HEAT FLOW AND GEOTHERMAL POTENTIAL ACROSS THE CENTRAL ANDEAN SUBDUCTION ZONE

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Abstract
Terrestrial heat flow and lithospheric thermal regimes in the western part of South America are influenced by various geodynamic processes caused by the subduction of oceanic lithosphere along the continental margin. Recently measured and revised heat-flow values across the Central Andean subduction zone (between 60-75°W and 15-30°S) show a variability corresponding to different ongoing tectonic processes. It was of interest (1) to investigate the effect of the different processes on the lithospheric thermal situation and (2) to quantify the temperature conditions at depths greater than those penetrated by boreholes. This is not only of academic importance but also essential for elucidating the potential for geothermal energy use in these regions. Several scenarios of processes and parameters affecting the thermal conditions were investigated at regional scale and constrained by surface heat flow from the Nazca Plate in the west towards the Chaco Basin in the east. Low heat flow of 20 mW/m^2 in the Coastal Cordillera can be explained by low shear stresses along the plate contact between the Nazca Plate and the South American Plate; high values ranging between 50 and 180 mW/m^2 in the active magmatic arc and the Altiplano can be achieved by assuming locally ascending magma and/or near-surface fluid circulation. In the Andean foreland, heat flow of 40 mW/m^2 is slightly lower than the heat flow of about 50 mW/m^2 in the adjacent Brazilian Shield farther east. Comparison of the active margins of the North American continent and the Central Andean subduction zone shows a similar heat-flow pattern, but there are differences in the subduction parameters and consequently in lithospheric thermal conditions.

Introduction
The orogenic system of the Central Andes is a present-day example of an ocean-continent collision zone, where the subduction zone is overridden by the South American continent advancing towards the oceanic Nazca Plate. As a result of processes linked to subduction and arc magmatism thickening of the continental crust, up to 70 km total thickness, occurs underneath the Eastern Cordillera and Altiplano areas (Isacks 1988; Francis and Hawkesworth 1994; Beck *et al.* 1996; and many others). The extreme increase in crustal thickness probably is caused by underplating of the Brazilian Shield under the Andean crust, which results in crustal shortening and uplift in the back-arc region (e.g. Schmitz 1994). Ongoing subduction of the oceanic Nazca Plate under the continent is relatively fast with a subduction rate on the order of 9 cm/a (DeMets *et al.* 1990). Despite the low-angle subduction of cold oceanic lithosphere, intensive magmatism is generated.
Based on this knowledge, it was of interest to get an improved insight into the surface heat-flow pattern and to learn how heat flow is related to the tectonic conditions and processes in the lithosphere, or the converse, to what degree lithospheric conditions can be deduced from surface heat flow. We focussed on an area comprising southern Peru, northern Chile, Bolivia, and northern Argentina between 60-75°W and 15-30°S.

Previous work
In the past two decades, the heat-flow conditions in the Central Andes and the Nazca Plate were the focus of several studies, which formed the basis for a heat-flow database for the western active continental margin of South America (Hamza and Munoz 1996 and references therein). Because of the paucity of boreholes that are suitable for continuous temperature logging, most heat-flow values were derived from lower quality bottom-hole temperatures measured in exploration wells, temperatures obtained in mines, or from subsurface water using geochemical thermometers. Because activities were limited to exploration areas, the temperature and hence heat-flow data differ in quality and distribution.
One-dimensional analytical estimates have been used to interpret the Central Andes surface heat-flow pattern (Giese 1994; Favetto *et al.* 1997). These models do not include effects related to the subduction process, such as underthrusting of cold oceanic lithosphere, frictional heat generation along the plate contact or mantle flow induced by the subducting slab. Several authors have studied the thermal structure of different subduction zones using numerical models or analytical calculations (see references in Springer 1999). All these models show large differences in lithospheric temperatures, which are mainly caused by different model inputs, such as the model geometry, petrophysical parameters, and effects linked with the subduction process itself. The objective of our temperature modeling was the interpreation of the surface heat-flow pattern in the Central Andes with regard to the ongoing tectonic processes in this particular area.

New heat-flow data
We were able to add, preferably in areas where no heat-flow data were available, new geothermal data to the preexisting database (see Springer and Förster 1998 for details). Temperature was logged in several boreholes and single temperature data from exploration wells, previously not available, were compiled from oil company files - ENAP (Chile) and YPFB (Bolivia). The temperature logs were obtained in 14 boreholes to a max. depth of 470 m in northern Chile located in the fore-arc region (Coastal Cordillera and Precordillera) and in the active magmatic arc (Western Cordillera). These borehole locations were grouped into 5 heat-flow sites (Fig. 1). The temperature profiles were analyzed for the influence of regional and local topography and fluid flow. For example, a terrain correction was applied to thermal logs in the Western Cordillera, whereas the terrain impact on the mean temperature gradients in the Coastal Cordillera was not significant. In addition to continuous temperature logs, a BHT data set of about 40 values from 6 boreholes was used in northern Chile (in the Precordillera and the Longitudinal Valley) to determine heat flow. In contrast, in Bolivia, about 1,500 BHT values were compiled for petroleum fields situated mainly in the Andean foreland, that is in the Subandean Ranges and Chaco (Fig. 1). For a small subset of boreholes, where multiple temperature values were measured at the same depth at different lapse time, BHTs were corrected by plotting them versus time (Horner plot) to obtain an extrapolated formation temperature. To correct the remaining single BHTs, we used a correction procedure based on derivating a general Horner slope as a function of depth using the individual Horner slopes plotted (see also Deming 1989). This generalized BHT-depth correction obtained for Bolivia then was applied in the same way to all BHTs for each exploration field.
To investigate thermal conductivity that has to be related to the temperature gradients, a total of 52 samples of igneous rock and 15 samples of sedimentary rock (breccia) representing the

formations penetrated by the wells were collected from outcrops in the Chilean fore-arc region. Thermal conductivity for each rock type occurring at each heat-flow site was measured and an average value calculated. Thermal conductivity on unsaturated hand samples from Chile (granodiorite, diorite, rhyolite, and andesite) was measured under laboratory conditions (25°C) using the half-space line source method. The effect of sample orientation on the thermal-conductivity value was considered. For the igneous rocks, the influence of the pore-space medium on thermal conductivity was neglected, and the laboratory values were considered as in-situ values. Thermal conductivity of the Chilean sedimentary rocks was based on the thermal conductivity of mineral constituents. Sample porosity was determined to be on the order of 15-20%. The volume percent of rock-forming minerals then was measured by X-ray diffraction of powdered samples. Thermal conductivity of minerals was taken from the literature. The in-situ thermal conductivity was determined from the matrix thermal conductivity and the porosity estimate. We considered the samples to be water-saturated in situ. Formation thermal conductivities used for the heat-flow determination in Bolivia are calculated from matrix thermal conductivity (Henry 1981) and porosity derived from porosity-depth functions (Coudert *et al.* 1995) considering water as pore-filling fluid. Bulk thermal conductivity then was corrected for the in-situ temperature according to a relation given by Sass *et al.* (1992).

A total of 20 heat-flow values was determined for 20 sites in Chile and Bolivia and added to the previous heat-flow database (Fig. 1). In addition, nine heat-flow values derived by Henry (1981) and Henry and Pollack (1988) in Bolivia were revised by adding new BHTs to the original data set and applying an area-specific porosity-depth correction in conjunction with a temperature correction to the thermal conductivity. The revised heat-flow values in Bolivia generally are lower by about 15%.

The heat-flow pattern

The contoured heat flow does not indicate any significant trend along strike of the Andean orogen. For example, clusters of heat-flow density obtained along the fore-arc (from southern Peru towards the south to about 30°S) show little variability. In contrast, a significant change in heat-flow density occurs in a W-E direction, which correlates with the N-S striking tectono-morphologic units. In this situation, changes across the different tectonic-morphologic units can be related to different thermal regimes.

From the mean heat-flow density averaged and projected N-S onto a W-E generalized lithospheric structure cross section (Fig. 2) the following trends are obvious: (1) within the oceanic Nazca Plate low values of about 30 mW/m² occur in the region of the Peru-Chile trench; (2) a minimum heat-flow density of about 20 mW/m² is observed in the Coastal Cordillera; (3) values increase toward the fore-arc region to 40-60 mW/m²; (4) heat flow varies from about 50 to 180 mW/m² in the areas of the magmatic arc and the Altiplano; (5) high values of about 80 mW/m² are typical for the back-arc region of the Eastern Cordillera, and (6) heat flow density is about 40 mW/m² in the Subandean Ranges and Chaco Basin.

With this pattern, the conditions in the Central Andes correlate with situations recognized in subduction zones in other parts of the world, seemingly reflecting ongoing geodynamic processes, as subduction of relatively cold oceanic lithosphere, induced mass flow in the asthenosphere and related crustal magmatism.

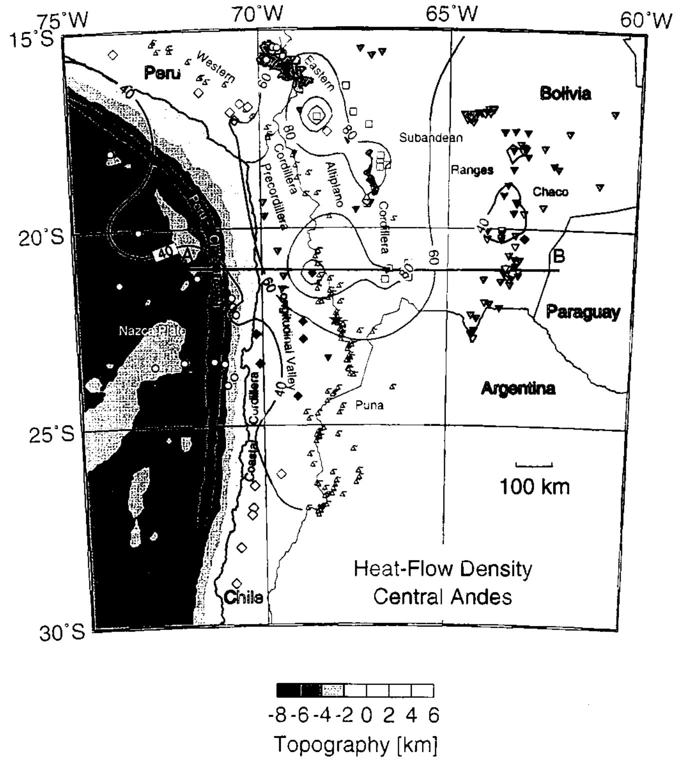

Figure 1. Heat flow and tectono-morphologic units in the Central Andes (Springer and Förster 1998). Black symbols: data obtained by Springer and Förster (1998); filled shaded symbols: location of petroleum fields, where BHTs were compiled but not used for heat-flow determination; white symbols: heat-flow sites reported in previous studies (heat-flow values derived from geochemical thermometers and thermal fluid discharge (Hamza and Munoz 1996) were not considered). Asterix shows location of the El Tatio geothermal field. Location of volcanos in the magmatic arc are identified by upright grey triangles with a small plume. Contour interval of heat flow-density is 20 mW/m². A-B is location of heat-flow profile shown in Figure 2.

Implications on heat flow and geodynamic processes from modeling

In order to distinguish the lithospheric thermal conditions in the different segments of the entire subduction zone and to get an improved insight into the different controlling factors on heat flow, modeling of possible scenarios of ongoing processes seemed to be suitable providing information beyond a description of heat-flow pattern Along a profile at about 21°S (see Fig. 1) from the Peru-Chile trench in the west to the Andean foreland in the east, surface heat flow is used to constrain quantitative models that were employed to investigate the influence of various effects on the thermal field.

The region of the Andean orogen between the trench and the volcanic front is described by 2-D subduction models. The subduction process of the Central Andes has continued since about 200 Ma, which substantiates the assumption of steady-state conditions. However, an essential condition for this assumption are constant subduction variables for that period of time. Some subduction parameters in the Central Andes vary considerably with time; the investigation of their influence on the thermal

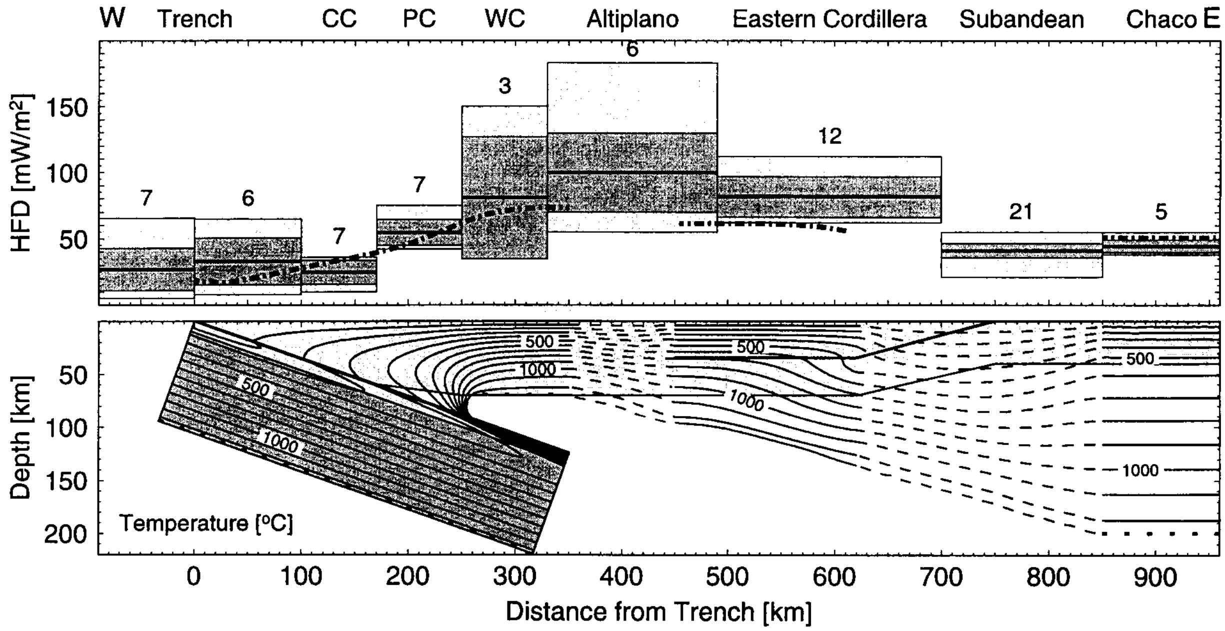

Figure 2. Compilation of separate model calculations (bottom) along the W-E profile (profile A-B on Figure 1) in comparison with calculated (dashed/dotted line) and measured heat flow (from Springer 1999). Measured heat flow projected on the profile was determined between 15 and 30°S. Mean heat-flow density for each tectono-morphologic unit shown as black line, mean absolute deviation dark shaded, and range of values light shaded. Number refers to number of measurements in each unit. Isotherms extrapolated between modeled section shown as dashed lines. 1250°C-isotherm dotted where used as boundary condition.

structure will improve our general understanding of whether steady-state calculations provide useful results (see also discussion in Springer 1999).

The back-arc region, characterized by crustal doubling, is analyzed by 2-D models describing simple underthrust phenomena. In contrast to the long-lasting subduction process, shortening in the back-arc region started in the Late Miocene. For this rather recent process steady-state conditions cannot be assumed. Thermal conditions in the Andean foreland then, are investigated using 1-D temperature models in which geometrical and petrophysical parameters were varied.

The numerical calculations show that the low surface heat flow of the Nazca Plate (30-40 mW/m²) does not match existing cooling models of oceanic lithosphere and may result from enhanced cooling by heat convection processes. Heat flow affected by heat conduction alone would yield 70 mW/m² for a lithosphere age of approx. 50 Ma as it is reported for the Nazca Plate in the area.

Approaching the fore-arc region from the west, a decrease of heat flow occurs as observed in other fore-arc regions over subduction zones. The pronounced heat-flow density minimum of 20 mW/m² in the fore-arc region certainly is a reflection of cooling in the continental crust as a result of the subduction of oceanic lithosphere. The observed heat-flow reduction is comparable to observations in the fore-arc region in southern central Mexico, where values decrease eastward from about 40 mW/m² to 13 mW/m² (Ziagos *et al.* 1985) and over the subducting Pacific plate in Canada (Lewis *et al.* 1988), where heat flow decreases from 50 mW/m² on the continental shelf to 25 mW/m² 30 km west of the volcanic arc. In the Pacific Northwest of the United States, where subduction has been active within the past few thousand years, the fore-arc region has a characteristic heat flow of about 40 mW/m², whereas the Pacific plate farther west has a value of 100 mW/m² (e.g. Blackwell *et al.* 1990). In contrast to the Central Andes, an accretionary wedge is developed in the fore-arc over the Cascades subduction zone, which can contribute to the reduction of surface heat-flow density (Wang *et al.* 1993). In general, it can be concluded that the difference in heat flow between the oceanic plate and the fore-arc correlates directly with increasing age of the oceanic lithosphere that is subducted. However, the magnitude of oceanic surface heat flow obviously does not affect the heat flow in the fore-arc to a great extent. In contrast, numerical models show that the shear stress along the plate contact between the oceanic plate and the continental lithosphere influences the lithosperic temperatures and thus the surface heat flow to a great extent. A maximum mean shear stress of about 15 MPa resulting in low frictional heat-generation rates is considered to be a reasonable value for the subduction regime in the Central Andes. Temperatures at the maximum depth of seismic coupling between the oceanic Nazca Plate and the overriding South American continental Plate (at about 45 km depth) are on the order of 250 to 300°C, whereas at the maximum depth of the plate contact (at about 60 km depth) temperatures are on the order of 300 to 350°C. The lithospheric temperature conditions in subduction zones may differ considerably, which can be deduced, for example, from earthquake activity. The more or less aseismic North American active margin is characterized by subduction of a very young and therefore relatively warm oceanic plate causing lithospheric temperatures higher than in the high-seismicity Central Andes.

The slight increase of heat flow to about 60 mW/m² from the Coastal Cordillera to the Precordillera is an expression of greater distance from the trench resulting in subsurface temperatures in the continental crust that are less affected by the cooling.

Volcanic arcs developed over subducting slabs of the lithosphere generally are characterized by high heat flow. For the Central Andes however, heat-flow data from the active magmatic arc are sparse and equivocal. Two heat-flow values are determined in the vicinity of the active magmatic arc in southern Peru, both being on the order of about 50 mW/m², but are considered of low reliability

(Henry 1981). Locally higher heat flow in the area of the volcanic arc seemingly extends eastwards into the Altiplano area and is not coincident with the location of the morphologic boundary between the volcanic arc and the Altiplano plateau. Heat flow in the Altiplano is constrained by 6 values, but has a large variability, from 60 to about 180 mW/m². No systematic sharp increase in heat flow from the fore-arc (Precordillera) to the volcanic arc is apparent as observed in other subduction zones, such as in the North American Cascades (Blackwell *et al.* 1982; Lewis *et al.* 1988) and in the Tohoku arc of Japan (Honda 1985). We interpret the higher heat-flow values as local anomalies caused by heat sources resulting from isolated magma chambers at shallow depths. However, to arrive with melting temperatures in the fore-arc region close to the magmatic arc, the presence of an asthenospheric mantle wedge at shallow depth (about 70 km) must be assumed, and the maximum extent of the wedge has to coincide with the position of the volcanic front. This thermally thinned lithosphere results in a surface heat flow on the order of 60-70 mW/m^2. To fit the local heat-flow anomalies of up to 180 mW/m^2, magma chambers at extremely shallow depth of about 4-6 km have to be considered.

The Altiplano as well as the Eastern Cordillera as areas of anomalous continental crustal thickness, up to 70 km experience crustal stacking since the Miocene (Schmitz 1994). The heat flow of about 80 mW/m² is high and comparable to values that are observed typically in back-arc regions, such as the Basin and Range (Blackwell *et al.* 1982). It was of interest to clarify whether the back-arc heat flow is a result of asthenosphere rise or an increased heat production rate resulting from the crustal doubling. 2-D crustal stacking models match the observed surface heat flow, and do not result in reverse temperature-depth distributions in the continental crust. The recent lithospheric thermal structure is mainly influenced by the initial temperature distribution assumed at the beginning of the crustal stacking process. We interpret the lithospheric thermal structure of the back-arc region by a transition from a lithosphere/asthenosphere boundary at shallow depth to a 'normal' lithospheric thickness for continental shelfs. Thus, the proposed thinned lithosphere beneath the Western Cordillera, Altiplano, and western part of the Eastern Cordillera, is similar to that proposed previously by other authors (e.g. Isacks 1988), but differs from that of Whitman *et al.* (1992). Melting temperatures in the lower crust (crust/mantle transition at about 70 km depth) result in a maximum surface heat flow on the order of 60 mW/m^2. An increase of surface heat flow because of increased heat production rate by crustal doubling cannot be observed yet at 10 Ma after the onset of thrusting. This becomes a significant effect after much longer times. Higher surface heat flow in the Eastern Cordillera could be attributed to transient effects on the thermal field by erosional processes. Analytical description of these effects shows for erosion rates of 0.2-0.4 mm/a in the last 10-15 Ma an increase in surface hear flow by about 10-30%.

In the Andean foreland, heat-flow density is about 40 mW/m², which is somewhat lower than the heat flow of about 50-60 mW/m² reported for the adjacent Brazilian Shield farther to the east (Hamza and Munoz 1996). Lithospheric thermal conditions correspond with those typical for shield areas. Temperature estimated for the crust/mantle transition are on the order of 400 to 600°C considering a lithospheric thickness of 150-200 km. However, the lower heat flow in the Chaco Basin may be affected by nonsteady-state thermal conditions caused by rapid burial in the last 10 Ma with a subsidence rate of 0.1-0.4 mm/a. Analytical evaluation of this problem suggests a decrease of heat flow of about 15% at the surface of the sedimentary sequence.

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