also used whole-rock chemistry to classify ophiolites into three different groups based on the inferred presence of calc–alkaline or tholeiitic trends as shown by the basalts of ophiolitic sequences. However, Pearce & Gale (1977) and Sun & Nesbitt (1978) suggested, as did Miyashiro (1975a, b, c), that some real geochemical variation exists among oceanic basalts from the different tectonic environments within oceanic lithosphere (*e.g.*, oceanic ridge-crest *versus* island arc *versus* back-arc basin). Therefore, the petrological origin of ophiolitic basalts is further complicated not only by metamorphism, but also by real geochemical differences reflecting tectonic environments.

The direction of element mobility for the metamorphosed oceanic *versus* ophiolitic ultramafic rocks is the same except for SiO_2, Al_2O_3 and K_2O (Table 4). However, the preliminary results of peridotite–seawater experiments (Seyfried & Dibble 1978) conflict with the geochemistry of metamorphic rocks, especially with respect to CaO. Calcium is lost from ultramafic rocks during metamorphism in both oceanic and ophiolitic rocks, and the leached calcium is deposited in the rocks associated with serpentinites, *e.g.*, rodingites (Barnes & O'Neil 1969, Barnes *et al.* 1972, 1978, Coleman 1977, Pfeifer 1977, Wenner 1979). Honnorez & Kirst (1975) described rodingites dredged from the Mid-Atlantic-ridge fracture zones; these formed by the alteration of a noritic gabbro. The element-mobility data support the formation of rodingites by fluids involved in the metamorphism of ultramafic rocks. CaO is also shown to be lost during metamorphism of basalts.

Tables 2 and 4 indicate that Na-enriched metabasalts (*i.e.*, spilites) can form from the interaction of seawater with basalt. Both oceanic and ophiolitic metabasalts demonstrate an enrichment in sodium, which agrees with the experimental data on basalt-seawater interaction. A comparison of the direction of mobility for the other elements in the experimentally derived metabasalts with the direction of those in the oceanic metabasalts demonstrates very good to excellent agreement. A comparison of oceanic and ophiolitic metabasalts shows a much greater variation in patterns of element mobility.

Further evidence for seawater involvement in the formation of spilites could be inferred from the data of Shaw *et al.* (1977). Enriched in sodium and water, spilites are also enriched six-fold in Li compared to the unmetamorphosed basalt. Seawater, brines and volcanic waters are obvious choices for the Li- and Na-enrichment in the spilites.

The data in Tables 2 and 4 indicate that the metamorphism of basaltic rocks could occur in the oceanic crust. Also, the wider variability in the major-element-mobility data for ophiolitic metabasalts may indicate the effects of more than one metamorphic event, with involvement of a fluid other than seawater. The data for the ultramafic rocks (Tables 3, 4) are inconclusive.

Pearce & Cann (1971) used the Ti, Zr and Y contents of four different ophiolitic basalts to demonstrate that the volcanic rocks have ocean-floor provenance. Smewing *et al.* (1975) argued that the major- and trace-element contents of Troodos metabasalts are significantly different from those formed at present-day constructive plate-margins, and proposed an origin at a slow-spreading ridge within a small, marginal ocean-basin. Coish (1977) asserted that metamorphism had little effect on TiO_2, P_2O_5, Zr, Y, Cr or Ni contents of metabasalts from the Betts Cove ophiolite, Newfoundland, and proposed an ocean-floor origin for the basalts. Beccaluva *et al.* (1977) determined 12 different trace-element contents for the rocks within the ophiolitic sequence from eastern Corsica and concluded that the ophiolitic metabasalts showed an ocean-floor affinity.

Rare-earth-element (*REE*) data from ophiolitic rocks are sparse; rocks from the Pindos suite, Greece (Montigny *et al.* 1973), the Troodos complex, Cyprus (Kay & Senechal

TABLE 5. GEOCHEMICAL CRITERIA USED BY BLAND (1978) TO DETERMINE THE ORIGINAL CHARACTER OF APPALACHIAN METABASALTS

Chemical Discriminator	Rock Types Distinguished	Reference
12-20 wt.% CaO + MgO*	selects rocks of similar tectonic affinities &	Pearce & Cann (1973)
>20% CaO + MgO*	eliminates ultramafic cumulates	Pearce (1976)
alkalies K_2O & Na_2O/K_2O ratio	OFB & RA from (LKT, CAB, SHO, OI)	Jakes & White (1972) Rogers et al. (1974)
F_1-F_2 discriminate function	WPB, SHO, OFB, (LKT & CAB)	Pearce (1976)
F_2-F_3 discriminate function	SHO, LKT, CAB, OFB	Pearce (1976)
Ti vs. Zr, ppm**	OFB, CAB, LKT	Pearce & Cann (1973)
Zr vs. Ti/100 vs. (3)Y, ppm	WPB, CAB, LKT, and OFB + CAB + LKT	Pearce & Cann (1973)
CaO wt % vs. Y, ppm	LKT & SHO plot to left of SCAT; OI, CON, OFB plot to right of SCAT; CAB plot within SCAT	Lambert & Holland (1974)

* coupled with TiO_2 content
** coupled with CaO + MgO content

SYMBOLS:
OFB = ocean-floor basalts
LKT = low-potassium tholeiites
CAB = calc-alkaline basalts
SHO = shoshonites
OI = oceanic-island basalts
CON = continental-rifting basalts
RA = rear-arc basalts
WPB = within-plate basalts
SCAT = standard calc-alkaline trend

1976, Smewing & Potts 1976) and the Point Sal ophiolite, California (Menzies *et al.* 1977) have been examined. Unfortunately, total agreement on the effect of metamorphism on the primary basalt-*REE* distributions is not evident. Menzies *et al.* (1977) summarized evidence that indicates light-*REE* mobility during zeolite-facies metamorphism of ophiolitic basalts. This mobility results in an increase in the total concentration of *REE* and a change in the profile characteristics due to Ce or La mobility. At the same time, greenschist-facies metamorphism has not changed the *REE* patterns of the primary basaltic lavas of ophiolite complexes (*e.g.*, Point Sal ophiolite). Conversely, Montigny *et al.* (1973), Kay & Senechal (1976), Smewing & Potts (1976), Coish & Church (1978) present evidence that *REE* abundances of ophiolitic basalts were not modified by metamorphism for the Pindos, Troodos and Betts Cove complexes. Clearly, more *REE* data are needed for the total stratigraphy of an ophiolite sequence before the question of *REE* mobility during metamorphism can be resolved.

A combination of major- and trace-element data is more convincing in demonstrating an ocean-floor origin for the ophiolitic metabasalts. Bland (1978) has confirmed that the tectonic origin of a metabasalt can be determined, but that more than one geochemical test must be applied in order to see through the metamorphic overprint. Table 5 summarizes the different criteria used by Bland (1978) to determine the tectonic setting of many different ages of the metabasalts in the Appalachian Blue Ridge and Piedmont. A more definitive statement about the origin of the ophiolite basalts could be made if a complete geochemical study were done on these rocks, similar to Bland's (1978), using a statistically significant sample size. Pearce & Gale (1977) have used a combination of whole-rock chemistry, trace-element and REE data of metabasalts to classify the tectonic environment (oceanic) asso-

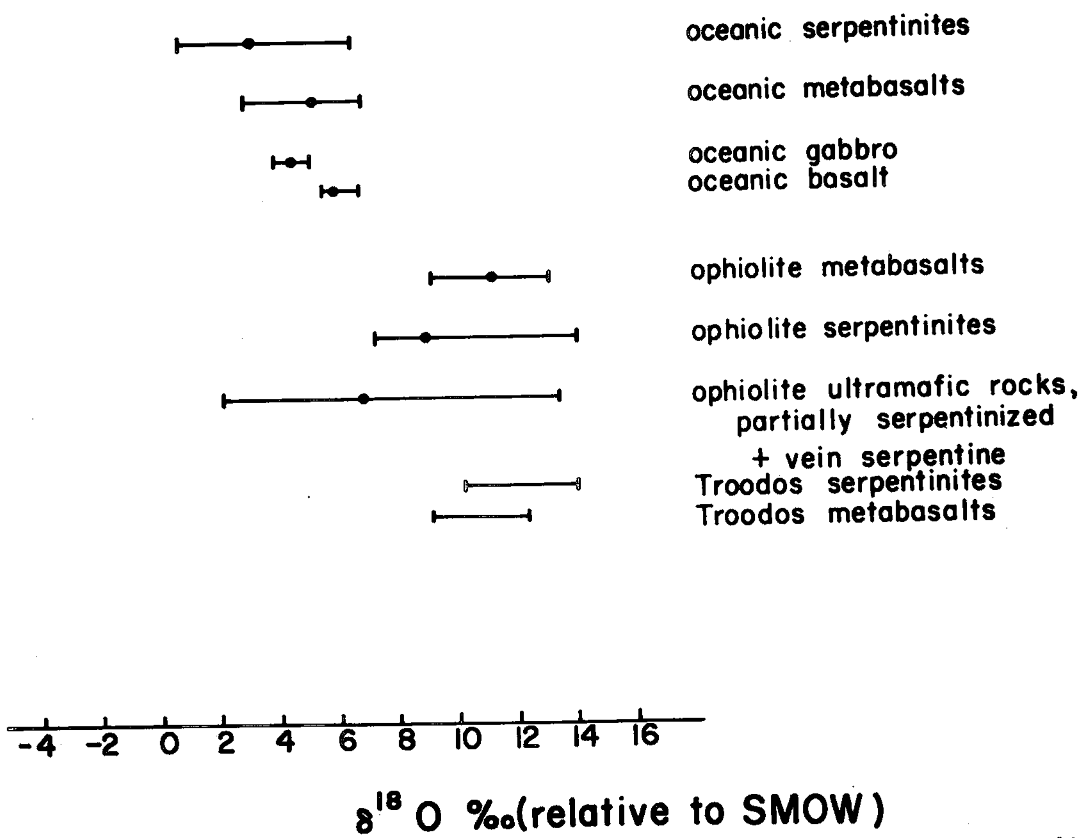

FIG. 4. Summary of whole-rock oxygen-isotope data obtained from Spooner *et al.* (1973, 1977a, b), Wenner & Taylor (1973), Magaritz & Taylor (1974).

ciated with the formation of massive-sulfide deposits related to ophiolites.

Oxygen-isotope data have been used to indicate the type of water involved in metamorphism as well as the temperature of metamorphism. Spooner *et al.* (1974, 1977a) argued for seawater involvement in the metamorphism of eastern Liguria, Pindos and Troodos ophiolitic basalts. However, Figure 4 shows that the ophiolitic metamorphic rocks are more enriched in $\delta^{18}O$ compared with the oceanic rocks. Some overlap is present in the data, especially for the partly serpentinized ultramafic rocks. However, these oxygen-isotope data alone do not necessarily provide conclusive evidence for seawater involvement.

Sheppard (1977) and Heaton & Sheppard (1977) presented both $\delta^{18}O$ and δD isotopic data for the metamorphosed Troodos pillow-lavas, sheeted intrusive complex, trondhjemites and upper gabbro. The δD values for Troodos rocks overlap with the few available measurements of oceanic metamorphic rocks. Mineral data are combined with whole-rock values to calculate models for δD and $\delta^{18}O$ fractionation assuming equilibrium, with the isotopic differences reflecting different temperatures (*i.e.*, different metamorphic grades. Heaton & Sheppard (1977) concluded that a large component of seawater was involved in the metamorphism of Troodos rocks.

Wenner & Taylor (1973) and Magaritz & Taylor (1974) documented a marked difference between oceanic and continental ophiolitic serpentinites on the basis of both oxygen- and hydrogen-istotope compositions. They argued against a seawater origin of the water involved in the metamorphism of the ophiolitic ultramafic rocks.

Recent measurements by Sakai & Tsutsumi (1978) of serpentine–water D/H fractionations between 100–500°C at 2 kbar suggest that deuterium exchange, in particular, may be controlled by nonequilibrium processes. The experimentally derived D/H fractionation factors indicate that a mixed fluid containing 50–75% magmatic water and temperatures higher than 300°C were involved in the formation of oceanic lizardite–chrysotile serpentinites; this result is not in agreement with previous work (Wenner & Taylor 1973). Sakai's & Tsutsumi's (1978) work illustrates the difficulty in using whole-rock isotopic analyses to determine the nature of the fluid involved in metamorphism or alteration if equilibrium isotopic fractionations are assumed.

The model of Spooner & Fyfe (1973) and Spooner *et al.* (1977a) for hydrothermal metamorphism of ophiolite metabasalts from eastern Liguria, Italy, is based on oxygen-isotope data, water contents and $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ ratios of the rocks. The metamorphic mineral assemblages indicate that temperature increased with depth in the basaltic lavas. The $\delta^{18}O$ values decrease with depth but do not reach the $\delta^{18}O$ composition of primary basalt. The $\delta^{18}O$ profile was assumed to be controlled by the temperature gradient. Different oxygen-isotope values and oxidation ratios were measured for cores *versus* rims of metabasalt pillows, indicating that isotopic and chemical equilibrium was not achieved during metamorphism. Spooner *et al.* (1977a) combined the oxygen-isotope data with the oxidation ratio $Fe^{3+}/(Fe^{2+}+Fe^{3+})$ to calculate the amount of water involved in the alteration of the basalt (10^3–10^4 : 1 water:rock ratio). Their calculations assume that the fluid involved in the alteration was seawater.

Measurements of $^{87}Sr/^{86}Sr$ ratios in the Troodos mineralized and metamorphosed dykes and mafic volcanic rocks (Chapman & Spooner 1977, Spooner *et al.* 1977b) yield values enriched in ^{87}Sr relative to fresh oceanic basalts. These authors suggested that seawater was the ore-forming fluid for the sulfide ore-deposits of the Troodos complex, a hypothesis substantiated by fluid-inclusion data from vein quartz coexisting with the sulfides (Spooner & Bray 1977). They gave the occurrence of the deposits as further evidence of a major oceanic hydrothermal-circulation system within the basalts.

Spooner & Fyfe (1973), Andrews & Fyfe (1976), Coleman (1977) and Rona (1978) have documented the evidence for hydrothermal systems at spreading centres with regard to seawater leaching of the basaltic oceanic crust to derive the metals for the massive sulfides of ophiolitic complexes. Spooner (1977) and Parmentier & Spooner (1978) have developed a model for Cyprus deposits, where a strong case can be made for the location of the sulfide deposits within the metabasalt layer as a result of oceanic hydrothermal circulation. A total geochemical study of ophiolite metabasalts associated with massive sulfides in Cyprus, Oman and Betts Cove has led Pearce & Gale (1977) to postulate that the basalts formed at a spreading axis in an oceanic back-arc basin rather than at a major oceanic ridge-crest. Unfortunately, the subsequent metamorphism and deformation of the ophiolitic metabasalts of the Whalesback cupriferous iron deposit, Newfoundland, do not permit the relationship between

TABLE 6. TYPICAL MINERALOGY OF OPHIOLITIC METABASALTS* AND METAPERIDOTITES*

Spilites:	chlorite, epidote, albite, actinolite ± sphene, zeolites, calcite
Serpentinites:	lizardite, chrysotile, magnetite ± brucite, antigorite

* Essential metamorphic mineralogy of oceanic meta-igneous rocks and continental ophiolitic rocks is same.

sulfide mineralization and sub-sea-floor metamorphism to be determined (Bachinski 1977).

Metamorphic mineralogy

As shown previously (Table 1), metaigneous rocks similar to those in ophiolite suites have been recovered in dredge samples from oceanic ridges and fracture zones. Table 6 summarizes the essential mineralogy of serpentinites and spilites (layers 2 and 4 in the stratigraphy of the ophiolite sequences). The metamorphic mineralogy is not very helpful in contrasting the oceanic *versus* continental ophiolitic environment – they are the same. The interesting problem is that both the serpentinites and spilites (Na-enriched metabasalts) can undergo metamorphism in the same range of temperature–pressure conditions (Moody 1976a, b, Moody & Meyer 1978, Meyer 1978). If that setting is defined in terms of zeolite- and greenschist-facies metamorphism, then the distinction between the timing of metamorphism and occurrence of serpentinites and spilites together in the ophiolite sequence can be made.

Many models of sub-sea-floor metamorphism (Spooner & Fyfe 1973, Bonatti *et al.* 1975, Coleman 1977, Elthon & Stern 1978, Humphris & Thompson 1978a, b) indicate increasing metamorphic grade with increasing depth. Oceanic metamorphism is depicted in these models as dying out in the gabbroic layer at conditions of upper-greenschist or amphibolite metamorphic facies.

Ophiolitic rocks that show this increasing grade of metamorphism down through the ophiolite sequence, from sediments to extrusive and then to intrusive mafic rocks (Fig. 1) are found in (1) eastern Liguria, Italy (Spooner *et al.* 1974, 1977a), (2) the Sarmiento complex, Chile (Elthon & Stern 1978), (3) the Chenaillet massif, France (Mevel *et al.* 1978), (4) Darvel Bay, Borneo (Hutchison 1978). Table 7 summarizes the best described of the known ophiolite sequences with respect to metamorphism. The difficulty in preparing the table was that information on the metamorphism of the total stratigraphic sequence is generally unavailable. Those ophiolites that give evidence for a possible oceanic episode of metamorphism reach upper-greenschist facies, although Mevel *et al.* (1978) described amphibolite-facies metamorphism in an ophiolite gabbroic layer. Amphibolites formed from metamorphism of the intrusive mafic layer have been observed in the oceanic environment (Table 1). These amphibolites are not to be confused with those produced at the base of the ophiolite in a metamorphic aureole that is clearly related to its tectonic emplacement (Dewey & Bird 1971, Jamieson 1979, McCaig & Kemp 1979).

TABLE 7. METAMORPHIC HISTORY OF OPHIOLITES*

Degree of metamorphism	Examples
Metamorphism in oceanic crust down to gabbro layer only; serpentinization during or after tectonic emplacement	Vourinos, Northern Greece Macquarie Island Bay of Islands, Newfoundland Blow-Me-Down, Newfoundland Betts Cove, Newfoundland Troodos, Cyprus Sarmiento complex, Chile[1] Point Sal, California[2] Semail, Oman Papua-New Guinea Chenaillet, France[3] E. Liguria, Italy[4] Darvel Bay, Borneo[5]
Polymetamorphism before and after emplacement, including regional metamorphism	Dunn Mtn., New Zealand[6] Southern Québec[7] Eastern Taiwan[8] Karmoy, Norway[9]

* newly published information modifies and adds to the original compilation of Christensen & Salisbury (1975). [1]Elthon & Stern (1978), [2]Menzies et al. (1977), [3]Mevel et al. (1978), [4]Spooner et al. (1974, 1977a), [5]Hutchison (1978), [6]Coombs et al. (1976), [7]Laurent (1975a, b), Laurent & Hébert (1978), Laurent et al. (1978), [8]Liou & Ernst (1979), [9]Sturt et al. (1979).

Most ophiolitic serpentinites are composed of lizardite–chrysotile rather than antigorite (Wenner & Taylor 1973, Magaritz & Taylor 1974, Wicks & Whittaker 1977, Prichard 1979), indicating a lower temperature of metamorphism than the antigorite field of stability (Moody 1976a, Evans 1977). However, Liou & Ernst (1979) reported antigorite in ultramafic rocks of the East-Taiwan ophiolite, and other upper-greenschist-facies minerals from the metabasalts. Clearly, depth of penetration of circulating ocean waters is important, as are metamorphic pressure–temperature conditions. In the case of most ophiolitic ultramafic rocks, amphibolite-facies metamorphism is too high a grade of metamorphism to have taken place in oceanic environments.

Amphibolite-grade oceanic metamorphism of ultramafic rocks is uncommon; Bonatti *et al.* (1970) have described anthophyllite and cummingtonite in a dunite. In fact, prograde metamorphism of serpentinite with formation of "metamorphic" olivines has been postulated to occur at the greenschist–amphibolite boundary (Vance & Dungan 1977, Dungan 1977) with the coexistence of antigorite and olivine. Johannes (1975) & Evans *et al.* (1976) determined the equilibrium breakdown of antigorite to forsterite + talc to occur at approximately 500°C at 2 kbar total pressure. Prograde metamorphism of a serpentinite to the amphibolite facies would produce the mineral assemblage forsterite + talc ± tremolite (Vance & Dungan 1977, Evans 1977), not the common metamorphic assemblage found in metamorphosed ophiolitic ultramafic rocks (Table 6). Therefore, the presence of an amphibolite-facies metamorphic assemblage in the ultramafic layer of an ophiolite probably indicates a prograde regional metamorphism of the ophiolite after emplacement of the ophiolite on the continent.

Metamorphic Models for Ophiolites

The discussion presented in the two previous sections indicates that ophiolitic basalts have an oceanic character. Metamorphism of layer 1, layer 2 and part of layer 3 (Fig. 1) probably occurs in the oceanic crust before tectonic emplacement of the ophiolite, whereas metamorphism of the lower part of layer 3 and all of layer 4 occurs during or after emplacement (Moody 1978). Detailed models of hydrothermal circulation systems at mid-oceanic ridges are in the process of being evaluated by geophysicists, geologists and petrologists. More information is needed before an internally consistent model for both fast- and slow-spreading ridges can be developed. The extent of metamorphism at the ridge crest, and as a function of age of the oceanic crust, is still unknown. The major consensus (Tables 7, 8) from the studies of both oceanic and ophiolitic rocks is that metamorphism of the ophiolitic sequence can occur within layers 1 and 2 but ceases at various different levels in layer 3 (gabbro, Fig. 1). The cessation of metamorphism in layer 3 is directly related to the limit of fluid penetration into the oceanic crust, which is unknown except for oceanic ridge-crests and transform faults. As further information about fluid penetration away from crests and faults is unlikely to emerge because of drilling limitations, quantitative modeling of the cooling, contracting crust will be required to shed light on the major oceanic–fracture systems away from the ridge crests.

Evidence gathered to date strongly suggests that serpentinization of the ultramafic layer occurs after and not before emplacement of the ophiolite. Certainly, the physical properties of peridotite *versus* serpentinite (Moody 1976a) are sufficiently different during deformation to suggest this (*i.e.*, the tectonic emplacement of a serpentinite would take place with the production of a mélange and complete disruption of the serpentine layer). Mélange production on a large scale has been described for subduction-zone ophiolites (Coleman 1977) but is not a widespread feature of other ophiolites. Therefore, tectonic-emplacement models point to the ophiolite metamorphism of the lower layers 3 and 4 occurring during or after emplacement, not before. The tectonic emplacement of some ophiolites (*e.g.*, at Bay of Islands and Semail) is marked at their bases by metamorphic aureoles of medium- to high-grade rocks including mylonites.

TABLE 8. SCHEME OF METAMORPHISM FOR OPHIOLITES*

Ophiolite Rocks	Oceanic Metamorphism	Obduction	Regional**
Marine Sediment	Zeolite	No metamorphism, or metamorphism in oceanic environment before tectonic transport	Zeolite
Basalt	Zeolite-greenschist (spilites)		Zeolite-greenschist
Diabase	Greenschist		Greenschist
Gabbro	Greenschist-amphibolite		Greenschist-amphibolite
Peridotite	Unmetamorphosed, except local serpentinization along fracture zones ± rodingites associated with serpentinites	± contact metamorphic aureole mélange, mylonites, serpentinization ± rodingites	Serpentinization, possible prograde metamorphism of serpentine
Conditions of Metamorphism	No deformation	Deformation at base of ophiolite slab with development of foliation there	Development of penetrative foliation

* modified from Coleman (1977)

** multiple stages of metamorphism possible, superposition of oceanic with continental regional metamorphism, including simple burial metamorphism without development of penetrative deformation.

Element mobilities during metamorphism are significant. Care must be exercised in reconstructing parent igneous rocks from their supposed metamorphic progeny. Several lines of geochemical and petrographic evidence must be assessed before definite conclusions can be reached about the parent igneous rock and its origin.

The metamorphic history of an ophiolite is an integral part of its geological history. Critical to an understanding of this metamorphism is the ability to decipher the geological events undergone by the ophiolite after emplacement on the continent, its emplacement history and then its possible oceanic provenance. It is safe to say that the unique importance of ophiolites in the understanding of global tectonic processes, coupled with the difficulty in unraveling their histories, will assure them a continuing central position in plate-tectonic studies in the foreseeable future.

Acknowledgements

This work was supported by National Science Foundation grant EAR75-21846. The author appreciates the opportunity provided by F. J. Wicks to investigate this interesting topic. Bruce Rosendahl provided stimulating discussion and help at various stages of manuscript preparation. I am deeply grateful to T. R. Worsley who gave critical support, provided discussion, and reviewed the manuscript.

References

ANDERSON, R.N., HOBART, M. A. & LANGSETH, M.G. (1979): Geothermal convection through oceanic crust and sediments in the Indian ocean. *Science* 204, 828-832.

——— & LANGSETH, M.G. (1977): The mechanisms of heat transfer through the floor of the Indian ocean. *J. Geophys. Res.* 82, 3391-3409.

ANDREWS, A.J. & FYFE, W.S. (1976): Metamorphism and massive sulphide generation in oceanic crust. *Geosci. Can.* 3, 84-94.

AUMENTO, F., LONCAREVIC, B.D. & ROSS, D.I. (1971): IV. Regional Studies. Hudson geotraverse: geology of the mid-Atlantic ridge at 45°N. *R. Soc. Lond. Phil. Trans.* A268, 623-650.

——— & LOUBAT, H. (1971): The mid-Atlantic ridge near 45°N. XVI. Serpentinized ultramafic intrusion. *Can. J. Earth Sci.* 8, 631-663.

BACHISKI, D.J. (1977): Alteration associated with metamorphosed ophiolitic cupriferous iron sulfide deposits: Whalesback mine, Notre Dame Bay, Newfoundland. *Mineral. Deposita* 12, 48-63.

BARNES, I. & O'NEIL, J.R. (1969): The relationship between fluids in some fresh alpine-type ultramafics and possible modern serpentinization, western United States. *Geol. Soc. Amer. Bull.* 80, 1947-1960.

———, ——— & TRESCASES, J.J. (1978): Present day serpentinization in New Caledonia, Oman and Yugoslavia. *Geochim. Cosmochim. Acta* 42, 144-145.

———, RAPP, J.B. & O'NEIL, J.R. (1972): Metamorphic assemblages and the direction of flow of metamorphic fluids in four instances of serpentinization. *Contr. Mineral. Petrology* 35, 263-276.

BECCALUVA, L., OHNENSTETTER, D., OHNENSTETTER, M. & VENTURELLI, G. (1977): The trace element geochemistry of Corsican ophiolites. *Contr. Mineral. Petrology* 64, 11-31.

BISCHOFF, J.L. (1969): Red Sea geothermal brine deposits: their mineralogy, chemistry and genesis. *In* Hot Brines and Recent Heavy Metal Deposits in the Red Sea (E. T. Degens & D. A. Ross, eds.), Springer-Verlag, New York.

——— & SEYFRIED, W.E. (1978): Hydrothermal chemistry of seawater from 25° to 350°C. *Amer. J. Sci.* 278, 838-860.

BJÖRNSSON, S., ARNÓRSSON, S. & TOMASSON, J. (1972): Economic evaluation of Reykjanes thermal brine area, Iceland. *Amer. Assoc. Petrol. Geol. Bull.* 56, 2380-2391.

BLAND, A.E. (1978): *Trace Element Geochemistry of Volcanic Sequences of Maryland, Virginia, and North Carolina and its Bearing on the Tectonic Evolution of the Central Appalachians.* Ph.D. thesis, Univ. Kentucky, Lexington, Ky.

BONATTI, E. (1976): Serpentinite protrusions in the oceanic crust. *Earth Planet. Sci. Lett.* 32, 107-113.

——— & HONNOREZ, J. (1976): Sections of the earth's crust in the equatorial Atlantic. *J. Geophys. Res.* 81, 4104-4116.

———, ——— & FERRARA, G. (1970): Equatorial mid-Atlantic ridge: petrologic and Sr isotopic evidence for an alpine-type rock assemblage. *Earth Planet. Sci. Lett.* 9, 247-256.

———, ———, KIRST, P. & RADICATI, F. (1975): Metagabbros from the mid-Atlantic ridge at 6°N: contact-hydrothermal-dynamic metamorphism beneath the axial valley. *J. Geol.* 83, 61-78.

BOSTRÖM, K., FARQUHARSON, B. & EYL, W. (1971): Submarine hot springs as a source of active ridge sediments. *Chem. Geol.* 10, 189-203.

CANN, J.R. (1978): Metamorphism in oceanic crust. *2nd Ewing Symp. Abstr. Program,* 8-9.

——— & MOORE, D.G. (1978): Oceanic basement probed. *Geotimes* 23, 17-19.

CHAPMAN, H.J. & SPOONER, E.T.C. (1977): ^{87}Sr enrichment of the ophiolitic sulphide deposits in Cyprus confirms ore formation by circulating seawater. *Earth Planet. Sci. Lett.* 35, 71-78.

CHERNOSKY, J.V., JR. (1975): Aggregate refractive indices and unit cell parameters of synthetic serpentine in the system $MgO–Al_2O_3–SiO_2–H_2O$. *Amer. Mineral.* **60**, 200-208.

CHRISTENSEN, N.I. & SALISBURY, M.H. (1975): Structure and constitution of the lower oceanic crust. *Rev. Geophys. Space Phys.* **13**, 57-86.

CHURCH, W.R. & COISH, R.A. (1976): Oceanic versus island arc origin of ophiolites. *Earth Planet. Sci. Lett.* **31**, 8-14.

CLAGUE, D.A. & STRALEY, P.F. (1977): Petrologic nature of the oceanic Moho. *Geology* **5**, 133-136.

COISH, R.A. (1977): Ocean floor metamorphism in the Betts Cove ophiolite, Newfoundland. *Contr. Mineral. Petrology* **60**, 255-270.

——— & CHURCH, W.R. (1978): The Betts Cove ophiolite, Newfoundland: some unusual chemical characteristics. *Amer. Geophys. Union Trans.* **59**, 408 (Abstr.).

COLEMAN, R.G. (1977): *Ophiolites: Ancient Oceanic Lithosphere?* Springer-Verlag, New York.

——— & KEITH, T.E. (1971): A chemical study of serpentinization – Burro Mountain, California. *J. Petrology* **12**, 311-328.

CONFERENCE PARTICIPANTS (1972): Ophiolites. *Geotimes* **17**, 24-25.

COOMBS, D.S., LANDIS, C.A., NORRIS, R.J., SINTON, J.M., BORNS, D.J. & CRAW, D. (1976): The Dun Mountain ophiolite belt, New Zealand, its tectonic setting, constitution and origin, with special reference to the southern portion. *Amer. J. Sci.* **276**, 561-603.

CORLISS, J.B., DYMOND, J., LYLE, M., COBLER, R., WILLIAMS, D., VON HERZEN, R. & VAN ANDEL, T. (1977): Observations of the sediment mounds of the Galapagos rift during the Alvin diving program. *Geol. Soc. Amer. Program Abstr.* **9**, 937.

———, LYLE, M., DYMOND, J. & CRANE, K. (1978): The chemistry of hydrothermal mounds near the Galapagos rift. *Earth Planet. Sci. Lett.* **40**, 12-24.

DEWEY, J.F. & BIRD, J.M. (1971): Origin and emplacement of the ophiolite suite: Appalachian ophiolites in Newfoundland. *J. Geophys. Res.* **76**, 3179-3206.

DUNGAN, M.A. (1977): Metastability in serpentine–olivine equilibria. *Amer. Mineral.* **62**, 1018-1029.

DYMOND, J., CORLISS, J.B., HEATH, G.R., FIELD, C.W., DASCH, E.J. & VEEH, H.H. (1973): Origin of metalliferous sediments from the Pacific Ocean. *Geol. Soc. Amer. Bull.* **84**, 3355-3372.

ELTHON, D. & STERN, C. (1978): Metamorphic petrology of the Sarmiento ophiolite complex, Chile. *Geology* **6**, 464-468.

EPP, D. & SUYENAGA, W. (1978): Thermal contraction and alteration of the oceanic crust. *Geology* **6**, 726-728.

EVANS, B.W. (1977): Metamorphism of alpine peridotite and serpentinite. *Ann. Rev. Earth Planet. Sci.* **5**, 397-447.

———, JOHANNES, W., OTERDOOM, H. & TROMMSDORFF, V. (1976): Stability of chrysotile and antigorite in the serpentinite multisystem. *Schweiz. Mineral. Petrog. Mitt.* **56**, 79-93.

FEHN, U. (1978): Qualitative models of spreading-center processes, including hydrothermal penetration: discussion. *Tectonophys.* **44**, 345-347.

FRANCHETEAU, J., NEEDHAM, H.D., CHOUKROUNE, P., JUTEAU, T., SÉGURET, M., BALLARD, R.D., FOX, P.J., NORMARK, W., CARRANZA, A., CORDOBA, D., GUERRERO, J., RANGIN, C., BOUGAULT, H., CAMBON, P. & HEKINIAN, R. (1979): Massive deep-sea sulphide ore deposits discovered on the East Pacific Rise. *Nature* **277**, 523-528.

FRANCIS, T.J.G. (1976): The ratio of compressional to shear velocity and rock porosity on the axis of the mid-Atlantic ridge. *J. Geophys. Res.* **18**, 4361-4364.

GASS, I.G. (1977): Origin and emplacement of ophiolites. *Geol. Soc. Lond. Spec. Publ.* **7**, 72-76.

———, NEARY, C.R., PLANT, J., ROBERTSON, A.H.F., SIMONIAN, K.O., SMEWING, J.D., SPOONER, E.T.C. & WILSON, R.A.M. (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.

GRAPES, R.H. (1976): Low grade alteration of basic rocks in Hokkaido, Japan. *J. Fac. Sci. Univ. Hokkaido Ser. IV*, **17**, 373-385.

GREEN, D.H. (1967): High-temperature peridotite intrusions. *In* Ultramafic and Related Rocks (P.J. Wyllie, ed.), John Wiley & Sons, Inc., New York.

HAJASH, A. (1975): Hydrothermal processes along mid-ocean ridges: an experimental investigation. *Contr. Mineral. Petrology* **53**, 205-226.

——— (1977): Experimental seawater/basalt interactions: effects of water/rock ratio and temperature gradient. *Geol. Soc. Amer. Program Abstr.* **9**, 1002.

HALL, J.M. & ROBINSON, P.T. (1979): Deep crustal drilling in the North Atlantic ocean. *Science* **204**, 573-586.

HEATON, T.H.E. & SHEPPARD, S.M.F. (1977): Hydrogen and oxygen isotope evidence for seawater–hydrothermal alteration and ore deposition, Troodos complex. *Geol. Soc. Lond. Spec. Publ.* **7**, 42-57.

HEKINIAN, R., ROSENDAHL, B. R., DMITRIEV, Y., FODOR, R.V., GOLL, R.M., HOFFERT, M., HUMPHRIS, S.E., MATTEY, D.P., NATLAND, J., PETERSEN, N., ROGGENTHEN, W., SCHRADER, E.L., SRIVASTAVA, R.K. & WARREN, N. (1977): Glomar Challenger completes 54th cruise. *Geotimes* **22**, 19-23.

HERMAN, M.B. LANGSETH, M.G. & HOBART, M.A. (1977): Heat flow in the oceanic crust bounding western Africa. *Tectonophys.* **41**, 61-77.

HONNOREZ, J. & KIRST, P. (1975): Petrology of rodingites from the equatorial mid-Atlantic fracture zones and their geotectonic significance. *Contr. Mineral. Petrology* **49**, 233-257.

HUMPHRIS, S.E. & THOMPSON, G. (1978a): Hydrothermal alteration of oceanic basalts by sea water. *Geochim. Cosmochim. Acta* **42**, 107-126.

——— & ——— (1978b): Trace element mobility during hydrothermal alteration of oceanic basalts. *Geochim. Cosmochim. Acta* **42**, 127-136.

HUTCHISON, C.S. (1978): Ophiolite metamorphism in northeast Borneo. *Lithos* **11**, 195-208.

HYNES, A. (1975): Comment on "The Troodos ophiolitic complex was probably formed in an island arc", by A. Miyashiro. *Earth Planet. Sci. Lett.* **25**, 213-216.

IRVING, E. (1970): The mid Atlantic ridge at 45° N. XIV. Oxidation and magnetic properties of basalt; review and discussion. *Can. J. Earth Sci.* **7**, 1528-1538.

JAKES, P. & WHITE, A.J.R. (1972): Major and trace element abundances in volcanic rocks of orogenic areas. *Geol. Soc. Amer. Bull.* **83**, 29-40.

JAMIESON, R.A. (1979): The origin of the dynamothermal aureole beneath the White Hills peridodite and its bearing on ophiolite emplacement. *Geol. Assoc. Can./Mineral. Assoc. Can. Program Abstr.* **4**, 60.

JOHANNES, W. (1975): Zur Synthese und thermischen Stabilität von Antigorit. *Fortschr. Mineral.* **53**, 1-36.

KAY, R. W. & SENECHAL, R.G. (1976): The rare earth geochemistry of the Troodos ophiolite complex. *J. Geophys. Res.* **81**, 964-970.

LAMBERT, R. ST. J. & HOLLAND, J.G. (1974): Yttrium geochemistry applied to petrogenesis utilizing calcium–yttrium relationships in minerals and rocks. *Geochim. Cosmochim. Acta* **38**, 1393-1414.

LAURENT, R. (1975a): Petrology of the Alpine-type serpentinites of Asbestos and Thetford mines, Quebec. *Schweiz. Mineral. Petrog. Mitt.* **55**, 431-455.

——— (1975b): Occurrences and origin of the ophiolites of southern Quebec, northern Appalachians. *Can. J. Earth Sci.* **12**, 443-455.

——— & HÉBERT, Y. (1978): Paragenesis of serpentine assemblages in tectonite and cumulate peridotites from the Quebec Appalachians. *Geol. Assoc. Can./Mineral. Assoc. Can. Program Abstr.* **3**, 441.

———, ——— & VALLÉE, M.A. (1978): Oceanic origin of ophiolitic volcanic rocks tested by their chemistry. *Geol. Assoc. Can./Mineral. Assoc. Can. Program Abstract.* **3**, 441.

LIOU, J. G. & ERNST, W.G. (1979): Oceanic ridge metamorphism of the East Taiwan ophiolite. *Contr. Mineral. Petrology* **68**, 335-348.

LISTER, C.R.B. (1972): On the thermal balance of a mid-ocean ridge. *Geophys. J. R. Astr. Soc.* **26**, 515-535.

——— (1974): On the penetration of water into hot rock. *Geophys. J. R. Astr. Soc.* **39**, 465-509.

——— (1977): Qualitative models of spreading-center processes, including hydrothermal penetration. *Tectonophys.* **37**, 203-218.

——— (1978): Qualitative models of spreading-center processes, including hydrothermal penetration: reply. *Tectonophys.* **44**, 348-353.

LONSDALE, P. (1977): Deep-tow observations at the Mounds abyssal hydrothermal field, Galapagos rift. *Earth Planet. Sci. Lett.* **6**, 92-110.

LOWELL, R.P. & RONA, P.A. (1976): On the interpretation of near-bottom water temperature anomalies. *Earth Planet. Sci. Lett.* **32**, 18-24.

MAGARITZ, M. & TAYLOR, H.P., JR. (1974): Oxygen isotope studies of serpentinization in the Troodos ophiolite complex, Cyprus. *Earth Planet. Sci. Lett.* **23**, 8-14.

MCCAIG, A.M. & KEMP, A.E. (1979): Emplacement history of the Pindos ophiolite, Greece. *Geol. Assoc. Can./Mineral. Assoc. Can. Program Abstr.* **4**, 66.

MELSON, W.G. & VAN ANDEL, T.H. (1966): Metamorphism in the mid-Atlantic ridge, 22° N latitude. *Marine Geol.* **4**, 165-186.

MENZIES, M., BLANCHARD, D. & JACOBS, J. (1977): Rare earth and trace element geochemistry of metabasalts from the Point Sal ophiolite, California. *Earth Planet. Sci. Lett.* **37**, 203-215.

MEVEL, C., CABY, R. & KIENAST, J.R. (1978): Amphibolite facies conditions in the oceanic crust: example of amphibolitized flaser-gabbro and amphibolites from the Chenaillet ophiolite massif (Hautes Alpes, Frances). *Earth Planet. Sci. Lett.* **39**, 98-108.

MEYER, D. (1978): *The Hydrothermal Origin of Spilites: An Experimental Study.* M.Sc. thesis, Univ. North Carolina, Chapel Hill, N.C.

MIYASHIRO, A. (1966): Some aspects of peridotite and serpentinite in orogenic belts. *Jap. J. Geol. Geogr.* **37**, 45-61.

——— (1973): The Troodos ophiolitic complex was probably formed in an island arc. *Earth Planet. Sci. Lett.* **19**, 218-224.

——— (1975a): Classification, characteristics, and origin of ophiolites. *J. Geol.* **83**, 249-281.

——— (1975b): Origin of the Troodos and other ophiolites: a reply to Hynes. *Earth Planet. Sci. Lett.* **25**, 217-222.

——— (1975c): Origin of the Troodos and other ophiolites: a reply to Moores. *Earth Planet. Sci. Lett.* **25**, 227-235.

———, SHIDO, F. & EWING, M. (1971): Metamorphism in the mid-Atlantic ridge near 24° and 30° N. *R. Soc. Lond. Phil. Trans.* **A268**, 589-603.

MONTIGNY, R., BOUGAULT, H., BOTTINGA, H. & ALLÈGRE, C.J. (1973): Trace element geochemistry and genesis of the Pindos ophiolite suite. *Geochim. Cosmochim. Acta* **37**, 2135-2147.

MOODY, J.B. (1976a): Serpentinization: a review. *Lithos* **9**, 125-138.

——— (1976b): An experimental study on the serpentinization of iron-bearing olivines. *Can. Mineral.* **14**, 462-478.

——— (1978): Serpentinites, spilites, and the metamorphism of ophiolites. *Geol. Assoc. Can./Mineral. Assoc. Can. Program Abstr.* **3**, 459.

——— & MEYER, D. (1978): Experimental verification of the metamorphic origin of spilites. *Geol. Soc. Amer. Program Abstr.* **10**, 193.

MOORES, E. M. (1975): Discussion of "Origin of Troodos and other ophiolites: a reply to Hynes", by A. Miyashiro. *Earth Planet. Sci. Lett.* **25**, 223-226.

——— & VINE, F.J. (1971): The Troodos massif, Cyprus and other ophiolites as oceanic crust: evaluation and implications. *R. Soc. Lond. Phil. Trans.* **A268**, 443-468.

MOTTL, M.J. (1976): *Chemical Exchange Between Sea Water and Basalt During Hydrothermal Alteration of the Oceanic Crust.* Ph.D. thesis, Harvard University, Cambridge, Mass.

———, CORR, R.F. & HOLLAND, H.D. (1975): Trace element content of the Reykjanes and Svartsengi thermal brines, Iceland. *Geol. Soc. Amer. Program Abstr.* **7**, 1206-1207.

——— & HOLLAND, H.D. (1978): Chemical exchange during hydrothermal alteration of basalt by seawater. I. Experimental results for major and minor components of seawater. *Geochim. Cosmochim. Acta* **42**, 1103-1116.

MUEHLENBACHS, K. & CLAYTON, R.N. (1976): Oxygen isotope composition of the oceanic crust and its bearing on seawater. *J. Geophys. Res.* **81**, 4365-4369.

NATLAND, J.H., ROSENDAHL, B., DMITRIEV, Y., FODOR, R.V., GOLL, R.M., HOFFERT, M., HUMPHRIS, S.E., MATTEY, D.P., PETERSEN, N., ROGGENTHEN, W., SCHRADER, E.L., SRIVASTAVA, R.K. & WARREN, N. (1979): Galapagos hydrothermal mounds: stratigraphy and chemistry revealed by deep-sea drilling. *Science* **204**, 613-616.

NISBET, E.G. & FOWLER, C.M.R. (1978): The mid-Atlantic ridge at 37 and 45° N: some geophysical and petrological constraints. *Geophys. J. R. Astr. Soc.* **54**, 631-660.

NOCKOLDS, S.R. (1954): Average chemical compositions of some igneous rocks. *Geol. Soc. Amer. Bull.* **65**, 1007-1032.

PARMENTIER, E.M. & SPOONER, E.T.C. (1978): A theoretical study of hydrothermal convection and the origin of the ophiolitic sulphide ore deposits of Cyprus. *Earth Planet. Sci. Lett.* **40**, 33-44.

PEARCE, J.A. (1976): Statistical analysis of major element patterns in basalts. *J. Petrology* **17**, 15-43.

——— & CANN, J.R. (1971): Ophiolite origin investigated by discriminant analysis using Ti, Zr, and Y. *Earth Planet. Sci. Lett.* **12**, 339-349.

——— & ——— (1973): Tectonic setting of basic volcanic rocks determined using trace element analysis. *Earth Planet. Sci. Lett.* **19**, 290-300.

——— & GALE, G.H. (1977): Identification of ore-deposition environment from trace-element geochemistry of associated igneous host rocks. *Geol. Soc. Lond. Spec. Publ.* **7**, 14-24.

PFEIFER, H.R. (1977): A model for fluids in metamorphosed ultramafic rocks. Observations at surface and subsurface conditions (high pH spring waters). *Schweiz. Mineral. Petrog. Mitt.* **57**, 361-396.

PIPER, D.Z. (1973): Origin of metalliferous sediments from the East Pacific Rise. *Earth Planet. Sci. Lett.* **19**, 75-82.

PRICHARD, H.M. (1979): A petrographic study of the process of serpentinization in ophiolites and the ocean crust. *Contr. Mineral. Petrology* **68**, 231-241.

PRINZ, J., KEIL, K., GREEN, J.A., REID, A.M., BONATTI, E. & HONNOREZ, J. (1976): Ultramafic dredge samples from the equatorial mid-Atlantic ridge and fracture zones. *J. Geophys. Res.* **81**, 4087-4103.

RIBANDO, R.J. TORRANCE, K.E. & TURCOTTE, D.L. (1976): Numerical models for hydrothermal circulation in the oceanic crust. *J. Geophys. Res.* **81**, 3007-3012.

ROGERS, J.J.W., BURCHFIELD, B.C., ABBOTT, E.W., ANEPOHL, J.K., EWING, A.H., KOEHNKEN, P.J., NOVITSKY-EVANS, J.M. & TALUKDAR, S.C. (1974): Paleozoic and lower Mesozoic volcanism and continental growth in the western United States. *Geol. Soc. Amer. Bull.* **85**, 1913-1924.

RONA, P.A. (1978): Criteria for recognition of hydrothermal mineral deposits in oceanic crust. *Econ. Geol.* **73**, 135-160.

ROSENDAHL, B.R. (1976): Evolution of oceanic crust. 2. Constraints, implications, and inferences. *J. Geophys. Res.* **81**, 5305-5314.

SAKAI, H. & TSUTSUMI, M. (1978): D/H fractionation factors between serpentine and water at 100° to 500°C and 2000 bar water pressure, and the D/H ratios of natural serpentinites. *Earth Planet. Sci. Lett.* **40**, 231-242.

SCOTT, R.B. & HAJASH, A., JR. (1976): Initial submarine alteration of basaltic pillow lavas: a microprobe study. *Amer. J. Sci.* **276**, 480-501.

SEYFRIED, W.E. & DIBBLE, W.E. (1978): Chemical exchange and secondary mineral formation during seawater peridotite interaction: an experimental study. *Geol. Assoc. Can./Mineral. Assoc. Can. Program Abstr.* **3**, 490.

SHANKS, W.C. & BISCHOFF, J.L. (1977): Ore transport and deposition in the Red Sea geothermal system: a geochemical model. *Geochim. Cosmochim. Acta* **41**, 1507-1519.

SHAW, D.M., VATIN-PÉRIGNON, N. & MUYSSON, J. R. (1977): Lithium in spilites. *Geochim. Cosmochim. Acta* **41**, 1601-1608.

SHEPPARD, S.M.F. (1977): Identification of the origin of ore-forming solutions by the use of stable isotopes. *Geol. Soc. Lond. Spec. Publ.* **7**, 25-41.

SLEEP, N.H. (1975): Formation of oceanic crust: some thermal constraints. *J. Geophys. Res.* **80**, 4036-4042.

——— & ROSENDAHL, B.R. (1979): Topography and tectonics of mid-oceanic ridge axes. *J. Geophys. Res.*, in press.

——— & WOLERY, T.J. (1978): Egress of hot water from midocean ridge hydrothermal systems: some thermal constraints. *J. Geophys. Res.* **83**, 5913-5922.

SMEWING, J.D. & POTTS, P.J. (1976): Rare-earth abundances in basalts and metabasalts from the Troodos massif, Cyprus. *Contr. Mineral. Petrology* **57**, 245-257.

———, SIMONIAN, K.O. & GASS, I.G. (1975): Metabasalts from the Troodos massif, Cyprus: genetic implication deduced from petrography and trace element geochemistry. *Contr. Mineral. Petrology* **51**, 49-64.

SPOONER, E.T.C. (1977): Hydrodynamic model for the origin of the ophiolitic cupriferous pyrite ore deposits of Cyprus. *Geol. Soc. Lond. Spec. Publ.* **7**, 58-71.

——— (1978): Ophiolitic rocks and evidence for hydrothermal convection of sea water within oceanic crust. *2nd Ewing Symp. Abstr. Program*, 36-37.

———, BECKINSALE, R.D., ENGLAND, P.C. & SENIOR, A. (1977a): Hydration, ^{18}O enrichment and oxidation during ocean floor hydrothermal metamorphism of ophiolitic metabasic rocks from E. Liguria, Italy. *Geochim. Cosmochim. Acta* **41**, 857-872.

———, ———, FYFE, W.S. & SMEWING, J.D. (1974): ^{18}O enriched ophiolitic metabasic rocks from E. Liguria (Italy), Pindos (Greece), and Troodos (Cyprus). *Contr. Mineral. Petrology* **47**, 41-62.

——— & BRAY, C.J. (1977): Hydrothermal fluids of seawater salinity in ophiolitic sulphide ore deposits in Cyprus. *Nature* **266**, 808-812.

———, CHAPMAN, H.J. & SMEWING, J.D. (1977b): Strontium isotopic contamination and oxidation during ocean floor hydrothermal metamorphism of the ophiolitic rocks of the Troodos massif, Cyprus. *Geochim. Cosmochim. Acta* **41**, 873-890.

——— & FYFE, W.S. (1973): Sub-sea-floor metamorphism, heat, and mass transfer. *Contr. Mineral. Petrology* **42**, 287-304.

STERN, C., DE WIT, M.J. & LAWRENCE, J.R. (1976): Igneous and metamorphic processes associated with the formation of Chilean ophiolites and their implication for ocean floor metamorphism, seismic layering, and magnetism. *J. Geophys. Res.* **81**, 4370-4380.

STURT, B.A., THON, A. & FURNES, H. (1979): The Karmoy ophiolite, southwest Norway. *Geology* **7**, 316-320.

SUN, S.S. & NESBITT, R.W. (1978): Geochemical regularities and genetic significance of ophiolitic basalts. *Geology* **6**, 689-693.

SYKES, L.R. (1971): Earthquake swarms and seafloor spreading. *J. Geophys. Res.* **75**, 6598-6611.

VANCE, J.A. & DUNGAN, M.A. (1977): Formation of peridotites by deserpentinization in the Darrington and Sultan areas, Cascade Mountains, Washington. *Geol. Soc. Amer. Bull.* **88**, 1497-1508.

VON HERZEN, R., GREEN, K.E. & WILLIAMS, D. (1977): Hydrothermal circulation at the Galapagos spreading center. *Geol. Soc. Amer. Program Abstr.* **9**, 1212-1213.

WENNER, D.B. (1979): Hydrogen, oxygen and carbon isotopic evidence for the origin of rodingites in serpentinized ultramafic rocks. *Geochim. Cosmochim. Acta* **43**, 603-614.

——— & TAYLOR, H.P., JR. (1973): Oxygen and hydrogen isotope studies of the serpentinization of ultramafic rocks in oceanic environments and continental ophiolite complexes. *Amer. J. Sci.* **273**, 207-239.

WICKS, F.J. & WHITTAKER, E.J.W. (1977): Serpentine textures and serpentinization. *Can. Mineral.* **15**, 459-488.

WILLIAMS, D.L., VON HERZEN, R.P., SCLATER, J.G. & ANDERSEN, R.N. (1974): The Galapagos spreading center: lithospheric cooling and hydrothermal circulation. *Geophys. J. R. Astr. Soc.* **38**, 587-608.

WOLERY, T.J. & SLEEP, N.H. (1976): Hydrothermal circulation and geochemical flux at midocean ridges. *J. Geol.* **84**, 249-275.

Received December 1978, revised manuscript accepted August 1979.