Reports

Geomagnetic Variations in the Eastern United States: Evidence for a Highly Conducting Lower Crust?

Abstract. *Temporal geomagnetic variations, recorded at ten stations across the east-central United States, are interpreted in terms of the electrical conductivity structure of the earth beneath this region. The results are surprising and suggest that the lower crust is highly conducting, having distinct lateral variations in conductivity beneath the Appalachian Mountains.*

We recently recorded temporal variations in the geomagnetic field at stations 50 km apart along a line from Clarksburg, West Virginia, to Locustville on the eastern shore of Virginia (Fig. 1). The line is oriented roughly perpendicular to the geologic strike of the region, passes through the U.S. Geological Survey's Geomagnetic Center near Fredericksburg, Virginia, and crosses the Allegheny Basin, Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain provinces of the eastern continental edge. (A schematic geologic cross section along this profile can be seen in Fig. 2). The geomagnetic variations, with periods of a few minutes to several hours, were recorded digitally with three-component flux-gate magnetometers, which were usually placed in back buildings of private residences and farms. Our objective was to obtain information on the deep electrical conductivity structure beneath the continental margin.

Geomagnetic variations with periods ranging from 1 second to several years have been used before to infer the conductivity structure of the earth both globally (*1*) and locally (*2*). Variations in the geomagnetic field due to electric currents flowing in the ionosphere and magnetosphere induce eddy currents in the earth with horizontal scale lengths of several thousand kilometers at mid-latitudes and vertical distributions of the order of the characteristic skin depth (*3*). The skin depth is a function of both the frequency of the variation and the electrical conductivity of the earth. The magnetic variations observed at the earth's surface are therefore the combined effect of the external and internal current flow. In the absence of lateral variations of electrical conductivity within the earth, the net effect of the induction (according to Lenz's law) is to approximately double the external horizontal variations while almost nullifying the vertical component. Where lateral conductivity contrasts exist, the induced currents flow preferentially in regions of higher horizontal conductance, giving rise to anomalously large vertical variation fields at the edges of these zones. These anomalies are perhaps best visualized in terms of the elementary Biot-Savart law. No vertical field is observed by a magnetometer situated over a horizontally uniform current sheet, but a net vertical field is observed where there is an imbalance of current on one side of the magnetometer relative to the other. The spatial and frequency dependence of these geomagnetic variation anomalies may be interpreted in terms of the lateral and vertical extent of the conductivity anomalies.

The geomagnetic data obtained in the survey were not simultaneously recorded at all ten stations. A technique of interpretation was therefore used in which the variations of the vertical component at a particular period and station are cross-correlated with corresponding variations of the two horizontal components (*4*). The final product of the analysis is a normalized vertical component (Z) deduced for a variation of unit magnitude in the horizontal component perpendicular to the geologic strike of the region. This normalized vertical component is complex, and its real and imaginary parts are plotted. There is an independent normalized vertical component deduced for a variation of unit magnitude in the horizontal component parallel to the geologic strike, but in approximately two-dimensional regions it is inconsistent from profile to profile, and we do not use it in our interpretation.

Continental margins can be classified by their response to these variations in the geomagnetic field. The contrast in conductivity between the ocean and the adjacent continent usually produces a major anomaly in the vertical variation field, which is known as the "geomagnetic coast effect" (*5*). The vertical geomagnetic variations, over a wide range of frequencies, are larger than usual at the continental edge,

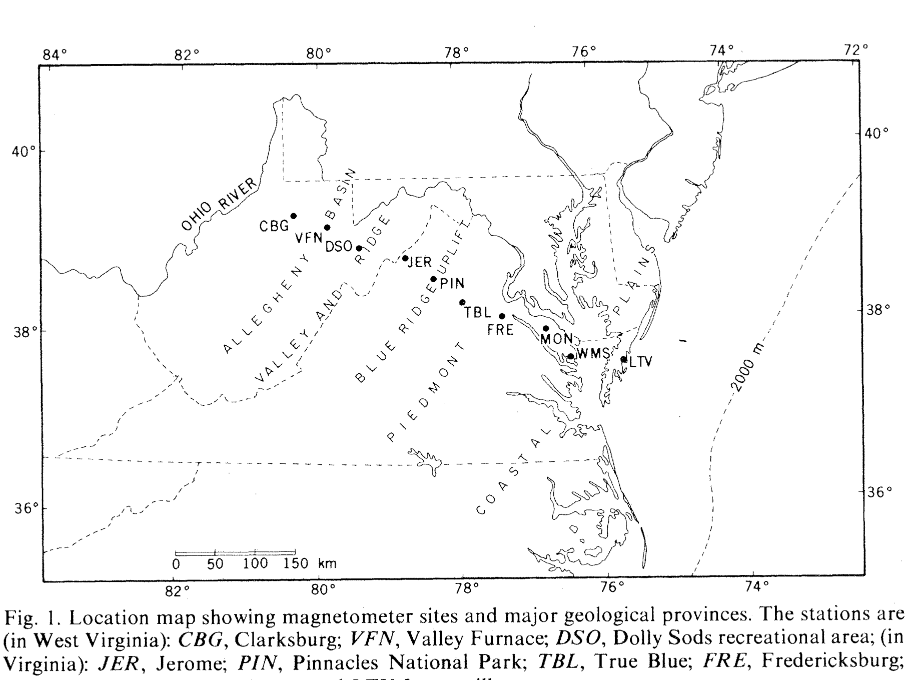

Fig. 1. Location map showing magnetometer sites and major geological provinces. The stations are (in West Virginia): *CBG*, Clarksburg; *VFN*, Valley Furnace; *DSO*, Dolly Sods recreational area; (in Virginia): *JER*, Jerome; *PIN*, Pinnacles National Park; *TBL*, True Blue; *FRE*, Fredericksburg; *MON*, Montross; *WMS*, Weems; and *LTV*, Locustville.

decaying slowly inland. The origin of this coast effect is evidently a concentration of the induced currents offshore, within either the highly conducting layer of seawater or a more highly conducting upper mantle beneath the ocean floor, or both.

Examples of the coast effect for several continental margins at a period of 1 hour are shown in Fig. 2A. The normalizing horizontal field is taken perpendicular to the mean continental edge in each case. Only the real part of the anomaly is shown. Everett and Hyndman (*6*) recognized that old, stable continental margins, such as those of southwestern Australia and the British Isles, exhibit larger, more persistent coast effects than the tectonically active margins, such as California. They suggest that the higher conductivities within the upper mantle beneath the landward side of these active margins both lowers the conductivity contrast across the margins and inductively damps the landward decay of the coast effect relative to that at the stable margins. The California data show, in addition to the less pronounced coast effect, a definite anomaly reversal coinciding with the Sierra Nevada Range, a relatively recent orogeny. The Peru data, clearly anomalous in comparison with the data for the other continental margins, probably reflect a large, highly conducting zone beneath the younger Andes (*7, 8*).

The eastern margin of North America is not a tectonically active region, and we would have expected a large, persistent coast effect. Hyndman and Cochrane (*9*) observed, however, that the Fredericksburg geomagnetic observatory records exceptionally small vertical variation fields at all frequencies despite its location at the edge of an eastward-thickening prism of highly conducting sediments and seawater. The data from our own stations, shown in Fig. 2A, confirm this surprisingly small coast effect and show in addition a marked reversal in the field due to a concentration of current well inland from the coast.

We have analyzed the results in terms of the electrical conductivity structure in the earth, using two-dimensional models (*8, 10*). These models have been used successfully to fit the observed data at other continental margins in terms of reasonable conductivity structures for the upper mantle and crust. Figure 2B compares the data at a period of 16 minutes with the response predicted by a model having "normal" crustal resistivities and an upper mantle conductivity structure suitable for stable continental regions (*11*). The experimental profiles at 16 minutes are similar in shape

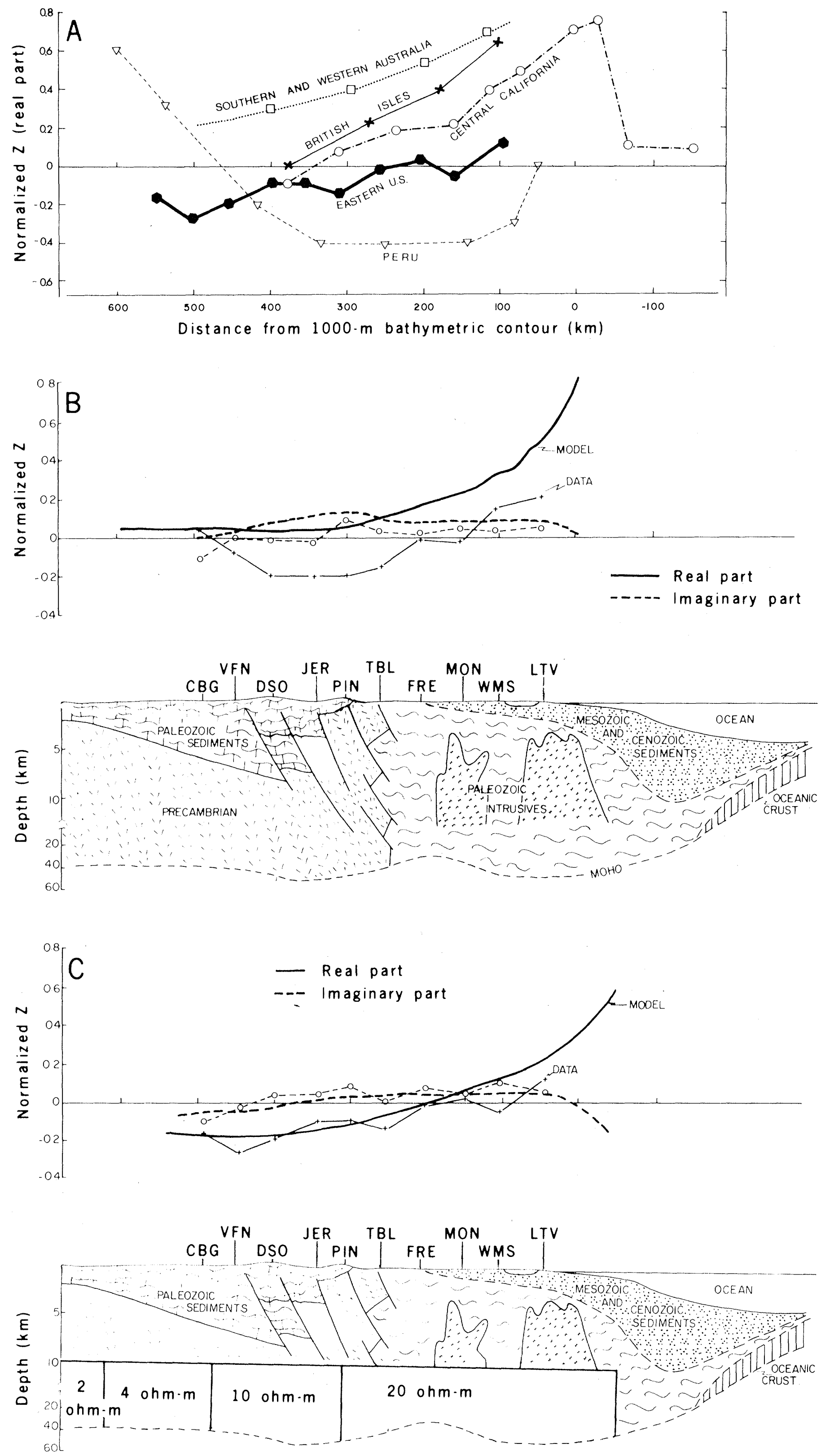

Fig. 2. (A) Real part of the normalized vertical field variations (Z), at a period of 1 hour, as a function of distance from the continental margin for several coasts: British Isles, measured eastward from the western margin of Ireland (*20*); central California (*21, 22*); Peru (*7*); southwestern Australia (*6*); and eastern United States (present survey). The rapid decay of Z amplitudes in the British Isles compared to the other "stable" (Australian) continental margin reflects flow of electric current in the Irish Sea. (B) Normalized vertical field variation at a period of 16 minutes compared with model results based on the geological cross section shown and on "normal" crustal and upper mantle conductivities (*11*). (C) Normalized vertical field variations at a period of 1 hour compared with the results obtained with a conductivity model which provides a reasonable fit to the data at all frequencies. Resistivities not shown directly on the cross section are discussed in (*11*).

to those obtained throughout the range 4 to 60 minutes. The fit of the data to the model at 16 minutes is clearly poor; it improves at shorter periods than 16 minutes but deteriorates at longer periods. Over the Coastal Plain, the vertical field amplitudes predicted by the model are too large. Moreover, the model does not predict an appreciable reversal in the real part of the vertical field at periods of 10 minutes and longer despite the generously high conductivities ascribed to the Allegheny Basin (*12*). We find that the observed attenuation of the vertical fields east of the Blue Ridge requires very high conductivity in the middle to lower crust beneath the Coastal Plain, but this by itself has the unwanted effect on model results of producing large vertical fields, of the wrong sign, west of the Blue Ridge. The observed fields can best be matched by continuing this lower crustal zone, with even higher conductivities, westward under the Appalachians and continental craton.

A two-dimensional conductivity structure which provides a reasonable fit to the data at all periods used is shown in Fig. 2C. This model is not unique, but every model tried that comes close to fitting the data predicts comparable conductivities at similar depths. We could not adequately fit the data with models in which the highly conducting zone was confined to the upper mantle. Besides, high conductivity in the upper mantle is usually associated with high heat flow, high seismic wave attenuation, and low P_n seismic wave velocities, which are not observed in the region. The proposed conductivity structure—a highly conducting lower crust with a definite lateral variation of conductivity in the vicinity of the Appalachians—is not inconsistent with other geophysical results from this region and elsewhere. High-conductivity lower crustal layers have often been invoked in other areas of the world in the interpretation of geomagnetic variation (*9*, *13*) and magnetotelluric (*14*) data. The proposed lateral change in conductivity beneath the Blue Ridge coincides with the boundary beneath the eastern and central provinces of the eastern United States defined on the basis of seismic heat flow and gravity data (*15*). To the east of this boundary the heat flow and Bouguer gravity are higher and the crust is thinner than to the west. Similar lateral variations in conductivity have been reported beneath recent orogenic belts such as the Andes (*7*) and the Rockies (*16*) and beneath ancient orogenic zones such as the Canadian Appalachians (*4*). The former anomalies probably result from unusually high upper mantle temperatures, whereas the latter result, like our own, is more difficult to explain geochemically or geophysically.

How can the conductivity of crystalline rock at a depth of 15 km be two to three orders of magnitude greater than that at the earth's surface? One explanation is that the rocks of the lower crust in the region are unusually water-rich. An amphibolitic lower crust has already been proposed for the study region (*17*) on the basis of gravity and seismic refraction data, and it is generally recognized (*18*) that such hydrated lower crustal rocks could have anomalously high conductivities. It is possible that during subduction at some continental margins segments of oceanic crust become trapped at shallow depths and retain their water-rich character over long periods of time. This would support the idea of Law and Riddihough (*19*) that conductivity anomalies found today in areas of no obvious tectonism may mark very ancient zones of orogeny and subduction.

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Aerosols and Polar Temperature Changes

Abstract. *Calculations indicate that aerosols are not directly responsible for the present increase in ice abundance in the Northern Hemisphere. Indeed it appears that aerosols cause heating of the atmosphere near the poles. The present background aerosol density at 85°S latitude causes a temperature increase of ~ 0.2°K, while that at 85°N causes an increase of ~ 0.05°K.*

Kukla and Kukla (*1*) report that the annual mean snow and ice coverage in the Northern Hemisphere increased by 12 percent in 1971 and that since then the coverage has fluctuated about this higher value. Hamilton and Seliga (*2*) suggest that aerosol particles in the atmosphere over both polar regions are responsible for the observed changes in surface temperature of the polar ice sheets and hence for ice abundance increases. They assume that aerosols increase the atmospheric turbidity and conclude that this causes a reduction in the surface temperature. This conclusion is based solely on the globally averaged annual atmospheric calculations of Rasool and Schneider (*3*). I have investigated the possibility that aerosols over the polar regions are directly responsible for the recent ice and snow increase by calculating, explicitly for summer conditions, the expected temperature change due to aerosols over both 85°N and 85°S latitude.

The physical conditions at both polar regions in summer differ from each other and from the average annual global condi-