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# The tectonic regime along the Andes: Present-day and Mesozoic regimes

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The analyses of the main parameters controlling the present Chile-type and Marianas-type tectonic settings developed along the eastern Pacific region show four different tectonic regimes: (1) a nearly neutral regime in the Oregon subduction zone; (2) major extensional regimes as the Nicaragua subduction zone developed in continental crust; (3) a Marianas setting in the Sandwich subduction zone with ocean floored back-arc basin with a unique west-dipping subduction zone and (4) the classic and dominant Chile-type under compression. The magmatic, structural and sedimentary behaviours of these four settings are discussed to understand the past tectonic regimes in the Mesozoic Andes based on their present geological and tectonic characteristics. The evaluation of the different parameters that governed the past and present tectonic regimes indicates that absolute motion of the upper plate relative to the hotspot frame and the consequent trench roll-back velocity are the first order parameters that control the deformation. Locally, the influences of the trench fill, linked to the dominant climate in the forearc, and the age of the subducted oceanic crust, have secondary roles. Ridge collisions of seismic and seismic oceanic ridges as well as fracture zone collisions have also a local outcome, and may produce an increase in coupling that reinforces compressional deformation. Local strain variations in the past and present Andes are not related with changes in the relative convergence rate, which is less important than the absolute motion relative to the Pacific hotspot frame, or changes in the thermal state of the upper plate. Changes in the slab dip, mainly those linked to steepening subduction zones, produce significant variations in the thermal state, that are important to generate extreme deformation in the foreland. Copyright © 2009 John Wiley & Sons, Ltd.

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## 1. INTRODUCTION

The examination of the present tectonic settings along the eastern Pacific region, and mainly along the South American continent, shed light to some geological processes associated with subduction in an Andean-type setting. The objective of this work is to show the geologic characteristics, mainly the structure, magmatism and basin evolution of a series of selected settings, in order to use these peculiarities to examine other past examples in the Andes, mainly during Mesozoic and early Cenozoic times.

There are many analyses that deal with the parameters that control the tectonic regime in a subduction zone. Since the early proposal of Forsyth and Uyeda (1975) that have shown that the slab pull forces are positively correlated with the donwndip length of a subduction zone, there were many studies of the processes controlling the tectonic regime. The complete analysis of Jarrard (1986), and the most modern studies of specific cases of Doglioni *et al.* (1999, 2007, 2009), Heuret and Lallemand (2005), Cruciani *et al.* (2005), Lallemand *et al.* (2005), Schellart (2008) and Guillaume *et al.* (2009) have shown that a large variety of structural environments and plate interactions at convergent margins may be illustrated by the two end members, the Marianas and the Peru–Chile plate boundaries. Marianas is characterized by an old oceanic crust that is underthrusting a tensional overriding plate at an almost vertical dip, accompanied by relatively modest maximum earthquakes. In contrast, the Peru–Chile plate boundary is characterized by rapidly converging, younger oceanic crust that is underthrusting a compressional overriding plate at a nearly horizontal dip, accompanied by very large earthquakes (Uyeda and Kanamori 1979). The mechanisms of the seismically decoupled extensional arcs with retreating upper plates, and strongly extensional arcs which also have backarc spreading have been analyzed by Scholz and Campos (1995).

The existing asymmetry between west and east Pacific subduction zones was explained by different mechanisms since the early days of the plate tectonics by several authors such as Bostrom (1971), Shaw *et al.* (1971) and Nelson and

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Temple (1972). These last authors were the first to propose an eastward main stream of the mantle, responsible for a velocity gradient in the mantle flow (see recent comments in Doglioni 2009). The present analysis will be restricted to a passive mantle model, in the sense of Scholz and Campos (1995) in which motion in the mantle is taken to be stationary in a hotspot reference frame to avoid the complexity of more advanced models that could be difficult to extrapolate in Mesozoic times (Doglioni *et al.* 2009).

On the other hand, the contrasting models of active convergent margins show that some subduction zones are dominated by a huge accretionary prism of largely oceanic sediments and rocks, while others show tectonic erosion where the forearc is composed of continental rocks that are progressively fractured and subducted, resulting in subsidence and extension (Hussong 1980; von Huene and Scholl 1991). Along the Andes and the eastern Pacific subduction zones there are good examples of the different subduction types, and the two main conceptual models are illustrated in Figure 1. However, Andean-type trenches are in fact often characterized by crustal erosion by subduction (e.g. von Huene and Scholl 1991; Ranero and von Huene 2000; Kukowski *et al.* 2001), rather than accretion (Moore 1986; Kukowski *et al.* 1994). Therefore, these models should be taken as extreme ends of potential settings, because combination of a forearc with severe subduction erosion may depict an extensional setting in the forearc similar to the one depicted in Figure 1b, with conventional compression in the retroarc as shown in Figure 1a. The first setting may be associated with a robust magmatic arc, with highly differentiated products, with a typical calc-alkaline volcanic suite, associated with a fold and thrust belt, with important shortening and a thick foreland basin (Figure 1a). On the other hand, the second setting (Figure 1b) depicts an attenuated crust under extension, with the arc developed in a rift setting, and characterized by poorly evolved volcanic rocks, mainly of basic composition; the back-arc is dominated by extensional basins where taphrogenic deposits accumulate.

In order to discuss the geological evidence associated with the different scenarios it will be necessary to do a brief discussion of the different parameters that affect the subduction in an Andean-type setting.

## 2. SUBDUCTION PARAMETERS IN THE ANDES

The subduction of a continental crust by an oceanic plate is far from being a simple plate interaction. There are several factors that affect the geological processes and the final products along a continental margin. Nevertheless, there is some consensus that the main parameters that control the geometry, coupling and tectonic setting of Andean-type subduction zone are: length of the Benioff zone, relative convergence rate, age of the downgoing slab, slab dip, direction of mantle flow, absolute motion of the over-riding plate and slab retreat, among others (Jarrard 1986; Daly 1989; Doglioni *et al.* 1999, 2007, 2009; Oncken *et al.* 2006). All these first-order oceanic parameters should be combined with second order features. The collision of aseismic and

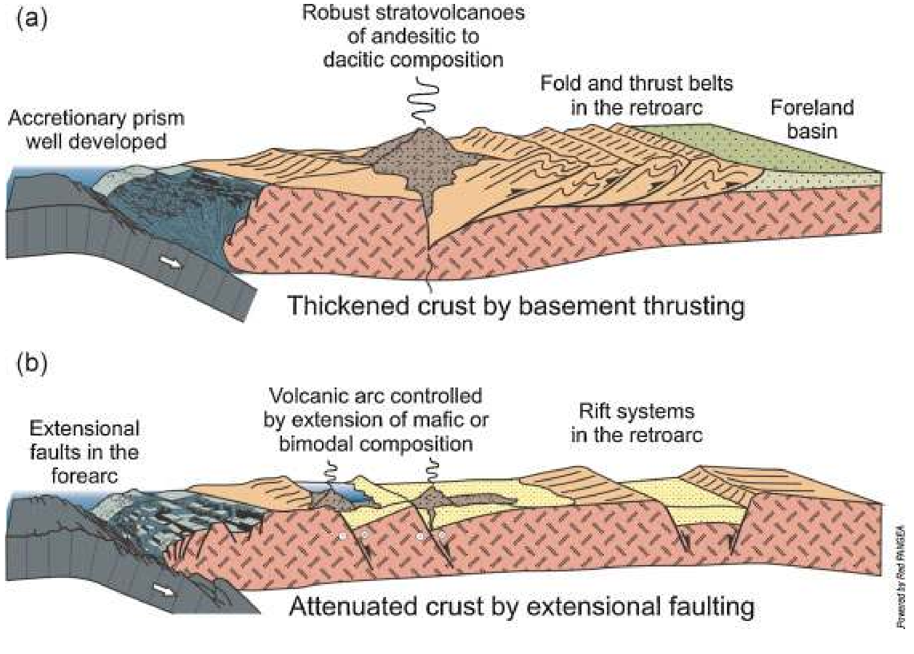

Figure 1. Contrasting conceptual models of Andean-type margins: (a) margin under compression, which is the dominant setting in most of the present Andes; (b) margin under extension as seen in northern Central America (see Discussion section in the text). Modified from Hussong (1980).

seismic ridges or the collision of fracture zones may generate changes in the regional stress state of the overriding plate, and localized tectonics in the Andean orogen (Pilger 1984; Ramos and Kay 1992; Gutscher *et al.* 2000; Spikings *et al*. 2001, 2008; Ramos 2005; Breitsprecher and Thorkelson 2009; Folguera and Ramos 2009).

On the top of that, weakness zones in the continental crust, such as old sutures among different Palaeozoic or Mesozoic terranes (McCrory 1996; Doglioni *et al.* 2007; Ramos 2008), or extensional faults of an earlier tectonic stage (Kley *et al.* 1999; Ramos 1999) will also exert an important control in the structural style and in localizing Andean deformation.

In recent years, the influence of climate has become evident after the proposal of Montgomery *et al.* (2001), Lamb and Davis (2003) and Oncken *et al.* (2006). As shown by Sobolev and Babeyko (2005), one of the main factors controlling mountain uplift in the Andes is the shear coupling at the plates' interface. The friction coefficient in the subduction channel is a first-order parameter to transmit deformation to the upper plate. The friction is directly related to the amount of sediments in the trench: starving trenches under extreme arid conditions, as the Perú–northern Chile trench, will have the maximum coupling, while the overfilled trenches in humid climates as in the southernmost and northernmost Andes will have minimum. Although there is a general consensus in this hypothesis, some authors e.g. Hartley (2003) casts doubts on the rain–shadow mechanism as responsible for the increased aridity related to the Andean uplift.

The kinematics between the upper and lower plate in the Andean subduction system following Daly (1989) can be expressed by the relationship between the roll-back of the subduction trench line and the motion of the overriding plate toward or away from the trench line within an asthenospheric reference frame (Dewey 1980). This is correct only in a passive mantle model (Scholz and Campos 1995), because if a global westward motion of the lithosphere is considered these premises are not valid (see discussion in Doglioni *et al.* 2009). If we take into consideration the shortening and stretching rates and the crustal erosion by subduction rate, the relations between the different rates are shown in Figure 2. These relations have been applied to the whole Andes, showing that the absolute motion of the upper plate relative to the Pacific hotspot frame was one of the most important parameters to predict the tectonic stress through time, as depicted by the trench roll-back velocity (Ramos 1999; Oncken *et al.* 2006).

A first-order control is the absolute motion relative to the Pacific hotspot reference frame of the over-ridding plate as demonstrated by Jarrard (1986) and Heuret and Lallemand (2005), which produces either the retreat of the trench hinge away from the upper plate (trench roll-back), generating widespread extension (Figure 3b), or the advance of the upper plate towards the oceanic plate generating a strong coupling and a robust compression (trench roll-back Vt > 0, Figure 3c) (Heuret and Lallemand 2005). Some examples show that the hinge line may stay almost fixed in an asthenospheric reference frame (neutral trench roll-back, Figure 3a), and these subduction systems will be quasistationary through time. If the shortening rate of the compressional system or stretching rate of an extensional system is taken into consideration, the relationship between trench roll-back rate and absolute motion can be expressed as shown in Figure 2. The system could be better depicted if the crustal removal of subduction erosion is taken into consideration (von Huene and Scholl 1991; Ranero and von Huene 2000).

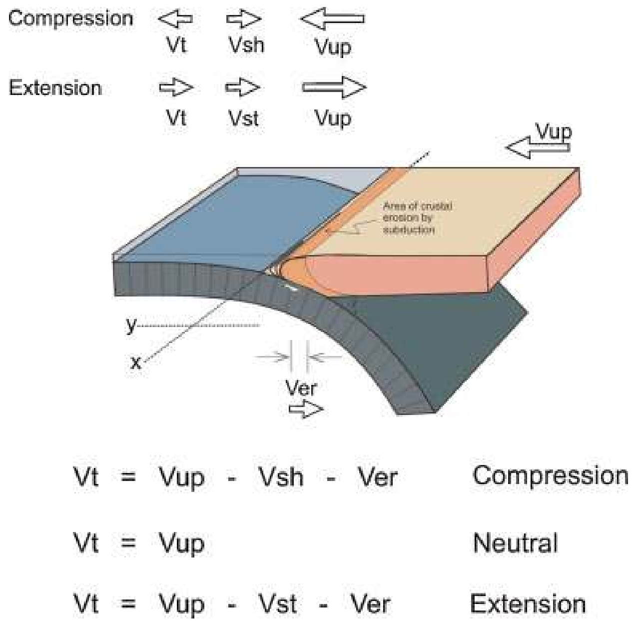

Figure 2. Main kinematic parameters controlling the tectonic regime in an Andean setting under subduction. Vt: trench roll-back velocity; Vup: upper plate absolute motion; Vsh: shortening rate; Vst: stretching rate and Ver: crustal erosion rate (modified from Daly 1989; Heuret and Lallemand 2005).

Some second-order controls in the kinematics, such as oceanic ridge collisions or fracture zone collisions, can be locally overimposed on the first-order control, yielding for example some localized extra compression in restricted areas. A good example of this interaction is the aseismic ridge collision of the Chile seismic ridge against the South American plate, which produced a wave of mountain uplift from south to north in the Patagonian Andes (see Ramos and Kay 1992).

Some other second-order factors that may change the first-order regime in the Andes are the local change of the slab dip, generally produced by collision of an aseismic ridge. The Juan Fernandez ridge collision from north to south in central Chile (Yañez *et al.* 2001) controlled the shallowing of the oceanic slab and the coupling increase that led to a

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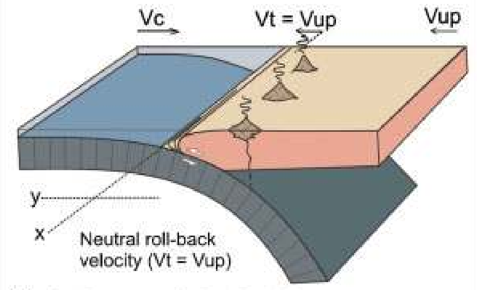
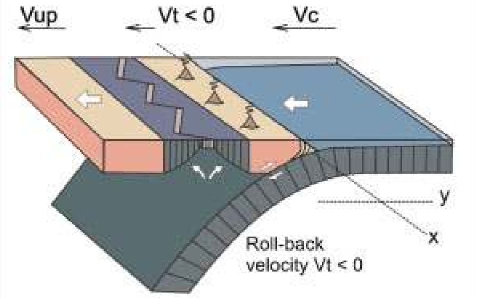
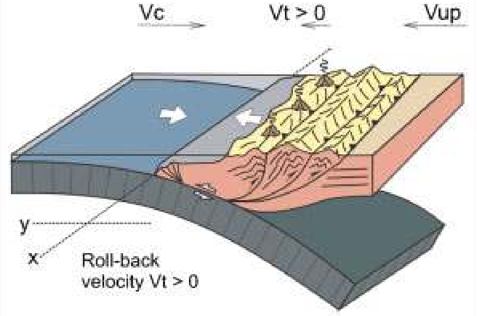


(a) **Stationary subduction hinge**



(b) **Retreating subduction hinge**



(c) **Forward migrating subduction hinge**

Figure 3. Main parameters in the present Andean settings: (a) trench roll-back velocity equal zero; (b) trench roll-back velocity ($Vt < 0$) in the Marianas type (after Uyeda 1983) and (c) trench roll-back velocity ($Vt > 0$) in the Chilean type (after Daly 1989; Heuret and Lallemand 2005). Vt: trench roll-back velocity; Vc and Vup: lower and upper plate velocity. See Discussion section in the text.

coeval north to south deformation in the foreland, up to the final uplift of the Sierras Pampeanas (Jordan *et al.* 1983a, b; Ramos *et al.* 2002), with important changes in the magmatism previous to the final gap at the flat-slab stage (Kay and Mpodozis 2002).

The deepening of the slab dip, mainly after a period of shallow to flat subduction, generates localized extension in the foreland that migrates towards the trench. This fact produces a generalized extensional collapse of the compressive structures in the upper plate as reported in the Neuquén Andes by Folguera *et al.* (2008) associated with an outstanding change in the magmatic behaviour (Kay *et al.* 2006). The detailed studies of the mantle flow through shear wave splitting analysis have shown important anisotropies that correlate with these changes in the slab geometry, mainly along the segment boundaries between contrasting geometries (Anderson *et al.* 2004).

## 3. PRESENT SUBDUCTION REGIMES

There is a large variety of tectonic settings in the subduction zones. The tectonic regime can be addressed through the structural style in the overriding plate, which is determined by its stress state. Jarrard (1986) classified each individual subduction zone into one of seven semiquantitative strain classes that form a continuum from strongly extensional with back-arc spreading to strongly compressional with active folding and thrusting. Four classes or subtypes have been selected in the present analysis from this continuum to portray the most frequent geological processes associated with different strain states. The four different scenarios are the Nicaragua, Sandwich, Oregon and Chile subduction zones, which together exemplify a large variety of magmatic rocks, structures and sedimentary basins seen in the Andes. The aim of this analysis is to identify in these present settings a series of simple geologic features that can be used to explore ancient subduction sites.

### *3.1. Nicaragua subduction zone*

The northern Caribbean subduction system is a key area to analyze the strain state through the structural style of deformation and the related behaviour of the magmatic arc. The first drilling of DSDP in the Guatemala forearc led Auboin *et al.* (1984a,b) to propose a new type of margin, the convergent–extensional active margin, based on the extensional structure on the landward as well as the seaward trench slopes. The collapse of the trench landward slope was interpreted as evidence of no accretion and generalized extension. However, a few years later Moore (1986), based on higher resolution techniques, demonstrated that structures at the base of the landward slope are most simply interpreted as resulting from the offscraping and accretion of the uppermost trench sediments. Subsequent studies demonstrated that the lack of sediments in the trench, less than a few hundred metres thick, was mainly due to important crustal erosion by subduction that produce in many cases important extensional faults and collapse of the forearc (Von Huene and Ranero 2003; Vannucchi *et al.* 2004). On the other hand, the Guatemala subduction is adjacent to the Polochic–Motagua left-lateral strike-slip zone, a plate boundary between the North America and Caribbean plates (Lyon-Caen *et al.* 2006). Guatemala has a special position as part of the Caribbean Plate relatively moving east–southeast, and immediately adjacent to the North American Plate, which is moving in a westward direction (Morgan *et al.* 2008). This large transcurrent fault produces an important disturbance in the strain field of Guatemala, and therefore we focus our attention further south in Nicaragua, to avoid these local effects.

Although the model fails to explain the nature of the structure found in the Guatemala forearc, the notion that a plate under subduction could have compression in the forearc and extension in the arc and in the back-arc regions, can be better seen in Nicaragua, farther from the influence of the plate boundary.

The new data on the Cocos–Caribbean Plate interaction predict convergence directions along the Middle American trench that are ∼10° counter-clockwise from trench-normal (DeMets *et al.* 2000). The existence of arc-normal extension in the Middle American Arc is recorded by GPS measurements which suggest an extension rate of ∼3 mm/year based on the average velocities between GPS data from the forearc and behind the arc (Turner *et al.* 2007; Morgan *et al.* 2008).

Evidence for extension in the back-arc is a long-accepted fact in Guatemala (Burkart and Self 1985; Guzmán-Speziale 2001; Lyon-Caen *et al.* 2006), where it is usually attributed as a by-product of the interaction of the Caribbean–North American plate boundary with the Middle American Arc. The extension in Nicaragua and in the offshore Nicaraguan Rise was early described by Mann and Burke (1984) and is presently attributed to a faster westward motion of North America relative to South America that is accommodated by the extension within the Caribbean Plate (Doglioni *et al.* 2007). As proposed by Tonarini *et al.* (2009) the upper plate extension is primarily related to the stretching generated by the faster westward advancement of North America relative to South America. However, some authors postulate that the distance between North America and South America was decreasing since the Eocene, which implies convergence between the Americas, and that extension is related to the eastward absolute motion of the Caribbean Plate (see for discussion Somoza 2007).

The magmatism within the volcanic arc is strongly controlled by intra-arc extension as described by Morgan *et al.* (2008). Nicaragua also has the advantage that the arc has migrated trenchward with time; therefore, unlike other arcs where the volcanic history is buried by each successive eruption, the past 20 Ma of arc volcanism is exposed in surface outcrops in Nicaragua (Plank *et al.* 2002). Three major volcanic events have occurred in Nicaragua since middle Tertiary time (Figures 4 and 5). First, the Oligocene was dominated by a rhyolitic plateau that formed the Highland ignimbrite. Second, the extrusion of basaltic to andesitic magmas along the Pacific coast as part of the Miocene volcanic arc was controlled by northwest-trending extensional

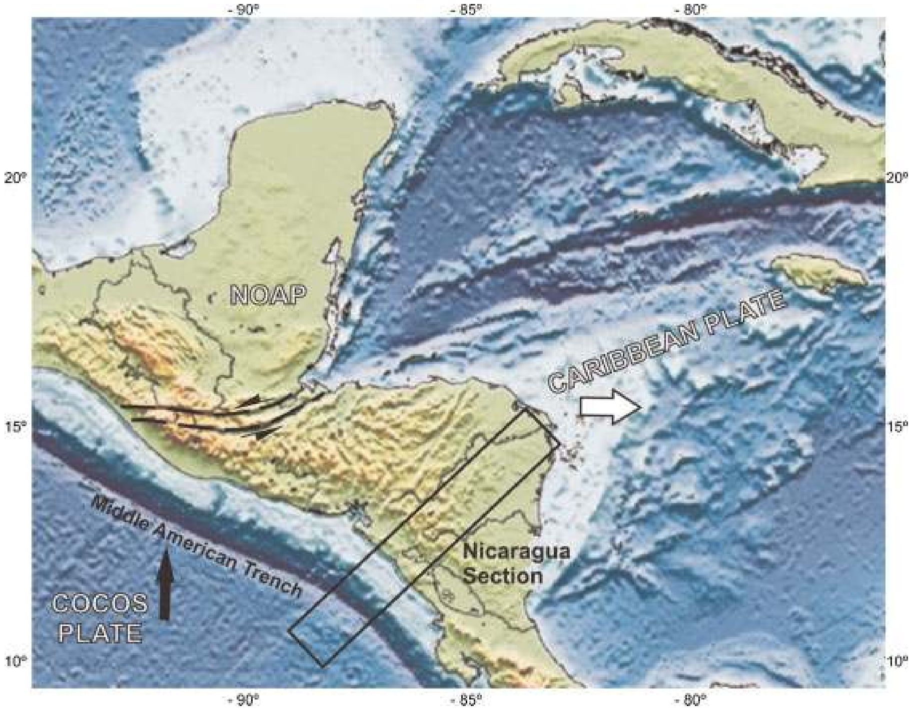


Figure 4. Regional location of the Nicaragua subduction zone depicted in Figure 5 in Central America with indication of the Polochic–Motagua left-lateral strike-slip fault zone that bounds the North American Plate (NOAP) with the Caribbean Plate. The large open arrows indicate the absolute motion of the Caribbean Plate with respect to North America, while the solid arrow indicates the convergence vector between Cocos and Caribbean plates (CO–CA) (based on DeMets *et al.* 2000).

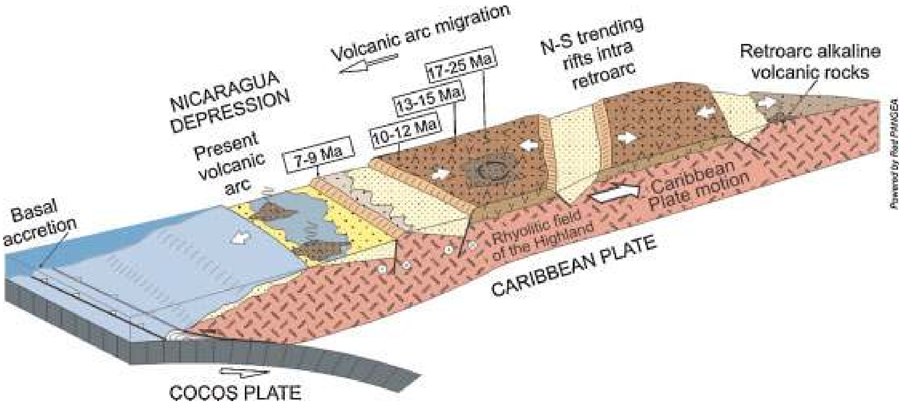


Figure 5. Present-day tectonic setting of subduction in Nicaragua. Note the basal accretion in the inner slope of the trench (Moore 1986), and the transtensional setting of the magmatic arc (Cáceres *et al.* 2005). Miocene arc migration was from the back-arc toward the trench (based on Plank *et al.* 2002). Rifting in the retroarc is oblique to the subduction trend (after Álvarez-Gómez *et al*. 2008). Location in Figure 4. See Discussion section in the text.

fracture zones. Third, a Pliocene–Pleistocene southwestward shift created the modern volcanic arc (Ehrenborg 1996). The Recent basic lavas from stratovolcanoes in the Nicaraguan Depression are calc-alkaline with tholeiitic affinities (Nyström *et al.* 1988; Darce *et al.* 1991). The modern volcanic rocks further to the northwest along the San Salvador Arc show similar affinities (Agostini *et al.* 2006). The Recent volcanic arc is controlled by a transtensional regime, and the initial neodymium isotope ratios show very small variations, between 0.51297 and 0.51301 and initial strontium isotopic composition ranges between 0.70357 and 0.70390. There is a mild shift toward higher Sr isotopic composition with respect to the mantle, but when compared with typical Andean suites these rocks are in general poorly evolved (see Stern 2004). There is no evidence in the lavas erupted throughout this magmatic arc of crustal assimilation in Nicaragua, based on geochemical or isotopic grounds. This was mainly explained by the thin continental crust, and young age of the oceanic crust (Carr *et al.* 2003; Shaw *et al.* 2006).

The age trend of the Cenozoic volcanics clearly indicates a trenchward propagation of the extension, similar to the rift structural propagation proposed behind the arc by Mann and Burke (1984). This extension coincides with the evaluation of the seismic moment tensor, which allows estimating the rate of deformation in the interior part of northern Central America that ranges from 10 to 17 mm/year towards the east–southeast (Cáceres *et al.* 2005).

As a result of this extension, an intra-arc basin is filled with coarse volcaniclastic and volcanic products, and depending on the balance between sediment supply and amount of extension, it could reach a low-energy lacustrine sedimentation as in the Managua and Nicaragua lakes. These basins have a series of characteristic proximal, medial and distal volcaniclastic facies as described for Guatemala by Vessell and Davies (1981). A set of rift basins can form behind the arc, and the sedimentation will be controlled by the local relief and the sediment and volcaniclastic supply.

As a partial conclusion it can be asserted that when the upper plate retreats, extension dominates in the arc and behind the arc as in the Nicaragua subduction type. The tectonic regime in the forearc will depend on the amount of crustal erosion by subduction, and could vary from moderate accretion to an extensional setting, in cases of robust crustal erosion (Houston *et al.* 2008).

### *3.2. South Sandwich subduction zone*

The only site along the western margin of the South American Plate where subduction is associated with back-arc spreading is in the South Sandwich volcanic arc. The oceanic Sandwich microplate is being subducted by South America at a convergence rate between 68 and 79 mm/year (Figure 6).

It is well established that the Earth's convecting upper mantle can be viewed as comprising three main reservoirs, beneath the Pacific, Atlantic and Indian oceans, and that the Pacific reservoir is at present contracting, while the others are growing. This produces a net mantle flow from the Pacific to the Atlantic trough as series of gateways, where the Drake Passage is one of them. The geochemical studies of Pearce *et al.* (2001) reported the Pacific signature in the volcanic rocks erupted in the South Sandwich Arc, confirming the existence of this outflow in the recent past (Figure 7). This evidence reinforces the proposal that the relative 'eastward' mantle flow could favour the bending of the slab and the foredeep fast subsidence along the hinge of W-directed subduction zones (Doglioni *et al.* 2007).

The tectonic setting indicates a moderate coupling between both the upper and lower plates. The South Sandwich Arc is entirely intra-oceanic, far-removed from any continental crust and, on the basis of magnetic anomalies, is situated on 10 Ma old oceanic crust of the Sandwich Plate (Barker and Hill 1981).

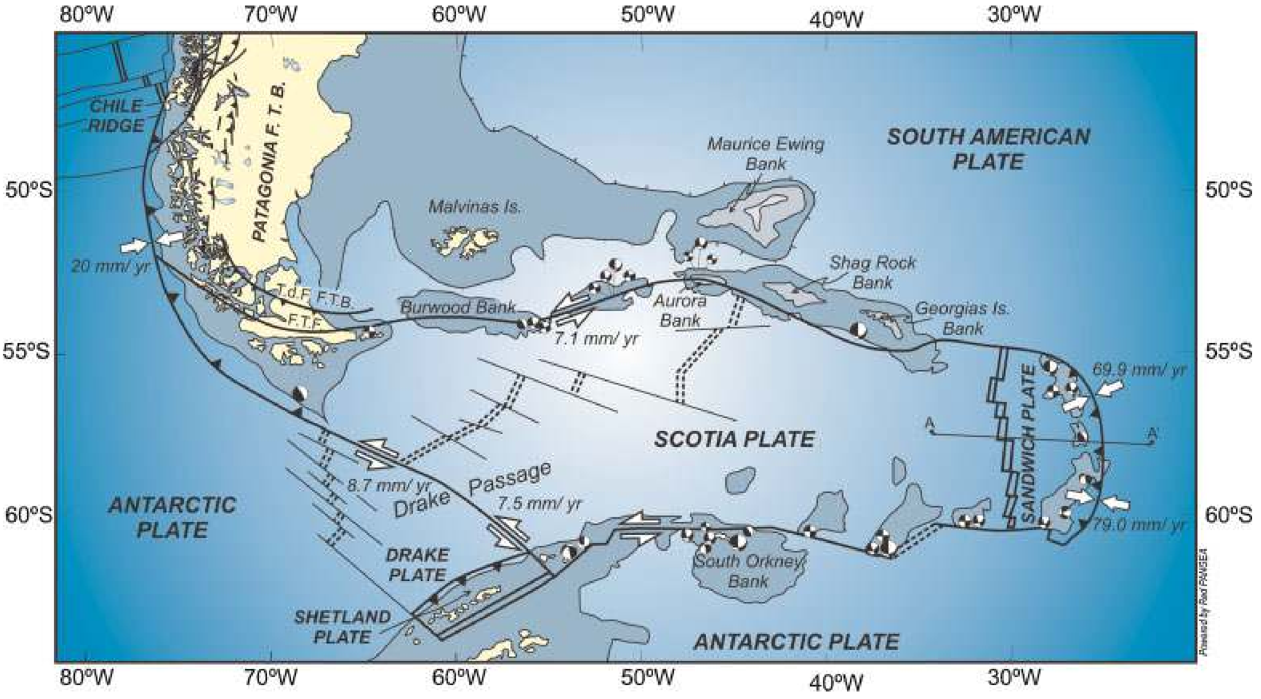


Figure 6. Tectonic setting of the Scotia Plate with the interaction between the South America and the Sandwich Plates (based on Barker 2001; Eagles *et al.* 2006; Ramos 2009, and references therein). Section A-A′ corresponds to Figure 7.

A new multichannel seismic reflection survey identified arc-ward tilted blocks in the mid-forearc indicating large scale gravitational collapse, consistent with earthquake data indicating normal extension at shallow depth in this area (Vanneste *et al.* 2002). This has been interpreted as evidence of extension related to crustal erosion by subduction.

The volcanic arc erupt low-K tholeiitic, tholeiitic and calcalkaline rocks with an important contribution from the altered oceanic crust in a depleted mantle setting. The degree of partial melting (∼20%) is slightly smaller than beneath ocean ridges, but considerably larger than in a typical Andean setting (Eissen *et al.* 2002). Initial strontium isotope ratios are in the range of 0.7038–0.7040, while the initial neodymium isotope ratios vary from 0.512968 to 0.513140, showing some enrichment regarding the average composition of the Scotia Sea oceanic crust (Pearce *et al.* 1995).

The back-arc spreading centre of the East Scotia Ridge has been active for at least 15 Ma and lies approximately 200 km to the west of the South Sandwich Arc. It shows a wide range of compositions varying from MORB-like to arc-like, although only a small number of samples indicates a pronounced subduction-derived component, and in general,

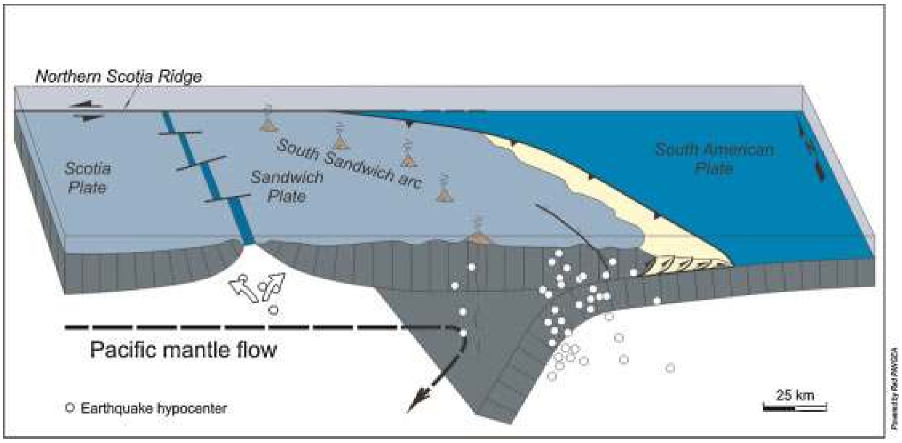


Figure 7. Marianas-type subduction in the southern extreme of South American Plate (based on Uyeda 1983; Vanneste *et al.* 2002; Leat *et al.* 2003; Barry *et al.* 2006). Pacific mantle flow after Pearce *et al.* (2001). See Discussion section in the text.

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subduction input to the back-arc magmatism is small (Barry *et al.* 2006).

There is little evidence of distributed extension within the interior of the Sandwich Plate, which suggests an environment of low interplate stress. The steepening of the subducting plate is controlled by the Pacific mantle flow, either by the dynamic eastward mantle flow (Doglioni *et al.* 2007), or the regional mantle flow as a result of the shrinking of the Pacific area (Pearce *et al.* 1995), producing a roll-back of the upper plate favouring back-arc extension.

### *3.3. Oregon subduction zone*

The pioneer work of Dickinson and Seely (1979) recognized among the large variety of continental margin arc-trench systems the noncontracted ones, which were exemplified by the Oregon subduction system. This type of setting is characterized by a back-arc region with no evidence of a well-built compressional deformation that leads to the development of a fold and thrust belt.

This setting is located in the northwestern part of the Unites States, contiguous to the Canadian boundary. The subduction of the oceanic Juan de Fuca Plate under the continental North American Plate produces the Cascadia volcanic arc (Figure 8). The Juan de Fuca Plate is one of the last remnants of the Farallon plate, which has been almost completely subducted beneath western North America during Mesozoic and Cenozoic times.

The convergence rate is estimated in 40 mm/year. The upper plate crustal thickness varies from 50 km in Washington to near 30 km for the thickest part of the Siletz terrane at the forearc (Scott 2003). The oblique subduction produces strain partitioning in the forearc.

Due to the important variability from north to south along the Cascadia Margin, the behaviour of the central Oregon segment has been selected to portray this subduction system, following Wells *et al.* (1998). This central segment is characterized by low seismicity, high extrusion rate in the volcanic arc and an incipient graben along the main volcanic axis produced by the dextral forearc rotation. The basement of the forearc is formed by the Siletz terrane, a sliver of seamount basalt accreted to North America in Mesozoic times. The Siletz terrane is translating northward along the margin relative to stable North America as well as rotating clockwise about a northern pivot (McCrory 1996).

The young (4–8 Ma), warm and heavily sedimented Juan de Fuca Plate, along with the incipient ongoing extension and high heat flow within the axial part of the Cascade Arc, led Schmidt *et al.* (2008) to the description of Cascadia as a hot subduction zone.

Volcanic products are characterized by stratovolcanoes with andesite, dacite and basalts of calcalkaline composition (Hildreth and Lanphere 1994), together with caldera-forming events associated with rhyolitic ignimbrites, and low-K tholeiites related to late monogenetic cones. Initial strontium isotope ratios in the central Oregon segment vary from 0.7034 to 0.7038 and the initial Nd-isotope ratios from 0.5127 to 0.5130 (Schmidt *et al.* 2008), showing no crustal components associated with assimilation or crustal melting. These characteristics are enhanced in the late monogenetic cones, which are closely associated with the incipient extension.

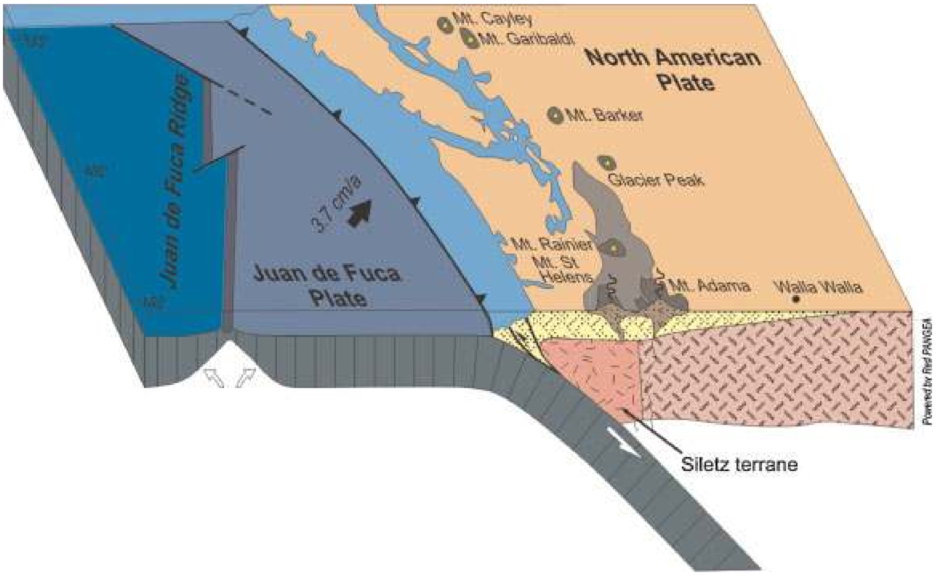

Figure 8. The Oregon subduction zone (based on Dickinson and Seely 1979; Wells *et al.* 1998; Gerdom *et al.* 2000 and Schmidt *et al.* 2008).

Basin formation at this setting is not significant and is represented by some thin alluvium and fluvial facies.

There is no doubt, at least in the central Oregon segment, that the compressional stress that deformed the accretionary prism (Gerdom *et al.* 2000) is not enough to deform the back-arc of the Cascadia volcanic arc. This neutral setting with null to mild deformation would be an early stage of a Chile-type subduction, and it has been explained as the result of slow absolute motion of the upper plate combined by subduction of very young oceanic crust (Heuret and Lallemand 2005).

### *3.4. Chile-type subduction*

This is the archetype of a strongly compressional setting as defined by Uyeda and Kanamori (1979), although as noticed by Jarrard (1986) there is an important variation from very strong to mild compression from northern to southern Chile. This variation follows the segments identified by Isacks and Barazangi (1977) and Jordan *et al.* (1983a), based on the different seismotectonic behaviours controlled by the subduction geometry, age of the oceanic crust, variations in the overridden velocity of the upper plate and friction coefficient in the subduction channel. The recent analysis of Yañez and Cembrano (2004) postulates the plate coupling between the oceanic and the continental plate as one of the most important controls. This plate coupling will depend on the age of the subducting plate and on the convergence rate. These factors control the geometry and deformation in the forearc which will depend on the age of the oceanic crust at a given convergent velocity. Similar conclusion were arrived by Ramos *et al.* (2004) based on the analysis of the shortening and the age of the oceanic crust. It is worth mentioning that the analysis of Oncken *et al.* (2006) arrived at different conclusions further north. Based on the relationship between shortening and convergent velocity, these authors found that when the convergence velocity decreased, the deformation increased, concluding that the upper plate shortening rate appears to be anti-correlated with the plate convergence rate, for all of the Neogene in the Central Andes.

Yañez and Cembrano (2004) interpreted that the arc-foreland deformation is controlled by the absolute plate velocity of the continental plate and the resistance at the slip zone. The absolute motion can be expressed by the trench roll-back velocity, which will be retreating when the overridden velocity goes away from the trench as proposed by Daly (1989) and Ramos (1999) in a passive mantle flow model (Scholz and Campos 1995) producing extension.

The central segment of Chile located between 28° and 32°S has been selected to illustrate the Chile-type subduction, because it represents one of the strongest compressional setting along the Andean margin (Figures 9 and 10). This segment coincides with the Pampean flat-slab subduction, responsible of the broken foreland that formed the Sierras Pampeanas, basement core uplifts related to the shallowing of the subducted Nazca Plate beneath South America (Jordan *et al.* 1983b; Ranero *et al.* 1997; Ramos *et al.* 2002).

The Nazca Plate at this segment has a convergence rate relative to South America orthogonal to the trench between 7.6 and 7.8 cm/year (Pardo *et al.* 2003), and an absolute motion of the upper plate in the Pacific hotspot frame of 1.6 cm/year toward the trench (Silver *et al.* 1998; Oncken *et al.* 2006). This trench roll-back when $Vt > 0$, is one of the main factors controlling the important shortening rate at these latitudes. The measurements of the fold and thrust belt shortening in different sections across the Andes between 28° and 32°S in the last 20 Ma show that shortening rates vary from 7.3 to 7.7 mm/year along the La Ramada northern section to 5.5–5.7 mm/year in the Aconcagua southern section (Ramos *et al.* 2004). These values are of the same order than the GPS displacements of ~4.5 mm/year measured across the orogenic front by Brooks *et al.* (2003). If we assume some elastic recovery of these displacements, there is a good correlation between absolute motion relative to the Pacific hotspot frame and GPS data. The deformation rates are larger than the 10% of the motion of the upper plate as proposed by Gripp and Gordon (2002).

There is a gap in the volcanic arc at these latitudes (Figure 9) produced by the Pampean flat-slab subduction (Ramos *et al.* 2002). The previous magmatic arc had conspicuous characteristics before coming to an end in the last 2 Ma. It had a clear trend from poorly evolved basalts in the Late Oligocene to more evolved calcalkaline products in the Miocene and Pliocene erupted through large stratovolcanoes. The andesites and dacites show a continuous increase of the La/Yb ratio that has been correlated with the fractionation of garnet in the source, and therefore with an increase of pressure related with crustal thickening by tectonic stacking at these latitudes (Kay *et al.* 1991; Kay and Mpodozis 2002). This increase in deformation is related to a general faster convergence rate after the Late Oligocene quiescence (Pardo Casas and Molnar 1987; Somoza 1998).

The structure varies from dominant thin-skinned to thick-skinned tectonics depending on the fragmented nature of the upper crust, where previous normal faults created weakness zones in the basement (Ramos *et al.* 1996; Kley *et al.* 1999; Cristallini and Ramos 2000). In extreme cases, as in the Pampean flat-slab segment (Figure 10), deformation produced basement uplift in the foreland as seen in the Sierras Pampeanas (Ramos *et al.* 2002). Time constraints indicate that most of the shortening has been produced during the late Neogene coeval with the shallowing of the subduction zone.

Figure 9. The Northern, Central and Southern Andes with the location of the different tectonic sections discussed in Figures 10–16.

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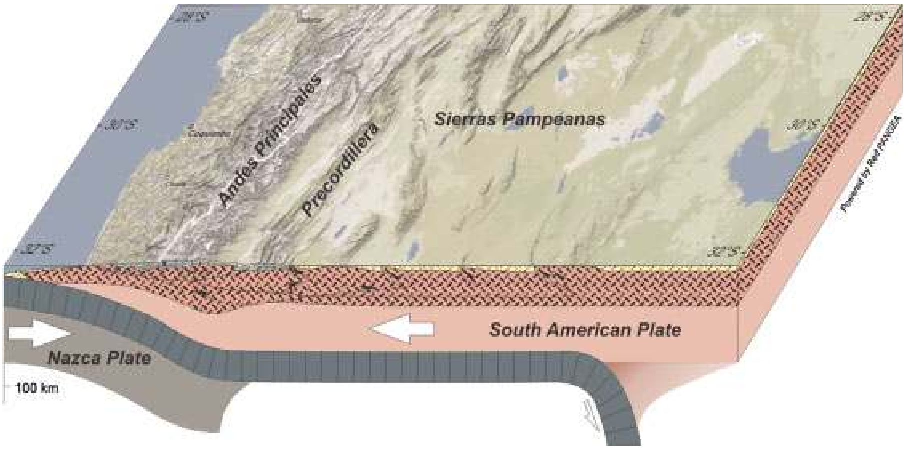

Figure 10. Chile-type subduction exemplified by the Pampean flat-slab segment. The slab geometry is after Cahill and Isacks (1992); crustal structure is based on Ramos *et al.* (2002); the asthenospheric wedge depicted through magneto–telluric sounding after Booker *et al.* (2004) (see location in Figure 9).

These deformations were associated with important crustal stacking and tectonic loading which produced broken foreland basin formation as depicted by Jordan (1995). A series of depocentres has been successively formed and they migrated to the foreland reaching thickness over 10 000 m (Ramos 1970; Jordan *et al.* 1983b; Giambiagi and Ramos 2002).

Based on all these characteristics, it should be emphasized that a strongly compressional regime is related to a mature volcanic arc with highly evolved magmatism that reach an end when the shallowing produces a flat-slab subduction (Kay *et al.* 1991); a belt of robust deformation in highly shortened fold and thrust belts, and important foreland basin sedimentation. This typical Chilean-type deformation is the result of an important westward absolute motion relative to the hotspot frame of the upper plate, between 34 and 45 mm/year (Gripp and Gordon 2002), which is almost several times larger than shortening rates at these latitudes (5–7 mm/year, Ramos *et al.* 2004). This produces that the trench is overridden by the upper plate and when $Vt > 0$ the trench is associated with a robust compression. The coupling between lower and upper plate is locally increased by the subduction of the Juan Fernandez aseismic ridge (Ranero *et al.* 1997; Yañez *et al.* 2001). The subduction of the aseismic ridge produced the extreme Pampean flat-slab segment (Jordan *et al.* 1983b; Ramos *et al.* 2002).

There is no doubt that this setting is producing the largest coupling between the lower and upper plate in the Andean system, but it is necessary to remark that most of the Chilean-type settings do not reach this stage. Along the Pacific margin of South America there are only two segments where collision of aseismic ridges is observed and therefore flat-slab subduction and extreme compression are achieved (see Gutscher *et al.* 2000; Ramos and Folguera 2009).

Extreme compression is not always related to the largest deformation and shortening in the Andes. There are good examples as in northern Chile and Bolivia, which show that thermal weakening by crustal and lithospheric mantle delamination during steepening of the oceanic slab will produce larger deformation (James and Sacks 1999; Kay *et al.* 1999; Kay and Coira 2009; Ramos 2009).

## 4. PAST SUBDUCTION IN THE ANDES

The observation of the Mesozoic palaeogeography, together with the relationship among structure, magmatism and basin formation in the Northern, Central and Southern Andes shows some striking characteristics as described by Mpodozis and Ramos (1990) and Ramos and Aleman (2000). The Mesozoic palaeogeography will be described from sections where extension was prevailing to areas where compression was dominant in order to correlate them with the depicted present-day settings.

### *4.1. Extensional regimes*

The whole Central Andes depict evidence of extension during Late Jurassic to Early Cretaceous times. There are good examples of extensional structures in central Chile, near Copiapó in the Sierra de Puquios (Mpodozis and Allmendinger 1992). There, in Quebrada Paipote (27°07′S and 69°50′W) a sequence of Valanginian rocks has been extended with a stretching factor over 100% (Figure 11a, b). This localized extension is characteristic of the Early Cretaceous basins not only in the Central Andes but also along the entire Pacific margin as seen from Colombia to southern Chile (Ramos and Aleman 2000).

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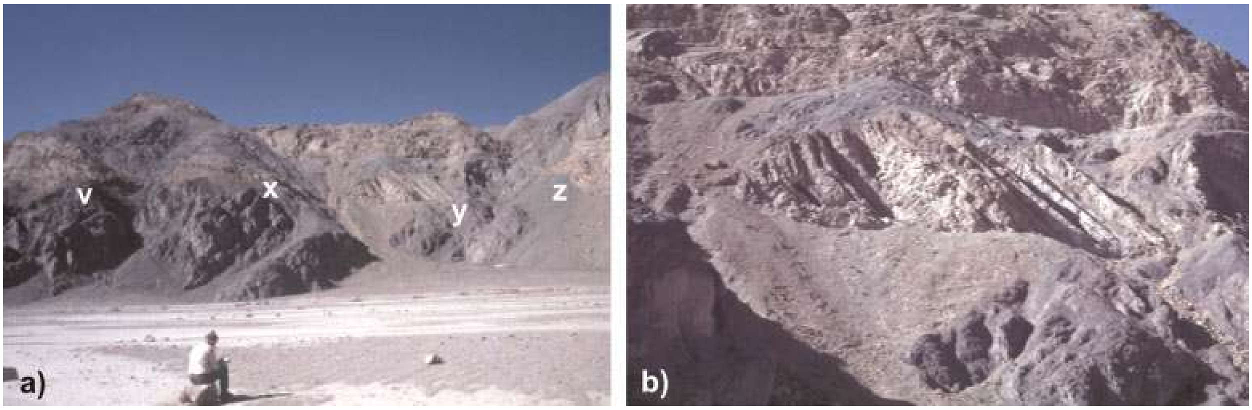

Figure 11. Evidence of extension in Quebrada Paipote, upper valley of Río Copiapó (27°5′S and 69°47′W). (a) A series of boudins or extensional duplexes developed in marine Valanginian carbonates in a ductile volcanic matrix (*v*, *x*, *y* and *z*) of tens of metres wide, bounded by gentle dipping normal faults; (b) detail of duplex *y*, where the cut-off angles of the structure can be seen: the upper normal fault has angles from 90 to 60°, while the lower fault has angles from 60 to 45°, both typical of cut-off angles of a normal fault (photo Ray Price). See location in Figure 9.

There is some variety in the geometry and distribution of the extension along the continental margin. Due to the important crustal erosion by subduction of the margin observed from Peru to northern Chile since Late Cretaceous time, ranging from 90 to over 200 km along the Pacific edge of the continent (Stern and Mpodozis 1991), there is not direct evidence of the tectonic setting of the forearc. However, the magmatic characteristics of the arc shed some light on the dominant process through time. Indirect evidence obtained in petrological grounds indicates that important crustal erosion is recorded in the volcanic rocks as suggested by transient peaks of the La/Yb ratio, known as the adakitic signal (Skewes *et al.* 2002; Kay *et al.* 2005). Absolute motion relative to Pacific hotspot frame of the Western Gondwana plate was to the northeast until the late Early Cretaceous break-up, when the South Atlantic Ocean began opening. South America started moving westward, and this change in the absolute motion was responsible for a variation along the Pacific margin of the trench roll-back velocities (from $Vt < 0$ to $Vt > 0$) (Somoza and Zaffarana 2008). This change produced significant modification in the magmatism, structure and mechanism of basin formation all along the Andean Margin (Mpodozis and Ramos 1990). The different segments have distinct geologic histories controlled by the crustal anisotropies and location along the margin. A series of representative segments have been selected to depict the geological settings.

### *4.1.1. Tarapacá segment (21°–27°S lat.)*

Northern Chile is a good example of important crustal erosion by subduction associated with an extensional regime since Early Jurassic times when the Tarapacá Basin was formed (Figure 12a). This basin was filled with several thousand metres of carbonate and terrigenous sediments (Harrington 1962; Coira *et al.* 1982; Naranjo and Puig 1984; Mpodozis and Ramos 1990, 2008).

The magmatic arc was dominated by tholeiitic basaltic rocks, gabbros and mafic dykes associated with calcalkaline andesites and basaltic andesite flows with almost no contribution from the underlying crust (Mpodozis and Ramos 1990; Scheuber *et al.* 1994; Oliveros *et al.* 2006). These basic rocks were dominant in the present Cordillera de La Costa and are very near to the present-day trench. The huge volumes of these rocks were interpreted as derived from a MORB-like source, but recent studies have demonstrated an origin associated with subduction, based on larger geochemical sampling (Kramer *et al.* 2005). The magma source is likely to be a depleted mantle metasomatized by fluids, which originated from dehydration of the subducted oceanic crust, with no evidence of slab melting (Oliveros *et al.* 2006). However, this magmatic arc was developed in a highly attenuated crust, as seen in the Antofagasta region (23°45́S), where there are alternating flows of andesites, mafic andesites, basalts and interbedded volcanic breccias, agglomerates and volcaniclastic rocks more than 10 000 m thick (Marinovic *et al.* 1995; Vicente 2005). The thickness and volume of these impressive Early to Late Jurassic sequences are consistent with the poorly evolved composition.

These igneous rocks were coeval with the infill of the Tarapacá Basin, a typical extensional trough with more than 5000 m of Lower Jurassic deposits (Figure 12a). Normal faults controlled the sedimentation of thin limestones, black shales and other clastic sediments interbedded with volcaniclastic deposits (Naranjo and Puig 1984). Further to the south, deposition was characterized by thick clastics that record an alluvial fan and shallow marine fan–delta

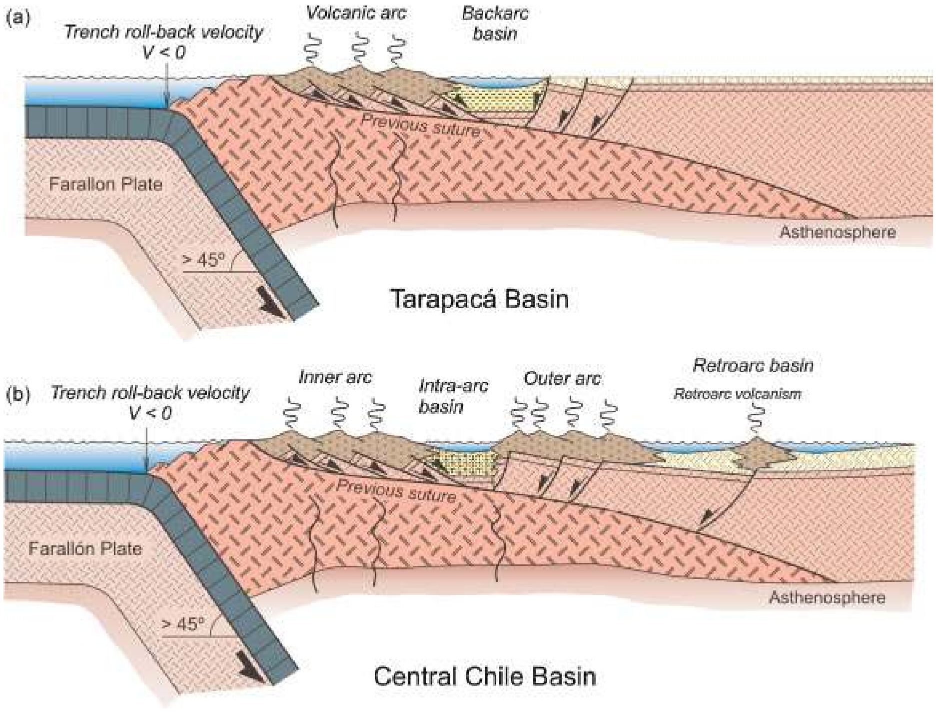

Figure 12. Palaeogeographic reconstruction of the Tarapacá Basin in northern Chile and Central Chile Basin at the latitude of the Aconcagua (based on Mpodozis and Ramos 2008) (see location in Figure 9).

complex developed in a fault-controlled extensional setting (Bell and Suárez 1995).

The extensional setting proposed by Auboin *et al.* (1973) within the geosynclinal theory is generally accepted, but within a framework of an active continental margin associated with a back-arc basin (Coira *et al.* 1982; Mpodozis and Ramos 1990). The different tectonic settings for this arc segment varies from: (1) a weakened trench-parallel sinistral shear zone (Scheuber and González 1999); (2) subsiding intra-arc basins related to arc normal extension in a low convergence rate regime (Grocott *et al.* 2002); (3) to an extensional continental arc margin associated with a back-arc basin (Rogers and Hawkesworth 1989; Mpodozis and Ramos 1990; Ramos 1999), where magmas have ascended rapidly in a short time interval with a relatively homogeneous geochemical character that dominated from Middle to Late Jurassic times (170–150 Ma). The arc rocks reached the surface without major interaction with the continental crust (Oliveros *et al.* 2006).

The poorly evolved character of the arc, the normal faults and the sedimentation are similar to the Nicaragua subduction zone, coherent with the back-arc basin development and associated sedimentation. This setting is better interpreted as controlled by the eastward absolute motion relative to the hotspot frame of the upper plate as depicted by Somoza and Zaffarana (2008), which produced a trench roll-back ($V_t < 0$) and generalized extension in a highly attenuated continental arc.

### *4.1.2. Central Chile Basin (28°–35°S lat.)*

The tectonic setting of this segment looks similar to the previous segment, but a detailed analysis shows significant differences. The main distinction is the development of an intra-arc basin that is bounded by an inner and an outer arc as shown in Figure 12b.

The inner arc developed along the Coastal Cordillera of central Chile, erupted more than 2000 km$^3$ of acid and 9000 km$^3$ of basic volcanic rocks forming a 15-km-thick pile of alternately marine and continental deposits during the Jurassic and Early Cretaceous (Vergara *et al.* 1995). The initial volcanics were more tholeiitic, changing to a more calcalkaline character in the younger rocks. The source of the magmas became more depleted with time due to an increase in degree of partial melting, and their compositions were modified by subduction-related fluids and contamination with a progressively thinner and younger crust (Levi 1973; Aguirre *et al.* 1989; Levi *et al.* 1989). The extension and subsidence resulted in low-relief topography close to sea level, in contrast with the present-day convergent Andean-type volcanism at the same latitude.

The outer arc consists of a thick pile of andesites and basaltic andesites exposed in the Cordillera Principal, reaching several thousand metres thickness, which are interbedded with thin carbonate marine deposits and alluvial and fluvial sediments (Rivano *et al.* 1985; Ramos 1988). Further to the east, minor retroarc basalts are interbedded with the platform deposits.

Sedimentation varies from dominant marine in the intra-arc basin to marine and continental in the back-arc region and subsidence was controlled by extensional faults (Ramos 1988; Legarreta and Uliana 1991; Mpodozis and Ramos 2008; Tunik and Álvarez 2008).

The tectonic setting of this segment was interpreted as dominated by extensional conditions, based on stratigraphic, structural and geochemical evidence. The strong extensional conditions in Early Cretaceous times have been interpreted as being produced by intense asthenospheric upwelling in an 'aborted marginal basin' between 27° and 33°S (Levi and Aguirre 1981; Äberg *et al.* 1984; Mpodozis and Ramos 1990). However, Charrier (1984) suggested the existence of an Early Cretaceous intra-arc basin in the present-day Coastal Cordillera, based on palaeogeographic considerations, criteria followed by subsequent interpretations (Ramos 1985, 1988; Charrier and Muñoz 1994; Vergara *et al.* 1995; Ramos and Alemán 2000; Fuentes *et al.* 2005).

Most of the previous tectonic interpretations assumed that the intra-arc basin stage was related either to a low-spreading rate of 5 cm/year in the Pacific ridge at that time (Äberg *et al.* 1984; Morata and Aguirre 2003), or to a low relative convergence velocity in the subduction zone (Ramos 1985). However, later studies suggested that the factor controlling the extensional setting was mainly related to the important eastward absolute motion of South America relative to the Pacific hotspot frame (Somoza 1995; Somoza and Zaffarana 2008), which resulted in a trench roll-back ($Vt < 0$) and generalized extension (Ramos 1999; Mpodozis and Ramos 2008).

The difference between northern and central Chile subduction during Mesozoic times could be related to different pre-Mesozoic continental fabrics. The existence of several basement terranes accreted during Palaeozoic times in the central Chile segment, would favour a more distributed extension as depicted in Figure 12b.

### 4.1.3. *Rocas Verdes Basin*

The Mesozoic Andes of southernmost Chile (see location in Figure 9) record one of the first reported and best-known marginal basins floored with oceanic rocks known as the 'rocas verdes' marginal basin as depicted in Figure 13 (Dalziel *et al.* 1974). There, ophiolitic pillow lavas and tuffs, sheeted dykes and gabbros, which are exposed through north-trending thrusts, are associated with abundant silicic lavas and pyroclastic rocks interbedded in the western areas with marine sediments (Stern *et al.* 1976; Mukasa and Dalziel 1996; Stern and de Wit 2003). Recent U-Pb zircon dates constrained the initiation of the 'rocas verdes' extensional basin age to 152–147 Ma (Calderón *et al.* 2007). Basalt geochemistry indicates typical oceanic tholeiites to transitional-type basalts and associated differentiates (Stern *et al.* 1976). These rocks form the Sarmiento (between 51° and 52°S) and Tortuga (55°S) ophiolite complexes (Allen 1982; Godoy 1978).

The magmatic arc is now represented by Jurassic and Cretaceous rocks exposed as part of the Patagonian Batholith. They are typical calcalkaline granitoids with arc affinities that show a progressive increase of the $\varepsilon Nd$ isotopic values with time from 5 to −4 attributed to large crustal magma chambers developed in the early stages (Hervé *et al.* 2007a).

The sedimentary rocks of the marginal basin show turbiditic and hemipelagic deep facies ranging to marine platform conditions, where the sediments have different sources (Dott *et al.* 1982). Craton-ward turbiditic and distal platform facies are interbedded with tuffs (Olivero and Martinioni 2001; Olivero *et al.* 2009), while in the inner facies pillow lavas, lava flows and volcanic breccias are indicating the proximity to the magmatic arc (Suárez and Pettigrew 1976; Dalziel 1988).

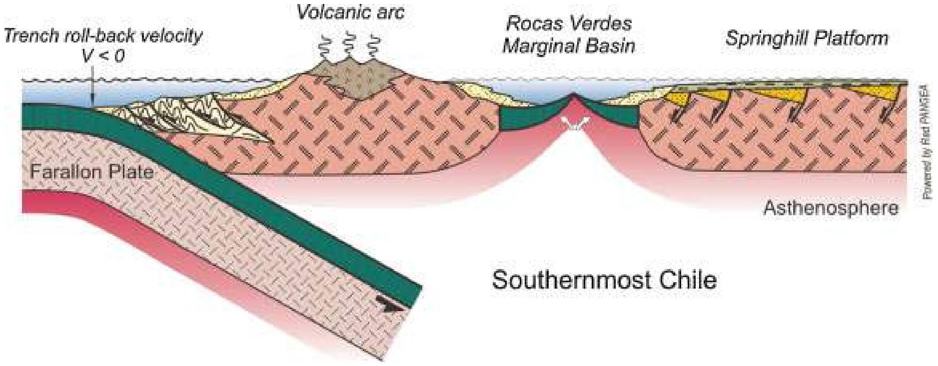

Figure 13. Palaeogeographic reconstruction of the 'rocas verdes' basin in southernmost Chile (based on Dalziel *et al.* 1974; Suárez and Pettigrew 1976; Ramos *et al.* 1986; Mpodozis and Ramos 1990) (see location in Figure 9).

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The tectonic interpretation for this marginal basin varies from a typical back-arc setting (Dalziel *et al.* 1974; Dalziel 1981), to a later aborted branch of the rift system formed during the opening of the Atlantic Ocean (Godoy 1979). Variations from this hypothesis relate the marginal basin to a failed arm of the Weddell Sea formed at approximately 150 Ma during the break-up of the Antarctic Peninsula (Alabaster and Storey 1990; Hervé *et al.* 2006; Mpodozis and Ramos 2008) in agreement with the recent proposal of Ghidella *et al*. (2002, 2007) based on the oldest magnetic anomalies of the Weddell Sea that could be as old as Middle Jurassic. If the failed arm model is accepted, as proposed by Hervé *et al.* (2007b), during the Early to Middle Jurassic the southernmost continental margin would not have subduction, been affected by a generalized extension. Subduction would not start until Middle-Late Jurassic times.

The tectonic setting of the southernmost Andes in the 'rocas verdes' marginal basin indicates an extreme extension that led to the break-up of the South American crust. This is a unique case for the Mesozoic in the Andes or along the eastern Pacific subduction zones, although some authors have proposed similar back-arc basins floored by oceanic crust in the Colombian Andes (Nivia *et al.* 2006; Bourgois *et al.* 1987). When compared with the Sandwich-type subduction previously analyzed, the polarity of the subduction zone is opposed. If the marginal basin model is accepted, it could be an excellent example showing that the influence exerted by the absolute motion relative to the hotspot frame of the upper plate is more important than the mantle flow, a conceptual case analyzed by Heuret and Lallemand (2005), although there are other alternative models (see Doglioni *et al.* 2007).

Nevertheless, when the entire Andean margin is examined, there are several cases of extreme extension that do not reach the formation of oceanic crust, as the Huarney Basin in Perú (Petford and Atherton 1995; Jaillard *et al.* 2000; Ramos and Alemán 2000) where a heavily attenuated crust was filled with more than 9 km of volcanic products. Another example is the Central Chile Basin with several kilometres of volcanic rocks (Vergara *et al.* 1995). If the early Mesozoic palaeogeography of the Patagonian Andes is examined between 38° and 52°S latitudes, it is evident an increase in the crustal attenuation in the back-arc basin to the south, being deeper as we move to the southernmost extreme (Ramos *et al.* 1982). This fact will favour a transitional change from an intra-arc continental basin to a back-arc extension, which will end with an oceanic-floored basin.

### *4.2. Change to compressional regimes*

#### *4.2.1. Stationary subduction*

It is well established that South America had an absolute plate motion to the northeast together with Africa, as part of West Gondwana during the early Mesozoic. This motion implied a trench roll-back ($Vt < 0$) with generalized extension. The change from extension as seen in the present-day Nicaraguan subduction to compression occurred near Aptian times. The change in the trench roll-back velocity (from $Vt < 0$ to $Vt > 0$) implies a transitional stage when the trench was quasistationary such as in the Oregon subduction where contraction was null and deformation negligible. Recent analyses of the absolute motion relative to the hotspot frame indicate that South America was quasistationary between 125 and 100 Ma, based in different circuits of hotspot tracks (Somoza and Zaffarana 2008). The examination of the palaeogeography between Aptian and Albian times shows a period of quiescence in the Central and Northern Andes as the one depicted in Figure 14.

The arrival of detrital sediments to the retroarc basins derived from the east occurred at the end of the Early Cretaceous as described by Jaillard *et al.* (2000). The Albian is characterized in the central Andes of Perú by marine transgressions associated with tectonoeustatic sea-level changes, and thermal subsidence is dominant. A similar setting is observed in Ecuador and Colombia at that time, when thermal subsidence controlled the sedimentation in the retroarc Oriente Basin (Jaillard *et al.* 2000). The sedimentation in the retroarc could be marine as in Perú and Bolivia or largely continental as in Argentina and Chile or mixed as in Ecuador and Colombia. The tectonic quiescence is interrupted by the Late Albian Mochica phase at 105–100 Ma in central and southern Perú (Mégard *et al.* 1984). The inception of this first compressional deformation coincides with the beginning of the westwards absolute plate motion of the South American Plate, as indicated by Somoza and Zaffarana (2008).

Magmatic activity in the arc region is prevailing through most of the continental margin.

#### *4.2.2. Beginning of Chile-type subduction*

A compressional regime started in most of the Andes at the beginning of the Late Cretaceous as early established by Auboin *et al.* (1973). This stage is reflected by important palaeogeographic changes, when in most of the Andes the first evidence of compression is recorded as the intra-Villeta unconformity of Colombia, Venezuela and Ecuador in the northern Andes (Jaimes and Freitas 2006), the Late Albian Mochica phase in Perú (Jaillard *et al.* 2000), and the Patagónides uplifts and deformation of the Neuquén embayment in central and southern Argentina (Zamora Valcarce *et al.* 2006). Both the biostratigraphic and the chronological constraints of these unconformities indicate an age comprised between the Late Albian and the Early Cenomanian, around 100 Ma, in complete agreement with the changes in the absolute motion of South America

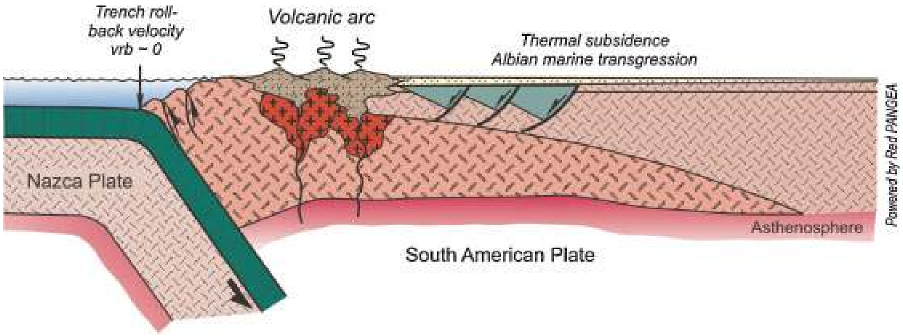

Figure 14. Quasistationary subduction zone along the Central Andes showing an upper plate absolute motion near to zero, with no contraction in the retroarc area. Minor deformation exists in the subduction complex. This model prevailed during late Early Cretaceous in the entire continental margin along Peru and Chile (see location in Figure 9).

associated with the final break-up of western Gondwana, and the final opening of the South Atlantic Ocean.

This scenario applies directly to the Central and Southern Andes. The tectonic regime for the Northern Andes had a first-order control in the accretion and collision of island arcs and oceanic plateaux (Spikings *et al*. 2005; Vallejo *et al*. 2009). However, a change in the absolute motion of South America at that time increased the convergence rate between the continent and the oceanic pieces, and therefore favoured the collision with island arcs and oceanic plateaux.

The central Chile segment has excellent constraints to portray these important changes (Figure 15). The inception of contraction and development of a fold and thrust belt episodically began in the Late Cretaceous. The structural style was controlled by a series of local factors such as previous weakness zones in the crust (Kley *et al.* 1999) and thermal regime with varying heat fluxes related to shifts in the magmatic arc position (Ramos *et al.* 2002). Alternation of thin- and thick-skinned sectors is common, as well as propagation of the deformation to the foreland, where in extreme cases is broken by basement uplifts (Jordan *et al.* 1983a).

The stationary stage is characterized by important calcalkaline magmatism in the arc, surrounded by an apron of volcanic and volcaniclastic facies, which interfingered the clastic terrigenous sedimentation in a wide basin mainly controlled by thermal subsidence.

The amount of shortening of the fold and thrust belts varies according to the structural style and the latitudinal position, with a decrease in general trend to the south. This trend has been interpreted as related to the age of the oceanic crust being subducted (Ramos *et al.* 2004) and to the friction between the upper and lower plate controlled by the increase in aridity to the north (Sobolev and Babeyko 2005).

The Andes are under a compressive regime since the Late Cretaceous with some localized exceptions in time and place. The Oligocene was a period of generalized extension along the Andean axis, as seen in central and southern Chile. A volcano–tectonic basin was developed along the magmatic arc in Late Oligocene times (Godoy *et al.* 1999; Charrier *et al.* 2002). This extensional stage is recorded in the extra-Andean Patagonia as in the Somun Cura Massif with important flood basalts (Kay *et al.* 2007). Both the volcano–tectonic basin and the flood basalts were related to significant changes in the absolute motion of the upper plate as recorded by Silver *et al.* (1998) in the Late Oligocene. These authors recognize a Late Oligocene to Early Miocene acceleration of the South America Plate relative to the hotspot reference frame, which led to the uplift of the modern Andes, after a period of nearly stable position of South America with a minimum absolute plate motion in the Oligocene.

### *4.3. Strike-slip regimes*

The present Andes have a dominant orthogonal deformation controlled by the slip vector between the lower and upper plate. As the convergence vector between the Nazca and South American plates has an average 75°E strike, the obliquity in the north- and northwest-trending margin is low. Regional seismicity confirms present-day trench-orthogonal shortening and a small component of trench-parallel dextral strike-slip motion, north of the Chile triple junction (46°30′S). Some crustal weakness zones have partitioned the deformation as in the Liquiñe–Ofqui fault zone that concentrates a dextral strike slip in the Patagonian Cordillera (Cembrano *et al.* 2002). The Andean deformation associated with subduction in this case produced low relief, almost none or minor contraction, and most of the observed strain is associated with the strike-slip displacements, as shown in Figure 16.

This low partitioned setting produced almost no deformation in the retroarc, which has not an active orogenic front, as in the highly partitioned settings previously described (Folguera *et al.* 2002).

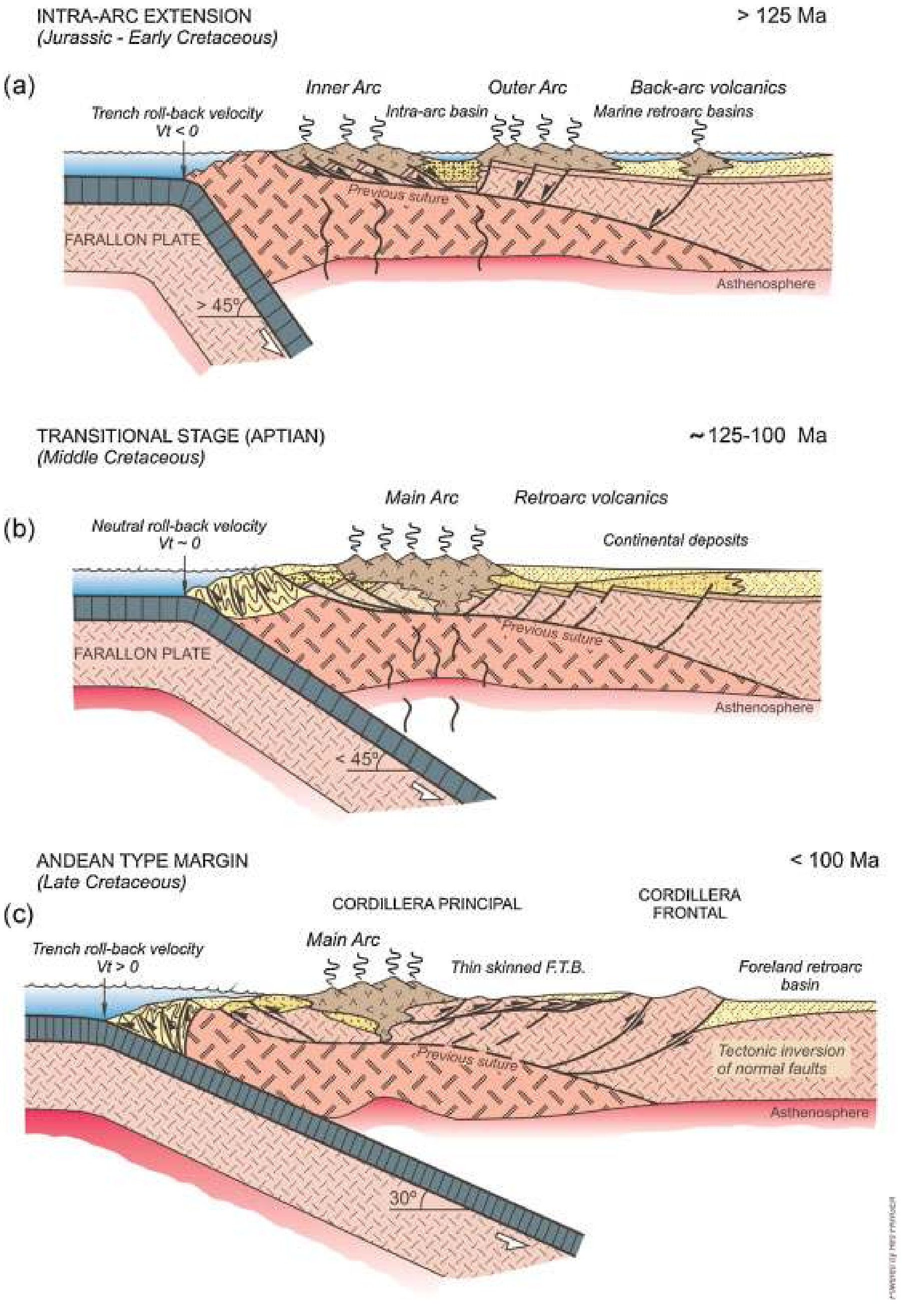

Figure 15. Changes from an extensional to a compressional regime in the central Andes of Chile and Argentina: (a) intra-arc extension during Jurassic–Early Cretaceous times; (b) non-contraction in a stationary stage between Aptian and Albian; (c) Present Andean compression after Late Cretaceous (modified from Ramos and Alemán 2000) (see location in Figure 9).

The magmatic arc is characterized by a series of well spaced stratovolcanoes of andesitic to basaltic composition (López and Escobar 1984; Dungan *et al.* 2001). The character of the arc magmatism is relatively less evolved than the typical compressional setting of the Central Andes, mainly due to its tectonic controlled setting. Minor transtensional or pull-apart basins are formed along the main structure.

This Andean setting, although not that frequent, is observed in several places along the margin, as the slip vector between the different oceanic plates and the South American Plate was rotating from a highly oblique north–northwest strike in the Early Jurassic to a present-day E-NE strike (see examples in Mosquera and Ramos 2006). Intraplate strain is heavily controlled by the orientation of the slip vector in these cases (Giambiagi and Martinez 2008).

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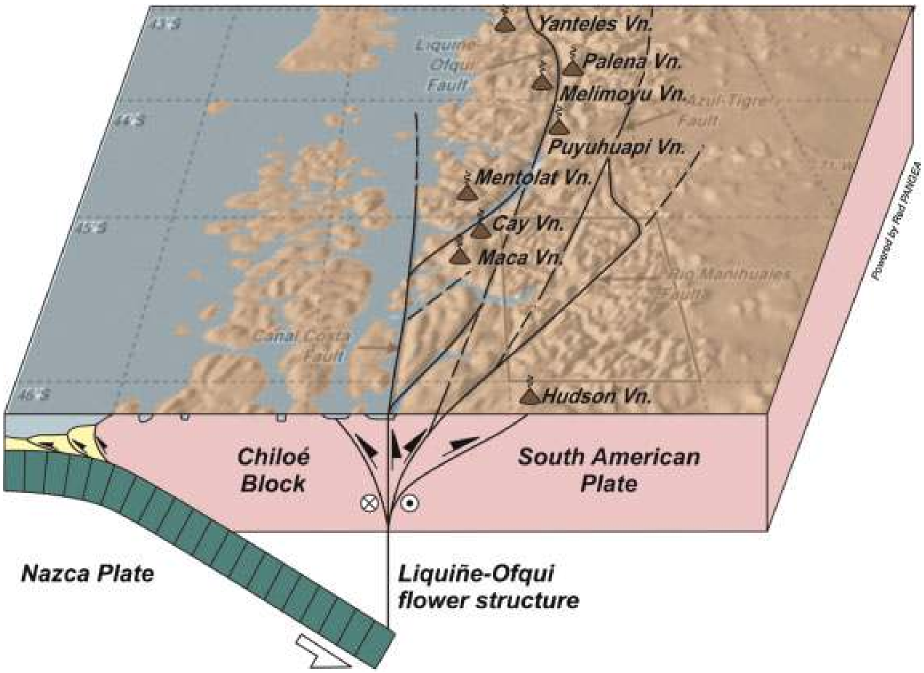

Figure 16. Strike-slip deformation along the Liquiñe–Ofqui Fault in southern Chile based on Thomson (2002). Note the concentration of the arc volcanoes along the main fault zone.

## 5. DISCUSSION

The previous examples of different types of Andean subduction settings show some interesting features to analyze the main controls of the tectonic regime. If the present settings are analyzed, it is clear that even with similar convergent rates and absolute motion of the upper plate, the strain associated with subduction decreases from a maximum in the central part of the Central Andes at the latitudes of Bolivia to a minimum to the north (south of Guayaquil Gulf, 3°S) and south (north of the Penas Gulf, approximately 46°30′S).

This symmetry in the strain behaviour was already noticed by Gephart (1994) and is clear when the amount of shortening is analyzed. The orogenic shortening recorded in the Bolivian Altiplano–Subandes system is about 320 km (Schmitz 1994; Allmendinger *et al.* 1997), while crustal shortening and crustal roots decrease to the Peruvian Andes up to the Guayaquil Gulf to less than ~170 km (Introcaso and Cabassi 2000, 2002). The difference is more striking in the Southern Andes, where crustal shortening goes down to less than 50 km. There is only one parameter, the age of oceanic crust, which decreases with the same pattern from the central part of the Andes to both extremes. On the other hand, the convergence/shortening ratio only decreases to the south and was interpreted as evidence of higher viscosity in the northern part, south of Guayaquil (Doglioni *et al.* 2007).

The age of oceanic crust that is being subducted varies from Early Eocene in the north at the Bolivian segment, to Quaternary at the triple junction among Nazca, South America and Antarctica plates, where the Chile spreading ridge is colliding with the trench (Tebbens *et al.* 1997). The other parameters that match this trend are the sediment fill and depth of the trench. The sedimentary fill is negligible along the southern Peru and northern Chile latitudes, where the trench is starving and the trench exceeds 5–6 km depth, contrasting with more than 2 km thickness and 2200 m depth of the trench at southern latitudes. This fact has been correlated with hyperarid conditions with null rains in the north, and over 6000 mm precipitation per year in the southern segment. This climatic variation was positively correlated with the friction between the upper and lower plates and the amount of shortening (Sobolev and Babeyko 2005).

Another factor that is producing changes in the tectonic regime is crustal delamination associated with steepening of the subducted slab (Kay and Coira 2009). The thermal weakening of the crust favour the important shortening observed in these regions.

The collision of aseismic ridges imposes some important variations in the local regime as seen in the Peruvian and Pampean flat-slab segments of the Andes, where coupling between the oceanic and continental plate increases, and deformation can even generate broken forelands (Jordan *et al.* 1983a,b).

The subduction of active ridges can also produce even more localized deformation as seen in the Patagonian Andes, where shortening and uplift are controlled by the different segments of the Chile ridge that collided against the margin (Ramos 2005).

The collision of fracture zones, like the Mocha fracture zone in southern Chile, associated with a small plateau of basaltic composition, can also produce important deformation in the forearc and in the retroarc (Folguera and Ramos 2009).

The effects of the eastward global mantle flow can be evaluated in the Sandwich subduction zone, which is the only segment with east polarity of subduction and that is forming an oceanic floored basin by back-arc spreading. The rest of the western margin of the South American Plate has an opposed polarity which will favour contraction. When the influence of the mantle flow is contrasted with absolute motion in the upper plate, as seen in the extensional driven 'rocas verdes' marginal basin, the control of the eastward drift of the upper plate is more important than the contractional effects of the eastward mantle flow in the formation of back-arc basins floored by oceanic crust.

However, the more contrasting change in the tectonic regime of the entire Andes is related to the past variations of the absolute motion of the upper plate relative to the hotspot reference frame, and its correlative trench roll-back velocity. In those times where plate motion has similar polarity than the subduction zone, which implies the existence of trench roll-back ($Vt < 0$), extension was generalized. Silver *et al.* (1998) suggested that Andean deformation and uplift are specifically the result of the increase in westward absolute motion of the South American Plate since 30 Ma. This parameter seems to be the most important control in the tectonic regime in the Andes.

Periods of increased convergence have been linked with uplift and deformation, whereas slow convergence rates have been associated with extensional tectonics (Sébrier *et al.* 1988; Scheuber *et al.* 1994). However, the variations in convergence rates as depicted by Pardo Casas and Molnar (1987) and Somoza (1998) have a significant role in increasing or decreasing the deformation, but subordinated to the absolute plate motion. Changes in the thermal state of the crust will overlook the influence of the convergence rates. As shown by Oncken *et al.* (2006) deformation in the Central Andes increases in the latest Cenozoic, even so it recorded a drop in the convergence rate.

Other parameters such as the absolute motion of the oceanic plate are difficult to evaluate since there is almost no difference in the present behaviour.

Local extensional features have been related to subduction erosion processes that lead to trench-ward gravitational collapse, forearc subsidence and extension that may not necessarily be directly linked to absolute motion under a high compressive regime and westward drift of the upper plate (von Huene and Ranero 2003; Houston *et al.* 2008).

## 6. CONCLUDING REMARKS

The present subduction of the eastern Pacific along the Americas shows different tectonic regimes that have been exemplified in four subduction zones:

(1) *Nicaragua subduction zone*: an extensional regime in the upper plate associated with poorly evolved continental magmatic arc, extensional back-arc and rift basins developed in continental crust.
(2) *Sandwich subduction zone*: an extensional regime in the upper plate associated with an island arc developed in oceanic crust and formation of an extensional oceanic floored back-arc basin controlled by the eastward mantle flow.
(3) *Oregon subduction zone*: a neutral to mildly deformed upper plate that can be interpreted as an early stage of the Chile-type subduction, associated with a volcanic arc with no contraction controlled by the almost stationary trench roll-back velocity, due to the young age of the oceanic crust subducted and the small absolute motion of the upper plate.
(4) *Chile-type*: a severe to mild compressional regime associated with a highly to moderate evolved magmatic arc, fold and thrust belt development and foreland basin formation along a continental margin with important deformation associated with the westwards absolute motion relative to the hotspot frame of the upper plate that overrides the trench.

The intrinsic characteristics of these different types when correlated with the geologic composition and palaeogeography of the Mesozoic Andes identified several contrasting regimes in the Andes. A common factor to all these tectonic regimes is the absolute motion of the upper plate relative to the Pacific hotspot frame, which is the first-order control in the deformation, uplift and orogenic development of the past and present-day Andean chain.

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