GEOPHYSICAL RESEARCH LETTERS, VOL. 16, NO. 5, PAGES 477-479, MAY 1989

COMMENT ON "LIMITING DEPTH OF MAGNETIZATION IN CRATONIC LITHOSPHERE"

B. Ronald Frost and Peter N. Shive

Department of Geology and Geophysics, University of Wyoming

Introduction

Toft and Haggerty [1988] present evidence supporting the contention that native metals are major contributors to the magnetic signature of the lower crust and that magnetization in the lower crust should be expected to increase with depth. We believe that the bulk of the petrologic and geochemical information does not support these contentions [Frost and Shive, 1986]. In the following discussion we will argue that the oxygen fugacity of the lower crust and upper mantle is not reducing enough to form native metals and that the reduction seen in the nodules is an artifact of metasomatism that, like many other metasomatic events in nodules, is likely to have been associated with fluids from the kimberlitic magma. We will further argue that the sources responsible for aeromagnetic anomalies are not likely to depend in a simple way on depth.

Oxidation Conditions of the Upper Mantle

Toft and Haggerty's model of native metals in the lower crust is appealing because it widens the field of candidate sources for wavelength magnetic anomalies and because it fits with our general concept that the Earth's crust and mantle become more reducing with depth. After all, native iron is present in the core while hematite is the major iron oxide on the surface of the earth. Surely a gradient in oxygen fugacity with depth, as is implied by Toft and Haggerty [1988], should be expected. However, there is ample evidence indicating that most of the upper mantle is not as reducing as the conditions that are presented here [Wood and Virgo, 1987]. We wish to review this evidence and to provide an alternative interpretation of the rocks described by Haggerty and Toft [1985].

Most peridotites from the upper mantle contain the common assemblage olivine - orthopyroxene - spinel +/- clinopyroxene. This assemblage is a displaced oxygen buffer, namely the equilibrium:

$$\underset{\text{in spinel}}{2\,Fe_3O_4} + \underset{\text{orthopyroxene}}{3\,Fe_2Si_2O_6} = \underset{\text{olivine}}{6\,Fe_2SiO_4} + O_2 \quad (1)$$

Using recent solution models for spinel, Wood and Virgo [1987] showed that most spinel peridotites equilibrated at oxygen fugacities within one log unit of the FMQ buffer. This indicates that the upper mantle (down to about 60 km) is not significantly more reducing than typical crustal igneous rocks [cf. Haggerty, 1973]. Indeed, this is corroborated by results of Haggerty and Tompkins [1983] who show that the oxygen fugacity indicated by ilmenite (with Ti-magnetite reduction lamellae) from kimberlite nodules lies between that of the FMQ and MW buffers.

Because the accumulated evidence indicates that the upper mantle is not highly reducing relative to common crustal rocks, Toft and Haggerty [1988] have a problem in explaining how the nodules they studied became so reduced. Such reduction cannot be accounted for by some simple chemical potential gradient between the lower crust and upper mantle since the upper mantle is not reducing enough to have native metals. Toft and Haggerty [1988] explain the reduction as being caused by a simple pressure effect that will drive oxygen buffers to relatively higher fO_2. This is not a reasonable explanation because the oxygen fugacity of a rock is controlled by buffering assemblages as well. If high pressure will move a certain buffer to higher oxygen fugacity relative to the same buffer at 1 bar, it will do the same to the oxygen fugacity as defined by the petrologic buffer in the nodules. The result would be no change in the relative oxygen fugacity.

Possible Cause for Highly Reducing Conditions Seen in Some Lower Crustal Nodules

An observation that is key to understanding the significance of the metals described by Toft and Haggerty [1988] is that they are texturally late and are associated with a late-stage metasomatic event that produced hornblende and scapolite [see Haggerty and Toft, 1985]. The question becomes, then, to what extend are these clearly metasomatized rocks characteristic of the lower crust and upper mantle? Toft and Haggerty [1988] clearly imply that the magnetic minerals in them are typical of the lower crust, at least the lower crust of West Africa. We contend that this is not necessarily true and that the metasomatic features could well be artifacts of the processes by which the nodules were entrapped and brought to the surface.

A key assumption to investigators studying mineral assemblages in lower crustal and mantle nodules is that these nodules have not been affected by their transport to upper crustal levels. However, evidence for metasomatic enrichment is widespread in mantle nodules [Menzies and Hawkesworth, 1987]. Indeed recent studies of zoned garnets from metasomatized mantle nodules in kimberlites indicate that the matasomatism took place very shortly (on the order of hundreds of years) before the entrapment of the nodule and its quenching by rapid transport to the surface [Smith and Boyd, 1987; Griffin and O'Reilly, 1987].

Given that realization, the highly reducing origin of the opaque phases in the nodules described by Toft and Haggerty (1988) can be explained by the following scenerio. We envision that the nodules originally crystallized at oxygen fugacities near those of the MW buffer, as indicated by the two-oxide thermometer in these rocks [Toft and Haggerty, 1988]. Long after the orig-

Paper number 88GL03830.
0094-8276/89/88GL-03830$03.00

inal assemblage formed, the nodules were invaded by a reducing fluid that was moving upward in advance of the kimberlite magma. This fluid caused both the marked reduction in the rock and the formation of hydrous phases. The nodules were then entrapped in the kimberlite melt and transported rapidly toward the surface.

Increase of Magnetization with Depth?

The susceptibilities of Toft and Haggerty's nodules are positively correlated with density and iron content. They conclude from this that magnetization intensities in the lower crust should increase with depth. If this were true, it could have an extremely important bearing on the "missing magnetization" problem, in which lower crustal rocks studied to date are not strongly magnetic enough to account for long wavelength magnetic anomalies [Shive and Fountain, 1988]. One would simply argue that samples from deeper in the crust could provide the necessary magnetization.

Unfortunately, there are several reasons why such a simple relationship of magnetization with depth is not justified by their study. First of all, it depends on the assumption that uncompressed density increases with depth. Although this may be true in a very general sense, detailed studies of lower crustal cross sections [Fountain and Salisbury, 1981] show a very heterogeneous mixture of rock types which would give a complex variation of density with depth.

Secondly, the conclusion assumes that magnetization intensity is well correlated with iron content and density. In fact, the total iron content is a much less important factor than the fraction of that iron in ferromagnetic phases. This "ferromagnetic efficiency factor" has no significant positive correlation with iron content or with density in typical lower crustal rocks [Williams et al., 1985; Shive and Fountain, 1988]. It is much more closely tied to mineral reactions like those accompanying granulite metamorphism [Schlinger, 1985; Mayhew and La Brecque, 1987] or serpentini-zation [Saad, 1969]. In serpentines, of course, the correlation with density is just the opposite of the relation postulated by Toft and Haggerty.

Finally, these rocks are weakly magnetic. They are, by Toft and Haggerty's own admission, not candidate sources for long wavelength magnetic anomalies. The most magnetic contains about 0.1% ferromagnetic volume, far less than the average for typical lower crustal rocks [Wasilewski and Fountain, 1982; Schlinger, 1985; Williams et al., 1985; Shive and Fountain, 1988], which are themselves too weakly magnetic to account for the anomalies. But the iron contents of these nodules (6-14%) are in the range of typical lower crust and upper mantle rocks. The nodules, therefore, are atypically depleted in ferromagnetics with respect to what has been observed and what is required for the lower crust. Because of this, they are not appropriate samples from which to draw broad conclusions about magnetization trends in the deep crust. At best, they suggest that magnetization increases with density for certain samples containing very small amounts of magnetic minerals.

Conclusions

One of the big problems in characterizing the mantle and the lower crust comes from the fact that petrologists cannot sample these rocks directly. We must instead rely upon the fortuitous samples that are provided by xenoliths or upthrust blocks. Unfortunately both sampling techniques tend to bias the type of samples that we see. When considering the significance of the metal-bearing rocks described by Toft and Haggerty [1988], it must be considered that these features could be an artifact of the process by which the nodules came to the surface. Of course, since one cannot sample "normal" lower crust or upper mantle without the assistance of kimberlites or alkali basalts, it cannot be proven that the metals are produced by the process we describe above. It is possible that the kind of late, reducing metasomatism that is described by Haggerty and Toft [1985] was locally present throughout the lower crust and the upper mantle. However, even if the rocks described by Haggerty and Toft [1988] are widespread in the mantle, they cannot be the source of long wavelength anomalies, because they do not contain enough magnetic material.

References

Fountain, D.M. and M.H. Salisbury, Exposed cross-sections through the continental crust: Implications for crustal structure, petrology and evolution. Earth Planet. Sci. Lett., 56, 263-277, 1981.

Frost, B.R. and P.N. Shive, Magnetic mineralogy of the lower continental crust. J. Geophys. Res. 91, 6513-6521, 1986.

Griffin, W.L. and S.Y. O'Reilly, The composition of the lower crust and the nature of the continental Moho - xenolith evidence, in Mantle Xenoliths, edited by P.H. Nixon, pp. 413-430, Wiley, New York, 1987.

Haggerty, S.E., Opaque mineral oxides in terrestrial igneous rocks. Rev. Min. 3, Hg101-Hg300, 1976.

Haggerty, S.E. and P.B. Toft, Native iron in the continental lower crust: petrological and geophysical implications, Science, 299, 647-649, 1985.

Haggerty, S.E. and L.A. Tompkins, Redox state of Earth's upper mantle from kimberlitic ilmenites. Nature, 303, 295-300, 1983.

Mayhew, M.A. and J.L. LaBrecque, Crustal geologic studies with magsat and surface magnetic data, Reviews of Geophys., 25, 971-981, 1987.

Menzies, M.A. and C.J. Hawkesworth, Mantle Metasomatism, Academic Press, London, 472p. 1987.

Saad, A., Magnetic properties of ultramafic rocks from Red Mountain, California. Geophysics, 34, 974-987, 1969.

Schlinger, C.M., Magnetization of the lower crust and interpretation of regional magnetic anomalies: Example from Lofoten and Vesteralen, Norway. J. Geophys. Res., 90, 11,484-11,504, 1985.

Shive, P.N. and D.M. Fountain, Magnetic mineralogy in an Archean crustal cross section: Implications for crustal magnetization. Jour. Geophys. Res., 93, 12177-12186, 1988.

Smith, D. and Boyd, R.F., Compositional heterogeneities in a high-temperature lherzolite nodule and implications for mantle processes, in Mantle Xenoliths, edited by P.H. Nixon, pp. 551-563, Wiley, New York, 1987.

Toft, P.B. and S.E. Haggerty, Limiting depth of magnetization in cratonic lithosphere. Geophys. Res. Let., 15, 530-533, 1988.

Wasilewski, P. and D.M. Fountain, The Ivrea zone as a model for the distribution of magnetization in the continental crust. Geophys. Res. Lett., 9, 333-336, 1982.

Williams, M.C., P.N. Shive, D.M. Fountain and B.R. Frost, Magnetic properties of exposed deep crustal rocks from the Superior Province of Manitoba. Earth Planet Sci. Lett., 76, 176-184, 1985.

Wood, B.J. and D. Virgo, Oxidation state of the upper mantle, ferric-ferrous ratios in coexisting minerals from spinel lherzolites. Geol. Soc. Amer. abstracts w. programs, 19, 896, 1987.

B. R. Frost and P. N. Shive, Department of Geology and Geophysics, University of Wyoming, Laramie, WY 82071.

(Received September 6, 1988;
revised November 18, 1988;
accepted January 13, 1989.)