Physics of the Earth and Planetary Interiors 173 (2009) 7–16

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Structural electrical anisotropy in the crust at the South-Central Chilean continental margin as inferred from geomagnetic transfer functions

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ARTICLE INFO

Article history:
Received 23 February 2008
Received in revised form
27 September 2008
Accepted 15 October 2008

Keywords:
Geomagnetic induction
Subduction zone processes
Anisotropy
South America

ABSTRACT

Induction vectors, as a visualization of geomagnetic deep sounding transfer functions, display an unique pattern at the South Chilean continental margin between latitudes 38°–41°S and longitudes 71°–74°W: at long periods of approx. 3000 s their real parts are uniformly deflected from the W–E direction (which would be expected due to the coast effect and/or anomalies beneath the roughly N–S striking Andean mountain chain) to the NE. Attempts to model this behavior with simple and geologically realistic 3-D models failed, but a reasonable data fit was obtained by employing 2-D models with a structurally anisotropic, lower crust. This anisotropy hints at a deeply fractured, fluid-rich crust with a major strike direction of 40°–50° (SW–NE), oblique to the continental margin and in accordance with the regional stress field in the region of the volcanic arc. A surprising result is that the anisotropy persists in the forearc and may even reach until the continental slope near the trench.

1. Introduction

Magnetotelluric (MT) transfer functions are commonly displayed as apparent resistivities and phases, both derived from the ratio of horizontal electric and magnetic fields (impedance). If the vertical magnetic field has been measured as well, the transfer function between vertical and horizontal magnetic fields (often termed “tipper” because the secondary field of a lateral conductivity variation tilts the magnetic field out of its horizontal direction in a one-dimensional setting) may additionally be used to derive an image of electrical conductivity in the earth:

$$B_z(T) = W_x(T)B_x(T) + W_y(T)B_y(T), \qquad (1)$$

where x, y, z denote cartesian, geomagnetic coordinates; B is geomagnetic induction and T is period. To distinguish it from MT sensu strictu this method is often referred to as geomagnetic deep sounding (GDS).

The complex-valued tipper $\boldsymbol{W} = (W_x, W_y)^t$ (t denotes transpose) is conveniently displayed as an “induction vector” or “arrow” for both real and imaginary parts, calculated according to:

$$\vec{P}(T) = Re\{W_x(T)\}\vec{e}_x + Re\{W_y(T)\}\vec{e}_y \qquad (2)$$

$$\vec{Q}(T) = Im\{W_x(T)\}\vec{e}_x + Im\{W_y(T)\}\vec{e}_y, \qquad (3)$$

with $\vec{e}_x$ and $\vec{e}_y$ as unity vectors in x- and y-direction. Plotted on a map and if only a single, two-dimensional conductivity anomaly is present, real vectors point away from regions of enhanced conductivity, while imaginary vectors change sign at a period where the real parts are maximal. We employ the commonly used term “vector” here, but note that this expression should be used with care when several induction anomalies are coupled (Siemon, 1997).

For reasons of simplicity presentation of real parts is usually preferred; plotting real vectors in unrotated coordinates is often referred to as “Wiese convention” (Wiese, 1962). At an ocean margin induction vectors (should) point away from and perpendicularly to the coastline due to the high conductivity of seawater in the range of $\sigma = 3$ S/m; this is the so-called “coast effect”, which may be observable far inland dependent on the resistivity (reciprocal of σ) of the continent.

This simple image is obscured if conductivity distribution is 3-D and/or anisotropic. Then conclusions concerning electrical strike directions may not be drawn intuitively any more; this became particularly evident at the Chilean continental margin, where – despite of the elongated, 2-D appearance of the coastline over thousands of kilometers – induction vectors in many near-coastal regions do not point away from the coast, but rather obliquely or even parallel to it.

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doi:10.1016/j.pepi.2008.10.017

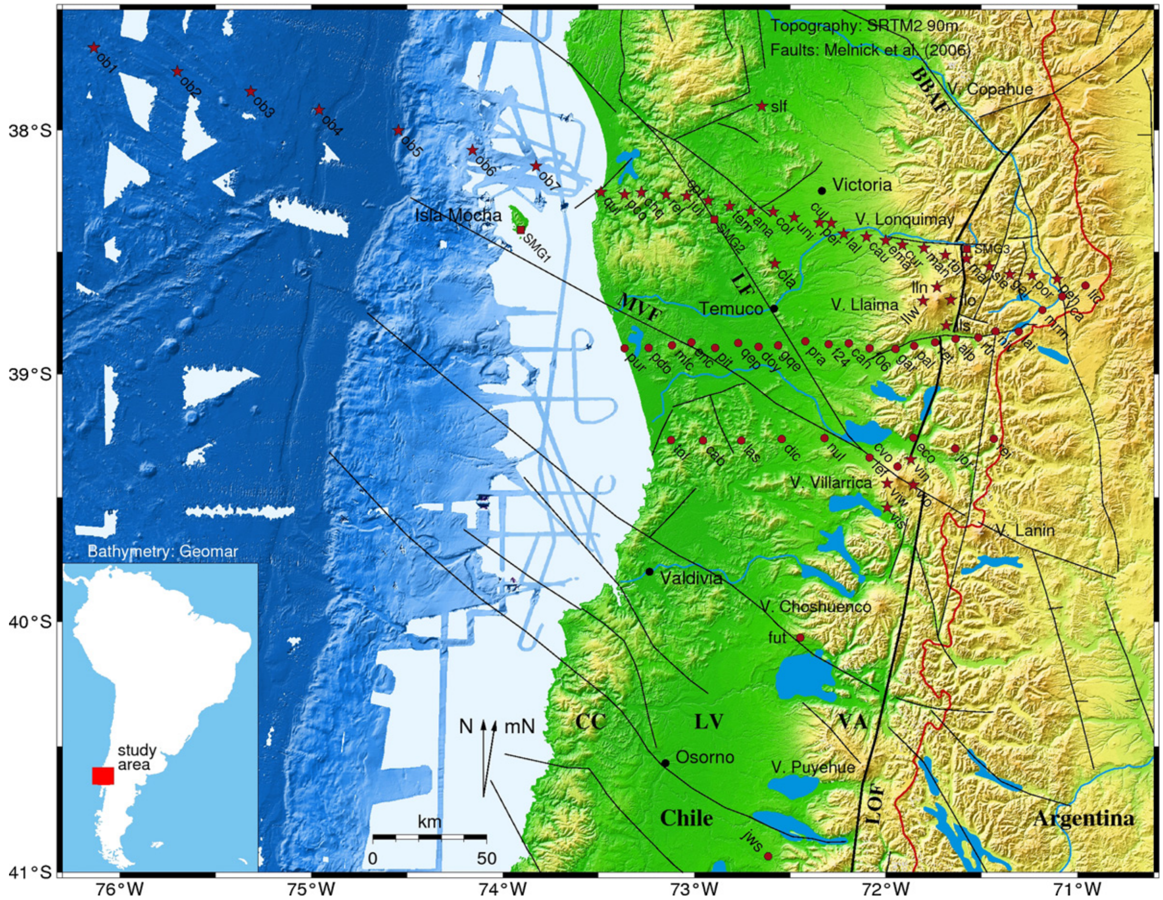

Fig. 1. Shaded relief map of the study area at the South Chilean margin. Topography is based on SRTM (NASA), swath bathymetry is from various cruises of R/V Sonne (Scherwath et al., 2006), fault traces (black lines) are modified from Melnick et al. (2006). Faults mentioned in the text: LOF, Liquiñe-Ofqui; LF, Lanalhue; MVF, Mocha-Villarrica and BBAF, Bío-Bío-Aluminé Fault, respectively. CC denotes Coastal Cordillera; LV, Longitudinal Valley; VA, volcanic arc; mN is magnetic north with a declination of 10°E from geographic N. Stars indicate sites from recent campaign 2004/2005, circles from 2000; SMG1–3 are monitoring sites operated by GFZ Potsdam.

2. Geological background and experiment layout

We report here on observations in South-Central Chile between latitudes 38°S and 41°S (Fig. 1), where the oceanic Nazca plate is subducted beneath the South American continent and the great earthquake of 22 May 1960 (moment magnitude $M_w = 9.5$) initiated (Cifuentes, 1989). Subduction is oblique with an angle of ~25° (i.e., N77°E) with respect to the plate margin and with a current velocity of ~6.5 cm/a (Klotz et al., 2006). The study area is located in the northernmost Patagonian (Neuquén) Andes and can be subdivided into several main morphotectonic units (e.g., Folguera et al., 2006; Melnick et al., 2006): (1) a narrow Coastal Platform comprising uplifted Tertiary marine and coastal sequences; (2) the Coastal Cordillera, formed by a Permo-Triassic accretionary complex and a late Palaeozoic magmatic arc; (3) the Longitudinal Valley, a basin filled with Oligocene–Miocene sedimentary and volcanic rocks, covered by Pliocene–Quaternary sediments; (4) the Main Cordillera, formed by the modern magmatic arc and intra-arc volcano-sedimentary basins; (5) the Loncopué Trough, already in Argentina, an extensional basin east of the Main Cordillera associated with abundant mafic volcanism; (6) the southern extension of the Agrio fold-and-thrust belt; and (7) the Mesozoic Neuquén Basin and the Cretaceous–Tertiary foreland basin to the east.

Subduction at the Chilean margin started already in the late Paleozoic, while Andean evolution began in the Jurassic, associated with the opening of the South Atlantic Ocean. In the Cretaceous widespread plutonism occurred in the Coastal Cordillera and in the area of the volcanic arc, where the Patagonian Batholith was formed. South of 38°S the position of the volcanic arc remained relatively constant through time with the exception of a significant broadening of the magmatic system (Muñoz et al., 2000) and an 80–100 km westward shift of the volcanic front in the late Oligocene–early Miocene with respect to its current position (Parada et al., 2007). This event was probably related to the breakup of the Farallon plate into Nazca and Cocos plates, respectively, and subsequent changes in plate convergence and subduction angle (Muñoz et al., 2000). For further description of the tectonic evolution see the overview articles by Stern (2004), Ramos and Kay (2006) and Glodny et al. (2006).

The modern Principal Cordillera is dominated by the Holocene volcanoes of the Southern Andean Volcanic Zone, with some of the most active volcanoes in South America, e.g., Villarrica, Llaima and Lonquimay (Gonzáles-Ferrán, 1994). The chain of stratovolcanoes is aligned parallel to the trench and along the Liquiñe-Ofqui Fault (LOF), a mega shear zone extending for over 1000 km from the triple junction of Antarctic, South American and Nazca plates to ~38°S (Cembrano et al., 1996, 2007). A NW–SE – thus obliquely to the trench – oriented fault system crosses the arc and forearc (e.g., Melnick et al., 2006), which may have been of importance for a major eruption in the Cordon Caulle volcanic complex immediately after the $M_w = 9.5$ earthquake (Lara et al., 2004). The Lanalhue Fault, in particular, is regarded as an inherited, continuously reactivated, pre-Andean structure, which is associated with deep-reaching seismicity (Yuan et al., 2006).