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Notes

Andean flat-slab subduction through time

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Abstract: The analysis of magmatic distribution, basin formation, tectonic evolution and structural styles of different segments of the Andes shows that most of the Andes have experienced a stage of flat subduction. Evidence is presented here for a wide range of regions throughout the Andes, including the three present flat-slab segments (Pampean, Peruvian, Bucaramanga), three incipient flat-slab segments ('Carnegie', Guañacos, 'Tehuantepec'), three older and no longer active Cenozoic flat-slab segments (Altiplano, Puna, Payenia), and an inferred Palaeozoic flat-slab segment (Early Permian 'San Rafael'). Based on the present characteristics of the Pampean flat slab, combined with the Peruvian and Bucaramanga segments, a pattern of geological processes can be attributed to slab shallowing and steepening. This pattern permits recognition of other older Cenozoic subhorizontal subduction zones throughout the Andes. Based on crustal thickness, two different settings of slab steepening are proposed. Slab steepening under thick crust leads to delamination, basaltic underplating, lower crustal melting, extension and widespread rhyolitic volcanism, as seen in the caldera formation and huge ignimbritic fields of the Altiplano and Puna segments. On the other hand, when steepening affects thin crust, extension and extensive within-plate basaltic flows reach the surface, forming large volcanic provinces, such as Payenia in the southern Andes. This last case has very limited crustal melt along the axial part of the Andean roots, which shows incipient delamination. Based on these cases, a Palaeozoic flat slab is proposed with its subsequent steepening and widespread rhyolitic volcanism. The geological evolution of the Andes indicates that shallowing and steepening of the subduction zone are thus frequent processes which can be recognized throughout the entire system.

Introduction

The pioneer work of Barazangi & Isacks (1976, 1979) described the first two well documented segments along the Andes without late Cenozoic arc magmatism and adscribed them to flat-slab subduction (Fig. 1). This cold subduction was associated with a subhorizontal Benioff zone identified in the retroarc area that was characterized by large and frequent intracrustal earthquakes driven by important basement shortening. As a result, important foreland basement uplifts took place in late Cenozoic times giving rise to the present Sierras Pampeanas (González Bonorino 1950; Jordan *et al.* 1983*a*, *b*). Another detailed seismotectonic study in the northern Andes recognized a flat-slab segment in the northern Colombian Andes with similar characteristics (Pennington 1981).

Multidisciplinary research performed during the last two decades, mainly based on seismological and geological data on the continents, and oceanographic studies in the adjacent areas, depict the present setting of these three segments, where shallowing of the Benioff zone was closely related to collision of aseismic ridges (Pilger 1981, 1984). However, it was only recently that geological evidence was obtained along the Andes showed steepening of past subhorizontal subduction.

The objective of the present study is to characterize geological processes linked to shallowing and steepening of the subduction zones and their geological consequences. We aim to characterize these parameters along the Andes in order to be able to identify palaeo flat slab segments during the Phanerozoic. Based on these premises, three palaeo flat slabs were identified in Cenozoic times. Even further, it is speculated that a late Palaeozoic flat slab could have developed in the Central Andes. These new data enhance the importance of flat-slab subduction through time, and indicate that it is not an anomalous feature of the present-day margin, but has been an important feature of the geological record and its frequency is higher than expected.

Present flat-slab subduction segments

Seismological data clearly show that there are three distinct segments with horizontal subduction along the Andean margin: the Bucaramanga, Peruvian and Pampean segments (Gütscher *et al.* 2000; Ramos 1999*a*). There is also a striking transition to a subhorizontal subduction in the Ecuadorian Andes (Gütscher *et al.* 1999*a*) that will be described to show the initial geological processes linked to the beginning of shallowing. These segments will be

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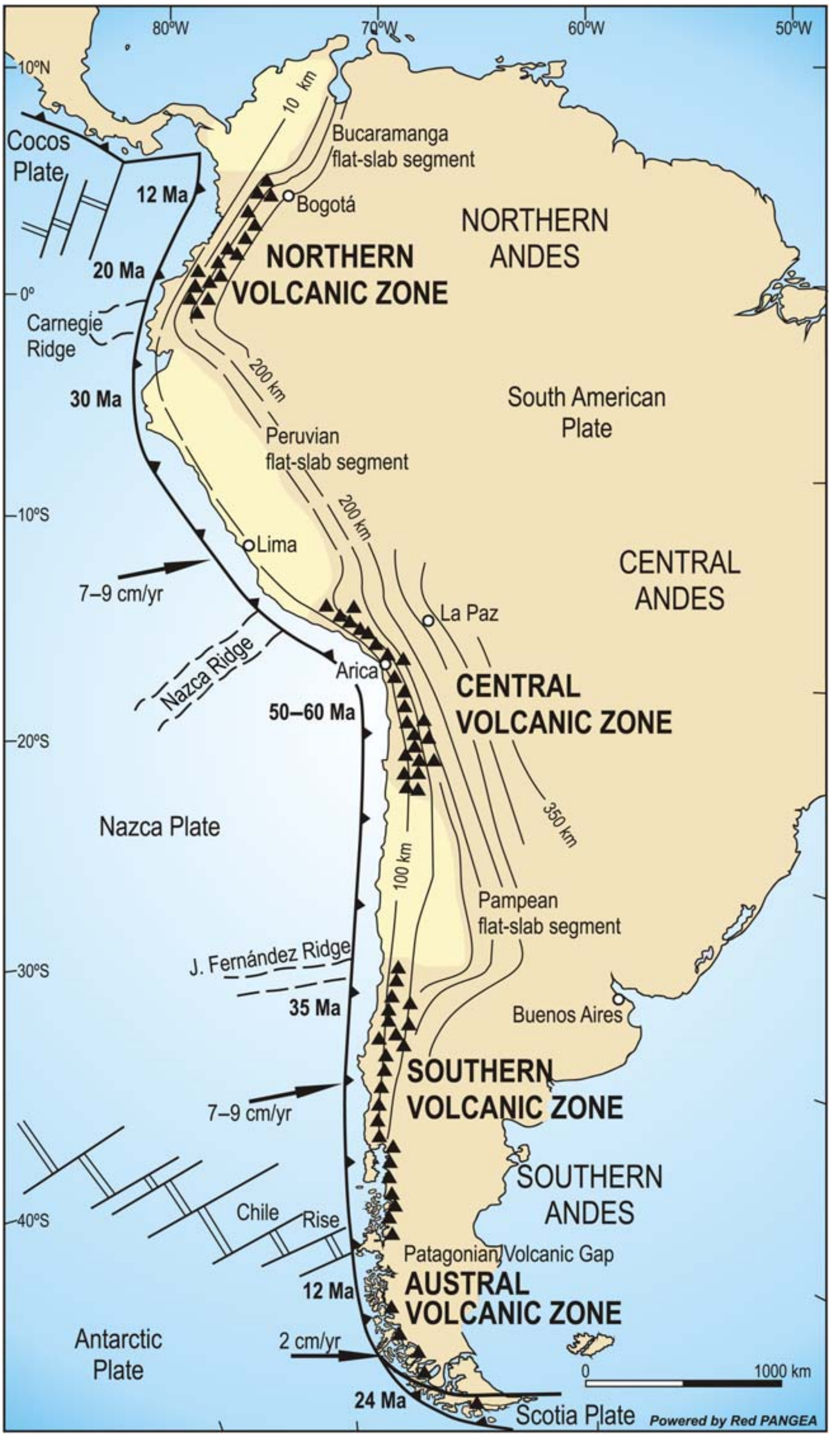

Fig. 1. Present flat-slab segments along the Andes (modified from Barazangi & Isacks 1976; Pennington 1981; Ramos 1999*a*; Gütscher *et al.* 2000).

described from south to north, in order to move from better known segments to less known settings.

Pampean flat-slab segment

This segment was one of the first where systematic data were collected to reconstruct the tectonic history associated with flat-slab subduction in the Andes (Isacks *et al.* 1982; Jordan *et al.* 1983*a*, *b*). The segment is located between 27° and 33°30′S latitude along the Pampean foreland. The highest segment of the Main Andes coincides with the central part of the Pampean flat slab, where mountain peaks, such as the Aconcagua (6967 m a.s.l.), the Mercedario (6850 m) and the La Ramada (6400 m) among others, correspond to tectonically uplifted areas with Miocene to Late Palaeozoic rocks above 6000 m (Ramos *et al.* 1996*a*). The description of the geological evidence will encompass the magmatic, sedimentological and structural history (Fig. 2), later linked to the oceanic features associated with the shallowing.

Magmatic evidence. The recognition of volcanic gaps in the Quaternary volcanic arc of the Andes emphasized the presence of cold subduction that coincides with the flat-slab segments (Barazanghi & Isacks 1976). Subsequent studies were able to

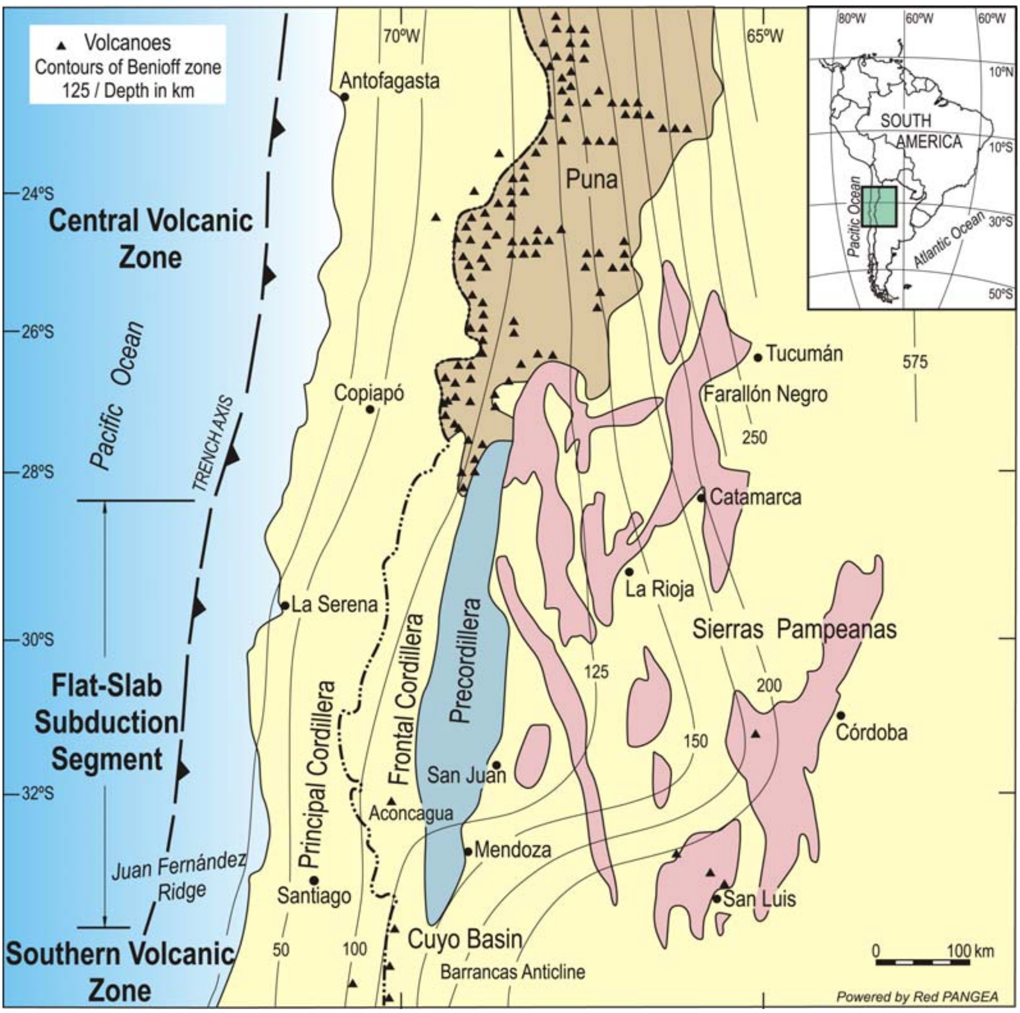

Fig. 2. Pampean flat-slab segment with indication of isobaths to the Nazca oceanic plate based on Cahill & Isacks (1992) (compare with the Benioff geometry proposed by Pardo *et al.* 2002 and Alvarado *et al.* 2005*a*, *b*); main basement uplifts of Sierras Pampeanas (Jordan *et al.* 1989), and location of the Precordillera fold and thrust belt (Ramos *et al.* 2002).

recognize that the gap had existed since Late Miocene times (Jordan *et al.* 1983*b*). Detailed petrographic studies performed in the late Cenozoic arc show that the geochemical signature changes in the main arc through time (Kay *et al.* 1987), and that the arc expanded towards the foreland region (Kay & Gordillo 1994). The geochemistry shows that the La/Yb ratios increased in Early to Late Miocene arc rocks, at the same time that crustal stacking thickened the crust (Kay *et al.* 1991; Kay & Mpodozis 2002; Litvak *et al.* 2007).

Geochronological data show that the main andesitic arc was active from 22–8.6 Ma (Fig. 3), although volumes of erupted magmas were drastically reduced throughout this time (Ramos *et al.* 1996*a*). A minor late rhyolitic eruption of Vacas Heladas Ignimbrites at 7.67 Ma was the last activity in the area (Ramos *et al.* 1989). Subsequent hydrothermal mineralization was widespread along the segment in El Indio, Valle del Cura and Maricunga mineral districts (Mpodozis *et al.* 1995; Kay & Mpodozis 2001). The latest activity east of the previous main arc was the eruption of the Cerro de Vidrio rhyolitic dome dated at 2.0 ± 0.2 Ma (Ar–Ar in glass) by Bissig *et al.* (2002) in Valle del Cura. Both rhyolitic episodes are interpreted as minor melts of the crust.

The expansion of the arc magmatism is first associated with a second dehydration front. At the latitude of the Aconcagua for example, the main Middle Miocene arc was characterized by large volumes of andesites and dacites in the Principal Cordillera, whereas in the Precordillera at *c*. 130 km east of the main arc, small volcanic centres and subvolcanic bodies were emplaced in Paramillos and Cerro Colorado (Kay *et al.* 1991). The main arc, as well as the second volcanic front, shifted eastward. The shifting and subsequent cessation of the magmatic arc simultaneously moved from west to east, and from north to south, ending at 5 ± 0.5 Ma west of Sierra de Aconquija (27°20′S lat.), 4.7 ± 0.3 Ma at the Pocho volcanic field (31°30′S lat.), and 1.9 ± 0.2 Ma in Sierra del Morro at 33°10′S lat. (Ramos *et al.* 2002).

Sedimentary evolution. Several retroarc foreland basins were formed along the flat-slab segment (Jordan 1984). Besides the general Andean trend of east migration of the synorogenic depocentres recorded from Late Cretaceous to Neogene times through the entire Andes (Ramos 1999*b*), the flat-slab segment superimposed a special character. East migration of the foreland system is linked to fragmentation of the foreland basement (Jordan *et al.* 1989). Detailed magnetostratigraphic studies show that subsidence rates were exceptional during the broken foreland stage (Reynolds *et al.* 1990). Locally, some depocentres recorded more than 10 000 m of continental fluvial deposits, such as in the Neogene depocentre of Sierra de Los Colorados at 29°S lat. (Ramos 1999*b*).

The beginning of the broken foreland stage coincided with the eastward advance of the shallowing of the subducted slab beneath the retroarc area. Sedimentological studies show that the Early Miocene foreland basin was cannibalized during the Miocene, with the largest subsidence rates experienced during the Middle Miocene inception of the Pampean flat-slab at these latitudes (Fig. 4).

Some basin remnants in the western interior areas between the Frontal Cordillera and the Precordillera, such as the Iglesia Valley basin, were reactivated as piggy-back basins by out-of-sequence thrusts (Beer *et al.* 1990; Zapata & Allmendinger 1996). There is also a great variation in the timing of deformation when the sedimentary record is compared from north to south. Synorogenic deposition gets younger to the east and to the south (Vergés *et al.* 2001), when comparing time of deposition along the Río San Juan and Jachal further north. The same trend is regionally observed along the entire segment (Jordan *et al.* 2001; Ramos 1999*b*).

Tectonic history. The timing of shortening in the Principal and Frontal cordilleras and the Precordillera show some striking relations when analyzed in conjunction with: (1) the shortening rates of the fold and thrust belts; (2) the propagation of the orogenic front; (3) the subsidence rate of the adjacent foreland basin; and (4) the uplift of Sierras Pampeanas (Fig. 5). The shortening of this fold-and-thrust belt was concentrated in a thin-skinned belt within the Principal Cordillera prior to the shallowing. This period recorded a shortening rate of 5.5–5.75 mm/a, and a slow propagation rate of 2.5 mm/a of the thrust or orogenic mountain front. The propagation rate increased to 13.3 mm/a soon after the beginning of shallowing, while the shortening was reduced to 3.6 mm/a. This change from thin to thick skinned shortening is also reflected in the subsidence rate of the foreland basin (Fig. 5).

This data – when compared with the tectonic evolution of the adjacent oceanic region – show close time and space relationships between collision of the Juan Fernández aseismic ridge against the margin and the beginning of the shallowing of the subducted slab (Yañez *et al.* 2001). The south and eastward shifting of the magmatic arc, the time of deformation and basin evolution accompany the migration of the Juan Fernández ridge along and beneath the upper plate, as clearly demonstrated by Pilger (1984), Gütscher *et al.* (2000) and Kay & Mpodozis (2002). The most active neotectonic

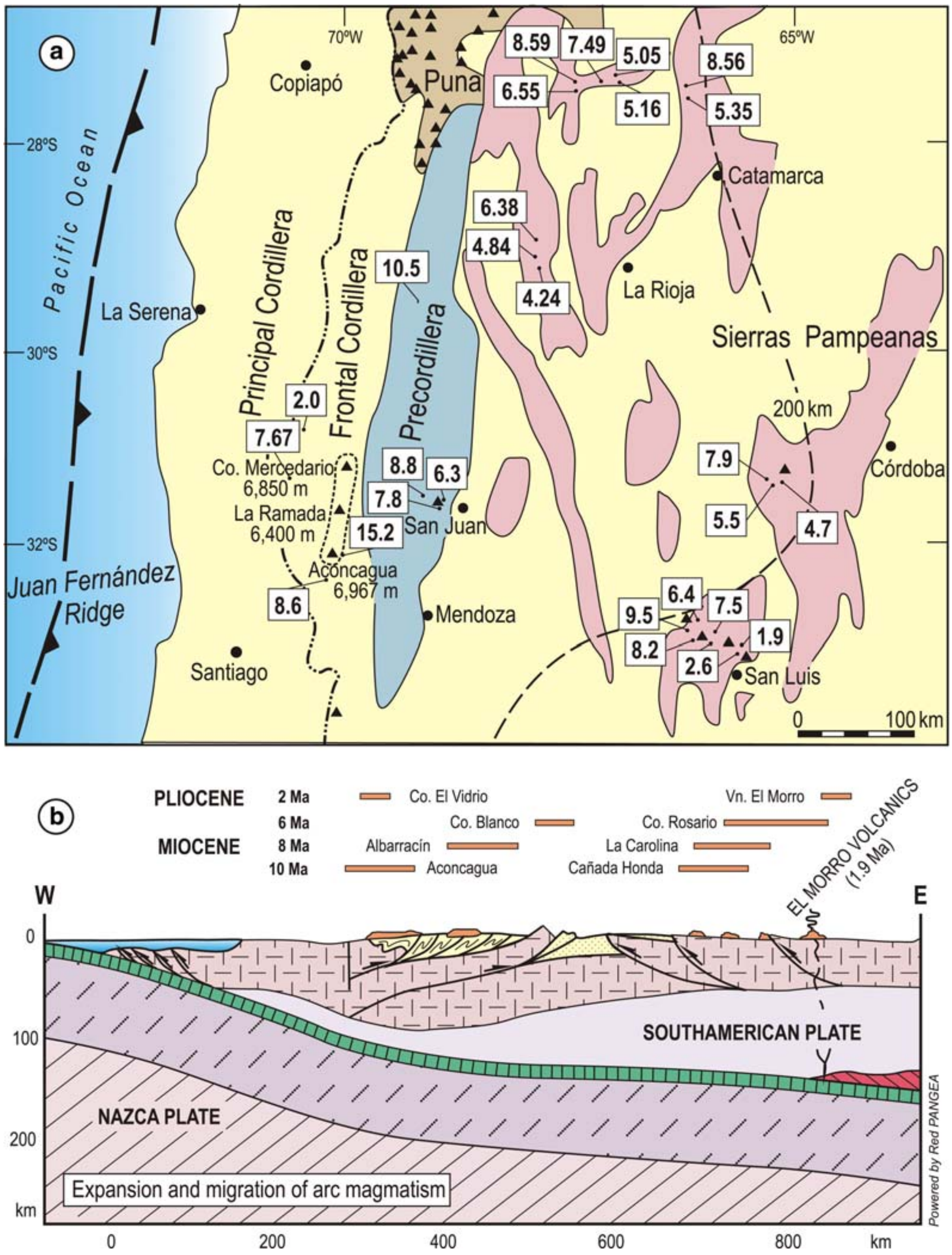

Fig. 3. Evolution of arc magmatism through time in the Pampean flat-slab: (**a**) Representative ages after Ramos *et al.* (2002) with indication of the isobath of 200 km depth corresponding to the oceanic slab; (**b**) Cross-section at crustal scale showing the expansion and migration of the main volcanic centers during the shallowing of the oceanic slab. Main elevations in the High Andes not related to the Quaternary volcanoes are also indicated.

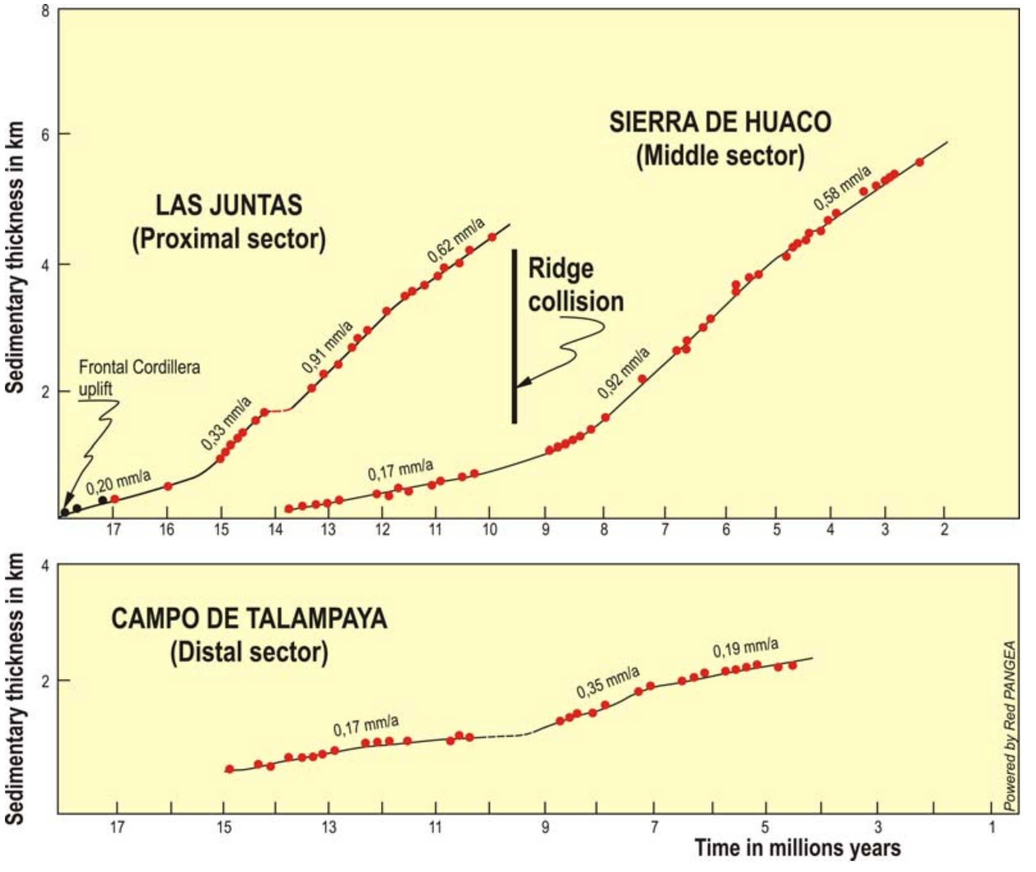

Fig. 4. Subsidence rates in the proximal, intermediate and distal areas of the Bermejo broken foreland basin, with indication of the beginning of flat-slab subduction at these latitudes (modified from Ramos 1999*b*). Seismostratigraphic data after Reynolds *et al.* (1990).

area corresponds to the Pie de Palo uplift, an area of high intracrustal seismicity (Kadinsky-Cade *et al.* 1985; Regnier *et al.* 1992) and a western Sierras Pampeanas block where an average uplift rate of 1.0 mm/a during the last 3 Ma has been observed (Ramos *et al.* 2002; Siame *et al.* 2006*a*). Pie de Palo is just above the track of the Juan Fernández ridge, as indicated by the coincidence between high density of earthquake epicentres and the projection of the oceanic feature (Kirby *et al.* 1996), and is located where the ridge is presently shallowing the subducting slab.

Peruvian flat-slab segment

This segment is encompassed between the Gulf of Guayaquil at 5°S and Arequipa at 14°S latitudes. It has been described by Barazanghi & Isacks (1976, 1979) based on global data of the ISC catalogue, and with more precision using local networks by Dorbath *et al.* (1986, 1991). This survey demonstrated that the subduction zone starts under the trench with a 30° dip until approximately 100 km depth (Fig. 6), where it becomes horizontal beneath the Eastern Cordillera and the Subandean zone (Dorbath *et al.* 1991). Pilger (1984) showed the kinematics between the Nazca Ridge collision and the shallowing of the central Peru segment. This region was examined again by Gütscher *et al.* (1999*b*), who challenged the previous proposal and instead of the collision of an aseismic ridge proposed that the large Peruvian flat-slab segment was the result of the Nazca Ridge and the Inca Plateau subduction. Precise timing of the Nazca Ridge collision, and constraints in the length of the ridge, support that collision started at *c*. 11.2 Ma at about 11°S, moving later to the present position, as depicted by Hampel (2002). The segment north of this latitude requires a collision of a plateau or other oceanic feature.

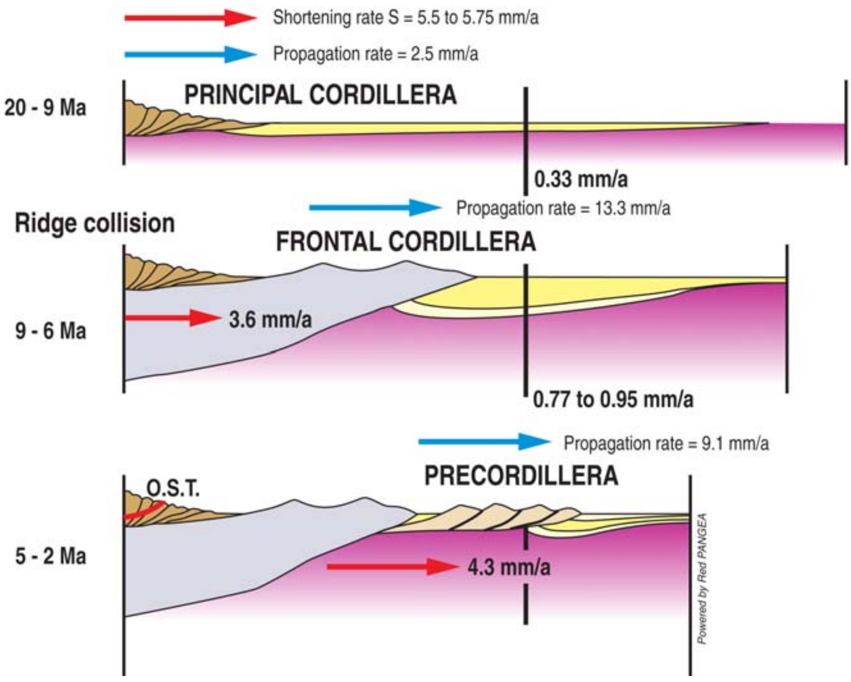

Fig. 5. The Aconcagua fold and thrust belt in the Central Andes at 32°S latitude with variations on shortening and propagation rates through time (after Ramos *et al.* 1996*b* and Hilley *et al.* 2004) and the subsidence rates in the foreland basin after Irigoyen *et al.* (2002).

The Peruvian flat-slab segment shares many common features with the Pampean flat slab. The second highest part of the Andes coincides with the Cordillera Blanca, with mountains such as Huascarán (6778 m a.s.l.), which is only 110 m lower than the Aconcagua massif, and other Late Miocene granitic peaks over 6000 m. The Cordillera Blanca is in the central part of an important basement high, which includes the Marañón Massif further to the east in the Eastern Cordillera. The Cordillera de Marañón is a basement uplift that exposed middle crustal rocks very similar in composition and metamorphic degree to the Sierras Pampeanas. The Peruvian segment also coincides with an area of no-arc volcanism, at least since latest Miocene times. Radiometric ages document several Cenozoic pulses of eastward magmatic migration (Aleman 2006). The cessation (*c*. 12 Ma) of magmatism in the northern part of the flat slab correlates with the complete subduction of the Inca Plateau and the arrival of the Nazca Ridge. As in the Pampean flat slab, the cessation of the main magmatic activity in the volcanic arc is followed by the emplacement of minor crustal melts of acidic composition. An example are the granites of Cordillera Blanca where McNulty *et al.* (1998) and Giovanni *et al.* (2006) reported U–Pb zircon ages as young as 6 Ma. The magmatic lull following Nazca Ridge subduction began at the end of the Miocene. Most of the emplacement of the Cordillera Blanca Batholith and coeval ignimbrites took place during the southern sweep of the Nazca Ridge (Aleman 2006).

Neotectonics in the forearc where the Nazca Ridge intersects the trench are described by Macharé *et al.* (1986). Further support includes active tectonics and uplift in the foreland region in the Fitzcarrald arch in the Subandean region, where the aseismic ridge is being presently subducted. Evidence consists of a radial drainage network and deformation of Pliocene–Recent fluvial deposits on both sides of this structural high (Espurt *et al.* 2007). Both forearc and foreland geology, together with the distribution of late Cenozoic arc volcanoes, highlight the relationships between aseismic ridge subduction, active uplift and cessation of magmatism.

Bucaramanga segment

The early proposal of Pennington (1981), based on limited seismological data, showed a shallow subduction zone beneath northern Colombia. This fact has been confirmed by the seismological studies of

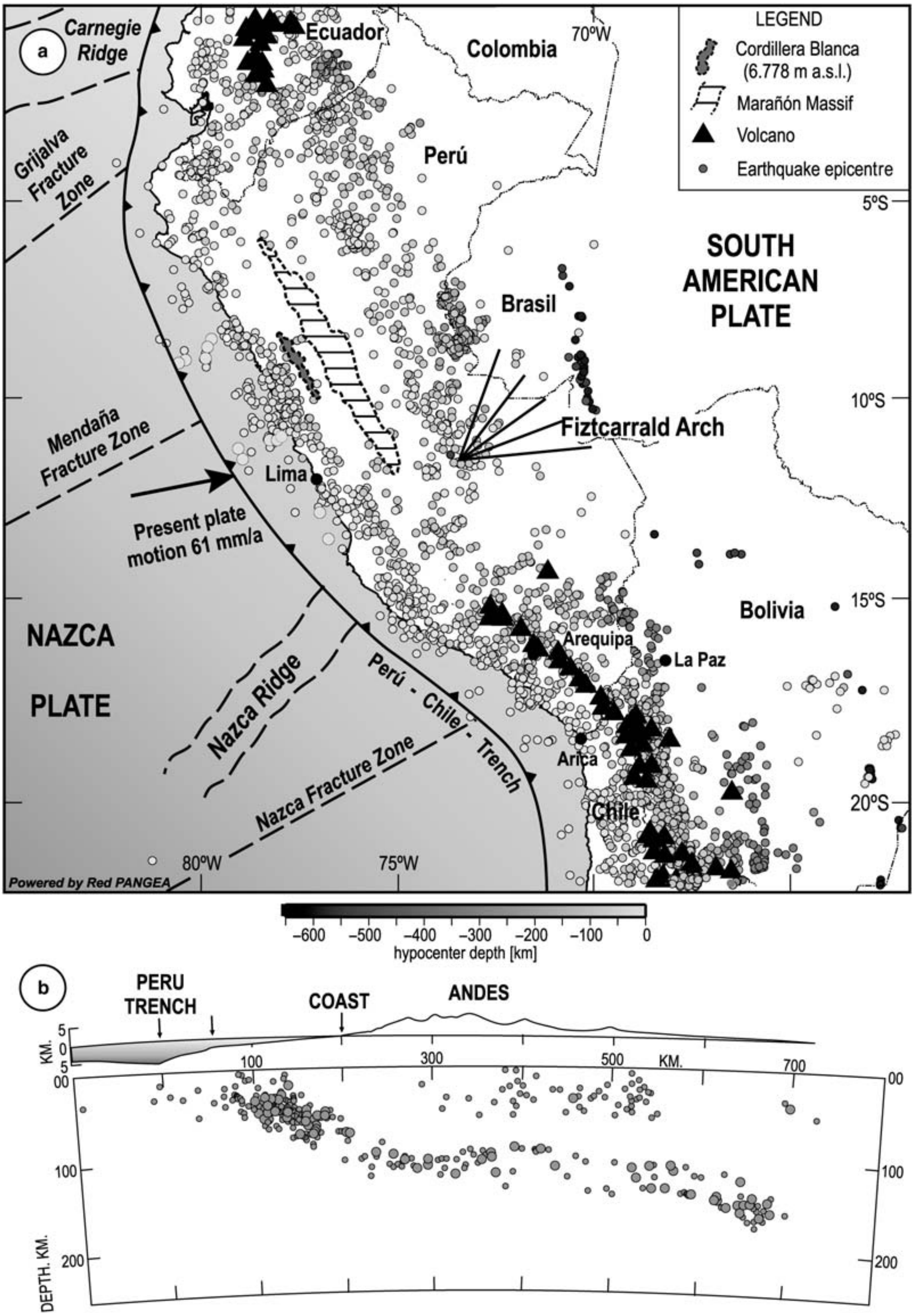

Fig. 6. (**a**) General features of the Peruvian flat slab based on Hampel (2002) and Aleman (2006). See the coincidence between the projection of the Nazca Ridge into the foreland and the uplift of the Fitzcarrald arch and associated alluvial fan (Espurt *et al.* 2007). (**b**) Geometry of Benioff–Wadatti zone beneath central Peru at 14–12°S latitude (based on Dorbarth *et al.* 1991).

Gütscher *et al.* (2000) in the Northern Andes north of 5°N, and the analysis made by Corredor (2003), who shows the shallow subduction produced by the recent subduction of the Caribbean plate beneath the Northern Andes. The dense concentration of intracrustal earthquakes of the Bucaramanga nest (Fig. 7) is associated with basement deformation and uplift of the Eastern Cordillera, characteristic of flat-slab subduction. However, an alternative hypothesis was advanced by Taboada *et al.* (2000), where most of this intraplate deformation at Bucaramanga was explained as a palaeo-Benioff zone associated with an old but still active subduction between the Panamá microplate and South America, after the middle Miocene collision of the Chocó block (12–13 Ma, Duque Caro 1990).

The cessation of the late Cenozoic magmatic arc north of Cerro Bravo and Nevados de Ruiz (Mendez Fajury 1989), as well as the intense widespread neotectonic intracrustal activity, is better explained by the flat slab model of Gütscher *et al.* (2000). Their regional seismic tomography depicts a cold mantle and lower crust in this segment.

The latest volcanic activity is exposed near Boyacá in the retroarc region in the northern part of the Eastern Cordillera. The Tunja and Paipa volcanoes, among others, are associated with

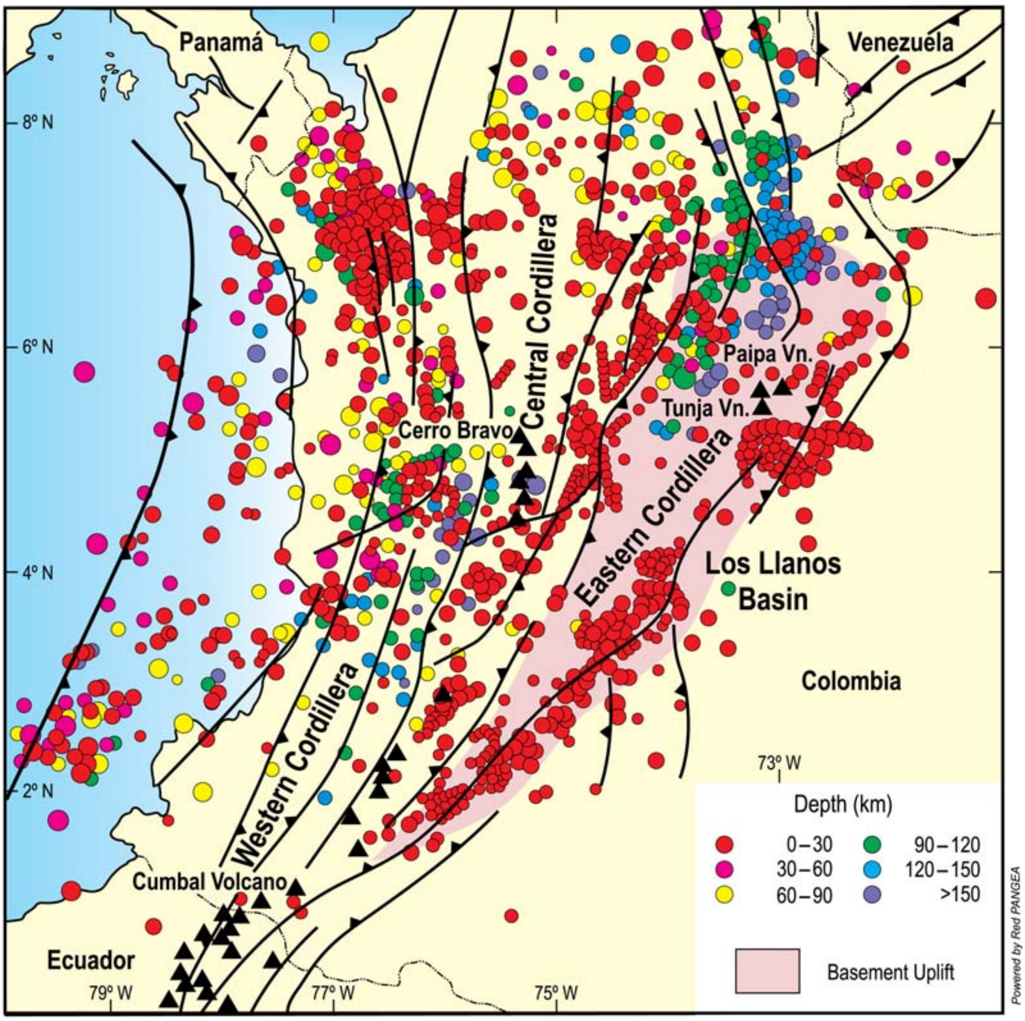

Fig. 7. Seismic activity and main morphostructural units of the Bucaramanga flat slab based on Dimate *et al.* (2003). Volcanic arc based on Mendez Fajury (1989) and retroarc volcanoes based on Cepeda (2004).

pyroclastic flows that range in age from 2.5–2.1 Ma for the oldest eruption, to pyroclastic flows younger than 1.5 Ma (Cepeda *et al.* 2004). This dominant Pliocene–Quaternary explosive volcanic activity has a high-K rhyolitic composition that resembles the last magmatic activity, characterized by the rhyolitic dome described by Bissig *et al.* (2002) in the Pampean flat slab. The rhyolitic composition of both areas, the residual thermal fields, and the mechanism of emplacement are very similar in both regions (Cepeda *et al.* 2004). This volcanic activity is better explained by the shallowing of the subducted Bucaramanga Pacific slab than by the inception of a new volcanic arc, as the result of the subduction zone that is being developed from the Caribbean margin of Colombia and Venezuela (Audemard & Audemard 2001).

Therefore, the flat slab hypothesis explains the active present uplift of the northern segment of the Eastern Cordillera, the cessation of arc magmatism, the neotectonic features associated with the tectonic inversion of previous rifts (Sarmiento-Rojas *et al.* 2006), the large intracrustal seismicity (Dimate *et al.* 2003) and the complex latest Cenozoic structure of the Pie-de-monte Llanero (Martínez 2006).

Incipient flat-slab subduction segments

One of the best lines of evidence of early-stage shallowing is documented inland of the collision of the Carnegie aseismic ridge (Gütscher 1999*a*). The volcanic arc of Colombia is composed of a line of individual volcanoes from Cerro Bravo at 5°N to Cumbal at 2°30′N latitude (Fig. 7). South of the border with Ecuador, it changes to a complex volcanic arc system, which is expanded towards the foreland. Active volcanoes are emplaced on the Western Cordillera, the Inter-Andean Valley, the Eastern Cordillera (or Cordillera Real) and in the Subandean zone across 120 km from the volcanic arc front.

Individual volcanoes, such as the Cayambé and Quimsacocha volcanoes, show a trend from old calc-alkalic volcanic rocks to a more recent new edifice with a typical adakitic signature (Beate *et al.* 2001; Samaniego *et al.* 2002). Although the origin of this adakitic signal was early ascribed to slab melting, this has been questioned with their formation being attributed to melting of thickened continental crust or forearc subduction erosion (Ramos 2004). Both processes, crustal thickening and forearc crustal erosion, are consistent with flat subduction (Kay & Mpodozis 2002).

The variation in the dip of the subducted slab has been addressed by the change in petrological characteristics, such as the depth of generation and degree of partial melting in the asthenospheric wedge (Bourdon *et al.* 2003), and in the expansion of the volcanic arc that coincides with the projection of the Carnegie ridge, an aseismic oceanic ridge that is now obliquely colliding against the margin (Gütscher *et al.* 1999*a*). The forearc crust is overthickened only in the segment where the Carnegie ridge (Fig. 1) is colliding against the margin, as demonstrated by wide-angle seismic data recently collected offshore (Gailler *et al.* 2007). This collision is also related to the abnormal present uplift of the Cordillera Real and the Subandean block that controls the Pastaza alluvial megafan (Bés de Berc *et al.* 2005). Uplift rates during the Pleistocene of 1.37–1.4 cm/a, associated with an exhumation of the late Cenozoic alluvial plain of 500 m, are closely linked to the Carnegie ridge collision (Christophoul *et al.* 2002; Baby *et al.* 2004). Important intracrustal seismic activity is related to the basement structure of the Cutucu high. This uplift may correlate with the fission track data for the Cordillera Real that shows more than 9 km uplift in late Cenozoic times (Spikings *et al.* 2001).

Another segment with incipient evidence of shallowing is the Guañacos segment, located between 36° and 38°30′S latitudes. It is characterized by strong neotectonic and intracrustal activity in both: i) the forearc region at the Nahuel Buta Cordillera and offshore Cretaceous–Paleogene Arauco Basin (36°30′–37°30′S; Melnick *et al.* 2006*a*) and ii) the western retroarc zone at the Guañacos fold and thrust belt (36°–38°S; Folguera *et al.* 2004*a*). The two sectors correspond to ancient deformed belts that have been suddenly reactivated in Late Pliocene to Quaternary times. The offshore Arauco Basin, which was previously uplifted in the Late Cretaceous, as indicated by fission track ages (Glodny *et al.* 2007), has been shortened since 3.6 Ma at a rate of 0.8 mm a^{-1} as an eastward vergent fold and thrust belt. On the other hand, recent neotectonics characterized the Guañacos fold and thrust belt, which was a Palaeogene basin inverted during Late Miocene times. The Pleistocene magmatic arc has migrated about 30 km to the east in this segment regarding the Pliocene volcanic front. Petrological studies performed in the Cenozoic arc at these latitudes show crustal thickening and subduction erosion, both processes consistent with shallowing of the subduction zone (Kay *et al.* 2005). Gravimetric studies show that the 36°–38°30′S segment is characterized by a long wavelength residual gravimetric anomaly that can only be explained (see density model in Alasonati Tašárová 2007; Hackney *et al.* 2006) by the shallowing by 10° of the subduction angle of the Nazca subducted plate. Therefore, the anomalous concentration of crustal earthquakes linked to unusual neotectonic activity in a 200 km wide subducted segment, may indicate incipient shallowing at the transition between the Central and Patagonian Andes since Late Pliocene times.

Another segment with an incipient flat slab is the Transmexican volcanic belt in central Mexico, which is related to the collision of the Tehuantepec aseismic ridge, although a different mechanism for uplift has been proposed (Ferrari 2006). A detailed analysis of this segment is outside the scope of this paper.

Past flat-slab subduction segments

There is a strong correlation between the segment with current arc volcanism in the Central Andes (see central volcanic zone in Fig. 1) and the area of past flat-slab subduction extending from southern Peru to northern Argentina (Fig. 8). A summary of the geological processes involved in the changes from normal to flat, and from flat to normal subduction, will be discussed updating the proposal of James & Sacks (1999) (also see Sebrier *et al.* 1988).

Altiplano flat-slab segment of Southern Peru

A period of flat-slab subduction was recorded in southern Peru and northern Bolivia, between 14° and 20°S latitudes (James & Sacks 1999). The evidence was similar to the previous described segments: (1) rapid cessation of the magmatic arc between 45 and 35 Ma; (2) widespread deformation and crustal thickening in the Eastern Cordillera; (3) the tectonothermal Zongo San Gabán effect that pervasively resets the Ar–Ar ages along 450 km, overprinting Permian and Triassic metamorphic rocks with a cryptic 38 Ma age; and (4) no igneous rocks of this age are known in this segment. This effect was interpreted as the result of heat advection by fluids at 38 Ma that predated the activity of the sub-Andean fold and thrust belt (Farrar *et al.* 1988). These processes were explained by a shallowing of the subducted slab that became subhorizontal at about *c*. 35 Ma and lasted until *c*. 25 Ma.

The steepening of the subduction zone was evidenced by widespread bimodal volcanism where rhyolites and basalts cover a wide area. As a result, great volumes of rhyolites up to 530 km^3 were spread on the present Altiplano and western slope of Eastern Cordillera between 26 and 22 Ma (Sandeman *et al.* 1995). During flat subduction the overlying lithosphere is hydrated by dewatering of the flat slab (James & Sacks 1999). Consequent steepening and expansion of the mantle wedge controlled the flow of hot asthenosphere and melting of the hydrated lithosphere beneath the Altiplano and Eastern cordilleras. Volcanic arc retreat is reflected by the shifting to the trench of the Tacaza arc between 29 and 15 Ma, the Upper Barroso arc

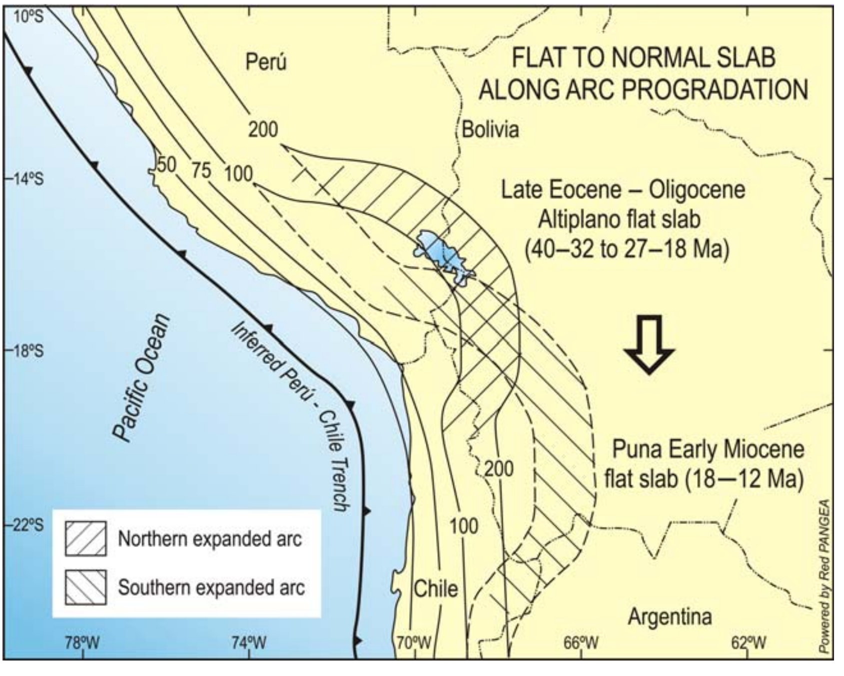

Fig. 8. Segments that recorded flat subduction in Late Eocene to Early Miocene times that correspond to the present Central Volcanic Zone (based on James & Sacks 1999 and Kay *et al.* 1999).

(10–6 Ma) and Lower Barroso in the last 3 Ma to meet the present frontal arc during the Pleistocene.

The main points of these processes are the weakening of the lithosphere during steepening of the subduction, delamination of the lithosphere and part of the lower crust (Kay & Kay 1993), and the collapse of the crust to form the Subandean fold and thrust belt. For further details, see James & Sacks (1999) and Kay *et al.* (1999).

Puna flat-slab segment of southern Bolivia–northern Argentina

This trend of shallowing progressed to the south, where another period of flat subduction was recognized between 20° and 24°S (Kay *et al.* 1999). The shallowing took place between 18 and 12 Ma, as recognized by the cessation of the magmatism, crustal shortening and deformation of the southern Altiplano and northern Puna. Precise timing of the deformation established by Allmendinger *et al.* (1997), Baby *et al.* (1995) and Oncken *et al.* (2006), together with the palaeogeography of the foreland basin (De Celles & Horton 2003) enabled the onset of the deformation in the Subandean region to be constrained to after 10 Ma.

Again, the same processes indicate that strong deformation in the axial part of the Puna and Eastern cordilleras were related to shallowing of the subduction zone, while steepening produced important hot asthenospheric flow, which in contact with the hydrated lithosphere (Oncken *et al.* 2006), led to important crustal and lithospheric delamination. As a result, huge rhyolitic calderas and ignimbritic fields are associated with thermal uplift and the consequent horizontal collapse and weakening of the crust with the deformation of the Subandean belt (Isacks 1988; Kay *et al.* 1999; Beck & Zandt 2002; Garzione *et al.* 2006).

Payenia segment

Arc related rocks were emplaced more than 550 km away from the trench during Late Miocene times, from 34°30′ to 37°45′S (Fig. 9), suggesting shallow subduction processes at that time (Kay

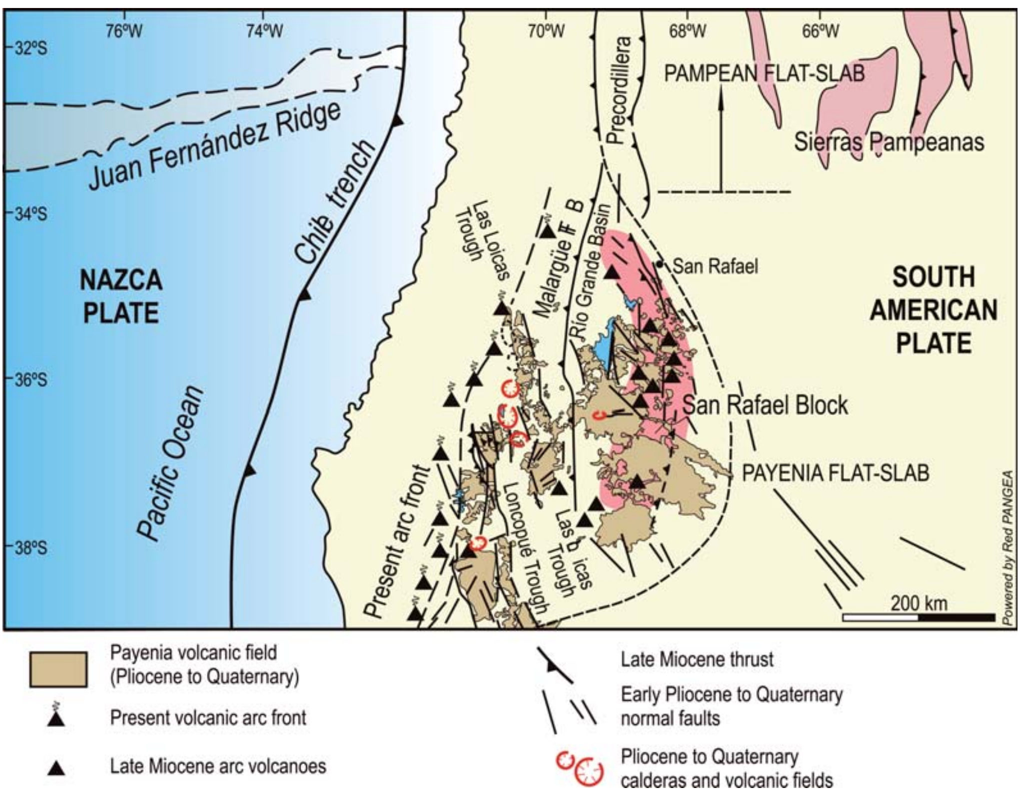

Fig. 9. Expansion of the magmatic arc during the Middle to Late Miocene showing the location of exhumed andesitic to dacitic arc rocks on the San Rafael block. Subsequent extensional structures, within plate basaltic flows, and huge rhyolitic calderas and ignimbritic flows along the main Andes suggest steepening of the subducted slab.

2001; Kay *et al.* 2006*a*, *b*). Intermediate positions of the arc are located on the eastern slope of the Andes near the drainage divide area (Nullo *et al.* 2002) to the east of the Late Oligocene arc, emplaced mainly on the western Andean slope. Easternmost centres were emplaced over the San Rafael block, a basement block that cannibalized the distal section of the Rio Grande foreland basin. The uplift of this block was associated with the foreland migration of the Malargüe fold and thrust belt to the east (Kozlowski *et al.* 1993; Manceda & Figueroa 1995). The San Rafael block was exhumed in Late Miocene times (Dessanti 1956; González Díaz 1964; Polanski 1964; Yrigoyen 1993, 1994). The Middle Miocene age assigned to the synorogenic sequences at the San Rafael block (Soria 1984; Marshall *et al.* 1986) points to a Late Miocene exhumation that coincides with the age of the dacites and andesites emplaced in the San Rafael block between 13 and 4 Ma.

In addition, the main phase of deformation in the eastern section of the Malargüe fold and thrust belt at these latitudes has been constrained to 13–10 Ma (Giambiagi *et al.* 2008), which indicates a genetic relationship between the initial phase of arc expansion, uplift of the main Andes, sedimentation in the adjacent foreland basin, and the breaking of the foreland area.

During latest Miocene–Early Pliocene times, this compressional crustal stage changed to an extensional regime with the development of extensional troughs across the area that had previously recorded arc expansion (Fig. 10) (Bermúdez *et al.* 1993; Melnick *et al.* 2006*b*; Folguera *et al.* 2008). Arc dynamics were characterized during this period by fast retreat to the present position on the western

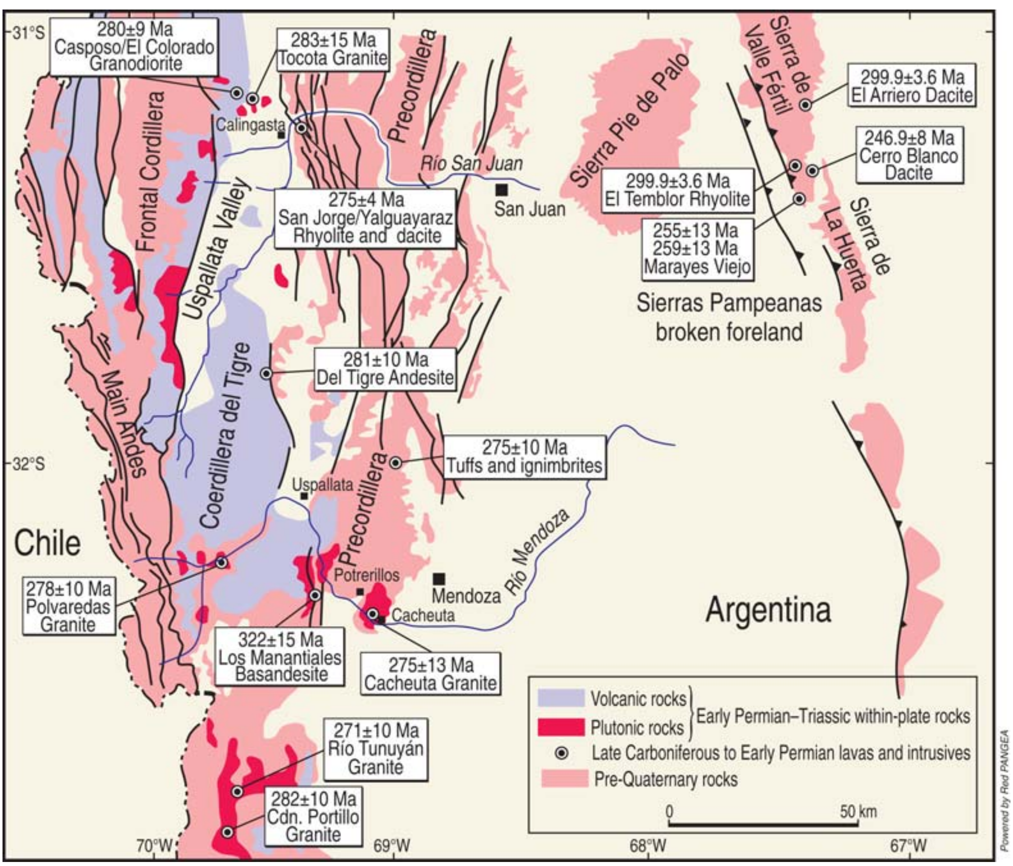

Fig. 10. Distribution of Upper Palaeozoic magmatic rocks and deformation in the southern Central Andes (based on Caminos 1979; Ramos *et al.* 1988; Varela *et al.* 1993; Mpodozis & Ramos 1989; Mpodozis & Kay 1990). Maximum expansion of arc volcanic rocks in the Early Permian was followed by subsequent extensional regime associated with the Choiyoi volcanic province.

flank of the Andes. Extensional deformation is associated at depth with crustal attenuation as well as anomalous sublithospheric heating inferred by teleseismic and tomographic analysis (Gilbert *et al.* 2006; Yuan *et al.* 2006). Gravimetric studies show high positive residual anomalies with areas submitted to extension, inferring an area of continuous asthenospheric upwelling in coincidence with the area of previous arc expansion (Folguera *et al.* 2007*a*). This extensional setting hosted rhyolitic associations derived from crustal melts at the highest collapsed sector of the Andes in the Las Loicas trough (Fig. 9) (Hildreth *et al.* 1984, 1991, 1999), whereas in foreland sectors it was associated with poorly differentiated mantle derived products (González Díaz 1972; Rossello *et al.* 2002; Kay *et al.* 2006*b*).

These two contrasting stages of deformation and arc dynamics, which occurred during the last 15 Ma between 34°30′ and 37°45′S, point to a scenario in which progressive shallow subduction from 15–5 Ma was followed by sudden slab steepening during the last 4 Ma, associated with the partial collapse of the orogen at these latitudes.

Palaeozoic flat-slab subduction segment?

Palaeozoic deformations exhumed by Andean events through the Southern Central Andes have been connected to collisional episodes (Ramos *et al.* 1984; Ramos 2004). Early Permian deformations of the San Rafael tectonic phase have also been related to collision of an unidentified X terrane (Mpodozis & Kay 1990). This deformation exhibits some peculiarities in the foreland sedimentation and is associated with a phase of orogenic collapse that led Mpodozis & Kay (1990) to propose structural instabilities after orogenic development. The analysis of the late Palaeozoic orogenies in other areas of Gondwana led Cawood & Buchan (2007) to argue that deformation is not always related to a collisional event. Furthermore, in this segment of the Andes, little attention has been paid to coeval arc dynamics, which constitutes a direct indicator of Benioff zone variations through time. The Early Permian San Rafael tectonic phase is associated with unique processes that resemble more those of Andean tectonics than those occurred in Palaeozoic times at these latitudes (Ramos & Folguera 2007): (1) arc related volcanic assemblages cover diachronically Early Permian compressive deformation features; (2) Early Permian arc abnormally expanded to extend through the entire region and probably its front shifted to the east; (3) extensional processes followed the main phase of orogenic building and intraplate rhyolitic sequences were erupted through the area of previous arc expansion; and (4) resetting of remanent magnetization in the area suggests abnormal lithospheric heating that preceeds eruption of intraplate melts. These facts point to a flat subduction cycle in Early Permian times, followed by slab steepening and consequent orogenic collapse in the Late Permian to Early Triassic, as proposed by Martínez *et al.* (2006).

Sedimentary evolution. Late Carboniferous–Early Permian 7000–8000 m thick marine to non-marine sequences are hosted along the eastern slope of the Principal Cordillera of Mendoza and San Juan (Fig. 10). Those are locally covering a Late Proterozoic basement indicating an important erosional hiatus prior to their deposition. The broad area uplifted in the Main Andes was the source of these sequences, which are characterized by coarsening-up cycles. This episode of mountain building, known as the San Rafael orogenic phase (280–270 Ma: Azcuy & Caminos 1987; Llambías *et al.* 1993; Cortés & Kleiman 1999), ended in the Lower Permian with an important angular unconformity.

From west to east these sequences were gathered in the Loma de los Morteritos and El Plata formations, with palynomorphs indicative of a Late Carboniferous to Early Permian age. These units, located on the eastern slope of the Frontal Cordillera, formed the maximum depocentre of the Late Palaeozoic in the region (Polanski 1958; Caminos 1965; Folguera *et al.* 2004*b*). To the east, Late Palaeozoic thicknesses fall in the western Precordillera region (Fig. 10), where several coarsening-up tectonostratigraphic units do not reach 500 m. These sequences, as determined by invertebrate and palynomorph associations (Ottone 1987), are coeval with the magmatic rocks and the structural deformation of the region.

This main depocentre of several thousand metres flanked the Early Permian belt of deformation, and pinch out to the platform area. The foreland basin started with shore sediments over which deltaic bodies and turbiditic lobes prograded, ending with braided fluvial systems (Heredia *et al.* 2002). Moreover, the dominance of westward palaeocurrents and lithoclasts of crystalline basement indicate that the basement may have been exhumed east of the Early Permian orogenic front, potentially as an incipient Sierras Pampeanas system, similar to the present setting of the Pampean flat slab (Fig. 2).

Lower Permian mesosiliceous lavas are part of the basal section of the Choiyoi Group. The upper part of this unit accumulated either in the Frontal Cordilleran or Precordilleran areas in a contrasting tectonic regime when compared to the basal member. As revealed by the structural style of the Andean fold and thrust belt at these latitudes, the main basement thrusts are the result of tectonic inversion of extensional faults that controlled the main depocentres of the Choiyoi Group (Cristallini & Ramos 2000; Rodríguez Fernández *et al.* 1997).

Magmatic evidence. Several studies have pointed out that Lower Permian calc-alkaline series, gathered with different names in the southern Precordilleran region, have unconformably covered the San Rafael unconformity in the Frontal Cordillera (Coira & Koukharsky 1976; Vilas & Valencio 1982; Cortés 1985; Kay *et al.* 1989; Rapalini & Vilas 1991; Sato & Llambías 1993; Sotarello *et al.* 2005). In addition, other isolated minor volcanic bodies with similar chemical patterns and Early Permian age have been found to the east up to 250 km away from their westernmost position (Fig. 10), on the Precordillera and Sierras Pampeanas domains (Rubinstein & Koukharsky 1995; Castro de Machuca *et al.* 2007). The magmatic arc was located mainly westward of the Frontal Cordillera during the Carboniferous (Hervé *et al.* 1987), which implies a strong eastward shifting and expansion from the Late Carboniferous to the Early Permian (Rodrígez Blanco 2004). Early Permian sequences are in turn separated by an erosional hiatus from an extensive intraplate rhyolitic association of the Choiyoi Group of Late Permian to Early Triassic age (Rapalini & Vilas 1991). On geochemical grounds, the plutonic and volcanic rocks of the Choiyoi Group define a large within plate volcanic province (Kay *et al.* 1989; Mpodozis & Ramos 1989) that covers important sectors of the Main Andes and Precordillera regions (Fig. 10). The area of Early Permian arc expansion coincides with a phase of extensional collapse with peak igneous activity around 260–240 Ma at these latitudes (Martínez 2004).

Tectonic history. A wide volcanic arc, in excess of 200 km, developed in Late Carboniferous–Early Permian times and has been exhumed along the Pampean flat slab zone. The volcanic sequences are interfingered in the west with a 7000–8000 thick turbiditic to deltaic succession whose easternmost section is preserved at the eastern Frontal Cordillera (Fig. 10). Towards the east, the volcanic rocks were emplaced over folded and thrust sequences deformed during the San Rafael orogenic phase. The sedimentary depocentre, characterized by the stacking of coarsening-up cycles, was affected by the Early Permian deformation. This basin was formed during the arc expansion stage, with its subsidence controlled by orogenic loading. It experienced rapid thinning towards the east in the present eastern Precordillera.

Regional analysis of the Late Carboniferous to Early Permian tectonics shows some striking facts. There are major crustal anisotropies east of the Main Andes that correspond to sutures formed as a result of Late Proterozoic to Early Palaeozoic terrane amalgamation (Ramos 1988). These sutures were reactivated with important strike-slip displacements in the Late Palaeozoic. The dominant right lateral displacements were caused by the oblique convergence of the subducting Pacific (Panthalassa) oceanic plate (Rapalini & Vilas 1991), which originated several deep transtensional depocentres (Fernández Seveso *et al.* 1993; Fernández Seveso & Tankard 1995). The depocentres are associated with alkaline eruptions typical of extensional intraplate settings (Koukharsky *et al.* 2001; Ramos *et al.* 2002), found in the Paganzo Basin. Fernández Seveso *et al.* (1993) discuss the relation between Early Permian compressive thrusting in the western Andean sector and transtension at the eastern foreland area. They propose that the origin of the extension could have been related to breaking up of the foreland basement due to crustal downwarping as found in modern analogues. This transtension in the Paganzo Basin would be a passive response in the foreland area to orogenic loading of the San Rafael thrust wedge. An alternative hypothesis would be to consider a high partitioned subduction system where displacements perpendicular to the trench would have been absorbed in the San Rafael fold and thrust belt; lateral displacements imposed by oblique convergence between plates would have been concentrated and localized in ancient lithospheric boundaries (Rapalini & Vilas 1991; Fernández Seveso *et al.* 1993). In this context, high oblique convergence and strong coupling associated with shallow subduction would be the condition for the development of a high strain partitioned subduction regime during Late Carboniferous–Early Permian times.

Arc expansion, stacking of the western sector of the fold and thrust belt during San Rafael tectonic phase, formation of foreland basins, and transtensional to transpressional reactivation of Proterozoic-early Palaeozoic sutures in the foreland area, ended in the tectonic wedge collapse. As a result, a multitude of rift systems were filled by the Choiyoi Group.

Rotation of half grabens produced erosional unconformities that separate Early Permian volcanics from the rest of the late Palaeozoic sequence. This zone of orogenic collapse coincides with the area of arc expansion and San Rafael orogenic compressional deformations, suggesting a common mechanism. Therefore, slab steepening and consequent asthenospheric injection in the broadened asthenospheric wedge, after shallow subduction, are the mechanisms proposed for the origin of the anomalously voluminous rhyolitic magmas of the Choiyoi Group and its extensional tectonic control. As a result, delamination of the lower crust took place after thickening and eclogitization during the San Rafael compressive phase. Sublithospheric heating due to slab steepening explains the massive crustal melting, as the lower crust was directly in contact with the rising asthenospheric flux (Martínez *et al.* 2006).

Normal to flat-slab transition

Several examples of different ages and several distinct segments of the Andes show that the transit from normal subduction to flat-slab subduction is associated with a series of events:

Migration of the volcanic front and expansion of the arc magmatism. It is important to note that migration of the arc is indicated by the location of the largest volume of magmatic rocks; although magmatism in the previous setting may last for several million years, but with insignificant volumes. Such migration involves a decreasing volume of magmatic rocks that parallel the decline of dehydration in the subducted slab. This migration can be correlated to crustal weakening of the foreland and subsequent faulting. Geochemical signature of these magmas changes with the distance to the trench as well as the depth of generation (Kay & Mpodozis 2002). Final products may be as far as 600 km from the trench, as in the Bucaramanga segment (Jaramillo & Rojas 2003; Cepeda *et al.* 2004), and up to 750 km in the Pampean flat slab (Kay & Gordillo 1994).

Uplift of the Main Andes. Tectonic uplift is well documented in the Peruvian segment and in the Pampean flat slab, where the Cordillera Blanca and the High Cordillera of Mendoza and San Juan encompass the highest sectors of the Andes with the Huascarán (6778 m) and the Aconcagua (6967 m) mountains. The main difference between these two segments is that the Peruvian one registers some extensional collapse of the Cordillera Blanca (Siame *et al.* 2006*b*), while the Aconcagua shows no evidence of extension (Ramos *et al.* 1996*b*). This could imply that extension is more related to slab buoyancy from ridge subduction of the prethickened continental crust, as proposed by McNulty & Farber (2002), than to orogenic collapse in the sense of Dewey (1988).

Broken foreland. Although the Sierras Pampeanas is one of the most typical features of the Pampean flat slab (Jordan *et al.* 1983*a*, *b*), most other areas have recorded basement uplifts. The Peruvian segment is characterized by the Marañón Massif (3400 m a.s.l.), a basement uplift of the Eastern Cordillera produced in Late Miocene times almost along the suture between an allochthonous terrane and the Gondwana margin. The larger area and elevations up to 5250 m reached by the Sierras Pampeanas in the Sierra de Aconquija could be related to the more segmented nature of the basement with several sutures and ophiolitic belts reactivated first as extensional faults during the opening of the South Atlantic, and later, as a thrust during the shallowing of the oceanic slab (Ramos *et al.* 2002). Other segments such as the Bucaramanga are related to the reactivation and uplift of the Eastern Cordillera of Colombia by tectonic inversion of extensional faults, partially coinciding with sutures (Cortés *et al.* 2006; Ramos & Moreno 2006). Even in a small segment as the Payenia flat-slab, the uplift of the San Rafael Block coincided with the maximum expansion of the arc. There is a close relationship between arc migration, thermal weakening of the crust and basement uplift (James & Sacks 1999; Ramos *et al.* 2002) during the shallowing of the oceanic slab. Some pervasive tectonothermal effects, such as the Zongo–San Gabán (Farrar *et al.* 1988) and the San Rafael effect (Rapalini & Astini 2005), are associated with this stage.

Basin subsidence. The increase in subsidence has a clear relationship with the approximation of the thrust front, as shown in several Subandean basins (Irigoyen *et al.* 2002; Jordan 1995). However, the subsidence achieves a critical collapse when the basement is broken and maximum thicknesses are obtained. This is seen in the Pampean flat slab, where more than 10 000 m of sediments in the synorogenic deposits of the Bermejo foreland basin have been reported by Ramos *et al.* (2002). There are incomplete records in other segments, but De Celles & Horton (2003) described several thousand metres in the Oligocene and Early Miocene of the Altiplano. The Payenia segment nicely depicts the migration and cannibalization of the previous basins until the broken foreland stage is reached.

Flat to normal slab transition

On the other hand, the processes related to the transition from flat-slab to normal subduction are less well known, but have interesting characteristics:

Rhyolitic flare-up. One of the first results of steepening of the subducted oceanic slab is the presence of large crustal melts that are suddenly erupted over the flat-slab area in thick continental crust (Kay *et al.* 1999). Recent studies demonstrate that these large lower crustal melts are associated with lithospheric removal, sinking of the eclogitized lower crust, and crustal delamination, as earlier proposed by Kay & Kay (1993).

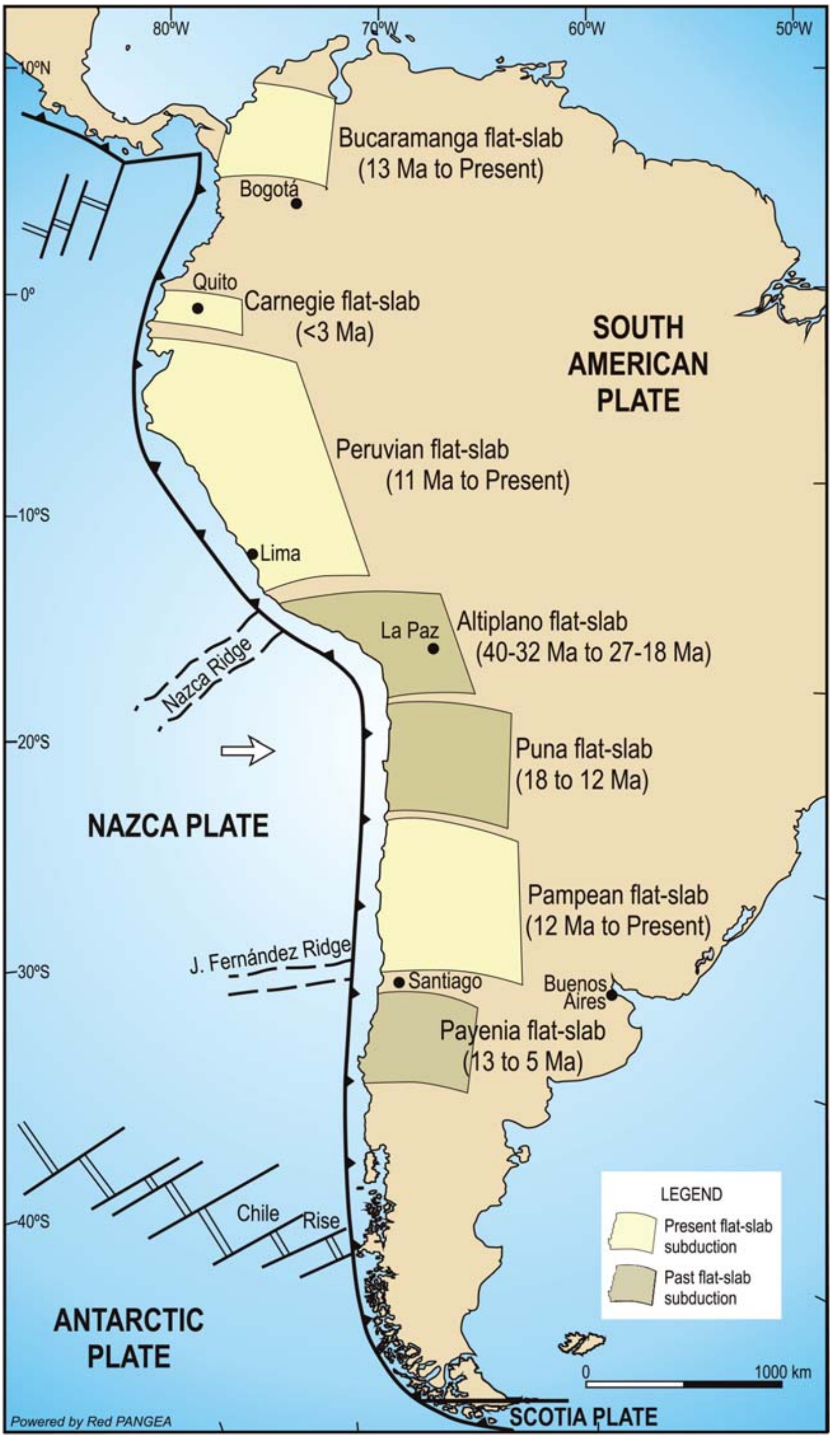

Fig. 11. Segments that have experienced shallowing of the subduction zone during Cenozoic times along the Andes. Note the almost continuous outline of flat-slabs.

Thermal uplift. This effect is a direct consequence of the lithospheric removal (Isacks 1988), although it has only been well documented in the Altiplano–Puna segment (Whitman *et al.* 1996; Allmendinger *et al.* 1997). Different geophysical tools have been used to confirm this evidence (see review in Oncken *et al.* 2006). Evidence of thermal uplift has not been documented in other segments. Reduced uplift in a thermal weakened area has been recently proposed in the Payenia segment with reduced geophysical datasets by Folguera *et al.* (2007*b*).

Extensional regime. The onset of the steepening of the subducted slab in some areas is associated with the vertical collapse by extension of the previous contracted structures. This is seen in the Payenia segment, where the pre-Miocene peneplain, uplifted in the Late Miocene, is segmented by normal faults (Ramos & Folguera 2005). Although the Puna has evidence of Pliocene extensional faulting that has been interpreted in different ways (Allmendinger *et al.* 1997), it is important here to note that extension occurs immediately after the thermal uplift of the area.

Intense deformation shifted to the foreland. The best example of migration of deformation that post-dates thermal uplift and some extension in the axial area, is the formation of the southern Subandean fold and thrust belt. The spatial and temporal relationships are clearly seen in southern Bolivia (Beck & Zandt 2002). In some other segments, this relationship is not evident, although in the Payenia flat slab, the Guañacos fold and thrust belt was developed after the emplacement of calderas and rhyolitic domes as well as the San Rafael block. This belt along the axis of the Andean Cordillera has evidence of neotectonic activity (Folguera *et al.* 2004*a*).

Widespread mafic within plate floods. The segment with thin crust, even after gentle shortening, shows an important basaltic flood linked to the inception of the steepening. These basaltic floods, in the Payenia segment, indicate a mantle-derived poorly-evolved magma of mafic composition and within plate signature (Kay *et al.* 2006*a*, *b*). Acidic rocks of Pliocene to Quaternary age in this area are scarce and are mainly small crustal melts as in Cerro Peceño, in the San Rafael Block.

In conclusion, it is interesting to show that when the present and past Cenozoic segments that had experienced flat-slab subduction are posted along the Andes (Fig. 11), an almost continuous belt of flat-slabs is outlined. The area that does not show evidence is Patagonia, although some studies postulate that the northern Patagonian massif between 40° and 43°S has experienced some shallowing during late Paleogene times (de Ignacio *et al.* 2001). There is no obvious trend or wave of shallowing, except among the Altiplano, Puna and Pampean segments, where there is some defined younging to the south. The other segments, at the present level of knowledge, show a random inception.

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