Reports

The East Coast Magnetic Anomaly

Abstract. *A model is proposed for the East Coast Magnetic Anomaly that, for the first time, incorporates an observed basement feature—a normal fault that consistently lies below the landward flank of the anomaly. The East Coast Magnetic Anomaly is similar to slope anomalies found over passive continental margins in many parts of the world. Thus the proposed model can be used to interpret slope anomalies in general.*

The East Coast Magnetic Anomaly (ECMA) was first revealed in its entirety as a result of an aeromagnetic survey of the eastern continental margin of the United States conducted by the U.S. Naval Oceanographic Office (*1*). Previous to that, numerous observations on a smaller scale, beginning with Keller *et al.* (*2*), had indicated the presence of such an anomaly. Summaries of the efforts to explain the ECMA are given by Drake *et al.* (*3*) and Rabinowitz (*4*). Magnetic anomalies arise principally from rocks that make up the basement. A weakness of all existing models of the ECMA is that information about the nature and configuration of the basement below the ECMA has been lacking.

The ECMA is a striking, continuous, linear feature extending from Georgia to Nova Scotia. It consists of a magnetic high flanked by magnetic lows. North of the New England Seamounts and south of Cape Hatteras, the ECMA is centered over the continental rise, whereas in the central region the center of the anomaly is near the shelf break and sometimes crosses onto the shelf. The latter is the case for the region of the Baltimore Canyon Trough east of Atlantic City, New Jersey, where line 6 from the Large Aperture Seismic Experiment (LASE) was shot. LASE line 6 is nearly coincident along its length with U.S. Geological Service (USGS) line 25 (*5*). The center of the ECMA on both of these lines is located on the continental shelf approximately 20 km west of the shelf break.

The three most frequent explanations for the cause of the ECMA are a buried continuous basement ridge (*6, 7*), an edge effect arising from the juxtaposition of rock bodies with different magnetic properties at a major crustal discontinuity (usually the ocean-continent boundary) (*7–9*), or a body with high magnetization below the anomaly (*10–12*). The idea of the basement ridge arose from the observation that a geologic layer in which seismic waves travel with high velocity became shallower near the shelf edge. Recent evidence (*13*), however, indicates that a layer that transmits seismic waves at low velocity underlies the rocks that transmit at high velocity, which is evidence against the existence of a shallow basement ridge. The edge-

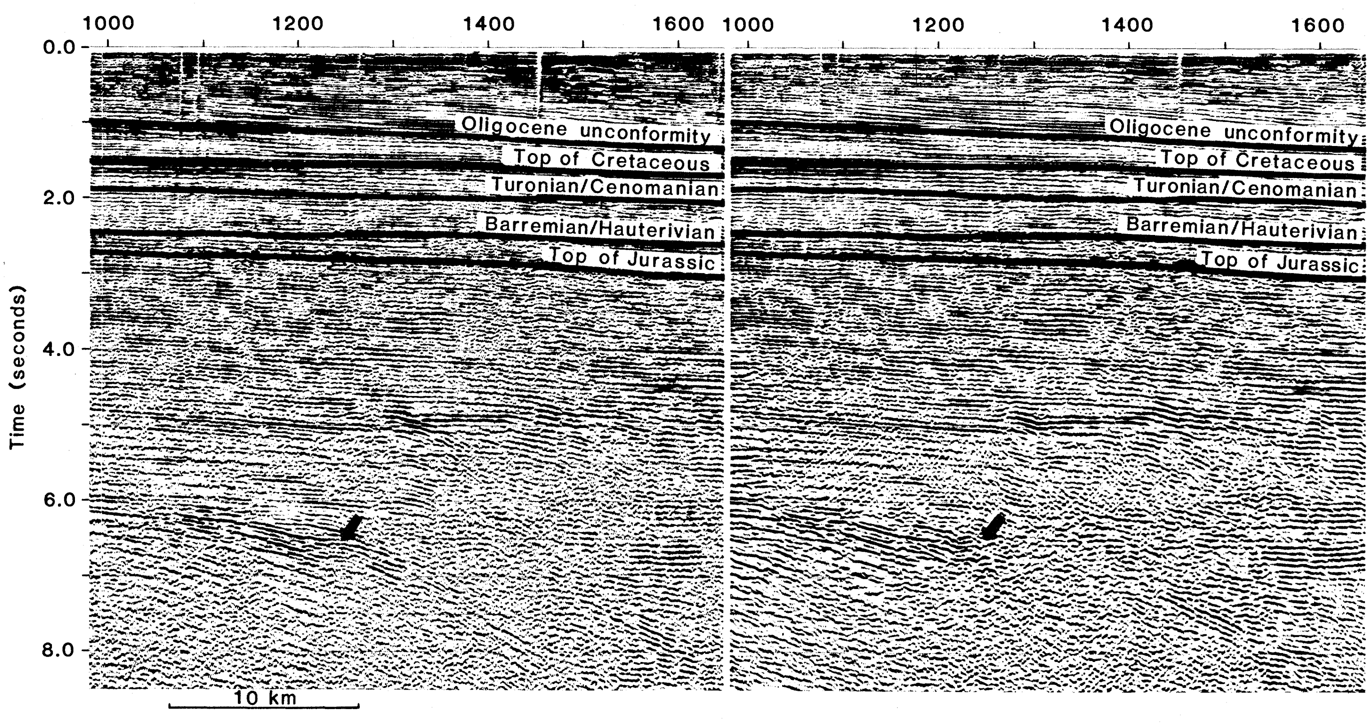

Fig. 1. Two time sections of LASE line 6. The time measured is the time for a sound wave to travel from the surface to a geologic boundary and back. The numbers along the top are the common-depth-point numbers, which correspond to where, along the line, measurements were taken. The prominent reflector at 6.5 seconds (approximately 16 km down) is believed to be the top of the basement or a geologic boundary close to basement. This boundary predates all the stratified layers seen in the Baltimore Canyon Trough, and we attribute the faulting that displaced it to early rifting. The arrows point to the diffraction for the normal fault.

effect models postulate that the rocks on the oceanic side are either less magnetic than the rocks on the continental side or that they are reversely magnetized. These models generally have difficulty explaining the negative anomaly that lies immediately landward of the ECMA positive anomaly. As for highly magnetized bodies below the ECMA, direct proof for them is lacking.

A proposed magnetic model. We were guided by the following considerations in the development of a new magnetic model for the ECMA.

1) A normal fault in the basement is observed in connection with the ECMA. We give an example of such an observation in Fig. 1, which shows two time sections for LASE Line 6. The right section of Fig. 1 has been migrated; the left, has not. What appears to be a dipping basement below 6 seconds on the unmigrated section is revealed to have been a diffraction that, in the right section, is collapsed to reveal a normal fault in the basement, the East Coast Boundary Fault. The fault lies about 100 km east of the coast. A diffraction similar to that on the left section of Fig. 1 is observed on USGS line 25 at shot point 2000. On USGS line 25, the fault occurs 20 km landward of the ECMA and 40 km landward of the present shelf break. Similar diffractions are observed on USGS line 26 (at shot point 1900) and on USGS line 6 (at shot point 1050) as well as on a large number of unpublished seismic reflection profiles in the Baltimore Canyon Trough. These diffractions all begin at about 6 seconds on the time sections, and they occur slightly landward of the ECMA. The correlation of the East Coast Boundary Fault with the landward gradient of the ECMA was important to the development of our model.

2) Highly positive magnetic amplitude is evidence for a strongly magnetic underlying body. Such a body is almost certainly associated with the normal faulting.

3) Finally we assumed that the ECMA must arise from causes similar to those responsible for slope anomalies observed at other margins. Therefore we designed a model similar to that proposed for the magnetic anomaly on the continental slope off southern Australia (*14*). A normal basement fault with a vertical offset of 5 km was an important feature of the Australian model. This vertical offset juxtaposed magnetized continental crust against water and sediments that are nonmagnetic and that overlie the downthrown continental block, giving rise to an "edge effect." While the edge effect was able to repro-

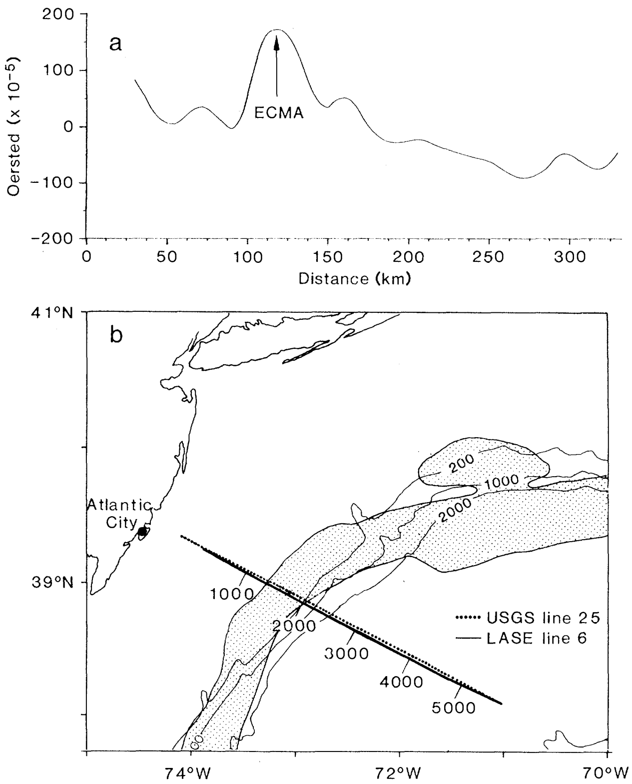

Fig. 2. (a) The magnetic amplitude observed along USGS line 25. The peak of the ECMA is indicated. (b) USGS line 25 and LASE line 6. The stippled area represents the peak of the ECMA. Along USGS line 25, the peak of the ECMA lies entirely on the shelf. Several common-depth-point numbers are indicated on LASE line 6 to facilitate comparison with Fig. 1. Bathymetric contours are in meters.

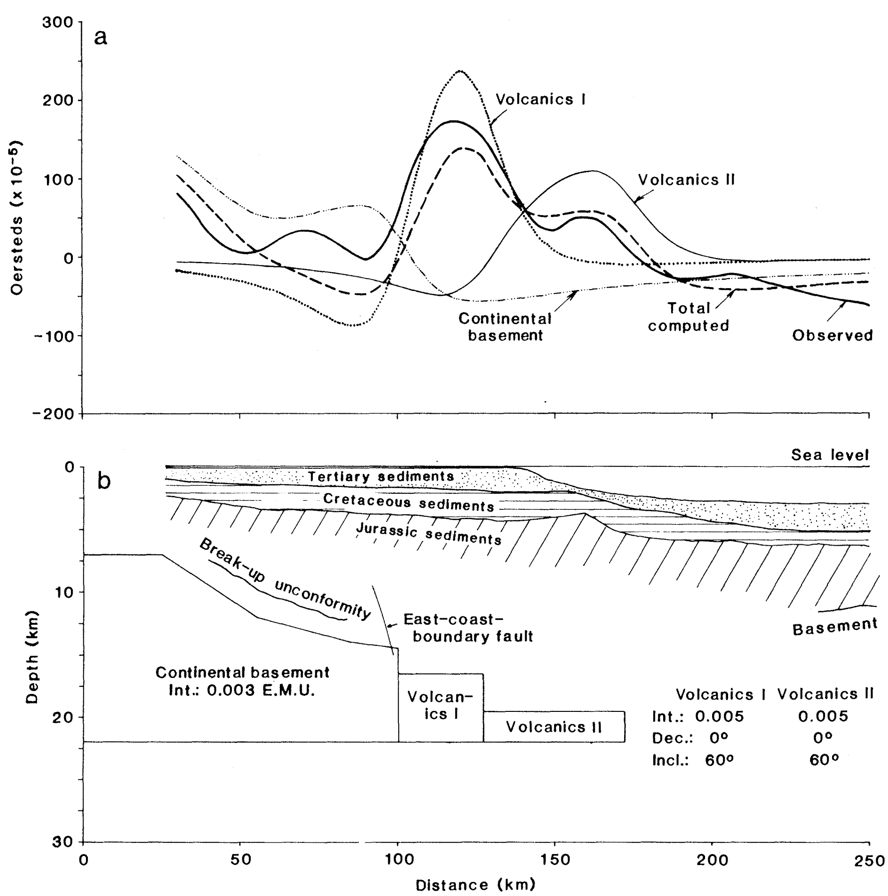

Fig. 3. (a) Comparison of the observed ECMA along USGS line 25 with the magnetic anomaly computed from our model. The individual contributions from the three components of the model—the continental basement and two "volcanic" blocks—are also indicated. (b) A two-dimensional model for the structure we believe is responsible for the ECMA. The position of the East Coast Boundary Fault is shown. The boundaries and identification are from the depth section for USGS line 25 by Grow (*5*). The blocks of the model lie below the breakup unconformity.

duce the most important features of the observed Australian anomaly, it was not able to match it completely; a composite model was needed. The completed model included a highly magnetized body within the 25-km-wide strip of the continental crust closest to the edge. Geologically this highly magnetized material can be thought to arise from intrusions and extrusions of volcanic material related to the fault in the basement.

The ECMA is an extended linear feature, so we used a two-dimensional model to explain it. The magnetic profiles for LASE line 6 and USGS line 25 were taken from a recent USGS map (*15*). The amplitude of the ECMA along USGS line 25 is lower than normal, and it has an unusual second lobe seaward of the main peak. Figure 2a shows the magnetic profile after regional effects have been filtered out.

Along LASE line 6, the seismic refraction data (*13*) do not constrain the basement depth exactly. A vertical offset of 2 km for the observed normal fault appears reasonable.

The magnetic anomaly can be modeled as a composite of two effects, namely highly magnetic material in the basement and an edge effect, as on the Australian margin. In the final model chosen for the ECMA, we assumed that the edge of the rift consists of two normal faults (about 25 km apart), one with a vertical offset of 2 km and the second with an offset of 3 km, and that intrusives with a high intensity of remanent magnetization are present in the downthrown blocks, as shown in Fig. 3. The seismic structure shown in Fig. 3 is from Grow (*5*). A standard two-dimensional magnetics calculation for the anomaly that would arise from each body was made. The parameters for the remanent magnetization that give good fit are an intensity of 0.005 emu, a declination of 0°, and an inclination of 60°. This is supported by the data of Opdyke and Wensink (*16*), who obtained average values for declination and inclination of 358° and 59°, respectively, from measurements of 12 samples of lower-Jurassic volcanics from White Mountain [also see (*17*)]. The value of the magnetic susceptibility chosen for the continental basement was 0.003 emu. The top of the continental basement is placed at a small depth beneath the breakup unconformity. Figure 3 indicates that this simple model yields good results.

Our model differs from earlier models in two important ways. First, the edge effect arises from a vertical fault because magnetized continental basement is juxtaposed against sediments. Second, the material with the higher magnetic intensity arises from highly magnetized material being intruded into a depression caused by early rifting (*18*) instead of from a basement ridge.

We suggest that the two blocks in the model are an approximation of a complicated succession of downthrown blocks along listric faults that begins at the normal fault in the basement. This succession undoubtedly varies along the normal fault, and such a variation would be reflected in the shape of the ECMA at different positions along the coast. In particular, since the eastern lobe of the ECMA is not observed along most of the trend of the ECMA, a highly magnetized block downthrown eastward is not an essential part of the model.

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17. Shallower directions of magnetization were found by T. E. Smith and H. C. Noltimier [*Am. J. Sci.* **279**, 778 (1979)] for rocks of similar age. But these shallower directions will not significantly change the results of the present calculations.
18. We have used the terms "intrusions" and "intruded blocks" somewhat loosely in this report. The high values of magnetization suggest that at least part of the rocks consist of extrusives. In Fig. 3 we have labeled these blocks "volcanics."
19. We thank John Ewing, Mary Rogan, and Charles Drake for reviewing our manuscript and Gulf Research & Development Company for permission to publish it.

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The Variability of Holocene Climate Change: Evidence from Varved Lake Sediments

Abstract. *Varved sediments from a lake near the present forest-prairie border in northwestern Minnesota provide an annual record of climate change for the last 10,400 years. Climate-sensitive mineral, chemical, and biological components show that the mid-Holocene dry interval between 8500 and 4000 years ago is asymmetrical and actually consists of two distinct drier pulses separated by a moister interval that lasted about 600 years. Cyclic fluctuations with periods of several hundred years were abrupt and persistent throughout the Holocene and are most clearly recorded within the two drier pulses.*

The mid-Holocene is recognized as a time of unusually warm or dry climate (or both) in Europe and North America (*1, 2*). In Minnesota, prairie vegetation such as grasses (Gramineae) and sagebrush (*Artemisia*) expanded eastward into forested regions of the state between about 8500 and 4000 years ago as climate became more arid (*3, 4*). This prairie period was drier than at present, but evidence is somewhat equivocal as to whether it was colder or warmer.

Elk Lake is situated in a forested region of Minnesota at the headwaters of the Mississippi River, close to the present forest-prairie border (Fig. 1). Elk Lake is typical of moderately deep (>20 m), dimictic, hardwater lakes with $CaCO_3$-rich sediments (marl) that are common in the glaciated regions of the north central and northeastern United States. It differs from most other lakes of this type, however, in that the entire Holocene sediment section has preserved annual layers of sediment (varves). The sediments contain several climate-sensitive components that record variability of climate changes, and the varves provide precise time calibration of the rates and timing of these changes. The presence of varves with climatically sensitive components and the location of Elk Lake in a part of North America with steep climatic gradients today (*1*) suggested that Elk Lake could provide a high-resolution (annual) paleoclimatic record of the Holocene.

Piston cores of the 20-m varved Holo-