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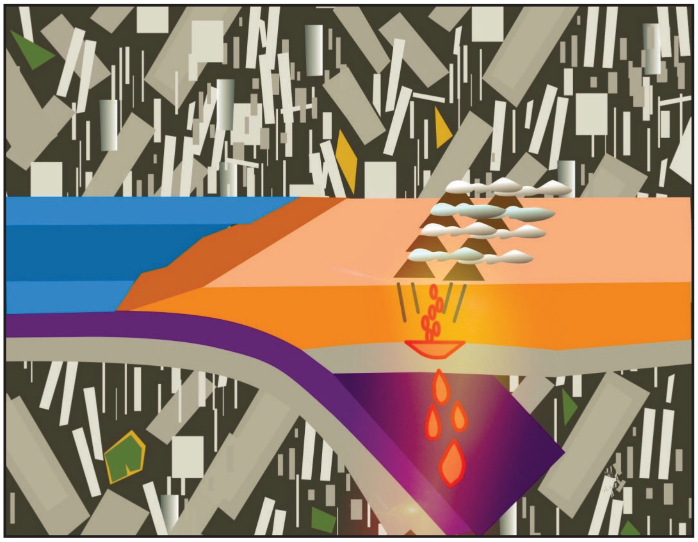

Igneous Rock Associations 25. Pre-Pliocene Andean Magmatism in Chile

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SUMMARY
Andean-type magmatism and the term 'andesite' are often used as the norm for the results of subduction of oceanic lithosphere under a continent, and the typical rock formed. Although the Andes chain occupies the whole western margin of South America, the most comprehensively studied rocks occur in the present-day Chilean territory and are the focus of this paper. Andean magmatism in this region developed from the Rhaetian-Hettangian boundary (ca. 200 Ma) to the present and represents the activity of a long-lived continental magmatic arc. This paper discusses Pre-Pleistocene volcanic, plutonic, and volcano-sedimentary rocks related to the arc that cover most of the continental mass of Chile (between the Pacific coast and the High Andes) between the latitudes of 18° and 50°S. They comprise most of the range of sub-alkaline igneous rocks, from gabbro to monzogranite and from basalt to rhyolite, but are dominated by the tonalite-granodiorite and andesite example members. Variations in the petrographic characteristics, major and trace element composition and isotopic signature of the igneous rocks can be correlated to changes in the physical parameters of the subduction zone, such as dip angle of the subducting slab, convergence rate and angle of convergence. Early Andean magmatic products (Jurassic to Early Cretaceous) are found along the Coastal Cordillera in the westernmost part of the Andes. The rock record of the subsequent stages (Late Cretaceous, Paleocene–Early Eocene, Middle Eocene–Oligocene, Miocene) is progressively shifted to the east, reflecting migration of the magmatic front towards the continent. Tectonic segmentation of the convergent margin, as attested by the magmatic record, may have occurred throughout the Andean life span but it is particularly evident from the Eocene onwards, where the evolution of the northern part of the Chilean Andes (north of 27°S latitude) is very different to that of the southern segment (south of 27°S latitude).

RÉSUMÉ
Le magmatisme de type andin et le terme « andésite » sont souvent les appellations utilisées pour décrire les résultats de la subduction de la lithosphère océanique sous un continent, et la roche typique formée. Bien que la chaîne des Andes occupe toute la marge ouest de l'Amérique du Sud, les roches les plus étudiées se trouvent dans le territoire chilien actuel et sont l'objet de cet article. Le magmatisme andin dans cette région s'est développé depuis la limite rhéto-hettangienne (environ 200 Ma) jusqu'à aujourd'hui et représente l'activité d'un arc magmatique continental persistant. Cet article a pour sujet les roches volcaniques, plutoniques et volcano-sédimentaires du pré-Pléistocène liées à l'arc qui couvrent la majeure partie de la masse continentale du Chili (entre la côte du Pacifique et les Hautes Andes) entre les latitudes de 18° et 50°S. Elles com-

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prennent la majeure partie de la gamme de roches ignées sous-alcalines, du gabbro à la monzogranite et du basalte à la rhyolite, mais sont dominées par des roches de type tonalite-granodiorite et andésite. Les variations des caractéristiques pétrographiques, de la composition des éléments majeurs et traces et de la signature isotopique des roches ignées peuvent être corrélées aux changements des paramètres physiques de la zone de subduction, tels que l'angle de pendage de la plaque plongeante, le taux de convergence et l'angle de convergence. Les premiers produits magmatiques andins (du Jurassique au Crétacé inférieur) se trouvent le long de la Cordillère de la Côte dans la partie la plus occidentale des Andes. La succession de roche des stades suivants (Crétacé supérieur, Paléocène – Éocène inférieur, Éocène moyen – Oligocène, Miocène) est progressivement déplacée vers l'est, reflétant la migration du front magmatique vers le continent. La segmentation tectonique de la marge convergente, comme l'attestent les enregistrements magmatiques, peut avoir eu lieu tout au long de la formation des Andes, mais elle est particulièrement évidente à partir de l'Éocène, où l'évolution de la partie septentrionale des Andes chiliennes (au nord de 27°S de latitude) est très différente de celle du segment méridional (sud de 27°S de latitude).

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INTRODUCTION

Andean magmatism is a general term referring to the plutonic, volcanic, and volcano-sedimentary rocks cropping out in the western border of the South American plate, spanning activity from ~200 Ma to the present day. As the modern volcanism in the Andean chain, these rocks are thought to represent the products of the long-lived subduction-related magmatism that is still active. A most remarkable product of Andean magmatism is 'andesite' (see for example Darwin 1844), an intermediate SiO_2–alkali content volcanic and subvolcanic lithology that commonly exhibits porphyritic texture, bearing quite large phenocrysts of plagioclase or clinopyroxene or amphibole, embedded in an intersertal groundmass, with glass, plagioclase microlites and titanomagnetite. Andesite can be found in other tectonic environments in our planet but is ubiquitous in areas where subduction magmatism is developed (e.g. Gill 1981). It is formed in continental arcs by the combination of processes such as fractional crystallization and the assimilation of crustal material by ascending, depleted mantle-derived basaltic melts. Therefore, Andean magmatism is basically the result of an active subduction of oceanic lithosphere under a continental edge that has transiently recycled variable amounts of the continent itself, mixing crust with juvenile melts from the asthenosphere below the South American subcontinental lithosphere (e.g. Pichler and Zeil 1971; Dostal et al. 1977; Zentilli and Dostal 1977; Hickey et al. 1986; Hildreth and Moorbath 1988; Stern 1991; Tormey et al. 1991; Wörner et al. 1992; Kay et al. 2005).

Even though subduction has remained active during this 200 million year time span (Mpodozis and Ramos 1989), the physical parameters controlling the plate convergence, such as the dip angle of the subducted slab, or the relative velocities of the Phoenix/Farallon/Nazca and South American plates, have changed through time (Pardo-Casas and Molnar 1987; Scheuber et al. 1994; Somoza 1998; Seton et al. 2012). The geological record can be used to track those changes back in time by means of: 1) the deformation of the upper crust through brittle and ductile structures that acted as lithospheric channels of magmatic and hydrothermal flux (e.g. the Atacama and Domeyko Fault systems, Fig. 1); 2) the chemical composition of the magmatic products themselves (and any by-products, such as mineral deposits) and their emplacement (or eruptive) mechanisms; and 3) the timing, volumetric fluxes and location of the magmatism during the 200 M.y. time span.

Although the Andes extend from Venezuela to the southern tip of Chile, in this review we summarize the different stages, in time and space, of the Andean magmatism restricted to the territory of Chile (present day 18°–40°S and 69°–71°W), focusing herein on the variation of the subduction conditions that led to significant changes in magma composition, volume and foci. Other aspects such as the structural framework of the arc magmatism or the associated mineral deposits are important but beyond the scope of the present review. The starting point is the Rhaetian–Hettangian boundary, the time span for the emplacement of the oldest rocks assigned to the activity of the Andean arc in several locations along the present-day Coastal Cordillera of Chile (18°–40°S) (Dallmeyer et al. 1996; Grocott and Taylor 2002; Sepúlveda et al. 2014). The Andean igneous rocks with ages up until the Hauterivian are largely exposed in this morphotectonic unit (Fig. 1). Subsequently, the position of the magmatic front has migrated eastwards as the trench advanced over the continent (Farrar et al. 1970; Levi et al. 1973; Dostal et al. 1977; Ramos and Aleman 2000), and as parts of the latter were removed through subduction erosion (Rutland 1971; Schweller et al. 1981). Hence, Late Cretaceous igneous units are preferentially located in the Central Depression or Pre-Cordillera, whereas younger igneous rocks are principally found from the Domeyko of the Pre-Cordillera to the east (Fig. 1). Names and characteristic of units for each described period are listed in Table 1.

This paper takes advantage of accessibility to databases for Chilean rocks only but does not deal with post-Miocene volcanism. Volcanic rocks in adjacent Bolivia and Argentina and Pleistocene to Recent volcanism have been treated comprehensively in Stern (2004), Wörner et al. (2018), de Silva and Kay (2018) and the literature cited within.

REGIONAL SETTING

The Pre-Andean Basement

The southern South American Plate was built mainly during the Phanerozoic, after the break-up of Rodinia that led to the formation of the Gondwana supercontinent, with a southwestern border mainly formed by the Rio de la Plata Craton and the Brazilian Shield (Cawood 2005; Bahlburg et al. 2009). Whereas the eastern side of the proto-South American plate has been either inland or a passive margin, its western side has intermittently been a convergent margin at least since the Edi-

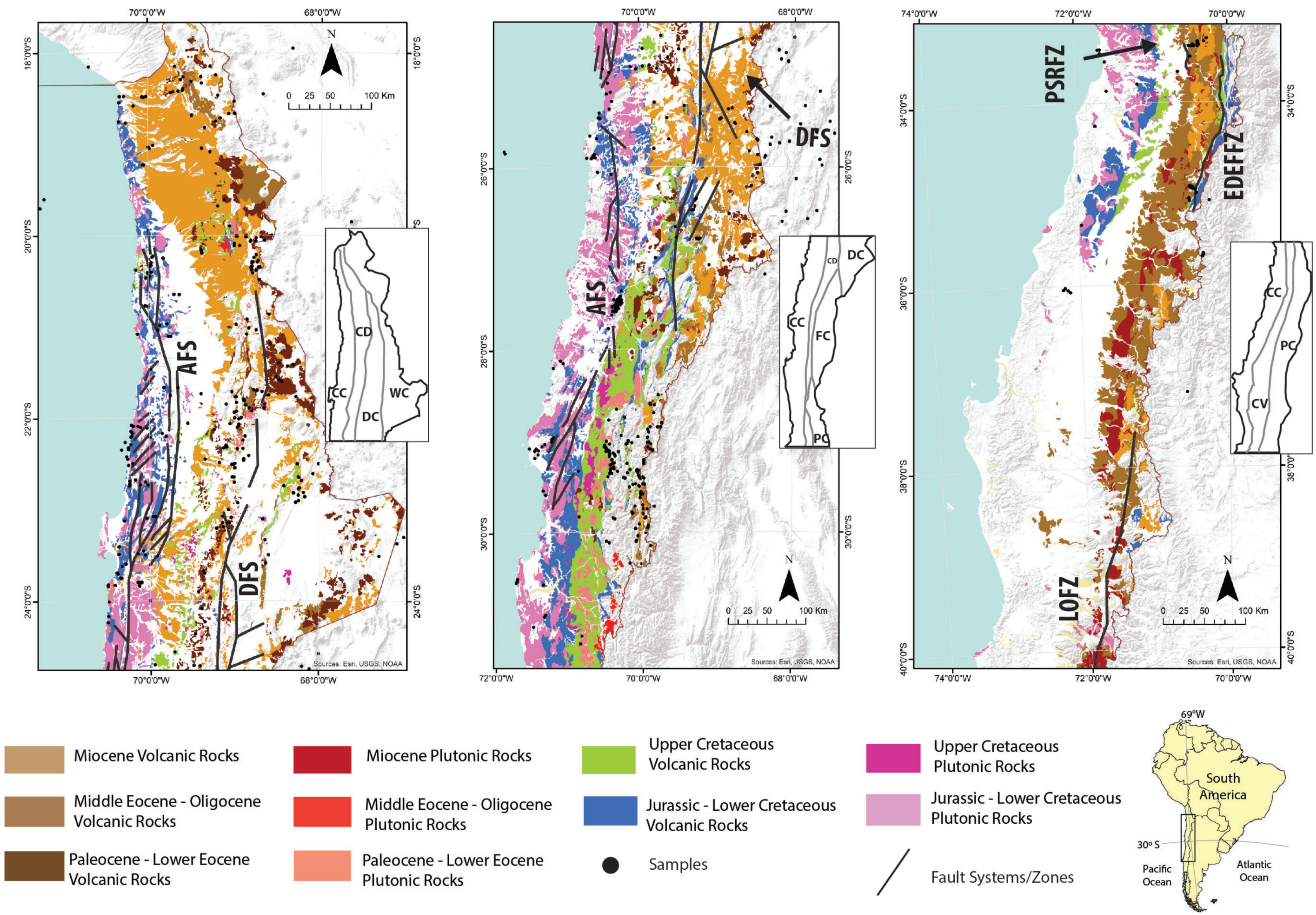

Figure 1. Simplified geological map of the Chilean territory between 18°30' and 40°S latitude, showing the distribution of Andean magmatism from the Jurassic to the Miocene (SERNAGEOMIN 2002), the main fault systems related to the Andean arc (González and Carrizo 2003; Lange et al. 2008; Niemeyer and Urrutia 2009; Armijo et al. 2010; Piquer et al. 2010). AFS: Atacama Fault System, DFS: Cordillera Domeyko Fault System, PSRFZ: Pocuro-San Ramón Fault Zone, EDEFFZ: El Diablo-El Fierro Fault Zone; LOFZ: Liquiñe-Ofqui Fault Zone Inset: main morphotectonic units in Chile, CC: Coastal Cordillera (or Coastal Range), CD: Central Depression, WC: Western Cordillera (also named "Principal Cordillera" or "High Andes", between 22° and 24°S it includes the Altiplano), DC: Domeyko Cordillera (also named "Precordillera", FC: Frontal Cordillera, PC: Principal Cordillera, CV: Central Valley.

Table 1. Names, main lithologies, ages and associated ore deposits (Maksaev 2001) for each described period of Andean magmatism.

	Units	Main Lithologies	Related Ore Deposits*	Age Range
Early Andean Magmatism	Sierra Laguna Beds, Agua Chica Fm, La Negra Fm, Cifuncho Fm, Pichidangui Fm	Basaltic andesite, Andesite		Rhaetian-Toarcian
	Oficina Viz Fm, La Negra Fm, Camaraca Fm, Los Tarros Fm, Punta Barranco Fm, Punta del Cobre Fm, Aeropuerto Fm, Agua Salada Volcanic Complex, Arqueros Fm, Ajial Fm, Veta Negra Fm	Andesite	Stratabound Cu–Ag, IOCG, Magenite-Apatite	Aalenian-Aptian
	Morro Mejillones Tonalite, Algodones Granite, Carrizal Bajo Plutonic Complex, Talinay Plutonic Complex, Cobquecura Pluton, Hualpén Pluton	Tonalite, Granodiorite		212–200 Ma
	Coastal Batholith	Diorite, Tonalite, Granodiorite	IOCG, Magnetite-Apatite	200–145 Ma
	Coastal Batholith	Tonalite, Granodiorite	IOCG, Skarn	145–100 Ma
Late Cretaceous	Suca Fm, Pachica Fm, Cerro Empexa Fm, Cerro Cortina Fm, Quebrada Mala Fm, Paradero del Desierto/Los Trigos Fm, Cerro Azabache Fm, Llanta Fm, Cerrillos Fm, Hornitos Fm, Viñita Fm, Los Elquinos Fm, Salamanca Fm, Lo Valle Fm, Plan de los Yeuques Fm	Andesite, Dacite minor rhyolite; locally basaltic andesite	Epithermal Au–Cu, Porphyry Cu	Albian-Maastrichtian
	Sierra Buitre Batholith, Illapel Plutonic Complex, Caleu Pluton, minor plutonic bodies	Granodiorite, Granite	Porphyry Cu–Au	100–65 Ma
Paleocene–Eocene	Icanche Fm, Chincado Fm, Calama Fm, Augusta Victoria Fm, Chile-Alemania Fm, Venado Fm, Estero Cenicero Fm	Dacite, Rhyolite Andesite	Porphyry Cu–Mo Epithermal Au–Cu	Danian-Lutetian
	Columtucsa-Japu, El Bosque, Loma Colorada, Cuarto Chinchillero, Encanto, and Cuncumén granites. Minor porphyry plutonic bodies	Granite, Granodiorite	Porphyry Cu–Mo	65–42 Ma
Up Eocene–Lw Miocene	North of 28°S: subvolcanic and caldera-type deposits	Dacite, Rhyolite	Porphyry Cu–Mo	Bartonian-Aquitanian
	South of 28°S: Abanico Fm, Cura-Mallín Fm	Basaltic andesite, Basalt		
	Shallow intrusive complexes and porphyries	Granodiorite, Granite	Porphyry Cu–Mo	42–21 Ma
Miocene	North of 27°S: Ignimbrites Oxaya, Lupica, Altos de Pica (Fm), Tambillo, Río Frío, Lauca , Collacagua, La Pacana, Toconao, Atana, Tucúraro, Patao, Cajón Tuyajto, Llano Las Vicuñas, Inés Chica, Los Cristales, San Andrés, Wheelwright, Laguna Verde. San Bartolo Group	Rhyolite, Dacite	Epithermal Au–Ag Porphyry Au	Burdigalian-Messinian
	South of 28°S: Farellones Fm (and equivalents)	Andesite	Porphyry Cu–Mo	
	Shallow intrusives	Granodiorite, Granite	Porphyry Cu–Mo	21–5 Ma

*IOCG: iron oxide–copper–gold deposits, Cu: copper, Au: gold, Ag: silver, Mo: molybdenum acaran–Cambrian boundary, following the Pampean Orogeny (Rapela et al. 1998; Escayola et al. 2007; Schwartz et al. 2008). Growth of the continent, however, was not only due to crust generation at its western side, because Mesoproterozoic basement exotic terranes would have amalgamated during the Grenville-age Sunsas Orogeny (Tosdal 1996; Lowey et al. 2004), Ediacaran–Cambrian (Rapela et al. 1998; Escayola et al. 2007), Ordovician (Ramos 1988), Devonian (Ramos 1988) and Permian periods (Ramos 2008b), allowing the continental mass to expand to the west and south. The Pampean (Cambrian) and Famatinian (Ordovician) arcs would have built a western belt of South American continental crust (Rapela et al. 1998; Otamendi et al. 2012), over the Grenville-derived Mesoproterozoic Arequipa massif and at the edges of the Precambrian Sunsás Orogen and Río de la Plata Craton (see Ramos 2008a and references therein). The activity of the Famatinian arc would have ended with the collision of the Cuyania terrane (Ramos et al. 1986), adding a part of Laurentia to the South American plate (Thomas and Astini 2003). The accretion of the Chilenia terrane just to the west of Cuyania would have taken place during the Devonian (Ramos et al. 1986) and later on, during the Carboniferous, subduction resumed at the edge of the continent (Mpodozis and Ramos 1989).

The Gondwana Cycle and Pre-Andean Stage

Carboniferous subduction led to the formation of an orogenic front known as the Gondwana orogenic cycle of the proto-Andes side of South America, which was characterized by intense magmatic activity of a continental arc and the development of an accretionary prism at the western border of the forearc crust (Mpodozis and Ramos 1989; Llambías et al. 1993). The orogeny reached its maximum with the 'San Rafael phase" at the end of the Permian (Llambías and Sato 1990; Tomezzoli and Japas 2006; Kleiman and Japas 2009). Also, during the Carboniferous–Permian, at the southern end of the continent, the Patagonia terrane would have accreted to the edge of Gondwana, giving the South American plate its final configuration (Ramos 2008; Ramos and Naipauer 2014). The precise timing for this collision is still debated (Chernicoff et al 2013; Pankhurst et al. 2014; Castillo et al. 2017).

By the end of the San Rafael phase the orogen started to collapse and a period of continental extension and rifting took place for ca. 50 M.y., from the Late Permian to the Late Triassic (Kleiman and Japas 2009). This particular tectonic scenario is known as the 'Pre-Andean' cycle and has been traditionally interpreted as a period of arrested subduction and extensive crustal reworking and anatexis, due to basalt underplating at the base of the thinned lithosphere (Mpodozis and Kay 1992; Llambías and Sato 1995). More recently though, several authors have questioned this model in light of new geochemical, petrological, geochronological and geological data, arguing that subduction may have persisted throughout the Late Paleozoic and the Mesozoic, making southwestern Gondwana a long-lived convergent margin (del Rey et al. 2016; Coloma et al. 2017; González et al. 2018; Oliveros et al. 2020). Recent global reconstructions also support the idea of an active subduction zone for western Pangea and Gondwana since the Carboniferous (Matthews et al. 2016; Riel et al. 2018). Regardless of the precise tectonic setting in the continent's margin prior to the initiation of the Andean magmatism, it is widely accepted that the crust underwent significant extension and thinning at the moment when the arc started its activity (Mpodozis and Kay 1992; Kleiman and Japas 2009). In addition to that, by the Rhaetian–Hettangian times the intense latitudinal drift to which the South American continental masses were subjected to during the Late Carboniferous to Late Triassic times ended, and the Andean margin acquired its present position toward the Early Jurassic (Torsvik and Cocks 2013). New data suggest that, at least during the latest Triassic, magma generation conditions in northern Chile were indistinguishable from those in the Eocene, but very different from that of the Jurassic (Zentilli et al. 2018).

EARLY ANDEAN MAGMATISM (200–100 Ma)

All along the Coastal Cordillera of northern Chile between 18°S and 40°S latitudes, discrete outcrops of metamorphic and epimetamorphic rocks are exposed (Hervé et al. 2007). In some locations, these constitute a metamorphic paired belt of low-temperature/high-pressure metasedimentary and metaigneous rocks to the west and high-temperature/low-pressure metasedimentary rocks to the east. They have been interpreted as the remnants of a Late Paleozoic (Devonian to Permian) accretionary prism (Hervé 1988). It was over this thinned crust at the very edge of the continent that the earliest Andean arc became emplaced at ca. 200 Ma, a geological setting known as the "First Stage of the Andean Tectonic Cycle" (*sensu* Charrier et al. 2007). Rhaetian to Toarcian volcanic units such as the La Negra, Agua Chica, Cifuncho and Pichidangui formations, Sierra de Lagunas beds in Chile, and the Chocolate Formation in southern Peru, and intrusive units such as the Morro Mejillones tonalite, the Algodones Granite, Carrizal Bajo Plutonic Complex, Talinay Plutonic Complex, Cobquecura Pluton and the Hualpén Pluton (Table 1) may represent the first magmatic pulses of the arc. Most of them were emplaced nearby or directly over metasedimentary sequences (Oliveros et al. 2018). These units were followed by intense magmatic activity recorded in the Los Tarros, Camaraca, Oficina Viz, La Negra, Punta del Cobre, Bandurrias, Aeropuerto, Punta Barranco, Ajial, Horqueta, Arqueros, Quebrada Marquesa, Veta Negra and Las Chilcas formations, and in several plutonic complexes (Vergara et al. 1995; Marschik and Fontboté 2001; Morata and Aguirre 2003; Kramer et al. 2005; Lucassen et al. 2006; Oliveros et al. 2006, 2007). The outcrops of Early Andean volcanic rocks comprise thick homoclinal sequences of porphyritic lava flows bearing large plagioclase and pyroxene phenocrysts and ubiquitous titanomagnetite (they have been traditionally named 'ocoita' for the locality Ocoa in central Chile). Epiclastic or siliciclastic sandstone, siltstone, and minor conglomerate and, in some localities, shallow marine limestone and related rocks, are intercalated with the volcanic flows. The base of the sequences, or the oldest units, may have pyroclastic rocks and even caldera-like deposits, suggesting a more volatile-rich style of magmatism at the start of the arc's activity (Vásquez et al. 2018). Other than that, deposits representing explosive magmatism are not the most common type among the early phases of Andean magmatism (Oliveros et al. 2018). The outcrops of the Early Andean plutonic rocks form an 800–2000 m altitude mountain range known as the Coastal Batholith (Fig. 1). Between latitudes 16° and 33°S, the Coastal Batholith is composed almost exclusively of Mesozoic intrusions, whereas south of 33°S the Paleozoic plutons of the Gondwana cycle become the largest exposed units (Fig. 1). The Mesozoic (200–100 Ma) intrusions are medium-grained and have ubiquitous plagioclase, biotite, amphibole, quartz and titanomagnetite; less common are pyroxene, alkali feldspar, apatite and titanite. The largest plutonic bodies have tabular shapes (resembling large sills), with the traditionally depicted vertical dyke-like bodies, showing evidence of incremental growth through extensional stress in the crust controlled by major faults (Grocott et al. 2009). Fine grained stocks also crop out and intrude both the volcanic and plutonic rocks, whereas epizonal porphyritic stocks are very rare; less differentiated microphaneritic to porphyritic dykes crosscut the volcanic sequences and, along with the aforementioned stocks, have been interpreted as feeders to the volcanism (Oliveros et al. 2006). Typical ore deposits of this Andean stage are the stratabound 'Manto' type copper, silver deposits and iron oxide–copper–gold (IOCG) types deposits, hosted mainly in the homoclinal volcano-sedimentary sequences and associated stocks and small intrusive units, with a distinct low-S/Fe type of mineralization (e.g. Boric et al. 2002; Sillitoe 2003).

According to regional and global plate reconstructions, the Phoenix Plate had a strongly oblique convergence against the South American plate from the Triassic–Jurassic boundary until at least its break-up into the Chasca and Cataquil plates, and later evolution to the Farallon/Aluk plates (Zonenshayn et al. 1984; Matthews et al. 2016). This resulted in a partition of the stresses, with arc-normal extension and arc-parallel sinistral transtension (Grocott and Taylor 2002) that dominated upper crustal deformation along the precursors of the Atacama Fault System (AFS), a paleo-trench parallel structure now exposed along 1000 km, in northern Chile (Fig. 1). Magmatic activity was then concentrated in intra-arc basins, located at sea level or slightly above, bounded to the east by marine back-arc or marginal basins with little volcanic activity (now exposed in the Central Depression and Domeyko and Frontal Cordilleras) (Rossel et al. 2013; Espinoza et al. 2019). The emplacement of the Jurassic to Early Cretaceous plutonic complexes is tightly related to the present-day traits of the AFS (Scheuber and González 1999; Cembrano et al. 2005); several mylonitic zones are developed along the interface of plutonic bodies and specific branches of the AFS, which acted as the footwalls or channels of magmatic flux (Cembrano et al. 2005). On the other hand, the intra-arc basins in which the volcanic flows and sediment were deposited, do not seem to have been controlled by the AFS as no spatial or temporal link has yet been observed, except for some Early Cretaceous depocentres in northernmost Chile (~21°S latitude, Vásquez et al. 2018).

The fact that the arc's foundation was upon a rather young crystalline basement at this time and that extensional tectonics prevailed, may have strongly influenced the composition of Early Andean magmatism, since the melts derived from the flux-induced melting of the asthenospheric wedge under the thin lithosphere did not stall at the base of the crust nor exchange material with it (Lucassen et al. 2006). Thus, the geochemical signature of the first pulses of Andean magmatism reflect primarily a mantle source and only limited crustal assimilation (Kramer et al. 2005; Lucassen et al. 2006; Rossel et al. 2013). This can be inferred from the low–intermediate SiO_2 content of both volcanic and plutonic rocks spanning 200 to 140 Ma (Fig. 2a), along with low Sr/Y and La/Yb and relatively high Eu/Eu* (Oliveros et al. 2018) (Fig. 2g, h) retained in these units.

Jurassic volcanic rocks are mainly basaltic andesite to andesite, with less significant amounts of basalt, and scarce rhyolite and dacite; younger volcanic rocks (140–100 Ma) are more differentiated, with andesite as the dominant lithology followed by dacite and rhyolite (Marschik and Fontboté 2001; Oliveros et al. 2006). By contrast the 200–100 Ma intrusive bodies have more varied compositions, but with a strong predominance of amphibole and biotite diorite and tonalite (Oliveros et al. 2018). In contrast with their Permian and Triassic counterparts, granite is rare amongst the Early Andean Plutonic complexes, and syenogranite completely absent (Oliveros et al. 2018). Some Norian–Rhaetian intrusive units, however, are monzogranite (e.g. the Algodones, La Estrella and Pichilemu plutons; Vásquez et al. 2011; Coloma et al. 2017). Bimodal plutonic complexes such as the Limarí Complex (Parada et al. 1999) have mafic and intermediate lithologies but also lack granite intrusive compositions. Thermobarometic conditions calculated from minerals in Jurassic and Early Cretaceous plutons suggest middle to upper crust emplacement for the magmas, with ranges of 150 to 400 MPa (González 1999).

Magmatic affinities for Jurassic volcanic and plutonic rocks are dominantly tholeiitic to low-K calc-alkaline (Fig. 2b), and intrusive rocks are mostly metaluminous having affinities to volcanic arc granite (VAG). Lower Cretaceous volcanic rocks may have tholeiitic affinities (particularly the units cropping out in central Chile at ca. 31°–33°S latitude) but the most common trend is that of a medium- to high-K calc-alkaline series. Systematic enrichment in large ion lithophile elements (LILE) relative to high field strength elements (HFSE) is a typical feature of Jurassic to Lower Cretaceous magmatism (Fig. 2c, d), suggesting a rather depleted mantle source that has been preferentially enriched in fluid-mobile elements, such as Rb, Sr and Ba, likely derived from a subducted (and altered) slab or from subducted sedimentary material (Vergara et al. 1995; Marschik and Fonboté 2001; Lucassen et al. 2006). It is widely accepted that by the Jurassic Andean magmatism was chiefly subduction related (Lucassen et al. 2006; Oliveros et al. 2007). Furthermore, the Sr–Nd–Pb isotopic compositions of igneous rocks spanning 200 to 100 Ma, require the combination of two sources, a depleted mantle and a Paleozoic crust, to be explained, which is also a characteristic of continental arc magmatism (Lucassen et al. 2006; Rossel et al. 2013). Even though the Early Andean magmatism is very homogeneous in its petrological and chemical composition, an evolution through time in key chemical parameters has been observed and can be

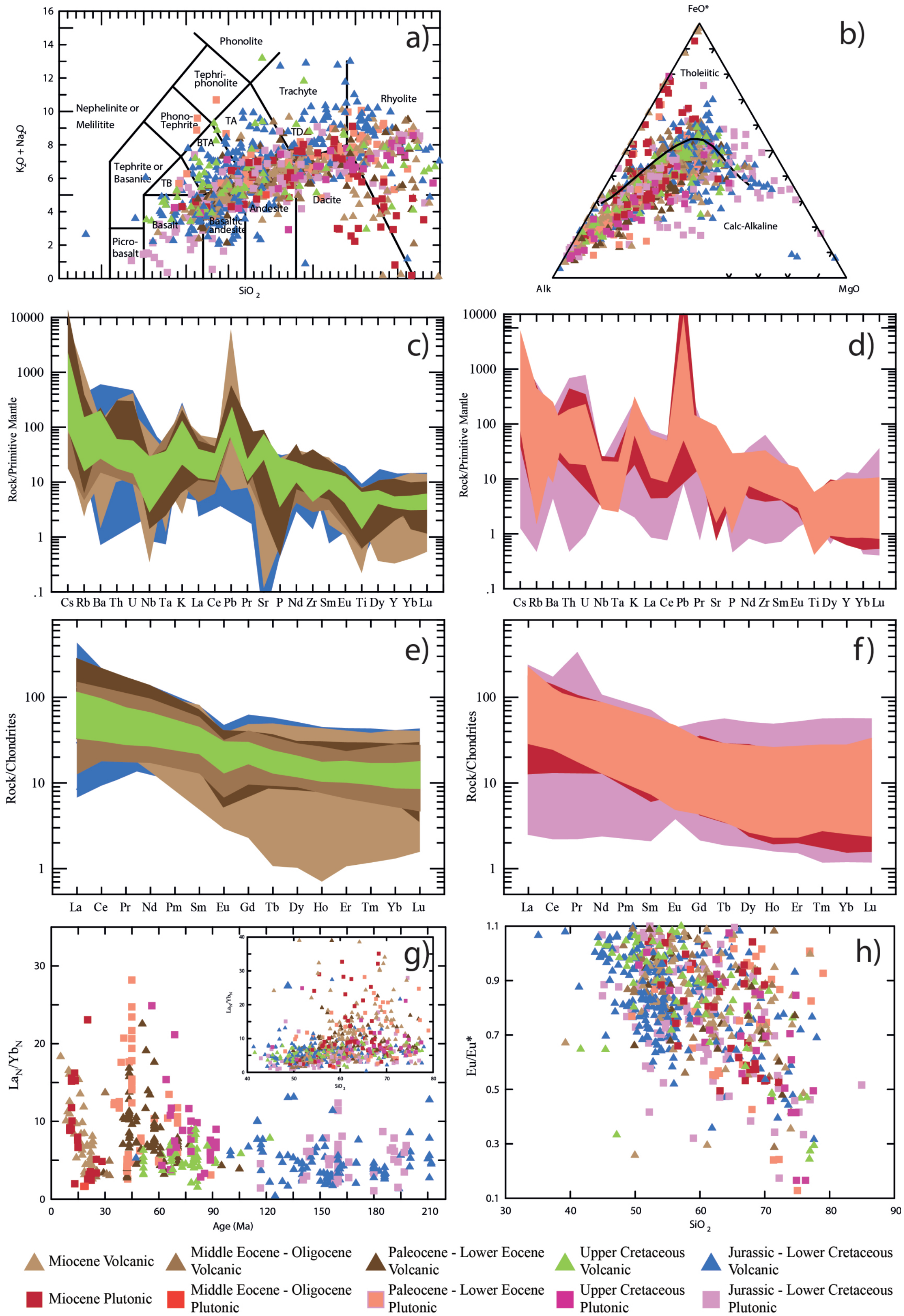

Figure 2. After Irvine and Baragar (1971): a) Total Alkali versus Silica (TAS) diagram, and b) Alkali-FeO*–MgO (AFM) diagram for Andean rocks; Primitive mantle-normalized trace elements composition for Andean: c) volcanic and d) plutonic rocks; Chondrite-normalized REE compositions for Andean rocks: e) volcanic and f) plutonic rocks; g) Chondrite-normalized La/Yb versus age (inset: chondrite-normalized La/Yb versus SiO_2); h) Eu/Eu* (Eu*=Eu/(Sm*Gd)$^{1/2}$) versus age plots. Chondrite and primitive mantle compositions are from Sun and McDonough (1989). Data and references are provided in the supplementary material SMT-1. BTA: basaltic trachyandesite, TA: trachyandesite, TB: trachybasalt, TD: trachydacite.

related to tectonic phases of crustal thickening or compressive deformation. For example, La/Yb and Sr/Y increase with time, suggesting that the depth of magma generation (and hence the thickness of the crust) may have increased from 200 to 100 Ma (Hascke et al. 2006; Mamani et al. 2010). Sr, Nd, Pb isotopic ratios for all plutonic and volcanic rocks between 18° and 31°S latitude exhibit a similar pattern (Fig. 3a, b), increasing $^{87}Sr/^{86}Sr_i$ and decreasing $^{143}Nd/^{144}Nd_i$ (εNd_i) with time, suggesting more involvement of crustal material as the arc evolved towards the present day (Mamani et al. 2010) (Fig. 3c, d). Nonetheless, a reverse pattern is observed for volcanic and plutonic rocks of central Chile, where isotopic ratios for Early Cretaceous units suggest a more depleted mantle source than for the Jurassic igneous rocks. This particular pattern would represent the formation of an ensialic or aborted marginal basin right behind the arc, with extensive crustal thinning during the Barremian to Albian (Vergara et al. 1995) (Fig. 4).

Another prominent characteristic of the Early Andean igneous rocks is the lack of unaltered samples or outcrops. The vast majority of the volcanic or plutonic units studied and described so far exhibit features of either very low to low grade metamorphism (Levi 1969; Losert 1974; Aguirre et al. 1999; Robinson et al. 2004), hydrothermal alteration or metasomatic/deuteric alteration, such as selective replacement of phenocrysts, devitrification, infilled veins and amygdules, or groundmass alteration. Typical secondary mineral assemblages include albite (or more precisely albitized plagioclase, in relation to Ca–Na exchange), quartz, calcite, chlorite–smectite and titanite. Less common secondary minerals are zeolites, celadonite, sericite, clays, adularia and actinolite. Deuteric alter-

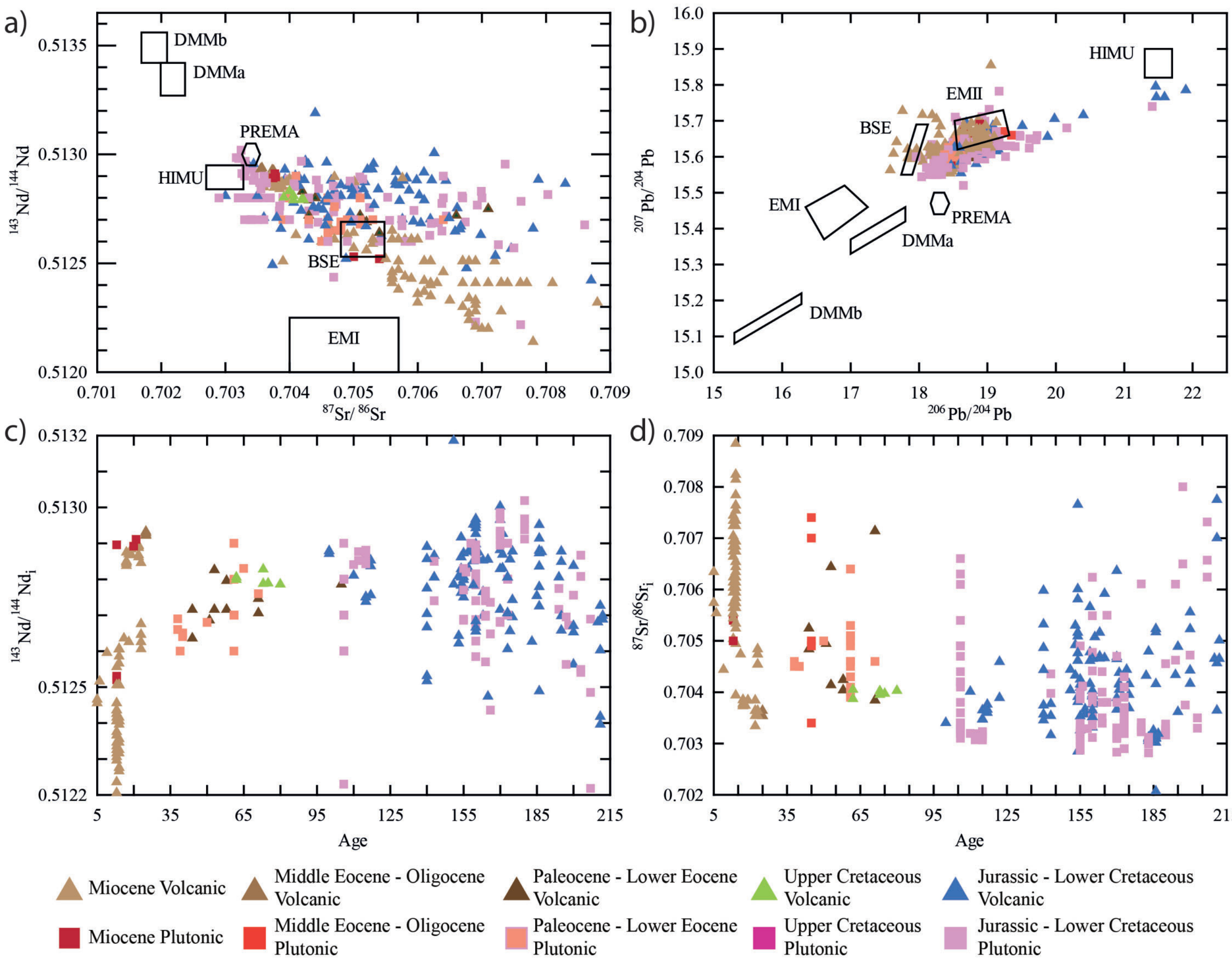

Figure 3. a) $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ and b) $^{206}Pb/^{204}Pb$ versus $^{207}Pb/^{204}Pb$ diagrams for Andean rocks; c) initial $^{143}Nd/^{144}Nd$ and d) initial $^{87}Sr/^{86}Sr$ versus age for Andean rocks. Mantle fields are from Zindler and Hart (1984). DMM: depleted mantle MORB; BSE: bulk silicate Earth; HIMU: high U/Pb mantle; PREMA: prevalent mantle; EM: enriched mantle.

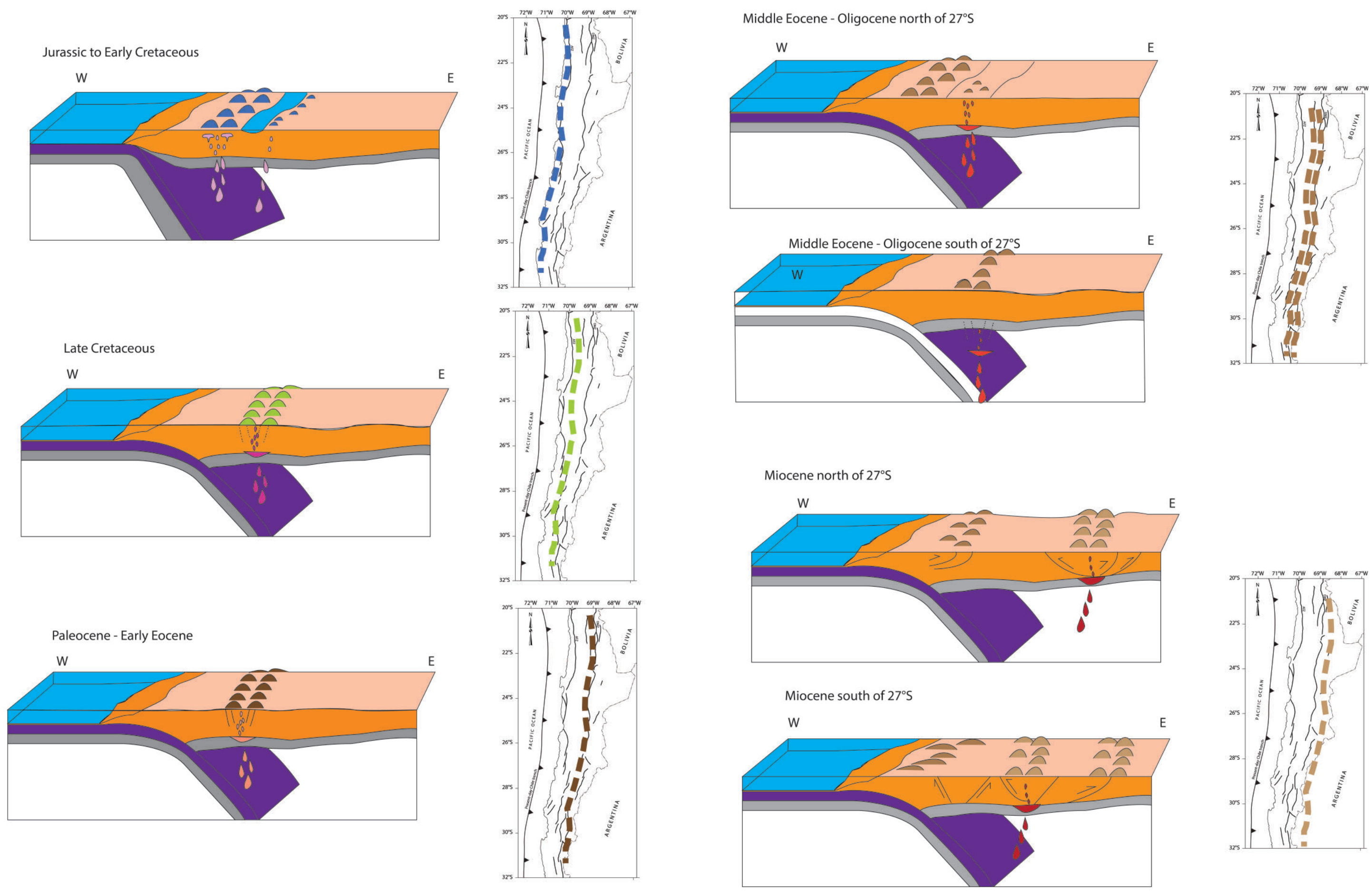

Figure 4. Schematic tectonic setting for Andean magmatism and arc position during the Jurassic–Early Cretaceous, Late Cretaceous, Paleocene–Early Eocene, Middle Eocene–Oligocene north of 27°S latitude, Middle Eocene–Oligocene south of 27°S latitude, Miocene north of 27°S latitude, Miocene south of 27°S latitude.

ation is commonly represented by replacement of either pyroxene or hornblende by pargasite. Independent of the origin of the secondary or late magmatic mineralogy, its ubiquitous occurrence is representative of high fluid flux through the upper crust and elevated thermal gradients (Losert 1974; Aguirre et al. 1999; Robinson et al. 2004), likely due to the magmatic activity of the arc (Fuentes et al. 2004; Robinson et al. 2004; Oliveros et al. 2006, 2007; Rossel et al. 2013).

LATE CRETACEOUS ANDEAN MAGMATISM (100–65 Ma)

The Peruvian Orogeny (ca. 90 Ma) separates the periods of magmatism and tectonic evolution into which the Andean orogenic cycle is subdivided (Coira et al. 1982; Charrier et al. 2007, 2015). The younger period is marked by the construction of a Cordilleran arc orogenic system and a rear arc domain that passed from a back-arc to a foreland basin stage at ~100 Ma (Fig. 4) (Charrier et al. 1996, 2007, 2015; Tunik et al. 2010; Aguirre-Urreta et al. 2011; Fennell et al. 2017). The changes induced by this compressive event can be correlated to the contrasting characteristic of the Late Cretaceous magmatism in comparison to the older arc products. First, igneous rocks younger than 100 Ma are located either in the eastern flank of the Coastal Cordillera or farther east, in the Central Depression or Pre-Cordillera. They represent a voluminous phase of Andean magmatism, although less voluminous than the previous stage (Fig. 1), and their composition, textures and structures are also different from the older rocks. Representative volcanic units of this period are the Suca, Pachica, Cerro Empexa, Cerro Cortina, Quebrada Mala, Paradero del Desierto/Los Trigos, Cerro Azabache, Llanta, Cerrillos, Hornitos, Viñita, Los Elquinos, Salamanca, Lo Valle and Plan de los Yeuques formations (Rivano and Sepúlveda 1991; Iriarte et al. 1996, 1999; Gana and Wall 1997; Emparán and Pineda 1999; Marinovic and García 1999; Tomlinson et al. 1999, 2010; Wall et al. 1999; Cortés 2000; Fuentes et al. 2002; García et al. 2004; Arévalo 2005; Matthews et al. 2006, 2010; Marinovic 2007; Espinoza et al. 2011, 2012; Blanco et al. 2012; Medina et al. 2012; Blanco and Tomlinson 2013; Gardeweg and Sellés 2013; Jara and Charrier 2014; Mosolf et al. 2019; Muñoz et al. 2018). Numerous plutonic bodies are also products of this magmatism, although in general their volume is much smaller than for the Jurassic to Lower Cretaceous intrusions (Fig. 1). Only between 28° and 31°S latitude do large plutonic complexes crop out, such as the Sierra Buitre Batholith or the Illapel Plutonic Complex (Rivano and Sepúlveda 1991; Morata et al. 2010). The dominant petrographic type among the Late Cretaceous plutonic rocks is by far the hypabyssal stocks and porphyries. Chemically, these younger arc products are also distinctive, showing evidence of incipient arc maturation and crustal thickening (Haschke et al. 2002, 2006; Mamani et al. 2010).

Volcanic rocks spanning 100 to 65 Ma in age are mainly porphyritic andesite, including the very large plagioclase phenocryst-bearing lavas known as 'ocoites' (Vergara et al. 1995), to dacite, with minor trachyte, trachyandesite, basaltic andesite, and scarce basalt. Only south of 33°S latitude, do basaltic andesite and basaltic lavas flows and tuff dominate Late Cretaceous volcanic deposits. Primary mineralogy consists of plagioclase, hornblende, pyroxene, titanomagnetite and minor quartz phenocrysts in an intersertal to trachytic groundmass. Pyroclastic rocks are also very common, and include dacitic to rhyolitic, vitric and crystalline tuff, commonly welded and forming ignimbrite deposits, in some cases with fluidal textures, as well as volcanic and epiclastic breccia and minor ashfall deposits. In spite of the more explosive volcanism that took place at this time, the units mostly crop out as homoclinal sequences with intercalations of lava flows and clastic beds. A few caldera-type deposits are known from the Late Cretaceous, such as the Condoriaco or Cerro el Indio dacitic dome and tuff deposits (Emparán and Pineda 1999). All these volcanic units are generally overlying or interbedded with red clastic continental sedimentary rocks of Lower to Upper Cretaceous age that would represent the first stages of foreland sediment accumulation in the Andean range (Charrier et al. 1996, 2007, 2015; Tunik et al. 2010; Aguirre-Urreta et al. 2011; Martínez et al. 2016; Fennell et al. 2017).

The plutonic activity of the Late Cretaceous is represented by numerous fine-grained to porphyritic stocks that range in composition from andesitic or microdioritic to rhyolitic, with a predominance of the more intermediate compositions that bear amphibole, biotite, pyroxene, plagioclase, quartz and titanomagnetite. Larger intrusions are usually medium- to fine-grained ranging from gabbro to syenogranite, with a predominance of monzodiorite to monzogranite. Mafic assemblages are hornblende–biotite, two pyroxenes or biotite; hornblende–pyroxene assemblages are also found but are less common. The Illapel Plutonic Complex is one of the largest units of this period; it is composed of four sub-units: mafic, trondhjemite, tonalite and granodiorite, reflecting a progressive differentiation of the magmatism (Morata et al. 2010; Ferrando et al. 2014). Along with the ca. 95 Ma Caleu pluton in central Chile, the Illapel Plutonic Complex records the transition from an extensional to a compressional tectonic regime and rapid cooling after emplacement (Parada et al. 2005; Ferrando et al. 2014).

Geochemically, the Late Cretaceous igneous rocks have intermediate to high SiO_2 contents of 53–70% (Fig. 2a), and major elements trends that reflect plagioclase, pyroxene, and amphibole fractionation during magma evolution. In terms of trace elements, there is a systematic enrichment of LILE over HFSE (Fig. 2c, d), indicative of slab-derived fluid-induced melting on the sub-arc mantle, whereas specific elements, such as La, Ba, Cs, Rb, Dy, Yb suggest a more significant contribution of crustal material to the magmatism, and amphibole control in the magma source, suggesting an incipient thicker crust above the arc (Haschke et al. 2006; Mamani et al. 2010) (Fig. 2e, f). This is also supported by the isotopic composition of the igneous rocks, which is more radiogenic in terms of initial $^{87}Sr/^{86}Sr$ and $^{208,207,206}Pb/^{204}Pb$ and less radiogenic for initial $^{143}Nd/^{144}Nd$ (εNd_i) (Fig. 3a, b). Thus, the original depleted mantle basaltic melts would have assimilated part of the continental crust. Magmatic affinities are largely medium- to high-K calc-alkaline, with minor low-K or tholeiitic trends (Fig. 2b).

North of 33°S the chemistry of plutonic and volcanic rocks ranging in age from ca. 100 to 65 Ma is interpreted to record products of continental arc-type magmatism under compression (see Parada et al. 2007 and references therein). Recently, Late Cretaceous volcanic units have been identified in the main Cordillera south of 33°S (at these latitudes, only plutonic rocks were recognized in the Chilean side of the Andes, in the Coastal Batholith) (Iannelli et al. 2017; Muñoz et al. 2018). These sequences are mainly composed of basalt and basaltic andesite with tholeiitic to transitional-OIB affinities. They have been interpreted as having been emplaced into an intra-arc basin, related to a sub-arc slab-window, with a dominant extensional tectonic regime at the time (Muñoz et al. 2018), suggesting that not only compressive stresses prevailed during the construction of the Late Cretaceous Andean arc.

PALEOCENE–EARLY/MIDDLE EOCENE ANDEAN MAGMATISM (65–45/40 Ma)

The evolution of the arc in this time frame is characterized by an extensional and transtensional tectonic setting, partly inherited from the previous Mesozoic stage, that ended with the 'Incaic Orogeny' (Charrier et al. 2007). Most of the volcanic and volcanoclastic units of this period unconformably cover the Lower Cretaceous sequences, suggesting that a likely compressive deformation event would have taken place during the Cretaceous to Paleogene transition. Such an event is called the 'K–T' or 'Incaic I' tectonic phase (Charrier et al. 2007). Between 21° and 27°S latitude, the Domeyko fault system (Fig. 1) is tightly related to the emplacement of the magmatic products of the Paleocene to Eocene arc (Fig. 4). South of 27°, the DFS and its relation to the magmatic units is not observed, likely due to the Miocene cover (Charrier et al. 2009).

The magmatic units of this stage are widely distributed from northern Chile (~18°S) to 35°S latitude, where outcrops are lost, and between 37° and 39°S latitude (Charrier et al. 2009). The volcanic products of this period are subalkaline basalt to rhyolite (Fig. 2a); these are mostly related to caldera-type deposits and pervasive hydrothermal alteration. Representative units cropping out at 18–30°S latitude are the Icanche, Chincado, Calama (lower member), Augusta Victoria, Chile-Alemania and Venado formations (García 1967; Chong 1973; Montaño 1976; Maksaev 1978; Sepúlveda and Naranjo 1982; Naranjo and Paskoff 1985). They are composed of andesitic lava flows and proximal pyroclastic deposits, bimodal sequences, high-K calc-alkaline rocks (Fig. 2b), and thick sequences of trachyandesitic to dacitic lava flows, that range in age from ca. 60 to 46 Ma (Marinovic et al. 1995; Blanco et al. 2003; Espinoza et al. 2012; Gardeweg and Sellés 2013). The sedimentary upper member of the Calama Formation hosts imbricated clasts that are interpreted as sediment accumulation due to tectonic reactivation of a meso-scale fault, such as the West Fault in the Chuquicamata mining district (Charrier et al. 2007). Consequently, these units are the precursors of the Eocene–Oligocene arc (Charrier et al. 2007). South of this latitude, the outcrops of Paleocene volcanic units decrease significantly, with the 63 Ma Estero Cenicero Formation the main volcanic sequence (Bergoeing 2016) (Fig. 1). Between 18° and 30°S latitude, the eruptive units are intruded by small stocks and sills of mainly felsic composition, such as the Columtucsa-Japu granitoid units (Gardeweg and Sellés 2013), the El Bosque and Loma Colorada monzogranite plutons (Emparán and Pineda 1999), the Cuarto Chinchillero diorite (Pineda and Emparán 2006) or the Encanto and Cuncumén plutons (Bergoeing 2016), with their ages ranging between 60 and 43 Ma. North of 26°S latitude, the small intrusive bodies of Paleocene and Eocene age are structurally controlled (Charrier et al. 2007, 2009 and references therein). Even though the outcrops of Paleocene–Eocene volcanic rocks decrease significantly south of 30°S, the plutonism was widespread and volumetrically important at these latitudes; the Cogoti Superunit of ca. 67–38 Ma is a good example of this (Parada et al. 1999) (Fig. 1).

Paleocene–Eocene magmatic units are distinctly medium- to high-K calc-alkaline, intermediate to felsic in composition (Fig. 2a, b) and characterized by low Sr/Y and La/Yb (Fig. 2g) that increase for younger sequences, suggesting a progressive deepening of the magmatic sources and consequently crustal thickening towards the Late Eocene (Charrier et al. 2007).

During the Early to Middle Eocene, the Incaic Orogeny (or 'Incaic II' tectonic phase) took place, likely inducing the formation of an 'Incaic Cordillera' (Charrier et al. 2009) some time between 50 and 30 Ma, as suggested by radiometric dating (ca. 38.5–44 Ma, Hammerschmidt et al. 1992; Tomlinson and Blanco 1997). Inversion of Cretaceous to Paleocene structures that controlled the emplacement of the previous arc led to significant crustal thickening (Charrier et al. 2007 and references therein). The uplift of the mountain chain implied high erosion rates and resulted in the accumulation of thick sedimentary sequences (Charrier et al. 2009). The conspicuous decrease of Paleocene–Eocene arc-related outcrops south of 30°S latitude may be due to higher exhumation and uplift during the Incaic Orogeny at these latitudes and increased erosion of the arc rocks. During this orogeny and related to the intrusion of small stocks and porphyries, important metallic ore mineralization developed, generating Cu–Mo porphyry deposits, such as Cerro Colorado, Spence and Lomas Bayas (Sillitoe and Perelló 2005; Mpodozis and Cornejo 2012 and references therein). This metallogenic belt is economically very significant in Peru (39 Mt Cu) but less so in Chile (12.7 Mt Cu) (Camus 2003).

MID EOCENE–EARLY MIOCENE ANDEAN MAGMATISM (45–22 Ma)

The tectonic, and consequently magmatic, evolution of the Andean arc after the Incaic Orogeny is significantly segmented along the Chilean margin. North of 27°S latitude the arc remained in the position of the former stage and a retro arc basin developed to the East (Charrier et al. 2007). Magmatic activity was channeled through trans-lithospheric discontinuities represented by the Domeyko Fault system (Charrier et al. 2009 and references therein) (Figs. 1 and 4). Large epizonal batholiths of granodioritic to granitic composition and shallower porphyry systems were the feeders of a magmatic hydrothermal flux that contributed to the accumulation of huge volumes of S and chalcophile base metals in the upper crust, generating some of the largest Cu–Mo porphyry-type deposits on Earth identified so far (Camus 2003), such as Chuquicamata (35–31 Ma, Charrier et al. 2009), Ministro Hales (35 Ma, Zentilli et al. 2018), El Abra (40 Ma, Ballard et al. 2001). A common feature of these magmatic units is their high Sr/Y (> 40) and La_N/Yb_N (> 40) which is known as the 'adakitic' signature and is thought to be related to either: a) melting of young and hot slabs during subduction (Defant and Drummond 1990); b) melting of newly underplated basaltic crust under a thick crust (Petford and Atherton 1996); c) eclogitization of a thickened lower crust (Kay and Mpodozis 2002); d) melting of the mafic crust tectonically eroded from the continental margin (Goss et al. 2013); e) fractionation from hydrous mafic magmas (garnet residue) at deep crustal levels and high-pressure melting of lower crust (Chiaradia et al. 2012; Rabbia et al. 2017); or f) hydrating of the oceanic slab in fracture zones (Reich et al. 2003), among other factors. These adakitic magmas are commonly associated with large porphyry copper and epithermal gold–copper deposits (Chiaradia et al. 2012), and if linked to garnet residues or eclogitization in the lower crust, they should be a direct result of the Incaic Orogeny.

These shallow intrusive complexes correspond to granodiorite and granite (and subvolcanic equivalents, dacite to rhyolite), with SiO_2 of 65–79 wt.%, and high alkali content. The alkaline affinities, however, may be the result of the intense hydrothermal alteration recorded in the plutonic and subvolcanic rocks (LOI > wt.%). The whole rock REE patterns indicate the absence of an Eu anomaly, suggesting hornblende fractionation in highly oxidized magmas and likely garnet was present during melting of the source (Zentilli et al. 2018) (Fig. 2e, f).

On the other hand, south of 28°S latitude a wide intra-arc extensional basin located east of the Incaic Cordillera, the Abanico basin, was developed (Fig. 4). The estimated dimensions of this basin are at least 1000 km, between present-day 28 and 39°S latitude (Charrier et al. 2005, 2007, 2009; Flynn et al. 2008), 70 km wide and 3 km in thickness, and with representative units the Abanico (Aguire 1960) and Cura Mallín formations (Niemeyer and Muñoz 1983).

The Abanico Formation is a 3100-m-thick sequence of mafic volcanic rocks and felsic pyroclastic and epiclastic deposits, interbedded with lacustrine sediments, and an upper section made of basaltic lava flows (Nyström et al. 2003). The geochemical signature of this unit is characterized by calc-alkaline to tholeiitic affinities (Fig. 2b), significant enrichment of LILE over HFSE, with distinct Nb–Ta depletions relative to primordial mantle, and light rare earth elements (LREE) enrichment with concave patterns for MREE and HREE (medium and heavy rare earth elements, respectively) (Nyström et al. 2003) (Fig. 2c–f). The isotopic composition of the volcanic units is rather uniform, with low (< 0.706) $^{87}Sr/^{86}Sr_i$ and εNd_i of between +5.6 and +5.8, suggesting a depleted mantle source for the magmas, with little contribution of continental crust (Nyström et al. 2003) (Fig. 3a, c). This agrees with the prevailing extensional tectonic conditions for the arc at these latitudes and time span (Nyström et al. 2003). Radiometric dating of volcanic rocks belonging to the Abanico Formation constrain an age for the magmatism between 31 (Vergara et al. 1999) and 25 Ma (Nyström et al. 2003), although younger episodes of volcanism have been reported (23 Ma, Muñoz et al. 2006). The Cura Mallín Formation is composed of andesitic, dacitic and rhyolitic volcanic rocks (Guapitrio member) and lacustrine and fluvial deposits (Río Pedregoso member) (Suárez and Emparán 1997). The geochronological (26.3–22.8 Ma) and stratigraphic relationship between the Abanico and Cura-Mallín formations suggests that both units represent a common tectonomagmatic setting (Jordan et al. 2001; Radic et al. 2002; Kay et al. 2006; Iannelli et al. 2017) of crustal extension and high heat flux that generated tholeiitic magmatism (Nystrom et al. 1993; Kay and Kurtz 1995; Charrier et al. 2002). Fuentes et al. (2004) and Muñoz et al. (2006) proposed a decline in the subduction component and an increase in the crustal contamination of the magmas to the east.

Even though the most representative sequences of the intra-arc basin are restricted to the Oligocene–Early Miocene period, the existence of older units in central Chile, located to the west of the Abanico Formation, with igneous rocks that can be related to magmatism in an extensional setting (e.g. the Cordón Los Ratones Beds, 33°S, Sellés and Gana 2001; Muñoz-Gómez et al. 2020) suggests that the initial stages of the basin may have started as early as 43 Ma, during the Mid Eocene.

MIOCENE ANDEAN MAGMATISM (22–5 Ma)

After the period of extension during the Oligocene and Early Miocene, an important regional tectonic event took place at ca. 22.7 Ma induced by the fragmentation of the Farallon Plate into the Nazca and Cocos plates (Barckhausen et al. 2001; Bello-González et al. 2018). The fragmentation resulted in a net increase of the plate convergence (Pardo-Casas and Molnar 1987; Somoza 1998; Bello-González et al. 2018) that triggered compression and the inversion of the crustal structures that previously accommodated the Abanico basin depocenters, as well as older Paleozoic discontinuities (Charrier et al. 2009) (Fig. 4). This period of increased plate convergence coincides with the Pehuenche Orogeny (Charrier et al. 2009), which took place between the end of the Oligocene and the beginning of the Miocene (Yrigoyen 1993) and represents the tectonic inversion in response to the change in convergence parameters (Ramos and Nullo 1993). The magmatic, tectonic and geomorphologic segmentation that characterized the development of the Andean margin north and south of 27°S latitude prior to the Late Miocene, persisted after 15 Ma and until the generation of the present-day flat slab segment at ca. 12–5 Ma (see below).

North of 27°S explosive felsic volcanism dominated the magmatic activity in the Western Cordillera, but the volcanic deposits covered the Pre-Cordillera and Altiplano domains into Bolivia and Argentina as well (Charrier et al. 2009). The enormous volume of silicic magmatism represented by ignimbrite deposits now exposed in these areas has been interpreted as a magmatic flare-up, probably linked to slab shallowing (de Silva 1989; Kay and Coira 2009). Representative units of this volcanism are the ignimbrites Oxaya, Lupica, Altos de Pica (Formation), Tambillo, Río Frío, Lauca , Collacagua, La Pacana, Toconao, Atana, Tucúraro, Patao, Cajón Tuyajto, Llano Las Vicuñas, Inés Chica, Los Cristales, San Andrés, Wheelwright, Laguna Verde, the San Bartolo Group (including ignimbrites Artola, Sifón, Yerba Buena, Pelón, Puripicar and Chaxas), and related shallow intrusive and subvolcanic units, whose ages range between the Early Miocene and Late Pliocene (Galli 1957; Galli and Dingman 1962; Montecinos 1963; García et al. 2004; Matthews et al. 2006; Matthews et al. 2010; Blanco et al. 2012; Clavero et al. 2012; Cornejo et al. 2013; García et al. 2013; Gardeweg and Sellés 2013; Henríquez et al. 2014). In general, these deposits are the result of pyroclastic flow or ash fall of dacitic to rhyolitic composition, generated in volcanic eruptions of Plinian type (Ramírez and Gardeweg 1982). Petrographically, the rocks correspond to vitric and crystalline ash tuff with high lithic content. Typical phenocrysts are plagioclase, quartz, biotite, and amphibole. They are geochemically rather uniform in composition, with SiO_2 content of 65–79% and calc-alkaline affinities (Kay and Coira 2009; Mamani et al. 2010) (Fig. 2a, b). Their Sr/Y, Sm/Yb and Dy/Yb ratios suggest that they derive from magmas generated and stored under a very thick crust with garnet in the source (Wörner et al. 2018) (Fig. 2e–g).

South of 27°S latitude, following the Pehuenche Orogeny, Andean magmatism developed above and slightly east of the inverted basin, and was characterized in the volcano-sedimentary sequences of the Farellones Formation (Klohn 1960) and related small and shallow intrusive bodies (Kurtz et al. 1997). Several isolated hills in the modern central depression basins (Santiago basin) are the remnant outcrops of these intrusions and volcanic rocks (Vergara et al. 2004). The age of the Farellones Formation is bracketed at between 22 and 17 Ma according to radiometric dating of plagioclase by the K/Ar and $^{40}Ar/^{39}Ar$ methods (Beccar et al. 1986; Aguirre et al. 2000). The formation is further subdivided into three members: the lower member comprises pyroclastic rocks and lacustrine deposits, the middle member is composed of basaltic-andesitic lava flows, and the upper member is composed of intermediate to felsic lava flows and domes (Nyström et al. 2003). The lower part of this unit is either concordant or slightly discordant to the Abanico Formation, suggesting only limited deformation exerted by the Pehuenche Orogeny at these latitudes (Nyström et al. 2003). The K_2O and Na_2O content of the volcanic rocks of the Farellones Formation are high enough to classify them as calc-alkaline in affinity and typically subduction-related (Nyström et al. 2003 and references therein) (Fig. 2a, b). The

La/Yb ratios are higher than those of the Abanico Formation, suggesting a deeper partial melting of the mantle source (Fig. 2e, f). REE patterns of the intermediate to acid rocks are sub-parallel, indicating that magmatic evolution likely occurred through fractional crystallization from primitive, or slightly hybridized, magmas (Nyström et al. 2003). In contrast, rhyolite units have distinct negative Eu anomalies and strongly concave-up REE patterns (Fig. 2f). This reflects the transitional geochemical and tectonic position of lower and middle members in contrast to the compressional regime for the upper member of the Farellones Formation. The isotopic composition of the Miocene igneous rocks is more variable than the Abanico magmas: εNd_i varies between +4.4 and +5.1 and Pb ratios are as follows: $^{206}Pb/^{204}Pb$ = 18.453–18.570, $^{207}Pb/^{204}Pb$ = 15.548–15.610 and $^{208}Pb/^{204}Pb_i$ = 38.262–38.478 (Fig. 3).

This period of the Andean magmatism terminated with the subduction of the Juan Fernández ridge, a process that started at ca. 12 Ma but was fully developed by the end of the Miocene, and which generated a tectonic segmentation that prevails until today, dividing the Chilean Andes into roughly three segments: 18°30' to 27°S, 27°–33°S and 33°–55°S latitudes (Barazangi and Isacks 1976; Jordan et al. 1983; Isacks 1988; Gutscher 2002; Yáñez et al. 2002; Ramos et al. 2002). The ridge subduction would have induced the flattening of the subducting plate between 27° and 33°S (Yáñez et al. 2001; Kay and Mpodozis 2002), eastward migration of the magmatism and, later, its ultimate shut-off in this segment, and thick-skinned deformation in the Frontal Cordillera. The resulting deformation and uplift were contemporaneous to the formation of Cu–Mo porphyry deposits.

For comprehensive reviews on the modern (Pleistocene to Recent) Andean volcanism, the reader is referred to the works of Stern (2004), Wörner et al. (2018), de Silva and Kay (2018) and the literature cited within.

CONCLUDING REMARKS

The rock record for Andean magmatism since the Rhaetian–Hettangian until the end of the Miocene, is geographically widespread, comprising most of the Chilean territory between 18°30' and 40°S latitudes (Fig. 1) and even down to 55°S. From the petrographic, stratigraphic, and geochemical characteristics of the igneous rocks that represent the evolving Andean arc it is possible to infer the following:

- Andean magmatism is of dominantly calc-alkaline affinity and includes sub-alkaline series where tonalite–granodiorite and andesite are the dominant lithologies. Exceptions are the Early Andean magmatism which is dominated by diorite/tonalite and basaltic-andesite lithologies, and the Miocene magmatism north of 27°S latitude, where the most abundant products are dacite/rhyolite and granite.
- Variations in the trace element and isotopic compositions of Andean igneous rocks through time and space mostly reflect distinct tectonic conditions for the magmatism, these being the main parameters controlling such variations as the angle of the subducting slab, the convergence rate and obliquity, and crustal thickness.
- The main magmatic source would have been the depleted sub-arc mantle, which assimilated variable amounts of Paleozoic crust through time.
- Tectonic segmentation of the arc may have occurred since the Cretaceous, but it is most evident from the Eocene onwards, where the magmatism north of 27°S latitude is significantly more silicic and evolved (related to increased contributions from Paleozoic crust and/or the lithosphere) than that emplaced south of 27°S latitude, which is dominated by more mafic lithologies and reflects a dominant depleted mantle source.

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REFERENCES

Aguirre, L., 1960, Geología de los Andes de Chile central (provincia de Aconcagua): Instituto de Investigaciones Geológicas, Boletín, Santiago, v. 9, 70 p.

Aguirre, L., Féraud, G., Morata, D., Vergara, M., and Robinson, D., 1999, Time interval between volcanism and burial metamorphism and rate of basin subsidence in a Cretaceous Andean extensional setting: Tectonophysics, v. 313, p. 433–447, https://doi.org/10.1016/S0040-1951 (99)00217-6.

Aguirre, L., Féraud, G., Vergara, M., Carrasco, J., and Morata, D., 2000, $^{40}Ar/^{39}Ar$ ages of basic flows from the Valle Nevado stratified sequence (Farellones Formation): Andes of central Chile: Congreso Geológico, n. 9, Actas, Puerto Varas, Chile, v. 1, p. 583–585.

Aguirre-Urreta, B., Tunik, M., Naipauer, M., Pazos, P., Ottone, E., Fanning, M., and Ramos, V.A., 2011, Malargüe Group (Maastrichtian–Danian) deposits in the Neuquén Andes, Argentina: Implications for the onset of the first Atlantic transgression related to Western Gondwana break-up: Gondwana Research, v. 19, p. 482–494, https://doi.org/10.1016/j.gr.2010.06.008.

Arévalo, C., 2005, Carta Los Loros, Región de Atacama: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 92, 53 p.

Armijo, R., Rauld, R., Thiele, R., Vargas, G., Campos, J., Lacassin, R., and Kausel, E., 2010, The West Andean thrust, the San Ramón fault, and the seismic hazard for Santiago, Chile: Tectonics, v. 29, TC2007, https://doi.org/10.1029/2008TC002427.

Bahlburg, H., Vervoort, J.D., Du Frane, S.A., Bock, B., Augustsson, C., and Reimann, C., 2009, Timing of crust formation and recycling in accretionary orogens: Insights learned from the western margin of South America: Earth-Science Reviews, v. 97, p. 215–241, https://doi.org/10.1016/j.earscirev.2009.10.006.

Ballard, J.R., Palin, J.M., Williams, I.S., Campbell, I.H., and Faunes, A., 2001, Two ages of porphyry intrusion resolved for the super-giant Chuquicamata copper deposit of northern Chile by ELA-ICP-MS and SHRIMP: Geology, v. 29, p. 379–386, https://doi.org/10.1130/0091-7613(2001)029<0383:TAOPIR>2.0.CO;2.

Barazangi, M., and Isacks, B.L., 1976, Spatial distribution of earthquakes and subduction of the Nazca plate beneath South America: Geology, v. 4, p. 686–692, https://doi.org/10.1130/0091-7613(1976)4<686:SDOEAS>2.0.CO;2.

Barckhausen, U., Ranero, C.R., von Huene, R., Cande, S., and Roeser, H., 2001, Revised tectonic boundaries in the Cocos plate off Costa Rica: implications for the segmentation of the convergent margin and for plate tectonic models: Journal of Geophysical Research, Solid Earth, v. 106, p. 19207–19220, https://doi.org/10.1029/2001JB000238.

Beccar, I., Vergara, M., and Munizaga, F., 1986, Edades K–Ar de la Formación Farellones en el cordón del cerro La Parva, Cordillera de los Andes de Santiago, Chile: Andean Geology, v. 0 (28–29), p. 109–113.

Bello-González, J.P., Contreras-Reyes, E., and Arriagada, C., 2018, Predicted path for hotspot tracks off South America since Paleocene times: Tectonic implications of ridge-trench collision along the Andean margin: Gondwana Research, v. 64, p. 216–234, https://doi.org/10.1016/j.gr.2018.07.008.

Bergoeing, J.P., 2016, Evolución geoquímica del magmatismo de la Región de Los Pelambres (31°S) entre el Cretácico Superior y el Mioceno superior: Implicancias para la evolución tectónica y metalogénica de los Andes de Chile Central: Unpublished Undergraduate thesis, Universidad de Chile, Santiago, Chile, 131 p.

Blanco, N., and Tomlinson, A.J., 2013, Carta Guatacondo, Región de Tarapacá: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 156, 115 p.

Blanco, N., Tomlinson, A., Mpodozis, C., Pérez de Arce, C., and Mathew, S., 2003, Formación Calama, Eoceno, II Región de Antofagasta (Chile), Estratigrafía e implicancias tectónicas: X Congreso Geológico Chileno, Concepción, Abstracts, v. 3, p. 10.

Blanco, N., Vásquez, P., Sepúlveda, F., Tomlinson, A., Quezada, A., and Ladino, M., 2012, Levantamiento Geológico para el fomento de la exploración de recursos minerales e hídricos de la Cordillera de la Costa, Depresión Central y Precordillera de la Región de Tarapacá (20°–21°S): Informe Registrado IR-12-50, SERNAGEOMIN, Santiago, 246 p.

Boric, R., Holmgren, C., Wilson, N.S.F., and Zentilli, M., 2002, The Geology of the El Soldado Manto Type Cu (Ag) Deposit, Central Chile, *in* Porter, T.M., *ed.*, Hydrothermal Iron Oxide Copper- Gold and Related Deposits: A Global Perspective, Volume 2; PGC Publishing, Adelaide, p. 185–205.

Camus, F., 2003, Geología de los sistemas porfíricos en los Andes de Chile: CODELCO-SERNAGEOMIN-Sociedad Geológica de Chile, Santiago, 267 p.

Castillo, P., Fanning, C.M., Pankhurst, R.J., Hervé, F., and Rapela, C.W., 2017, Zircon O- and Hf-isotope constraints on the genesis and tectonic significance of Permian magmatism in Patagonia: Journal of the Geological Society, v. 174, p. 803–816, https://doi.org/10.1144/jgs2016-152.

Cawood, P.A., 2005, Terra Australis Orogen: Rodinia breakup and development of the Pacific and Iapetus margins of Gondwana during the Neoproterozoic and Paleozoic: Earth-Science Reviews, v. 69, p. 249–279, https://doi.org/10.1016/j.earscirev.2004.09.001.

Cembrano, J., González, G., Arancibia, G., Ahumada, I., Olivares, V., and Herrera, V., 2005, Fault zone development and strain partitioning in an extensional strike-slip duplex: A case study from the Mesozoic Atacama fault system, Northern Chile: Tectonophysics, v. 400, p. 105–125, https://doi.org/10.1016/j.tecto.2005.02.012.

Charrier, R., Wyss, A., Flynn, J.J., Swisher III, C.C., Norell, M.A., Zapatta, F., McKenna, M.C., and Novacek, M.J., 1996, New evidence for late Mesozoic–early Cenozoic evolution of the Chilean Andes in the upper Tinguiririca valley (35°S), central Chile: Journal of South American Earth Sciences, v. 9, p. 393–422, https://doi.org/10.1016/S0895-9811(96)00035-1.

Charrier, R., Baeza, O., Elgueta, S., Flynn, J.J., Gans, P., Kay, S.M., Muñoz, N., Wyss, A.R., and Zurita, E., 2002, Evidence for Cenozoic extensional basin development and tectonic inversion south of the flat-slab segment, southern Central Andes, Chile (33°–36°S.L.): Journal of South American Earth Sciences, v. 15, p. 117–139, https://doi.org/10.1016/S0895-9811(02)00009-3.

Charrier, R., Bustamante, M., Comte, D., Elgueta, S., Flynn, J.J., Iturra, N., Muñoz, N., Pardo, M., Thiele, R., and Wyss, A.R., 2005, The Abanico extensional basin: regional extension, chronology of tectonic inversion and relation to shallow seismic activity and Andean uplift: Neus Jahrbuch für Geologie und -Paläontology Abhandlungen Band, v. 236, p. 43–77, https://doi.org/10.1127/njgpa/236/2005/43.

Charrier, R., Pinto, L., and Rodríguez, M.P., 2007, Tectonostatigraphic evolution of the Andean Orogen in Chile, *in* Moreno, T., and Gibbons, W., *eds.*, The Geology of Chile: The Geological Society, London, p. 21–114, https://doi.org/10.1144/GOCH.3.

Charrier, R., Farías, M., and Maksaev, V., 2009, Evolución tectónica, paleogeográfica y metalogénica durante el Cenozoico en los Andes de Chile norte y central e implicaciones para las regiones adyacentes de Bolivia y Argentina: Revista de la Asociación Geológica Argentina, v. 65, p. 5–35.

Charrier, R., Ramos, V.A., Tapia, F., and Sagripanti, L., 2015, Tectono-stratigraphic evolution of the Andean Orogen between 31 and 37°S (Chile and Western Argentina), *in* Sepúlveda, S.A., Giambiagi, L.B., Moreiras, S.M., Pinto, L., Tunik, M., Hoke, G.D., and Farías, M., *eds.,* Geodynamic Processes in the Andes of Central Chile and Argentina: Geological Society, London, Special Publications, v. 399, p. 13–61, https://doi.org/10.1144/SP399.20.

Chernicoff, C.J., Zappettini, E.O., Santos, J.O.S., McNaughton, N.J., and Belousova, E., 2013, Combined U–Pb SHRIMP and Hf isotope study of the Late Paleozoic Yaminué Complex, Río Negro Province, Argentina: Implications for the origin and evolution of the Patagonia composite terrane: Geoscience Frontiers, v. 4, p. 37–56, https://doi.org/10.1016/j.gsf.2012.06.003.

Chiaradia, M., Ulianov, A., Kouzmanov, K., and Beate, B., 2012, Why large porphyry Cu deposits like high Sr/Y magmas?: Scientific Reports, v. 2, 685, https://doi.org/10.1038/srep00685.

Chong, G., 1973, Reconocimiento geológico del área Catalina, Sierra de Varas y estratigrafía del Jurásico del Profera, Provincia de Antofagasta: Unpublished Undergraduate thesis, Universidad de Chile, Santiago, Chile, 248 p.

Clavero, J., Sparks, R.S., and Polanco, E., 2012, Geología del Volcán Parinacota, Región de Arica y Parinacota: Carta Geológica de Chile, Serie Geología Básica, v. 132, 2 p.

Coira, B., Davidson, J., Mpodozis, C., and Ramos, V., 1982, Tectonic and magmatic evolution of the Andes of northern Argentina and Chile: Earth-Science Reviews, v. 18, p. 303–332, https://doi.org/10.1016/0012-8252(82)90042-3.

Coloma, F., Valin, X., Oliveros, V., Vásquez, P., Creixell, C., Salazar, E., and Ducea, M.N., 2017, Geochemistry of Permian to Triassic igneous rocks from northern Chile (28°–30°15'S): Implications on the dynamics of the proto-Andean margin: Andean Geology, v. 44, p. 147–178, https://doi.org/10.5027/andgeoV44n2-a03.

Cornejo, P., Matthews, S., Mpodozis, C., Rivera, O., and Riquelme, R., 2013, Carta El Salvador, Región de Atacama: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 158, 80 p.

Cortés, J., 2000, Hoja Palestina, región de Antofagasta: Mapas Geológicos, SERNAGEOMIN, Santiago, v. 19.

Dallmeyer, R.D., Brown, M., Grocott, J., Taylor, G.K., and Treloar, P.J., 1996, Mesozoic magmatic and tectonic events within the Andean plate boundary zone, 26°–27°30'S, north Chile: Constraints from $^{40}Ar/^{39}Ar$ Mineral Ages: The Journal of Geology, v. 104, p. 19–40, https://doi.org/10.1086/629799.

Darwin, C., 1844, Geological observations on the volcanic islands and parts of South America visited during the voyage of H.M.S. 'Beagle': D. Appleton and Company, New York, reprinted 1891, https://doi.org/10.5962/bhl.title.61452.

Defant, M.J., and Drummond, M.S., 1990, Derivation of some modern arc magmas by melting of young subducted lithosphere: Nature, v. 347, p. 662–665, https://doi.org/10.1038/347662a0.

de Silva, S.L., 1989, Altiplano-Puna volcanic complex of the central Andes: Geology, v. 17, p. 1102–1106, https://doi.org/10.1130/0091-7613(1989)017<1102:APVCOT>2.3.CO;2.

de Silva, S.L., and Kay, S.M., 2018, Turning up the heat: High-flux magmatism in the central Andes: Elements, v. 14, p. 245–250, https://doi.org/10.2138/gselements.14.4.245.

del Rey, A., Deckart, K., Arriagada, C., and Martínez, F., 2016, Resolving the paradigm of the late Paleozoic–Triassic Chilean magmatism: Isotopic approach: Gondwana Research, v. 37, p. 172–181, https://doi.org/10.1016/j.gr.2016.06.008.

Dostal, J., Zentilli, M., Caelles, J.C., and Clark, A.H., 1977, Geochemistry and origin of volcanic rocks of the Andes (26°–28°S): Contributions to Mineralogy and Petrology, v. 63, p. 113–128, https://doi.org/10.1007/BF00398774.

Emparán, C., and Pineda, G., 1999, Área Condoriaco-Rivadavia, Región de Coquimbo: Mapas Geológicos, SERNAGEOMIN, Santiago, v. 12.

Escayola, M.P., Pimentel, M.M., and Armstrong, R., 2007, Neoproterozoic backarc basin: Sensitive high-resolution ion microprobe U–Pb and Sm–Nd isotopic evidence from the Eastern Pampean Ranges, Argentina: Geology, v. 35, p. 495–498, https://doi.org/10.1130/G23549A.1.

Espinoza, F., Matthews, S., and Cornejo, P., 2011, Carta Catalina, Región de Antofagasta: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 129, 63 p.

Espinoza, F., Matthews, S., and Cornejo, P., 2012, Carta Los Vientos, Región de Antofagasta: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 138, 72 p.

Espinoza, M., Montecino, D., Oliveros, V., Astudillo, N., Vásquez, P., Reyes, R., Celis, C., González, R., Contreras, J., Creixell, C., and Martínez, A., 2019, The synrift phase of the early Domeyko Basin (Triassic, northern Chile): Sedimentary, volcanic, and tectonic interplay in the evolution of an ancient subduction-related rift basin: Basin Research, v. 31, p. 4–32, https://doi.org/10.1111/bre.12305.

Farrar, E., Clark, A.H., Haynes, S.J., Quirt, G.S., Conn, H., and Zentilli, M., 1970, K–Ar evidence for the post-Paleozoic migration of granitic intrusion foci in the Andes of northern Chile: Earth and Planetary Science Letters, v. 10, p. 60–66, https://doi.org/10.1016/0012-821X(70)90064-6.

Fennell, L.M., Folguera, A., Naipauer, M., Gianni, G., Rojas Vera, E.A., Bottesi, G., and Ramos, V.A., 2017, Cretaceous deformation of the southern Central Andes: synorogenic growth strata in the Neuquén Group (35°30'–37°S): Basin Research, v. 29, p. 51–72, https://doi.org/10.1111/bre.12135.

Ferrando, R., Roperch, P., Morata, D., Arriagada, C., Ruffet, G., and Córdova, M.L., 2014, A paleomagnetic and magnetic fabric study of the Illapel Plutonic Complex, Coastal Range, central Chile: Implications for emplacement mechanism and regional tectonic evolution during the mid-Cretaceous: Journal of South American Earth Sciences, v. 50, p. 12–26, https://doi.org/10.1016/j.jsames.2013.11.007.

Flynn, J.J., Charrier, R., Croft, D.A., Gans, P.B., Herriott, T.M., Wertheim, J.A., and Wyss, A.R., 2008, Chronologic implications of new Miocene mammals from the Cura-Mallín and Trapa Trapa formations, Laguna del Laja area, south central Chile: Journal of South American Earth Sciences, v. 26, p. 412–423, https://doi.org/10.1016/j.jsames.2008.05.006.

Fuentes, F., Vergara, M., Aguirre, L., and Féraud, G., 2002, Relaciones de contacto de unidades volcánicas terciarias de los Andes de Chile central (33°S): una rein-

terpretación sobre la base de dataciones $^{40}Ar/^{39}Ar$: Revista Geológica de Chile, v. 29, p. 151–165, https://doi.org/10.4067/S0716-02082002000200004.
Fuentes, F., Aguirre, L., Vergara, M., Valdebenito, L., and Fonseca, E., 2004, Miocene fossil hydrothermal system associated with a volcanic complex in the Andes of central Chile: Journal of Volcanology and Geothermal Research, v. 138, p. 139–161, https://doi.org/10.1016/j.jvolgeores.2004.07.001.
Galli, C., and Dingman, R., 1962, Cuadrángulos Pica, Alca, Matilla y Chacarilla con un estudio de aguas subterráneas: Provincia de Tarapacá: Carta Geológica de Chile, Instituto de Investigaciones Geológicas (IIG), Santiago, Chile, v. 3 (2,3,4,5), 125 p.
Galli, O.C., 1957, Las formaciones geológicas en el borde occidental de la Punan de Atacama. Sector de Pica, Tarapacá: Minerales, v. 12, p. 14–26.
Gana, P., and Wall, R., 1997, Evidencias geocronológicas $^{40}Ar/^{39}Ar$ y K–Ar de un hiatus Cretácico Superior-Eoceno en Chile central (33–33°30'S): Andean Geology, v. 24, p. 145–163.
García, F., 1967, Geología del norte grande de Chile: Sociedad Geológica de Chile, Symposium sobre el Geosinclinal Andino 1962, Santiago, Chile, no. 3, 138 p.
García, M., Gardeweg, M., Clavero, J., and Hérail, G., 2004, Hoja Arica, Región de Tarapacá: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, Chile, v. 84, 150 p.
García, M., Fuentes, G., and Riquelme, F., 2013, Carta Miñimiñi, Regiones de Arica y Parinacota y de Tarapacá: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 157, 51 p.
Gardeweg, M., and Sellés, D., 2013, Geología del Área Collacagua-Rinconada, Región de Tarapacá: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 148, 82 p.
Gill, J.B., 1981, Orogenic Andesites and Plate Tectonics: Springer-Verlag, Berlin, 392 p., https://doi.org/10.1007/978-3-642-68012-0.
González, G., 1999, Mecanismo y profundidad de emplazamiento del Plutón de Cerro Cristales, Cordillera de la Costa, Antofagasta, Chile: Revista Geológica de Chile, v. 26, p. 43–66, https://dx.doi.org/10.4067/S0716-02081999000100003.
González, G., and Carrizo, D., 2003, Segmentación, cinemática y cronología relativa de la deformación tardía de la Falla Salar del Carmen, Sistema de Fallas de Atacama, (23°40'S), norte de Chile: Revista Geológica de Chile, v. 30, p. 223–244, https://doi.org/10.4067/S0716-02082003000200005.
González, J., Oliveros, V., Creixell, C., Velásquez, R., Vásquez, P., and Lucassen, F., 2018, The Triassic magmatism and its relation with the Pre-Andean tectonic evolution: Geochemical and petrographic constrains from the High Andes of north central Chile (29°30'–30°S): Journal of South American Earth Sciences, v. 87, p. 95–112, https://doi.org/10.1016/j.jsames.2017.12.009.
Goss, A.R., Kay, S.M., and 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: Journal of Petrology, v. 54, p. 2193–2234, https://doi.org/10.1093/petrology/egt044.
Grocott, J., and Taylor, G.K., 2002, Magmatic arc fault systems, deformation partitioning and emplacement of granitic complexes in the Coastal Cordillera, north Chilean Andes (25°30'S to 27°00'S): Journal of the Geological Society, v. 159, p. 425–443, https://doi.org/10.1144/0016-764901-124.
Grocott, J., Arévalo, C., Welkner, D., and Cruden, A., 2009, Fault-assisted vertical pluton growth: Coastal Cordillera, north Chilean Andes: Journal of the Geological Society, v. 166, p. 295–301, https://doi.org/10.1144/0016-76492007-165.
Gutscher, M.-A., 2002, Andean subduction styles and their effect on thermal structure and interplate coupling: Journal of South American Earth Sciences, v. 15, p. 3–10, https://doi.org/10.1016/S0895-9811(02)00002-0.
Hammerschmidt, K., Döbel, R., and Friedrichsen, H., 1992, Implication of $^{40}Ar/^{39}Ar$ dating of early Tertiary volcanic rocks from the north-Chilean Precordillera: Tectonophysics, v. 202, p. 55–81, https://doi.org/10.1016/0040-1951(92)90455-F.
Haschke, M., Siebel, W., Günther, A., and Scheuber, E., 2002, Repeated crustal thickening and recycling during the Andean orogeny in north Chile (21°–26°S): Journal of Geophysical Research, v. 107, p. ECV 6-1–ECV 6-18, https://doi.org/10.1029/2001JB000328.
Haschke, M., Günther, A., Melnick, D., Echtler, H., Reutter, K.-J., Scheuber, E., and Oncken, O., 2006, Central and southern Andean tectonic evolution inferred from arc magmatism, *in* Onken, O., Chong, G., Franz, G., Giese, P., Götze, H.-J., Ramos, V.A., Strecker, M.R., and Wigger, P., *eds.,* The Andes: Active Subduction Orogeny: Springer, Berlin, p. 337–353, https://doi.org/10.1007/978-3-540-48684-8_16.
Henríquez, S., Becerra, J., and Arriagada, C., 2014, Geología del Área San Pedro de Atacama, Región de Antofagasta: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 171, 99 p.
Hervé, F., 1988, Late Paleozoic subduction and accretion in southern Chile: Episodes, v. 11, p. 183–188, https://doi.org/10.18814/epiiugs/1988/v11i3/005.
Hervé, F., Faundez, V., Calderón, M., Massonne, H.-J., and Willner, A.P., 2007, Metamorphic and plutonic basement complexes, *in* Moreno, T., and Gibbons, W., *eds.,* The Geology of Chile: The Geological Society, London, p. 5–20, https://doi.org/10.1144/GOCH.2.
Hickey, R.L., Frey, F.A., Gerlach, D.C., and López-Escobar, L., 1986, Multiple sources for basaltic arc rocks from the southern volcanic zone of the Andes (34°–41°S): Trace element and isotopic evidence for the contributions from subducted oceanic crust, mantle, and continental crust: Journal of Geophysical Research, v. 91, p. 5963–5983, https://doi.org/10.1029/JB091iB06p05963.
Hildreth, W., and Moorbath, S., 1988, Crustal contribution to arc magmatism in the Andes of central Chile: Contributions to Mineralogy and Petrology, v. 98, p. 455–489, https://doi.org/10.1007/BF00372365.
Iannelli, S.B., Litvak, V.D., Fernández Paz, L., Folguera, A., Ramos, M.E., and Ramos, V.A., 2017, Evolution of Eocene to Oligocene arc-related volcanism in the North Patagonian Andes (39°–41°S), prior to the break-up of the Farallon plate: Tectonophysics, v. 696–697, p. 70–87, https://doi.org/10.1016/j.tecto.2016.12.024.
Iriarte, I., Arévalo, C., and Mpodozis, C., 1999, Hoja La Guardia, Región de Atacama: Carta Geológica de Chile, Serie Mapas Geológicos, SERNAGEOMIN, Santiago, v. 13.
Iriarte, S., Arévalo, C., Mpodozis, C., and Rivera, O., 1996, Mapa Geológico de la Hoja Carrera Pinto, Región de Atacama: Mapas Geológicos, SERNAGEOMIN, Santiago, v. 3.
Irvine, T.N., and Baragar, W.R.A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Journal of Earth Sciences, v. 8, p. 523–548, https://doi.org/10.1139/e71-055.
Isacks, B.L., 1988, Uplift of the central Andean plateau and bending of the Bolivian orocline: Journal of Geophysical Research, v. 93, p. 3211–3231, https://doi.org/10.1029/JB093iB04p03211.
Jara, P., and Charrier, R., 2014, New stratigraphical and geochronological constraints for the Mezo-Cenozoic deposits in the High Andes of central Chile between 32° and 32°30'S: Structural and palaeogeographic implications: Andean Geology, v. 41, p. 174–209, https://doi.org/10.5027/andgeoV41n1-a07.
Jordan, T.E., Isacks, B.L., Allmendinger, R.W., Brewer, J.A., Ramos, V.A., and Ando, C.J., 1983, Andean tectonics related to geometry of subducted Nazca plate: Geological Society of America Bulletin, v. 94, p. 341–361, https://doi.org/10.1130/0016-7606(1983)94<341:ATRTGO>2.0.CO;2.
Jordan, T.E., Burns, W.M., Veiga, R., Pángaro, F., Copeland, P., Kelley, S., and Mpodozis, C., 2001, Extension and basin formation in the southern Andes caused by increased convergence rate: A mid-Cenozoic trigger for the Andes: Tectonics, v. 20, p. 308–324, https://doi.org/10.1029/1999TC001181.
Kay, S.M., and Coira, B.L., 2009, Shallowing and steepening subduction zones, continental lithospheric loss, magmatism, and crustal flow under the Central Andean Altiplano-Puna Plateau, *in* Kay, S.M., Ramos, V.A., and Dickinson, W.R., *eds.,* Backbone of the Americas: Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision: Geological Society of America, Memoirs, v. 204, p. 229–259, https://doi.org/10.1130/2009.1204(11).
Kay, S.M., and Kurtz, A., 1995, Magmatic and tectonic characterization of El Teniente region: Final report (unpublished): Corporación Nacional del Cobre (CODELCO), 180 p.
Kay, S.M., and Mpodozis, C., 2002, Magmatism as a probe to the Neogene shallowing of the Nazca plate beneath the modern Chilean flat-slab: Journal of South American Earth Sciences, v. 15, p. 39–57, https://doi.org/10.1016/S0895-9811(02)00005-6.
Kay, S.M., Godoy, E., and Kurtz, A., 2005, Episodic arc migration, crustal thickening, subduction erosion, and magmatism in the south-central Andes: Geological Society of America Bulletin, v. 117, p. 67–88, https://doi.org/10.1130/B25431.1.
Kay, S.M., Burns, W.M., Copeland, P., and Mancilla, O., 2006, Upper Cretaceous to Holocene magmatism and evidence for transient Miocene shallowing of the Andean subduction zone under the northern Neuquén Basin, *in* Kay, S.M., and Ramos, V.A., *eds.,* Evolution of an Andean Margin: A Tectonic and Magmatic View from the Andes to the Neuquén Basin (35°–39°S lat): Geological Society of America, Special Papers, v. 407, p. 19–60, https://doi.org/10.1130/2006.2407(02).
Kleiman, L.E., and Japas, M.S., 2009, The Choiyoi volcanic province at 34°S–36°S (San Rafael, Mendoza, Argentina): Implications for the Late Palaeozoic evolution of the southwestern margin of Gondwana: Tectonophysics, v. 473, p. 283–299, https://doi.org/10.1016/j.tecto.2009.02.046.
Klohn, C., 1960, Geología de la Cordillera de los Andes de Chile central (provincias de Santiago, O'Higgins, Colchagua y Curicó): Instituto de Investigaciones Geológicas, Boletín, v. 8, 95 p.
Kramer, W., Siebel, W., Romer, R.L., Haase, G., Zimmer, M., and Ehrlichmann, R.,

2005, Geochemical and isotopic characteristics and evolution of the Jurassic volcanic arc between Arica (18°30' S) and Tocopilla (22°S), North Chilean Coastal Cordillera: Geochemistry, v. 65, p. 47–78, https://doi.org/10.1016/j.chemer.2004.01.002.

Kurtz, A.C., Kay, S.M., Charrier, R., and Farrar, E., 1997, Geochronology of Miocene plutons and exhumation history of El Teniente region, central Chile (34°–35°S): Revista Geológica de Chile, v. 24, p. 75–90.

Lange, D., Cembrano, J., Rietbrock, A., Haberland, C., Dahm, T., and Bataille, K., 2008, First seismic record for intra-arc strike-slip tectonics along the Liquiñe-Ofqui fault zone at the obliquely convergent plate margin of the southern Andes: Tectonophysics, v. 455, p. 14–24, https://doi.org/10.1016/j.tecto.2008.04.014.

Levi, B., 1969, Burial metamorphism of a Cretaceous volcanic sequence west from Santiago, Chile: Contributions to Mineralogy and Petrology, v. 24, p. 30–49, https://doi.org/10.1007/BF00398751.

Levi, B.D., 1973, Eastward shift of Mesozoic and Early Tertiary volcanic centers in the Coast Range of central Chile: Geological Society of America Bulletin, v. 84, p. 3901–3910, https://doi.org/10.1130/0016-7606(1973)84<3901:ESOMAE>2.0.CO;2.

Llambías, E.J., and Sato, A.M., 1990, El batolito de Colangüil (29°–31°S) Cordillera Frontal de Argentina: estructura y marco tectónico: Revista Geológica de Chile, v. 17, p. 89–108.

Llambías, E.J., and Sato, A.M., 1995, El batolito de Colangüil: transicién entre orogénesis y anorogénesis: Revista de la Asociación Geológica Argentina, v. 50, p. 111–131.

Llambías, E.J., Kleiman, L.E., and Salvarredi, J.A., 1993, Magmatismo gondwánico de Mendoza, *in* Ramos, V.A., *ed.,* Geología y Recursos Naturales de Mendoza, Relatorio XII Congreso Geológico Argentino, p. 53–64.

Loewy, S.L., Connelly, J.N., and Dalziel, I.W.D., 2004, An orphaned basement block: The Arequipa-Antofalla Basement of the central Andean margin of South America: Geological Society of America Bulletin, v. 116, p. 171–187, https://doi.org/10.1130/B25226.1.

Losert, J., 1974, Alteration and associated copper mineralization in the Jurassic volcanic rocks of the Buena Esperanza mining area (Antofagasta Province, Northern Chile): Departamento de Geología, Universidad de Chile, Publicación v. 41, p. 51–85.

Lucassen, F., Kramer, W., Bartsch, V., Wilke, H.-G., Franz, G., Romer, R.L., and Dulski, P., 2006, Nd, Pb, and Sr isotope composition of juvenile magmatism in the Mesozoic large magmatic province of northern Chile (18–27°S): indications for a uniform subarc mantle: Contributions to Mineralogy and Petrology, v. 152, p. 571–589, https://doi.org/10.1007/s00410-006-0119-y.

Maksaev, V., 1978, Cuadrángulo Chitigua y sector occidental del cuadrángulo Cerro Palpana, Región de Antofagasta: Cartas Geológicas de Chile, Instituto de Investigaciones Geológicas (IIG), Santiago, Chile, v. 31, 55 p.

Maksaev, V., 2001, Reseña metalogénica de Chile y de los procesos que determinan la metalogénesis Andina: Lecture Notes (Unpublished), Universidad de Chile, Santiago.

Mamani, M., Wörner, G., and 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 and space: Geological Society of America Bulletin, v. 122, p. 162–182, https://doi.org/10.1130/B26538.1.

Marinovic, N., 2007, Carta Oficina Domeyko, Región de Antofagasta: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 105, 43 p.

Marinovic, N., and García, M., 1999, Hoja Pampa Unión, región de Antofagasta: Mapas Geológicos, SERNAGEOMIN, Santiago, v. 9.

Marinovic, N., Smoje, I., Maksaev, V., Hervé, M., and Mpodozis, C., 1995, Hoja Aguas Blancas, Región de Antofagasta: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 70, 150 p.

Marschik, R., and Fontboté, L., 2001, The Punta del Cobre Formation, Punta del Cobre-Candelaria area, northern Chile: Journal of South American Earth Sciences, v. 14, p. 401–433, https://doi.org/10.1016/S0895-9811(01)00036-0.

Martinez, F., Arriagada, C., Peña, M., Deckart, K., and Charrier, R., 2016, Tectonic styles and crustal shortening of the Central Andes "Pampean" flat-slab segment in northern Chile (27°–29°S): Tectonophysics, v. 667, p. 144–162, https://doi.org/10.1016/j.tecto.2015.11.019.

Matthews, K.J., Maloney, K.T., Zahirovic, S., Williams, S.E., Seton, M., and Müller, R.D., 2016, Global plate boundary evolution and kinematics since the late Paleozoic: Global and Planetary Change, v. 146, p. 226–250, https://doi.org/10.1016/j.gloplacha.2016.10.002.

Matthews, S., Cornejo, P., and Riquelme, R., 2006, Carta Inca de Oro, Región de Atacama: Serie Geología Básica, SERNAGEOMIN, Santiago, v. 102, 79 p.

Matthews, S., Espinoza, F., Cornejo, P., and Venegas, C., 2010, Carta Altamira, Regiones de Antofagasta y Atacama: Serie Geología Básica, SERNAGEOMIN, Santiago, v. 121, 66 p.

Medina, E., Niemeyer, H., Wilke, H.W., Cembrano, J., García, M., Riquelme, R., Espinoza, S., and Chong, G., 2012, Cartas Tocopilla y María Elena, Región de Antofagasta: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 141–142, 150 p.

Montaño, J.M., 1976, Estudio geológico de la zona de Caracolas y áreas vecinas, con énfasis en el Sistema Jurásico, provincia de Antofagasta, II Región, Chile: Unpublished PhD thesis, Universidad de Chile, Santiago, Chile, 169 p.

Montecinos, F., 1963, Observaciones de Geología en el Cuadrángulo de Campanani, Departamento de Arica, Provincia de Tarapacá: Unpublished Undergraduate thesis, Universidad de Chile, Santiago, Chile, 109 p.

Morata, D., and Aguirre, L., 2003, Extensional Lower Cretaceous volcanism in the Coastal Range (29°20'–30°S), Chile: geochemistry and petrogenesis: Journal of South American Earth Sciences, v. 16, p. 459–476, https://doi.org/10.1016/j.jsames.2003.06.001.

Morata, D., Varas, M.I., Higgins, M., Valencia, V., and Verhoort, J., 2010, Episodic emplacement of the Illapel Plutonic Complex (Coastal Cordillera, central Chile): Sr and Nd isotopic, and zircon U–Pb geochronological constraints: VII SSAGI South American Symposium on Isotope Geology, No. 7. Brasilia (Brasil).

Mosolf, J.G., Gans, P.B., Wyss, A.R., Cottle, J.M., and Flynn, J.J., 2019, Late Cretaceous to Miocene volcanism, sedimentation, and upper-crustal faulting and folding in the Principal Cordillera, central Chile: Field and geochronological evidence for protracted arc volcanism and transpressive deformation: Geological Society of America Bulletin, v. 131, p. 252–273, https://doi.org/10.1130/B31998.1.

Mpodozis, C., and Cornejo, P., 2012, Cenozoic tectonics and porphyry copper systems of the Chilean Andes: Society of Economic Geologists, Special Publication, v. 16, p. 329–360.

Mpodozis, C., and Kay, S.M., 1992, Late Paleozoic to Triassic evolution of the Gondwana margin: Evidence from chilean frontal Cordilleran batholiths (28°S to 31°S): Geological Society America Bulletin, v. 104, p. 999–1014, https://doi.org/10.1130/0016-7606(1992)104<0999:LPTTEO>2.3.CO;2.

Mpodozis, C., and Ramos, V.A., 1989, The Andes of Chile and Argentina, *in* Ericksen, G.E., Cañas Pinochet, M.T., and Reinemud, J.A., *eds.,* Geology of the Andes and its Relation to Hydrocarbon and Mineral Resources: Circum-Pacific Council for Energy and Mineral Resources, Earth Sciences Series 11, p. 59–90.

Muñoz, M., Fuentes, F., Vergara, M., Aguirre, L. Olov Nyström, J., Féraud, G., and Demant, A., 2006, Abanico East Formation: petrology and geochemistry of volcanic rocks behind the Cenozoic arc front in the Andean Cordillera, central Chile (33°50'S): Revista Geológica de Chile, v. 33, p. 109–140, https://doi.org/10.4067/S0716-02082006000100005.

Muñoz, M., Tapia, F., Persico, M., Benoit, M., Charrier, R., Farías, M., and Rojas, A., 2018, Extensional tectonics during Late Cretaceous evolution of the Southern Central Andes: Evidence from the Chilean main range at ~35°S: Tectonophysics, v. 774, p. 93–117, https://doi.org/10.1016/j.tecto.2018.06.009.

Muñoz-Gómez, M., Fuentes, C., Fuentes, F., Tapia, F., Benoit, M., Farías, M., Fanning, C.M., Fock, A., Charrier, R., Sellés, D., and Bustamante, D., 2020, Eocene arc petrogenesis in Central Chile (c. 33.6°S) and implications for the Late Cretaceous–Miocene Andean setting: tracking the evolving tectonic regime: Journal of the Geological Society, v. 177, p. 258–275 https://doi.org/10.1144/jgs2019-042.

Naranjo, J.A., and Paskoff, R., 1985, Evolución cenozoica del piedemonte andino en la Pampa del Tamarugal, norte de Chile (18–21°S) (Abstract): IV Congreso Geológico Chileno, Antofagasta, Abstracts, v. 1, p. 149–165.

Niemeyer, H., and Muñoz, J., 1963, Hoja de La Laja, Región del Biobío: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 57, 52 p.

Niemeyer, H., and Urrutia, C., 2009, Transcurrencia a lo largo de la Falla Sierra de Varas (Sistema de fallas de la Cordillera de Domeyko), norte de Chile: Andean Geology, v. 36, p. 37–49, https://doi.org/10.4067/S0718-71062009000100004.

Nyström, J., Parada, M.A., and Vergara, M., 1993, Sr–Nd isotope composition of Cretaceous to Miocene volcanic rocks in central Chile, A trend towards a MORB signature and a reversal with time (Abstract): II International Symposium on Andean Geodynamics, Abstracts, p. 21–23.

Nyström, J., Vergara, M., Morata, D., and Levi, B., 2003, Tertiary volcanism during extension in the Andean foothills of central Chile (33°15'–33°45'S): Geological Society of America Bulletin, v. 115, p. 1523–1537, https://doi.org/10.1130/B25099.1.

Oliveros, V., Féraud, G., Aguirre, L., Fornari, M., and Morata, D., 2006, The Early Andean Magmatic Province (EAMP): $^{40}Ar/^{39}Ar$ dating on Mesozoic volcanic and plutonic rocks from the Coastal Cordillera, northern Chile: Journal of Volcanology and Geothermal Research, v. 157, p. 311–330, https://doi.org/

10.1016/j.jvolgeores.2006.04.007.
Oliveros, V., Morata, D., Aguirre, L., Féraud, G., and Fornari, M., 2007, Jurassic to Early Cretaceous subduction-related magmatism in the Coastal Cordillera of northern Chile (18°30'–24°S): geochemistry and petrogenesis: Andean Geology, v. 34, p. 209–232, https://doi.org/10.5027/andgeoV34n2-a03.
Oliveros, V., González, J., Espinoza Vargas, M., Vásquez, P., Rossel, P., Creixell, C., Sepúlveda, F., and Bastias, F., 2018, The early stages of the magmatic arc in the southern central Andes, *in* Folguera, A., Contreras-Reyes, E., Heredia, N. and 14 others, *eds.,* The Evolution of the Chilean-Argentinean Andes: Springer Earth System Sciences. Springer, Cham, p. 165–190, https://doi.org/10.1007/978-3-319-67774-3_7.
Oliveros, V., Vásquez, P. Creixell, C., Lucassen, F., Ducea, M.N., Ciocca, I., González, J., Espinoza, M., Salazar, E., Coloma, F., and Kasemann, S.A., 2020, Lithospheric evolution of the Pre- and Early Andean convergent margin, Chile: Gondwana Research, v. 80, p. 202–227, https://doi.org/10.1016/j.gr.2019.11.002.
Otamendi, J.E., Ducea, M.N., and Bergantz, G.W., 2012, Geological, petrological and geochemical evidence for progressive construction of an arc crustal section, Sierra de Valle Fértil, Famatinian Arc, Argentina: Journal of Petrology, v. 53, p. 761–800, https://doi.org/10.1093/petrology/egr079.
Pankhurst, R.J., Rapela, C.W., López De Luchi, M.G., Rapalini, A.E., Fanning, C.M., and Galindo, C., 2014, The Gondwana connections of northern Patagonia: Journal of the Geological Society, v. 171, p. 313–328, https://doi.org/10.1144/jgs2013-081.
Parada, M.A., Nyström, J.O., and Levi, B., 1999, Multiple sources for the Coastal Batholith of central Chile (31°–34°S): geochemical and Sr–Nd isotopic evidence and tectonic implications: Lithos, v. 46, p. 505–521, https://doi.org/10.1016/S0024-4937(98)00080-2.
Parada, M. A., Féraud, G., Fuentes, F., Aguirre, L., Morata, D., and Larrondo, P.,2005, Ages and cooling history of the Early Cretaceous Caleu pluton: testimony of a switch from a rifted to a compressional continental margin in central Chile: Journal of the Geological Society, v.162(2), 273–287.
Parada, M.A., López-Escobar, L., Oliveros, V., Fuentes, F., Morata, D., Calderón, M., Aguirre, L., Féraud, G., and Figueroa, O., 2007, Andean magmatism, *in* Moreno, T., and Gibbons, W., *eds.,* The Geology of Chile: The Geological Society, London, p. 115–146, https://doi.org/10.1144/GOCH.4.
Pardo-Casas, F., and Molnar, P., 1987, Relative motion of the Nazca (Farallon) and South American Plates since Late Cretaceous time: Tectonics, v. 6, p. 233–248, https://doi.org/10.1029/TC006i003p00233.
Petford, N., and Atherton, M., 1996, Na-rich partial melts from newly underplated basaltic crust: The Cordillera Blanca Batholith, Peru: Journal of Petrology, v. 37, p. 1491–1521, https://doi.org/10.1093/petrology/37.6.1491.
Pichler, H., and Zeil, W., 1971, The Cenozoic rhyolite-andesite association of the Chilean Andes: Bulletin Volcanologique, v. 35, p. 424–452, https://doi.org/10.1007/BF02596965.
Pineda, G., and Emparán, C., 2006, Geología del área Vicuña-Pichasca, Región de Coquimbo: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 97, 27 p.
Piquer, J., Castelli, J.C., Charrier, R., and Yáñez, G., 2010, The Cenozoic of the upper Teno River, Cordillera Principal, Central Chile: stratigraphy, plutonism and their relation with deep structures: Andean Geology, v. 37, p. 32–53, https://doi.org/10.4067/S0718-71062010000100002.
Rabbia, O.M., Correa, K.J., Hernández, L.B., and Ulrich, T., 2017, "Normal" to adakite-like arc magmatism associated with the El Abra porphyry copper deposit, Central Andes, Northern Chile: International Journal of Earth Sciences, v. 106, p. 2687–2711, https://doi.org/10.1007/s00531-017-1454-0.
Radic, J. P., Rojas, I., Carpinelli, A., and Zurita, E., 2002, Evolución tectónica de la cuenca terciaria de Cura-Mallín, Región Cordillera Chileno Argentina (36°30'-39°00'S): XIII Congreso Geológico Argentino, El Calafate, Abstracts, v. 3, p. 233–237.
Ramírez, R., and Gardeweg, M., 1982, Geología de la Hoja Toconao, Región de Antofagasta: Carta Geológica de Chile, SERNAGEOMIN, Santiago, v. 54, 117 p.
Ramos, V. A.,1988, Late Proterozoic-early Paleozoic of South America-a collisional history: Episodes, v. 11, 168–174.
Ramos, V.A., 2008a, The basement of the central Andes: The Arequipa and related terranes: Annual Review of Earth and Planetary Sciences, v. 36, p. 289–324, https://doi.org/10.1146/annurev.earth.36.031207.124304.
Ramos, V.A., 2008b, Patagonia: A Paleozoic continent adrift?: Journal of South American Earth Sciences, v. 26, p. 235–251, https://doi.org/10.1016/j.jsames.2008.06.002.
Ramos, V.A., Alemán, A., 2000, Tectonic evolution of the Andes, *in* Cordani, U.J., Milani, E.J., Thomaz Filho, A., and Campos, D.A., *eds.,* Tectonic Evolution of South America: International Geological Congress, Rio de Janeiro, p. 635–685.
Ramos, V.A., and Naipauer, M., 2014, Patagonia: where does it come from?: Journal of Iberian Geology, v. 40, p. 367–379, https://doi.org/10.5209/rev_JIGE.2014.v40.n2.45304.
Ramos, V., and Nullo, F., 1993, El volcanismo de arco cenozoico, *in* Ramos, V., *ed.,* Geología y Recursos de Mendoza: Congreso Geológico Argentino, p. 149–160.
Ramos, V.A., Jordan, T.E., Allmendinger, R.W., Mpodozis, C., Kay, S.M., Cortés, J.M., and Palma, M., 1986, Paleozoic terranes of the central Argentine-Chilean Andes: Tectonics, v. 5, p. 855–880, https://doi.org/10.1029/TC005i006p00855.
Ramos, V.A., Cristallini, E.O., and Pérez, D.J., 2002, The Pampean flat-slab of the Central Andes: Journal of South American Earth Sciences, v. 15, p. 59–78, https://doi.org/10.1016/S0895-9811(02)00006-8.
Rapela, C.W., Pankhurst, R.J., Casquet, C., Baldo, E., Saavedra, J., and Galindo, C., 1998, Early evolution of the Proto-Andean margin of South America: Geology, v. 26, p. 707–710, https://doi.org/10.1130/0091-7613(1998)026<0707:EEOTPA>2.3.CO;2.
Reich, M., Parada, M.A., Palacios, C., Dietrich, A., Schultz, F., and Lehmann, B., 2003, Adakite-like signature of Late Miocene intrusions at the Los Pelambres giant porphyry copper deposit in the Andes of central Chile: metallogenic implications: Mineralium Deposita, v. 38, p. 876–885, https://doi.org/10.1007/s00126-003-0369-9.
Riel, N., Jaillard, E., Martelat, J.-E., Guillot, S., and Braun, J., 2018, Permian–Triassic Tethyan realm reorganization: Implications for the outward Pangea margin: Journal of South American Earth Sciences, v. 81, p. 78–86, https://doi.org/10.1016/j.jsames.2017.11.007.
Rivano, S., and Sepúlveda, P., 1991, Hoja Illapel. Región de Coquimbo: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 69, p. 1–132.
Robinson, D., Bevins, R.E., Aguirre, L., and Vergara, M., 2004, A reappraisal of episodic burial metamorphism in the Andes of central Chile: Contributions to Mineralogy and Petrology, v. 146, p. 513–528, https://doi.org/10.1007/s00410-003-0516-4.
Rossel, P., Oliveros, V., Ducea, M.N., Charrier, R., Scaillet, S., Retamal, L., and Figueroa, O., 2013, The early Andean subduction system as an analog to island arcs: Evidence from across-arc geochemical variations in northern Chile: Lithos, v. 179, p. 211–230, https://doi.org/10.1016/j.lithos.2013.08.014.
Rutland, R.W.R., 1971, Andean orogeny and ocean floor spreading: Nature, v. 233, p. 252–255, https://doi.org/10.1038/233252a0.
Scheuber, E., and Gonzalez, G., 1999, Tectonics of the Jurassic–Early Cretaceous magmatic arc of the north Chilean Coastal Cordillera (22°–26° S): A story of crustal deformation along a convergent plate boundary: Tectonics, v. 18, p. 895–910, https://doi.org/10.1029/1999TC900024.
Scheuber, E., Bogdanic, T., Jensen, A., and Reutter, K.-J., 1994, Tectonic development of the north Chilean Andes in relation to plate convergence and magmatism since the Jurassic, *in* Reutter K.-J., Scheuber E., and Wigger P.J., *eds.,* Tectonics of the Southern Central Andes: Structure and Evolution of an Active Continental Margin: Springer, Berlin, p. 121–139, https://doi.org/10.1007/978-3-642-77353-2_9.
Schwartz, J.J., Gromet, L.P., and Miró, R., 2008, Timing and duration of the calc-alkaline arc of the Pampean Orogeny: implications for the Late Neoproterozoic to Cambrian evolution of Western Gondwana: The Journal of Geology, v. 116, p. 39–61, https://doi.org/10.1086/524122.
Schweller, W.J., Kulm, L.D., and Prince, R.A., 1981, Tectonics, structure, and sedimentary framework of the Peru-Chile Trench, *in* Kulm, L.D., Dymond, J., Dasch, E.J., Hussong, D.M., Roderick, R., *eds.,* Nazca Plate: Crustal Formation and Andean Convergence: Geological Society of America Memoirs, v. 154, p. 323–350, https://doi.org/10.1130/MEM154-p323.
Sellés, D., and Gana, P., 2001, Geología del Área Talagante - San Francisco de Mostazal. Regiones Metropolitana de Santiago y del Libertador General Bernardo O'Higgins: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 74, 30 p.
Sepúlveda, P., and Naranjo, J.A., 1982, Hoja Carrera Pinto, región de Atacama: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 53, 62 p.
Sepúlveda, F.A., Vásquez, P., and Quezada, A., 2014, Cartas Patillos y Oficina Victoria, Región de Tarapacá: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 167–168, 70 p.
SERNAGEOMIN, 2002, Mapa Geológico de Chile. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, v. 751.
Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shephard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., and Chandler, M., 2012, Global continental and ocean basin reconstructions since 200 Ma: Earth-Science Reviews, v.

113, p. 212–270, https://doi.org/10.1016/j.earscirev.2012.03.002.

Sillitoe, R.H., 2003, Iron oxide-copper-gold deposits: an Andean view: Mineralium Deposita, v. 38, p. 787–812, https://doi.org/10.1007/s00126-003-0379-7.

Sillitoe, R.H., and Perelló, J., 2005, Andean Copper Province: tectonomagmatic settings, deposit types, metallogeny exploration and discovery, *in* Hedenquist, J.W., Thompson, J.F.H., Goldfarb, R.J., and Richards, J.P., *eds.,* One Hundredth Anniversary Volume: Economic Geology, p. 845–890, https://doi.org/10.5382/AV100.26.

Somoza, R., 1998, Updated Nazca (Farallon) –South America relative motions during the last 40 My.: Implications for mountain building in the central Andean region: Journal of South American Earth Sciences, v. 11, p. 211–215, https://doi.org/10.1016/S0895-9811(98)00012-1.

Stern, C.R., 1991, Role of subduction erosion in the generation of Andean magmas: Geology, v. 19, p. 78–81, https://doi.org/10.1130/0091-7613(1991)019<0078:ROSEIT>2.3.CO;2.

Stern, C.R., 2004, Active Andean volcanism: its geologic and tectonic setting: Revista geológica de Chile, v. 31, p. 161–206, https://doi.org/10.4067/S0716-02082004000200001.

Suárez, M., and Emparán, C., 1997, Hoja Curacautín, Regiones de la Araucanía y del Bíobio: Carta Geológica de Chile, SERNAGEOMIN, Santiago, v. 71, 105 p.

Sun, S.-s., and McDonough, W.F., 1989, Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes, *in* Saunders, A.D., and Norry, M.J., *eds.,* Magmatism in the Ocean Basins: Geological Society, London, Special Publications, v. 42, p. 313–345, https://doi.org/10.1144/GSL.SP.1989.042.01.19.

Thomas, W.A., and Astini, R.A., 2003, Ordovician accretion of the Argentine Precordillera terrane to Gondwana: a review: Journal of South American Earth Sciences, v. 16, p. 67–79, https://doi.org/10.1016/S0895-9811(03)00019-1.

Tomezzoli, R.N., and Japas, M.S., 2006, Resultados paleomagnéticos preliminares en las sedimentitas neo-paleozoicas de la Formación El Imperial, bloque de San Rafael, Mendoza: Revista de la Asociación Geológica Argentina, v. 61, p. 370–382.

Tomlinson, A., and Blanco, N., 1997, Structural evolution and displacement history of the West Fault System, Precordillera, Chile: Part 1, postmineral history (Abstract): VIII Congreso Geológico Chileno, Antofagasta, Abstracts, v. 3, p. 1878–1882.

Tomlinson, A.J., Cornejo, P., and Mpodozis, C., 1999, Hoja Potrerillos, región de Atacama: Mapas Geológicos, SERNAGEOMIN, Santiago, v. 14.

Tomlinson, A.J., Blanco, N., and Dilles, J.H., 2010, Carta Calama, Región de Antofagasta: Carta Geológica de Chile, Serie Preliminar, SERNAGEOMIN, Santiago, v. 8, 43 p.

Tormey, D.R., Hickey-Vargas, R., Frey, F.A., and López-Escobar, L., 1991, Recent lavas from the Andean volcanic front (33° to 42°S); Interpretations of along-arc compositional variations, *in* Harmon, R.S., and Rapela, C.W., *eds.,* Andean Magmatism and Its Tectonic Setting: Geological Society of America, Special Papers, v. 265, p. 56–78, https://doi.org/10.1130/SPE265-p57.

Torsvik, T.H., and Cocks, L.R.M., 2013, Gondwana from top to base in space and time: Gondwana Research, v. 24, p. 999–1030, https://doi.org/10.1016/j.gr.2013.06.012.

Tosdal, R.M., 1996, The Amazon-Laurentian connection as viewed from the Middle Proterozoic rocks in the central Andes, western Bolivia and northern Chile: Tectonics, v. 15, p. 827–842.

Tunik, M., Folguera, A., Naipauer, M., Pimentel, M., and Ramos, V.A., 2010, Early uplift and orogenic deformation in the Neuquén Basin: constraints on the Andean uplift from U–Pb and Hf isotopic data of detrital zircons: Tectonophysics, v. 489, p. 258–273, https://doi.org/10.1016/j.tecto.2010.04.017.

Vásquez, P., Glodny, J., Franz, G., Frei, D., and Romer, R.L., 2011, Early Mesozoic plutonism of the Cordillera de la Costa (34°–37°S), Chile: constraints on the onset of the Andean Orogeny: The Journal of Geology, v. 119, p. 159–184, https://doi.org/10.1086/658296.

Vásquez, P., Sepúlveda, F., Quezada, A., Aguilef, S., Franco, C., and Blanco, N., 2018, Cartas Guanillos del Norte y Salar de Llamara, Regiones de Tarapacá y Antofagasta: Carta Geológica de Chile, Serie Geología Básica, SERNAGEOMIN, Santiago, v. 195–196, 93 p.

Vergara, M., Levi, B., Nyström, J.O., and Cancino, A., 1995, Jurassic and Early Cretaceous island arc volcanism, extension, and subsidence in the Coast Range of central Chile: Geological Society of America Bulletin, v. 107, p. 1427–1440, https://doi.org/10.1130/0016-7606(1995)107<1427:JAECIA>2.3.CO;2.

Vergara, M., Morata, D., Villarroel, R., Nyström, J., and Aguirre, L., 1999, ^{40}Ar/^{39}Ar ages, very low-grade metamorphism and geochemistry of the volcanic rock from "Cerro El Abanico", Santiago Andean Cordillera (33°30'S, 70°30'–70°25'W) (Abstract): IV International Symposium on Andean Geodynamics, Abstracts, v. 1, p. 785–788.

Vergara, M., López-Escobar, L., Palma, J.L., Hickey-Vargas, R., and Roeschmann, C., 2004, Late tertiary volcanic episodes in the area of the city of Santiago de Chile: new geochronological and geochemical data: Journal of South American Earth Sciences, v. 17, p. 227–238, https://doi.org/10.1016/j.jsames.2004.06.003

Wall, R., Sellés, D., and Gana, P., 1999, Área Til Til-Santiago, Región Metropolitana: Mapas Geológicos, SERNAGEOMIN, Santiago, v. 11.

Wörner, G., Moorbath, S., and Harmon, R.S., 1992, Andean Cenozoic volcanic centers reflect basement isotopic domains: Geology, v. 20, p. 1103–1106, https://doi.org/10.1130/0091-7613(1992)020<1103:ACVCRB>2.3.CO;2.

Wörner, G., Mamani, M., and Blum-Oeste, M., 2018, Magmatism in the Central Andes: Elements, v. 14, p. 237–244, https://doi.org/10.2138/gselements.14.4.237.

Yáñez, G., Ranero, C.R., von Huene, R., and Díaz, J., 2001, Magnetic anomaly interpretation across the southern central Andes (32°–34°S). The role of the Juan Fernandez Ridge in the late Tertiary evolution of the margin: Journal of Geophysical Research, v. 106, p. 6325–6345, https://doi.org/10.1029/2000JB900337.

Yáñez, G., Cembrano, J., Pardo, M., Ranero, C., and Sellés, D., 2002, The Challenger-Juan Fernández-Maipo major tectonic transition of the Nazca–Andean subduction system at 33–34°S: geodynamic evidence and implications: Journal of South American Earth Sciences, v. 15, p. 23–38, https://doi.org/10.1016/S0895-9811(02)00004-4.

Yrigoyen, M., 1993, Los depósitos sinorogénicos terciarios, *in* Ramos, V., *ed.,* Geología y Recursos de Mendoza: Congreso Geológico Argentino, p. 123–148.

Zentilli, M., and Dostal, J., 1977, Uranium in volcanic rocks from the central Andes: Journal of Volcanology and Geothermal Research, v. 2, p. 251–258, https://doi.org/10.1016/0377-0273(77)90002-6.

Zentilli, M., Maksaev, V., Boric, R., and Wilson, J., 2018, Spatial coincidence and similar geochemistry of Late Triassic and Eocene–Oligocene magmatism in the Andes of northern Chile: evidence from MMH porphyry type Cu–Mo deposit, Chuquicamata District: International Journal of Earth Sciences, v. 107, p. 1097–1126, https://doi.org/10.1007/s00531-018-1595-9.

Zindler, A., and Hart, S., 1986, Chemical geodynamics: Annual Review of Earth and Planetary Sciences, v. 14, p. 493–571, https://doi.org/10.1146/annurev.ea.14.050186.002425.

Zonenshayn, L.P., Savostin, L.A., and Sedov, A.P., 1984, Global paleogeodynamic reconstructions for the last 160 million years: Geotectonics, v. 18, p. 181–195.

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