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Introduction to *Electrical Properties of the Earth's Mantle*

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The mantle is the largest of the concentric regions that constitute the Earth's interior. Lying beneath an oceanic or continental crust which may be 6 to 75 (or more) km thick, the mantle region extends to the boundary with the Earth's liquid core. The most detailed characterization of the mantle is provided by the velocity-depth profiles obtained from the seismic waves (DZIEWONSKI and ANDERSON, 1981). A generally abrupt rise in velocity, the Mohorovicic discontinuity, bounds the crust and the 'upper mantle'. Between about 100 and 220 km deep, a low velocity zone is encountered beyond which the velocity increases continuously and in steps near 400, 670, and perhaps 770 km. The name 'lower mantle' is assigned to the region from about 1000 km to the start of the core at 2890 km deep.

Motions of crustal plates indicate that sections of an outer, relatively rigid shell of the Earth (the lithosphere) drift over a weak, yielding layer (the asthenosphere). This plastic layer corresponds to the low velocity zone and is presumably a region of partial melting. Only the seismic velocity, density, and pressure of the Earth's interior are rather well established. Much mantle research effort is now focused on such topics as composition, phase changes, partial melting, temperature profiles, and thermal convection. Each of these subjects could benefit from a better understanding of the electrical properties of this region.

At least five characteristics of mantle material can affect the observed electrical properties. (1) Laboratory studies demonstrated that for a particular composition and phase the conductivity rises almost exponentially with the negative reciprocal of the temperature (TOZER, 1970). Because the Earth's temperature, in general, increases with depth, the conductivities increase with depth accordingly. (2) At increased depths within the Earth, the enhanced temperatures and pressures cause a re-adjustment of the mineral structure; such major changes are recorded as phase transition steps in the seismic velocity (ANDERSON, 1967). The observed conductivity is modified by such phase steps. (3) The major composition and phase changes within the Earth have been identified seismically and used to delineate some internal

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boundaries. The mantle is considered to be mostly silicates in which magnesium-rich olivine dominates down to the 400 km level where a transition to spinel may occur; perovskite and oxides of magnesium and iron may be important in the lower mantle. The electrical properties must exhibit analagous changes (SHANKLAND, 1975). (4) There seems to be increasing evidence that a partial melt exists in the upper mantle region with corresponding seismic velocity decreases and conductivity increases (SHANKLAND, O'CONNELL and WAFF, 1981). (5) Known lateral inhomogeneities in the Earth should show covariant electrical behavior. For example, the cold, poorly conducting oceanic lithosphere can extend several hundred kilometers into the upper mantle in a subduction zone (TOKSÖZ, 1975). Also, surface heat flow observations indicate lateral inhomogeneities (JARVIS and PELTIER, 1986) implying convection involving asthenospheric materials (POLLACK and CHAPMAN, 1977; ANDERSON and DZIEWONSKI, 1984).

The Earth's silicates that are insulators at surface temperatures are semiconducting at mantle temperatures; three conditions contribute to this property. One is the presence of impurities with a misfitting valency in the crystal lattice. It is generally assumed that this 'impurity semiconduction' is important only at the very top of the upper mantle. The second is the existence of ions that are free to move. This 'ionic semiconduction' increases with depth rapidly because of the increasing temperature, but the corresponding pressure increase probably quenches the 'ionic' contribution beneath about 400 km and almost surely by 670 km. The third is the presence of free electrons because of thermal agitation. This 'electronic semiconduction' increases with temperature thus becoming the dominant process deeper than about 400 km.

Almost a century ago, SCHUSTER (1890) concluded from his spherical harmonic analysis of the daily variations of the quiet magnetic field that '... the Earth does not behave as a uniformly conducting sphere, but the upper layers must conduct less than the inner layers'. The first quantitative estimates of the deep-Earth conductivity had to await the mathematical capability and geomagnetic curiosity of Chapman about 30 years later (CHAPMAN, 1919; CHAPMAN and WHITEHEAD, 1922; CHAPMAN and PRICE, 1930; CHAPMAN and BARTELS, 1940). Since that time, refined mathematical techniques, improved data bases, and the application of computers have constantly increased our understanding of the electrical properties of the inaccessible Earth structure. A review of the early studies of deep conductivity may be found in Price's 1970 article in which he emphasized some of the special difficulties such as the effects of highly conducting surface layers upon the computations.

To determine the conductivity of the Earth's mantle, two analysis methods are currently in use. In 'forward' modeling, a trial Earth conductivity profile is investigated for its electromagnetic response to an external field; then the profile is adjusted until the response is in agreement with the observations over the study region. This method can be quite demanding of computer time for two- or three-dimensional models. Ambiguities arise occasionally with more than one conductivity profile

Table 1

Earth conductivity profiles

Figure	File Name	Apx. Depth	Remarks	References
1.	Global Models 1939–69			
	LAPR39	0–1250	global Sq, Dst	Lahiri and Price, 1939; Price, 1973
	RIKI50	0–1400	misc. data sources	Rikitake. 1950; 1966
	MCDO57	0–2900	LAPR39 + secular change	McDonald, 1957
	CANT60	100–600	see Eckhardt *et al.*, 1963	Cantwell, 1960
	YUKU65	380–1900	ring current	Yukutake, 1965
	BANK69	0–1700	ring current	Banks, 1969; 1972
2.	Global Models 1970–74			
	BFRS70	100–700	Sq, Dst 27-d variations	Berdichevsky *et al.*, 1970; 1973
	PRKR70	0–3200	rework Banks, 1969, data	Parker, 1970
	SCJA72	0–1000	pulsations, bays, Sq, Dst	Schmucker and Jankowski, 1972
	BANK72	230–1250	model summary	Banks, 1972
	JADY74	0–2951	Sq, 27-d, annual variations	Jady, 1974
	FARO74	300–1500	with BFRS70	Fainberg and Rotanova, 1974
	SCHM74	0–1000	see Haak, 1980	Schmucker, 1974
	DMRB77	0–1450	all available data	Dmitriev *et al.*, 1977
3.	Global Models 1974–1983			
	PRKN74	60–430	Sq	Parkinson, 1974
	DUCM80	0–2900	annual means	Ducruix *et al.*, 1980
	ISIK80	320–2020	Sq, Dst, annual, solar cycle	Isikara, 1980
	ACMC81	0–2875	secular impulse	Acache *et al.*, 1980
	ROKI82	350–1200	various methods	Rokityansky. 1982
	JAPA83	0–1200	Dst	Jady and Paterson, 1983
4.	Pacific Models			
	LAUN74	0–500	near Calif.; see Drury, 1978	Launay, 1975
	LAHA75	0–800	Hawaii	Larsen, 1975
	FILL80	7–1350	NE Pacific	Filloux, 1980
	LWGR81	0–200	Juan de Fuca	Law and Greenhouse, 1981
	OLJA84	0–250	Juan de Fuca	Oldenburg *et al.*, 1984
	OLCA84	0–250	near Calif.	Oldenburg *et al.*, 1984
	OLNC84	0–250	N. cent. Pacific	Oldenburg *et al.*, 1984
5.	Atlantic Models			
	POVH76	0–215	NW Atlantic	Poehls and Von Herzen, 1976
	BEBJ78	7–125	Iceland	Beblo and Björnsson, 1978
	CFGL80	0–1000	Bermuda	Cox *et al.*, 1980
6.	North American Models			
	SWIF67	70–300	SW USA; see Parkinson & Jones, 1979	Swift, 1967
	COHY70	0–450	W Canada	Cochrane and Hyndman, 1970
	PORA71	0–560	W USA; see Gough, 1974	Porath, 1971
	GOUG73	0–475	W North America	Gough, 1973
	BEGK74	0–350	E Canada	Bailey *et al.*, 1974

Table 1—*continued*

Figure	*File Name*	*Apx. Depth*	*Remarks*	*References*
	LATU75	60–1000	Tucson, USA	LARSEN, 1975
	CSNA86	10–610	N America region	CAMPBELL and SCHIFFMACHER, 1986
7.	European Models			
	VBFF77	40–450	E Europe	VANYAN *et al.*, 1977
	KOPO80	40–2000	Russian platform	KOVTUN and POROKHOVA, 1980
	JOKE82	0–150	N Finland and Norway	JONES, 1982
	ADKM83	3–280	Karelia	ADAM *et al.*, 1983
	ADPB83	10–560	Pannonia	ADAM *et al.*, 1983
	JOSA83	0–250	Scandinavia	JONES *et al.*, 1983
	CSEU86	10–590	Europe region	CAMPBELL and SCHIFFMACHER, 1986
8.	Other Continental Models			
	HAAK77	0–700	Ethiopia	HAAK, 1977
	LSEA81	0–700	SE Australia	LILLEY *et al.*, 1981
	LCEA81	0–700	Central Australia	LILLEY *et al.*, 1981
	CSAU86	250–550	Australia region	CAMPBELL and SCHIFFMACHER, 1987
	CSEA86	190–560	E Asia region	CAMPBELL and SCHIFFMACHER, 1986
	CSCA86	90–640	Central Asia region	CAMPBELL and SCHIFFMACHER, 1986

accommodating the same surface field observations. Magnetometer array and magnetotelluric techniques favor 'forward' modeling to investigate the crust and topmost mantle regions. In the inverse modeling, a conducting substructure profile is obtained from a 'transfer function' that translates, on a theoretical basis, either the orthogonal electric and magnetic fields or the separated internal and external magnetic fields (observed at the Earth's surface) into depth and conductivity of an equivalent substitute layered Earth structure that would provide the observed response. Full mantle determinations are limited only by the available natural field periods (hours to months); but the resolution is generally poor, lateral heterogeneity is not accommodated, and results differ somewhat for the various mathematical approaches in use. Often for both 'forward' and 'inverse' methods, constraints imposed by the mathematical representation itself affect the form (and therefore the validity) of the conductivity profile that is produced. Excellent reviews of the analysis techniques have been published by WAIT (1982) and ROKITYANSKY (1982).

The following eight figures (itemized in Table 1) summarize some of the published conductivity results using a common scale display. At the present time, the values that were determined for depths greater than 1000 km seem so highly speculative that they are not shown in these examples. At the left half of each figure, the conductivity scale is linear, and the depth is displayed to 600 km to compare the small scale features reported at the top of the upper mantle. The right half of each figure is a logarithmic conductivity display to depths of 1000 km. The code identification of each plot represents the name of the author(s), the year of publication and sometimes the location, as referenced in Table 1. To produce this common plot of results, it was necessary to take some liberties with the original publications. For example, continuous line plots were drawn through point values, and occasionally a centerline of an author's distribution of values was estimated. The interested reader should refer to the original publication of each result.

In the first three figures, grouped chronologically, are the whole-Earth models of conductivity. Between 1939 and 1969 (Figure 1), we see a great variation in the estimated conductivities, particularly at shallow depths. The 400 km step that appears in most of the models seemed to have been created by the authors to accommodate the seismic-velocity discontinuity that was known to exist at that level. Many recent researchers find values in the range of 0.1 to 0.001 S/m for the topmost mantle to about 400 km; most of these early global models would be acceptable. At depths below this step, recent works seem to find values of about 0.1 to 3.0 S/m; models RIKI50 and BANK69 would be anticipating the present values for that region. In Figure 2, model SCJA72 seems to have quite low values at shallow-mantle depths compared to the other conductivity results. Interestingly, model BFRS70 may be the first global model to indicate an abnormal high-conducting layer near the topmost mantle. A value of approximately 1 S/m near 1000 km is obtained by all these models. In Figure 3, models DMRB77 and JAPA83 appear to be in disagreement with most of the others for the upper mantle. It seems to me that the present global model would be one with a gradually rising conductivity from about 50 km down to about 400 km and with values between 0.01 and 0.1 S/m. A rapid rise in conductivity near 400 to 500 km could cause an order of magnitude

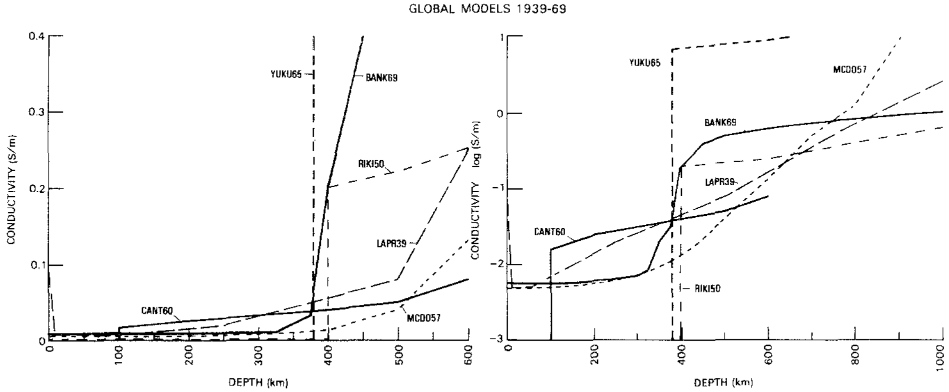

Figure 1
Global conductivity profiles 1939 to 1969. Refer to model code list in Table 1. Left, linear conductivity (S/m) versus depth (km). Right, log conductivity versus depth.

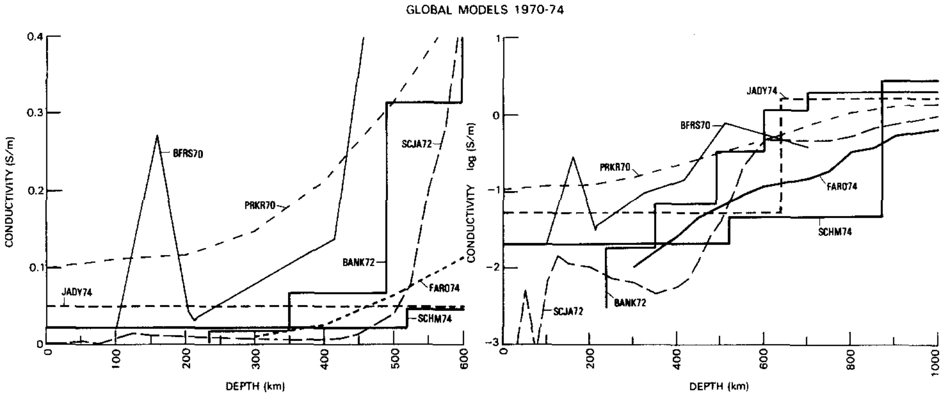

Figure 2
Similar to Figure 1 only 1970 to 1974 profiles.

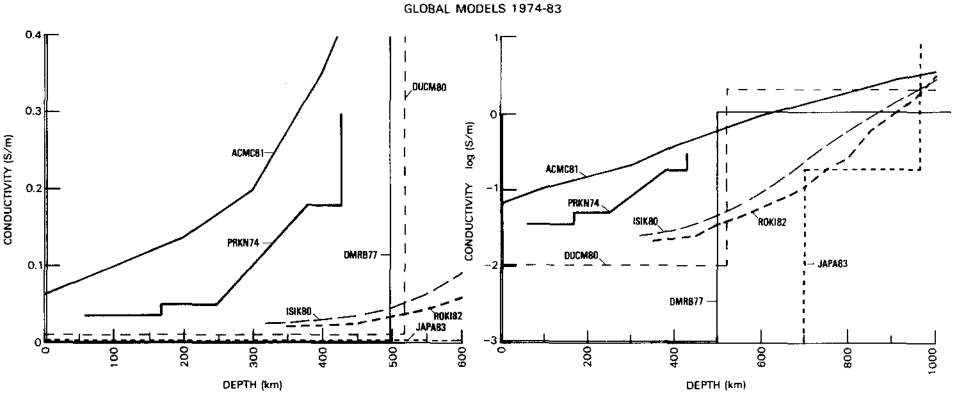

Figure 3
Similar to Figure 1 only 1974 to 1983 profiles.

increase in conductivity over a 50 to 100 km transition zone. Below this transition, it seems that the conductivity should rise gradually to a value near 1.0 to 3.0 S/m.

A group of Pacific Ocean model-conductivity profiles is illustrated in Figure 4. The interesting feature of these is the appearance of narrow layers of relatively high conductivity, usually near the low velocity zone of the upper mantle. The great differences between profiles may be ascribed to the lateral heterogeneity between the variety of regions sampled. For example, LAHA75 was thought to be representative of a mantle plume, and LWGR81 and OLJD84 sampled a subduction region near active volcanoes. Most models favor a high conducting layer about 10 times its surrounding levels, ranging 10 to 50 km thick somewhere in the depth range of about 50 to 150 km.

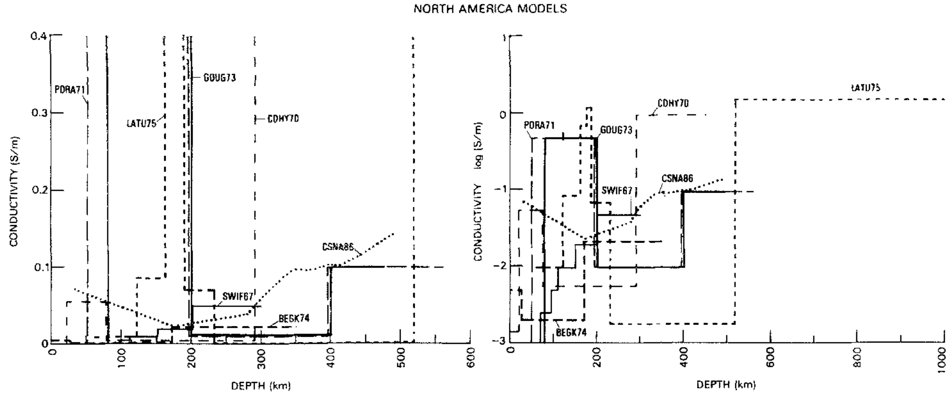

Figure 4
North America continental region conductivity profiles. Refer to model code list in Table 1. Left, linear conductivity (S/m) versus depth (km). Right, log conductivity versus depth.

Only a few conductivity determinations have been made in the Atlantic Ocean region. Figure 5 illustrates the results that are generally similar to those reported for the Pacific region. Note that the BEBJ78 Iceland model has a shallow location of the high conducting layer; this island is near the mid-Atlantic ridge of hot upwelling mantle magma.

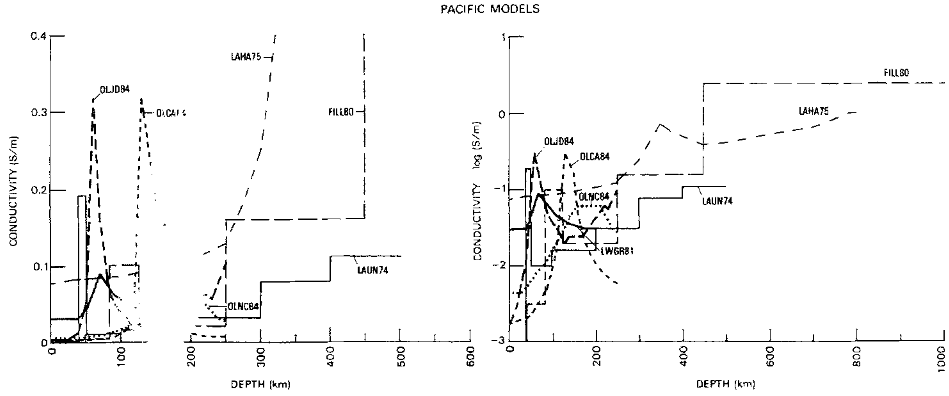

Figure 5
Similar to Figure 4 except that the Pacific Ocean region is shown.

Figure 6 shows the North American data set. The variety of conductivity profiles probably reflects the distribution of study locations. The CSNA86 profile describes a rather broad continental region, but most other profiles are quite local representations of unique geologic conditions. Many of these examples show a high conducting layer near the top of the upper mantle, as did the ocean models.

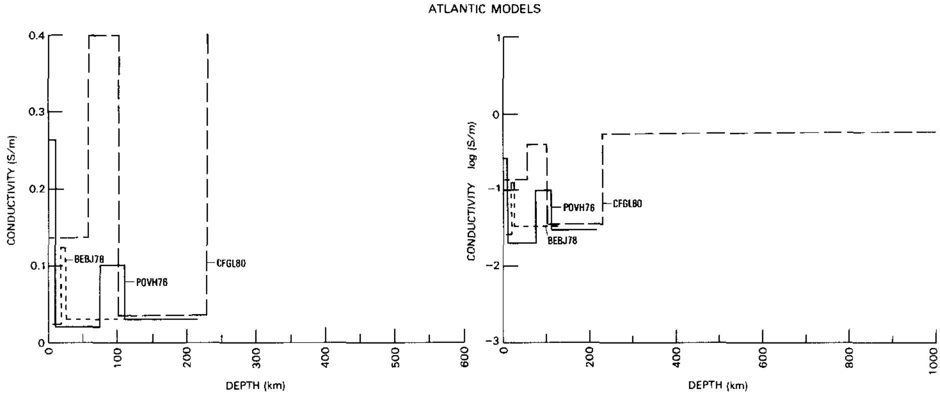

Figure 6
Similar to Figure 4 except that the Atlantic Ocean region is shown.

Figure 7 shows the European profiles. Note that models VBFF77, KOPO80, and ADPB83 indicate extremely low conductivity values at the top of the upper mantle and no special high conducting layer; this situation may be typical of cold shield regions. Except for these three models, the range of reported values is similar to that for North America. CSEU86 is a regional model, whereas the others are more locally determined (see Table 1).

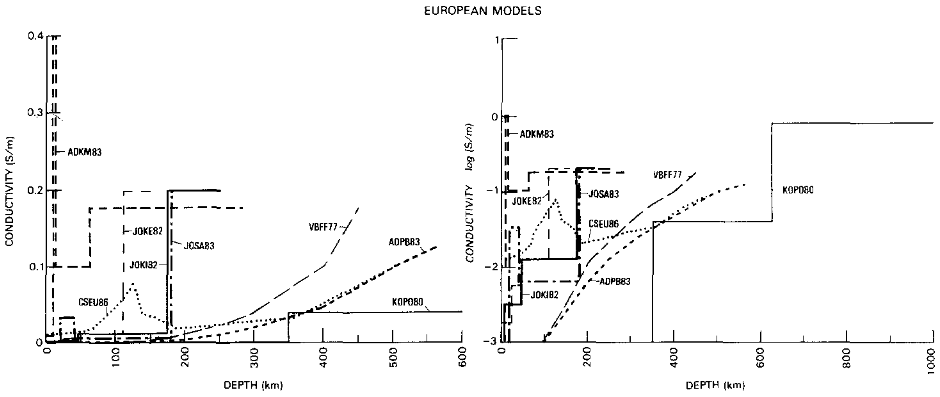

Figure 7
Similar to Figure 4 except that the Europe continental region is shown.

Figure 8 is a collection of conductivity determinations for Asia, Africa, and Australia. It is interesting that no high conducting layers appear in the three models created from data over the Australian shield. The three regional models, CSCA86, CSEA86, and CSAU86, indicate lower conductivity below the 400 depth than the other models. The East African model (HAAK77), with the shallow, high conducting layer, is near a continental plate spreading center where hot, upwelling magma is expected to be near the surface.

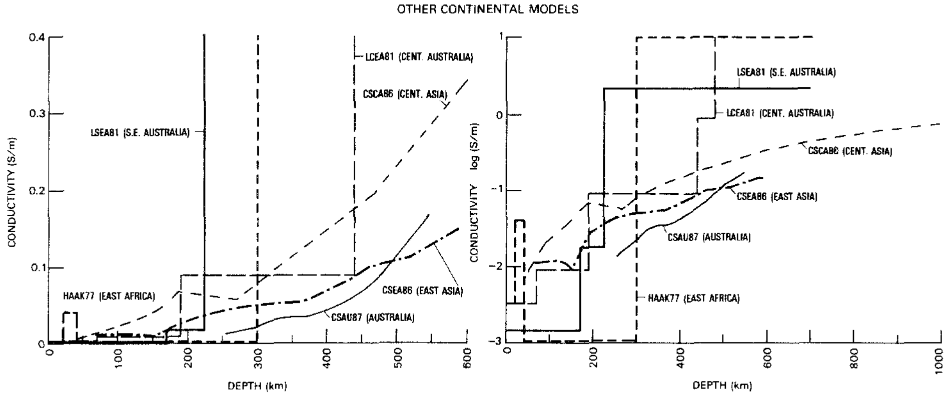

Figure 8

Similar to Figure 4 except that other miscellaneous continental regions are shown.

Although the 50 model profiles described above certainly show a great diversity in appearance, within an order of magnitude there seems to be an agreement in the general level of conductivity to be expected for the mantle region. Many of the profiles may have been selected with guidance from the seismic data on transition locations. However, not all the profile differences can be ascribed to noise, field-source variations, or modeling techniques. There is strong reason to believe that the profiles give valid evidence of a heterogeneous electrical structure of the mantle, especially in the uppermost regions. In the more recent publications, there is a greater interest in exploring the interrelationship of conductivity profiles with the composition, thermal, and seismic properties of the mantle that justify this lateral inhomogeneity.

This special issue of PAGEOPH is a collection of research papers representative of the recent international efforts to understand the electrical properties of the Earth's mantle. The incentive to prepare such a collection grew from a special scientific session on this topic at an assembly of the International Association of Geomagnetism and Aeronomy that convened at Prague, Czechoslovakia, in August 1985. Most of the presentations printed here have been expanded since that meeting, and several new works have been added to complete the topic coverage. The collection will open with a review of the seismic properties important to an understanding of the conductivity profiles. Next, the papers concerning interrelations between mantle conductivity and other basic properties of the Earth will be presented. Discussions of some conductivity modeling methods are in the central part of this issue. The final topic is the review of the special research programs in various countries. The purpose of this volume is to bring together a sample of representative research on an interesting topic at the growing edge of geophysics. We ask the reader's forgiveness for not being able to cover all aspects of the Earth's electrical properties in this limited space.

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