EMRIDGE: The Electromagnetic Investigation of the Juan de Fuca Ridge

G. S. HEINSON*
Research School of Earth Sciences, Australian National University, Canberra, A.C.T. 2601, Australia
A. WHITE
School of Earth Sciences, Flinders University, Adelaide, South Australia 5042, Australia
L. K. LAW
Pacific Geoscience Centre, Geological Survey of Canada, Sidney, British Columbia, Canada
Y. HAMANO, H. UTADA, T. YUKUTAKE
Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Japan
J. SEGAWA and H. TOH
Ocean Research Institute, University of Tokyo, Nakano-ku, Japan

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Abstract. From July to November 1988, a major electromagnetic (EM) experiment, known as EMRIDGE, took place over the southern end of the Juan de Fuca Ridge in the northeast Pacific. It was designed to complement the previous EMSLAB experiment which covered the entire Juan de Fuca Plate, from the spreading ridge to subduction zone. The principal objective of EMRIDGE was to use natural sources of EM induction to investigate the processes of ridge accretion. Magnetotelluric (MT) sounding and Geomagnetic Depth Sounding (GDS) are well suited to the study of the migration and accumulation of melt, hydrothermal circulation, and the thermal evolution of dry lithosphere. Eleven magnetometers and two electrometers were deployed on the seafloor for a period of three months. Simultaneous land-based data were made available from the Victoria Magnetic Observatory, B.C., Canada and from a magnetometer sited in Oregon, U.S.A.

Changes in seafloor bathymetry have a major influence on seafloor EM observations as shown by the orientation of the real GDS induction arrows away from the ridge axis and towards the deep ocean. Three-dimensional (3D) modelling, using a thin-sheet algorithm, shows that the observed EM signature of the Juan de Fuca Ridge and Blanco Fracture Zone is primarily due to non-uniform EM induction within the ocean, associated with changes in ocean depth. Furthermore, if the influence of the bathymetry is removed from the observations, then no significant conductivity anomaly is required at the ridge axis. The lack of a major anomaly is significant in the light of evidence for almost continuous hydrothermal venting along the neo-volcanic zone of the southern Juan de Fuca Ridge: such magmatic activity may be expected to have a distinct electrical conductivity signature, from high temperatures, hydrothermal fluids and possible melt accumulation in the crust.

Estimates of seafloor electrical conductivity are made by the MT method, using electric field records at a site 35 km east of the ridge axis, on lithosphere of age 1.2 Ma, and magnetic field records at other seafloor sites. On rotating the MT impedance tensor to the principal axis orientation, significant anisotropy between the major (TE) and minor (TM) apparent resistivities is evident. Phase angles also differ between the principal axis polarisations, and TM phase are greater than 90° at short periods. Thin-sheet modelling suggests that bathymetric changes accounts for some of the observed 3D induction, but two-dimensional (2D) electrical conductivity structure in the crust and upper mantle, aligned with the ridge axis, may also be present. A one-dimensional (1D) inversion of the MT data suggests that the top 50 km of Earth is electrically resistive, and that there is a rise in conductivity at approximately 300 km. A high conductivity layer at 100 km depth is also a feature of the 1D inversion, but its presence is less well constrained.

1. Introduction

Mid-oceanic ridge (MOR) systems provide the key to understanding how Earth's oceanic lithosphere is generated. At these spreading centres, upwelling mantle partially melts as a result of pressure relief, and this melt migrates and solidifies to create new oceanic crust. Fractures in the upper crust permit hydrothermal circulation of seawater, which de-
creases with depth as porosity falls due to crack closure and sealing. As the electrical conductivity of melt and hydrothermal fluids is many orders of magnitude greater than the conductivity of the host rock (e.g. Becker et al., 1982; Tyburczy and Waft, 1983; Cox et al., 1986) EM techniques are admirably suited to the task of mapping the processes of ridge accretion and the thermal evolution of new oceanic lithosphere.

Relatively few EM experiments have been conducted in a MOR environment. MT measurements were made by Filloux (1981, 1982) across the East Pacific Rise at 12°N and 21°N, and two magnetometers were deployed by Law and Greenhouse (1981) across the northern end of the Juan de Fuca Ridge. The electrical conductivity properties of MOR determined by these experiments were in reasonable agreement, suggesting a high-conducting layer beginning at a depth of 20-40 km, and a deeper conductivity rise below 200 km. Similar electrical structures were found by Beblo and Bjornsson (1980) from land measurements made in Iceland across the Mid-Atlantic Ridge. MT soundings above MORs have also been made on ice; for example, Trofimov and Fonarev (1976) obtained MT estimates above the Gakkel Ridge in the Arctic Ocean. Controlled Source Electromagnetic (CSEM) measurements have been used to determine the electrical conductivity at spreading ridges (Francis, 1985; Evans et al., 1991), and exploration potential has been developed and tested (Nobes et al., 1986).

The EMRIDGE experiment was conducted in the northeast Pacific Ocean across the Juan de Fuca Ridge, from July to November 1988, as a result of collaboration between institutions based in four countries; Figure 1 shows the location of the experiment. It was designed to complement the large EM array study known as EMSLAB which spanned the entire Juan de Fuca Plate, from the ridge axis to the subduction zone beneath the Cascade Mountain belt in the states of California, Oregon and Washington, U.S.A., and British Columbia, Canada (EMSLAB Group, 1988; Filloux et al., 1989; JGR Special Issue, 1989). The principal objectives of EMSLAB were to examine the electrical conductivity structure of the lithosphere and upper mantle, from ridge accretionary processes to the subduction zone and beyond; and to observe oceanographic phenomena using EM techniques (Filloux et al., 1989; Chave et al., 1989). Although a high fraction of the existing seafloor apparatus were employed during EMSLAB (Filloux et al., 1989) the number were not sufficient for the detailed study of the Juan de Fuca Ridge. This paper reports on the EMRIDGE experiment to investigate the processes active in the generation of new oceanic crust, using a dense array of EM apparatus within a small region centered on the southern-most segment of the Juan de Fuca Ridge.

2. Tectonics

The Juan de Fuca Ridge, shown in Figure 1, marks the boundary between the Pacific and Juan de Fuca Plates, and has a spreading half-rate of 29 km Ma⁻¹ (Riddihough, 1984; Blackman and Forsyth, 1989). The ridge is approximately 500 km from the coastline of northwest America. Understanding of the processes active at the Juan de Fuca Ridge has been improved dramatically by a series of geophysical and geological investigations, such as high-resolution mapping by SEABEAM, SeaMARC and GLORIA (USGS Juan de Fuca study group, 1986; Crane et al., 1985), submersible diving programs and by closely spaced magnetic surveys. These have revealed that the Juan de Fuca Ridge is divided into at least six segments, each 50 to 150 km long (Johnson and Holmes, 1990), consistent with patterns observed at the East Pacific Rise (Macdonald et al., 1988) and the Mid-Atlantic Ridge (Sempé et al., 1990).

Deployment sites for the EMRIDGE seafloor instruments, shown in Figure 2, were chosen on the basis of a survey by the submersible ALVIN and from SeaMARC II data. These sites, with the three closest EMSLAB deployment sites and seafloor bathymetry, are shown in Figure 2, and are listed in Table I. The transect lies across the most southerly segment of the Juan de Fuca Ridge, known as the Southern Symmetrical Ridge (Johnson and Holmes, 1990) or Cleft segment (e.g. Chadwick et al., 1991), and is approximately 37 km from the Blanco Fracture Zone. Ridge axis deployment sites were along the ‘Elongated Summit Depression’ (between 44°38'N, 130°23'W and 44°35'N, 130°24'W), which appears to be a smooth and relatively flat lava flow, varying in width from 1 to 2 km, at a depth of 2240 m (Crane et al., 1985).