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The structure and evolution of the Central Andean orogene - insights from crustal seismic investigations

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Abstract

The available seismic data on the crustal structure of the Central Andes allow to draw a new picture of the Andean evolution. The deep Andean root, as it is deduced from gravimetric and seismological observations, must bee seen in a new light. The seismic signature of the foreland-Moho gets lost beneath the eastern Altiplano at about 60 km depth. No clear Moho-arrivals are observed beneath the Altiplano and the Western Cordillera. In the forearc, a 70 km discontinuity beneath the Precordillera rises towards the continental margin. Tectonic crustal stacking in the backarc and "undercrusting" in the forearc and arc are crustal thickening processes which indicate a different crustal evolution that is reflected in the crustal structure. Petrological processes as the hydration of the peridotitic mantle wedge to serpentine and amphibole in the forearc are the key for understanding the seismic signature of the Andean lithosphere.

Resúmen

Los datos sísmicos sobre las estructuras corticales de los Andes Centrales, disponibles hasta la fecha, permiten dar nuevas imagenes de la evolucion Andina. La raíz profunda de los Andes, determinada por observaciones gravimétricas y sismológicas, tiene que ser interpretada de otra manera. La signatura sísmica del Moho en el antepaís se pierde debajo de la Cordillera Oriental a unos 60 km de profundidad. No hay evidencias claras para un Moho debajo el Altiplano y la Cordillera Occidental. En el antearco, una discontinuidad de 70 km debajo de la Precordillera se eleva hacía el margen continental. En el trasarco, los movimientos tectonicos predominan y en el arco y antearco "undercrusting" es el proceso principal, responsable para el engordamiento cortical, lo cual se refleja en las estructuras. Procesos petrológicos tal como la hidratación de la cuña mantelica de peridotita a serpentinita son la llave para la comprensión de las estructuras sísmicas de la litósfera Andina.

Keywords: Central Andes; seismic refraction studies, Moho, crustal structure and evolution.

Introduction

The knowledge on the structure and evolution of the Andean orogene has developped considerabely during the last decades, based on geological and geophysical studies. Geophysical data evidencing extreme thickening of the Andean crust were first presented by [1] who interpreted the results of seismological (surface waves) investigations pointing to an overall crustal thickness of 70 km beneath the Altiplano. More recent data between 20° and 26°S Latitude allow for the determination of seismic discontinuities and broad low velocity zones (LVZ) [2, 3], regional and local gravity anomalies [4,5], and extremely high electrical conducting zones (HCZ) [6, 7]]. Crosscutting thrust systems have been proposed to explain the thick crust beneath the Central Andes [8]. Backarc thrusting in combination with magmatic addition in the Western Cordillera [9] and thermal uplift and lithospheric thinning are discussed to explain plateau uplift of the Altiplano [10].

In this paper we present a comprehensive model to explain the seismic structure of the Central Andean crust, characterized by a pronounced asymmetry between the forearc and the backarc region. Hydration of the peridotitic mantle wedge in the forearc, underplating of magmatic rocks in the arc and tectonic thickening by crustal thrusting in the backarc are seen as the principle processes in Andean evolution.

Geophysical and geological data on the crustal structure

Seismic refraction investigations were carried out between 20° and 25°S latitude (Fig. 1). The gross crustal structure along a profile at 21.5°S is characterized by a 40 km thick craton-type foreland crust in the east, increasing to 55 and about 70 km thickness beneath Eastern Cordillera and easternmost Altiplano, respectively, evidenced by overcritical reflections [2]. High velocity (6.8 km/s) discontinuities in the middle to upper crust of the Eastern Cordillera are interpreted as detached and overthrust lower crustal (and mantle) material at the base of thrust slices in the backarc crust (Fig. 2) [11,12].
No clear Moho reflections are reported for the Altiplano/Western Cordillera from deep seismic refraction studies. The derived low average crustal velocities down to 40-50 km depth in that region, ranging from 6.0 to 6.1 km/s, are in good coincidence with results of a regional broadband study in the Bolivian Altiplano [13]. In the Precordillera a discontinuity with a velocity increase to 7.9 km/s at about 65-70 km depth can be derived, interpreted as the recent crust/mantle boundary in the forearc [2].

Towards west, average crustal velocities increase to 6.3 km/s beneath the Precordillera and 6.6 km/s beneath the Coastal Cordillera. Intracrustal high velocity layers al 20 km depth beneath the coast (7.2 km/s) and 35-40 km depth beneath the Precordillera (6.8-7.0 km/s) are interpreted as the base of the Mesozoic lower crust before the uplift of the Andean orogene took place. The Moho of the subducted Nazca plate can be traced from 15 km depth beneath the trench to 40 km in the Coastal Cordillera, proven by overcritical reflections and first arrivals [2,14].

Derived from gravimetric measurements, the decrease of the Bouguer anomaly to values of -450 mGal on the Altiplano is one of the most outstanding features in this region [4,5]. This regional trend is attributed to the deeply seated Moho [4] assuming a constant density contrast between crust and upper mantle to calculate the residual gravity field.

Principle crustal thickening processes for Andean evolution

The amount of Cenozoic shortening, that contributes to the tectonic thickening of the Central Andes, was calculated by several authors for the backarc region to 210 - 230 km [8,15,16]. Due to the uncertainities in crustal thickness, which might vary between 60 and 70 km (as shown above), and shortening values varying between 200 and 250 km, alternative models for the quantitative estimation of crustal thickening must be considered, which all can explain the actual crustal thickness beneath the Subandes and the Cordillera Oriental, but they are not able to explain the thick crust beneath the Altiplano completely. Considering the low rates of tectonic shortening in the arc and forearc regions, other processes must be responsible for crustal thickening there.

The Preandean basement is exposed in the Coastal Cordillera of N-Chile, consisting mainly of pyroxen gneisses, amphibolites, and gabbros [17], which indicate a deeply exposed crust. The high velocity material at 20 km depth (7.2 km/s) beneath the coast (Fig. 2) is interpreted as the base of the Mesozoic crust [2,18]. Towards the Western Cordillera, this crustal level deeps down to about 40 km depth [3]. Originally, this crustal material must have been underlain by the peridotitic mantle lithosphere. During the subduction process, fluids released from the downing oceanic crust will produce hydration of the hanging gabbroic lower crust as well as the peridotitic mantle in the order of a 100 km wide and 30 km thick layer during some 10 Ma of subduction.

The same process would have undergone restites of Mesozoic intrusives which contribute considerabely to the forearc crust [19]. Hydrated basic and ultrabasic material, converted to serpentine and amphibole, satisfies the geophysical data for this region. However, for the Western Cordillera, a high heat flow density value of about 100 mW/m^2 [20, 21] would lead to a dehydration of serpentine at moderate depth (temperatures above 550 to 600°C), with a transition to peridotite (high P-wave velocity and density).

[10] estimated the input from the recent magmatic arc system to a maximum of 5 km, considering a volcanic coverage of 0,5 km with a proportion of 1:10 between volcanic products and magmatic input.[22] attribute 30% of the crustal volume, that means about 20 km thickness, of the Western Cordillera in Peru (8°S) to crustal underplating by magmatic processes. Considering the high volcanic activity in the preceding magmatic arc systems of the Central Andes, a 10 km thick layer of magmatic material may be assumed for the forearc region [19]. The amount of eroded material at the western edge of the Southamerican continent can be estimated to more than 4.500 km^3/km trench for the last 150 Ma, projecting data of [22] from Peru further south. This corresponds to a 30 km thick and 150 km wide crustal segment that has been removed from the forearc. Almost the same amount of material is lacking in the deeper forearc and arc crust to explain the geophysical crustal signature. The existing geophysical data do not support an unique interpretation on the structure and evolution of the deeper forearc and arc crust (dashed zone in Fig. 2). There are at least three candidates (hydration of peridotitic mantle; underplating of eroded material from the continental margin and magmatic underplating) which satisfy the geophysical parameters and which are viable within reasonable scenarios for the Andean evolution.

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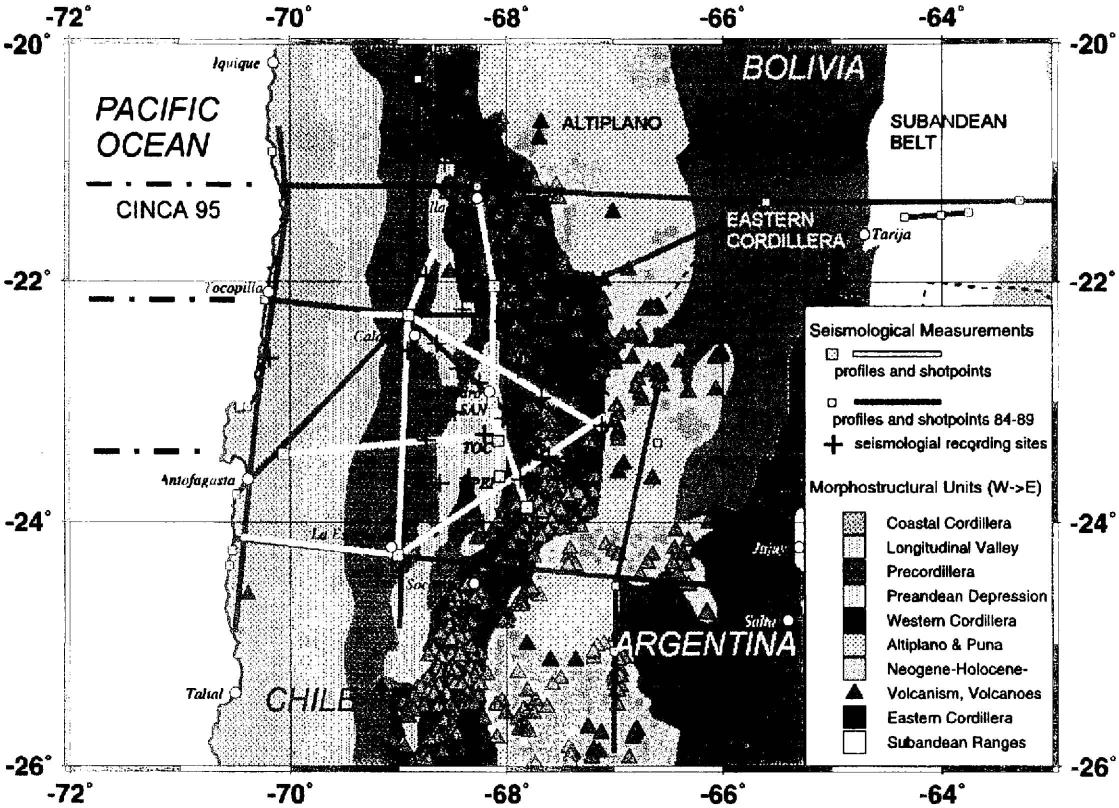

Fig. 1. Location map showing the seismic refraction profiles in the Central Andes [2, 3, 14]

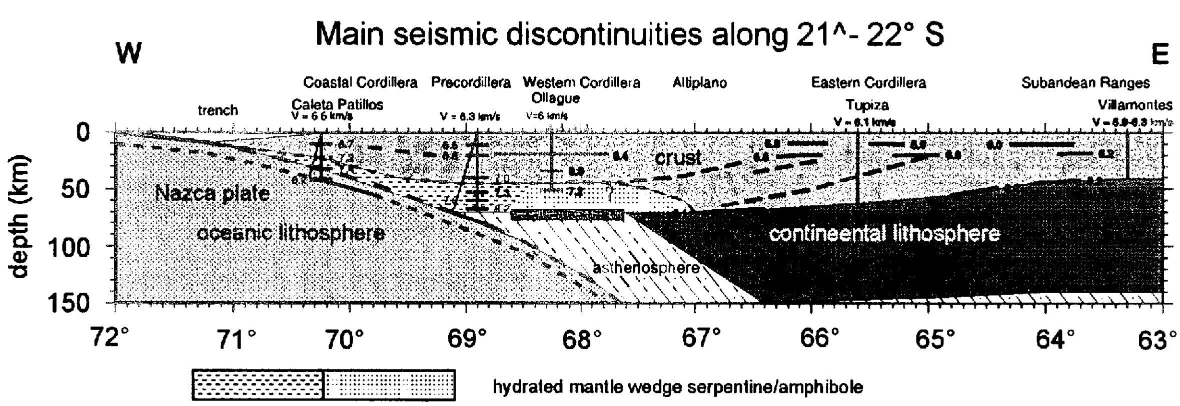

Fig. 2. Interpretative cross section along 21°-22° S in the Central Andes. Crustal structures can be traced from the Coastal Cordillera towards the Western Cordillera with increasing thickness of upper and lower crust. The shallow high velocity discontinuities in the Coastal Cordillera [2] are correlated to the elevated position of the lower crust (the 7.2 km/s discontinuity marks the base of the lower crust. Discontinuities with similar velocities in the Pre- and Western Cordillera exist at 35-45 km depth. Intracrustal reflections are interpreted as reflections from the base of the upper crust. The deeper discontinuities may be generated in a crust/mantle transition zone of inhomogeneous composition. There are no clear Moho observations from seismic refraction studies beneath the magmatic arc and the western Altiplano; thick dashed line from converted phases [13, 24]. Intracrustal discontinuities in the backarc are correlated to thrusting on a crustal scale [11](dashed lines]. The shape of the subducted Nazca plate is determined by Moho observations [2,14] and by the earthquake hypocenters (25].

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