

Evolutionary cycles during the Andean orogeny: repeated slab breakoff and flat subduction?

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ABSTRACT

Tectonomagmatic similarities between the modern Chilean flat-slab region and pre-Neogene magmatic episodes suggest that they represent analogues to flat subduction. Evolutionary patterns in each magmatic suite include (i) increasing La/Yb ratios and Sr- and Nd-isotopic enrichment through time, (ii) eastward-migration of magmatism after periods of transpressional/transensional intra-arc deformation, and (iii) subsequent termination and virtual absence of main-arc activity for 5–10 Myr. These patterns may reflect slab shallowing followed by flat subduction and thickening of the overlying crust. If repeated, they require interchanging episodes of slab

steepening. Increasing convergence rates force slab kinking and eventual failure of the oversteepened slab, followed by rebound of the slab tip (owing to lack of further slab pull), flat subduction and termination of subduction-related magmatism. Rapid subduction leads to shallow overriding of the detached slab fragment. Eclogitization of the gradually steepening slab tip at depth and subsequent slab pull permits asthenospheric corner flow and subduction-related magmatism.

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Introduction

Variations in the distribution and chemistry of Neogene magmatic rocks in north Chile (22–33°S) tend to reflect changes in dip of the subducting Nazca plate and thickness of the overlying lithospheric mantle and crust (Kay *et al.*, 1987, 1991; Coira *et al.*, 1993). Eastward migration of subduction-related magmatism followed by compressive deformation and subsequent termination of main-arc andesitic volcanism by ~ 10 Ma, and virtual cessation of volcanic activity by ~ 5 Ma (Kay *et al.*, 1999) are diagnostic for the present flat-slab region between 28° and 33°S (Barazangi and Isacks, 1976; Cahill and Isacks, 1992). Cessation of volcanism in the flat-slab region is attributed to displacement and/or suppression of the asthenospheric wedge. Geochemical characteristics accompanying this Neogene tectonomagmatic evolution include increasing La/Yb ratios (i.e. steepening REE patterns) and increasing 'crust-like' initial Sr- and decreasing initial Nd-isotopic signatures of arc magmatic rocks (Leeman, 1983; Kay *et al.*, 1987, 1991; Davidson *et al.*, 1988; Hildreth and Moorbath,

1988; McMillan *et al.*, 1993). The present contribution shows that these tectonomagmatic and geochemical features are part of a larger scale cyclic evolution that is diagnostic of the entire north Chilean Andean orogeny, and offer an integrative dynamic model with which to explain this cyclicity.

Geological framework

In northern Chile (21–26°S), repeated eastward stepwise shifts of main-arc magmatism between Jurassic and Present have generated a collage of four largely parallel, eastward-younging magmatic arcs, each separated by ≤ 100-km-wide gaps with no or only sparse magmatic rocks (Coira *et al.*, 1982; Scheuber *et al.*, 1994): the largely Jurassic arc along the present Coastal Cordillera, the mid-Cretaceous arc aligning the Longitudinal Valley, the late Cretaceous–Eocene arc largely seated in the Chilean Precordillera and the Neogene and modern central volcanic zone (CVZ) including the Western Cordillera (Fig. 1). A compilation was made of geochemical, magmatic and tectonic data from pre-Neogene magmatic rocks (data from Rogers and Hawkesworth, 1989; Makshev, 1990; Döbel *et al.*, 1992; Williams, 1992; Heumann *et al.*, 1993; Mpodozis *et al.*, 1993; Lucassen and Franz, 1994; Pichowiak, 1994; Trumbull *et al.*, 1999), and data from late Cre-

taceous–late Eocene magmatic rocks as published and discussed in Haschke *et al.* (2002). The palaeo-arc studied herein represents the base for the modern Andean evolution, and it is stressed that its tectonomagmatic and geochemical features are integral parts of repeated evolutionary patterns affecting the entire north Chilean Andean orogeny (200 Ma–Present).

Like the present subhorizontal subduction segments in northern Chile, subduction from late Cretaceous–late Eocene was influenced by substantially increasing convergence rates between the Farallon (Nazca) and South American Plate (Isacks, 1988). Most of the subduction-related magmatism (~ 78–49 Ma) occurred during low convergence rates (< 5 cm yr⁻¹; Pardo-Casas and Molnar, 1987; Somoza, 1998), at a highly oblique subduction angle within an intra- and back-arc horst-and-graben type extensional tectonic setting in the upper plate (Charrier and Reutter, 1994). According to Pardo-Casas and Molnar (1987), reconfiguration of SE-Pacific oceanic plates at ~ 49 Ma led to almost arc-normal convergence and more than doubling convergence rates, coeval with termination of intra- and back-arc extension (~ 44 Ma; Charrier and Reutter, 1994). Subsequently high convergence rates are consistent with late Eocene Incaic horizontal shortening (~ 15 km; Günther *et al.*, 1998) and crustal thickening in the Chilean Precordillera (~ 38.5 Ma;

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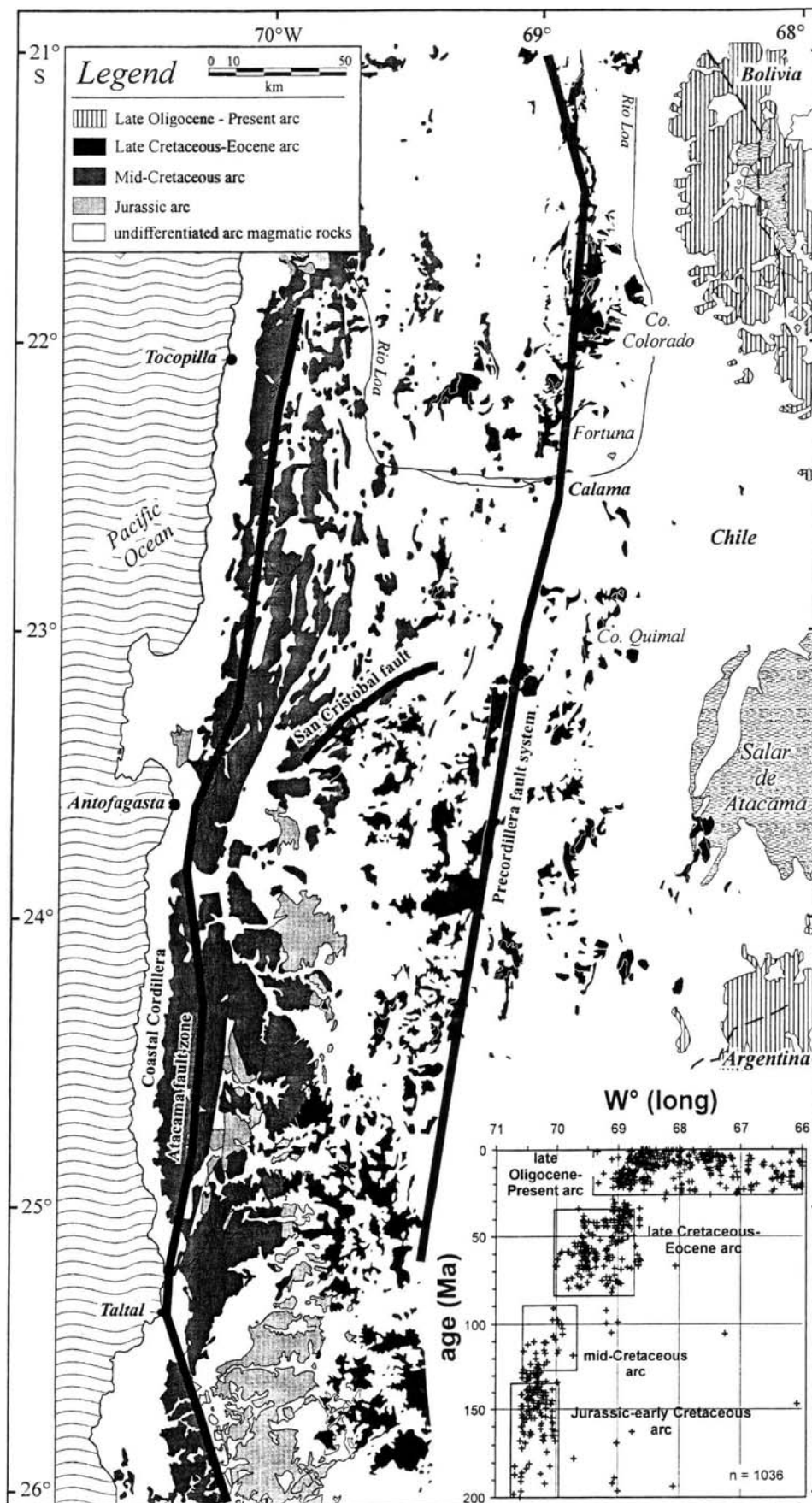


Fig. 1 Simplified geological map of the Andes in northern Chile, schematically showing the distribution of pre-Neogene and Neogene magmatic rocks in the southern Central Andes. Black lines mark trench-linked strike slip fault zones in each arc. Inset: Plot of age of Andean magmatic rocks of the Northern Central Andes vs. longitude (after Scheuber *et al.*, 1994).

Döbel *et al.*, 1992). Following Incaic transpressional deformation, arc magmatic activity between 20 and 26°S terminated and convergence rates decreased substantially, before they increased again in late Oligocene (~26 Ma, Somoza, 1998) coeval with resuming arc magmatism in the area of the present Western Cordillera.

Establishing reliable convergence parameters for older Andean magmatic episodes is more difficult because of larger uncertainties involved in plate motion reconstructions. Earlier studies proposed a sinistral oblique convergence for the Jurassic arc to explain the transtensional deformation and left-lateral offset along the Atacama fault zone (135–130 Ma), and higher convergence rates and less oblique subduction for the mid-Cretaceous arc to account for the Peruvian shortening and thickening of the crust (90–80 Ma; Scheuber *et al.*, 1994) and offset along the San Cristobal fault (Fig. 1). Like the late Cretaceous–Eocene arc, magmatic activity in the older palaeo-arcs terminated after transpressional or transtensional tectonic activity along the arc, and resumed after 5–10 Myr of relative magmatic quiescence up to 100 km further east.

Geochemical evolution

In the northern Chilean palaeo-arcs the gradual increase of La/Yb ratios is the result of gradually decreasing heavy REE contents (such as Yb). Decreasing Yb and Y (and other heavy rare earth elements) and increasing Sr contents (as well as increasing Na₂O and Al₂O₃) are sensitive to monitor changing lower pressure plagioclase- and clinopyroxene-dominated residual mineralogies

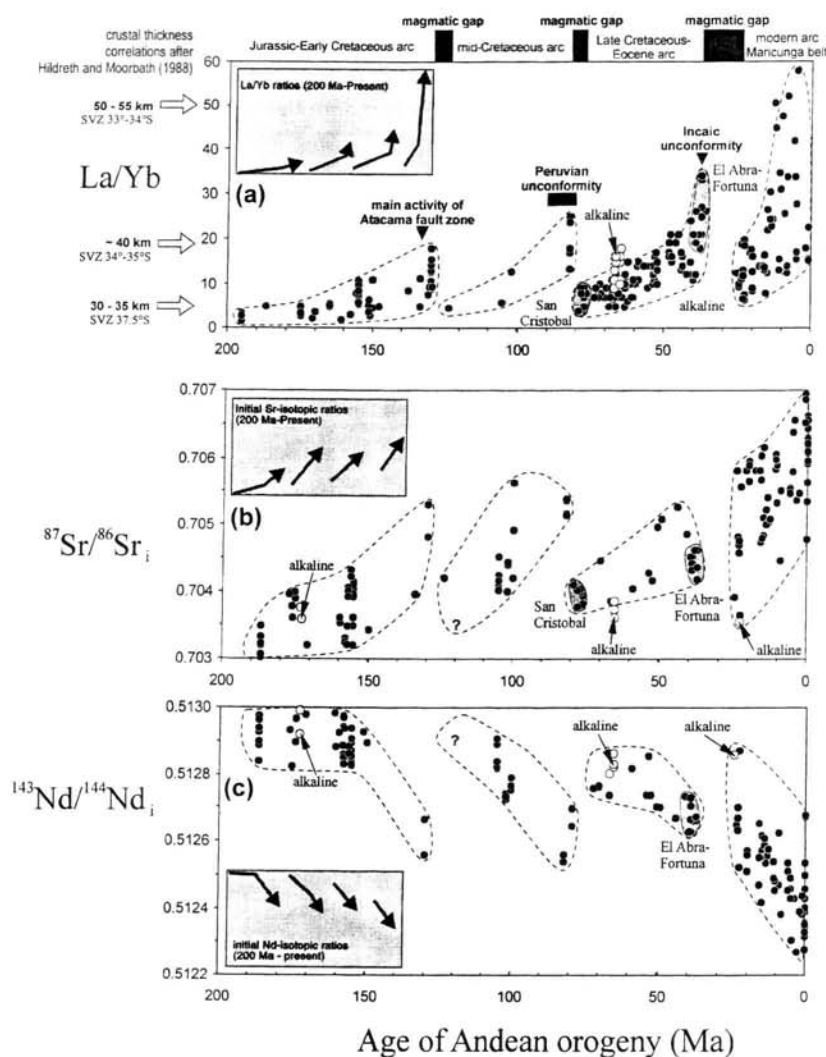


Fig. 2 Plot of age (Myr) of Andean orogeny: (a) vs. La/Yb ratios, (b) vs. initial $^{87}\text{Sr}/^{86}\text{Sr}_i$ ratios, and (c) vs. $^{143}\text{Nd}/^{144}\text{Nd}_i$ ratios. The highest La/Yb ratios and most enriched Sr- and Nd-isotopic values in each magmatic episode correlate with transpressional/transtensional intra-arc deformation. Periods without magmatism correlate with flat-slab type subduction followed by stepwise eastward arc migration of up to 100 km. Alkaline magmatism in each magmatic episode occurred after onset of arc magmatism in the back-arc and is not part of the main-arc geochemical trend of increasing La/Yb ratios.

towards higher pressure, amphibole- and garnet-bearing mineral assemblages, when migrating through the garnet stability field at > 12 kbar, or > 40 km crustal thickness (Rushmer, 1993; Rapp and Watson, 1995; Petford and Atherton, 1996).

La/Yb ratios in late Cretaceous–Eocene arc magmatic rocks rise gradually (from < 10 in late Cretaceous dacites and rhyolites to 34 in late Eocene syn-/post-tectonic granitoids) as a result of decreasing Yb contents (2.2–4.2 p.p.m. to 0.6–

1.5 p.p.m.), and Sr_i values increase (0.7039–0.7045) and Nd_i values decrease (0.51276–0.51265) with decreasing age. The small contrast between late Cretaceous and late Eocene main-arc melts in terms of Sr_i and Nd_i isotopic ratios rule out major compositional, structural or age changes during petrogenesis. Moreover, the presence of less-enriched back-arc alkaline rocks ($\text{Sr}_i = 0.7036\text{--}0.7046$, $\text{Nd}_i = 0.51280\text{--}0.51286$) argue against isotopic enrichment by recycling of old mantle lithosphere during east-

propagating Neogene Andean arc magmatism, as proposed by Rogers and Hawkesworth (1989). In addition, late Cretaceous–Eocene magmatic rocks lack correlation between increasing Sr_i and Nd_i isotopic enrichment and increasing SiO_2 and decreasing Sr content, in contrast to most younger CVZ silicic volcanic rocks erupted through thicker crust (e.g. Rogers and Hawkesworth, 1989; Trumbull *et al.*, 1999). This correlation is attributed to upper crustal contamination during low-pressure differentiation. Such evolutionary Andean series correlating with crustal thickening are reported through time from late Oligocene to late Miocene lavas in the Maricunga belt (26–28°S, Kay *et al.*, 1994), and along the southern volcanic zone (Hildreth and Moorbath, 1988) (Fig. 2a–c). Therefore, the moderate Sr- and Nd-isotopic enrichment in late Cretaceous–Eocene main-arc magmatic rocks is probably a consequence of higher pressure (deep crustal) enrichment. Otherwise late Cretaceous–Eocene main-arc volcanic and intrusive rocks in northern Chile show strong evolutionary similarities in geochemical and isotopic signatures through time with those seen in Neogene magmatic rocks (Fig. 2a–c), such as the small-volume of alkaline magmatic rocks in the arc to back-arc transition (67–66 Ma, Cerro Quimal and Cerro Colorado; Makshev, 1990) during the early stage of magmatic activity (see alkaline Segerstrom and Maquinas lavas in Kay *et al.*, 1994). These chemical and isotopic evolutionary trends are characteristic of Andean palaeo- and modern arcs in northern Chile (insets of Fig. 2a–c). Moreover, the La/Yb increase tends to accelerate progressively to higher values each time magmatism shifted stepwise eastward and establishes on thicker crust. The correlation of increasing La/Yb ratios in palaeo-arc magmatic rocks and crustal thickening can be verified by temporal correlation of highest La/Yb ratios with shortening and thickening of arc crust (about 90–80 Ma: Peruvian tectonic phase, about 38.5 Ma: Incaic tectonic phase) in each magmatic episode, except for the Jurassic arc. Structural studies on the oldest Andean magmatic arc show no evidence of contractional deformation (Scheuber *et al.*, 1994), consistent with a lack

of significant increase in La/Yb (Fig. 2a).

Of importance for the present model is that each palaeo-arc magmatic episode was characterized by termination and lack of subduction-related magmatic activity for 5–10 Myr after crustal thickening, followed by stepwise eastward migration of the main-arc front, similar to the modern north Chilean flat-slab region.

Changing subduction geometry during the Andean orogeny

In spite of some intra-arc variations in the evolution of Andean magmatic arcs (21–26°S), on the larger scale of the complete Andean orogeny these arcs show strikingly similar chemical, magmatic and tectonic evolutionary patterns. The main issue is how to interpret these repeated magmatic gaps of 5–10 Myr connecting the Andean arc magmatic episodes. One explanation is a repeated and extremely systematic subduction of oceanic plateaus every 30–40 Myr at exactly the same location throughout the Andean orogeny (see Gutscher *et al.* 2000a). Alternatively, a geodynamic model is envisaged in which termination of subduction-related magmatism reflects onset of flat subduction. Temporal magmatic gaps after each magmatic episode represent the time needed to re-steepen the slab and reshape a sufficiently hot asthenospheric mantle wedge to induce arc magmatism (Fig. 3a–d). One mechanism of slab steepening may be progressive eclogitization of the slab tip and onset of subsequent slab-rollback. The effect of slab-rollback may be reflected by incipient back-arc rifting and alkaline magmatism during the early stage of arc magmatism (as seen during late Cretaceous and late Oligocene back-arc magmatism).

Increasing convergence rates result in slab kinking and bending between the rapidly subducting hydrated shallow slab and the deeper and already eclogitized part of the slab. It is considered unlikely that this deep eclogite slab portion will resume to shallow depths after onset of rapid subduction, as slab shallowing would require 'squeezing out' asthenospheric material between the slab and the overlying plate vs. an opposite directed corner flow: the preferred model

herein predicts that rapid subduction and overriding of a shallow subducting slab over a steepened and more dense (eclogitic) slab portion will result in slab breakoff, and that late Eocene crustal shortening could eventually reflect such an event. Rapid overriding above the detached sinking eclogite slab portion (Fig. 3c) may have prevented partial melts of the slab edge from rising up into the overriding upper plate. Analogous to modern flat subduction, the lack of slab pull is responsible for flat subduction and the virtual absence of arc magmatism between the late Eocene and late Oligocene in northern Chile (Fig. 3c–d), and may reflect the time required for eclogitization and subsequent re-steepening of the slab. In fact, the westward migration of Neogene arc magmatism to the present Western Cordillera, north of the Chilean flat-slab region, may reflect the onset of such a cycle, and slab-rollback may explain the scattered occurrence of Oligocene mafic alkaline back-arc flows at 26–28°S (Kay *et al.*, 1994).

Discussion

Although the model presented herein can account for many chemical, magmatic and tectonic features, the question remains why the evolution of the modern Chilean flat-slab region was characterized by widening of the arc (i.e. slab shallowing), whereas the late Eocene arc narrowed prior to cessation of arc magmatism (slab steepening, Fig. 1 inset). One explanation is that the concept is wrong and arbitrary sampling simply reflects apparent narrowing of the late Eocene arc. Another possibility is that instead of flat subduction, subduction ceased from late Eocene to late Oligocene. Both explanations are unsatisfying as the dataset compiled and used to evolve the model is dense and leaves little room for additional magmatic gaps, and reconstructed convergence rates for the period from 40 to 26 Ma are between 5 and 10 cm yr⁻¹ (Somoza, 1998), which is sufficient to induce (flat) subduction.

Repeated stepwise eastward arc migration during the Andean orogeny and the actual eroded Jurassic arc along the Coastal Cordillera are evidence of substantial forearc erosion, and the question arises where this

Fig. 3 Model of repeated flat subduction during late Cretaceous to late Oligocene arc magmatism in Northern Chile (a) 78–48 Ma: onset and progressive eclogitization at the tip of the slab leads to slab-pull, slab-rollback and successive slab steepening followed by incipient back-arc rifting. These processes correlated with low convergence rates and high obliquity. (b) 48–39 Ma: continuous slab-rollback during increasing convergence rates and decreasing convergence obliquity. Termination of crustal stretching and transitional tectonic regime. (c) 39–37 Ma: slab break-off after exceeding a critical angle between a less dense hydrated upper basaltic slab portion and a denser eclogitized lower portion of slab. Removal of the denser eclogite portion allows rebound of the slab and subsequent flat subduction. Lack of eclogite (i.e. lack of sufficient slab-pull) is responsible for flat subduction after slab-breakoff, preventing subduction-related magmatism. This episode correlates with transpression and crustal shortening (Incaic tectonic phase) at high convergence rates and almost arc-normal convergence. (d) 37–26 Ma: virtually flat subduction and lack of subduction-related magmatism after slab breakoff and rebound until about 26 Ma. Time needed to (re)initiate slab steepening (owing to onset of eclogitization). Arc magmatism resumes as slab steepens to allow a sufficiently hot mantle wedge. Slab rollback causes incipient back-arc rifting and alkaline magmatism (Segerstrom flows and Maquinas lavas).

material has been transferred through time. Underplating such forearc eroded material may account for substantial forearc crustal thickening as seen beneath the Chilean Precordillera (~ 70 km; Schmitz *et al.*, 1999), but is unlikely to cause crustal thickening beneath the arc and thus to correlate with increasing La/Yb ratios. Underplating of material eroded off the continental edge is likely to be a compositional melange of variable crustal components of different age, and is expected to cause considerable variation in Sr_i and Nd_i ratios through time; presumably more than the one seen during the Andean orogeny.

Another problem may be the lack of adakites after slab failure resulting from plunging of the slab into a relatively hot asthenospheric mantle

wedge (suggested by Gutscher *et al.*, 2000b). In fact, the chemistry of the syn post-Incaic El Abra–Fortuna batholith shows some resemblance to

rocks interpreted as adakites. Chemical criteria of typical slab-melts (as given in Table 1) show extremely low Yb (as low as 0.29 p.p.m.) and Y, and

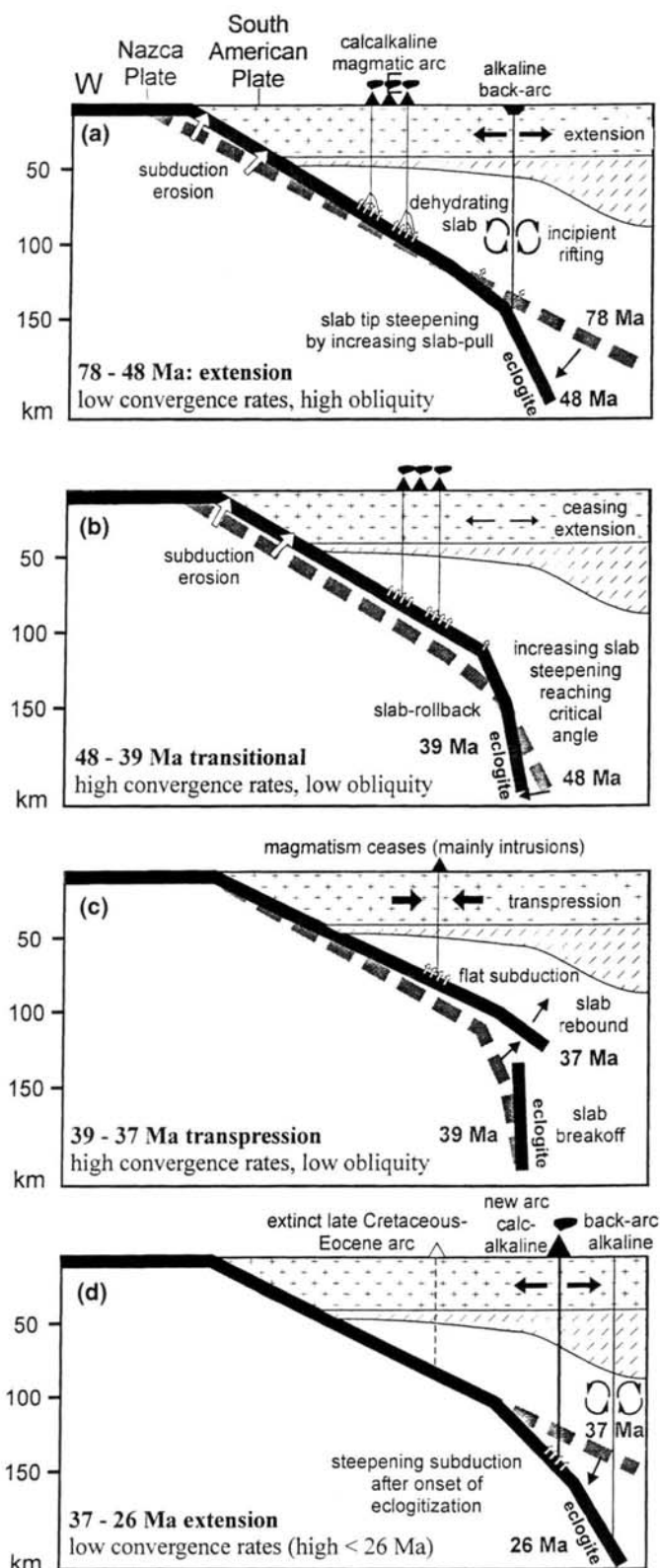


Table 1 Characteristics of magmas (> 60 wt% SiO₂)

	Slab melts ('adakites')		Syn-/post-tectonic El Abra/Fortuna batholith
	Kay (1978)	Smith <i>et al.</i> (1979)	Haschke <i>et al.</i> (2001) and previous authors
La/Yb	30–57	108–238	18–34
Sr/Y	–	177–344	19–57
Sr	1783–2600	1520–2650	302–612
Yb	0.948–0.633	0.52–0.29	0.6–1.5
Y	–	7.7–9.9	8.0–22
Na ₂ O	3.22–3.7	2.23–5.34	4.0–5.5
Al ₂ O ₃	15.2–15.5	13.7–18.4	16.5–17.8

very high Sr (as high as 2650 p.p.m.) contents (see Kay, 1978; Smith *et al.* 1979). North Chilean late Eocene syn/post-tectonic granitoids show higher Yb contents (0.6–1.5 p.p.m.), lower La/Yb ratios (18–34) and much lower Sr concentrations (Sr 302–612 p.p.m.), and most importantly they occur directly above the thickened crustal keel of the late Eocene magmatic arc where Incaic crustal shortening caused crustal thickening. Adakites tend to occur off the main-arc axis and are rarely part of temporally coherent main-arc magmatic series.

Evolution of these chemical characteristics may not be representative for the entire central Andean volcanic zone (CVZ) as sampling reveals a considerable range in La/Yb ratios; however, it is relevant for the present study that there is an evolutionary cycle tying tectonic, magmatic and geochemical features together, no matter what interpretation is applied (see Fig. 2a–c). Based on results from the recent central Andean magmatic arc, this may be diagnostic of crustal thickening, followed by slab shallowing and subsequent cessation of arc magmatism.

A previous similar approach to establish geochemical patterns during almost 200 Myr of Andean subduction magmatism was conducted by Rogers and Hawkesworth (1989), but their work addressed the issue of crust generation and concentrated on chemical constraints without taking changing convergence parameters and associated tectonic settings into account.

It is not suggested that the entire Andean orogeny was as simple as the model outlined here. In fact, each pre-Neogene magmatic episode comprises its own and far more complex evolution than could possibly have

been elaborated in the present study, but on a larger scale the evolution of Andean palaeo-arc magmatic episodes in northern Chile has generated clear and distinct tectonic, magmatic and geochemical patterns, establishing palaeo-arc magmatic episodes as distinct analogues of the modern Neogene sequence. Recognizing such patterns may help identifying how cyclic variations in subduction dynamics modulate the nature and composition of the magmatism generated there. This is particularly important for the Andes, as they have been the model region for understanding magmatic and tectonic effects of subduction on modern and ancient continental margins since the earliest days of plate tectonics.

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