The Architecture, Chemistry, and Evolution of Continental Magmatic Arcs

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Annu. Rev. Earth Planet. Sci. 2015. 43:299–331

First published online as a Review in Advance on February 27, 2015

The *Annual Review of Earth and Planetary Sciences* is online at earth.annualreviews.org

This article's doi:
10.1146/annurev-earth-060614-105049

Keywords

arc magmatism, continental, crustal sections, geochemistry, crustal growth

Abstract

Continental magmatic arcs form above subduction zones where the upper plate is continental lithosphere and/or accreted transitional lithosphere. The best-studied examples are found along the western margin of the Americas. They are Earth's largest sites of intermediate magmatism. They are long lived (tens to hundreds of millions of years) and spatially complex; their location migrates laterally due to a host of tectonic causes. Episodes of crustal and lithospheric thickening alternating with periods of root foundering produce cyclic vertical changes in arcs. The average plutonic and volcanic rocks in these arcs straddle the compositional boundary between an andesite and a dacite, very similar to that of continental crust; about half of that comes from newly added mafic material from the mantle. Arc products of the upper crust differentiated from deep crustal (>40 km) residual materials, which are unstable in the lithosphere. Continental arcs evolve into stable continental masses over time; trace elemental budgets, however, present challenges to the concept that Phanerozoic arcs are the main factories of continental crust.

1. INTRODUCTION

Continental arcs, also known as Andean-type or Cordilleran-type arcs, represent the product of subduction magmatism where the upper plate is continental and/or accreted transitional lithosphere. The active-type example is the Andean arc of South America. Well-studied deeply exhumed analogs to the Andean volcanic arc occur as composite batholiths along western North America. The South and North American arcs are complements to each other—one exposes the surficial products and is active, whereas the other provides intrusive sections after the volcanic rocks have been eroded. Subduction magmatism is driven by dehydration reactions in the downgoing slab, whether the upper plate is oceanic, continental, or transitional (Gill 1981). For that reason, petrology and tectonics textbooks commonly treat these situations as comparable. However, this is an oversimplification, as continental arcs are significantly more tectonically complex, typically form in areas of thick crust, have compositions that are higher in silica, and can be much longer lived than island arcs. Thus, the magmatic mechanisms operating in Andean arcs contain another layer of complexity compared with those in oceanic island arcs (e.g., Jagoutz & Kelemen 2015). Unraveling continental arc evolution from petrologic, geochemical, and tectonic perspectives is challenging and has great significance for understanding the formation and evolution of continental crust.

Classic papers on Andean-type arc magmatism, based on either the plutonic-dominated record in North America or the volcanic-dominated archive of the Andes, date back to the 1960s to 1980s (Bateman & Eaton 1967, Kistler & Peterman 1978, DePaolo 1981, Gromet & Silver 1987, Hildreth & Moorbath 1988). Experimental work on dehydration melting of mafic rocks (Wolf & Wyllie 1994, Rapp & Watson 1995), together with a more detailed understanding of wet melting of peridotites (Grove et al. 2012), has clarified plausible mechanisms for generating intermediate arc magmas. The 1980s and 1990s also brought the discovery of several new tilted crustal sections through magmatic arcs and xenolith localities, some of which expose the deeper crust of Andean arcs (e.g., Pickett & Saleeby 1993). Subsequently, new research on arc magmatism focused on magmatic fluxes and relationships between arc magmatism and the tectonics of the Americas (Ducea 2001, DeCelles et al. 2009, Paterson et al. 2011). Thermodynamic models have elucidated melting relations in the deepest and least-exposed parts of the arc systems—the lower crust (e.g., Dufek & Bergantz 2005). Another critical new direction for arc magmatism was the study of the foundering of arc roots, an apparent requisite for magmatism to proceed in long-lived Andean-type systems (Kay & Kay 1993, Saleeby et al. 2003).

This article considers several interrelated Andean-type arc topics: the relationship between the extrusive and intrusive levels and the vertical structure of such arcs, arc composition in relation to complementary roots, tectonic causes for magmatic flux variability, and the incorporation of arcs into stabilized continental crust. We draw exclusively from data from the Americas. Similar arcs exist in the geologic record; they are mentioned and compared with the examples reviewed here.

2. GEOLOGIC BACKGROUND AND EXAMPLES

2.1. Terminology

Subduction-related magmatism takes place in the upper plate of convergent margins, rendering magmatic arcs (**Figure 1**). If both plates are oceanic, they are referred to as oceanic or island arcs. The western Aleutians and the Marianas are modern examples of this end-member (Ishizuka et al. 2011). If the upper plate is continental, they are referred to as continental, Cordilleran-type, or Andean-type arcs. The modern Andes are the best example of this end-member (Mamani et al.

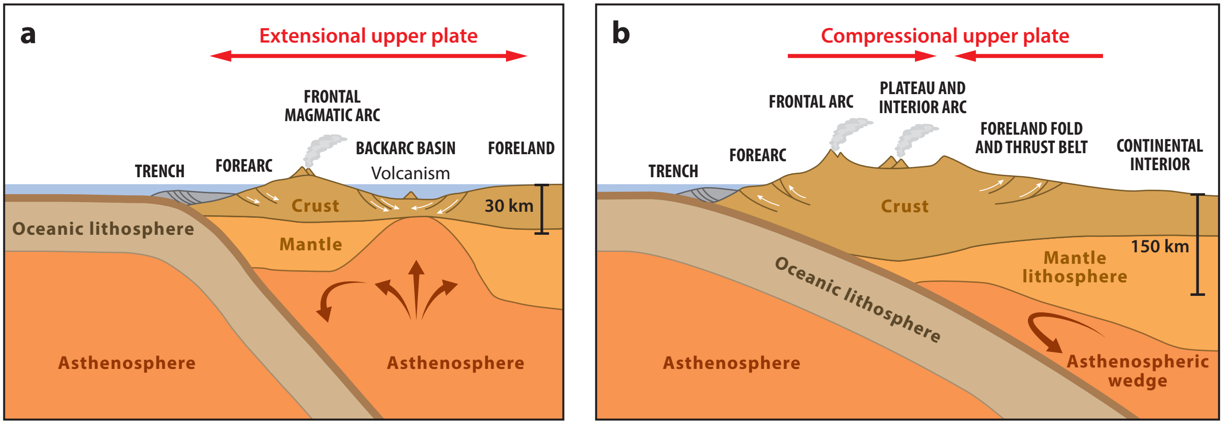


Figure 1

Schematic cross section through a continental subduction system with its two end-members: (*a*) extensional and (*b*) compressional.

2010). Arc-like magmatism also takes place during the continental collision that commonly follows subduction (e.g., Searle 2013). Although not substantially different from subduction-related magmatism, syncollisional magmatism is more complex and is not addressed in this review.

Within the spectrum of island and continental arcs, there are transitional oceanic and continental arcs (**Figure 1**). Transitional island arcs are long lived, with time-integrated accumulations of accreted or deeply subducted sediments and arc magmatic products potentially playing an assimilant role in making intermediate magmas. The Caribbean arc is an example (Marchesi et al. 2007). Transitional continental arcs are those formed onto passive continental margins after subduction initiation. Although they are commonly formed in submarine environments, they can grow on thinned continental crust with thick sedimentary accumulations. In these examples, the proximal host provides the silica enrichment for intermediate magmas. The Japan arc is an example (Kimura & Yoshida 2006 and references therein). This article focuses mainly on continental arcs sensu stricto.

2.2. Extensional Versus Compressional Arcs

The upper plate of a continental arc can be extensional, compressional, or neutral. Under extension, the upper plate develops basins that can occur anywhere from the backarc to the forearc region, with crustal thickness remaining relatively small (~30 km). Some earlier Andean arcs were American continental areas separated by sizable marine basins that formed across extended continental crust [e.g., the Jurassic arc of Chile (Rossel et al. 2013) and the Famatinian arc (Otamendi et al. 2012)]. In contrast, compressional arcs form while the upper plate undergoes crustal and lithospheric thickening, as is the case for the modern Central Andes. The crust under such arcs can be ~70 km thick (Isacks 1988), and the backarc areas develop large plateaus such as the Altiplano-Puna and the inferred Mesozoic–Cenozoic plateaus of western North America (Chamberlain et al. 2012). Moreover, large fold and thrust belts develop on the inboard side, with material being fed from the continental interior into the core of the orogen (**Figure 1**). Overall, the upper plate contains a wide (up to hundreds of kilometers) region of thicker crust. Under extreme thickening, and when the slab dip is shallow, convection in the mantle wedge is shut off because there is too much accumulated lithosphere to allow room for asthenospheric mantle to convect above the slab. Magmatism either migrates inboard or temporarily shuts off under such circumstances, as in the southern part of the central Andes today. These conditions provide snapshots of the life of arcs, cycling between extensional and compressional states (e.g., DeCelles et al. 2009, Girardi et al. 2012) due either to large-scale changes in subduction parameters or to episodes of root foundering.

Volcanic covers of compressional arcs commonly lie along elevated regions such as the Western Cordillera of the central Andes or the dissected early Sierra Nevada (House et al. 1998), as a consequence of thickened crust. Extensional arcs form across more subdued uplands such as the Cascades or even the partly submerged Jurassic arcs of California (Busby-Spera 1988) and Chile (Rossel et al. 2013).

2.3. Compositional Diversity

Most arcs occur as linear or arcuate tracks of volcanoes that are 25–150 km wide and parallel to the trench ∼100–125 km above the subducting slab (**Figure 1**) (Stern 2002, Grove et al. 2012). This is the depth above which slabs render most of their water via solid dehydration reactions, releasing it into the overlying mantle wedge (Hacker et al. 2003). The solidus of the mantle wedge is lowered because the presence of water promotes extensive wet peridotite melting and generation of basalts (Gaetani & Grove 1998). Most igneous rocks formed above subduction zones contain significant amounts of volatiles (H_2O, CO_2), have a large range of silica contents (**Figure 2*a***), are calc-alkaline (**Figure 2*b***), and have distinctive trace elemental patterns as compared with rocks from other tectonic settings (Pearce & Peate 1995). This is thought to be due to the presence of water in the source region and the stability of hydrous phases that are otherwise rare within the upper mantle.

Peridotite melting leads to the formation of basalts, although low-percent partial melts formed at shallow mantle levels (typically not applicable to continental arcs) can, under certain circumstances, generate basaltic andesites or high-Mg# andesites (Kelemen 1995, Müntener et al. 2001,

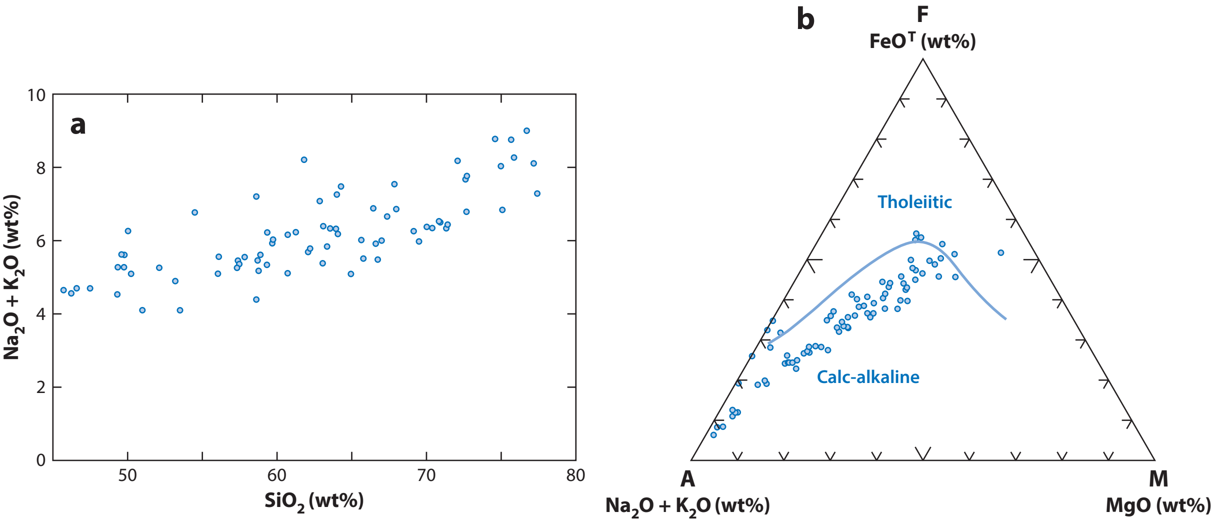


Figure 2

(*a*) Diagram of silica versus total alkalis ($Na_2O + K_2O$), showing a typical compositional range of a suite of cogenetic arc-related rocks constituting a segment of the Coast Mountains composite batholith in British Columbia. (*b*) AFM ternary diagram showing the calc-alkaline compositions of the rocks in panel *a*. Figure constructed using data from Girardi et al. (2012).

Goss et al. 2013). This cannot be volumetrically significant at global scale. The origin of basalts and basaltic andesites in arcs has unresolved details (Grove et al. 2012) but is fairly well understood. However, continental arcs are on average more silicic than basalt, and therefore require an additional step in their magmatic evolution (Rudnick 1995). The nature of this additional step has been a long-standing issue in igneous petrology: Closed-system fractionation, assimilation of framework rocks, remelting of preexisting mafic rocks located in the deep crust, or a combination of these is plausible for silica enrichment and sympathetic geochemical trends (see Section 6). Regardless, generating large volumes of intermediate rocks on average also requires large amounts of residual masses that are not depleted peridotites (common mantle olivine-rich rocks) (Ducea 2002); such materials are rarely seen in surface exposures but are postulated to form abundantly at depths greater than those exposed in orogenic belts (Saleeby et al. 2003, Lee et al. 2006).

2.4. Major Continental Arcs of the Americas

Below we describe the major subduction-related arcs of the Americas, other significant arcs in the geologic record, and some of the tilted sections that expose deeper segments of arcs.

2.4.1. Extinct arcs. The western North American Cordillera comprises a continuous belt of arc products (mostly intrusive) from Alaska to Baja California (**Figure 3*a***). These are the great North American batholiths, with ages ranging from Triassic to Eocene (**Table 1**) (Anderson 1990). All these batholiths are the products of the subduction of the Farallon plate and its derivatives under North America. The main batholithic segments, from south to north, are the Peninsular Ranges batholith (Baja California and southernmost California), the Sierra Nevada batholith and adjacent terrains (California), the Idaho batholith (Idaho and Montana), and the Coast Mountains batholith (Washington, British Columbia, and Alaska). Among them, the Sierra Nevada batholith is one of the most studied arc segments on Earth (Bateman & Eaton 1967, Saleeby 1990), owing greatly to its easy access and outstanding exposures. The Coast Mountains batholith is the world's largest continuous composite batholith, having produced $>10^6$ km^3 of granitoid magmas over its >150 Myr of evolution. The locations of arcs vary over time, and during periods of shallow subduction they are found significantly inland compared with the average distance from the trench; such is the case with the belt of arc-related magmatism that formed during the Laramide orogeny (75–35 Ma) in the interior of the North American Cordillera due to shallow subduction (Barton 1996). This extensive belt of plutons that makes up the Cordilleran interior arc is well exposed in Arizona, Nevada, and parts of Utah, but similar interior plutons are found elsewhere during shallow subduction. Central American Mesozoic–Cenozoic batholithic belts constitute much of the modern forearc for the active arc above the Cocos subducting plate (Ducea et al. 2004). In South America, subduction commenced during the Cambrian along the western proto-Andean margin. Numerous extinct arc segments exist; of them, the most significant Paleozoic arcs are the Pampean (Cambrian) and Famatinian (Ordovician), which form extensive belts of plutonic and volcanic rocks occupying much of the Central and Southern Andes. Permian to Mesozoic intrusive suites, such as the Peruvian coastal batholith (Mamani et al. 2008, Demouy et al. 2012), are similar in size and composition to the great North American batholiths.

2.4.2. Active arcs. Volcanic arcs occur along most of the western side of Central and South America (**Table 1**; **Figure 3*b***). These consist of the Trans-Mexican volcanic belt (Ferrari et al. 2012); the Central American arc (Wegner et al. 2011); and the northern (Hall et al. 2008, Stern 2011), central (Mamani et al. 2010), and southern (Hildreth & Moorbath 1988, Stern & Kilian 1996) segments of the Andes. Gaps between segments of Quaternary volcanoes reflect special

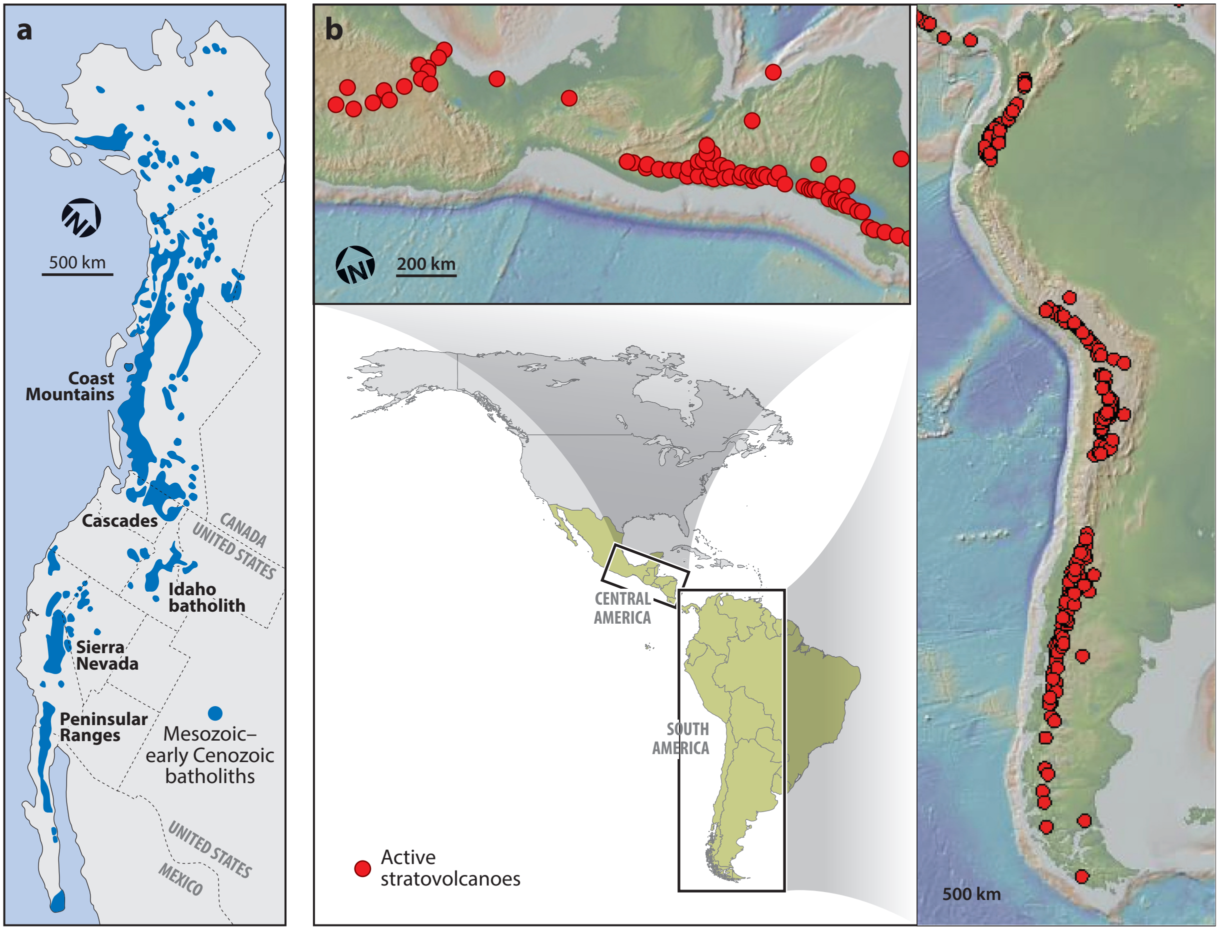


Figure 3

(*a*) Map showing the locations of major North American Mesozoic to early Cenozoic batholiths. Modified with permission from Paterson et al. (2011). (*b*) Map showing the distribution of the most important active stratovolcanoes (*red circles*) along the modern subduction margins of Central and South America. Constructed using GeoMapApp software.

conditions (ridge subduction, ultrashallow slabs) inferred to prevent magma generation (Kay et al. 2005). The Cascades arc in the Pacific Northwest marks the subduction of the Juan de Fuca plate under North America—the last subducting segment of the remaining eastern Pacific realm (Schmidt & Grunder 2011)—and the eastern part of the Aleutian arc transitions to continental as it extends onto the crust of the Alaska Peninsula.

2.4.3. Major continental arcs outside the Americas. Several post–Rodinia breakup (<700 Ma) continental arcs occur outside of the Americas. Older Precambrian arcs exist as well, but their preservation is poor due to subsequent orogenic reworking. Among them (**Table 1**), some of the most significant arcs are the Gangdese arc, in southern Tibet (>200–50 Ma); the Lachlan arc, in eastern Australia (450–340 Ma); the Caledonian arc of the Appalachians, in the eastern United States (550–460 Ma); the Variscan arc, in Europe (370–290 Ma); and the Fiordland arc, in New Zealand (170–100 Ma).

Table 1 List of some major subduction-related continental and transitional continental magmatic arcs since the breakup of Rodinia (~750 Ma)

Arc	Location	Age range (Ma)	Exposure[a]
Cascades	Northwestern United States	35–0	Volcanic
Andes (sensu stricto), with three geographic subdivisions	Western South America	200–0	Mixed
Trans-Mexican volcanic belt and ancient correlatives	Mexico to Panama	160–0	Volcanic
Sierra Nevada	California	250–80	Plutonic
Peninsular Ranges	Baja, Mexico	200–80	Plutonic
Fiordland	New Zealand	170–100	Plutonic
Idaho batholith	Northwestern United States	160–80	Plutonic
Coast Mountains	Southeastern Alaska and British Columbia	200–50	Plutonic
Gangdese	Southern Tibet	250–40	Plutonic
Ladakh-Kohistan	Himalaya	100–50	Mixed
Variscan	Western and central Europe	350–290	Plutonic
Pampean-Famatinian	Peru to Argentina	550–465	Plutonic
Appalachian Caledonian	Eastern United States	560–440	Plutonic
Lachlan	Eastern Australia	450–340	Plutonic
European Caledonian	Europe, various	500–400	Plutonic
European Cadomian	Europe, various	650–500	Plutonic

[a]Denotes main exposure levels: volcanic, plutonic, or mixed.

2.4.4. Deeply exhumed arcs. **Table 2** lists significant tilted exposures of Phanerozoic continental and transitional continental arcs along with their ages and paleodepths. It also lists the main xenolith localities where arc-related assemblages from the deepest crust and uppermost mantle are found. Of the tilted sections, the Sierra de Valle Fértil (central Argentina) is an exceptionally well-exposed section through the middle to lower crust of a transitional arc, documenting the nature of mafic magmatism and its differentiation to higher silica contents at 15–25 km depths (Otamendi et al. 2012). The Salinian block in central coastal California possesses similarities to the Valle Fértil area in terms of exposure depths and compositions and in that it was built onto

Table 2 Tilted exposures of island and continental arcs and ranges of paleodepths

Arc	Location	Type	Age range (Ma)	Depth range (km)	Reference
Kohistan	Pakistan, India	Island	100–50	0–55	Jagoutz & Behn 2013
Talkeetna	Alaska	Island	200–150	0–10; 20–30	Hacker et al. 2011
Gobi-Tianshan	Mongolia	Transitional	300–280	0–15	Economos et al. 2012
Sierra de Valle Fértil	Argentina	Continental	500–470	10–30	Otamendi et al. 2012
Southern Sierra	California	Continental	160–80	5–30	Chapman et al. 2012
Salinia	California	Continental	95–80	5–30	Kidder et al. 2003
Fiordland	New Zealand	Continental	170–100	15(?)–50	De Paoli et al. 2009
Coast Mountains	British Columbia	Continental	180–50	5–35	Gehrels et al. 2009
Cascades core	Washington	Continental	95–65	10–35	Miller et al. 2009

a relatively thin continental crust (Kidder et al. 2003, Chapman et al. 2014). The deeply exposed parts of the Coast Mountains batholith (Girardi et al. 2012), the Cascades core (Miller et al. 2009), and the southern Sierra Nevada (Saleeby 1990) sections are examples of longer-lived segments of deep arc crust; in addition to abundant mafic rocks and evidence for incorporation of upper plate rocks via partial melting, these segments show extensive high-temperature metamorphism and partial melting to generate granulitic residues. Even deeper assemblages of arc roots are found in xenolith suites and are either granulitic, similar to the exposed sections mentioned above, or eclogitic; the world's best deep arc suites are the central Sierra Nevada (Ducea & Saleeby 1998) and Colombian Mercaderes (Rodriguez-Vargas et al. 2005) xenolith localities. The deepest part of the Cretaceous Fiordland arc section, in New Zealand, tectonically exposes similar eclogitic rocks, but their discovery is recent and study is in progress (De Paoli et al. 2009).

3. SPATIAL FOOTPRINTS AND TEMPORAL PATTERNS

3.1. Lateral Geometry of Arcs

The typical width of active continental arc magmatism is ∼20–30 km at any given time, depending on magma focusing. Therefore, the typical arc footprint can be simplified as a 25-km-wide rectangular area parallel to the trench. Additionally, backarc regions, which also generate magmas, may extend the magmatic footprint beyond the main (frontal) arc. The time-integrated footprint of an Andean arc can be very large in that the frontal arc magmatism can sweep inboard or outboard relative to a fixed location within the upper plate. Most commonly, arcs migrate continuously at rates of 1–5 mm/yr (Gehrels et al. 2009, Cecil et al. 2012). The classic explanation for these sweeps is a change in slab dip. In contrast, the location of arc magmatism can suddenly migrate by hundreds of kilometers, as is the case for the well-studied inboard migration of magmatism in the western United States during the latest Cretaceous Laramide orogeny. Although changes in slab dip due to subduction of seamounts and plateaus are plausible reasons for such sudden episodes of magmatic migration, an equally plausible explanation is that trenches migrate during catastrophic episodes of subduction erosion (inboard) or accretion of terranes such as island arcs (outboard). Regardless of whether the migration is steady state or is a dramatic and sudden jump relative to the trench, the net result is that long-lived magmatic arcs can leave a footprint several hundreds of kilometers wide from the trench to the interior of the upper plate. The overall structural width of the arc can then be subsequently widened by extensional collapse of the upper plate. The Coast Mountains batholith in southeastern Alaska and British Columbia was active between 210 and 50 Ma (Gehrels et al. 2009) and has a total width of 250 km; in the central Andes, post-Jurassic volcanic or plutonic arc-related rocks have a width of 300–650 km.

3.2. Lifetime and Fluxes of Arcs

Continental arcs tend to have longer life spans than island arcs if subduction is long lived; the Andes arc grew over ∼500 Myr, whereas island arcs are documented to be active for at most ∼50–60 Myr (Paterson et al. 2011), typically terminated by a collisional event. It is common for continental arc segments to be active for over 100 Myr. The Andes and the North American Cordillera have incorporated several island arcs as terranes into the continental margin by tectonic accretion.

Fluxes of magma can be calculated for select arcs for which enough geochronometric and surface mapping data are available. Ages of continental arcs are typically determined using U-Pb systematics on zircon (Mattinson 2013), because intermediate calc-alkaline rocks contain abundant zircon. Magmatic fluxes are quantified as magmatic addition rates (volume per kilometer length of arc per time) or, most commonly, as apparent intrusive rates (surface area per time) (see Paterson

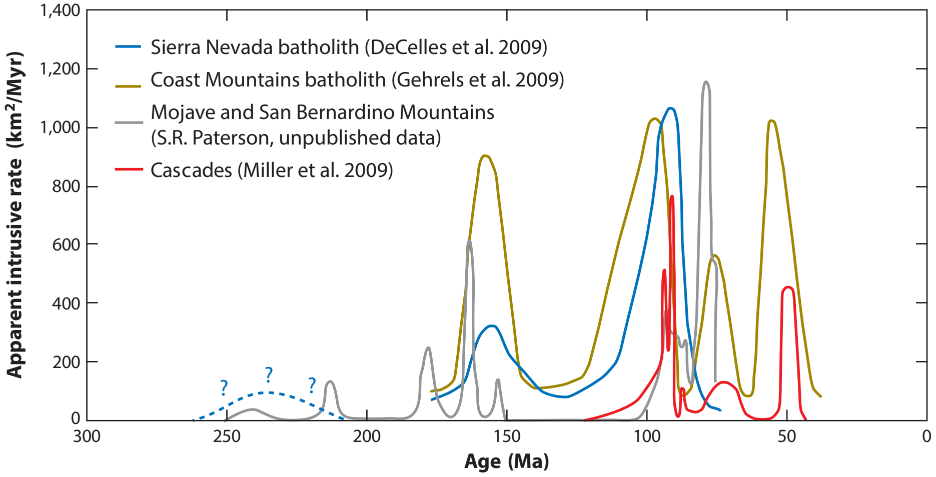


Figure 4

Apparent magmatic intrusive fluxes in the North American batholiths (from Ducea 2001, Paterson et al. 2011), showing the non-steady-state behavior of magmatism in subduction systems. Apparent intrusive rate is equal to the surface area of a given age range within the arc region divided by time (in km^2/Myr). See Paterson et al. (2011) for more detailed definitions.

et al. 2011 for a review). Intrusive rates can vary by an order of magnitude during the lifetime of a continental arc (e.g., Gehrels et al. 2009) and are characterized by 5–20-Myr high-flux (flare-up) events (∼1,000 km^2/Myr) separated by longer (30–40 Myr) magmatic lulls (∼100 km^2/Myr). This tempo is such that flare-up events dominate the mass budget of arcs (Ducea & Barton 2007). **Figure 4** shows apparent intrusive fluxes for the main North American batholiths (Paterson et al. 2011). A complementary record of arc magmatism can be obtained from volcanic rocks, as well as from the detrital archive accumulated in forearcs and backarcs from arc erosion. All existing lines of evidence suggest that the non-steady-state behavior of the North American arcs is typical for continental arcs (DeCelles et al. 2009) as well as most island arcs (Jicha et al. 2006), with 60–90% of magmatic additions representing flare-ups (Ducea et al. 2015).

4. A VERTICAL SCAN OF CONTINENTAL ARCS

From top to bottom, continental arcs are made of (*a*) a volcanic cover with hypabyssal bodies typically intruded into the volcanics; (*b*) a batholith, i.e., a large accumulation of hundreds to thousands of stocks, dikes, and sills (Coleman et al. 2004, Gehrels et al. 2009); and (*c*) a root region made primarily of mafic-ultramafic cumulates and residues complementing the surface and batholithic intrusions, as well as mafic rocks representing frozen basaltic melts (Saleeby et al. 2003). **Figure 5** shows a schematic cross section through a continental arc, as explained below.

The transition depth range between volcanic and plutonic is not sharp but occurs immediately under the 2–4-km-thick volcanic carapace. It is common for subvolcanic bodies to intrude into slightly older volcanics. Beneath that boundary lie the batholiths. The transition from felsic/intermediate batholiths to more mafic deeper crust varies from arc to arc and is located at ∼20–30 km depth. The deeper crust typically comprises mafic intrusives and mafic and ultramafic cumulates and restites (see below). In contrast to the overall verticality of primary structure in the shallow to mid-crust, most planar features in the deep crust (cumulate layers, metamorphic

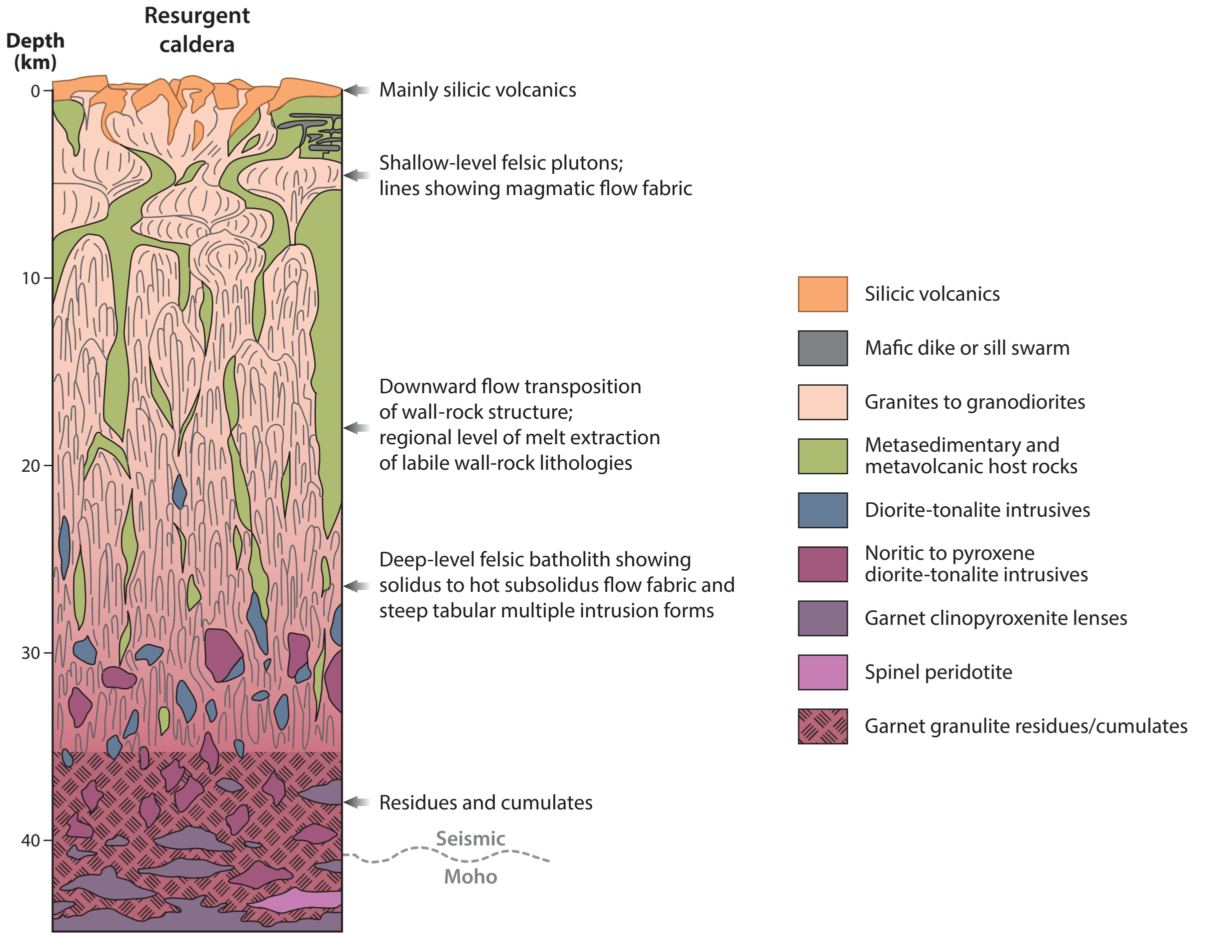


Figure 5

Schematic cross section through a continental arc from the volcanic cover to the top of the arc root (after Saleeby et al. 2003 and Paterson et al. 2011). The vertical continuation of the root is represented by abundant garnet- and/or amphibole-bearing pyroxenites, which gradually give way to typical upper mantle peridotites below 60–100 km depth. The depicted section is based on structural relations of an oblique crustal section from ~5–35 km depth at the southern end of the Sierra Nevada.

foliation, solidus to hot subsolidus plastic fabrics) tend to be near-horizontal. The depth to the change from steep to horizontal primary structure is a key feature of the architecture of a continental arc (**Figure 5**).

4.1. Volcanoes

Exposures of active arcs are dominated by volcanic constructs. Large Andean stratovolcanoes can reach 4 km above the average local elevation (De Silva & Francis 1989) and are built over several millions of years (5–10 Myr), yet unless the edifices are collapsed or subject to unusually high erosion rates, only a fraction of the eruption record is exposed (see Paterson et al. 2011). Voluminous stratovolcanoes hold up the high-elevation Western Cordillera of the Andes. In contrast, extinct arcs tend to be eroded to plutonic levels, with the volcanic cover preserved only as remnants, either as blocks preserved within the largely plutonic record or as relics eroded away into the sedimentary basins. It is rare for an arc to preserve a window into both its volcanic top and its plutonic root [for notable exceptions see parts of the Laramide Cordilleran interior arcs, Arizona and Nevada (Barton 1996)]. Despite the large volumes erupted in continental arc volcanoes, the volcanic-to-plutonic ratio is highly variable but small, ranging from 1:2 to 1:20 (Paterson et al. 2011). This suggests that the greatest volume of magma freezes at depth in arc magmatism, and only a small volume erupts.

The principal eruptive centers in continental arcs include stratovolcanoes and large calderas. Many of the Andean stratovolcanoes alternate rhyolite-dacite ash-flow tuffs with andesitic lava flows. Central edifice eruptions are complemented by the formation of secondary cones, domes, and calderas, including large resurgent calderas. Stratovolcanoes have a spacing of about 50–80 km along arc strike (**Figure 1**). Rare windows into the volcanic archive are provided by deep canyons carved through the southern Peruvian arc; the Colca and Cotahuasi Rivers in southern Peru expose a 4-km-thick record of andesitic/dacitic volcanism spanning 10–15 Myr (Thouret et al. 2007). Roots of volcanoes display hypabyssal bodies intruded into the volcanic cover, as is the case for extinct and partially eroded edifices such as the Aconcagua paleovolcano (Irigoyen et al. 2000). These proximal subvolcanic levels are the richest in hydrothermal ore deposits (Sillitoe 1997). In the extinct arcs of North America, dismembered and tilted fragments of the volcanic cover are occasionally found as framework rocks to younger plutons, as is the case for the 100 Ma Minarets caldera, which is intruded by the 93–88 Ma Tuolumne intrusive suite in the central Sierra Nevada (Fiske & Tobisch 1994).

4.2. Batholiths

Most intrusive continental arcs are exposed to relatively shallow (5–10 km) paleodepths (see Chapman et al. 2012 for a review exemplifying the Sierra Nevada, illustrated in **Figure 6**), as indicated by igneous barometric techniques (e.g., Al in hornblende) or pressure determinations on framework metamorphic assemblages (Barton et al. 1988). These exposures are typically deeper than the volcanic-hypabyssal transition but rarely exceed the upper fifth of a typical Cordilleran batholith. At these depths, the great majority of all Cordilleran batholiths are intermediate (tonalite to granodiorite) in composition. They represent a combination of frozen melts and the cumulate crystal loads frozen in the crust. Typically, they have numerous mafic enclaves, attesting to the presence of mafic magmatism in their heat and mass budgets, but true gabbroic intrusives are subordinate. The predominant geometry of plutons in Cordilleran batholiths is one of numerous stocks, many of them composite, commonly bounded by vertical contacts with metasedimentary framework rocks displaying steep to vertical foliation and lineation acquired during the emplacement of plutons. The general appearance is one of vertical pathways, with plutons being pushed upward and framework rocks engaged into downward return flow (e.g., Saleeby et al. 2003). Geodynamic models suggest that the entire lower part of the crust beneath continental arcs engages in a convective process of crustal overturn (Babeyko & Sobolev 2005), thus facilitating the vertical transport suggested by field observations in batholiths.

The subvolcanic accumulation of intermediate calc-alkaline magmas in continental arcs makes up the Cordilleran batholiths. These record arc migrations through time, as well as flare-up events, better than the volcanic record does. Map areas consist of 90–95% batholithic material and subordinate metamorphic framework. Domains that represent the immediate roots to volcanic edifices can be identified in some batholiths—for example, the Tuolumne and Whitney intrusive suites of the Sierra Nevada (**Figure 6**), whose map views reflect the ring fractures of large calderas with nested stratocones. These are among the latest plutons of the Sierras, and they stand out in **Figure 6** as shallower intrusives. Although a wide range of chemical compositions exists in

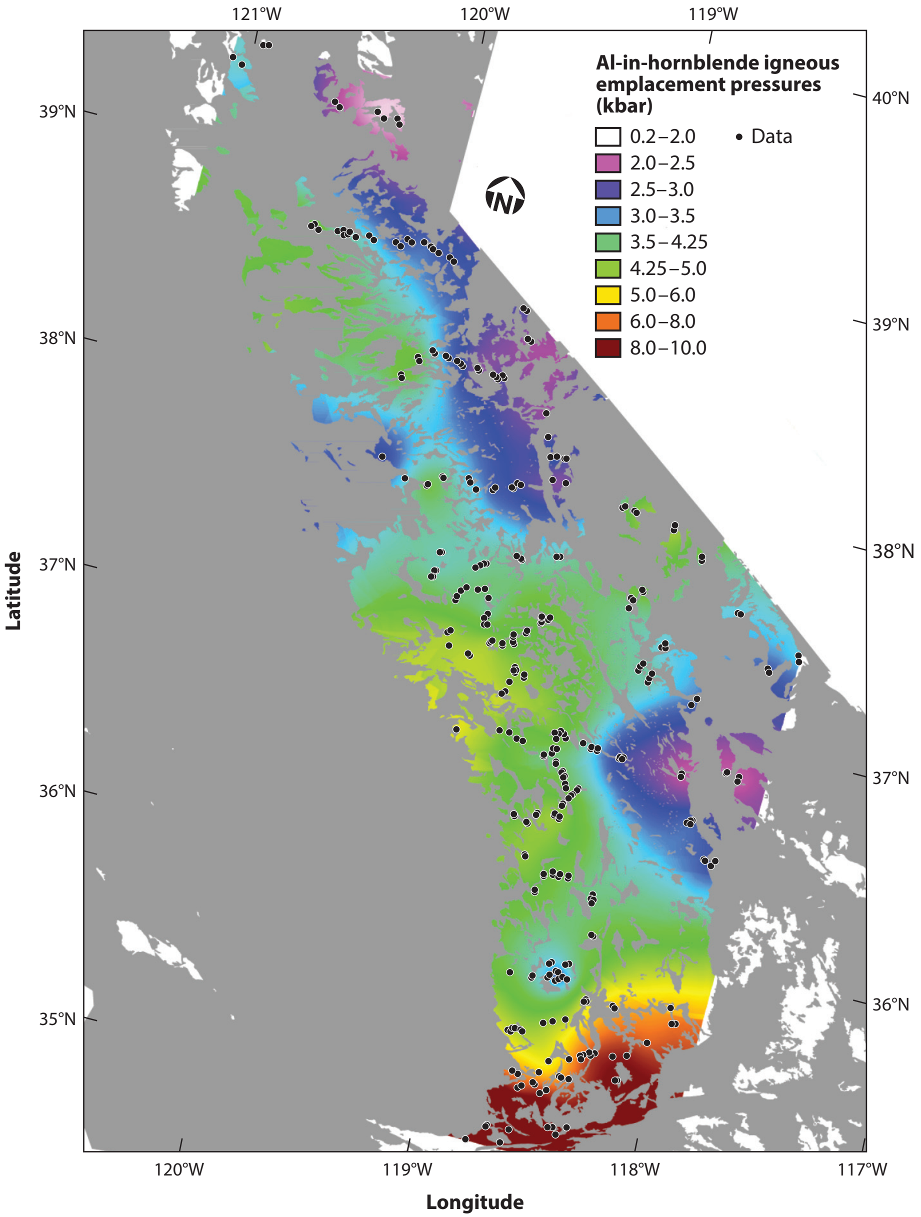


Figure 6

Intrusive pressures in kilobars (each kilobar represents approximately 3.3 km below surface) contoured across the Sierra Nevada batholith (from a synthesis by Chapman et al. 2012). The great majority of Cordilleran batholiths, including this one, are exposed to relatively shallow levels (∼7–8 km on average). Black dots are individual data points used for contouring.

most batholiths, the majority of plutons are tonalities and granodiorites (see Section 5). Magma transport is predominantly vertical (Paterson & Fowler 1993). Geochemical and mineral mode variations are minimal in the map view of batholiths progressing from the subvolcanic to deep levels (20–35 km deep).

The process of assimilation of host rocks is inefficient at most exposed batholithic levels to account for first-order compositional variations, suggesting that such variations are attained at deeper levels (DePaolo 1981), from a poorly understood depth range of melting, assimilation, storage, and homogenization (the MASH zone) (Hildreth & Moorbath 1988). Limited assimilation and partial melting of most fertile framework rocks such as pelitic-psammitic assemblages are evident in metamorphic pendant rocks located at >20 km paleodepth (Zeng et al. 2005), but the net effect of these partial melts on compositional variations is only locally significant. Evidence for fractionation of batholithic melts exists at all exposed levels, in the form of cumulates (Zak et al. 2007). This is a minor process in generating volumetrically significant magmatic variations, because plagioclase, which is the main phase seen in cumulates, is a difficult phase to segregate from an intermediate magma on the basis of density contrast. From volcanic levels to >30 km depth, the crust is to first order just the carrier and resting place for arc magmas, whereas most geochemical diversity is acquired at deeper levels, in the arc roots.

4.3. Arc Roots

A transition from vertical to subhorizontal planar fabrics occurs at 20–35 km beneath Cordilleran batholiths. In rare instances offered by oblique arc sections—e.g., the Salinian arc (Kidder et al. 2003) and the Famatinian arc in the Sierra de Valle Fértil (Otamendi et al. 2012) (**Figure 7**)—this transition can be observed. It marks the bottom of batholiths and is characterized by a significant downward increase in mafic material (commonly cumulates). Paleohorizontality is best approximated using facing criteria in cumulates. Stock-like plutons can still intrude into the nearly horizontal framework, but they are less common and reflect the very latest stages of magmatism, when the deeper crustal section was already being unroofed (Chapman et al. 2014).

At these mid- to deep crustal levels, the most abundant rocks are mafic additions from the mantle (amphibole-bearing gabbros and amphibolitized mafites), preexisting metasedimentary rocks, and various basement rocks of the upper plate. They are typically metamorphosed under amphibolite to granulite facies (Depine et al. 2008) during arc magmatism, and framework rocks are commonly migmatized. Numerous interactions exist between the new mafic additions and the framework rock, and they are detailed in Section 6. A characteristic of some (Fiordland, southern Sierra Nevada, Salinia), but not all (e.g., Sierra de Valle Fértil) deeper arc sections is that the mafic-dominated material has partially remelted via dehydration reactions involving hornblende and with new garnet growth on the solidus. We hypothesize that those arcs that have been long enough lived and had thick enough crust to experience this dehydration remelting of the lower crust are the ones that generate higher-silica rocks in the upper crust and convectively removable residues (see Section 5). The most common migmatitic texture observed in the field among sections that experienced remelting (**Figure 8**) is the growth of isotropic large (>3–5 mm) garnet crystals surrounded by plagioclase-rich leucosomes. In all exposed sections, the dominant mineral is plagioclase. In summary, the majority of exposed arc roots have paleodepths of 20–35 km and contain upper amphibolite to granulite facies rocks and new mafic additions from the mantle, and they commonly display migmatitic fabrics, occurring either due to melting of fertile framework assemblages or as the product of partial melting of the recently intruded mafic component.

Still, modern arcs such as the central Andes have much thicker crust [up to 75–80 km (Gilbert et al. 2006)] than the above-mentioned exposed sections. The composition of the true deep

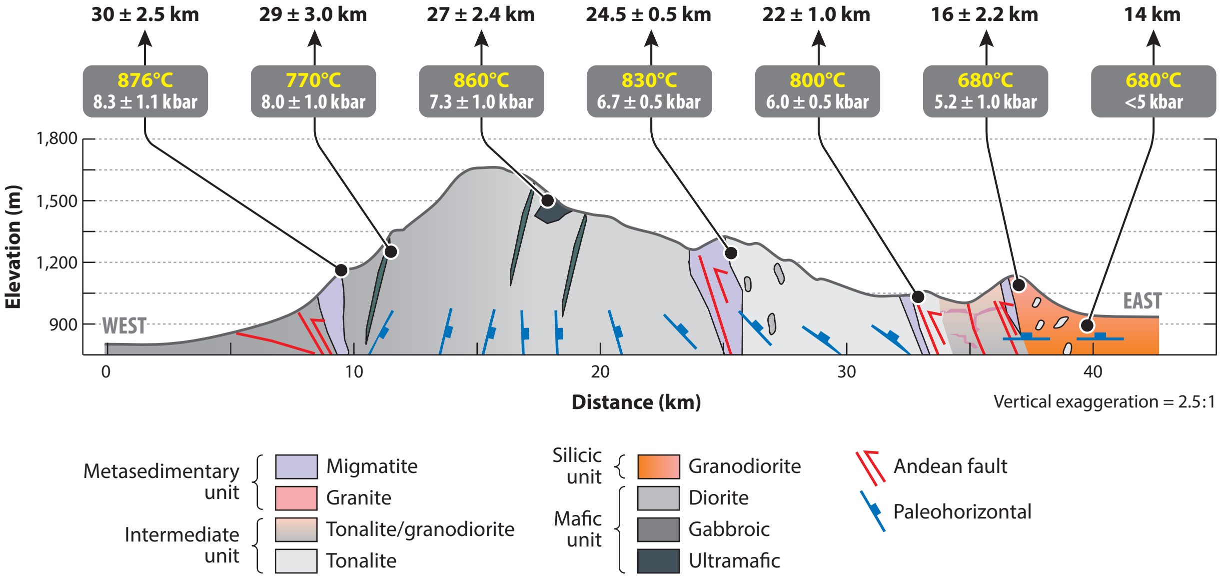


Figure 7

A simplified cross section through the Sierra de Valle Fértil (Argentina) mountain range showing the transition from arc root assemblages on the left (west) to the main batholith toward the right (east), with equilibration pressures and temperatures and equivalent depths below the surface (after Tibaldi et al. 2013). This tilted arc crustal section is part of the Ordovician Famatinian arc.

parts of the crust under a continental arc may be exposed only in New Zealand, in Fiordland (De Paoli et al. 2009). The other remarkably deeply exhumed arc section is the Kohistan arc (Jagoutz & Schmidt 2013 and references therein), although Kohistan is not truly a continental arc but rather a transitional oceanic arc. Both contain rocks that were as deep as 55 km below the surface during arc formation and show a gradual transition from shallower plagioclase-bearing igneous cumulates/residues and granulite facies rocks to plagioclase-free garnet-rich lithologies (Clarke et al. 2013). Below approximately 50 km, the arc root becomes dominated by pyroxene with amphibole and with or without garnet; these rocks, which are complementary to arc rocks and eclogite facies rocks formed in equilibrium with a melt (Lee et al. 2006), are sometimes referred to as arclogites. Arclogites are better known as xenoliths incorporated in volcanic rocks that erupted from arc regions; the world's best examples are found in Miocene volcanic rocks from the Sierra Nevada (Ducea & Saleeby 1996, Lee et al. 2000) and Quaternary rocks from the Mercaderes region, in the northern Andes (Rodriguez-Vargas et al. 2005).

The Sierra Nevada arclogites are garnet clinopyroxenites with various amounts of amphibole and orthopyroxene and are also referred to as low-Mg pyroxenites by Lee et al. (2006). These xenoliths are samples from a pressure range of 1.2–2 GPa, indicating that they may occupy a large depth range within the arc root section (see Saleeby et al. 2003 for a review). As xenoliths reaching as much as 15 cm in diameter, they do not provide a geologic context for observation; however, these samples and others (garnet-free clinopyroxenites, amphibole clinopyroxenites, etc.), which are less studied because they do not contain assemblages suitable for barometry, represent our best physical evidence for the nature of continental arc roots from ∼35 to >70 km deep. Indeed, the greatest range of depth for thick compressional arc roots appears to be populated by plagioclase-free residual and/or cumulate material that is rich in clinopyroxene, amphibole, and/or

Figure 8

Typical mafic migmatitic textures in deeply exposed sections of arcs that experienced a secondary melting event. This photograph is from the Grimes Beach area in the Salinian Coast Belt, central California, which is a deep crustal exposure of a late Cretaceous continental arc (Kidder et al. 2003, Chapman et al. 2014). Photograph by M.N. Ducea.

garnet. These rare xenolith assemblages are similar in composition to predictions made by dehydration melting experiments on wet basalts and andesites at >40 km (Wolf & Wyllie 1994, Rapp & Watson 1995) and thermodynamic models using the MELTS algorithm (Ducea 2002), and to the Fiordland field exposures, where eclogitic rocks are exposed (Clarke et al. 2013).

5. GEOCHEMISTRY: COMPOSITIONAL AVERAGES

5.1. Volcanic Arcs and Batholiths

Continental arcs are characterized by a wide range of major elemental compositions from basalts to rhyolite, typically without compositional gaps (**Figure 2**). This diversity makes estimates of compositional averages rather difficult. Basalts are relatively common in island arcs (Gill 1981, Grove et al. 2012) but much less common in continental arcs. For example, less than 6% of the exposed Sierra Nevada batholith (>250,000 km^2 of plutons including the main batholith, its dismembered southern California blocks, and parts that are covered by younger sediments in the Great Valley) is mafic (Coleman & Glazner 1998). Even the most mafic rocks within the wide spectrum of compositions in most Cordilleran arcs are typically not primitive mantle melts. The average major elemental compositions of the volcanic record of the Central Andes, the Cascades arc, the Central American volcanic belt (Costa Rica), and the Trans-Mexican volcanic belt are

Table 3 Average major elemental compositions (in wt% oxides) and trace elemental parameters of continental arcs

Arc section	SiO_2	TiO_2	Al_2O_3	FeO^T	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Sr/Y	La/Yb	Eu*
Cascades arc	58.34	0.94	16.65	6.26	0.12	4.62	6.85	3.76	1.43	0.22	29.74	8.80	0.96
Central America arc	55.58	0.85	17.91	7.56	0.16	3.81	7.83	3.30	1.27	0.22	36.28	8.46	0.98
Trans-Mexican volcanic belt	58.18	1.16	16.32	6.60	0.12	4.58	6.45	4.14	2.01	0.33	39.19	17.70	0.84
Central Andes	61.65	0.80	15.97	4.86	0.10	2.58	4.86	3.79	3.07	0.27	40.59	25.67	0.81
Coast Mountains batholith	64.03	0.59	16.69	4.41	0.10	2.05	4.77	4.27	2.09	0.19	58.58	24.86	0.92
Sierra Nevada batholith	63.09	0.65	15.98	4.91	0.10	2.59	5.07	3.43	2.99	0.30	42.79	28.71	0.91

The first four arc segments are volcanic rocks of Quaternary to Modern ages. The last two are the largest segments of Cordilleran batholiths in North America and span an age range comprising most of the Mesozoic and, in the case of the Coast Mountains batholith, the Paleogene. Eu* is the Eu anomaly (see sidebar, Trace Elemental Parameters).

given in **Table 3**. They are based on more than 20,000 data points; most of those data points are compiled within the GEOROC (**http://georoc.mpch-mainz.gwdg.de/georoc/**), NAVDAT (**http://www.navdat.org**), and Central Andes (**http://andes.gzg.geo.uni-goettingen.de**) online databases. Average major elemental compositions of two major North American batholithic segments are also presented in **Table 3**: the Sierra Nevada and the Coast Mountains batholiths. Most batholith data are available online in NAVDAT. In addition to major elements, we present some key average trace elemental parameters qualitatively indicative of the average depth of differentiation: Sr/Y, La/Yb, and Eu* (see sidebar, Trace Elemental Parameters).

The average compositions of these arc sections are clearly different, and their silica and other major oxide compositions range between those of island arcs and upper continental crust (**Figure 9**). The Central American arc, although clearly built on continental crust, is typical of an island arc in its average major elemental chemistry. Low silica averages appear to be typical

TRACE ELEMENTAL PARAMETERS

1. Sr/Y: High Sr/Y ratios in intermediate rocks require that plagioclase did not fractionate or was not on the solidus of the melting reaction; low Y concentration suggests that garnet may have been present among the residue or fractionation phases. High Sr/Y ratios (>25) are indicative of a deeper crustal level of processing in magmas; positive correlations between Sr/Y and crustal thickness exist in modern arc magmas from the Andes.
2. La/Yb: Steep rare earth element (REE) patterns (corresponding to chondrite-normalized ratios of La/Yb >10) also mark the increasing role of garnet and/or amphibole in magmatic differentiations for intermediate rocks, therefore providing an additional proxy for crustal thickness.
3. Eu*: The Eu anomaly (Eu*) is the ratio of trace element Eu measured in an igneous rock to a model Eu concentration that would make the REE patterns, from light REE to heavy REE, smooth. Eu's two neighboring elements, whose concentrations are averaged, are Nd and Gd. When plagioclase is a main phase involved in differentiation, intermediate rocks will have a negative Eu anomaly (and the Eu* will be a number distinctively lower than 1) because of the ability of plagioclase to partition unusually large amounts of Eu compared with other REE. If plagioclase is not involved, there will be no Eu anomaly, and the Eu* should be close to 1.

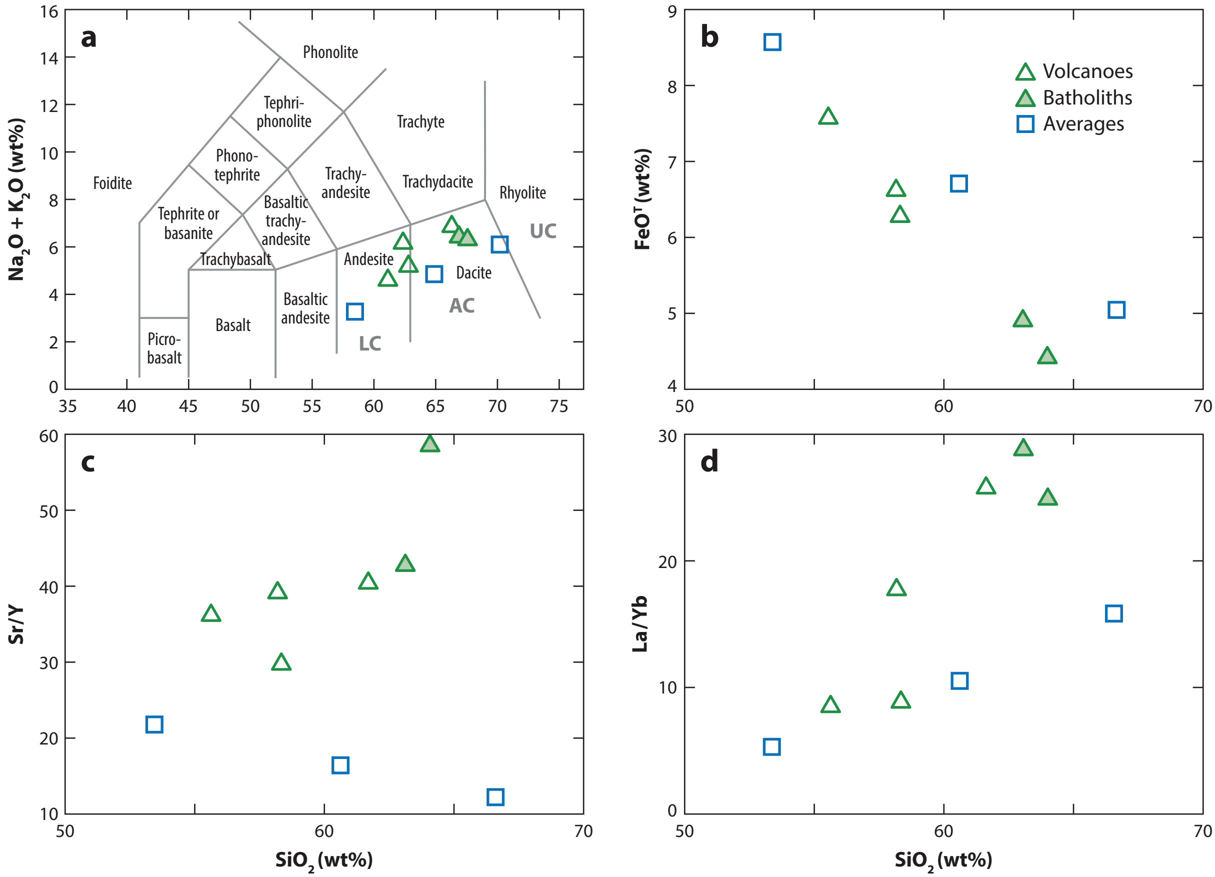


Figure 9

Silica versus (*a*) total alkalis, (*b*) total iron oxide (FeO^T), (*c*) Sr/Y, and (*d*) La/Yb for six major arc sections discussed in the text, compared with average continental crust and average island arcs. Abbreviations: AC, average crust; LC, average lower crust; UC, average upper crust (compositions from Rudnick & Gao 2003). Classification of volcanic rocks in panel *a* is from LeBas et al. (1986).

of modern extensional arcs, whereas the central Andean segment, which is the only modern compressional arc, has higher silica (>60 wt% SiO_2) on average. The two plutonic averages are higher in silica on average than volcanic rocks, although that too may reflect the fact that both the Sierra Nevada and the Coast Mountains batholiths have been compressional arcs, on average, through their long histories. These numbers illustrate the difficulty of determining an average chemical composition of arc magmas, but they do suggest that extensional arcs are less silicic than compressional arcs.

The average compositions of the Sierra Nevada and Coast Mountains batholiths and the central Andean volcanic arc straddle the boundary between a dacite and an andesite (or a tonalite/granodiorite), more silicic than island arcs (**Table 4**) and similar to recent estimates of the composition of bulk continental crust (see Rudnick & Gao 2003 for a review). Strictly in terms of major elemental compositions, the continental arcs of the Americas are the best matches to average continental crust—better than either island arcs or magmas formed at any other tectonic setting.

Table 4 Average major elemental concentrations (in wt% oxides) in arc volcanoes, batholiths, and roots compared with island arcs and various estimates of bulk continental crust

Material	SiO_2	TiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	P_2O_5
Volcanic cover[a]	58.44	0.94	16.71	6.32	3.90	6.50	3.75	1.94	0.26
Batholiths[a]	63.56	0.62	16.34	4.66	0.10	2.32	4.92	3.85	2.54
Arc roots[b]	44.78	1.29	13.21	12.73	11.78	12.93	1.24	0.27	0.32
Upper crust[c]	66.0	0.5	15.2	4.5	2.2	4.2	3.9	3.4	—
Continental crust[c]	57.03	0.9	15.9	9.1	5.3	7.4	3.1	1.1	—
Continental crust[d]	60.60	0.72	15.90	6.71	4.66	6.41	3.07	1.81	0.13
Continental crust[e]	63.2	0.6	16.1	4.9	2.8	4.7	4.2	2.1	0.2
Island arc crust[f]	57.72	0.64	15.16	6.69	7.95	7.32	2.95	1.27	0.14

[a]From **Table 3**.
[b]Ducea 2002.
[c]Taylor & McLennan 1985.
[d]Rudnick & Gao 2003.
[e]Weaver & Tarney 1984.
[f]Kelemen et al. 2004.

Because most arcs exposed to batholithic levels do not have their volcanic cover, it is hard to compare the chemistry of volcanic tops with that of their plutonic equivalents for any given arc. In rare cases where at least part of both records is available, such as the Cretaceous part of the Sierra Nevada, the comparison between major elemental averages does not show much of a difference between the two. This finding contrasts with the evidence from some island arcs, like the Jurassic Talkeetna arc, that the plutonic volume contains more silicic (tonalite and granodiorite) materials than the mostly basaltic volcanics do (Kelemen et al. 2004). We suggest that the major and trace elemental geochemistry of volcanoes and underlying batholiths is to first order similar, and there is no evidence that some crustal filter (e.g., density) operates at a large scale to fractionate total arc crust. Since the volume of magmas in arcs is so strongly dominated by plutonic materials, the composition of batholiths probably more accurately reflects the average of the arc, if slight differences do exist between volcanic and intrusive rocks.

All trace elemental indicators of depth of melt fractionation (Sr/Y, La/Yb, and Eu*) indicate that continental arcs, and especially compressional ones, were fractionated out of a garnet-rich and plagioclase-poor reservoir, at >40–45 km below the surface (Saleeby et al. 2003). Average Sr/Y and La/Yb are elevated in batholiths and volcanic arcs and correlate with silica (**Figure 9**), suggesting that the higher the silica content in an arc, the deeper the average fractionation depth and, by inference, the thicker the crust. In addition, these trace elemental ratios are remarkably different from upper crustal and bulk crustal averages. Crustal average ratios of Sr/Y (∼10–12), La/Yb (∼10), and Eu* (0.6–0.8) suggest that if arc magmatism was responsible for their differentiation, the continents represent an amalgamation of relatively thin arcs with primarily granulitic residues rather than the thicker compressional arcs discussed here.

5.2. Root Composition

The composition of the domain below the transition of primary arc structure from dominantly vertical to horizontal can be determined using the deep crustal sections mentioned above (e.g., Otamendi et al. 2012, Chapman et al. 2014) and, with less geologic control, using xenoliths from the deepest part of arc crust (Ducea 2002, Chin et al. 2013). Roots are primarily a mix of mafic magmas from the mantle, cumulate/residual assemblages from which more felsic materials evolve and ascend, and lesser amounts of preexisting crust, which is also typically residual and melt depleted. On major elemental diagrams, typical cumulate/residual major elemental trends are orthogonal to the main differentiation trend of the arc magmas. These trends are caused by the relative abundances of plagioclase, amphibole, pyroxenes, and garnet. These in turn vary as a function of the average arc chemistry, the proportion of preexisting supracrustal material, and the depth of the differentiation and melt extraction processes. The Salinian and the Sierra de Valle Fértil lower crustal exposures reflect a mix of cumulates and mafic and intermediate melts at 20–25 km deep and average basaltic andesite (e.g., Ducea et al. 2003, Otamendi et al. 2012). The deeper parts of the Sierra Nevada batholith as well as equivalent depths from under the modern Andes in Colombia are known from granulite and eclogite facies xenoliths (Ducea 2002, Rodriguez-Vargas et al. 2005). The estimated root composition of these areas (**Table 4**) reflects the predominance of clinopyroxene, which is mixed with various proportions of low-silica garnet and amphibole. The average root composition is less silicic than average mantle peridotite and corresponds to materials that are at least 0.15 g/cm^3 denser than peridotite (Hacker et al. 2003).

5.3. Radiogenic and Stable Isotopes

Overall, continental arc magmas show large upper plate inputs in their radiogenic isotopes (Sr, Nd, Pb, and Hf), although exactly how radiogenic they are on average is quite variable given the overall heterogeneity of continental lithosphere. The contribution of the upper plate can be most easily constrained if the upper plate is old. Nd isotopes are especially robust indicators of lithospheric residence age—the older the lithosphere, the more negative ε_{Nd} values are (Ducea & Barton 2007). Negative excursions of Nd isotopes indicate an increased contribution from the upper plate, although these isotopes cannot distinguish between crustal versus mantle lithospheric contributions. Arcs emplaced into relatively old upper plate show clear cyclic behavior of radiogenic isotopes with time (these trends are determined within the silica concentration window of 55–65 wt%). Most instructive are the negative Nd isotopic excursions in the North American Cordillera, because they correlate with high-flux events (Barton 1996). Similar trends are observed for the central Andes in Sr isotopes (e.g., Haschke et al. 2002, Mamani et al. 2010), clearly indicating cyclic upper plate involvement, with increased upper plate contributions during high-flux magmatic events. Major advances in measuring Hf isotopes in situ on zircon crystals will undoubtedly lead to large databases of age–Hf isotope correlations in arcs and their associated sedimentary records (Laskowski et al. 2013).

Elevated $\delta^{18}O$ in igneous rocks (>7‰ relative to standard mean ocean water) requires the presence of a recycled supracrustal component, as mantle-derived magmas have ratios around 5.5 ($\pm$0.5). Sedimentary rocks in contact with the hydrosphere can have $\delta^{18}O$ ratios as high as 20–25. That makes $\delta^{18}O$ the best tool for fingerprinting preexisting supracrustal components. On average, arc magmas from continental settings have $\delta^{18}O$ of ~8.5 (Ducea & Barton 2007), clearly indicating that preexisting crust that was close to the surface is an important component in arc magmas. Early phases of arc magmatism and high-flux magmatic events tend to exhibit increased $\delta^{18}O$ values and upper plate radiogenic isotopic signatures (Ducea & Barton 2007).

One of the observations emerging from vertical studies of arcs is that single vertical sections through various arcs show similar isotopic signatures from top to bottom (e.g., Coleman & Glazner 1998, Ducea 2002, Girardi et al. 2012), indicating, again, that much of the heterogeneity in arcs at surface or shallow intrusive levels is inherited from very deep in the crust and mantle. Overall, the isotopic record of continental arcs leaves little doubt that a significant portion of the magmatic budget (around 50% on average) is derived from the upper plate.

6. PETROLOGIC MODELS

The origin of granite and Cordilleran-type batholithic belts has been a focus of petrology for almost 250 years (see Pitcher 1993 for review). A modern rendering of this question is more concerned with the various compositional components that contribute mass and enthalpy and with the processes that control fractionation, melting, assimilation, mixing, and eruption. Continental and island arcs share many features, but have two important differences: (*a*) Continental crust acts as a physical, compositional, and thermal filter and buffer, and (*b*) crustal signatures from both subducted sediment and thick supracrustal packages can complicate mass flux and balance calculations. So, although an isotopic signature of sediment can be established in the mantle source region or in the crust, the differentiation processes that produce the diversity of magmas typical of continental arcs occur primarily in the crust. One would expect that continental arcs would reflect the greater thickness of the crust in the chemical controls exerted by phases like garnet (Lee et al. 2006), the availability of supracrustal sediments, and the enhanced diversity of volcanic styles, including the large-volume calderas (De Silva 1989, Mamani et al. 2010, Salisbury et al. 2011).

What are the sources, sites, and processes that produce the repeating crustal-scale compositional stratification of continental arcs (Jagoutz 2014)? The advent of isotopic and crystal-chemical techniques, especially microanalysis (Wallace & Bergantz 2005, Ramos & Tepley 2008), has revealed that continental arcs, once thought to originate simply as crustal melts in geosynclines (Bateman & Eaton 1967), are instead mixtures of fractionating juvenile mantle and crustal materials. Hence, the notion of continental arc products "imaging their source" in any simple way is misplaced (Davidson et al. 2005), as source regions are not fixed in composition or time. The stochastic growth of the thermal prograde envelope during arc magmatism (Annen et al. 2006) and the return of residual products of coupled fractionation and assimilation to the mantle by delamination (Jagoutz & Schmidt 2013) produce an incomplete record of arc magmagenesis. Here we discuss the most generic aspects of that process.

One of the greatest obstacles to understanding the chemical dynamics of the mantle-crust connection in continental arcs is that samples of mafic liquids are rare. Mantle xenoliths are the primary means by which such processes can be inferred (Ducea & Saleeby 1998). The few exposed arc or crustal sections dominated by mafic igneous rocks are mostly from island arcs, juvenile continental arcs, and extensional settings, and they generally don't preserve extensive outcrops of high-pressure assemblages (DeBari 1994, Barboza & Bergantz 2000, Greene et al. 2006, Jagoutz et al. 2007, Larocque & Canil 2010, Otamendi et al. 2012). Nonetheless, there is a commonality between continental arc xenoliths and island arc exposures in that the deepest mafic sequences are cumulates, with typically high- to moderate-Mg# garnet pyroxenite, gabbronorites, and amphibole gabbro with locally abundant dunites (Müntener et al. 2001, Lee et al. 2006, Jagoutz 2014), depending on the depth at which juvenile mantle input initially occurs. The cumulate character of these rocks is confirmed by the fact that the compositions, textures, and modes are unlike melts in equilibrium with such a solid, as confirmed from piston cylinder experiments (Müntener et al. 2001, Blatter et al. 2013, Nandedkar et al. 2014). Even given complexities that arise over differing initial H_2O contents that will control the appearance of amphibole and the subsequent liquid line of descent (Jagoutz et al. 2011), the record from the deep and/or ultramafic and mafic arc crust is that it is dominated by cumulate processes, efficiently expelling more evolved melts and leaving a residue that is typically very low in incompatible elements. This is the setting where the initial transition to higher silica takes place, dominated initially by olivine and subsequently by pyroxene, amphibole, Fe-Ti oxides, or some combinations of the above involving plagioclase as a function of initial H_2O content and pressure (Davidson & Arculus 2006, Davidson et al. 2007, Larocque

& Canil 2010). Importantly, fractional crystallization models are typically successful in predicting the association of mafic cumulates and more evolved magmas (Lee & Bachmann 2014).

The transition from largely sill-like mafic cumulates to intermediate bodies of tonalities that then transition up to granodiorites can be remarkably abrupt. In the Sierra de Valle Fértil arc crustal section in Argentina, this transition can be on the order of a few to tens of meters (Otamendi et al. 2009). This transition also marks a distinct change in the character of the plutonic rocks in that they no longer are obviously fully cumulate or have a sill-like form. Instead, their compositions, textures, and modes suggest that they are variably cumulate even within a single map unit. It is this variably cumulate character of the diorite-tonalite-granodiorite assemblages that produces much of the spread in major elemental diagrams (**Figure 2**). This absence of pervasive silicic cumulates reflects the interplay between the increase in melt viscosity and decrease in crystal density with increasing SiO_2, and a change in the way that enthalpy is related to crystallinity, with silicic rocks having an extended temperature interval over which they crystallize relative to more primitive compositions (Bergantz 1990, Dufek & Bachmann 2010, Lee & Bachmann 2014). This allows them to persist as hypersolidus mushes, subject to repeated open-system input and partial homogenization during which melt extraction is less efficient and takes place at higher melt fractions than in mafic bodies (Bachmann & Bergantz 2008b, Burgisser & Bergantz 2011). These crystal-rich mushes can be erupted as large-volume homogeneous sheets (Hildreth 1981, Bachmann & Bergantz 2008a) and produce some of the most voluminous explosive silicic eruptions. If the silicic mushes do not erupt, they can produce rhyolites by a process of interstitial melt extraction (Bachmann & Bergantz 2004, 2008c).

The mid- and upper crustal silicic units also become the repository for much of the crustal mass that is assimilated and fluxed upward. Thus, continental arcs have a dual nature in terms of process: a deep crust dominated by fractionation in the mafic "engine room," yet leaving cumulate residues and extracted melts that have enriched isotopic, or crustal, assimilation signatures. In the lower crust, much of the evidence for crustal assimilation resides largely in the isotopic record, as expressed by mafic rocks with radiogenic Sr and Nd and by zircon with elevated $\delta^{18}O$. The majority of the assimilated mass is mixed with and expelled with silicic melts escaping from mafic mushes, a process termed MASH (melting, assimilation, storage, and homogenization) by Hildreth & Moorbath (1988). Continued, but less efficient, assimilation occurs in the mid- to upper crust, producing magmas that have significant mass largely inherited from the lower to mid-crust, but where the dominant process of differentiation is crystal-melt fractionation. This is because silicic melts are cooler and upper crustal temperatures are lower, making significant crustal assimilation more difficult.

In this view, the process of crustal assimilation is wholesale, in that assimilated crustal materials are not simply melts produced by proximal-contact metamorphic melting but instead are generated by progressive envelopment in the regional thermal aureole of the prograde fractionating arc. This implies a three-dimensional heat transfer regime as mafic magmas coalesce and digest lower crustal framework rocks, some of which may even be mafic precursors. However, simple contact melting is not particularly efficient in generating voluminous intermediate magmas by dehydration melting and migmatization alone, and requires basaltic mass fluxes that are extreme (Dufek & Bergantz 2005). In addition, such melts will not have the volatile contents required to stabilize amphibole, which is common in intermediate silicic rocks in continental arcs (Jagoutz & Schmidt 2013). In summary, the presence of enriched isotopic signatures from the deepest mafic/ultramafic cumulates to upper crustal granodiorites and related volcanic rocks reflects the interplay between fractionating and migrating crystal-rich systems initiated by juvenile mantle input, with significant mass contributions by assimilation primarily in the deep and mid-crust. This is promoted and sustained by continued mantle input. There is ample evidence for repeated basaltic intrusion and mixing with the evolving silicic mid- and upper crust (Ruprecht et al. 2012); however, the significance of this process as an essential part of producing the compositional spectrum, largely driven by crystal-melt fractionation, is unclear.

A volcanic example of this progression occurs at the Aucanquilcha volcanic cluster in the Chilean Andes, which preserves 11 Myr of arc activity (Grunder et al. 2008). The compositional trends mirror those of the xenolith and deep crustal section records: a compositionally diverse andesite-dacite sequence culminating in a compositionally restricted, more H_2O-rich silicic dacite composition.

Further progress in understanding the timescales and controls on fractionation-assimilation processes will require a more detailed understanding of the mechanics of melt extraction and movement in crystal-rich systems. Simple models such as compaction do not capture the richness of multiphase processes exhibited by the rock record. And though there is still much to learn about the dynamics, the processes can be remarkably efficient in moving melts out of mushes and blending them during progressive assimilation and magma mixing.

7. TECTONICS AND EVOLUTIONARY TRENDS

Arcs evolve together with their hosting plate margins. Long-lived arcs display cyclic changes in their chemistry, isotopes, and fluxes. Some of the most important evolutionary features of continental arcs are summarized below.

7.1. Arc Initiation and S-Type Plutons

Early stages of continental arcs and transitional continental arcs commonly represent the product of mafic magma emplacement into a former passive margin. Passive margins are thick accumulations of $\geq$15 km of siliciclastic material. Such sediments are melt fertile in the mid- to lower crust. Earlier plutons in arcs of the Americas are dominated by S-type plutons, reflecting derivation from a passive margin source (see sidebar, Granitoid Types). For example, the Cambrian Pampean arc in South America is emplaced into the Puncoviscana formation, which is a classic passive margin sequence (Ramos 2008). Similarly, the Salinian arc was emplaced into the Cordilleran Paleozoic miogeoclinal sequence and its Mesozoic cover, leading to the formation of magmas enriched in radiogenic isotopes with high $\delta^{18}O$ (Kistler & Champion 2001, Chapman et al. 2014) in the early stages of magmatism. A similar trend was observed in the earlier stages of magmatism in the Coast Mountains batholith (Wetmore & Ducea 2011), with high-$\delta^{18}O$ magmas initially and plutons that are either S-type or crossover I- to S-type. Over time, the supracrustal input derived from partial melting of these sedimentary sequences decreases after a few tens of millions of years, and plutons become I-type. Unless a new mass of melt-fertile sedimentary material is tectonically added to the arc region upper plate by thrusting or diapiric rise of sediments from the subducting slab (e.g., Hall & Kincaid 2001, Behn et al. 2011), no new S-type plutons should form later in the evolution of the arc.

GRANITOID TYPES

I-type granitoids are igneous rocks typical of subduction-related magmas, and are primarily derived from mafic ascendants that originated in the mantle. S-type granitoids are magmatic rocks derived from the partial melting of sedimentary protoliths.

7.2. Accretion of Arcs

Numerous accreted arcs have been identified along the western margins of the Americas (e.g., Saleeby 1983, Ramos 2008). They represent allochthonous terranes that, following accretion, constitute part of the lithospheric framework in which continental arcs develop. Many, or most, probably represent fringing arcs that were separated from adjacent continental blocks by marginal basins that closed, leading to accretion. The collection of these accreted terranes that host younger arc magmatism is an integral part of subduction-related magmatism at Cordilleran margins. Such accreted terranes also include rifted continental ribbons and oceanic plateaus, or seamount chains. The initial accretionary structures are prone to remobilization as upper (subduction) plate thrust, strike-slip, or normal faults, although integrated upper plate deformation typically leads to a steep regional structural fabric at mid- to upper crustal arc levels (Saleeby et al. 2003, Gehrels et al. 2009), which ascending arc magmas mimic in their overall structural geometry.

7.3. Retroarc Thickening

Many compressional arcs have backarc fold and thrust belts dipping into the orogen (DeCelles 2004). The shortening associated with these structures is large (hundreds of kilometers), potentially doubling crust and mantle lithosphere thickness (Ducea 2001). Some of these shortening structures are preserved in the immediate vicinity or even within the arc regions themselves (Dunne & Walker 2004), whereas many others in the Americas are located farther into the continental foreland.

On the one hand, mass balance considerations indicate that the crowding effect from retroarc shortening alone can freeze mantle wedge corner flow (DeCelles et al. 2009), therefore slowing down the normal asthenosphere-derived melt supply into the crust. On the other hand, it represents a mechanism for delivering melt-fertile crustal materials into the thickened lower crust and a potential trigger of flare-ups (Ducea 2001). Over 60% by volume of the well-studied arcs, such as the Sierra Nevada, were formed during flare-up events dominated by upper plate lithospheric (crust and mantle) material (Ducea & Barton 2007, Girardi et al. 2012), based on radiogenic isotopes, and follow major events of retroarc shortening by about 15–25 Myr in North America (DeCelles 2004). This observation led to the hypothesis that thermal relaxation driven by retroarc shortening and crustal thickening is a major trigger for high-flux magmatism in continental arcs (DeCelles et al. 2009).

7.4. Trench-Side Underplating and Relamination

More than half of modern trenches are erosive (von Huene & Scholl 1991, Clift & Vannucchi 2004, Stern 2011). The process by which sedimentary accumulations at trenches are removed and entrained with the slab is referred to as subduction erosion. What happens to the eroded material over the long term? Some is subducted to great depths into the mantle, but the majority is reincorporated into the upper plate (Hacker et al. 2015). Steady-state sediment melting or a steady-state influx of sediment into the upper plate via dehydration reactions (Plank & Langmuir 1998) cannot explain the cyclic nature of magmatism and the significant increases in upper plate materials during high-flux events. Instead, two mechanisms have been put forward to explain the en masse enrichment of upper crustal materials in some arcs (excepting the initiation of arcs across passive margins): tectonic underplating and relamination. Both require that large amounts of sedimentary and other crustal materials be transported rather catastrophically into the root zones of arcs and eventually undergo partial melting. Some investigators have even argued that mixing of trench-side partial melts of metasedimentary materials is the most significant process driving silica enrichments in arc magmas (Castro et al. 2010). Tectonic underplating is a structural process by which trench sediments and parts of the forearc are thrust under the main arc during periods of shallow subduction; thrust sheets of upper plate material are transferred to the downgoing plate only to be reattached to the upper plate beneath the mid- to lower arc crust (Ducea et al. 2009). Relamination, in contrast, is a convective process by which large amounts of eroded sediment from the subducting plate detach and rise diapirically through the mantle wedge beneath arcs (Hacker et al. 2011). Both of these processes require large pulses of sediments to be subducted, unlike the continuous process of sediment subduction along a narrow subduction channel (Cloos & Shreve 1988). Examples of continental arcs that are underlain by synarc sediments transferred from the trench region are the Swakane gneiss in the Cascade core region (Gordon et al. 2010), the Salinian–Sierra de Salinas schist area in central coastal California (Kidder & Ducea 2006), and equivalents in southern California.

7.5. Convective Removal of Arc Roots

The making of large volumes of intermediate-silica, high-Sr/Y, and high-La/Yb magmas requires the formation of significant residues rich in pyroxenes, garnet, and amphibole (arclogites). Arclogites are convectively removed (i.e., delaminated) at the end of high-flux events, probably not as wholesale delamination events as once hypothesized (Kay & Kay 1993) but by progressive entrainment of small bodies into the convective circulation beneath the arc (Currie et al. 2015). Delamination of arc roots is a requirement constrained by both geochemistry (on average, arcs leave behind a feldspar-free residue not seen in the lower crust) and mass balance [shortening estimates from retroarc thrusting alone would require periods when lithosphere exceeded the depth to the slab interface (Ducea & Barton 2007)]. The process of arc root delamination has been intensely studied over the past decade in both island (Jull & Kelemen 2001, Jagoutz et al. 2013) and continental (Saleeby et al. 2003, Ducea et al. 2013) arcs. Most studies converge on the conclusion that the removal of pyroxene-rich materials in island arcs and arclogites in continental arcs, and their recycling into subarc mantle, is a common process for removing large amounts of low-silica residues, and one that keeps the mantle wedge open to corner flow. Geophysical evidence supports the idea that dense bodies dominated by pyroxene and lesser garnet float within the upper mantle beneath some arcs, such as the Sierra Nevada (Zandt et al. 2004, Jones et al. 2014), as evidenced by geologically recent (Pliocene) convective removal (Ducea & Saleeby 1998). In the case of the Sierra Nevada, the special plate tectonic circumstances of basal support by slab flattening followed by the rapid opening of a slab window seem to explain prolonged maintenance of the dense root in a gravitationally metastable state followed by rapid, even catastrophic, convective removal. Granulite residues, which form in thinner (or shorter-lived) arcs, in contrast, are not prone to delamination. Such residues represent a small proportion of those formed in a thicker continental arc that experienced one or multiple compressive (and flare-up) events.

7.6. Cyclic Behavior of Long-Lived Arcs

Continental arcs are characterized by relatively constant mafic melt production in the mantle wedge, although that can be decreased by crowding during shortening events from either the trench or the foreland side. Thickening events force filtration of mafic magmas into lower crustal reservoirs that ultimately flare up in large batholith-forming episodes (DeCelles et al. 2009), which leave behind large amounts of residues, mostly plagioclase-poor, pyroxene-dominated rocks. Pyroxenites and arclogites are convectively removed from the bottom of the lithospheric section (Currie et al. 2015). Following convective removal, the arc enters an extensional phase dominated by easier access of mafic magmas to the upper crust, less involvement of preexisting upper plate lithosphere, and possible development of backarc basins (**Figure 10**). The cycle is repeated during later thickening events, which can be driven by either regional stresses or far-field changes in plate motions. The active arc locus overprints older arc products in forearc areas (e.g., the Jurassic arc in central Chile) or backarc areas (e.g., the Eocene arc in southern Peru and the Cambrian–Ordovician arcs in Argentina and Bolivia).

8. FROM ARCS TO STABLE CONTINENTS

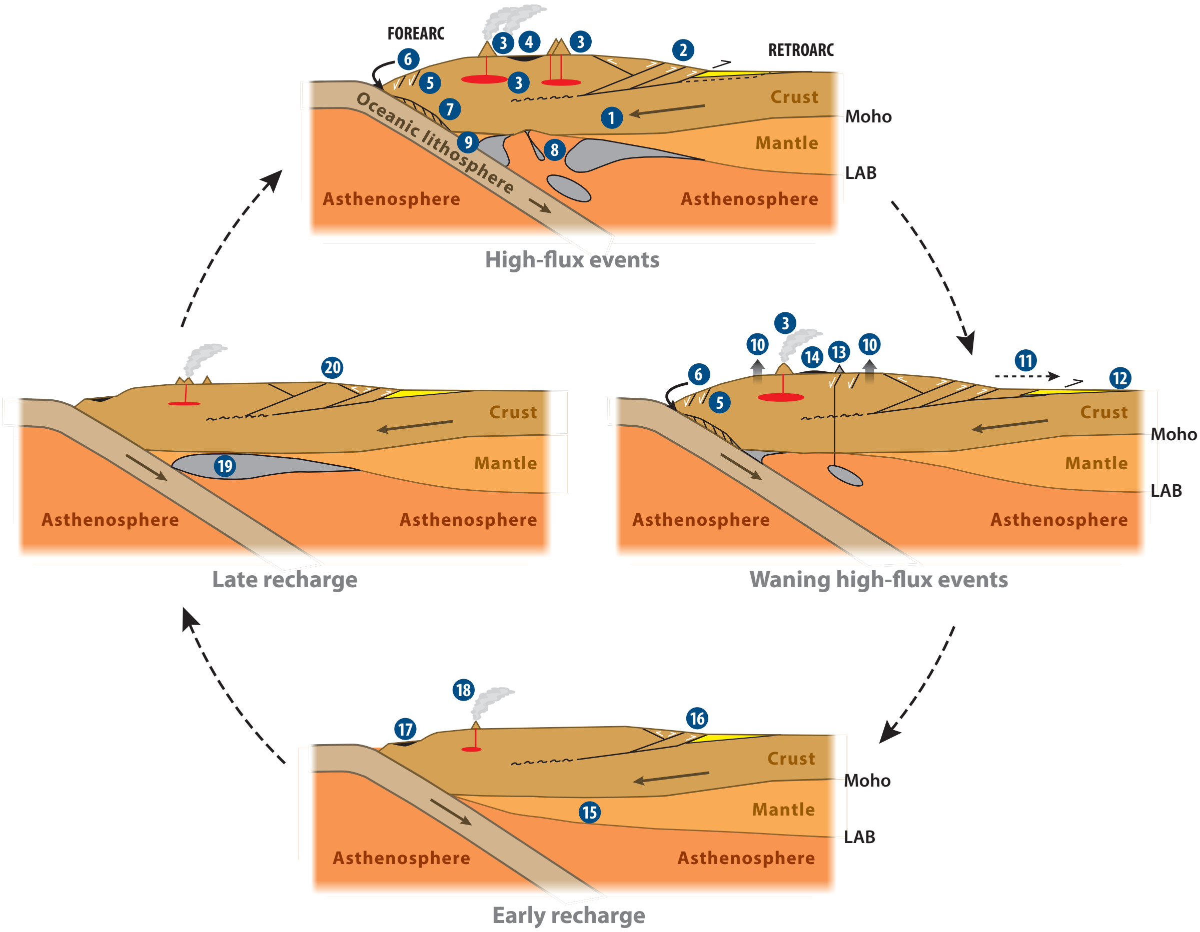
Mature continental arcs have major elemental compositions similar to those of continental crust (Taylor & McLennan 1985, Rudnick & Gao 2003). Because magmatism in no other tectonic environment produces average upper crustal magmas so similar to bulk continental crust, any actualistic view of crustal growth has to consider such arcs as the principal factory for making continents. The mechanism for refining a felsic crust is straightforward to first order (**Figure 5**): a large, Andean-scale arc filter makes over ~20–30-km-thick felsic batholith and large stratovolcano provinces (Ducea 2001, 2002), which are separated rather abruptly at depth by mafic to ultramafic roots that are prone to removal (Jagoutz & Behn 2013). Subsequent to convective removal, the remnant crust is felsic despite the significant input of new material from the mantle via basaltic melts (Jagoutz & Schmidt 2013). Arcs are then incorporated into collisional events and complete the Wilson cycle [e.g., the Gangdese arc in northern Himalaya and southern Tibet (Ding et al. 2003)].

However, prior to the root-removal concepts that emerged over the past 15 years or so, scholars commonly postulated that island arcs were the factories of continental crust (Taylor & McLennan 1985). That model is one of arc formation in an oceanic-only subduction realm (similar to the Western Pacific today), followed by arc-continent collision. However, the main magmatic products of island arcs are closer to basalt and are definitely less silica rich than the continents. Other important mismatches exist, such as the low K_2O concentrations of island arcs. But the trace elemental record of island arcs and their relatively shallow depths of fractionation and line of descent (<30 km) are consistent with the island arc model for continental generation: low Sr/Y, low La/Yb, and sizable Eu anomalies are present in both the average sedimentary record and most island arcs, but not in modern or young continental arcs. The trace elemental paradox is the main limitation to the hypothesis that continental crust was made over time in continental arcs whose ultramafic roots were then convectively removed.

One possible reconciliation for this paradox is that most continental crust was formed in short-lived arcs emplaced into thinned continental crust covered by thick accumulations of passive margin sediments, such as the Famatinian arc (Otamendi et al. 2012) and the Salinian arc (Chapman et al. 2014). This model, however, requires that the location of the arc migrate continuously before the crust is significantly thickened by magmatism, a condition that needs to be investigated in more detail. Alternatively, most continental crust may have been formed by mechanisms other than the plate tectonics–driven processes observed in the Phanerozoic (see Hawkesworth et al. 2010 for a review).

9. SUMMARY AND OUTLOOK

Continental arcs represent the thickest and most diverse associations of igneous rocks on Earth. From top to bottom, they literally build an entire lithospheric section above a subduction zone. Although commonly studied from the perspective of a large-scale igneous process driven exclusively by plate tectonics, continental arcs would not diversify to their observed compositional complexities without various local and regional tectonic triggers: crustal thickening and development



1 Underthrusting of craton
2 Upper crustal shortening
3 High-flux arc magmatism
4 Subsidence of hinterland bobber basins
5 Forearc normal faulting and collapse
6 Forearc tectonic erosion
7 Forearc underplating
8 Eclogite removal by delamination and RTI
9 Increased interplate coupling
10 Regional isostatic uplift of hinterland (<1 km)
11 Rapid forward propagation of retroarc thrust belt
12 Rapid forward migration of foreland flexural wave
13 Mafic magmatism associated with extension
14 Inversion of bobber basins
15 Rethickening of hinterland lithosphere
16 Internal shortening, slow forward propagation of thrust belt
17 Forearc subsidence, sediment accumulation
18 Magmatic arc lull
19 Magmatic recharge, eclogite development
20 Internal shortening in thrust belt

Figure 10

Diagram showing the cyclic behavior of Andean arcs, alternating high-flux events that follow crustal thickening with lower-flux, more-mafic magmatism subsequent to convective removal of thick arc roots. Abbreviations: LAB, lithosphere-asthenosphere boundary; RTI, Rayleigh–Taylor instability. Figure modified with permission from DeCelles et al. (2009).

of retroarc fold and thrust belts, tectonic underplating of forearc sediments, (possible) relamination of subducted sediments, convective removal of roots, etc. Geochemical and isotopic variability in these arcs changes cyclically through time as a result of this tectonic forcing. Geochemically, the upper portions of these arcs yield average compositions that straddle the boundary between an andesite and a dacite, and the downward transition to a mafic to ultramafic residue underpinning is relatively abrupt. The residue is prone to convective removal in the mantle, the single most compelling process that drives continental crust toward a more silicic overall composition.

Major challenges and unresolved issues remain. Among them, the trace elemental budget of continental arcs must be reconciled with the fact that average continents, as preserved in the sedimentary record, do not require a garnet-rich residue, whereas igneous rocks, on average, do. The mechanisms by which the roots of arcs founder in the mantle remain poorly understood. Clearly, such arcs would not exist as composite batholiths without large amounts of residual material having been removed. Does that removal occur wholesale at large scales, or is it a continuous dripping process? These end-member models have significantly different consequences in terms of the structural evolution of arc regions. Finally, the realization that metasediments are commonly incorporated into arcs and can contribute significantly to the melt budget makes one rethink the significance of I-type versus S-type granites and the fact that a continuum of hybrid granitoids exists between these two end-members in continental arc environments.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

We acknowledge funding from the National Science Foundation Petrology and Geochemistry program (EAR-1019525 and EAR-0907880 to M.N.D. and EAR-1049884 to G.B.) and from the Romanian Executive Agency for Higher Education, Research, Development and Innovation Funding (UEFISCDI) (project PN-II-ID-PCE-2011-3-0217).

LITERATURE CITED

Anderson JL, ed. 1990. *The Nature and Origin of Cordilleran Magmatism*. Geol. Soc. Am. Mem. 174. Boulder, CO: Geol. Soc. Am.

Annen C, Blundy JD, Sparks RSJ. 2006. The genesis of intermediate and silicic magmas in deep crustal hot zones. *J. Petrol.* 47:505–39

Babeyko AY, Sobolev SV. 2005. Quantifying different modes of the Late Cenozoic shortening in the Central Andes. *Geology* 33:621–24

Bachmann O, Bergantz GW. 2004. On the origin of crystal-poor rhyolites: extracted from batholithic crystal mushes. *J. Petrol.* 45:1565–82

Bachmann O, Bergantz GW. 2008a. Deciphering magma chamber dynamics from styles of compositional zoning in large silicic ash flow sheets. *Rev. Mineral. Geochem.* 69:651–74

Bachmann O, Bergantz GW. 2008b. The magma reservoirs that feed supereruptions. *Elements* 4:17–21

Bachmann O, Bergantz GW. 2008c. Rhyolites and their source mushes across tectonic settings. *J. Petrol.* 49:2277–85

Barboza SA, Bergantz GW. 2000. Metamorphism and anatexis in the mafic complex contact aureole, Ivrea Zone, Northern Italy. *J. Petrol.* 41:1307–27

Barton MD. 1996. Granitic magmatism and metallogeny of southwestern North America. *Trans. R. Soc. Edinb. Earth Sci.* 87:261–80

Barton MD, Battles DA, Bebout GE, Capo RC, Christensen JN, et al. 1988. Mesozoic contact metamorphism in the western United States. In *Metamorphism and Crustal Evolution of the Western United States*, Vol. 7, ed. WG Ernst, pp. 110–78. Englewood Cliffs, NJ: Prentice Hall

Bateman PC, Eaton JP. 1967. Sierra Nevada batholith. *Science* 158:1407–17

Behn MD, Kelemen PB, Hirth G, Hacker BR, Massonne HJ. 2011. Diapirs as the source of the sediment signature in arc lavas. *Nat. Geosci.* 4:641–46

Bergantz GW. 1990. Melt fraction diagrams: the link between chemical and transport models. In *Modern Methods of Igneous Petrology: Understanding Magmatic Processes*, ed. J Nicholls, JK Russell, pp. 240–57. Chantilly, VA: Mineral. Soc. Am.

Blatter D, Sisson T, Hankins WB. 2013. Crystallization of oxidized, moderately hydrous arc basalt at mid- to lower-crustal pressures: implications for andesite genesis. *Contrib. Mineral. Petrol.* 166:861–86

Burgisser A, Bergantz GW. 2011. A rapid mechanism to remobilize and homogenize highly crystalline magma bodies. *Nature* 471:212–15

Busby-Spera CJ. 1988. Speculative tectonic model for the lower Mesozoic arc of the southwest Cordilleran United States. *Geology* 56:1121–25

Castro A, Gerya T, Garcia-Casco A, Fernandez C, Diaz-Alvarado J, et al. 2010. Melting relations of MORB–sediment mélanges in underplated mantle wedge plumes; implications for the origin of Cordilleran-type batholiths. *J. Petrol.* 51:1267–95

Cecil M, Rotberg GL, Ducea MN, Saleeby JB, Gehrels GE. 2012. Magmatic growth and batholithic root development in the northern Sierra Nevada, California. *Geosphere* 8:592–606

Chamberlain CP, Mix HT, Mulch A, Hren MT, Kent-Corson ML, et al. 2012. The Cenozoic climatic and topographic evolution of the western North American Cordillera. *Am. J. Sci.* 312:213–62

Chapman AD, Ducea MN, Kidder S, Petrescu L. 2014. Geochemical constraints on the petrogenesis of the Salinian arc, central California: implications for the origin of intermediate magmas. *Lithos* 200–1:126–41

Chapman AD, Saleeby JB, Wood DJ, Piasecki A, Kidder S, et al. 2012. Late Cretaceous gravitational collapse of the southern Sierra Nevada batholith, California. *Geosphere* 8:314–41

Chin EJ, Lee CT, Tollstrup DL, Xie LW, Wimpenny JB, Yin QZ. 2013. On the origin of hot metasedimentary quartzites in the lower crust. *Earth Planet. Sci. Lett.* 361:120–33

Clarke GL, Daczko NR, Miescher D. 2013. Identifying relic igneous garnet and clinopyroxene in eclogite and granulite, Breaksea Orthogneiss, New Zealand. *J. Petrol.* 55:1921–38

Clift P, Vannucchi P. 2004. Controls on tectonic accretion versus erosion in subduction zones: implications for the origin and recycling of the continental crust. *Rev. Geophys.* 42:RG2001

Cloos M, Shreve L. 1988. Subduction-channel model of prism accretion, melange formation, sediment subduction, and subduction erosion at convergent plate margins. *Pure Appl. Geophys.* 128:455–500

Coleman DS, Glazner AF. 1998. The Sierra Crest magmatic event: rapid formation of juvenile crust during the Late Cretaceous in California. In *Integrated Earth and Environmental Evolution of the Southwestern United States: The Clarence A. Hall, Jr. Volume*, ed. WG Ernst, CA Nelson, pp. 253–72. Columbia, MD: Bellwether

Coleman DS, Gray W, Glazner AF. 2004. Rethinking the emplacement and evolution of zoned plutons: geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California. *Geology* 32:433–36

Currie C, Ducea MN, DeCelles PG, Beaumont C. 2015. Geodynamic models of Cordilleran orogens: gravitational instability of magmatic arc roots. *Geol. Soc. Am. Mem.* 212:1–22

Davidson JP, Arculus RJ. 2006. The significance of Phanerozoic arc magmatism in generating continental crust. In *Evolution and Differentiation of the Continental Crust*, ed. M Brown, T Rushmer, pp. 135–72. Cambridge, UK: Cambridge Univ. Press

Davidson JP, Hora JM, Garrison JM, Dungan MA. 2005. Crustal forensics in arc magmas. *J. Volcanol. Geotherm. Res.* 140:157–70

Davidson JP, Turner S, Handley H, Macpherson C, Dosseto A. 2007. Amphibole "sponge" in arc crust? *Geology* 35:787–90

De Paoli MC, Clarke GL, Klepeis KA, Allibone AH, Turnbull IM. 2009. The eclogite-granulite transition: mafic and intermediate assemblages at Breaksea Sound, New Zealand. *J. Petrol.* 50:2307–43

De Silva SL. 1989. Altiplano-Puna volcanic complex of the central Andes. *Geology* 17:1102–6

De Silva SL, Francis PW. 1989. Correlation of large ignimbrites—two case studies from the central Andes of N. Chile. *J. Volcanol. Geotherm. Res.* 37:133–49

DeBari SM. 1994. Petrogenesis of the Fimbala gabbroic intrusion, northwestern Argentina, a deep crustal syntectonic pluton in a continental magmatic arc. *J. Petrol.* 35:679–713

DeCelles PG. 2004. Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin system, western U.S.A. *Am. J. Sci.* 304:105–68

DeCelles PG, Ducea MN, Kapp P, Zandt G. 2009. Cyclicity in Cordilleran orogenic systems. *Nat. Geosci.* 2:251–57

Demouy S, Paquette JL, de Saint Blanquat M, Benoit M, Belousova EA, et al. 2012. Spatial and temporal evolution of Liassic to Paleocene arc activity in southern Peru unraveled by zircon U-Pb and Hf in-situ data on plutonic rocks. *Lithos* 155:183–200

DePaolo DJ. 1981. A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra-Nevada and Peninsular Ranges, California. *J. Geophys. Res.* 86(B11):470–88

Depine GV, Andronicos CL, Phipps-Morgan J. 2008. Near-isothermal conditions in the middle and lower crust induced by melt migration. *Nature* 452:80–83

Ding L, Kapp P, Zhong D, Deng W. 2003. Cenozoic volcanism in Tibet: evidence for a transition from oceanic to continental subduction. *J. Petrol.* 44:1833–65

Ducea MN. 2001. The California arc: thick granitic batholiths, eclogitic residues, lithospheric-scale thrusting, and magmatic flare-ups. *GSA Today* 11:4–10

Ducea MN. 2002. Constraints on the bulk composition and root foundering rates of continental arcs: a California arc perspective. *J. Geophys. Res.* 107:B112304

Ducea MN, Barton MD. 2007. Igniting flare-up events in Cordilleran arcs. *Geology* 35:1047–50

Ducea MN, Gehrels GE, Shoemaker S, Ruiz J, Valencia VA. 2004. Geologic evolution of the Xolapa Complex, southern Mexico: evidence from U-Pb zircon geochronology. *Geol. Soc. Am. Bull.* 116:1016–25

Ducea MN, Kidder S, Chelsey JT, Saleeby JB. 2009. Tectonic underplating of trench sediments beneath magmatic arcs: the central California example. *Int. Geol. Rev.* 51:1–26

Ducea MN, Kidder S, Zandt G. 2003. Arc composition at mid-crustal depths: insights from the Coast Ridge Belt, Santa Lucia Mountains, California. *Geophys. Res. Lett.* 30:1703

Ducea MN, Paterson SR, DeCelles PG. 2015. High-flux magmatic events in subduction systems. *Elements* 11. In press

Ducea MN, Saleeby JB. 1996. Buoyancy sources for a large, unrooted mountain range, the Sierra Nevada, California: evidence from xenolith thermobarometry. *J. Geophys. Res.* 101(B4):8229–44

Ducea MN, Saleeby JB. 1998. The age and origin of a thick mafic-ultramafic keel from beneath the Sierra Nevada batholith. *Contrib. Mineral. Petrol.* 133:169–85

Ducea MN, Seclaman AC, Murray KE, Jianu D, Schoenbohm LM. 2013. Mantle-drip magmatism beneath the Altiplano-Puna plateau, central Andes. *Geology* 41:915–18

Dufek J, Bachmann O. 2010. Quantum magmatism: magmatic compositional gaps generated by melt-crystal dynamics. *Geology* 38:687–90

Dufek J, Bergantz GW. 2005. Lower crustal magma genesis and preservation: a stochastic framework for the evaluation of basalt-crust interaction. *J. Petrol.* 46:2167–95

Dunne GC, Walker JD. 2004. Structure and evolution of the East Sierran thrust system, east-central California. *Tectonics* 23:TC4012

Economos RC, Paterson SR, Said LO, Ducea MN, Anderson JL, Padilla AJ. 2012. Gobi-Tianshan connections: field observations and isotopes from an early Permian arc complex in southern Mongolia. *Geol. Soc. Am. Bull.* 124:1688–701

Ferrari L, Orozco-Esquivel T, Manea V, Manea M. 2012. The dynamic history of the Trans-Mexican Volcanic Belt and the Mexico subduction zone. *Tectonophysics* 522:122–49

Fiske RS, Tobisch OT. 1994. Middle Cretaceous ash-flow tuff and caldera-collapse deposit in the Minarets Caldera, East-Central Sierra Nevada, California. *Geol. Soc. Am. Bull.* 106:582–93

Gaetani GA, Grove TL. 1998. The influence of water on melting of mantle peridotite. *Contrib. Mineral. Petrol.* 131:323–46

Gehrels GE, Rushmore M, Woodsworth G, Crawford M, Andronicos C, et al. 2009. U-Pb geochronology of the Coast Mountains batholith in north-coastal British Columbia: constraints on age and tectonic evolution. *Geol. Soc. Am. Bull.* 121:1341–61

Gilbert H, Beck S, Zandt G. 2006. Lithospheric and upper mantle structure of central Chile and Argentina. *Geophys. J. Int.* 165:383–98

Gill J. 1981. *Orogenic Andesites and Plate Tectonics*. Berlin: Springer-Verlag

Girardi JD, Patchett PJ, Ducea MN, Gehrels GE, Cecil MR, et al. 2012. Elemental and isotopic evidence for granitoid genesis from deep-seated sources in the Coast Mountains batholith, British Columbia. *J. Petrol.* 53:1505–36

Gordon SM, Bowring SA, Whitney DL, Miller RB, McLean N. 2010. Time scales of metamorphism, deformation, and crustal melting in a continental arc, North Cascades USA. *Geol. Soc. Am. Bull.* 122:1308–30

Goss AR, Kay SM, Mpodozis C. 2013. Andean adakite-like high-Mg andesites on the northern margin of the Chilean-Pampean flat-slab (27–28.5°S) associated with frontal arc migration and fore-arc subduction erosion. *J. Petrol.* 54:2193–234

Greene AR, DeBari SM, Kelemen PK, Blustajn J, Clift PD. 2006. A detailed geochemical study of island arc crust: the Talkeetna arc section, south-central Alaska. *J. Petrol.* 47:1051–93

Gromet LP, Silver LT. 1987. REE variations across the Peninsular Ranges batholith: implications for batholithic petrogenesis and crustal growth in magmatic arcs. *J. Petrol.* 28:75–125

Grove TL, Till CB, Krawczynski MJ. 2012. The role of H_2O in subduction zone magmatism. *Annu. Rev. Earth Planet. Sci.* 40:413–39

Grunder AL, Klemetti EW, Feeley TC, McKee CM. 2008. Eleven million years of arc volcanism at the Aucanquilcha volcanic cluster, northern Chilean Andes: implications for the life span and emplacement of plutons. *Trans. R. Soc. Edinb. Earth Sci.* 97:415–36

Hacker BR, Abers GA, Peacock SM. 2003. Subduction factory. 1. Theoretical mineralogy, density, seismic wave speeds, and H_2O content. *J. Geophys. Res.* 108:B12029

Hacker BR, Kelemen PB, Behn MD. 2015. Continental lower crust. *Annu. Rev. Earth Planet. Sci.* 43:167–205

Hacker BR, Kelemen PB, Rioux M, McWilliams MO, Gans PB, et al. 2011. Thermochronology of the Talkeetna intraoceanic arc of Alaska: Ar/Ar, U-Th/He, Sm-Nd and Lu-Hf dating. *Tectonics* 30:TC1011

Hall ML, Samaniego P, Le Pennec JL, Johnson J. 2008. Ecuadorian Andes volcanism: a review of Late Pliocene to present activity. *J. Volcanol. Geotherm. Res.* 176:1–6

Hall PS, Kincaid C. 2001. Diapiric flow at subduction zones: a recipe for rapid transport. *Science* 292:2472–75

Haschke M, Siebel W, Gunther A, Scheuber E. 2002. Repeated crustal thickening and recycling during the Andean orogeny in north Chile (21°–26°S). *J. Geophys. Res.* 107(B1):6–18

Hawkesworth CJ, Dhuime B, Pietranik AB, Cawood PA, Kemp AIS, Storey CD. 2010. The generation and evolution of the continental crust. *J. Geol. Soc. Lond.* 167:229–48

Hildreth W. 1981. Gradients in silicic magma chambers: implications for lithospheric magmatism. *J. Geophys. Res.* 86(B11):10153–92

Hildreth W, Moorbath S. 1988. Crustal contributions to arc magmatism in the Andes of central Chile. *Contrib. Mineral. Petrol.* 98:455–89

House MA, Wernicke BP, Farley KA. 1998. Dating topography of the Sierra Nevada, California, using apatite (U-Th)/He ages. *Nature* 396:66–69

Irigoyen MV, Buchan KL, Brown RL. 2000. Magnetostratigraphy of Neogene Andean foreland-basin strata, lat 33°S, Mendoza Province, Argentina. *Geol. Soc. Am. Bull.* 112:803–16

Isacks BL. 1988. Uplift of the central Andean plateau and bending of the Bolivian orocline. *J. Geophys. Res.* 93(B4):3211–31

Ishizuka O, Tani K, Reagan MK, Kanayama K, Umino S, et al. 2011. The timescales of subduction initiation and subsequent evolution of an oceanic island arc. *Earth Planet. Sci. Lett.* 306:229–40

Jagoutz O. 2014. Arc crustal differentiation mechanisms. *Earth Planet. Sci. Lett.* 396:267–77

Jagoutz O, Behn MD. 2013. Foundering of lower island-arc crust as an explanation for the origin of the continental Moho. *Nature* 504:131–34

Jagoutz O, Kelemen PB. 2015. Role of arc processes in the formation of continental crust. *Annu. Rev. Earth Planet. Sci.* 43:363–404

Jagoutz O, Müntener O, Schmidt MW, Burg JP. 2011. The roles of flux- and decompression melting and their respective fractionation lines for continental crust formation: evidence from the Kohistan arc. *Earth Planet. Sci. Lett.* 303:25–36

Jagoutz O, Müntener O, Ulmer P, Pettke T, Burg JP, et al. 2007. Petrology and mineral chemistry of lower crustal intrusions: the Chilas Complex, Kohistan (NW Pakistan). *J. Petrol.* 48:1895–953

Jagoutz O, Schmidt MW. 2013. The composition of the foundered complement to the continental crust and are-evaluation of fluxes in arcs. *Earth Planet. Sci. Lett.* 371–72:177–90

Jagoutz O, Schmidt MW, Enggist E, Burg JP, Hamid D, Hussain S. 2013. TTG-type plutonic rocks formed in a modern arc batholith by hydrous fractionation in the lower arc crust. *Contrib. Mineral. Petrol.* 166:1099–118

Jicha BR, Scholl DW, Singer BS, Yogodzinski GM, Kay SM. 2006. Revised age of Aleutian Island arc formation implies high rate of magma production. *Geology* 34:661–64

Jones CH, Reeg H, Zandt G, Gilbert H, Owens TJ, Stachnik J. 2014. P-wave tomography of potential convective downwellings and their source regions, Sierra Nevada, California. *Geosphere* 10:503–33

Jull M, Kelemen PB. 2001. On the conditions for lower crustal convective instability. *J. Geophys. Res.* 106(B4):6423–46

Kay RW, Kay SM. 1993. Delamination and delamination magmatism. *Tectonophysics* 219:177–89

Kay SM, Gody E, Kurz A. 2005. Episodic arc migration, crustal thickening, subduction erosion and magmatism in the south-central Andes. *Geol. Soc. Am. Bull.* 117:67–88

Kelemen PB. 1995. Genesis of high Mg# andesites and the continental crust. *Contrib. Mineral. Petrol.* 120:1–19

Kelemen PB, Hanghoj K, Greene AR. 2004. One view of the geochemistry of subduction-related magmatic arcs, with an emphasis on primitive andesite and lower crust. In *Treatise on Geochemistry*, Vol. 3: *The Crust*, ed. RL Rudnick, pp. 593–659. Oxford, UK: Pergamon. 1st ed.

Kidder S, Ducea MN. 2006. High temperatures and inverted metamorphism in the schist of Sierra de Salinas, California. *Earth Planet. Sci. Lett.* 241:422–37

Kidder S, Ducea MN, Gehrels G, Patchett PJ, Vervoort J. 2003. Tectonic and magmatic development of the Salinian Coast Ridge Belt, California. *Tectonics* 22:TC001409

Kimura JI, Yoshida T. 2006. Contributions of slab fluid, mantle wedge and crust to the origin of quaternary lavas in the NE Japan arc. *J. Petrol.* 47:2185–232

Kistler RW, Champion DE. 2001. *Rb-Sr whole-rock and mineral ages, K-Ar, $^{40}Ar/^{39}Ar$, and U-Pb mineral ages, and strontium, lead, neodymium and oxygen isotopic compositions for granitic rocks from the Salinian composite terrane, California*. Open-File Rep. 01-453, US Geol. Surv., Menlo Park, CA

Kistler RW, Peterman ZE. 1978. *Reconstruction of crustal blocks of California on the basis of initial Sr isotopic compositions of Mesozoic granitic rocks*. Prof. Pap. 1071, US Geol. Surv., Washington, DC

Larocque J, Canil D. 2010. The role of amphibole in the evolution of arc magmas and crust: the case from the Jurassic Bonanza arc section, Vancouver Island, Canada. *Contrib. Mineral. Petrol.* 159:475–92

Laskowski AK, DeCelles PG, Gehrels GE. 2013. Detrital zircon geochronology of Cordilleran retroarc foreland basin strata, western North America. *Tectonics* 32:1027–48

LeBas MJ, Le Maitre RW, Streckheisen A, Zanettin B. 1986. A chemical classification of volcanic rocks based on the total alkali–silica diagram. *J. Petrol.* 27:745–50

Lee CT, Bachmann O. 2014. How important is the role of crystal fractionation in making intermediate magmas? Insights from Zr and P systematics. *Earth Planet. Sci. Lett.* 393:266–74

Lee CT, Cheng X, Horodyskyi U. 2006. The development and refinement of continental arcs by primary basaltic magmatism, garnet pyroxenite accumulation, basaltic recharge and delamination: insights from the Sierra Nevada, California. *Contrib. Mineral. Petrol.* 151:222–42

Lee CT, Yin Q, Rudnick RL, Chesley JT, Jacobsen SB. 2000. Osmium isotopic evidence for Mesozoic removal of lithospheric mantle beneath the Sierra Nevada, California. *Science* 289:1912–16

Mamani M, Tassara A, Wörner G. 2008. Composition and structural control of crustal domains in the Central Andes. *Geochem. Geophys. Geosyst.* 9:Q03006

Mamani M, Wörner G, Sempere T. 2010. Geochemical variations in igneous rocks of the Central Andean orocline (13°S to 18°S): tracing crustal thickening and magma generation through time. *Geol. Soc. Am. Bull.* 122:162–82

Marchesi C, Garrido CJ, Bosch D, Proenza JA, Gervilla F, et al. 2007. Geochemistry of Cretaceous magmatism in eastern Cuba: recycling of North American continental sediments and implications for subduction polarity in the Greater Antilles Paleo-arc. *J. Petrol.* 48:1813–40

Mattinson JM. 2013. Revolution and evolution: 100 years of U–Pb geochronology. *Elements* 9:53–57

Miller RB, Paterson SR, Matzel JP. 2009. Plutonism at different crustal levels: insights from the ∼5–40 km (paleodepth) North Cascades crustal section, Washington. *Geol. Soc. Am. Spec. Pap.* 456:125–49

Müntener O, Kelemen P, Grove T. 2001. The role of H_2O during crystallization of primitive arc magmas under uppermost mantle conditions and genesis of igneous pyroxenites: an experimental study. *Contrib. Mineral. Petrol.* 141:643–58

Nandedkar R, Ulmer P, Müntener O. 2014. Fractional crystallization of primitive, hydrous arc magmas: an experimental study at 0.7 GPa. *Contrib. Mineral. Petrol.* 167:1–27

Otamendi JE, Ducea MN, Bergantz GW. 2012. Geological, petrological and geochemical evidence for progressive construction of an arc crustal section, Sierra de Valle Fertil, Famatinian Arc, Argentina. *J. Petrol.* 53:761–800

Otamendi JE, Ducea MN, Tibaldi AM, Bergantz GW, de la Rosa JD, Vujovich GI. 2009. Generation of tonalitic and dioritic magmas by coupled partial melting of gabbroic and metasedimentary rocks within the deep crust of the Famatinian magmatic arc, Argentina. *J. Petrol.* 50:841–73

Paterson SR, Fowler TK. 1993. Reexamining pluton emplacement processes. *J. Struct. Geol.* 15:191–206

Paterson SR, Okaya D, Memeti V, Economos R, Miller RB. 2011. Magma addition and flux calculations of incrementally constructed magma chambers in continental margin arcs: combined field, geochronologic, and thermal modeling studies. *Geosphere* 7:1439–68

Pearce JA, Peate DW. 1995. Tectonic implications of the composition of volcanic arc magmas. *Annu. Rev. Earth Planet. Sci.* 23:251–86

Pickett DA, Saleeby JB. 1993. Thermobarometric constraints on the depth of exposure and conditions of plutonism and metamorphism at deep levels of the Sierra Nevada batholith, Tehachapi Mountains, California. *J. Geophys. Res.* 98:609–29

Pitcher WS. 1993. *The Nature and Origin of Granite*. London: Chapman & Hall

Plank T, Langmuir CH. 1998. The chemical composition of subducting sediment and its consequences for the crust and mantle. *Chem. Geol.* 145:325–94

Ramos FC, Tepley FJ. 2008. Inter- and intracrystalline isotopic disequilibria: techniques and applications. *Rev. Mineral. Geochem.* 69:403–43

Ramos VA. 2008. The basement of the Central Andes: the Arequipa and related terranes. *Annu. Rev. Earth Planet. Sci.* 36:289–324

Rapp RP, Watson EB. 1995. Dehydration melting of metabasalt at 8–32 kbar: implications for continental growth and crust-mantle recycling. *J. Petrol.* 36:891–931

Rodriguez-Vargas A, Koester E, Mallmann G, Conceição RV, Kawashita K, Weber MBI. 2005. Mantle diversity beneath the Colombian Andes, Northern Volcanic Zone: constraints from Sr and Nd isotopes. *Lithos* 82:471–84

Rossel P, Oliveros V, Ducea MN, Charrier R, Scaillet S, et al. 2013. The Early Andean subduction system as an analog to island arcs: evidence from across-arc geochemical variations in northern Chile. *Lithos* 179:211–30

Rudnick RL. 1995. Making continental crust. *Nature* 378:571–78

Rudnick RL, Gao S. 2003. Composition of the continental crust. In *Treatise on Geochemistry*, Vol. 3: *The Crust*, ed. RL Rudnick, pp. 1–64. Oxford, UK: Pergamon

Ruprecht P, Bergantz GW, Cooper KM, Hildreth W. 2012. The crustal magma storage system of Volcán Quizapu, Chile, and the effects of magma mixing on magma diversity. *J. Petrol.* 53:801–40

Saleeby JB. 1983. Accretionary tectonics of the North American Cordillera. *Annu. Rev. Earth Planet. Sci.* 15:45–73

Saleeby JB. 1990. Progress in tectonic and petrogenetic studies in an exposed cross-section of young (∼100 Ma) continental crust, southern Sierra Nevada, California. In *Exposed Cross Sections of the Continental Crust*, ed. MH Salisbury, pp. 132–58. Dordrecht, Neth.: D. Reidel

Saleeby JB, Ducea MN, Clemens-Knott D. 2003. Production and loss of high-density batholithic roots. *Tectonics* 22:TC001374

Salisbury MJ, Jicha BR, de Silva SL, Singer BS, Jimenez NC, Ort MH. 2011. $^{40}Ar/^{39}Ar$ chronostratigraphy of Altiplano-Puna volcanic complex ignimbrites reveals the development of a major magmatic province. *Geol. Soc. Am. Bull.* 123:821–24

Schmidt ME, Grunder AL. 2011. Deep mafic roots to arc volcanoes: mafic recharge and differentiation of basaltic andesite at North Sister Volcano, Oregon Cascades. *J. Petrol.* 52:603–41

Searle M. 2013. Crustal melting, ductile flow, and deformation in mountain belts: cause and effect relationships. *Lithosphere* 5:547–54

Sillitoe RH. 1997. Characteristics and controls of the largest porphyry copper-gold and epithermal gold deposits in the circum-Pacific region. *Aust. J. Earth Sci.* 44:373–88

Stern CR. 2011. Subduction erosion: rates, mechanisms, and its role in arc magmatism, and the evolution of the continental crust and mantle. *Gondwana Res.* 20:284–308

Stern CR, Kilian R. 1996. Role of the subducted slab, mantle wedge and continental crust in the generation of adakite from the Andean Austral Volcanic Zone. *Contrib. Mineral. Petrol.* 23:263–81

Stern RJ. 2002. Subduction zones. *Rev. Geophys.* 40:4

Taylor SR, McLennan SM. 1985. *The Continental Crust: Its Composition and Evolution*. Oxford, UK: Blackwell

Thouret JC, Wörner G, Gunnell Y, Singer B, Zhang X, Souriot T. 2007. Geochronologic and stratigraphic constraints on canyon incision and Miocene uplift of the Central Andes in Peru. *Earth Planet. Sci. Lett.* 263:151–66

Tibaldi A, Otamendi JE, Cristofolini EA, Baliani I, Walker BA, Bergantz GW. 2013. Reconstruction of the Early Ordovician Famatinian arc through thermobarometry in lower and middle crustal exposures, Sierra de Valle Fértil, Argentina. *Tectonophysics* 589:151–66

von Huene R, Scholl DW. 1991. Observations at convergent margins concerning sediment subduction, subduction erosion, and the growth of continental-crust. *Rev. Geophys.* 29:279–316

Wallace GS, Bergantz GW. 2005. Rationalizing heterogeneity in crystal zoning data: an application of shared characteristic diagrams at Chaos Crags, Lassen volcanic center, California. *Contrib. Mineral. Petrol.* 149:98–112

Weaver BL, Tarney J. 1984. Empirical approach to estimating the composition of the continental crust. *Nature* 310:575–77

Wegner W, Wörner G, Harmon RS, Jicha BR. 2011. Magmatic history and evolution of the Central American Land Bridge in Panama since Cretaceous times. *Geol. Soc. Am.* 123:703–24

Wetmore PH, Ducea MN. 2011. Geochemical evidence of a near-surface history for the source rocks of the central Coast Mountains batholith, British Columbia. *Int. Geol. Rev.* 53. doi: 10.1080/00206810903028219

Wolf MB, Wyllie PJ. 1994. Dehydration-melting of amphibolite at 10 kbar: the effects of temperature and time. *Contrib. Mineral. Petrol.* 115:369–83

Zak J, Paterson SR, Memeti V. 2007. Four magmatic fabrics in the Tuolumne batholith, central Sierra Nevada, California (USA): implications for interpreting fabric patterns in plutons and evolution of magma chambers in the upper crust. *Geol. Soc. Am. Bull.* 119:184–201

Zandt G, Gilbert H, Owens TJ, Ducea MN, Saleeby JB, Jones CH. 2004. Active foundering of a continental arc root beneath the southern Sierra Nevada in California. *Nature* 431:41–46

Zeng LS, Saleeby JB, Ducea MN. 2005. Geochemical characteristics of crustal anatexis during the formation of migmatite at the Southern Sierra Nevada, California. *Contrib. Mineral. Petrol.* 150:386–402

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