CRUSTAL THICKNESSES AND GENERAL ISOSTATIC BALANCE OF THE PERUVIAN ANDES FROM OBSERVED AND PREDICTIVE SHORTENING

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INTRODUCTION

Peruvian Andes are bounded in the west by the Perú-Chile trench and in the east by the Brazilian shield. This part of the Andes is formed by two parallel cordilleras named Western Cordillera and Eastern Cordillera. From the middle part and to the south, a significant widen of the system takes place. An elevated plateau between the two cordilleras is present: the Altiplano, which has a mean elevation of 4 km. Morphological units are completed with the Subandean zone to the east of the Eastern Cordillera and the Cordillera de la Costa to the southwest of the Western Cordillera and coastal plain. See Benavídez-Cáceres (1999) for more information.

Andean geodynamics, in particular Peruvian Andes, involve two processes at global scale: (a) subduction of a young oceanic lithosphere (Nazca plate) below the Sudamerican coastal margin, and (b) continuous progress of the Sudamerican plate westwards.

Peruvian Andes from 5° S to 18° S latitudes involve the greatest « flat-slab » type subduction zone of the world, located between 5° S and 15 ° S latitudes. It exhibits low heat flow and has not active volcanism. It has been considered that the buoyancy is connected with the delay of the basalt-eclogite phase change (Sacks, 1983). Then, southwards, the oceanic slab gradually takes its normal dip. There, there is high heat flow and active volcanism.

The goal of this study is to find crustal thicknesses and to determine the large scale isostatic state of the Peruvian Andes to better understand the tectonic style and deformation.

CRUSTAL THICKNESSES

Crustal thicknesses have been determined on seven Peruvian Andes cross sections (Fig. 1) from inversion of the regional Bouguer anomalies using wavelengths that agree with the Andean width. Crustal thicknesses change from 64 km to 71 km (Table I) in very good agreement with those of Bolivian Andes (Miranda and Introcaso, 2000) and Argentina-Chile Andes (Introcaso et al.., 2000) until 33° S – 34° S latitude. Peruvian Andes crustal thickness is approximately 67 km ± 3 km in average.

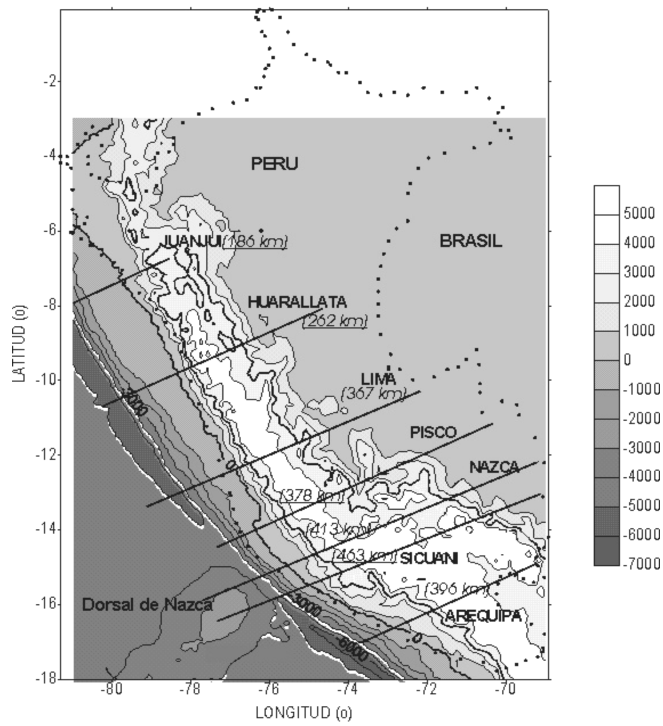

Fig. 1. Peruvian Andes. Topography and location of the studied cross sections

PREDICTIVE (S'_h) SHORTENING AND OBSERVED (S_h) SHORTENING

Shortenings and crustal thicknesses control both the tectonic style and the deformation (Ramos et al., 2002). Knowing the isostatic state (compensation or no compensation and the mechanisms present: Airy, flexural, ...) it is possible to determine crustal deformation at large scale.

By comparing both observed and predictive shortenings: $S_h - S'_h = \Delta S$ (1) we have indicators of general isostatic state ($\Delta S>0$, $\Delta S=0$, $\Delta S<0$). In fact, to calculate the predictive shortening S'_h an exact balanced theoretical model is used, in which the topographic elevation is the only input. From this value, and using - for instance - hydrostatic formulas, it is possible to obtain Andean roots. Observed shortening S_h, obtained from Andean elevation and Andean root values (from gravity inversion, seismic depths, etc.), must be compared with S'_h according to (1).

In fact, expression (1) is similar to an isostatic anomaly (AI) because it is obtained by comparing the observed gravity effect of the real crust with the gravity effect originated by a theoretical crustal model. And the latter is similar to an observed model, although it is exactly compensated.

We have calculated shortenings on crustal scale at the following Peruvian Andes cross sections: Juanjuani (J), Huarallata (H), Lima (L), Pisco (P), Nazca (N), Sicuani (S) and Arequipa (A) (Fig. 1). Before this work, Isacks (1988) and Introcaso et al. (2000) among others, have carried out similar studies. The excess of Andean masses (Andean elevations) have been calculated here in 2D and named A_t [km^2]. We have assumed a standard crustal thickness T_n = 33 km (Bullen, 1963; Woollard, 1969; Introcaso et al., 1992) and the following density values: σ_t (sea level and upwards) = 2.67 g/cm^3; σ_c (crust below sea level) = 2.90 g/cm^3; σ_m (upper mantle) = 3.30 g/cm^3. So, we have (Introcaso et al., 1992; Introcaso et al., 2000):

A_r (crustal root area) = 6,.675 A_t (topographic area) (2)

with A_r and A_t in km^2. From (2), and with T_n = 33 km, the predictive shortening S'_h [km^2] will be:

$S'_h = (A_t + A_r)/ T_n$ = 0,.23257 A_t (3)

With the density values informed by Woollard (1969) and Isacks (1988): σ_c (density of the whole crust) = 2.93 g/cm^3, σ_m (upper mantle density) = 3.32 g/cm^3 and keeping T_n = 33 km, we have:

S'_h = 0,.25796 A_t (km^2) (4)

With density values with only one decimal digit: σ_c = 2.9 g/cm^3 and σ_m = 3.3 g/cm^3, we will have:

S'_h = 0,.25 A_t (km^2) (5)

S'_h for each section have been obtained assuming expression (3) with σ_t = 2.67 g/cm^3, or the same density of Bouguer correction that is more realistic than 2.93 g/cm^3 or 2.9 g/cm^3 of (3) or (4), and evaluating A_t (km^2) in the seven cross sections of Fig. 1, using the moving window method (Isacks, 1988; Introcaso et al., 1992).

Keeping A_t (km^2) calculated for the seven sections we have defined the observed Andean root A_r (observed in km^2 from inversion of regional Bouguer anomaly with: $\sigma_c - \sigma_m$= -0.4 g/cm^3 agreeing with (3)).

Table I involves: crustal thicknesses, A_t, $A_{r\ pred}$, $A_{r\ obs}$, S'_h, S_h and the differences in absolute value of $A_{r\ obs}/A_t$ and 6.675 (exact compensation from (2)), and relative errors of S'_h and S_h.

Location	Maximum crustal thickness (km)	A_t (km^2)	$A_{r\ pred}$ (km^2)	S'_h (km)	$A_{r\ obs}$ (km^2)	S_h (km)	$\lvert A_{r\ obs}/A_t - 6.675 \rvert$	$(S_h - S_h')/S_h'$ (%)
J, -7° S	64	751	5,011	175	5,400	186	0.52	6.3
H, -10° S	71	999	6,666	232	7,631	262	0.96	12.9
L, -11.9°S	67	1,071	7,145	249	11,034	367	3.62	47.4
P, -13.1°S	69	1,425	9,514	331	11,058	378	1.08	14.2
N, -14.1°S	68	2,035	13,585	473	11,583	413	0.98	-12.6
S, -14.9°S	64	2,374	15,847	552	12,901	463	1.24	-1.6
A, -16.1°S	65	1,668	11,137	388	11,396	396	0.15	2.1

Table I. Predictive and observed shortenings of the seven studied sections

DISCUSSION AND CONCLUSIONS

Cabassi (doctoral thesis, 2002) has added the following methods for isostatic analysis of Peruvian Andes:

A – Linear relationships between mean Bouguer anomalies (or Free Air anomalies) and mean altitudes

B – Elastic crustal flexion

C – Airy system

D – Isostatic geoid undulation

The linear formulas obtained using (A) for Peruvian Andes were compared with similar relationships informed by Introcaso et al. (2000) for the isostatically compensated Chile-Argentina Andes (22° S – 34° S latitudes), and so Cabassi (2002) concluded that Peruvian Andes are compensated, at least in general terms.

However, this method does not point out which is the isostatic mechanism present in Peruvian Andes. From (B), (C) and (D) it was possible to analyse the general isostatic balance and the local mechanism present in each section. So, Peruvian Andes taken as a whole are compensated in Airy system as pointed out by the very low elastic thickness (5 km to 10 km necessary to justify the Bouguer anomalies) in (B), the low amplitude of the isostatic anomalies in (C), and the isostatic metric anomalies in (D) consistent with (C). The local isostatic analysis in each section with wavelengths lower than the Andean width has revealed no compensation in some areas.

Our isostatic analysis from shortening points out no isostatic compensation in Lima cross section (relative error: 47 %), only general tendency to compensation in Huarallata, Pisco and Nazca (relative errors lower than 15 %, between –12.6 % and 14.2 %), and very good isostatic compensation in Juanjuani, Sicuani and Arequipa sections (low relative errors: 6 %, -2 % and 2 % respectively).

From 15° S latitude and southwards, heating could have an effect in the Andean building.

The evaluation of isostatic balance in Peruvian Andes from shortening is a quick and general method that involves the whole Andean masses. However, we must point out the isostatic shortening indicators (ΔS) informed here have no more resolution than the corresponding to general Andean width. In spite of this, the ΔS indicators can be used on partial widths, for example only in the Eastern Cordillera or only in the Western Cordillera.

Finally, from 7° S to 34° S latitudes, the Airy compensation system is present with crustal thicknesses that, in general terms, doubles the normal crustal thickness.

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