Why are marine magnetic anomalies suppressed over sedimented spreading centers?

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ABSTRACT

The absence of lineated marine magnetic anomalies over sedimented, recent spreading centers has been observed in several areas. We propose that magnetic anomalies can be suppressed as a result of pervasive hydrothermal reactions underneath thick blankets of sediment. The relatively impermeable sediment cover produces comparatively closed hydrothermal systems, which increase the residence time of the hot fluids in basaltic layer 2, causing more thorough leaching of the remanence-carrying iron-titanium oxides and diminishing the marine magnetic anomalies. This contrasts with lesser alteration at sparsely or unsedimented zones of extension with more open circulation. Conversely, spreading ridges and oceanic crust characterized by absent or subdued lineated anomalies may signal sites of extensive hydrothermal mineralization. This process might also provide an explanation for some magnetic "quiet zones," such as in the Gulf of California, the Gulf of Aden, and the northern Red Sea.

INTRODUCTION

Analyses of lineated marine magnetic anomalies in the context of the Vine-Matthews-Morley hypothesis have resulted in major advances in the understanding of sea-floor spreading and the evolution of ocean basins. However, large areas of oceanic crust are characterized by apparently incoherent or very low amplitude magnetic anomalies (magnetic "quiet zones"), uninterpretable in terms of sea-floor spreading. Occasionally, very young (Brunhes age) ocean crust also fails to produce significant anomalies. In this paper we reconsider some of the causes that might give rise to such "nonmagnetic" young oceanic crust.

MARINE MAGNETIC ANOMALIES: SOURCE AND EVOLUTION

The highest amplitude marine magnetic anomalies typically occur over the youngest oceanic crust at accretion centers, and the amplitudes are usually significantly lower for older crust flanking the spreading axes (e.g., Vine and Wilson, 1965). In addition, studies of magnetic anomalies over spreading centers (Talwani et al., 1971; Klitgord et al., 1975) and the magnetic properties of dredged and drilled Brunhes age submarine basalts (Irving, 1970; Johnson and Atwater, 1977; Levi, 1983) indicate that the source of the magnetic anomalies over young crust is predominantly in oceanic layer 2, probably the upper 0.5–1 km. It is now generally accepted that the observed age-dependent diminution of anomaly amplitudes (at least to 20 Ma) is caused largely by progressive low-temperature oxidation of the original titanomagnetite of the extrusive oceanic crust (Irving, 1970; Marshall and Cox, 1972; Bleil and Peterson, 1983), whose composition is $x\mathrm{Fe_2TiO_4}(1-x)\mathrm{Fe_3O_4}$, x being equal to 0.6 ±0.1 mol% (Johnson and Hall, 1978; Marshall, 1978). Upon extrusion, the basalts undergo weathering in the low-temperature marine environment, and the titanomagnetites are topotactically oxidized to cation deficient spinels—titanomaghemites; this results in lower spontaneous magnetization and an increase in the critical size of superparamagnetic to single-domain magnetic transition (Butler, 1973). Both of these processes cause a decrease in the specific remanence intensities and a parallel reduction of the amplitude of the magnetic anomalies. However, basalts whose degree of alteration does not exceed low-temperature oxidation often retain their primary remanence direction (Marshall and Cox, 1972) and are sources for the great majority of coherent sea-floor-spreading magnetic anomalies.

EXAMPLES OF BRUNHES AGE CRUST LACKING MARINE MAGNETIC ANOMALIES

By contrast, there are examples of young ocean crust apparently produced at spreading centers that are not accompanied by magnetic anomalies. They include the Guaymas Basin of the Gulf of California (Larson et al., 1972; Bischoff and Henyey, 1974), and in the northeast Pacific Ocean, the Paul Revere Ridge and Winona Basin (Davis and Riddihough, 1982), Middle Valley of the northern Juan de Fuca Ridge (Davis and Lister, 1977), and the Escanaba Trough on the southern Gorda Ridge (Raff and Mason, 1961). In addition to the absence of interpretable magnetic anomalies, each of these areas is overlain by sediments several hundred metres to more than 1 km thick (Moore, 1970; Bischoff and Henyey, 1974; Davis and Lister, 1977; Davis and Riddihough, 1982), and it has been hypothesized (e.g., Larson et al., 1972) that there is a causal relation between the sediment cover and the subdued magnetic anomalies.

MECHANISMS

Intrusives

Two mechanisms have been advanced to explain how a thick sediment blanket might inhibit production of lineated magnetic anomalies. According to the first model (Irving, 1970; Vogt et al., 1970), magmas crystallizing under sediment will not form extrusive pillow lavas but will cool more slowly to produce intrusive dikes or sills that have larger grain sizes and correspondingly lower specific remanence intensities and lower stabilities than extrusive rocks of similar composition. (A similar explanation using salt rather than sediments was recently proposed for the northern Red Sea by Girdler, 1985.) However, dikes cored at subbasement

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depths of more than 500 m at DSDP sites 417D and 418A possess remanence intensities and stabilities comparable to the extrusive pillow basalts and much greater than the extrusive ponded flows both above and below the dikes (Levi, 1979). In this case, the grain sizes of the magnetic minerals in the flows, which can be tens of metres thick, exceed those in the dikes. In another example, dikes from a 3-km vertical section in eastern Iceland (Bleil et al., 1982) exhibit magnetization intensities and stabilities very similar to the subaerially extruded flows. It is thus not possible to predict the relative magnetic intensities and stabilities of dikes and flows of the same composition and low-temperature oxidation.

Elevated Temperature

The second explanation recognizes that the Curie temperatures of stoichiometric unoxidized titanomagnetites produced at spreading centers are low, between 100 and 200 °C (Johnson and Atwater, 1977; Johnson and Hall, 1978; Marshall, 1978; Prévot et al., 1979). Elevated temperatures above these Curie points expected at the base of thick sediment blankets and in the basalts of young oceanic crust would thus decrease the spontaneous magnetization of the underlying rocks and reduce and possibly eliminate the observed anomalies.

There are two problems with this explanation. First, once the crust had cooled below the Curie point, it would then become magnetized. Because of the sediment blanket, cooling would take longer than normal, but the process would be virtually the same as for unsedimented crust. Lineated magnetic anomalies with a chronology (delayed and perhaps geographically distorted in accordance with sediment thickness among other factors) would be produced. Examples such as the southern Gorda Ridge/Escanaba Trough and the Gulf of California, where no magnetic anomalies are apparent over crust as old as 3 Ma, suggest that this does not occur.

Second, the titanomagnetites of submarine basalts are highly susceptible to chemical alteration under a wide range of conditions. It is difficult to conceive that they could remain chemically unaltered even after short periods (months to years) at elevated temperatures. Such alteration causes drastic modification of their magnetic properties, including magnetization intensities and Curie points. For example, even near 4 °C, low-temperature oxidation of titanomagnetites reduces the spontaneous magnetization (as noted earlier to explain the reduction in magnetic anomaly amplitudes over normal older crust) but also increases their Curie temperatures. Complete low-temperature oxidation of titanomagnetite can increase Curie points to as high as 400 °C (Readman and O'Reilly, 1972; Johnson and Hall, 1978; Marshall, 1978). Titanomagnetite alteration at the higher temperatures of 200–400 °C, which might be expected beneath a significant sediment blanket, would probably result in two phases (Ozima and Larson, 1970): (1) a nonmagnetic titanium-rich phase composed of ilmenite ($FeTiO_3$) and/or rutile (TiO_2), and (2) a highly magnetic titanium-poor magnetite phase having a Curie temperature between 500 and 580 °C. Furthermore, laboratory thermomagnetic analyses suggest that the total room-temperature spontaneous magnetization of these product phases often exceeds the initial magnetization of the primary titanomagnetites (e.g., Ozima and Larson, 1970). Thus, at temperatures above 100 °C, the initial low Curie-point phases that would prevent magnetization beneath sediments are likely to be modified to minerals with higher Curie points and higher than normal basalt magnetizations.

Hydrothermal Leaching

We propose that pervasive hydrothermal alteration of sea-floor basalts at sedimented spreading centers might offer the most efficient process for suppressing marine magnetic anomalies. First reported by Studt (1959) from geothermal fields in New Zealand, the reduction of magnetization in submarine basalts by metamorphism and/or hydrothermal alteration was documented by Matthews et al. (1965), Luyendyk and Melson (1967), and Opdyke and Hekinian (1967). These authors noted that such effects would reduce or eliminate the magnetic anomalies at the sea surface. Zietz (1970) suggested that such metamorphism might contribute to the production of magnetic "quiet zones" by the prolonged effect of sediment burial of older ocean crust. Rona (1978a, 1978b) specifically noted that some marine hydrothermal deposits are characterized by lower than expected marine magnetic anomalies, and he hypothesized that hydrothermal alteration in basalt would destroy the titanomagnetite minerals, consequently subduing the associated magnetic anomalies (see also Johnson et al., 1982). It seems to us that Rona's idea can be extended by recognizing that deposition of a thick sediment blanket contemporaneous with volcanism would cause even more pervasive hydrothermal alteration of the basement rocks and thus lead to a more widespread reduction of magnetization and magnetic anomalies.

It is now clear that hydrothermal circulation is a primary mechanism for cooling newly formed oceanic lithosphere (Bodvarsson and Lowell, 1972; Lister, 1972) and for determining the geochemical balances of sea water and marine sediments (Bonatti, 1981). Of particular relevance to this discussion is the effect of hydrothermal circulation on the Fe concentration in basalts. Measurements of hydrothermal fluids in active volcanic and hydrothermal areas in Indonesia and Iceland show great enrichment of the Fe content in the hydrothermal fluids relative to normal sea water (Zelenov, 1964; Björnsson et al., 1972). Moreover, 350 °C hydrothermal fluids sampled at 21°N on the East Pacific Rise are also highly enriched in iron relative to normal sea water (Edmonds et al., 1982). In addition, laboratory experiments of basalt/sea-water reactions at appropriate pressures and elevated temperatures between 100 and 500 °C show many-fold increases in the iron abundance of the reacting hot fluids relative to the initial sea water (Bischoff and Dickson, 1975; Hajash, 1975; Mottl et al., 1979).

The depletion of iron in holocrystalline tholeiites as compared with glassy pillow basalts is thought to be due to removal by hydrothermal circulation (Corliss, 1972). The replacement of magnetite by anatase pseudomorphs and a corresponding decrease in saturation magnetization below 2 km of the 3.1-km crustal section in eastern Iceland is consistent with iron leaching by hydrothermal fluids (Hall, 1985), and drilling in Cyprus (Hall et al., 1985) has shown similar iron depletion. These independent lines of evidence indicate that hydrothermal fluids are highly effective in removing iron from basalts.

The pathways for hydrothermal circulation at spreading centers are principally faults and contraction cracks. In the absence of a sediment cover, hydrothermal fluids vent directly into the overlying cold sea water where they are immediately quenched. The presence of numerous inactive hydrothermal vents on mapped segments of spreading ridges such as the Galápagos spreading center near 86°N (e.g., Corliss et al., 1979) and the East Pacific Rise (McDonald et al., 1980) suggests that many individual hydrothermal vents have rather short lifetimes. Hence, at sparsely sedimented spreading centers, where hydrothermal fluids vent directly to the sea floor, the basalts are likely to have only limited exposure to chemical reaction and leaching by hydrothermal fluids. In such "open" hydrothermal systems, only a relatively small fraction of the rock will be in intimate contact with hydrothermal fluids. The bulk of the iron oxides may remain relatively unaffected. This would explain why high magnetization intensities and coherent high-amplitude magnetic anomalies are observed at exposed spreading centers even in the presence of hydrothermal activity (Klitgord et al., 1975).

At extensively sedimented spreading centers, however, the system of hydrothermal circulation is not open. The sediment cover acts as a cap enclosing the hydrothermal fluids, and only allows release and quenching in limited areas of faulting or thin cover. Hydrothermal fluids may thus have a comparatively long residence time in the basalt, and will cool more slowly while they thermally and chemically equilibrate with the basalt and the overlying sediment. This would result in more complete basalt alteration, leaching of the iron oxides, and diminishing of the corresponding marine magnetic anomalies. We suggest, therefore, that for relatively young, highly sedimented ocean crust, the absence of significant magnetic anomalies may be a positive indicator of regions of pervasive hydrothermal activity. Subdued magnetic anomalies over sedimented ocean crust might thus provide preliminary clues in searching for hydrothermal ore deposits. The particular (ore) minerals precipitating from the hydrothermal solutions are not, of course, predictable from the magnetic anomalies. They will vary, depending upon such factors as the basalt composition and its metal concentrations, as well as temperature, pressure, oxygen fugacity, the alkalinity of the circulating fluids, and the water/rock ratio of the system.

It is important to recognize that a thick sediment blanket deposited contemporaneously with volcanism is not a sufficient condition for pervasive hydrothermal alteration because it does not guarantee the availability of fluid (sea water) or its access to the heat source (magma). However, in the presence of ample hot fluids, the sediment cover is likely to be a critically important factor determining the extent of alteration of the underlying basalts.

IMPLICATIONS

The contrasting effects of "open" and "closed" hydrothermal systems on the extent of mineralization and leaching of magnetic minerals may account for Rona's observation (Rona, 1978a) that only 2 of 17 listed hydrothermal deposits at oceanic spreading centers were accompanied by low-amplitude magnetic anomalies (measured at sea level). It seems likely that the remaining 15 examples with "normal" amplitude magnetic anomalies reflect more "open," sparsely sedimented hydrothermal systems. These would cause less extensive and more localized hydrothermal alteration and demagnetization, not detectable by sea-level magnetometer measurements.

One of Rona's two hydrothermal deposits with low-magnetic anomalies occurs over the Atlantis II Deep in the Red Sea. There, 200 m of hot, dense brines and soft muds (Emery et al., 1969) have probably acted as a blanket, producing a "closed" hydrothermal system and more pervasive and extensive alteration of the underlying basalts. The mineral content of the muds in this deep is the highest in the Red Sea, and it is now regarded as having a high economic potential (Zierenberg and Shanks, 1983). Sediment-hosted sulfides at spreading centers over which there are no magnetic anomalies have now been observed in the southern Guaymas Basin of the Gulf of California (Koski et al., 1985), the Escanaba Trough (Morton, 1985), and the Middle Valley of the northern Juan de Fuca Ridge (E. E. Davis, 1985, personal commun.).

Finally, it seems reasonable to build on the suggestion of Zietz (1970) that metamorphism could be the origin of "quiet zones" and to propose that extensive hydrothermal alteration at a spreading center might also sometimes result in large areas of poorly magnetized ocean crust. Examples of candidate "quiet zones" include: (1) the margins of the Gulf of Aden, where 0.5–1.5 km of sediment overlie poorly magnetized oceanic crust in the age range 20–10 Ma (Laughton et al., 1970); (2) the northern Red Sea, where contemporaneous salt flowage over the spreading center (Girdler, 1985) might have served to produce a sealed hydrothermal system, suppressing lineated magnetic anomalies in Neogene oceanic crust; (3) the thickly sedimented Jurassic oceanic crust along the margin of the northwest Atlantic Ocean, off the east coast of the United States (Zietz, 1970; Vogt et al., 1970). It seems possible that these areas of ocean floor may have been created in narrow, highly sedimented rifts, which would have provided the required conditions for pervasive hydrothermal alteration. With the initiation of a new program of ocean drilling, we suggest that our hypothesis can be tested either by drilling in nonmagnetic, young, sedimented spreading centers or in accessible crustal depths in a magnetic "quiet zone."

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