

**Magnetotelluric Response of the Northern Cordillera:
Interpretation of the Lithospheric Structure of the SNORCLE
Transect, Line 2a and Connector Line**

By

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of the requirements for the degree of
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TRANSECT, LINE 2A AND CONNECTOR LINE**

BY

GRANT WENNBERG

**A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University
of Manitoba in partial fulfillment of the requirements of the degree
of**

Master of Science

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ABSTRACT

Magnetotelluric (MT) soundings were made at 54 sites in the northern British Columbia and Yukon, Canada, along the SNORCLE Transect Corridor 2, in the summer and fall of 1999. The sites are located in the Northern Cordillera between latitude 56° - 61° N and 128° - 134° W, and cross over the Stikine, Cache Creek, Quesnellia, Dorsey, Kootenay, Slide Mountain and Cassiar terranes.

Analysis of MT data indicates that the region has approximately two dimensional (2D) structure with a geoelectric strike azimuth of -45° . The methods used in the strike analysis included Groom Bailey tensor decompositions, multi-site multi-frequency tensor decompositions, induction vector examinations, and skew determinations.

Two-dimensional MT model images show narrow (< 20 km) conductive zones (< 2 ohm.m) beneath the Cache Creek Terrane (< 5 km depth), Slide Mountain Terrane (Sylvester Allochthon) (< 3 km depth), and Dorsey Terrane (< 2 km depth) in the shallow upper crust. The enhanced conductivity of the Cache Creek and Slide Mountain terranes is attributed to localized mineralization, whereas the enhanced conductivity of the Dorsey Terrane is attributed to either the widespread occurrence of graphitic or metalliferous rocks or localized sulphides or oxides. The enhanced conductivity in the Slide Mountain and Cache Creek terranes corresponds with zones of high reflectivity. The MT results support the hypothesis that the Dorsey, Cache Creek, and Slide Mountain terranes are thin accreted terranes.

The MT models reveal enhanced conductivity (< 1 ohm.m) centered at 10 km depth on two separate profiles along Corridor 2 and enhanced conductivity (< 1 ohm.m) centered at 15 km depth along Corridor 3. The enhanced conductivity is interpreted to be

associated with metasedimentary rocks. The MT images reveal that the Stikine Terrane is dominantly resistive (>1000 ohm.m) and forms a resistive wedge that tapers eastward beneath the accreted Cache Creek, Quesnellia, Cassiar, and Slide Mountain terranes. The high resistivity of the Stikine wedge corresponds with Devonian to Permian arc volcanics and platform carbonates that are overlain by Triassic and Lower Jurassic arc volcanics, volcanoclastics, and arc-derived clastics, which are intruded by comagmatic plutonic rocks. The resistive area also corresponds with low reflectivity. The resistivity structure provides support for the hypothesis that the Stikine Terrane forms a laterally extensive terrane onto which smaller, thinner terranes are overlain.

West of the Stikine wedge is a northeast dipping conductor (< 50 ohm.m) at the southwest end of Line 2a. A similar structure occurs on Corridor 3 over 400 km to the northeast. The geometry of the conductor suggests that the enhanced conductivity is associated with subduction related processes.

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CHAPTER 1-INTRODUCTION

The Canadian Cordillera is a 2000 km long, 750 km wide orogen, extending from the Arctic ocean to the continental United States. Part of the northern Cordillera is a Phanerozoic accretionary tectonic zone, formed from numerous terranes accreted to the stable margin of western North America from the Jurassic to the early Tertiary (Gabrielse et al. 1991). The rocks and structures of the Cordillera become progressively younger from east to west.

LITHOPROBE is Canada's national, collaborative, multidisciplinary Earth science research project established to develop a comprehensive understanding of the evolution of the North America continent (Clowes, 1997). The Slave-Northern Cordillera Lithospheric Evolution (SNORCLE) Transect (Fig. 1.1) examines the tectonic evolution of the southern Yukon and northern British Columbia through an integrated geological and geophysical study.

Magnetotellurics (MT) is an electromagnetic method that can be used for examining the tectonic structures of a region. In the summer and fall of 1999, a regional-scale magnetotelluric survey was completed within the Northern Cordillera as part of the fifth phase of the LITHOPROBE program (Fig. 1.1). The survey involved two major MT lines and more than 200 audio-frequency MT (AMT), broad-band MT, and long period MT stations. It was located between 56° and 64°N and between 122° and 135°W.

Corridor 2 included a total of 85 MT stations deployed along the Alaskan Highway and British Columbia Highway 37. The corridor crosses a region that has experienced substantial deformation and tectonism, which makes the MT data appealing for examining large-scale tectonic elements and their relationships. This thesis will focus

on Line 2a, which is the part of Corridor 2 that is orientated roughly north-south between Stewart and Watson Lake (Fig. 1.2). This study will also examine MT stations deployed between Watson Lake on Line 2 and Line 3 on a line orientated roughly east-west (Fig. 1.2). This line is referred to as the Connector Line in this thesis. There are 54 MT soundings on the Connector Line and Line 2a.

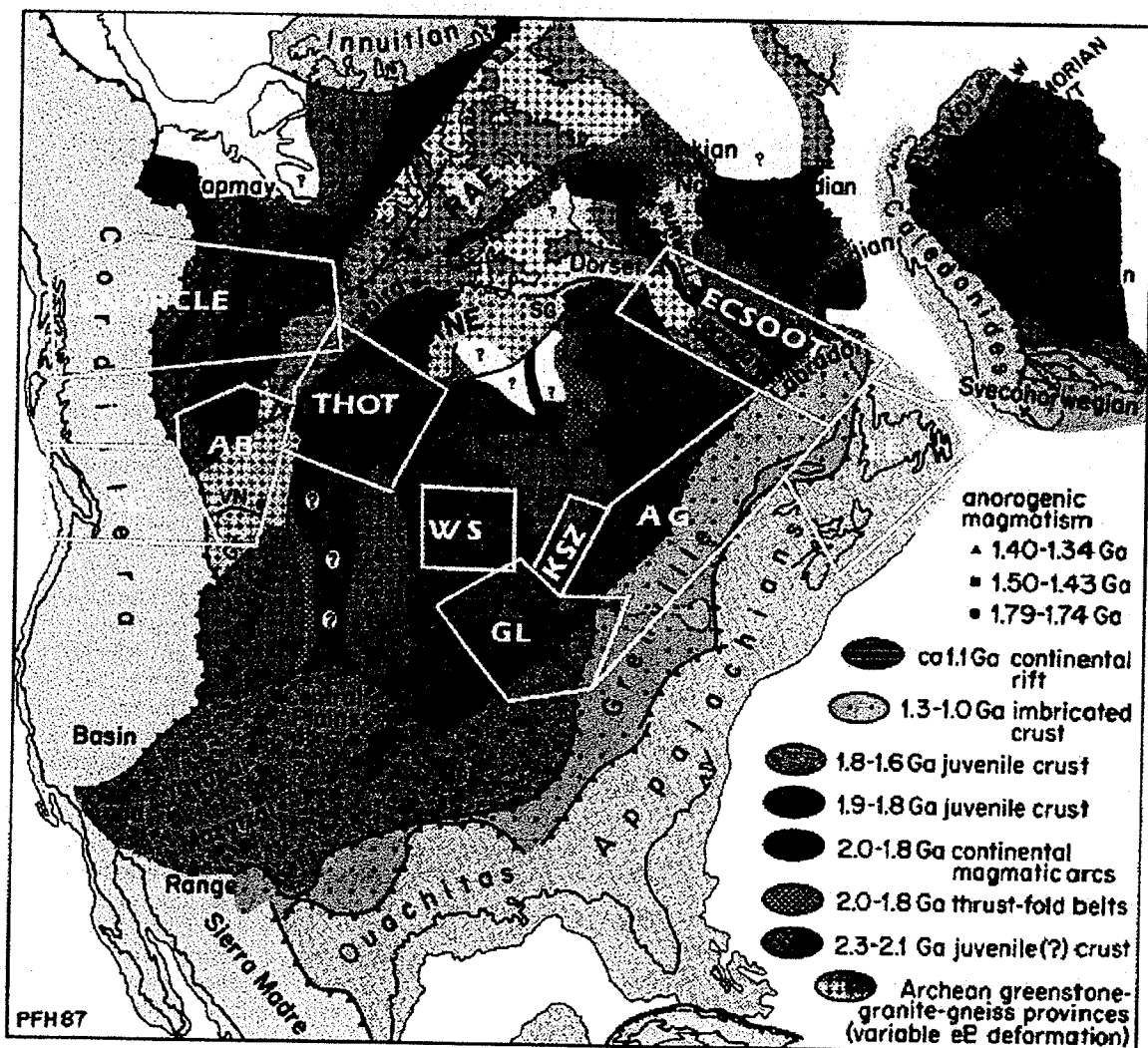


Figure 1.1 Map of North America featuring major tectonic subprovinces, and LITHOPROBE transects including the SNORCLE Transect (Clowes, 1997).

Terranes and Tectonic Elements of Northwestern North America

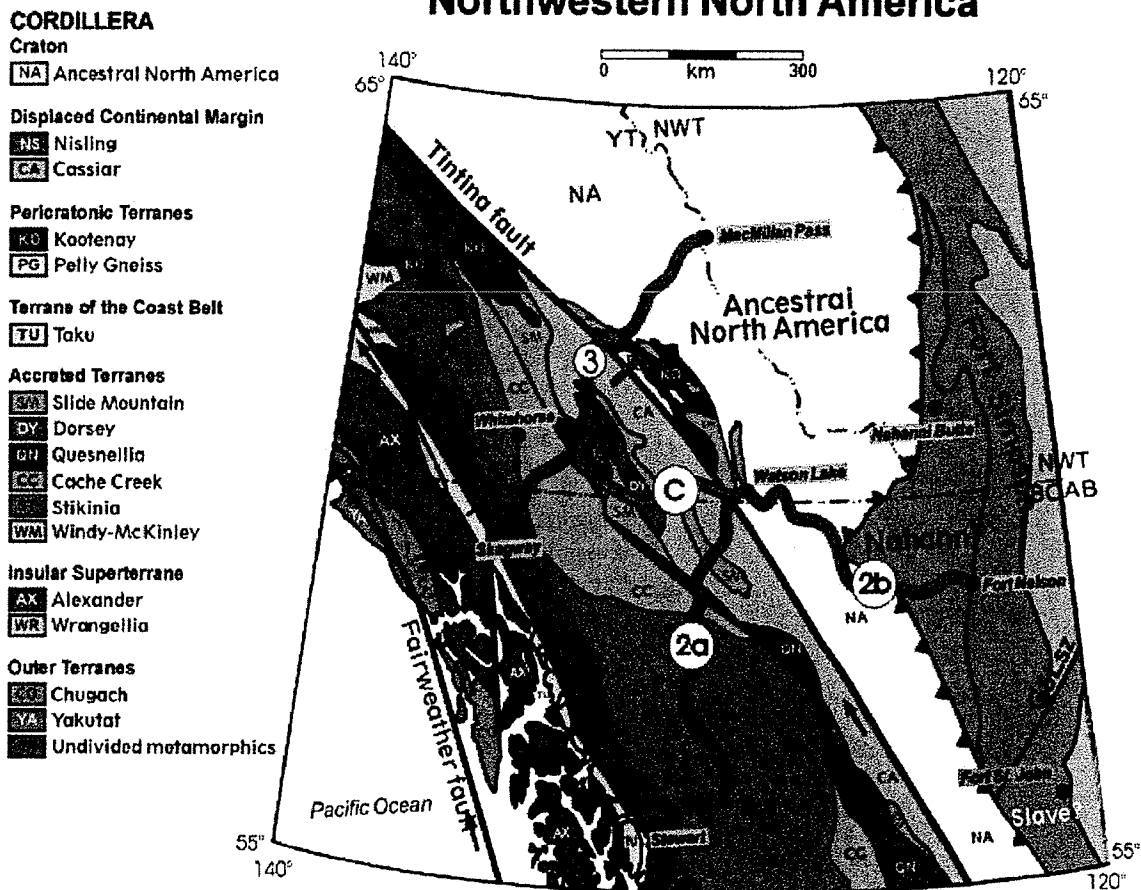


Figure 1.2 Terrane map of northwestern North America showing the location of SNORCLE corridors 2 and 3. The Connector Line is labeled C, lines 2a and 2b are labeled 2a and 2b respectively (modified from Clowes, 1997).

1.1 ELECTRICAL RESISTIVITY OF ROCKS

Electromagnetic (EM) fields in the earth are affected by the electrical properties of the rocks. The electrical conductivity of a material is a measure of its ability to conduct electric current flow. The reciprocal of conductivity is resistivity, which is the ability of a material to resist current flow. Most rock-forming minerals are poor conductors.

There are two mechanisms of conduction in the subsurface: (1) ionic (or electrolytic) conduction, and (2) metallic (or electronic) conduction. Ionic conduction

occurs when ions move through the liquids in the pore spaces of the rock. The conductivity of an ionic solution depends on the mobility and number of ions in solution. Mobility is determined by the restrictions on ion movement and depends on temperature, and to some extent pressure (Keller, 1988). As the temperature increases above freezing, the viscosity of the fluid decreases and the mobility of the ions will increase, resulting in increased conductivity. The conductivity is also dependent on the salinity, whereby an increase in salinity will increase the conductivity (McNeill, 1991). Ionic conduction is an important mechanism in most near-surface and crustal rocks.

Metallic conduction occurs when the charge carriers are electrons. The outermost and most loosely-held electrons in metals do not remain attached to the individual atoms, but become free to wander about within the solid (Parkinson, 1983). These electrons are available for conduction. This type of conduction occurs within metallic mineral deposits and in graphitic rocks. The bulk electrical resistivity of the subsurface depends on the amount of conduction, as well as the geometric distribution of the minerals within the rock. For example, if graphite is present in thin continuous layers at depth the bulk conductivity would increase significantly, whereas if it is present in discontinuous form there will be only a modest increase in conductivity.

One empirical relationship that is used to describe the conductivity of a medium is Archie's Law (Archie, 1942):

$$\sigma_m = \sigma_f \eta^m \quad (1.1)$$

where σ_m is the conductivity of the bulk medium, σ_f is the conductivity of fluid, η is the porosity, and m is an empirical constants that depends on grain shape and degree of connectivity of the grains (Jones, 1992). Archie's Law indicates that a rock's

conductivity is directly related to porosity, and also depends on the tortuosity of the pores, grain shape, and the grain distribution.

Rocks typically decrease in resistivity from igneous to metamorphic, sedimentary, and then sediments (Palacky, 1987). High resistivities observed in igneous and metamorphic rocks result from small inter-granular porosity. Fracturing in these types of rocks due to mechanical breakage can increase porosity, but in general igneous and metamorphic rocks have resistivities greater than 1000 ohm.m (Fig. 1.3).

Upper Crust

The resistivity of the upper crust is highly variable and depends on the local geology. Resistivity values for unconsolidated sediments and sedimentary rocks vary from 0.5 to 100 000 ohm.m, depending on the porosity, fluid content, and clay content. The high porosity of unconsolidated sediments makes them more conductive than sedimentary rocks (Palacky, 1987). Sand and gravel can be resistive if their water saturation is low, while argillite, shale, and slate, which are formed by consolidation of clay-rich substances, are more conductive (Fig. 1.3). The porosity of sedimentary rocks is mostly inter-granular and is generally high (20%-60%). Clay-rich sedimentary rocks have very low resistivity (5-30 ohm.m), as do graphite-rich metasedimentary rocks (0.1-10 ohm.m), such as graphitic schist (Palacky, 1987).

Middle and Lower Crust

For most tectonic settings the conductivity of the Earth increases at depths greater than 15 km (Hyndman and Shearer, 1989). The conductance of the middle to lower crust

in Phanerozoic areas has a mean value of 200-500 S compared with approximately 20 S for the Precambrian Shield locations. The areas of low resistivity in the middle to lower crust generally correlate with zones of high seismic reflection (Hyndman and Shearer, 1989) and low seismic refraction velocity (Hyndman and Klemperer, 1989). The regions of enhanced conductivity in the middle and lower crust have been attributed to either one of, or a combination of, the following: (1) saline fluids, (2) carbon grain-boundary films, (3) conducting minerals, (4) partial melts or (5) faults.

Geophysical modelling and laboratory experiments have been performed to examine the middle and lower crustal conductivity. Modelling has suggested that fluid in the middle and lower crust will rise rapidly to the brittle-ductile transition zone, and accumulate there in extensive reservoirs with high horizontal permeability but low vertical permeability (Bailey, 1990). Enhanced conductivity caused by fluids in the middle and lower crust is dependent on the ambient temperature. Jones and Gough (1995) argue that the mid-crustal conductor observed in the southern Cordillera is associated with hot saline water and silicate melt in fractures and other interconnected spaces. The conductivity also depends on the salinity of the fluids and the geometry and interconnection of the pores (Nesbitt, 1993).

An alternative theory for high conductivity in the middle to lower crust is the presence of carbon films on grain boundaries (Mareschal et al. 1992; Wannamaker, 1997). Carbon films can occur when continental deformation and metamorphism disperse carbon from its original placement as fluid species. The increase in conductance in the Phanerozoic may be caused by an increase in the crust of organic-rich sediment (Wannamaker, 1997).

Upper Mantle

Our current knowledge of the resistivity of the upper mantle is based mostly on laboratory experiments in which olivine rocks are measured under upper mantle conditions. Other estimates of upper mantle resistivity are derived from long-period MT surveys (e.g. Jones and Ferguson, 2001) including analysis of the daily variation of the magnetic field (e.g. Schultz et al. 1993).

Enhanced conductivity has been observed in the upper mantle in some Archean regions (Schultz et al. 1993; Jones, 1992; Mareschal et al. 1994). The conductivity has been attributed to both partial melting and hydrogen being dissolved in olivine (Karato, 1990). From laboratory studies the presence of volatiles has also been proven to have a profound effect on resistivity (Wang et al. 1999; Hirsch, 1990).

Evidence from MT and seismic surveys performed in the Canadian Shield suggests that the mantle is anisotropic (Kellet et al. 1992; Mareschal et al. 1995; Ji et al. 1996; Eaton et al. 2002). Results in the Grenville Front area of Canada show obliquity between the polarization direction of the fast split shear (SKS) wave and the most electrically conductive direction in the upper mantle in regions near a transcurrent shear zone. The seismic results are interpreted to be controlled by lattice-preferred orientation of olivine and the MT results by shape-preferred orientation of olivine (Ji et al. 1996). Eaton et al. (2002) examined seismic and MT data from the Great Slave Lake shear zone. The MT results reveal that the MT strike direction in the upper mantle differs significantly from the MT strike at shallower levels, in contrast with the result from the Grenville Front. There is agreement in the direction of the long period strike and the overall SKS direction.

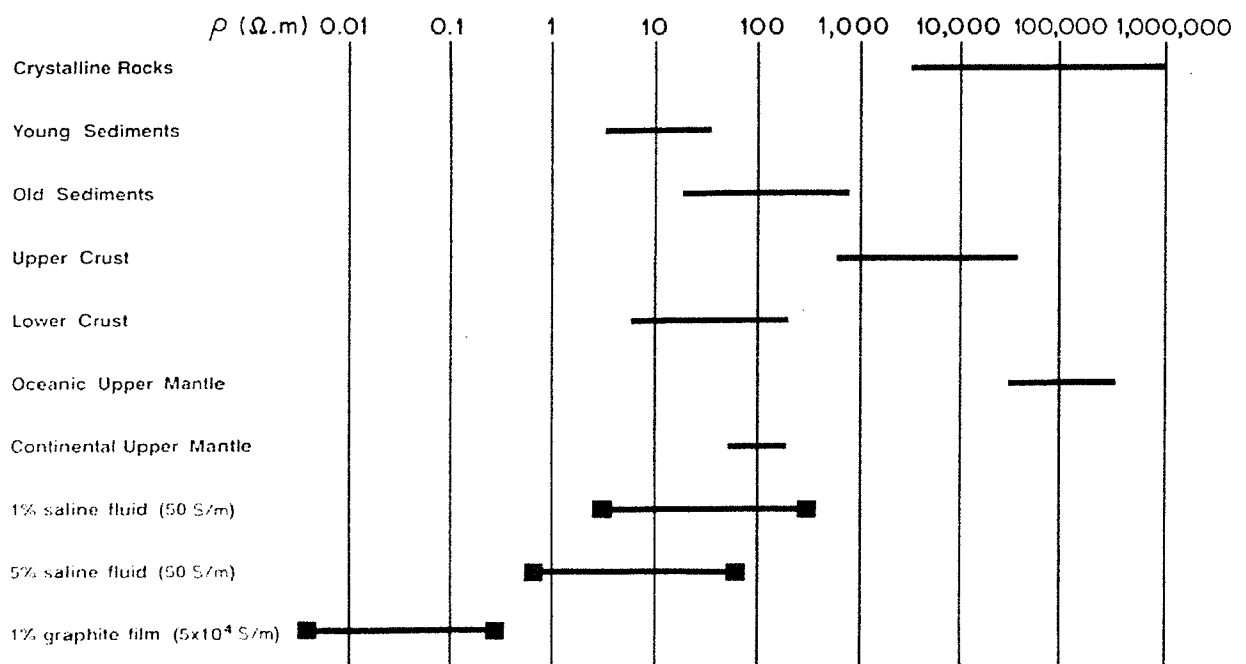


Figure 1.3 Resistivity and conductivity ranges for different rock types (Jones, 1992).

1.2 SCOPE OF THESIS

The SNORCLE MT survey was a joint project involving the Geological Survey of Canada (GSC) and LITHOPROBE. The MT data collection was contracted out to Geosystem Canada and was overseen by personnel from the Geological Survey of Canada and the University of Manitoba. The author participated in the data collection, analysis, and interpretation of the data from the survey.

Data collection for Corridor 2 began in fall 1999 and was completed in early winter of 1999. The author participated in the survey under the direction of the Geosystem crew chief. The author then participated in the preliminary processing of the data was at the GSC in Ottawa, Ontario in winter 2000. This work included merging of the MT (broad-band) and long period (LiMS) responses and removal of spurious data from each site. Subsequent analysis and interpretation of Corridor 2 data was completed

by the author at the University of Manitoba and during several visits to the GSC. Work at the GSC was guided by Dr. Juanjo Ledo and Dr. Alan Jones.

This thesis contains a description of the analysis and interpretation of the MT data from SNORCLE Corridor 2. In Chapter 1 I have introduced the study area and research objectives, and briefly reviewed the resistivity properties of rocks. Chapter 2 contains a description of the regional geology and geophysics of the Northern Cordillera. The following chapter contains an introduction to EM theory and to the MT methods used in the study, including impedance estimation, tensor decomposition, modelling and inversion. Chapter 4 contains a description of the MT survey, including the site locations, data collection procedures, and equipment. Chapters 5 and 6 describe the data processing and MT responses and Chapter 7 describes the non-linear conjugate gradient and Occam inversion techniques. Chapter 8 includes the MT results and interpretation of the findings with other geophysical information. Chapter 9 describes the conclusions of the thesis research.

CHAPTER 2-REGIONAL GEOLOGY AND GEOPHYSICS

In this chapter, the geological setting and geophysical surveys completed around the SNORCLE and Southern Cordillera areas will be described.

2.1 INTRODUCTION

The LITHOPROBE SNORCLE transect Corridor 2 is located in the Canadian Cordillera in northern British Columbia and southern Yukon Territory (Fig. 1.2). The region is characterized by oceanic and island-arc terranes accreted to western North America since the Neoproterozoic. The terranes are predominantly allochthonous and are characterized by a distinct or unique geological and tectonic history.

The Cordillera can be subdivided into two distinct parts: the northeast part that encompasses ancestral North American rocks and the southwest part that consists of accreted terranes. Separating the two parts is the Tintina Fault, a northwest trending transcurrent fault, which since the Cretaceous has had ~450 km of dextral displacement accommodating the relative movement of the Pacific ocean crust and the North American continent (Lowe et al. 1994) (Fig. 1.2).

The tectonic framework of the Cordillera is described in terms of morphogeological belts consisting of tectonostratigraphic rock assemblages and component terranes (Fig. 2.1). The belts vary in thickness, from 3 km in the west to 50 km in the east (Gabrielse et al. 1991). The morphogeological belts are defined in terms of the accumulated affect of the geological processes that have occurred from middle Proterozoic to Cenozoic time. Each belt has different physiography, metamorphism, volcanism, plutonism, and structural styles that were inherited from their original terranes

(Gabrielse et al. 1991). The morphogeological belts within the study area are the Intermontane belt, Omineca belt, and Foreland belt.

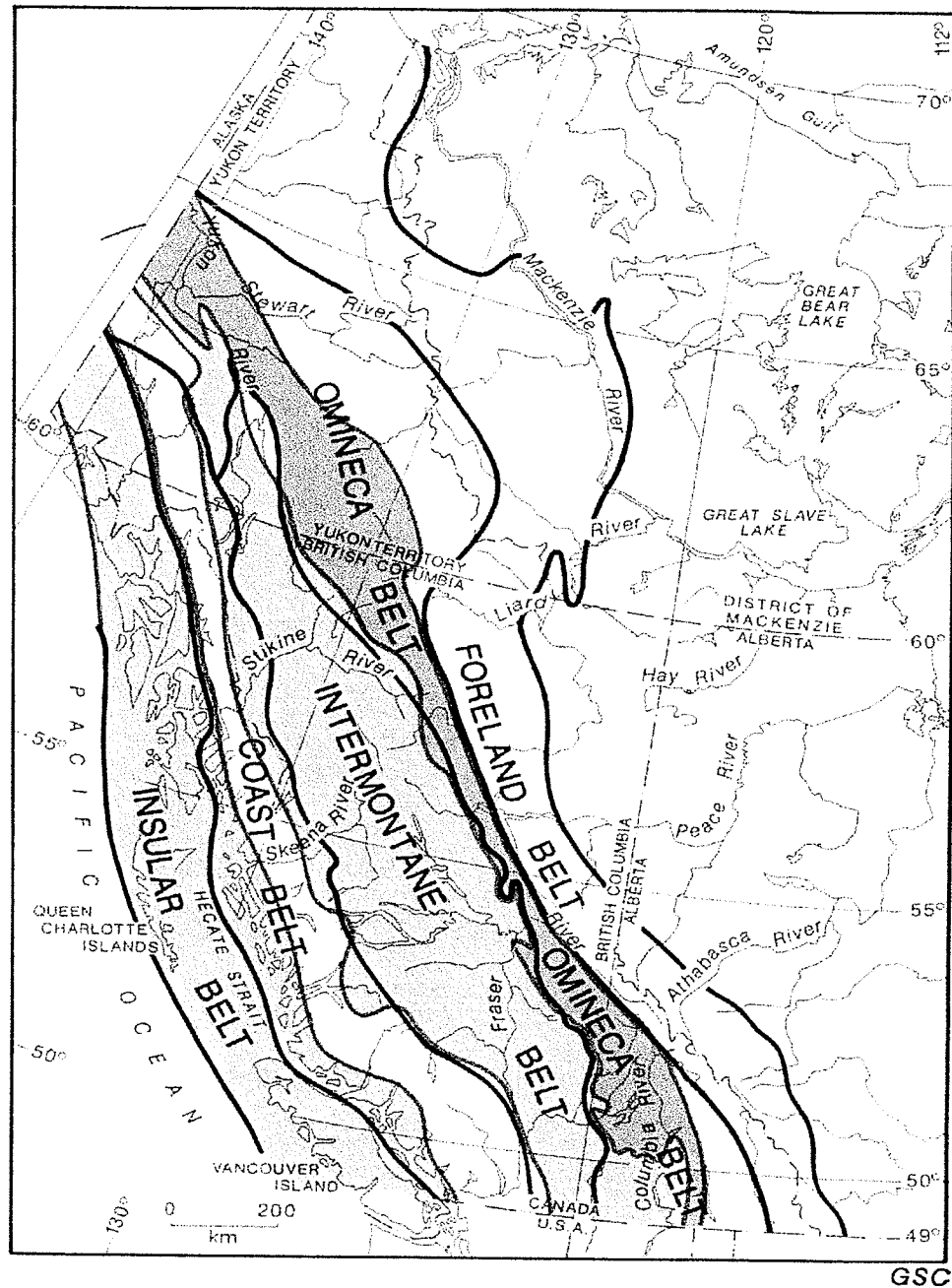


Figure 2.1 Location of the five morphogeological (Gabrielse et al. 1991).

2.2 FORELAND BELT

The Foreland Belt is the easternmost morphogeological belt in the Cordillera, and represents the boundary of Cordilleran deformation in ancestral North America. The eastern margin of the belt is the boundary between deformed strata of the foothills and mountain systems and the undeformed strata underlying the Interior Plains to the east (Gabrielse et al. 1991). The belt forms the eastern mountain ranges and foothills of the Rocky Mountains (Fig. 2.1, 2.2, and 2.3).

The Foreland Belt is composed of imbricated and folded miogeoclinal and clastic wedge assemblages deposited on, and adjacent to, the stable craton of ancestral North America (Gabrielse et al. 1991). It contains an easterly-tapering prism of dominantly sedimentary rocks. The tectonic assemblages present in the belt include: Precambrian crystalline basement gneiss; clastic rift sequences of Middle and Late Proterozoic and earliest Paleozoic ages; carbonate-clastic passive continental margin and thin platform assemblages of Middle and Late Proterozoic, Paleozoic and early Mesozoic ages; and clastic wedges of Devonian-Mississippian, Late Jurassic-Early Cretaceous, and latest Cretaceous-Early Tertiary ages (Gabrielse et al. 1991).

2.3 OMINECA BELT

The Omineca Belt is an uplifted region that has been intensely folded, metamorphosed, and intruded by granitic rocks (Fig. 2.1). The belt straddles the boundary between the accreted terranes and Ancestral North America. Within the study area the eastern boundary coincides with the Rocky Mountain trench (Fig. 2.2), and the western

boundary is defined by a decrease in metamorphic grade on the western slope of the Kaska Mountains (Gabrielse et al. 1991).

Throughout most of the Omineca Belt a series of northwesterly aligned structural culminations and depressions give a discontinuous character to the topography (Gabrielse et al. 1991). The depressions are mostly underlain by low-grade sedimentary rocks that extend west from the Foreland belt, while the culminations include core zones of moderate- to high-grade metasedimentary rocks which locally enclose slices and wedges of lower Proterozoic gneiss (Gabrielse et al. 1991). The core zones are overlain by less deformed rocks, which are in turn overlain by easterly directed, folded thrust sheets containing sedimentary, volcanic, and plutonic rocks. Gneisses representing the deformed late Proterozoic, Devonian, Mesozoic, and Tertiary intrusions are distributed throughout the belt.

On a regional scale, the Omineca Belt comprises an imbricated succession of folded thrust sheets of Mesozoic age, which indicate an easterly direction of tectonic transport toward the craton. During late Cretaceous and early Tertiary time the Omineca was further disrupted by several northwest trending dextral faults, most notably the Tintina Fault (Fig. 1.2), which repeated the belt along hundreds of kilometers of overlap length and doubled its width in the Yukon Territory (Gabrielse et al. 1991).

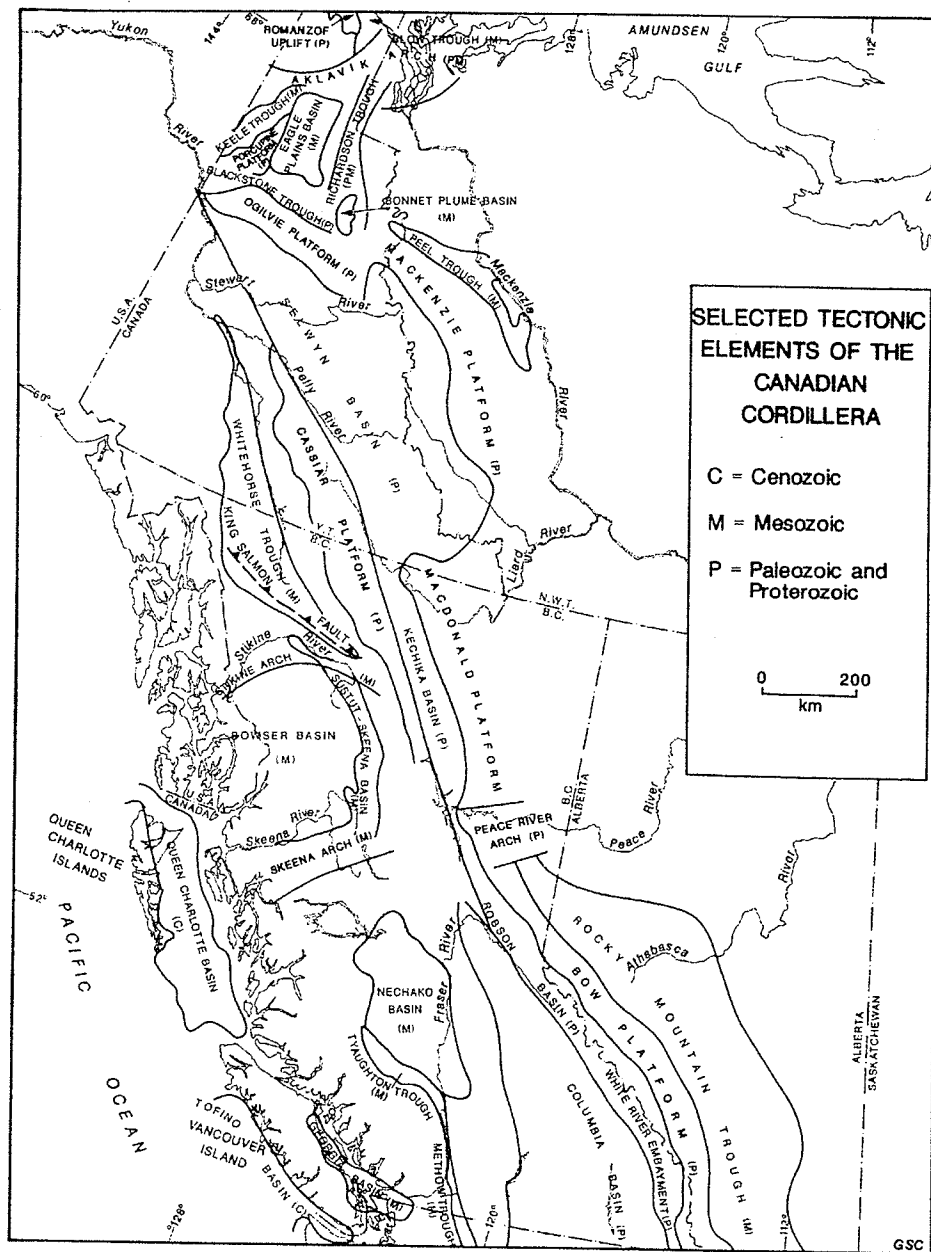


Figure 2.2 Tectonic features of the Canadian Cordillera (Gabrielse et al. 1991).

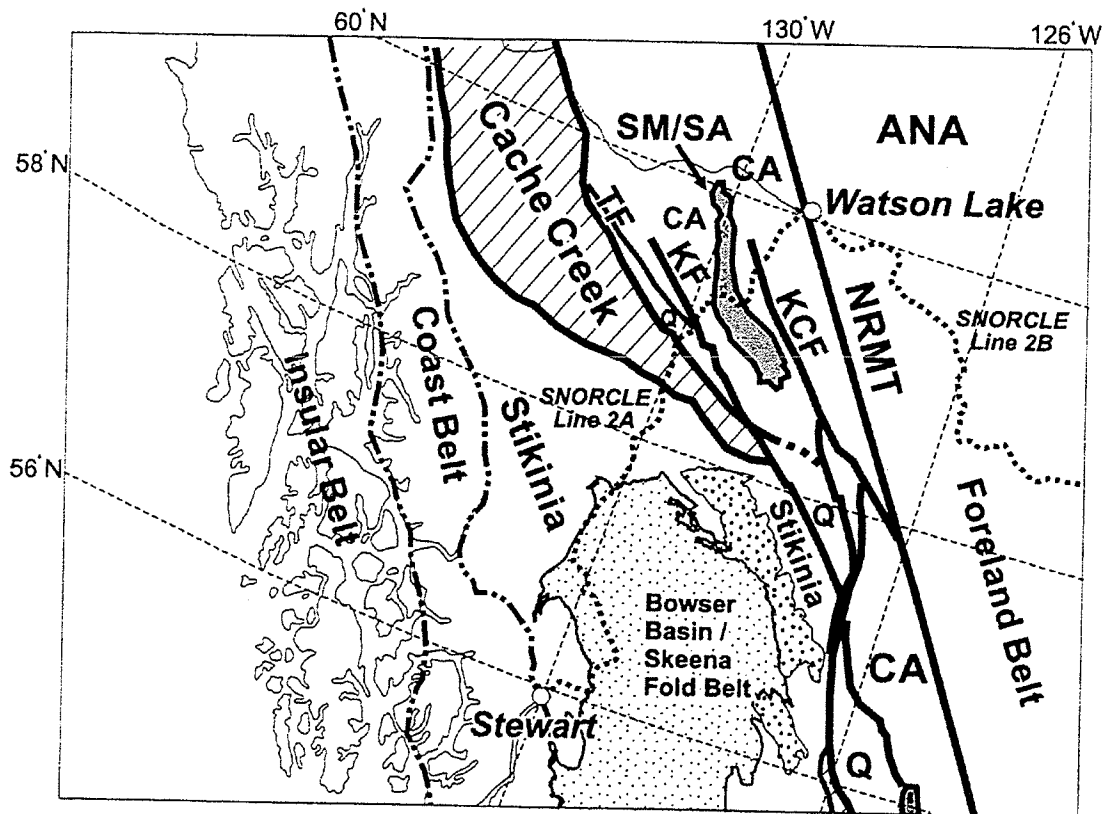


Figure 2.3 Location of major features of study area. Heavy lines are major faults, dash-dot lines are the boundaries between Insular, Coast, and Intermontane belts. Dot lines are Lines 2a, and 2b. Abbreviations: ANA Ancestral North America; CA Cassiar Terrane; SM/SA Slide Mountain Terrane, Sylvester Allochthon; Q Quesnellia; KCF Kechika Fault; KF Kutcho Fault; TF Thibert Fault; NRMT Northern Rocky Mountain Trench (modified from Evenchick et al. 2001).

2.4 INTERMONTANE BELT

The Intermontane Belt is topographically lower and contains less variation in relief than the Omineca Belt. A prominent exception is a series of ranges, referred to as the Skeena Mountains located in northwestern British Columbia (Fig. 2.2). Found on the eastern edge of the Skeena Mountains are regional strike-slip faults including the Kutcho and Teslin faults, which separate the Intermontane Belt from the Omineca Belt (Gabrielse et al. 1991).

The Intermontane Belt is largely coextensive with the Intermontane superterrane, which is an amalgamation of the Stikine, Quesnellia, Slide Mountain and Cache Creek terranes (Gabrielse et al. 1991). These terranes are overlapped by sediments derived from uplift resulting from contraction during terrane amalgamation and accretion.

Stratified rocks in the Intermontane Belt are rarely metamorphosed to grades higher than greenschist. Granitoid rocks are predominantly of I-type and associated with late Triassic, early Jurassic, late Cretaceous, and early Tertiary volcanism (Gabrielse et al. 1991). Volcanic and sedimentary rocks are widely distributed. Sedimentary rocks occur in thick successions in the Skeena Mountains, and Spatsiz and Nechako plateaus, where they define the Sustut-Skeena, Nechako, and Bowser basins (Gabrielse et al. 1991).

2.5 TERRANES AND LOCAL GEOLOGY

The geology of the Canadian Cordillera is subdivided into terranes (Fig. 1.2). A terrane is a part of the Earth's crust that preserves a geologic record different from in neighboring areas (Gabrielse et al. 1991). Corridor 2 crosses from west to east the Stikine, Cache Creek, Slide Mountain, Dorsey, Kootenay, Quesnellia, and Cassiar terranes (Fig. 1.2).

2.5.1 STIKINE TERRANE

The Stikine Terrane (also called Stikinia), is a transported allochthonous terrane within the Intermontane Belt containing late Triassic to middle Jurassic mafic to felsic volcanic rocks, inter-layered with clastic sedimentary and carbonate rocks, and intermediate composition plutons (Lowe et al. 1994; Monger et al. 1991). Part of the

contact between Stikinia and the Cache Creek Terrane is obscured by Cretaceous and Tertiary plutonism and metamorphism in the Coast Belt (Fig. 1.2) (Monger et al. 1991). The plutonism consists of basalt to rhyolite flows and pyroclastic rocks, interbedded with carbonate, shale, volcanic sandstone, and minor chert. Analyses of the volcanic flows suggest that Stikinia formed in an arc environment.

South of the King Salmon Fault (Fig. 2.3), south-southwest directed thrust faults are associated with Triassic and lower Jurassic volcanic and sedimentary rocks. This area includes a zone of imbricate structures formed during a collision between the Stikine Terrane and the Cache Creek Terrane before Jurassic time, which was succeeded by further convergence and uplift during the Late Jurassic (Gabrielse et al. 1991).

Bowser Basin

The Bowser Basin is located within the Stikine Terrane (Fig. 2.3) in northwestern British Columbia. Syntectonic Jurassic-Cretaceous sediments in the basin are consistent with an obducted oceanic crust and island arc environment (Cookenbo et al. 1997; Hannigan et al. 1995).

The Bowser Basin includes fractured Late Paleozoic siliceous carbonates, Triassic reefal mounds and associated shallow-water platformal carbonates, Jurassic-Cretaceous non-marine fluvial and marginal to deep-water marine clastics, and unconsolidated Quaternary till (Hannigan et al. 1995). Hannigan et al. (1995) suggests that the basin has economic hydrocarbon accumulations preserved in Permian to recent strata. The cap rock for the hydrocarbon is Jurassic-Cretaceous shale, fine-grained volcanoclastics, and tight carbonates and the source material includes Jurassic shales,

Lower Permian black shales, and minor interspersed coal seams. The structures within the Bowser Basin include anticlinal structures that have been subjected to episodes of intense faulting (Hannigan et al. 1995).

2.5.2 CACHE CREEK TERRANE

The Cache Creek Terrane is a large, disrupted, assemblage of oceanic rocks and subduction complexes that extends from central Yukon Territory to southern British Columbia (Cordey et al. 1987). Rocks are typically lower Mississippian to middle Jurassic radiolarian chert and argillite, distinctive masses of shallow-water carbonates, basalt, gabbro, alpine-type ultramafic rocks, and calc-alkaline volcanic rocks (Monger et al. 1991). The geology of the terrane is characterized by extreme stratigraphic and structural disruption, with most internal contacts being faults. The degree of deformation increases progressively from west to east (Gabrielse et al. 1991).

The King Salmon Fault (Fig. 2.3) in northern British Columbia separates the early Mesozoic Stuhini and Takwahoni assemblages of Stikinia from cleaved rocks of the upper Paleozoic and Mesozoic Cache Creek and Kutcho assemblages (Fig. 2.3) (Gabrielse et al. 1991). The eastern boundary of the Cache Creek Terrane in North British Columbia is formed by the Teslin Fault.

2.5.3 SLIDE MOUNTAIN TERRANE

The Slide Mountain Terrane is the easternmost accreted terrane in the northern Cordillera and is mostly in fault contact with the Kootenay and Cassiar terranes. The terrane is composed of mafic volcanic rocks with related ultramafic, mafic, and granitic

bodies, and predominantly fine grained clastic rock and chert. The rocks are of mid-to late Paleozoic and, rarely, Triassic age (Monger et al. 1991; Monger, 1989).

Within the SNORCLE study area the Slide Mountain Terrane forms part of the Sylvester Allochthon. The Sylvester Allochthon is a thrust-imbricated set of assemblages with oceanic to pericratonic arc affinity, lying in structural juxtaposition above para-autochthonous strata of the Cassiar Terrane (Nelson, 2002). The assemblages are late Paleozoic ocean-margin rocks of the Slide Mountain Terrane; Late Paleozoic arc and carbonate strata; and a deformed and metamorphosed pericratonic unit, which resembles rocks of the Dorsey Terrane (Nelson, 2002).

2.5.4 DORSEY TERRANE

The Dorsey Terrane is composed of rocks similar to both the Slide Mountain and Quesnellia Terrane, except that it contains no volcanic rocks (Monger et al. 1991). Three members have been recognized. The lowest member is a carbonate unit that ranges from a few meters to 70 meters thick. The intermediate member (~300 m thick) is mainly thick bedded, cryptocrystalline to fine-grained cherty limestone of Pennsylvanian age (Monger et al. 1991). The shallowest member consists of green phyllite with magnetite porphyroblasts, conglomerate, grit, schist, quartzite, sandstone, argillite (~300 m thick), and chert (~500 m thick) (Monger et al. 1991).

Recent work has suggested that the Dorsey Terrane is not a distinct entity, but forms part of an allochthonous suite (Nelson, 2002; Harms and Stevens, 1996), and may have close affinity to those of other terranes such as the Yukon-Tanana (Big Salmon Complex), Kootenay (Dorsey Assemblage), and Quesnellia (Klinkit Assemblage) (Roots, 2002).

2.5.5 *QUESNELLIA TERRANE*

The Quesnellia Terrane is an accreted terrane composed of upper Paleozoic and lower Mesozoic volcanic and sedimentary strata and associated plutonic rocks (Monger et al. 1991). Clastic rocks, mafic to felsic volcanic rocks, and carbonate rocks are overlain by upper Triassic and lower Jurassic calc-alkaline to alkaline volcanic rocks and related intrusive rocks, argillite, volcanic sandstone, and local carbonate (Monger, 1989). Stratigraphically and structurally, the terrane overlies the Slide Mountain, Kootenay, and Cassiar terranes (Monger et al. 1991).

2.5.6 *KOOTENAY TERRANE*

The Kootenay Terrane is a pericratonic terrane composed of variably metamorphosed Paleozoic strata comprising pelite, quartz grit, and basic to acidic volcanic rocks, with Devonian and older intrusions that were deformed prior to deposition of late Paleozoic pelite, conglomerate sandstone, limestone, and basic volcanic rock (Monger, 1989). In part the strata resembles coeval "North America" strata to the east, but the latter contain no record of Paleozoic deformation and intrusion (Monger, 1989).

2.5.7 *CASSIAR TERRANE*

The Cassiar Terrane is a fragment of ancestral North America displaced from its original position (Gordey et al. 1991). It is composed of Upper Precambrian to Devonian platformal carbonate rocks, sandstone, and graptolitic shale (Monger, 1989). The rocks are displaced by an uncertain amount along dextral transcurrent faults in the Tintina and Northern Rocky Mountain trenches.

2.6 GEOPHYSICAL INVESTIGATIONS OF THE SNORCLE TRANSECT

Regional gravity, magnetic, MT, and seismic surveys have been completed in the Cordillera that complement information available from geological studies.

2.6.1 EM METHODS

Ledo et al. (2001, 2002a) determined electromagnetic images of the Tintina Fault from the 1999 MT LITHOPROBE data. Three separate profiles crossing the Tintina Fault (line 200, 300, and 400) were examined (Fig. 1.2). Two-dimensional inversion of the TM and TE apparent resistivity and phase along each profile using the algorithm of Rodi and Mackie (2001) revealed similarities in the resistivity structure (Fig. 2.4). The three models include conductive structures ($\sim 1\text{-}10\ \Omega\cdot\text{m}$) below the surface trace of the Tintina Fault zone up to 5 km depth, which are thought to be associated with the fault system (Labeled **A**). To the southwest, another conductor is present below 5 km depth (labeled **B**) and to the northeast another conductive structure is resolved (labeled **C**). Finally, all three models have low conductivity at > 5 km depth below the surface trace of the Tintina Fault zone (Labeled **D**).

Ledo et al. (2002b) have also examined the MT data for Corridor 3. The results will be discussed in detail in chapter 8. Wolyneć (2000) examined MT soundings from fifteen sites from Corridor 3 extending from near Skagway, Alaska to the southern end of Canol Road in southern Yukon Territory (Fig. 1.2). Analysis of the data and modelling revealed approximately two-dimensional crustal structure with a $\text{N}37^\circ\text{W}$ regional strike and localized three-dimensional effects (near Carcross, Yukon Territory) interpreted to be

associated with local mineralization. Two-dimensional modelling revealed: (1) a thin (<1 km) conductive layer interpreted to be associated with the metasedimentary rocks of the Whitehorse Trough; (2) an isolated conductor at <10 km depth in the upper crust beneath the Whitehorse Trough; and (3) a moderately conductive mid to lower crust; and (4) an eastward-dipping conductor in the lower crust and mantle (Wolyniec, 2000).

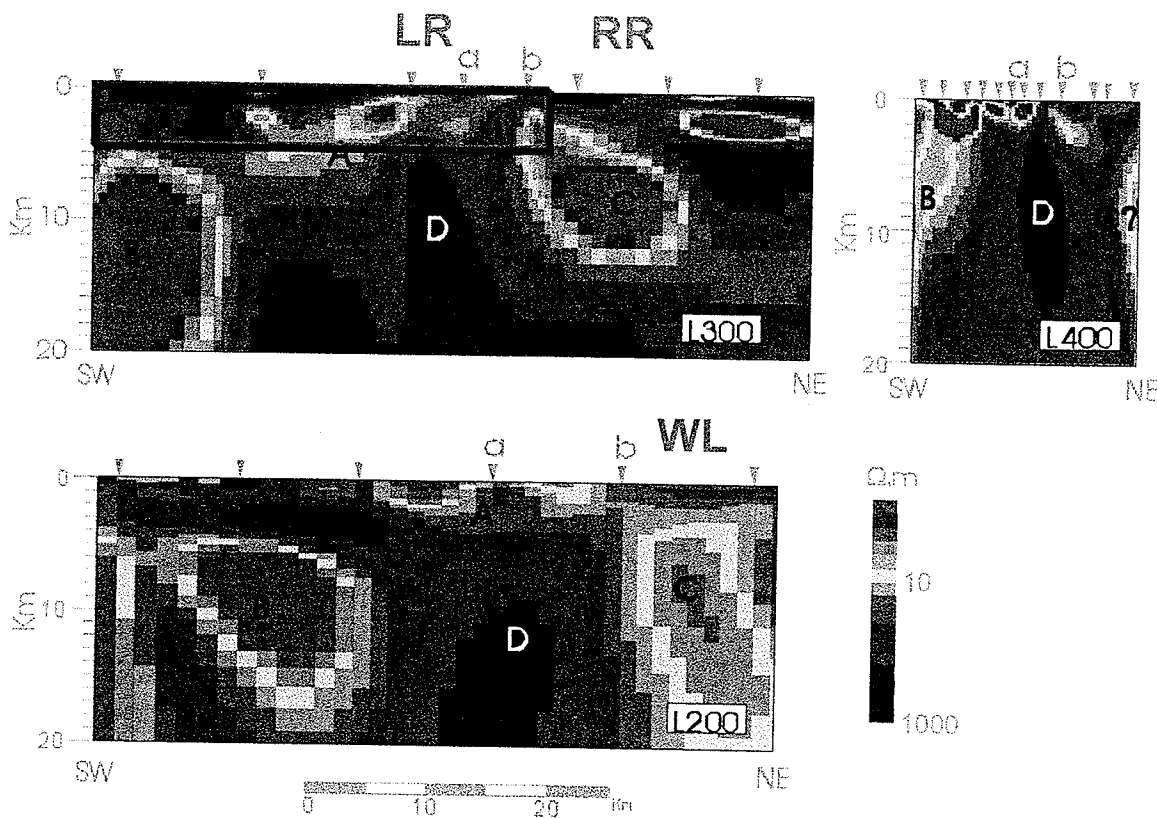


Figure 2.4 Two-dimensional MT resistivity models obtained by inversion using both TE and TM mode apparent resistivities and phases. Triangles show MT site positions (Ledo et al. 2001). Features marked "A", "B", "C", and "D" are discussed in the text.

2.6.2 SEISMIC REFLECTION AND REFRACTION

LITHOPROBE seismic reflection data were collected during the fall 1999 along Corridor 3, Line 2a (or line 22), and Line 2b (or Line 21) (Fig 2.5). The data quality was determined to be generally very good with reflections visible throughout most of the crust (Cook et al. 2001). No seismic data was collected along the Connector Line.

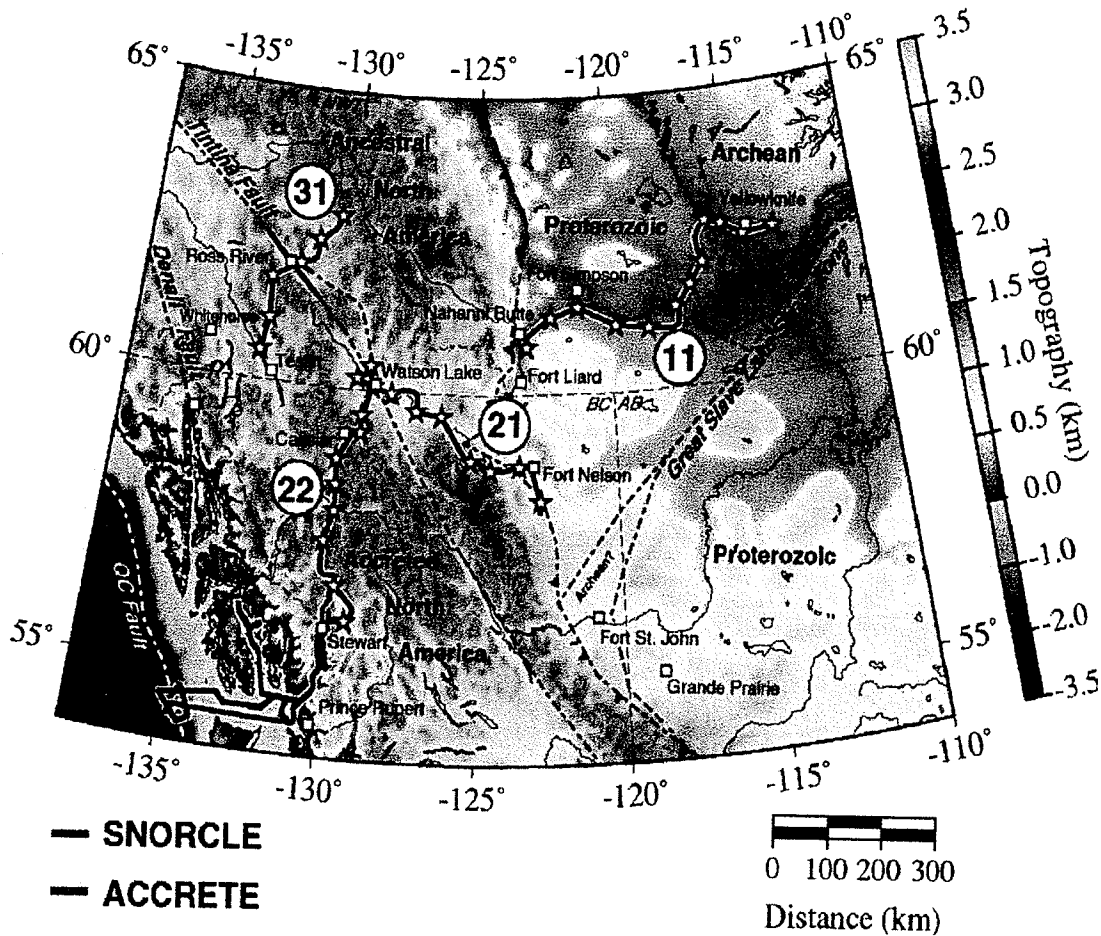


Figure 2.5 Terrane map of northwestern North America that shows the location of SNORCLE seismic lines 3, 2a, and 2b (from Clowes, 1997).

Figure 2.6 illustrates the interpreted seismic section along Line 2 (Clowes and Hammer, 2002). The results indicate that the North American rocks are present at depth beneath much of the Northern Cordillera. Cook et al. (2001) proposed that the North

American rocks extend as a westward tapering wedge of layers that can be followed from outcrops of Proterozoic strata in the Foreland Belt to the lowermost crust of the Intermontane Belt. Along both Corridors 2 and 3, the wedge thins and disappears near the Moho (Cook et al. 2001). Other conclusions drawn from seismic reflection data are:

1. On Line 3 the North American wedge is very thin, whereas along Line 2 it terminates about 40-50 km southwest of Dease Lake.
2. The Tintina and Kechika faults penetrate the North American wedge, whereas other faults appear to be confined to the crust above the wedge. The wedge layering is therefore older than the youngest movement on the Tintina Fault.
3. Accreted rocks, with the exception of much of the Stikinia, are confined to the crust above the wedge. The accreted terranes east of Stikinia have only a limited depth extent of less than 5 km (Synder et al., 2002). Evenchick et al. (2001) further suggests that the Cache Creek and Slide Mountain (Sylvester Allochthon) form thin flaps or nappes lying in the Stikine Terrane and Ancestral North America.

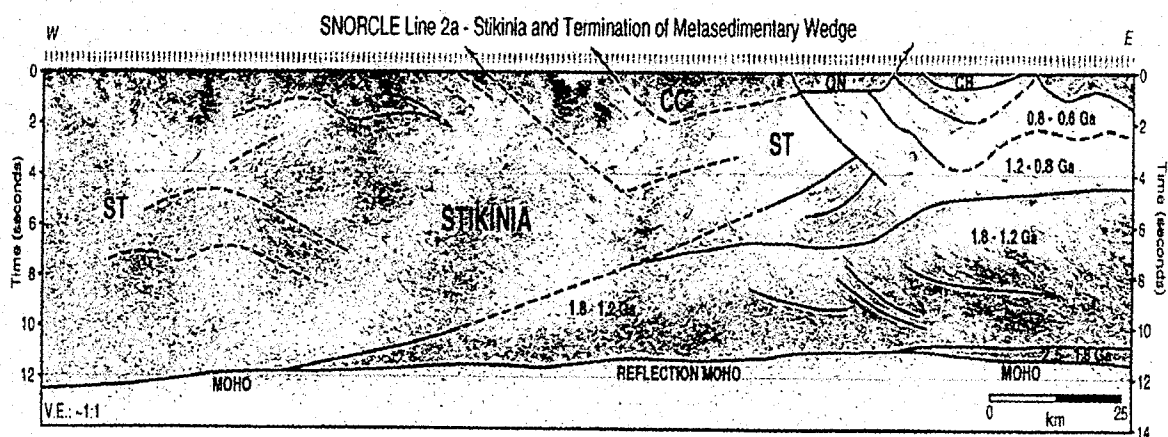


Figure 2.6 SNORCLE Line 2a interpreted migrated seismic reflection section (from Clowes and Hammer, 2002). CB: Cassiar Batholith ↑: known faults.

LITHOPROBE seismic refraction/wide-angle reflection profiles were collected along the Line 2a and Line 2b profiles (Fig. 2.6). Figure 2.7 shows the profile location for the Line 2a portion of the seismic refraction data and Figure 2.8 shows the seismic velocity model from Clowes and Hammer (2002) for Line 2a. Forward modelling and inversion of the seismic data reveals significant structural differences across the Tintina Fault (Creaser and Spence, 1999; Hammer et al. 2000; Clowes and Hammer, 2002). The upper crust east of the Tintina Fault has slower apparent velocity than it does to the west, and the crust east of the Tintina Fault is thinner (~36 km) than the crust to the west (~40 km) (Creaser and Spence, 1999). Analysis and interpretation of the refraction data has revealed (Creaser and Spence, 1999; Hammer et al. 2000; Clowes and Hammer, 2002):

1. The Tintina Fault does not appear to be associated with any significant deep penetrating velocity anomaly.
2. The base of the Moho is a significant velocity discontinuity.
3. The Moho has significant topography across the seismic profile and appears to be deepest (~40 km) just west of the Tintina Fault, and most shallow (~35 km) east of the Tintina Fault.

2.6.3 GRAVITY AND MAGNETICS DATA

Gravity and magnetic surveys provide information on regional trends. Geiger and Cook (1995) present gravity and magnetic data over an area that covers 1.6×10^6 km² in northwestern Canada (Fig. 2.9, 2.10). The western boundary of the area is coincident with the B.C.-Alaska border, and the eastern boundary follows a line linking the eastern tips of Lake Athabasca to the Coronation Gulf in the Arctic Ocean east of Great Bear Lake.

Bouguer gravity data gridded at 5 km spacing are dominated by a regional gravity low associated within the Cordillera (Fig. 2.9) (Geiger and Cook, 1995). In contrast, the Tintina fault is associated with a relative gravity high, which coincides with high and low trends curving northwest as the fault extends north (Geiger and Cook, 1995).

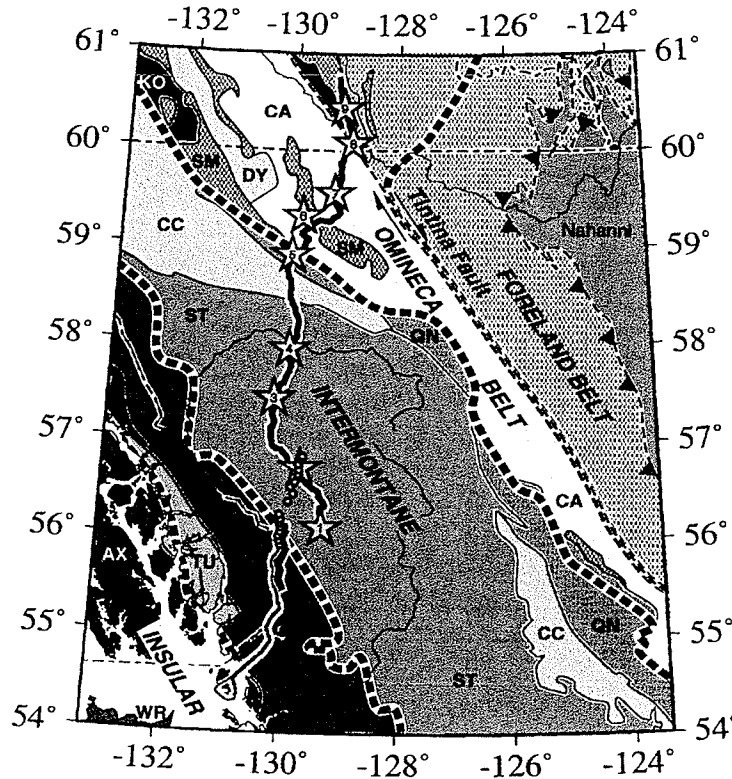


Figure 2.7 Location of the seismic refraction profile for Line 2a with markers indicating profile location (from Clowes and Hammer (in press)).

2.6.4 TELESEISMIC STUDIES

The deep structure of the northern Cordillera has been investigated using teleseismic studies. Two significant upper mantle P-wave velocity anomalies were located using tomographic inversion of teleseismic P-wave travel times (Frederiksen et al. 1998). The first anomaly is characterized by a high velocity, relatively shallow (>100 km) response centered at approximately 142°W and 60°N, and is interpreted as being the

edge of the Pacific slab from the southern Alaska subduction zone. The second anomaly is characterized by a large elongate southwest dipping (450-500 km depth) low velocity response centered at 136°W and 60°N. It is interpreted to represent the boundary between the Cordilleran lithosphere and a colder cratonic mantle root (Frederiksen et al. 1998).

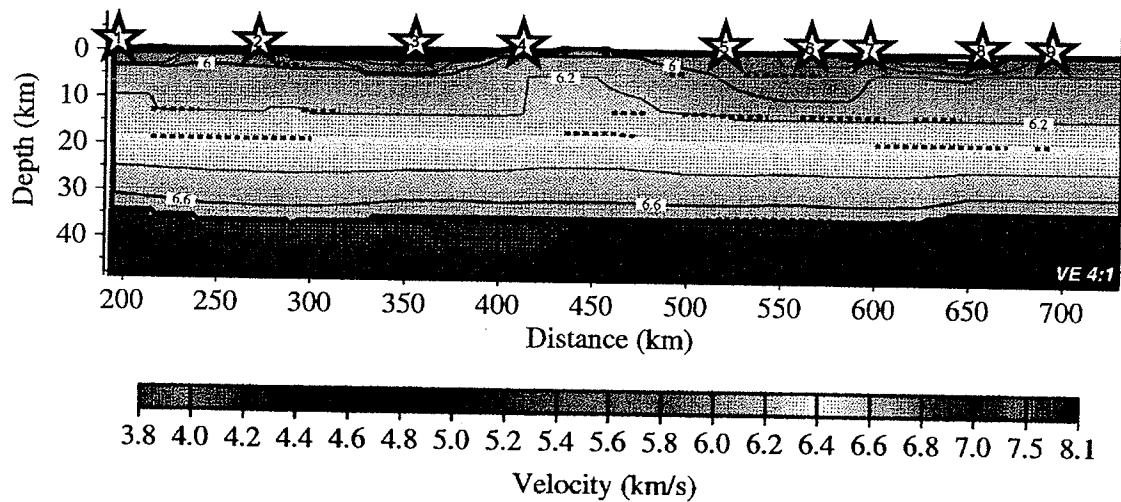


Figure 2.8 Seismic velocity model for Line 2a (R. Clowes, pers. Comm. 2002).

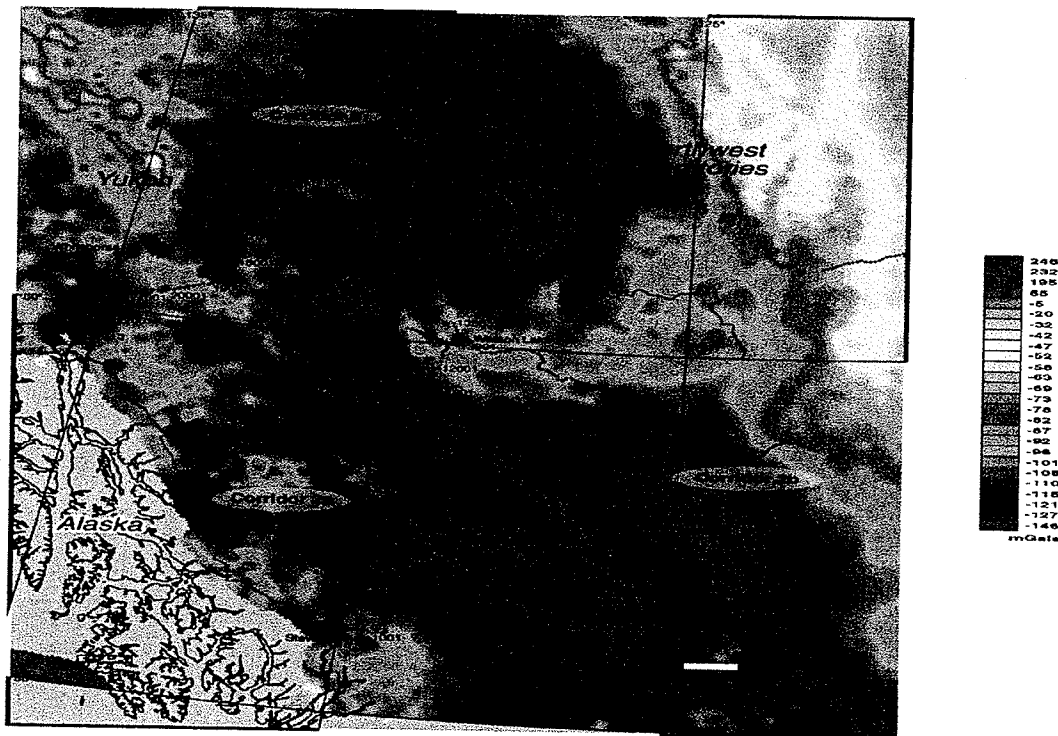


Figure 2.9 Gravity anomaly map of northwest Canada. The position of SNORCLE Lines 2a, 2b and 3, are marked as bold lines on map (from GSC 1999a).

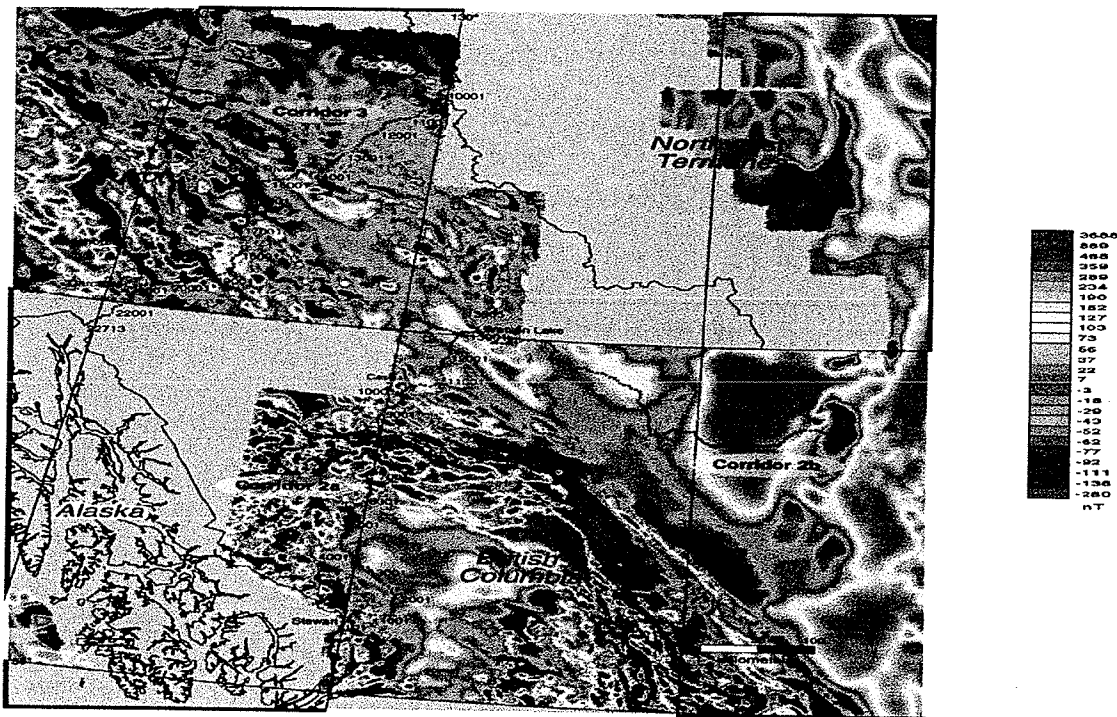


Figure 2.10 Magnetic anomaly map of northwest Canada (from GSC 1999b).

2.6.5 HEAT FLOW

Recent studies have examined the heat flow in the northern Cordillera. Heat flow values obtained in the Intermontane Belt within the SNORCLE region (56° - 61° N) indicate heat flow averages $79 \pm 14 \text{ mWm}^{-2}$ (Jessop et al. 1984). Lewis and Hyndman (1998, 1999, and 2001) conducted additional heat flow measurements along the SNORCLE transect to examine the transition from low to high values. A considerable variation along strike was also observed: south of 59° N the average heat flow value is $78.5 \pm 14.2 \text{ mWm}^{-2}$, while north of 59° N it was $103.3 \pm 21.0 \text{ mWm}^{-2}$ (Lewis and Hyndman, 1998). Areas with higher heat flow values are likely regions of recent subduction and/or terrane collision. The high heat values are interpreted to suggest a

larger amount of heat flowing into these areas from the asthenosphere (Lewis and Hyndman, 1998).

2.7 SOUTHERN CORDILLERA

Southern British Columbia displays many elements of the Canadian Cordillera system. LITHOPROBE studies of the southern Cordillera are almost complete. From the geological and geophysical studies it has been determined that the lithosphere of the Cordillera has evolved through episodes of rifting, seafloor spreading and plate separation, followed by subduction, basin closing and plate accretion. An interpreted cross section of the southern Cordillera derived from LITHOPROBE results is illustrated in Figure 2.11.

2.7.1 EM INVESTIGATION OF SOUTHERN CORDILLERA

Many EM surveys have been completed in the Southern Cordillera and the results synthesized in recent review papers (Jones and Gough, 1995; Ledo and Jones, 2001). Marquis et al. (1995) conducted an MT experiment as part of LITHOPROBE's Southern Cordillera transect study in order to examine the boundary of the Intermontane and Omineca morphogeological belts. Amongst other results, their study reveals (1) high electrical conductivity in the middle and lower parts of the crust in the study region, and (2) a depth dependency of geoelectric strike.

The depth to the top of the mid-crustal conductive layer decreases from 15-17 km across the Intermontane Belt to 8-10 km in the Omineca Belt (Marquis et al. 1995). The top of the conductor is coincident with increased seismic reflectivity, as shown from LITHOPROBE seismic reflection data. The eastward shallowing also corresponds with

an increase in heat flow such that the top of the conductive and reflective zones remains at the depth of the 400-450°C isotherm. Marquis et al. (1995) attribute the coincidence between high heat flow and high conductivity to the presence of small amounts of aqueous fluid trapped in the middle crust by a ductile shear zone.

The geoelectric strike was observed to vary from N25°W in the upper 5-10 km of the crust, to N20°E for the middle/lower crust, and to N60°E for the upper mantle (Marquis et al. 1995). The strike variation is interpreted to be due to the strike of the terranes in the uppermost part of the crust, and the strike of the ancestral North American rocks beneath the terranes.

Jones and Gough (1995) examined over 400 MT soundings from the southern Cordillera. They found that the lower crust is generally conductive throughout the Cordillera west of the Foreland Belt. The data revealed both 2D structure and 3D variation within the conductor. The conductor has highest conductivity along the Coast Belt and Omineca Belt. The enhanced conductivity is interpreted to be caused by fluids, mostly saline waters or silicate melts, in interconnected fractures. Lateral changes in conductivity may result from variations in fracture density, temperature, and the sources of hot fluid, such as the subducting Juan de Fuca plate under the Coast Belt, and mantle upflow under the Omineca Belt (Jones and Gough, 1995).

Ledo and Jones (2001) examined the regional geoelectric structure of the central-southern Canadian Cordillera determined from the inversion of MT data along five east-west profiles crossing all the belts. The structure includes a generally resistive crust in the Intermontane Belt for all profiles. In contrast, a two order of magnitude variation in the lower crustal resistivity is observed along strike in the Omineca Belt. Enhanced

conductivity is observed to the south in a region of Eocene extension, and lower conductivity is observed to the north. Ledo and Jones (2001) propose that the observed resistivity structure is controlled in part by fluids, with brines dominating, but with partial melts also contributing at the base of the crust in specific localities. The along-strike variation in conductivity within the Omineca belt is attributed to a variation in fluid content and interconnectivity of pore space and or veins, with the lowermost crust of the southern Omineca Belt being partially molten. Furthermore, Ledo and Jones (2001) suggest that mantle derived fluids may contribute to the lower crustal resistivity.

2.7.2 OVERVIEW OF THE CORDILLERA

The development of the Cordillera, and more specifically the Southern Cordillera, can be summarized as follows

(<http://www.geop.ubc.ca/LITHOPROBE/transect/scordsum.html>, 04/17/01):

1. Development of a west facing passive margin at 1600 Ma that lasted through the Paleozoic, followed by rifting at 750 Ma and breakup of the continent well before ~540 Ma causing an ocean basin to the west.
2. An orogenic event (~370 Ma) produced volcanism and plutonism west of the miogeocline and minor contractional folding and faulting of the shelf strata.
3. Convergence of North America with the oceanic basin, causing basin terranes to amalgamate with one another offshore. The amalgamated terranes then converged with North America. As the terranes accreted the mountains were thrust upwards causing the "great push" and the continental area expanded westward. The accreting Intermontane superterrane resulted in formation of the Rocky Mountains/foreland Belt and the Omineca Belt (Monger et al. 1982). The Insular

superterrane accreted during the mid-Cretaceous forming the Coast Belt as the suture with the Intermontane superterrane. Strike slip faulting occurred between 100 and 40 Ma in the western part of the Cordillera and accommodated northward motion of the terranes relative to North America. The region of convergence of the subducting Juan de Fuca plate is currently west of Vancouver Island.

4. Around 58 Ma the Southern Cordillera underwent a transition from east-west shortening and crustal thickening (compression) to large scale east-west crustal stretching and thinning (extension) along with continued strike-slip motion to the west, allowing deep crustal rocks to be brought to the surface. Since this period of extension the interior has been relatively dormant, while the western margin has undergone subduction-related tectonism whereby the Juan de Fuca pushes under Vancouver Island and Washington State causing earthquakes and volcanic belts.

2.8 ELECTRICAL RESISTIVITY OF FAULT SYSTEMS

The SNORCLE Transects cross many faults (i.e Tintina, Kutcho, Ketchika, and Teslin) that may influence the resistivity structure. Magnetotelluric data collected over major fault systems have shown regions of both enhanced conductivity and resistivity (Jones et al. 1992; Unsworth et al. 1999; Pous et al. 1999; and Ledo et al. 2002a).

MT data from four profiles crossing the Fraser River strike-slip fault indicate that it penetrates the entire crust (Jones et al. 1992). The profiles are consistent in showing a rapid change in response with lateral distance that may be due to a change in the conductivity in the lower crust at the location of the fault, with higher conductivity to the west. The conductivity of the lower crust changes markedly beneath the fault across a zone that is ~15 km wide. Two-dimensional inversion confirmed this result, and also

imaged a narrow vertical zone (5-12 km depth) of enhanced conductivity (~ 10 ohm.m) associated with the fault itself that is thought to be electrically connected to the lower crust.

An MT study was performed on the Parkfield and Carrizo segments of the San Andreas Fault in Central California in 1997 (Unsworth et al. 1999). The Parkfield segment has regular small earthquakes and creep events, while the Carrizo segment appears to be locked. The goal of the survey was to image the electrical resistivity structure of the fault zone. For both segments, two-dimensional modelling indicated narrow (~ 300 - 600 m) zones of high conductivity extending to depths of 2-4 km in the core of the fault. At Parkfield, the zone is an order of magnitude higher in conductivity than at Carrizo suggesting higher concentrations of fluids for the more seismically active part (Unsworth et al. 1999).

A high electrical conductive zone at lower crustal depth was observed beneath the Betic Chain, Spain using MT (Pous et al. 1999). Elongated high conductivity zones in the upper crust and middle crust were interpreted to be related to fluid circulation through and along both sediments and faults.

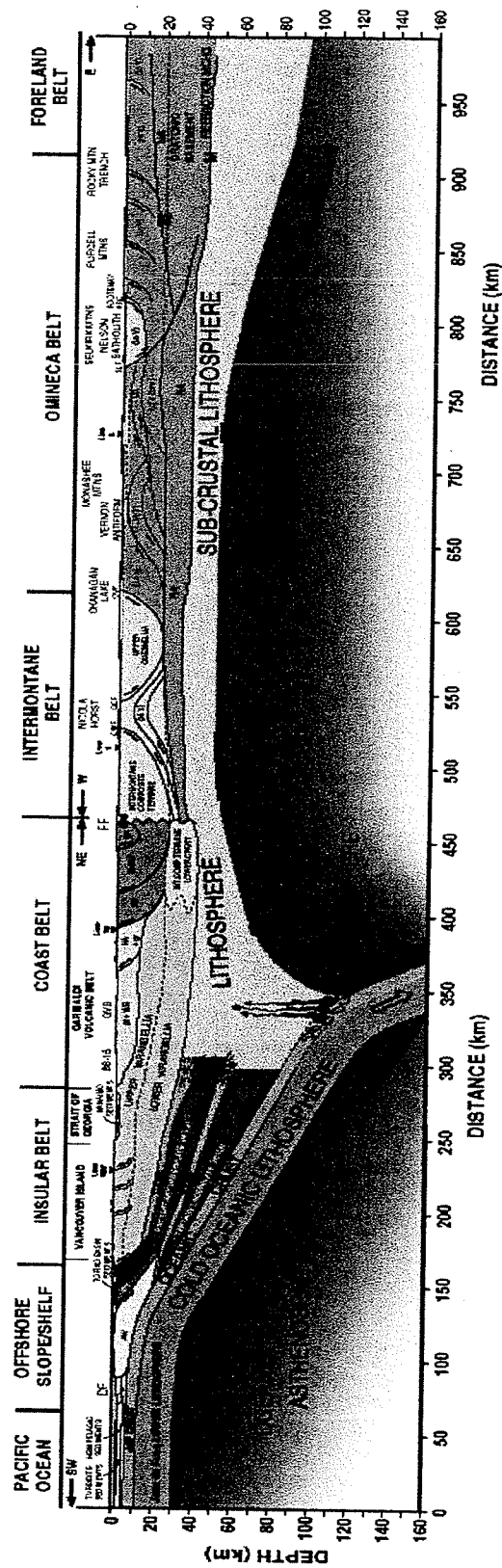


Figure 2.11 Cross section of the Southern Cordillera as interpreted from LITHOPROBE studies (from Clowes et al. 1995).

As mentioned above, Ledo et al. (2001, 2002a) examined MT data from sites in the Tintina Fault Zone (TFZ) (Fig. 2.4) consisting of two regional profiles separated by more than 350 km along strike and one short profile located 35 km south of the northern profile. Enhanced conductivity ($\sim 1\text{-}10\text{ ohm.m}$) is present at different depths within the crust. Ledo et al. (2002a) suggest that the enhanced conductivity is caused by an electronic conduction mechanism in interconnected mineralized zones. In contrast to other large scale strike slip faults, the middle and lower crust beneath the TFZ is highly resistive. The high resistivity indicates that fault zone processes that result in interconnected conducting phases are not generic, but are controlled locally.

From the previous studies it is apparent that the conductivity signature of a particular fault zone depends on a variety of features. Enhanced conductivity or resistivity in any fault zone may be caused by such factors as (Jones et al. 1992; Pous et al. 1999; and Unsworth et al. 1999):

- (1) rock type
- (2) a small increase in porosity and fluid circulation
- (3) an increase in salinity of the pore fluid
- (4) an increase in partial melt
- (5) zones acting as a conduit for escape of deeply penetrating meteoric waters
- (6) distribution and alignment of carbon.

CHAPTER 3 – MAGNETOTELLURIC THEORY

3.1 BASIC ELECTROMAGNETIC THEORY

All EM phenomena are governed by Maxwell's equations

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad \nabla \times \mathbf{H} = -\frac{\partial \mathbf{D}}{\partial t} + \mathbf{J} \quad (3.1)$$

$$\nabla \cdot \mathbf{B} = 0 \quad \nabla \cdot \mathbf{D} = q_o$$

where $\mathbf{B}=\mu\mathbf{H}$, $\mathbf{D}=\epsilon\mathbf{E}$, and $\mathbf{J}=\sigma\mathbf{E}$, and where $\mathbf{E}$ is the electric field, $\mathbf{B}$ is the magnetic induction field, $\mathbf{H}$ is the magnetic field strength, $\mathbf{D}$ is the electric displacement, $\mathbf{J}$ is the electric current density, q_o is the free charge density, ϵ is the permittivity, σ is the conductivity, μ is the magnetic permeability, and t is the time. In this thesis, “x” is defined as the north direction, “y” is defined as the east direction, and “z” is defined as the vertically downward direction.

Consider a region of uniform conductivity, permeability and permittivity.

Assuming the electric and magnetic fields have a positive harmonic time dependence e.g $E(x,y,z,t)=E(x,y,z)e^{i\omega t}$ and ω is angular frequency. Maxwell's equation can be combined to give:

$$\begin{aligned} \nabla^2 \mathbf{E} - (i\omega\mu\sigma - \omega^2\mu\epsilon)\mathbf{E} &= 0 \\ \nabla^2 \mathbf{H} - (i\omega\mu\sigma - \omega^2\mu\epsilon)\mathbf{H} &= 0 \end{aligned} \quad (3.2)$$

which is referred to as the Helmholtz wave equation. For most EM problems this equation is solved for piece-wise uniform media and appropriate initial boundary conditions.

3.1.1 EM FIELDS IN LAYERED EARTH

For a finite source, EM fields in a layered earth can be represented as a superposition of plane waves with varying angles of incidence (Ward and Hohmann, 1988). The EM fields can be described in terms of two independent systems. For a simple source consisting of an external line current oriented parallel to the x-axis the fields can be fully described by E_x , H_y , and H_z . This mode is referred to as the transverse electric (TE) mode. In a horizontally layered earth the TE mode is characterized by the absence of a vertical electric field and electric current flows in horizontal loops. For an infinitely wide grounded electric-dipole source oriented parallel to the x-axis, the fields are described in terms of E_y , E_z , and H_x . This mode is referred to as the transverse magnetic (TM) mode. The TM mode is characterized by the absence of a vertical magnetic field and electric current flows in vertical loops.

The solution for the EM fields for a TE or TM current system is generally derived using the one non-zero component. The TE solution is obtained from

$$\frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} - (i\omega\mu\sigma - \omega^2\mu\epsilon)E_x = 0 \quad (3.3)$$

and the TM solution is obtained from

$$\frac{\partial^2 H_x}{\partial y^2} + \frac{\partial^2 H_x}{\partial z^2} - (i\omega\mu\sigma - \omega^2\mu\epsilon)H_x = 0. \quad (3.4)$$

The remaining non-zero field components are obtained from Maxwell's equations.

Expressing the spatial variations in the y-direction in the spatial frequency (k_y) domain yields

$$\frac{\partial}{\partial y} \equiv ik_y \quad \frac{\partial^2}{\partial y^2} \equiv -k_y^2 \quad (3.5)$$

where k_y depends on the geometry and distance from the source. In this case equation 3.3 becomes,

$$\frac{\partial^2 E_x}{\partial z^2} - \theta^2 E_x = 0 \quad (3.6)$$

where

$$\theta^2 = i\omega\mu\sigma - \omega^2\mu\varepsilon + k_y^2. \quad (3.7)$$

Within a uniform layer the solution for the equation 3.6 can be written

$$E_x(k_y, z, \omega) = A(k_y, \omega)e^{\theta z} + B(k_y, \omega)e^{-\theta z} \quad (3.8)$$

where the first term is associated with upwards propagation of signals and the second term is associated with downwards propagation of signals.

3.1.2 EM THEORY FOR A UNIFORM HALF SPACE

For an external source the fields will decrease to zero as the depth increases to infinity. For a uniform half-space $A(k_y, \omega)=0$ defining the field at $z=0$ as

$E_x(k_y, z=0, \omega)=E_{x0}(k_y, \omega)$, the solution for the electric field for a half space can now be written

$$E_x(k_y, z, \omega) = E_{x0}(k_y, \omega)e^{-z\Re(\theta)}e^{-iz\Im(\theta)} \quad (3.9)$$

$\Im(\theta)$ is a term describing a phase change relative to the surface, and $\Re(\theta)$ is the term describing the exponential decay of the field magnitude with depth.

3.1.3 SKIN DEPTH

The exponential decrease in the magnitude of the field can be expressed by

$$\left| \frac{E_x(k_y, z, \omega)}{E_{x0}(k_y, \omega)} \right| = e^{-z\Re(\theta)} = e^{-\frac{z}{\delta}}. \quad (3.10)$$

The skin depth δ is defined as the depth at which the magnitude is attenuated to $1/e$ of its surface value. For a spatially uniform source $k_y=0$ and the expression for the skin depth is:

$$\delta = \frac{1}{\Re(\theta)} = \left[\frac{2}{-\omega^2 \mu \epsilon + \sqrt{\omega^4 \mu^2 \epsilon^2 + \omega^2 \mu^2 \sigma^2}} \right]^{\frac{1}{2}} \quad (3.11)$$

For the frequencies general used in MT surveys ($10^{-4} \sim 10^4$ Hz), for which $\omega \epsilon \ll \sigma$, the expression can be reduced to

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} \quad (3.12)$$

Notice that the depth of penetration depends on both the conductivity and the frequency as shown in Figure 3.1.

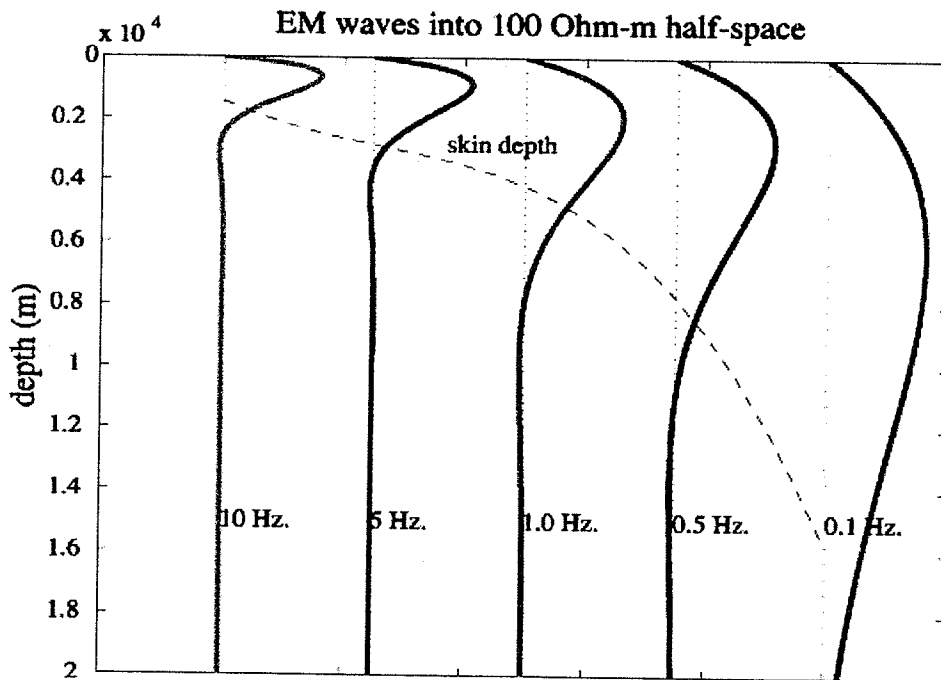


Figure 3.1 Illustration showing the skin depth effect with depth in a 100 ohm.m half space (modified from Livelybrooks, 2001).

3.2 THE MAGNETOTELLURIC METHOD

The MT method is an EM method in which natural electric and magnetic fields are measured as a function of time, in order to determine conductivity structures in the Earth's crust and upper mantle (Vozoff, 1991). The ratio of the horizontal electrical and magnetic field, as a function of frequency, yields the MT impedance. The MT impedance tensor $\mathbf{Z}(\omega)$ contains the transfer functions between the horizontal components of the electric and magnetic fields (Vozoff, 1991)

$$\mathbf{E}(\omega) = \mathbf{Z}(\omega)\mathbf{H}(\omega) \quad (3.13)$$

where

$$\mathbf{E}(\omega) = \begin{bmatrix} E_x(\omega) \\ E_y(\omega) \end{bmatrix} \quad \mathbf{H}(\omega) = \begin{bmatrix} H_x(\omega) \\ H_y(\omega) \end{bmatrix} \quad \mathbf{Z}(\omega) = \begin{bmatrix} Z_{xx}(\omega) & Z_{xy}(\omega) \\ Z_{yx}(\omega) & Z_{yy}(\omega) \end{bmatrix}. \quad (3.14)$$

The impedance is commonly interpreted in terms of its amplitude (or corresponding resistivity) and phase. It is determined by the local resistivity structure and signal frequency.

3.2.1 MT RESPONSE FOR A UNIFORM HALF SPACE

For a uniform half-space the diagonal components of the impedance are zero $Z_{xx}(\omega)=Z_{yy}(\omega)=0$ and the off-diagonal components of the impedance tensor ($\mathbf{Z}$) are defined by

$$Z_{xy}(\omega) = -Z_{yx}(\omega) = \frac{E_x(\omega)}{H_y(\omega)} = -\frac{E_y(\omega)}{H_x(\omega)} = \frac{i\omega\mu_0}{\theta} \quad (3.15)$$

For frequencies employed in MT surveys and for a uniform source the equation for the impedance becomes

$$Z_{xy}(\omega) = \frac{i\omega\mu_0}{\sqrt{i\mu_0\sigma\omega}} = \sqrt{i}\sqrt{\omega\mu_0\rho} = \sqrt{\omega\mu_0\rho}e^{\frac{i\pi}{4}}. \quad (3.16)$$

where ρ is the resistivity of the half-space

$$\rho = \frac{|Z_{xy}(\omega)|^2}{\omega\mu}. \quad (3.17)$$

The resistivity can be determined from the impedance at any frequency. The phase of the impedance represents the phase lead of the horizontal electric field component over the horizontal magnetic field component. In a uniform half-space this phase lead is constant and is defined by

$$\phi_{xy} = \frac{\pi}{4}. \quad (3.18)$$

3.2.2 MT RESPONSE FOR A 1D EARTH

In a layered (1D) medium (with layer $i+1$ deeper than i), the impedance is defined by the recursive relationship

$$Z_i(\omega) = \frac{i\omega\mu}{\theta_i} \left[\frac{\theta_i Z_{i+1}(\omega) + i\omega\mu \tanh(\theta_i h_i)}{\theta_i Z_{i+1}(\omega) \tanh(\theta_i h_i) + i\omega\mu} \right] \quad (3.19)$$

where $Z_i(\omega)$ and $Z_{i+1}(\omega)$ are the impedances at the top of layer i and $i+1$, h_i and σ_i are the thickness and conductivity of layer i . The base of the layered sequence is treated as a uniform half space for which the impedance is given by equation 3.17. In a layered medium, the off diagonal components of the impedance tensor are equal i.e.

$Z_{xy}(\omega) = -Z_{yx}(\omega)$, and are defined by the equation 3.19 for the surface of the top layer, and the diagonal components are zero.

In a layered or 1D earth the resistivity determined from equation (3.17) is termed an apparent resistivity $\rho_a(\omega)$. The apparent resistivity is a weighted average resistivity over the penetration of the signals.

Figure 3.2 shows the MT response for a model consisting of a 100 m thick resistive layer (100 000 ohm.m) or conductive layer (10 ohm.m) located at 1 km depth in a 1000 ohm.m background. For the model with the conductive layer as the period increases the phase initially increases to values over 45° and it then decreases to values less than 45° . These effects occur at periods for which the skin depth is comparable to the depth of the conductive layer. The phase values slowly converge back to 45° at longer periods. At periods around 0.1 second, the apparent resistivity is biased towards the resistivity of the embedded conductive layer. At longer periods (> 0.1 s) it asymptotically converges to the resistivity of the background medium. For the embedded resistive layer the opposite effects occur. The phase initially decreases below 45° and the apparent resistivity is biased towards the resistivity of the embedded layer. The apparent resistivity and phase responses are not as sensitive to the resistive layer as they are to the conductive layer.

3.2.3 INDUCTION SCALE LENGTH

In a layered media the penetration depth of the signals can be examined using the inductive scale length (Schmucker and Jankowski, 1972), which is defined

$$C(\omega) = \frac{Z(\omega)}{i\omega\mu_o} \quad (3.20)$$

The real part of $C(\omega)$ provides a measure of the weighted mean depth of the inductive current distribution. It is used to define a frequency-dependent depth-scale $z^*(\omega)$. The

imaginary part of $C(\omega)$ can be used to calculate the apparent resistivity (ρ^*) at $z^*(\omega)$ using the equation

$$\rho^*(z^*) = 2\omega\mu_o(\Im[C(\omega)])^2. \quad (3.21)$$

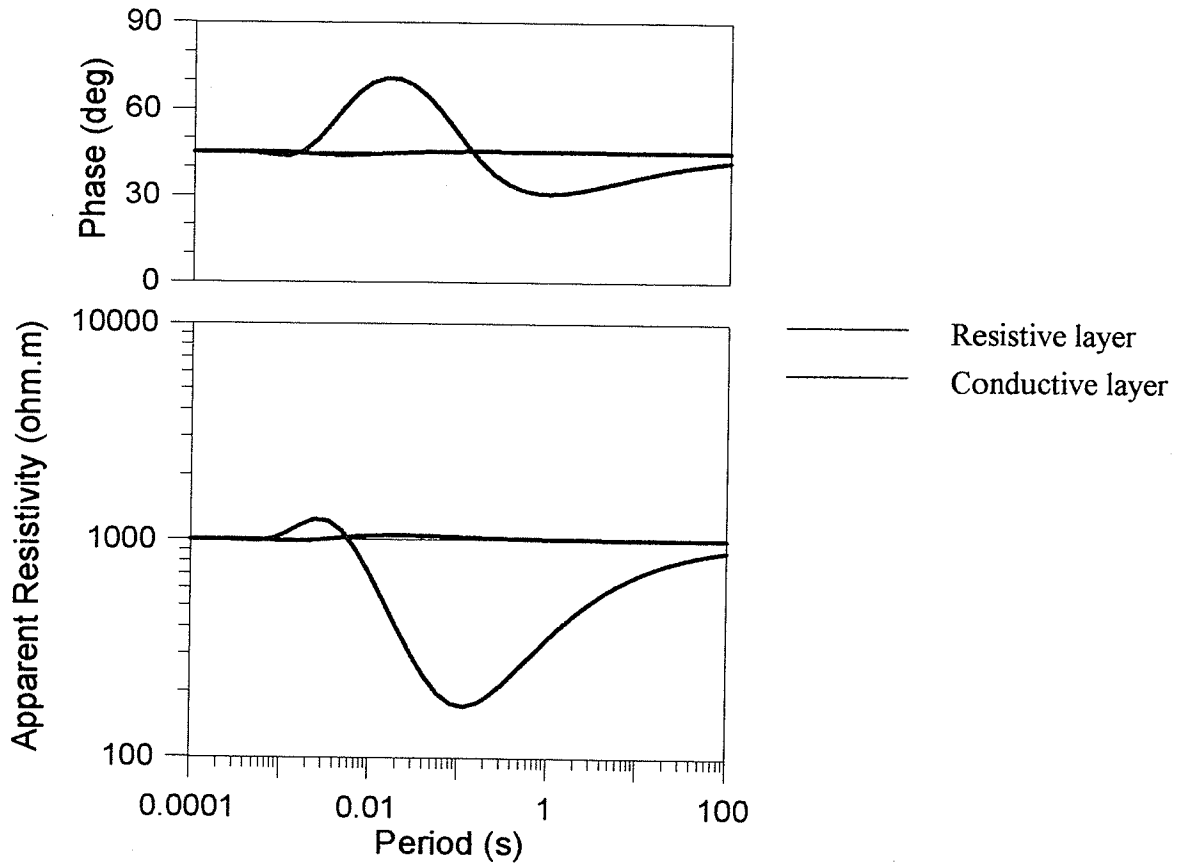


Figure 3.2 The MT responses for a conductive layer and a resistive layer in a layered medium. The response for the buried resistive layer is in blue and the response for the buried conductive layer is in red. The half space response is in black.

3.2.4 MT RESPONSE FOR A 2D EARTH

In a 2D structure the resistivity is invariant in one horizontal direction, the geoelectric strike direction. The solution for the impedance is no longer a simple recursive relationship. If the geoelectric strike is parallel to the x-axis then $Z_{xx} = Z_{yy} = 0$,

$Z_{xy} = -Z_{yx}$, $Z_{xy} = Z_{TE}$ and $Z_{yx} = Z_{TM}$. The TE mode involves electric current flowing parallel to the structure, whereas the TM mode involves electric current flowing perpendicular to the structure.

Figure 3.3 shows the apparent resistivity and phase pseudosection for a 2D structure consisting of a resistive block adjoining a conductive block. Pseudosections are contour plots of the apparent resistivity or phase, with the vertical axis corresponding to period and the horizontal axis to profile location. Close to the contact, the MT response is sensitive to both blocks. The TE apparent resistivity is continuous across the interface between the blocks. The apparent resistivity in the resistive block decreases gradually as the conductive block is approached. The smooth transition occurs because the TE mode measures the electric field parallel to the geoelectric strike and from EM boundary conditions this component of the field is continuous. At distance from the contact, the apparent resistivity asymptotically converges to the resistivity of the underlying block (Fig. 3.3).

The TM mode apparent resistivity is significantly different from the TE apparent resistivity. Approaching the contact on the resistive block side, the apparent resistivity increases to values greater than the resistivity of the underlying block and at the contact, there is a discontinuity in the response. For the TM mode the electric field component is perpendicular to the strike of the contact between the two blocks. The discontinuity in the response is caused by surface charges formed along the vertical plane of this contact.

The TE phase is continuous across the boundary between the two blocks. The phase values increase above 45° on the resistive side of the block and decrease below 45° on the conductive side of the block. The TM phase values are discontinuous across the

boundary. The phase values decrease below 45° on the resistive side of the block and above 45° on the conductive side of the block. The TM phase values are more affected by the interface of the conductive block.

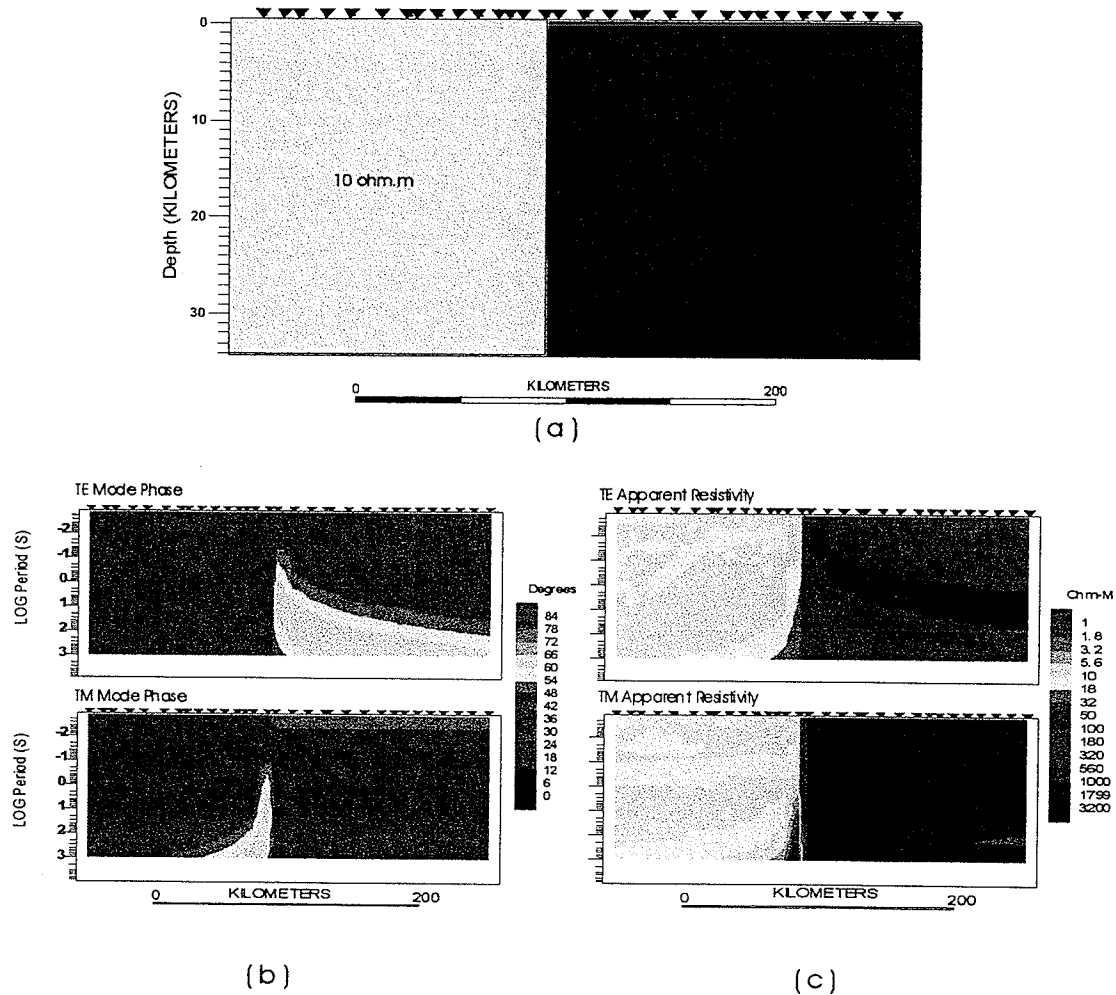


Figure 3.3 (a) Two dimensional model, (b) pseudosections of the phase response, and (c) pseudosections of the apparent resistivity response. The triangles on the position axis show the locations of the MT sites used to form the pseudosections.

For the 2D case in which the measurement direction is not aligned with geoelectric strike then $Z_{xx} = -Z_{yy} \neq 0$. In this case it is possible to rotate the coordinate

system to align the data with the strike. When the coordinate system is rotated through an angle $+\theta$ (clockwise direction), the rotated impedance tensor ($\mathbf{Z}'$) is defined:

$$\mathbf{Z}' = \mathbf{R}\mathbf{Z}\mathbf{R}^T \quad (3.22)$$

where $\mathbf{R}$ is the rotation matrix:

$$\mathbf{R} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \quad (3.23)$$

and $\mathbf{R}^T$ is the transpose. After rotation to the principal axis $Z'_{xx}=Z'_{yy}=0$.

3.2.5 INDUCTION VECTORS

The induction vector and tipper are parameters derived from the transfer function between the vertical component of the magnetic field and the horizontal components. The parameters are important in MT studies because they provide an estimate of the geoelectric strike and information on the resistivity structure. For uniform EM source fields the magnitude of the tipper and induction vector is close to zero, except near lateral conductivity contrasts. The tipper and induction vector are therefore very useful for mapping horizontal conductivity variations.

The transfer function between the vertical magnetic field and the two horizontal magnetic field components is (Vozoff, 1991; Orange, 1989):

$$H_z(\omega) = T_x(\omega)H_x(\omega) + T_y(\omega)H_y(\omega) \quad (3.24)$$

For a 2D structure with a strike in the x-direction, $T_x = 0$ and:

$$H_z = T_y H_y \quad (3.25)$$

The transfer function describes the tipping of the magnetic field out of the horizontal plane and is called the tipper (Vozoff, 1991; Orange, 1989). The tipper is a complex-

valued parameter. Its magnitude is typically between 0.1 and 0.5, but at strong conductivity contrasts it can be as large as 1.0 (Vozoff, 1991).

The separate real and imaginary components of the transfer function are also useful. They are used to define the real C_r and imaginary (or quadrature) induction vectors C_q (Vozoff, 1991):

$$C_r = -\Re(T_x)\mathbf{i} - \Re(T_y)\mathbf{j} \quad (3.26)$$

$$C_q = \pm\Im(T_x)\mathbf{i} \pm \Im(T_y)\mathbf{j} \quad (3.27)$$

where $\mathbf{i}$ and $\mathbf{j}$ are unit vectors in the north and east directions. The length of the real induction vector is proportional to the conductivity contrast at the boundary, but decreases with increasing distance from the boundary. In most MT studies the real component of the induction vector is reversed so that it points towards areas of enhanced conductivity. For a 2D structure the imaginary component of the induction vector is either parallel or anti-parallel to the real component. If the imaginary component of the induction vector is not orientated parallel or anti-parallel to the real component it provides an indication of the presence of 3D structures.

Figure 3.4 shows the real and imaginary tipper pseudosection for a simple 2D model (Fig. 3.3a). Non-zero real and imaginary tipper components occur at the boundary between the two blocks. The width of the anomalous zone at the boundary, and the magnitude of the real tipper component increase with period.

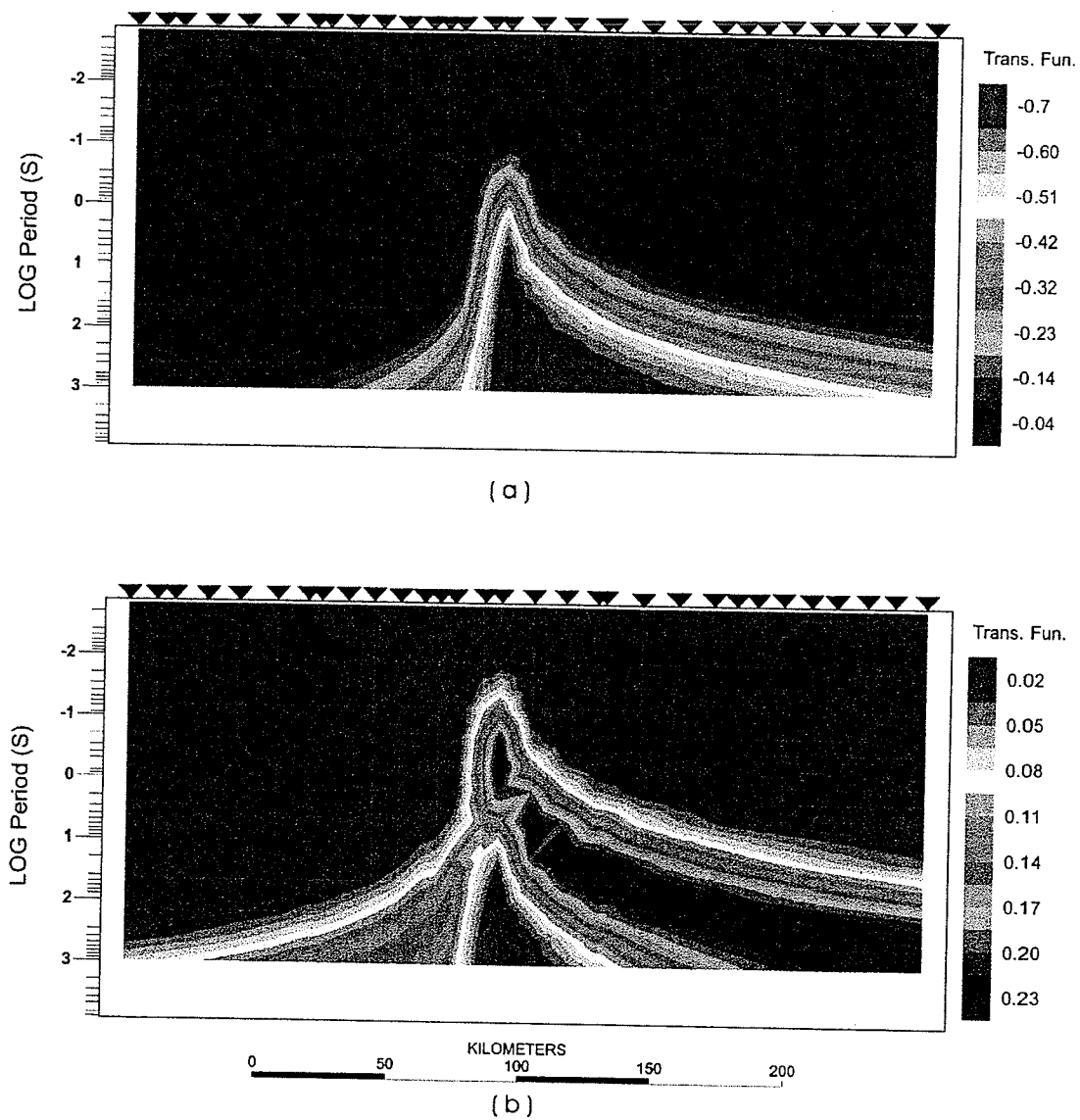


Figure 3.4 Tipper component along profile shown in Figure 3.3a. (a) Pseudosection of real component of induction vector. (b) Pseudosection of imaginary component of induction vector.

3.3 MAGNETOTELLURIC DATA ACQUISITION

3.3.1 MT INSTRUMENTATION

MT soundings are usually carried out using simultaneous recordings of two horizontal electrical components (E_x , E_y), and three magnetic field components (B_x , B_y , and B_z). Figure 3.5 is a schematic diagram illustrating the field layout. Two additional horizontal magnetic components (R_x , R_y) may be recorded at a remote reference site for the purposes of noise reduction. The remote reference site is typically hundreds of meters to several tens of kilometers from the main site (Vozoff, 1991). The magnetic recordings usually involve measurements of the magnetic flux density ($\mathbf{B}=\mu\mathbf{H}$) and are made in units of nT.

The two components of the electric field are measured using orthogonal grounded electric dipoles (Fig. 3.5). The dipoles measure the voltage variation $V(t)$ between grounded electrode pairs a distance L apart. The electric field can then be determined by using

$$\mathbf{E}(t) = -\frac{\mathbf{V}(t)}{L}. \quad (3.28)$$

It is usually recorded in units of mV/km ($= \mu\text{V/m}$).

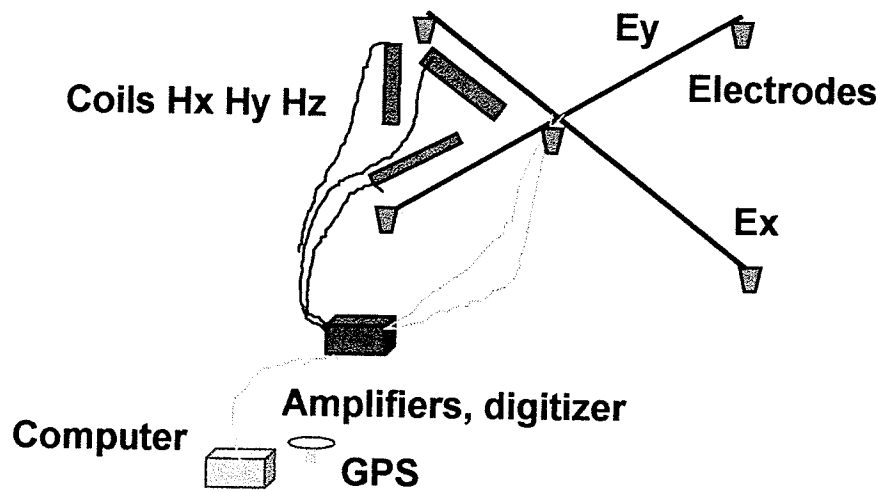


Figure 3.5 Illustration of the field layout for measure the five EM components in MT surveys (modified from Livelybrooks, 2001).

The distance L must be large enough that the Earth's response is much greater than the noise generated within the electrodes themselves, which depends on the chemical nature of the materials involved and the local conditions such as temperature and contact (Vozoff, 1991). For the LITHOPROBE survey the typical electric dipole length was approximately 100 m.

For the SNORCLE MT data the typical frequency range was 1000 Hz – 0.001 Hz or 0.001 s to 1000 s. Therefore, a few days of data recording was needed to obtain high quality data for periods less than 1 second and up to a week of data recording was need to obtain high quality data for periods greater than 1 s.

3.3.2 MAGNETOTELLURIC SOURCES

For the periods utilized in MT surveys, there are two main sources of EM signals: thunder storms in the atmosphere, and electric current systems in the magnetosphere and ionosphere. In both cases the sources are far enough from the Earth, and the resistivity

contrast between the rocks and air is sufficient, for the EM fields to be treated as plane waves (Ward and Hohmann, 1988).

The atmosphere is the main source for natural EM fields at periods less than 1 (Vozoff, 1991). These signals arise from electrical storms in the lower atmosphere. The lightning from atmospheric storms radiates an EM field that propagates great distances in the wave-guide formed by the resistive (10^{-13} S/m) lower atmosphere lying between the more conductive Earth and ionosphere. The resultant fields induced in the Earth are relatively uniform because the conductivity of the Earth is much greater than that of the atmosphere, and the signals propagate vertically downwards when entering the crust (Vozoff, 1991).

At periods longer than 1 s, the EM signals used in MT surveys originate in the upper ionosphere and magnetosphere (Fig. 3.5) (Vozoff, 1991). The magnetosphere is the region confined by the Earth's magnetic field, modified by the solar wind, and the ionosphere is a highly conductive region where charged particles of ionized oxygen and nitrogen are denser than at higher or lower levels of the atmosphere. Variations in the Earth's EM field are related to interactions of the solar wind (charged particles ejected from the sun) with plasma layers formed in the magnetosphere and ionosphere (Orange, 1989). The ions emitted in solar storms disturb the magnetic field of the Earth and causes low-frequency energy to penetrate to the surface of the Earth. The resulting electric and magnetic fields at the surface are dominantly horizontal.

The SNORCLE Line 2a MT sites are located in the sub-auroral zone, and the Connector Line sites are located near the border of the auroral zone and sub-auroral zone. High geomagnetic latitude MT data is often influenced by electrojet current systems

(Garcia et al. 1997). The electrojet is a low altitude (100-120 km) current system whose position is strongly time dependent. It is usually constrained to lie within an oval band between 58°-75°N geomagnetic latitude. During the day the oval weakens in intensity and moves to higher latitudes, whereas at night the oval gets more intense and moves to lower latitudes (Garcia et al. 1997). Since the electrojet is so close to the earth, the ionospheric currents produce short wavelength, non-plane source fields that corrupt the natural plane waves desirable for MT surveys.

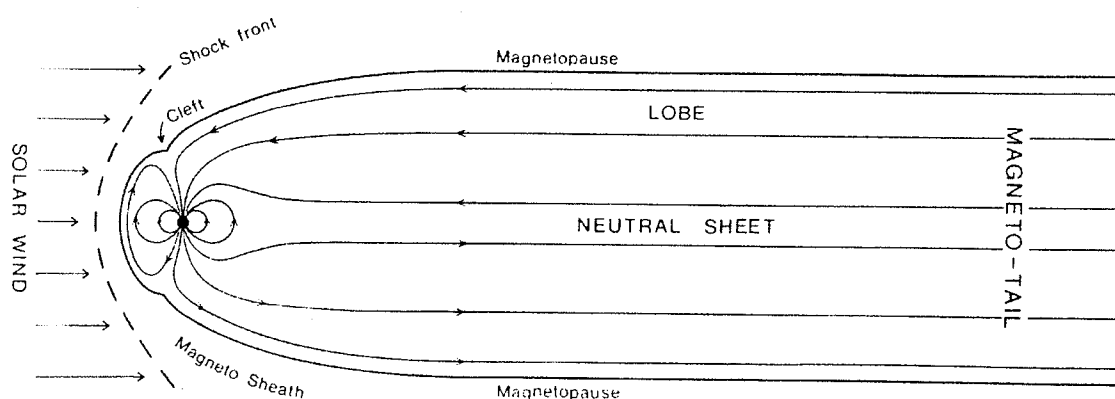


Figure 3.6 Major features of the magnetosphere current system. The Earth and atmosphere are the spherical features (circular in cross section) in the center (from Parkinson, 1983).

3.4 MT DATA PROCESSING AND ANALYSIS

The object of MT data processing is to extract impedances and induction vector responses from noisy electric and magnetic field time series (Vozoff, 1991). The impedances and induction vector responses can then be used to examine the conductivity

structure. Most MT data processing is done in the frequency domain, as the theory and algorithms are simpler than in the time domain.

3.4.1 REMOTE-REFERENCE IMPEDANCE ESTIMATION

Impedance estimation is performed by determining the tensor $\mathbf{Z}(\omega)$ from the observed data. Spectral analysis based least-squares (LS) is the most basic method used in determining the impedance (Gamble et al. 1979a; 1979b). The method involves minimizing the quantity $|\mathbf{E} - \mathbf{Z}^{\text{LS}}\mathbf{H}|^2$ for a large number of magnetic and electric values. The solution for $\mathbf{Z}^{\text{LS}}$ can be written (using the notation of Gamble et al. 1979a):

$$\mathbf{Z}^{\text{LS}} = [\mathbf{E}\mathbf{H}][\mathbf{H}\mathbf{H}]^{-1} \quad (3.29)$$

where $[\mathbf{AB}]$ is the crosspower matrix defined by:

$$[\mathbf{AB}] = \begin{bmatrix} S_{AxBx} & S_{AxBy} \\ S_{AyBx} & S_{AyBy} \end{bmatrix} \quad (3.30)$$

and $\mathbf{S}$ is the crosspower between components of $\mathbf{A}$ and $\mathbf{B}$. The least-squares estimate for the impedance contains autopowers of the magnetic field components (S_{HxHx} , S_{HyHy}) in the denominator. Any noise in the magnetic field time series will bias these autopowers upwards and the impedance estimate downwards.

Remote-reference impedance estimation involves using the magnetic fields recorded from a nearby site to reduce the effects of magnetic field noise. For correct results, the MT signals should be coherent between both sites and the noise should be incoherent. If a reference field $\mathbf{R}$ is measured simultaneously with $\mathbf{E}$ and $\mathbf{H}$, the following estimate of the impedance

$$\mathbf{Z} = [\mathbf{E}\mathbf{R}][\mathbf{H}\mathbf{R}]^{-1} \quad (3.31)$$

will be unbiased by any uncorrelated noise (Gamble et al. 1979a).

The distance between the remote reference site and the main site is limited by the decrease in coherency of the magnetic field with increasing distance (e.g. Ferguson, 1988). Modern remote reference sites are normally located within 10-20 km of the main site. However, for sites close to sources of strong cultural noise, the remote reference may need to be further away to avoid the noise.

3.4.2 ROBUST IMPEDANCE ESTIMATION

The remote reference and LS impedance estimates are effective in dealing with Gaussian electric and magnetic field noise, but are less effective for non-Gaussian error distributions. The goal of robust impedance estimation is to remove the effects of non-stationary non-uniform MT fields and non-stationary non-Gaussian noise from impedance estimates (Chave et al. 1987; Larson et al. 1996; Egbert and Booker, 1986).

The basic principle of robust estimation is the determination of multiple spectral estimates from a segmented time series and the removal or deweighting of outlying estimates that would not be accommodated by the least squares methods. With robust impedance estimation best results are obtained at short periods, but the largest bias is observed to occur at long periods. Consequently, for optimum MT results long recording times are needed. The robust processing of the SNORCLE data used the cascade decimation method, and algorithms developed by Chave et al. (1987) and Larson et al. (1996).

Cascade decimation

Cascade decimation is a technique that allows the computation of robust power spectra and impedances. The method processes running spectral estimates and

compensates for bad data points without discarding large amounts of good data. The data are passed through a cascade sequence of digital low pass filters and decimation by two operators (Wight and Bostick, 1980; Jones and Jodicke, 1984). For a given level of the cascade decimators a sequence of data is produced. A Hanning window and sine and cosine transforms are applied to records of 32 consecutive points. An evenly spaced frequency distribution on a log scale can be produced using two estimates (sixth and eighth harmonics) from each series (Wight and Bostick, 1980).

For the SNORCLE data, robust coherency based sorting based on the cascade decimation routine was used to process all sites. The routine was developed by Jones and Jodicke (1984). Coherency-sorted values of the local **E** and **H** fields and the remote **H** field were used to derive the spectral matrix. A coherency of 0.95 was desired and data with coherency below 45% were rejected.

Larson Method

The Larson robust algorithm uses an iterative reweighting of time series data. The stages of the method includes (Larson et al. 1996)

- 1) Time series are first preprocessed by subdividing them into smaller time sections such that coherency exists at long periods.
- 2) Linear trends are then removed from all data sections and the time series is prewhitened.
- 3) Outliers in the electric and magnetic time series are identified and replaced.
- 4) Whitening is then applied so that all frequencies make approximately the same contribution to the LS or remote reference estimates. Frequency domain weights

are used to make the weighted residuals approximately Rayleigh-distributed and to reject non-Rayleigh distributed residuals.

- 5) Poor estimates of the vertical magnetic field transfer function can occur if the horizontal magnetic components are correlated, but this effect can be minimized by rotating the magnetic components so that one component accounts for most of the coherence with the electric component.
- 6) Robust estimates are made using the weighted corrected time series.

Errors in the transfer function are calculated using jackknife estimates of the solution covariance (Larson et al. 1996; Efron and Stein, 1981).

Chave Method

The code developed by Chave et al. (1987) utilizes estimates beyond a specific distance from the current best estimate, and assigns weights to these estimates that become less as the difference increases. It therefore determines the best weight for a given value while down-weighting outliers (Egbert and Booker, 1986; Chave et al. 1987; Chave and Thompson, 1989). In the algorithm developed by Chave et al. (1987) maximum or M-estimates are combined with section averaging spectral techniques to obtain robust estimates of transfer functions. In the most recent implementations of the method, data with a disproportionately large influence on the response are downweighted and uncertainties are estimated using a jack-knife approach.

3.4.3 GALVANIC DISTORTION AND STATIC SHIFT

Galvanic distortion arises from electrical charges accumulating on near-surface electrical boundaries of surficial inhomogeneities, resulting in an MT response that does not accurately represent the regional conductivity structure. If the size of the near-surface inhomogeneities are much smaller than the signal penetration, the distortion will primarily affect the electric field response and will be independent of frequency. This distortion can be defined

$$\mathbf{Z}^{obs} = \mathbf{RCZR}^T \quad (3.32)$$

where $\mathbf{Z}^{obs}$ is the observed impedance, $\mathbf{Z}$ is the true regional impedance, $\mathbf{C}$ is the distortion tensor, and $\mathbf{R}$ is the rotation matrix defined by equation 3.23.

When the coordinate system is not aligned with the geoelectric strike, galvanic charges cause mixing of the impedances. This is commonly referred to as MT tensor distortion. For the situation when the coordinate system is aligned with the geoelectric strike, galvanic distortion affects the two horizontal electric field components (E_x , E_y) independently, causing a scaling of the impedance magnitude and apparent resistivity response. This condition is termed static shift (Jones, 1988). A vertical displacement occurs on the apparent resistivity curves by a constant scaling factor for all frequencies. It has no effect on the curve shape or the phase response (Vozoff, 1991).

Chave and Smith (1994) examined magnetic field galvanic distortion. This distortion occurs in the presence of more significant near-surface heterogeneities and is frequency-dependent because it contains a component proportional to the impedance. It involves a scaling of the two principle MT responses by frequency-dependent, complex factors (Chave and Smith, 1994).

3.4.4 SKEW

The Swift impedance skew S is a parameter that provides a measure of the three-dimensionality of the conductivity structure near the site. The parameter, which is invariant with rotation angle respect to the measurement rotation angle is defined:

$$S = \frac{|Z_{xx} + Z_{yy}|}{|Z_{xy} - Z_{yx}|} \quad (3.33)$$

For a 1D structure in which $Z_{xx}=Z_{yy}=0$ or a 2D structure in which $Z_{xx}=-Z_{yy}$ the skew will equal zero. For a 3D structure these relations will, in general, not hold allowing the skew to be used as an indicator of dimensionality (Vozoff, 1991).

Phase sensitive skew is another indicator of local 3D distortion that is based on the impedance phase. Unlike the Swift skew the phase sensitive skew will not be affected by tensor distortion. Typically, if the phase sensitive skew is greater than 0.3 the data may be considered 3D, and if the phase sensitive skew is less than 0.3 than the dimensionality is ambiguous.

3.4.5 TENSOR DECOMPOSITION

Bahr (1988), Groom and Bailey (1989), and McNeice and Jones (2001) have developed tensor decomposition methods. This study uses algorithms based on theory proposed by Groom and Bailey (1989) and McNeice and Jones (2001).

Groom Bailey Method

The Groom Bailey (GB) method tests quantitatively the hypothesis that the regional geoelectric structure can be characterized by a 1D or 2D model with galvanic

distortion. The purpose of the GB theory is to determine the dimensionality of the large-scale structure and, if the structure is 2D, to obtain a regional strike direction.

The Groom-Bailey tensor decomposition (Groom and Bailey 1989, 1991; Groom et al. 1993) method involves fitting a physical model, based on galvanic electric field distortion, to observed MT data. The method is based on two assumptions:

- (1) the regional geoelectric structure is either one or two dimensional, and
- (2) the impedance tensor consists of two parts: the regional 1D or 2D induction, and a local, independent, telluric distortion.

The purpose of this decomposition is to separate local and regional parameters by product factorization. The three dimensional distortion tensor $\mathbf{C}$ (see equation 3.32) is factored using:

$$\mathbf{C} = g\mathbf{TSA} = g \begin{pmatrix} 1 & -t \\ t & 1 \end{pmatrix} \begin{pmatrix} 1 & e \\ e & 1 \end{pmatrix} \begin{pmatrix} 1+s & 0 \\ 0 & 1-s \end{pmatrix} \quad (3.34)$$

The two matrices $\mathbf{T}$ and $\mathbf{S}$ represent transforms of the impedance: $\mathbf{T}$ (twist) provides a measure of the local rotation of the electric field, and $\mathbf{S}$ (shear) provides a measure of the local polarization of the electric field. The twist and shear are often expressed as angles using:

$$\theta_s = \tan^{-1}(e) \quad (3.35)$$

$$\theta_t = \tan^{-1}(t) \quad (3.36)$$

$\mathbf{A}$ and g are both scaling factors: $\mathbf{A}$ defines the anisotropy that splits the two apparent resistivity curves by magnifying the amplitude of the electric field in one direction and reducing it in the perpendicular one; and g is the site gain, which shifts both curves by the same factor (Groom et al. 1993; Groom and Bailey, 1989).

The seven parameters that are used for the GB factorization are strike, twist, shear, and the two complex impedance terms corresponding to the TE and TM impedance. The parameters of the decomposition model may be found by fitting the eight variables at each frequency of the measured impedance. This is done by minimizing the χ^2 , or least square misfit, between the observed and model decomposition coefficients. Alternatively the factorization can be applied to multiple frequencies in which the strike, twist, and shear are constrained to be independent of frequency whereas the TE and TM impedance responses are allowed to vary with frequency.

If the distortion model is appropriate for the geological setting the GB method correctly determines the impedances in the direction of principle axes. However, it may be unclear which impedance term corresponds to the TE and TM mode. Consequently there is a 90° ambiguity in the estimate for the strike.

Multi-site Multi-frequency Tensor Decomposition

McNeice and Jones (2001) present an extension to Groom-Bailey decomposition in which the most appropriate strike direction and telluric distortion parameters for a range of frequencies and a set of sites is determined. The method is based on obtaining the global minimum in a least squares fit on the GB model to the full data set.

There is an inherent instability in the determination of regional strike in the presence of noise and galvanic distortion that in some data sets leads to large uncertainty in the results (Jones and Groom, 1993). In these cases it is more appropriate to derive the regional strike in a statistical manner in which all the physical constraints implicit to the decomposition model are imposed simultaneously. The McNeice and Jones (2001)

procedure provides an estimate of the degree to which a whole data set fits a 2D model with 3D galvanic distortions.

The model parameters are determined by minimizing a misfit function between the observed and modeled decomposition coefficients. An objective function normalized by the data variances is chosen so as to reduce any bias arising from the frequency and position dependence of experimental error and the frequency dependence of impedance magnitudes. The objective function is given by:

$$\gamma^2 = \sum_{j=1}^S \sum_{k=1}^N \left(\sum_{i=1}^4 \left[\frac{\Re(\alpha_i^{obs}) - \Re(\alpha_i^{model})}{\sigma_{\alpha_i}} \right]^2 + \sum_{i=1}^4 \left[\frac{\Im(\alpha_i^{obs}) - \Im(\alpha_i^{model})}{\sigma_{\alpha_i}} \right]^2 \right) \quad (3.37)$$

where S is the number of magnetotelluric sites, N is the frequencies, and σ is the standard deviation of the summary coefficients. The terms α_i are formed by the sum or difference of the four impedance terms. Assuming both the modeled and observed coefficients have a Gaussian distribution a χ^2 test can be applied to determine the degree of fit between the data and the model.

3.5 MT MODELLING

MT forward modelling is the process of calculating the theoretical MT response for a specified geoelectric model. For 1D modelling the MT response is calculated using a recursive relationship (equation 3.19) (Vozoff, 1991). For 2D modelling the solution for the EM fields is more complicated because the resistivity varies in both vertical and horizontal directions. With 2D and 3D modelling, numerical approaches such as the integral equation, finite element, finite difference, and thin sheet methods are used.

The finite element method involves employing a mesh design consisting of rectangular elements. To solve for the resistivity the finite element method divides the subsurface into a number of discrete blocks. The mesh must be padded with extra rows and columns well outside the target area to limit boundary effects. The finite difference method discretizes 2D or 3D structures into piecewise rectangular grids and calculates the unknown EM fields at the points of space using finite differences. Finite differences are better suited than the integral equation for modelling arbitrarily complex geometries.

3.6 INVERSION

3.6.1 OVERVIEW

Inversion is a procedure for determining the physical earth parameters from a set of observed data. The method involves minimizing some functional which penalizes data misfit and model structure. The misfit can be measured using techniques such as least squares and non-normalized absolute value.

With the inversion method, the interpreter first develops an initial guess of the resistivity structure called the starting model. The starting model resistivities are assigned through the use of a grid that conceptually subdivides the materials underlying the survey line into grid elements. The grid blocks are chosen to be small so the locations of the block boundaries do not affect the final model (deGroot-Hedlin and Constable, 1990). The inversion program then uses the predicted responses from the forward problem to modify the model parameters, and minimize the misfit to the data.

3.6.2 1D INVERSION

One-dimensional inversion uses a layered model and iteratively adjusts the thickness and conductivity of these layers to best fit the data (Constable et al. 1987). Generally, for the 1D case, the fit to the data increases if the number of layers increases. However, at some point the layer thickness will be below the resolving capabilities and the model will begin to exhibit oscillations not required by the sounding data. Fitting a simple layered model is therefore a delicate balance between suppressing structure by including too few parameters in the model and introducing spurious structure by including too many parameters (Constable et al. 1987).

The philosophy of the Occam method is to allow the model as much flexibility as possible and suppress complexity. This method generates a smooth model by fitting the data within a tolerance for an over-parameterized model, while also limiting the roughness, which is the integral of the square of the first or second derivative of the resistivity with respect to depth. For a continuous model parameter the roughness is defined:

$$\Psi = \int (dm / dz)^2 dz \quad (3.38)$$

where m is the $\log(\rho)$ and z is the depth. In practical inversion schemes a numerical equivalent of this express is used. The tolerance is a normalized χ^2 misfit used to evaluate the misfit:

$$\tau = \sqrt{\frac{1}{M} \sum_{i=1}^M \frac{(g_i - F_i[m])^2}{\sigma_i^2}} \quad (3.39)$$

where g_i is the observed data, $F_i[m]$ is the forward modelling responses from model m , σ_i is the uncertainty in the i th datum, and M is the number of data points. Statistically, the tolerance should be ~ 1 , and the roughness as small as possible.

3.6.3 2D INVERSION

In the 2D inversions discussed, both the TE and TM mode responses are inverted to develop a model. The TE and TM modes are sensitive to different structures and resistivity values in the Earth. For example, the TE mode is more sensitive to changes in conductivity, but has less resolution of the location of structures with depth, and the TM mode is more sensitive to lateral boundaries. Consequently, modelling of TM data will provide an accurate interpretation of the horizontal extent and presence of thin resistive layers, whereas modelling of TE data will resolve only the depth and conductivity thickness of the conducting regions (Agarwal et al. 1993).

A number of 2D inversion methods have been developed. For the LITHOPROBE SNORCLE MT data, 2D Occam inversion (deGroot and Constable, 1990), and NLGG inversion (Mackie and Rodi, 1996, Rodi and Mackie, 2001) were used. The Occam inversion method is capable of inverting apparent resistivity, phase, and tipper data, while the NLGG method is capable of inverting only apparent resistivity and phase.

Occam Method

The Occam inversion determines the smoothest model for a specified level of misfit. For a 2D model the earth is parameterized into a grid of many rectangular prisms, each having a uniform conductivity (deGroot-Hedlin and Constable, 1990). The grid is termed a regularization mesh, and the individual blocks within the grid are made smaller than the data resolution length. For the most accurate results the model complexity must

be adequate to represent the complexity of the real Earth's response. The forward calculations are performed using a rectangular array of nodes (finite-element code by Wannamaker *et al.* 1987). The inversion program defines the regularization grid using a subgrid superimposed on the finite element mesh.

NLCG Method

Makie and Rodi (1996) and Rodi and Mackie (2001) use a non-linear conjugate gradient (NLCG) method that minimizes a Tikhonov regularization function combining the data misfit and model roughness. The regularization function is defined

$$S(m) = (d - F(m))^T R_{dd}^{-1} (d - F(m)) + \tau |L(m - m_0)|^2 \quad (3.40)$$

where L is a linear Laplacian operator, τ is regularization parameter, and R_{dd} is the error covariance matrix

$$R_{dd} = \begin{bmatrix} \sigma_1^2 & 0 & 0 & 0 \\ 0 & \sigma_2^2 & 0 & 0 \\ 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \sigma_n^2 \end{bmatrix}. \quad (3.41)$$

The parameter $F(m)$ is calculated using a finite difference algorithm. Note that the misfit between the observed and modeled data, the first term in equation 3.40, is closely related to the normalized χ^2 misfit and the roughness is defined using a Laplacian operator. The implementation of the program uses a finite difference code for the forward model calculations and the regularization grid for the inversion is the same grid as used in the finite difference computations. The NLCG method uses less computer time than other methods, allowing the use of larger model grids and data sets, as well as more frequencies for each site (Mackie *et al.* 1997).

CHAPTER 4 – SNORCLE NORTHERN CORDILLERA MAGNETOTELLURIC

SURVEY

4.1 INTRODUCTION

MT soundings were completed in the Northern Cordillera in the fall of 1999. A total of 41 MT stations were located on Line 2a (Alaska Highway) and 16 MT stations were located on the Connector Line (Highway 37) (Fig. 1.2, Fig. 4.1). The Line 2a sites were deployed on the Stikine, Cache Creek, Quesnellia, Slide Mountain and Cassiar terranes, whereas the Connector Line sites were deployed on the Cache Creek, Slide Mountain, Kootenay, Dorsey, and Cassiar terranes.

Two types of MT instrumentation were used in the survey. LiMS systems were used for collecting long period data and MT systems were used for collecting broadband data. The LiMS station spacing was 30 km and the MT station spacing was 15 km. It was necessary for the MT sites to be closer spaced in order to examine the upper crust response with minimal aliasing, whereas the 30 km station spacing was adequate for the LiMS sites to examine the deeper crustal and upper mantle response. The duration of the LiMS recordings was 1 to 2 weeks. The duration of the MT recordings was 2 to 3 days. Collection with the LiMS and the broadband ADU systems was performed simultaneously.

The MT and LiMS site locations for Line 2a and the Connector Line are listed in Table 4.1 and Table 4.2 respectively. The MT survey was completed at relatively high geomagnetic latitude. The geomagnetic coordinates for the survey extend from 63.6° N to 64.5°N and from 80.1° W to 75.8° W.

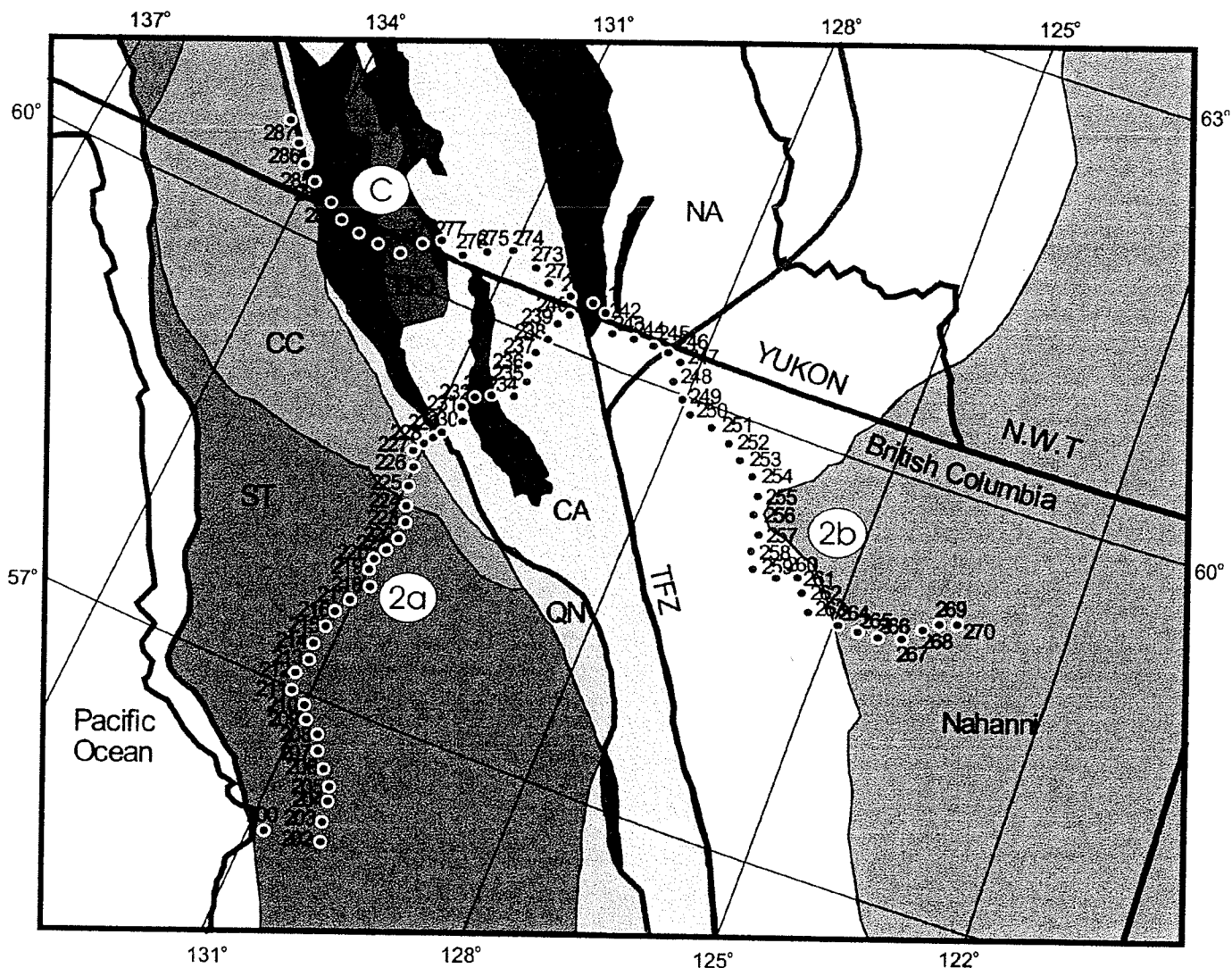


Figure 4.1 Map showing locations of MT sites for Corridor 2 and the Connector Line (geology modified from Monger and Berg, 1984). See Figure 1.3 for definition of abbreviations. Red lines denote geological belt boundaries. This study involves analysis of data from Line 2a and the Connector Line (labeled "C").

Table 4.1 Locations of MT sites on Line 2a.

Site	Latitude (N)	Longitude (W)	Instrument	Terrane
200	56°02'17"	129°53'49"	LiMS, ADU	Stikine
202	56°09'33"	129°17'45"	LiMS, ADU	Stikine
203	56°15'54"	129°20'43"	ADU	Stikine
204	56°21'32"	129°16'55"	LiMS, ADU	Stikine
205	56°27'36"	129°23'10"	ADU	Stikine
206	56°33'54"	129°35'09"	LiMS, ADU	Stikine
207	56°38'26"	129°41'56"	ADU	Stikine
208	56°44'45"	129°46'19"	LiMS, ADU	Stikine
209	56°48'42"	129°57'17"	ADU	Stikine
210	56°54'43"	130°04'26"	LiMS, ADU	Stikine
211	56°57'07"	130°14'09"	ADU	Stikine
212	57°05'48"	130°16'58"	LiMS, ADU	Stikine
213	57°12'03"	130°13'15"	ADU	Stikine
214	57°18'10"	130°14'56"	LiMS, ADU	Stikine
215	57°26'35"	130°12'59"	ADU	Stikine
216	57°33'33"	130°09'28"	LiMS, ADU	Stikine
217	57°40'35"	130°01'51"	ADU	Stikine
218	57°52'59"	129°57'32"	LiMS, ADU	Stikine
219	57°53'37"	130°02'40"	ADU	Stikine
220	58°00'29"	130°01'48"	LiMS, ADU	Stikine
221	58°03'22"	129°52'35"	ADU	Stikine
222	58°10'13"	129°51'21"	LiMS, ADU	Stikine
223	58°17'17"	129°52'02"	ADU	Stikine
224	58°23'47"	129°56'31"	LiMS, ADU	Stikine
225	58°30'57"	130°01'28"	ADU	Cache Creek
226	58°38'48"	130°01'08"	LiMS, ADU	Cache Creek
227	58°46'05"	130°05'52"	ADU	Cache Creek
228	58°53'13"	130°01'33"	LiMS, ADU	Quesnellia
229	58°57'25"	129°51'48"	ADU	Quesnellia
230	59°03'16"	129°45'14"	LiMS, ADU	Cassiar
231	59°07'37"	129°49'19"	ADU	Cassiar
232	59°14'20"	129°42'22"	LiMS, ADU	Slide Mountain
233	59°17'09"	129°27'16"	ADU	Slide Mountain
234	59°19'50"	129°13'19"	LiMS, ADU	Cassiar
235	59°25'38"	129°11'01"	ADU	Cassiar
236	59°32'39"	129°13'58"	LiMS, ADU	Cassiar
237	59°39'32"	129°12'21"	ADU	Cassiar
238	59°45'38"	129°08'42"	LiMS, ADU	Cassiar
239	59°52'57"	129°08'49"	ADU	Cassiar
240	59°58'54"	129°03'32"	LiMS, ADU	Cassiar
241	60°02'27"	128°54'19"	ADU	Slide Mountain

Table 4.2 Locations of MT sites on the Connector Line.

Site	Latitude	Longitude	Instrument	Terrane
272	60°04'00"	129°14'05"	LiMS, ADU	Cassiar
273	60°06'01"	129°28'08"	ADU	Cassiar
274	60°09'21"	129°43'40"	LiMS, ADU	Cassiar
275	60°11'52"	130°02'59"	ADU	Cassiar
276	60°07'14"	130°16'53"	LiMS, ADU	Cassiar
277	60°04'00"	130°31'05"	ADU	Slide Mountain
278	60°04'22"	130°50'47"	LiMS, ADU	Dorsey
279	60°01'30"	131°05'31"	ADU	Dorsey
280	59°54'22"	131°18'29"	LiMS, ADU	Slide Mountain
281	59°54'45"	131°35'52"	ADU	Slide Mountain
282	59°55'09"	131°52'40"	LiMS, ADU	Slide Mountain
283	59°59'00"	132°06'32"	ADU	Slide Mountain
284	60°04'54"	132°20'39"	LiMS, ADU	Kootenay
285	60°07'46"	132°36'25"	ADU	Slide Mountain
286	60°12'28"	132°51'08"	LiMS, ADU	Quesnellia
287	60°19'27"	133°01'48"	ADU	Quesnellia

4.2 SURVEY EQUIPMENT

The equipment used in the MT survey was provided by Geosystem Canada and the GSC. Typical hardware for each site included telluric lines, electrodes, magnetometers, acquisition systems (ADU or LiMS) and 12 V car batteries to power the instruments.

The LiMS sites used a long period magnetotelluric system (LiMS) developed at the GSC. During acquisition the data for each site were stored in the LiMS internal memory. For the LiMS sites flux gate magnetometers were used to measure the three components of the magnetic field. The three sensors are housed within one container.

The MT sites were run using a multi-method network geophysical measurement system, GMS-06 developed by Metronix. The GMS components include the analog/digital signal conditioning units (ADU-06) running MAPPROS software. For the MT sites three induction coil sensors housed in individual containers were used to

measure the three components of the magnetic field. During acquisition the data were stored on either the ADU internal flash disk or directly on the hard disk of the field computer. The MAPROS software has features such as semi-automatic definition of sensor field setup, system self-test, in-field system calibration, real time data acquisition and processing, robust estimation of transfer functions, and display of time series and EM-parameters.

4.3 DATA COLLECTION

Data collection was performed by personnel from the GSC, University of Manitoba, and Geosystem Canada. Site locations were chosen based on the slope of the terrain, access to the sites, and the distance to sources of cultural noise, such as towns or power lines. The duration of the MT recordings at sites where LiMS instruments were deployed was two days and the duration of MT recordings at sites without LiMS instruments was three days. The duration of the LiMS soundings was either 7 or 14 days depending on location. The 14 day recordings were done at every second site.

Telluric lines were generally aligned to magnetic north-south and east-west, and the lengths were as close to 100 m as possible. For the combined MT and LiMS sites, common Pb-PbCl₂ electrodes were used for both systems. The magnetometer coils for the ADU-06 and LiMS systems were generally orientated vertically and parallel to magnetic north and magnetic east. For the MT system the magnetometers were typically buried in three of the four quadrants formed by the electrode cables. Both LiMS and MT systems used precise GPS satellite controlled timing in the collection of the data.

The LiMS magnetometers and horizontal induction coils of the MT system were buried at least a foot underground. The vertical induction coils were installed with the top either beneath the ground or flush with the ground surface. In some cases due to rocky terrain or permafrost it was not possible to bury the coil to this depth in which case it was back buried. In addition, where possible the telluric lines were weighted down by branches in order to decrease noise. For a more complete description of MT field procedure refer to Wolynech (2000) and for a complete description of LiMS field procedure refer to Wennberg (1999).

The LiMS systems recorded data with a period range of 4 to 10,000 s using a sampling rate of 1 s. The MT systems recorded data with a period range of 0.001 to 100 s. For the MT data collection the ADU was programmed using multiple time windows, with sampling rates of 0.5 s, 0.016 s, and 0.002 s for the different windows. For the 0.002 s sampling rate, the typical length of the time window was of a scale of minutes. For the 0.016 s sampling rate, the typical length of the time window was of a scale of minutes to hours. Finally, for the sampling rate of 0.5 s, the length of the time window was generally more than 6 hours.

No systematic problems were encountered during the data collection. Quality control procedures were implemented at each stage of the data collection. The MT crew assessed the status of the equipment on a daily basis and field procedures were adhered to.

4.4 DATA PROCESSING

Many programs were used in the data processing of the MT data. In the field the program QUICKLOOK, which was developed by Metronix for visual inspection of time

series segments, was used to examine data quality. The following programs were then used for subsequent data processing. The theory of these programs is discussed in section 3.6.2.

- (1) RBST_CD, which is a cascade decimation routine with coherency sorting developed by Alan Jones.
- (2) ADU_ROB, which was developed by Larsen et al. (1996) for robust processing of time series.
- (3) RRRMT8, which was developed by Chave et al. (1987) for robust processing of time series.

4.4.1 ADU-06 DATA

Geosystem Canada provided the MT impedances and spectra data in SEG EDI (Society of Exploration Geophysicists Electronic Data Interchange) format. The MT data were initially processed by Geosystem employees Mr. Gary McNeice and Mr. Mark Kitchen using cascade decimation robust impedance estimation. The Line 2a sites were later reprocessed using Larson's robust algorithm because initial impedance estimates were noisy due to the low signal levels that occurred during the recordings. An optimal remote reference for each site was chosen based on the distance from the main site and the length of overlap between the two recordings.

4.4.2 LIMS DATA

The LiMS data were processed at the Geological Survey of Canada by the author and GSC personnel Ms. Jessica Spratt and Dr. Juanjo Ledo. Impedance estimation was performed using robust methods. Calculation of MT parameters was performed using

cascade decimation and editing of cross powers. Further processing was needed for poorer quality sites. In these cases robust processing of time series using the Larson or Chave code was done.

4.4.3 PROCESSING AND MERGING OF DATA SETS

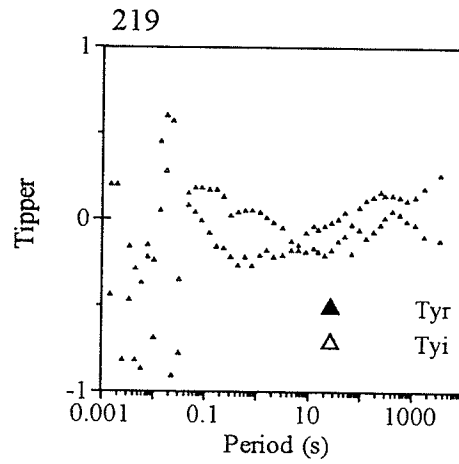
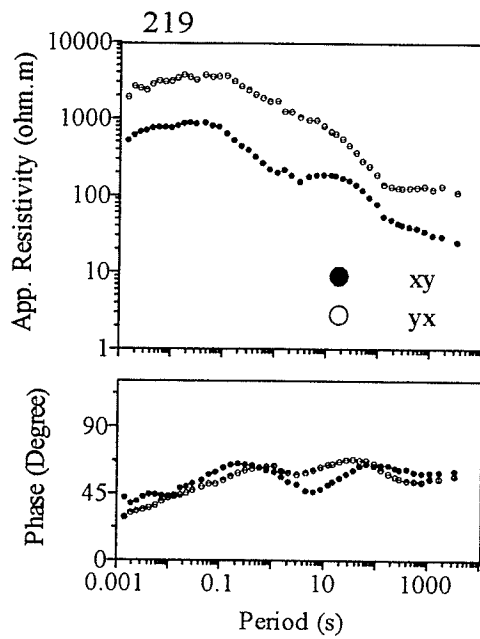
In order to obtain a complete MT response extending over the period range (0.001 s to 10,000 s) the MT and LiMS response were merged. Merging of the data was completed at the GSC at Ottawa. In this procedure the LiMS data were resampled at 5 s in order to calculate the longer period response. The 5 s and 1 s responses were then merged. Finally, the optimal period ranges for merging the LiMS and MT data were selected and the two data sets were merged together. The optimal period ranges were chosen based on the data quality and so as to provide a smooth transition between the overlap of the two data sets. Merging did not occur at the same period for different sites, but the period of the transition between the data sets was usually between 10 s and 0.1 s.

The data were rotated to true north during merging. The final data were imported into a GEOTOOLS MT workstation for further processing, analysis and display.

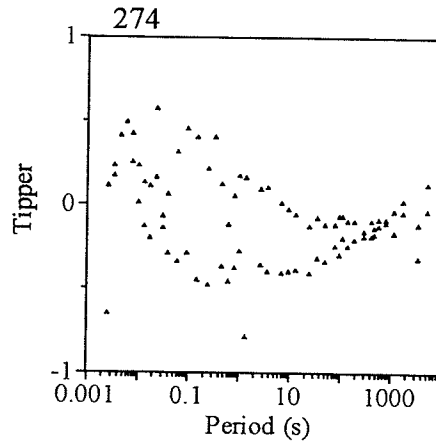
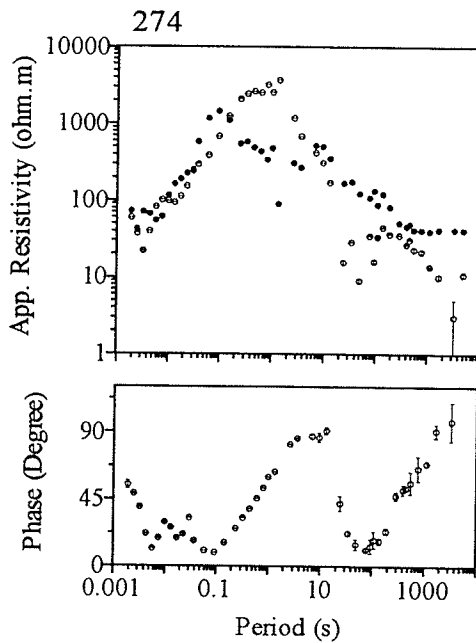
Appendix A shows the resistivity, phase and vertical magnetic field transfer function (tipper) responses generated from the raw data.

4.5 FINAL MT RESPONSES

Examination of the raw MT responses indicates that the quality of the SNORCLE MT data is fair. The apparent resistivity, phase, and tipper response from a typical good quality site (219) and poor quality site (274) are shown Figure 4.2. The xy phase data for site 274 is not plotted because it does not lie in the range from 0° to 90°.



(a)



(b)

Figure 4.2 (a) Apparent resistivity, phase response and tipper response for site 219. (b) Apparent resistivity, phase response and tipper response for site 274. The data for both sites have been rotated to a true north-south coordinate system. Note the difference in data quality (scatter) for the two sites.

4.5.1 OVERVIEW OF DATA

The overall quality of MT data for Line 2a and the Connector Line is poorer than the quality of data from Corridor 3. The poorer data quality is attributed to the occurrence of relative low levels of geomagnetic signals during the second half of the Northern Cordillera MT survey. For Line 2a, the high quality data have error values corresponding to less than 3% impedance error. Typically, the signal to noise ratio is lowest for periods greater than 100 s, and in the case of site 232 in the MT dead band (0.1-10 s).

The Connector Line has poorer quality data than Line 2a. Table 4.3 lists the sites and period ranges with poor data. In general, the higher quality data have error values corresponding to less than 5% impedance error. The errors are typically larger at periods > 100 s and for sites 272, 273, 275, 278, and 279 the errors are at least an order of magnitude larger in the MT dead band (0.1-10s). Sites 274 and 276 have very erratic phase and apparent resistivity responses over most of the period range.

The quality of the tipper data for both the Connector Line and Line 2a is quite poor. At most sites the long period (> 100 s) and short period (< 0.1 s) responses are erratic.

Table 4.3 Poor quality data at sites on the Connector Line.

Site	Period Range (s)			
	Apparent Resistivity		Phase	
	xy mode	yx mode	xy mode	yx mode
272	> 700	> 700	> 700	1-10, > 700
273	>200	> 200	1-10, > 200	1-10, > 200
274	0.01 – 10	> 10	< 0.1	<0.03, > 1
275				> 0.1
276		> 0.01		0.001 – 10 000
277	< 0.01, > 200		< 1, > 70	> 100
278	< 0.003, 0.03–1	< 0.003	< 0.003, 0.07–1	< 0.003, 0.07–1
279	0.01–1, > 100	> 100	0.1–1, > 30	0.2–0.8, > 100
280				
281			> 1000	> 3000
282				
283				
284	< 0.01	< 0.01	< 0.01	< 0.01
285		> 100		> 100
286			< 0.07	> 10
287		> 1000		> 10

Note: Table lists period ranges in which the impedance error exceeds 5%.

4.5.2 EDITING OF DATA

The data were edited in order to exclude bad data points from the subsequent analysis. Most of the data removal was from the MT dead band around 1 s period and from short (<0.001 s) and long (>100 s) periods. Data were removed based on two considerations:

- (1) if the corresponding response had apparent resistivity error values larger than half a decade, or
- (2) if the response of a particular period was significantly different from the adjacent values.

CHAPTER 5 – MAGNETOTELLURIC TENSOR ANALYSIS AND GEOELECTRIC STRIKE DETERMINATION

5.1 INTRODUCTION

Tensor analysis is the first step used in determining the dimensionality of the response. A preliminary examination of dimensionality can be performed for each site in a survey by: (1) comparing the apparent resistivity and phase responses of off diagonal tensor elements and (2) examining the skew (as discussed in section 3.6.6). The application of these procedures in the present study is described in section 5.2.

If the MT response corresponds to a 2D or approximately 2D structure, the next step in an MT analysis is determining the geoelectric strike. The strike of the electrical conductivity structure can be defined using several methods. The geoelectric strike for this study was determined using: (1) GB tensor decompositions, (2) multi-site GB tensor decompositions, and (3) induction vector responses. Maximum phase split orientations and Swift strike rotations were also examined, but will not be presented in this thesis since in the presence of galvanic distortion these methods are less robust than GB methods for determining strike. The dimensionality and strike can be determined as a function of period and the exploration depth for these parameters estimated using the skin depth and the induction scale or Schmucker depth (see section 3.1 and 3.2).

The programs used to calculate the GB decompositions, multi-site decompositions, and induction vectors in this research were provided by the Geological Survey of Canada. The GB decompositions and multi-site decompositions were done using the programs **dcmp** and **strike**, which were written by Dr. Ross Groom, Dr. Alan

Jones and Mr. Gary McNeice, and the induction vectors were computed using the programs **mtmap** and **GEOTOOLS**.

5.2 RELATIONSHIP BETWEEN PERIOD AND SIGNAL PENETRATION

The relation between period and depth can be examined by skin depth and Schmucker depth, as discussed in sections 3.1 and 3.2. The Schmucker depths for two representative sites on the Connector Line and two representative sites on Line 2a are shown in Figure 5.1. Table 5.1 lists the Schmucker period depth for periods between 0.001 and 1000 s. The Schmucker depths were derived for both off-diagonal components of the impedance (xy and yx).

The Schmucker depth is approximately the same for both the xy and yx components at periods less than 0.01 s, but diverges slightly more for both components at longer periods (Fig. 5.1). The largest difference between the xy and yx components occurs at site 239 at 1000 s period. From Figure 5.1 it is apparent that:

- periods less than 1 s correspond to signal penetration less than ~10 km
- periods of ~1 s to ~10 s correspond to signal penetration less than ~20 km (i.e. upper crustal depth)
- periods of 10 s to 100 s correspond to signal penetration less than ~40 km (i.e. crustal depth) except for more conductive sites such as site 272
- periods greater than 100 s corresponds to signal penetration greater than ~40 km (i.e. upper mantle) at most sites

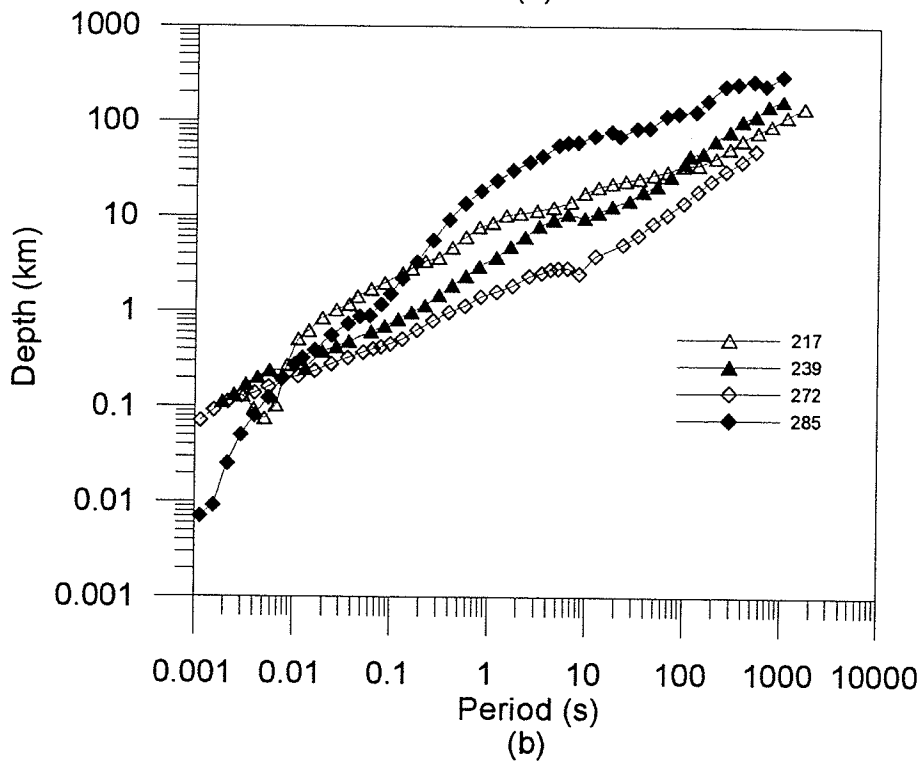
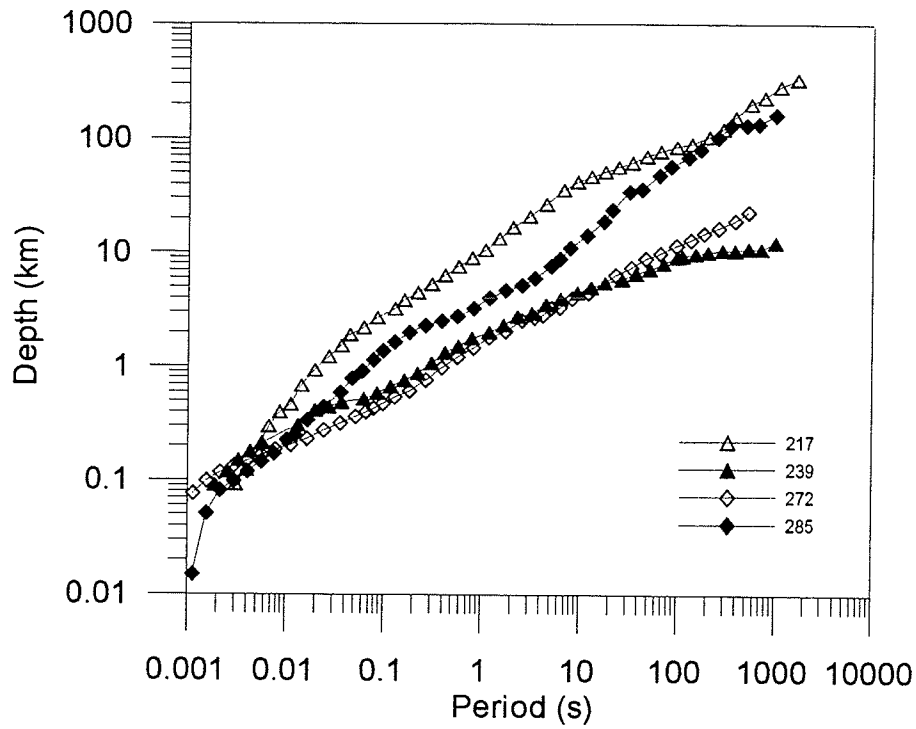


Figure 5.1 Schmucker depth versus period for representative sites along Corridor 2. (a) xy mode and (b) yx mode.

Table 5.1 Schmucker depths (km) at seven periods for both the *xy* and *yx* mode for four sites along Corridor 2.

Period (s)	Depth (km)							
	217		239		272		285	
	<i>xy</i>	<i>yx</i>	<i>xy</i>	<i>yx</i>	<i>xy</i>	<i>yx</i>	<i>xy</i>	<i>yx</i>
0.001			0.08	0.10	0.07	0.07	0.014	0.007
0.01	0.46	0.50	0.29	0.22	0.19	0.20	0.225	0.270
0.1	3.0	2.3	0.64	0.79	0.47	0.45	1.4	1.5
1	10.4	8.5	1.9	3.5	1.6	1.5	3.8	22
10	43	18	5.5	10.0	3.3	3.3	14	70
100	86	34	9.2	36	12	14	65	125
1000	275	110	12.5	165			163	300

5.3 PRELIMINARY EXAMINATION OF DIMENSIONALITY

From examination of the raw data (Appendix A) it is apparent that for most sites the off diagonal components of the impedance differ in both apparent resistivity and phase, and therefore the responses are not 1D. Considering that the responses are not 1D, further analysis needs to be performed to determine whether

- (1) the responses are from a 2D structure,
- (2) the responses are from a 2D structure with local galvanic distortion, or
- (3) the responses are from a 3D structure.

One indicator of dimensionality is skew, as discussed in section 3.8.1. Sites with low skew values (< 0.3) are generally not three dimensional or highly distorted, although there are some exceptions (Groom and Bailey, 1991). The Swift skew for the Connector Line and Line 2a is shown in Figure 5.2. Although the phase sensitive skew provides a more definitive indication of dimensionality (Bahr, 1988) it was not used because the appropriate computer programs were not available at the time of the thesis research.

For both the Connector Line and Line 2a low skew values (< 0.3) occur at periods less than 10 s. At periods between 10 to 10 000 s higher skew values (typically 0.3 to 0.6) are observed on the Connector Line and very high skew values (~ 1.0) occur for sites 281 and 274. For Line 2a higher skew values of 0.3-0.6 are observed at periods between 10 and 10 000 s in two parts of the line. On the north part of Line 2a typical skew values of 0.3 to 0.6 are observed and values as high as 1.0 are reached at site 225. On the south part of the Line 2a skew values are typically higher than 0.5 at longer periods and even higher (> 0.7) at sites 200, 205, and 208.

The skew results indicate that for the most part the upper crust along Line 2a and the Connector Line have a 2D resistivity structure. Based on the higher skew values observed at longer periods the deeper structure is moderately 3D on the Connector Line and northern parts of Line 2a. 3D structure is also present at depth along the southern portion of Line 2a. The observations suggest that the structure of the study area is dominantly 2D but with some 3D structure present at lower crustal depths in the north and south of the study area.

5.4 OVERVIEW OF STRIKE DETERMINATION

Induction vectors, GB strike determination, and multi-site multi-frequency tensor decompositions are methods for determining geoelectric strike of 2D structures. For many data sets fitting all MT sites to a single regional strike is difficult, for example Marquis et al. (1995) makes this observation for data from the Intermontane and Omineca Belts of the southern Cordillera. In this situation, careful consideration of the data quality, dimensionality, and method must be made in order to determine an accurate regional

strike angle. The procedures used for determining the regional geoelectric strike for Line 2a and the Connector Line are shown in Figure 5.3.

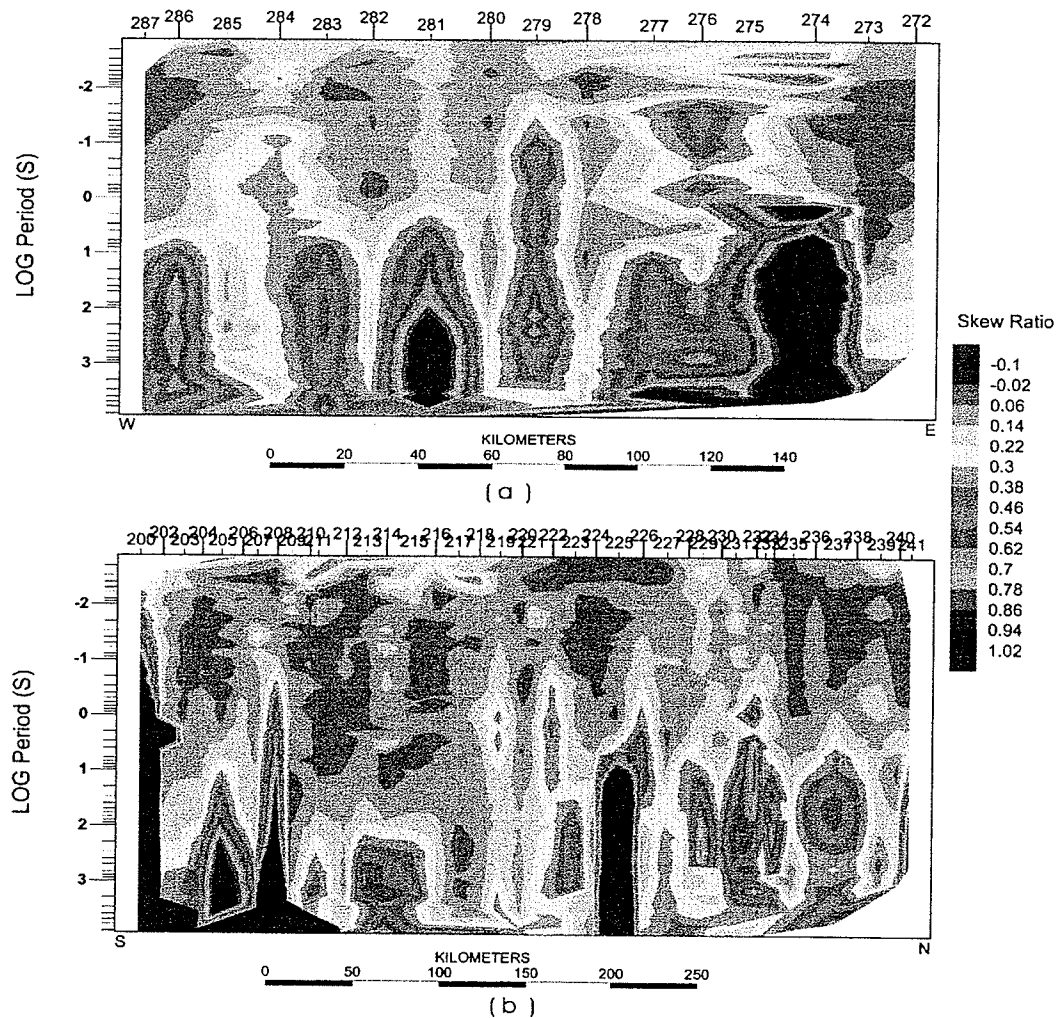


Figure 5.2 Contoured skew values for the (a) Connector Line and (b) Line 2a.

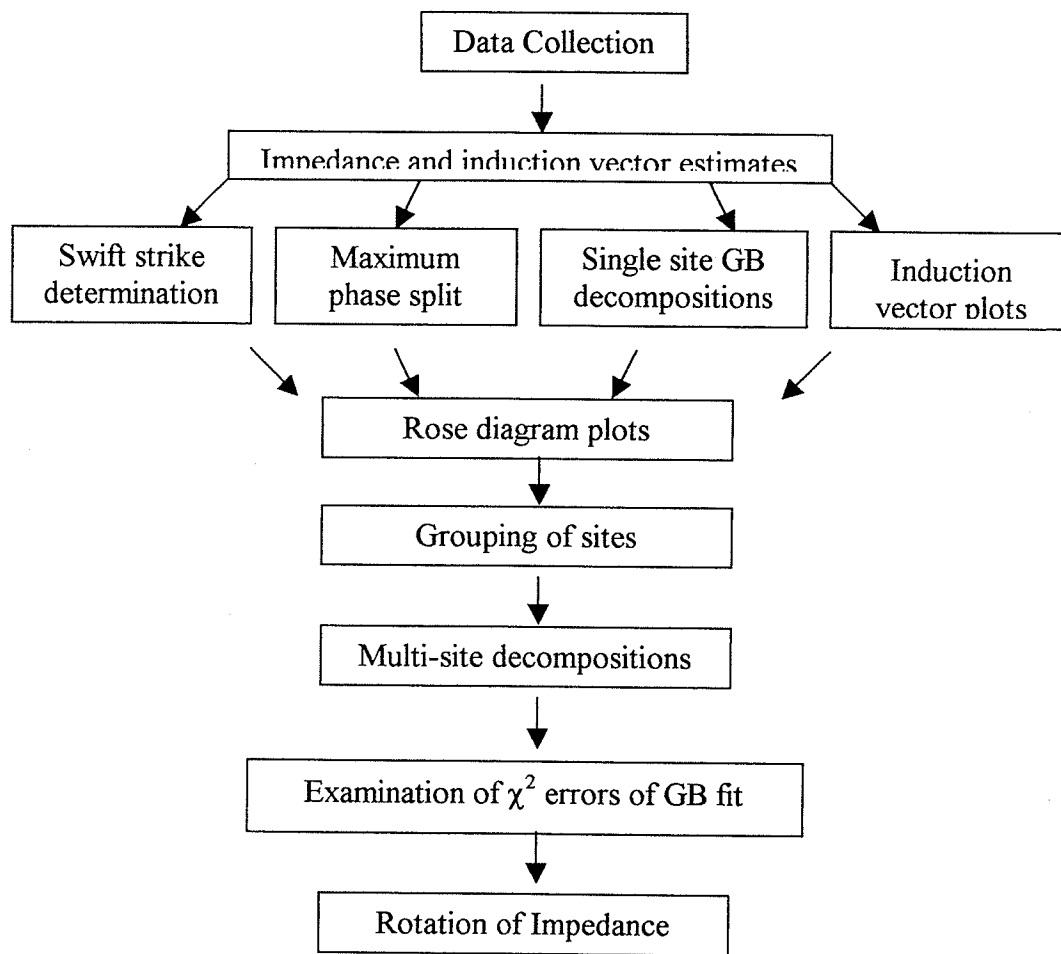


Figure 5.3 Analysis scheme used in this study to determine geoelectric strike.

5.5 GROOM BAILEY TENSOR DECOMPOSITIONS

The GB tensor decomposition can be used to parameterize the level of galvanic distortion due to near surface heterogeneities, to define the dimensionality of the regional geoelectric structure, to define the regional geoelectric strike, to define the strike of the local distortion, and to correct the impedance tensor for distortion effects (see section 3.6.4). In this study the method is used to parameterize the level of distortion, to define the regional strike, and to investigate the dimensionality of the regional resistivity structure. This analysis was done for all of the Corridor 2 data, but the following

description will be restricted to the data for the Line 2a and the Connector Line and to the period range 0.001 s to 1000 s.

In order to examine the spatial and period (depth) variation in the geoelectric strike the GB analysis was performed in a number of steps with the strike and decomposition parameters being constrained over progressively larger period ranges and number of sites at each step. The basic steps were:

- (1) single-site narrow-band decompositions
- (2) single-site broad-band decompositions
- (3) multi-site narrow-band decompositions
- (4) multi-site narrow-band with strike constrained to specified value
- (5) multi-site broad-band decompositions
- (6) multi-site broad-band with strike constrained to specified value.

The results of these decompositions are described in the following sections.

5.5.1 ONE-DECADE BAND DECOMPOSITIONS

The first step in the GB decompositions involved fitting a decomposition model in which the strike, twist, and shear were constrained to be constant over one-decade wide bands for periods between 0.001 s to 1000 s. The strike direction ambiguity was resolved by choosing the strike angle closest to -45° the azimuth of the regional geological strike defined by geologic maps (e.g. Monger and Berg, 1984). An example of the GB decompositions results for a representative site is shown in Figure 5.4. Shear results for all sites on Line 2a and the Connector Line are shown in Figures 5.5 and 5.6 respectively, and the strike results are shown in Figure 5.7. The full results are given in Appendix B.

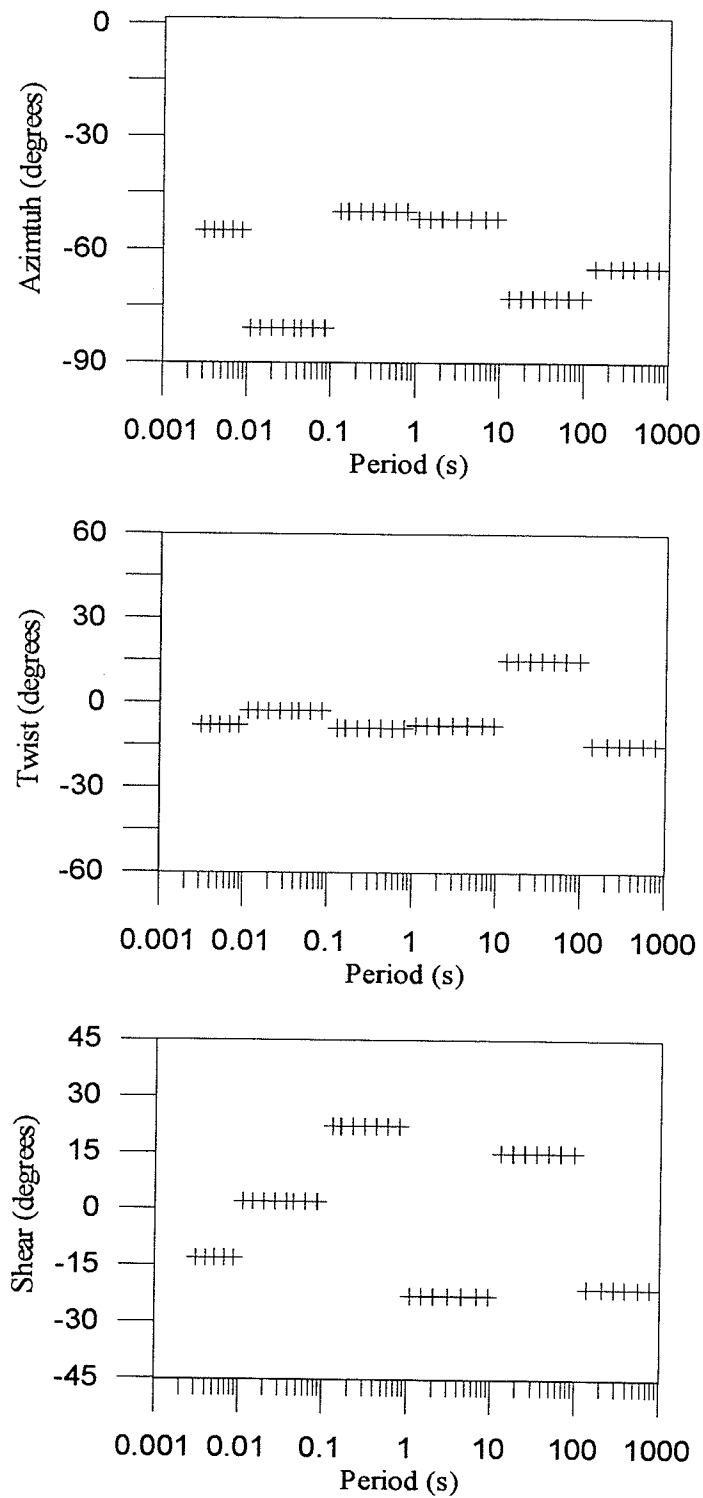
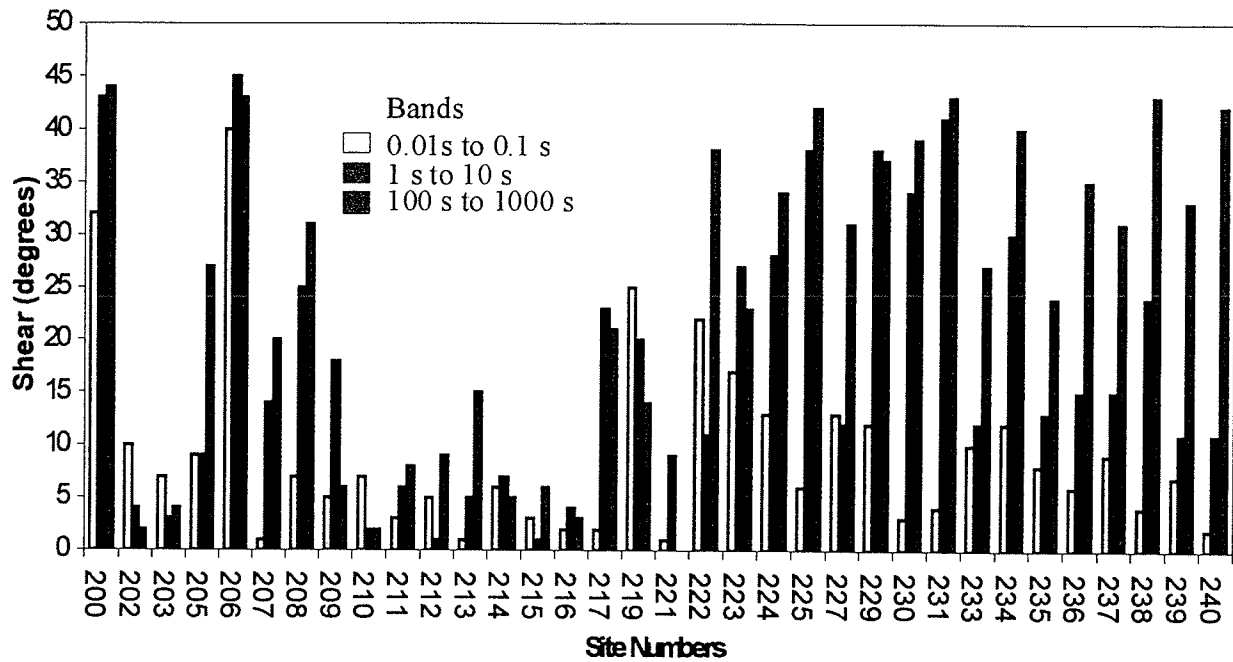


Figure 5.4 Groom Bailey decompositions for site 217 showing the regional azimuth, twist, and shear.

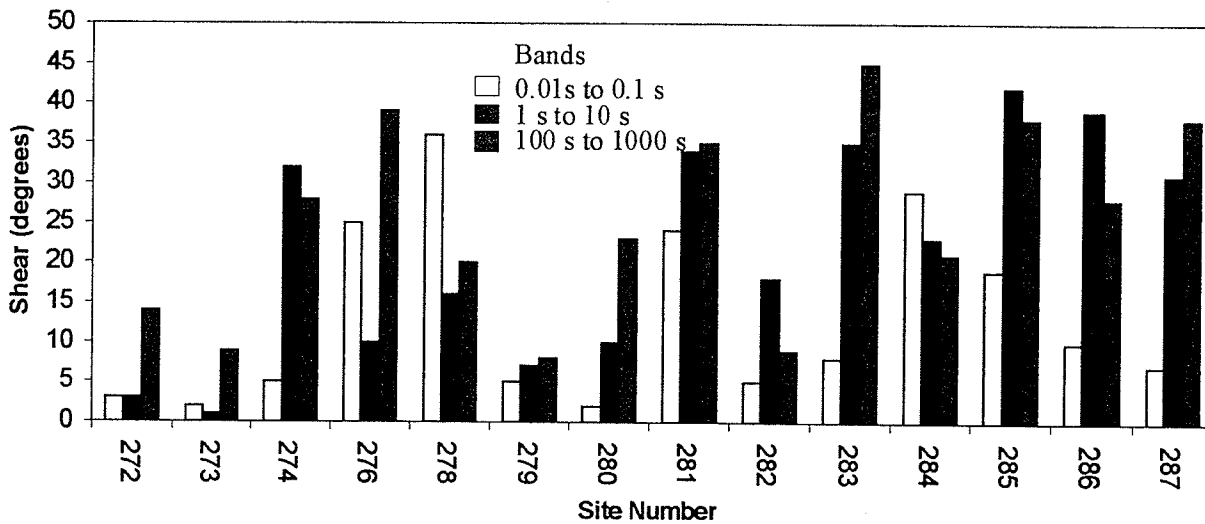
Shear and Twist

The magnitude of the shear and twist provide an indication of the level of distortion at particular periods. Sites 222 to 234 have shear values higher than 25° for periods greater than 1 s, indicating that these sites are moderately distorted at long period. The twist values for the same sites and same periods are lower. Sites 210 to 216 have very low shear values. For the Connector Line, sites 274, 276, 281, 283, 285, and 287 have shear and twist values that are typically higher than 25° at periods greater than 0.1 s, again indicating moderate distortion at long periods. Most of the remaining sites for Line 2a and the Connector Line have twist and shear values less than 15° .

Figure 5.6 summarizes the shear results in histogram form. The shorter period band has very low distortion ($<10^\circ$) for 70% of the sites. For the middle (0.01-0.1 s) and longer period bands (100-1000 s) the sites show a broad range of distortion levels. The distortion results suggest that the physical model on which GB decompositions is based (as discussed in section 3.6.4), represents only an approximation of the structure in the study area and perhaps the presence of additional distorting sources distributed though the crust (e.g. Ferguson et al. 1999).



(a)



(b)

Figure 5.5 Shear results for one-decade band GB analysis for (a) Line 2a and (b) the Connector Line.

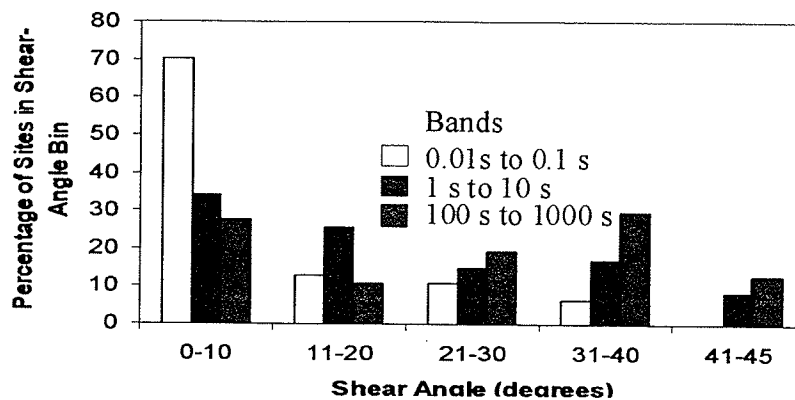


Figure 5.6 Distribution of shear at sites in the Connector Line and Line 2a expressed as a percentage. Results are for three period bands 0.01-0.1 s, 1-10 s, 100-1000 s. The shear values have been grouped into 10° bins.

5.5.1.1 Geological Strike results

0.001-1 s Period

At periods less than 1 s the geoelectric strike directions are typically parallel or subparallel to the orientation of terrane boundaries (Fig. 5.7). Strike directions for sites deployed on the Slide Mountain and Cache Creek terranes are parallel to the geological strike and change only slightly between the three bands. Several sites deployed within the Stikine Terrane and Cassiar Terrane have a more north-south strike direction (-30°).

1-10² s Period

The geoelectric strike orientations are similar for the two one-decade bands between 1 and 100 s period. The majority of sites in the western portion of the Connector Line have strike angles of approximately -60° to -80° , but some strikes of -10° to -20° are observed at 10-100 s. Sites near the Tintina Fault (at the margin of ancestral North America) have strikes that are parallel to the fault. Sites in the southern two-thirds of Line 2a have strike directions of approximately -45° .

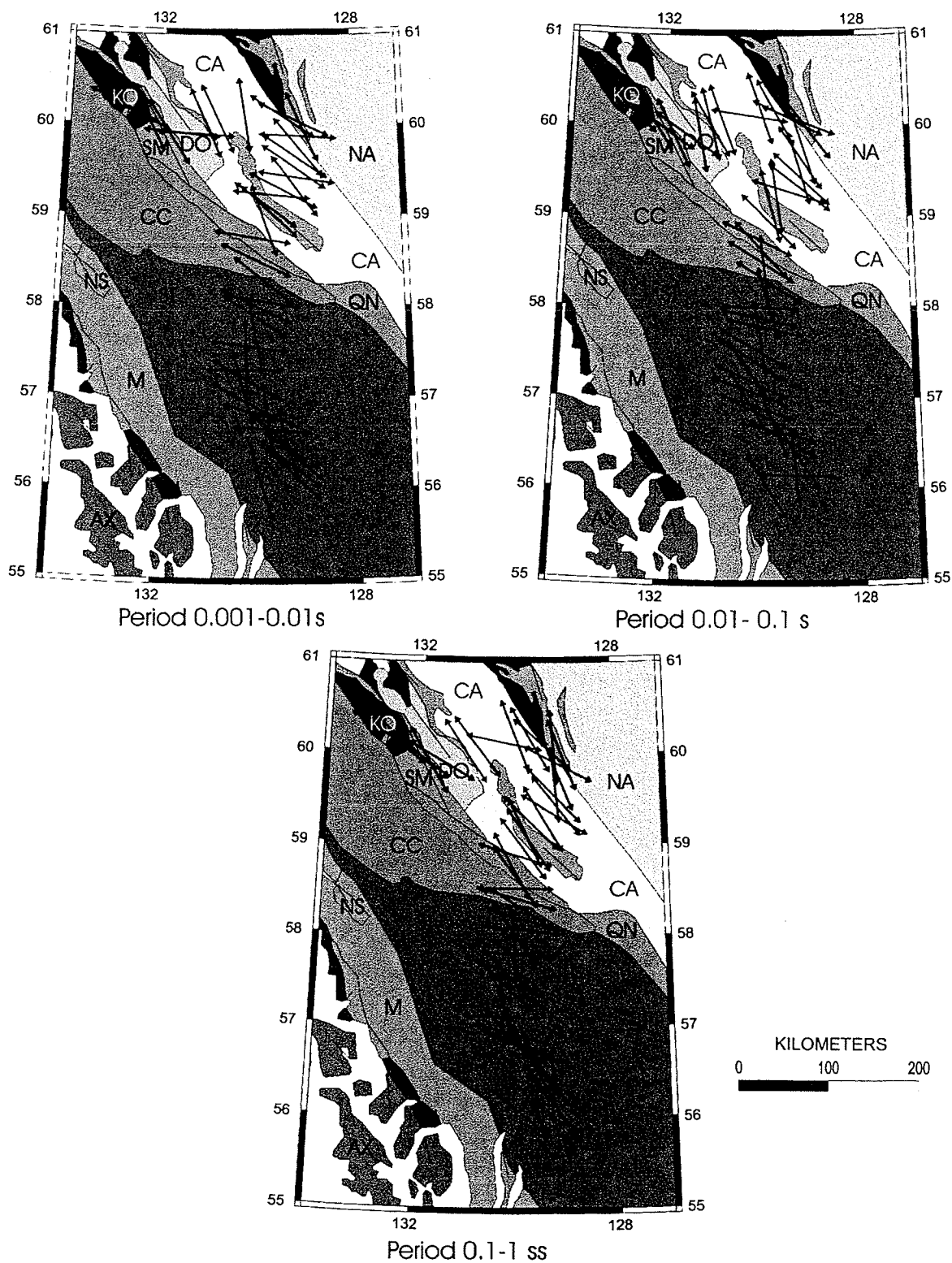


Figure 5.7 Regional strike directions determined from one-decade band GB tensor decompositions. See Figure 1.3 for terrane abbreviations.

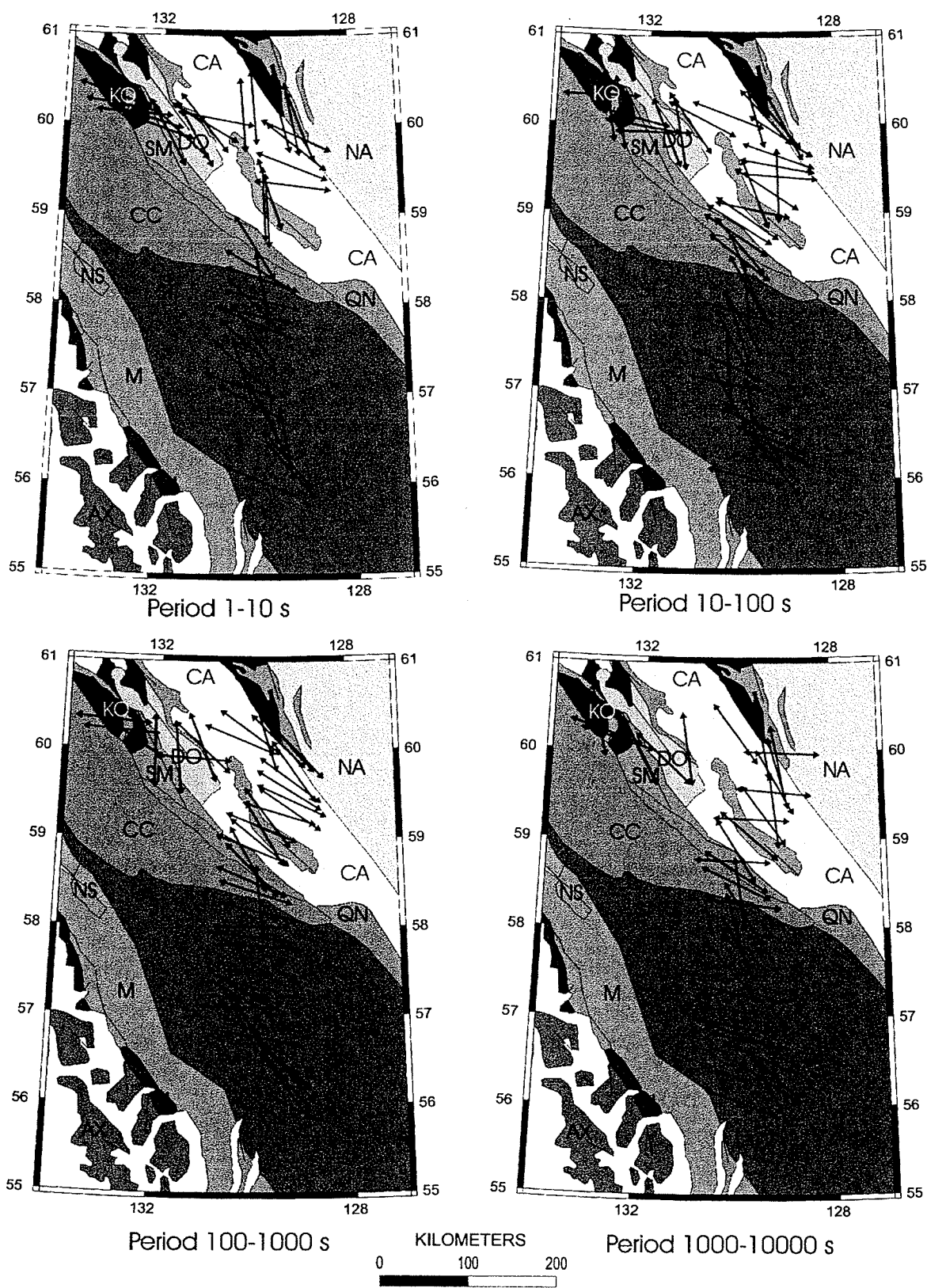


Figure 5.7 cont.

10²-10³ s Period

The strike directions at 100-1000 s are similar to the strike direction for the shorter bands, except that the variation from site to site is more gradual. The strike directions are consistent between adjacent sites. The western portion of the Connector Line has strike directions that are either nearly east-west (-75°) or nearly north-south (-10°). Considering the 90° ambiguity of the GB method these strikes may all be in the same direction. Sites deployed on the Cassiar Terrane, Slide Mountain Terrane, Quesnellia Terrane, Cache Creek Terrane, and the northern half of the Stikine Terrane have relatively similar strike directions of approximately -50° to -70°. Sites in the northern Stikine Terrane and Cache Creek Terrane have a more east-west strike direction than other sites on the profile.

10³-10⁴ s Period

At 1000-10 000 s period, most sites have strike angles that range from -40° to -55°. The change in strike direction from site to site is relatively gradual as for the 100-1000 s band. However, the sites northern half of Stikinia have a more north-south strike direction than at shorter periods.

5.5.2 BROADER BAND GROOM BAILEY TENSOR DECOMPOSITIONS AND ROSE DIAGRAMS

Additional GB decompositions were done using larger bandwidths in order to reduce the statistical variation present in the one-decade results. The GB results were performed over three overlapping period bands: 0.01-3 s, 1-300 s, and 100-10 000 s (Fig. 5.8).

Rose diagrams are used to examine and classify the resulting strike distribution. Rose diagrams plot the frequency distribution of the strike estimates and were constructed using the program **gbRose** provided by the GSC. They were constructed separately for Line 2a and the Connector Line using error weighted estimates (Fig. 5.9). The program assigns a weighting factor of 1 to the station with the smallest error (E_{min}) and then calculates the rest of the weightings for the stations based on the smallest error. Thus, the weighting (W_{site}) for a station with an error E_{site} will be

$$w_{site} = \frac{E_{min}}{E_{site}} \quad (5.1)$$

In order to allow for the 90° ambiguity in strike determination, the results have been rotated into the northwest quadrant.

0.01-3 s Short Period Band

At periods of 0.01-3 s, corresponding to signal penetration in the upper crust (see section 5.2), the GB strike directions tend to be parallel to terrane boundaries (Fig 5.8). Only some sites in western portion of the Connector Line and the southern portion of Line 2a have GB strike directions oblique to terrane boundaries. The Rose diagrams for Line 2a show the -40° to -50° bin is the most common strike range and the Rose diagrams for Connector Line show the -50° to -60° bin is the most common strike range.

1-300 s Intermediate Period Band

At periods of 1-300 s, corresponding to signal penetration in the crust and upper mantle, the GB strike direction tends to be irregular. Groups of sites have consistent strikes, but the Rose diagram plots indicate no dominant strike direction across the study

area. Sites have strike azimuths that gradually change from -45° in the Quesnellia Terrane to -25° in the northern part of the Stikine Terrane. Sites within 20 km of the Tintina Fault zone have geoelectric strike directions similar to the azimuth of the fault (-45°). The Rose diagram bin with the least misfit corresponds to the azimuth range -40° to -50° . The Rose diagram for the Connector Line suggests that the best resolved strikes have an azimuth of -60° to -70° .

100-10 000 s Long Period Band

At periods of 100-10 000 s, corresponding to signal penetration in the mantle, the Rose diagrams show the dominant strike direction is between -40° and -50° for Line 2a. The Rose diagrams for the Connector Line show that the most common strike direction is between -60° to -70° , but also show that a number of sites have strike between -20° to -30° .

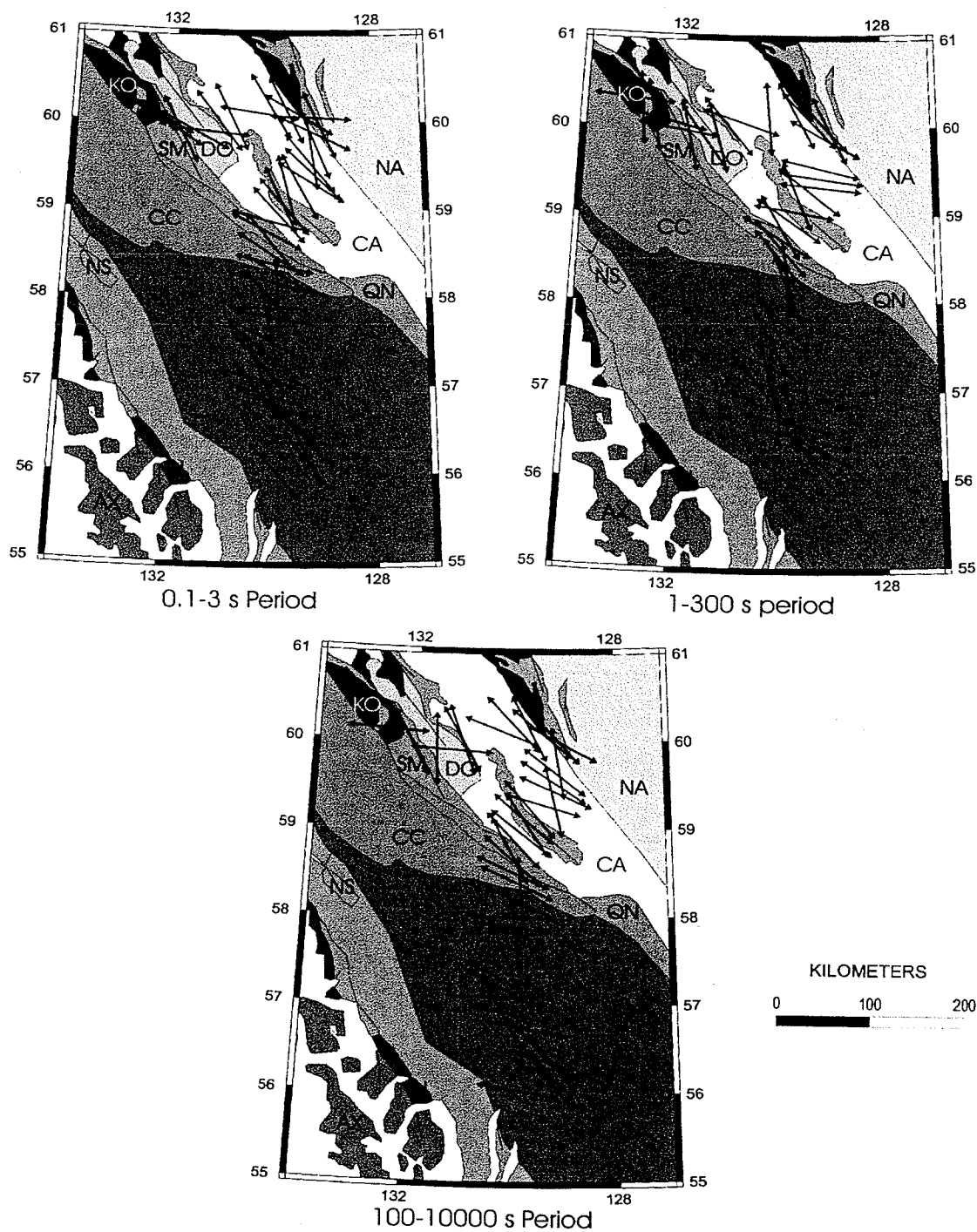


Figure 5.8 Regional strike directions determined for three overlapping bands 0.01-3 s, 1-300, and 100-10 000 s.

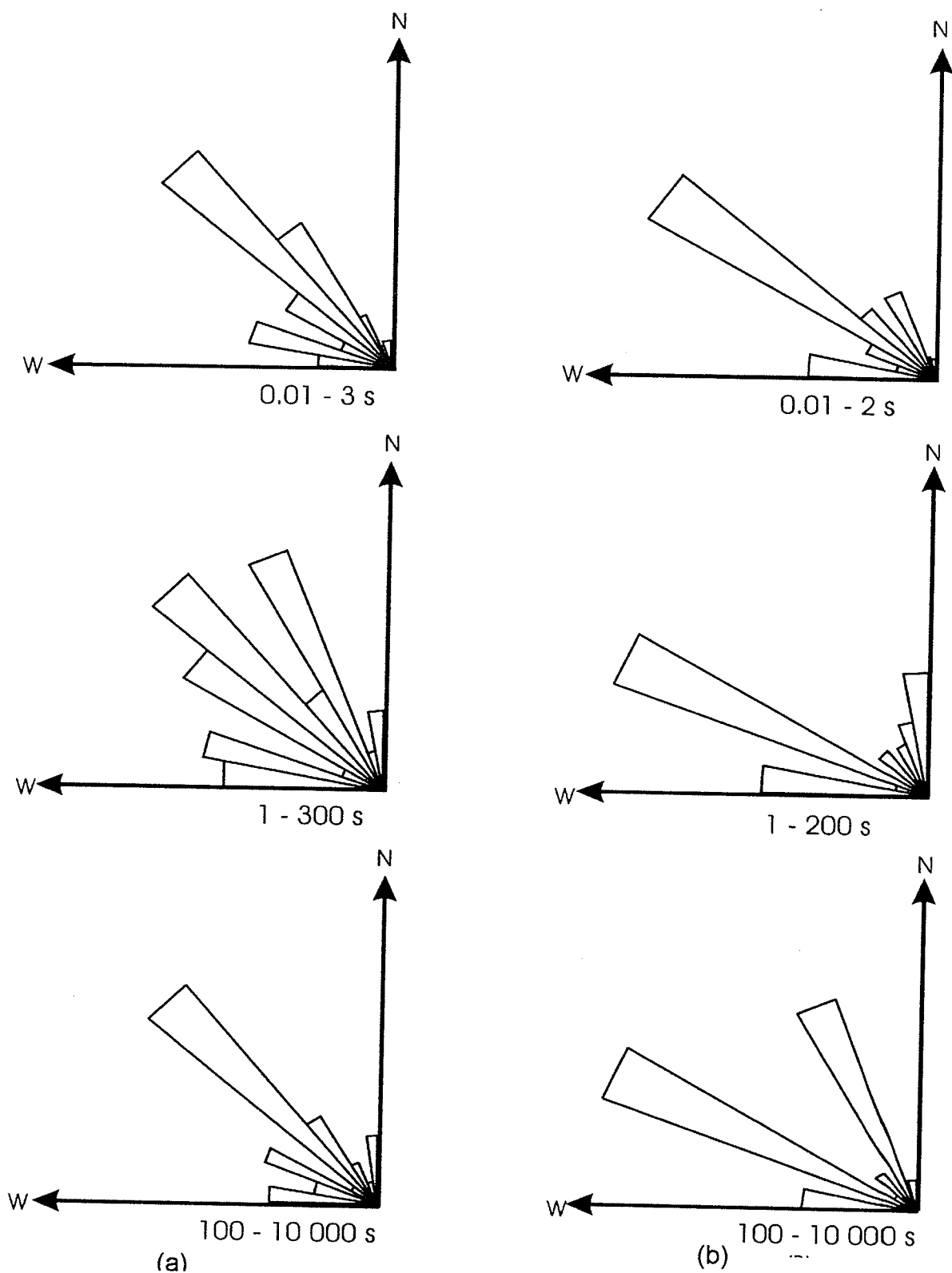


Figure 5.9 Rose diagrams for three bands with data weighted by misfit error for (a) Line 2a and (b) the Connector Line. The angle of each bin is 10° .

5.6 MULTI-SITE TENSOR DECOMPOSITIONS

Further strike analysis was performed using multi-site multi-frequency tensor decompositions (see section 3.6.7). Multi-site tensor decomposition provides an indication of the degree to which a whole data set fits a regional 2D model with 3D galvanic distortions (McNeice and Jones, 2001). The strike analysis for the multi-site decompositions was done separately for Line 2a and the Connector Line. The maximum bandwidth and the number of sites used in each computation, were restricted by the readily available computer power. The error value determined for each site and for each band is an average error that is determined in a statistical manner, as discussed in section 3.6.7. For some sites the minimization involved in the GB decomposition did not converge.

A first set of multi-site decompositions was performed using all sites and small bandwidths. In these decompositions the strike value was allowed to vary. A second set of decompositions was then run with the strike constrained. The error response was compared to the unconstrained strike error in order to examine the compatibility of the whole data set with this strike. Additional multi-site decompositions were then performed using broader period ranges and the maximum number of sites allowed by the computer program.

5.6.1 LINE 2A

Narrow-band Decompositions-Strike Unconstrained

The strike and error results for the narrow-band multi-site tensor decompositions are shown in Table 5.2. Strike values ranged from -37° to 58° for all bands. The error

values were highest for the 5 s to 300 s band. At the longest periods (100 s to 3 000 s, and 100 s to 10 000 s) the error values were typically lower and less than 30.

Narrow-band Decompositions-Strike Constrained to -45°

The previous GB strike analyses have indicated that a geoelectrical strike of approximately -45° is reasonable for most sites. The next step in the strike analysis is to examine whether a constrained strike of -45° is appropriate for all sites. The multi-site analysis was repeated with the strike constrained to this value. The error values obtained with a constrained strike of -45° are tabulated in Table 5.3. This analysis was not performed for the 10-100 s band because the strike value for this band was already -45°.

Figure 5.10 compares the errors for the analyses with unconstrained and constrained strikes. Except for isolated sites there is no significant increase in error values when a constrained strike of -45° is adopted. For the 0.01-0.1 s band, only sites 209, 210, 218, and 239 had a significant increase in error. Otherwise most sites had similar error, and in some cases a smaller error than when the strike was unconstrained (e.g. 229, 230, and 231). For the 0.1-1 s band, sites 219, 229, 230, 231, and 233 had larger error values with the constrained strike, while site 223 had a smaller error. For the 1-10 s band, the error values for sites 204, 207, 226, 234 and 236 increased considerably with a strike of -45°, but sites 208, 216, and 226 had smaller error values. Lastly, for the 100-1000 s band, no sites had a significant increase in error with a strike of -45°, but some sites had a considerable error improvement (e.g. site 208).

Table 5.2 Strike and error results of the narrow-bandwidth multi-site tensor decompositions for Line 2a.

Site	Period Band (s)				
	0.01-0.1	0.1-1	1-10	10-100	100-1000
Strike	-58°	-37°	-58°	-45°	-49°
Error					
200	132	76	6	19	1
202	6	20	34	127	93
203	12	16	66	131	15
204	3		72	9	16
205	10	8	646	109	50
206	1	1	1	1	1
207	23	33	92	25	32
208	311	67	167	164	724
209	31	48		107	24
210	68	25	2	53	93
211	10	7	9	130	200
212	7	22	6	167	10
213	13	22	102		111
214	2	21	17	205	367
215	8	8			116
216	8	61	110	209	39
217	81	30	13	25	1
218	140	48	21	14	3
219	6	105		23	76
220	8	19	14	58	7
221	212	135	16	100	26
222		36	17	7	1
223	22	127	17		3
224	12	89	6	20	2
225	19	15	297	31	29
226	23	33	84	106	1
227	216	13	6	10	3
228	209	34	3	1	1
229	148	59	10	12	1
230	377	84	23	4	2
231	267	105	1	1	24
233	69	14	70	24	38
234	2	16	243	36	27
235	39	19	191	93	30
236	38	13	314	36	59
237	11	205		33	14
238	73	55	14	14	1
239	32	25	16	32	29
240	56	247	51	3	1

Table 5.3 Strike and error results of the narrow-bandwidth multi-site tensor decompositions for Line 2a with a constrained strike of -45° .

Strike Site	Period Band (s)			
	0.01-0.1 -45°	0.1-1 -45°	1-10 -45°	100-1000 -45°
200	103	70	27	13
202	5	26	9	63
203	13	32	64	16
204	3	27	177	5
205	15	6	706	41
206	1	2	1	82
207	29	66	152	38
208	301	42	68	281
209	173	42	90	27
210	171	20	5	93
211	8	7	16	184
212	9	18	13	7
213	12	43	88	129
214	4	30	16	383
215	14	5	22	114
216	38	32	50	36
217	98	36	8	1
218	308	53	19	2
219	18	182	190	86
220	8	22	10	8
221	159	119	19	33
222		25	12	1
223	20	63	55	4
224	11	64	1	3
225	37	23	256	5
226	6	45	21	15
227	165	22	82	21
228	301	34	1	1
229	29	112	18	3
230	23	271	36	1
231	120	60	2	1
233	83	94	17	2
234	24	6	594	20
235	11	9	292	38
236	31	6	627	26
237	12	252	295	26
238	52	137	99	39
239	121	20	53	7
240	21	433	68	1

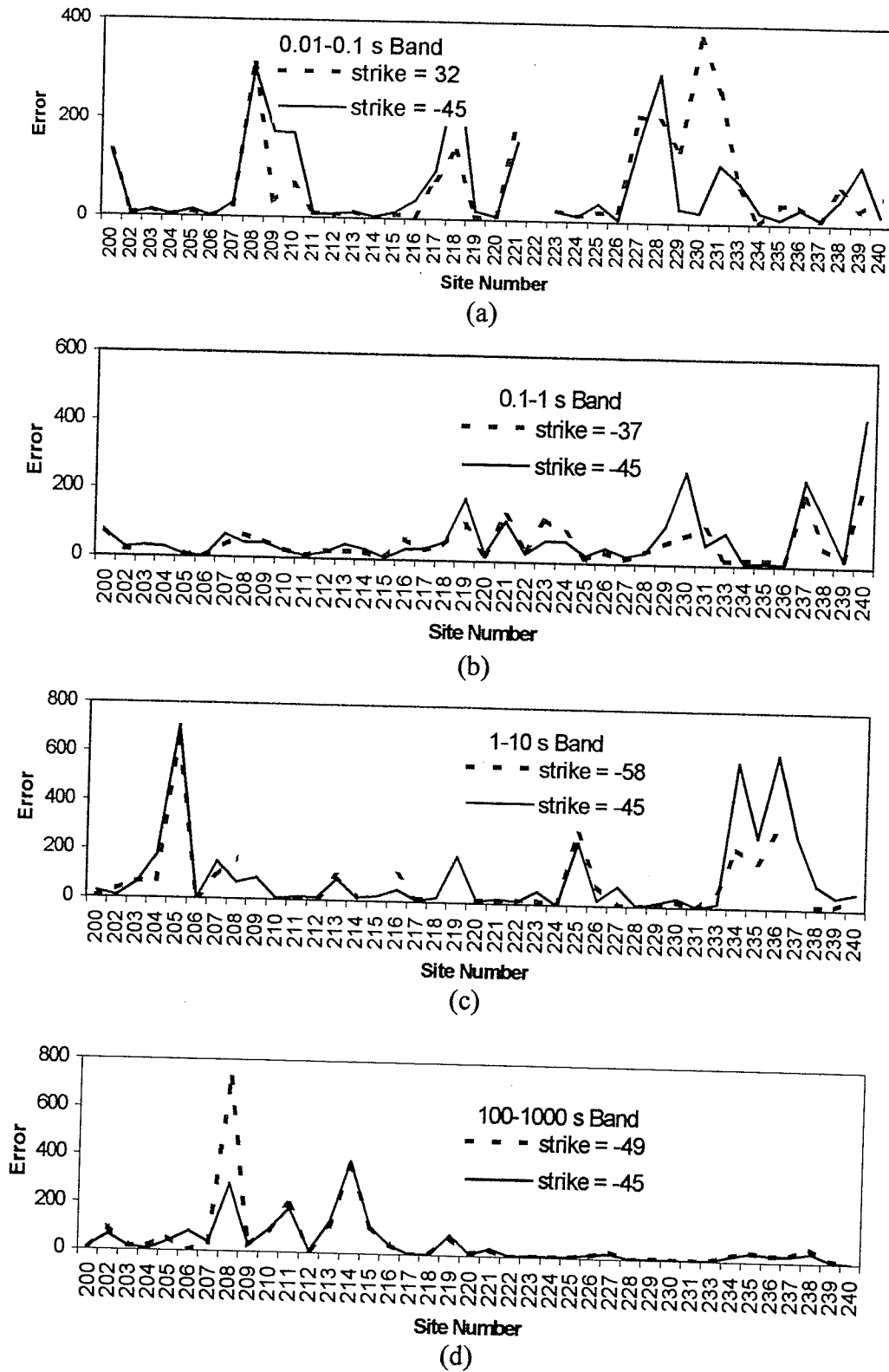


Figure 5.10 Graphs comparing errors for the non-constrained multi-site decompositions with those for multi-site decompositions with a constrained strike of -45° for period bands of (a) 0.01-0.1 s, (b) 0.1-1 s, (c) 1-10 s, and (d) 100-1000 s.

Broad-Band Decomposition-Strike Unconstrained

Longer period bands (with some overlap) were also used to examine frequency dependence of the strike with greater statistical accuracy than in the previous analysis. In order to allow for the large data set it was necessary to divide the profile into a north segment, which consisted of sites 210 to 240, and a south segment, which consisted of sites 200 to 230. The results of the analyses are tabulated in Table 5.4. The strike value determined for bands 0.01 to 3 s (north segment), 1 to 300 s (south segment), 100 to 1000 s (north and south segments), was within 6° of -45° . The 1 to 300 s for the northern sites and the 0.01-3 s results for the southern sites both deviated significantly from -45° .

Broad-band Decomposition- Strike Constrained to -45°

The multi-site decompositions for the middle band were then completed using a constrained strike of -45° , since for this period band the multi-site multi-frequency decompositions determined a strike value that deviated the most significantly from -45° (Table 5.5). Figure 5.11 compares the error values for the sites with unconstrained and constrained strike. From examination of the error values it is apparent that for the southern segment of Line 2a the error is very similar for strike angles -40° and -45° . However, for the northern portion of Line 2a several sites (e.g. 233, 235 and 238) show a significant increase in error associated with the change from -64° to -45° strike. Other sites show a significant decrease (e.g. 234, 236, and 239). The narrow-band and broad-band multi-site decompositions provide strong overall support for a strike of -45° for Line 2a.

Table 5.4 Strike and error results of the broader band multi-site multi-frequency tensor decompositions for Line 2a.

Site	Period Bands (s)					
	Southern Sites			Northern Sites		
	0.01-3	1-300	100-10 000	0.01-3	1-300	100-10 000
Strike	-58°	-50°	-45°	-41°	-65°	-51°
200	24	80	9			
202	33	260	14			
203	95	112	16			
204	50	80	1			
205	269	808	21			
206	2	1	8			
207	36	77	71			
208	231	722	103			
209	34	74	45			
210	21	159	50	84	169	32
211	17	300	48	10	636	35
212	9	238	50	19	90	49
213	208	655	26	118	451	17
214	701	798	93	464	752	83
215	26	547	12	25	641	9
216	37	433	38	19	751	40
217	119	52	2	68	39	2
218	135	39	12	208	30	13
219	283	60	151	361	33	143
220	17	92	62	21	106	64
221	245	150	130	241	113	113
222	40	19	2	82	22	2
223	14	304	11	192	663	10
224	47	16	62	134	21	6
225	311	48	1	157	9	1
226	307	105	52	123	287	73
227	85	42	1	93	170	1
228	207	2	2	115	1	2
229	371	14	3	250	30	3
230	321	4	4	79	5	4
231				328	1	4
233				163	9	2
234				27	102	27
235				164	108	53
236				119	181	3
237				415	110	23
238				150	60	26
239				75	110	15
240				464	23	7

Table 5.5 Strike and error results for the broad-band multi-site tensor decompositions for Line 2a with a constrained strike of -45° .

Site	Period Band (s)	
	Southern Sites	Northern Sites
	1-300	1-300
Strike	-45°	-45°
87200	15	
202	349	
203	140	
204	61	
205	692	
206	1	
207	58	
208	880	
209	91	
210	150	150
211	339	339
212	225	225
213	604	604
214	781	781
215	536	536
216	546	546
217	50	50
218	39	39
219	58	58
220	102	102
221	152	152
222	20	20
223	400	400
224	18	18
225	36	36
226	111	111
227	29	29
228	2	2
229	16	16
230	5	5
231		1
233		118
234		48
235		245
236		120
237		92
238		98
239		8

5.6.2 CONNECTOR LINE

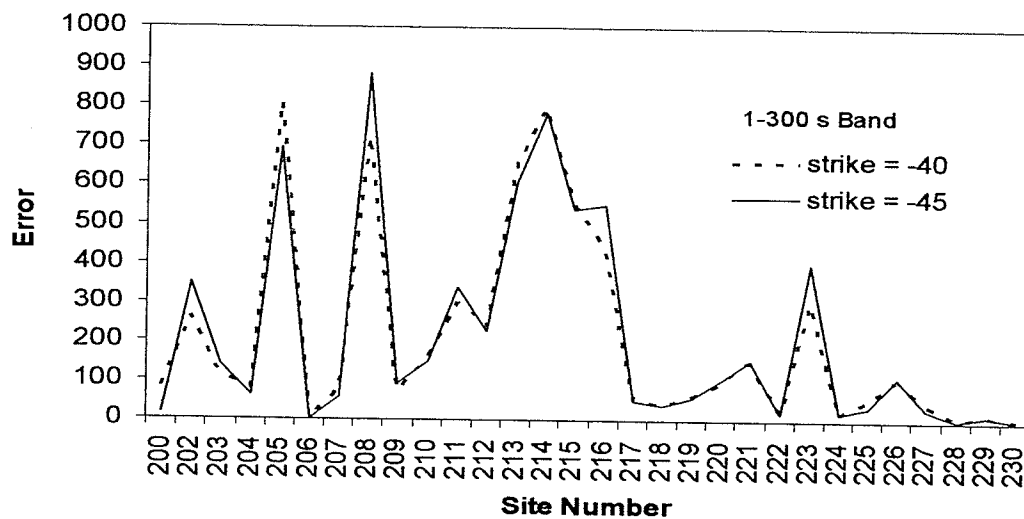
The procedures for the strike analysis for the Connector Line were similar to those for Line 2a. Multi-site decompositions were performed for all sites using both narrow and broad-bandwidths. The Connector Line had fewer sites than Line 2a so in some cases larger bandwidths could be used.

Narrow-band Decomposition-Unconstrained Strike

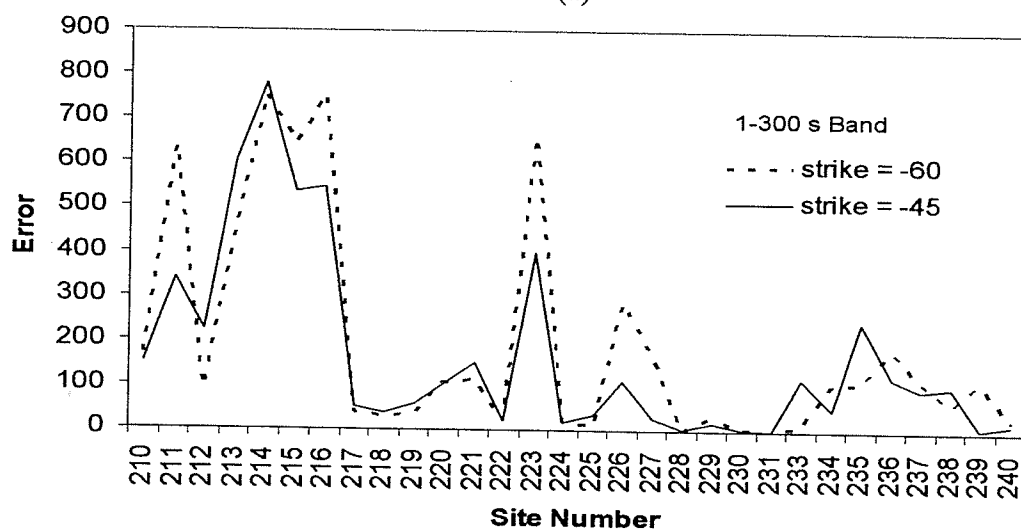
As with Line 2a, initial multi-site decompositions were completed using one-decade wide bands. The results of the decompositions are shown in Table 5.6. Only the 1-10 period band gave a strike value that deviated by over 10° from -45° . For the remaining bands the averaged strike value of the strikes is -44.5° .

Broad-band Decompositions-Unconstrained Strike

The three overlapping broad bands (0.01-2 s, 1-200 s, and 100-10 000 s), which were used in the Line 2a GB and Rose diagram analysis, were used for the next Connector Line decomposition analysis. The error and strike results are presented in Table 5.7. For the 0.01-2 s band the decomposition determined a strike value of -48° , which is very similar to -45° , but the 1-200 s and 100-10 000 s bands had strike values of -70° and -62° respectively. The -70° strike value is consistent with the -68° strike value determined from the multi site decomposition for the 1-10 s band and the preferred strike direction of -60° to -70° from the Rose diagrams.



(a)



(b)

Figure 5.11 Graphs comparing errors for the non constrained multi-site decomposition and multi-site decomposition with a constrained strike of -45° for period band 1-300 s for (a) south segment and (b) north segment.

Table 5.6 Strike and error results of the narrow-band multi-site multi-frequency tensor decompositions for the Connector line.

Site Strike	Period Band (s)				
	.01-.1	.1-1	1-10	10-100	100-1000
	-41°	-55°	-68°	-37°	-45°
272	3	61	16	44	11
273	3	14	48	111	136
274	993	99		13	2
275	95	753	671	10	6
276	95	288	93	1	1
278	318	320	18	50	5
279	217	23	214	70	88
280	149		79	136	53
281	5	32	183	37	84
282	171	5	33	109	
283	133	32	21	5	1
284	198	83	26	44	3
285	41	6	10	1	1
286	37	61	26	1	1
287	19	37	80		1

Table 5.7 Strike and error results of the broad-band multi-site tensor decompositions for the Connector line.

Site Stike	Period Band (s)		
	.01-2 -48°	1-200 -70°	100-10 000 -62°
272	91	321	12
273	26	446	323
274	2957	365	47
275	781		261
276	374	15	1
278	224	26	3
279		108	
280	77	203	16
281	111	139	5
282	132	98	4
283	300	16	1
284	133	23	2
285	51	5	
286	248	1	
287	74	72	9

Broad-band Decompositions-Constrained Strike to -45°

The next step in the strike analysis was to constrain the strike to particular values and compare the errors with the unconstrained results. Strike angles of -30°, -45°, and -60° were used in this analysis. The consideration of multiple angles was unnecessary for the Line 2a data, since all methods supported a strike of approximately -45°. The error values for the constrained-strike decompositions are tabulated in Table 5.8.

Table 5.8 Strike and error results of the broad-band multi-site tensor decompositions for the Connector line with a constrained strike.

Site	Period Band (s)					
	.01-2	.01-2	.01-2	1-200	1-200	1-200
Strike	-30°	-45°	-60°	-30°	-45°	-60°
272	109	96	66	111	71	217
273	15	23	40	165	107	284
274	1846	2734	4167	39	48	142
275	646	723	1133			
276	532	391	269	15	13	13
278	186	218	252	192	69	22
279				78	115	126
280	78	77	80	247	369	296
281	350	131	70	46	168	394
282	52	123	151	174	187	144
283	998	424	86	10	8	3
284	213	146	94	115	69	37
285	65	59	22	2	3	2
286	509	319	101	1	1	1
287	473	105	155	26	11	7

Site	Period Band (s)		
	100-10 000		
Strike	-30°	-45°	-60°
272	23	16	12
273	1640	646	305
274	23	19	40
275	284	270	262
276	1	1	1
278	9	4	3
279	2190	1714	527
280	15	16	16
281	37	56	5
282	18	10	4
283	2	2	1
284	2	2	2
285	1480	1480	1480
286			
287	9	9	9

For the short period band (0.01-2 s) the lowest error values occur for the southeast sites 272-279. Most sites have the smallest error for a strike of either -60° or -30° . This variation in strike direction for the shorter periods is reflected by the range of strikes noted in the Rose diagrams (Fig. 5.9). In general, if a site has a lowest error at -30° , then the error value would increase at -45° , and increase more significantly at -60° . Likewise, if the error values were lowest for -60° they increase at -45° and more significantly at -30° . A strike azimuth of $\sim -45^\circ$ provides the best overall strike for periods of 0.01-2 s on the Connector Line because it lies between -60° and -30° and fits all sites relatively well.

For the middle period band the smallest error for the southeast sites (272-289) occurs for a strike of -30° or -45° . For the northwest sites (283-287) the smallest error occurs for a strike of -60° . These results suggest that -45° is a reasonable overall strike for the 1-200 s period band, which is in contrast to Rose diagram results which suggest a strike direction of -60° to -70° .

For the longer period band (100-10 000 s) the lowest errors for most sites occur at -60° strike. This result correlates well with Rose diagrams for the same period band.

5.7 INDUCTION VECTORS

Induction vector plots were generated for periods of 0.05 s, 0.5 s, 5 s, 50 s, 500 s, and 1300 s (Fig. 5.12). The periods were chosen to be approximately in the middle of the one-decade bands used in the tensor decomposition analysis and to provide satisfactory representation of the induction vector response with period. For each specified period, three spectral estimates were averaged to generate the plots. The induction vectors were examined and unresolved vectors are from Figure 5.12. The real and imaginary

component of the induction vector for each site and the corresponding error estimates are shown in Appendix C.

0.05 s and 0.5 s Period

At most sites the real induction vectors at short periods (less than 0.5 s) are not well resolved (see Appendix C). The resolved induction vectors have variable directions, but some consistent trends can be observed. The vectors at sites near the Tintina Fault zone are pointing towards the surface location of the fault. A reversal of induction vectors occurs on the Line 2a profile in the Quesnellia Terrane; the vectors point towards the boundary of the Cache Creek and Quesnellia terranes.

5 s Period

At 5 s period, the real and imaginary induction vectors are better resolved than at shorter periods. The length of the induction vectors is similar to 0.05 s, but the directions are less variable from site to site. As at shorter periods, induction vector reversals are evident near the Tintina Fault zone and near the boundary between the Cache Creek and Quesnellia terranes. The vectors near the Tintina Fault zone have lengths of typically less than 0.25 units and the vectors near the boundary between the Cache Creek and Quesnellia terranes are less than 0.5 units. The induction vectors at sites in the western portion of the Connector Line and the southern portion of Line 2a point dominantly to the southwest.

50 s Period

The lengths of the real induction vector at 50 s period are typically less than 0.4 units. As at shorter periods, there is an induction vector reversal near the Tintina Fault zone and near the Cache Creek and Quesnellia terranes. The induction vector lengths near

the Tintina Fault are approximately 0.2 to 0.4 units and the lengths in the Cache Creek and Quesnellia terranes are typically 0.2 units. For most sites in the southern portion of Line 2a the induction vectors have a length of 0.1 to 0.2 units and point in a southwest direction towards the coast.

The imaginary induction vectors at 50 s period have a length of less than 0.05 units. At sites where both the real and imaginary components have significant length the two components tend to be parallel or antiparallel indicating 2D structure.

500 s Period

At 500 s period, the real induction vectors directions are relatively uniform. South of the Cache Creek terranes the magnitude of the vectors is less than 0.2 and their direction is to the southwest. North of the Cache Creek terrane the vectors tend to be longer and to point towards the Tintina Fault Zone. The imaginary components are generally much smaller than the real components (Appendix C) and at a number of sites on Line 2a the imaginary component is oriented at an oblique angle to the real component.

1300 s Period

At 1300 s period, the real induction vector directions and lengths are similar to the induction vectors at 500 s. The imaginary vectors are mostly orientated in an oblique direction to the real induction vectors (Appendix C). Sites in the Line 2a profile in the Cassiar Terrane have the longest vector length (>0.3 units), and point towards the Tintina Fault zone.

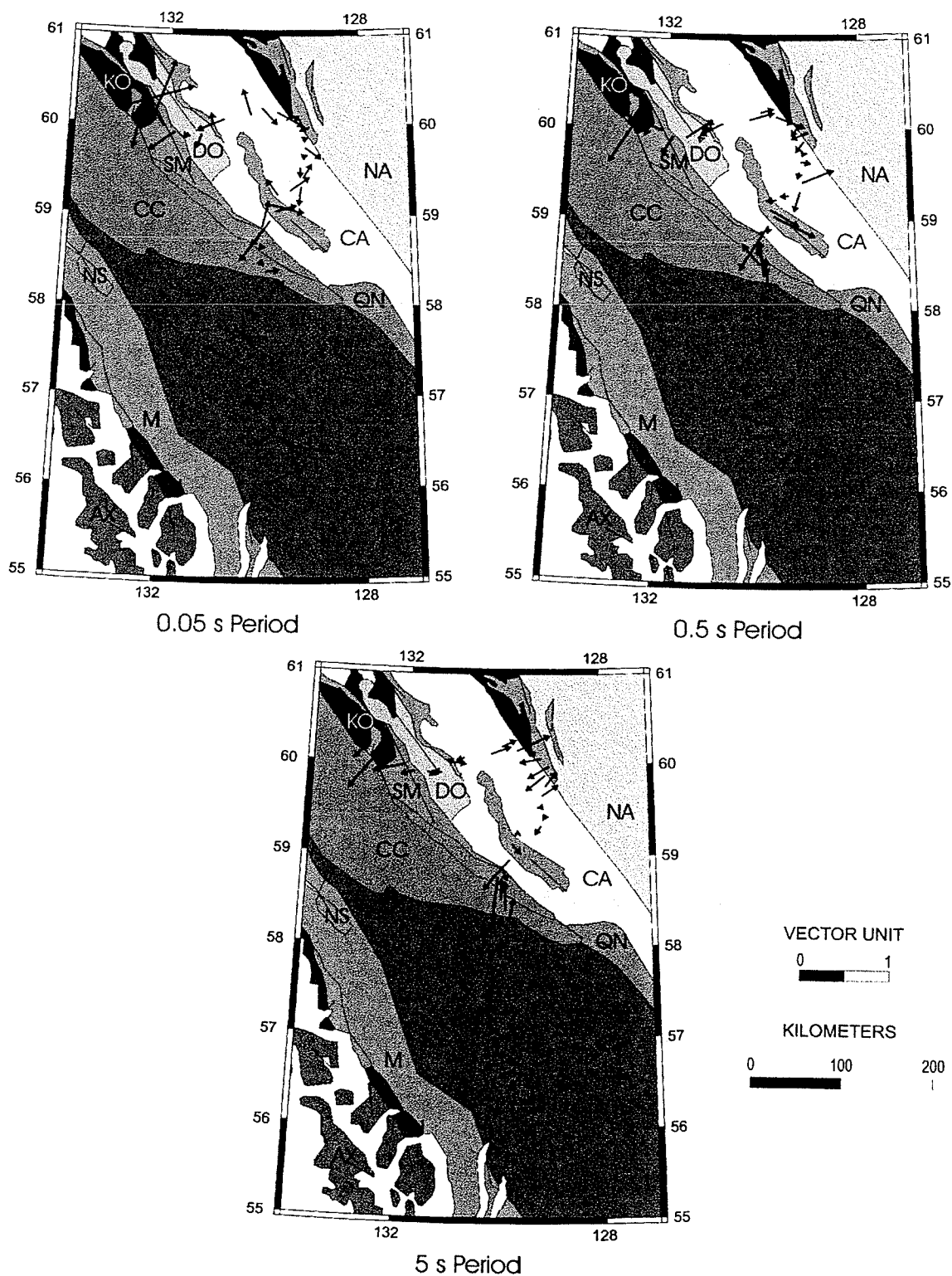


Figure 5.12 Induction vector plots for the periods 0.05 s, 0.5 s, 5 s, 50 s, 500 s, and 1300 s. Note that the vectors are plotted using the Parkinson convention in which the real component of the arrow is reversed so as to pivot towards areas of enhanced conductivity. Error estimates are shown in Appendix C.

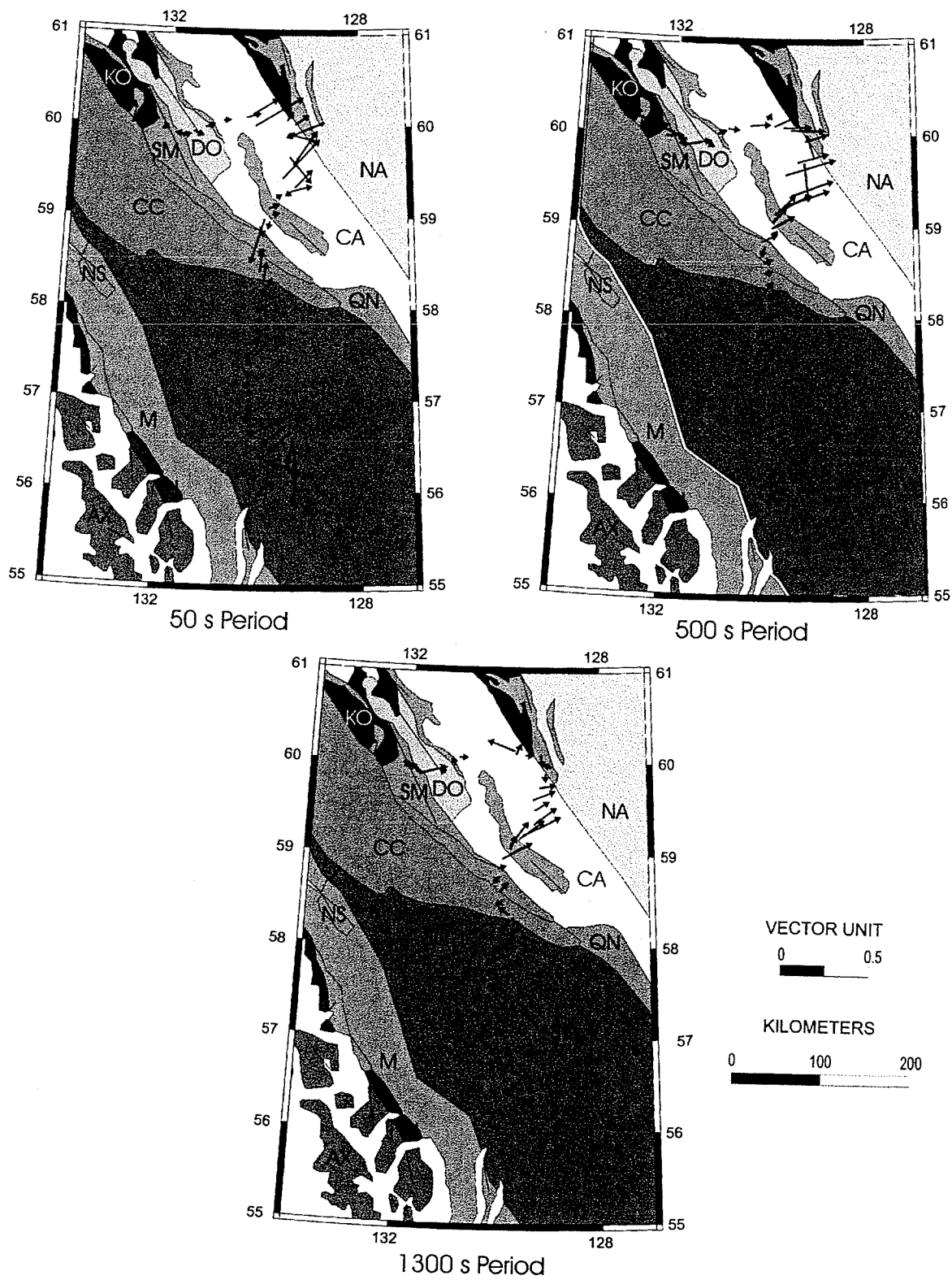


Figure 5.12 cont

5.8 FINAL GEOELECTRIC STRIKE

In order to permit examination of the data using pseudosections and 2D modeling and inversions, it is necessary to adopt a uniform geoelectric strike for the study area. The tensor decomposition and induction vector analysis have indicated that the data is sufficiently 2D for this approach to be reasonable.

5.8.1 OVERALL GEOELECTRIC STRIKE

Previous strike analyses indicate that a geoelectric strike of -45° is the appropriate azimuth for Line 2a and the Connector Line data. This result is based on single-site decompositions (Rose diagrams), multi-site decompositions, and induction vector results.

This result compares well with other northern Cordillera studies. Ledo et al. (2001) determined a strike of -50° for Line 3 and a strike of -45° for a smaller profile south of Line 3 (Fig. 1.2). Wolynech (2000) determined a strike of -37° for 16 sites in the western end of Line 3.

The northern Cordillera results contrast with southern Cordillera results. As discussed in 2.7.3, Marquis et al. (1995) determined that the strike varied as a function of frequency in the Omineca and Intermontane belts. They concluded that the geoelectric strike varies from $N25^\circ W$ for the first 5-10 km of the crust, to $N20^\circ E$ for the middle/lower crust, to $N60^\circ E$ for the upper mantle. Ledo and Jones (2001) suggest that for periods less than 1 s there is no preferred geoelectric strike across the whole southern Cordillera on a scale smaller than site spacing. At periods greater than 1 s the strike was grouped spatially into sites with a strike of -30° and 15° .

5.8.2 LOCAL GEOELECTRIC STRUCTURE

Short Periods (< 3 s)

From the geoelectric strike analysis it is apparent that the short period MT response (<3 s) is influenced by the upper crustal geology of the terranes. The Rose diagrams of single site GB strike decompositions and misfits observed in multi-site multi-frequency strike decompositions, suggest some local variations from a 2D structure with a strike of -45° .

The multi-site decompositions show several clusters of sites with increased error (>50). Sites 207-211 and 216-223 in the Stikine Terrane have increased misfits, while single site results show some variation in strike results. Skew values for sites 208, 209, and 222 are high at periods < 1 s (Fig. 5.2), suggesting the influence of local 2D and 3D structures.

Large misfits are observed at sites 227-233 crossing the Quesnellia, Cassiar, and Slide Mountain terranes, and sites 274-280 crossing the Cassiar, Slide Mountain, Dorsey, and Slide Mountain terranes. High skew values are also observed for sites 274-278 (Fig. 5.2), suggesting the influence of 3D structure on the response.

Ledo et al. (2001) found similar results for the short period response in the southern Cordillera. They attribute the absence of a preferred strike in this period range to 3D crustal heterogeneity. As shown by the Rose diagram and multi-site multi-frequency decomposition results the MT response in the northern Cordillera does show an overall preferred strike of -45° , but there is some local variation.

Intermediate Periods (1-100 s)

The geoelectric strike for the intermediate response (1 s to 300 s) is difficult to define. Rose diagrams indicate considerable variability in strike, but the multi-site multi-frequency decompositions define -45° as the preferred strike. As with the shorter period response, clusters of sites including 200-217 (Stikine Terrane), 223-226 (near the Stikine Terrane and Cache Creek Terrane boundary), 233-239 (Cassiar Terrane), 275-282 (Dorsey, Slide Mountain, and Cache Creek terranes) have increased misfit (>50). For the southern sites in the Stikine Terrane the high misfit is accompanied with high skew values (Fig. 5.2), while the single site decompositions show many sites with a strike angle of approximately -45° . Similarly, for sites 223-226 the high misfits correspond to high skew values (Fig 5.2)

The induction vectors have reversals near the Tintina Fault zone, and near the Cache Creek and Quesnellia terranes. Only the southern portion of Line 2a has consistent induction vector directions that point to the southwest. These sites are located within 200 km of the coast. This consistent response is likely the large-scale coast effect associated with enhanced current flow in the conductive ocean water.

These strike results for the northern Cordillera suggest some heterogeneity in the mid to lower crust. Although there is some scatter in the intermediate period results there is no clear division of results into areas with different strike angles as noted by Ledo et al. (2001).

Long Period (>100 s)

For the upper mantle and mantle response, the Rose diagrams and multi-site multi-frequency decompositions indicate tighter clustering of strikes. Sites in the south end of Line 2a (206-220) show the largest misfit in the multi-site multi-frequency decompositions. These sites are associated with large skew values (Fig. 5.2) suggesting a 3D effect. The best fitting strike for the Connector Line is -60° , which differs for results in the southern part of Line 2a (-45° , Table 5.4). The induction vectors point more consistently southwest on Line 2a consistent with the interpretation of the coast effect trend. The relatively high skew values (Fig. 5.2), high shear values (Appendix B), and the oblique real and imaginary induction components (Appendix C) observed at long periods (> 100 s) suggest the influence of 3D structures on the response.

5.9 SELECTION OF MT DATA FOR EXAMINATION AND INVERSIONS

5.9.1 STRIKE DIRECTION

The TE and TM modes responses for Line2a and the Connector Line determined from the initial data set using the strike of -45° . The TE mode corresponds to the electric currents parallel to -45° , and the TM mode corresponds to the electric currents perpendicular to -45° . The period range for examining the TE and TM modes response is between 0.001 to 10 000 s. Appendix D shows all the edited Connector Line and Line 2a sites rotated to -45° azimuth.

5.9.2 ASSESMENT OF GB MODEL

The GB decomposition method was used for determining geoelectric strike. However, it does not necessarily follow that GB data (data corrected for galvanic distortion using the GB method) should be used in the 2D modeling and inversion. Several factors suggest that the GB model of galvanic distortion is not fully applicable for this data set. The factors include: (1) the errors for the individual sites increase significantly when the twist, shear, or azimuth are constrained (Fig 5.13), (2) the GB method is designed to correct for local near-surface distortions and not for cases in which distortions are present throughout the crust, which is likely occurring in the SNORCLE region, which has undergone intense deformation and tectonism, and (3) the χ^2 results are relatively high for most sites indicating that the GB model provides an inadequate fit to the observed data (Fig. 5.14).

The shear results shown in Figures 5.5 and 5.6 support the above interpretation. For the classical GB model a near-surface structure produces a frequency-independent shear. However, for the Connector Line and Line 2a, the shear values increase with period, indicating that the amount of galvanic distortion increases with period. This effect may be attributed to the distribution of 3D heterogeneities throughout the crust. The frequency-dependent distortion will contribute to the high χ^2 values in Figure 5.14.

Booker (2002) examines the problems of the GB decomposition. These include:

- 1) The GB model rarely fits data at a statistically acceptable level over a wide bandwidth.
- 2) The GB method multiplies all impedance error estimates by a constant, which is not a physically reasonable.

- 3) The GB misfit to the impedance is systematic in that one pair of the off diagonal elements of the impedance may fit the GB model over a wide bandwidth with constant parameters while the other off diagonal elements are poorly fit.

Considering the points noted above, the subsequent examination and analysis of the MT response in this study will be based on the edited observed data. The data are therefore not corrected for shear and twist. Note that as long as the regional strike is determined correctly, galvanic distortion will affect only the apparent resistivity response and not the phase response. In the inversions of the MT data, the error floor for the apparent resistivity is increased relative to the phase error in order to allow for both static shift and more complex galvanic distortion.

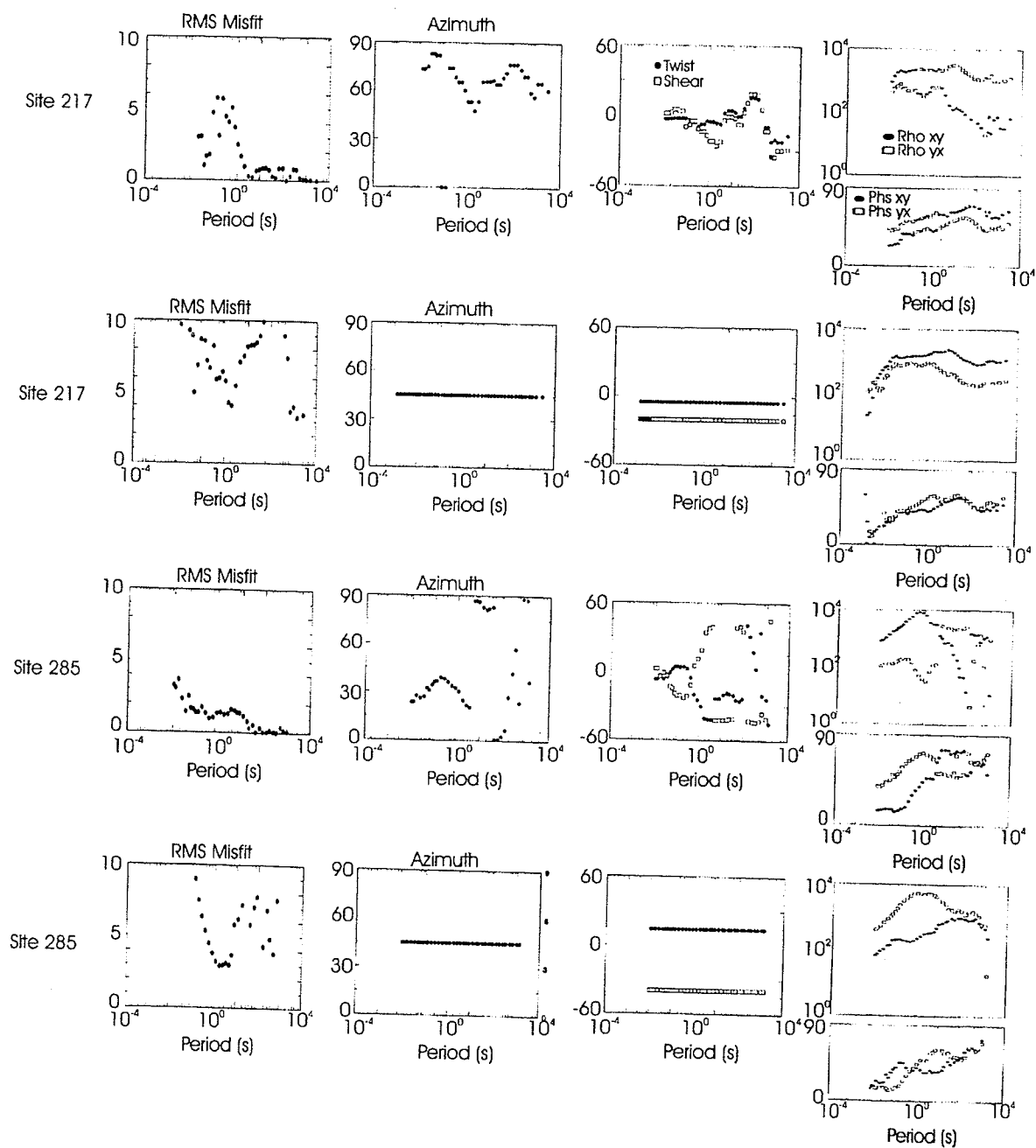


Figure 5.13 Illustration showing the effect of GB decomposition on the error and data for (a) site 217 with strike, twist and shear unconstrained, (b) site 217 with fixed strike, twist and shear, (c) site 285 with strike, twist and shear unconstrained, and (d) site 285 with fixed strike, twist and shear. Note the large increase in RMS misfit that occurs when the GB model is applied.

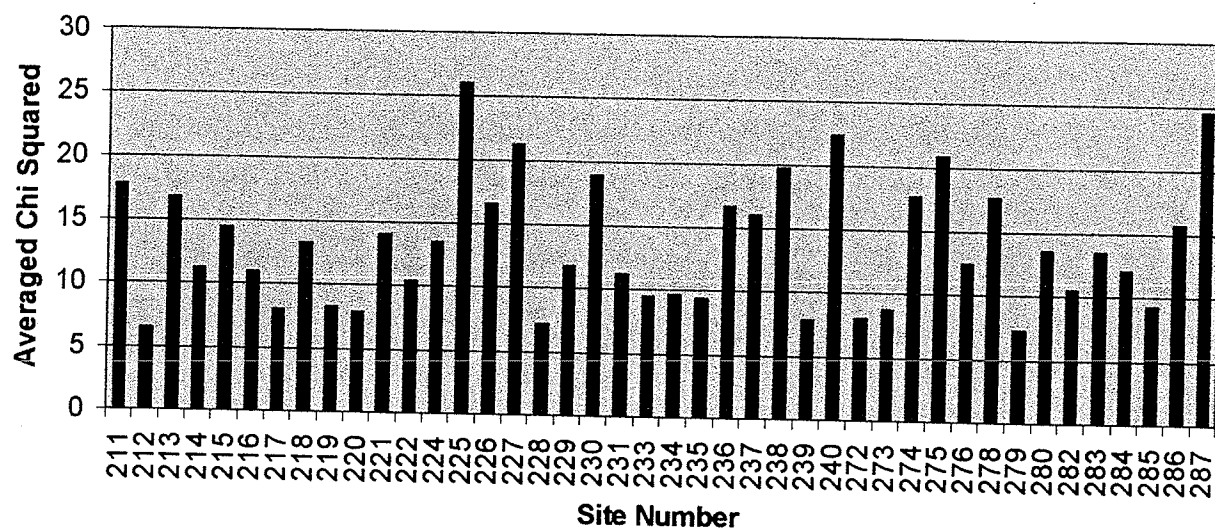


Figure 5.14 Average normalized χ^2 values (for each site) for the 0.01 s to 1000 s band for the Connector Line and Line 2a with a constrained strike of -45° .

CHAPTER 6-MAGNETOTELLURIC RESPONSE

6.1 INTRODUCTION

Pseudosections of the TE and TM apparent resistivity, phase and tipper were constructed in order to examine the large-scale resistivity response of the study region. For both Line 2a and the Connector Line the MT sites are projected onto a line that is perpendicular to the geoelectric strike.

6.2 MT RESPONSE PSEUDOSECTIONS

Prior to construction of the pseudosections, the data for each site were carefully edited and evaluated (Section 4.6.2), so only the high quality data for each site are presented. The tipper pseudosections show the component of the tipper parallel to the profile (perpendicular to strike).

6.2.1 CONNECTOR LINE

Construction of pseudosections (and 2D modelling) requires the projection of the MT sites onto a line perpendicular to the geoelectric strike. Parts of the Connector Line are subparallel to this projection direction, and when the MT sites are projected, some sites that are physically separated by 10 to 15 km, become very close and in some cases switch order (Fig. 6.1). Site 287 switched order with the adjacent site and was therefore excluded from the pseudosections and 2D modelling.

The apparent resistivity, phase, and tipper responses vary laterally and with period across the Connector Line profile (Fig. 6.2, 6.3, and 6.4). In some areas the TE and TM response is quite similar, but in other locations the responses differ indicating the presence of 2D structures.

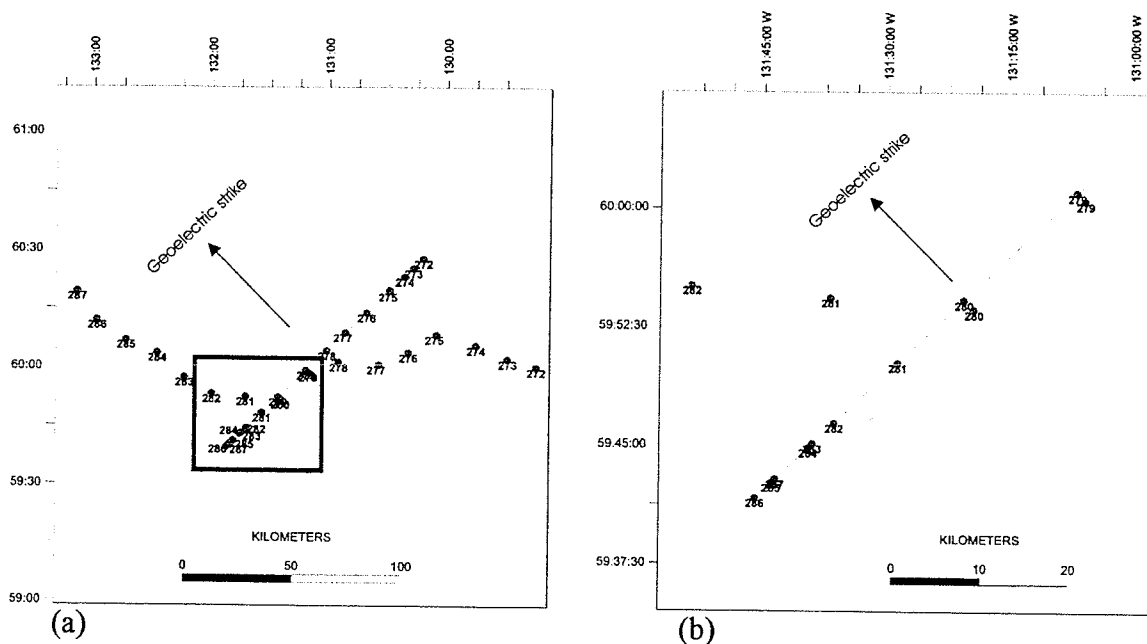


Figure 6.1 Projection of the Connector Line sites. (a) The full data set and (b) Enlargement showing the change in ordering of site 287 with adjacent sites 286 and 285.

Short Periods (<1 s)

At periods less than 1 s, the apparent resistivity for both the TE and TM modes is similar, and varies greatly across the profile (Fig. 6.2). The lowest apparent resistivity values (5 ohm.m) occur at site 279 in the Dorsey Terrane, and the highest apparent resistivity values occur at site 282 (3200 ohm.m) in the Slide Mountain Terrane (3200 ohm.m) (Fig. 6.2).

The phase for periods less than 1 s is similar for both modes, and varies from low phase in the west to high phase beneath the Dorsey and parts of the Cassiar Terranes (Fig. 6.3). There are high phases ($> 50^\circ$) at sites 279 and 276, and low phases ($< 30^\circ$) at sites 282, 283, and 285. Lower phase ($< 30^\circ$) is also at site 277, within the Slide Mountain Terrane.

As discussed in Chapter 3 conductive zones will be associated with low apparent resistivity and phases exceeding 45° and resistive zones will be associated with high

apparent resistivity and phase values of less than 45° . The apparent resistivity and phase pseudosections have some parts that do not correlate. For example, an anti-correlation between the phase and apparent resistivity occurs at site 276 within the Cassiar Terrane, where both the apparent resistivity (>1000 ohm.m) and phase ($> 60^\circ$) are high.

Both the real and imaginary tipper components (T_{yr} and T_{yi}) have similar magnitudes at short periods (Fig. 6.4). The responses are noisy at some sites corresponding to the unresolved induction vectors discussed in Section 5.7 and shown in Appendix C. Where resolved, the tipper has magnitude less than 0.4 and varies irregularly from site to site.

Intermediate Periods (1-100 s)

For periods of 1 to 100 s the apparent resistivity pseudosections for both the TE and TM modes varies spatially across the pseudosection (Fig. 6.5). As observed at shorter periods, the TE and TM mode responses are similar. For both modes, a high apparent resistivity zone (>3200 ohm.m) is present in the western portion of the profile. A low apparent resistivity zone (< 2 ohm.m) occurs at site 279, in the Dorsey Terrane. Higher conductivity (< 50 ohm.m) is also observed in the Cassiar Terrane. Sites 275, 274, 273, and 272 have low apparent resistivity values (~ 10 ohm.m) at approximately 100 s period.

Between 1 and 100 s period the phase response for both modes is more spatially uniform than the apparent resistivity response, suggesting the presence of static shift or distortion effects in the apparent resistivity response (Fig. 6.4). The TE and TM mode phase increases to values greater than 45° for the region between sites 284 to site 273,

except for site 276, which has a lower phase (40°). Both modes exhibit low phase ($< 35^\circ$) at the sites located at either end of the profile.

In the tipper response, both components have magnitude of less than 0.4. The eastern part of the profile is dominated by negative Tyr responses (northeast pointing Parkinson induction vectors) but there is a change of sign at sites 273 and 272. This reversal was also observed in figure 5.12. For the western part of the profile the Tyr response is positive at periods less than 20 s corresponding to southwest pointing Parkinson induction vectors.

Longer Periods (>100 s)

At long periods (> 100 s) the pseudosections show the apparent resistivity varies across the profile, from values as low as 1 ohm.m in the middle of the profile to > 1000 ohm.m in the western portion of the profile (Fig. 6.3). Between sites 286 and 281 the apparent resistivity is high for both modes (100-3200 ohm.m). At site 281, a transition takes place and between sites 280, 279, and 278 the apparent resistivity values for both modes are very low (< 2 ohm.m). In the eastern portion of the profile, in the Cassiar Terrane, the TE mode apparent resistivity is very low (< 5 ohm.m) and the TM mode apparent resistivity is moderate (> 30 ohm.m).

In contrast to the apparent resistivity response at periods greater than 100 s, the phase and tipper responses are relatively uniform across the profile. The TE and TM mode phase is high (typically $> 50^\circ$) (Fig. 6.4). At sites 272 and 273 there is a significant difference between the TE and TM mode phase, in which the TE mode phase is relatively high ($> 50^\circ$) and the TM mode phase is relatively low ($< 35^\circ$).

The tipper magnitudes are generally smaller (<0.2) at long periods than at short periods. At periods of <1000 s the Tyr response is dominated by negative values (northwest pointing Parkinson induction vectors) and at longer periods the response the response at most sites is very small.

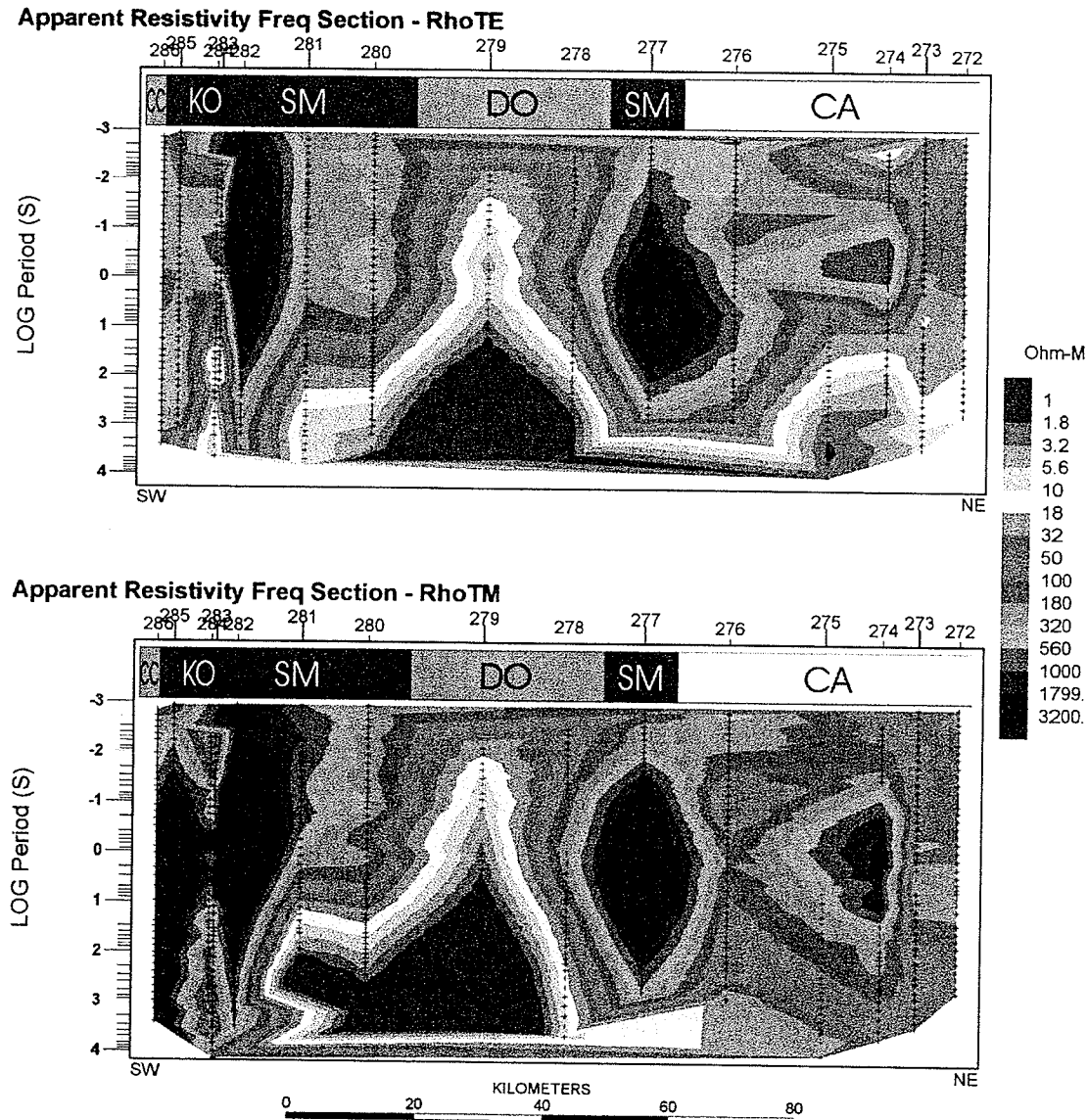


Figure 6.2 Apparent resistivity pseudosection for the TE and TM modes for the Connector Line. CC: Cache Creek Terrane, KO: Kootenay Terrane, SM: Slide Mountain Terrane, DO: Dorsey Terrane, CA: Cassiar Terrane. Crosses "+" represent data points used in the contouring. A smoothing factor of 0.02 has been applied in both horizontal and vertical directions.

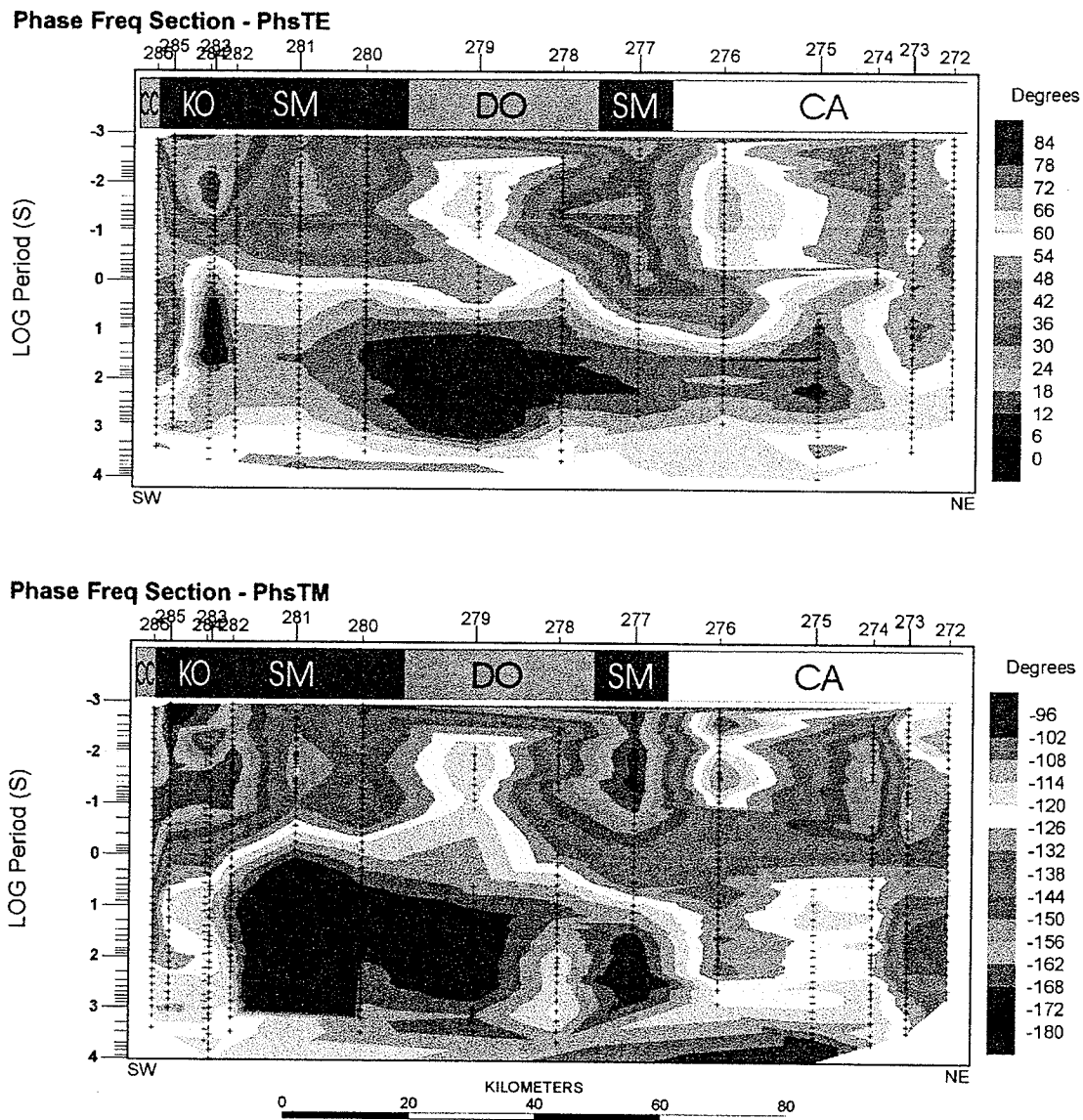


Figure 6.3 Phase pseudosection for the TE and TM modes for the Connector Line.

6.2.2 LINE 2A

As for the Connector Line, the Line 2a sites were projected onto a straight line oriented perpendicular to geological strike (Fig. 6.5). The projection again caused some sites to become very close and others to switch order. In order to remove these problems, sites between 203 and 210 were excluded from the pseudosections and subsequent 2D

inversion. Sites 200 and 202 were also excluded from the 2D analysis due to poor data quality of the response at site 200, and the indication of significant 3D structure at these sites, as discussed in section 5.5.

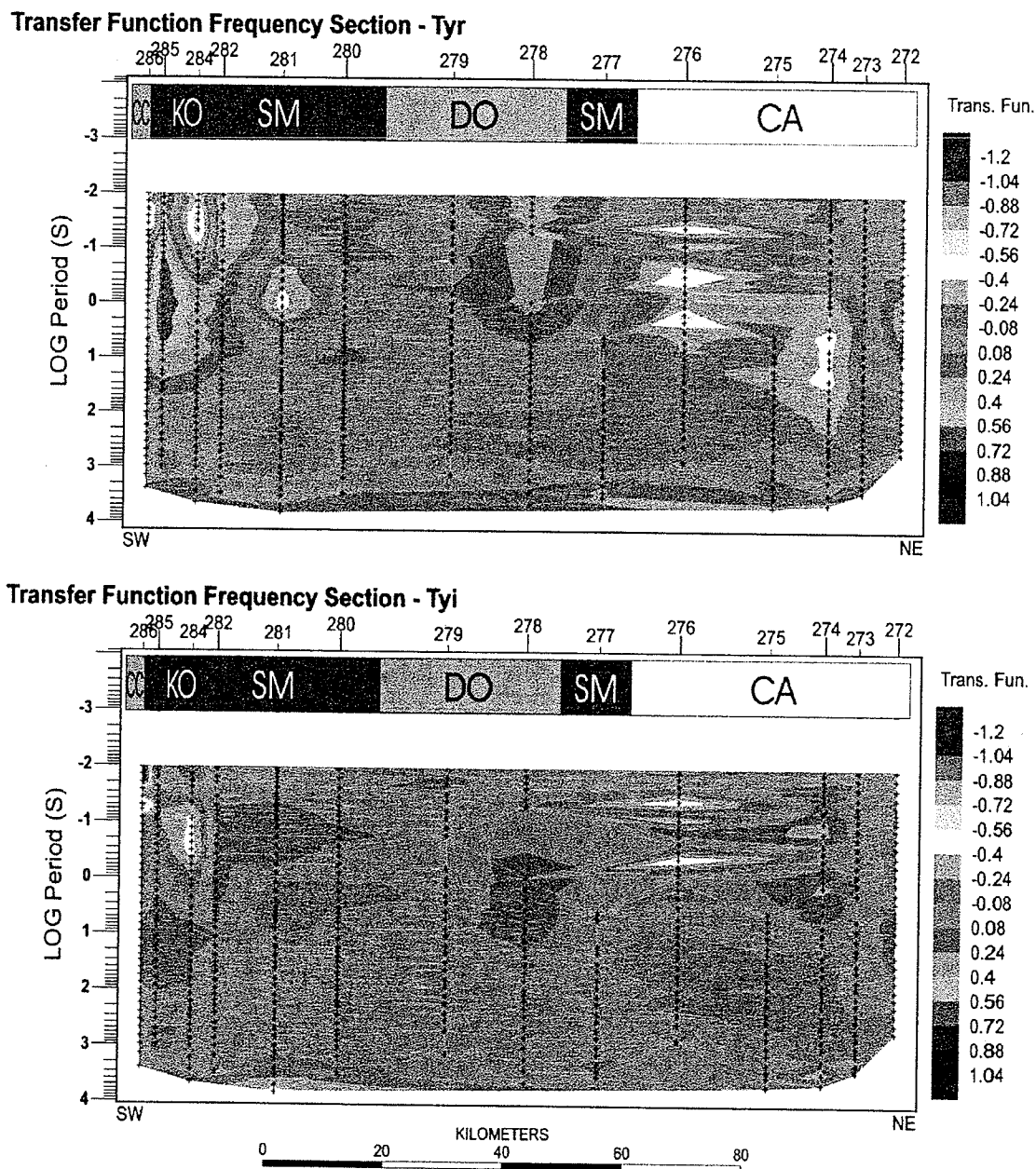


Figure 6.4 Tipper pseudosection for the TE and TM modes for the Connector Line. Tyr: real component of the tipper, Tyi: imaginary component of the tipper. Ty corresponds to the component of the tipper perpendicular to the strike. Positive values for Tyr correspond to southwest pointing imaginary induction vectors.

Overall, as with the Connector Line, the apparent resistivity, phase, and tipper response for Line 2a vary both laterally across the profile, and with period (Fig. 6.6, 6.7, and 6.8). The apparent resistivity section varies from site to site more than the phase suggesting the presence of static shift or galvanic distortion in the apparent resistivity response.

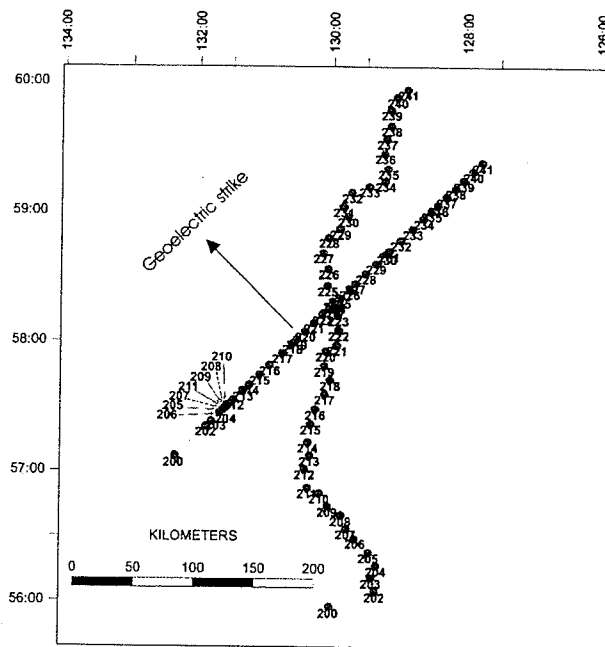


Figure 6.5 Projection of Line 2a sites onto a straight line.

Short Periods (<1 s)

The apparent resistivity (Fig. 6.6) for periods less than 1 s for both the TE and TM modes is typically between 50 and 3200 ohm.m and is similar for both modes. Only sites 232 (Slide Mountain) and 216 (Stikinia) have apparent resistivity values less than 30 ohm.m.

At periods less than 1 s, the TE and TM modes have similar phase responses, except at site 229, where the TE phase is relatively high ($> 50^\circ$) and the TM phase is relatively low ($< 40^\circ$) (Fig. 6.7). Anomalous phase values over 50° occur for sites 225 and 226 in the Cache Creek Terrane and at sites 232 and 233 in the Slide Mountain Terrane. Sites deployed on the Stikine Terrane have a consistent phase response between 30° and 40° , except for site 215, which has slightly higher phase ($>45^\circ$) for both modes at very short periods (< 0.01 s).

The phase response (Fig. 6.7) at sites located in the Stikine, Cache Creek, Quesnellia, Slide Mountain and Cassiar terranes correlates very well with the apparent resistivity response (Fig. 6.6). The high phase ($>50^\circ$) noted for site 232 and 233 within the Slide Mountain Terrane and sites 225 and 226 within the Cache Creek Terrane corresponds to low apparent resistivity (<10 ohm.m).

The magnitude of the tipper response at short periods for both the Tyr and Tyi components is typically less than 0.4. Higher magnitudes (>0.4) occur for both components between sites 217 and 219; 223 and 231; and 234 and 235. The responses at sites 217-219, which are in the Stikine Terrane, correspond to southwest pointing real Parkinson induction vectors. The responses for sites 223-231 define induction vector reversals centred near the southwest and northwest margins of the Quesnellia terrane.

Intermediate Periods (1-100 s)

The apparent resistivity response at 1 to 100 s period is similar to the short period (< 1 s) response (Fig. 6.6). At sites 227-231 in the Quesnellia and Cassiar terranes the response is much more resistive (100-3200 ohm.m) than the adjacent sites (225, 226, 232

and 233) in the Cache Creek and Slide Mountain terranes. In the more resistive area the TM mode has higher apparent resistivity values ($> 1000 \text{ ohm.m}$) than the TE mode ($\sim 500 \text{ ohm.m}$). The adjacent sites located in the Slide Mountain and Cache Creek terranes have apparent resistivity values less than 10 ohm.m . Within Stikinia and along the northern portion of the profile, both modes have similar apparent resistivity values, varying from 100 to 3200 ohm.m .

For both the TE and TM modes, the phase is high ($>45^\circ$) from 1 to 100 s along most of the line (Fig. 6.7). The highest phase ($>70^\circ$) for both modes occurs between sites 231 and 235. There is a low TE and TM phase response ($<35^\circ$) at site 240 and low TM phase at adjacent sites (225, 231, and 241). The two modes have similar phase responses along the line except for sites 225 and 226 where the TE phase is anomalously low (30°), but the TM phase is high ($> 60^\circ$) and at sites 238, 239, and 241, where the TE phase is greater than 60° .

The phase response contrasts with the apparent resistivity response at certain locations. At sites 228, 229, and 230 the phases are high ($>50^\circ$) suggesting a conductive structure but the apparent resistivity response is also high ($> 500 \text{ ohm.m}$). At sites 218 and 219 where the phase is greater than 70° and the apparent resistivity response is again relatively resistive ($> 100 \text{ ohm.m}$).

The tipper response (Fig. 6.8) at intermediate periods defines two reversals in the real induction vector. The relative complex response noted at shorter periods between sites 223 to 231 simplifies at intermediate periods to a single reversal centred on site 226 at the southwest margin of the Quesnellia Terrane. The data for sites 236 to 241 also

define a reversal, centred between sites 238 and 239. In both reversals the tipper magnitude reaches values of 0.4 units.

Longer Periods (100- 10 000 s)

At long periods, the apparent resistivity (Fig. 6.6) response for both the TE and TM modes is quite similar. At sites 211-212 and 226-227, both modes have very low apparent resistivity values (< 10 ohm.m), and at sites 228-229 and 230-231 both modes are more resistive (> 300 ohm.m). These sites may be affected by static shift. A significant contrast between the two modes occurs in the Cassiar Terrane. The TE mode has very low apparent resistivity values (< 3 ohm.m) for sites northeast of 231 (except 240), whereas the TM mode is more resistive at these sites (except 235).

In some areas the apparent resistivity and phase pseudosection correlate very well. High phase for both the TE and TM modes occurs at sites 211, 212, 213, 226, and 233 and corresponds with low apparent resistivity values (< 5 ohm.m). The TE phase is very high for sites 232, 233, 234, 235, 236, 237, 238, and 239, consistent with the low apparent resistivity values. The TM phase is low for sites 236, 237, 238, 239, 240, and 241, consistent with the resistive TM apparent resistivity response.

At long periods (> 100 s) the phase (Fig. 6.7) is typically high ($> 45^\circ$), but less than it is for the intermediate periods (1-100 s). The highest phase ($> 70^\circ$) occurs for the TE mode at sites 232 to 237 but the TM phase is lower for these sites. Site 240 has relatively low TE and TM phase (20° - 30°) and in the southern portion of the profile sites 211 and 212 have relatively high phase ($> 60^\circ$) for both modes.

The magnitude of the tipper response is low at long periods. The reversal at the northeast end of the profile shifts to the northeast at periods longer than 100 s. The Tyr response is dominated by relatively small (<0.4) negative values northeast of site 228 (northeast pointing Parkinson induction vectors) and relatively small positive values between sites 216 and 221.

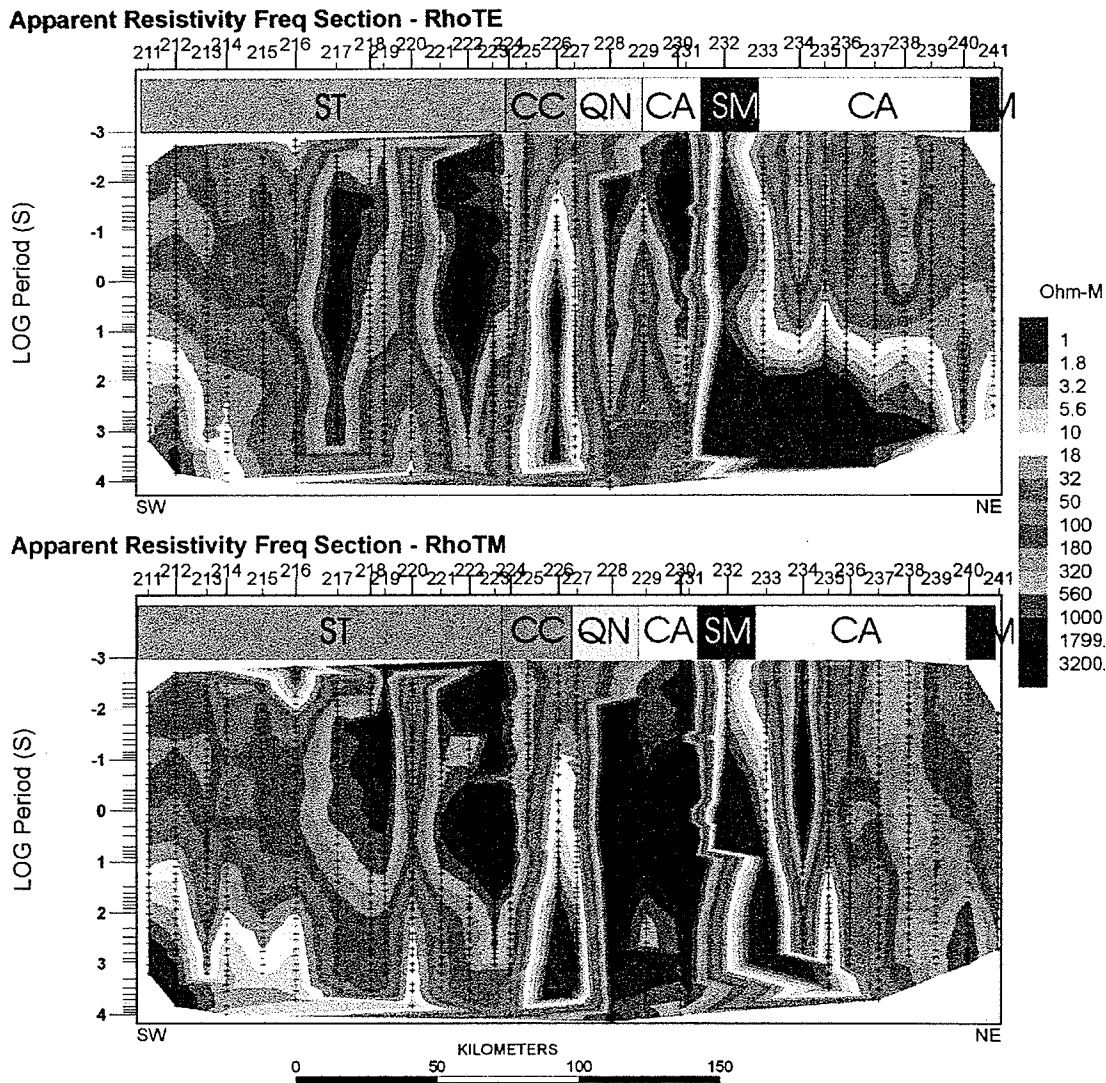
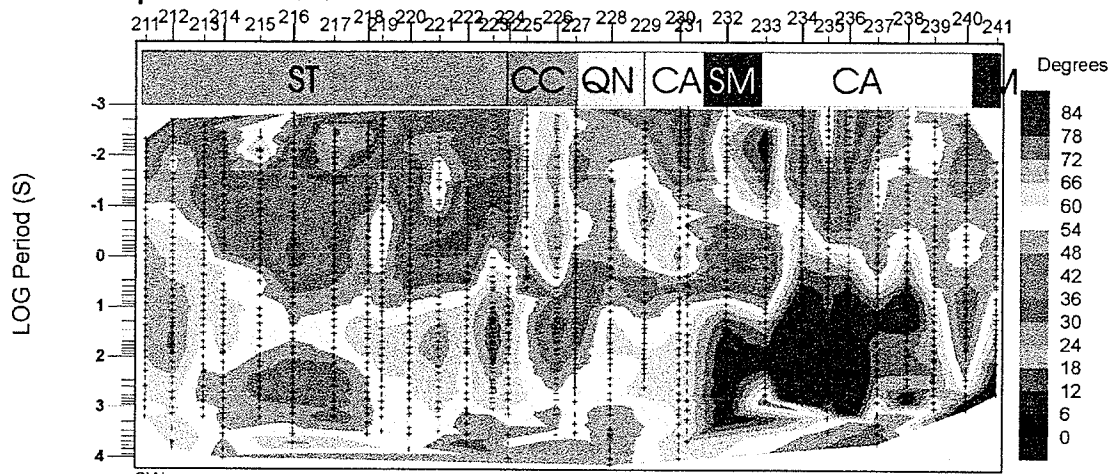


Figure 6.6 Apparent resistivity pseudosection for the TE and TM modes for Line 2a.

Phase Freq Section - PhsTE



Phase Freq Section - PhsTM

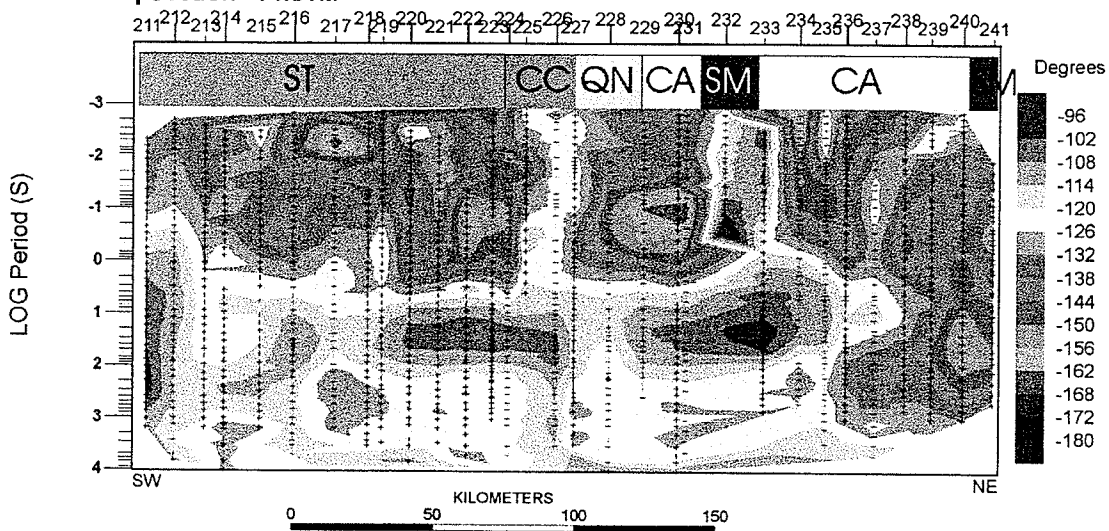
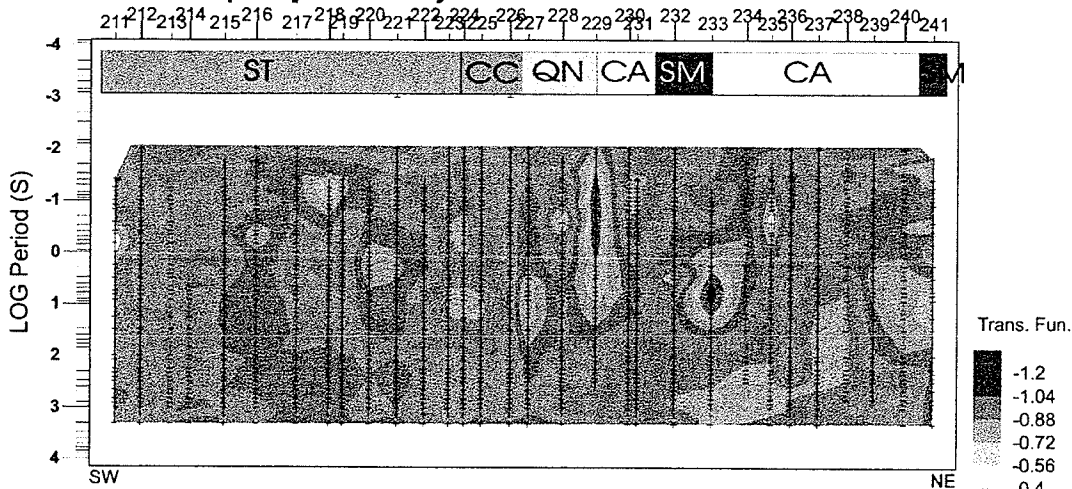


Figure 6.7 Phase pseudosection for the TE and TM modes for Line 2a.

Transfer Function Frequency Section - Tyr



Transfer Function Frequency Section - Tyi

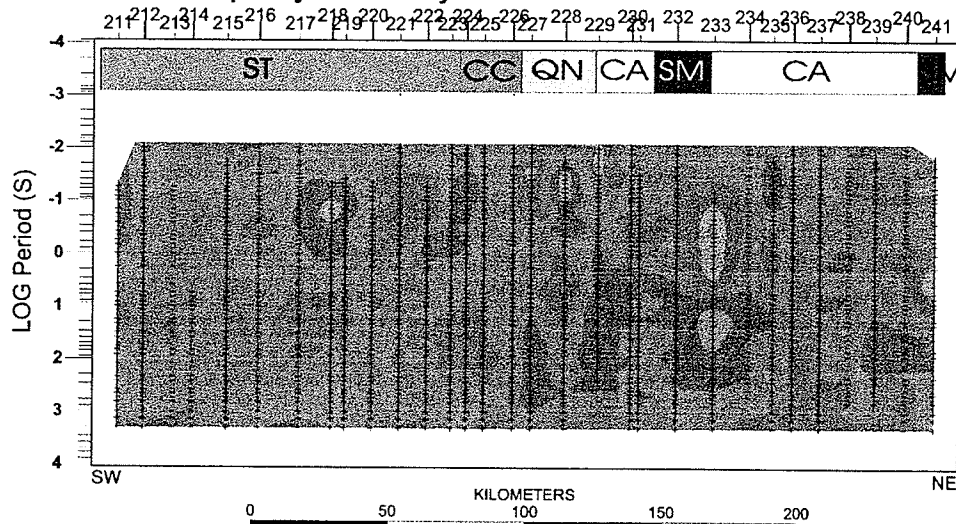


Figure 6.8 Tipper pseudosection for the TE and TM modes for the Connector Line. Tyr: real component of the tipper, Tyi: imaginary component of the tipper.

6.2.3 COMPARISON BETWEEN LINE 2A AND THE CONNECTOR LINE

Detailed comparison of the phase and apparent resistivity pseudosections for Line 2a and the Connector Line suggests that the conductivity structure for the northern half of Line 2a is similar to the that of the Connector Line.

The apparent resistivity and phase pseudosections for the Connector Line and Line 2a are shown in Figures 6.9 and 6.10. The areas with strong correlation between Line 2a and the Connector Line are marked "A", "B", "C", and "D". When the locations of the zones "A", "B", "C", and "D" on the two profiles (Fig. 6.11) are compared they are found to be consistent with a strike with an azimuth of approximately -45° . This result provides further evidence that the MT geoelectric strike is -45° and that the data can be examined using two-dimensional methods.

Region A

The region labeled "A" is located beneath the Kootenay Terrane (Connector Line) and Cassiar and Quesnellia terranes (Line 2a). The region is resistive, with high TE apparent resistivity values (~ 500 ohm.m) and very high TM apparent resistivity values (>3200 ohm.m) for both profiles. The phase response for this region is low ($<40^{\circ}$) for both the TE and TM modes and for both profiles, which is consistent with the apparent resistivity response

Region B

The region labeled "B" is located beneath the Dorsey Terrane (Connector Line) and beneath the Slide Mountain (Line 2a). It is a very conductive region. The apparent resistivity values for site 279, 232 and 233, decrease to less than 5 ohm.m at periods greater than 10 s. Similarly, the phase values for both profiles and both modes are very high ($>75^{\circ}$).

Region C

The region labeled "C" is located beneath the Cassiar terrane in both profiles. It is a resistive region. High apparent resistivity values (>3200 ohm.m) are observed at site

277 for both modes around 1 s, which correlate with high apparent resistivity (1000 ohm.m) values for site 234. The phase for the same region is low for the TE and TM mode for the same period (<30°).

Region D

Finally, the region labeled “D” is also located beneath the Cassiar terrane. It is a resistive region. High apparent resistivity (1000 ohm.m) is observed at site 274 for the Connector Line for both modes at 0.1 to 1 s, which correlates with high apparent resistivity values (500 ohm.m) for site 238 at the same periods for both modes. The corresponding phase is lower than the adjacent area for both profiles and for both modes at the same period (<40°).

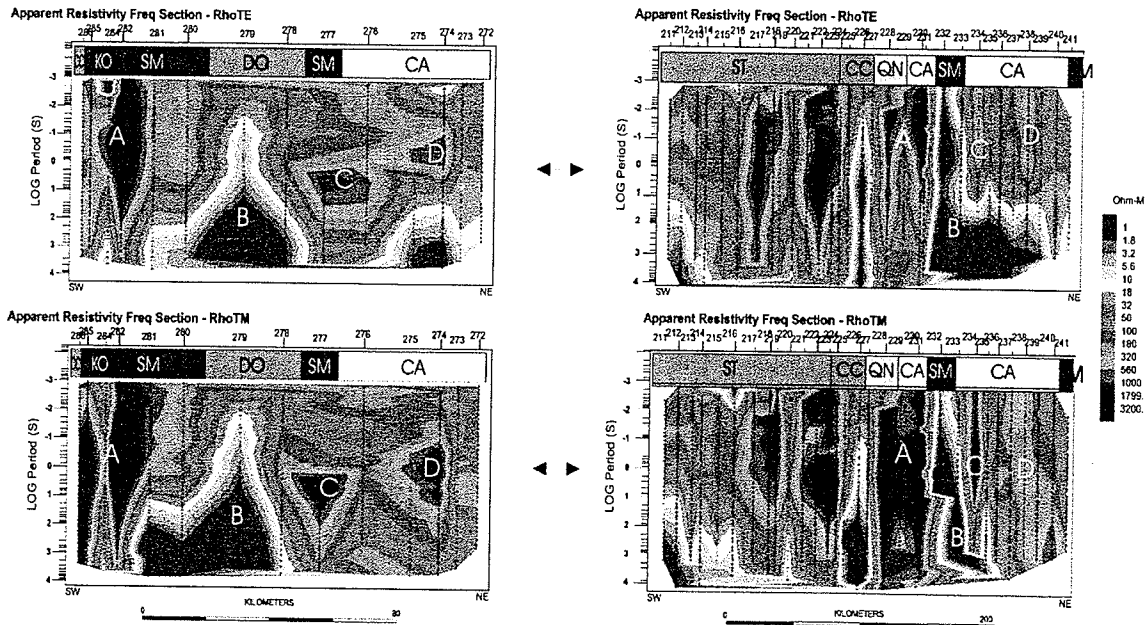


Figure 6.9 Apparent resistivity pseudosections for the Connector Line and Line 2a.

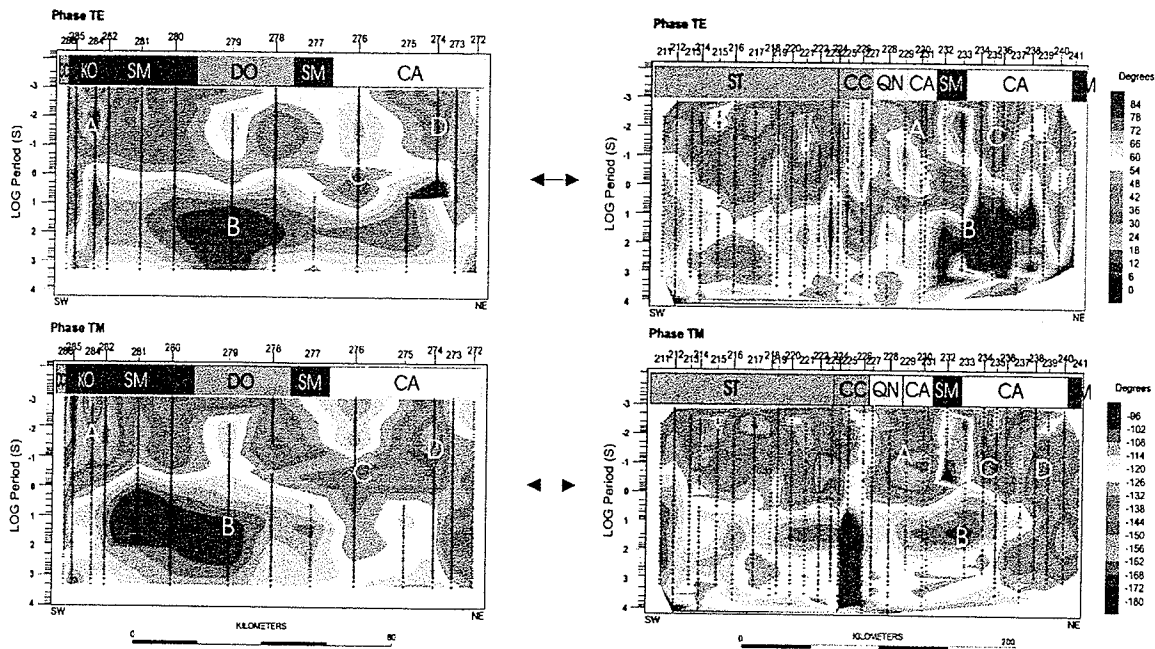


Figure 6.10 Phase pseudosection for the Connector Line and Line 2a.

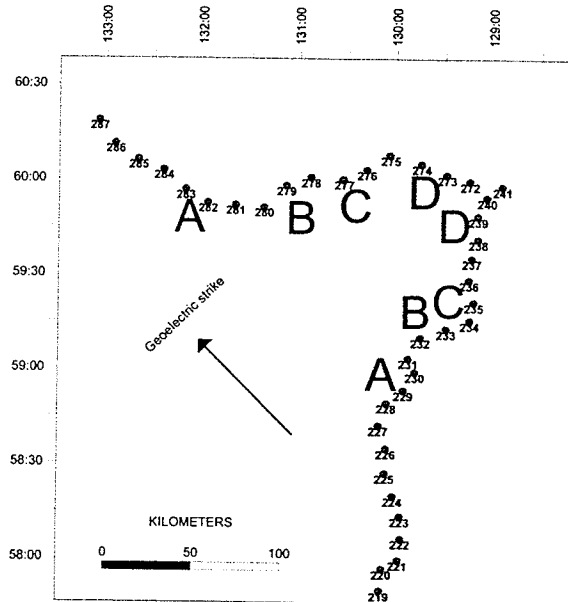


Figure 6.11 Map showing the location of regions with similar MT responses for Line 2a and the Connector Line 2a.

CHAPTER 7- MODELLING

7.1 INTRODUCTION

This chapter describes the construction of 2D models for Line 2a and the Connector Line. The models are based on fitting the TE and TM components of the edited observed data (uncorrected for galvanic distortion) presented in the pseudosections in Chapter 6. Two different 2D inversion methods were used for the data set: (1) Occam, and (2) non-linear conjugate gradient (NLGC). This chapter describes the inversion methodology and results.

Inversion Strategy

Many inversions of the Connector Line and Line 2a data were run in order to examine the uniqueness and resolution of the resulting models. The inversion input parameters (error floors, starting model), as well as the specified data fitted: TE and/or TM modes, phase, apparent resistivity, and/or tipper were varied in the different inversions. In many cases the results for past inversions were examined and used to adjust the input parameters for following inversion.

7.2 TWO-DIMENSIONAL OCCAM INVERSION

The Occam inversions are described first in this thesis because this method provides lower resolution models than the NLGC method. The finite-element mesh used in the Occam method must be discretized more finely than the regularization grid and therefore for a given level of computer resources the Occam inversion provides less resolution than the NLGC method that uses a common regularization and finite-difference grid. The GEOTOOLS MT program implements the 2D Occam inversion

technique developed by deGroot-Hedlin and Constable (1990), which uses the finite-element code of Wannamaker et al. (1987) in its forward modeling calculations.

Design of Mesh and Grid

The 2D Occam inversion model is parameterized in terms of a regularization grid composed of rectangular cells superimposed onto a finite element mesh. The procedure for constructing the finite element mesh and regularization grid is outlined in the GEOTOOLS manual (GEOTOOLS, 1997). The regularization grid is optimally defined so that row thickness increases geometrically with depth. From experimentation by the author it was determined that in order for the inversion program to run successfully, the ratio of the column width to the row thickness for cells in the grid should be less than 6. The model was extended for hundreds of kilometers on either side of the actual MT profile and to hundreds of kilometers depth in order to decrease edge effects. The models were verified using the GEOTOOLS program prior to the inversions in order to confirm that the finite-element mesh and regularization grid conformed to the appropriate size and skin depth relationships.

Inversion Parameters

Error floors were applied to the data because of uncertainties in the spectral estimates of the errors. The apparent resistivity, phase and tipper errors were determined by examination of the magnitude and quality of the components. For most inversions a basic 5% impedance error floor was used. A 5% impedance error floor corresponds to a 2.86° phase error and 10% apparent resistivity error in logarithmic space. For some

inversions the apparent resistivity error floor was set to be larger than the phase error in order to allow for static shift in the apparent resistivity. For the tipper, GEOTOOLS specifies the error floor in terms of the variance, i.e. if 0.01 is specified in GEOTOOLS then the tipper error is ± 0.1 .

For most inversions the specified maximum number of iterations was 15 and the target tolerance was set to 1.0. For the final model for each profile the inversion was rerun with the tolerance set to a value equal to the lowest value achieved in the previous inversion plus 10%. This procedure was performed in order to avoid overfitting the data.

Starting Model

The starting model for each inversion was a uniform half-space. Results were obtained using different starting half spaces to determine if the inversions converged to the same result.

7.2.1 CONSTRUCTION AND INVERSION OF OCCAM MODELS FOR LINE 2A

Profile

For the OCCAM inversions, Line 2a was divided into three overlapping segments in order to accommodate the available computer power and inversion limitations. The north segment includes sites 241 to 226, and crosses the Cache Creek, Quesnellia, Cassiar, and Slide Mountain terranes. The south segment includes sites 211 to 227, and crosses the Stikine, Cache Creek and Quesnellia terranes. The central segment includes sites 221-232, and crosses the Stikine, Cache Creek, Quesnellia, Cassiar and Slide Mountain terranes. The central segment was included in the modelling because it includes an

induction vector reversal near the margin of the Cache Creek and Quesnellia terranes, as discussed in section 5.7 and 6.2.

Finite Element Mesh and Grid

Table 7.1 lists the parameters of the models and the parameters of some of the Occam inversions completed. The number of free parameters corresponds to the number of regularization grid elements, and was chosen to be 500 for all inversions. The optimum model for the segment is shown in bold in Table 7.1 and was chosen based on the tolerance, roughness, and the fit of the data at individual sites (Appendix E).

Table 7.1 Occam inversion completed for the Line 2a profile.

Model		Input Parameters							Inversion Results				
No. Inversion	Mesh Nodes		No. Data	No. Sites	Error			Half space ohm.m	No. of Iterations		Iteration Results		
	Y	Z			ρ	ϕ	Tipper		Specified	Completed	Roughness	Tolerance	
North segment													
1	83	63	986	17	10	5	-	100	14	14	33.94	9.05	
2	105	71	986	17	10	5	-	100	7	7	29.19	9.14	
3	105	71	986	17	10	5	-	100	17	17	66.87	7.34	
4	88	73	920	16	10	5	-	100	15	15	77.17	7.96	
5	88	73	920	16	10	5	-	100	8	15	40.08	8.9	
Central segment													
6	85	75	981	12	20	10	0.1	100	2	2	10.85	4.27	
7	85	75	981	12	20	10	0.1	100	13	13	29.79	3.66	
8	85	75	981	12	10	5	0.1	100	7	15	40.37	7.67	
South segment													
9	104	71	983	17	10	5	-	100	6	15	21.89	5.01	
10	104	71	952	17	10	5	-	100	10	13	8.53	6	
11	104	71	952	17	10	5	0.015	100	16	16	31.6	4.64	

Note: the model and response of the inversion marked in bold are discussed below. Dash means that the corresponding data type was not included in the inversion. The apparent resistivity and phase error are listed in terms of the corresponding percentage error on the impedance.

Data and Errors

The types of data were adjusted for the three segments of Line 2a (Table 7.1). The apparent resistivity and phase responses for both the TE and TM modes were inverted for all three segments of Line 2a (Fig. 7.1). From the induction vector analysis an induction vector reversal is observed near the boundary of the Cache Creek and Quesnellia terranes for periods of 0.05 s to 50 s (Fig. 5.12). For this reason, for the middle segment, the tipper response was included in the inversion (Fig. 7.2).

Data for the same fifteen periods were fitted in each of the inversions (0.001, 0.0032, 0.0082, 0.022, 0.046, 0.12, 0.32, 0.82, 2.2, 5.6, 12, 38, 100, 260, and 680 s). These periods are sufficient for representing the frequency-variation of the observed responses.

Inversions

The roughness and tolerance for each iteration for the specified inversion for each segment are shown in Table 7.2. The model obtained in the iteration marked in bold in Table 7.2 was chosen to be the final Occam model for each segment. In some cases, such as for the north segment and central segment, the final iteration from the inversion using the increased tolerance target was not selected. Although the final iteration would have provided the absolute smoothest model, the iteration selected provided a better fit to the data for the less distorted sites. Visual inspection suggested the models from the final iteration were not significantly different from the models chosen.

Table 7.2 The tolerance and roughness for each iteration for Line 2a.

North Segment			Central Segment			South Segment		
Iteration	Tolerance	Roughness	Iteration	Tolerance	Roughness	Iteration	Tolerance	Roughness
1	10.54	15.19	1	4.35	9.42	1	6.47	11.99
2	10.17	16.80	2	4.27	10.56	2	6.22	9.77
3	10.07	15.40	3	4.27	19.82	3	6.00	10.01
4	9.75	17.04	4	4.23	20.24	4	6.00	9.59
5	9.64	23.19	5	4.22	21.69	5	6.00	9.13
6	8.73	65.86	6	4.16	27.79	6	6.00	8.73
7	8.60	52.98	7	3.96	21.28	7	6.00	8.76
8	8.56	46.90	8	3.96	21.24	8	6.00	8.66
9	8.10	71.79	9	3.96	21.23	9	6.00	8.65
10	8.01	67.64	10	3.89	25.74	10	6.00	8.53
11	7.99	70.92	11	3.83	29.49	11	6.00	8.57
12	7.98	70.46	12	3.86	22.59	12	6.00	8.57
13	7.98	75.50	13	3.74	26.88	13	6.00	8.63
14	7.97	71.24	14	3.69	33.90			
15	7.96	77.18	15	3.66	29.70			

7.2.1.1 North Segment

Fit to Data

Comparison of the pseudosections of the observed and model apparent resistivity and phase data show for the north segment that the large-scale features in the observed data are represented in the model response (Fig 7.1, 7.2). Although a tolerance of only 8.56 is achieved (Table 7.2). Appendix E shows the data fit at individual sites. Much of the misfit comes at sites 228 to 233. At site 232 the fit to the data for the phase response is very poor at all periods. For example, the model TE phase response at periods greater than 10 s is approximately 30°, but the observed values are over 75°. A better fit to both the apparent resistivity and phase responses is achieved at either ends of the profile, more specifically for sites 226, 227, and 234 to 241.

The poor fit at sites 228 to 232 may be due to local 3D components in the response. The skew values for site 232 at periods greater than 10 s were relatively high

(> 0.3 , Fig. 5.2), indicating 3D structure and the GB decompositions did not converge for this site. At site 231 the poor fit to the data correlates with observed high shear ($>35^\circ$) values at periods greater than 0.1 s (Fig. 5.5), which indicate high levels of distortion.

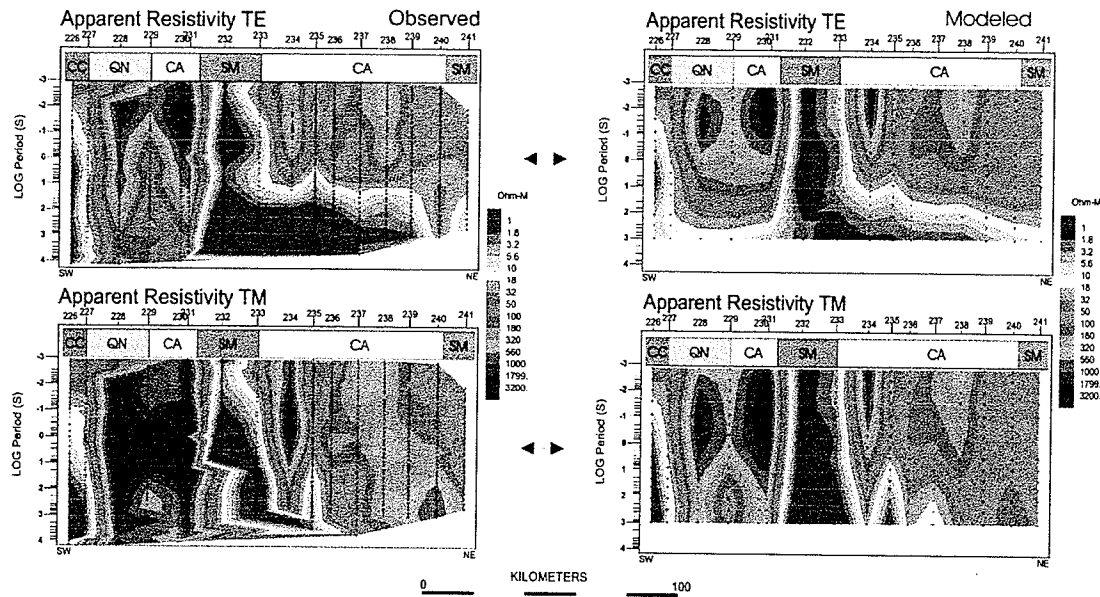


Figure 7.1 Comparison of the observed and modeled apparent resistivity response for the north segment of Line 2a.

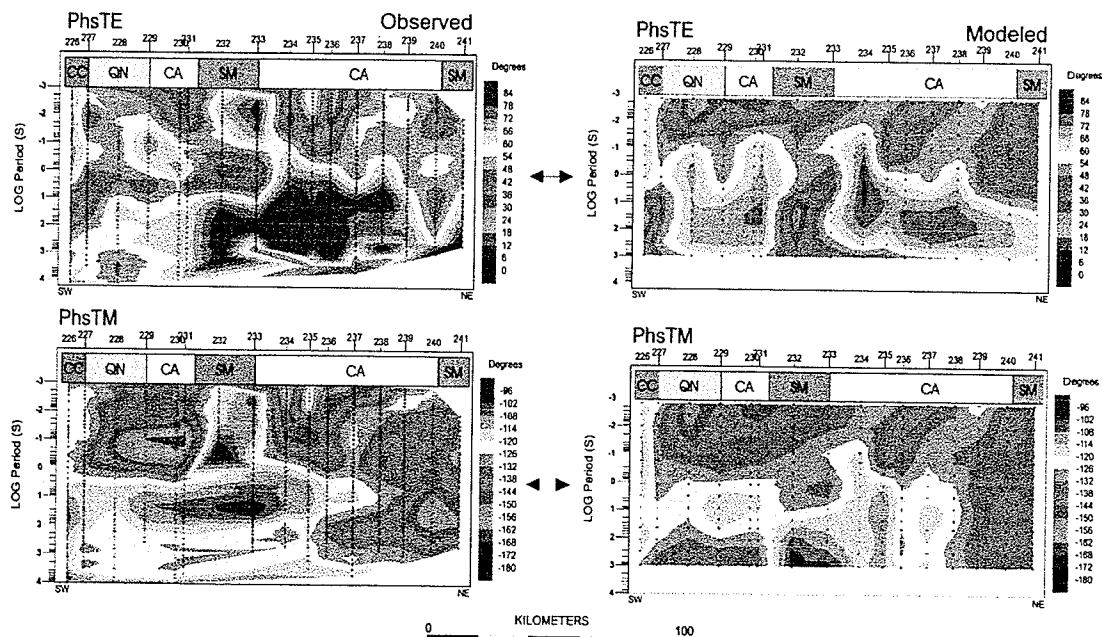


Figure 7.2 Comparison of the observed and modeled phase response for the north segment of Line 2a.

Examination of Model

The Occam model for the north segment is characterized by a number of significant structures in the crust (Fig 7.3). The small narrow conductive zone labeled X beneath the Cache Creek Terrane contains resistivity values as low as 1 ohm.m. A larger conductive zone (labeled Y) located beneath the Slide Mountain Terrane and adjacent Cassiar Terrane extends from the surface to 40 km depth and has resistivity values of 1 to 2 ohm.m. Further north from 10 to 40 km depth beneath the Cassiar Terrane there is another large conductive zone (labeled E), which has resistivity values of 0.5-2 ohm.m. At depths of less than 25 km, beneath sites 227 to 231, the structure is characterized by a resistive zone (1000 ohm.m, labeled B').

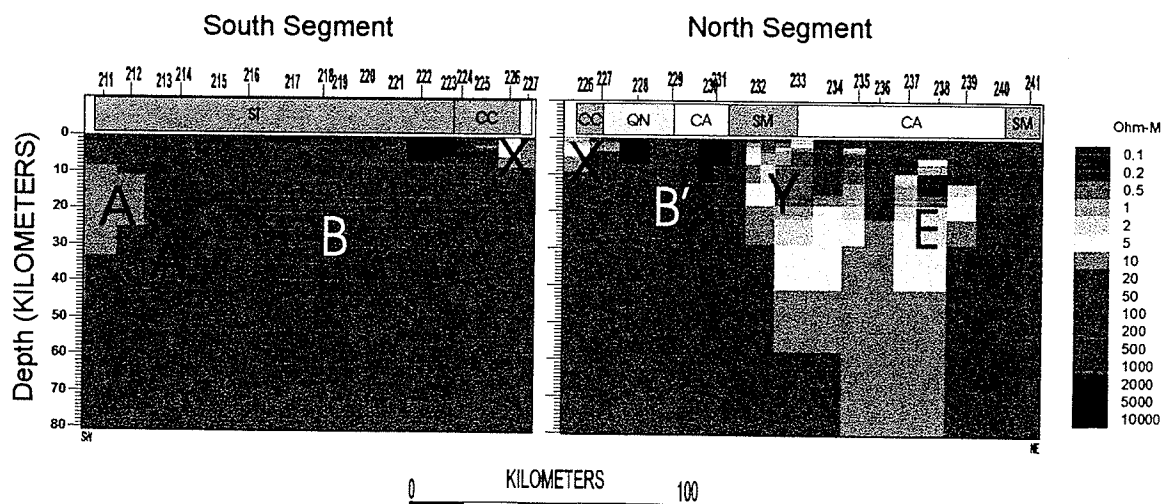


Figure 7.3 Occam model for (a) south segment Line 2a profile and (b) the north segment. Labelled features are discussed in text.

7.2.1.2 South Segment

Fit to data

Based on an examination of the apparent resistivity and phase pseudosections response for the south segment (Fig. 7.4, 7.5, Appendix E), the Occam model response

provides a relatively good fit to the observed data even though a tolerance of only 8.53 was achieved. The phase response for sites 225 and 227 provides a poor fit to the data. This misfit may be caused by 3D structure or distortion. Site 225 is highly distorted, as indicated by the high skew values (> 1) (Fig. 5.2) and high shear values ($> 35^\circ$) (Fig. 5.5) at periods greater than 10 s and a large χ^2 misfit of the (> 20) of the GB model (Fig. 5.14). For the whole segment, the long period model response (> 100 s) provides a poorer fit to the data than the short period response, which is consistent with the increased shear and skew values noted at longer periods (Fig. 5.2, 5.5).

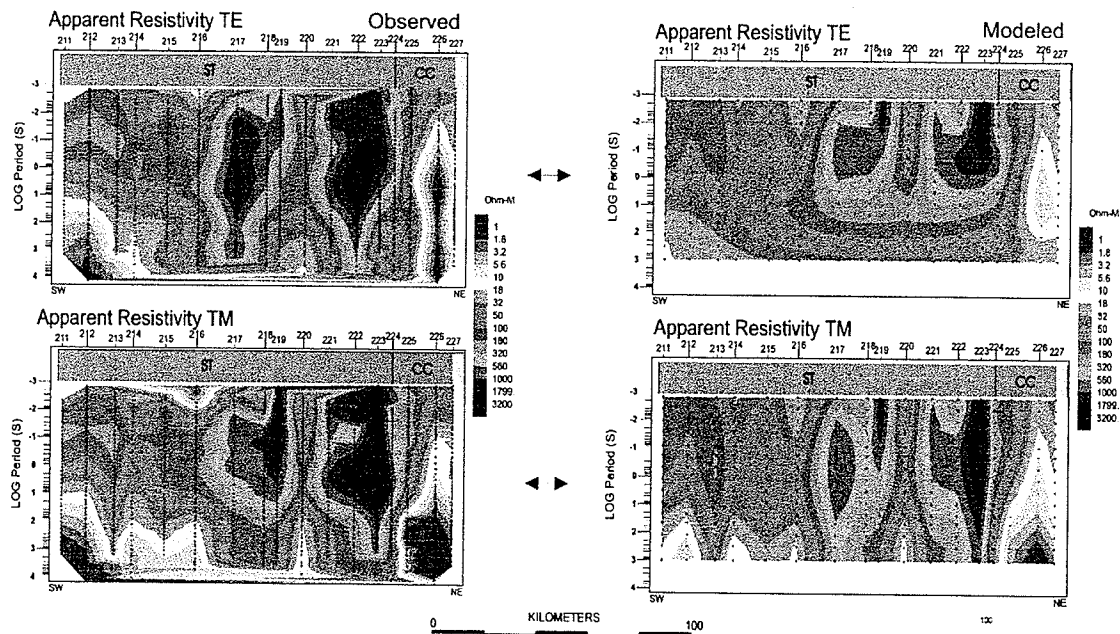


Figure 7.4 Comparison of the observed and modeled apparent resistivity response for the south segment of Line 2a.

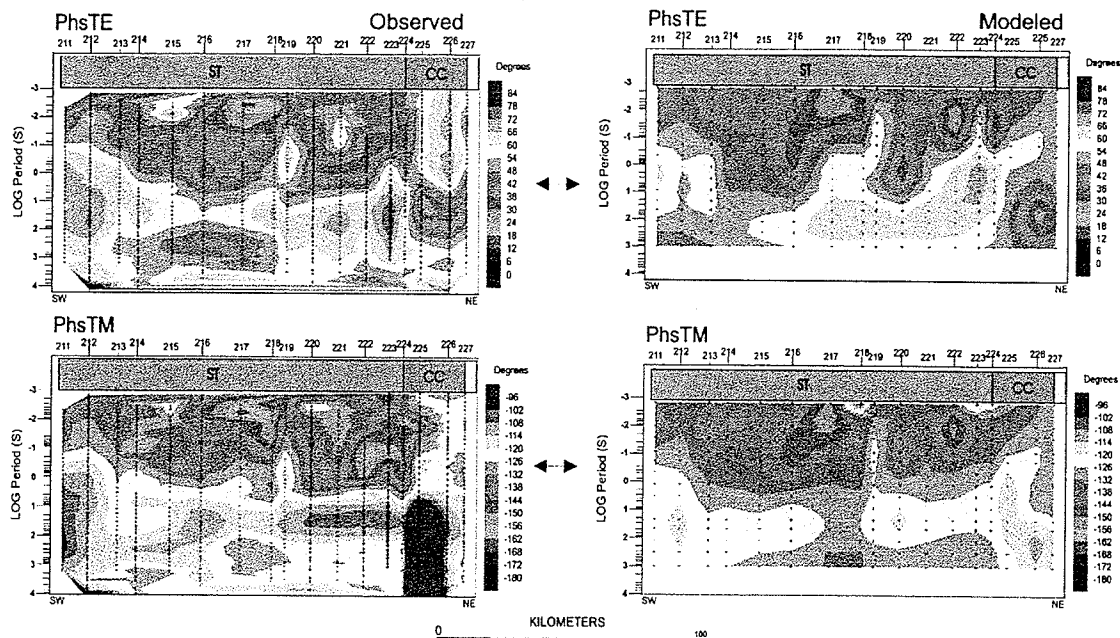


Figure 7.5 Comparison of the observed and modeled phase response for the south segment of Line 2a.

Examination of Model

The Occam model for the south segment of Line 2a is characterized by a moderately conductive zone with an upper surface that dips to the northeast (labeled **A**, Fig. 7.3) at crustal and lithospheric mantle depths in the south portion of the profile, a large resistive wedge (labeled **B**, Fig. 7.3) in the Stikine Terrane at crustal depths, and a smaller conductor (labeled **X**, Fig. 7.3) in the Cache Creek Terrane at shallow depths (< 7 km). Conductor **A** is more conductive in the southwest (~10 ohm.m) and becomes gradually most resistive (20-50 ohm.m) further north and at greater depth. It is defined by low apparent resistivity values for both modes (Fig. 7.4) and high phase values for both modes (Fig. 7.5). The resistive wedge (labeled **B**) overlies conductor **A** at crustal depths and is defined by both high apparent resistivity values for both modes. Conductor **X** (1 ohm.m) occurs beneath the Cache Creek Terrane and is defined by the response at site

226. This conductor was also noted in the inversion results for the north segment Occam model.

7.2.1.3 Central Segment

Fit to Data

Based on an examination of the model apparent resistivity and phase pseudosections for the central segment and the fit at individual sites (Appendix E), the Occam model provides a marginal fit to the data. A tolerance of 3.56 was achieved. The model apparent resistivity (Fig. 7.6) and phase (Fig. 7.7) responses have the same general form as the observed response but several areas of misfit are evident. At site 228 the model TM phase and apparent resistivity responses provide a poor fit to the observed data. The model TM phase at periods less than 0.1 seconds is very high ($>60^\circ$), whereas the observed response is approximately 30° (Fig. 7.7). A moderate fit is achieved to the observed tipper response. The model tipper response includes a reversal at intermediate periods at site 226 but the magnitude of the real component of the model tipper is larger than the magnitude of the observed response.

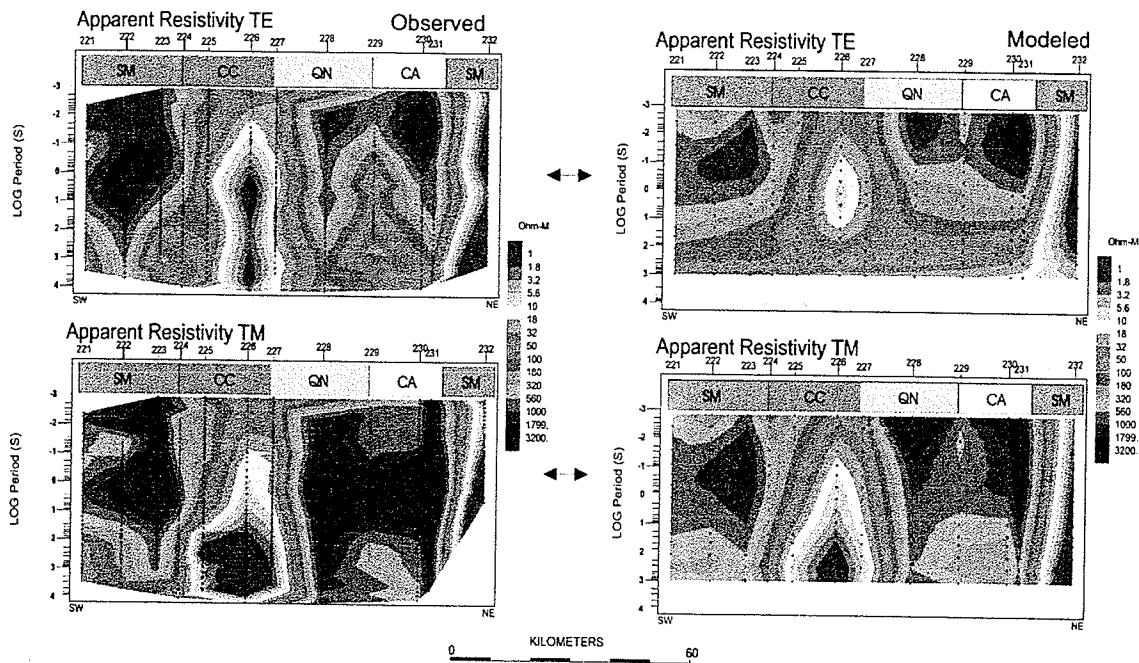


Figure 7.6 Comparison of the observed and modeled apparent resistivity response for the central segment of Line 2a.

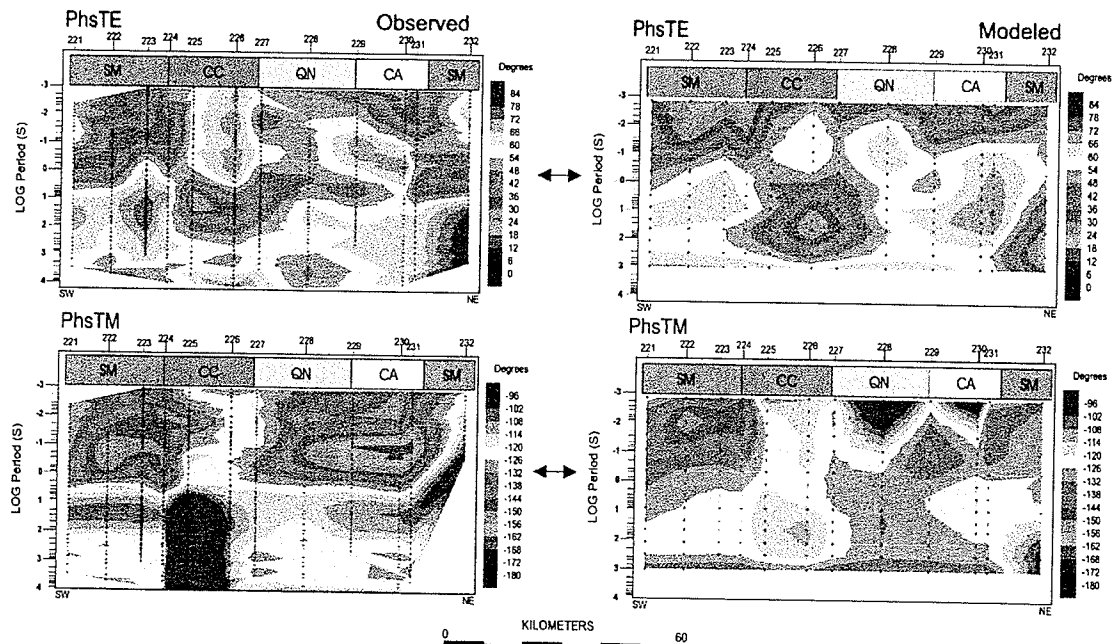


Figure 7.7 Comparison of the observed phase and modeled phase response for the central segment of Line 2a.

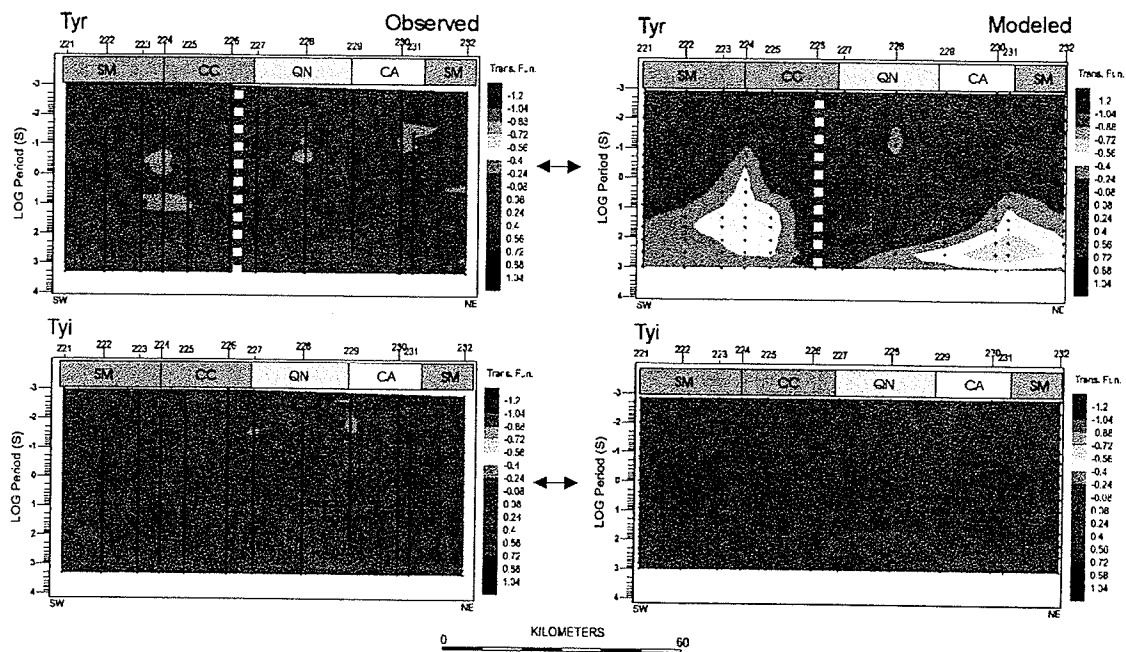


Figure 7.8 Comparison of the observed and modeled real (Tyr) and imaginary (Tyi) tipper components for the middle segment of Line 2a. The dashed white line indicates location of induction vector reversal (see Fig. 5.12).

Examination of Model

The central segment Occam model has a very similar form to the corresponding parts of the Occam models derived for the north and south segments (without the inclusion of the tipper data) (Fig. 7.9). Again, labels **X** and **Y** denote conductive zones (1-5 ohm.m) in the upper crust (<10 km) beneath the Cache Creek and Slide Mountain terranes respectively. In the central segment model, conductor **X** overlies a large resistive zone (labeled **B**, Fig. 7.2) that encompasses most of the profile south of site 229. The resistive zone is relatively homogeneous with resistivity values ranging from 500 to 2000 ohm.m. This feature is approximately ten times more resistive than in models for the north and south segments of the line.

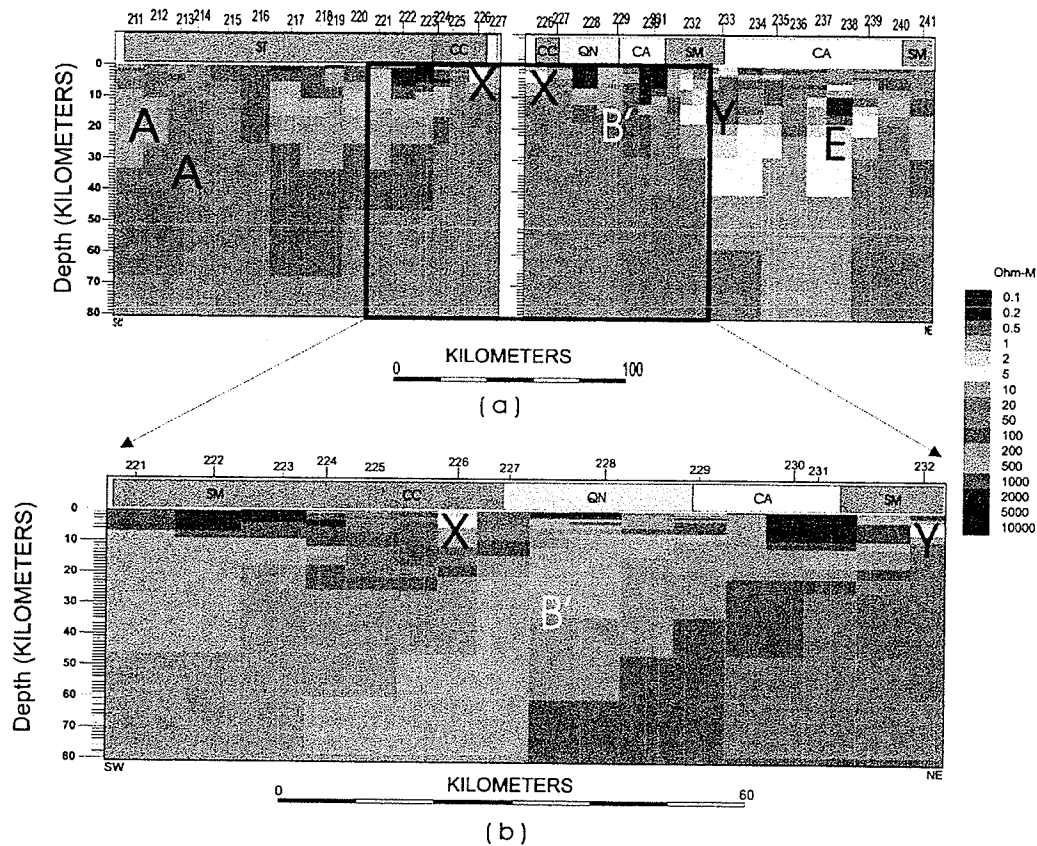


Figure 7.9 Occam models for Line 2a (a) north and south segment (b) central segment.

7.2.2 CONSTRUCTION AND INVERSION OF OCCAM MODELS FOR THE CONNECTOR LINE

Profile

Since the Connector Line includes only 14 sites, it can be inverted as one segment with the available computer resources. The initial inversions excluded sites 287 and 283 and subsequent inversions excluded sites 287, 286, and 283 due to the close proximity of these sites after their projection (as discussed in section 6.2.1).

Finite Element Mesh and Grid

Table 7.3 lists the parameters of the models of some of the Occam inversions completed for the Connector Line. The number of free parameters for the regularization grid was 500 for all inversions completed. As with the Line 2a models, the optimum model for the Connector Line is shown in bold in Table 7.3.

Table 7.3 Occam inversion completed for the Connector Line profile.

Model		Input Parameters							Inversion Results			
No. Inversion	Mesh Nodes		No. Data	No. Sites	Error			Half space Ohm.m	No. of Iterations		Iteration Result	
	Y	Z			ρ	ϕ	Tipper		Specified	Completed	Roughness	Tolerance
1	82	70	758	14	10	2.5	-	100	5	5	49.2	9.78
2	95	67	758	14	10	5	-	100	2	2	35.74	9.44
3	95	67	855	14	10	5	0.1	100	13	13	24.6	7.08
4	84	67	682	13	10	5	-	100	8	8	30.77	8.36
5	86	71	682	13	10	5	-	100	6	7	65.05	6.18
6	84	67	682	13	10	5	-	100	12	15	12.55	9.3

Note: see Table 7.1 for note on entries in the the table.

Data and Errors

Two Occam models were constructed for the Connector Line, the first by inverting the TE and TM mode apparent resistivity and phase data (Model A), and the second by including the tipper data (Model B). Fifteen periods (680 s, 220 s, 100 s, 38 s, 15 s, 5.6 s, 1.8 s, 0.68 s, 0.26 s, 0.1 s, 0.038 s, 0.018 s, 0.0068 s, 0.0026 s, and 0.001 s) were inverted for Model A and twelve periods (680 s, 220 s, 68 s, 18 s, 4.6 s, 1.2 s, 0.38 s, 0.1 s, 0.032 s, 0.01 s, 0.0032 s, and 0.001 s) were inverted for Model B. Only 12 periods were used in the second inversion because of limitations on the total number of

data that could be inverted. The periods chosen sufficiently represented the variation of the observed responses. The input parameters for the inversions are shown in Table 7.3.

Inversions

For each of the Occam inversions a maximum of fifteen iterations was specified with the target tolerance initially set to 1. As with Line 2a, for the Connector Line, the inversions were then rerun, but with a 10% value added to the lowest tolerance in the previous inversion. As with the Line 2a inversions, visual examination of the results suggested this final run did not produce a significantly improved model. The roughness and tolerance for each iteration for the specified inversion for Model A and Model B is shown in Table 7.4.

Table 7.4 The tolerance and roughness for each iteration for the Connector Line.

Model A			Model B		
Iteration	Tolerance	Roughness	Iteration	Tolerance	Roughness
1	7.09	54.40	1	8.81	11.69
2	6.50	64.71	2	8.29	17.07
3	6.43	58.16	3	8.19	14.48
4	6.28	66.82	4	8.15	13.32
5	6.18	65.09	5	8.09	13.18
6	6.18	65.05	6	7.82	15.36
7	6.15	82.32	7	7.71	16.86
			8	7.63	18.13
			9	7.57	17.82
			10	7.46	18.81
			11	7.44	19.40
			12	7.43	18.92
			13	7.08	24.60

7.2.2.1 Model A

Fit to Data

Comparison of the pseudosections of the observed and modeled apparent resistivity and phase data shows that the large scale features of the observed data are represented in the model response (Appendix F, Fig. 7.10 and Fig. 7.11). A tolerance of 6.18 is achieved between the observed and modeled response.

The model response reproduces specific features of the observed response. High phase for both modes is observed for both the observed ($<65^\circ$) and model ($>50^\circ$) response between 1 to 100 s for sites 278 to 281. The poor fits at sites 274 and 279 for the TE and TM modes for the phase response may be due to local 3D components. Both sites have skew values greater than 0.7 at long periods (> 100 s). The poor fit at site 276 for both modes and both the apparent resistivity response may be due to a high level of distortion, as indicated by high shear values ($>35^\circ$). Finally, the poor apparent resistivity fit for sites 282 and 277 for both modes may be due to static shift effects.

Examination of Model

Model A (Fig. 7.12) is characterized by a large conductive zone (labeled **F** and **G**) beneath the Dorsey Terrane, which extends into the lower crust and mantle, a small conductor (labeled **E**) beneath the Cassiar Terrane in the upper crust, and two resistive zones (labeled **B** and **B'**) in the upper crust that are adjacent to the large conductive zone. The conductor **F** (< 1 ohm.m) occurs at upper to middle crustal depths (5-15 km) beneath site 279. The deeper parts of the body dips to the northeast, where it becomes more resistive (~ 5 ohm.m) in the lower crust and mantle, and is labeled **G**.

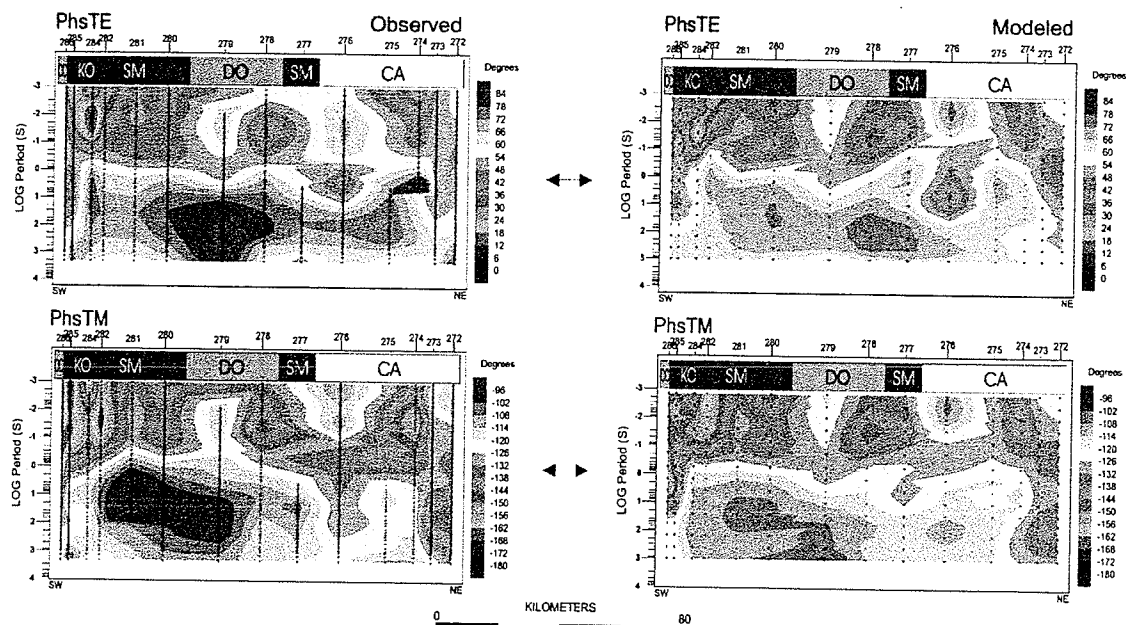


Figure 7.10 Comparison of the observed and model phase response for Model A.

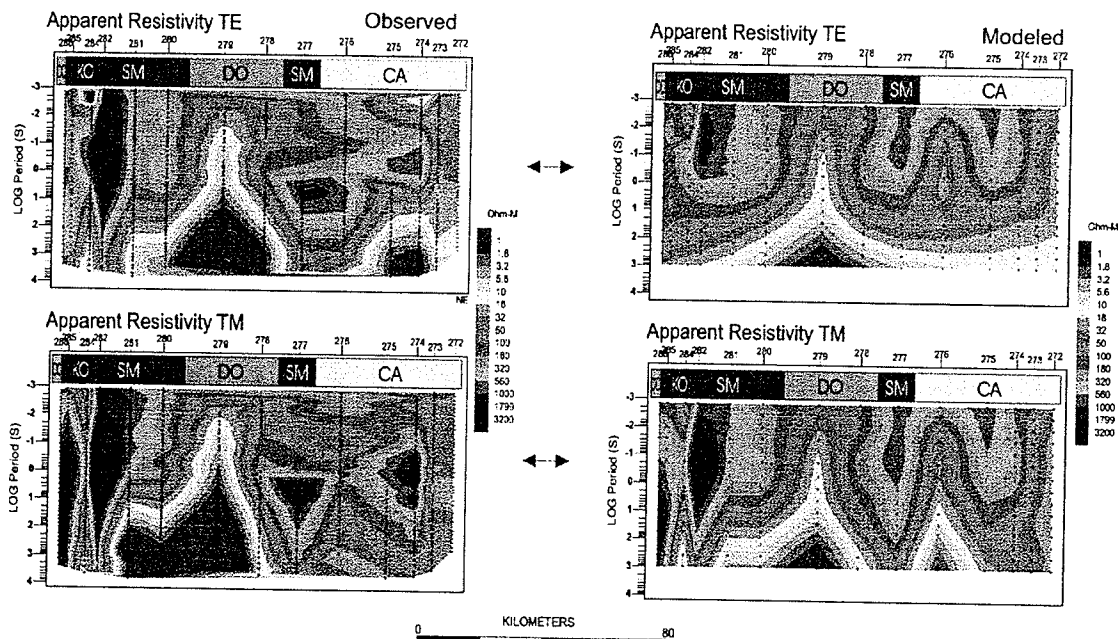


Figure 7.11 Comparison of the observed and modeled apparent resistivity response for Model A.

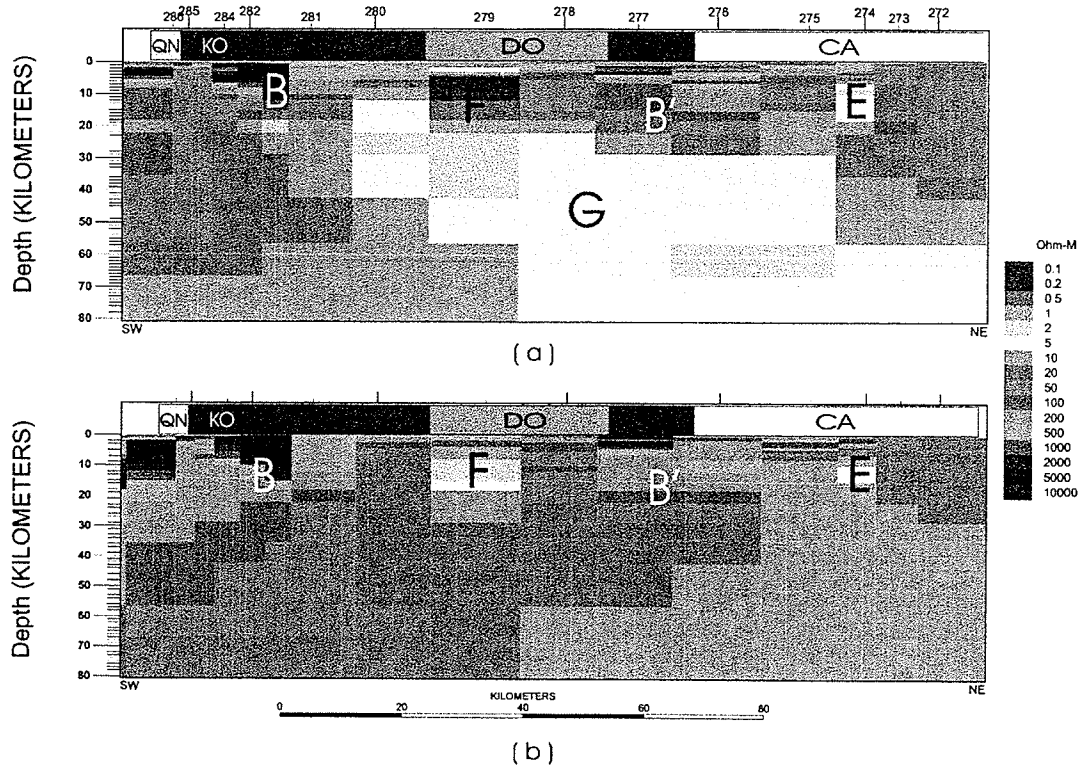


Figure 7.12 Occam model for the Connector Line for (a) inversion of apparent resistivity and phase data (Model A), and (b) inversion of apparent resistivity, phase, and tipper data (Model B).

7.2.2.2 Model B

Fit to Data

Comparison of the pseudosections of the observed and modeled apparent resistivity and phase response shows that most of the features in the observed data are represented in the model (Appendix F, Fig. 13, Fig. 14, and Fig. 15). A tolerance of 7.08 is achieved for Model B.

Inclusion of the tipper data in the inversion resulted in a generally worse fit to the apparent resistivity and phase data. The fit to the data at sites 274, 276, 277, 279, and 282 was poor as noted for Model A. However for Model B, the TM phase response has a distinctly poorer fit to the observed response for all the sites except for 274, 277, and 279.

At site 279, the fit to the observed apparent resistivity response is improved when the inversion includes the tipper data.

The tipper response for Model B shows partial correlation with the observed response (Fig. 7.15). Many additional inversions were run to try and improve the fit between the observed and modeled response (e.g using different error floors), but with only a limited success. For the final inversion, the real component of the tipper for the model response compares well with the observed response for sites in the Cassiar Terrane at periods greater than 10 s. However, poor fits to the data occur for the real component at sites 280 and 281 at periods greater than 100 s. A poor tipper fit also occurs for site 278 for both the real and imaginary components at periods less than 1 s.

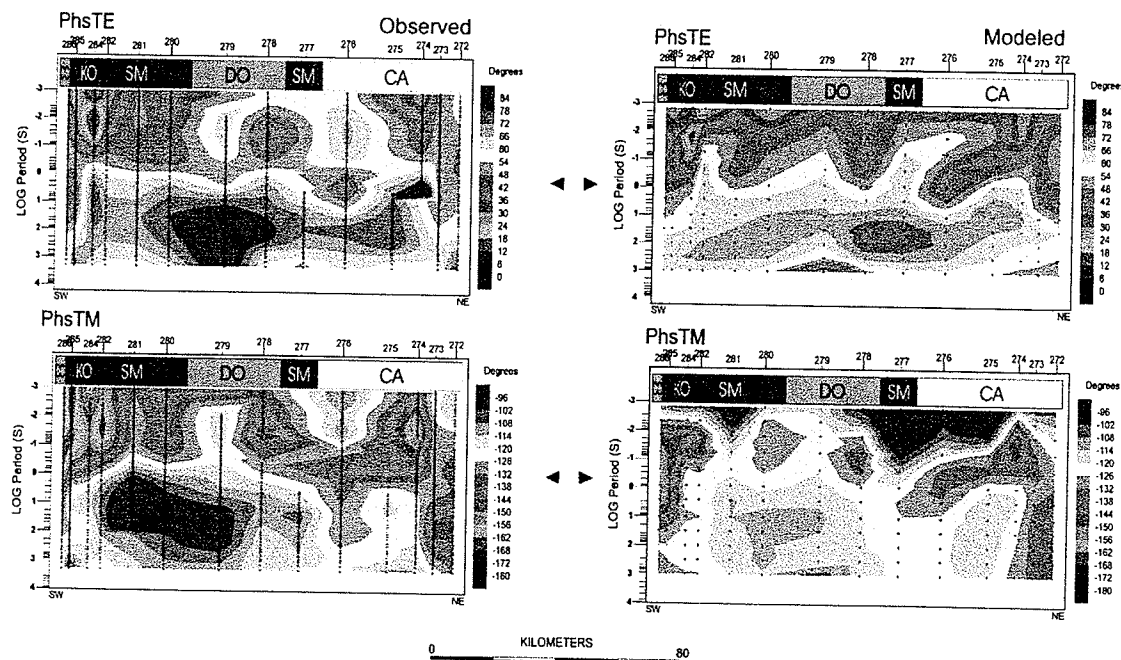


Figure 7.13 Comparison of the observed and model phase response for Model B.

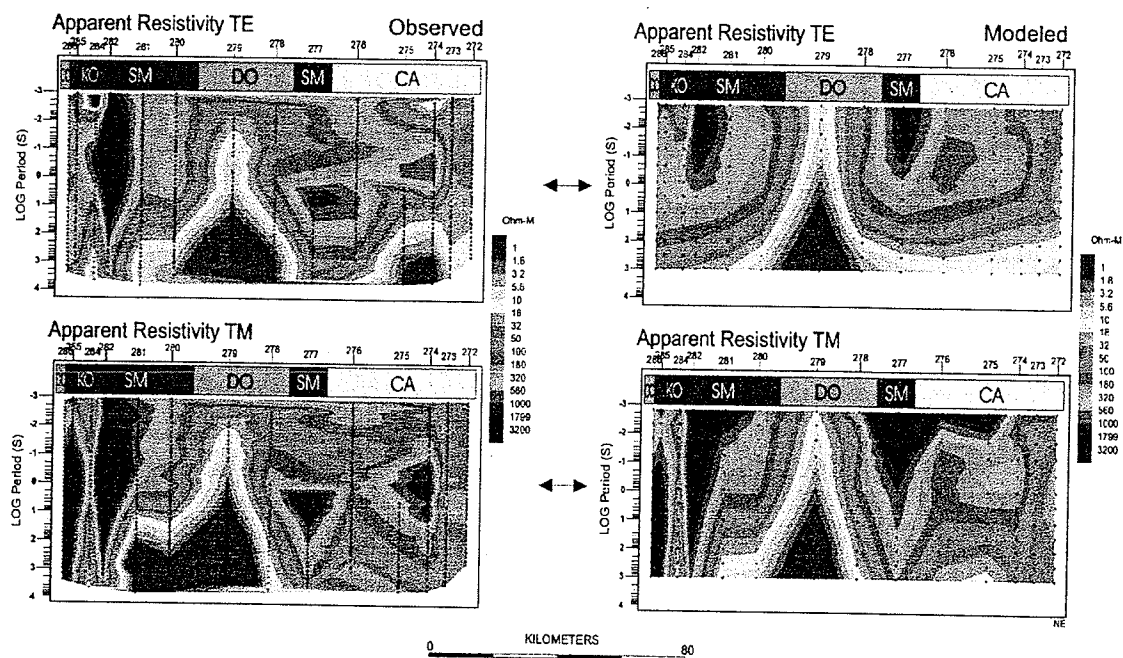


Figure 7.14 Comparison of observed and model apparent resistivity response for Model B.

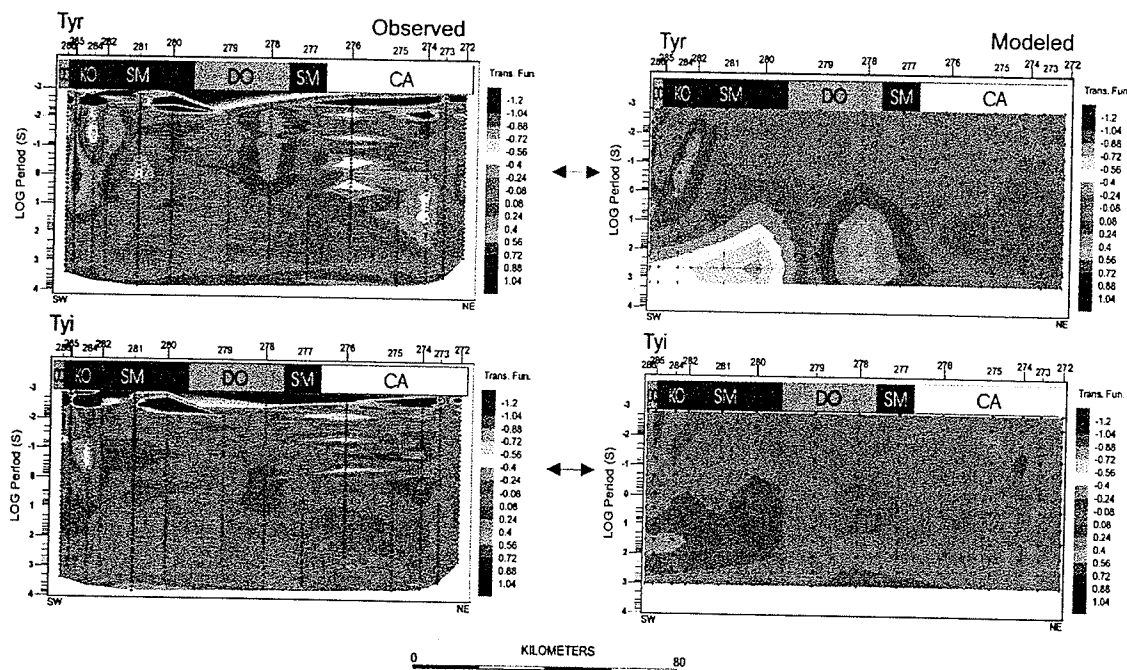


Figure 7.15 Comparison of the observed and model real (Tyr) and imaginary (Tyi) tipper components for Model B.

7.2.2.3 Comparison of Model A and Model B

Models A and B (Fig. 7.12) have similar resistivity structures at less than 20 km depth. The conductance of conductor **F** for Model A is ~10 000 S, whereas the conductance for conductor **F** for Model B is ~6000 S. At greater depths, the crust beneath sites 275 to 280 for Model B is more resistive, with resistivity values ranging from 20 to 100 ohm.m, than the same region for Model A, which includes a conductor (labeled **G**) with resistivity values of 5 ohm.m. Because Model B is based on more data than Model A and provides a partial fit to the observed tipper data it is the preferred Occam model for the Connector Line.

7.3 TWO-DIMENSIONAL NLCG INVERSION

Two-dimensional NLCG inversions were performed to better determine the resistivity structure of the subsurface. For the NLCG inversions, the algorithm from Mackie and Rodi (1996) and Rodi and Mackie (2001) was implemented using GEOTOOLS software.

Mesh Design

In the NLCG method the finite difference mesh defining the model is also used as the regularization grid in the inversion (Rodi and Mackie, 2001). The design of the rows and columns depends on the station spacing and the resistivity of the starting half space. Stations are separated by at least one column. As with the Occam models, the parameterized NLCG model was extended for hundreds of kilometers on either side of

the actual MT profile and to hundreds of kilometers depth in order to decrease edge effects.

Input Data and Inversion Parameters

For the NLCG inversion the input parameters are the starting model, error values on apparent resistivity and phase data, rms error for termination of the inversion, the regularization value *Tau*, and the quit error percent.

- 1) The starting model for the inversions in this study was a uniform half space of 100 ohm.m, 200 ohm.m or 500 ohm.m. The inversions for the different starting models converged to similar models indicating that the final model was relatively independent of the starting model (see Appendix G).
- 2) A 5% impedance error floor was used that corresponds to a 2.86° phase error and a 10% apparent resistivity error (Ferguson et al. 1999).
- 3) The *rms* error, which is related to tolerance (as discussed in section 3.8) is the error at which the program will terminate if it is reached before the specified maximum number of inversion iterations is reached (Mackie et al., 1997). It was set to 1.0 for the inversions in this study.
- 4) The regularization parameter *Tau* controls the tradeoff between fitting the data and adhering to the model constraint (Mackie et al., 1997). It controls the amount of smoothing in the model. It is related to the parameter τ in equation 3.40.
- 5) The parameter *quit error* determines when the program terminates (Mackie et al., 1997).

7.3.1 CONSTRUCTION AND INVERSION OF NLCG MODELS FOR LINE 2A

For the NLCG inversions the TE and TM modes were inverted both separately and together in order to determine which mode or both constrains the different features in the models. The TE mode and TM mode inversion alone can not accurately represent the true structure of the earth, but instead provides insights into the resistivity structure by allowing examinations of the similarities and differences of the features derived from the different modes.

Profile

For the inversion for Line 2a, the southern part of the profile (sites 200, 202, 203, 204, 205, 206, 207, 208, 209, and 210) was again excluded from the models, as discussed in section 6.2.2.

Inversion and Input Parameters

The input parameters for the final models are shown in Table 7.5. For Line 2a, 37 periods were used in the inversion (0.000733 s, 0.001 s, 0.0015 s, 0.0018 s, 0.0032 s, 0.0026 s, 0.0046 s, 0.0068 s, 0.01 s, 0.015 s, 0.022 s, 0.032 s, 0.046 s, 0.068 s, 0.1 s, 0.15 s, 0.22 s, 0.32 s, 0.46 s, 0.68 s, 1.0 s, 1.5 s, 2.2 s, 3.2 s, 4.6 s, 6.8 s, 10 s, 15 s, 22 s, 32 s, 46 s, 68 s, 100 s, 150 s, 220 s, 380 s, and 680 s). The mesh dimensions were 90 columns and 60 rows.

Table 7.5 Input parameters for the final NLCG models.

Model	Error Rho	Error ϕ	Tau	Quit Error	Final Iteration	Specified rms
TE	10%	2.5%	10	1%	54	1
TM	10%	2.5%	10	1%	48	1
TE & TM	10%	2.5%	10	1%	59	1

7.3.1.1 NLCG Inversion with One Mode

Fit to Data-TE Mode

Figure 7.16 compares the apparent resistivity and phase pseudosections for the TE data inversions. Based on examination of the pseudosections there is a good fit achieved between the modeled and observed data at most sites (Fig. 7.16). The average rms for all sites for the final iteration is 5.7. Only sites 217, 220, 222, 226, and 231 have rms error values greater than 8.0, as shown in Table 7.6. The resistivity values for sites 219, 220, 223, 226, 228, 232, and 240 have poorer longer period (> 1 s) fits than at shorter periods. Conversely, the phase at sites 219, 226, 232, and 234 have better shorter period (< 100 s) fits to the data.

The apparent resistivity misfit may in part be due to static shift, which causes a scaling of the apparent resistivity curve independent of period, as discussed in section 3.6.5. In order to examine the effects of static shift on the data set, many inversions were run, some with manual scaling of the apparent resistivity curves by an appropriate scaling factor and others with an increased apparent resistivity error chosen in order to decrease the contribution to the misfit from static shift effects. Examination of the modeled and observed data indicates that the large misfits for a number of the sites occurred whether the sites were shifted or not shifted.

Table 7.6 RMS values for the TE NLCG model for Line 2a.

Site	RMS Error	Site	RMS Error	Site	RMS Error
211	2.09	222	9.20	233	2.70
212	1.87	223	5.41	234	5.28
213	2.55	224	3.45	235	4.56
214	2.88	225	2.99	236	4.54
215	2.84	226	8.28	237	3.91
216	2.60	227	4.70	238	5.09
217	10.32	228	6.96	239	3.29
218	3.13	239	5.63	240	6.72
219	5.64	230	7.67	241	5.06
220	8.36	231	12.12		
221	3.03	232	5.66		

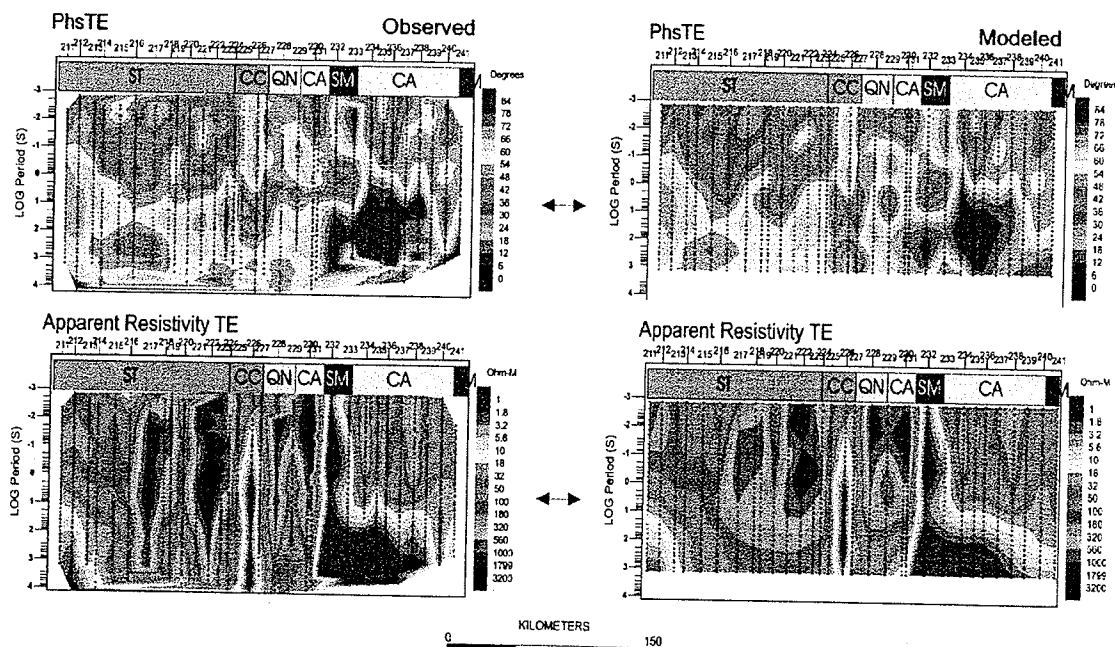


Figure 7.16 Comparison between the TE observed and model response.

Fits to Data-TM Mode

In the inversion of the TM data the average rms misfit to the data is 2.55. The response from the north portion of the line, including sites 234, 235, 236, 237, 238, 239, 240, and 241 fits the observed response extremely well, with rms error values at most northern sites less than 3, as shown in Table 7.7. Both the model phase and apparent

resistivity responses are similar to the observed data (Fig. 7.17). The only inconsistency between the model and the observed data occurs at periods less than 0.01 s for sites 214, 215, and 216, but even at these periods the large scale features in the observed response are reproduced in the model response.

Table 7.7 RMS values for the TM NLCG model for Line 2a.

Site	RMS Error	Site	RMS Error	Site	RMS Error
211	1.65	222	2.77	233	3.78
212	1.45	223	3.21	234	2.05
213	1.64	224	3.12	235	1.82
214	3.46	225	3.39	236	2.28
215	3.33	226	2.27	237	1.27
216	4.46	227	1.38	238	1.14
217	1.77	228	2.22	239	1.60
218	3.29	239	2.22	240	1.72
219	2.27	230	2.42	241	1.63
220	2.05	231	2.18		
221	3.54	232	2.91		

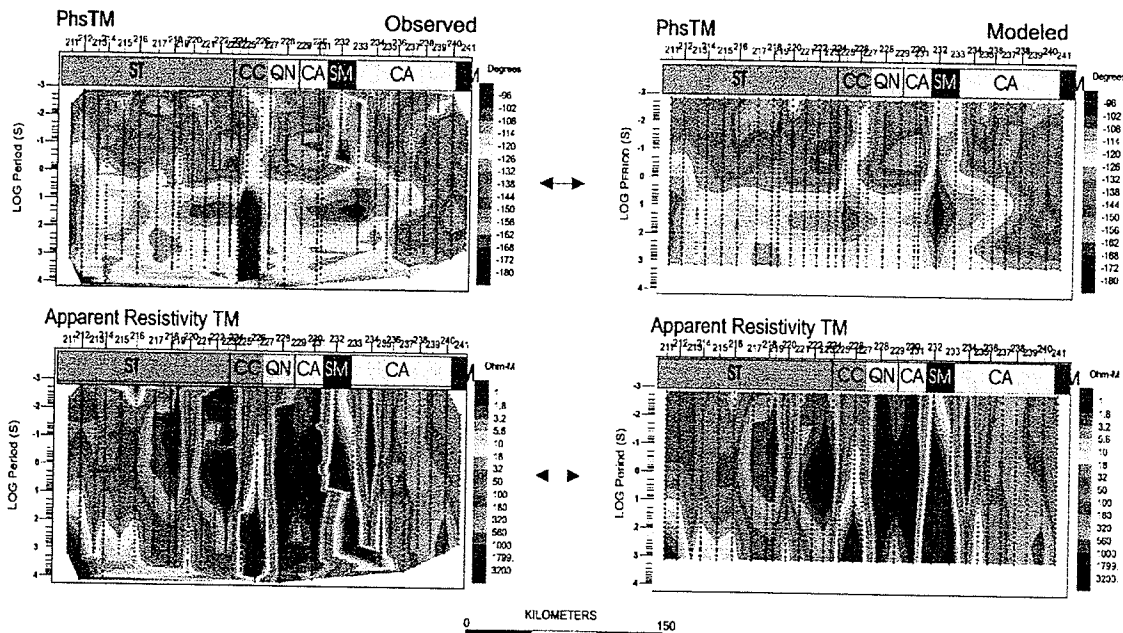


Figure 7.17 Comparison between the TM observed and model response.

Examination of Models-TE Mode and TM Mode

Examination of the TE and TM mode models shows that there are some common features, and some differences. Analysis of the models provides insight into the resistivity structure of the profile. For example, in areas where both the TE and TM mode model response is resistive, then likely the true resistivity structure is resistive, and similarly if both the TE and TM mode response is conductive, then likely the true resistivity structure is conductive.

The dominant feature of the models derived from the TE and TM mode response is a very resistive ($\sim 10\,000$ ohm.m) block beneath sites 216 to 231 (labeled **B**), which is in the northern portion of the Stikine Terrane, and the Cache Creek, Quesnellia, and Cassiar terranes (Fig. 7.18). The feature extends through the upper crust and into the lower crust for the TM mode model, and penetrates to mantle depths for the TE mode model. West of the resistive block, starting at ~ 10 km depth at sites 211 to 215 in the Stikine Terrane, is an eastward dipping conductor (< 1 ohm.m, labeled **A**), which extends from the upper crust to the lower crust. On top of the resistive block in the upper crust (< 5 km depth) beneath the Cache Creek and Slide Mountain terranes are thin conductive zones (< 1 ohm.m), labeled **X** and **Y** respectively. The horizontal extent of the zones coincides with the width of the Cache Creek and Slide Mountain terranes. The conductors **X** and **Y** are more conductive in the TE mode model (< 1 ohm.m) than in the TM mode model (~ 5 ohm.m). For the TE mode model, a large northeast dipping conductor (< 1 ohm.m, labeled **E**) is present beneath sites beneath the Cassiar Terrane and extends from 5 km to depths into the upper mantle. This same conductor is less conductive for the TM mode and does not penetrate to mantle depths.

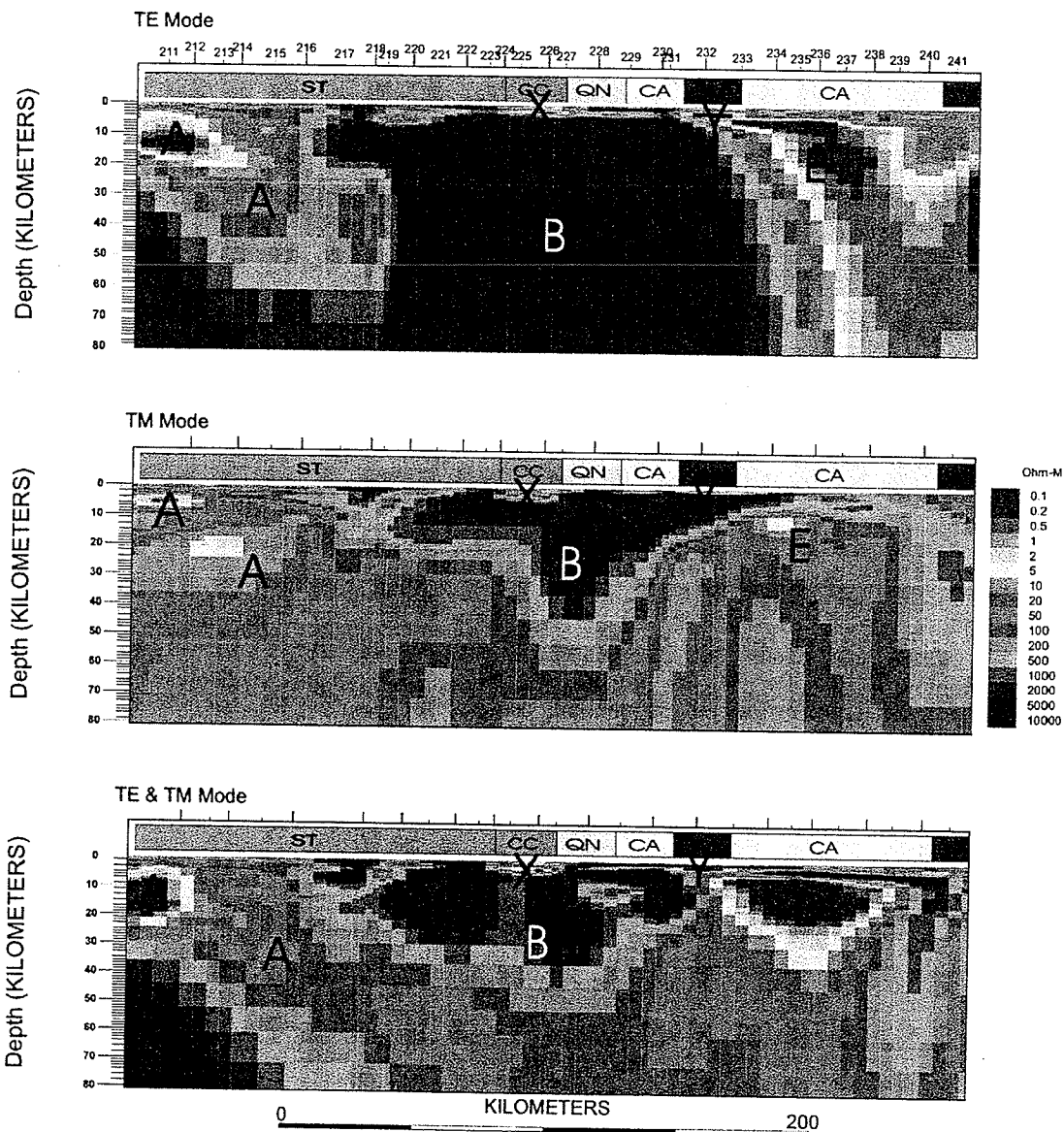


Figure 7.18 Inversion models determined from the TE mode data, the TM mode data, and the TE and TM mode data for Line 2a.

7.3.1.2 TE - TM model

Fit to data

Figure 7.19 compares the observed and model apparent resistivity and phase responses for the inversion of the TE and TM data. A good fit is achieved between the

modeled and observed response. The average rms misfit for all sites is 5.48 rms error.

Most sites have responses with rms error values less than 7, but a small number of sites (222, 226, and 231) have an rms error of ~9, as shown in Table 7.8. As with the TE mode model, there is a locally poor fit at sites 217 and 231, which is attributed to the presence of static shift at these sites. As for the TE mode data, the static shift was examined by manual shifting of the apparent resistivity curve and by increasing the apparent resistivity error floor, but no significant improvement was made in the model fits.

Overall the model phase responses are similar to the observed phase responses (Fig. 7.19). A poor fit to the observed phase is observed at short periods (<0.1 s) for sites 215 and 230, and at long periods (> 10 s) for sites 240 and 241. The misfit at site 240 corresponds with high χ^2 values (>20) (Fig. 5.14) in the GB decomposition suggesting the presence of 3D structure.

Table 7.8 RMS values for the TE and TM NLCG model for Line 2a.

Site	RMS Error	Site	RMS Error	Site	RMS Error
211	2.60	222	9.27	233	4.79
212	2.59	223	4.98	234	5.57
213	1.78	224	2.40	235	5.78
214	3.88	225	5.14	236	3.89
215	3.17	226	8.97	237	4.40
216	4.19	227	4.56	238	7.78
217	8.48	228	6.38	239	4.90
218	4.28	229	6.84	240	5.66
219	3.95	230	6.85	241	5.42
220	5.69	231	9.69		
221	3.57	232	4.32		

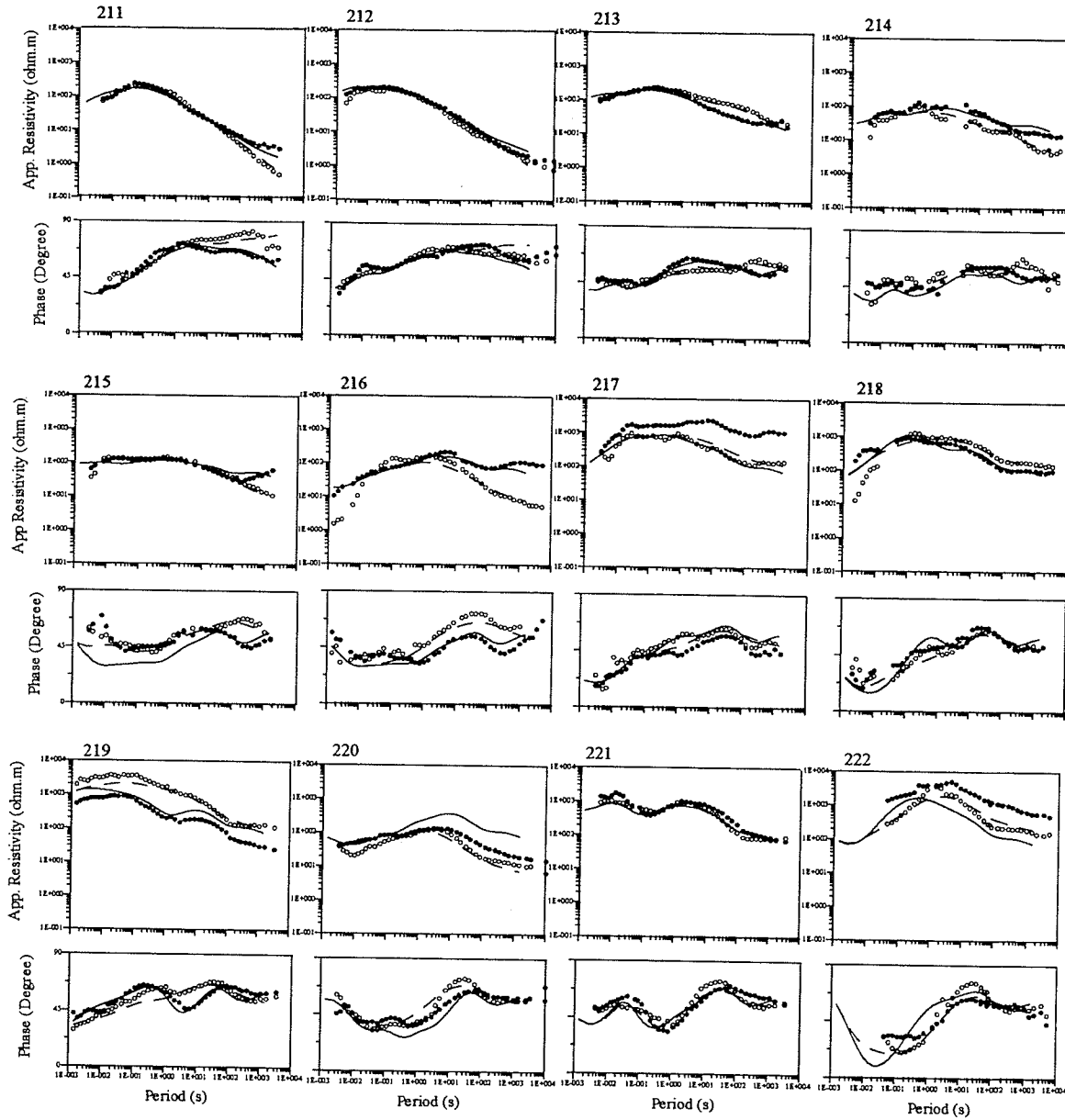


Figure 7.19 Comparison between the combined TE and TM model response with the observed response for Line 2a. Open circles are TM data and closed circles are TE data. The solid black line is modeled TE data and the dashed line is modeled TM data.

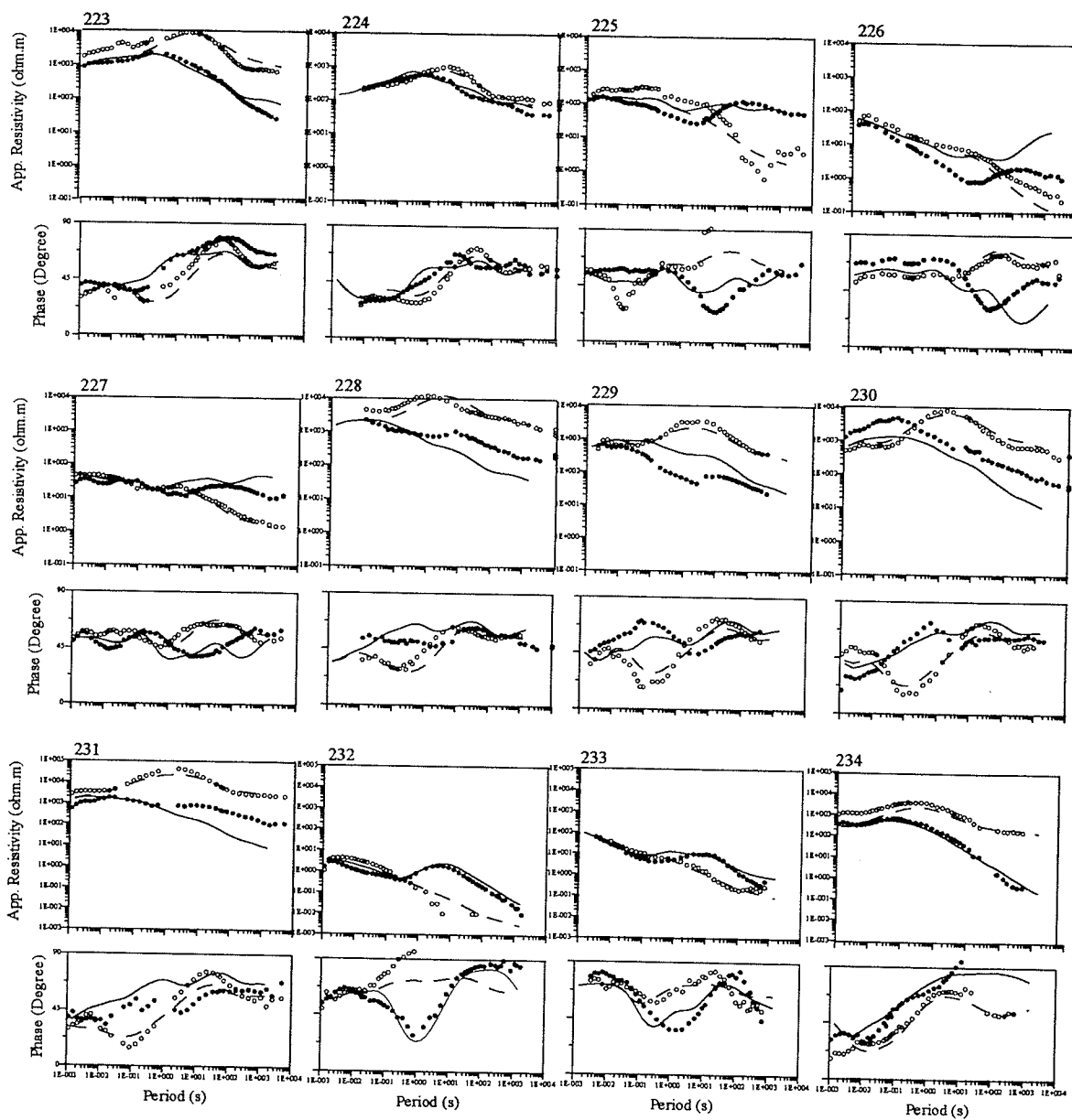


Figure 7.19 cont.

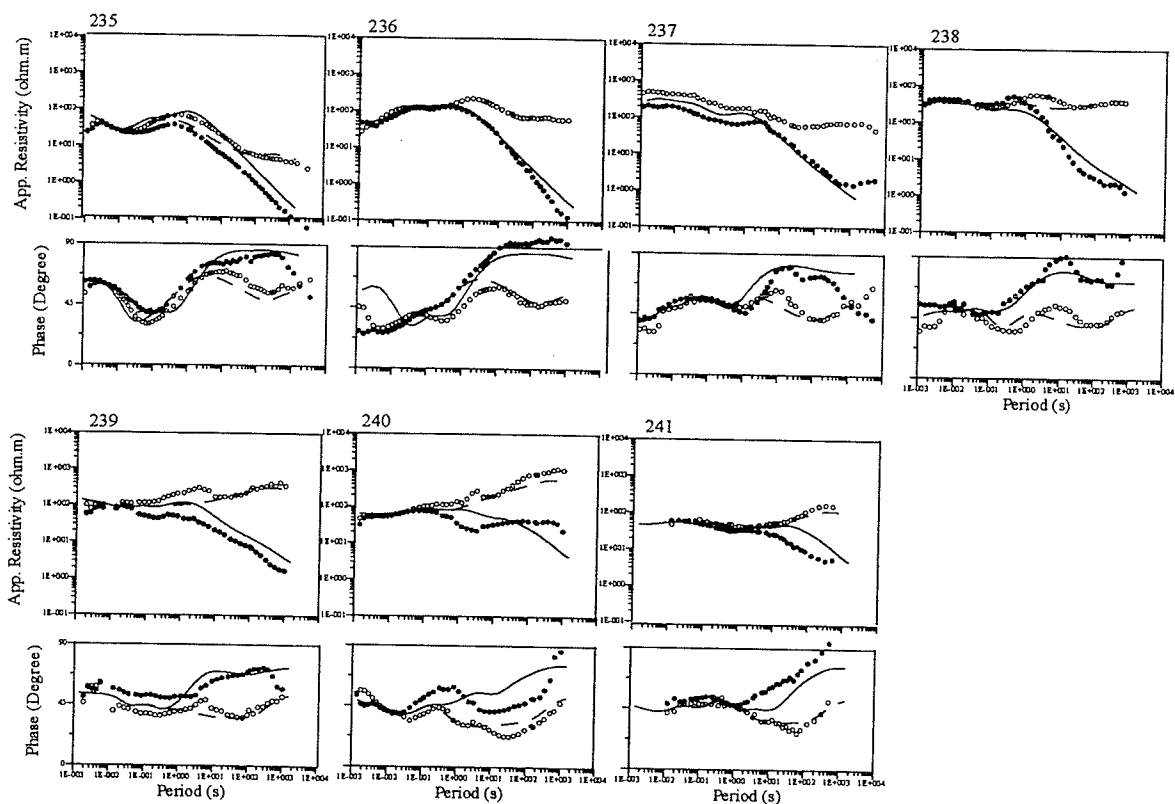


Figure 7.19 cont.

Examination of TE - TM Model

The TE - TM model (Fig. 7.18) is characterized by two shallow upper crustal conductors and a number of larger structures in the underlying crust and mantle. Narrow (< 20 km) conductive zones occur beneath the Cache Creek (labeled X) and Slide Mountain (labeled Y) terranes in the shallow upper crust (<3 km depth). The resistivity in these zones reaches values as low as 2 ohm.m. These features also occur in the individual TE and TM models providing confidence that they represent the true structures.

The deeper structure is dominated by the large resistive (> 1000 ohm.m) body beneath the northern Stikine Terrane and adjacent terranes to the north. This body is

labeled **B**. Beneath the Stikine Terrane the body extends from the surface to ~ 30 km depth. Further northeast, the upper surface dips to the northeast, reaching a depth of ~10 km beneath the Slide Mountain Terrane. The results suggest that beneath the Slide Mountain Terrane the lower surface of the body dips to the southeast forming a wedge-shaped point at the northeastern margin.

The conductor **E** ($< 2 \text{ ohm.m}$) forms an elongate body beneath the Cassiar Terrane. It extends approximately 60 km along the transect from 7 to 17 km depth. The upper surface of the body is approximately flat at its southern end but it dips to the northeast beneath the center of the Cassiar Terrane. The lower surface of the body deepens towards the center of the Cassiar Terrane, but is poorly resolved due to the skin depth effect (Section 3.1).

At the southern end of the profile there is a northwest dipping conductor (labeled **A**). This structure is most conductive at the end of the profile, where its resistivity reaches values less than 1 ohm.m , but it has a less conductive ($< 50 \text{ ohm.m}$) extension that dips northeast beneath the Stikine Terrane.

7.3.1.3 *TE - TM Model with Different Tau Values*

Figure 7.20 compares the 2D NLCG models for Line 2a obtained with regularization factors (τ) of 1, 10 and 50. The τ value controls the trade-off between fitting the data and adhering to the model constraint, as discussed in section 7.3. The three models have rms error values of 6.35, 5.48, and 6.79 respectively. As expected, the models with higher τ are smoother.

The *Tau* value has little effect on the geometry of the large resistive zone labeled **B**, but had a large effect on the geometries of conductors **A**, **Y**, and **E**. For a *Tau* of 50, conductor **A** no longer appears as a slab-like feature dipping to the northeast as it does for the model with a *Tau* of 10. For the model with *Tau* of 50 the south end of the profile has no distinct contact, but is conductive (< 50 ohm.m) at all depths (< 80 km) in the model. With a *Tau* value of 1, conductor **E** is very small and limited to crustal depths of less than 10 km, whereas with a *Tau* value of 50 the conductor extends to mantle depths greater than 60 km. A significant feature of the three models is that the upper surface of the slab has the same slope.

With a *Tau* value of 1 the model response over fits parts of the observed response at the cost of underfitting other parts. Conversely, the model with the *Tau* value of 50 is overly smooth resulting in the resistivity features, which are unrealistically gradual. The model with the *Tau* value of 10 is taken as the final model in this study because it provides a reasonable fit to the data while being relatively smooth.

7.3.1.4 Comparison between NLCG and Occam Models

Similar features (labeled **A**, **B**, **X**, **Y**, and **E**) are observed in both the Occam and NLCG models (Fig. 7.21) and provide confidence that these features exist. A description of the similar features as defined by the NLCG and Occam models is as follows.

- The region marked **A** is a conductive (< 2 ohm.m) zone. Its upper surface starts at ~5 km depth and dips in an northeast direction ($\sim 30^\circ$) through the middle and lower crust.

- The regions marked X and Y are thin conductors (<2 ohm.m) in the shallow upper crust.
- The region marked E is a conductive (<1 ohm.m) feature in both models, but is slightly larger in the NLCG model.

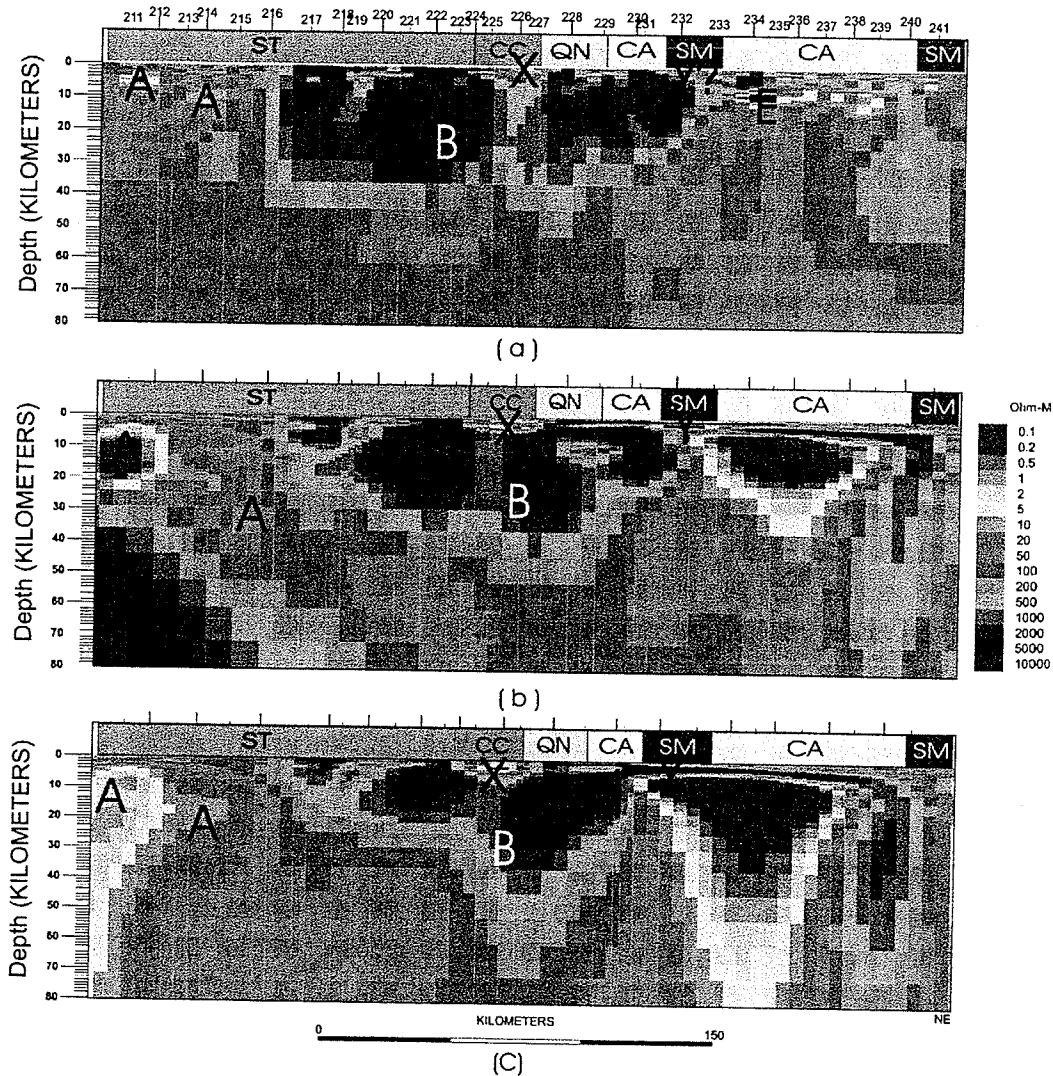


Figure 7.20 Comparison of NLCG inversion models along Line 2a. The inversions used the various τ values: (a) 1, (b) 10, and (c) 50.

Resistor B is significantly different in both the models. For the NLCG model, resistor B is very extensive, over 50 km wide and 30 km deep, and has resistive values

greater than 1000 ohm.m. This same region is more conductive for the Occam model particularly beneath conductor X where the resistivity is approximately 20 to 50 ohm.m. The Occam model for the central part of Line 2a, which included inversions of the tipper data (Fig. 7.9) was more resistive in this region, and more similar to the NLCG model. Considering this factor, and the better fit to the data for the NLCG model, it is likely that this region is a large resistive zone.

The NLCG model is taken as the better model for the Line 2a data because it uses a finer regularization grid, uses more periods in the inversion, and provides a better fit to the data than the Occam models. The Occam model, is useful for confirming the existence of the structure in the model as greater confidence can be placed on structures derived using separate algorithms.

7.3.2 CONSTRUCTION AND INVERSIONS OF NLCG MODEL FOR THE CONNECTOR LINE

Profile

As discussed above, the data from sites 282 and 283 were excluded from the inversions of the Connector Line data.

Inversion and Input Parameters

The input parameters for the final inversions are shown in Table 7.9. The same 37 periods were inverted for the Connector Line as for Line 2a. The mesh and grid dimensions consisted of 95 columns and 60 rows. The resistivity of the starting half space for the inversions is 100 ohm.m.

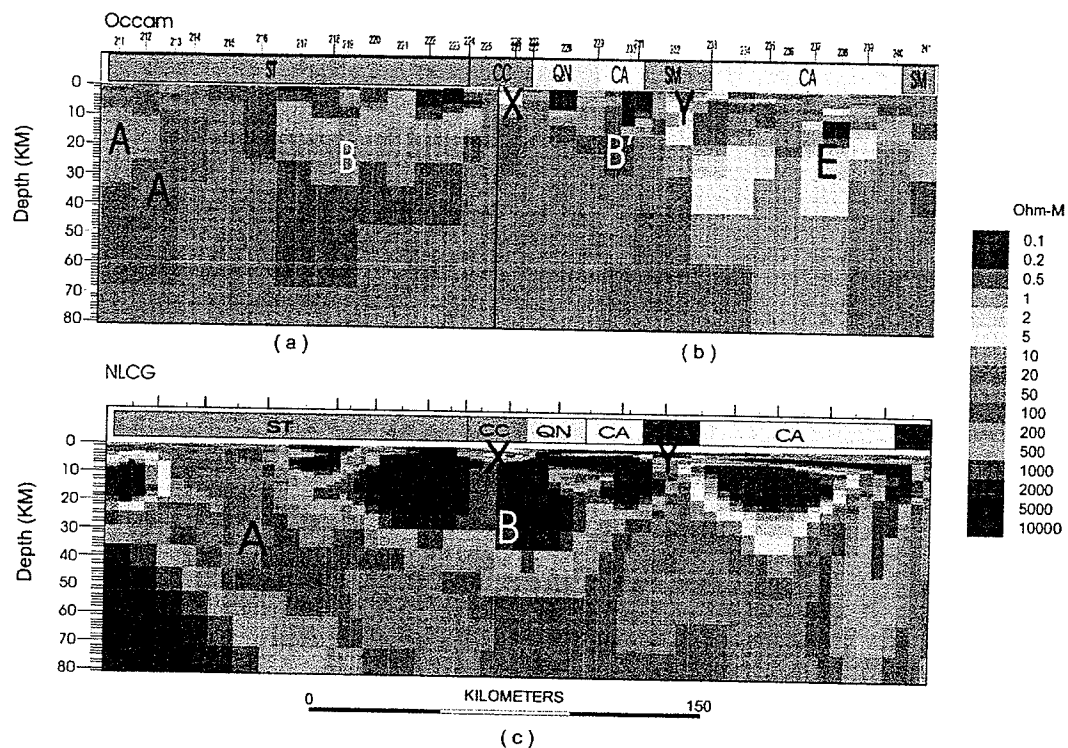


Figure 7.21 Final 2D inversion models for (a) the south segment of the Line 2a profile (Occam), (b) the north segment of the Line 2a profile (Occam), and (c) the NLCG model for the Line 2a profile.

Table 7.9 Input parameters for NLCG models.

Model	Error ρ	Error ϕ	Tau	Quit Error	Final Iteration	Specified rms
TE	10%	2.5%	10	1%	48	1
TM	10%	2.5%	10	1%	57	1
TE & TM	10%	2.5%	10	1%	48	1

7.3.2.1 NLCG Inversion with One Mode

As with the NLCG models for Line 2a, the TE and TM modes will be inverted both separately and together in order to examine the resolution of particular structures.

Fit to Data-TE Mode

Figure 7.22 compares the observed and model apparent resistivity and phase pseudosections for the inversions of the TE data. Large-scale features in the observed response are reproduced in the model response (Fig. 7.22). An rms misfit of 6.37 is achieved for the TE model. Only sites 284, 282, 277, and 276 have rms misfits over 8. The large misfit at site 276 is associated with high shear values ($>35^\circ$), which indicate a significant amount of distortion at periods greater than 100 s (Fig. 5.5). At site 277 the GB minimization failed to converge. Finally, the high rms error value for site 274 corresponds with high skew values (> 0.9) at periods greater than 1 s (Fig. 5.2), which suggest the presence of 3D structure.

Table 7.10 RMS values for the TE NLCG model for the Connector Line.

Site	RMS	Site	RMS
286	2.75	278	3.45
285	3.57	277	9.10
284	10.23	276	9.02
282	11.34	275	5.06
281	5.42	274	7.27
280	2.72	273	3.52
279	2.50	272	2.31

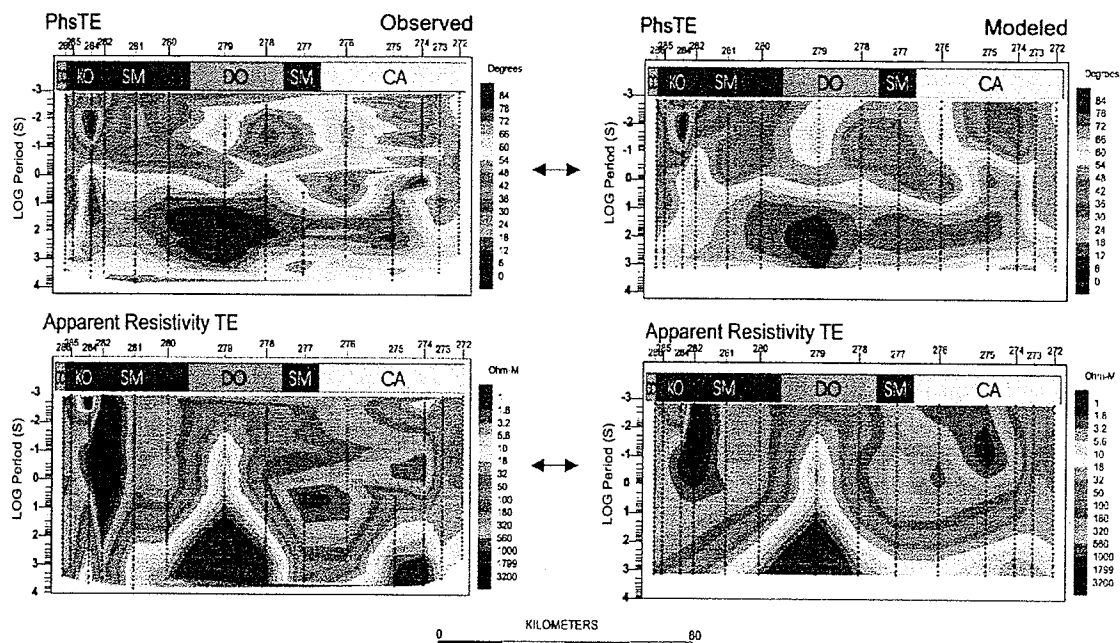


Figure 7.22 Comparison between the TE observed and model response.

Fits to Data-TM Mode

Figure 7.23 compares the apparent resistivity and phase pseudosections for the inversions of the TM data. An rms misfit of 2.71 was achieved between the modeled and observed response. Site 281 has a marginal fit (rms error of 6.25) between the modeled and observed response for periods 0.1 to 1 s for both the apparent resistivity and phase response (Fig. 7.23). High levels of distortion (GB decomposition failed) and high skew values (>0.5) indicating 3D structure (Fig. 5.2) are observed at this site. Other sites have rms misfits of less than 3, as shown in Table 7.11, indicating that the model response provides a good fit to the observed response.

Table 7.11 RMS values for the TE NLCG model for the Connector Line.

Site	RMS Error	Site	RMS Error
286	1.82	278	1.70
285	2.89	277	1.76
284	2.83	276	2.30
282	2.83	275	0.88
281	6.25	274	2.94
280	2.13	273	2.22
279	1.73	272	1.56

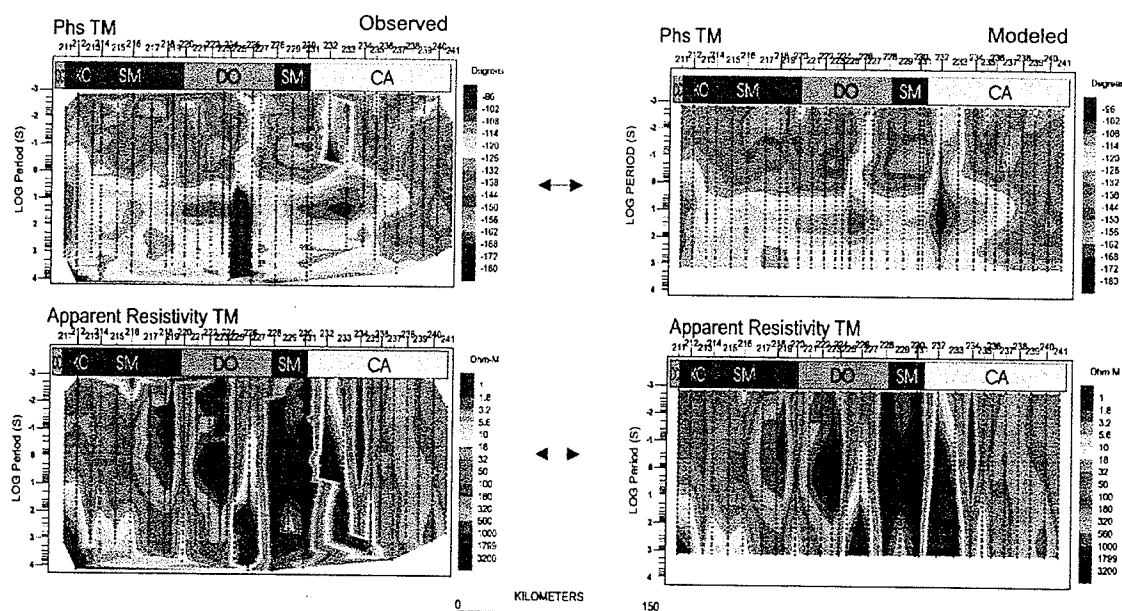


Figure 7.23 Comparison between the TM observed and model response.

Examination of Model TE Mode and TM Mode

As shown in Figure 7.24, the TM model has most of the same features as the TE model (**B**, **B'**, **F**, and **E**), except that the TM model is more conductive (~ 5 ohm.m, labeled **F** and **G**) at depths greater than 8 km for most of the profile and the resistors **B** and **B'** are less extensive. The structure beneath site 272 also has different resistivity in the two models. The conductors labeled **E** and **F** have a similar for in the two models.

7.3.2.2 TE-TM model

Fit to data

Figure 7.25 compares the observed and modelled apparent resistivity and phase responses for the inversions of the TE - TM model. An rms misfit of 5.92 between the observed and modeled response is achieved. As with the inversion that included only one mode, sites 284, 282, 276, and 274 had larger rms values compared to the other sites, as shown in Table 7.12. The large rms values for these sites are again attributed to either one of or a combination of: galvanic distortion or 3D induction effects. At other sites the features in the observed data are reproduced in the modeled response (Fig. 7.25).

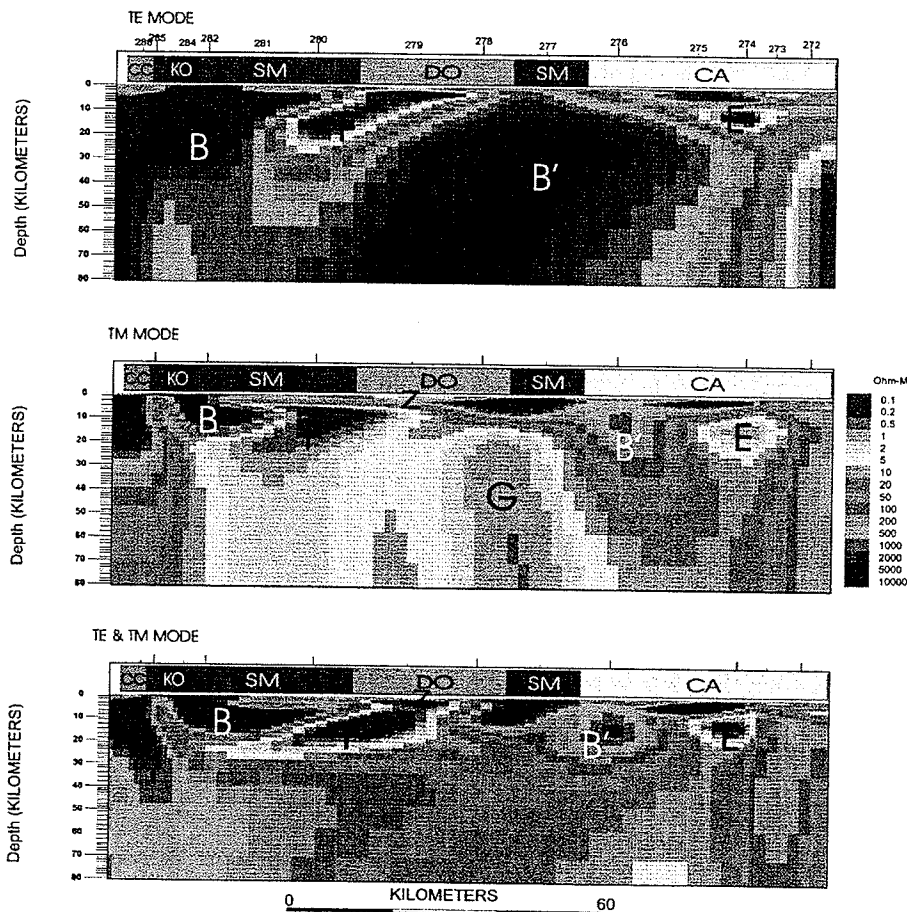


Figure 7.24 NLCG models for the Connector Line determined from the TE mode data, the TM mode data, and both the TE and TM mode data.

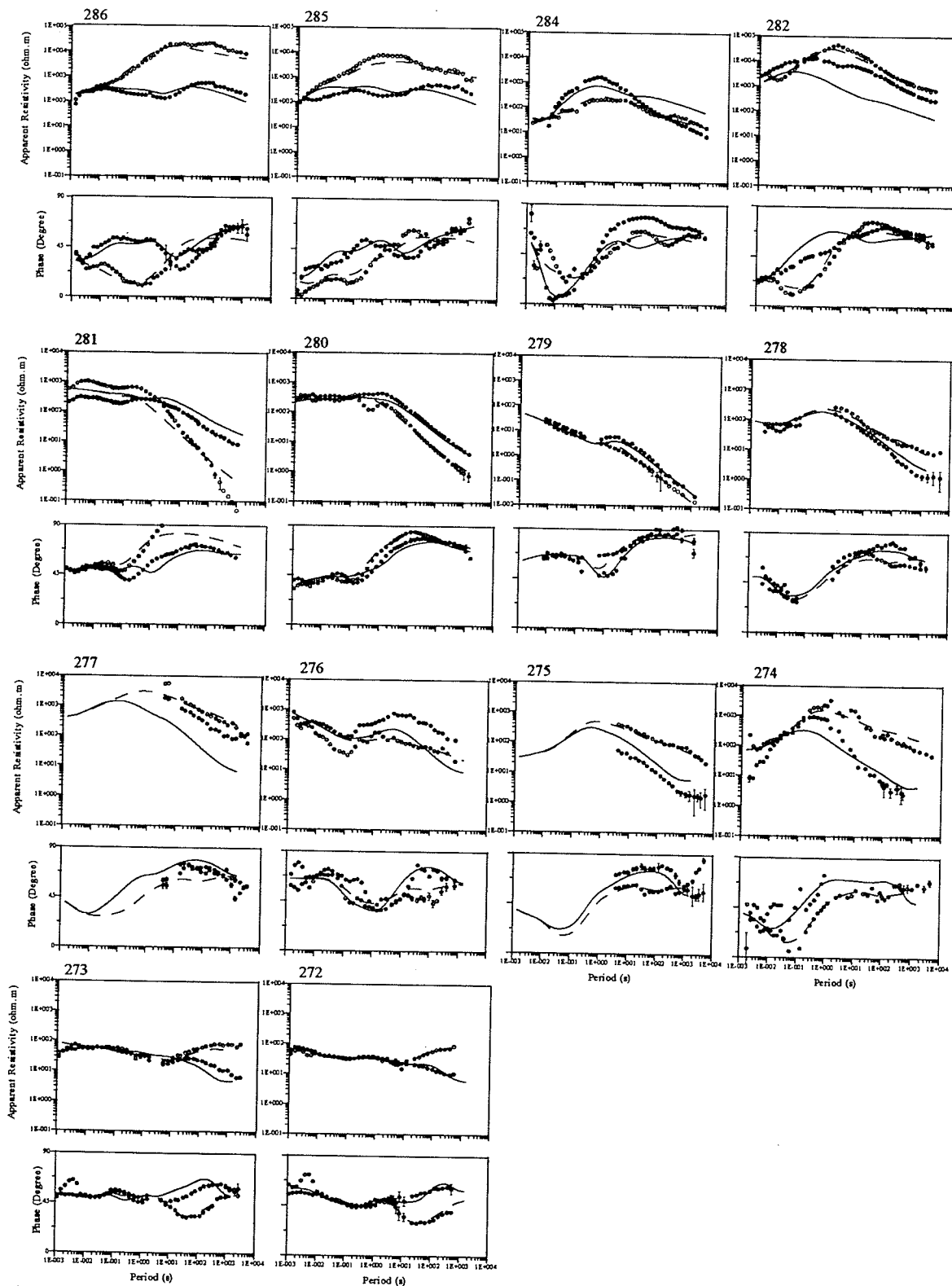


Figure 7.25 Comparison between the combined TE and TM model with the observed response for the modeled portion of the Connector Line. White circles are TM data and black circles with black outline are TE data. The solid black line is modeled TE data and the dashed line is modeled TM data.

Table 7.12 RMS values for the TE and TM NLCG model for the Connector Line.

Site	RMS	Site	RMS
286	4.12	278	3.05
285	4.58	277	7.82
284	7.30	276	7.98
282	9.91	275	3.33
281	6.67	274	9.09
280	2.01	273	3.21
279	3.05	272	2.28

Examination of TE-TM Model

The TE - TM model has similar resistivity features to the TE model and the TM model (labeled **B**, **B'**, **F**, and **E** in Fig. 7.24). It includes a very shallow upper crustal conductor (<1 ohm.m) at depths less than 2 km beneath the Dorsey Terrane. The deeper structure contains resistive zones extending from near the surface to 12 km depth beneath the Slide Mountain and Kootenay terranes (labeled **B**) and from the surface to 30 km depth beneath the eastern segment of the Slide Mountain Terrane and the Cassiar Terrane (labeled **B'**). Lying between the two resistive zones in the model, beneath sites 281 to 279, is a strong conductor (labeled **F**), which has roughly the same size in all the NLCG models. The top surface of the conductor occurs at about 3 km depth beneath the northern Dorsey Terrane and dips to southwest around 15 km. The TE-TM model also includes a conductor at ~10 km depth within the Cassiar Terrane (labeled **E**), which is present in all of the NLCG models for the Connector Line.

7.3.2.3 TE-TM Model with Different *Tau* Values

Figure 7.26 compares the 2D NLCG models with *Tau* values of 1, 10 and 50 for the Connector Line profile to determine which *Tau* value is more appropriate. The rms values for the models are 5.66, 5.92, and 6.40 respectively. The three models show the same basic resistivity structure, suggesting the features of the model are well resolved. The *Tau* value had relatively little effect on sites 286 to 280 in the western portion of the profile and 276 to 272 in the eastern portion of the profile. Conductor **E** has approximately the same conductivity and depth extent in the models with a conductance of approximately 5000 S. The main difference between the models is the resistivity and extent of conductors **Z** and **F**. For the model with a *Tau* value of 1 the conductors are separated by a resistive zone, whereas for the models with a *Tau* value of 10 or 50 and increased smoothing the conductors merge into a single body. As for Line 2a, the model with a *Tau* value of 10 is chosen as the best model.

7.3.2.4 Comparison between NLCG, and Occam Models

Common features of the NLCG and Occam resistivity models are marked "**B**", "**B'**", "**F**" and "**E**" in Figure 7.27. Both models include conductor **E** in the crust (~10 km depth) beneath the Cassiar Terrane and include resistive zones **B** and **B'** in the upper crust. The **F** conductor is larger in the NLCG model in which it extends to the middle and lower crust. It is limited to the upper 15 km for the Occam model. The NLCG model includes two separate conductors labeled **Z** and **F** beneath the Dorsey and Slide Mountain terranes, whereas in the Occam model the conductors are merged together (in a similar manner as in the NLCG model for large values of *Tau*).

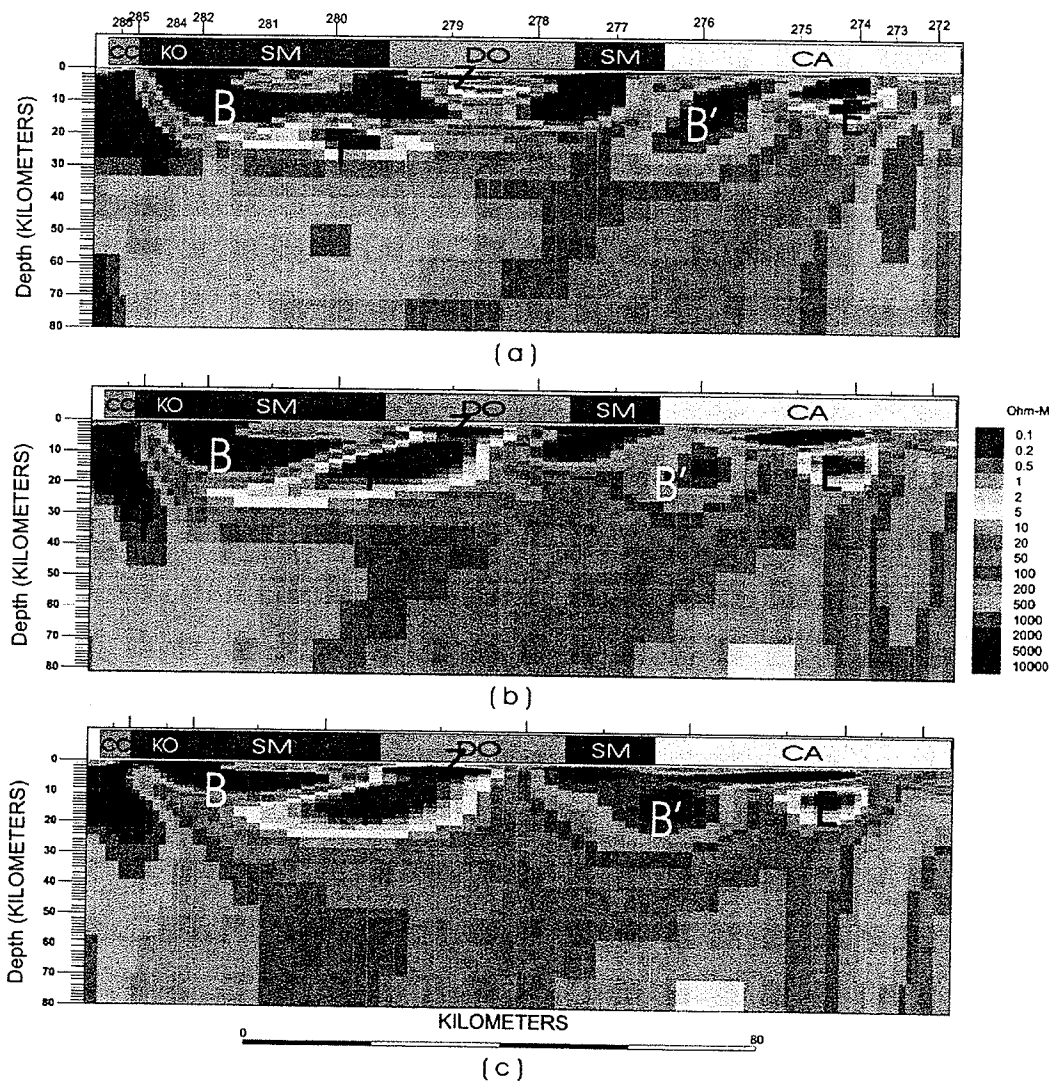


Figure 7.26 Comparison of NLCG inversion models along Line 2a. The inversions used the various τ values: (a) 1, (b) 10, and (c) 50.

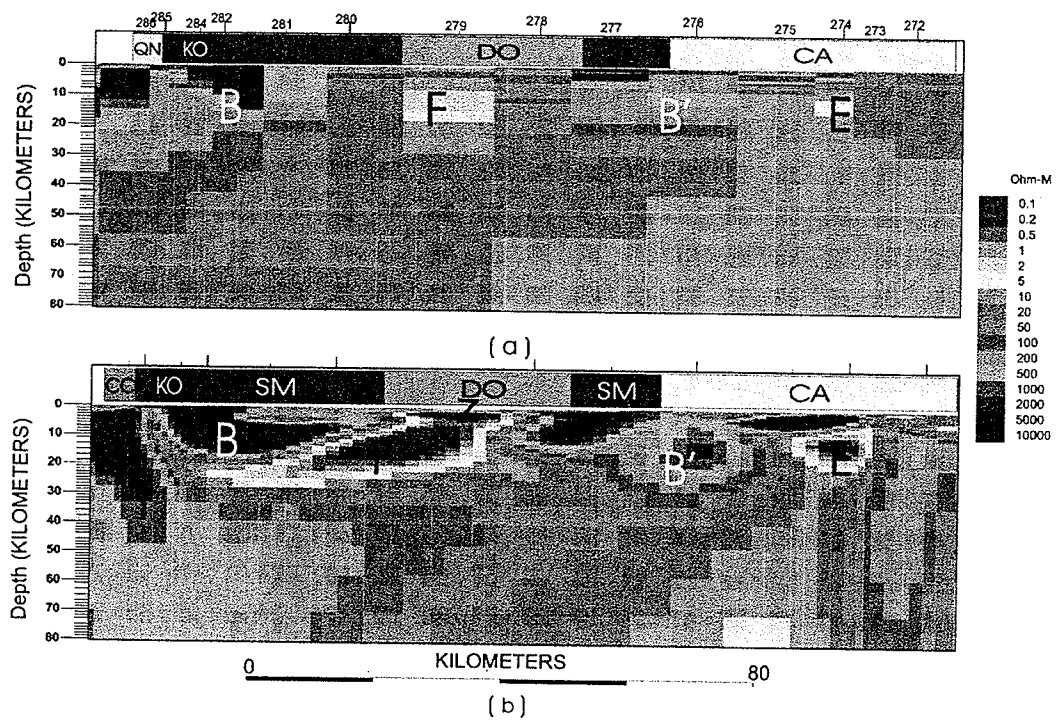


Figure 7.27 Comparison between the (a) Occam model and (b) the NLCG model for the Connector Line.

CHAPTER 8 – DISCUSSION AND INTERPRETATIONS

This chapter describes the interpretation of the MT responses and resistivity models. The MT results are integrated with other geological and geophysical information in order to develop a geological interpretation for the Line 2a and Connector Line region.

8.1 FINAL RESISTIVITY MODELS

The examination of the MT data, dimensionality, distortion, geoelectric strike directions, apparent resistivity, phase and induction vector responses, and the subsequent modelling and inversion, has provided the foundation from which geological interpretations can be made. The NLCG models will be used as the primary result from which to develop geological interpretations. Figure 8.1 shows the final MT models up to 10 km depth and Figure 8.2 shows the final MT models up to 80 km depth.

8.2 GEOMETRY OF RESISTIVITY STRUCTURE

A number of structures in the resistivity models for the Line 2a and Connector Line profiles have similar geometry. These features have been marked **B**, **B'**, and **E** on Figures 8.1 and 8.2. The Connector Line model contains resistive zones extending from near the surface to 20 km depth beneath the Slide Mountain and Kootenay terranes, and from the surface to 30 km depth beneath the southern segment of the Slide Mountain Terrane and northern Cassiar Terrane, (labeled **B** and **B'** respectively in Fig. 8.1 and Fig. 8.2). Based on a strike azimuth of -45° these resistive zones are approximately along strike from the resistive zone labeled **B** in Line 2a and are interpreted as forming part of the same resistive structure. A similar structure is observed in Corridor 3 models obtained

from Ledo et al. (2002b) (Fig. 8.3). The resistive zones **B** and **B'** are separated by a conductor (labeled **F**) on the Connector Line profile. There is a small conductor, labeled **X**, on the Line 2a model but this is not interpreted to be part of the same conductor.

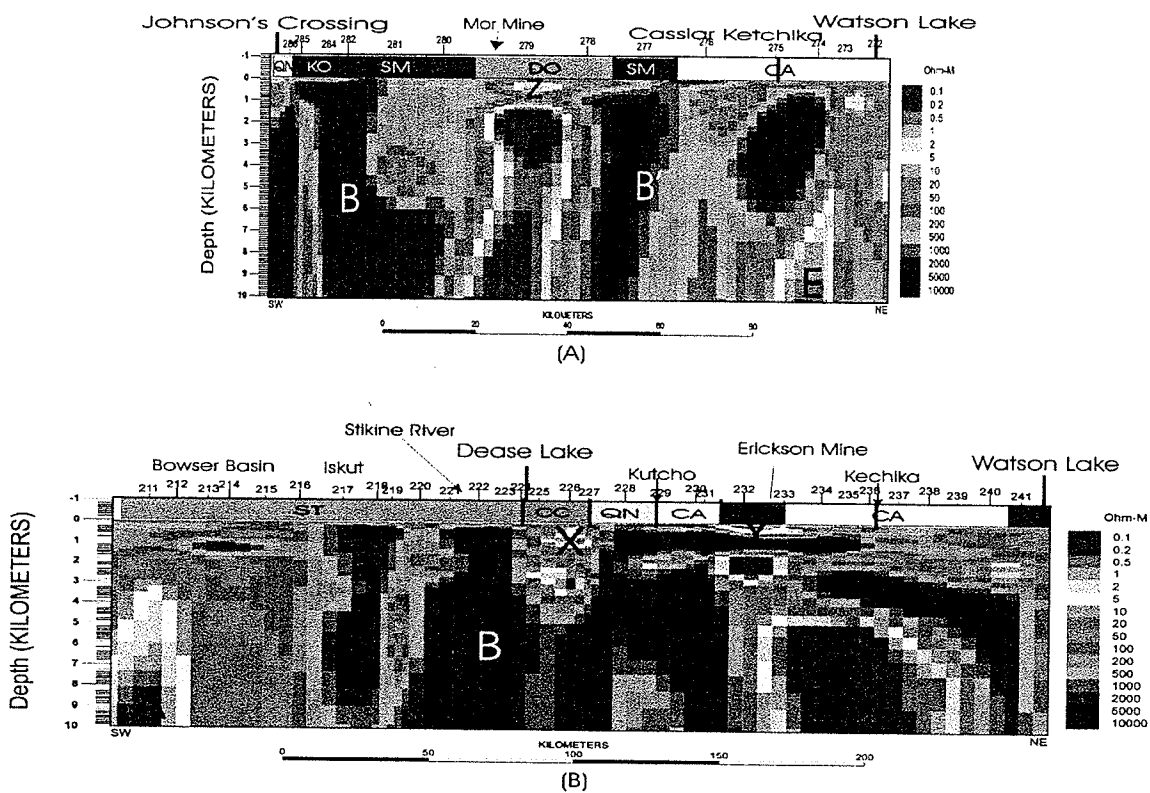


Figure 8.1 Final (NLCG) MT model showing the upper 10 km for (a) the Connector Line and (b) Line 2a. Faults are marked as purple lines on the geology bar. Locations of major faults, mines, and towns are also labeled.

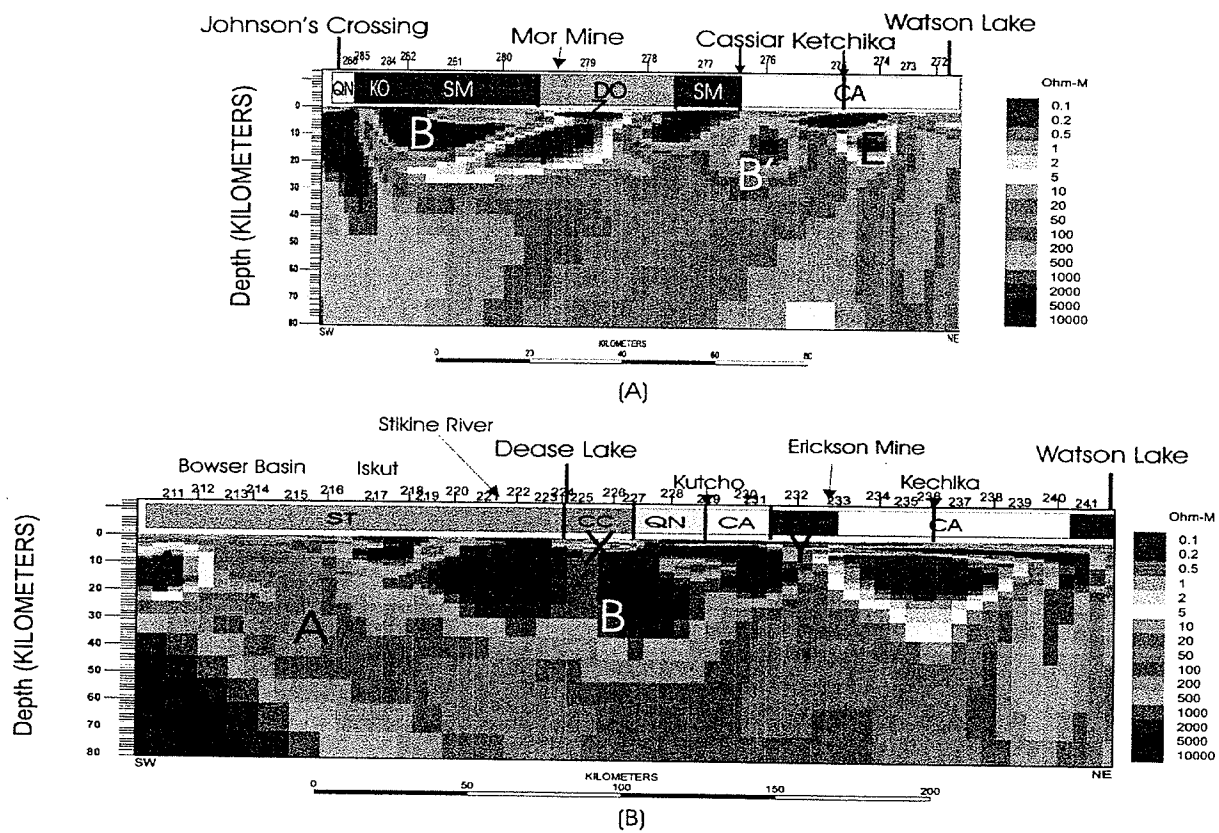


Figure 8.2 Final (NLCG) MT model for (a) the Connector Line and (b) Line 2a.

Conductor **E** appears at approximately the same depth (~10 km) and location in the Cassiar Terrane on Line 2a and the Connector Line. It is possible that the same feature is being crossed by both profiles. The different orientation of the two lines relative to the geological strike will contribute to the change in cross-sectional shape of the body in the two models. A conductor also occurs in the Cassiar Terrane on Line 3 but at a greater depth (around 20 km) than the corresponding conductors on Line 2a and the Connector Line (Fig. 8.3). The conductor is also present in the resistivity models of the Tintina Fault zone (Fig. 2.4) where it is labeled **B**.

There is a conductive structure (labeled **A**) visible on both the Line 2a and Line 3 profiles that is not seen on the Connector Line profile because of the shorter length of this line. A similar dipping body is noted at the southwestern end of the MT model for Line 3 (Wolynech, 2000; Ledo *et al.* 2002b) and for Line 2a. The most conductive part of the body for both profiles is located on the oceanward end. The depth to the top of the conductor on Line 2a (>10 km) is shallower than the depth of the conductor on Line 3 (>20 km), but this difference may be explained by the position of the lines. The dip of the structure imaged on Line 2a is also shallower than the dip on Line 3, but this difference may be explained by the oblique orientation of Line 3 relative to the coast. The results therefore suggest that the same or a very similar body is being imaged on Corridor 2 and Corridor 3.

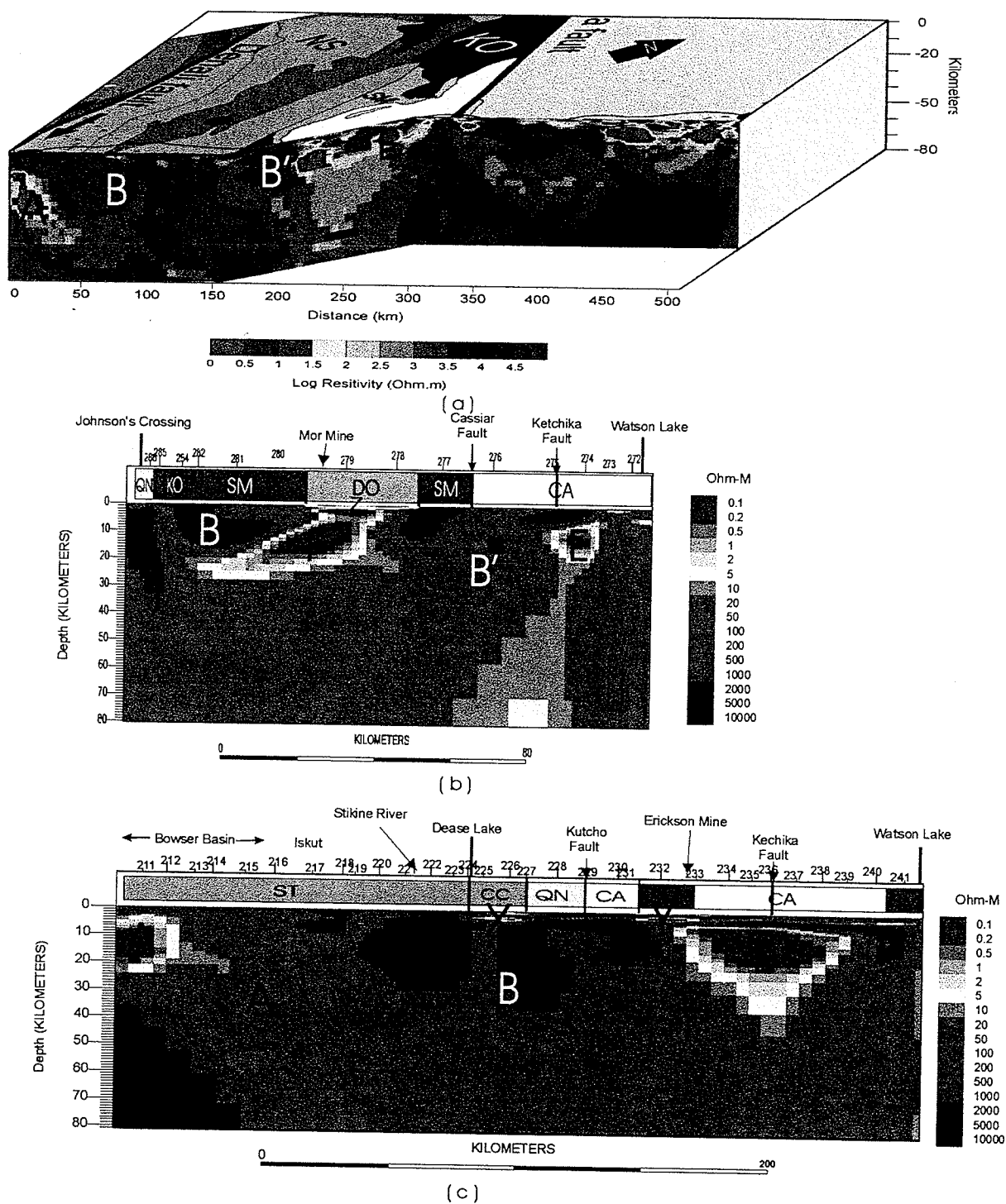


Figure 8.3 MT models from north to south in the northern Cordillera for (a) Line 3 (modified from Ledo et al. 2002b), (b) Connector Line, and (c) Line 2a. The location of the lines is shown in Figure 1.2.

8.3 SHALLOW CRUSTAL RESPONSE

The following section includes a geological interpretation of the upper crustal (< 5 km) resistivity structure for Line 2a and the Connector Line.

8.3.1 DORSEY TERRANE

Previous studies have suggested that the Dorsey Terrane, which is composed of mostly green phyllite containing magnetite porphyroblasts, schist, sandstone, argillite, and chert rocks, forms a thin surface terrane in the shallow upper crust (Monger et al., 1991). The MT results, which show a surface conductor (1 ohm.m, labeled **Z**) that is less than 1.5 km thick (Fig. 8.1a), provide support for this hypothesis.

Because there are only two MT sites in the Dorsey terrane, it is not possible to determine whether the whole terrane is composed of conductive rocks or whether there are localized conductors near sites 278 and 279. In the former case the enhanced conductivity could be explained by the widespread occurrence of graphitic or metalliferous rocks. In the latter case the high conductivity may be due to a localized presence of sulphides or oxides. Volcanogenic massive sulphides occur at the Mor mine in the Yukon Territory less than 15 km west of site 279 (Fig. 8.1).

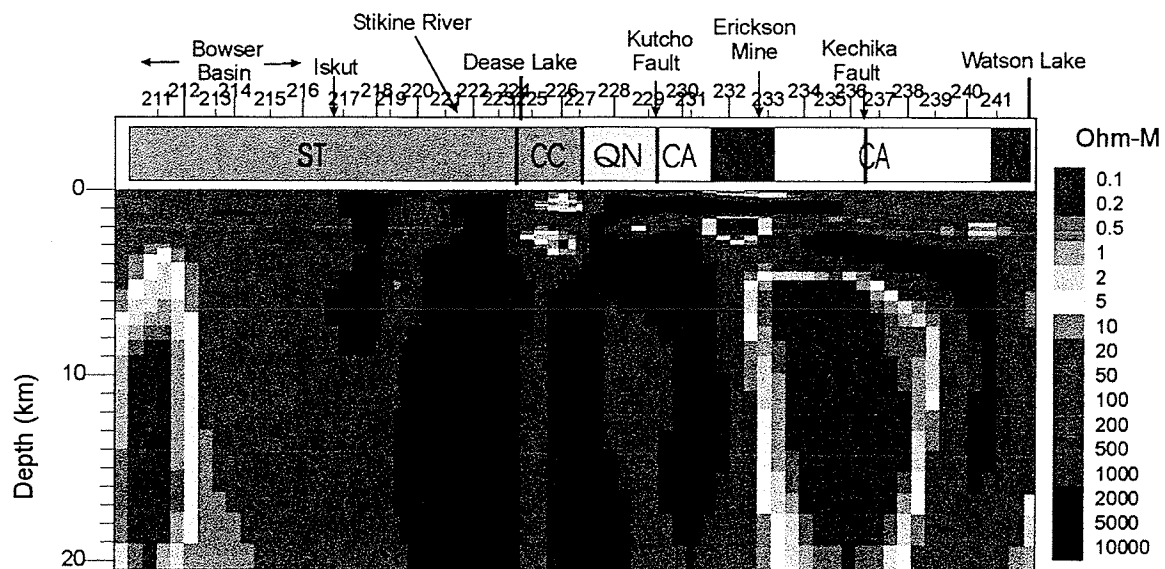
An alternative hypothesis is that the enhanced conductivity, which is present mostly beneath site 279, is associated with only the upper Dorsey assemblage. This assemblage comprises schist and phyllite containing magnetite porphyroblasts, as discussed in section 2.5.4 (Nelson, 2002). The lower Dorsey Assemblage is interpreted to have no magnetite and may therefore be more resistive.

8.3.2 *SLIDE MOUNTAIN TERRANE*

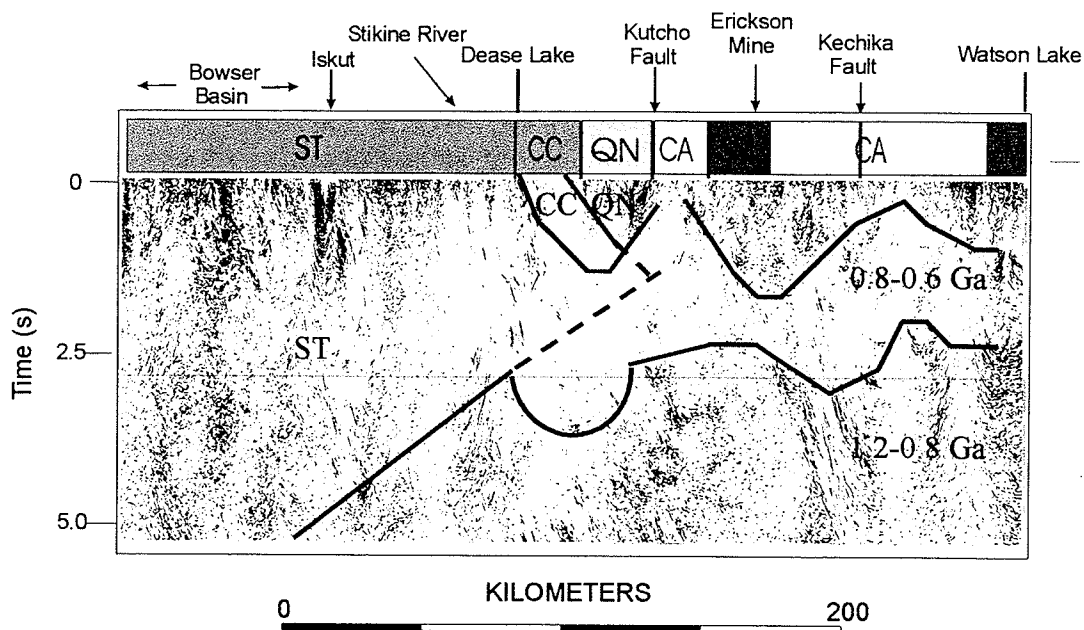
The Slide Mountain Terrane is composed of mafic volcanics with related ultramafic, mafic, and granitic bodies, and predominantly fine grained clastic rocks and chert (Monger et al., 1991, Monger, 1989). The metamorphic grade ranges from sub-greenschist facies to staurolite-kyanite grade (Struik, 1986). The terrane is interpreted from geological mapping and seismic reflection data to form a relatively thin surface layer, as discussed in section 2.6.2 (Evenchick et al., 2001; Cook et al. 2001; Synder et al. 2002; Clowes and Hammer, 2002).

Seismic reflection data have indicated that the accreted terranes east of Stikinia, such as Slide Mountain Terrane, have only a limited depth extent of less than 5 km. This interpretation is based on the depth extent of an upper crustal reflectivity response (Synder et al., 2002). Figure 8.4 compares the migrated seismic reflection data with the NLCG resistivity model for Line 2a.

A thin conductive zone approximately 3 km thick is present beneath the southwest part of the Slide Mountain Terrane on the Line 2a profile (labeled Y on Fig. 8.1b) and corresponds with the zone of high reflectivity (Fig. 8.4). A similar, but less conductive feature occurs on Line 3 (Ledo et al., 2002b) at similar depths (Fig. 8.3). However, there is no corresponding conductor in the Connector Line model.



(a)



(b)

Figure 8.4 (a) MT model and (b) migrated seismic reflection data for Line 2a (modified from Cook et al., 2001).

The regional gravity (Fig. 2.9) and magnetic (Fig. 2.10) data do not further define the local structure of the Slide Mountain Terrane. The conductor is associated with a Bouguer gravity low (~ 130 mgals) for both Line 2a and Line 3 (Ledo et al., 2002b), but this low is likely associated with a topographic high rather than with Slide Mountain rocks. The conductor on Line 2a is associated with a slight magnetic high (125 nT), but a similar high is not observed along the Line 3 profile.

One suggestion for the enhanced conductivity at depths (< 2 km) beneath the Slide Mountain Terrane is localized mineralization. The Erickson (gold), Table Mountain (gold), and Cassiar (asbestos and jade) mines are located within 15 km of the conductor at site 232 (Fig. 4.1). Rocks of this region have been affected by alteration (Sketchley and Sinclair, 1991). If this alteration involved precipitation of graphite films on grain boundaries it would provide an explanation for the enhanced conductivity. As discussed in Section 1.1 metallic conduction in graphite films can enhance conductivity.

8.3.3 *CACHE CREEK TERRANE*

The MT models include a shallow conductive (< 5 ohm.m) body in the Cache Creek Terrane. Geological mapping indicates the terrane is mostly made up of oceanic rocks consisting of Jurassic radiolarian chert and argillite, distinctive masses of shallow-water carbonates, basalt, gabbro, alpine-type ultramafic rocks, and calc-alkaline volcanics, as discussed in section 2.5.2 (Monger et al., 1991). The terrane is characterized by a distinct gravity low (-130 mgals) and magnetic low (-280 nT) where it is crossed by the profile.

The enhanced conductivity in the Cache Creek Terrane corresponds with high seismic reflectivity (Fig. 8.4). The MT results, which delineate a conductivity that is approximately 5 km, thick support seismic interpretations (Synder et al., 2002) that also suggest that the Cache Creek Terrane is relatively thin (< 5 km) (Fig. 8.4).

The presence of mining operations in the Cache Creek Terrane indicates that sulphide mineralization could be the source of the enhanced conductivity. Mihalynuk and Cordey (1997) and Barret et al. (1996) examined geochemical data from the northern Cache Creek Terrane that indicated mineralization. Barret et al. (1996) noted massive sulphide lenses occurring over a strike range of 3.5 km. The lenses consist of mainly pyrite with subordinate sphalerite and chalcopyrite. Alteration effects, mainly Na depletion and variable additions of Mg, Ca, Si, and Fe, occur at least 100 m below and 20 m above the mineralized horizon lens (Barret et al. 1996).

8.3.4 BOWSER BASIN

The Bowser Basin is mostly made up of clastic rocks (Monger, 1989). Analysis of aeromagnetic data collected over the Bowser Basin reveals that the basin is less than 3 km deep near sites 211 and 212 and becomes progressively shallower (1-2 km) north to site 220 (Lowe, 1999).

The MT models (Fig. 8.1) suggest that the resistivity of the Bowser Basin is variable, with values ranging from 10 to 1000 ohm.m. The most conductive sediments (10 ohm.m) are located beneath site 215 and the most resistive sediments (1000 ohm.m) are located beneath site 218.

8.4 CRUSTAL RESPONSE

The following section examines the MT response for the crustal scale features and integrates other geophysics to assist in the geological interpretation.

8.4.1 CASSIAR TERRANE

The Cassiar Terrane is characterized by variable resistivity on both the Line 2a and Connector Line profiles. It includes a conductor (< 2 ohm.m, labeled **E**) centered near 10 km depth that is overlain by a resistive zone (> 1000 ohm.m). Observation of the conductor on both Line 2a and the Connector Line and a similar body on Corridor 3 indicates a large-scale source for the enhanced conductivity. It is possible that the source of the enhanced conductivity is graphitic rocks from the terrane. Geological descriptions of the terrane indicate that it includes graptolite shale (Monger, 1989) indicating the presence of carbonaceous rocks. If the metamorphic grade is high enough the carbonaceous shale could be conductive and if present in sufficiently large volumes it could account for the observed response.

The conductor in the Cassiar Terrane profile has a variable seismic response. On Line 2a, the conductor is centered between low reflectivity of the interpreted accreted or displaced rocks at shallow depths (< 10 km) and higher reflectivity of the westward tapering wedge. The seismic refraction velocity models do not show any anomaly at the location of the conductor. Because the MT method provides poor resolution of the base of conductors, it is likely that the entire Cassiar conductor lies above the westward tapering wedge and thus within the accreted or displaced rocks.

8.4.2 STIKINE TERRANE

In geological interpretations the Stikine Terrane extends to the east beneath thin accreted terranes such as the Cache Creek, Quesnellia, and Slide Mountain terranes. The resistivity models show that the Stikine Terrane is resistive (> 500 ohm.m for Line 2a, Line 3, and the Connector Line). It forms a very extensive feature (labeled B and B' on Fig. 8.1, 8.2, and 8.3), correlatable across the three LITHOPROBE lines (Section 8.2). The high resistivity of the body is consistent with the geology of the terrane, which consists of mafic to felsic volcanic rocks inter-layered with clastic sedimentary and carbonates rocks, and intermediate-composition plutons (Lowe et al., 1994 and Monger et al., 1991).

The MT models resolve the lower surface of the resistive body. If this surface is correlated with the base of the Stikine Terrane, the Line 2a model suggests that the terrane may pinch out with an eastern margin near site 233. The western extent of the resistor is defined by a dipping conductive structure, which will be examined later.

Comparison of the MT results and the seismic reflection results reveals that a zone of low seismic reflectivity in the Stikine Terrane and beneath the Cache Creek, Quesnellia, Cassiar and Slide Mountain terranes corresponds to the high resistivity zone. The low-reflectivity, high-resistivity zone also corresponds with a high velocity zone in the seismic refraction velocity models (Clowes and Hammer, 2002).

The MT model (Fig 8.2) shows that the large resistive zone is bounded in the west by a dipping conductive structure. This structure is not imaged in the seismic reflection data and cuts through a region interpreted to consist of Stikine Terrane rocks (Fig. 2.6, Clowes and Hammer, 2002).

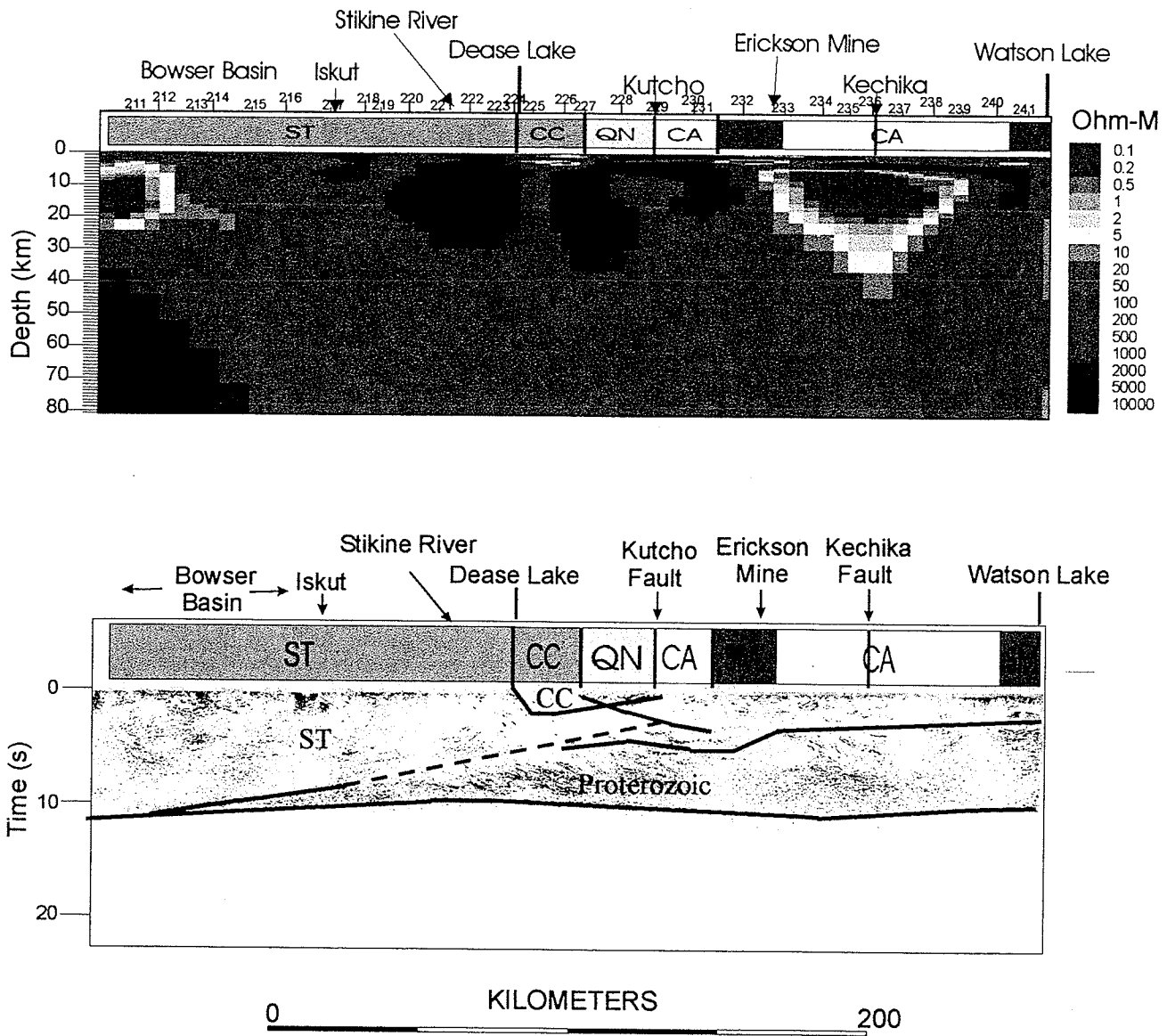


Figure 8.5 (a) MT model and (b) migrated seismic reflection data for Line 2a (modified from Cook et al., 2001).

8.4.3 WESTWOOD TAPERING WEDGE

The westward tapering wedge of high seismic reflectivity beneath the Stikine Terrane is interpreted to be Proterozoic rocks. The wedge pinches out near site 211 and extends northeastward to the surface near site 242 (Fig. 4.1). The seismic refraction velocity model (Fig. 2.8) shows no increase in velocity in the wedge.

The deeper parts of the resistivity model for the area between sites 233 and 239 are poorly resolved due to the presence of an overlying conductor (labeled E), interpreted to be within the overlying Cassiar Terrane. However, further to the southwest the resistivity models indicate enhanced conductivity in the westward tapering wedge relative to the overlying Stikine Terrane rocks. The tapering wedge interpreted as Proterozoic metasedimentary rocks (Evenchick et al., 2001; Synder et al., 2002). The MT results support this hypothesis because metasedimentary rocks would be expected to be more conductive than the predominantly resistive rocks forming the Stikine Terrane.

The MT results provide only low resolution of the contact between the Stikine Terrane rocks and the North American rocks along Line 2a. Where the contact is most shallow it lies beneath the conductor labeled E in the Cassiar Terrane. Further southwest the contact occurs at lower crustal depths where the MT method provides less resolution. However, the MT results do show that there is no major conductor at the contact.

8.5 LITHOSPHERIC SLAB CONDUCTOR

A northeast dipping conductor is observed at the southwest end of Line 2a and Line 3. The source of the enhanced conductivity in this slab will be discussed in the following section.

8.5.1 GEOPHYSICAL RESPONSES IN THE VICINITY OF THE SLAB CONDUCTOR

Although the dipping conductor occurs at different depths in the Line 2a and Line 3 profiles, its geometry is remarkably similar. As discussed in Section 8.2, the difference between the body on the two Corridors may be due to the position and orientation of the profiles.

Modelling of gravity data across the western margin of the continent using constraints from SNORE line 22 and ACCRETE seismic data defines a Moho that deepens with distance inland from the continental margin (Hammer and Clowes, 2000). Comparison of the density and resistivity models suggests that near the coast the conductor lies in the lower crust rather than in the lithospheric mantle.

The seismic reflection results for Line 2a poorly define a northeast dipping feature at approximately 6 seconds (Fig. 2.6) within the Stikine Terrane (Clowes and Hammer, 2002). The seismic refraction models include a northeast dipping structure at depths of < 15 km in the northwest of the Stikine Terrane, but they indicate relatively uniform velocity in the area of the dipping conductor.

Lewis et al. (2002) examined the heat flow values of the Cordillera, as discussed in section 2.6.4. South of 59° in the area containing the Line 2a slab conductor the average heat flow was 73 mW/m^2 , but north of 59° , in the area containing the Corridor 3 slab, the average heat flow was 105 mW/m^2 . The regions of higher heat flow are interpreted as regions of most recent subduction and/or terrane collision.

8.5.2 INTERPRETATION OF SLAB CONDUCTOR

The absence of any significant seismic signature associated with the dipping conductor suggests that the enhanced conductivity is caused by a minor geological constituent rather than a large-scale change in rock type. The geometry of the conductor suggests it may be caused by processes associated with subduction of the Kula plate beneath North America.

In the northern Cordillera, subduction ceased around 20 Ma (Gabrielse et al. 1991). If the conducting slab observed in Lines 2a and 3 is associated with subduction, the enhanced conductivity is unlikely to be due to thermal effects or the fluids released during the subduction. It is more likely to be associated with remnant effects from the subductor such as abducted sediments or metamorphic reactions in the overlying crust caused by fluids released during subduction. The observation of similar conductors in regions of very different heat flow supports the interpretation that the enhanced conductivity is not due to thermal effects or active fluids. The presence of enhanced conductivity at lower crustal depths in the southwest and mantle depths in the northeast suggest that both products of metamorphic reactions and obducted sediments may contribute to the enhanced conductivity.

8.5.3 RESISTIVITY IMAGES IN AREAS OF ACTIVE SUBDUCTION

A dipping conductor is observed beneath the actively subducting Juan de Fuca Plate in the southern Cordillera in both Vancouver Island (Kurtz et al., 1990) and the Cascade subduction zone in Oregon (Wannamaker et al. 1989). Both MT studies show a conductive zone at crustal depths that is interpreted as being caused by the presence of

fluids released from the subducting Juan de Fuca plate. Kurtz et al. (1990) suggest the enhanced conductivity is due to saline fluids supplied both by water subducting with the oceanic crust and by dehydration reactions.

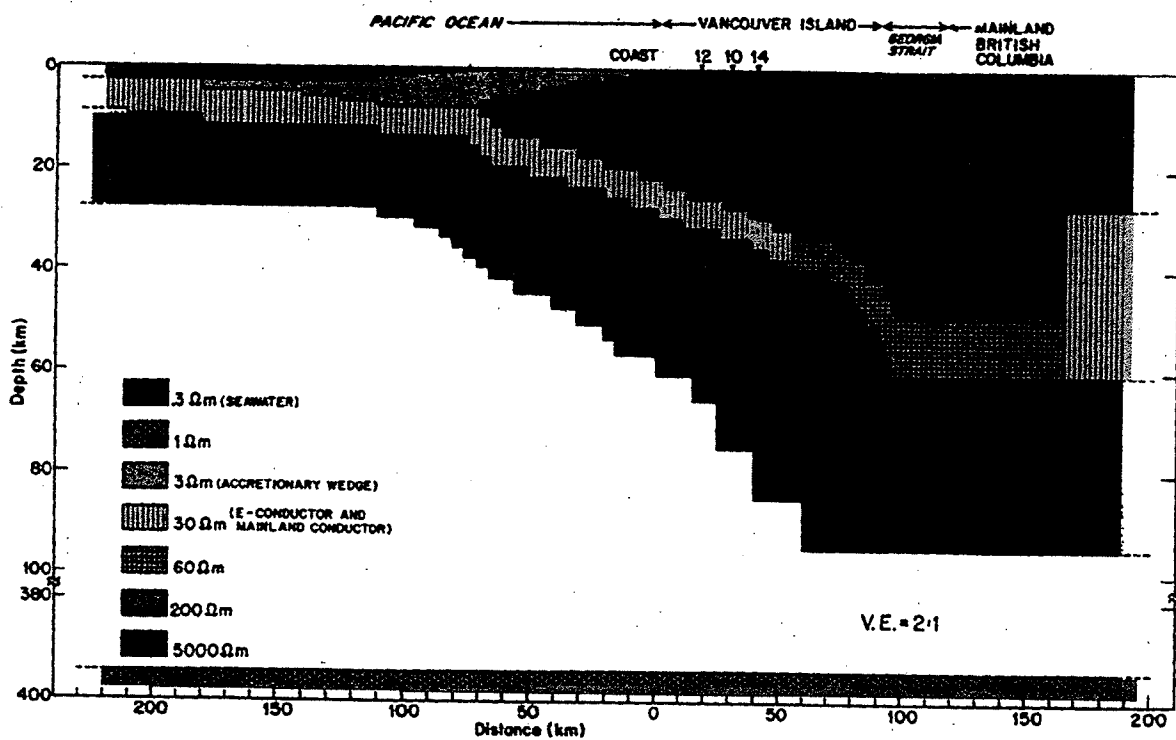


Figure 8.6 Resistivity model of actively subducting Juan de Fuca Plate (after Kurtz et al. 1990).

Lazaeta et al. (2000) and Schwarz and Kruger (2000) have investigated the upper lithospheric structure and subduction induced processes in the Andes region of South America using MT and geomagnetic soundings. Resistivity models are shown in Figure 8.6 and 8.7. No significant eastward dipping slab feature is observed at the coast, but enhanced conductivity is observed in the back arc area in the western Cordillera. Schwarz

and Kruger (2000) suggest that the areas of enhanced conductivity may be attributed to three factors: (1) a rise of fluids released from the subducted Nazca plate, (2) partially melted crust, or (3) thrust tectonics with related detachment zones that may involve fluids (Schwarz and Kruger, 2000). Lezaeta et al. (2000) suggest that the back arc conductor is controlled by the rheological regime and the temperature at depth.

Similar rheological controls may have affected the initial formation of the conductors in the northern Cordillera. Fluids would have risen from the Kula plate surface and perhaps could have been trapped by an impermeable layer in the crust (Jones, 1987; Hyndman, 1988; Cassidy and Ellis, 1991, 1993). Alternatively, the temperature may have controlled metamorphic reactions in the crust involving the fluids. The conductor therefore records the paleotemperature distribution at the time of its formation.

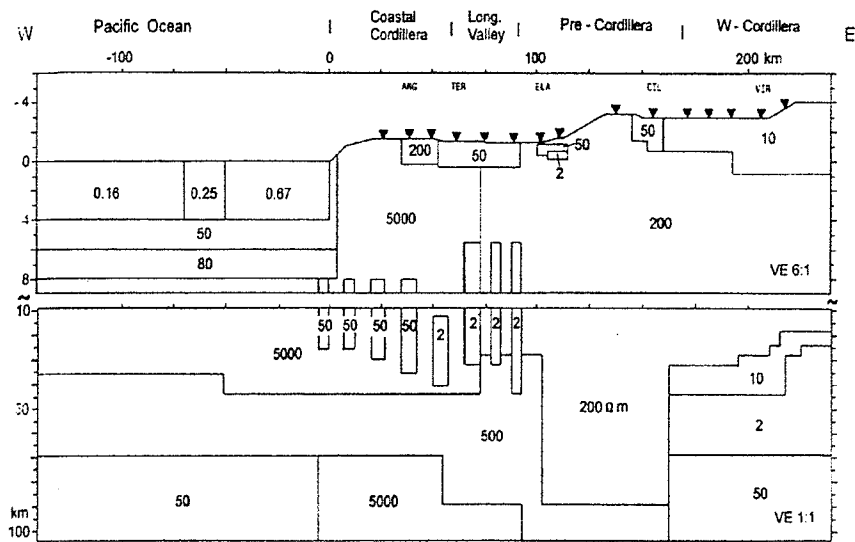


Figure 8.7 Composite electrical cross section of the southern central Andes extending from the Pacific coast of northern Chile to the lowlands of southern Bolivia at about 21°45 S latitude (Schwarz and Kruger, 2000).

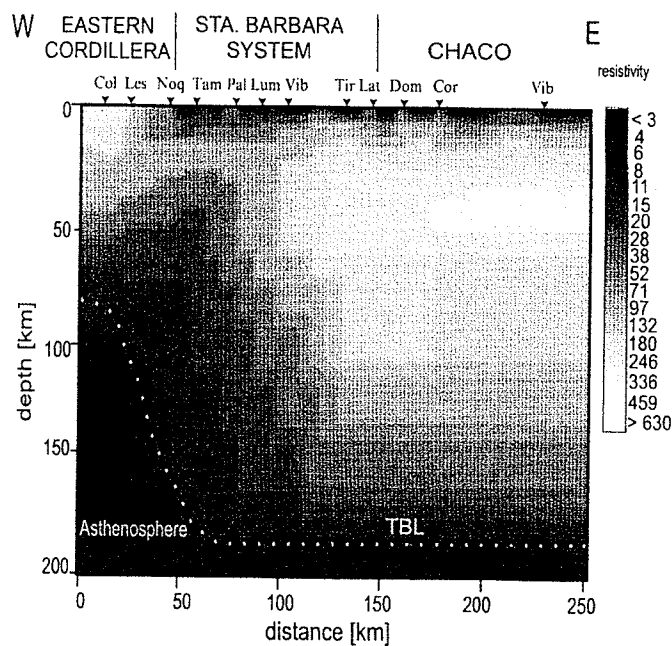


Figure 8.8 Magnetotelluric model of northwestern Argentinean Andes. The white dotted curve in the model suggests the location of the bottom of the thermal boundary layer (TBL) at temperatures of 1500 K (Lezaeta et al., 2000).

CHAPTER 9 – CONCLUSIONS

9.1 OVERVIEW

MT data were collected in 1999 along Corridors 2 and 3 of the LITHOPROBE SNORCLE Transect in order to provide increased understanding of the tectonic evolution of the Canadian Cordillera. MT soundings were made at fifty-four sites located on Line 2a between Stewart and Watson Lake (Line 2a) and on the Connector Line in northern British Columbia and Yukon.

MT impedances were determined using robust methods with codes developed by Jones (Jones and Jodicke, 1984), Larson (Larson et al. 1996) and Chave (Chave et al. 1987). The apparent resistivity and phase responses were calculated from the impedances. Groom Bailey (GB) tensor decompositions, multi-site multi-frequency tensor decompositions, and induction vectors were used to determine the geoelectric strike angle. The dimensionality and distortion were examined using the skew and the misfit of the GB tensor decompositions.

MT data inversion using the Occam and NLCG methods was performed to determine 2D resistivity models. Results of seismic reflection and refraction, heat flow, gravity and magnetics were then integrated with the MT results in order to examine the crustal and lithospheric structure.

9.2 GEOELECTRIC STRIKE DETERMINATION

From examination of the MT impedances, it is apparent that the off-diagonal impedance response for most sites is different, and therefore the underlying resistivity structure is not 1D. The skew suggests that the MT response is approximately 2D.

However, high skew in particular areas and at long periods indicates the influence of 3D structures.

Rose diagrams of single-site GB decomposition results were used to examine and classify the strike distribution. For Line 2a the short (0.01 s to 3 s) and long (100 s to 10 000 s) period data indicated a well-defined strike of -40° to -50° , while the intermediate period (1 s to 300 s) were more scattered. For the Connector Line, the Rose diagrams indicated a strike of -50° to -60° for the shorter periods (0.1 to 2 s) and of -60° to -70° for the middle (1 s to 200s) and long (100 s to 10 000 s) periods.

Multi-site multi-frequency tensor decompositions were used to further examine the geoelectric strike and to determine the misfit for each site when the data were constrained to the regional strike angle. For both the Connector Line and Line 2a the decompositions revealed that a -45° strike is appropriate for the data set. The tensor decompositions showed that the shear values for the MT sites tended to increase with increasing period, indicating the presence of heterogeneities distributed throughout the crust. High χ^2 values indicate that the basic GB model provides a relatively poor fit to the Connector Line and Line 2a data. Consequently the edited observed data rather than the GB corrected data were used in the subsequent modelling and inversion.

The induction vector analysis revealed two distinct induction vector reversals near the border between the Cache Creek and Quesnellia terranes and near the Tintina Fault Zone (Fig. 5.12). Several sites in the southeast of the Stikine Terrane were influenced by the coast effect and were not used in the subsequent 2D modeling.

9.3 MODELLING RESULTS AND INTERPRETATIONS

Two-dimensional Occam and NLCG inversions were completed for the Connector Line and Line 2a. The resulting 2D models fitted the overall form of the observed responses, but there were localized misfits. For both the Occam and NLCG models sites 217, 222, 225, 228, 231, 232, 274, 276, and 282 had the largest contribution to the error misfit. This misfit is interpreted to be due to galvanic distortion and localized 3D effects.

The two inversion algorithms produced similar models, providing additional confidence that the structures in the models are present in the Earth. The MT results in association with other geophysical results, support the following interpretations:

- The Dorsey Terrane forms a thin surface terrane in the shallow upper crust that is less than 2 km thick. Enhanced conductivity ($< 1 \text{ ohm.m}$) in the terrane is attributed to either: (1) widespread occurrence of graphitic or metalliferous rocks or, (2) localized sulphides or oxides. The enhanced conductivity may occur in only the upper Dorsey Terrane assemblage, which is composed of schist and phyllite with magnetite porphyroblasts.
- The Cache Creek and Slide Mountain terranes, which form part of the Sylvester Allochthon, are thin, conductive terranes, less than 5 km and 3 km thick respectively. The oceanic rocks of the Cache Creek Terrane have a resistivity of 5 ohm.m , whereas the Slide Mountain Terrane rocks have a resistivity of $< 2 \text{ ohm.m}$. The enhanced conductivity for these terranes is interpreted to be due to localized mineralization. Rocks of this region have been affected by alteration that could have resulted in precipitation of graphite films on grain boundaries. The

enhanced conductivity in the Cache Creek and Slide Mountain terranes corresponds with higher seismic reflectivity.

- The resistivity of the sedimentary rocks in the Bowser Basin varies from 10 to 1000 ohm.m. The most conductive sediments (10 ohm.m) are located beneath site 215 and the most resistive sediments (1000 ohm.m) are located beneath site 218.
- The conductors present at ~10 km depth in the Cassiar Terrane for Lines 2a and the Connector Line are interpreted to be part of the same body. The different orientation of the two lines relative to the geological strike accounts for the change in shape of the body in the two models. This conductor corresponds to a conductive feature beneath the Cassiar Terrane on Line 3 centered at 15 km depth. The enhanced conductivity is interpreted to be due to graphitic metasediments.
- The Stikine Terrane is dominantly resistive (>1000 ohm.m). Northeast of site 217, it defines a resistive eastward tapering wedge beneath the Cache Creek, Quesnellia, Cassiar, and Slide Mountain terranes. The resistive area corresponds with low seismic reflectivity. The resistivity structure of the Stikine, Cache Creek, Quesnellia, Cassiar, and Slide Mountain terranes provides support for the hypothesis that the Stikine Terrane forms a laterally extensive terrane onto which smaller, thinner terranes are overlain. The eastern margin of the wedge is beneath the surface position of site 233.
- Beneath the Stikine wedge the seismic reflectivity increases and defines a westward tapering wedge that is interpreted to be made up of Proterozoic metasedimentary rocks (Evenchick et al., 2001; Synder et al., 2002). The westward tapering wedge is an order of magnitude more conductive than the

overlying rocks of the Stikine Terrane. The resistivity of this region is poorly resolved in the northeast due to the overlying conductor in the Cassiar Terrane.

- A northeast dipping conductor at the southwest ends of Line 2a and Corridor 3 is likely associated with the past subduction of the Kula Plate. The geometry of the conductor in the two profiles is very similar despite considerable difference in the present heat flow in the areas. The observations suggest the source of the enhanced conductivity is remnant effects of subduction such as metamorphic reactions in the overlying crust and/or the presence of obducted sediments rather than the present thermal and fluid regime.

9.4 THESIS OVERVIEW AND FUTURE WORK

The primary objectives of this study have been achieved. The resistivity structure of the subsurface beneath Line 2a and the Connector Line has been determined. New information from the MT study has been used for understanding the processes involved in the structure and formation of the Northern Cordillera.

The results presented in the thesis suggest the station spacing used on the LITHOPROBE survey was larger than optimal for determining the crustal response of thin accreted terranes such as the Dorsey Terrane, Slide Mountain Terrane, and Cache Creek Terrane. It is apparent that a dense profile (at 7.5 km spacing) would provide more information on the crustal response. However, the LITHOPROBE data do provide reconnaissance information on these terranes.

In addition, interpretations would be more precise if seismic data were collected along the Connector Line joining Corridor 2 and Corridor 3. Detailed comparison of the

MT and seismic results provides additional information to that available from the independent interpretation of these results.

Inclusion of several additional processing steps may have contributed to the study including: (1) additional tensor decompositions including magnetic distortion, (2) additional 2D inversion with greater consideration of static shift, (3) analysis of Line 2b data to better define the Ancestral North American rocks, and (4) full integration of Corridor 2 and 3 results for full geological interpretation. These steps should be considered in future studies.

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Appendix A: Lithoprobe 1999 MT Data

This appendix shows the raw apparent resistivity and phase responses from Corridor 2 and the Connector Line collected as part of the 1999 SNORCLE MT field survey. Refer to Table 4.1 for site locations. For sites 275 and 277 two data sets are displayed. The sites with the prefix “mt” include only broadband data and sites with the prefix “lim” include only LiMS data.

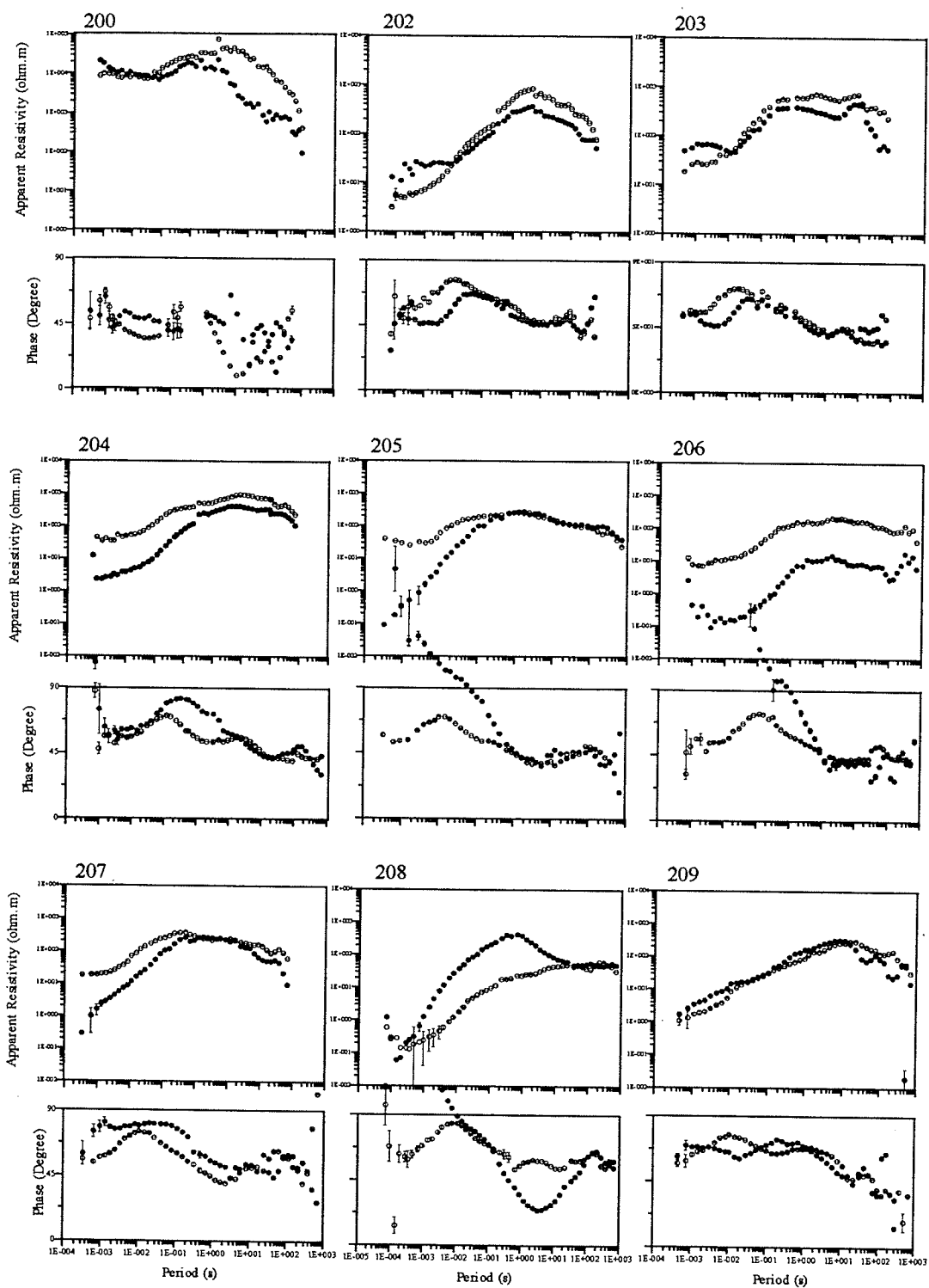


Figure A.1 Unedited MT apparent resistivity and phase data rotated to true north.

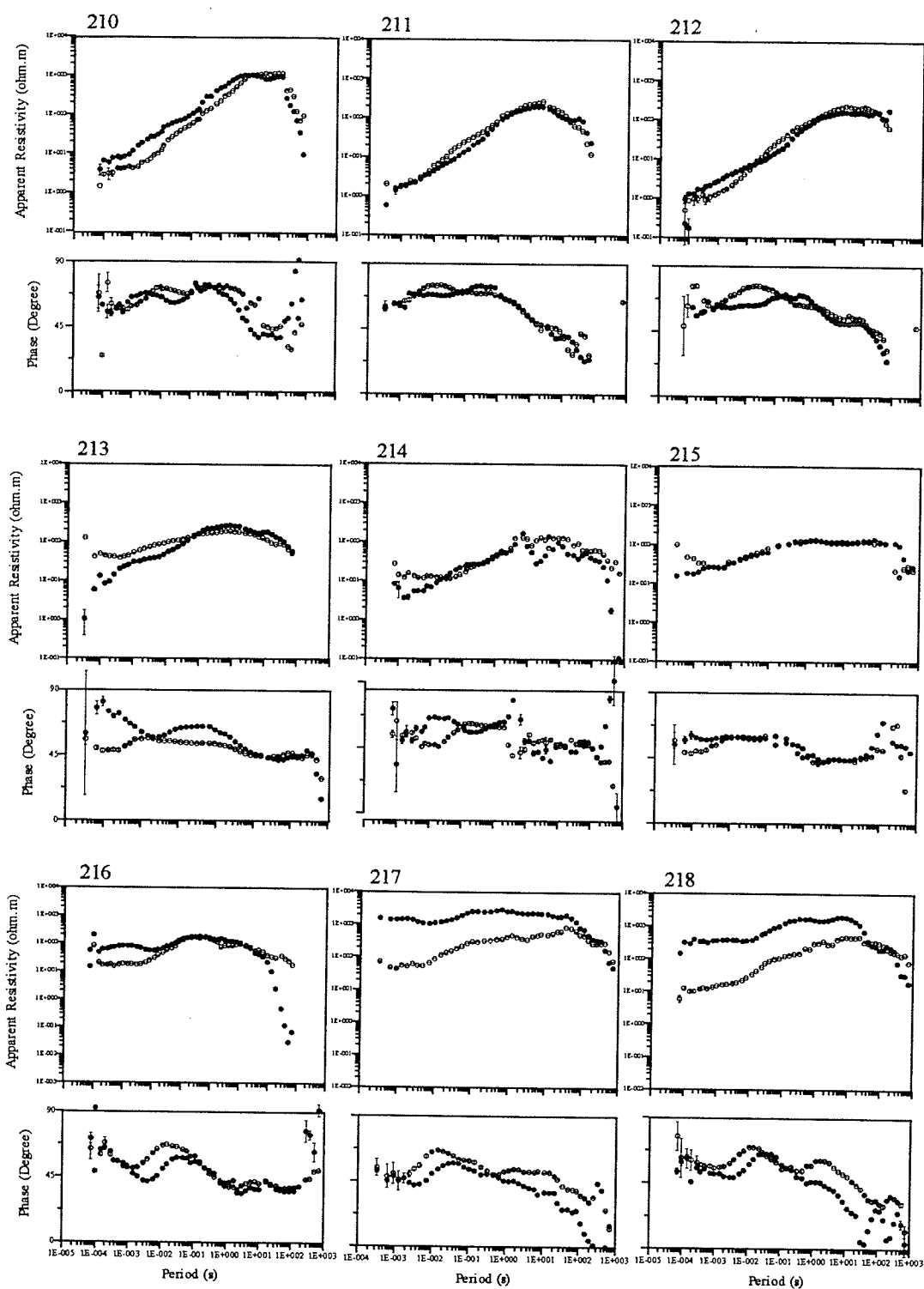


Figure A.1 cont.

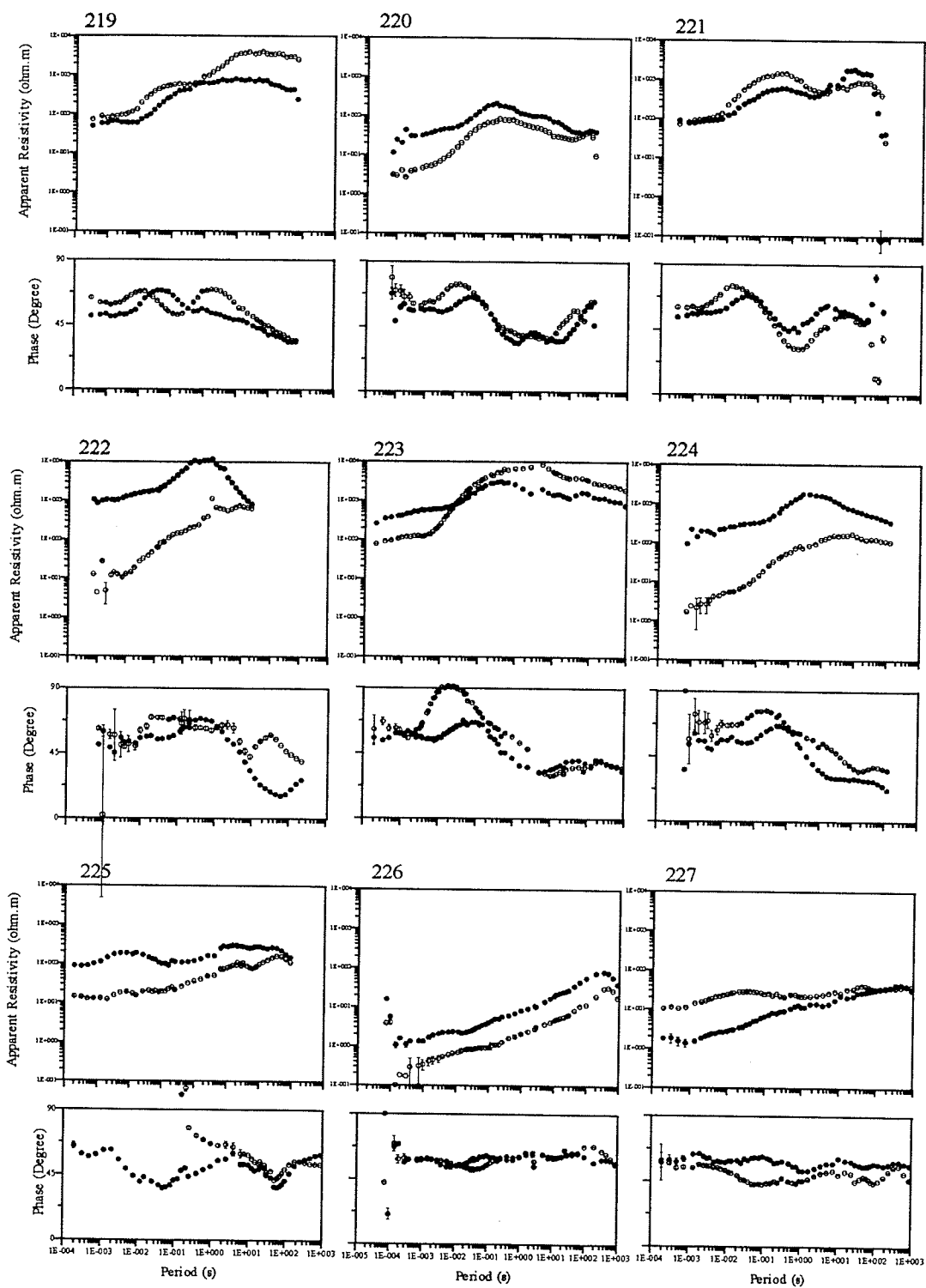


Figure A.1 cont.

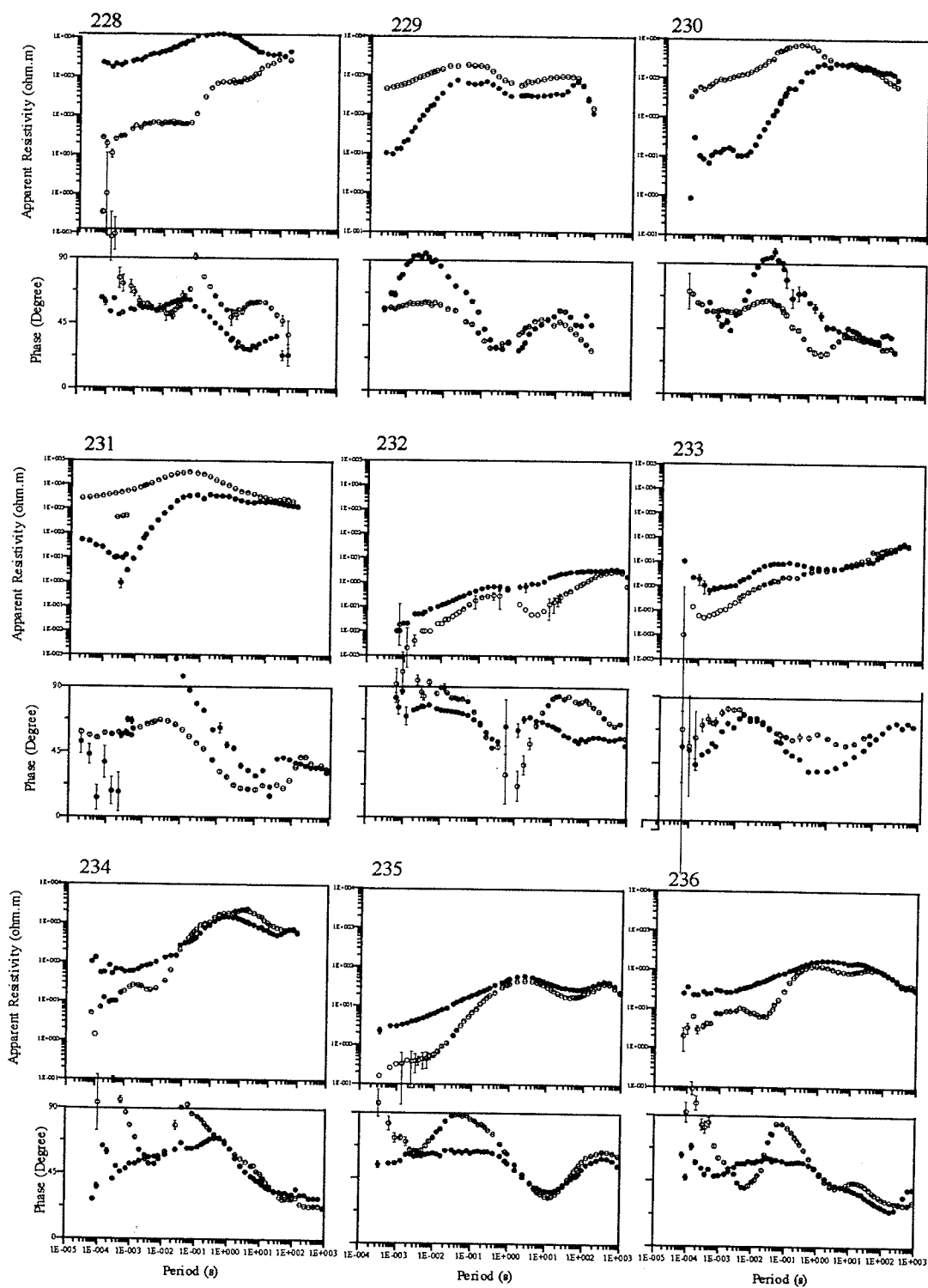


Figure A.1 cont.

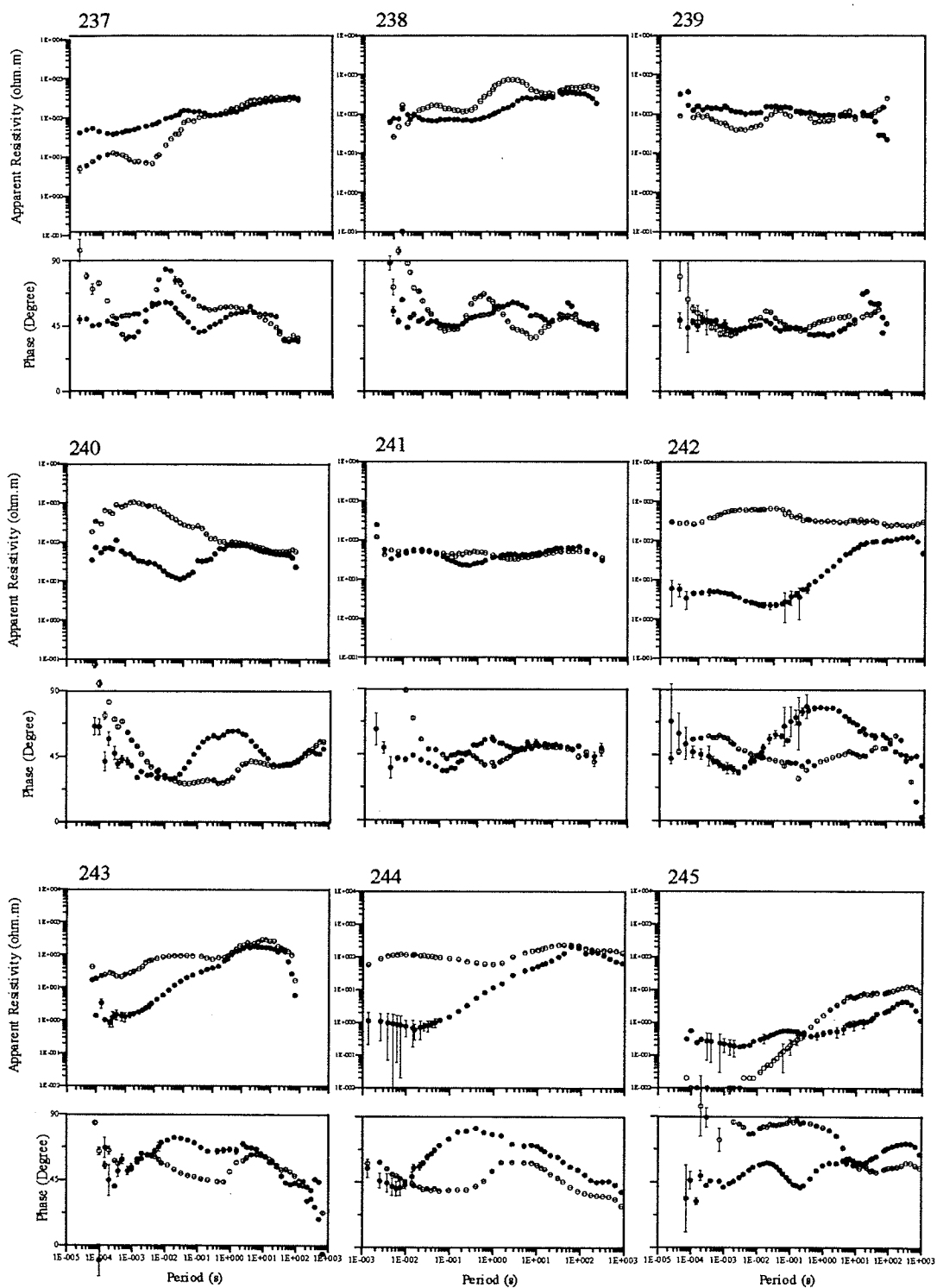


Figure A.1 cont.

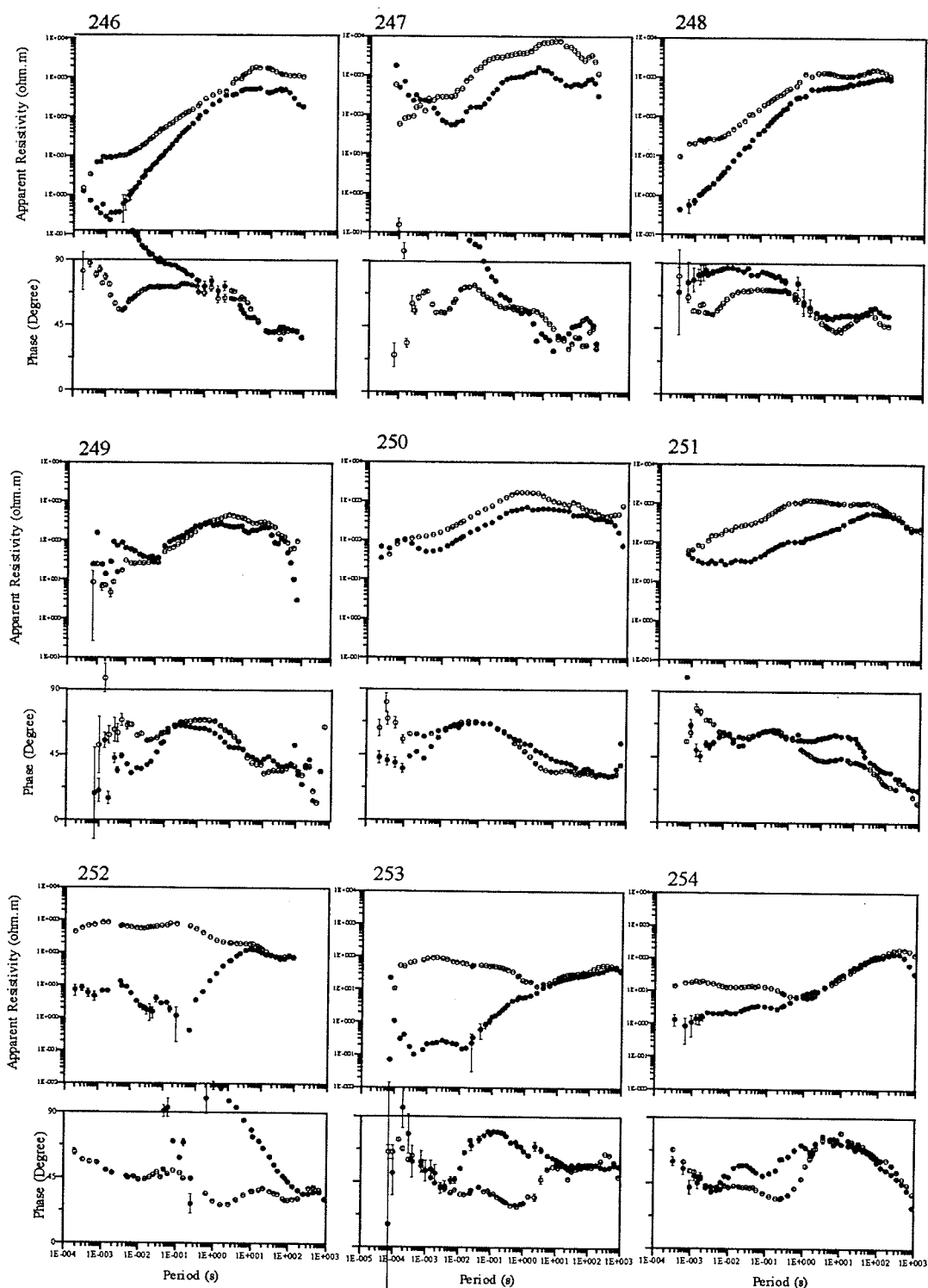


Figure A.1 cont.

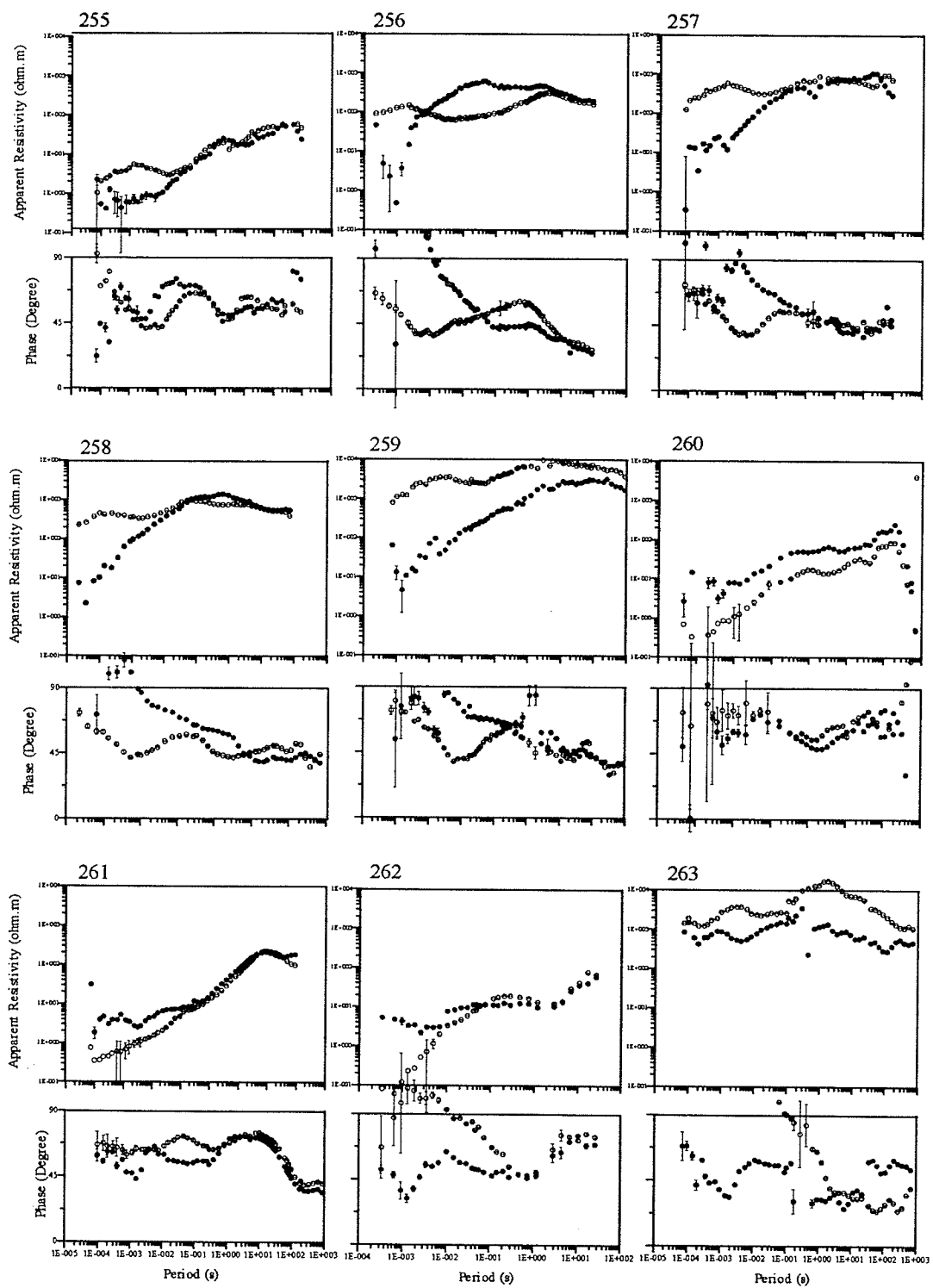


Figure A.1 cont.

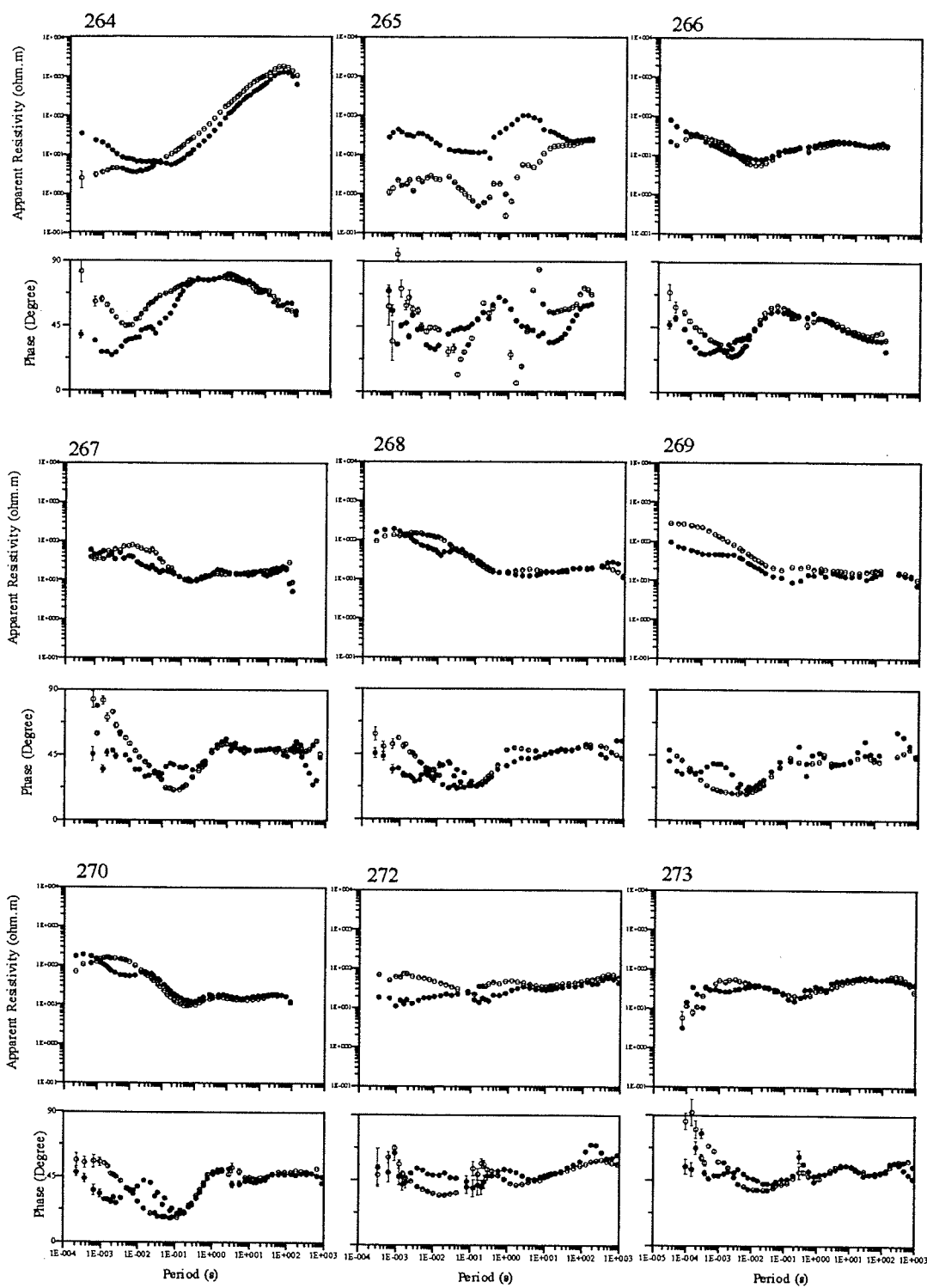


Figure A.1 cont.

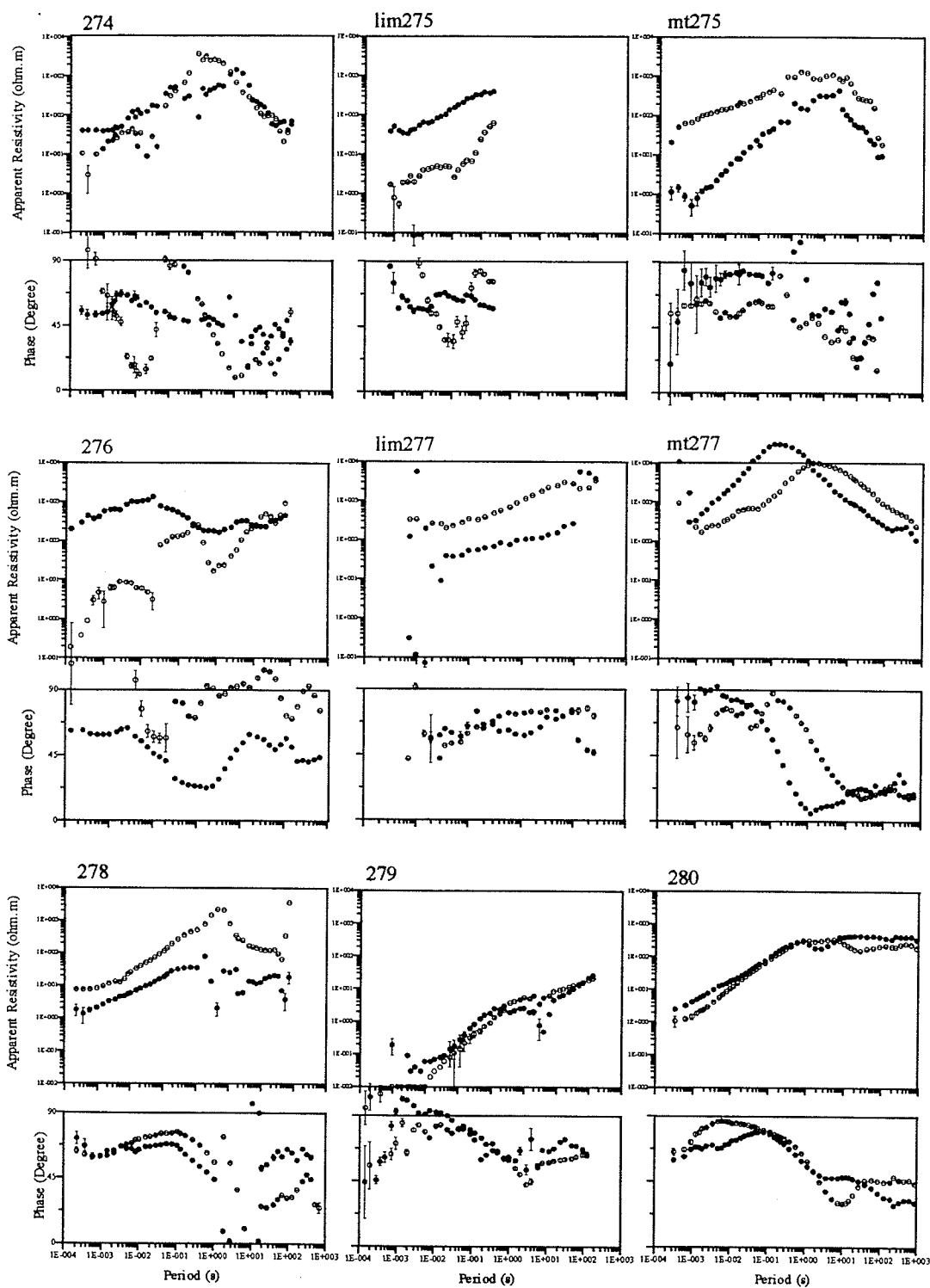


Figure A.1 cont.

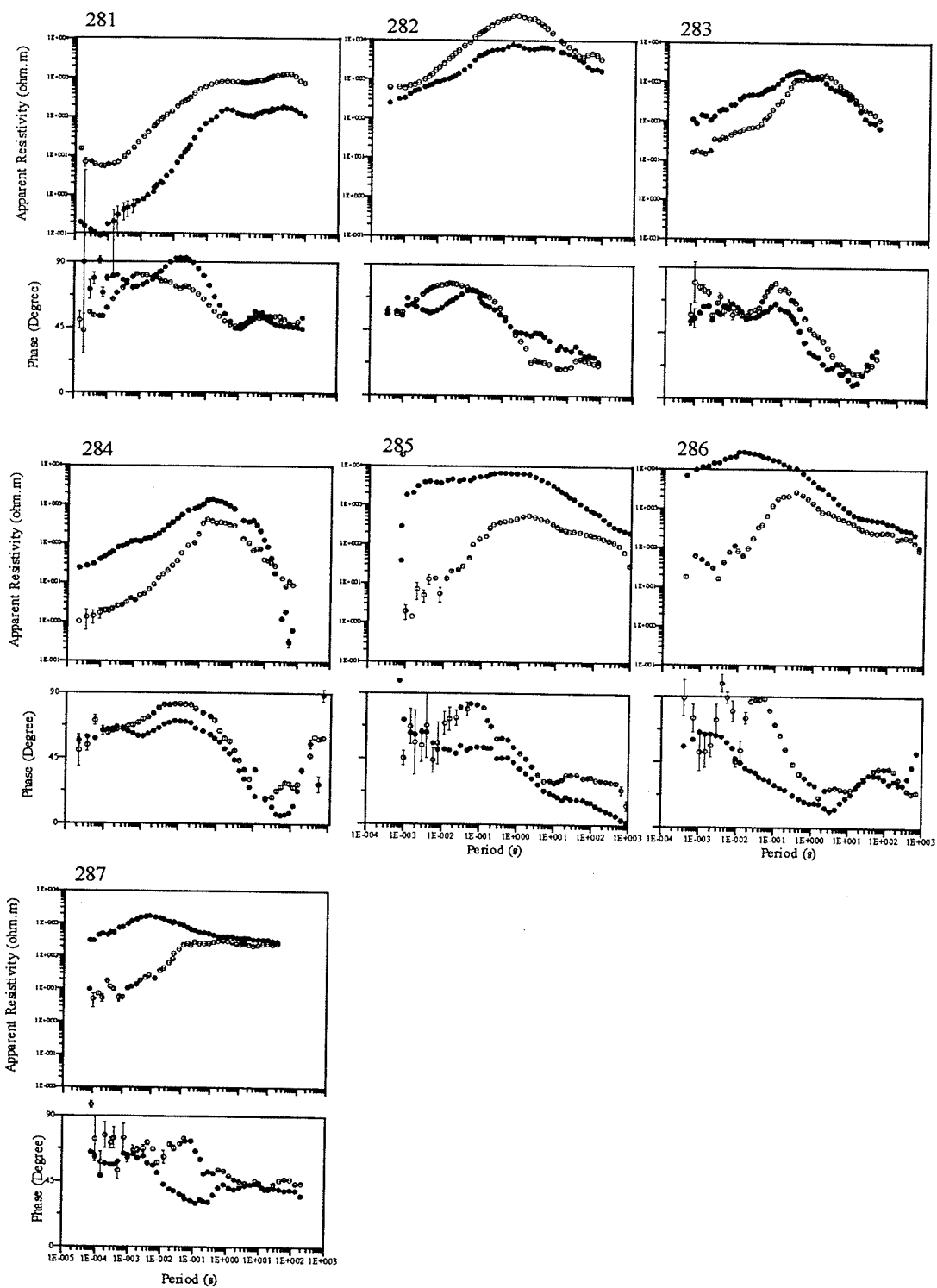


Figure A.1 cont.

Appendix B: Unconstrained GB Tensor Decompositions

This appendix lists the GB decomposition results for the study area and Line 2b. The following table includes azimuth, twist, and shear, as discussed in section 3.6.7. For sites that are blank or have "error" listed, the GB minimization could not converge to an acceptable minimum. Sites with the prefix "sno" refer to stations where both MT and LiMS data were collected, while sites with no prefix only include MT data.

Table B.1 Azimuth values for unconstrained one-decade GB decompositions.

Site	Azimuth (degrees from true north)						
Bands	0.001-0.01	0.01-0.1	0.1-1.0	1.0-10	10-100	100-1000	1000-10 000
sno200	76	52	34		39		
sno202	38	39	29	41	42	51	30
sno204				Error			
sno206	45	31	53	65	59	44	
sno208	64	72	26			3	
sno210	37	28	26	34	21	16	
sno212	80	55	20	26	18	54	
sno214		58	63	55	9	35	
sno216	9	27	36	56	69	68	46
sno218	21	18	17			81	
sno220	53	23	45	34		12	
sno222		7	17		63	26	47
sno224	7	68			80	31	41
sno226				Error			
sno228	16	11	17	73	31	54	
sno230	32	46		86	11	60	
lim232				Error			
sno234	41	34	32	5	86	85	
sno236	26	56	46	15	23	35	
sno238	53	65	62	33	26	83	
sno240	57	56	65	64	59	36	
sno243	26	25	2	16	44	72	
sno245	4	49	78	81	81	89	
sno247	63	37	38		46	21	
sno249	24	69		71	29	19	
sno251	50	20	81	31	53	63	
sno253	9	23	14	15	22	31	
sno255	47	53	44	16		18	
sno257	84	31	41	74	3	23	
sno259	44	19	66	3	5	35	
sno261	25	79	46		55	74	
sno263			70	19	34	71	
sno265	56	72	45	52	24	81	
sno267	79	47	39	34	24	53	
sno269	17	56	38	21	24	71	
sno273	53	41	46	63	37	36	
sno275	82	35	69	1	25		
lim277				Error			
sno279		71	28	28	68	68	
sno281	87	12	14	54	77	80	
sno283	66	35	33	14	9	59	
sno285	27	34				19	
sno287	59	43		14	1		

203	37	40	57	41	41	47
205	72	76	50	5	31	49
207	60	35	58	9	23	36
209	31	30	8	77		32
211	19	60	40	30	74	66
213	27	21	74		10	31
215	73	62	55	19	35	55
217	55	81	50	52	73	65
219	21	8	84	11	18	6
221	10	75	15	33	23	25
223	32	39	25	10	77	
225	22	26			35	25
227	15	39	58	30	40	82
229	67	43	55	30	26	44
231	5	60	70		15	49
233	33	81	57	50	25	13
235	20	53		8	7	27
237	18	68	84	81	24	40
239	90	14	29	25	34	45
242	33	88	82	11	62	77
244	39	16	4	5	43	72
246	42	73	84	76	66	45
248	61	13	17	84	47	26
250	13	48	70	16	31	25
252	49	17	24		29	51
254	24	73		77	28	31
256	39	27	39			16
258	22				8	29
260	17		52	49	44	77
262		83	36		49	74
264	21	25	14	87	43	68
266	37	46	46	50	29	56
268	67	23	63	31	23	63
270	34	9		50	20	63
272	22	50	72	19	46	45
274	36	86	52	87	74	68
276	82	11	11	82	21	
278	57	78	26	1	20	36
280	60	73	35	74	86	4
282	70	62	63	48	11	12
284	61	4	39	44	90	25
286	25	43	28	1	80	4

Table B.2 Twist values for unconstrained one-decade GB decompositions.

Site	Twist (degrees)						
Bands	0.001-0.01	0.01-0.1	0.1-1.0	1.0-10	10-100	100-1000	1000-10 000
sno200	4	22	-19	-20	-60	-19	
sno202	7	7	7	6	7	14	6
sno204				Error			
sno206	-20	-7	-27	44	36	22	
sno208	-3	-4	-11	46	48	55	
sno210	-6	-4	-5	6	9	16	
sno212	-1	3	2	3	5	6	
sno214	1	7	4	-1	-3	-24	
sno216	-3	-2	1	-1	-5	-11	-13
sno218	2	4	9	-9	-13	-16	
sno220	3	4	3	4	10	11	
sno222		-2	-8	-31	-30	-5	-22
sno224	2	-2	21	-24	-21	8	-6
sno226				Error			
sno228	2	0	7	-2	-31	11	
sno230	10	4	5	15	5	-33	
lim232				Error			
sno234	1	2	2	6	16	15	
sno236	-1	4	4	0	38	44	
sno238	-2	-2	-7	0	7	21	
sno240	-4	-3	-3	-6	-21	-8	
sno243	-4	-2	-2	-9	-9	-34	
sno245	3	-6	-7	-8	-9	-8	
sno247	19	37	37	-3	31	-29	
sno249	-4	-3	-3	1	7	8	
sno251	-4	-3	-3	10	5	-10	
sno253	-2	-4	-6	-8	14	15	
sno255	-7	-7	-16	-9	1	8	
sno257	5	7	15	2	-11	-23	
sno259	-9	-2	-14	1	-2	-18	
sno261	-1	2	3	-10	-15	-29	
sno263	-18	-19	-7	-42	-42	2	
sno265	2	4	-27	-22	-4	4	
sno267	-3	1	1	-1	3	12	
sno269	1	-1	0	-3	6	-1	
sno273	1	2	1	1	6	7	
sno275	38	11	13	12	45	60	
lim277				Error			
sno279		19	27	24	-24	31	
sno281	16	13	11	17	34	38	

sno283	3	2	-9	-6	-1	31
sno285	-4	1	-26	-28	-26	-47
sno287	1	1	-10	-15	-4	-7
203	-5	-1	0	-1	13	17
205	-3	-2	-1	-10	-20	-33
207	2	8	6	-4	-5	-11
209	8	0	2	2	-1	2
211	1	-2	-3	1	-7	-14
213	-1	2	-2	-5	-10	-25
215	2	3	2	-1	-6	-9
217	-8	-3	-9	-8	15	-15
219	5	11	15	10	8	11
221	-3	-4	-1	4	10	11
223	0	-4	1	2	17	17
225	-2	2	-4	-23	30	36
227	2	-2	-5	-4	-4	-24
229	-13	-11	-9	-25	-29	-38
231	-1	-15	17	10	4	-36
233	4	8	11	11	12	20
235	0	-1	-5	-6	5	24
237	0	3	4	14	37	36
239	-3	1	8	1	17	25
242	0	-5	-1	24	-14	-29
244	3	1	3	10	-3	-27
246	7	4	3	0	-2	17
248	5	4	1	-1	13	28
250	2	2	7	3	1	3
252	2	-14	-22	-53	-17	60
254	1	2	4	9	8	19
256	0	-5	-7	-30	-32	45
258	7	-9	-11	-8	-13	-33
260	-8	-8	-1	-2	-10	-41
262		5	-2	-15	-6	41
264	1	0	-1	2	18	31
266	0	0	1	-2	1	18
268	-2	-1	1	-1	2	11
270	-1	-1	-1	2	4	2
272	1	-1	-5	6	6	4
274	3	4	5	30	49	45
276	1	-12	-10	-1	1	60
278	-9	-27	11	7	6	3
280	3	3	6	4	-11	-6
282	-1	-5	-7	-16	-11	-10
284	5	15	11	11	30	25
286	-1	-1	-9	-9	0	60

Table B.3 Shear values for unconstrained one-decade GB decompositions.

Site	Shear (degrees)						
Bands	0.001-0.01	0.01-0.1	0.1-1.0	1.0-10	10-100	100-1000	1000-10 000
sno200	27	32	38	43	43	44	
sno202	12	10	13	4	1	2	-29
sno204				Error			
sno206	40	40	39	45	43	43	
sno208	-1	7	-26	25	27	31	
sno210	13	7	1	-2	5	2	
sno212	7	5	-1	1	-1	-9	
sno214	-8	-6	13	7	-11	-5	
sno216	-11	2	-3	4	5	3	
sno218	15	-8	-15	13	14	-26	
sno220	-1	-15	-12	-15	12	-20	
sno222		22	23	11	33	38	41
sno224	-6	-13	19	28	-31	-34	-32
sno226				Error			
sno228	-1	7	-1	-43	-40	-41	
sno230	-16	3	16	34	37	39	
lim232				Error			
sno234	4	12	13	30	34	-40	
sno236	6	-6	-6	15	-23	-35	
sno238	13	4	15	24	22	-43	
sno240	3	-2	-1	11	31	42	
sno243	8	9	11	10	30	31	
sno245	9	21	6	5	7	24	
sno247	37	31	31	40	41	45	
sno249	8	-2	6	9	-4	18	
sno251	1	5	8	26	29	29	
sno253	12	9	6	5	30	41	
sno255	-1	4	12	-33	32	-24	
sno257	17	-7	4	-15	22	30	
sno259	18	15	15	18	22	36	
sno261	3	-4	-10	17	21	-33	
sno263	26	33	36	39	43	44	
sno265	-5	8	-42	35	33	19	
sno267	5	-1	-2	-2	-2	25	
sno269	-8	5	6	-5	1	29	
sno273	8	-2	-7	1	5	9	
sno275	-23	16	-9	17	35	24	
lim277				Error			
sno279		5	11	-7	-45	8	
sno281	22	24	26	34	35	35	

sno283	-3	8	19	35	35	-45
sno285	6	19	38	42	38	38
sno287	3	-7	25	31	35	-38
203	8	7	8	3	4	4
205	8	9	1	9	21	27
207	14	-1	-8	14	20	20
209	8	5	10	-18	13	6
211	10	3	4	6	13	8
213	-6	1	-7	5	13	15
215	0	3	-2	1	5	6
217	-13	2	22	-23	15	-21
219	26	25	-26	20	18	14
221	-8	-1	4	9	2	0
223	15	17	22	27	-29	-23
225	1	-6	17	38	-36	-42
227	5	13	4	12	22	31
229	3	12	-2	38	37	37
231	17	4	-30	41	41	43
233	-1	-10	-6	-12	-30	-27
235	-2	-8	10	13	10	-24
237	9	-9	-13	15	-24	-31
239	-7	7	1	11	-13	-33
242	9	6	6	33	40	39
244	7	9	6	15	41	39
246	15	12	10	16	28	33
248	9	-5	-4	21	29	31
250	11	5	-7	17	18	24
252	6	29	26	-25	35	-44
254	7	-5	-1	-4	13	22
256	-7	-22	-18	30	37	39
258	6	6	8	19	24	31
260	4	18	12	15	29	32
262	16	16	-8	3	20	28
264	15	14	16	-18	-15	14
266	3	-4	-1	-2	-13	25
268	1	1	2	-9	-12	27
270	2	2	3	-8	-4	21
272	-3	3	3	3	10	14
274	5	5	26	32	26	28
276	11	-25	-23	10	44	39
278	25	36	45	16	22	20
280	-1	-2	1	10	18	-23
282	15	5	7	18	12	9
284	-5	-29	-16	-23	19	-21
286	-3	-10	12	39	-43	-28

Appendix C: Real and Imaginary Components of the Induction Vector

This appendix shows the real and imaginary components of the induction vector for Line 2a and the Connector Line, as discussed in section 3.5. For purposes of display, the MT sites were divided into two groups: the south group includes sites 225 to 200 and the north group includes sites 226 to 287. The induction vector direction is reversed as to point toward areas of enhanced conductivity.

The induction vectors are also plotted with the error ellipse to indicate the uncertainty in the response. Sites with poor tipper data were removed. At 0.05 s the real and imaginary induction vector components for sites 207, 214, 215, and 276 were removed due to poor data quality. Similarly, at .5 s sites 214, and 228 were removed, and are not present in the following Figures.

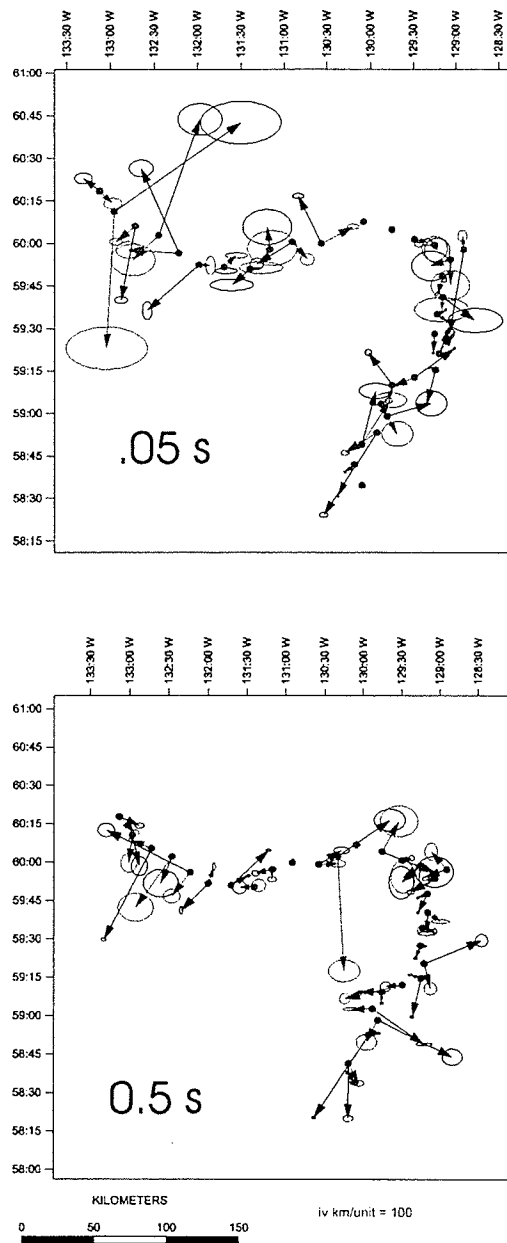


Figure C.1. Real and imaginary induction vector for the north group. The real component of the induction vector is plotted in black and the imaginary component is plotted in red. Induction vector scale: 1 unit equals 100 km.

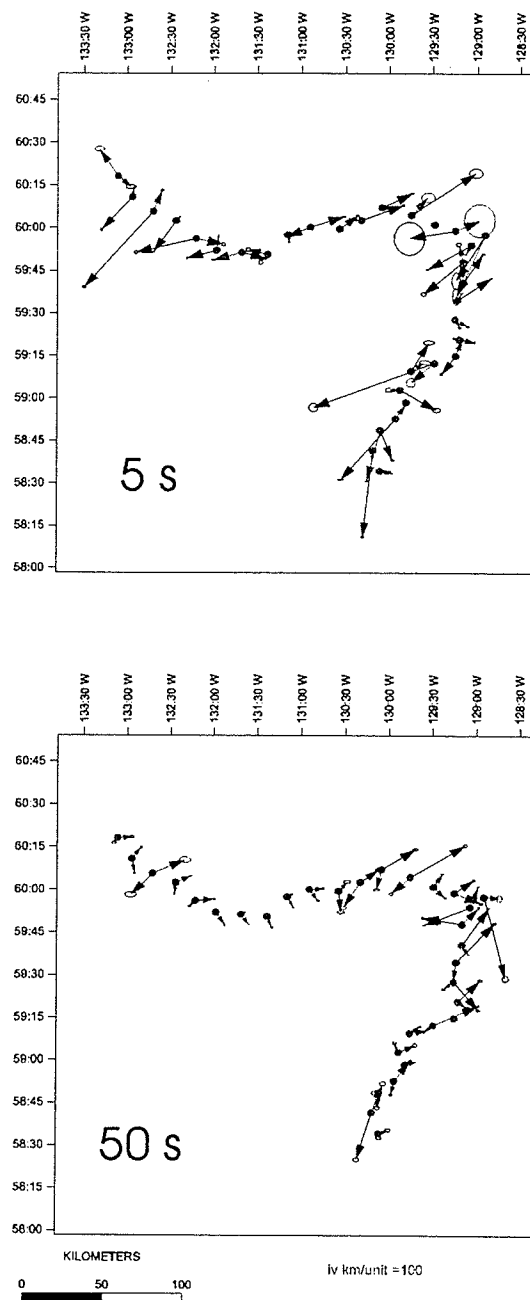


Figure C.2 Real and imaginary induction vector for the north group. Induction vector scale: 1 unit equals 100 km.

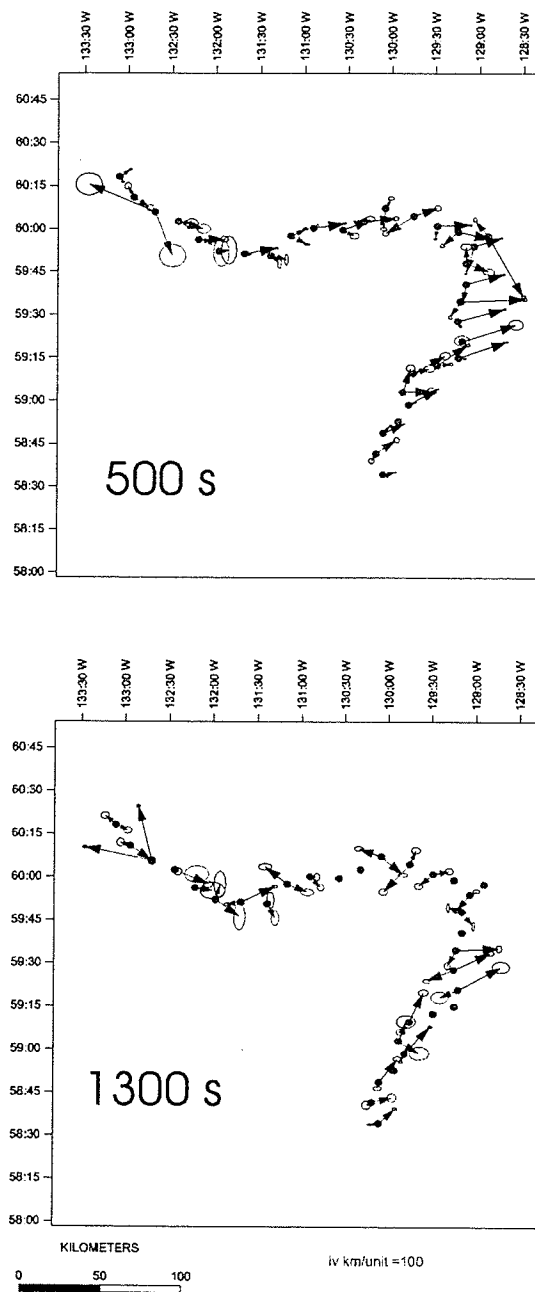


Figure C.3 Real and imaginary induction vector for the north group. Induction vector scale: 1 unit equals 100 km.

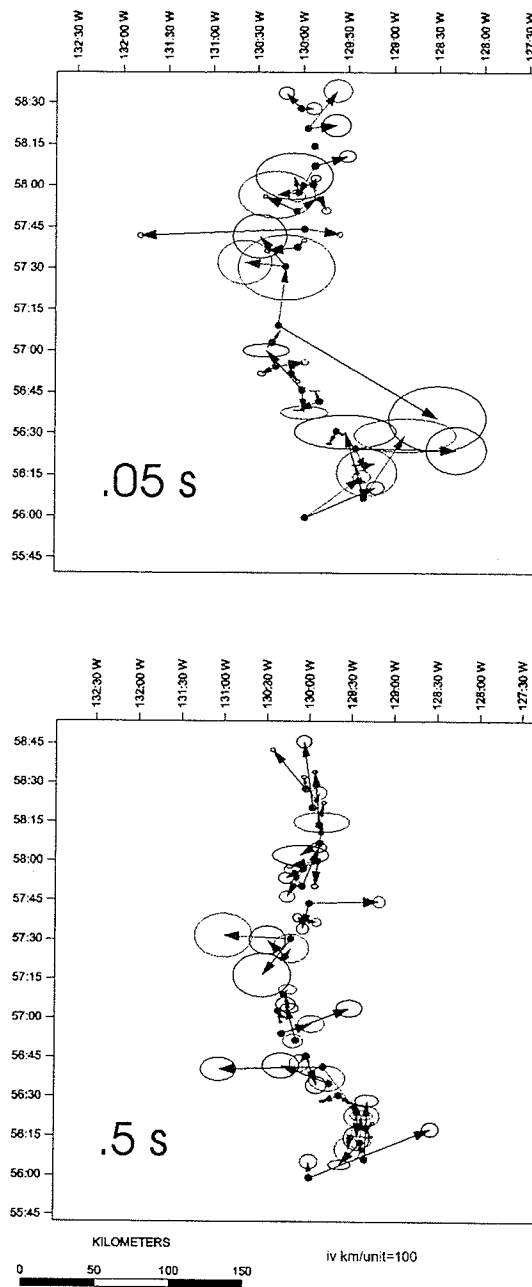


Figure C.4 Real and imaginary induction vector for the south group. Induction vector scale: 1 unit equals 100 km.

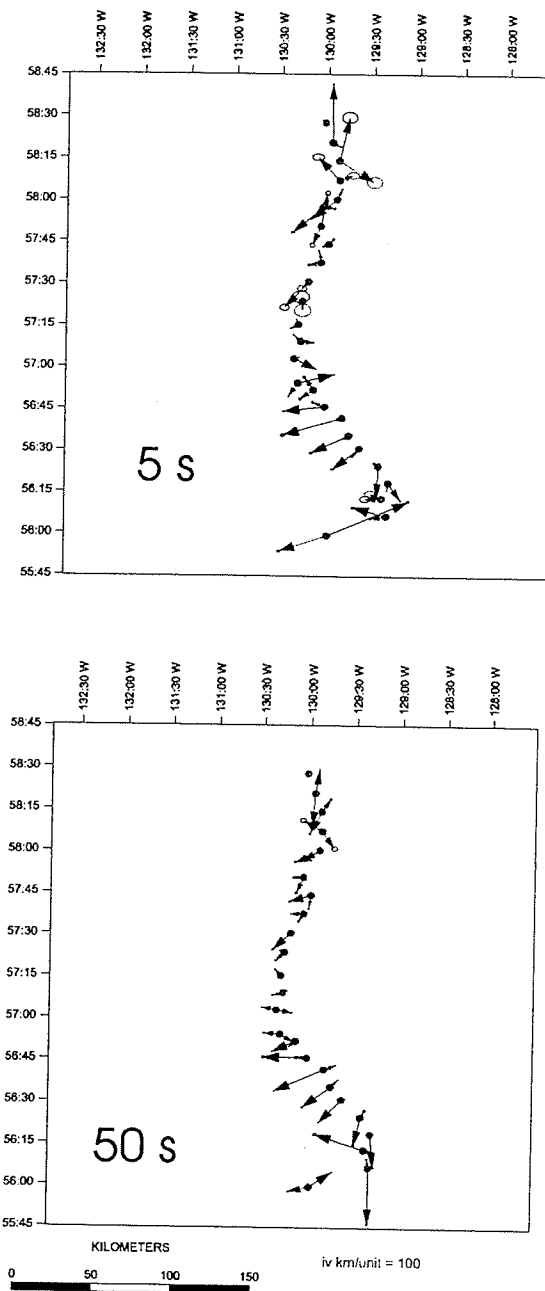


Figure C.5 Real and imaginary induction vector for the south group. Induction vector scale: 1 unit equals 100 km.

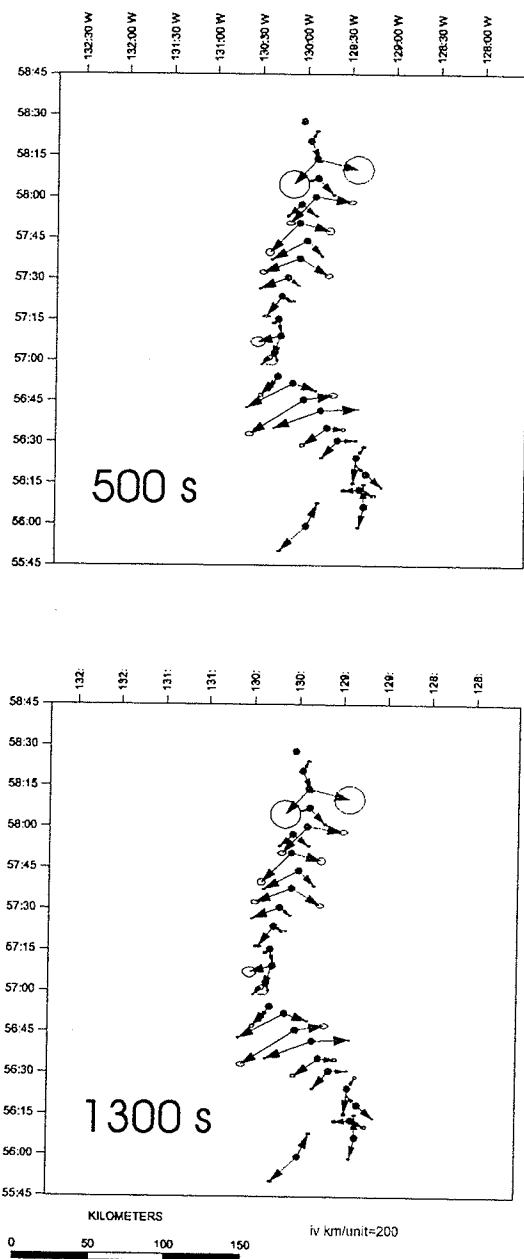


Figure C.6 Real and imaginary induction vector for the south group. Induction vector scale: 1 unit equals 200 km.

Appendix D: Edited Data Rotated to -45° Azimuth

As discussed in section 5.8, the strike analysis has indicated that a geoelectric strike of -45° is appropriate for Line 2a and the Connector Line. This appendix shows the edited data (see section 4.5.2) for the Connector Line and Line 2a rotated to an azimuth of -45°. The TE response corresponds to electric currents flowing parallel to -45° and the TM currents flowing perpendicular to -45°.

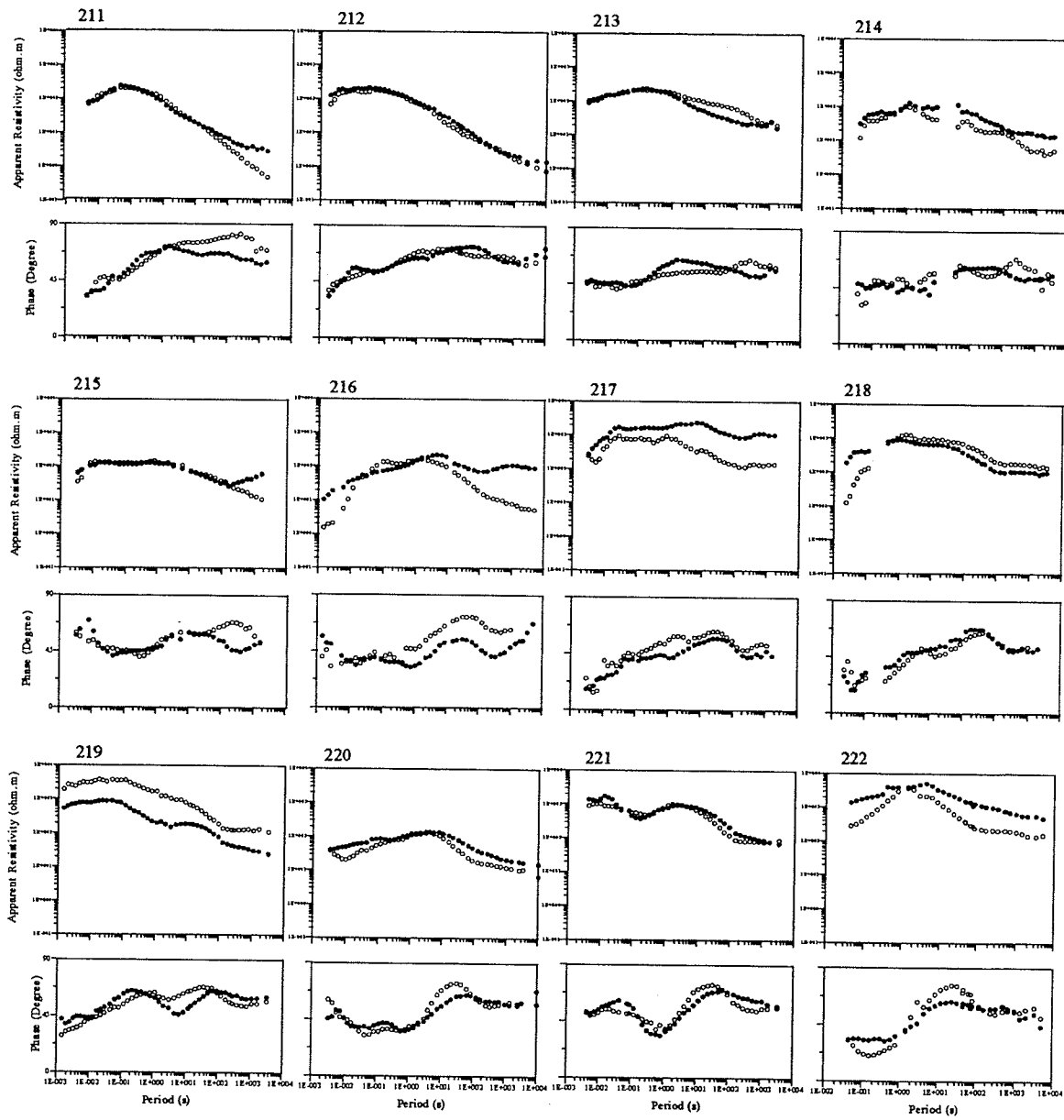


Figure D.1 The edited apparent resistivity and phase response for Line 2a. The TE data is plotted as solid circles and TM data is plotted as open circles with black outline.

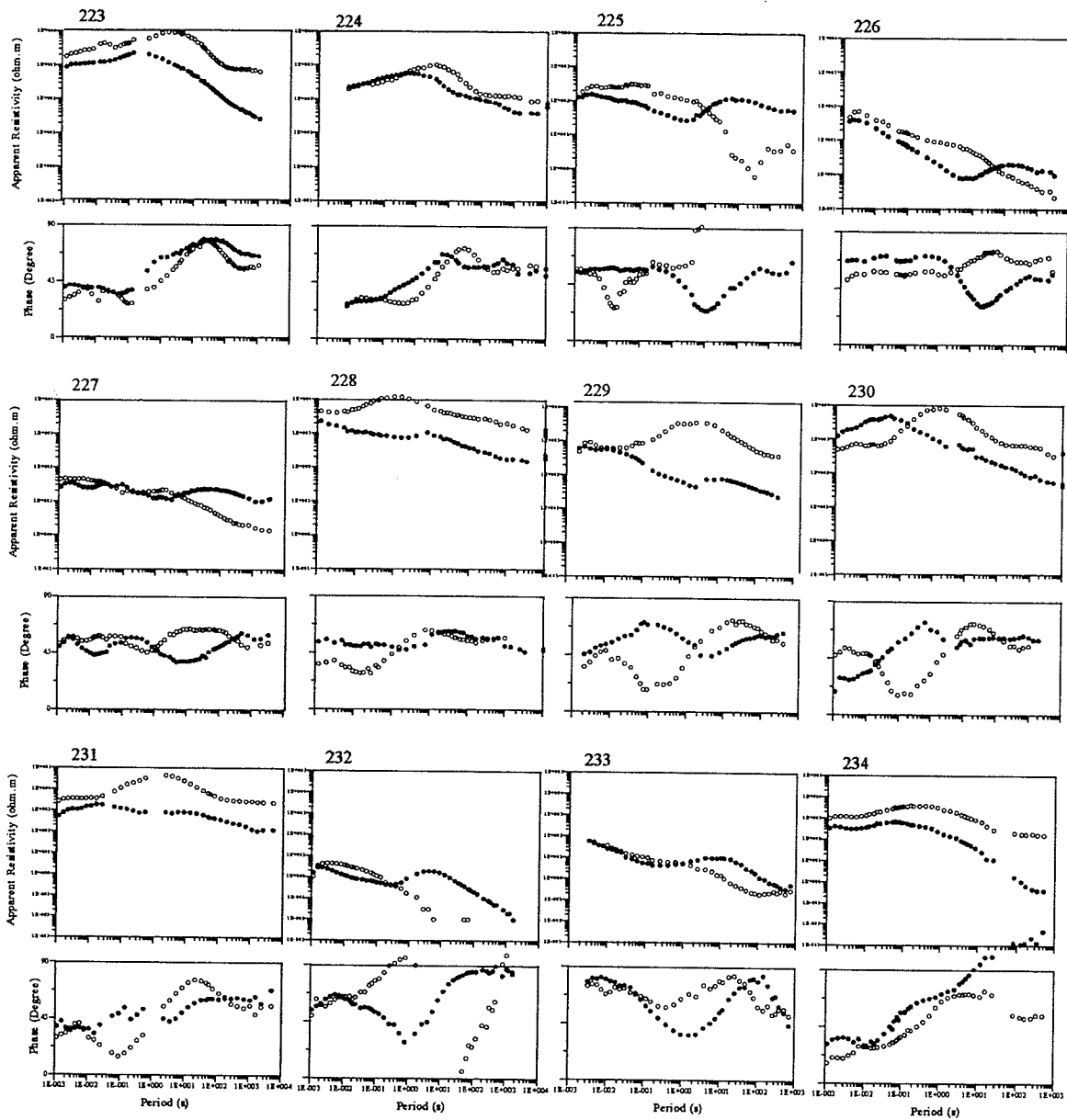


Figure D.1 cont.

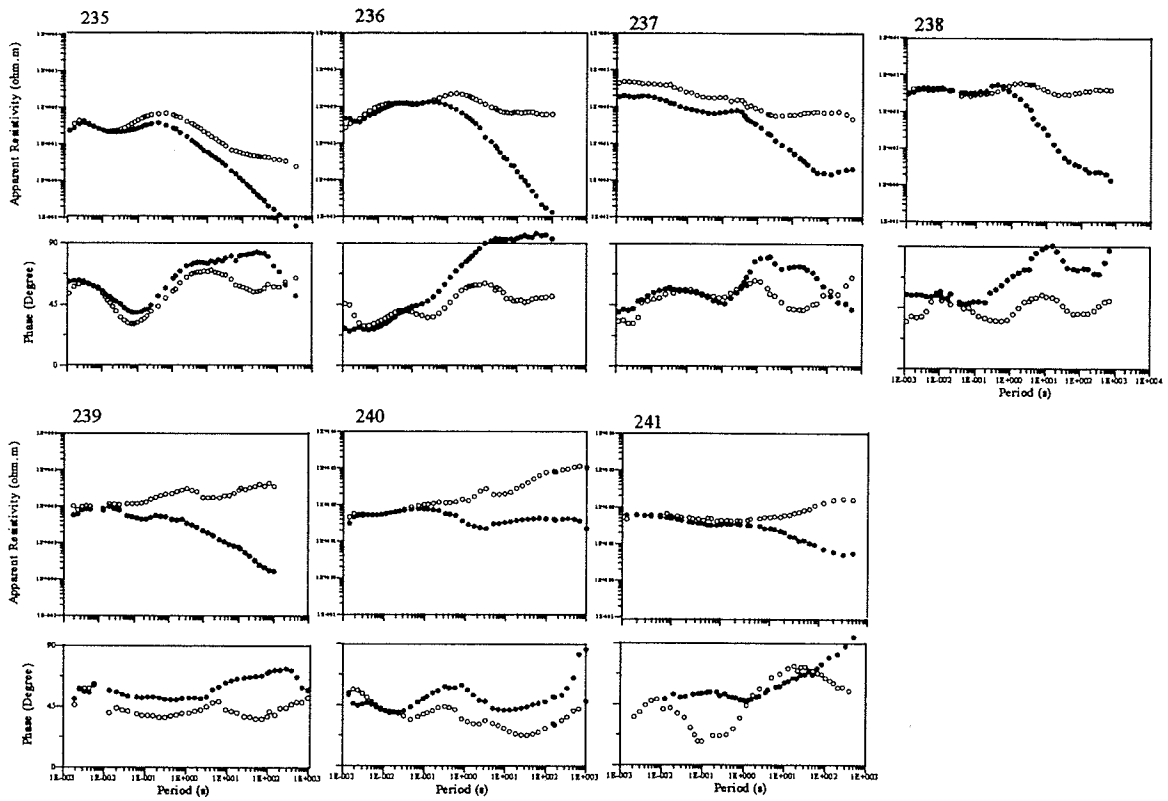


Figure D.1 cont.

Appendix E: Fit of the Occam Model for Line 2a

This appendix compares the responses of three 2D Occam inversion models for Line 2a (Fig. 7.9) with the observed data. The north and south segments include the phase and apparent resistivity data in the inversion, and the central segment includes the phase, apparent resistivity, and tipper data. The TE data are plotted in black and the TM data are plotted in cyan. The observed data are plotted using discrete symbols. The model responses are plotted as lines.

North Segment

The north segment includes sites 241 to 226 located on the Cache Creek, Quesnellia, Cassiar, and Slide Mountain terranes. The contoured responses are shown in Figure 7.1 and 7.2 and the response at individual sites in Figure E.1 and E.2.

Central Segment

The central segment includes sites 221 to 232 located on the Stikine, Cache Creek, Quesnellia, Cassiar, and Slide Mountain terranes. The contoured responses are shown in Figure 7.6, 7.7, and 7.8 and the responses at individual sites in Figure E.3, E.4, and E.5.

South Segment

The south segment includes sites 211 to 227 located in the Stikine, Cache Creek, and Quesnellia terranes. The contoured response are shown in Figure 7.4 and 7.5 and the responses at individual sites in Figure E.6 and E.7.

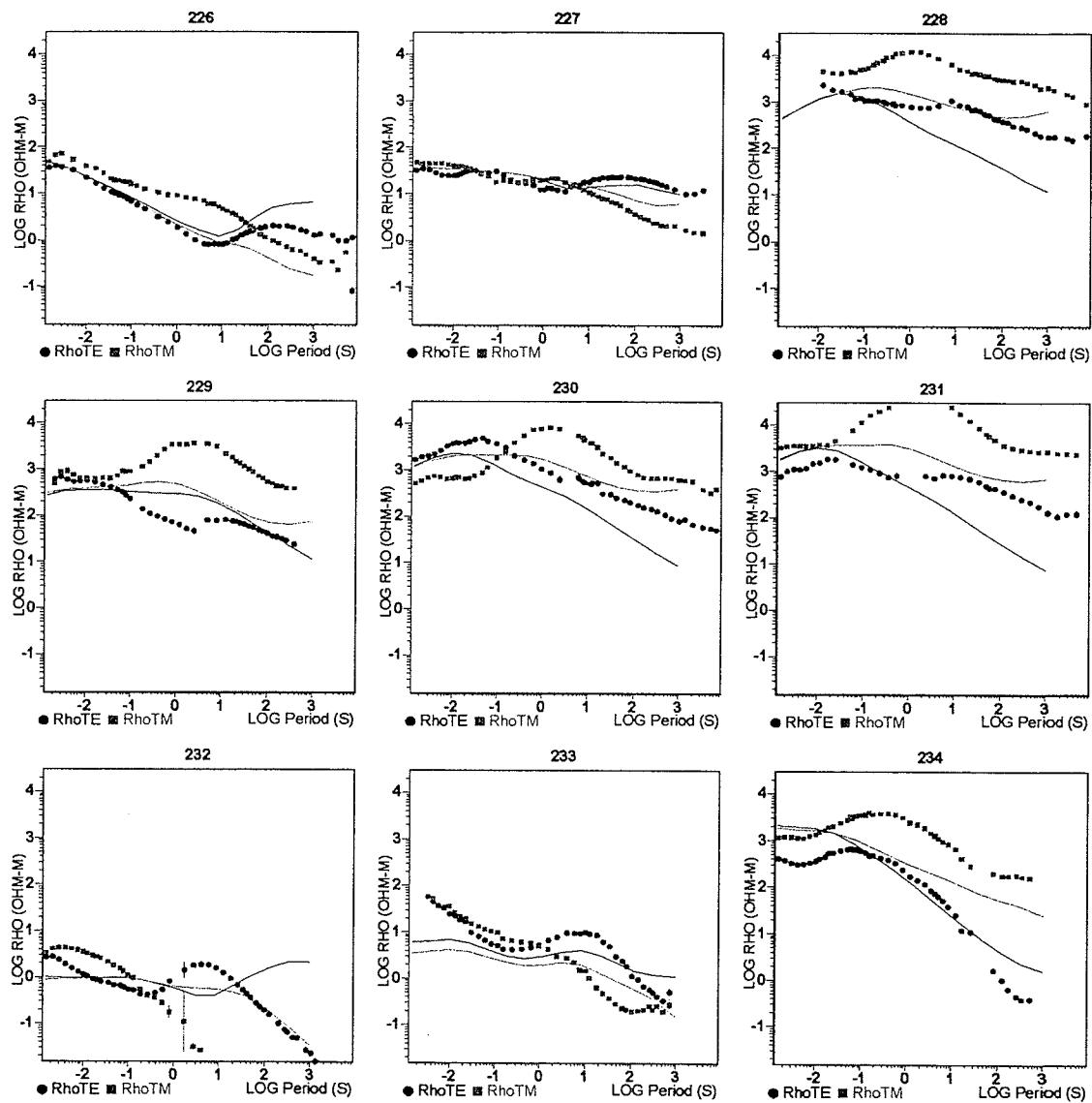


Figure E.1 Comparison of the observed and modeled apparent resistivity response for the north segment of Line 2a.

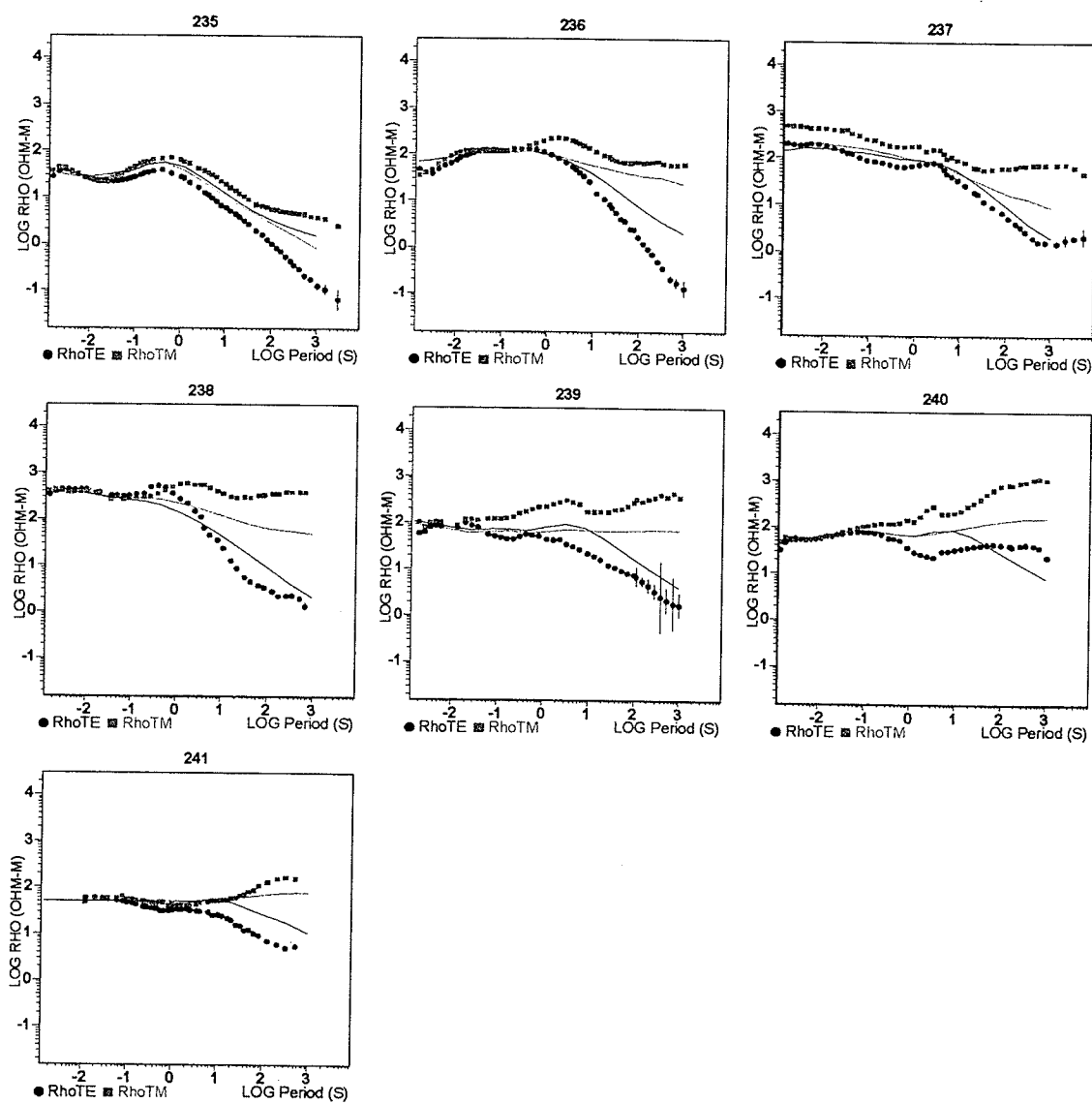


Figure E.1 cont.

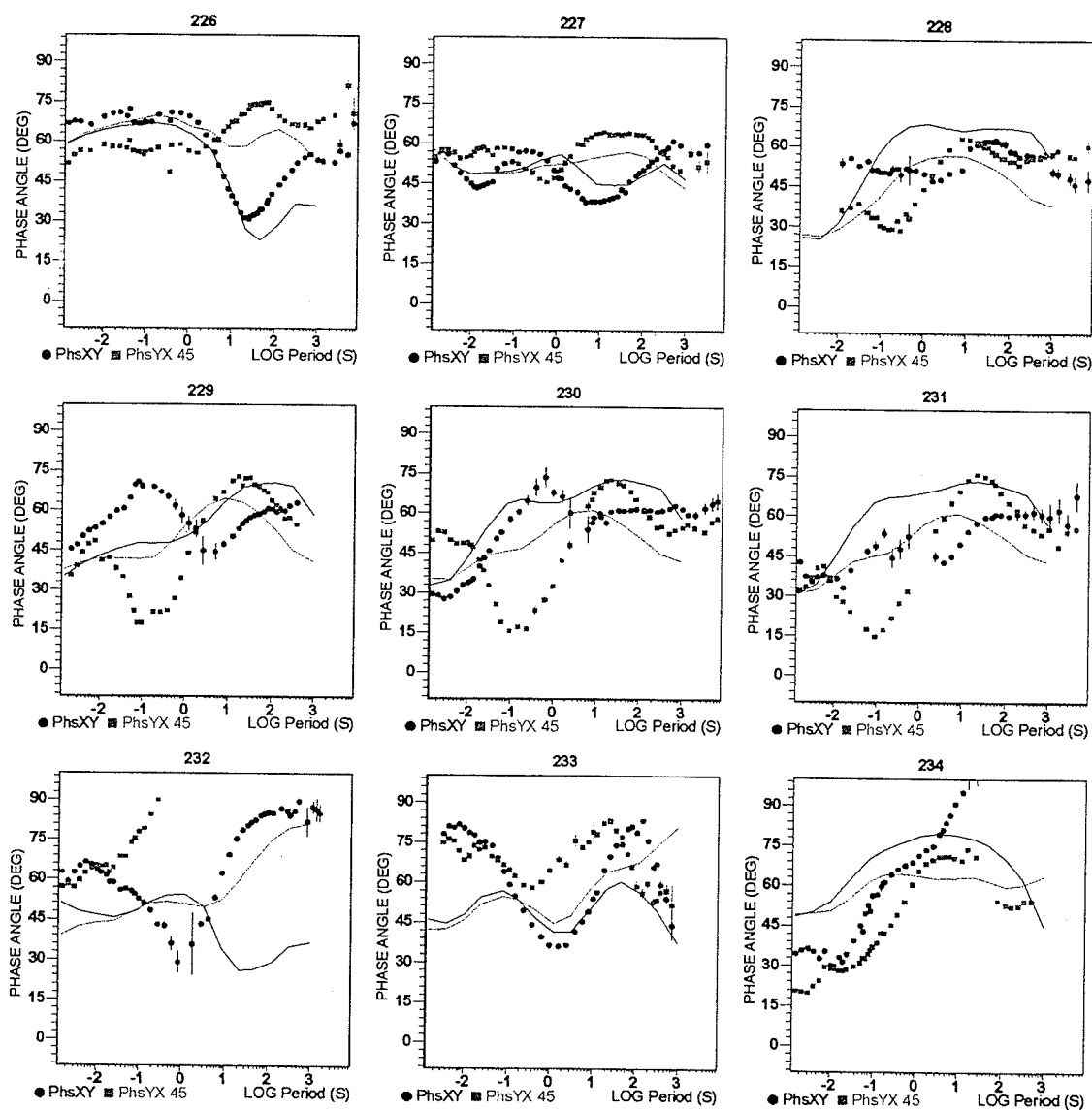


Figure E.2 Comparison of the observed and modeled phase response for the north segment of Line 2a.

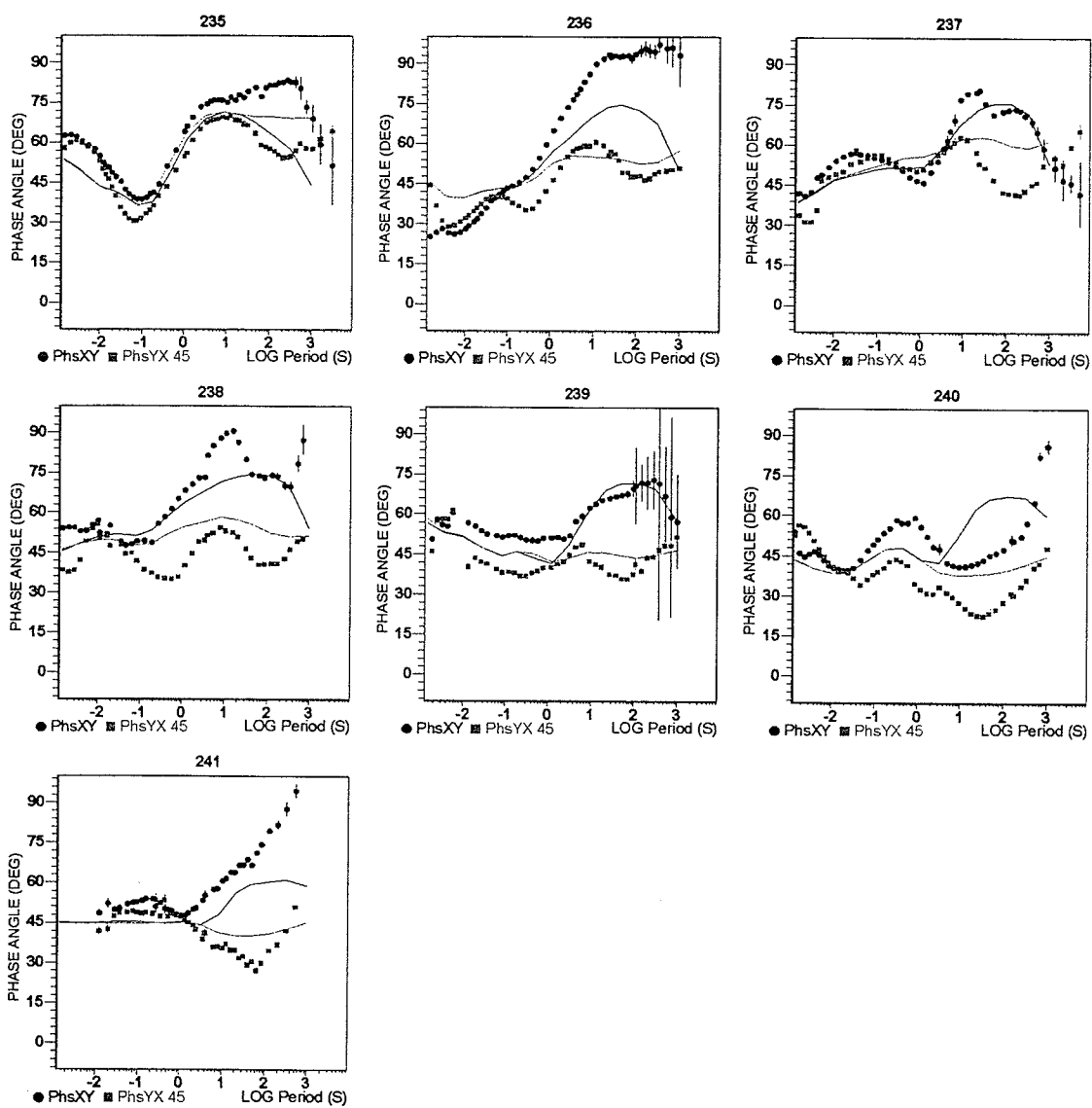


Figure E.2 cont.

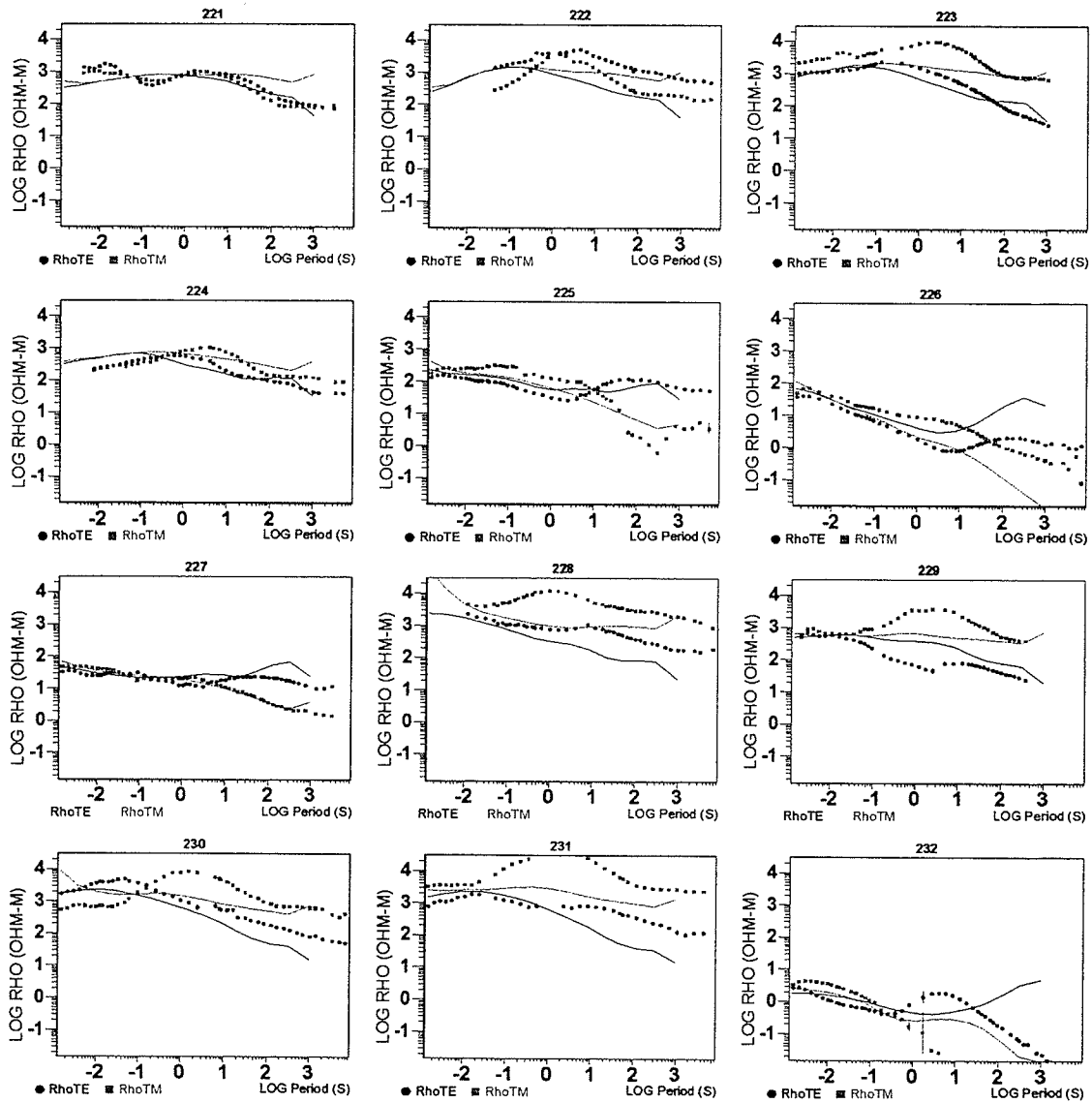


Figure E.3 Comparison of the observed and modeled apparent resistivity response for the central segment of Line 2a.

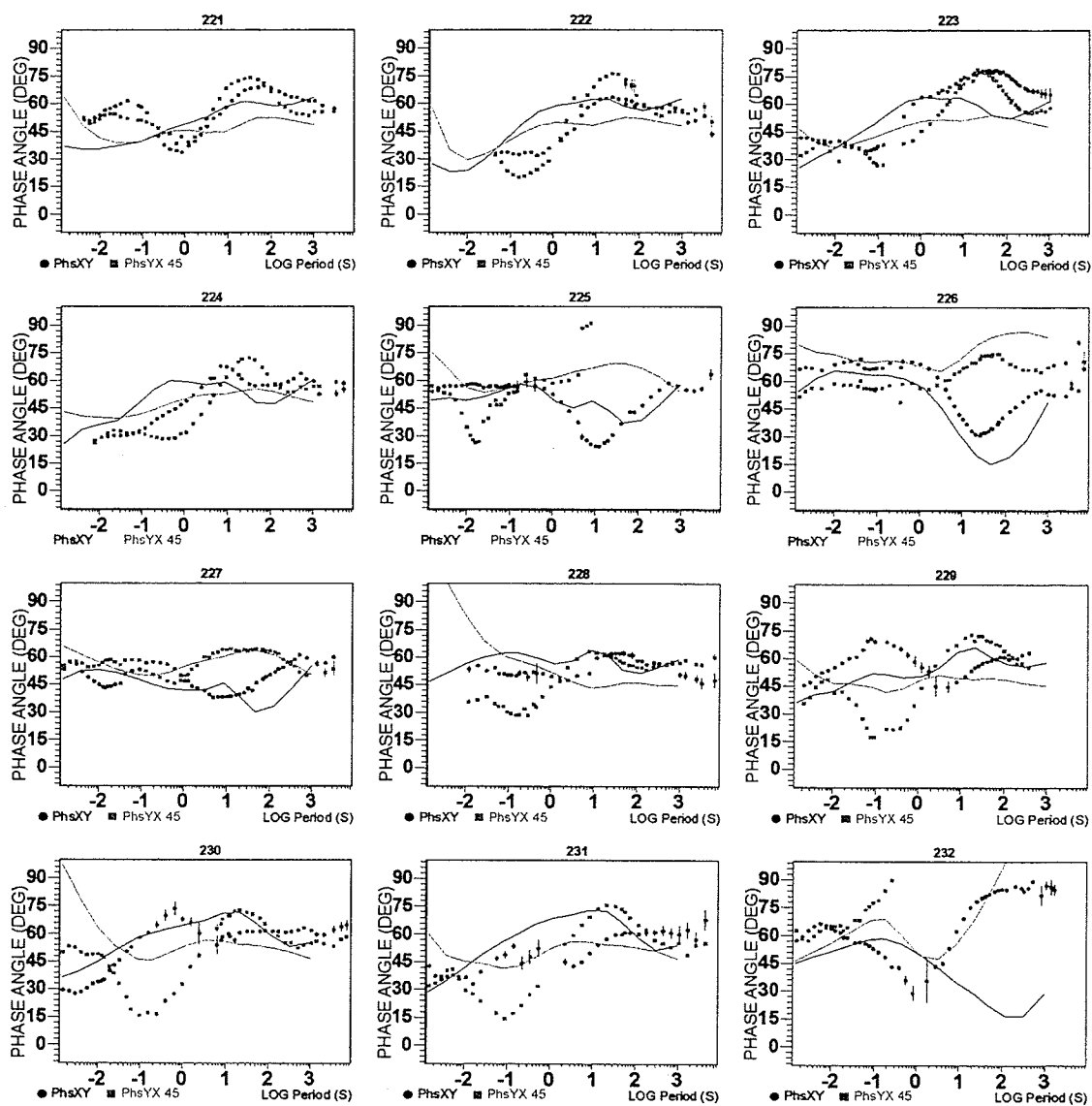


Figure E.4 Comparison of the observed and modeled phase response for the central segment of Line 2a.

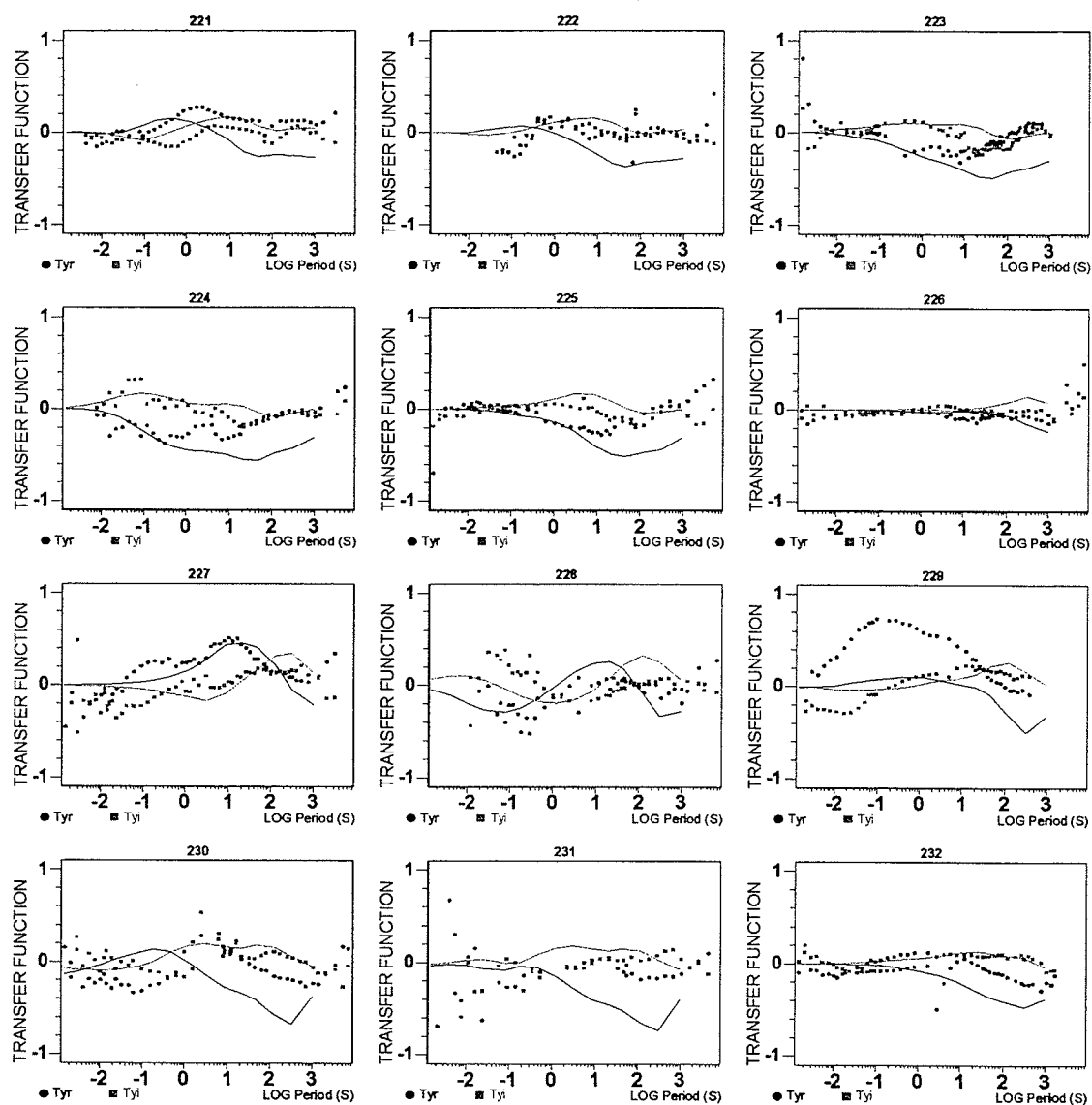


Figure E.5 Comparison of the observed and modeled real component of the induction vector (Tyr) and imaginary component of the induction vector (Tyi) response for the central segment of Line 2a.

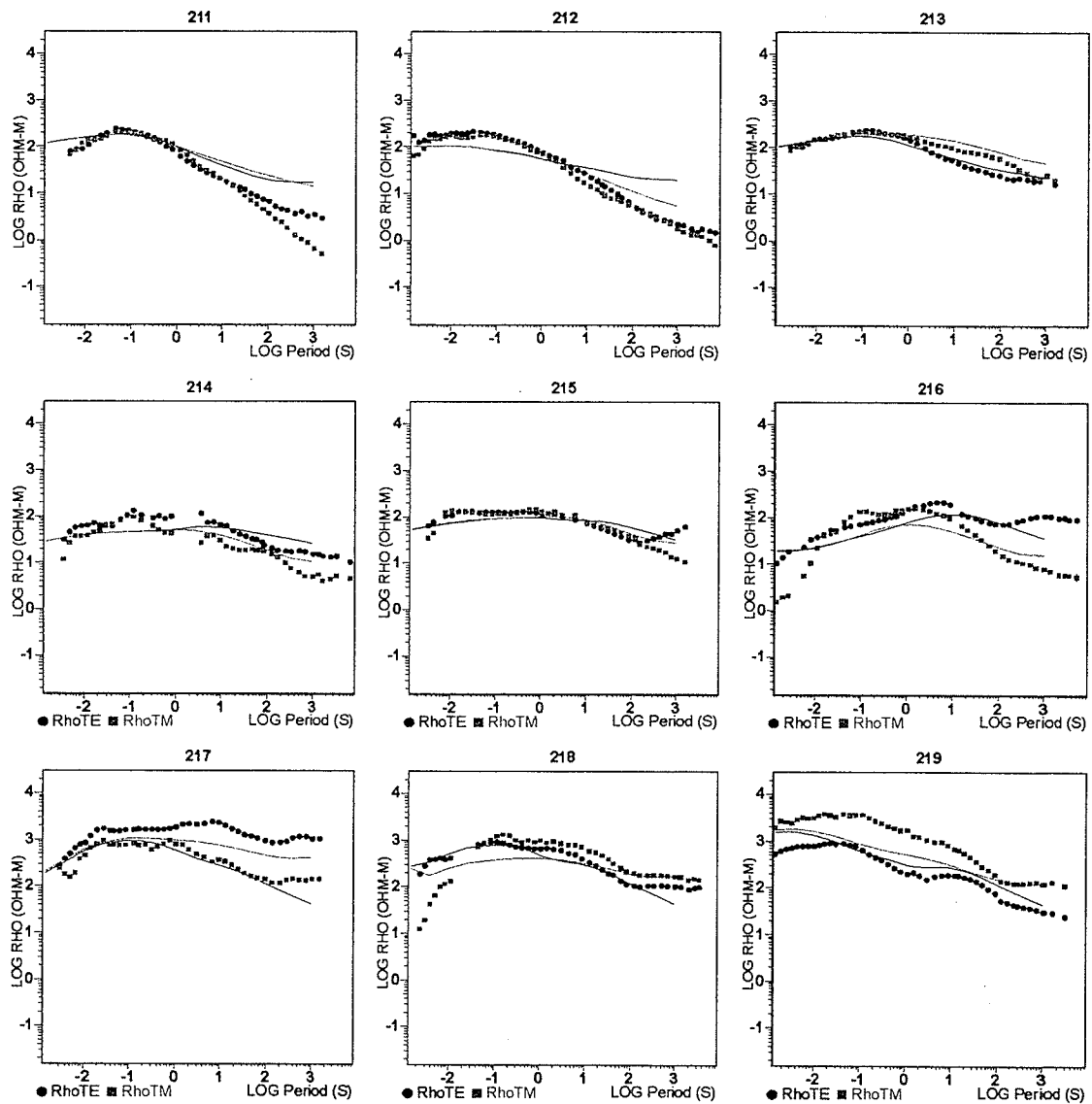


Figure E.6 Comparison of the observed and modeled apparent resistivity response for the south segment of Line 2a.

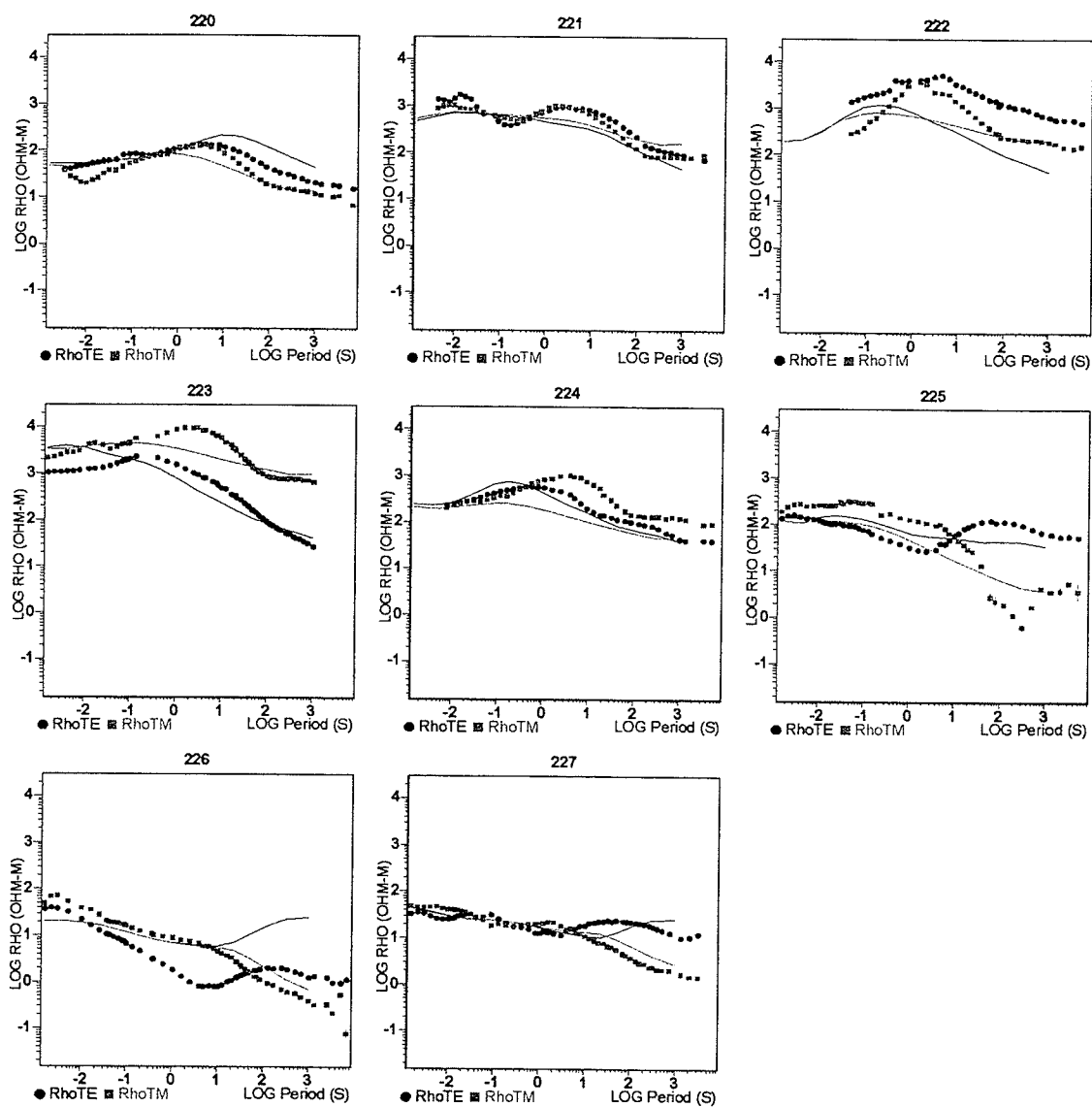


Figure E.6 cont.

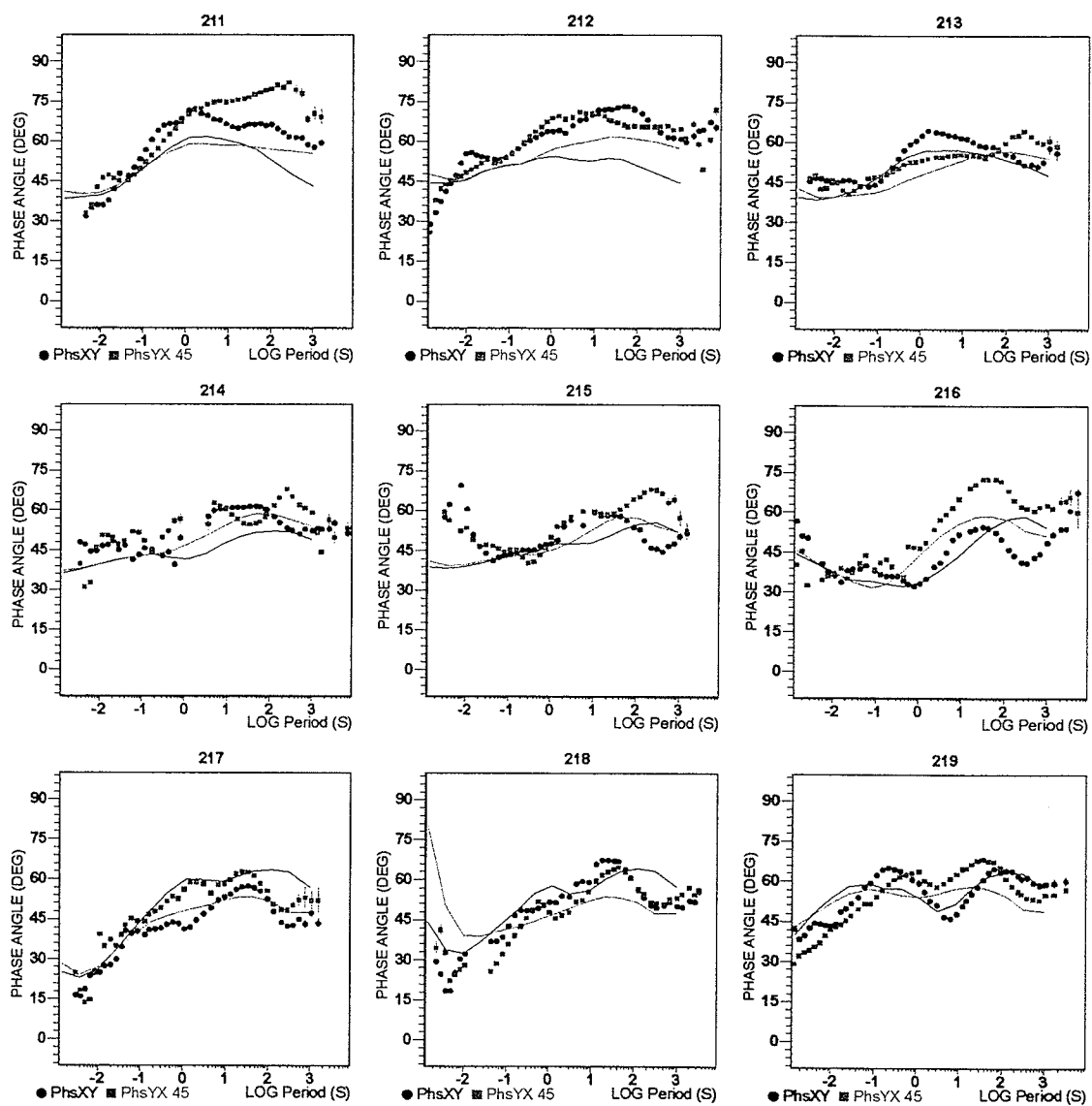


Figure E.7 Comparison of the observed and modeled phase response for the south segment of Line 2a.

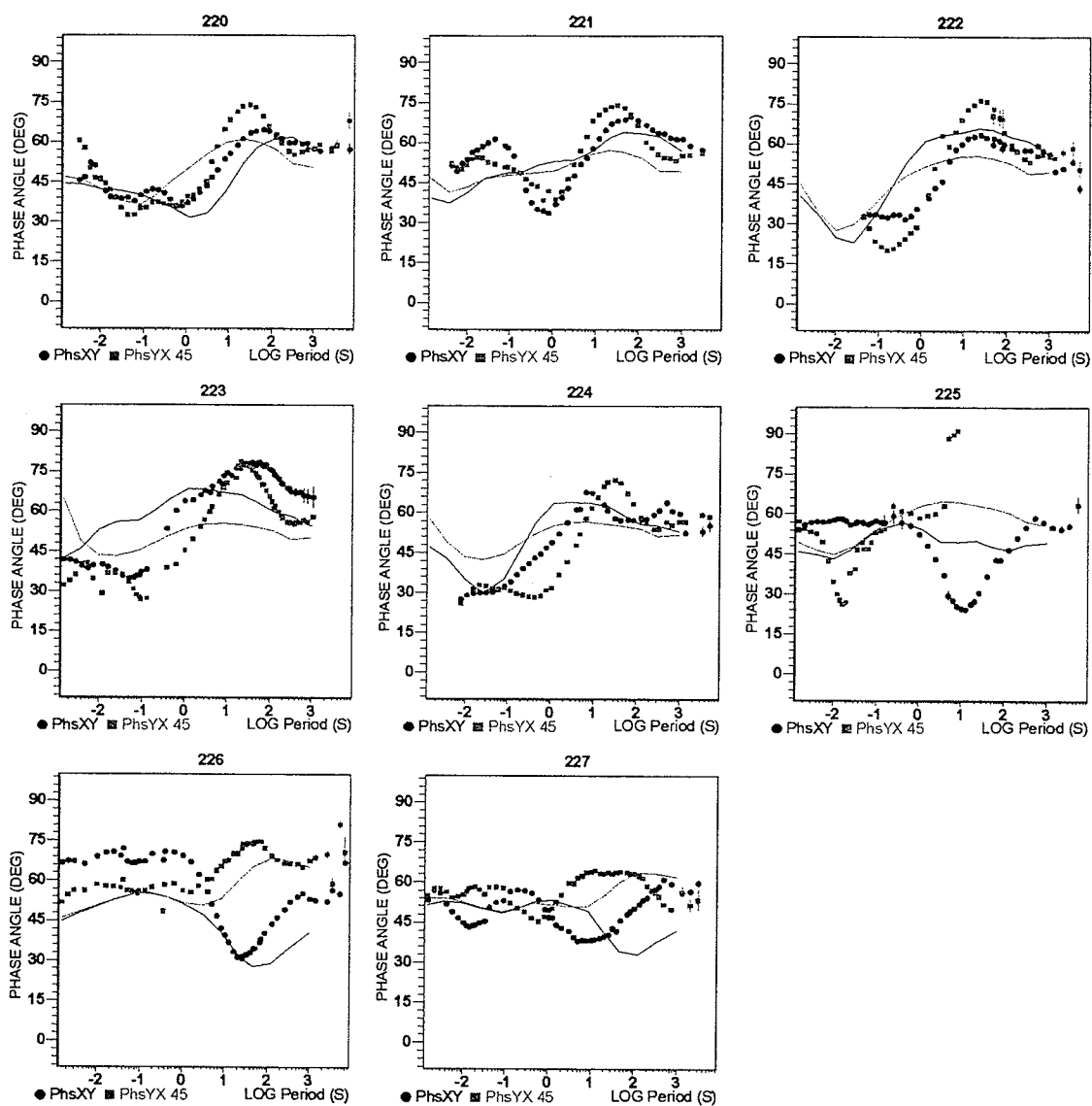


Figure E.7 cont.

Appendix F: Fit of the Occam model for the Connector Line

This appendix compares the response of the Connector Line Occam model with the observed data (Fig. 7.15). The Model A inversion included the apparent resistivity and phase response (Fig. F.1 and F.2), and the Model B inversion included the apparent resistivity, phase, and tipper response (Fig. F.3, F.4, and F.5). The TE observed and modeled data is plotted as solid black circles and black lines, and the TM observed and modeled data is plotted as solid cyan circles and cyan lines.

Model A

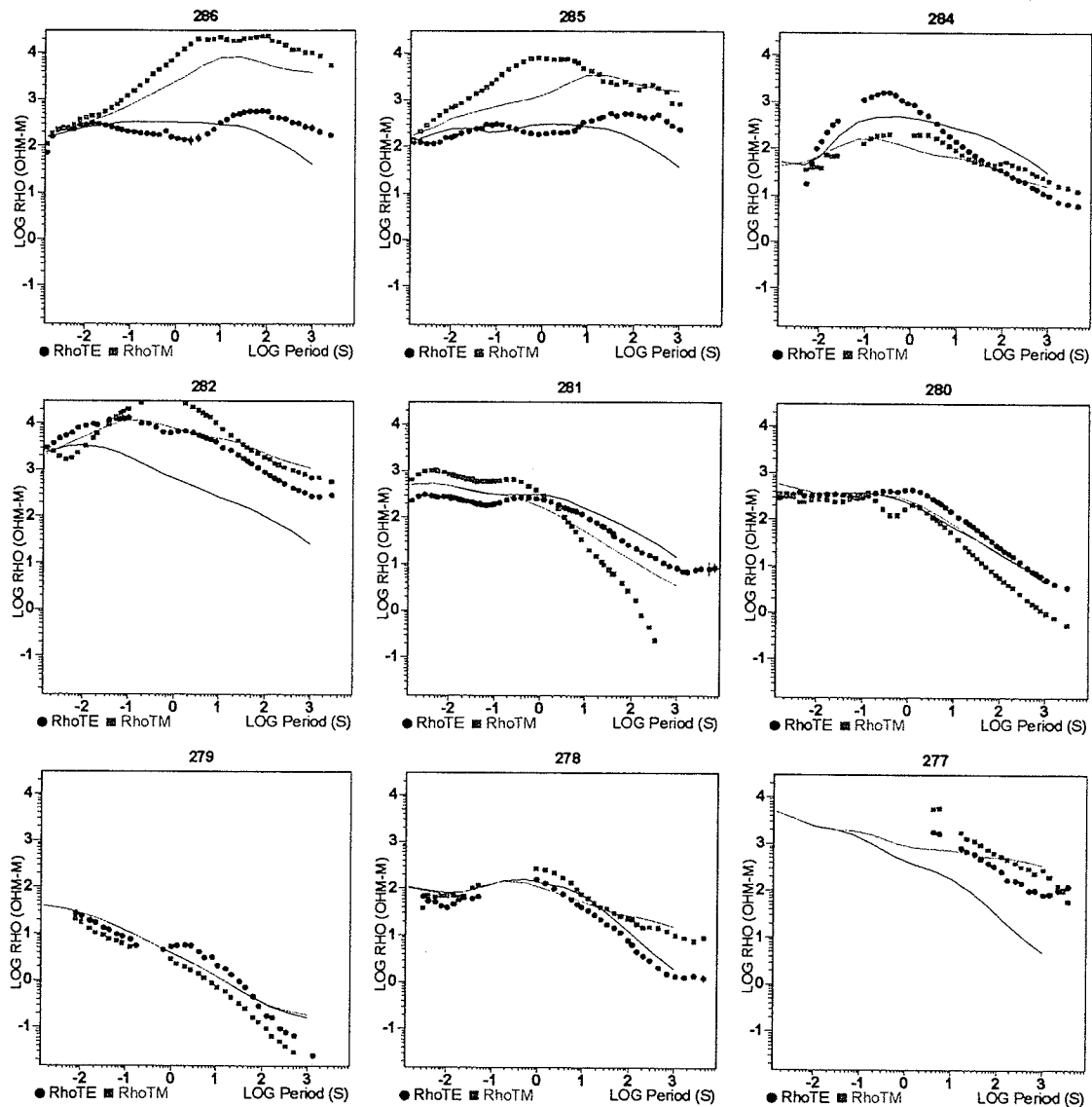


Figure F.1 Comparison of the observed and modeled apparent resistivity response for Model A of the Connector Line.

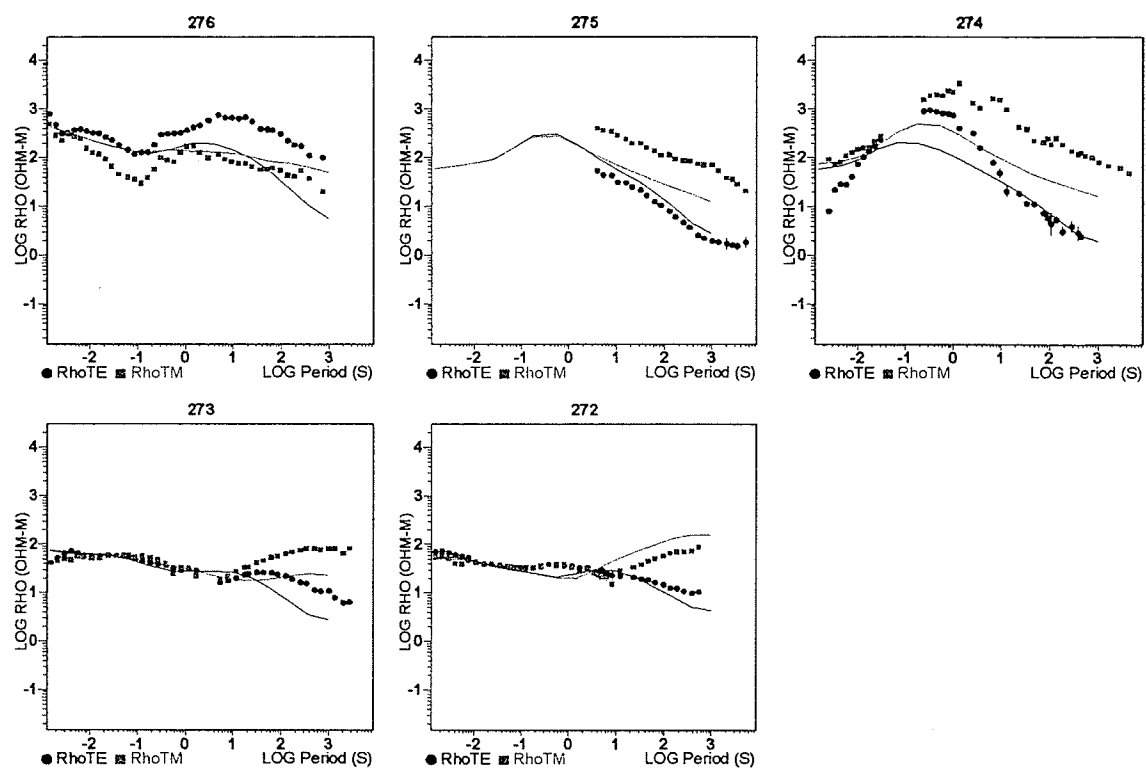


Figure F.1 cont.

Model A

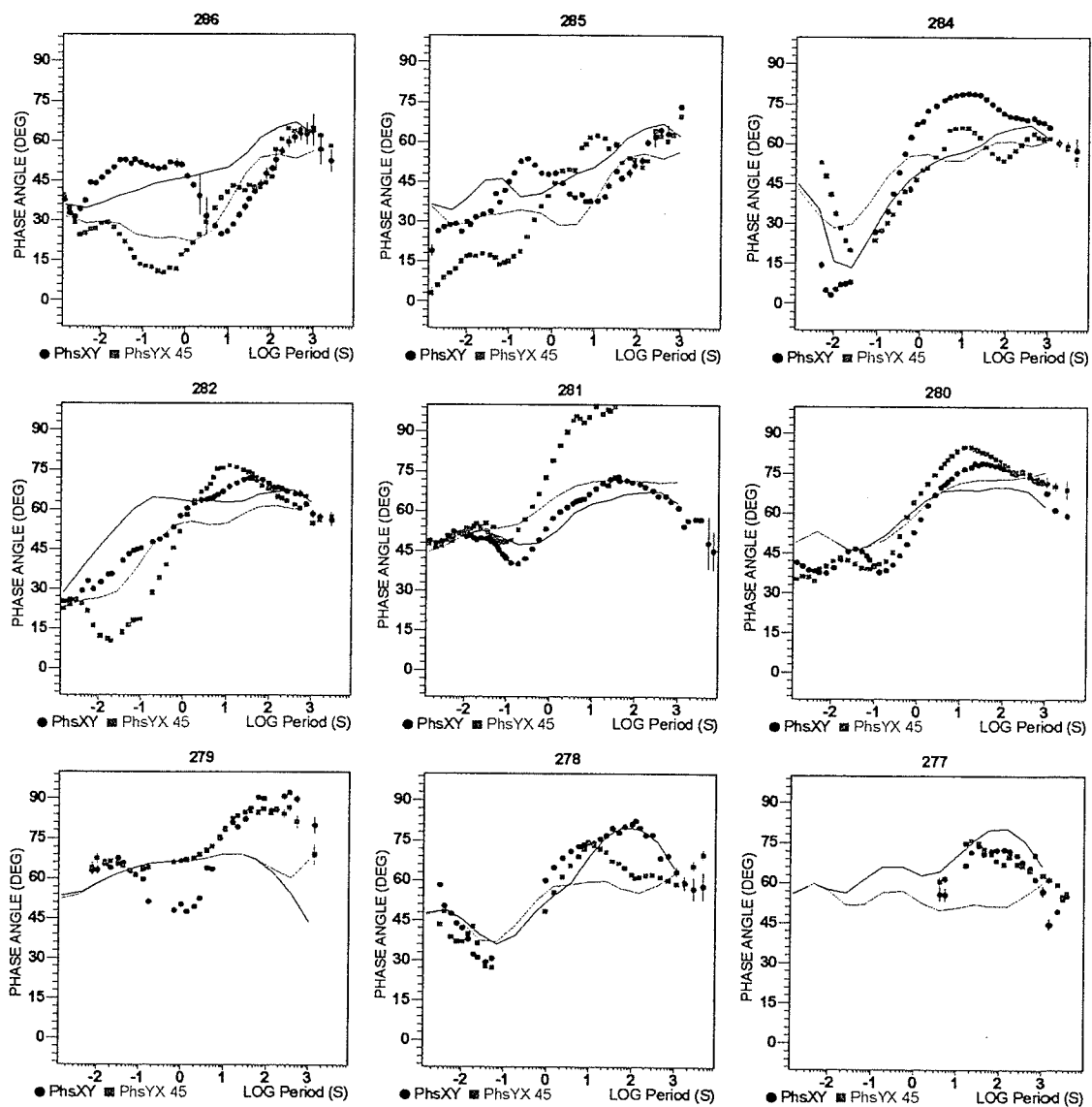


Figure F.2 Comparison of the observed and modeled phase response for Model A of the Connector Line.

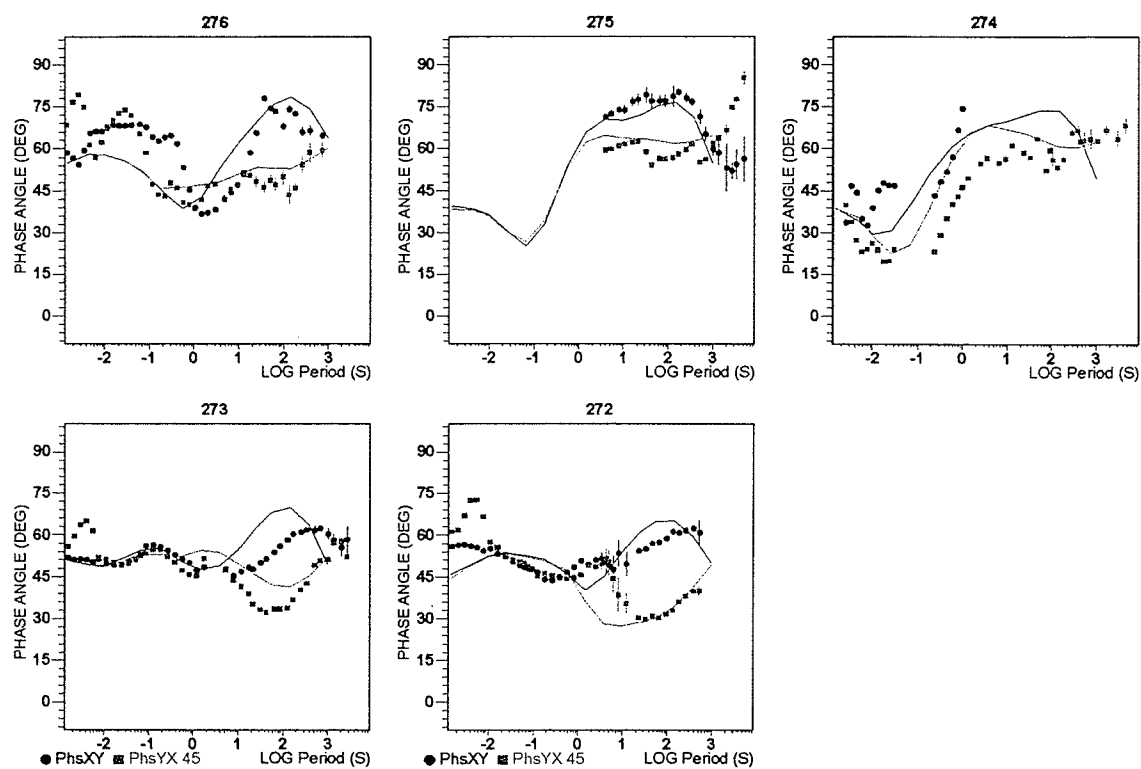


Figure F.2 cont.

Model B

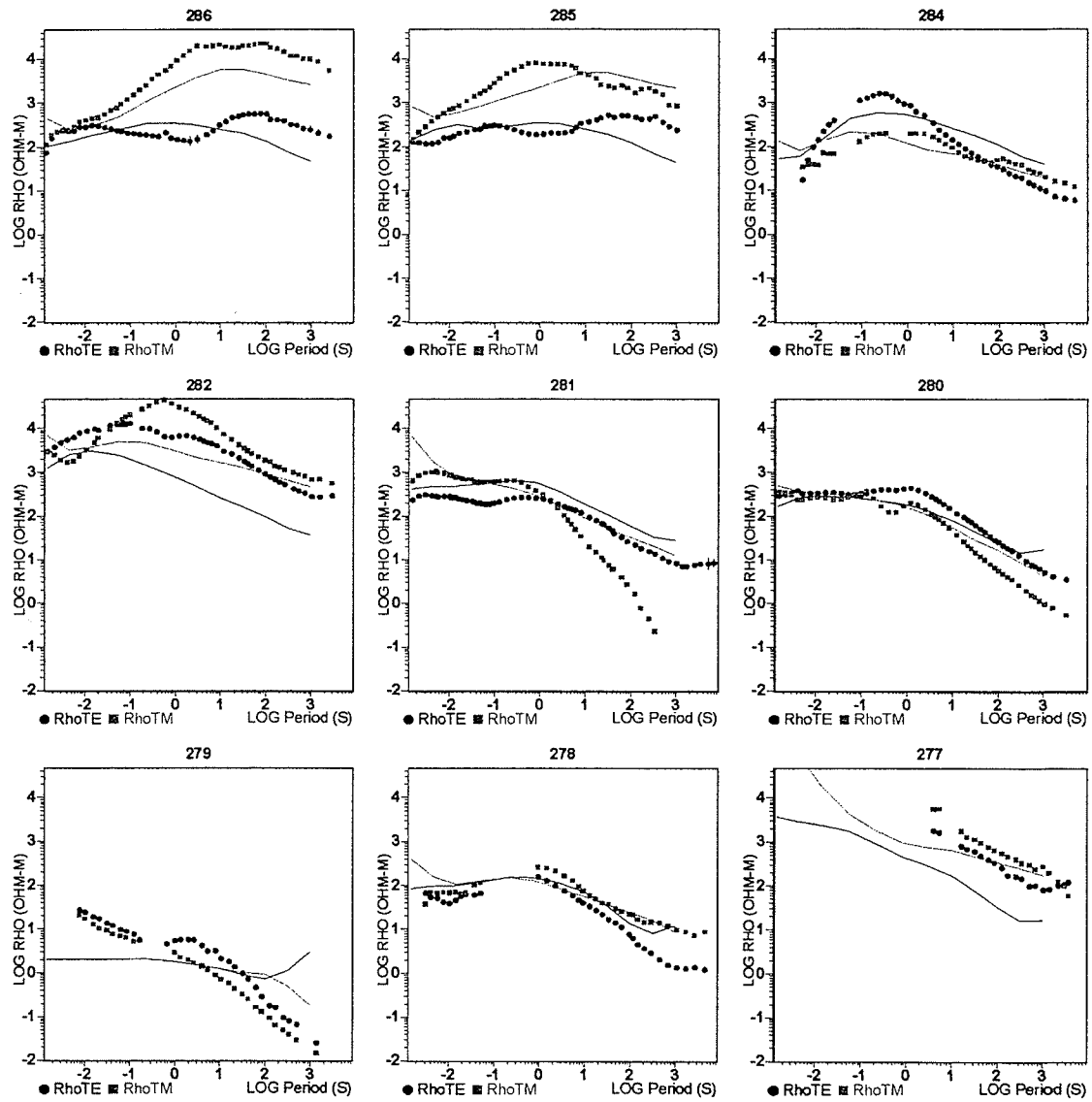


Figure F.3 Comparison of the observed and modeled apparent resistivity response for Model B of the Connector Line.

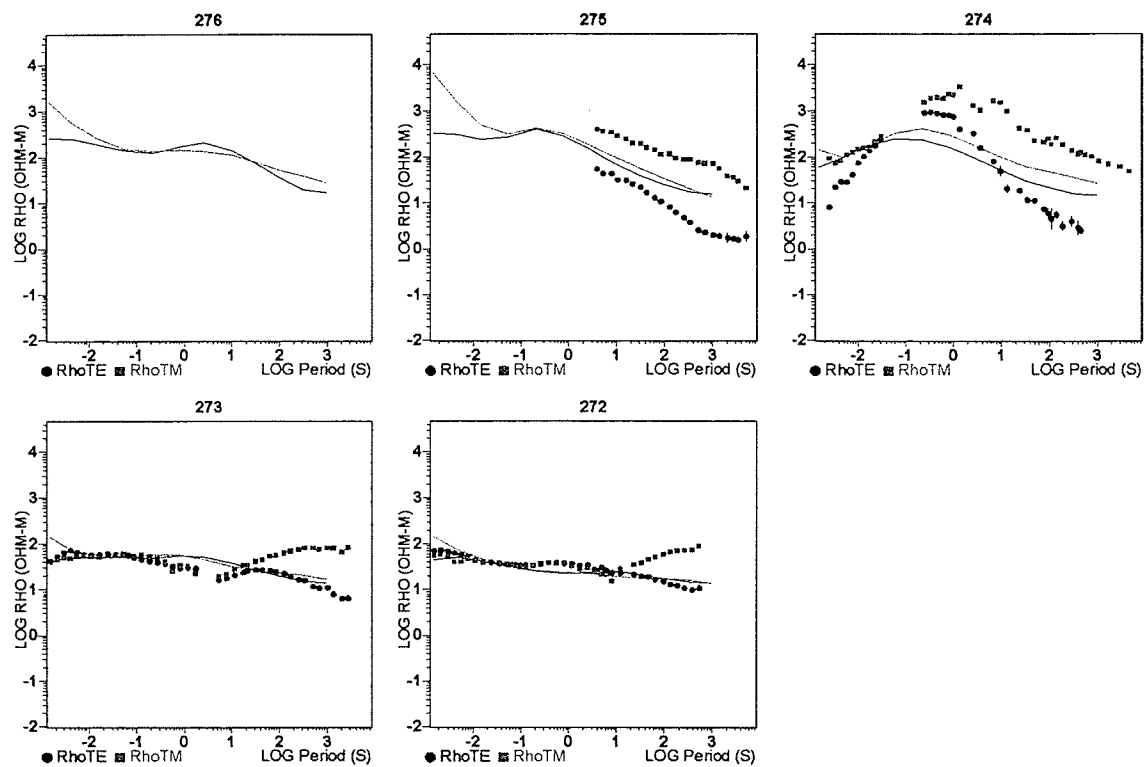


Figure F.3 cont.

Model B

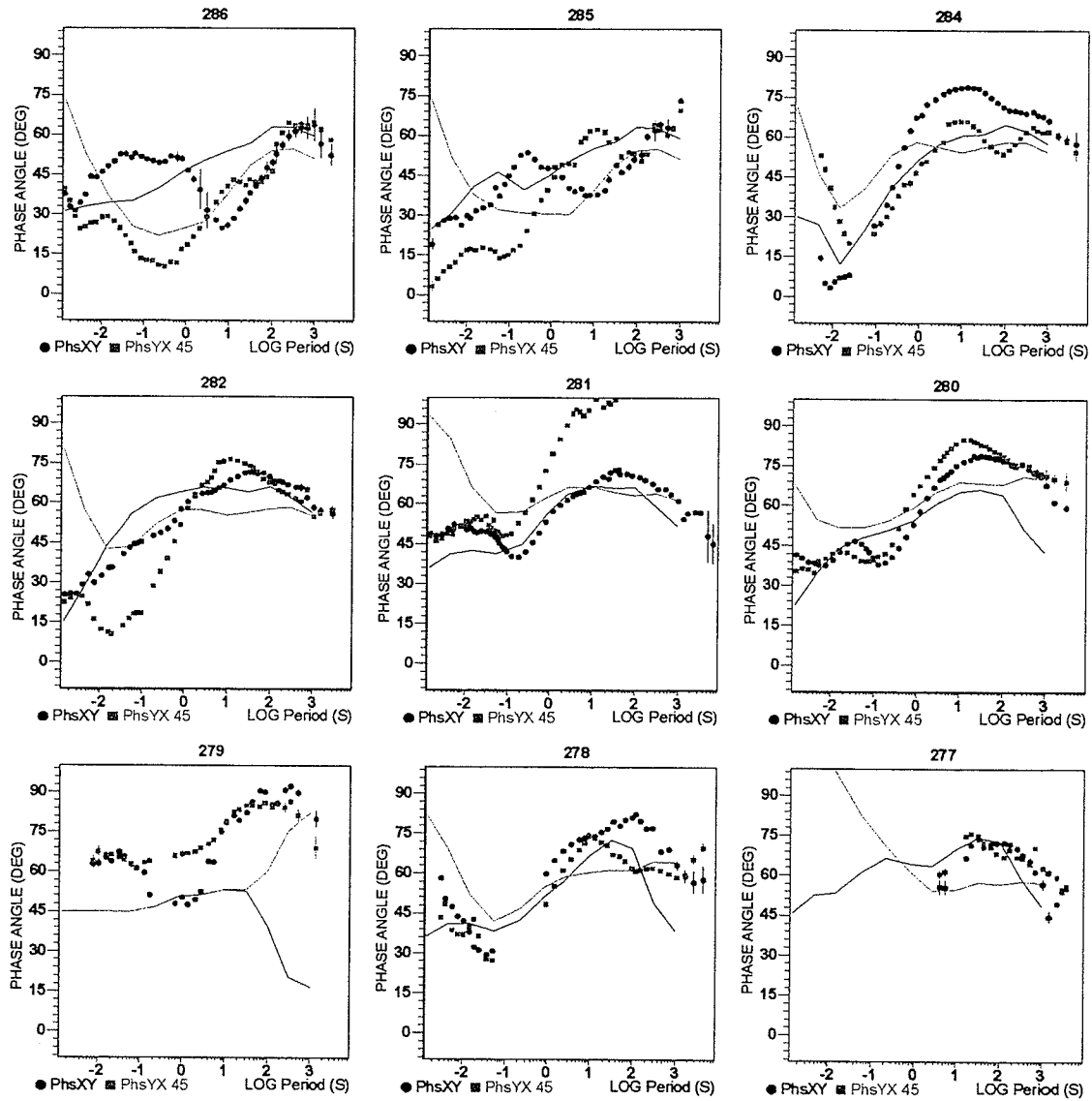


Figure F.4 Comparison of the observed and modeled phase response for Model B of the Connector Line.

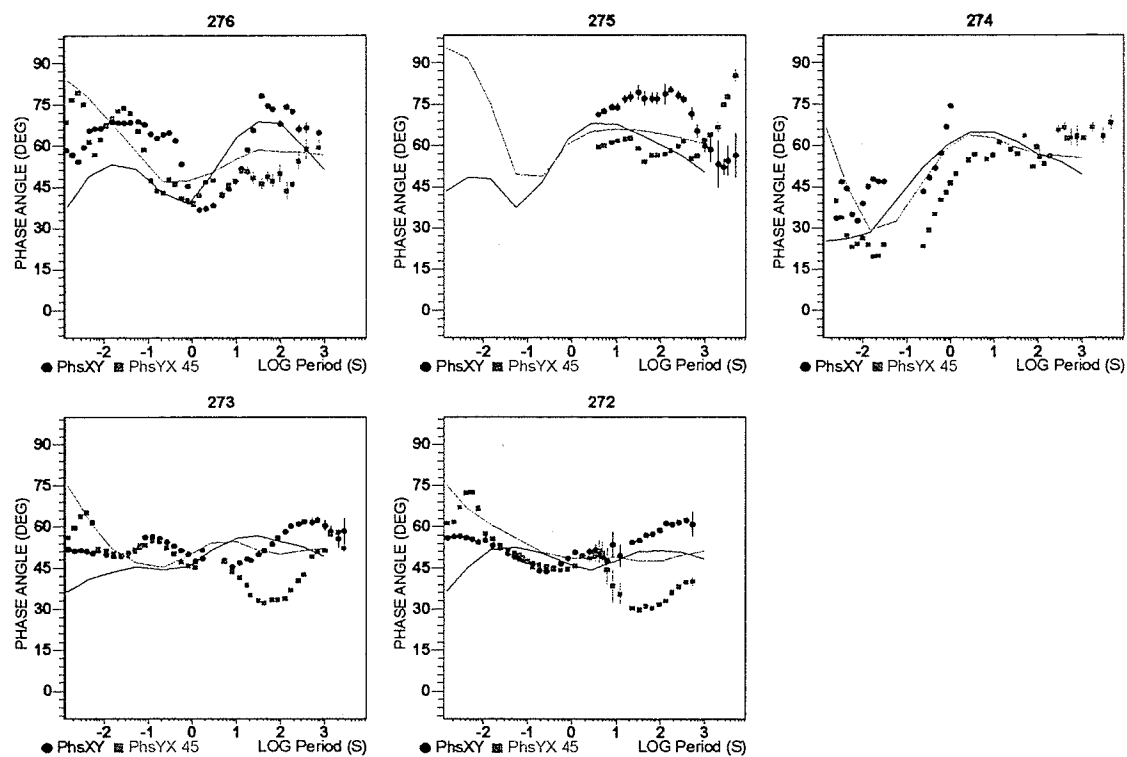


Figure F.4 cont.

Model B

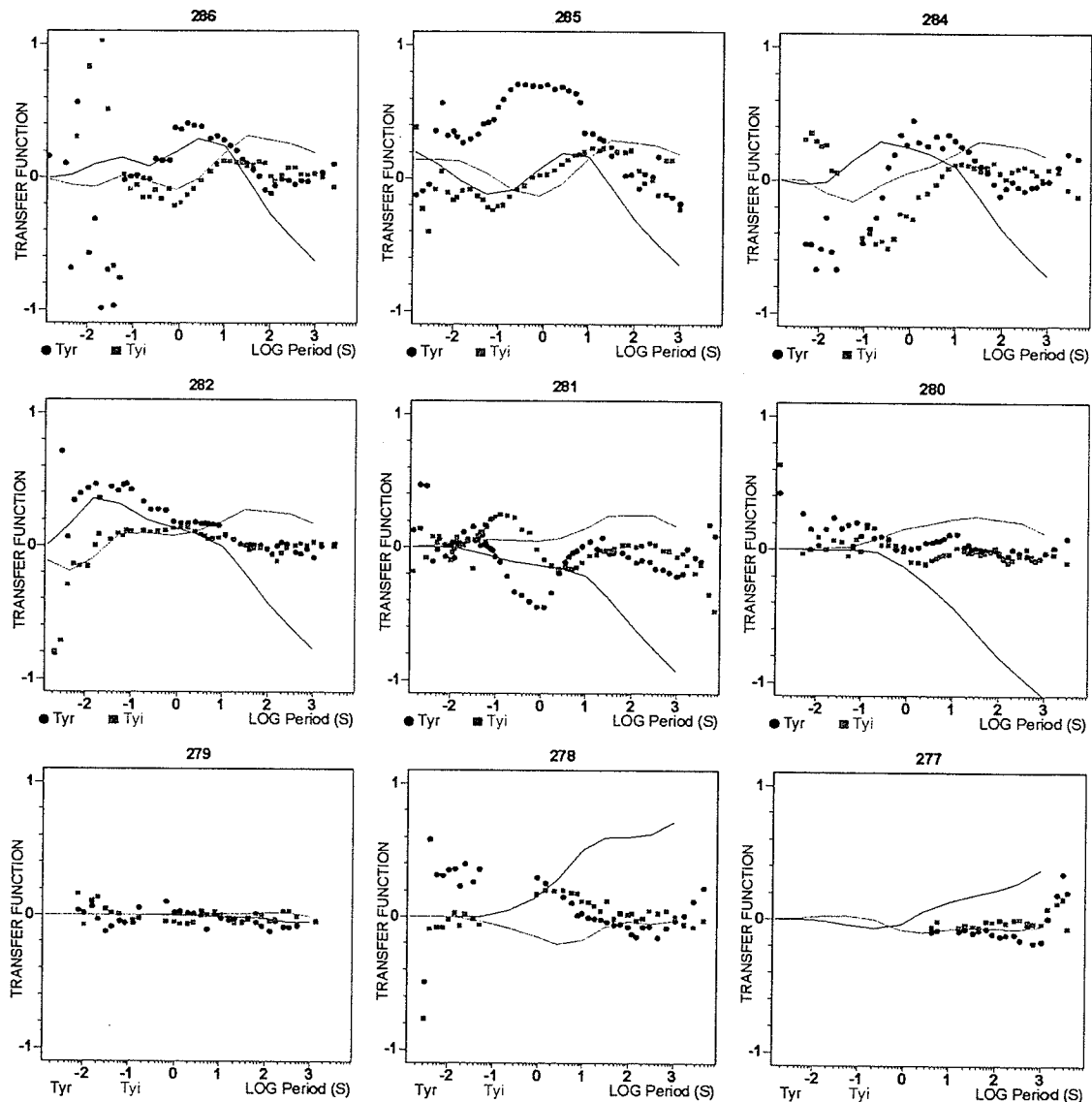


Figure F.5 Comparison of the observed and modeled tipper response for Model B of the Connector Line.

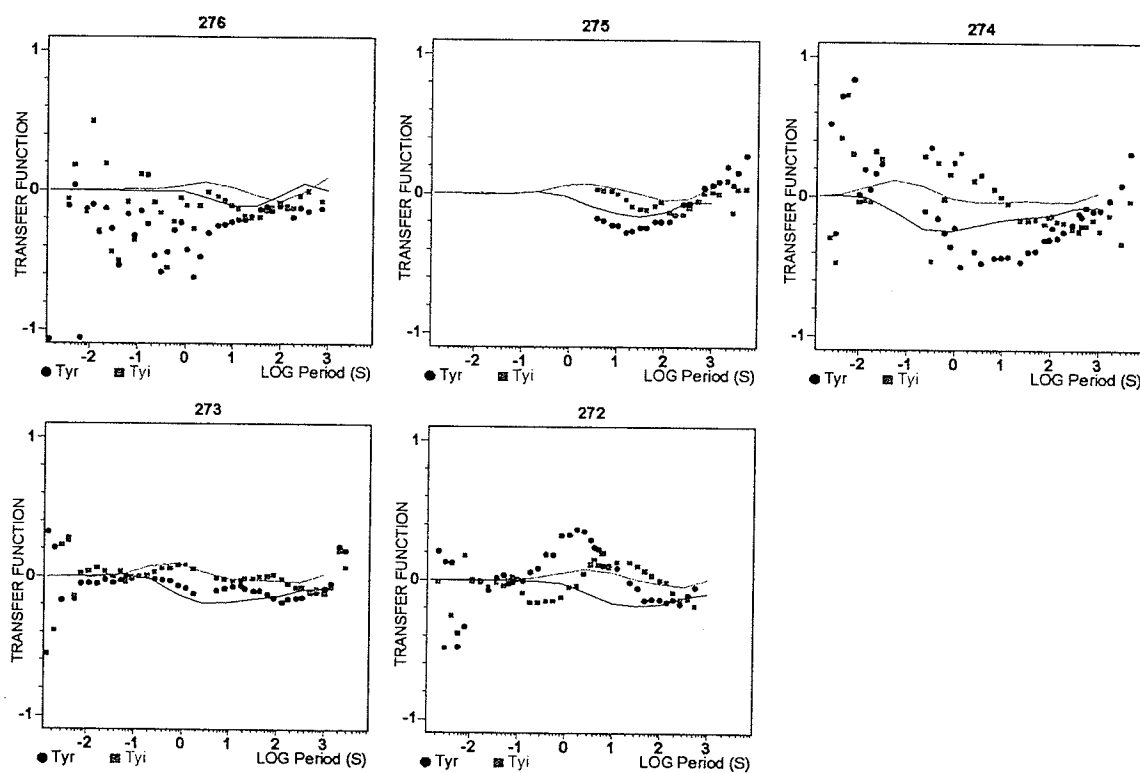


Figure F.5 cont.

Appendix G: NLCG Inversion Results with different Starting Halfspace

This appendix shows the NLCG models obtained with different starting half-spaces for Line 2a. Inversions were completed for a starting half-space of resistivity 100 ohm.m, 500 ohm.m and 1000 ohm.m. Both the TE and TM modes were included in the inversion. Figure G.1 shows the model obtained for starting half-space resistivity of 100 ohm.m and 1000 ohm.m. The two inversions converge to very similar final models.

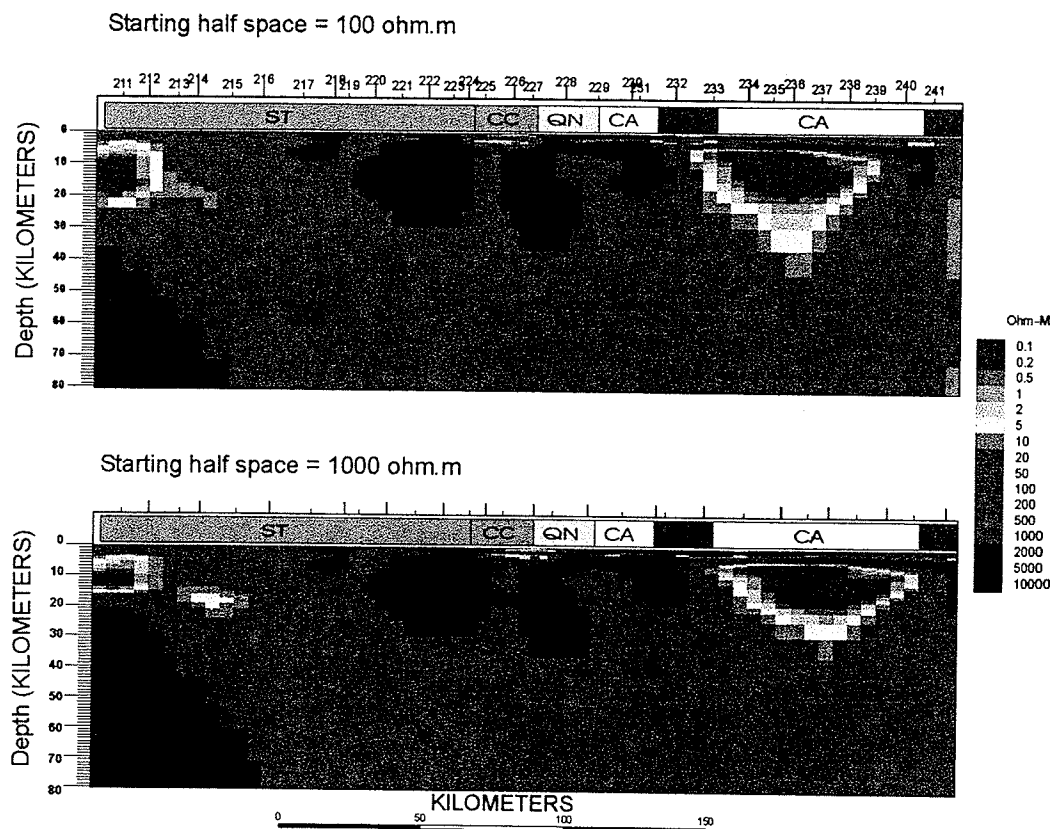


Figure G.1 NLCG model for Line 2a with same input parameters, but different starting half space.