GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 13, PAGES 1597-1600, JUNE 15, 1996

Deep electrical conductivity structures of the Appalachian Orogen in the southeastern U.S.

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Abstract. Long period magnetotelluric data across the southeastern Appalachians image deep crustal and upper mantle relics of ancient orogenic events. Inversions of the responses show: (1) Beneath the Appalachian mountains there is a sub-horizontal conductor at 15 - 20 km depth which dips to the southeast at the surface trace of the Brevard fault. (2) At the location of the Central Piedmont suture, there is a crustal conductor which dips towards the southeast, interpreted as a structure related to the Acadian suture. (3) Upper mantle conductors were found at 80 km depth northwest of the Blue Ridge and at 140 km depth southeast of the Eastern Piedmont. Between these, there is a northwest-dipping resistive gap, possibly representing the remnant structure of the Alleghanian collision.

Introduction

The Atlantic continental margin (Fig. 1) is a simple passive margin that belies its complex tectonic history of multiple orogenies. Cambrian extensional tectonics created the Iapetus and Theic-Rheic oceans, and Inner Piedmont and Eastern Piedmont terranes, between the North American and African cratons, with three subsequent major tectonic events. First, the Inner Piedmont was thrust over North America during the Ordovician to Silurian Taconic orogeny. The Eastern Piedmont then collided with North America as the Iapetus Ocean closed in the Devonian Acadian orogeny Finally, the Alleghanian orogeny records Late Palæozoic collision between Gondwana and North America, creating of Pangæa and building the Appalachian mountains. This orogen exposed North American basement through tectonic windows (e.g., Grandfather Mountain Window).

The deep crustal structure of the southeastern Appalachians (Fig. 4a) is mostly inferred from seismic reflection studies [e.g., *Cook et al.*, 1983]. Profiles over the Blue Ridge and Valley & Ridge regions show a package of subhorizontal reflectors at depths of 6 km to 15 km over 260 km in horizontal extent. These reflectors are interpreted as underthrust sediments, implying that the Alleghanian orogeny horizontally displaced pre-existing geological provinces. East of the Brevard Fault the seismic interpretation is not unique, and other geophysical surveys are necessary to reveal the internal structure of this multiply-deformed orogenic belt.

During Spring, 1994, we conducted a deep-probing magnetotelluric (MT) survey in the Carolinas, Tennessee and Kentucky from the coast inland for over 600 km. Our experiment was coordinated with a high-frequency MT survey (P.E. Wannamaker) and deployment of an array of ocean-bottom instruments (A.D. Chave and colleagues). The total experiment is comparable in scale and scope to the EMSLAB experiment [*EMSLAB*, 1989] which studied the active margin of northwestern North America. However, in comparison with the many EM studies of active continental margins, the electrical nature of the lithospheric transition from an oceanic to a continental plate beneath a passive margin has not previously been studied.

Prior electromagnetic studies

Induction arrows, which display the vertical to horizontal magnetic field ratio and point towards current concentrations in zones of enhanced conductivity, from geomagnetic depth sounding (GDS) studies across the northern Appalachians in the 1970s show weak coast effects and point towards the mountains [see *Greenhouse and Bailey*, 1981]. These observations imply high conductivity in the lower crust, with conductivity increasing from the coast westwards but terminating west of the Appalachians. Controlled-source, electromagnetic experiments support the existence of increased conductivity in the lower crust beneath the Appalachians in the Adirondacks [*Connerney et al.*, 1980] and the Georgia Piedmont [*Thompson et al.*, 1983]. The spatial colocation of this conductor with surface metamorphic grade led *Greenhouse and Bailey*, [1981] to propose a crustal evolution model involving free water in the lower crust.

Data acquisition and analyses

Our MT survey was undertaken to image these Appalachian conductors with higher precision than before. The data were acquired with a new generation, high-sensitivity, ring-core fluxgate-based magnetotelluric system (LIMS: Long-period Intelligent MT System). Twenty-seven sites were occupied using fifteen LIMS during March-May, 1994. Most of them were on

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Paper number 95GL03601
0094-8534/96/95GL-03601$05.00

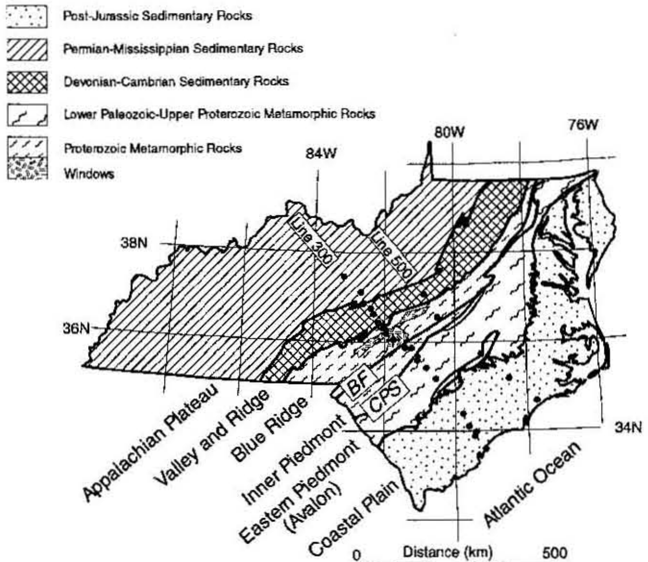

Figure 1. Magnetotelluric site locations (dots) and geological provinces. BF: Brevard fault; CPS: Central Piedmont Suture.

the main profile (Line 300, Fig. 1), with five on an auxiliary profile (Line 500) for 2D control. The sampling interval was 5 s, with a recording duration of typically three weeks, but which ranged from one to seven weeks.

The MT responses from all Inner Piedmont sites on the 300 line exhibit strong current channeling effects and out-of-quadrant phases even after tensor decomposition. At these long periods, electrical current is flowing almost exclusively along the geological strike direction (TE mode responses), and it proved almost impossible to obtain high quality estimates of the perpendicular responses (TM responses) due to low signal levels and high noise levels. The geomagnetic responses are relatively free of severe regional-scale distortion.

Impedance tensors and geomagnetic transfer functions, with jackknife error bounds, were estimated using robust, remote-reference methods 6 and 8 described in *Jones et al.* [1989]. Below 100 s, method 6 (Jones-Jödicke) gave superior estimates. Between 100 s and 1,000 s the two methods gave virtually identical results. Above 1,000 s, method 8 (Chave-Thompsom) gave superior estimates. The responses were merged in the period band 100-300 s.

Induction arrows

Short period real induction arrows at Blue Ridge stations (Fig. 2a) show off-profile components, indicative of 3D structure. This suggests that the distribution of the exposed resistive basement window crust has a southwestern edge on the main profile at depth. Note the strong convergence of induction arrows toward the Central Piedmont Suture. Longer period induction arrows point towards the Appalachian mountains, consistent with previous GDS studies further north. These arrows are pointing away from the boundary between the Eastern Piedmont and the Coastal Plain, suggesting resistive structures beneath that boundary.

In the Coastal Plain, the Line 300 induction arrows are pointing at a large angle to the profile, showing 3D effects with anomalies to the east (the ocean) and south. However, their components projected along the profile are consistent with the magnitudes observed at the two Line 500 coastal plain sites, suggesting that the causative anomalies have little mutual inductive coupling. We can therefore validly remove the effect of the off-profile anomaly to the southwest by projecting the induction arrows along the profile.

Tensor decomposition

The data were tensor decomposed, using the *Groom-Bailey* [1989] approach, to derive the regional 2D strike and remove the effects of galvanic scatterers. Decomposition was applied initially to each site and period independently, with physically meaningful but otherwise unconstrained regional strike and distortion parameters. The strike direction histogram (not shown) showed a strong preference for a strike of ≈N50°E, consistent with a best-fitting overall strike direction of N50°E obtained from multi-site, multi-period analyses.

Careful scrutiny showed however period-dependent strikes for a geographic subset of sites. Line 300 sites east of the Brevard fault, and all Line 500 sites, display a period-independent preference for a strike of around N50°E. In contrast, Line 300 sites west of the Brevard fault display a best-fitting strike of ≈N50°E only at periods >1,000 s, consistent with the distribution of the induction arrows (Fig. 2b). At shorter periods, the minimum misfit rotates smoothly clockwise from 50° through 90° to N120°E (taking the $\pi/2$ ambiguity into account), which is almost perpendicular to the profile. This is consistent with the distribution of induction arrows at 107 s, where the sites on the Blue Ridge and Valley & Ridge show off-profile arrows (Fig. 2a).

We interpret this as another expression of upper crustal resistive basement rocks associated with Grandfather Mountain Window (GMW). The period-dependent strike and short period induction arrows imply that the sites affected are located on NW-SE trending upthrust Precambrian block exposed at the GMW

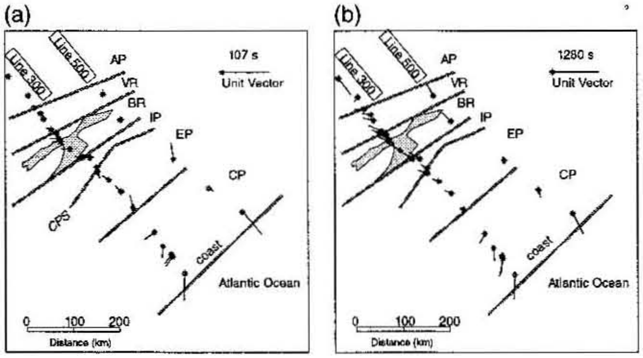

Figure 2. (a) real induction arrows for the period of 107 s. (b) those for the period of 1280 s. CPS: Central Piedmont Suture AP: Appalachian Plateau; VR: Valley & Ridge; BR: Blue Ridge; IP: Inner Piedmont; EP: Eastern Piedmont; CP: Coastal Plain.

but lying beneath the surficial sequences further to the NW. This interpretation is supported by the period-independent strike observed at the Valley & Ridge site on Line 500, where there are no mapped upthrust basement blocks.

The most consistent strike direction for the data is N50°E, and accordingly distortion models were fit to the data with that assumed strike direction. The remaining two unknowns, the static shift scalings of the ρ_a curves, were determined as part of the inversion procedures.

Data pseudosections

The tensor decomposed TM phase pseudosection exhibits a low phase ($< 45°$) region southeast of Central Piedmont Suture in the period range 20-1,000 s (Fig. 3a), which requires a resistive gap in the upper mantle. High phase is evident beneath the Valley & Ridge and Blue Ridge at 20-100 s, and to the NW of the Blue Ridge at periods >3,000 s. These features correspond to lower crustal and upper mantle conductors.

The TE phase pseudosection (Fig. 3b) displays a broad (in space and period) high phase region beneath the Valley & Ridge and Blue Ridge. High phase (>60°) is apparent throughout the profile at long periods. The site at 74 km shows high phases at short periods, which suggests a shallow conductive anomaly. This anomaly is also detected by the geomagnetic transfer functions.

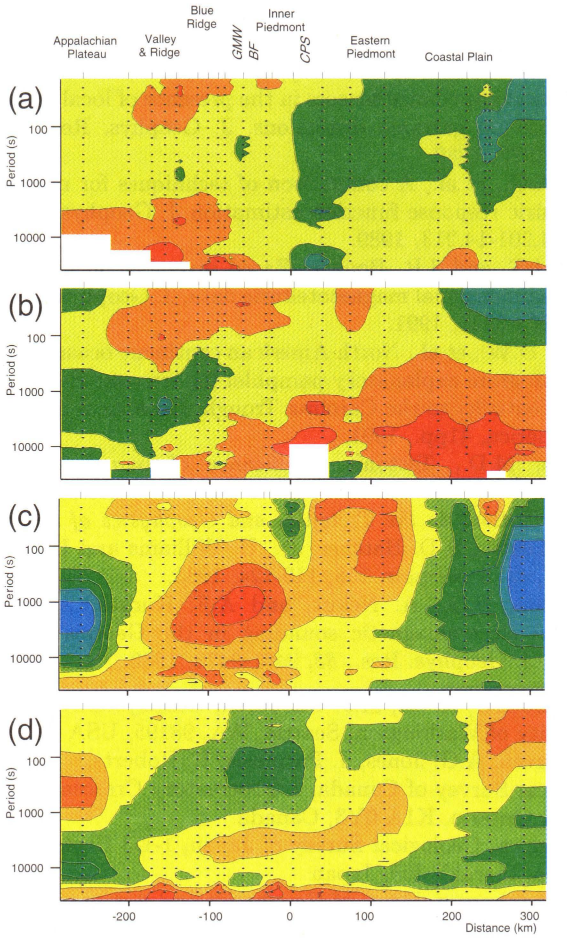

Figure 3. Pseudo sections of the decomposed phase ((a) TM mode, and (b) TE mode). Pseudo sections of the projected magnetic transfer function ((c) real part, and (d) imaginary part).

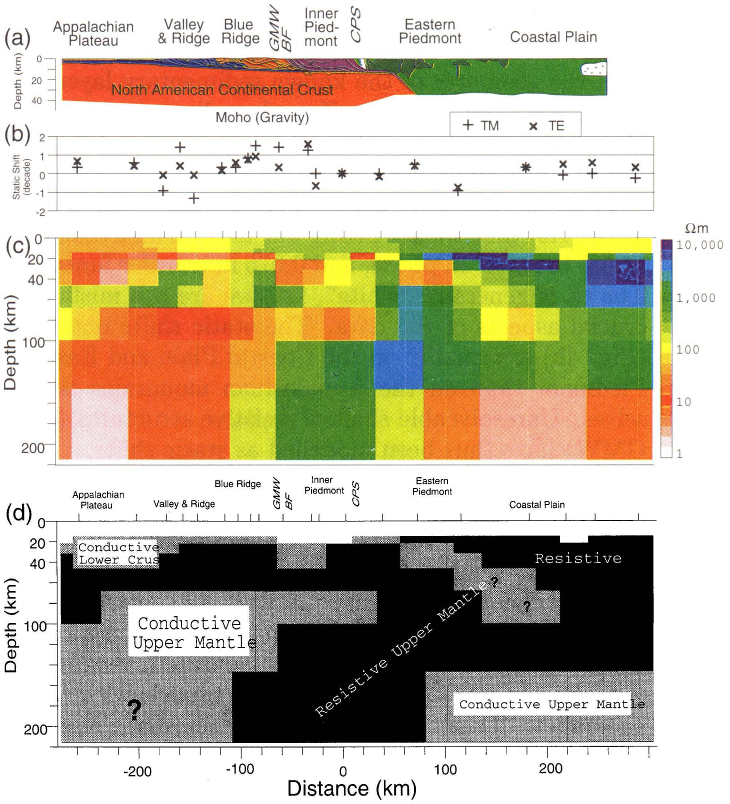

Figure 4. (a) Conventional geologic section, (b) distribution of static shifts, (c) final resistivity model, (d) simplified interpretation of the model

The geomagnetic transfer function data were projected perpendicular to strike (Figs. 3c & d). The most notworthy responses around the Appalachians are at ≈1200 s beneath the Blue Ridge (positive anomaly) and at the NW edge of the profile (negative anomaly). At the coast, the strong peak at 100 - 1000 s is due to the well-known "coast effect". There is a striking positive anomaly (+0.2) beneath the Eastern Piedmont, which requires a conductor to the NW.

Two-dimensional inversion

Two-dimensional inversions were performed on the decomposed regional impedances and projected geomagnetic transfer functions. Joint and independent inversions of the TE, TM and GDS data were undertaken, but here we report only on the joint inversion of all three datasets. Model structure and static shifts were used as model parameters, and data misfit, model roughness and static shift norm were simultaneously minimized using the ABIC criterion of *Ogawa and Uchida* (submitted to Geophys. J. Internat.).

To account for "geological noise", we assumed a 10% error floor for apparent resistivity, an equivalent error floor for phase, and an error floor 0.05 for geomagnetic transfer functions. Our data are insensitive to structure at depths shallower than ≈8 km, and any shallow structure derived is strongly influenced by the static shift parameters. Thus, shallow structure was required to vary little laterally. The initial model was a 100 Ω·m half space with a fixed 0.25 Ω·m ocean of known bathymetry with the geometry of the known sedimentary layer offshore, e.g., the Carolina Trough sedimentary wedge, [*Rankin et al.*, 1991], with resistivity fixed at 1.0 Ω·m. Initial static shifts were set to zero.

The final resistivity model (Fig. 4c) has an RMS misfit of 1.45, thus we are fitting our data to an average of 14.5% in ρ_a, 4° in phase, and 0.075 in transfer function. The fit is generally "white", i.e., we are not misfitting crucial aspects of the data. The static shifts obtained (Fig. 4b) are smaller on the Coastal Plain and Eastern Piedmont than on the Appalachian mountains themselves. Unresolveable shallow resistive structures (e.g., GMW) have thus been modelled as static shifts.

We also inverted these data using *deGroot-Hedlin and Constable's* [1990] Occam2 and *Smith and Booker's* [1991] RRI codes, and all major anomalies were found using a variety of static shift assumptions and data subsets. Inversion of the Line 500 data gave a fuzzy version of the final model, supporting our assumption of two-dimensionality. In addition, separate inversions of the TE, TM and GDS data all gave models with these anomalies. Thus, we consider that the main features imaged in Fig. 4c are "robust", and will not change significantly upon further analysis and modeling.

Discussion and Conclusions

A cartoon illustration of our interpretation of the final resistivity model is shown in Fig. 4d. One of the most significant results is that the lower crust, marked as "North American Basement" in the seismic interpretations (Fig. 4a), is horizontally conductive from the Appalachian Plateau to the Blue Ridge. Given current tectonic models, this conductor cannot due to sediments of the Valley & Ridge covered by overthrust rocks, but is deeper and begins at lower crustal depths of 18-20 km. The conductor deepens to the southeast of the Brevard fault. The probable age of this feature excludes fluids as the cause of the low resistivities, but rather conductive minerals (sulphides, graphite) emplaced during orogenic processes. It is unknown whether these processes predate, or are coeval with, the Appalachian orogens.

Another crustal conductor projects up to the Central Piedmont Suture and dips to the southeast. This feature is required by the transfer functions and the TE high phase around the Eastern Piedmont but does not create a TM phase response because of its dipping nature. From the local tectonic setting, we suggest that this conductor represents trapped sedimentary rocks (Inner Piedmont) emplaced during Acadian orogeny.

Other than the above conductor, the crust is resistive beneath the Eastern Piedmont and Coastal Plain. This may be explained by crust of oceanic origin [*Cox et al.*, 1986], consistent with a gravity anomaly interpretation of oceanic crustal material [*Thomas*, 1983].

In the upper mantle, there are conductors at 60 km depth to the west of the Inner Piedmont, and at 140 km depth east of Eastern Piedmont. However, the low TM phase southeast of the CPS requires a resistive gap between these conductors. The resistive part dips to the northwest, and implies a resistive upper mantle (relict African plate?) trapped by the Alleghanian orogeny.

Acknowledgments. This project was funded by NSF grant EAR-9018111. The work was undertaken while YO was on an exchange at the Geological Survey of Canada, supported by the Japan International Cooperation Agency. Alan Chave provided his robust processing code. Constructive reviews from Jagdish Gupta, Dave Eaton, Randy Mackie, Volker Haak, and an unknown referee, improved this paper. Geological Survey of Canada Contribution 28495.

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(received April 14, 1995; revised September 14, 1995;
accepted October 12, 1995.)