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Seismic ridge subduction and topography: Foreland deformation in the Patagonian Andes

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Abstract

The Patagonian Andes recorded several episodes of active ridge subduction in the last 80 million years. An analysis of the spatial and temporal relation between the present segment of collision of the Chile ridge and the digital topography of the foreland shows a correlation with the beginning of deformation and uplift in the inner sector of the Patagonia fold and thrust belt. Several magmatic episodes related to the collision such as near trench magmatism, adakite emplacement, OIB plateau basalts in the retroarc, and the arc volcanic gap, are associated with the uplift and deformation of the Patagonian Cordillera.

Based on these correlations, a collision of the Aluk (or Phoenix)-Farallon ridge during Paleogene times south of 43°30′ is identified. Changes in magmatic patterns, molasses deposits, deformation and uplift of the Patagonian Cordillera constrain the region affected by the collision. Similar evidence implies a third period of collision in the Late Cretaceous, based on the occurrence of adakitic rocks, arc magmatic gap, and deformation along the southern Patagonian Andes. This earliest hypothesized collision would require the existence of a new oceanic microplate between the Pacific and the Aluk plates during Late Cretaceous times.

Present rapid isostatic rebound related to the continental ice cap retreat in the Patagonian Andes is restricted to the region south of Chile triple junction (46°30′S). The uplift rate here is more than two times more rapid than normal isostatic rebounds recorded in the Northern Hemisphere, and requires an abnormally hot mantle with low viscosity. This abnormal mantle may be a consequence of several episodes of ridge collision and development of asthenospheric windows that are inconsistent with periods of cold flat-slab subduction proposed by some authors to explain the arc volcanic gaps.

Keywords: Andes; Ridge collision; Ridge subduction; Patagonia; Deformation; Uplift

1. Introduction

The collision of different segments of the Chile oceanic seismic ridge and the uplift of the Patagonian Andes in late Cenozoic times is associated with

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different geologic processes in the foreland. Digital elevation models from the continental side as well as the bathymetry of the adjacent ocean floor allow a link to be established between the present colliding segment and the topographic contrast with areas immediately north and south of the collided ridge. The analysis of these processes in the present geologic setting, where a segment of the Chile ridge is colliding, may help in identifying older collisions such as the ones occurred in Paleogene and late Cretaceous times.

The relationship between timing and space of ridge collision and uplift of the Patagonian Andes has been proposed by several authors (Ramos, 1989; Forsythe and Prior, 1992; Ramos and Kay, 1992; Flint et al., 1994; Ramos et al., 1994; Gorring et al., 1997). The Patagonian Andes, as a consequence of a series of ridge collisions, had several pulses of uplift producing important crustal stacking in the foreland during late Cretaceous, Eocene, and late Miocene times. However, recent studies mainly based on the analysis of timing and origin of deformation along the Patagonian fold and thrust belt proposed a different hypothesis, where seismic ridge collision produced a volcanic gap as result of flat-slab subduction (Suárez et al., 2000a, Suárez and de la Cruz, 2001).

In order to evaluate both alternatives, the tectonic setting and the topographic changes in the present region of ridge subduction will be analyzed. Fig. 1 illustrates the location in the Patagonian Andes where seismic ridge subduction is currently taking place, outlining the major oceanic and continental tectonic features associated with the collision.

The collision of the Chile ridge against the trench is taking place at the latitude of the Taitao Peninsula

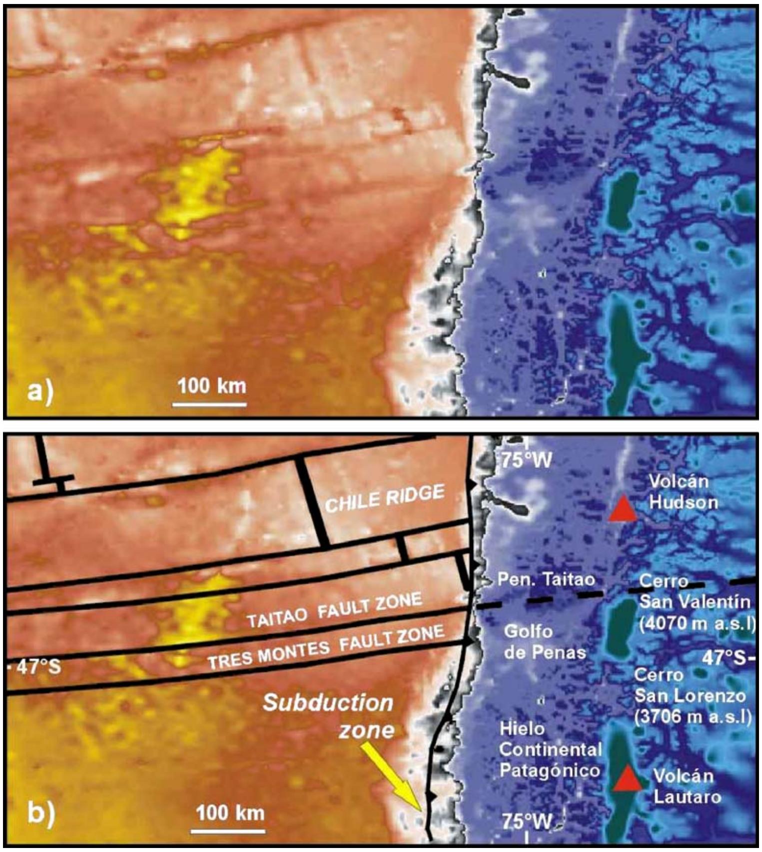

Fig. 1. (a) Bathymetric data in the oceanic side combined with digital topography of the Andes at these latitudes based on U.S.G.S digital models. (b) Note the major topographic change in the Patagonian Andes, south and north of the projection into the continent of the Taitao Fault Zone. The Hudson is the last active volcano in a segment where the collision of the Chile Ridge has not occurred yet (based on Forsythe and Prior, 1992).

(46°30′S latitude), just north of Penas Gulf, along the Pacific margin of southern Chile (Forsythe et al., 1986; Bourgois et al., 1996; Lagabrielle et al., 1999). The active volcanic front in the Southern Volcanic Zone associated with subduction of the oceanic crust ends at the Hudson volcano (46°00′SL) (Stern et al., 1976). Arc volcanism resumes in the Austral Volcanic Zone after a gap of about 350 km, at the Lautaro volcano (48°59′SL) showing a strong adakitic signature, which indicates partial melting of a buoyant young oceanic lithosphere (Stern and Kilian, 1996).

2. Ridge collision and topography

Bathymetric data from the oceanic crust region adjacent to the Chile ridge, together with the digital topography provided by the U.S.G.S., are illustrated in Fig. 1. The digital elevation indicates an uplift of more than 2000 m south of the Taitao Fault Zone along the axis of the cordilleran region. Fig. 2 shows the drastic change in elevation north and south of the latitude 46°30′S, where the collision is taking place.

The Taitao fault zone limits the northern end of a segment subducted more than 3 My ago, as established by Cande and Leslie (1986). North of that zone is the segment where present subduction is under way, colliding the southernmost Chile ridge segment with the Taitao Peninsula (Forsythe and Prior, 1992). As a result of that collision, important crustal erosion occurred (Bourgois et al., 1996) and the off-scraping of the ridge is leading to the tectonic emplacement of the oceanic crust as an ophiolite (Mpodozis et al., 1985; Guivel et al., 1999).

The Cerro San Valentín massif with its present elevation of 4070 m a.s.l. is bounded to the north by a 2000 m decrease in elevation that coincides with the landward projection of the Taitao Fault Zone (Fig. 2). On the other hand, to the south of this mountain are Cerro San Lorenzo (3706 m) and the mountain chain encompassed by the Hielo Continental Patagónico Norte (Northern Continental Ice Cap). Several peaks within this chain are over 3000 m a.s.l. (Cerro Fitz Roy, 3375 m; Cerro Bertrand 3200 m, among others).

The elevation of these granitic mountains indicates a minimum uplift, as these Miocene intrusives have been unroofed by erosion that eliminated at least 4 or 5 km of the country rocks, as demonstrated further south in the Torres del Paine by vitrinite studies of the sedimentary cover by Skarmeta and Castelli (1997). Another striking feature is the north–south trend of these uplifts which is parallel to the trench (Fig. 1).

The uplift mechanism could be considered as thermally driven. However, at these latitudes the collision of this southern segment took place as long as 6 to 10 million years ago, and the oceanic asthenospheric window is situated beneath the foreland, more than 400 km to the east of these mountains (Murdie et al., 1993; Gorring et al., 1997). Therefore,

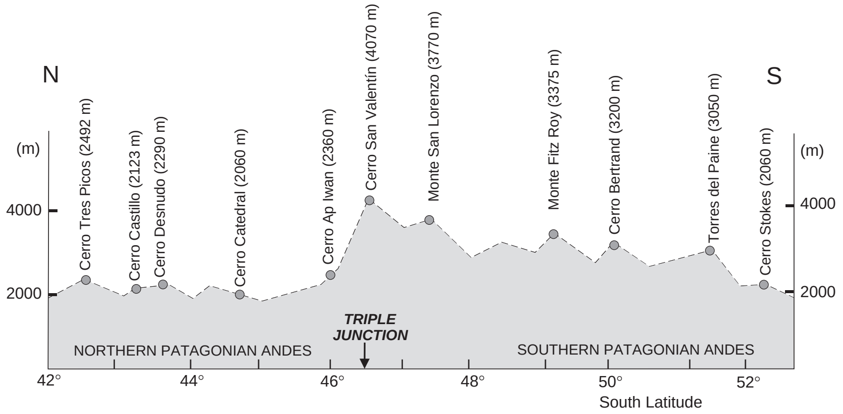

Fig. 2. North–south topographic section of the Patagonian Andes where maximum elevation is indicated at each latitude, excluding volcanic edifices. Present Chile ridge collision is taking place at 46°30′S.

the heat produced by the ridge subduction or the asthenospheric windows has largely been dissipated beneath this region, and the present topographic anomaly is difficult to relate to a thermal anomaly.

On the other hand, crustal stacking seems to be a more appropriate mechanism as there is a spatial coincidence between this southern segment and the development of the Patagonian fold and thrust belt (Ramos, 1989; Alvarez-Marrón et al., 1993; Kraemer et al., 2002). South of the triple junction there is a substantial amount of shortening in the foothills absorbed by the sedimentary cover, that can be correlated with the basement shortening and uplift of the inner part of the Patagonian Andes. This orogenic shortening varies from north to south from 25 to 45 km (Ramos, 1989).

This high topography is maintained 14–12 m.y. after the ridge collision at these latitudes (Cande and Leslie, 1986), as it can be seen in the southern segment of the Patagonian Cordillera in Torres del Paine area. The elevation of these granitic plutons is between 2670 m (Cerro Almirante Nieto) and 3050 m (Cerro Payne Grande) above sea level.

North of the triple junction there is only a modest deformation, with minor shortening. Crustal stacking in this region was controlled by partial tectonic inversion (see Fig. 3), and large areas of the extensional Mesozoic basin are still preserved beneath the surface at these latitudes (Ramos, 1989).

3. Arc volcanic gap

Suárez et al. (2000a) proposed an alternative mechanism to explain the volcanic gap. These authors suggested that the shallowing of the Wadati-Benioff zone could have produced flat-slab subduction and shut off arc magmatism. However, there is abundant evidence that in areas of present flat-slab subduction the thermal flux is low, and always flat-slab segments are associated with cold continental lithosphere, as the asthenospheric wedge has retreated far away into the foreland and the subducted plate cools the upper plate (Barazangi and Isacks, 1976; Henry and Pollack, 1988; Kay and Abbruzzi, 1996; Ramos and McNulty, 2002). Some authors have proposed that as a consequence of flat-slab subduction slab break off may occur, and as a result of that hot convecting asthenosphere produced melting and eruption of rhyolites, as in the Basin and Range, following the Laramide episode (see Oldow et al., 1989). None of these features are observed at these latitudes. Another feature closely linked to flat-slab subduction is the strong coupling between the continental and oceanic lithospheres that leads to basement foreland deformation as described by Jordan et al. (1983). This disrupts the foreland causing basement uplifts like the Sierras Pampeanas.

The thermal state near the triple junction has been studied by Murdie et al. (1993) and Daniel et al.

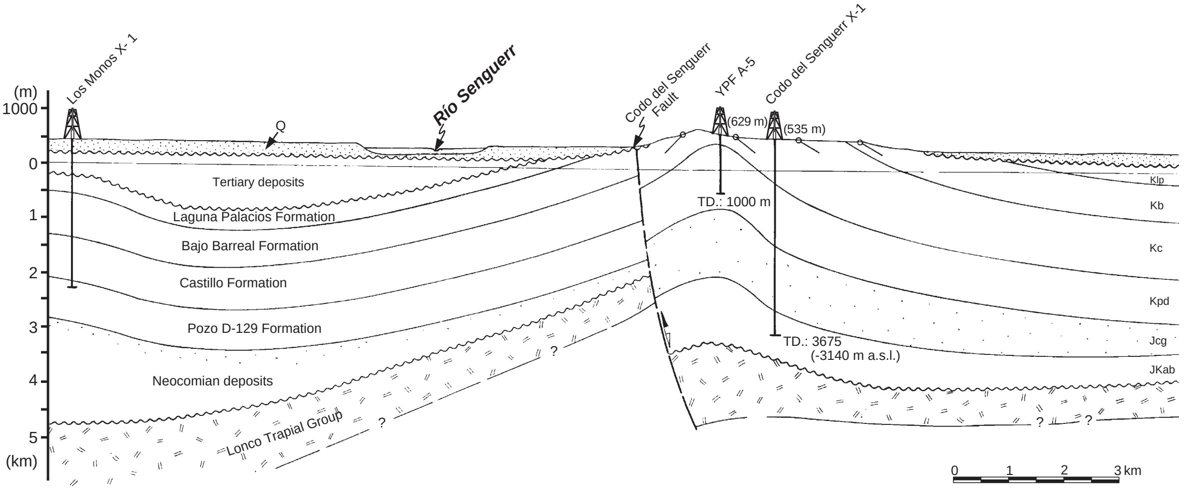

Fig. 3. Mild tectonic inversion in the foreland north of the Aysen triple junction in the Codo del Río Senguerr at 46°00′SL. The structural section is constrained by a seismic reflection line (modified from Ramos, 1999).

(1996). These authors assumed that the temperature field required to explain the gravity anomalies observed in the region indicates an active asthenospheric wedge and a higher than normal heat flux. Petrologic studies on the retroarc plateau basalts indicate an abnormal heat source in the mantle located at 80–90 km depth with temperatures of the order of 1400 to 1450 °C (Cheadle and Petford, 1993), incompatible with the low thermal gradient of a flat-slab subduction. Geochemical and isotopic models of the plateau basalts suggest an abnormally hot mantle (Kay et al., 1993; Le Moigne et al., 1996; Kay and Gorring, 1999). The estimated volumes of these plateau basalts require eruptions of 0.2 km^3/year, rates similar to other flood basalt provinces around the world, as for example the Paraná basalts, characterized by high thermal gradients (Petford et al., 1996).

The foreland basement at these latitudes is exposed in the Deseado Massif, which still preserves the extensional Mesozoic graben systems and does not denote any tectonic inversion at surface (Ramos, 2002a) or only has a mild inversion in the subsurface as seen in the La Golondrina basin further east (Homovc and Constantini, 2001).

The Wadati-Benioff zone according to the model elaborated by Daniel et al. (1996) south of the triple junction has a 30° dip of the oceanic slab which is not consistent with the flat-slab subduction proposed by Suárez et al. (2000a) to explain the volcanic gap. Based on previous considerations, the hypothesis advanced by Stern et al. (1976) and Mpodozis et al. (1985) is still a valid alternative to explain the volcanic gap. These authors related the dehydration of the oceanic slab in the subduction complex, producing sediment melting and emplacement of felsic rocks in the forearc, prior to the interaction with the asthenospheric wedge as the cause of the volcanic gap.

4. Timing of deformation

The late Cenozoic episode of ridge collision related to the Chile Ridge shifted from south to north, starting 14 My ago at 52°S latitude, and migrating up to 46°30′ at present. The effects of this collision are well documented by off-scraping of oceanic crust and emplacement of ophiolites associated with subduction erosion (Bourgois et al., 1996), near-trench felsic and MORB-like magmatism (Mpodozis et al., 1985; Forsythe et al., 1986; Lagabrielle et al., 1994; Le Moigne et al., 1996), adakite emplacement (Kay et al., 1993), rapid mountain uplift and development of a fold and thrust belt (Ramos, 1989; Kraemer et al., 2002), and retroarc OIB magmatism (Ramos and Kay, 1992; Gorring et al., 1997).

However, some authors pointed out that deformation is not restricted to the time of ridge collision (Ray, 1996; Suárez and de la Cruz, 2001), expressing doubts about the cause–effect relationship between these two processes, mainly because they found Paleogene and even older deformations in several areas of the Patagonian Cordillera. Although there is no doubt that major orogenic uplift in the Tres Montes-Esmeralda segment has occurred at about 6–8 million years ago, as indicated by new Ar/Ar data on the granitoids of Cerro San Lorenzo (Welkner, 2000), this does not mean that it is the only episode of deformation recorded in the region. The synorogenic deposits of Río Frías and Santa Cruz Formations began their deposition as far back as 19 million years ago at these latitudes, as shown by the Ar/Ar ages of the interbedded tuffs (Feagle et al., 1995). However, effective topographic uplift, as inferred from isotopic studies of paleosoils of the Santa Cruz Formation (Blisniuk and Strecker, 2001), occurred more recently. A period of rapid convergence started at about 20 My ago (Pardo Casas and Molnar, 1987), which accounts for the beginning of deformation, but final uplift seems to be closely linked with the subduction of this Chile Ridge segment. The spatial and temporal correlation between the uplift of Cerro San Lorenzo and the age of collision proposed by Cande and Leslie (1986), provides a better fit to isotopic data derived from paleosoils (Blisniuk and Strecker, 2001). The time lag between rapid uplift and collision was interpreted as a result of increased transpression as young and buoyant oceanic lithosphere was approaching the trench in a regime of low partitioning (Folguera and Ramos, 2001, 2002).

Further south in the Torres del Paine area there are also good constraints on the time of deformation and uplift. In this region, Skarmeta and Castelli (1997) established the beginning of the Miocene uplift at about 12 million years in the inner sector, based on different databases. The subsidence curves from stratigraphic sections around Lago Nordenskjold, together with the well Toro 1-b, show that uplift started at 12 million years, and that the granites of Torre del Paine had a cover about 4 to 5 km thick, that was removed by erosion during uplift. On the other hand, the emplacement of these granitic bodies is bracketed between 13±1 Ma and 12±2 Ma (K/Ar in biotite), and based on structural considerations (Skarmeta and Castelli, 1997) as well as petrologic analyses (Michael, 1983), these authors demonstrate that the intrusions are syntectonic. There is a remarkable coincidence between the collision of this southern segment of the Chile ridge between 14 and 12 million years (Cande and Leslie, 1986) and the deformation of the cover, the uplift and the emplacement of these granitic plutons.

5. Paleogene collision

Aside from the well documented Late Cenozoic collision there is evidence of several previous ridge collisions registered in the Pacific margin of Patagonia (Cande and Leslie, 1986, Ramos and Kay, 1992; Ramos et al., 1994). Among them, the Paleogene collision is related with the second most important episode of deformation that produced conspicuous unconformities in the inner region of the Southern Patagonian Andes, mainly south of 50°S (Skarmeta and Castelli, 1997; Kraemer et al., 2002), and locally in the Cosmelli basin at Meseta Buenos Aires latitudes (Flint et al., 1994).

5.1. Time of deformation

This tectonism is related to a period of rapid convergence (Pardo Casas and Molnar, 1987) in general terms associated with the Incaic orogeny, that controlled the collision of the Farallon-Aluk ridge against the trench south of 43°30′ (Cande and Leslie, 1986; Ramos and Kay, 1992). The evidence of deformation increases to the south of this latitude, and reaches the maximum deformation at the Fueguian Cordillera. Due to the orientation of the convergence vector in the north–northeast quadrant, it is evident that those segments more orthogonal to this trend, such as the Fueguian Andes with a northwest to east–west direction, have recorded the largest deformation. For example, the initiation of foreland basin deposits in the Malvinas basin occurred during the middle to the late Eocene (Galeazzi, 1996), at a time when the main deformation is recorded in the Leticia Formation (Ghiglione et al., 2002). These authors bracketed the main Paleogene deformation between 43.6 and 39.2 Ma in the Fueguian fold and thrust belt along the Atlantic coast (54°S), based on growth strata and progressive angular unconformities in the synorogenic deposits of the Leticia Formation.

Further north and west along the Darwin Cordillera (52°S), based on fission track data, Nelson (1982) established the main uplift related to the closure of Rocas Verdes basin between 43 and 38 Ma, with uplift rates up to 0.5 mm/year. Further north at the latitude of Torres del Paine (51°S), Skarmeta and Castelli (1997) recognized the main Paleogene uplift, that coincided with the involvement of the basement in the fold and thrust belt, between late Paleocene and late Eocene times. The unconformity that separates the Maestrichtian-Danian marine deposits from the continental member of the lower Río Turbio Formation is dated in the late Paleocene–early Eocene by Malumián (2002) at 50°30′–51°SL. The Río Turbio Formation has important coal seams typical of a molasses deposit interbedded with shallow marine deposits that grade upsequence to the continental Río Guillermo Formation. This unit consists of synorogenic deposits of latest Eocene to early Oligocene age.

There are isolated continental deposits of Paleogene age preserved between Lagos Belgrano and Strobel (approx. 48°S) and south of Lago Cardiel (49°S). These deposits bearing coal seams and littoral shallow facies have been interpreted as molasses deposits related to some deformation in the inner areas (Kraemer et al., 2002). These deposits are locally better developed in the Cosmelli basin (approx. 47°S) where Suárez et al. (2000b) and Troncoso et al. (2002) described a continental sequence bearing coal seams of late Paleocene–early Eocene age. This unit defined as Ligorio Márquez Formation overlies with an angular unconformity folded rocks of Divisadero Group (early Cretaceous, Ramos et al., 1982). This relationship defines an episode of deformation in the late Paleocene–early Eocene.

The Paleogene basin in the central part of the Southern Patagonian Cordillera (50°SL) shows an asymmetric section, typical of a foreland basin with a rapid thickening towards the west along the foothills (see Fig. 1 of Malumián, 2002). This foreland basin reaches a maximum thickness further south where it attains up to 3600 m at 52°SL (Biddle et al., 1986). The subsidence curve of the basin indicates a rapid increase of the subsidence rate at about the middle Eocene (Ramos, 2002a).

Based on the previous evidence it can be established that uplift and deformation were recorded in the Patagonian fold and thrust belt between late Paleocene and early Eocene times in the northern and central areas, and up to the middle to the late Eocene in the southernmost Patagonian Andes.

5.2. Arc volcanic gap and retroarc volcanism

The Patagonian batholith and the satellite bodies located further east along the foothills recorded a persistent magmatic activity related to subduction since the Jurassic up to the Late Cenozoic. However, there is no dated plutonic activity dated with Paleocene or Eocene ages (see recent review of Suárez and de la Cruz, 2001). This is also confirmed by a volcanic gap that took place during most of the Paleocene and Eocene times in the magmatic arc (Ramos et al., 1982).

At the same time as the volcanic arc gap is recorded, important alkaline basalts are widespread in the retroarc. These basalts have typical OIB signature and have been interpreted as evidence of an asthenospheric window formed during an episode of ridge collision (Ramos and Kay, 1992; Kay et al., 2002).

The majority of these retroarc volcanic plateau, represented by the Posadas Basalt, were erupted between 44° and 52°S latitude, coinciding in time and space with the region affected by the ridge subduction (see Figs. 4 and 5). New data from Meseta Buenos Aires indicate two pulses of activity, one at 43.85±0.8 Ma, 44.30±0.9 Ma and 41.22±0.8 Ma, and a younger one at 39.43±0.6 Ma and 39.34±0.6 Ma (K/Ar in whole rock, Flynn et al., 2002). The oldest basalt corresponds to a 58.6±2 Ma reported by Morata et al. (2000) in the same area.

These dates indicate an Ypresian (53–46 Ma) to Lutecian (46–40 Ma) age for the Posadas Basalt, early to middle Eocene after the I.U.G.S. (2000) time scale. These basalts are associated with extended and densely emplaced essexite dike swells all along the foothills of the Patagonian Cordillera between Lago Buenos Aires and Torres del Paine (Ramos, 2002b).

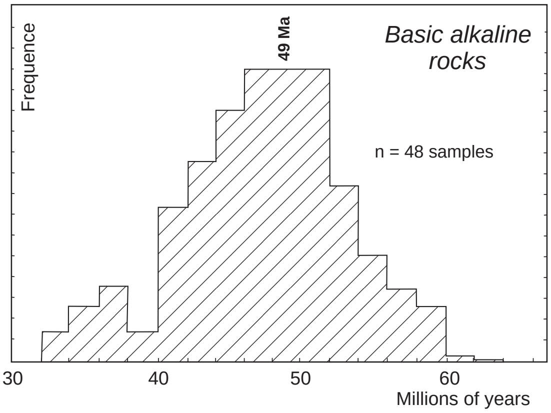

Fig. 4. Frequency distribution of K/Ar ages of Posadas Basalt and related alkaline rocks in the retroarc region of Patagonia between 45° and 52°S weighted by the standard error of each measurement.

The ages of the essexites and the Posadas Basalts overlap indicating a period of maximum activity between 53 and 43 Ma in the northern sector (Ramos, 1982a). These ages have been confirmed by new Ar/Ar ages in Lago Pueyrredón (43.0±0.1 Ma, Kay et al., 2002), similar to old K/Ar ages in the same locality (43.5±7 Ma, Ramos and Drake, 1987). The ages of the Posadas Basalt are summarized in Fig. 4.

5.3. Paleogene segmentation of the Patagonian Cordillera

There is a remarkable segmentation of the Paleogene magmatism in the Patagonian Cordillera (Fig. 5). A series of calc-alkaline rocks represented by up to 1500 m of dacites, andesites and minor basalts in lavas, pyroclastic flows, tuffs and volcaniclastic deposits, constitutes the main arc in the Principal Cordillera in the region of Collipilli, Ventana, El Maitén and Corcovado (38° to 43°S). These thick sequences disappear at about 43°30′S latitude. Several petrologic and geochemical studies demonstrated the subduction related signature of these rocks (Rapela et al., 1983, 1988).

South of this latitude there is a gap in the arc volcanism, occurring at the same time as major basaltic lavas are extruded in the retroarc. Further south these

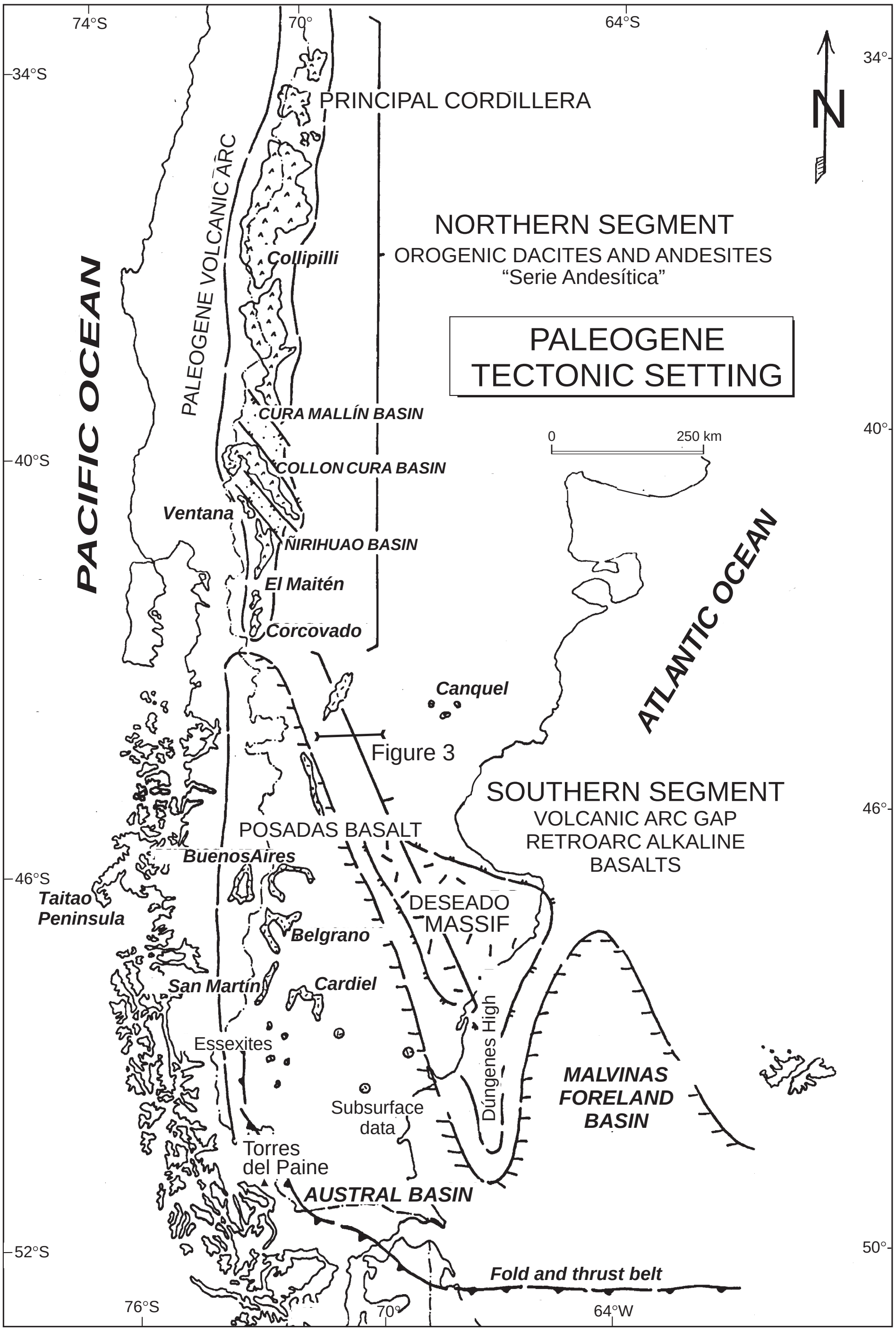

Fig. 5. Paleogene paleogeography of the Patagonian Cordillera with indication of the main magmatic domains. Note that south of 43°30′S there is no evidence of an active magmatic arc.

lavas are known as the Posadas Basalt, widely exposed in the foreland region as well as in the subsurface of the Austral basin (Ramos, 1982a,b). The change between a continuous Paleogene volcanic arc and the beginning of the OIB alkaline basaltic magmatism occurred at the latitude of the Chiloé Island in the Pacific margin. This latitude was proposed by Cande and Leslie (1986) as the approximate latitude where the collision of the Farallon-Aluk (Kula) ridge against the trench happened at about 63 Ma (Fig. 6). The geological evidence in the foreland can be used to precisely locate the latitude where the collision took place, which caused a major compositional change in magmatism.

The alkaline magmatism associated with the volcanic gap permits a plate reconstruction of the region affected by the collision of the Aluk-Farallon ridge as far south as 52°S latitude. This area has an extensive magmatism in the foreland, that in sectors was widespread in the extra-Andean region close to the Atlantic coast. This magmatic activity has been interpreted as produced by the development of asthenospheric windows related to the collision of an active oceanic spreading center between 53 and 43 Ma (Ramos and Kay, 1992; Kay et al., 2002). This is the time span when several molasses basins, associated with the beginning of foreland subsidence in the foothills of the Patagonian Cordillera, formed during the Incaic orogeny. These were subsequently uplifted, and deformed in the inner sectors of the Patagonian fold and thrust belt as proposed by Kraemer et al. (2002). The age and degree of deformation gets younger and more intense towards the south, parallel to the south migration of the collision as proposed by Cande and Leslie (1986). Once more it can be seen that there is a close correlation in time and space between the collision of an oceanic spreading center, deformation in the fold and thrust belt, cessation of arc volcanism and development of alkaline retroarc basalts.

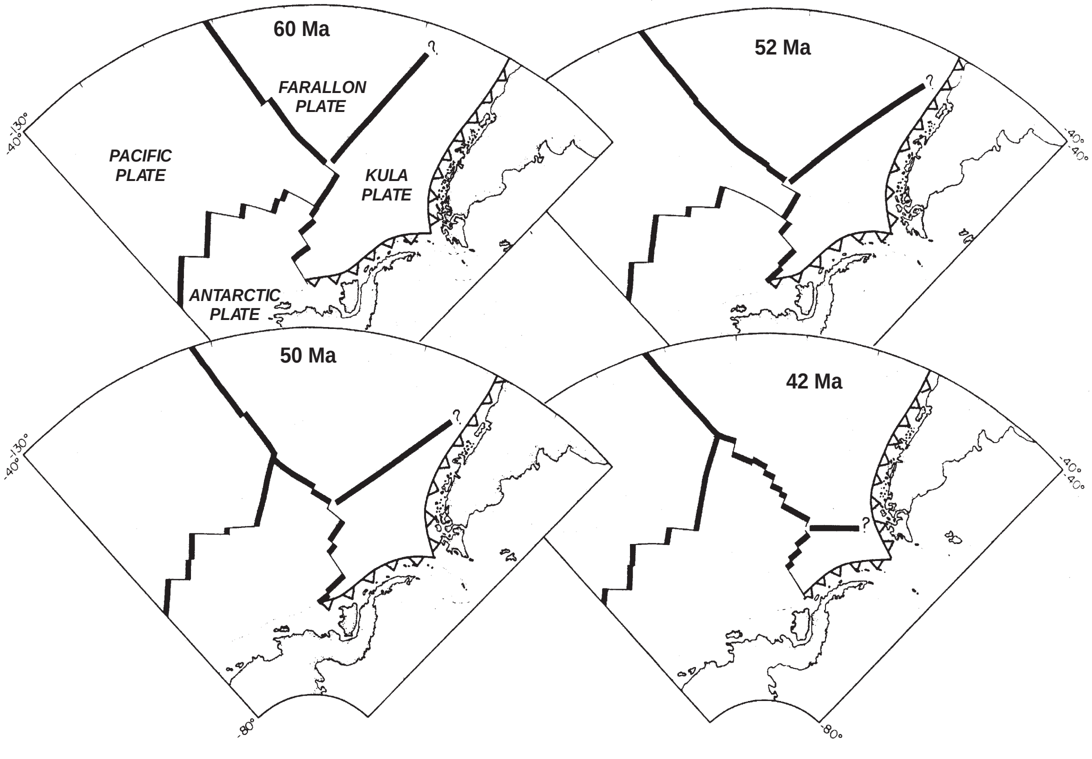

Fig. 6. Paleogene ridge collision of the Aluk (or Phoenix)-Farallon oceanic ridge against the Patagonian Andes continental margin (modified from Cande and Leslie, 1986). Compare the collision site along the margin between 52 and 50 Ma with paleogeography of Fig. 5.

6. Cretaceous collision

The evidence suggesting a Cretaceous collision is not as well established as the Late Cenozoic or Paleogene collisions. The best evidence is based on the isolated exposures of the Puesto Nuevo Adakite (approx. 49°S), similar in isotopic and geochemical composition to the Cerro Pampa Adakite (12–13 Ma), that clearly indicate melting of young oceanic crust as demonstrated by Kay et al. (1993) associated with the subduction of a segment of the Chile ridge.

The emplacement of the Puesto Nuevo Adakite coincides with an important magmatic arc gap as described by Ramos et al. (1982) and recently demonstrated by Suárez and de la Cruz (2001) after 79 Ma. The age of subduction is constrained by old K/Ar dates of the adakites between 84.5±6 Ma and the 76.7±5 Ma (Riccardi, 1971). The collision could have taken place at about 80 My ago, as indicated by the arc gap during most of the Late Cretaceous at these latitudes (Ramos et al., 1994). There is evidence of an angular unconformity between the early Cretaceous rocks and the Puesto Nuevo Adakite. This corresponds to the widespread deformation recorded during this time interval along the Fueguian and Patagonian Andes from 52 to 44°S, described as part of the Patagónides deformation (see review in Ramos, 2002a).

The collision of the Aluk (or Phoenix)-Pacific oceanic ridge along the Pacific trench of New Zealand proposed by Bradshaw (1989) for mid Cretaceous time could be part of the same episode of collision that produced the volcanic gap and the Puesto Nuevo Adakite. If not, there is need in the late Cretaceous for another spreading center-associated with an unknown oceanic microplate in the southeast Pacific.

7. Concluding remarks

The collision of the Chile ridge with the trench in Late Cenozoic times, in addition to all the processes described above, also triggered the beginning of glaciation in southernmost South America. The oldest glaciation in the entire Patagonian Cordillera is recorded in Meseta Buenos Aires at about 6 million years (Mercer, 1976) at approximately 47°S, within the segment comprised between Taitao and Esmeralda fault zones (Ramos, 1989; Gorring et al., 1997). Collision in this segment occurred 6 million years ago, and as a consequence, the resulting uplift produced a topographic barrier athwart of the dominant westerlies winds that triggered the first recorded glaciation. A similar effect is described for the last glacial maximum (LGM) at about 19 ka by Wenzens (2002), that found a close correlation between the topography originated by ridge collisions and the extension of the continental ice caps. These studies together with the Ivins and James (2002) model on the isostatic response to deglaciation, mainly based on the last 5 ka mass fluctuation of the Patagonian ice fields, show that mantle viscosities seem to be lower (on the order of 5 to 0.2×10^{18} Pa s) than in normal continental shields (approx. 10^{21} Pa s). The results of the Little Ice age (LIA, 1400–1750 AD) show an abnormally rapid response, that these authors related to an abnormally hot mantle as a consequence of slab window formation due to oceanic spreading center subduction beneath the Patagonian Cordillera during the Cenozoic.

Recent GPS measurements of vertical displacements indicate ongoing vertical uplift related to LIA and younger ice retreats up to 20 mm/year (Bevis et al., 2002), more than two times the uplift rates currently recorded in Fennoscandia and Hudson Bay (5–10 mm/year). This is a clear indication of abnormal heat flow beneath the Patagonian Cordillera (Lagabrielle et al., 2000), probably controlling a low viscosity in the mantle. The thermal setting near the triple junction has an estimated heat flow higher than 100 mW/m^2 which would have enhanced the late Cenozoic uplift and deformation during the last Cenozoic seismic ridge subduction. This thermal state is incompatible with flat subduction, which implies a cold regime in the mantle and lower crust (Fig. 7).

There is strong evidence that several spreading centers have interacted with the trench at the margin of the South American plate in the last 80 million years along the subduction zone of the Patagonian Cordillera. This interaction is documented by abrupt changes in uplift, deformation, and magmatism. As the collisions of these active seismic ridges were associated with periods of rapid convergence in the

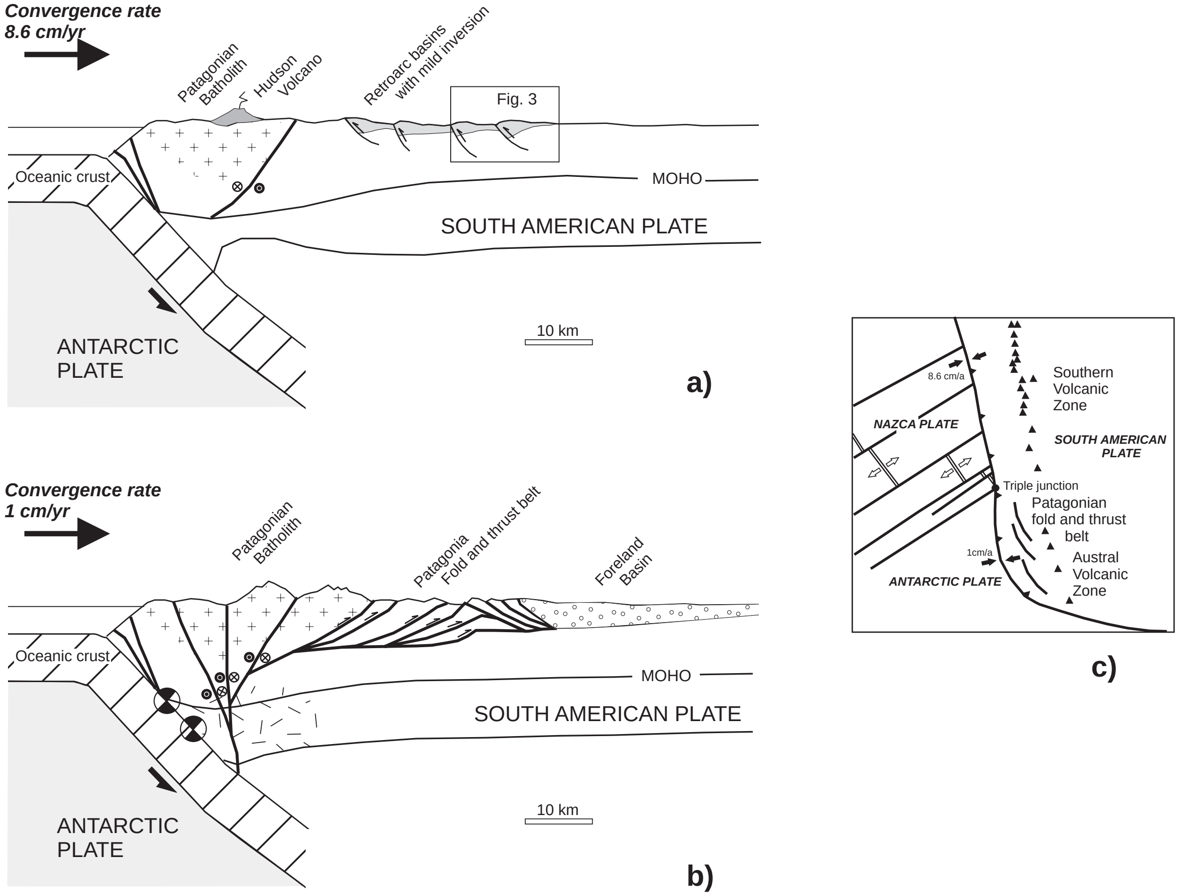

Fig. 7. Present tectonic setting of the Patagonian Cordillera. (a) North of the triple junction, prior to the seismic ridge subduction. Note the active volcanic arc, and the mild subduction of the retroarc region, as illustrated in Fig. 3. (b) South of the triple junction. Note that shortening and uplift are favored by a ductile lower crust and the low viscosity of the mantle indicated with a stipple pattern (modified from Ramos, 1989). (c) Inset indicating the plate kinematic of the triple junction between Nazca, South America, and Antarctic plates.

Late Cretaceous, in the Paleogene and the Neogene, their effects were superimposed to an increase of orogenic activity generated by acceleration of the convergence rates. However, the climax of this deformation and the rapid uplift coincided in time and space with the ridge collision, as documented in the most recent interactions between the spreading center and the trench. These last uplifts triggered glaciation in the southernmost Andes, as a response to the topographic barriers to the westerly winds, and even Little Ice Age deglaciation, had a rapid and abnormal 20 mm/year uplift controlled by the low viscosity of the mantle associated with an abnormal thermal regime as a consequence of the oceanic ridge collisions.

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