Chapter 11

Interpretation of the conductivity models

An interpretation of the regional conductivity structures determined by the 3-D modeling is given in the context of other geophysical and geological results, limiting the discussion to the conductivity regions which were best resolved.

The high conductivity zones (HCZ) in the study area are from west to east (see fig.11.1):

1) The horizontally elongated conductor(s) following the trends of the Atacama fault system (AFS). The narrow HCZ (∼7 km wide) starts at shallow depths and extends as vertical dike(s) at least down to 7 km.

2) The HCZ in the Precordillera (PC) can be separated into two blocks. A shallow structure (<5 Ωm) between 2 and 10 km deep in the form of approximately N-S elongated conductors along the Precodillera fault system (PCFS); a deeper block below 10 km depth with lateral N-S gradient of conductivity decreasing from north to south. Its central part (at 20.5°S) extends to the west in the Longitudinal Valley.

3) A shallow, highly conductive layer 2 km thick covers the Altiplano. Another HCZ (≤ 5 Ωm) below the 15-20 km depth extends between the eastern part of the Western Cordillera and the Altiplano. The HCZ bends to NNW, which is similar to the NNW-SSE trend of the magmatic arc.

11.1 A deep or a shallow source of the fluids in the Atacama fault?

The highly conductive vertical dike(s) ($\rho \leq 5$ Ωm) in the Coastal Cordillera located at the surface correlates with the Atacama fault (AF). The conductor changes in strike along N-S and coincides with the still active NNW-SSE shear zone crossing the Salar Grande to the south (fig.11.1; CC). To decide if the dike lengthens further south of 21°S, following the trend of the AF, additional MT sites would be required. It can be presumed that it does extend to the south, as supported by two independent observations. For example, the strong

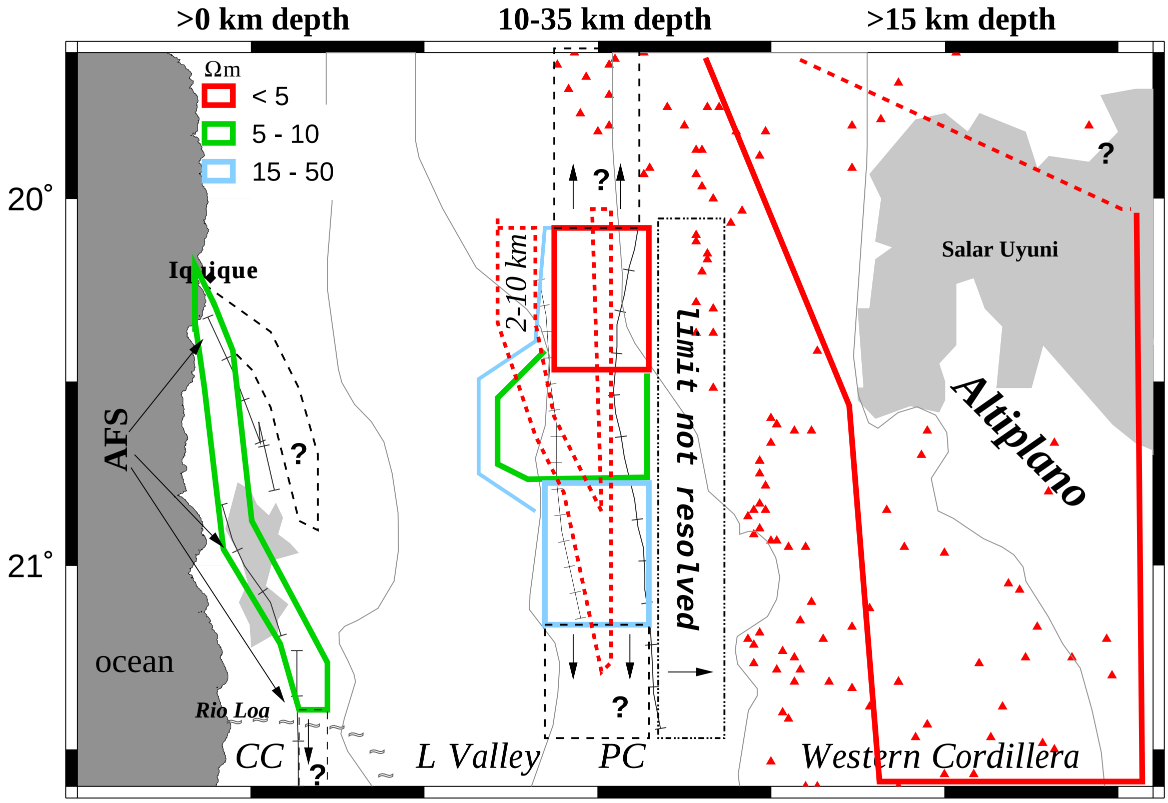

Figure 11.1: Plan view of the principal high conductivity zones (HCZ) resolved by the 3-D modeling projected on the geographical Southern Central Andes map. The HCZs located in the regional faults of the Andean convergence system are: *AFS*: in the Atacama fault system of the Coastal Cordillera, shallow conductive vertical dike(s) with strike varying along N-S, *L Valley and PC*: In the thrust-fault system of the Longitudinal Valley and Precordillera (PC), and the West Fissure (WF) shear zone, vertical dikes with varying strike along N-S in the upper crust (< 10 km) and a N-S gradient HCZ at mid-crustal levels. Beneath the eastern part of the magmatic arc (Western Cordillera) and the Altiplano, a NNW-SSE striking regional HCZ (<2 Ωm) beneath 15 km depth. Gray triangles indicate the volcanoes of the recent magmatic arc and the APVC in the Altiplano. *Top:* Resistivity ranges (Ωm) of the HCZs and the corresponding depth levels.

current channeling affecting the magnetotelluric data indicates the presence of elongated conductors. The longer they are, the higher the current density becomes (Chapter 6), and therefore the channeling effect becomes stronger. The second observation is the 2-D model obtained by Krüger [1994] at latitude 22°S, in which several parallel N-S vertical conductive dikes at depths between 10 and 30 km were included to explain the MT data, interpreted as vertical pathways of fluids in the crust of the Coastal Cordillera and western Long Valley (Schwarz and Krüger [1997]). However, the induction arrows, which show 3-D effects, were not explained. The conductive dikes modeled by Krüger [1994] (at latitude 22°S) may also be three dimensional. This suggests that the orientation of the dike-like conductors does not require that they necessarily strike N-S or have infinite lengths.

Another branch of high conductivity to the east (fig.11.1) can not be ruled out by the MT data (section 10.1), and can be correlated with the several faults and lineaments known in the region (Section 3.1). The depth of the dike(s) is at least 7 km. Because of the screen effect produced by the ocean together with the strong galvanic distortion produced by the conductive dikes −detected in the N-S electric field components− (strong current channeling;

section 7), their resolution further in depth is not possible.

The average temperatures of the lithophere in the forearc of the Southern Central Andes decrease from east to west, suggesting a more brittle regime in the direction of the trench (section 3.1). The temperatures in the Coastal Cordillera are below 200°C (Springer [1999]) where the oceanic Moho lies at a depth of about 40 km (Giese et al. [1999]; see fig.11.3). The rheological characteristics in the Coastal Cordillera are supported by several geophysical results: high P-wave seismic velocities of about 6.8 km/s detected in the crust down to 30 km depth (Wigger et al. [1994]), a positive isostatic residual field (70 mGal; Götze et al. [1994]), a low seismic attenuation (e.g., Haberland [1999]), and evidence of seismic events in the crust (Lüth [2000]). From here it can also be inferred that the crust has a high density. Under these conditions, partial melts cannot develop[1], thus an assumption of a conductivity enhancement due to dehydration reactions from melting processes must be discarded. On the other hand, graphite as the cause of the high conductivity observed in the dikes is ruled out because this can not be preserved in active orogenes.

The conductivity enhancement in fracture zones can be explained by a flux of salinary fluids along them and/or by mineralizations from metamorphic reactions. Furthermore, it is not unrealistic to say that fracture zones within a brittle regime can propagate in depth along a whole crust which is subject to shear stresses from an active subduction zone. Under low temperature conditions ($< 300°$ C) no metamorphic reactions occur, thus saline and/or ore fluids can freely flow within the long fracture paths, circulating as electrolytic under hydrostatic pressures (see model in fig.11.3; AF). But where do the fluids come from?

Fluids from the slab

Fluids play an important role in the subduction zone and the overlying mantle wedge (e.g., Giese et al. [1999]). At the levels of the oceanic Moho (40-50 km depth) underlaying the Coastal Cordillera, the transition from the coupling (seismogenic) zone[2] to the cool mantle wedge occurs (fig.11.3). High V_p/V_s ratios detected in this zone are interpreted as a serpentinized mantle, i.e, hydrated (Giese et al. [1999]) but most probably not fluid free given the low seismic attenuations characterizing this zone (Schilling and Giese [1998]). It is therefore questionable that the mantle −if it was present in this region− is feeding the crust with an upward fluid flux, for example, along the Atacama fault, assuming it as a deep active shear zone. On the other hand, it is a theme under discussion if in the seismic coupling zone water can be liberated from the subducting slab (e.g., Peacock [1996]). If this is true, such fluids can use the fractures of the brittle continental crust as the conduit of transport, and thus reach higher levels according to the geometry of the fractures. If they are rich in salines, long period magnetotelluric measurements carried out on-shore would detect them at greater depths as good conductors if the ocean was not present. Our magnetotelluric data are unable to define the lower depth of the conductive dikes surpassing ∼10 km, and was explained as being due to the strong current channeling produced by the ocean and the shallow dike-like conductors.

---

[1] Melting reactions in the mantle and crust starts at temperatures above 600°C.

[2] between the oceanic slab and continental plate.

Fluids from the crust

In the crust, porous rocks can retain water from dehydration reactions which occurred during a past metamorphism. The Coastal Cordillera was subject to progradational metamorphic reactions in the Jura (210-120 Ma), and may have continued with retrograde metamorphism during the emplacement of the arc to the east. Metamorphic fluid fluxes and crustal porosities are maintained long after the end of dehydration metamorphism (>100 Ma), and fluid production ends after about 70 Ma (e.g., Thompson and Connolly [1990]). The source of the fluids circulating in the active Atacama fault can be such older metamorphic reactions. Water may have been trapped in the fractured rocks.

Fluids from the surface

Meteoric (surficial) waters can easily flow downward through fractures in a brittle regime. This is the most realistic argument with regard to the source if the fluids are really only circulating in the upper crust along fractures which do not exceed mid-crustal levels. Hence the conductive dikes would extend until ∼10 km depth.

Besides the meteoric water, that is rainwater and fluvial sources, surficial fluids may also have come originally from thermal convections developed at mid-crustal level excited by intrusions. Also, a "seismic pumping" effect can be their origin: Water is sucked into fault zones during the dilatancy phase of an earthquake producing motion (Newton [1990]). This can be an argument in favor to explain the HCZ in the Coastal Cordillera, assuming that the crust is seismically active in this region.

Mineralizations

Mineralizations in the active shear zone or ore fluids can also enhance conductivity. Ore minerals have higher densities than the average crust, leading to enhance the P-wave velocities and resulting in positive isostatic residual field, in accordance with the observations in the Coastal Cordillera (e.g., Giese et al. [1999]). On the other hand, highly conductive minerals such as illmenite, magnetite and pyrhotine can develop aligned in shear zones (Heikamp et al. [1994]). The widespread nitrate deposits east of the Atacama fault (Chapter 3) are probably related to metallogenetic events, where ore fluids may have been channeled in the Atacama fault system, such as that from epithermal gold-silver (Chong [1994]).

The origin of the fluids in the Atacama fault can be a combination of the mechanisms explained above. However, the hypothesis regarding the upward migration of water into the crustal fractures released from the seismogenic zone, can not be supported by the MT observations. The levels of the slab are beyond the penetration depths of the MT data. Measurements carried out off-shore are required to resolve this zone (Chave, pers. comm.).

11.2 Precordillera Fault system

In the Precordillera (PC), elongated conductors (<5 Ωm) with varying strike along N-S extend vertically in the upper crust (from 2 to 10 km depth; fig.11.1). These most probably have lateral finite extensions, which would explain the strong 3-D effect detected in the magnetotelluric data (Chapter 8). The upper crustal dike-type conductors can be related to the Precordillera fault system, and hence explain the conductivity enhancement as being due to salinary fluids circulating in the fractures of the brittle upper crust (temperatures <200°C; fig.11.3). In the western PC as well as part of the Longitudinal Valley, a N-S thrust-fold system has been inferred from an isostatic model (fig.11.3; west of 69°W), and is interpreted as the west-flank of the Miocene-Holocene tectonic Altiplano uplift which developed in connection with ignimbrite-magmatism (Victor [2000]). The thrust-fold in the western PC as well as the West Fissure (WF) shear zone are geological structures recognizable in the field (fig.11.1; PC). The upper crustal dikes at latitude 20.5°S correlate well with the PC thrust-fold system and the WF (fig.11.3). The depth of the WF (∼25 km) is presumed by accounting for the isostatic model of the thrust-fold system by Victor [2000], the geothermal gradient and the low seismic velocity zone at a 30-40 km depth modeled by Yuan et al. [2000] from P-S converted seismic phases. Thus, the crust in the Precordillera can be considered to have a brittle regime at depths above 30 km, whereas at depths below about 30 to 40 km it undergoes a brittle-ductile transition (with temperatures between 300°C and 500°C; fig.11.3). The temperatures in the lower crust and upper mantle do not exceed 650°C, indicating that partial melt is not possible here, supported also by the lack of high seismic attenuation registered in this zone (e.g., Haberland [1999]).

A larger high conductivity zone (HCZ) extends below the conductive dikes at depths between 10 and 35 km, with a N-S gradient of conductivity decreasing from north (<5 Ωm) to south (>10 Ωm; PC in fig.11.1). Although the lower boundary is not well constrained, it could be constrained by inserting another HCZ at the levels of the oceanic crust (70-90 km depth at 69°W; fig.11.3), which is seen to give an equivalent response under the 2-D approximation (models in Section 9.2.1; discussion in Section 10.3).

The origin of the fluids in the fractures can be argued in a similar manner for the PC-fault system as was done for the Atacama fault system. The conductive dikes of the upper crust may be fed by meteoric water trapping as well as ore fluids (inferred from the huge porphyry copper in Chuquicamata at latitude 22°S, associated with the West Fissure zone; Reutter et al. [1995]). Water released from fractured hydrated porous rock, remaining from older metamorphic reactions, can also be a possibility for the brittle crust.

In the Precordillera however, the rheology and the tectonic history differ from the crust of the near coast. The last important compressional deformation in the Precordillera occurred about 35 Ma ago (Reutter et al. [1995]), when the crust was thickened subsequently subject to a retrograde metamorphism (Reutter, pers. comm.). Thermotectonic modeling has shown that a lithosphere subject to a strong and sudden thickening by overthrusting will need a long period of time (>100 Ma) to recover its original thermal state (Thompson [1981]). Within a period of about 70 Ma the crust can still undergo metamorphic reactions, adjusting fluid productions (Thompson and Connolly [1990]). This model can be suitable for the Precordillera if

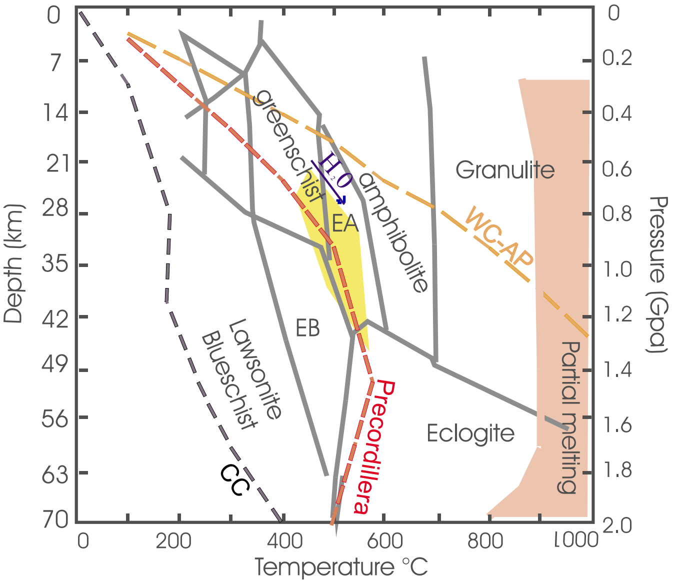

Figure 11.2: P-T diagrams of metamorphic facies down to a 70 km depth determined experimentally for different hydrous rocks characteristic of subduction zones (Peacock [1996]). In addition, P-T paths taken from the geotherms after Springer and Förster [1998] at latitude 21°S are drawn as *dashed lines* for the Coastal Cordillera (*CC*; black), Precordillera (gray) and the region between the Western Cordillera and Altiplano (*WC-AP*; light gray). *EB:* Epidote blueschist, *EA:* Epidote amphibolite. Within 20-30 km depths at temperatures of 300° to 500°C water is released in the phase transformation of greenschist to epidote amphibolite. This zone coincides with the mid-crustal conductor of the *Precordillera*.

we relate the pressure-temperature diagrams of metamorphic hydrous rocks which characterize a subduction zone (Peacock [1996]) with the geotherms estimated by Springer and Förster [1998] for the Precordillera (fig.11.2). The mid-crust undergoes intermediate metamorphic reactions (temperatures from 300°C to 550°C) where greenschists transform to epidote amphibolite (fig.11.2; EA) indicating the first appearance of water, and liberating fluids break down in the absence of partial melting (Wannamaker [1986]). At greater depths (30-45 km; fig.11.2) the crust contains wet rocks with epidote blueschist or epidotite amphibolite. At the lowest crustal depths, the P-T diagram indicates a composition of eclogite (dry rock) for the ductile lower crust of the Precordillera (fig.11.2; 45-60 km depth and T=500-600°C), which does not indicate conductivity enhancement since eclogite can not retain water. If the region near the slab were identified with higher conductivity values (fig.11.3; alternative conductor), and thus with dehydration reactions from the slab, the fluids released into the mantle wedge would have no connection with the fluids of the mid-crust if the lower crust is composed of eclogites.

It is proposed that continuing metamorphic reactions in the mid-crust, which liberate fluids from cracks and ascend into the fractures of the Precordillera fault system, are the cause of the conductivity enhancement at mid-crustal levels (10-30 km). In the north the conductivity is clearly higher than to the south, which may be related to the different volcanic history known at these latitudes. North of 21°S magmatism ceased about 25 Ma, whereas to the south volcanism is younger (<10 Ma; de Silva [1989]). If magmatism and tectonic compression would occurred simultaneously (Victor [2000]), then tectonic overthrusting would have started at about 10 Ma in the south whereas to the north it would have began ∼30 Ma ago (Victor [2000], pers. comm.). In this manner, according to a thermotectonic model of a thickened crust by overthrusting that induces a thermal perturbation over time (Thompson [1981]), metamorphic reactions may evolve under different P-T conditions from north to south in the Precordillera. This suggests that a distinct production of fluids in the crust might develop north and south of 21°S. A ∼30 Ma thickened crust can lead to a higher production of fluids (and hence higher electrical conductivity values in the north) than a recently deformed crust subject to younger metamorphism. An additional explanation is that in the north, where magmatism is older (>25 Ma) than in the south (<10 Ma), the crust might be more fractured due to a cooler and more brittle regime than in the south, allowing the fluids to be better interconnected and hence the electrical conductivity to be enhanced.

The seismic reflector called ”Quebrada Blanca Bright Spot” (QBBS) by Lüth [2000] extends east of the Precordillera at a depth of 40 km and ascends to the east to 25 km beneath the Western Cordillera (fig.11.3; QBBS). If it were caused by a thin layer of highly connected porosity (”aquitards”), able to retain minuscule steady state crustal saline fluid fluxes (Thompson and Connolly [1990]), then this layer should be also highly conductive. This zone was not resolved by the 3-D modeling (fig.11.1); strong 3-D effects indicated by the data impede the constraint of the conductivity values. In the 2-D approach, the data of the Ancorp profile were seen to be insensitive to such a conductivity structure (Schwalenberg [2000]), but this is subject again to the uncertainty given by the 3-D effects. The possibility that the QBBS reflector is a ”side effect” has also been discussed (e.g., R. Patzig, pers. comm.), and if it is really due to saline fluids in interconnected pores, then it is very probable that the reflector changes along N-S, in accordance with the MT obervations with regard to a N-S strike conductivity variation. On the other hand, a well filled aquitard requires neither a good porous connection nor fluids rich in salines to be reflective, whereas these are the controlling factors to enhance conductivity. If the pores are poorly connected and/or the fluids contain small amounts of salines, then the aquitard will show no sign of enhanced conductivity (Thompson and Connolly [1990]) .

11.3 Magmatic arc - Altiplano

In between the Western Cordillera (the modern magmatic arc) and the Altiplano, a high conductivity zone (HCZ) extends beneath 20 km (<2 Ωm; fig.11.3), and is interpreted as partial melting (Brasse et al. [2000]), confirmed also by relating the P-T phase diagrams of metamorphic reaction with the P-T path of the Western Cordillera-Altiplano estimated at longitude 68°W (fig.11.2; curve WC-AP).

The NNW-SSE bending of the HCZ (fig.11.1) correlates with the bending of the volcanic arc, which seems to be related to the distinctly different volcanic activity (and probably tectonic development) between the northern and southern regions of latitude 21°S.

The extension in depth of the HCZ can not be resolved by the MT data in the 2-D approximation, however, to keep the fit with the model responses the resistivity values at depth >60 km in the whole Altiplano should not exceed 20 Ωm (Schwalenberg [2000]). As was discussed in section 10.3, the present stage of the 3-D modeling cannot rule out the possibility of a low resistive layer below the Moho between the Precordillera and Altiplano, reflecting a wet mantle wedge.

In addition, an electrical asthenosphere[3] beneath the Altiplano may be also exist, given the elevated temperatures estimated in this zone (≥1250°C; Springer and Förster [1998]; fig.11.3) and the high seismic attenuations (Whitman et al. [1992]). The electrical asthenosphere would exceed 100 km depth in the centre of the Altiplano, if we agree to correlate it with the seismic attenuations (Whitman et al. [1996]) and the geotherms estimated at latitude 21°S (Springer and Förster [1998]). These depths are, however, beyond the resolution of the MT data. Also, the models of seismic attenuation by Whitman et al. [1992] were obtained from a coarse net of stations; thus the result may be not well constrained.

In the Puna (24°S), in contrast, the seismic attenuation zone is shallower and extends even to the backarc beneath the Eastern Cordillera (Whitman et al. [1996]; Schurr [2001]). At this latitude in the Eastern Cordillera, a high conductivity zone (HCZ; <10 Ωm) below 70-80 km depth, obtained by 2-D inversion of MT data, correlates with this "weakened" zone. The HCZ was interpreted as the electrical asthenosphere by considering the depth of the thermal boundary layer (1250°C) estimated from heat flow measurements (Hamza and Muñoz [1996]) and empirical heat flow-depth curves (Lezaeta et al. [2000]).

To prove the hypothesis of an electrical-seismic asthenosphere changing in depth along strike in the Southern Central Andes, a denser net of long period MT sites as well as a denser seismological net in the Altiplano and backarc is required.

---

[3] conductive mantle due to melts, fluids and volatiles, with its top at the thermal boundary layer 1250°C

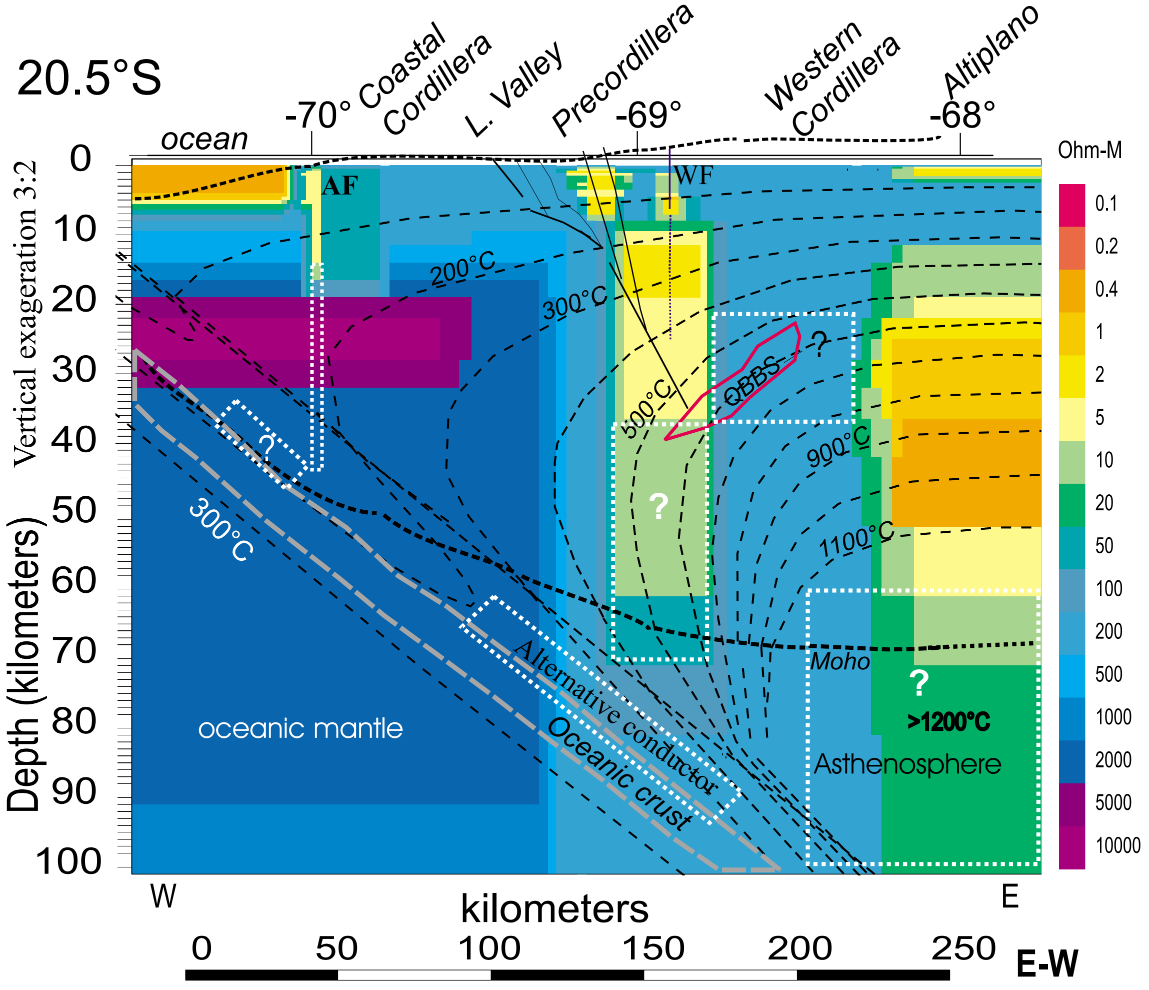

Figure 11.3: W-E cross section of the 3-D resistivity model (ρ= Ohm-M) at latitude 20.5°S (fig.11.1). High conductivity zones are indicated by red to yellow colors (0.1-5 Ωm). Inserted are the geotherms after Springer and Förster [1998], topograpy, continental *Moho* after seismic refraction (Wigger et al. [1994]) and the oceanic crust. In the Long.Valley and Precordillera is shown the thrust-fold system associated with the west-flank of the tectonic uplift of the Altiplano (Victor [2000]) and the West Fissure (WF) strike-slip fault. Near the coast (70°W) is located the Atacama mega-fault (**AF**). White dotted lines indicate either the conductivity zone that is alternative for the model or the structures not resolved (?). *QBBS:* The seismic reflector "Quebrada Blanca Bright Spot" (Lüth [2000]). See text for explanation.