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Progress report on U.S. Geological Survey-Department of Energy Interagency Agreement DE-A121-83MC20422-Task No. 4, Electromagnetic geophysics applied to sediment subduction and deep source gas

by

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PROGRESS REPORT ON U.S. GEOLOGICAL SURVEY-DEPARTMENT OF ENERGY

INTERAGENCY AGREEMENT DE-A121-83MC20422-TASK NO. 4,

ELECTROMAGNETIC GEOPHYSICS APPLIED TO SEDIMENT SUBDUCTION AND

DEEP SOURCE GAS

William D. Stanley and Joseph L. Plesha

PREFACE

The following text and figures consists of a progress report prepared for a USGS/DOE sponsored research project to locate deep sedimentary units in the U.S. Cordillera related to subduction-accretion processes. The material was presented at a DOE Peer Review session held in Bethesda, Maryland, April 10-11, 1985. The written summary was prepared in the specific manner prescribed by DOE for the Peer Review and the figures are black and white copies of slides used in the presentation.

INTRODUCTION

Part of the Interagency Agreement for Deep Source Gas research initiated by the Dept. of Energy (DOE) and the U. S. Geological Survey in FY83 specified a task related to location and mapping of deep sediment wedges associated with active or fossil subduction zones and determination of their lithology and tectonic history to allow estimates of deep source gas potential. Recent research has proven the utility of deep crustal sounding using the magnetotelluric (MT) method. This technique along with other geophysical methods is employed for this task to meet the objectives described in this review summary. Project funding has been apportioned about equally between salaries for the Branch of Geophysics (Denver) project personnel and field survey and data reduction expenses. The project has been funded at 0.5 FTE (Full time equivalence), 1.5 FTE, and 1.1 FTE salary levels for FY83-85 (fig. 1) and has resulted in field surveys with a total of 106 mid-deep crustal (20-25 km penetration) electromagnetic soundings and 20 deep crustal-mantle (30-100 km penetration) soundings completed in the U. S. Cordillera.

PROJECT OBJECTIVES

Specific project objectives (fig. 2) include the study of compressed forearc basins of Mesozoic and Tertiary age associated with fossil subduction zones in the U. S. Cordillera, with emphasis on characterization of their electrical and density properties to pinpoint deeply emplaced sediments. The main questions to be answered are whether there are large volumes of deeply emplaced sediments (greater than 10 km depth) in fossil subduction zones that could act as deep gas sources, and further whether, in fact, these sediments become downthrust to mantle depths. The latter question is important in evaluation of the mantle as a methane generator and whether mantle methane emissions are primordial or due to subducted organic carbon. Thus the project objectives include both practical resource evaluation and long term theoretical aspects.

BACKGROUND RESEARCH

Background research pertinent to the project (fig.4) include investigation of subduction zone behavior related to the ultimate destiny of carbonaceous sediments at convergent margins. Pelagic sediments at a subduction zone are either subducted or incorporated into accretionary wedges. Forearc basin sediments, often consisting of thick sections of flysch, as well as accretionary wedges of pelagic sediments are inevitably subjected to compression and partial subduction (and/or obduction) by docking of "microcontinents" riding on the oceanic plate (fig. 4) or by continental collisions. Such research is at the heart of several other projects in the Deep Source Gas program. Pertinent to this project are the results from recent MT soundings in the Pacific Northwest and in accreted terrains of eastern Europe. Interpretations of magnetotelluric soundings in western Washington by Stanley (1984) and in the Carpathian region of Europe by Picha and others (1984) show that compression of forearc basins may result in thrusting of sedimentary rocks to depths greater than 20 km (fig. 5). The significance of such compressed basins to the deep source gas program can be more fully investigated with the example of the Carpathian region where extensive gas fields have been developed in molassic units overlying the nappes and autochthonous Mesozoic strata (fig. 7). Deep plays to depths of over 7 km have also been established. The possible charging of lower crust-mantle regions with carbon can also be evaluated from such examples as typified in figure 5.

RELATION TO OVERALL PROGRAM

The overall program of deep source gas research can be divided into studies of active subduction zones and those oriented to fossil zones (fig. 7). The field surveys of this project are largely of fossil zones. Part of these surveys interface with geologic and geochemical studies of the Olympic Peninsula Subduction Complex. The theme of this project's geophysical studies are broadly related to geological and geochemical studies of the Alaskan Brooks Range and the Franciscan Formation of Northern California, both Mesozoic accreted terrains. However, although the focus of this project has been primarily on Mesozoic fossil subduction features, field surveys have not been done specifically in the Brooks Range of Alaska or Franciscan terranes of California. Instead, the deep sounding surveys have been designed to test field examples of compressed basins at former convergent margins for deep downthrusting of sedimentary units.

BUDGET AND COST EFFECTIVENESS

Funding for this project, as indicated in figure 1, has included salary support and administrative costs at levels from 0.5 FTE(FY83) to 1.5 FTE(FY84). This salary support has been for the principal investigator (PI), W. D. Stanley, and for two other geoscientists in the Branch of Geophysics, James Towle and Carol Finn. Towle was responsible for the deep crustal-mantle soundings and Finn is working with a gravity and aeromagnetic data base compiled in the Branch of Geophysics to assist the MT sounding interpretations. In addition to the research geophysicists, two electronic technicians and two geologic field assistants have been used in the project to maintain geophysical equipment, process data, and assist with the field work. Current commercial costs for MT data acquisition alone is above $3000 per sounding and the project has produced 106 mid-lower crustal MT soundings and 20 deep crustal-mantle soundings, in addition to gravity data analysis and extensive geological and geophysical interpretive efforts. Cost effectiveness for field surveys is aided by USGS developed efficient, real-time instrumentation for MT soundings and extensive experience by the PI and other researchers in regional tectonic studies using deep electrical sounding methods. In addition, the geological expertise of other USGS scientists working on the deep source gas research and others not directly involved support the project. Contacts with European associates make possible a broader look at the mechanics of forearc basin compression as evidenced in the Carpathian data of figure 5. An extensive Petroleum Information well log file is available for study of sedimentary parameters and the Branch of Geophysics has one of the country's best equipped petrophysics laboratory for study of geophysical parameters of rocks at temperatures up to 1000° C.

TECHNICAL APPROACH AND METHODOLOGIES

The questions asked in this research place stringent requirements on geophysical methods for providing the necessary answers. In order to investigate possible sedimentary units at depths greater than 10 km, deep seismic reflection techniques are frequently used with success offshore at convergent margins and in deep onshore basins. However, much of the Pacific Northwest portion of the U. S. Cordillera is covered with volcanic rocks which diminish the effectiveness of seismic methods. Deep electrical sounding methods have been used in surveys of the Columbia Plateau, Parana Basin, Brazil, and Alps-Carpathian region of Europe, for example, to provide structural and stratigraphic information not obtainable from other geophysical methods. Figure 5 illustrates the wide range of resistivities for the rocks types involved in a fossil subduction zone setting. This broad dynamic range in rock resistivities establishes the utility of MT surveys to locate deeply emplaced sediments. An abbreviated outline of the MT method is provided in figures 8 and 9.

Motivation for further studies of accreted terrains in the Pacific Northwest was provided by the results described in Stanley (1984), shown in figure 10. The extent of the conductive section at depth on the west end of profile AA' (figure 10b) was mapped with 35 additional MT soundings in FY83 and the shape of the conductivity anomaly section is suggestive of a compressed basin. This feature is now called the Western Washington Conductivity Anomaly (WWCA). Its relation to paleosubduction zones in the Cordillera is depicted in figure 11. A number of forearc basins have been identified in this part of the Cordillera and MT surveys have been done in portions of the basins where tectonic evidence suggests there may have been severe downthrusting during accretionary episodes.

The proximity of the Methow Trough of Washington to the WWCA (fig. 11) means that it is a particularly pertinent study area, both from its own intrinsic value as an interpreted compressed forearc basin (Tennyson and Cole, 1978) and possible analogys with the WWCA. Other field studies have been carried out in northern California and southwestern Oregon where geologic evidence suggests that there may be highly compressed and possibly downthrust forearc basin sediments. The Great Valley Mesozoic system has not been studied because geologic evidence indicates that the basin sediments have not been highly compressed.

Application of magnetotellurics to reach the project objectives involves widely spaced sounding locations (10-30 km) in order to study the main features of possible compressed basins. The spacing of sounding locations can be done adaptively in the field with the design capability of the instrumentation to process the data in real-time and perform one-dimensional interpretations on-site. Nominal real-time soundings cover a frequency range from .001 to 12 Hz, allowing investigations to depths of up to 20-25 km typically. In addition to the real-time MT system, an automated, lower frequency MT system has been employed in selected locations to sound to greater depths, up to 100-150 km, allowing investigations of the crust-mantle interface as well as definition of deeper crustal features not resolvable with the real-time system.

Interpretation and post-processing of the field data is outlined in figure 12. Refinement of the data processing in the central office generally involves a study of rotational (strike-dip parameters) information and additional curve construction from optimal data. Interpretation starts with derivation of one-dimensional (1D) models to fit the data using both interactive graphics systems and automated generalized inversion techniques. Further modelling, as exhibited in figure 9, involves computation of two-dimensional (2D) models, and in some instances, three-dimensional (3D) models to study the MT survey data. MT data are being combined with other geophysical data for more refined interpretations. An updated gravity and aeromagnetic data base for the Pacific Northwest has been compiled by Carol Finn and Dave Williams of the Branch of Geophysics, and gravity-magnetic models coincident with the MT profiles are being computed to aid identification of compressed basin parameters. MT surveys in northern California to study possible compressed basin sediments in the Klamath Mountain region was interfaced with deep seismic refraction surveys performed by the USGS. Utilization of the USGS owned Petroleum Information well log file has been an essential part of identification of sediment parameters, although this study has been largely confined to Tertiary and younger sediments because of limited drilling activity in the Pacific Northwest. Rock samples have been collected in several areas and their electrical and density properties are being evaluated in the Branch of Geophysics petrophysics laboratory.

RESULTS AND CONCLUSIONS

Interpretation of the large amounts of data generated in FY83 and FY84 are still continuing, but preliminary 1D models have outlined the shape of a possible compressed forearc basin buried beneath volcanic rocks in western Washington which we call the WWCA (fig. 13). An additional cross-section through the WWCA is shown in figure 14 along profile CC′ (fig. 13) for comparison with the cross-section for profile AA′ shown in figure 10b. Cross-sectional volume calculation for the conductive unit (WWCA) along profiles AA′ and CC′ are roughly equivalent. This suggests differential compression of a basin of approximately 7-10 km original thickness, with maximum compression occurring on CC′. A study of the Methow Trough of northern Washington has also provided evidence of the possible deep thrusting of sediments similar to that postulated for the WWCA and Carpathians. Two preliminary MT 1D cross-sections are shown in figure 15 along with a geologic section compiled by Barksdale (1975). Cretaceous continental sandstones and marine sandstones and shales appear to have been warped into a broad syncline during Tertiary accretionary episodes and thick sections of Jurassic Newby Fm. (black shales and volcanics) and older autochtonous rocks may have been thrust to large depths.

Other results to date include comparison of MT data from across the Klamath Mountains of northern California to seismic refraction profiles along the same profile (Gary Fuis, USGS, writ. comm.). In addition, a preliminary study has been completed of the fossil Cretaceous subduction zone in southwest Oregon where I hypothesized that accretion may have thrust Tertiary and Cretaceous forearc basin sediments underneath the Klamath Mountains complex. Because of time limitations, these preliminary results will not be discussed.

FUTURE RESEARCH

The study of compressed forearc basins will continue in FY85 with field work planned for study of two Alaskan accreted terranes, the Kahlitna terrane and the Manley terrane, both consisting partially of thick stratigraphic sections of Mesozoic flysch. The tectonic history of these systems suggest that they are likely candidates for deep downthrusting of sediments. The project will also coordinate with geochemical studies as selected by DOE management and provide tectonic models for time-thermal history research of the typical forearc basin as a guide to maturation profiling. Interpretation and refinement of existing geophysical data models will procede concurrently with new data acquisition.

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Tennyson, M. E., and M. R. Cole, 1978, Tectonic significance of upper Mesozoic Methow-Pasayten sequence, northeastern Cascade Range, Washington and British Columbia: in Mesozoic Paleogeography of the western United States, D. G. Howell and K.A. McDougall, editors; Pacific Section, S.E.P.M., p. 499-508.

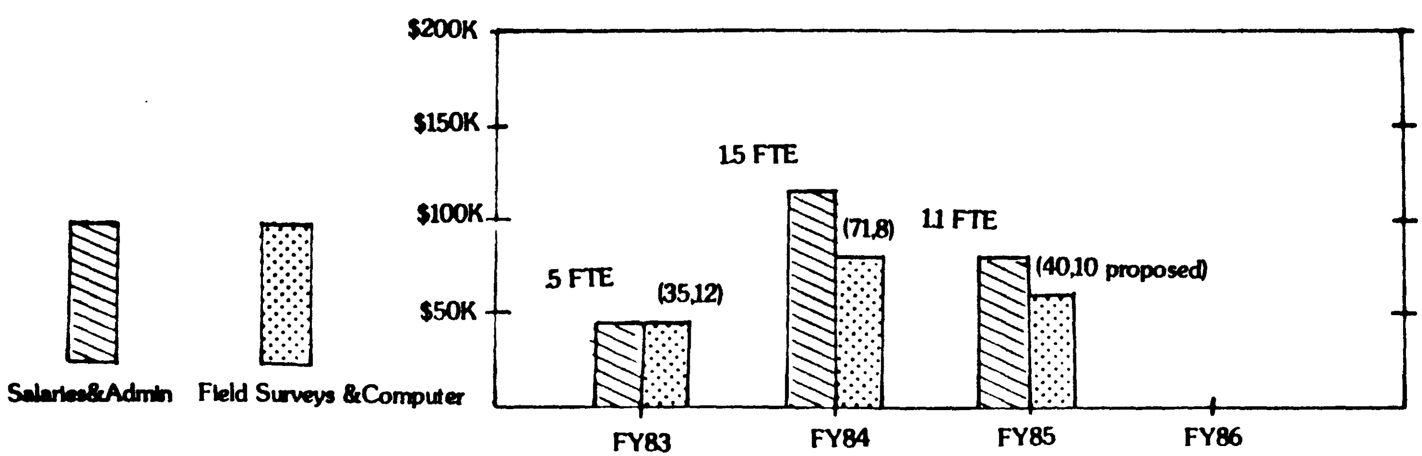
PROJECT TITLE: *ELECTROMAGNETIC GEOPHYSICS APPLIED TO SEDIMENT SUBDUCTION AND DEEP SOURCE GAS*

ORGANIZATION: *U S GEOLOGICAL SURVEY*

PRINCIPAL INVESTIGATOR: *WILLIAM D STANLEY*

PERIOD OF PERFORMANCE: *CONTINUING (startup June, 1983)*

PROJECT FUNDING:



★ ★(71,8) number of crustal, deep-crust-mantle MT soundings completed

Figure 1-Project introduction

PROJECT GOALS:

locate and study deep sedimentary complexes in active and fossil subduction zones of the U. S. Cordillera using deep electromagnetic soundings and supporting geophysics

SPECIFIC PROJECT OBJECTIVES:

(1) Study Mesozoic-Cenozoic fossil subduction zones for occurence of partially subducted or accretion downthrust sedimentary complexes

(2) Analyze electrical, magnetic and density properties of possible deep sediments

(3) Define ultimate depth of downthrusting of sedimentary complexes during episodic accretion. Answer question: Do these sediments get thrust downward into the mantle routinely?

(4) Define tectonic history of compressed forearc basins and related thermal history to aid in assessment of deep gas potential.

Figure 2-Project goals and objectives

BACKGROUND RESEARCH

SUBDUCTION ZONE BEHAVIOR

Destiny of carbonaceous sediments

(1) pelagic sediments are subducted or incorporated into accretionary wedges

(2) forearc basin sediments and accretionary wedges subject to accretionary compression and downthrusting

DEEP ELECTROMAGNETIC SOUNDINGS IN FOSSIL SUBDUCTION ZONES

Recent results from Pacific Northwest, U. S. and Alps-Carpathian region indicate deep emplacement of sediments during accretionary episodes

Figure 3-Project background research

MODEL FOR FOREARC BASIN SUTURING

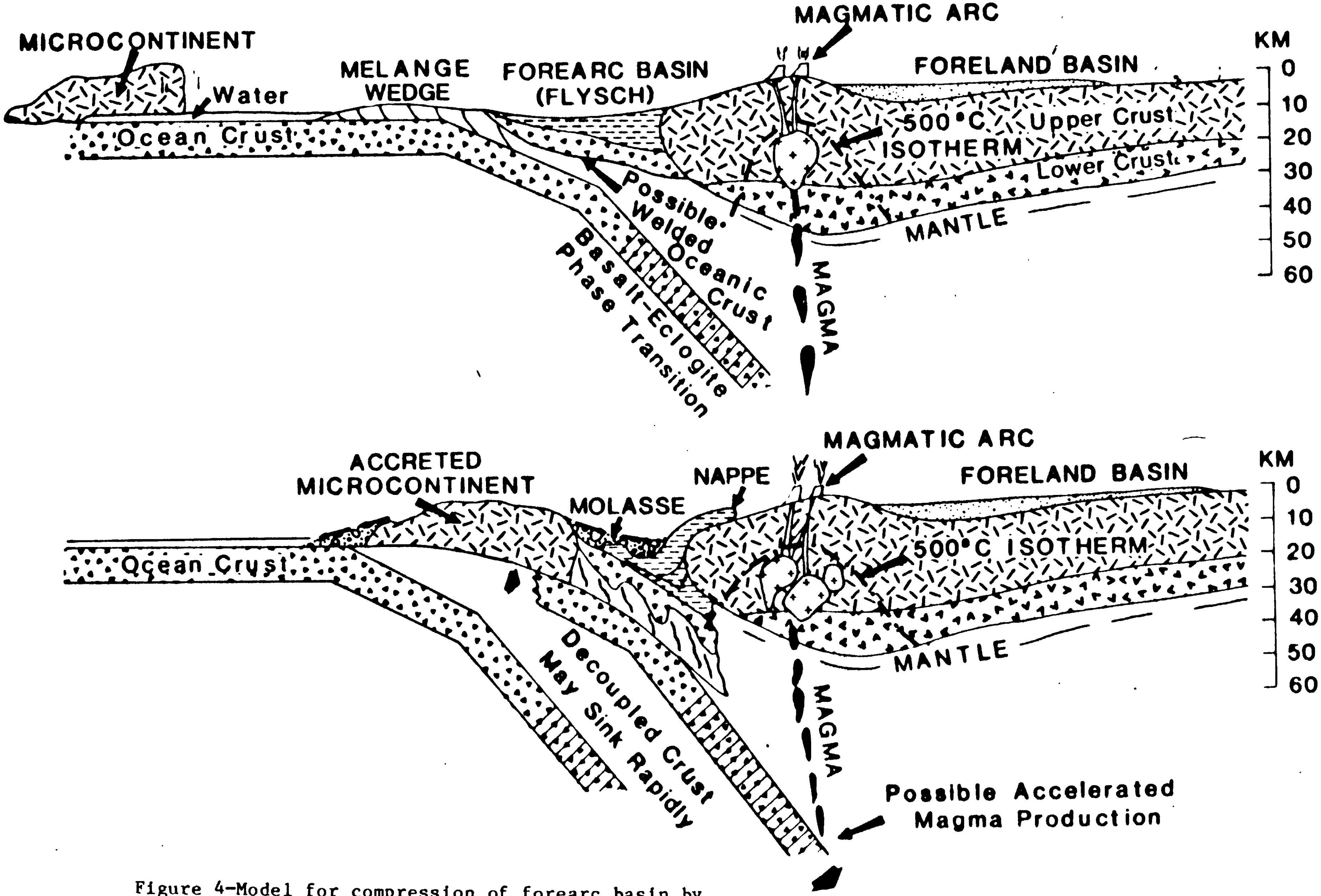


Figure 4–Model for compression of forearc basin by microcontinent accretion (suturing).

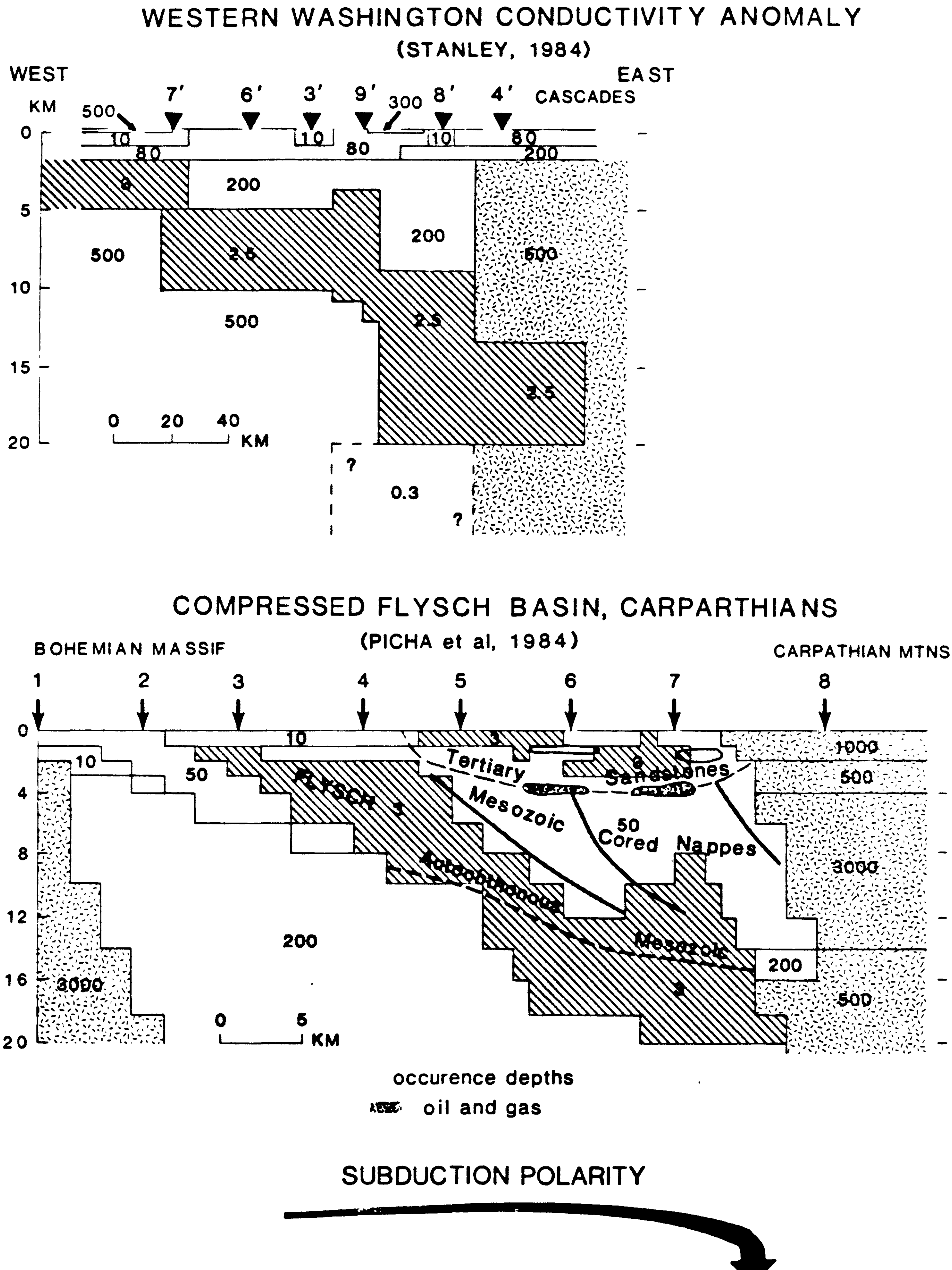


Figure 5-Comparison of two-dimensional MT models for western Washington and Carpathian Mtns surveys. Numbers in model indicate unit resistivities, in ohm-m.

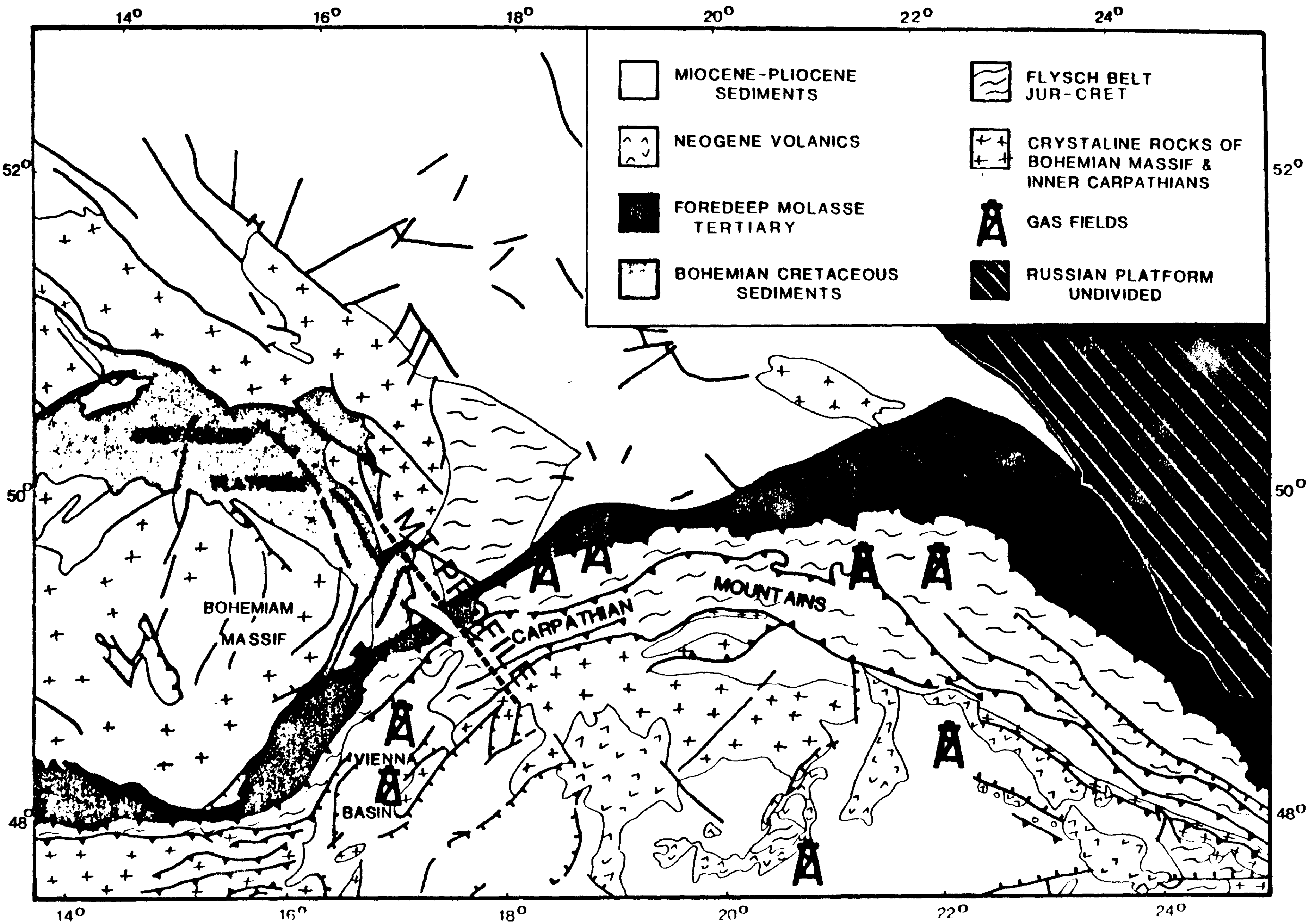


Figure 6-General geology and distribution of gas fields in MT survey area of western Carpathians-Bohemian Massif, eastern Europe.

RELATIONSHIP TO OTHER DEEP GAS PROJECTS

ACTIVE SUBDUCTION ZONE GEOPHYSICAL AND GEOLOGICAL INVESTIGATIONS

Subduction Zone Tectonic Studies

Eastern Aleution Subduction Zones

Deep Source Gas Study of Lesser Antilles (Barbados)

FOSSIL SUBDUCTION ZONE GEOLOGICAL AND GEOPHYSICAL STUDIES

Alaskan Brooks Range Deep Source Gas Study

Franciscan Fm. of Northern California

Olympic Peninsula Subduction Complex

Deep Investigative Geophysical Studies THIS PROJECT

Figure 7-Relationship of deep geophysical studies project to other deep source gas projects

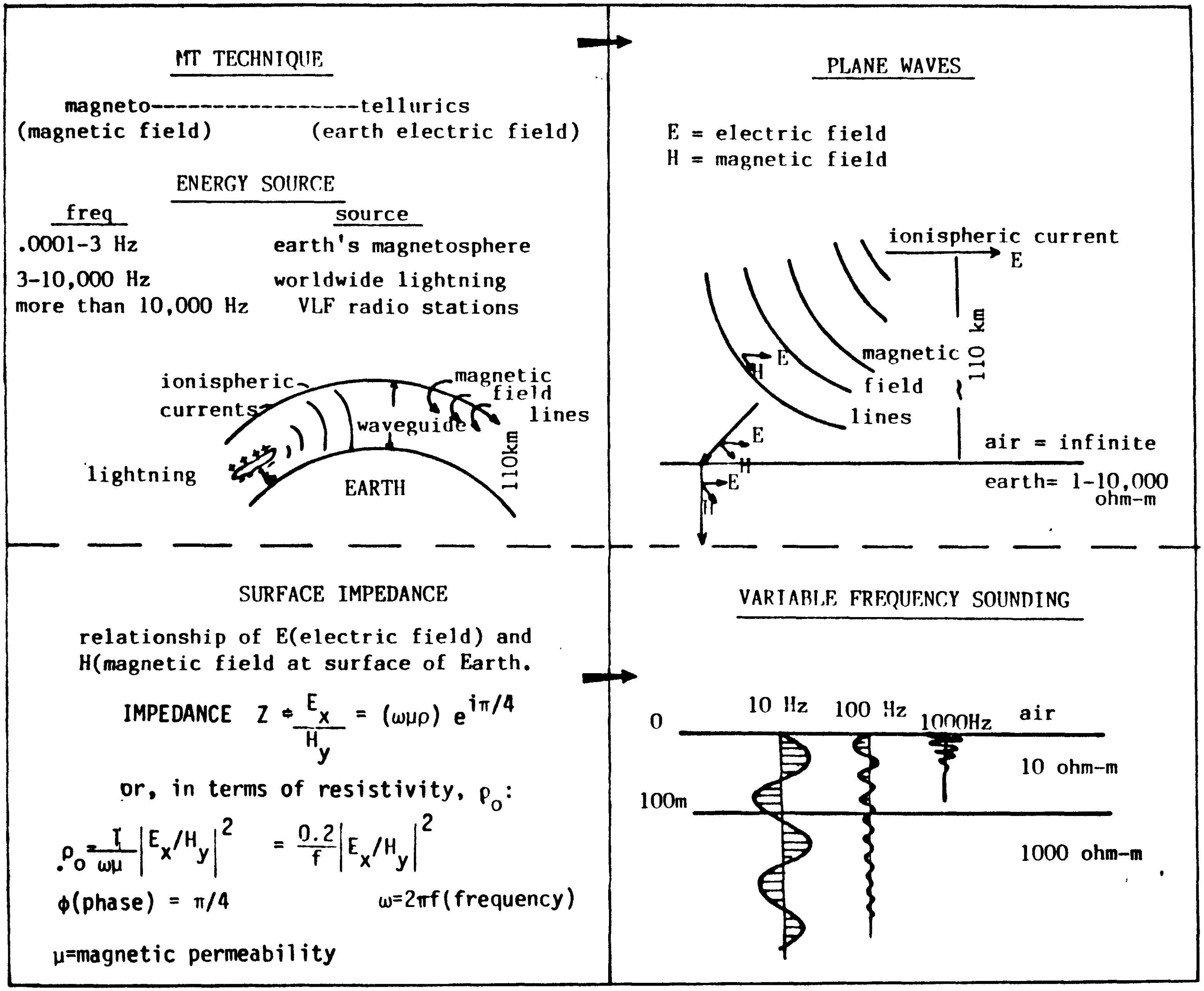


Figure 8-Abbreviated tutorial of magnetotelluric(MT) method

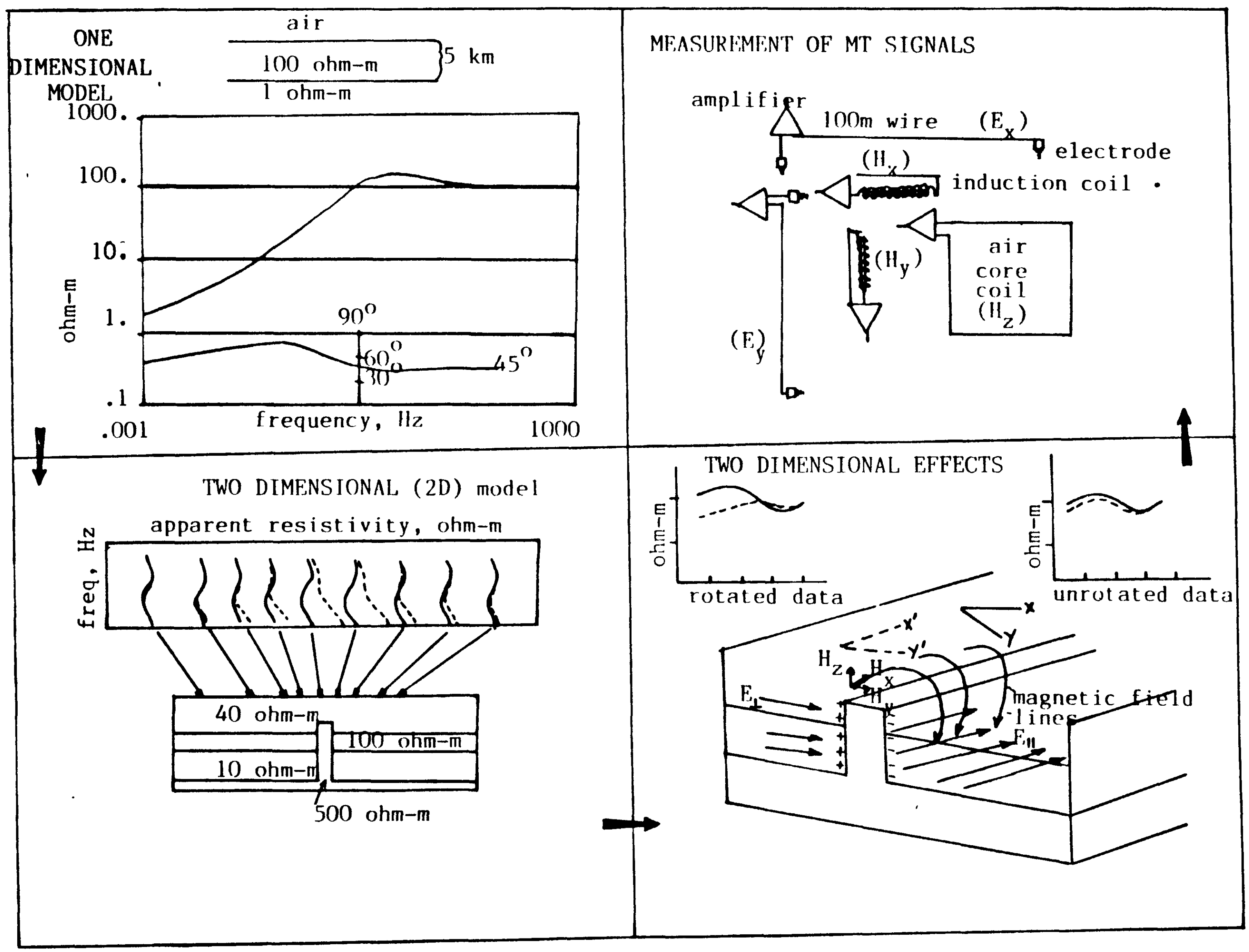


Figure 9-Abbreviated tutorial of magnetotelluric(MT) method

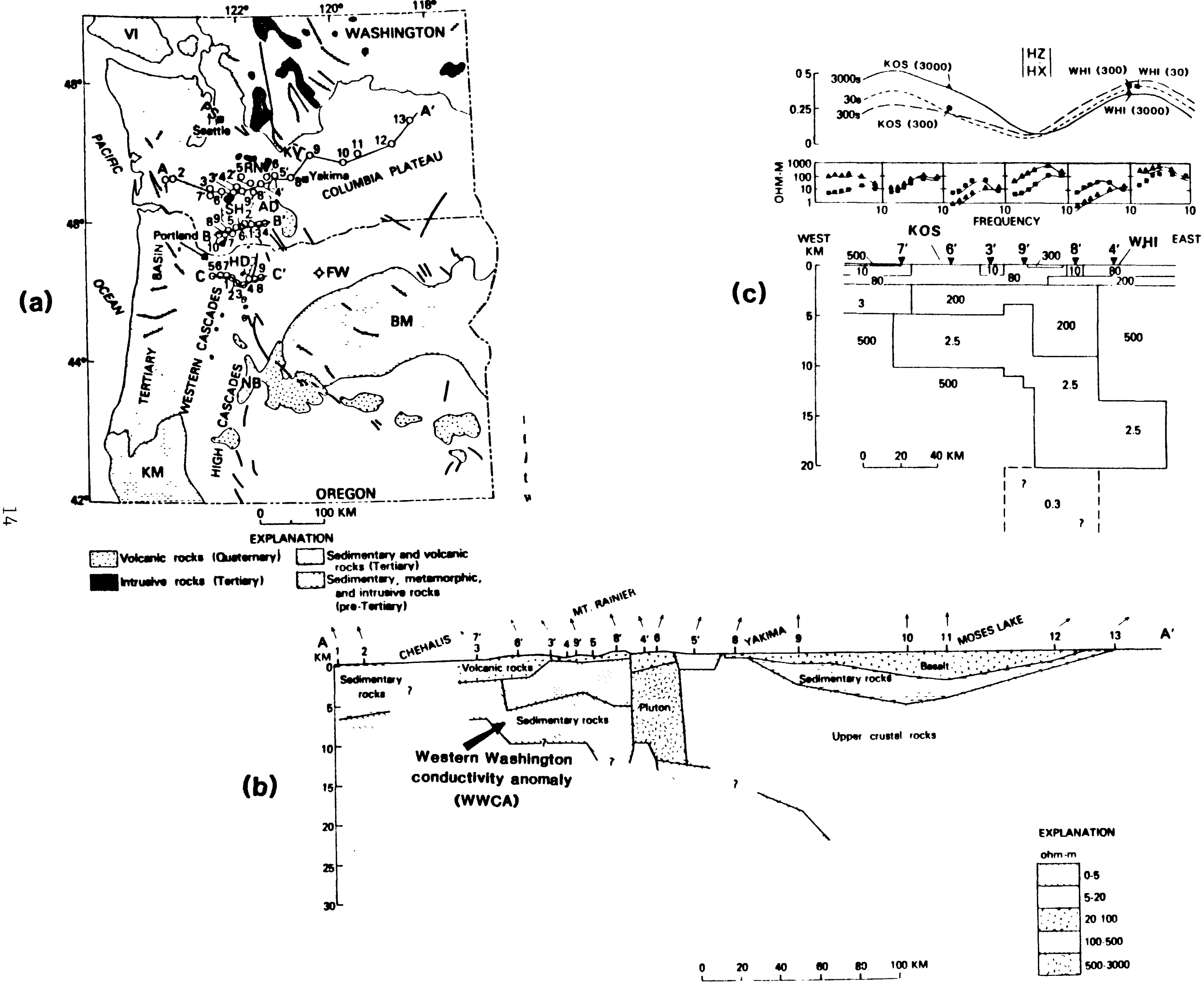


Figure 10(a)-Location of initial MT survey in Cascades and Columbia Plateau of Washington State

Figure 10(b)-One-dimensional (1D) interpretation of MT data

Figure 10(c)-Two-dimensional (2D) interpretation of MT data, profile AA′, with measured and computed resistivity data

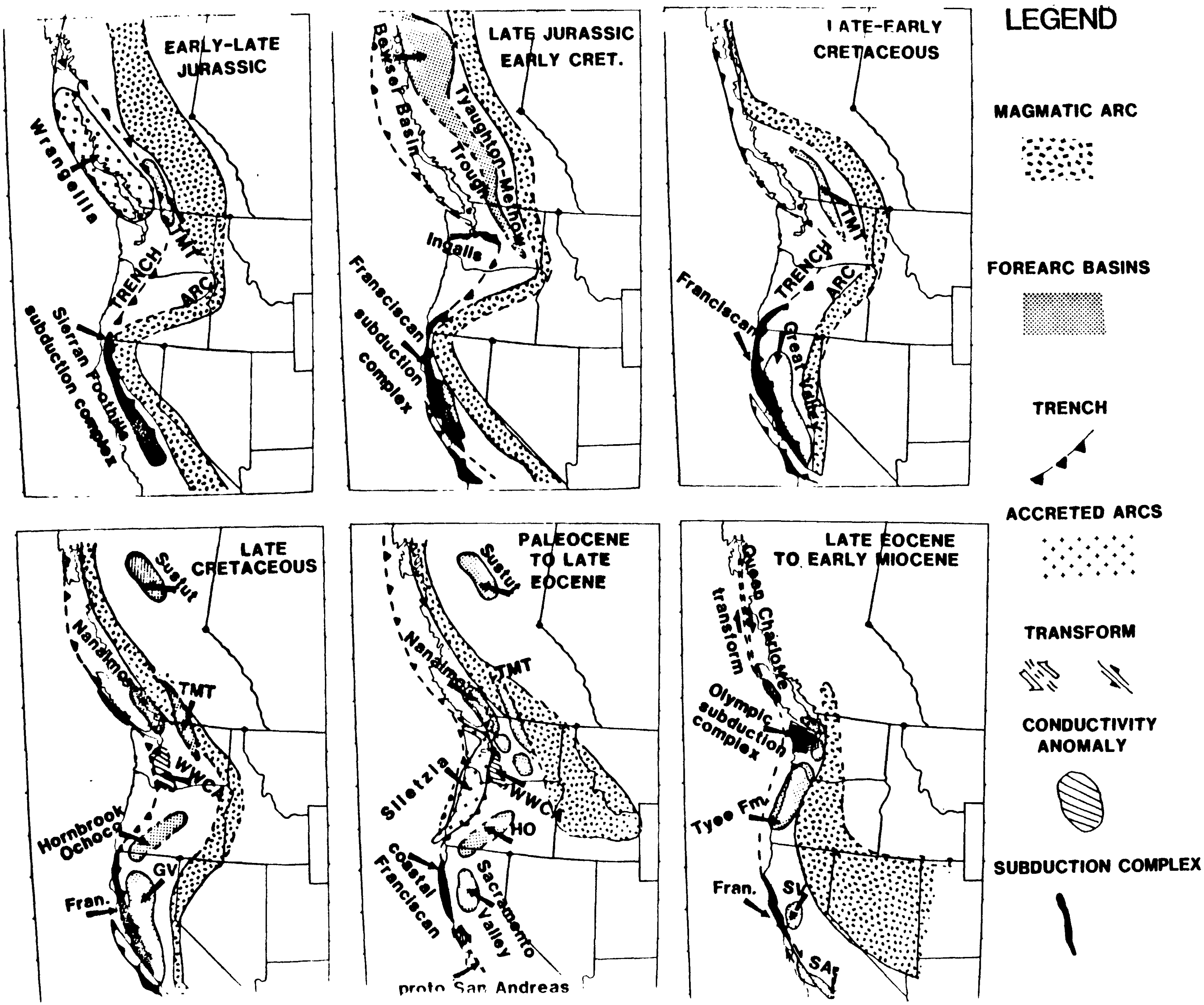


Figure 11-Early Jurassic to Early Miocene arc-trench development and forearc basins of the Cordillera. Modified from Dickinson (1976) with Hornbrook-Ochoco Basin of Nilsen (1984) and other features added.

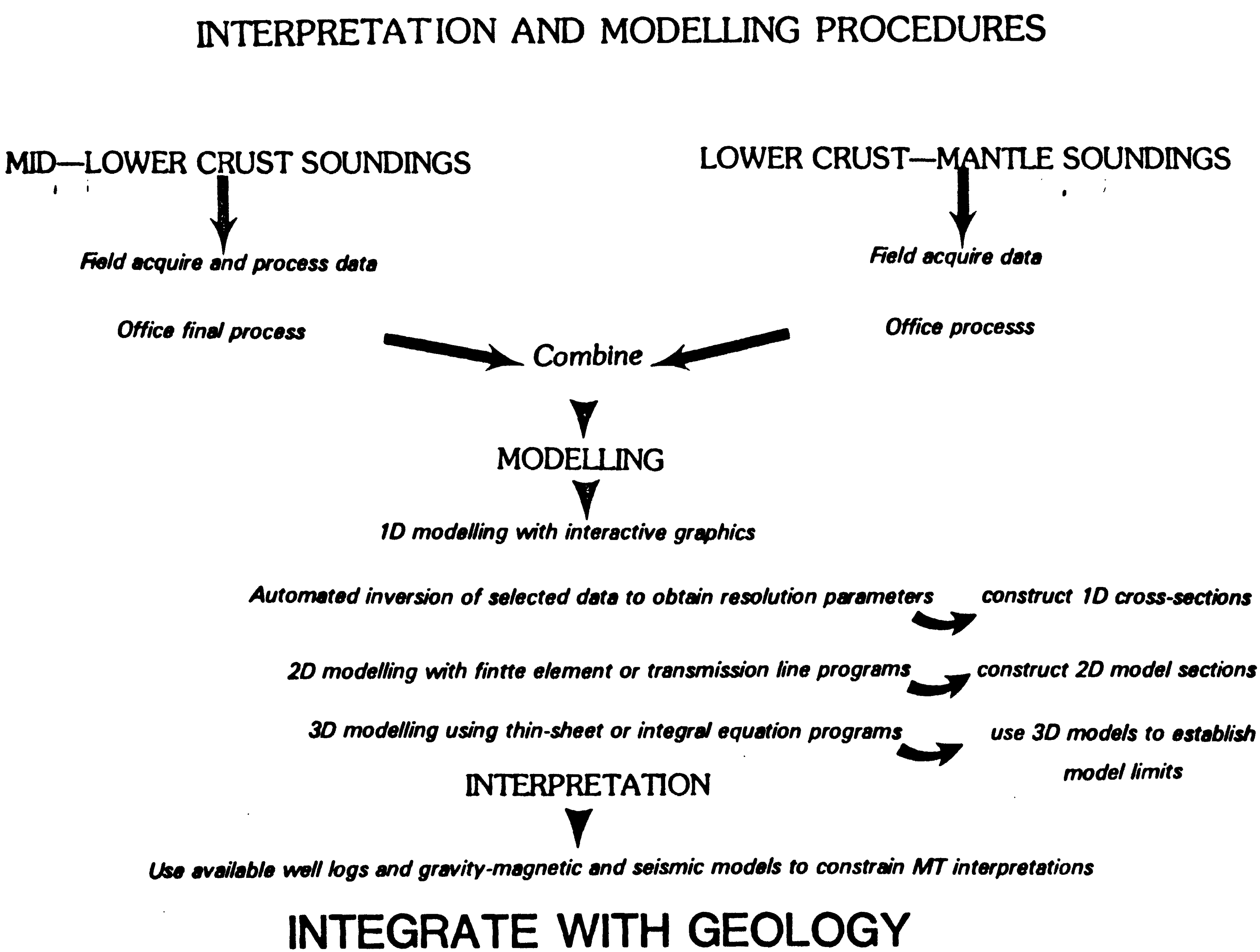


Figure 12-Outline of MT data processing and modelling procedures

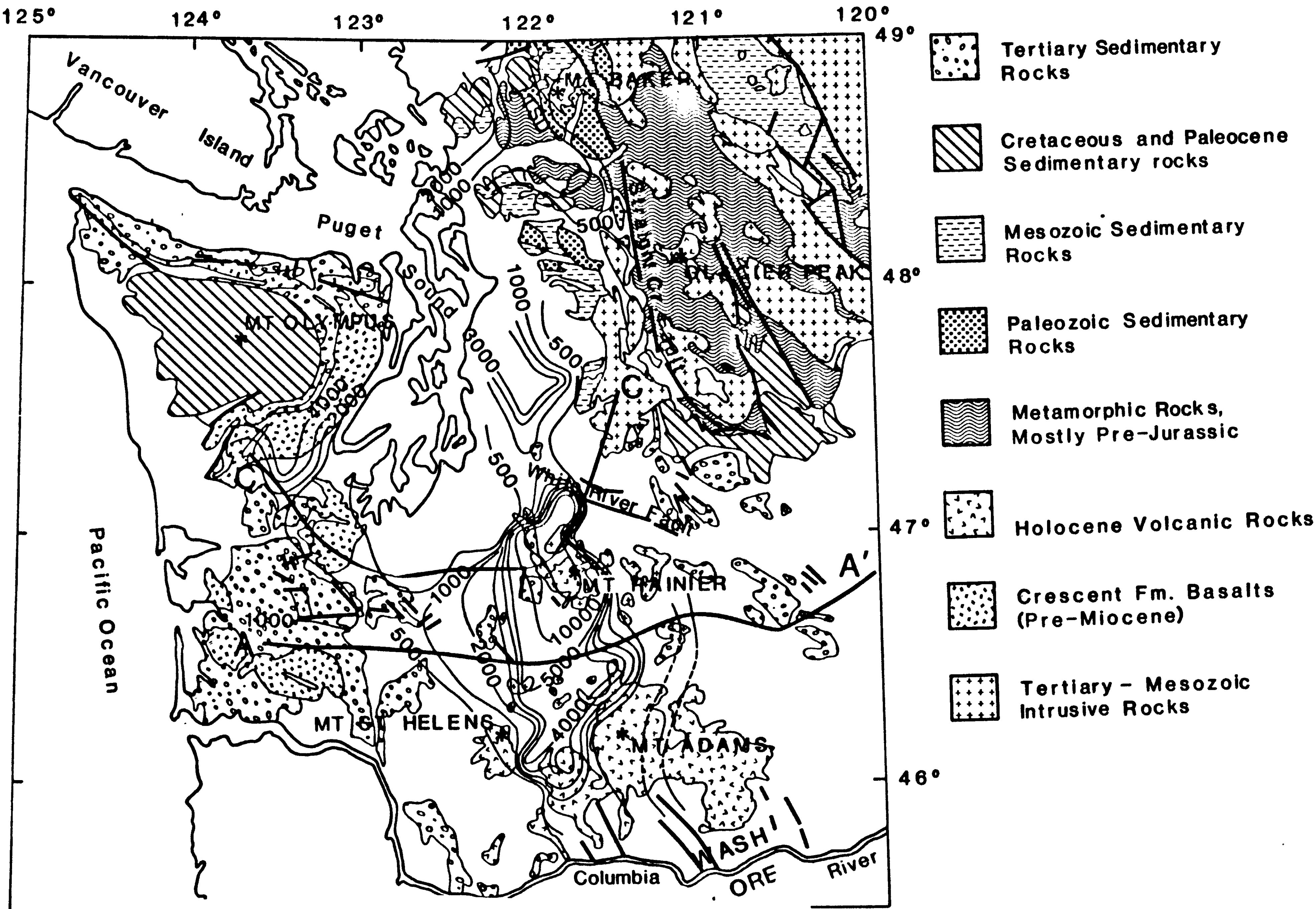


Figure 13-Contours of integrated conductance for western Washington Conductivity Anomaly (WWCA) derived from 78 MT soundings (35 sponsored by DOE in FY83). Integrated conductance is obtained by summing individual layer thicknesses divided by their resistivity (for depths 0-20 km).

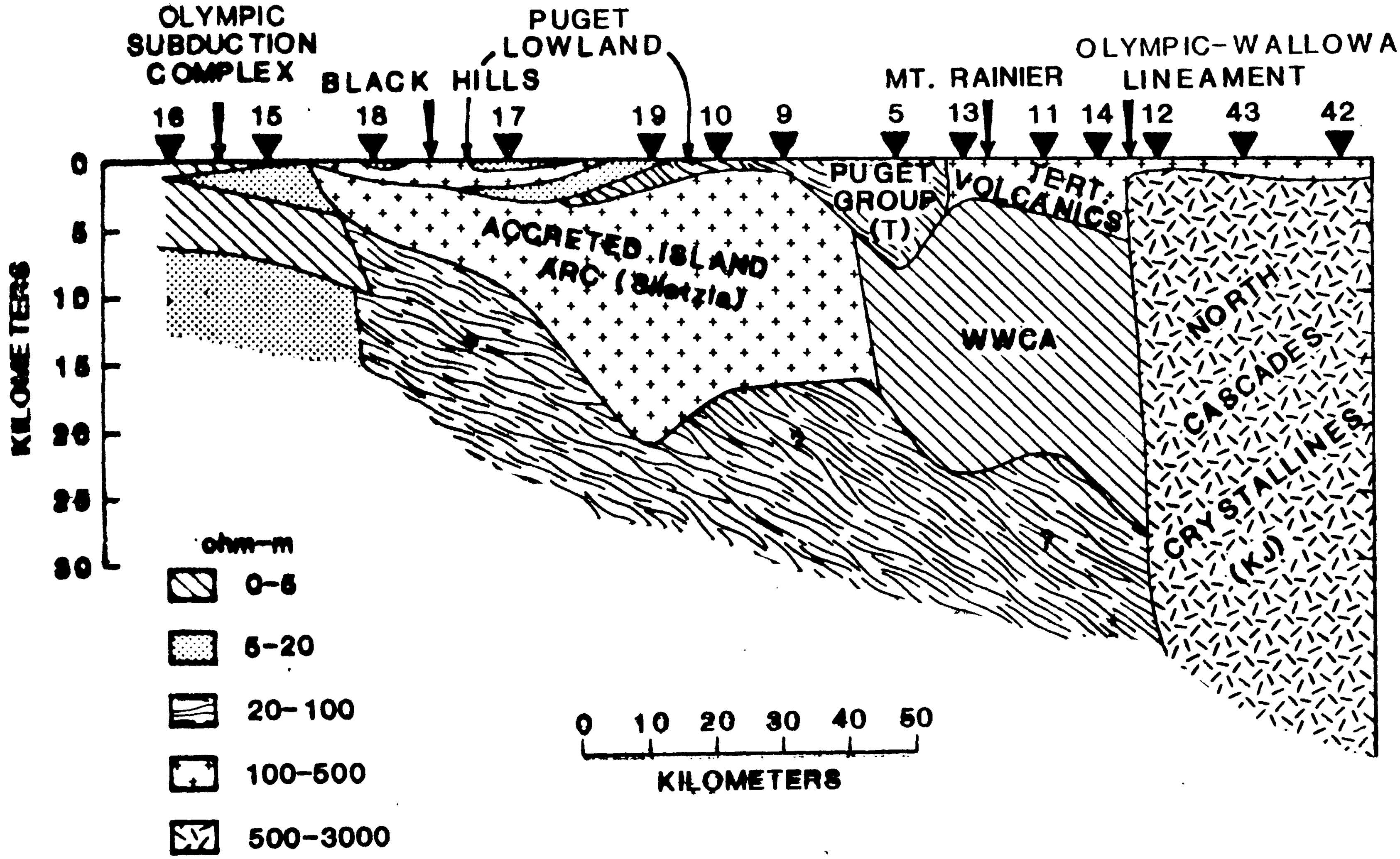


Figure 14-One-dimensional interpretaton of MT soundings from profile CC′ of fig. 13.

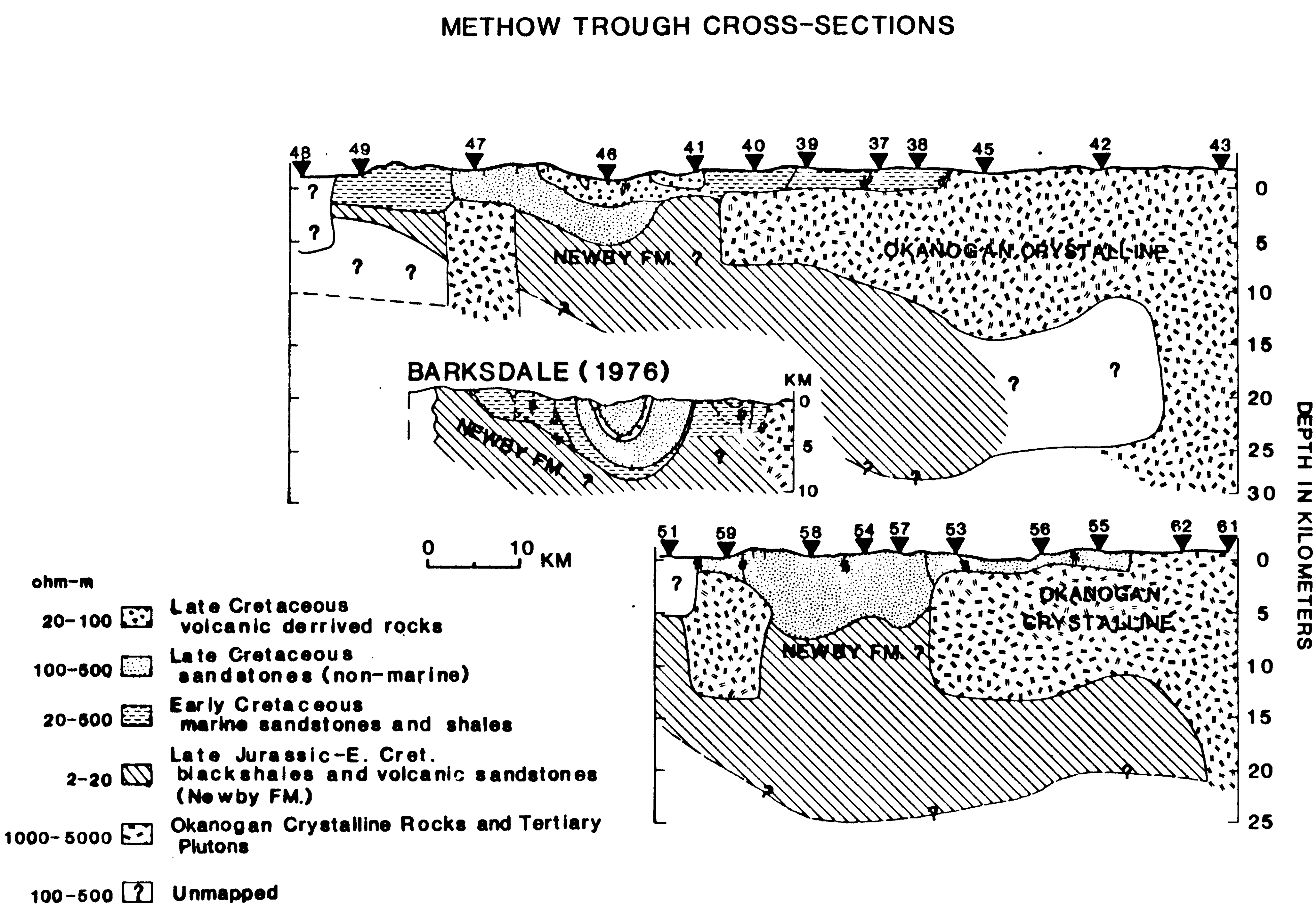


Figure 15-One-dimensional interpretation of MT soundings from two east-west profiles across the Methow Trough of northern Washington with geologic cross-section from Barksdale (1975).

FUTURE RESEARCH

CARRY OUT MT SURVEYS IN COMPRESSED FLYSCH BASINS OF ALASKA

HELP PLAN GEOCHEMICAL FIELD SURVEYS OVER POSSIBLE DEEP SOURCE GAS TARGETS

REFINE THERMAL—TECTONIC MODELS OF COMPRESSSED FOREARC BASINS

CONDUCT LITERATURE AND COLLEAGUE RESEARCH OF NON—U·S· COMPRESSED FOREARC BASINS

Figure 16-Future research plans