



Evolutionary geochemical patterns of Late Cretaceous to Eocene arc magmatic rocks in North Chile: implications for Archean crustal growth

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Abstract. Repeated eastward shifting of subduction-related magmatism between Jurassic and Present generated a collage of four magmatic arcs in North Chile (21–26°S). Focussing on the Late Cretaceous-Eocene arc, this study explores the evolution of geochemical and isotopic signatures of arc magmatic rocks through time. Temporal geochemical variations include systematic steepening of heavy rare earth element patterns and increasing Sr and Al contents with decreasing age. Gradually increasing La/Yb and Sr/Y ratios between ~78 Ma and 39 Ma appear to monitor gradual crustal thickening by newly underplated basaltic crust, whereas sharply rising La/Yb and Sr/Y ratios in late Eocene syn/post-tectonic granites and granodiorites reflect Incaic (38.5 Ma) shortening and thickening of arc crust to ~45 km, consistent with regional tectonic field constraints. Support for the timing and magnitude of crustal thickening comes from similarities with chemical signatures from the modern southern volcanic zone (SVZ), from trace element modeling and from regional geologic constraints. On the scale studied, the geochemical variations presented correspond to a temporal transition from common Phanerozoic island-arc type to Archean type high-Al trondhjemite-tonalite-dacite (TTD) and granodiorite (TTG) crust. Comparisons with adjacent older and younger Andean magmatic arcs in this region show similar geochemical patterns; the thicker the crust the more high-Al TTD/TTG like the chemical signatures are. On the larger scale of the Andean orogeny, our results support earlier models of Archean crustal growth which suggest that large portions of early Earth's high-Al TTD/TTG type continental crust may have been generated by recycling mafic underplate of thick orogenic crust.

1 Introduction

Geochemical and experimental petrological work indicate that early Earth's continental trondhjemite-tonalite-dacite (TTD) and granodiorite (TTG) crust was generated by partial melting of a basaltic protolith transformed into a garnet-

bearing amphibolite or eclogite, yet the geodynamic setting is subject of controversy (Martin, 1999). Debate centers on the problem of whether Archean TTD/TTG suites were generated by melting of (1) subducting basaltic ocean crust (e.g. Defant and Drummond; 1990; Martin, 1999), or (2) contamination within deep (underplated) basalt beneath overthickened (>40 km) orogenic crust (e.g. Atherton and Petford, 1993; Feeley and Hacker, 1995; Petford and Atherton, 1996; Petford and Gallagher, 2001; Haschke et al., 2002a). Both scenarios generate melts with geochemical signatures diagnostic of Archean high-Al TTD/TTG (i.e. low Yb and Y concentrations, high Al, Na and Sr contents, and high La/Yb and Sr/Y ratios). Although most Phanerozoic dacite-granodiorite (island-arc type) suites are high in Yb and Y, with low Al, Na and Sr contents, and low La/Yb and Sr/Y ratios. Modern TTD/TTG type rocks are rare, but where they do exist they simulate the conditions that led to widespread crustal growth in the Archean and provide potential keys to unlock our basic understanding of continental evolution (Martin, 1999).

Slab melting during the Archean is perhaps more widely accepted as higher heat flow presumably induced rapid subduction of smaller and younger (hotter) plates, optimizing the conditions for slab melting. However, remelting (magmatic recycling) of mafic underplate at the base of overthickened orogenic crust is more controversial as it implies early growth and existence of an overall thick (>40 km) Archean crust. A detailed study of long-term subduction-related magmatism along an ~500 km long section in the central Andean foreland may provide support for this rival hypothesis. I compiled major and trace element and Sr and Nd isotopic data for 501 samples of Andean magmatic rocks from North Chile (21–26°S) with ages from 200 Ma-Present. New analyses of Late Cretaceous-Eocene magmatic rocks are published in Haschke et al. (2002a). The complete data compilation is available upon request. It is by no means complete, but rather awaits further work as the interplay of geochemical and tectonic patterns presented may have a large impact on early Earth's crustal evolution models.

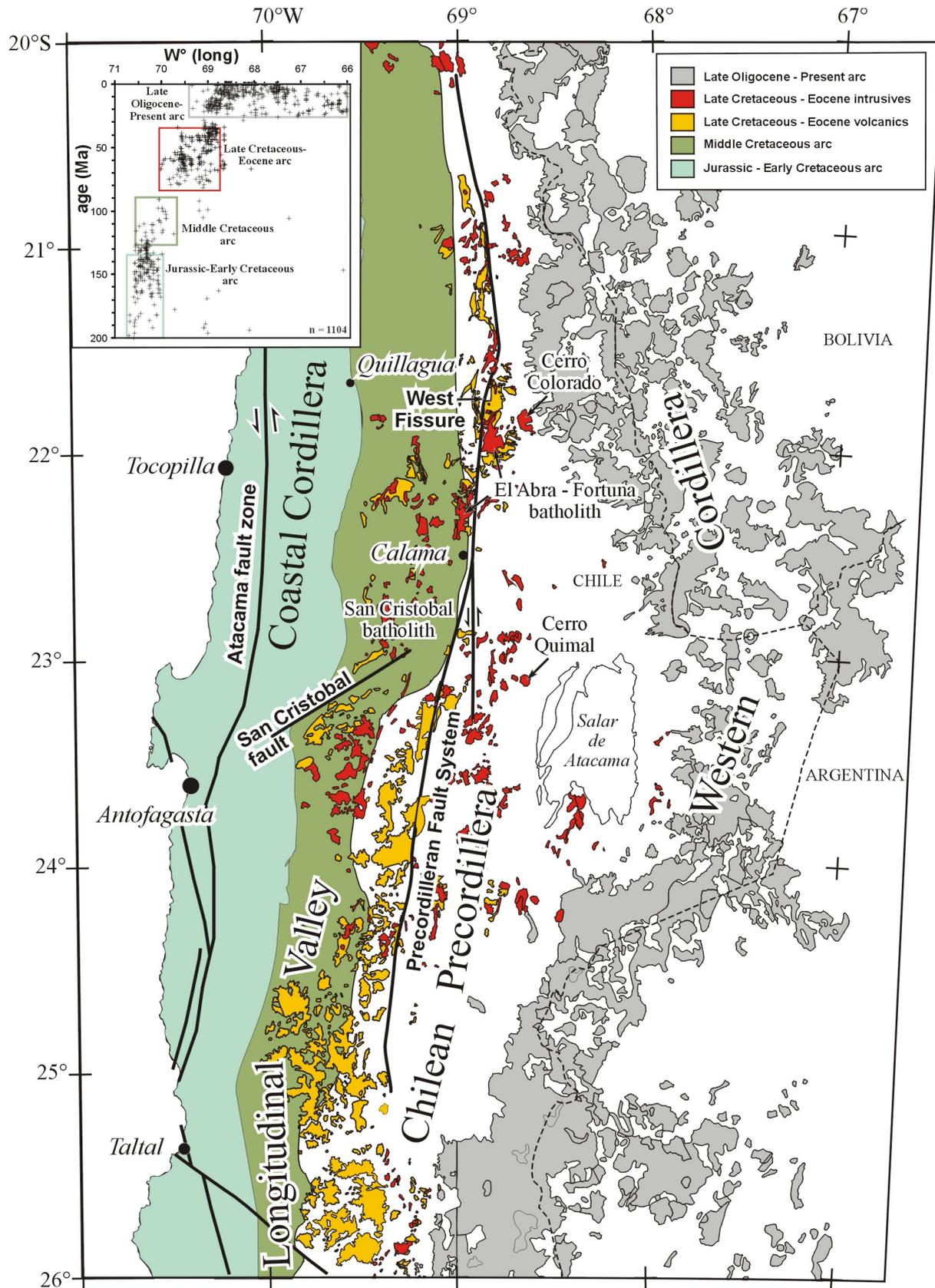


Fig. 1. Simplified geologic map of North Chile with distribution of Jurassic-Present arc magmatic rocks in the central Andean foreland. Black lines mark trench-linked strike slip fault zones in each arc system. Inset shows plot of age of central Andean magmatic rocks vs longitude (compiled by Scheuber et al., 1994).

2 Tectonic and geologic framework

The study area forms the western foreland of the modern central Andean Western Cordillera volcanic arc in North Chile. Stepwise, eastward shifting arc magmatism from the Jurassic to the Present generated a collage of four largely parallel, eastward younging magmatic arcs (Coira et al., 1982; Scheuber et al., 1994; Fig. 1): the mainly Jurassic island-arc type chain along the present Coastal Cordillera, the more evolved mid-Cretaceous arc parallel to the Chilean Longitudinal Valley, the mature Late Cretaceous-Eocene continental arc largely corresponding to the Chilean Precordillera and the late Oligocene-late Miocene orogenic arc and modern Western Cordillera. Like a window to the past, this paleo-arc magmatic assemblage is restricted to the central Andean foreland between 21°–26°S. North and south of these latitudes, the paleo and modern volcanic arcs merge into the main Cordillera. Systematic and clear geochemical patterns like the ones shown in this study cannot be produced north and south of this section.

The Mesozoic and Cenozoic tectonic history of North Chile (21°–26°S) is well established from earlier regional geologic studies (e.g. Reutter et al., 1991; Scheuber and Reutter, 1992; Döbel et al., 1992; Scheuber et al., 1994; Günther et al., 1998). Each paleo-magmatic episode ended simultaneously with major tectonic activity along the main-arc axis; either transtension and crustal stretching (Araucanian tectonic episode (135–130 Ma) in the Jurassic arc – Scheuber et al., 1994) or transpression and crustal shortening (Peruvian unconformity (90–80 Ma) – Scheuber et al., 1994; Incaic unconformity (38.5 Ma) – Döbel et al., 1992), followed by magmatic quiescence of 5–10 m.y. Subsequent arc magmatic activity established up to 100 km further to the east. The amount of crustal shortening and thickening tend to increase with decreasing age of each magmatic arc.

The first arc system of the Andean Cycle (Jurassic-Early Cretaceous arc) was built up since the Sinemurian in the area of the present Coastal Cordillera (Fig. 1). This arc is composed of lavas, mafic to felsic dikes, tuffs and large plutons of gabbroic to granodioritic composition. Most lavas are basaltic andesite flows interstratified with terrestrial and marine intercalations, indicating that the surface of this island-arc type volcanic chain was, more or less, at sea level (Scheuber and Reutter, 1992). Some volcanic products reach thicknesses of ~10 km (e.g. near Antofagasta) suggesting substantial crustal subsidence. Numerous suites of high angle faults and orogen-parallel dikes (>40% of the outcropping rocks), together with deepening marine back-arc basins, suggest that the gain in crustal volume occurred in an overall extensional tectonic regime with (rift-like) filling of opening interstices by melt. Transtension was accommodated by tearing apart crustal blocks and transtensional strike-slip motion along the trench-linked Atacama fault zone (Fig. 1). There is no evidence of significant tectonic crustal thickening during this magmatic episode.

The tectonomagmatic history of the middle Cretaceous arc system is more enigmatic. Arc-magmatic rocks were em-

placed in the subsiding back-arc basin of the previous, now magmatically inactive, (Jurassic) arc system and the lack of a significant angular unconformity between the sedimentary substrate and the lavas (Jensen, 1985) suggests that extensional tectonics continued up to the mid-Cretaceous. Only the last stage of this arc was accompanied by transpressive crustal shortening and subsequent strike-slip motions along the San Cristobal fault leading to intense folding and, in some places, to foliation and cleavage development in volcanic and sedimentary rocks (Scheuber and Reutter, 1992). The age of this deformation is constrained by radiometrically dated deformed rocks, by the post-deformational emplacement of radiometrically dated plutons (San Cristobal batholith; Maksiyev, 1990), and by an angular unconformity between the deformed sequence and an overlying volcanic sequence of Late Cretaceous-Eocene age (90–80 Ma: Peruvian tectonic episode; Scheuber et al., 1994).

Unlike older Andean paleo-arcs in North Chile, the Late Cretaceous-Eocene arc tuffs, lavas and ignimbrites above this unconformity were deposited together with redbeds above the sea level. More than 3000 m of red-bed type conglomerates interstratified with marine intercalations are diagnostic of a considerable relief contrast between the arc and back-arc region. Late Cretaceous alkaline gabbros to diorites (Cerros Quimal and Colorado, Fig. 1) intruding the red-beds in this arc to back-arc transition are consistent with an extensional tectonic regime (Charrier and Reutter, 1994). In contrast, the youngest magmatic rocks of this paleo-arc system (El Abra-Fortuna batholith, Fig. 1) were generated simultaneously and subsequent to late Eocene Incaic transpressional deformation, which shortened the arc crust by about 9 km (or 14.5% tectonic crustal thickening, Günther et al., 1998). Like the older Andean arc systems, arc magmatic activity ceased after orogen-parallel transcurrent movements along the West Fissure (Precordilleran fault system; Reutter et al., 1991), and was reinstalled in the Late Oligocene/Early Miocene up to 100 km by the modern Western Cordillera volcanic arc. Maximum crustal thicknesses of ~70 km beneath the present Andean volcanic arc are constrained by recent refraction experiments, broadband passive recording of earthquakes in the subducted plate, and modeling of the gravity field (Wigger et al., 1994). The results of my study illustrate how the major and trace element, and Sr and Nd-isotopic compositions of Andean arc-magmatic rocks traced this long-term tectonic and magmatic evolution and progressive crustal thickening of the Andean convergent continental margin.

3 Geochemical changes of late Cretaceous-Eocene main-arc magmatic rocks in North Chile (21°–26°S)

3.1 Major and trace elements

Late Cretaceous-Eocene arc magmatism in North Chile produced a larger volume calc-alkaline suite of medium to high-K basaltic andesites to dacites and rhyolites, a smaller volume back-arc suite of alkaline gabbros to granodiorites, and

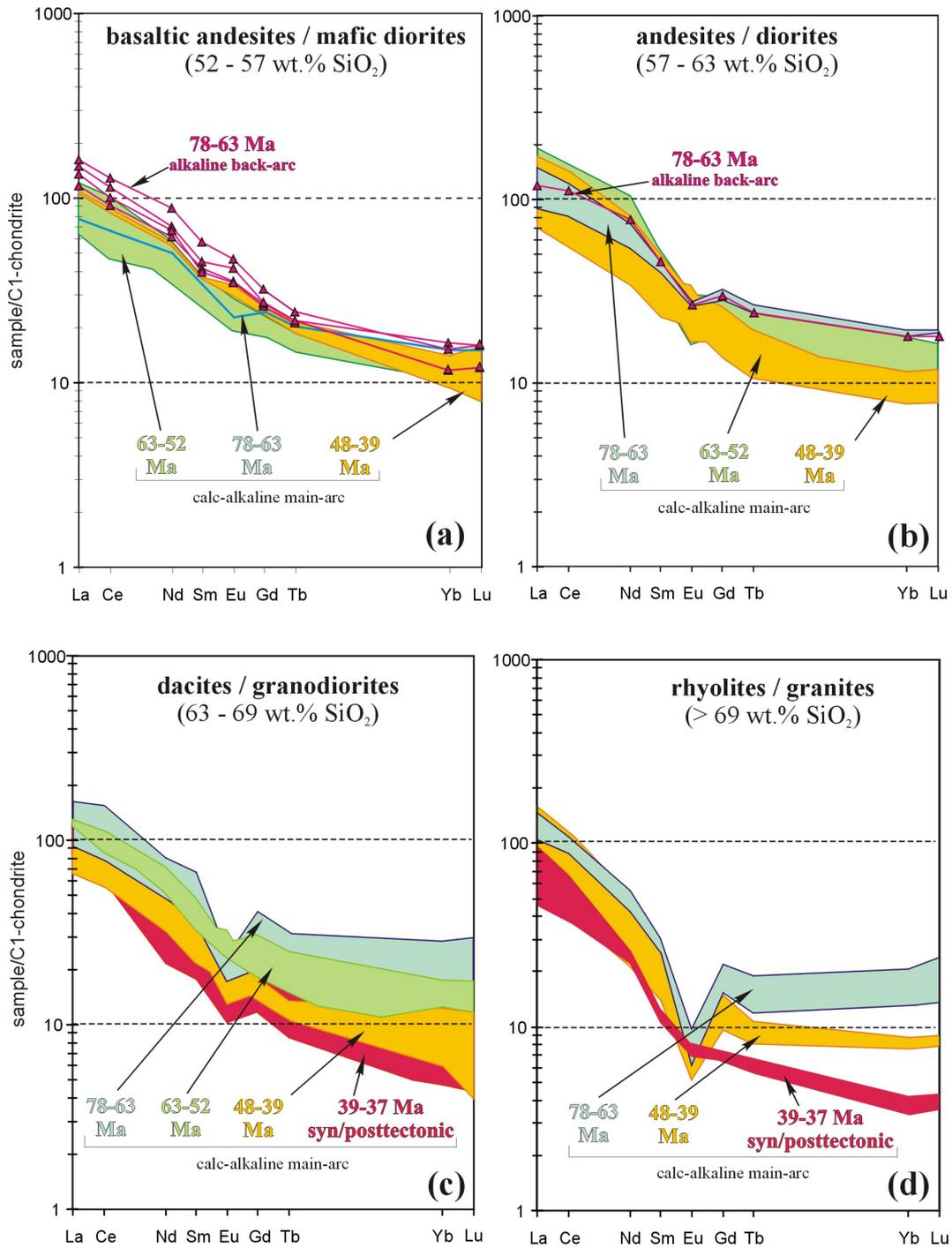


Fig. 2. REE patterns of Late Cretaceous-Eocene arc magmatic rocks in North Chile. (a) basaltic andesites and mafic diorites, (b) andesites and diorites, (c) dacites and granodiorites, (d) rhyolites and granites. Note increasing heavy REE fractionation with time and increasing SiO₂ content.

some scattered calc-alkaline mafic andesitic centers aligned with across-arc fracture zones (Fig. 1). As is typical for most magmatic rocks of the central volcanic zone (CVZ) and the southern volcanic zone (SVZ), the high Ba/Nb ratios (>30) of Late Cretaceous-Eocene rocks from both the calc-alkaline and alkaline magmatic suites are consistent with primary melt generation from a metasomatized mantle wedge above

a dehydrating subducting slab (e.g. Hildreth and Moorbath, 1988; Kay et al., 1991).

The study stresses that intermediate and silicic Late Cretaceous-Eocene arc magmatic rocks at equal SiO₂ show compositional variations with decreasing age, such that the greatest chemical contrast within this arc system occurs between the oldest (Late Cretaceous) and the youngest (late

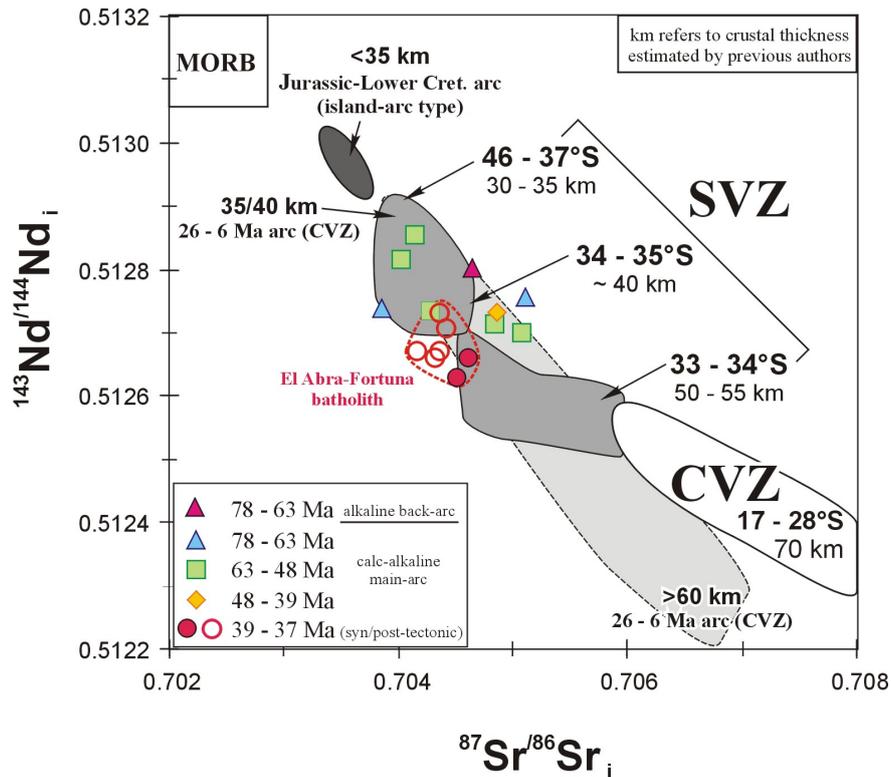


Fig. 3. Correlation of initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios vs initial $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios. Late Cretaceous-Eocene rocks partly overlap with Sr and Nd isotopic compositions from the SVZ between 37°S and $35^\circ\text{--}34^\circ\text{S}$, where crustal thicknesses are inferred to increase from 30–35 km to 40 km, and portions of the SVZ between $34^\circ\text{--}33^\circ\text{S}$ where crustal thicknesses range from 50–55 km. Island-arc-type Jurassic arc with thin crust shows lower $^{87}\text{Sr}/^{86}\text{Sr}$ and higher $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios; SVZ volcanic rocks North of 34°S , and Late Miocene arc and CVZ with crust $>50\text{--}55$ km show more “crust-like” signatures.

Eocene) dacitic-granodioritic and rhyolitic-granitic rocks (Fig. 2a–d). The complete data base is published in Haschke et al. (2002a).

The most mafic main-arc rocks are basaltic andesites (mafic diorites) with high alumina (Al_2O_3 18–19.6 wt.%) and low MgO (<5 wt.%), Ni (<30 ppm) and Cr (<100 ppm) contents. They are characterised by mainly overlapping REE patterns with small negative Eu anomalies (Eu/Eu^* 0.8–0.9, Fig. 2a). La/Yb (5–7 to 11–16) and Sr/Y (<25 to >40) ratios increase due to decreasing Yb (2.1–2.5 to 1.4–2.4 ppm) and Y (18–36 to 14–24 ppm) and increasing Sr contents (400–500 to 700–900 ppm) through time, but there are no major differences in REE fractionation between the older (Late Cretaceous) and younger (Mid-Late Eocene) rocks, although the Late Eocene syn/post-tectonic El Abra-Fortuna batholith lacks mafic compositions.

In the back-arc, the alkaline gabbros (Cerros Quimal and Colorado) show slightly higher MgO (<6 wt.%), Ni (up to 82 ppm), and Cr (up to 134 ppm) contents relative to mafic main-arc rocks, although MgO contents are still low relative to primitive mantle-derived basalts and for equilibration with mantle peridotite. The back-arc alkaline mafic diorites (78–63 Ma) are characterized by light REE enriched patterns (Fig. 2a) with higher La/Yb (11–16) and Sr/Y ratios (>50), which may indicate lower partial melting degrees

about 100 km east of the main-arc magmatic front, consistent with their overall LILE and HFSE-enriched signatures.

The andesitic main-arc compositions show more fractionated and overlapping REE patterns (Fig. 2b) with larger negative Eu anomalies (Eu/Eu^* 0.6–0.9) than the mafic andesites, and slightly steepening heavy REE patterns through time. Most intermediate compositions are characterized by gradually increasing La/Yb (5–7 to 14–26) and Sr/Y ratios (5–20 to 30–60) through time, due to decreasing Yb (2.5–3.7 to 1.1–1.9 ppm) and Y (24–32 to 13–20 ppm) concentrations, and increasing Sr contents (350–470 to 530–920 ppm).

Dacitic-granodioritic main-arc compositions show more fractionated heavy REE patterns and decreasing negative Eu anomalies with decreasing age (Eu/Eu^* 0.5–0.7 to 0.6–1.0; Fig. 2c). La/Yb and Sr/Y values increase through time, from mostly low La/Yb (6–9) and Sr/Y (<20) ratios to higher La/Yb (12–17) and Sr/Y (15–45) in the Mid-Late Eocene. The evolution of increasing La/Yb from Late Cretaceous to mid-late Eocene, syn/post-tectonic granodiorites is due to progressively decreasing Yb (5.9 to 0.8 ppm) and Y (57 to 10 ppm), and increasing Sr contents (mostly 250–350 to 330–670 ppm). The youngest (late Eocene) syn/post-tectonic granodiorites show the highest La/Yb (18–27) and Sr/Y (28–69) ratios among dacitic and granodioritic compositions from this arc system (Fig. 2c).

Table 1. Geochemical characteristics of adakites versus Archean TTG and Late Eocene arc rocks from North Chile

	Characteristics of magmas (>60 wt.% SiO ₂)			
	slab melts ("adakites")		Archean TTG Martin (1987)	syn/post-tectonic El Abra/Fortuna batholith Haschke et al. (2002a)
	Kay (1978)	Smith et al. (1979)		
La/Yb	30–57	108–238	23–156	18–34
Sr/Y	–	177–344	19–174	19–57
Sr	1783–2600	1520–2650	mostly >300–700	302–612
Yb	0.948–0.633	0.52–0.29	0.13–0.71	0.6–1.5
Y	–	7.7–9.9	mostly 4–20	8.0–22
Na ₂ O	3.22–3.7	2.23–5.34	mostly 4.03–5.14	4.0–5.5
Al ₂ O ₃	15.2–15.5	13.7–18.4	mostly 15.02–16.29	16.5–17.8

Rhyolitic-granitic main-arc rocks show extremely fractionated REE patterns with strongly steepening heavy REE patterns with decreasing age, and decreasing negative Eu anomalies (Eu/Eu* 0.2–0.4 to 0.8, Fig. 2d). The oldest rhyolites show mainly low La/Yb (7–12) and Sr/Y (1–6) ratios, progressively increasing to La/Yb (11–25) and Sr/Y (4–18) in mid-late Eocene. The Late Eocene syn/post-tectonic granites have the highest La/Yb (19–34) and Sr/Y ratios (19–54) among rhyolitic-granitic compositions of this paleo-arc. These systematic changes are due to progressively decreasing Yb (2.2–4.2 to 1.3–1.5 ppm) and Y (21–49 to 17–30 ppm), and increasing Sr contents (mostly 53–156 to >300 ppm) with decreasing age. Even lower Yb (0.6–0.7 ppm) and Y (8–16 ppm) contents, and higher Sr concentrations (224–634 ppm) account for even higher La/Yb and Sr/Y of the syn/post-tectonic granites. These systematic changes in trace element compositions are accompanied by progressively increasing Al and Na contents through time; from Al₂O₃ 15.8 to 17.0 wt.%, and Na₂O from 4.0 to 4.5 wt.% in dacites-granodiorites, and in rhyolites-granites from Al₂O₃ 12.7 to 15.6 wt.%, and Na₂O from 3.3 to 4.1 wt.%.

3.2 Sr-Nd isotopes

Initial Sr and Nd isotopes of Late Cretaceous-Eocene arc magmatic rocks are overall enriched ("crust-like") relative to melts from the depleted asthenospheric mantle and MORB (Fig. 3). Although ⁸⁷Sr/⁸⁶Sr ratios increase slightly (from 0.7039–0.7045 to 0.7042–0.7046) and ¹⁴³Nd/¹⁴⁴Nd ratios decrease slightly (from 0.51265–0.51276 to 0.51263–0.51271), the overall contrast is low and rules out major compositional or structural changes during petrogenesis. A major change is first seen between pre- and post-Miocene magmatic rocks (see Rogers and Hawkesworth, 1989). Higher ⁸⁷Sr/⁸⁶Sr ratios and lower ¹⁴³Nd/¹⁴⁴Nd ratios may indicate involvement of old (enriched) lithospheric mantle (Rogers and Hawkesworth, 1989) or continental crust (e.g. Hildreth and Moorbath, 1988; Wörner et al., 1988; Davidson et al., 1990; Feeley and Davidson, 1994; Feeley and Hacker, 1995).

However, the higher ⁸⁷Sr/⁸⁶Sr ratios and lower ¹⁴³Nd/¹⁴⁴Nd ratios lack correlation with decreasing Sr and increasing SiO₂ (Fig. 4a–b), which is commonly attributed to upper crustal contamination during lower pressure differentiation (Rogers and Hawkesworth, 1989; Wörner et al., 1988, 1994; Trumbull et al., 1999). Together with the systematic changes in trace element signatures, this moderate Sr and Nd isotopic enrichment in Late Cretaceous-Eocene main-arc magmatic rocks may be due to higher pressure, deep crustal enrichment (see discussion in Rogers and Hawkesworth, 1989).

The back-arc alkaline rocks show overall lower ⁸⁷Sr/⁸⁶Sr ratios (0.7036–0.7046) and higher ¹⁴³Nd/¹⁴⁴Nd ratios (0.51280–0.51286), relative to the main-arc rocks. This rules out the hypothesis of increasing ⁸⁷Sr/⁸⁶Sr ratios and decreasing ¹⁴³Nd/¹⁴⁴Nd ratios by recycling old mantle lithosphere during east-propagating Andean arc magmatism, as proposed by Rogers and Hawkesworth (1989). A more detailed elaboration on the geochemistry of Late Cretaceous-Eocene magmatic rocks is published in Haschke et al. (2002a).

4 Magma source variations

Overall, the geochemical signatures of Late Cretaceous rocks (high Yb and Y concentrations, low Sr contents, low La/Yb and Sr/Y ratios) are similar to those of low-Al TTD/TTG (as described by Drummond and Defant, 1990), whereas those of the late Eocene syn/post-tectonic rocks (low Yb and Y concentrations, high Sr contents, high La/Yb and Sr/Y ratios) resemble those of high-Al TTD/TTG (Table 1).

Partial melts of a deep basaltic source (≥12 kbar) will have low Yb and Y and high Sr concentrations (and consequently high La/Yb and Sr/Y ratios), as seen in the late Eocene syn/post-tectonic granodiorites and granites, if garnet and amphibole but no or only minor plagioclase are residual in the source (Rapp and Watson, 1995; Petford and Atherton, 1996). Residual amphibole is indicated by the middle REE depletion (Fig. 2c–d), whereas high Sr, Al₂O₃ and Na₂O contents and absent Eu anomalies indicate lack of plagioclase.

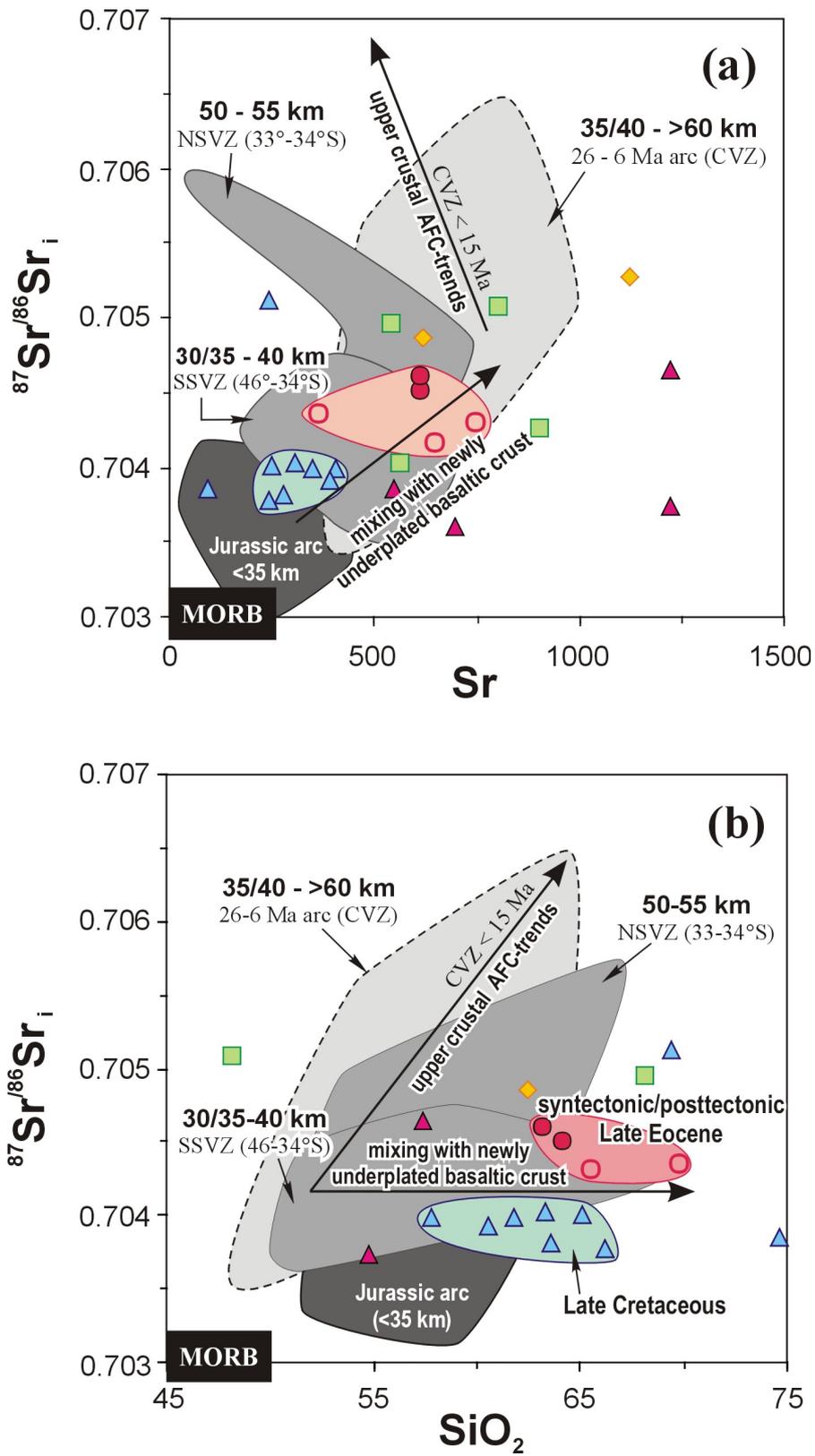


Fig. 4. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios (a) vs Sr concentrations [ppm] and (b) vs SiO_2 [wt.%]. Same legend as in Fig. 3. SVZ and CVZ volcanic rocks show increasing crustal contamination by upper crustal (lower pressure) AFC-trends with crustal thickening. $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic ratios of Late Cretaceous-Eocene magmatic rocks cannot be explained by upper crustal AFC processes, but are consistent with signatures from melting and mixing with partial melts from deep (underplated) mafic crust.

Even when amphibole is present, more important is the onset of garnet stabilization at higher pressure deeper in the crust. Garnet stabilization changes the melt compositions dramatically with increase in Si and decrease in Fe, Mg, Y and Yb, like that seen in the late Eocene syn/post-tectonic granitoids after Incaic crustal shortening, in experimental high-Al TTD/TTG's at 12 kbar (Rushmer, 1993; Rapp and Watson, 1995), and in the granitoid Cordillera Blanca batholith in Peru (Atherton and Petford, 1993; Petford and Atherton, 1996). The latter was interpreted as being generated by melting newly underplated garnet and/or amphibole-bearing (hydrous) basaltic crust.

The compositions of these melts are also similar to primary dacitic melts from subducting oceanic crust (also known as "adakites", Table 1). However, adakites are generally expected in forearc regions, not above the arc crustal keel (Atherton and Petford, 1993), and they generally lack such a systematic geochemical evolution of increasing La/Yb ratios as the one seen in Late Cretaceous-Eocene arc magmatic rocks. Furthermore, the abrupt La/Yb increase in the syn/post-tectonic late Eocene granodiorites and granites occurred coeval with Incaic shortening and thickening of the crust. It is therefore plausible that the latest (late Eocene) increase in La/Yb monitored continental crustal dynamics rather than slab melting. Following this argument, it is conceivable that the gradual increase in La/Yb ratios prior to late Eocene crustal shortening (from Late Cretaceous to Mid-Eocene) also reflects gradual crustal thickening. However, the tectonic record from this period lacks evidence of crustal shortening, and therefore the crustal thickening inferred may be due to other processes such as successive magmatic underplating.

I envisage a model which takes both increasing crustal thickening and mixing between mantle-derived basalts and crustal melts from newly underplated basaltic crust into account. Successive underplating and stalling of hot mantle-derived basalts at or near the base of the crust triggers two main parallel operating processes:

- (1) progressive deepening of the MASH crust-mantle boundary zone (MASH = melting, assimilation, storage, homogenization, after Hildreth and Moorbath, 1988) through time and transforming initial lower pressure gabbroic to higher pressure garnet- and amphibole-bearing source mineralogies, and
- (2) remelting and increasing crustal melt proportions from newly underplated basaltic lower crust. The ability of incoming basalt to melt pre-existing underplate (amphibolite) has been investigated recently. Results suggest that the amount of incoming mantle basalt need not to be large to promote melting, and that the timescale of melting will be in the order of thousands of years only (Petford and Gallagher, 2001).

In this model, the Late Cretaceous andesite-dacite-rhyolite (island-arc type) suite from North Chile represents mainly derivatives from mantle-derived basalts with little or no in-

fluence from crustal melt. Recharging hot mantle basalts into the MASH zone causes remelting (recycling) below the newly underplated basaltic crust at greater depth. The recharging mafic melt will hybridise with the more silicic crustal melts from the newly underplated basaltic crust, producing hybrid melts with geochemical and isotopic compositions reflecting the amount of hybridisation between mafic mantle and silicic crustal melt rather than the original source signature. Successive underplating and ponding of hot mantle basalts throughout the more than 40 m.y. that this arc was active probably lead to substantial thermal weakening and remelting of the mafic arc crustal base. Such rheologically and thermally weakened arc crust provides ideal mechanical conditions for shortening of arc crust during the late Eocene transpressional tectonic regime (Incaic phase, Döbel et al., 1992). The declining presence and complete lack of mafic main-arc igneous rocks in the Late Eocene syn/post-tectonic El Abra-Fortuna granodiorites and granites may reflect primary crustal melts with little or no contribution of mantle-derived basalts, since subduction-related magmatism ceased after Incaic deformation.

This model can account for the gradually increasing silicic crustal melt proportions as seen in main-arc magmatic rocks between Late Cretaceous and Late Eocene, but also accounts for the relatively constant Sr and Nd isotopic compositions with time, as the (lower) crustal source consists of freshly underplated mantle-derived basalts with little variation in composition and age.

4.1 Estimating paleo-arc crustal thicknesses (Late Cretaceous – Late Eocene)

The main-arc REE patterns and initial Sr and Nd isotopic signatures of Late Cretaceous-Mid Eocene main-arc magmatic rocks in North Chile (prior to Incaic deformation) are similar to those seen in the southern SVZ between 46°–34°S (Fig. 3 and 4a–b), where crustal thicknesses are inferred to increase from 30–35 to about 40 km (Hildreth and Moorbath, 1988). Geochemical and isotopic characteristics of late Eocene syn/post-tectonic granitoids also overlap the field of late Oligocene volcanic rocks in the Maricunga belt (26°–28°S, Kay et al., 1994), and that of the southern SVZ between 35°–34°S, where crustal thicknesses of about 40 km were estimated (Hildreth and Moorbath, 1988).

SVZ volcanic magmas between 34°–33°S are thought to have travelled through thicker crust (50–55 km), and most initial $^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of late Eocene syn/post-tectonic granitoids are lower and higher, respectively, or only partly overlap this SVZ field (Fig. 3 and 4a–b). Using these analogue along-arc variations in geochemistry and crustal thicknesses in the SVZ, I estimate roughly that mafic underplating in the Late Cretaceous–Eocene paleo-arc may have thickened the arc crust by 5–10 km, from 30–35 km to about 40 km. Subsequent late Eocene Incaic shortening and thickening of the crust lowered the arc crustal base to about 45 km. This estimate is consistent with balanced

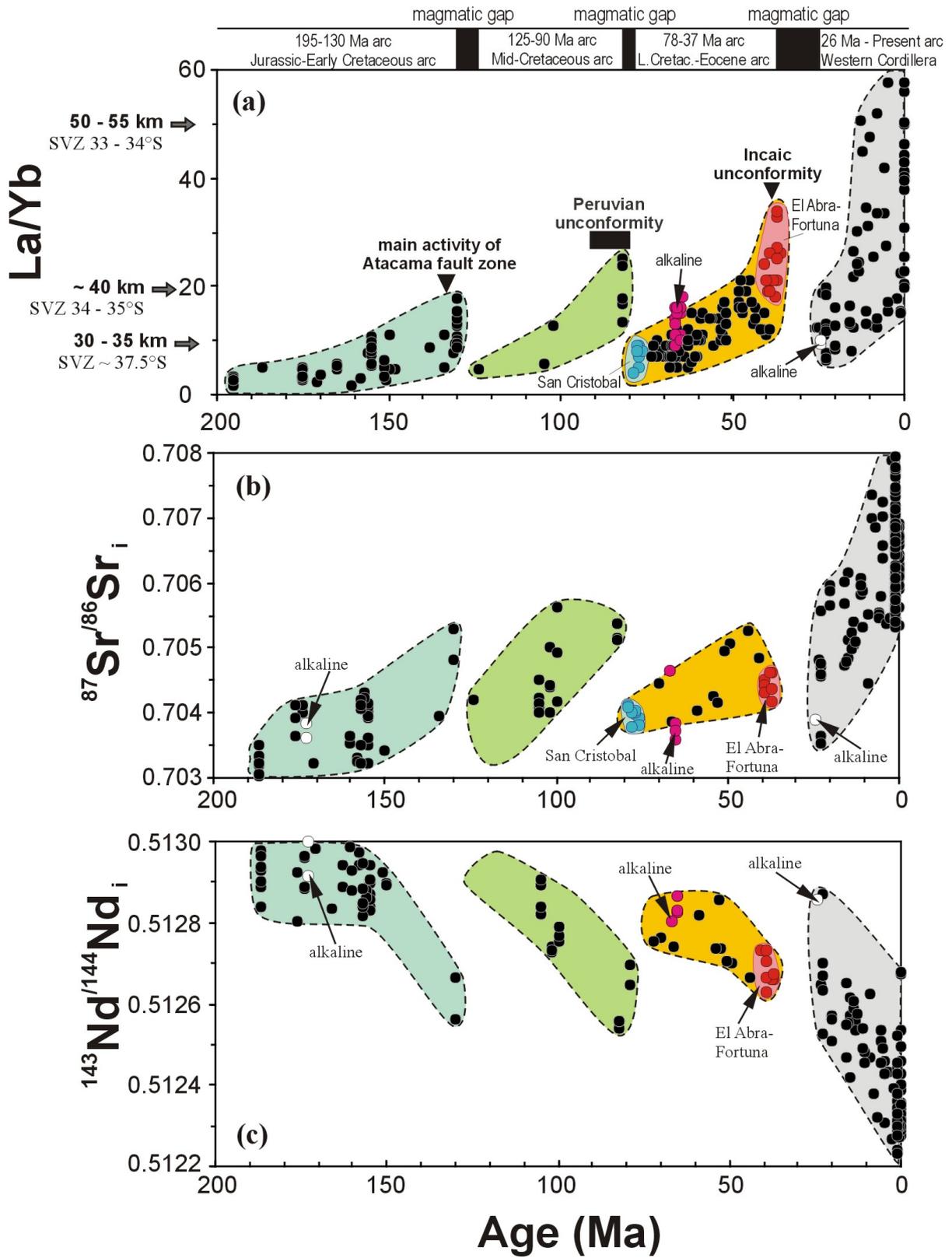


Fig. 5. Plot of age of Andean magmatic rocks (a) vs La/Yb, (b) vs initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, and (c) vs $^{143}\text{Nd}/^{144}\text{Nd}$ -isotopic ratios, showing correlation of higher La/Yb ratios and higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{143}\text{Nd}/^{144}\text{Nd}$ isotopes with decreasing age in each arc system. Episodes of transensional or transpressional tectonic activity are followed by magmatic gaps of 5–10 m.y., and subsequent stepwise eastward migration of main-arc magmatic activity.

across-arc structural sections of Incaic crustal shortening in this region (7–8 km, Haschke and Günther, 2002).

This correlation is consistent with results from numerical trace element modeling. Simulations of melting lower crustal basaltic source mineralogies at variable depth suggest that the late Eocene syn/post-tectonic granitoids can be explained by partial melting of garnet-bearing amphibolite with up to 10 wt.% garnet (Haschke et al., 2002a), reflecting pressures ≥ 12 kbar or ≥ 40 km crustal thickness (Rushmer, 1993; Rapp and Watson, 1995). Eclogitic residues (> 10 wt.% garnet) at pressures ≥ 15 kbar (or ≥ 50 km crustal thickness) produce higher La/Yb and Sr/Y ratios (Rapp and Watson, 1995) than those seen in the late Eocene syn/post-tectonic granitoids, suggesting that late Eocene arc crustal thicknesses after Incaic crustal shortening (38.5 Ma, Döbel et al., 1992) were less than 50 km.

Comparing the Late Cretaceous-Eocene evolutionary geochemical and isotopic patterns with those of other Andean arc magmatic rocks also revealed that increasing La/Yb ratios and higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and lower $^{143}\text{Nd}/^{144}\text{Nd}$ ratios through time are diagnostic of all paleo-arc systems in North Chile (Fig. 5a–c).

Within each arc-magmatic episode, increasing La/Yb ratios correlate with (tectonic and magmatic) arc crustal thickening except for the Jurassic arc. Regional geologic constraints from the oldest Andean magmatic arc system show no evidence of crustal shortening and/or significant crustal thickening (Scheuber et al., 1994), consistent with overall low La/Yb ratios which do not appear to increase with decreasing eruption age (Fig. 5a). The first indication of significant crustal thickening comes from the mid-Cretaceous arc, where the Peruvian unconformity indicates shortening and thickening of the crust between 90–80 Ma (Scheuber et al., 1994). Even though this tectonomagmatic period is not well constrained (due to lack of outcrops), the overall trend of increasing La/Yb ratios is clear. From ~ 200 Ma-Present, this pattern restarted each time the axis of main-arc magmatic activity migrated to the east. The constraints of this pattern on the plate tectonic changes during the Andean orogeny are discussed in a separate paper (see Haschke et al., 2002b).

In spite of repeated arc shifts, basaltic underplating from 200 Ma-Present implies that large amounts of basaltic crust were added to the base of the continental crust. This will have significant effects on the seismic nature of the lower crust and crust-mantle boundary. P-wave velocities (V_p) in the lowermost 20 km of the central Andean crustal column beneath the Coastal Cordillera, Longitudinal Valley, Chilean Precordillera and Western Cordillera at 23.5°S range from 7.3–7.7 km/s (Schmitz et al., 1999). Both the lowermost crustal thickness and the range of V_p shown are well within the expected range for crustal thickening (up to 25 km) and V_p (7.1–7.8 km/s) predicted by Furlong and Fountain (1986).

5 Discussion – implications on Archean crustal growth

Subduction-related magmatism at convergent plate margins is the main mechanism for crustal growth (Rudnick, 1995). The key to relate the evolutionary geochemical patterns shown in this study to Archean crustal growth lies in the temporal transition from low-Al to high-Al TTD/TTG. The low-Al TTD/TTG type rocks appear to relate to thin island-arc type (Late Cretaceous) crust, whereas high-Al TTD/TTG type rocks tend to accompany overthickened orogenic (> 40 km, late Eocene) crust. Main-arc rocks with intermediate ages are characterised by transitional compositions, intermediate between low-Al and high-Al TTD/TTG, consequently reflecting intermediate crustal thicknesses.

Such transitions are characteristic of the entire Andean orogeny (200 Ma-Present, Fig. 5a–c). One important implication is that Archean high-Al TTD/TTG crust may be associated with melting of, or contamination within, the deep arc crust (> 40 km). As a rule of thumb, these patterns suggest: The thicker the arc crust, the more do major and trace element compositions of arc magmatic rocks resemble that of Archean high-Al TTD/TTG or adakitic rocks. It is clear that neither the low-Al type is restricted to the Phanerozoic, nor the high-Al type to the Precambrian period (unlike proposed by Drummond and Defant, 1990).

If correct, then Archean TTD/TTD crust must have been thicker, or, in other words, orogenic crust was more widespread than today, and if remelting the mafic base of thick arc crust was a key mechanism for TTG/TTD type crustal growth, which mechanism was responsible for thickening the crust during Archean times?

Recent investigations of modern anomalous thick orogenic crust (Andes, Himalaya) indicate that crustal shortening is very efficient in thickening the crust (e.g. Allmendinger et al., 1997). One important requirement for crustal shortening at convergent plate margins is rapid convergence (e.g. Nazca plate versus South American plate: 8.7 cm/a; Scheuber and Giese, 1999). Even higher plate motion and convergence rates are inferred for the Archean, as higher heat flow in early Earth's history presumably induced fast rifting and consequently fast subduction of smaller and hotter plates (Martin, 1999). Slab melting may have been characteristic for the Archean, but can slab melting alone account for rapid (adakitic or TTG/TTD type) crustal growth? Results of trace element modeling of adakites from previous authors and experimental petrologic work both suggest that adakites are products of very low partial melting degrees (3–7 vol.%; Kay, 1978; Smith et al., 1979; Kay et al., 1993). If this is correct, how can adakites alone explain rapid crustal growth in the Archean? Even assuming that adakite production was more abundant in early Earth's history, it probably could not have produced the large amount of Archean high-Al TTD/TTG type continental crust.

I propose that non-collisional as well as collisional (Andean-type and/or Himalayan-type) tectonic crustal shortening and thickening was more widespread and common in the Archean than today, and that Archean crust was over-

all thicker than today (46–52 km: Artemieva and Mooney, 2001; ≥ 35 –50 km: Kröner, 1991), and mostly basaltic (Abbott et al., 1997). Crustal shortening may have been facilitated by the generally assumed higher Archean thermal gradients, since warmer lithosphere is rheologically weaker and therefore easier to deform. This is also consistent with the general accepted idea that Archean plate motions and convergence rates were faster than today (e.g. Martin, 1999), since more rapid convergence probably caused strong coupling inducing crustal shortening in the overlying plate. If this is true, then Precambrian high-Al TTD/TTG crust reflects remnants of thick ancient (Andean or Himalayan-type) orogens. Much of Archean (lower) orogenic crust may have been lost to the mantle by subsequent delamination through time (Kay and Kay, 1991).

This model does not rule out slab melting during early Earth's history, but it supports previous work highlighting the importance of magmatic underplating (e.g. Atherton and Petford, 1993; Petford and Atherton, 1996; Petford and Gallagher, 2001) in TTG/TTD generation. Regardless of which process dominated the generation of high-Al Archean TTD/TTG crust (slab melting or recycling of mafic underplate), both had to operate efficiently and on a large scale in order to account for the distribution of existing Archean high-Al TTD/TTG crust.

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