

Density Inhomogeneities, Tectonics, and Stresses in the 21° S Andean Subduction Zone: 1. A Geophysical Model and Tectonics

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Abstract—Most convergent zones of the Earth are conceived in terms of the underthrusting of the oceanic lithosphere beneath stable or weakly deformed continents. However, we believe that the Andean subduction zone is a region in which the lithospheric material moves downward on both the oceanic and continental sides. The movement is strongly asymmetric: the rate estimates are about 7–8 cm/yr for the Nazca oceanic plate and about 1–2 cm/yr for the northwestward drift of South America. Although the continental lithosphere moves slower than the oceanic lithosphere by an order of magnitude, the pull-down of the South American craton lithosphere is a factor that plays a key role in interpreting the origin of the thickened Andean crust. The Andean mountain system develops under conditions of lateral compression and is controlled by large-scale deformations and accumulation of the light crustal material above the sinking root consisting of the denser material of the lower continental crust and upper mantle of the South American craton and Nazca subducting plate.

INTRODUCTION

The convergent zone between the Nazca plate and South American continent (Andean subduction zone) is characterized by extreme values of all geophysical parameters (Fig. 1a). The following features are most important.

- GPS experiments [Leffer *et al.*, 1997; Norabuena *et al.*, 1998; Klotz *et al.*, 1999; Kendrick *et al.*, 1999] showed (Fig. 1b) that the Nazca plate moves horizontally eastward along the trench at a rate of about 7–8 cm/yr and the Andes move to the east toward the continent at a rate of about 1–2 cm/yr relative to the rigid core of the South American craton, i.e., the Andes slowly “migrate” landward into the South American continent. All motions (including the northwestward drift of South America) give a convergence rate of about 10 cm/yr in the Andean subduction zone, which is presently one of the highest rates in the world.
- The seismic focal Benioff zone is traceable down to a depth of 670 km; earthquakes recorded here have magnitudes reaching 7.3 (data of the ISC Seismological Bulletin over the instrumental period).
- The topography contrast reaches 13 km: the oceanic trench is ~7 km deep, whereas Andean volcanoes have heights of ~6 km and the Puna and Altiplano plateaus are ~4 km high.
- Above the Puna and Altiplano plateaus in the Central Andes, geoid anomalies are estimated at ~+60 m and Bouguer anomalies are estimated at ~-400 mGal; along with the crustal thickness reaching 70 km here,

this characterizes one of the largest lithosphere density anomalies of the Earth.

Thus, the study region is interesting for gravity modeling studies in conjunction with the modeling and analysis of the stress–strain state of the Earth’s interiors.

REVIEW OF RESEARCH ON THE ANDEAN LITHOSPHERE TECTONICS

Presently, an intricate structure and geodynamics of the Andean lithosphere have been revealed. The pre-Cordilleran fault zone separates the Andean mountain belt from coastal regions to the west, and the Sub-Andean overthrust zone separates it from the Chaco Plain to the east (Fig. 2). Both the coastal regions bordering the Andean belt in the west and the Chaco Plain bordering it in the east are dominated by subhorizontal boundaries in the upper crust, negligible recent vertical movements, and lower heat flow. The coastal regions have apparently been stable since the Jurassic, and the South American craton, since the Proterozoic [Tosdal, 1996; Rapela *et al.*, 1998]. In contrast, periods of sedimentation, orogenesis, rifting, and magmatic activity occurred in the Andes at least from the Proterozoic [Cladouhos *et al.*, 1994; Sempere *et al.*, 1997]. The last activation, which continues in the present, is dated at the Late Oligocene–Early Miocene [Sempere *et al.*, 1990]. The Andes are characterized by numerous nearly vertical faults and geological boundaries, high

rates of recent vertical movements, high heat flow [Henry and Pollack, 1988], and volcanic activity. Four along-strike trending physiographic provinces (further subdivided into smaller subprovinces) are distinguished in the Andes: (1) the West Cordilleras andesitic volcanic arc; (2) the mountainous Altiplano and Puna plateaus; and the fold-thrust sedimentary complexes of (3) the Eastern Cordilleras and (4) Sub-Andean region.

The following processes are related to the origin of the thickened Andean crust in various provinces: magmatic underplating [James, 1971; magmatic crustal intrusions [Francis and Hawkersworth, 1994]; vertical uplift of blocks [Zeil, 1979]; thin-layered deformations in the fold-thrust belt of the Sub-Andean region [Allmendinger, 1983]; and thin-layered deformations involving the consolidated basement in Eastern Cordilleras [Kley, 1996].

Since the Jurassic, the Andes have been dominated by crustal shortening estimated by various authors at 210 to 670 km, and the post-Oligocene time accounted for at least 150 km of this amount [Sheffels, 1990; Schmitz, 1994; Giese *et al.*, 1990; Baby *et al.*, 1997; Kley and Monaldi, 1998]. The contribution of the tectonic horizontal shortening to the crustal thickening in the Central Andes should not be less than 30% [Kley and Monaldi, 1998]. The crustal shortening in the Andean mountain belt implies either the related shortening of the lithosphere or its subduction. Petrological analysis of magmas yield evidence of possible "exfoliation" of the lower lithosphere from the upper lithosphere under the Central Andes [Kay *et al.*, 1994], which supports the idea of the South American craton subduction under the Andean mountain belt.

The ideas of driving forces and of the role of horizontal and vertical tectonics in the Andean subduction

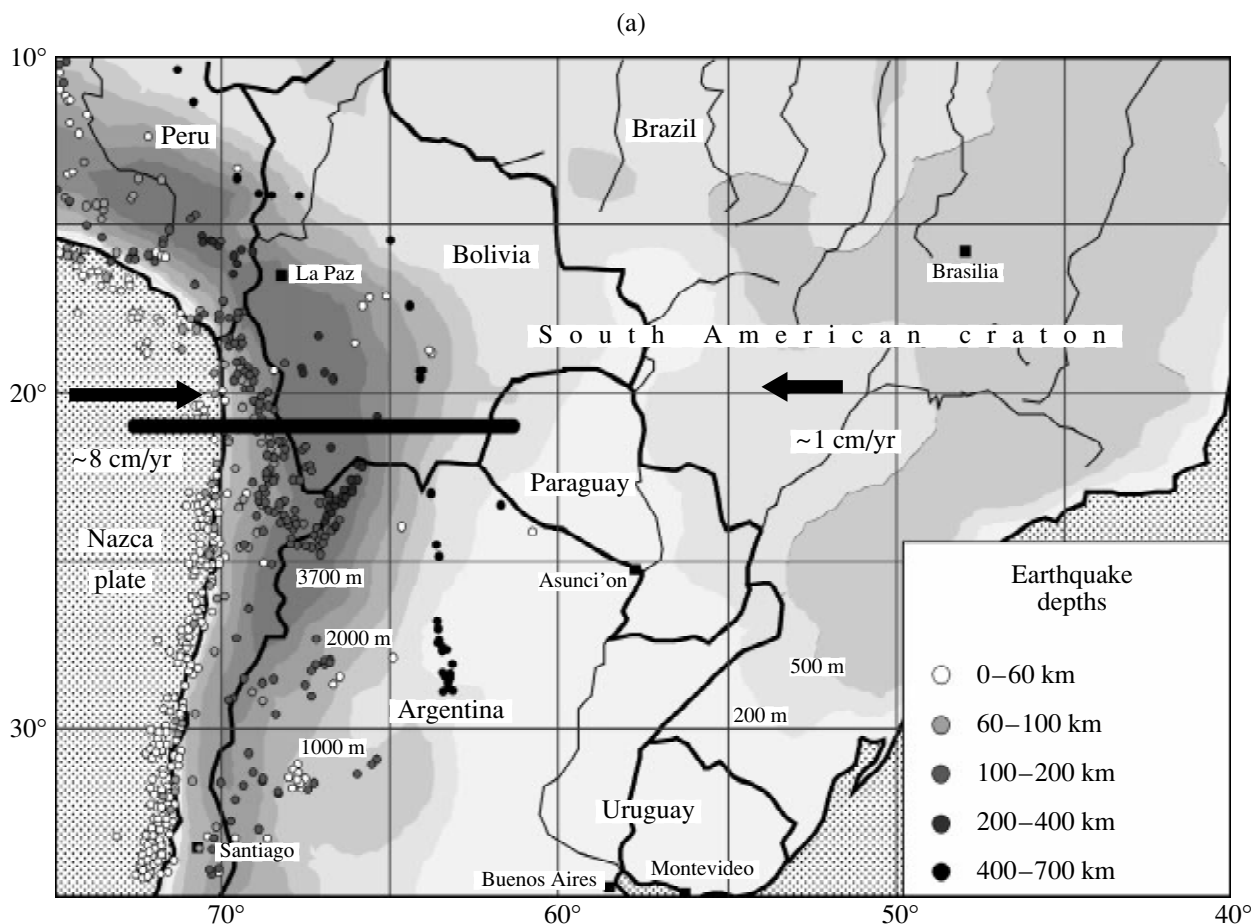


Fig. 1. (a) Map showing the modeled profile and the seismicity (earthquakes with available fault plane solutions) of the Andean subduction zone. The shades of gray in areas of the South American continent indicate topography heights, the darkest area in the central Andes having heights above 3.7 km. The stress state of the lithosphere was estimated using focal mechanisms of earthquakes that occurred within a two-degree band around the profile. (b) Results of two-year GPS observations available from the site <http://www.earth.nwu.edu/research/snapp.html>. The arrows show the movements at Andean sites relative to the rigid core of the South American craton. The arrow in the left bottom corner, marked as GPS NZ-SA, shows the motion of the Nazca plate toward South America, reconstructed from measurements at island sites on the Nazca plate. The arrow marked as NUVEL-1A 77 mm/yr is the velocity of the Nazca plate motion, calculated from the NUVEL-1A model.

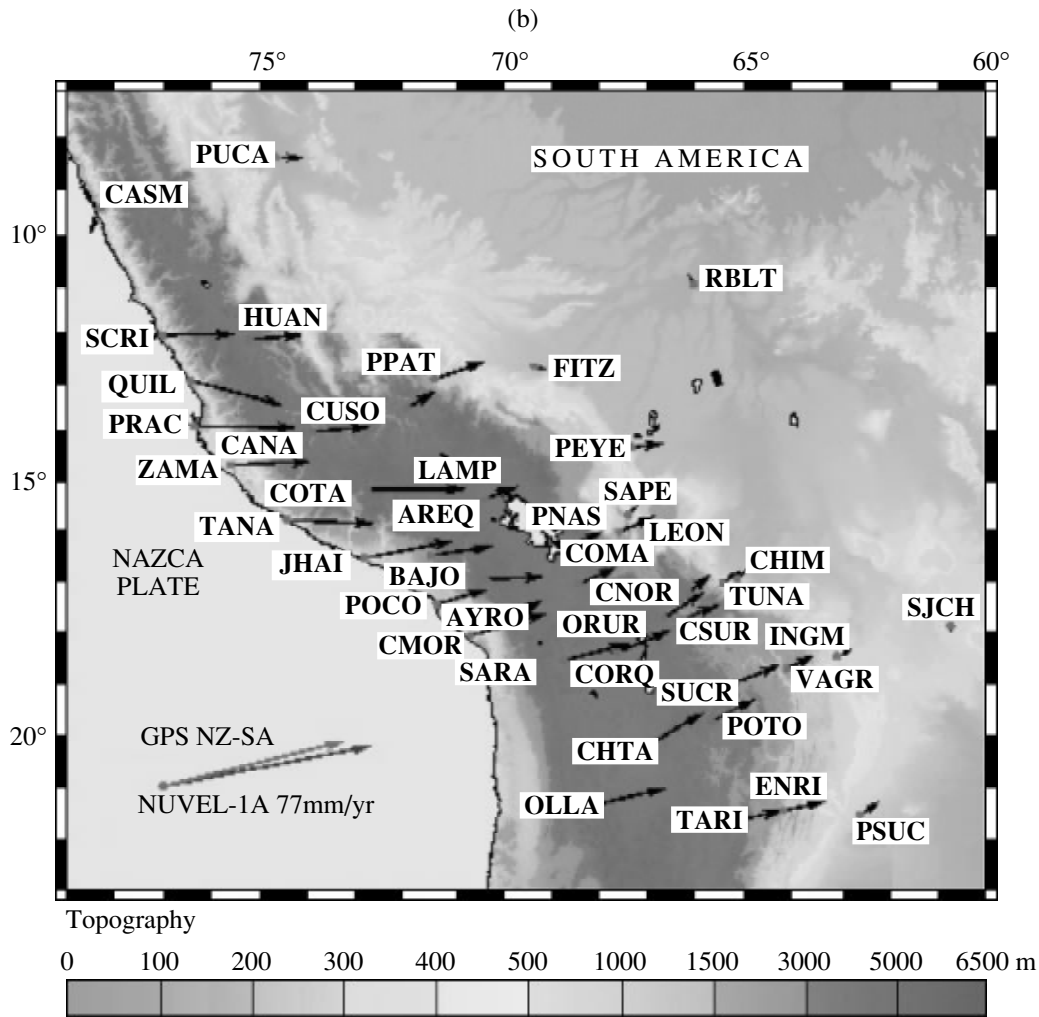


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zone were always disputable and continuously changed. In the early model of Grow and Bowin [1975], this zone was treated in terms of the underthrusting of the oceanic plate beneath the relatively stable continental margin. In their analysis of the tectonic shortening at the Andean convergent margin, Jordan *et al.* [1983] and Ben-Avraham and Nur [1987] argued that the plate collision (“horizontal tectonics”) is the main driving force of this process. On the other hand, Isacks [1988] postulated the important role of isostasy in the mountain building and crustal thickening processes in the Andes (“vertical tectonics”). Later, based on the minimum-work principle, Masek and Duncan [1998] showed that the formation of the large-scale thrust system in foldbelts of the Eastern Cordilleras minimizes the work done to overcome the forces of gravitation and friction. The formation of thin-layered nappes in the Sub-Andean region requires that they be underlain by either a weakened layer or a detachment plane. The important role of the gravitational force in the folding and thrusting in orogenic belts was demon-

strated in *in-situ* modeling studies [Guterman, 1980, 1987; Ramberg, 1981; Dixon and Tirrul, 1991]. In the model of Giese *et al.* [1990], the activation and uplift of the Andes were associated with a hypothetical asthenospheric bulge under the Altiplano plateau.

REVIEW OF RESEARCH ON THE STRESS-STRAIN STATE IN THE ANDEAN SUBDUCTION ZONE

The stresses in the Nazca plate were studied on the basis of both seismological constraints on focal mechanisms of earthquakes [Schneider and Sacks, 1987; Mercier *et al.*, 1992; Assumpcao, 1992; Govers *et al.*, 1992; Comte and Suarez, 1995] and numerical and analytical modeling results.

Zhao and Takemoto [2000] modeled kinematically the plate interaction in the subduction zone. They showed that the stationary slip of the oceanic plate is inconsistent with the GPS observations in southwestern

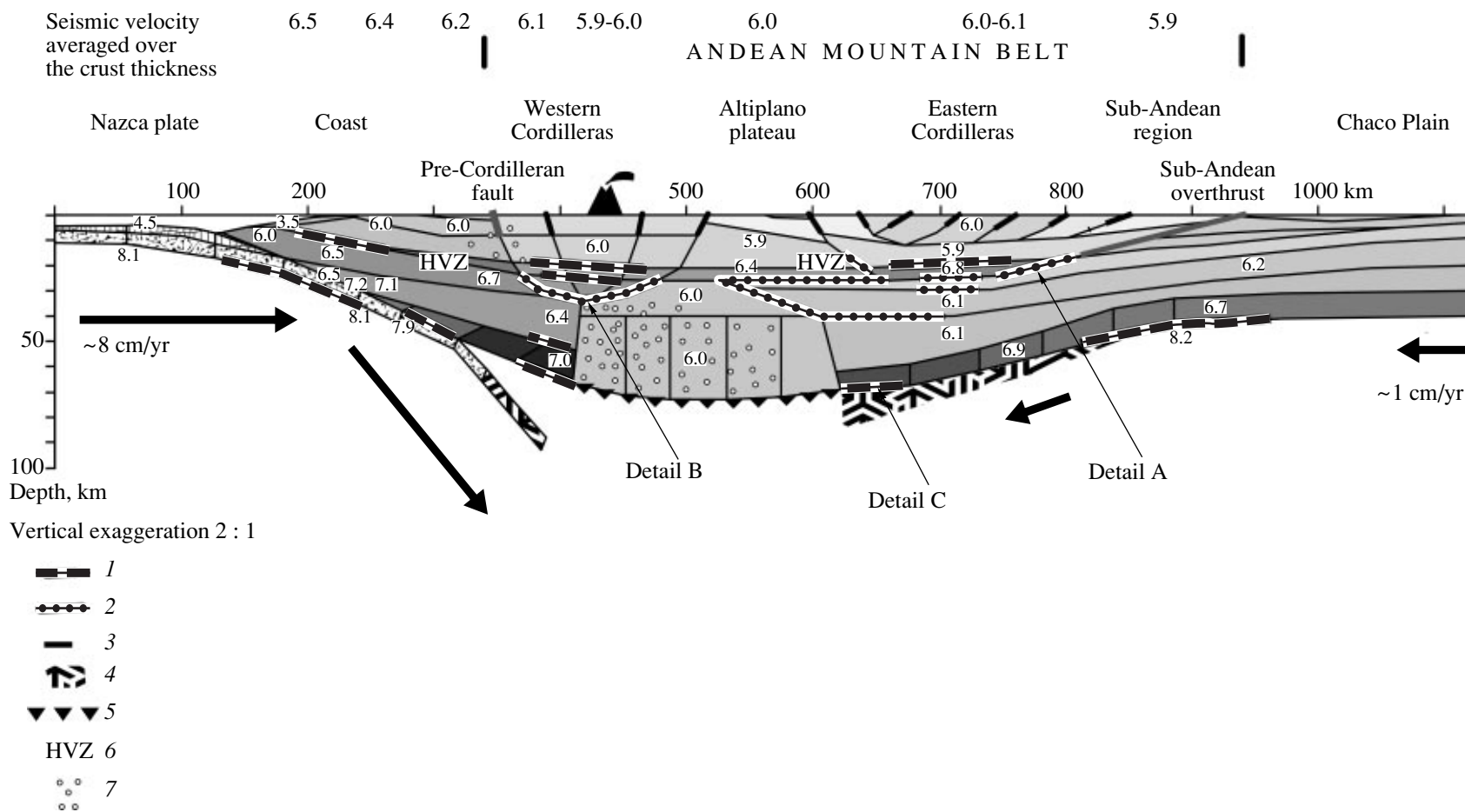


Fig. 2. Geophysical model of the Andean lithosphere. Seismic velocities are shown by numbers within blocks (in km/s), and shades of gray indicate density values: (1) seismic refractors; (2) zones of reflector concentrations; (3) geological boundaries, faults, thrusts, etc.; (4) postulated eclogitization of the oceanic and lower continental crust; (5) approximate depth of the quartz-coesite transformation; (6) higher velocity zones; (7) lower electrical resistivity zones.

Japan. The most adequate model is a combination of a stationary slip with some amount of motion "stuck" in the plate contact zone, the accumulated energy being repeatedly released via earthquakes. The stationary slip and seismicity in the subduction zone account for about 35 mm/yr, and the 10-mm/yr motion is transmitted into the Andes and accounts for the mountain building there [Leffer *et al.*, 1997 and Norabuena *et al.*, 1998].

The mechanical state of the Andean lithosphere was analyzed from the standpoint of the then available simplified ideas concerning the structure of the Andes [Froidevaux and Isacks, 1984; Lyon-Caen *et al.*, 1985]. Considering the geoid anomalies, topography, and horizontal push forces exerted by the trench, Davies [1981, 1983] estimated the stresses on the cross section along the subducting oceanic plate.

Based on generalized models of subduction zones, finite-element estimates of stresses were obtained in terms of a 2-D elastoplastic problem [Whittaker *et al.*, 1992; Houseman and Gubbins, 1997]. The distribution of stresses of maximum and minimum compression was analyzed using the model of thick spherical shells [Stefanick and Jurdy, 1992; Tanimoto, 1998]. Wortel and Cloetingh [1985] solved the 2-D problem of an elastic thick (~100 km) homogeneous plate in order to estimate the distribution and values of the active stresses in the Nazca plate near the trench.

Allowing for the elastic forces arising during the bending of a homogeneous plate, Pope and Willett [1998] calculated a 2-D viscoplastic thermomechanical evolution model for a cross section of the subduction zone represented by three layers: the subducting oceanic plate and a two-layer continental plate consisting of the crust and lithospheric mantle. The crustal thickening in the Andean mountain belt was shown to be possible if the lithospheric mantle is detached and dragged down by the subducting oceanic plate.

However, there are still no estimates of stresses caused by density inhomogeneities even for general simplified models; nor have model calculations of stresses been performed which would incorporate the whole body of the available information on the lithosphere structure in the Andean subduction zone.

A SYNTHETIC MODEL OF THE ANDEAN SUBDUCTION ZONE LITHOSPHERE ON THE 21° S PROFILE

Initial Data

The Andean subduction zone has been extensively studied over the last decade (Fig. 2). The seismic structure of the crust was studied by the deep seismic sounding method [Wigger *et al.*, 1994; Patzwahl *et al.*, 1998] and using reflected waves (ANCOR group [Lueschen *et al.*, 1998]); detailed gravity survey results are reported in [Goetze *et al.*, 1990, 1994; Koesters *et al.*, 1997; Goetze and Kirchner, 1997]. Higher conductivity zones are delineated from magnetotelluric soundings

[Echternacht *et al.*, 1997]. The shape of the subducting Nazca plate in the deep mantle (down to 670 km; Benioff zone) was reconstructed from earthquake epicenters [Cahill and Isacks, 1992]. The configuration and depth of the Pre-Cordilleran fault are shown according to the 33° S data of Zapata and Allmendinger [1996]. Both seismic reflection data [Allmendinger, 1986] and magnetotelluric soundings [Pomposiello *et al.*, 1999] support the existence of a weakened zone continuing the Sub-Andean overthrust under the area of the fine-layered tectonics in the Sub-Andean region. Marret *et al.* [1994] regard this zone as a base of the fold complex.

Gravity Modeling

New detailed data on the Andean crust structure (Fig. 2) allowed the reconstruction of the density distribution (Fig. 3) [Romanyuk *et al.*, 1999] resolving many more details than previous density models [Grow and Bowin, 1975; Goetze *et al.*, 1994; Goetze and Kirchner, 1997]. The lower crust and upper mantle beneath the Eastern Cordilleras and Altiplano plateau are the regions seismically least studied. They were additionally subdivided into vertical model blocks the density of which was determined from the linear gravity data inversion [Strakhov and Romanyuk, 1984; Romanyuk, 1995]. Since low effective viscosities of the continental lithosphere were obtained even in the coldest coastal areas (10^{21} – 10^{22} nm) [Whitman, 1994], the model should be close to an isostatic equilibrium at a depth of 300 km in the ocean and to the east of the Eastern Cordilleras. The amount of hydrostatic disequilibrium in the model constructed (Fig. 4) characterizes the values and spatial distribution of force variations caused by density inhomogeneities in the gravity field (vertical tectonics).

Lithosphere of the Andean Subduction Zone

The Andean subduction zone is supposedly a region in which the lithosphere material presently moves downward beneath both the ocean and the continent. This motion is strongly asymmetric. Although the oceanic lithosphere moves slower than the continental lithosphere by an order of magnitude, the pull-down of the South American craton lithosphere is of key significance for elucidating the origin of the thickened Andean crust. The Andes mountain system forms under the conditions of strong lateral compression as a response to large-scale deformations [Marret *et al.*, 1994; Coney and Evenchik, 1994] and accumulation and floating-up of the lighter crustal material under the sinking root, which consists of denser material composing the lower continental crust and upper mantle of the South American craton and the subducting slab of the Nazca plate.

The upper crust of the Andes formed at the Ordovician and Devonian time as a marine backarc sedimentary basin on/near the Proterozoic basement of the

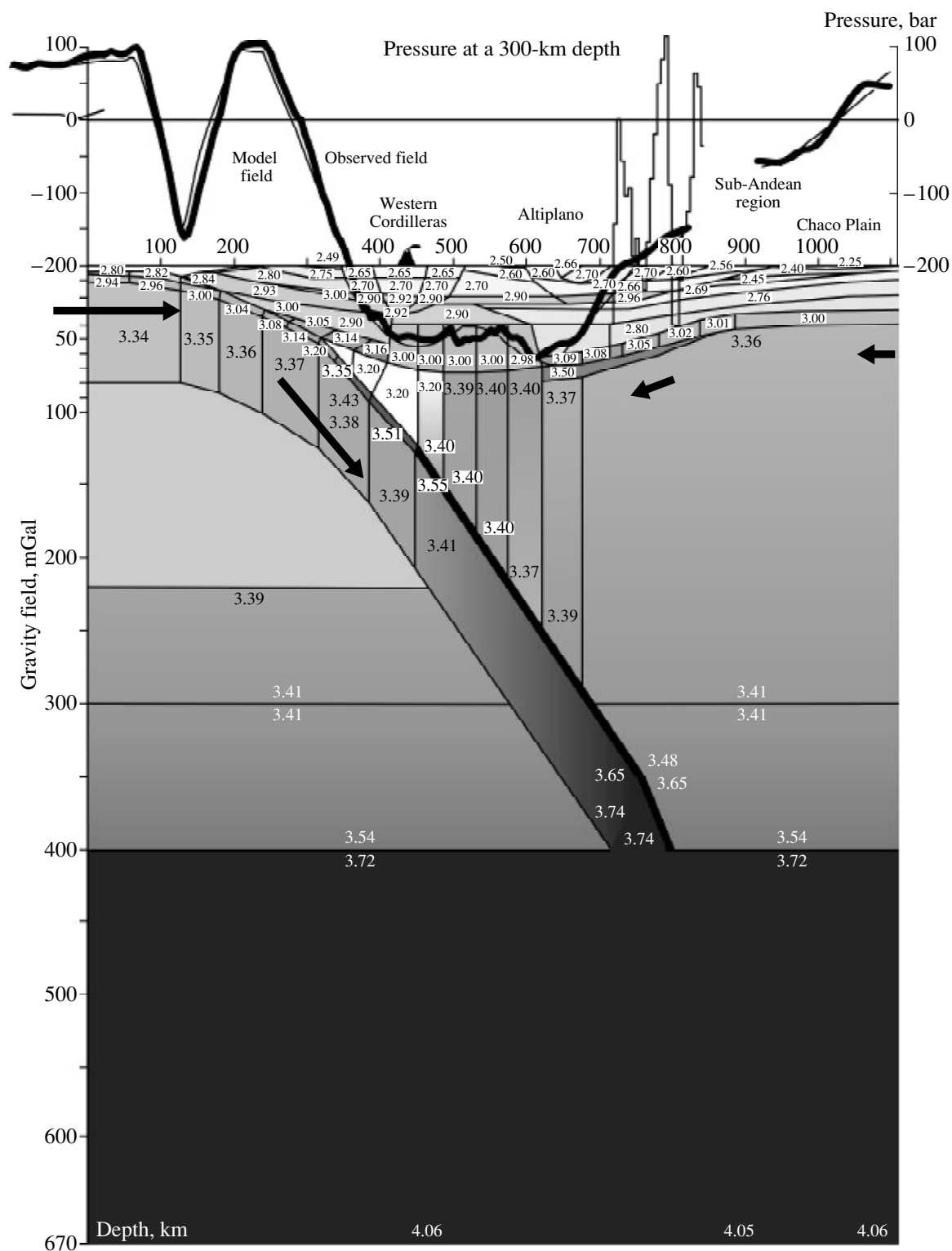


Fig. 3. Density model of the Andean subduction zone. Densities are indicated by numbers within blocks; double numbers characterize the vertical gradient within a block. The scale for the observed gravity curve (Bouguer anomalies above the continent and free-air anomalies above the ocean) and model gravity curve is to the left. The columns show the relative hydrostatic pressures (right-hand scale) at a 300-km depth west of the ocean trench and under the Eastern Cordilleras.

South American craton. Between the Ordovician and Oligocene, this basin experienced short episodes of sedimentation, orogenesis, rifting, metamorphism, and magmatism [Moore, 1994; Cladouhos *et al.*, 1994; Bahlburg and Herve, 1997; Klepeis and Austin, 1997]. Presently, the upper crust has a lens shape thickening to 20–25 km under mountains and thinning out near the coast and Sub-Andean overthrust.

The low velocity layer (HVL) between the upper and lower crust of the Andes can be interpreted as a relic of the basificated or oceanic crust. This layer is more rigid and less deformable than the surrounding rocks and thereby plays an important role in the redistribution of lateral compressive stresses.

It is supposed that, not later than in the Oligocene, the crust under the Eastern Cordilleras and Sub-Andean region began to thicken due to underthrusting of the South American craton beneath the Andes along the Sub-Andean overthrust. The Miocene tectonic activation in the Andes [Sempere *et al.*, 1990; Mercier *et al.*, 1992] was initiated by eclogitization and/or another type of high-pressure metamorphism in the lower crust of the subducting South American craton when the per-

manent P - T conditions were attained in the process of evolution. Since that time, high-density facies began to pull down the continental lithosphere, thereby enhancing the role of the vertical tectonics.

The oblique contact between the surface of the South American craton and the termination of the high-velocity zone (HVZ), marked as detail A in Fig. 2, is the most prominent feature in the reflection record section [Allmendinger and Zapata, 1997]. The rigid edge of the HVZ acts as a “scraper” removing sediments from the moving craton. These young sediments mixed with the Ordovician and Silurian marine deposits of the backarc basin and deformed along with the latter, thereby producing the fold-thrust thin-layered complex of the Sub-Andean region [Kley, 1996].

The South American craton moves as a whole under the Sub-Andean zone, but its layers start moving independently of each other under the Eastern Cordilleras. The upper crust still moves as a rigid body, and this region approximately correlates with the concentration of reflectors in Fig. 2. Middle crust layers start to flow and deform like a viscous fluid; the associated folding inside the layers thickens them.

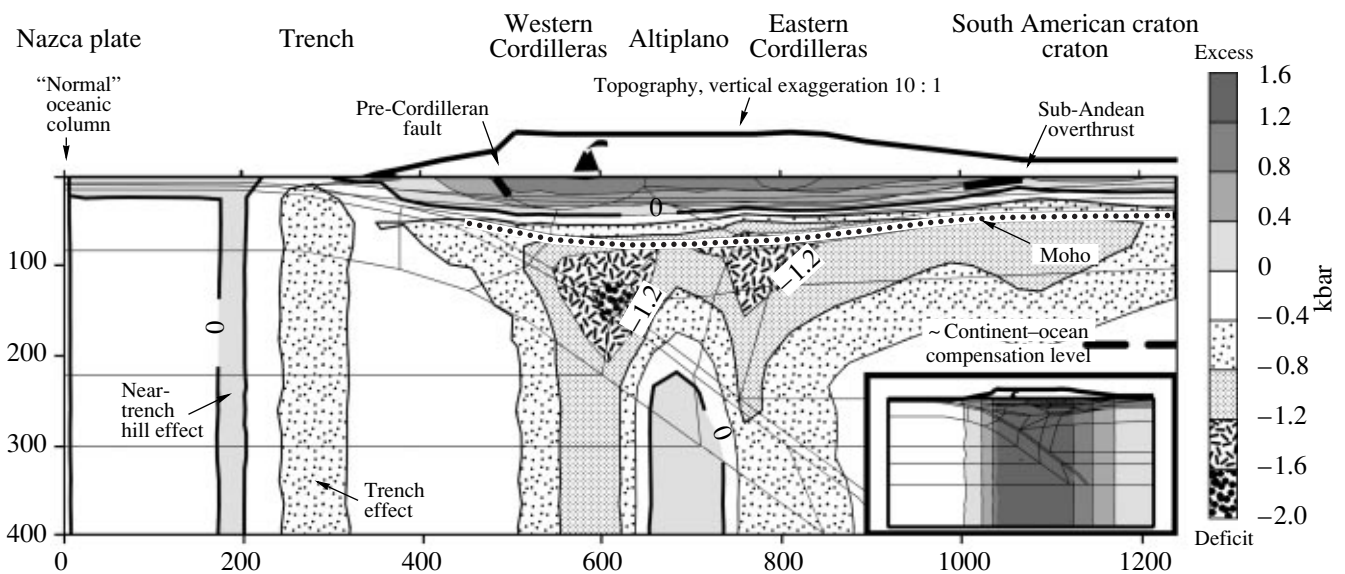
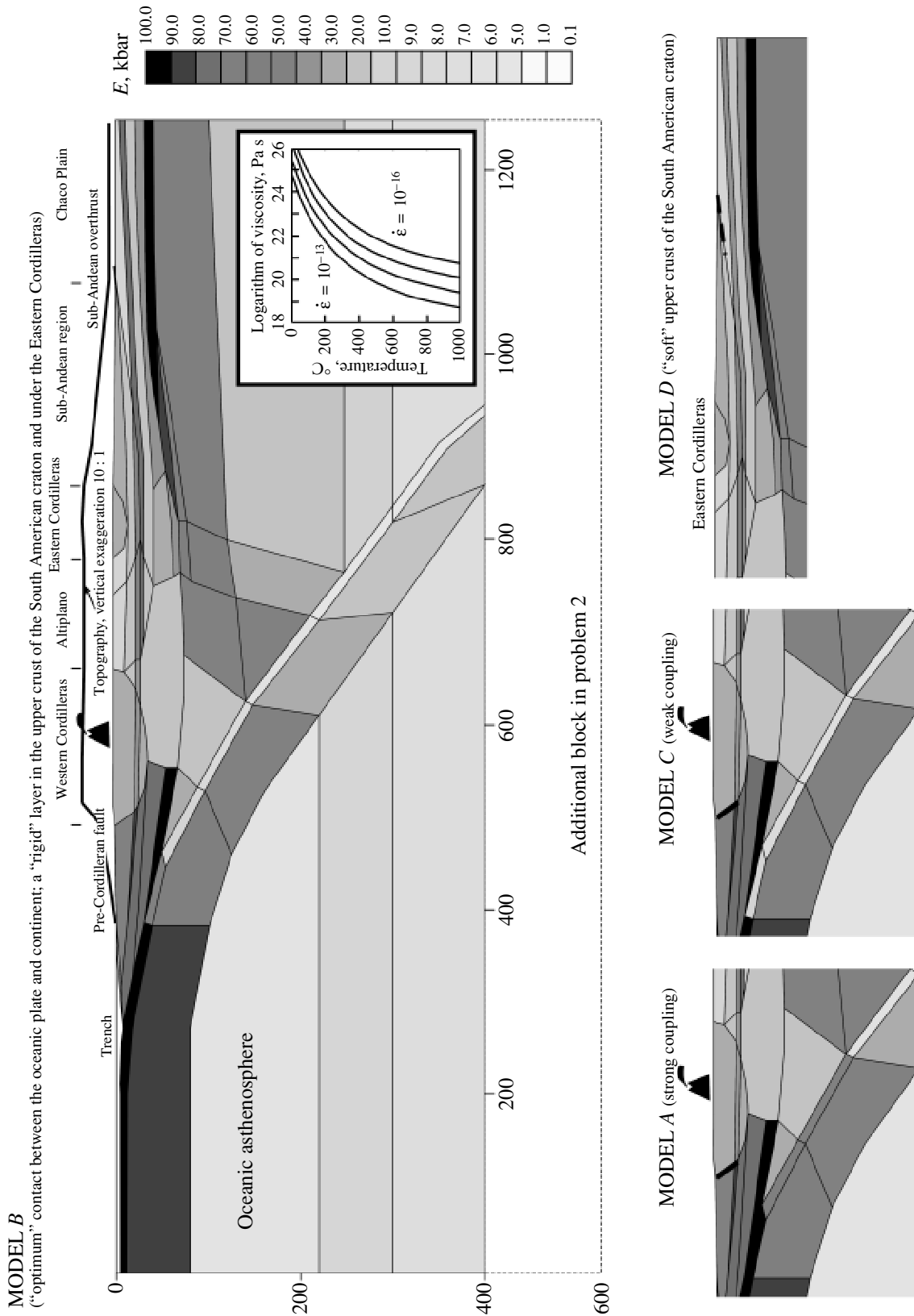


Fig. 4. Distribution of the model hydrostatic pressure deviations from the “normal” oceanic column whose position is shown by the arrow on the left. At each point, the difference between the pressures of the model and “normal” oceanic column masses overlying the given point was calculated. The topography and continental crust rocks of the Andean mountain belt produce excess pressure (1 kbar under the highest mounts) in the upper crust with respect to lighter water and oceanic sediments. The occurrence of denser crustal (below 5 km) and mantle (below 10 km) rocks in the “normal” oceanic column gradually compensates for the excess pressure, the compensation level lying above the continental Moho. The lower continental crust and the subcrustal mantle are characterized by a pressure deficit with respect to the oceanic column, reaching a maximum value of about –1.5 kbar in the mantle wedge. At greater depths, the deficit is partly compensated for by the heavy subducting slab and by the heavy eclogitic root of the pulled-down South American craton. The “recompensation” is also observed under the Altiplano plateau. The model boundaries of the positive (under the Altiplano plateau) and negative (under the Western and Eastern Cordilleras) anomalies of the hydrostatic pressure at great depths (400–600 km) under the oceanic plate correlate well with physiographic boundaries between these provinces. For comparison, the right bottom inset shows the topography excess pressure in an auxiliary model in which the density in all blocks is constant. The topography excess pressure increases toward the center of the Andean mountain belt but is depth independent because no variations in the lithosphere density are present.

Metamorphic transformations in the downgoing continental lithosphere gradually increase both the densities and seismic velocities at the crust base to their mantle values. For this reason, the refraction Moho "is

lost" under the Eastern Cordilleras, and the structural base of the crust of the underthrusting South American craton does not coincide with the presently recorded seismic refraction M surface between the Altiplano pla-



teau and the Eastern Cordilleras but occurs lower (detail C in Fig. 2).

As yet, the seismic refraction Moho has not been observed beneath the western Cascade Range and the Altiplano plateau. Moreover, seismic studies yield no evidence for the layered structure in the middle and lower crust, and gravity modeling did not reveal here appreciable lateral density inhomogeneities, although the average density was found to exceed by $\sim(0.1\text{--}0.2)$ g/cm³ the average density of the average crust of the South American craton which was pulled under the Eastern Cordilleras. Since electromagnetic studies [Echternacht *et al.*, 1997] point to an abrupt drop in the electrical resistivity within this block, the recent magmatic activity which effaced all previously existing structures is believed to be a dominating process here. Rocks of the middle and upper crust and upper mantle are pierced by magma intrusions and are metamorphically reworked. The ultimate depth of the stable quartz existence is about 70 km (quartz-coesite transition [Cloos, 1993]), and it is adopted here as a tentative crust-mantle boundary. Isostatic continental Moho estimates also give a depth of about 70 km [Goetze *et al.*, 1994].

Presumably in the Late Jurassic, the volcanic island arc complex was underthrust beneath an oceanward part of the backarc basin [Rapela *et al.*, 1998], which doubled the volcanoclastic crust between the coast and contemporary volcanic arc. The cold crust is characterized here by high averages of seismic velocities and density.

The Western Cordilleras are separated from adjacent areas by nearly vertical fault zones; the latter, along with other inner faults and deep seismic reflectors, form a "cup-like" structure (detail B in Fig. 2). Its origin can be interpreted in terms of the protrusion of the material from inner parts of the "cup". No marked density inhomogeneities are observed inside the "cup".

The Western and Eastern Cordilleras differ in their geology and formation mechanism, as well as the structure of the underlying crust. The only formation feature common to the both systems is the accumulation of a light material in the upper crust above the much less deformable descending HVZ layer. Although the Altiplano plateau has an elevation of about 3.7 km above sea level, this region is conceived as a sedimentary basin between the still higher mountain systems of the Western and Eastern Cordilleras [Masek *et al.*, 1994; Lamb and Hoke, 1997].

Seismic constraints on the transition zone between the Sub-Andean region and Chaco Plain being scarce, the crustal structure is shown here arbitrarily by horizontal layers. The sedimentary basin floor topography was estimated from density modeling.

THE SUBDUCTING OCEANIC NAZCA PLATE AND MANTLE WEDGE

The oceanic crust of the subducting Nazca plate (circa 30–40 Ma) is approximated by two layers: 2.8-g/cm³ basalt layer 2 and 2.95-g/cm³ gabbro layer 3 [Orcutt, 1987; Johnson and Semyan, 1994]; the density in the layers increases with plate depth. Layer 2 is believed to wedge out at a depth of 20 km, because basalt pores should close at pressures existing there and the density of basalts should then be close to that of gabbro. The Nazca plate mantle is believed to consist of harzburgite, which is gradually, at greater depths, replaced by spinel lherzolite, the average density being 3.34 g/cm³ [Scott and Stevenson, 1989; Cordery and Morgan, 1993]. Seismic data on the asthenosphere occurrence depth are unavailable, and the plate thickness is adopted in accordance with the age.

The most active area of the contact between the continental and oceanic plates is between the trench and volcanic arc, where the oceanic crust experiences dehydration and metamorphism (the basalt-eclogite transition is the most important metamorphic transformation) [Ahrens and Schubert, 1975; Dumitru, 1991; Ponko and Peacock, 1995]. Two processes that are most important for the gravity modeling are (1) the density increase in the rapidly descending (and therefore colder than the ambient mantle) oceanic plate and (2) the mantle wedge effect of the fluid released by the oceanic plate; this fluid leads to the serpentinization of the mantle cone and to the "wet" melting of mantle wedge peridotites, which forms the volcanic arc [Davies and Stevenson, 1992]. The upper mantle beneath the Andes includes the lighter mantle cone (~ 3.2 g/cm³), the sinking heavy lithospheric root of the Andean lithosphere (~ 3.4 g/cm³), and the "normal" continental mantle of the South American craton (~ 3.36 g/cm³). Mantle densities at depths of 200 to 670 km were taken in accordance with the standard columns [Dziewonski and Anderson, 1981; Lerner-Lam and Jordan, 1987].

Fig. 5. Young modulus distribution in the Andean lithosphere. More rigid parts (dark shades): the entire oceanic lithosphere (gradually softening with depth), the lower and middle cold crust of coastal regions, and the upper and lower crust and subcrustal continental lithosphere of the South American craton. Softer parts (light shades): the oceanic asthenosphere, sediments, the hydrated mantle wedge, and the lower and middle crust of the Western Cordilleras and Altiplano, affected by magmatism. Four model versions were considered: A, "strong coupling" between the continental and oceanic plates; B, "optimum coupling"; C, "weak coupling"; D, weak upper crust of the South American craton. Model B is regarded as an optimum one. The inset in the model B plot shows the estimated viscosity versus temperature at strain rates (ϵ) ranging from 10^{-16} to 10^{-13} s⁻¹ [Pope and Willett, 1998].

Rheological Parameters

Rheological properties of rocks depend not only on the mineral composition but also on temperature, load value, strain rate etc. [Kirby, 1980; Ranalli and Murphy, 1987; Carter, 1987; Cloething and Burov, 1996; Burov *et al.*, 1998; Chen *et al.*, 1998]. The temperature, load, and strain rate increase the plasticity of material, so that the rigidity of the medium drops with the increasing depth (Fig. 5). The cold cratonic quartz-diorite crust have a weakened mid-crust layer at depths of 10 to 20 km, and the mantle composition dominated by olivine localizes the elastic plate bottom at depths of ~ (80–100) km under platform regions (“cold” geotherm) and at ~ (60–80) km under a ~40-Ma ocean floor. The heat flow and the subduction rate of the oceanic plate provide constraints on the temperature distribution in the subducting oceanic plate and surrounding mantle [Ponko and Peacock, 1995]. High subduction rates of about 10 cm/yr imply that the oceanic plate should be effectively elastic down to depths of 300–400 km.

The rigidity of the medium dramatically drops in the contact zone between the oceanic and continental plates, where the oceanic crust is subjected to dehydration, because the presence of even negligible amounts of water weakens mantle minerals [Brodholt and Refson, 2000]. However, since estimates of the fluid release depth vary within wide limits, we considered four models of the contact zone between the oceanic and continental plates: models *A*, *B*, and *C* with, respectively, strong, optimum, and weak coupling, and model *D*, in which the upper continental crust of the South American craton is weakened compared to model *B*.

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