Oligo-Holocene evolution of the southern part of the Central Andes: volcanism and tectonic

José Antonio Naranjo[1]*, Víctor Villa[1], Cristián Ramírez[1] and Carlos Pérez de Arce[2]

(1) Departamento de Geología Regional, Servicio Nacional de Geología y Minería, Av. Santa María 0104, Providencia, Santiago.

(2) Laboratorio de Geocronología, Servicio Nacional de Geología y Minería, Tiltil 1993, Ñuñoa, Santiago.

**Email: jose.naranjo@sernageomin.cl*

Abstract: The complex evolution of the southern Central Andes Volcanic Zone (SCAVZ) in Chile, between 25º and 27º30' S, has been elucidated based on comprehensive mapping over recent years. Several volcanic pulses, including volcanic complexes, calderas and ignimbrites, have been identified and their timing and kinematic constrained. As a result, nine Lower Miocene to Pleistocene ignimbrites units have been mapped and their probable caldera source identified, and the volcanoes have been grouped into six Lower Miocene to Holocene chronostratigraphic units. In addition, two main thrust systems of NE-SW and NS orientations are recognized. The first, located in the Precordillera, was active between 25-10 Ma and extends over 200 km to the NE through the Pedernales-Arizaro thrust fault. The second system, located within the volcanic arc, include N-S contractional structures developed in pulses between the middle Miocene and the Pleistocene. Apparently, there is a cause-effect relationship between tectonic pulses and the development of volcanism through the generation of tectonic spaces, favoring large magma volumes storing at upper crustal levels. Volcanoes, and coexisting calderas, are the result of the same tectonic causes that, in turn, previously produced shortening and conjugated extensions.

Key words: Southern Central Andes Volcanic Zone, Andean Uplift, Upper Cenozoic Volcanic Arc, Ignimbrites and calderas.

Introduction

The southern Central Andes Volcanic Zone (SCAVZ) has a complex evolution, which is poorly recorded in the normal stratigraphic record. Hyper-arid conditions, since the Miocene, mean there is a scarcity of field sections or geological profiles. Despite this we have been able to elucidate the complex evolution of the region through comprehensive mapping of the southern part of Upper Cenozoic volcanic arc of the central Andes (25°-27°30'S, Naranjo et al., 2013a, 2013b, in prep.) and numerous radiometric dating (K-Ar, Ar/Ar and U-Pb). Several volcanic pulses, including volcanic complexes, calderas and ignimbrites, have been identified and their timings and kinematics constrained. These new findings support the hypothesis that the Cenozoic volcanic arc has evolved concomitantly with the Andean uplift and its tectonic deformation. The main purpose of this work is to further our understanding of the key processes involved in the development of the Andean orogen and volcanic arc, in the SCAVZ, through new insights of the evolutionary stages.

Volcano-ignimbrite units

Volcanoes

Based on geochronologic data, relative erosion rates, stratigraphic relationships and geographic distributions, hundreds of volcanoes in the area have been grouped into six Mio-Holocene volcanic chronostratigraphic units (Naranjo *et al.*, 2013 a, b, in prep.). The morphology of the volcanic edifices, and their products, have been remarkably preserved due to the erosive processes remaining stable and extremely weak since Middle Miocene times. Through the Mio-Pliocene these volcanic units have been affected by catastrophic caldera-forming processes.

Ignimbrites

Several caldera complexes have been recognized in the area. Through detailed correlations the previously defined ignimbrite stratigraphy in this Andean segment (Naranjo and Cornejo, 1992; Clavero *et al.*, 1998; Siebel *et al.*, 2001; Schnurr *et al.*, 2007; Clavero *et al.*, 2012; Ramírez, 2014) has been improved. Thus, nine Lower Miocene to Pleistocene ignimbrites units have been mapped and their probable caldera source identified. These ignimbrite units constitute mark horizons interbedded with the volcanic chronostratigraphic unit groups. The information about the ignimbrite stratigraphy, geochronology, caldera source and volumetric data is summarized in Table 1.

Rio Frío – Pajonales ignimbrite group (24-15 Ma)

The older level corresponds to Río Frío Ignimbrite, characterized as an amphibole-rich, highly-welded tuff. This ignimbrite is disconformably overlied by Pajonales ignimbrite characterized by cineritic and pumice-rich deposits interbedded with lag-breccia horizons.

Vega Helada-Juncalito ignimbrite group (24-16 Ma)

The older Vega Helada Ignimbrite is a medium to high-grade welded, biotite and quartz bearing tuff. The younger Juncalito Ignimbrite, corresponds to a lithic, ash and pumice-rich non-welded breccia tuff.

Chixi Ignimbrite (~14 Ma)
This is a dark gray scoriaceous lapilli matrix with bread-crust bombs ignimbrite, with an oxidized, lithic-rich upper layer.

Salar Grande – San Andrés Ignimbrites (13-9 Ma)
The Salar Grande corresponds to a 100 m thick ignimbrite succession of pink, white and yellow interbedded cineritic pumice and cristal-rich levels, with lag breccia and high-grade welded horizons. The sequence is disconformably overlaid by a white to light-pink, ashy with biotite and pumice, non-welded San Andrés Ignimbrite. Both units were generated at the Salar Grande caldera.

Los Colorados Ignimbrites (~9 Ma)
Corresponds to a dark pink, elongated vesicles pumice rich ignimbrite, with a shard and quartz rich matrix. Locally, gray to brown vitrofiric levels are also present.

Wheelwright Ignimbrite (6,6-4 Ma)
This is a non-welded and lithic-rich deposit, with yellow highly vesicular and gray pumices, with a beige cineritic, manly biotite matrix. This unit was originated at the Wheelwright caldera (Clavero et al., 2012).

Las Parinas Ignimbrite (~5 Ma)
This is a pink to white, poorly to non-consolidated, ash and pumice-rich, crystal-poor ignimbrite. The main crystals correspond to biotite, plagioclase and quartz. This unit formed due to the collapse of the Pampa de Los Bayos caldera.

Laguna Verde Ignimbrite (4-3 Ma)

This unit is observed as a widespread blanket that corresponds to an indurated to welded ignimbrite with a lower pink and an upper gray layers. Flatten granular pumice-like gray to yellow fragments are typically present. The matrix corresponds to fine shard-rich ash, with abundant coarse copper-colored biotite and embayed quartz.

Caletones Cori Ignimbrite (~1 Ma)

Finally, the Caletones Cori shield ignimbrite corresponds to a crystal rich tuff, with plagioclase, biotite and pyroxene in a pinkish gray poorly welded ashy matrix.

Tectonics

Two main thrust systems of NE-SW and NS orientations are recognized. Faults of the system located at the Pre-Cordillera are sinuous, with NNE-SSW preferential orientation at the Domeyko Range, south of the Salar de Pedernales (Fig. 1). The contractional kinematic of these faults was active between 25 and 15 Ma and extends over 200 km to the NE through the Pedernales-Arizaro thrust fault (Naranjo *et al.*, 2013a), which was active between ~15-14 Ma. Seemingly contemporary with the Domeyko Range structures, the N-S Claudio Gay thrust system was developed to the east.

Within the volcanic arc N-S contractional structures are observed with differential shortening of up to 40% within 10 km. The activity of this system was developed in pulses between the middle Miocene (15 Ma) and Upper Miocene (~9 Ma). Minor Plio-Pleistocene (4-2 Ma) contractional structures are also observed towards the eastern boundary of the arc.

Discussion

At least two clusters of calderas, spatially and temporally associated to the main thrust faults systems, have been detected in the southern part of the central Andes. (1) Following the shortening along the NE-SW Pedernales-Arizaro fault (14 Ma), which obliterated the Aguilar-Infieles caldera system margins, the SE oriented Salar Grande and Pampa de los Bayos calderas were formed between 13 and 5 Ma. (2) Farther south, the Wheelwright, Laguna Amarga and Laguna Escondida calderas successively formed between 6.5 and 4 Ma and aligned 60° oblique to the contractive Claudio Gay Fault System (Fig. 1).

The location of the calderas enables the inference of where the feeder plutons (magma chambers and reservoirs) were emplaced. These plutons occupied supracrustal spaces aligned at oblique angles to the main thrust strikes.

The age these reservoirs existed for is given by the oldest and youngest ignimbrites it produced. Thus, lapses of 10 to 7 million years can be determined for Aguilar-Infieles and Pampa Salar Grande-Pampa de los Bayos systems, respectively. On the other hand, the Wheelwright, Laguna Amarga and Laguna Escondida caldera system, would have originated from reservoirs that were active at least 2.5 million years.

Tectonic spaces generated due to tensional stress fields may decrease the upper crusts bulk density and conversely increase the lithostatic gradient. Consequently a "sponge" effect results which, in conjunction with the "buoyancy" given by the depressurizing magma, favors suction and vertical magma traction towards higher, less dense, levels (Saint Blanquat et al., 1998). Based on this model, it is suggested that, in this area the reservoirs "grew" in perennial spaces generated by tensional stress fields. Recently this model has been proposed by Naranjo et al.

(2014) for the Lazufre bulging deformation area affecting the Lastarria, Cordón del Azufre and Bayo complexes (Pritchard and Simonds, 2002; Froger et al., 2007; Ruch et al., 2008, 2009; Anderssohn et al., 2009; Budach et al., 2013; Naranjo et al., 2013b). This deformation would be the consequence of ascending magmas through tectonic spaces oriented 30° from the Pedernales-Arizaro fault, which, to the SE, allowed the formation of the associated 10-9 Ma Los Colorados caldera reservoir. Notably, in the studied area of the volcanic arc no normal or transcurrent structures associated with volcanism have been detected.

Conclusions

The geology of the southern segment of the Central Andes volcanic arc reveals important links between surface, subsurface processes and volcanism. A detailed understanding of the contractional structures that controlled the Andean uplift must include a multidisciplinary study such as geochronology, geomorphology, volcanology, and many others associated with geochemical and geophysical studies. The tectonic control of the magmatic ascent and storage, and its relation with differentiation mechanisms, has not yet been fully understood. Its studies may provide many insights into the workings of magma plumbing systems within the crust in this part of the Andes. Potentially, there is a cause-effect relationship between tectonic pulses and the development of volcanism through the generation of tectonic spaces capable of storing large volumes of magma. Volcanoes, and the coexisting calderas, are the result of the same tectonic causes that, in turn, previously produced shortening and conjugated extensions.

Acknowledgments

This is a contribution of the Plan Nacional de Geología (PNG) of the Departamento de Geología Regional, Servicio Nacional de Geología y Minería. The PNG Project N°8011 maps (Carta Geológica de Chile: Áreas Salar de Agua Amarga y Portezuelo del León Muerto, Áreas Salar de Pajonales y Cerro Moño and Áreas Cerro Panteón de Aliste y Cerro Colorado) are acknowledged.

References

Anderssohn, J.; Motagh, M.; Walter, T.R.; Roseneau, M.; Kaufmann, H.; Oncken, O. 2009. Surface deformation time series and source modeling for a volcanic complex system based on satellite wide swath and image mode interferometry: The Lazufre system, central Andes. Remote Sensing of Environment 113: 2062-2075.

Budach, I.; Brasse, H.; Diaz, D. 2013. Crustal-scale electrical conductivity anomaly beneath inflating Lazufre volcanic complex, Central Andes. Journal of South American Earth Sciences 42: 144-149.

Clavero, J.; Gardeweg, M.; Mpodozis, C. 1998. Mapa Geológico Preliminar del área de Salar de Piedra Parada, Región de Atacama. Servicio Nacional de Geología y Minería, 1 mapa escala 1:100.000, Santiago.(*)

Clavero, J.; Mpodozis, C.; Gardeweg, M.; Valenzuela, M. 2012. Geología de las Áreas Laguna Wheelwright y Paso San Francisco, Región de Atacama. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 139-140: 32 p., 1 mapa escala 1:100.000. Santiago.

Froger, J.L.; Remy, D.; Bonvalot, S.; Legrand, D. 2007. Two scales of inflation at Lastarria-Cordon del Azufre volcanic complex, central Andes, revealed from ASAR-ENVISAT interferometric data. Earth and Planetary Science Letters 255 (1-2): 148-163. DOI: 10.1016/j.epsl.2006.12.012.

Naranjo, J.A.; Cornejo, P. 1992. Hoja Salar de la Isla. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, No. 72, escala 1:250.000.

Naranjo, J.A.; Villa, V.; Venegas, C. 2013a. Geología de las áreas Salar de Aguilar y Portezuelo del León Muerto, Regiones de Antofagasta y Atacama. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 151-152 p., 1 mapa escala 1:100.000.

Naranjo, J.A.; Villa, V.; Venegas, C. 2013b. Geología de las áreas Salar de Pajonales y Cerro Moño, regiones de Antofagasta y Atacama. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica 153-154, 1 mapa escala 1:100.000. Santiago.

Naranjo, J.A.; Villa, V.; Ramirez, C.; Pérez de Arce, C. 2014. Miocene to Recent geological evolution of the Lazufre segment in the Andean volcanic arc. *AGU submitted resume.*

Naranjo, J.A.; Ramirez, C.A., Villa, V. C. En preparación. Geología de las áreas Cerro Panteón de Aliste y Cerro Colorado, Región de Atacama. Servicio Nacional de Geología y Minería, Carta Geológica de Chile, Serie Geología Básica, 1 mapa escala 1:100.000. Santiago.

Pritchard, M.E.; Simons, M. 2002. A satellite geodetic survey of large-scale deformation of volcanic centres in the central Andes. Nature 418: 167-171.Froger et al., 2007

Ramírez, C.A. (2014). Análisis de Litofacies y Geocronología de las Ignimbritas Salar Grande, Región de Atacama, Andes Centrales de Chile (25°45´S – 26°15´S). Memoria de Título, Universidad de Chile, 85 p.

Ruch, J.; Anderssohn, J.; Walter, T.R.; Motagh, M. 2008. Caldera-scale inflation of the Lazufre volcanic area, South America, evidenced by InSAR. Journal of Volcanology and Geothermal Research 174 (4): 337-344. DOI: 10.1016 / j.jvolgeores.2008. 03.009.

Ruch, J.; Manconi, A.; Zeni, G.; Solaro, G.; Pepe, A.; Walter, T.R.; Lanari, R. 2009. Different deformation scales and stress field change in the Lazufre volcanic area, Central Andes Geophysical Research Letters 36. doi:10.1029/2009GL041276.

Saint Blanquat, M. (de), Tikoff, B., Teyssier, C., Vigneresse, J.L., 1998. Transpressional kinematics and magmatic arcs. In: Holdsworth, R.E., Strachan, R.A., Dewey, F.J. (Eds.), Continental Transpressional Tectonics: Geological Society, London, Special Publications, vol. 135, pp. 327–340.

Schnurr, W.B.W.; Trumbull, R.B.; Clavero, J.; Hahne, K.; Siebel, W.; Gardeweg, M. 2007. Twenty-five million years of silicic volcanism in the southern central volcanic zone of the Andes: Geochemistry and magma genesis of ignimbrites from 25 to 27 °S, 67 to 72 °W. Journal of Volcanology and Geothermal Research 166: 17–46.

Siebel, W.; Schnurr, W.; Hahne, K.; Kraemer, B.; Trumbull, R.; van den Bogaard, P.; Emmermann, R. 2001. Geochemistry and isotope systematics of small-to-medium volume Neogene-Quaternary ignimbrites in the southern central Andes: evidencie for derivation from andesitic magma sources. Chemical Geology 171:2013-237

.

Table 1. Volcano and ignimbrite units and their caldera source in the southern Central Volcanic Zone, between 24.5º and 27ºS.

	Volcano Chronostratigraphic unit(*)	Ignimbrite unit groups	Age (Ma)	Caldera System (diameter in km)	Volume (km^3)
Pleistocene	5 y 6	Caletones-Cori	0.5	Shield Ignimbrite	2.5
Pliocene	4	Laguna Verde	4-3	Laguna Amarga-Laguna Escondida (~33 and 40 x 16)	630
Miocene		Parinas	5	Pampa de los Bayos (14)	50
		Wheelwright	6.6-4	Wheelwright (19)	100
		Los Colorados	10-9	Los Colorados (33)	250
	3	Salar Grande - San Andrés	12-10	Salar Grande (50 x 25)	220
		Chixi	14	Juan de la Vega (22 x 17)	<4
	1 and 2	Vega Helada - Juncalito	24-16	Aguilar-Infieles (~42 and 38 x 23)	2.500 - 3000
		Rio Frio - Pajonales	24-15		

(*) After Naranjo and Cornejo (1992), Naranjo et al., (2013a, b, En preparación).

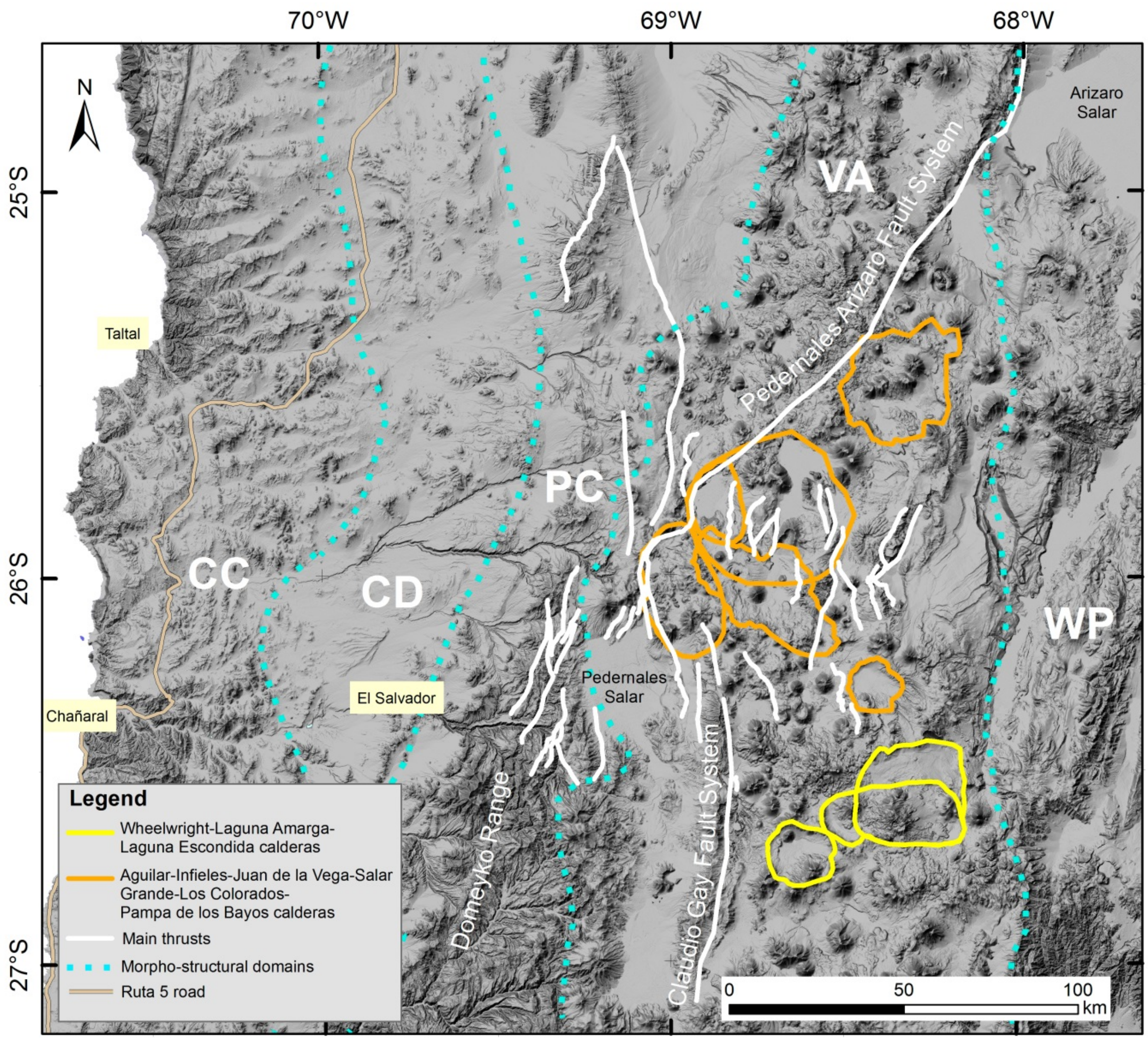

Fig. 1. DEM image of Central Andes between 24.5º and 27ºS, showing the main morphostructural domains (after Accocella et al., 2007), thrusts and calderas. CC: Coastal cordillera, CD: Central Depression, PC: Precordillera, VA: Upper Cenozoic Volcanic Arc, WP: Western Puna.