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The BC87 Dataset: Tectonic Setting, Previous EM Results, and Recorded MT Data

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As part of project LITHOPROBE, magnetotelluric data were acquired at twenty-seven sites along a 150 km east-west profile in southeastern British Columbia straddling the complex tectonic boundary between ancestral North American rocks and those of the easternmost accreted terranes. These data, named the *BC87 dataset*, display complex effects due to both three-dimensional induction and galvanic scattering at virtually all scale sizes, from that of the electrode array (<50 m) to that of the large plutonic Nelson batholith (150×50 km surface extent). The dataset was distributed widely in order to compare and contrast different schemes for extracting the underlying predominant two-dimensional structure, and to test differing interpretational algorithms on data from a complex crystalline terrane. The MT data are shown, and the tectonic setting described. Also, seismic and previous EM studies of the region are described.

1. Introduction

The recent DNAG (Decade of North American Geology) volume on the Canadian Cordillera (GABRIELSE and YORATH, 1991a) gives excellent background information on the tectonic framework of British Columbia (B.C.). It is within North America's Cordillera that terrane concepts of crustal accretion were first developed (CONEY *et al.*, 1980). However, notwithstanding the vast amount of geological knowledge of the region, fundamental questions remain to be answered (GABRIELSE and YORATH, 1991b). Amongst these are the nature of the basement beneath the accreted terranes and the configuration of the western margin of ancestral North America at the onset of rifting and its temporal development.

The BC87 MT dataset was recorded as part of the Canadian multidisciplinary LITHOPROBE program (CLOWES *et al.*, 1993) of study of the accretionary history of the Canadian Cordillera in southern B.C. The study area spans two of the five recognized geological and physiographic belts of the Canadian Cordillera (Fig. 1) that are the principal tectonic elements by which the gross structure and morphology of the orogen are recognized; their boundaries are, in the main, coincident with major terrane boundaries. The principle objective of the work in southeastern B.C. was to determine the geometric link between the thin-skinned structures of the Foreland Belt and the deeply-rooted compressional structures of the Omineca Belt (Fig. 1). At the latitude of the LITHOPROBE transect, we define the boundary separating the Foreland belt and the Omineca belt to be the Kootenay Arc (Fig. 2).

In 1987 twenty-seven wide-band magnetotelluric (MT) responses were obtained along a 150 km east-west profile (Figs. 2 and 3). The MT profile begins at the Rocky Mountain Trench above autochthonous North American basement, traverses across the Purcell Anticlinorium (PA), the Kootenay Arc (KA), the Nelson Batholith (NB) and ends on the Valhalla gneiss complex (VC).

These data typify modern MT data acquired in crystalline domains; they are excellent quality, but highly complex, and the MT impedance tensors are "full", i.e., all four tensor elements contain information. As such, the dataset gives the EM community a chance to compare modern distortion removal methods and two-dimensional inverse procedures to the recovered regional responses. In

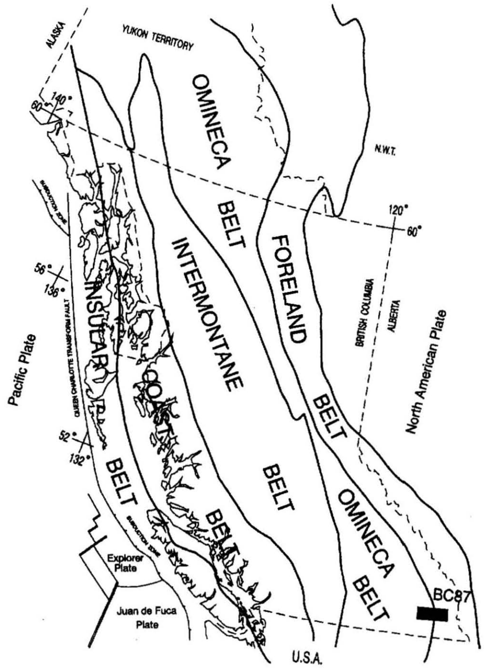

Fig. 1. Generalized map of the Canadian Cordillera showing the five morphogeological belts and the region of study.

this paper, the tectonic setting of the data is described, and previous EM and other geophysical studies of the region are discussed.

2. Tectonic Setting and Previous Geophysical Results

The 1985 seismic reflection survey (COOK *et al.*, 1987, 1988) acquired data along a series of lines (1–5) from the Rocky Mountain Trench to the Valhalla core complex (Figs. 2 and 3). The interpreted crustal geometry, shown in Fig. 4, was derived from these seismic reflection data (COOK *et al.*, 1988). In the main, these data confirmed prior tectonic models of the region.

To the east, stratified Mesoproterozoic to Mesozoic miogeoclinal and platformal rocks of the Foreland belt, developed along the long-lived western margin of ancestral North America, are detached along a regional decollement at mid-crustal depths (12–25 km) in an eastwards-tapering prism. These rocks have been shortened (by 50%) and translated up to 200 km northeastwards onto ancestral North America during Late Jurassic to Early Tertiary convergence between the North America craton and allochthonous terranes to the west (MONGER *et al.*, 1982). Rocks of the Purcell Anticlinorium (PA) were formed during the Mesoproterozoic, between 1450 Ma and 850 Ma, in the Purcell Belt basin on, and adjacent to, the western margin of the craton. These rocks were then deformed by a series of west-dipping, imbricate, north-northwest trending thrust faults during convergence. The southern Rocky Mountain Trench is a long, linear, topographic feature which forms the eastern boundary of the PA. The dominant structural style of this belt is "thin-skinned", with the deformation interpreted to be mainly confined to the sedimentary wedge above autochthonous North American basement.

These structures are interpreted to be truncated beneath the Kootenay Arc by a major

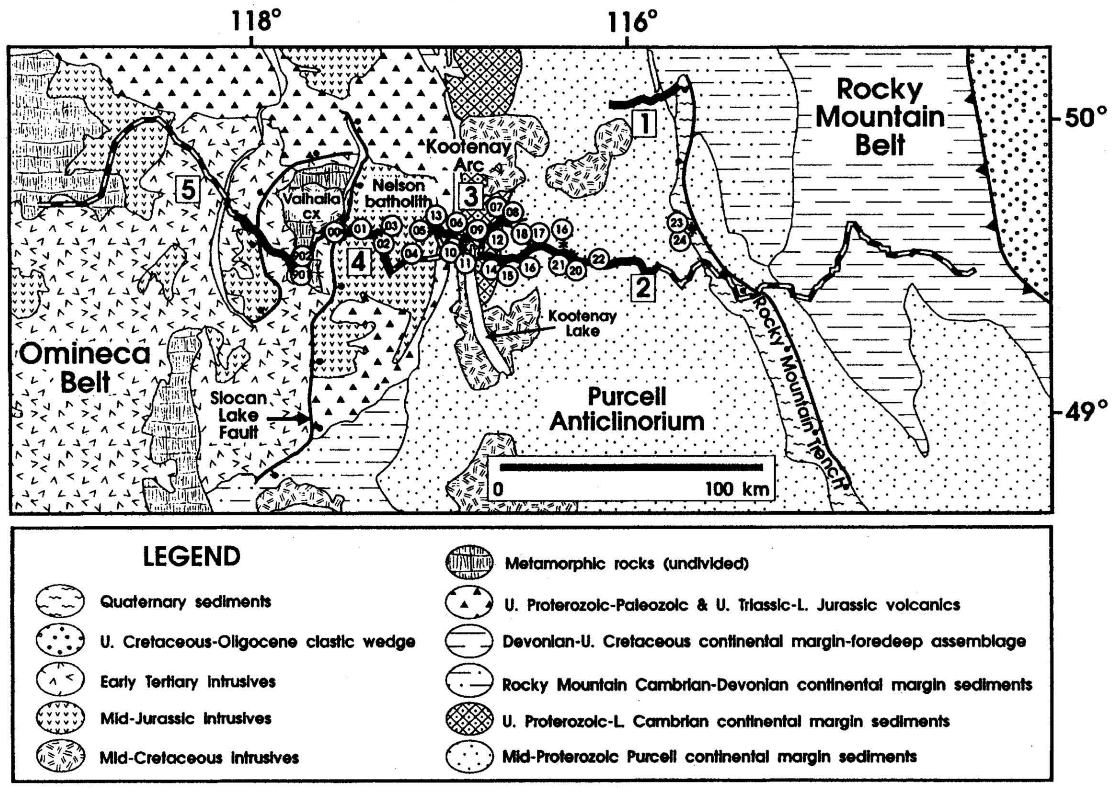

Fig. 2. Simplified geology map of the region (based on COOK *et al.*, 1988) showing the locations of the MT sites (numbers in circles), the seismic reflection lines (solid lines with associated numbers in squares) and seismic refraction receiver points (dashed line). Overlapping circles indicate local/remote 10-channel pairs.

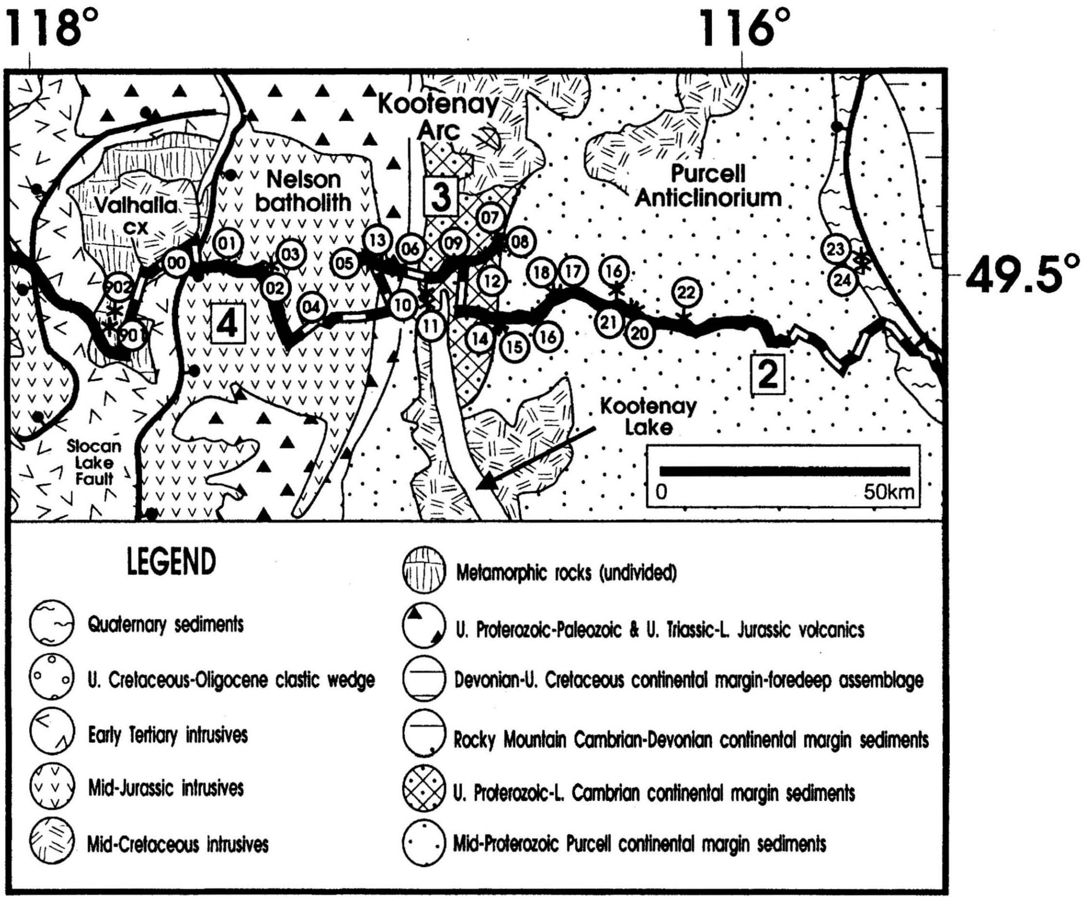

Fig. 3. MT site locations in greater detail. The geological patterns are those used for Fig. 2.

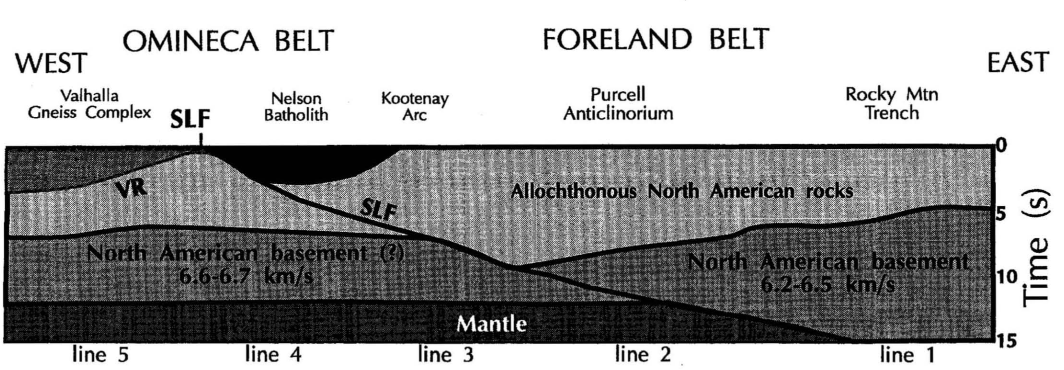

Fig. 4. Interpreted geological cross-section from the seismic reflection studies (based on COOK *et al.*, 1988). Also shown are the lower crustal V_p velocities (from ZELT and WHITE, 1993).

crustal-scale Eocene normal fault, the Slocan Lake Fault (SLF). VARSEK and COOK (1991) present two tectonic models, differing only in the style of early development of the accretionary complex, for this boundary based on the data from seismic line 3. The SLF is interpreted to offset autochthonous North American basement by about 7–8 km, east-side-downwards, and also possibly to offset the Moho at a location some 75 km to the east of the surface expression of the SLF. From isotopic ratios, the western limit of North American basement is interpreted to be located beneath the Omineca Belt ≈100 km west of the SLF (ARMSTRONG *et al.*, 1977). Interpretation of seismic reflection data from the whole of the southern Canadian Cordillera (COOK *et al.*, 1991) suggests that North American basement extends some 500 km to the west of the SLF as far as the Fraser fault, which marks the Coast belt/Insular belt boundary at this latitude (Fig. 1).

The Omineca belt straddles the complex, tectonic boundary between the deformed miogeoclinal Foreland belt rocks and the easternmost, Mid-Jurassic, accreted terranes (Terrane I of MONGER *et al.*, 1982). It comprises mainly penetratively-deformed Mesoproterozoic rocks, extensively underlain by metamorphic and granitic rocks, in structural culminations and depressions. The Valhalla gneiss complex (VC), a domal-shaped Cretaceous to Early Tertiary metamorphic core complex, is an example of the former. The Mid-Jurassic Nelson batholith intrudes the accreted terranes to the west of the Kootenay Arc, and is truncated on its western boundary by the SLF.

At the south-eastern edge of seismic line 5, the upper crust is seismically transparent to about 4.0 s (to the "Valhalla reflector", VR in Fig. 4), beneath which is a complex zone of reflections down to about 8 s (22 km). Few reflections exist in the depth range 22–35 km beneath the VC, and yet there are interpreted weak Moho reflections at about 35 km at its western extremity (COOK *et al.*, 1987, 1988; EATON and COOK, 1990).

The SCoRE90 seismic refraction experiment recorded shots along line 2–5 (Fig. 2) with a 1 km station spacing (WHITE *et al.*, 1992; ZELT and WHITE, 1993; C. A. Zelt, personal communication). These data confirm a variation in crustal thickness with an increase of 7 km, from 34 km to 41 km, at about the location suggested by the seismic reflection interpretation. In addition, these data provide evidence for an increase in compressional wave velocity, V_p, in the lower crust (depths >20 km) from 6.2–6.5 km/s (average of 6.35 km/s) beneath the Foreland Belt to 6.6–6.7 km/s (average of 6.6 km/s) beneath the Omineca Belt. This transition takes place over at most 85 km, and is at the location of the Slocan Lake Fault (WHITE *et al.*, 1992; ZELT and WHITE, 1993). Such a velocity variation argues against a simple geometric continuation of North American Basement, as suggested by COOK *et al.* (1987, 1988).

The Kootenay Arc region appears to be the location of a number of significant geological/geophysical markers throughout the whole crust.

It represents the surface position of the initial $^{87}Sr/^{86}Sr = 0.704$ line for the Triassic-Early Jurassic igneous rocks (CLOWES *et al.*, 1993).

It is the eastern limit of Eocene magmatism (ARMSTRONG and WARD, 1991).

It is the location of a major extensional fault of crustal extent (SLF). This feature is considered to have provided a conduit for channelling lower crustal and mantle Pb and CO_2 to higher crustal levels (BEAUDOIN *et al.*, 1991).

It is the location of a change in lower crustal V_p velocity (ZELT and WHITE, 1993).

In addition, there are other geophysical signatures in the continental lithosphere associated with the transition from the Foreland belt to the Omineca belt.

The crust beneath the Foreland belt is thicker (41 km) than beneath the Omineca belt (34 km) (ZELT and WHITE, 1993).

Moho temperature is modelled to be 300°C higher beneath the Omineca belt (1100–1200 K) than beneath the Foreland belt (850–950 K) (LOWE and RANALLI, 1993).

The lithosphere thins rapidly from east (130 km) to west (40–50 km) (see LOWE and RANALLI, 1993, and references therein).

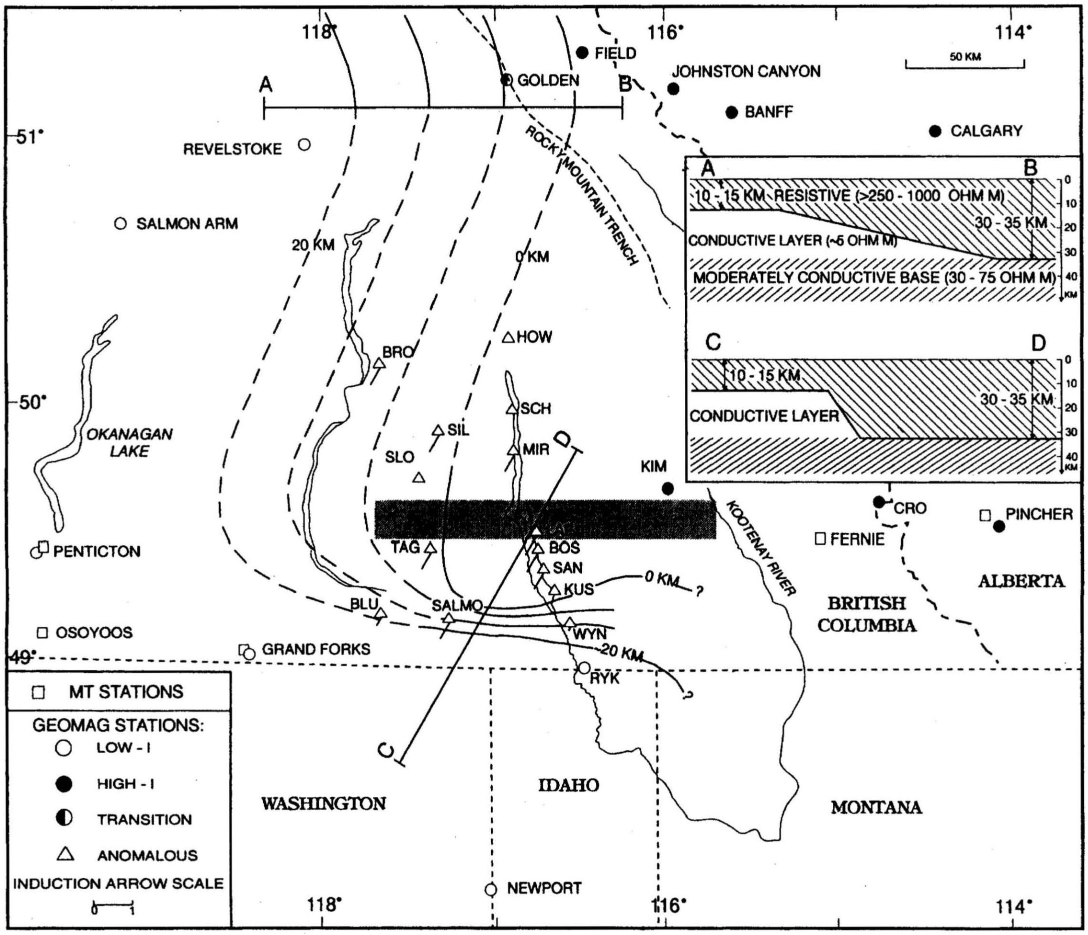

Fig. 5. Real (reversed) induction arrows, and **I** values, for stations in the vicinity of Kootenay Lake. The contours show the thickness of an interpreted lower crustal conducting layer, and the two models are cartoons illustrating the difference in the width of the transition zone from the north (profile A-B) to the south (profile C-D). The proposed structural model is from LAJOIE and CANER (1970). The shaded rectangle shows the location of the BC87 stations.

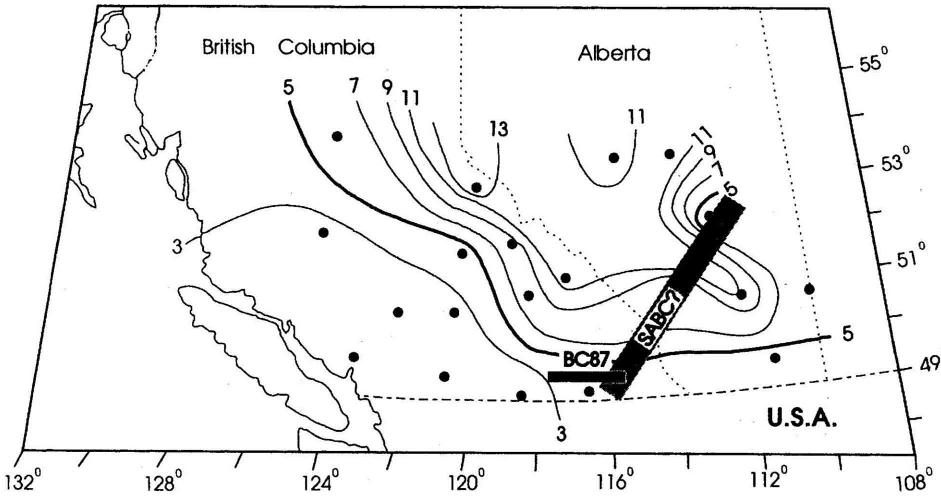

Fig. 6. Vertical field component Fourier amplitude map at a period of 25.3 min for the four hour interval 21:50–00:50, 6–7 July 1980 (redrawn from Fig. 3 of GOUGH *et al.*, 1982).

The base of the crust beneath the Foreland belt has a brittle rheology (LOWE and RANALLI, 1993).

3. Previous EM Studies in the Region

From the early-1960s it was recognized that the region of the Kootenay Arc represents a boundary in electrical conductivity, based on the ratios of the vertical to horizontal magnetic field amplitudes, **I**. HYNDMAN (1963) found evidence for a change from low-**I** in the west to high-**I** in the east on crossing Kootenay Lake. CANER and CANNON (1965) illustrated that low-**I** is a general feature of the Cordillera and ascribed this observation, coupled with the observation of an upper mantle with low *Pn* velocity and high heat flow values, to confirmation of the proposal by WHITE and SAVAGE (1965) of a rise in the mantle isotherms beneath the region.

A profile of Geomagnetic Deep Spunding (GDS) sites at 51°N by CANER *et al.* (1967) confirmed Hyndman's observation at 49.5°N of a marked change at 117–118°W from low-**I** to high-**I**. Their modelling studies suggested that a highly conducting layer, of 1 S/m, came to within 25–35 km of the surface in southwestern B.C. west of Kootenay Lake. MT data from stations across southern B.C. and southwestern Alberta were interpreted as indicating a resistive crust (>250 Ω·m) overlying a more conducting mantle (30–50 Ω·m) at a depth of 30–35 km to the east of Kootenay Lake (CANER *et al.*, 1969). In contrast, data from the western stations were interpreted as evidence for a lower crustal conducting layer (10±5 Ω·m) beginning at a depth of 15±5 km with thickness of 20–40 km, overlying a mantle of the same resistivity as to the east.

The transition zone in the region of Kootenay Lake was studied in detail using a twenty-station GDS network by LAJOIE and CANER (1970). They found that the transition zone from "resistive" lower crust to "conductive" lower crust has a more complex geometry than a simple 2D change across 117–118°W (Fig. 5). The final model is of a 3D transition zone involving a major structural change from north-south to east-west at a latitude just north of the U.S./Canadian border (49°12′) passing beneath the town of Salmo (Fig. 5). The transition changes also from gradual (100 km width) on the north-south part to near-vertical on the southern east-west part. Further GDS stations in central B.C. indicated the extent of the region of anomalously low-**I**

Table 1. Co-ordinates of the BC87 dataset sites.

Station	Reference	Latitude	Longitude	Elevation (m)	Azimuth
lit902	lit902	49.6167	−117.7333	671.	+32
lit901	lit901	49.5433	−117.7167	671.	−22
lit000	lit000R	49.7000	−117.5000	549.	−19
lit001	lit001R	49.7000	−117.4217	853.	−4
lit002	lit003	49.6958	−117.3083	1036.	−17
lit003	lit002	49.7000	−117.3000	1006.	+44
lit004	lit004R	49.6333	−117.1333	792.	0
lit005	lit005R	49.7050	−117.0333	1280.	+10
lit013	lit013R	49.7083	−117.0000	1128.	+20
lit006	lit006R	49.6917	−116.9500	1036.	−40
lit011	lit010	49.6417	−116.8750	533.	+25
lit010	lit011	49.6500	−116.8736	547.	−10
lit009	lit009R	49.7056	−116.7917	671.	+41
lit012	lit012R	49.7167	−116.7050	945.	+20
lit007	lit008	49.7417	−116.6667	1219.	−5
lit008	lit007	49.7333	−116.6667	1067.	+30
lit015	lit014	49.5917	−116.6667	1768.	−30
lit014	lit015	49.5958	−116.6625	1768.	+10
lit016	lit016R	49.6083	−116.5750	1372.	−40
lit018	lit017	49.6500	−116.5125	1219.	+30
lit017	lit018	49.6500	−116.4967	1219.	+20
lit019	lit019R	49.6528	−116.3361	1006.	+30
lit021	lit020	49.6194	−116.2917	975.	−10
lit020	lit021	49.6167	−116.2833	975.	−30
lit022	lit022R	49.6028	−116.1472	1036.	+30
lit023	lit024	49.7083	−115.6528	914.	0
lit024	lit023	49.6917	−115.6514	884.	0

which covered B.C. up to the Rocky Mountain Trench (Caner *et al.*, 1971).

Caner *et al.* (1971) proposed speculative 3D structural models to describe these observations; in all three there was a lower crustal conductor to the west of Kootenay Lake, and a lower crustal/upper mantle conductor to the south of the region. Dragert and Clarke (1977) somewhat refined these models with the suggestion that the southern conductor may be bounded in its lateral extent and was at an oblique angle to the north-south edge of the B.C. conductor. Dragert and Clarke (1977) was tentatively associated this conductor, trending at an angle of some 45°E, with a buried Precambrian rift (Kanasewich, 1968).

A large-scale magnetometer array study by Camfield *et al.* (1970) showed features which support the model in Fig. 5. The vertical field amplitudes (H_z) for most of the events exhibit a distinct geometry with an attenuation in amplitude to the west of Kootenay Lake and to the south of the U.S./Canadian border (Figs. 6–11 in Camfield *et al.*, 1970). The H_z amplitudes do not increase again to the east in the U.S. until the North American Central Plains conductivity anomaly (NACP; see Jones, 1993) is sensed at the borders to the Dakotas. A later array study of the region by Gough *et al.* (1982) again showed a strong attenuation of H_z in the western and southern parts of the array (Fig. 6). The maps from this array were considered by Gough *et al.* (1982) to support Dragert and Clarke's (1977) suggestion of a conductivity anomaly associated with the "Kanasewich-rift". In later papers, Gough has referred to this anomaly as the "Southern Alberta-British Columbia" (SABC) anomaly; its trace, taken from Gough (1986), is illustrated in Fig. 6. The evidence for the existence of such a laterally-bound anomaly, in contrast to one of larger spatial extent (e.g., Fig. 5), is weak as there have been few studies in Idaho and Montana reported in the literature. Certainly the H_z amplitude map of Fig. 6 does not support the presence of an elongated conductor, although a very localized one around one station in Alberta is apparent. The EMSLAB array maps (GOUGH *et al.*, 1989) are equivocal on this question, although GOUGH *et al.* (1989) consider that they support the existence of the SABC conductor. They do, however, express surprise that "the (SABC) currents stopped at the border".

In contrast to the emphasis on the two-dimensional geometry of the region derived from the seismic reflection and refraction data (Fig. 4), the EM studies show emphatically that the deep-crustal geology is three-dimensional (Figs. 5 and 6). There is a marked change in dimensionality just north of the U.S./Canadian border, which concurs with the contrast between the 2000-km-long linearity of the Canadian segment of the Cordillera compared with the complexity of the conterminous U.S. segment.

4. The BC87 Dataset

The locations of the MT stations are shown in Figs. 2 and 3, and their geographical co-ordinates, reference sites, elevations, and azimuthal direction of the H_x and E_x sensors, are tabulated in Table 1. The data were acquired by commercial contract to Phoenix Geophysics (Toronto) Ltd., and were recorded with a real-time MT-16 system using a HP9000-series computer. The telluric field variations were measured with typically 100 m bipoles, in a cross-configuration, with non-polarizable Pb-PbCl electrodes. The magnetic fields were measured with coils for the horizontal components and an air loop for the vertical component. All data were recorded with a remote magnetic reference; in some cases the sites were 7-channel single station, in others they were 10-channel dual station pairs (shown in Fig. 2 by overlapping circles). In all cases, the remote sites (labelled 'R' in Table 1 for the 7-channel sites), were of the order of 500 m–1,500 m from the main site. Data in the range 384 Hz–1 Hz were processed in narrow frequency bands containing two frequencies (the 6th and 8th harmonics of the dataset length). Longer period data, 1 s–1820 s, were processed using a cascade decimation scheme (WIGHT and BOSTICK, 1980) with robust adaptation (similar to method 6 of JONES *et al.*, 1989).

The data at each site were acquired in a co-ordinate system which permitted the longest telluric lines; the horizontal magnetic components were oriented into the same co-ordinate system as the telluric array (see Table 1). The cross-spectra were rotated into a geographic co-ordinate system and distributed to the EM community, mainly via anonymous ftp-login.

Figures 7 and 8 show the apparent resistivities and phases of the off-diagonal elements for these data, and their errors ($\pm 1\sigma$), in a geographic co-ordinate system, with x denoting north and y east, i.e., the Z_{xy} responses are for a north-directed electric field and an east-directed magnetic field. Site-to-site correlations are apparent, but are visually not as dominant as the strong site-to-site variations.

The main features of these data, in geographic co-ordinates, have been discussed by JONES *et al.* (1988), in which the complexity of the data is stressed. In particular, large-scale 3D effects are present in much of the data, as well as small-scale effects due to local distortions. Evidence of the former is the consistent phase distortion for B-polarization data acquired on the Nelson batholith. Distortion effects, and their removal, on data from some of the sites can be found in GROOM and BAHR (1992), for sites *lit000* (named *EMR000* in that publication), *lit001* (*EMR001*), *lit003* (*EMR003*) *lit005* (*EMR005*) *lit011* (*EMR011*) *lit017* (*EMR017*) and *lit902* (*EMRW02*), GROOM *et al.* (1993), for sites *lit000* and *lit900* (*LITW02*), and JONES AND GROOM (1993), for sites *lit007* and *lit008*.

With the exception of the ρ_{yx} and ϕ_{yx} data from periods in excess of 300 s, the off-diagonal

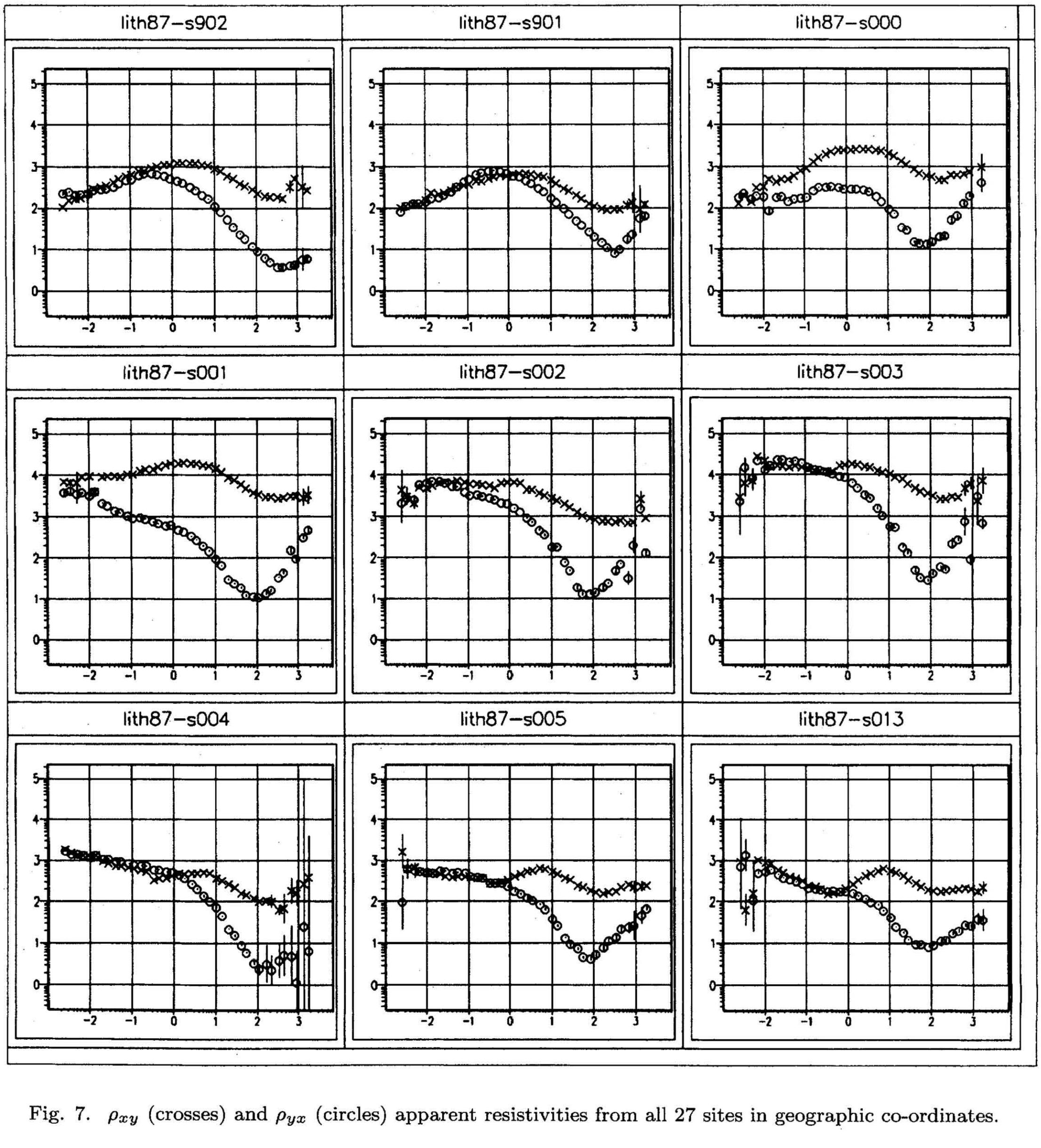

Fig. 7. ρ_{xy} (crosses) and ρ_{yx} (circles) apparent resistivities from all 27 sites in geographic co-ordinates.

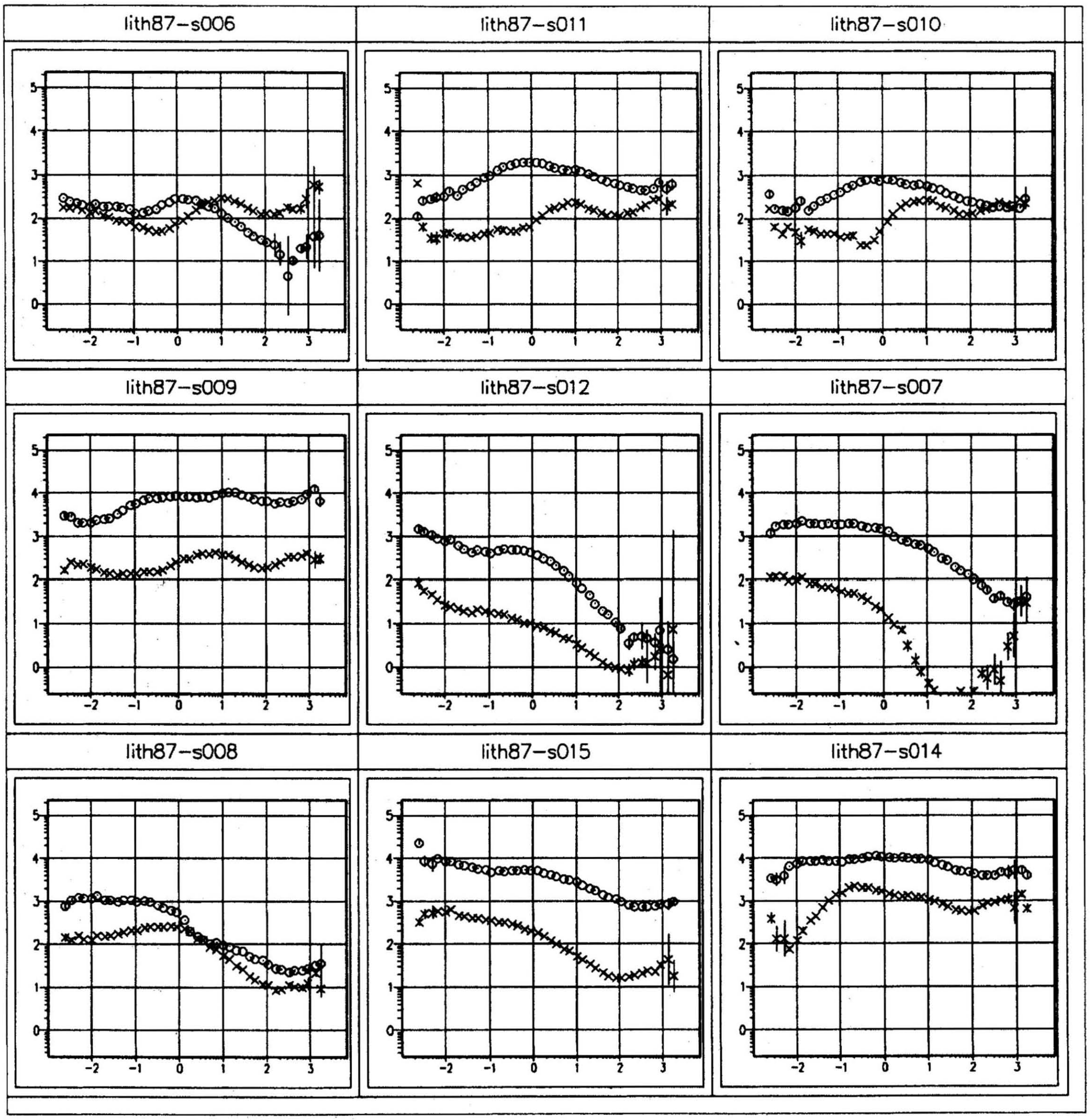

Fig. 7. (continued).

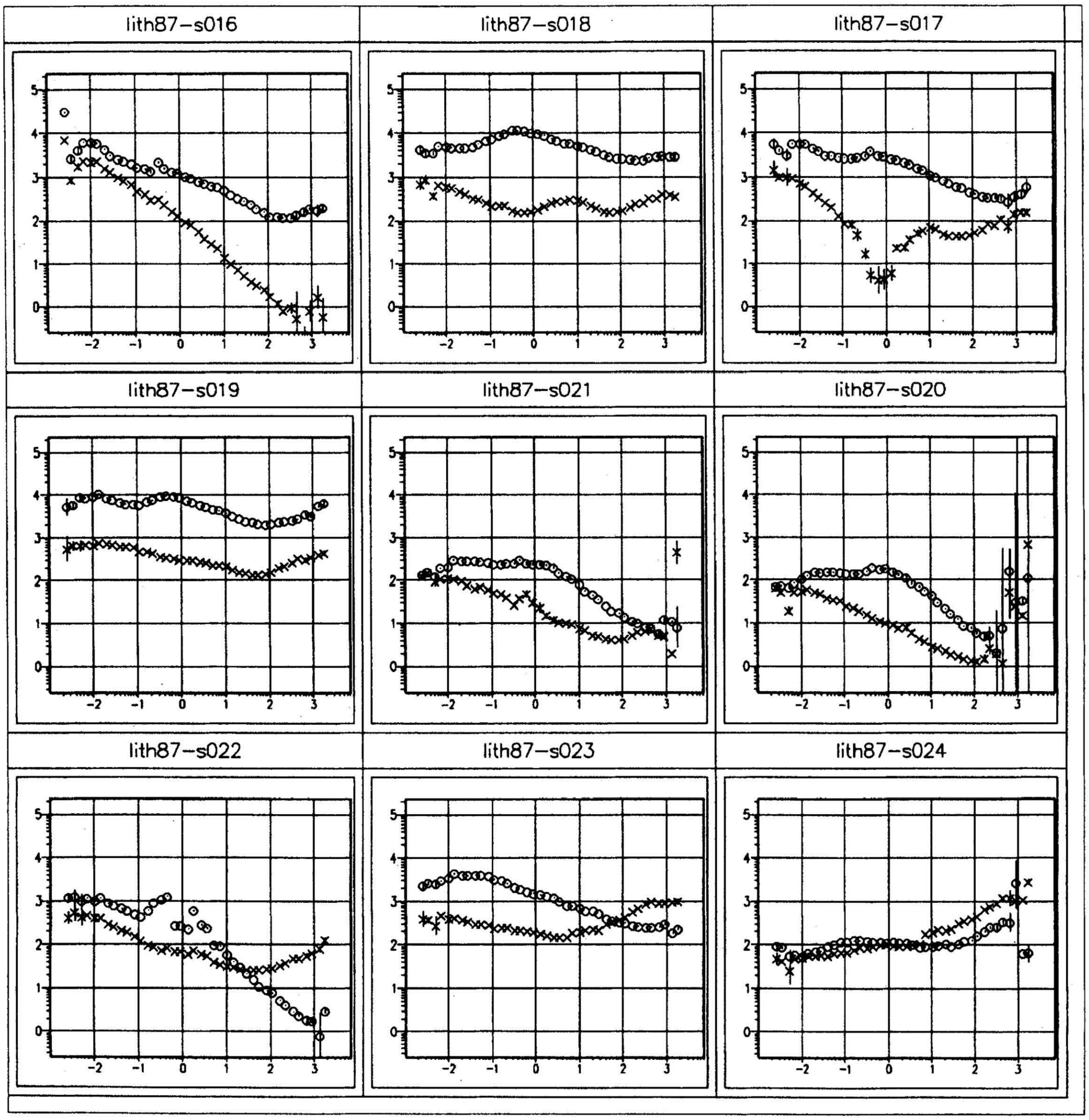

Fig. 7. (continued).

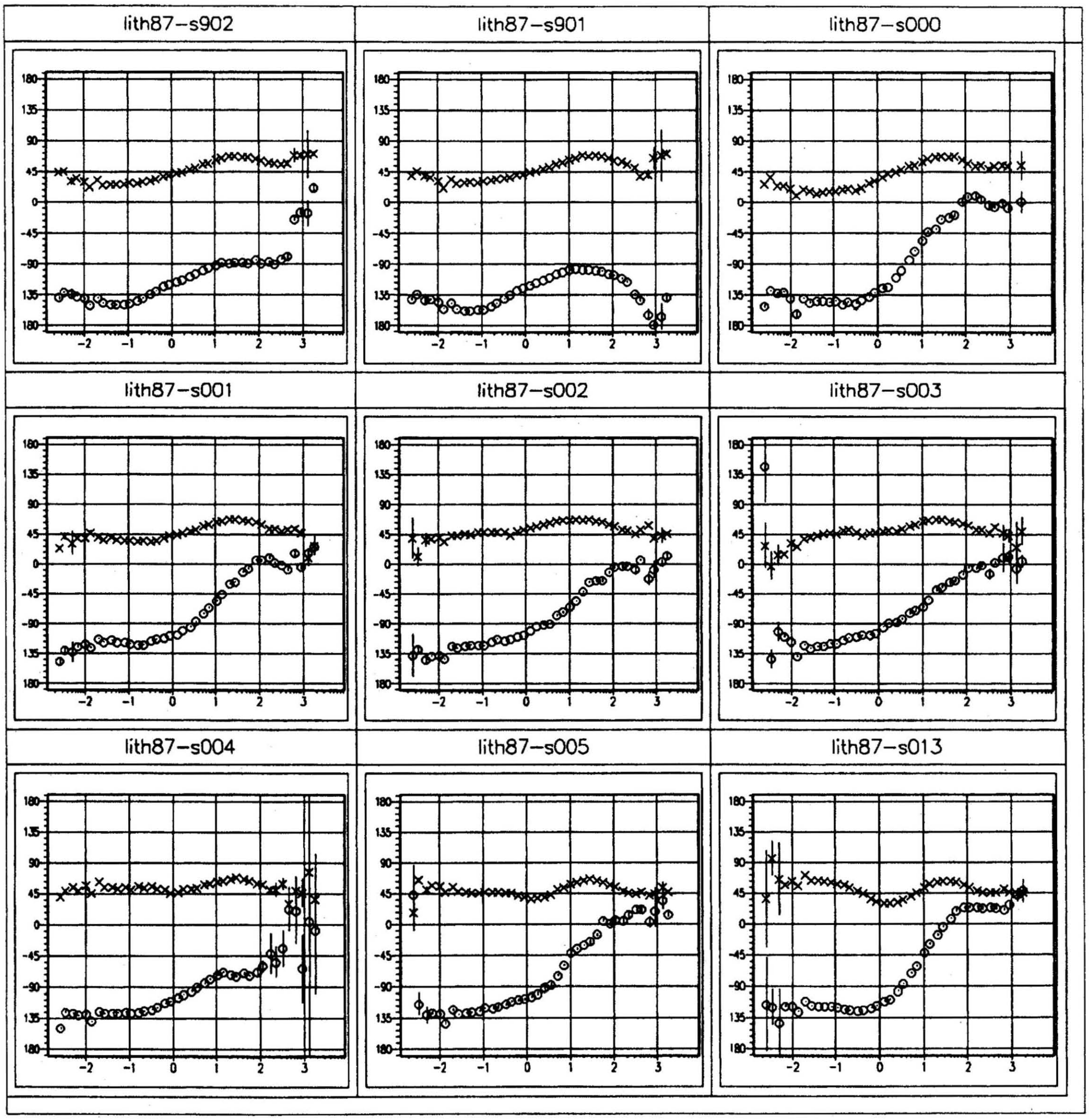

Fig. 8. ϕ_{xy} (crosses) and ϕ_{yx} (circles) phases from all 27 sites in geographic co-ordinates.

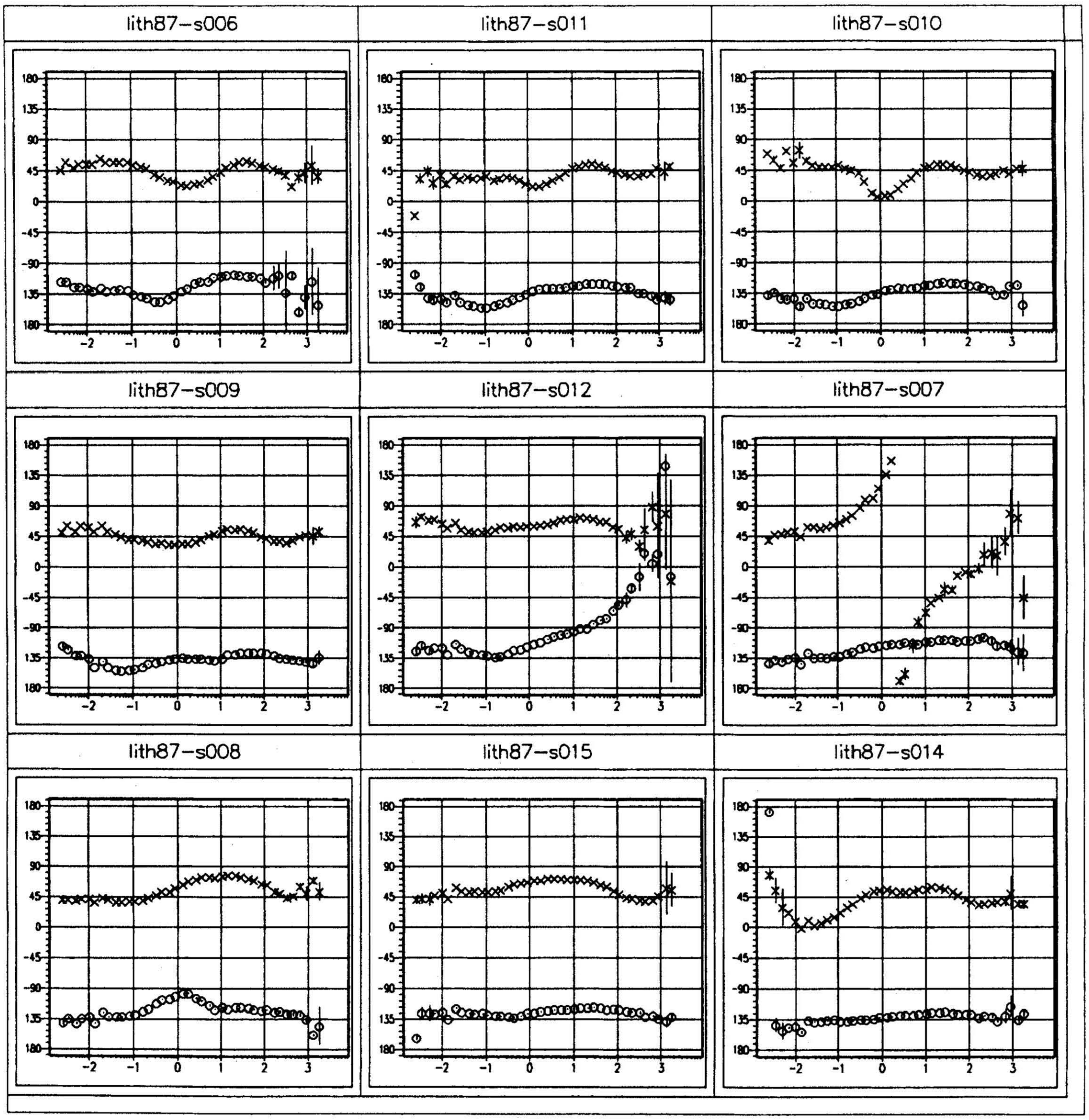

Fig. 8. (continued).

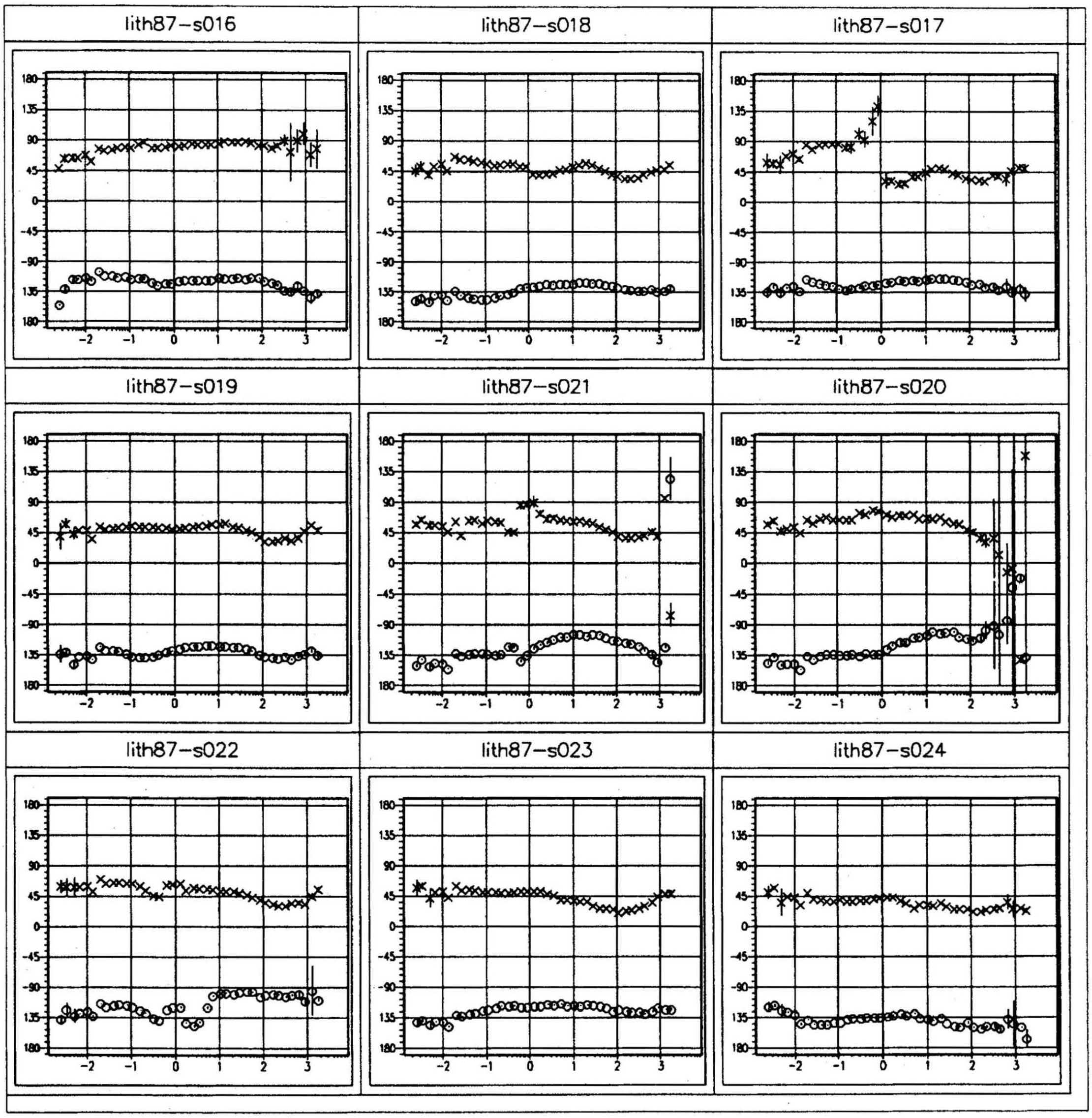

Fig. 8. (continued).

responses from local/remote pair 901/902 are virtually identical. In sharp contrast, the off-diagonal responses from local/remote pair 007/008 belie their very close proximity to each other (within 1 km). There are obviously severe local distortion effects affecting the responses for site 007.

Large scale regional 3D distortion is apparent on ϕ_{yx} data from all sites on the Nelson batholith (000, 001, 002, 003, 004, 005, and 013). At periods greater than about 3 s, the phases exceed the bounds for valid 2D interpretation. The skin depth at this period for the resistivity of the batholith (>10,000 Ω·m) far exceeds the thickness of the batholith, and is of the order of its lateral dimensions (150×50 km). Also note that the data from site 006, lying just off the batholith and within 4 km of site 013, does not display these phase distortion effects. Accordingly, the most significant EM effect of the batholith is due to the charges on its boundaries which distort the EM fields galvanically.

In addition to these MT data, the vertical field responses yield GDS transfer functions for each site. A plot of the real part of the T_{zy} component is given in JONES *et al.* (1988). In the main, these data are dominated by shallow regions of enhanced conductivity. At periods in excess of 100 s the horizontal loop sensor response has fallen such as to make the long period estimates unreliable. However, there is visible consistency with the southward directed induction arrows illustrated in Fig. 5.

Phoenix Geophysics (Toronto) Ltd., particularly George Elliot and Gerry Graham, are thanked for their attention to detail and the high quality of the BC87 dataset. Don White and Colin Zelt provided the digital files from which Figs. 2, 3 and 4 were constructed. Reviews of an earlier version of this manuscript by Ron Kurtz and Colin Zelt are appreciated.

The BC87 dataset is available, either in SEG-EDI format or in impedance format, on application to the author by email to jones@cg.emr.ca.

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