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LIMITATIONS OF OPHIOLITE COMPLEXES AS MODELS FOR THE MAGNETIC LAYER OF THE OCEANIC LITHOSPHERE

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Abstract. We propose that only those ophiolite complexes whose magnetic properties and metamorphic grade correspond to comparable stratigraphic units of in-situ oceanic crust should be used for modeling the magnetic properties of the oceanic lithosphere. Because drilling of the igneous oceanic crust by the Deep Sea Drilling Project (DSDP) has penetrated a maximum of 0.6 km, only the upper extrusives (pillow basalts and associated flows) of an ophiolite complex can be used in this direct comparison. Previously published and new data of submarine basalts are used for establishing *minimum constraints* for the magnetic properties of the extrusive rocks of ophiolite complexes. These criteria are:

1) initial Curie points (T_C) should be between 100° – 450°C (for $T_C \gtrsim 200°C$ the saturation magnetization versus temperature curves should be irreversible);
2) $\bar{J}_{NRM}$ (intensity of magnetization) $> 1\text{x}10^{-4}$ gauss ($1\text{x}10^{-1}\text{Am}^{-1}$);
3) $\bar{Q}$ (ratio of remanent to induced magnetization) > 1;
4) alteration of the upper extrusives should not exceed zeolite facies metamorphism.

These necessary but not sufficient criteria were applied to five ophiolite complexes, of which only two satisfied all the requirements. The remaining ophiolite complexes were probably subjected to a metamorphic event either during or subsequent to their original emplacement as part of the oceanic lithosphere.

Introduction

In order to determine the thickness and composition of the source layer of the marine magnetic anomalies one must obtain samples from the oceanic crust. Such rocks have been obtained from dredge hauls, through the efforts of the Deep Sea Drilling Project (DSDP), and from ophiolite complexes. Of course, it is best to obtain in situ samples from present day oceanic crust as supplied by DSDP, or from expeditions to the mid-Atlantic ridge such as the Canadian effort at 45°N, project FAMOUS at the mid-Atlantic ridge near 37°N and the recent expedition to the Galapagos spreading center.

The magnetic results of the two expeditions to the mid-Atlantic ridge generally suggest that at spreading centers only a thin magnetic layer of the order of 500-1000 m is required to explain the source of the anomalies (*Irving et al.*, 1970; *Carmichael*, 1970; *Prévot et al.*, 1976; *Johnson and Atwater*, 1977). [Of course, a thicker source layer for the anomalies would be required if recent findings of *Johnson and Atwater* (1977), that a significant fraction of the oriented samples within the median valley in the FAMOUS area have reversed inclinations, prove to be the rule rather than the exception.]

In contrast, results from the deeper basement penetrations by DSDP [e.g., Leg 37 (*Ryall et al.*, 1977); Leg 45 (*Johnson*, 1976); Leg 49 (*Steiner et al.*, 1973)] show that the magnetization intensity of the samples is usually far below values obtained at spreading centers. In addition, some of these deeper DSDP holes have sections which are magnetized opposite to the sense of the anomaly observed at the drilling site. In addition, it is not uncommon to encounter sediment and/or voids within the igneous column. These results imply that a much thicker magnetic layer is required to account for the observed anomalies. The inferred thicknesses vary from site to site, and they depend on the particular analysis, leading sometimes to inferred thicknesses in excess of 2.5 km (*Scientific Party*, 1975; *Harrison*, 1976). In view of the large thickness of the magnetic layer inferred from the DSDP results it is important to recognize that to date the maximum penetration of the oceanic igneous crust is only 583 m on Leg 37. It is therefore imperative to obtain samples from deeper layers in the oceanic lithosphere. With the exception of occasional intrusives dredged mostly in the vicinity of fracture zones (*Watkins and Paster*, 1971; *Fox and Opdyke*, 1973), the only presently available sources of such samples are ophiolite complexes.

Because many of our current beliefs about the stratigraphy and physical properties of the oceanic lithosphere are made by direct analogy with ophiolite complexes (*Coleman*, 1971; *Dewey and Bird*, 1971; *Moores and Vine*, 1971; *Salisbury and Christensen*, 1978), it is natural to also study their magnetic properties so as to infer the gross magnetic properties of the oceanic lithosphere, particularly the deeper sections, not yet reached by deep drilling of present oceans. In addition to being the only source of samples from the deeper portions of the oceanic crust, ophiolite complexes introduce a host of complexities which are still in hot debate. For one thing, ophiolite complexes are by definition not presently part of the oceanic crust; many ophiolite complexes are of Mesozoic age and older. Also, there is no universal agreement on the nature of the origin of ophiolite complexes. Are they representative of oceanic crust which was formed at spreading centers; are they relics of processes occurring at subduction zones; or are they associated with fracture zones? It is quite possible that ophiolite complexes might be products of each of these environments; if so, by what means can the different "types" of ophiolite complexes be distinguished? In addition, many ophiolite complexes have been subjected to varying degrees of metamorphism, and it is not easy to determine when the metamorphism occurred. Is it ocean-floor metamorphism (at low or high temperatures) or does it represent the obduction onto the continent or an even later event? Although some of the above difficulties might be of only secondary importance to some fields of study, their understanding is essential to magnetic investigations as both the magnetic properties of minerals and their chemical stability are extremely sensitive to even moderate reheating (~200°C) for relatively short periods of time. For these reasons it would be useful to have some guidelines by which to select those ophiolite complexes which are most promising for modeling the magnetic properties of the "deeper" layers responsible for the marine magnetic anomalies.

Constraints from Present Oceanic Crust

Extensive drilling by DSDP during the past few years has provided an immense amount of data about the petrology, alteration and magnetic properties of the upper few hundred meters (depth < 0.6 km) of the igneous crust of the world's oceans, crust whose age ranges from 2 to ~150 million years (*Lowrie et al.*, 1973; *Ryall et al.*, 1977; *Johnson and Hall*, 1976; *Johnson*, 1976; *Lowrie*, 1977; *Steiner et al.*, 1978; *Marshall*, 1978). In addition, similar types of data have been obtained by expeditions to the mid-Atlantic spreading center from where very young material, of the order of several thousand years, has been recovered (*Schaeffer and Schwarz*, 1970; *Irving et al.*, 1970; *Carmichael*, 1970; *Park and Irving*, 1970; *Prévot et al.*, 1976; *Johnson and Atwater*, 1977). Although the magnetic properties of these samples vary broadly, we shall see later that they are nevertheless useful for establishing a framework for discriminating between ophiolite complexes. Table 1 lists some properties of oceanic basalts retrieved from present oceans.

Hence, as *minimum* conditions for an ophiolite complex, before it is used for modeling the magnetic properties of the oceanic lithosphere, the magnetic properties of its upper extrusives should correspond to those of submarine basalts from present oceans, as outlined in Table 1. If these minimum conditions are not satisfied, then the ophiolite complex

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TABLE 1. Properties of basalts from present oceans (depth < 0.6 km).

T_C : $100° - 450°C$ [For $T_C \gtrsim 200°C$ irreversible J_S (saturation magnetization) versus T (temperature) curves are observed]

J_{NRM} : $1 - 1000 \times 10^{-4}$ Gauss ($1\text{-}1000 \times 10^{-1}$ Am^{-1})

Q > 1

Metamorphic
Grade : Not beyond zeolite facies metamorphism

1. T_C, initial Curie point;
2. J_{NRM}, intensity of natural remanent magnetization;
3. Q, the ratio of remanent to induced magnetization;
4. Degree of metamorphism.

in question should probably not be used for modeling the magnetic properties of the oceanic crust. If the minimum criteria are satisfied, then further geologic, petrologic, geochemical and magnetic evaluation of the underlying strata should be undertaken prior to using the ophiolite complex for magnetic modeling.

Application of "Minimum Conditions" to Ophiolite Complexes

Ophiolite complexes typically exhibit varying degrees of structural deformation, so that it is very difficult to assess the original thicknesses of their various stratigraphic units. Hence, we shall only use the geologically determined upper-most extrusive basalts of an ophiolite sequence for comparison with the sampled layer of extrusive basalts of present oceans. For example, only the upper pillow basalts from North Head on Macquarie Island (*Butler et al.*, 1976) are considered in Table 2. Similarly, the Vourinos ophiolite complex of central Greece is not included in the comparison below, because its pillow basalt sequence is missing.

Table 2 contains data for the upper-most extrusive units of five ophiolite complexes which we have been studying for the last few years. ($\bar{J}_{NRM}$ and $\bar{Q}$ represent geometric means of the respective parameters.)

Comparison of the data of Tables 1 and 2 shows that the properties of the upper extrusives of the Macquarie Island ophiolite complex and of the Troodos Massif correspond in every category to the properties of the corresponding extrusives from existing oceans. Thus, these two ophiolite complexes pass the initial selection process and are good candidates for further considerations for modeling the magnetic properties of the oceanic crust. In contrast, the properties of the extrusives from the Smartville ophiolite complex do not correspond in any category to those of their oceanic counterparts. Hence, the Smartville ophiolite complex should probably not be used for modeling the magnetic properties of the oceanic crust.

The data for the Othris and Oman ophiolite complexes are more difficult to interpret. $\bar{J}_{NRM}$ of the upper extrusives of these two units corresponds to those of the oceanic extrusives, and the $\bar{Q}$ value of the Oman extrusives also just overlaps that of the oceanic basalts. In addition, the zeolite facies metamorphic grade of these two ophiolite complexes is sufficiently low to be considered. However, both the Oman and Othris ophiolite complexes exhibit essentially reversible J_S(saturation magnetization) versus T (temperature) curves with $T_C > 450°C$, which has been observed only rarely in submarine basalts.

Thus, of the five ophiolite complexes that we have considered, only for two do the properties of the upper extrusives correspond in every category to those of extrusive basalts from existing oceans. Ranking these ophiolites in order of decreasing potential for modeling the magnetic properties of the oceanic crust we have: Macquarie Island ophiolite complex and the Troodos Massif of Cyprus, the Oman Massif, the Othris ophiolite complex of Greece, and the Smartville ophiolite complex of California.

Discussion

Data have been accumulating in recent years, showing that the iron-titanium oxides which crystallize in submarine basalts near spreading centers are of a rather restricted compositional range; that is, in these rocks the titanomagnetite solid solution series $xFe_2TiO_4(1-x)Fe_3O_4$ crystallizes with $0.55 < x < 0.68$, where x is the mole fraction of ulvöspinel (*Ozima et al.*, 1974; *Johnson and Hall*, 1978; *Marshall*, 1978). The Curie point of this phase ranges between 120° and 150°C (*Akimoto et al.*, 1957), and, when the J_S versus T runs are done in vacuum, reversible curves are observed (*Schaeffer and Schwarz*, 1970; *Ozima and Ozima*, 1971). These titanomagnetites oxidize topotactically at ambient sea-floor temperatures (1° -4°C) to cation-deficient titanomagnetites (i.e. titanomaghemites), and they have been observed in this metastable state in oceanic crust as old as 150 million years (e.g., *Marshall*, 1978). T_C of this phase increases with increasing degree of oxidation up to about 400°C (*Readman and O'Reilly*, 1972). It has been shown in laboratory experiments that titanomaghemites are structurally unstable at temper-

TABLE 2. Properties of pillow basalts of some ophiolite complexes.

Ophiolite Complex	$\bar{J}_{NRM}$ (Gauss)	$\bar{Q}$	T_C	Degree of Metamorphism
Macquarie Island	5×10^{-4} (1)	10 (1)	280 - 360°C, Irreversible (1)	Low temperature oxidation; unmetamorphosed (2)
Troodos Massif, Cyprus	80×10^{-4} (3,4)	5.7 (3,4)	180 - 360°C, Irreversible (4)	Zeolite facies (5)
Oman Massif	49×10^{-4}	1.3	550 - 570°C, Reversible	Zeolite facies (6)
Othris, Greece	3×10^{-4}	0.5	525 - 590°C, Reversible	Zeolite facies (7)
Smartville, California	0.5×10^{-4}	0.3 (4)	560 - 590°C, Reversible (4)	Greenschist facies (4)

1. *Butler et al.*, 1976
2. *Varne and Rubenach*, 1972
3. *Vine and Moores*, 1972
4. *Levi and Banerjee*, 1977
5. *Gass and Smewing*, 1973
6. *Smewing, private communication*, 1977
7. *Hynes*, 1974

atures as low as 150°C in some circumstances (*Johnson and Merrill,* 1973; *Ryall and Ade-Hall,* 1975), unmixing to highly magnetic, titanium-poor titanomagnetites and to relatively non-magnetic titanium-rich phases. It is possible that unmixing might occur at temperatures significantly lower than 150°C, if sufficient time were available. The unmixing upon heating is responsible for the irreversible character observed during the J_s versus T runs of titanomaghemite (*Schaeffer and Schwarz,* 1970; *Ozima and Ozima,* 1971; *Ozima et al.,* 1974).

Thus, the discovery in an ophiolite complex of titanomaghemite phase with an irreversible J_s versus T curve and an initial $T_c < 450°C$ is a very sensitive diagnostic, strongly suggesting that the unit in question has not seen temperatures above 150°C since its formation. In ophiolite complexes whose upper extrusives exhibit reversible J_s versus T curves with $T_c > 450°C$, the unmixing of the titanomaghemites had presumably occurred sometime during the rock's history prior to its arrival in the laboratory. This implies exposure to an unknown temperature greater than at least 40°C. (This represents an approximate upper limit to the ambient temperature on Cyprus to which the upper extrusives might have been exposed there.) Further rough estimates of the maximum temperature reached by the samples can be obtained from the degree of metamorphism of the silicate minerals.

It has been suggested (*Butler et al.,* 1976; *Levi et al.,* 1975; *Banerjee et al.,* 1977) that extrusives with $T_c > 500°C$ and having reversible J_s versus T curves might represent normal spreading center processes, caused by reheating due to contact metamorphism and/or hydrothermal circulation. Although this scheme is consistent with laboratory experiments (*Johnson and Merrill,* 1973; *Marshall and Cox,* 1971; *Ryall and Hall,* 1975; *Levi et al.,* 1975) and with thermal models for the oceanic lithosphere near spreading centers (e.g., *Sleep,* 1975; *Kusznir and Bott,* 1976), it is not a unique explanation. The hypothesis of the spreading-center origin of these high T_c extrusives would be strengthened by the presence of overlying extrusives which had not been subjected to reheating and still exhibit $T_c < 450°C$ and irreversible J_s versus T curves, as is the case for the Macquarie Island ophiolite complex (*Butler et al.,* 1976). Hence, it is possible, for example, that extrusives from the Oman Massif do indeed represent spreading-center alteration; however, until one discovers overlying unheated extrusives, associated with the ophiolite complex, this interpretation cannot be verified.

It might be argued that requiring the presence of titanomaghemite in the extrusives of an ophiolite complex is too stringent and that, although the magnetic properties of upper extrusives certainly undergo major changes at even low temperatures, the deeper layers (sheeted dikes and below) might undergo only relatively minor changes of their magnetic properties due to heating; this is because of their relatively slow cooling and lower equilibration temperatures upon initial crystallization (probably suggesting that the titanomagnetites were subjected to deuteric high temperature oxidation). Although this argument might be intrinsically correct, it cannot be adequately tested and probably varies for different ophiolite complexes. In addition, let us suppose that post-formation reheating is sufficient to unmix the titanomaghemites of the upper extrusives but does not affect the chemistry and crystallography of the deeper units; however, annealing and associated grain growth are likely to drastically affect their magnetic properties.

Furthermore, in all models for the magnetic properties of the oceanic lithosphere the extrusives are thought to be the chief contributors to the marine magnetic anomalies. In trying to model the magnetic properties of the oceanic crust we seek the relative contributions of the different layers. Hence, if the upper extrusives have been magnetically altered through unmixing, then it is impossible to accurately assess the relative contributions of the underlying strata, even if they are assumed to be unaltered.

Although it might be that the presence of titanomaghemite in the extrusives of an ophiolite complex would prove to be the single most sensitive selection criterion, our present imperfect understanding of the magnetic properties of the oceanic lithosphere requires that we rely on as many ubiquitous properties as are available. Because essentially all submarine basalts of present oceans satisfy all four criteria listed in Table 1, all of these should be used for selecting ophiolite complexes for magnetic modeling.

In conclusion, we would like to argue that only ophiolite complexes whose upper extrusives satisfy all the criteria of Table 1 should be considered candidates for modeling the magnetic properties of the oceanic crust.

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