EVOLUTION OF A LONG-LIVED VOLCANIC COMPLEX: THE CHACHANI CASE STUDY (SOUTH PERU)

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The study of numerous individual volcanoes carried out in the Central Andean Volcanic Zone over the past 20 years has provided information to better understand active volcanism in the Peruvian Andes. However, large-sized, dormant volcanic complexes remain much less understood due to their complexity or because the impact of individual active volcanoes on populated areas has led researchers to prioritize their study on the most recent composite cones. Large, long-lived volcanic complexes have not yet been considered in volcanological studies in Peru, although they belie a rich history of eruptive activity that may be more recent than previously thought. The Chachani Volcanic Complex (CVC) is one of the few Andean volcanic complexes in which the relationships between stratigraphy, chronology and compositional changes are considered to understand the compositional evolution of a long-lived magmatic system.

1. THE UPDATED GEOLOGIC MAP

The CVC has been described in previous studies as one single Pleistocene volcanic unit called “Volcánico Barroso”, i.e. the upper unit of Barroso Group (Mendivil, 1965). The National Geological Map of Arequipa N° 33-s (scale 1/100,000, INGEMMET, 2000) represents the Nevado Chachani as a group of three volcanic edifices of Pleistocene age. They are, in chronological order, the Nocarane and Chachani stratovolcanoes, and Cortaderas dome-coulees, all belonging to the Barroso Group. More recently, Suaña (2011) described a preliminary chrono-stratigraphic evolution of Chachani complex based on field work. According to Suaña (2011), the volcanic complex consists of a cluster of eight stratovolcanoes and dome groups that were active during the entire Pleistocene. Kaneoka and Guevara (1984) report a K/Ar age of 0.28±0.10 Ma, which is roughly located in the Uyupampa lava field west of Nevado Chachani. Based on field work, a 2009 SPOT5 scene and Google Earth images and 40Ar/39Ar ages, the 1:50,000 scale updated geologic map and chrono-stratigraphy together with analysis of major and trace elements of 74 lava samples have enabled us to determine the temporal and compositional evolution of the entire CVC (Table 1 & Fig. 1)

Table 1. 40Ar/39Ar ages of CVC (B. Jicha, Department of Geosciences, University of Wisconsin-Madison).

Sample	Edifice	Unit	UTM coordinates North	UTM coordinates East	Lithology	Material	$^{40}Ar/^{39}Ar$ age (ka±2σ)
Cha- 02-32	Cabrería	Ca-1	8196348	230640	lava	groundmass	56.5±31.6
Cha- 08-44	Chachani	Cha-6	8210279	227958	lava	groundmass	130.3±38.4
Cha-08- 31	Chachani	Cha-1	8204909	230078	lava	groundmass	131.5±3.7
Cha- 02-33	Uyupampa	Uyu-1	8206885	216438	lava	groundmass	231.7±36.2
Cha-04-02	Airport Domes	Da-8	8196669	217651	lava	plagioclase	291.6±44,7
Cha- 02-04-JC	Airport domes	Da-3	8195641	225903	lava	groundmass	368.8± 61.9
Cha-12-05	Airport Domes	Da-1	8202150	227400	Lava	groundmass	397±40
Cha-02-19	Colorado	Col-1	8221403	223762	lava	groundmass	641.8±88,2
Cha- 02-17	Estribo	Estr-10	8208953	234803	lava	groundmass	694.1±74.9
Cha- 02-06-JC	Nocarane	Noc-5	8199784	231938	lava	groundmass	754.0±9.5
Cha- 02-24	Estribo	Est-8	8215060	237388	lava	plagioclase	808.5±62,7
Cha- 02-26	Chingana	Noc-2	8217759	234368	lava	groundmass	916.5±41.1
Cha-08-07	Yura Tuff		8214022	217998	Pumice	Plagioclase	1278.1±46

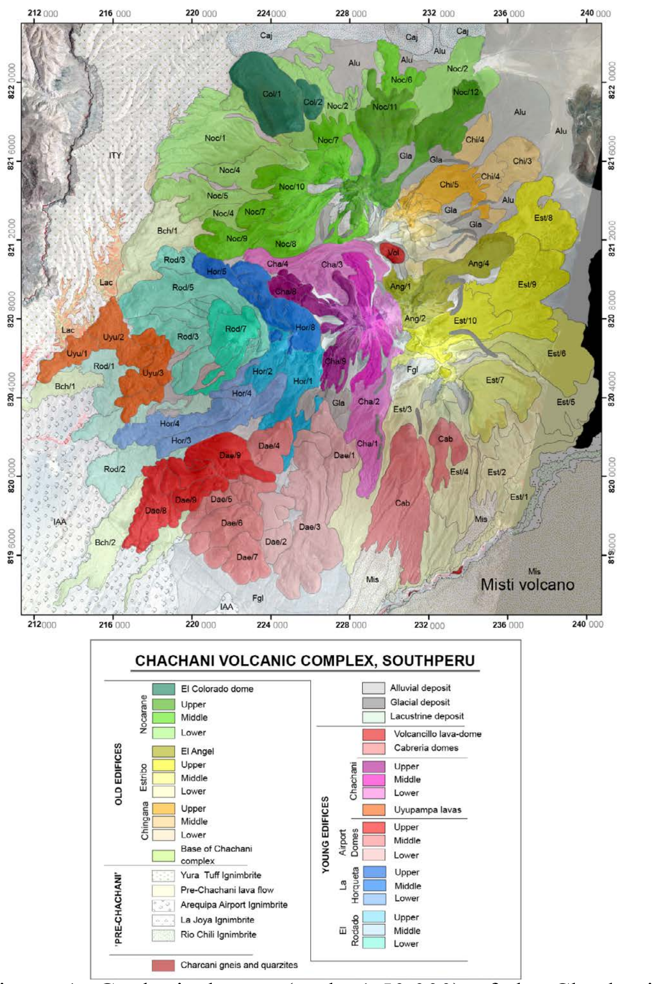

Figure 1. Geological map (scale 1:50,000) of the Chachani Volcanic complex, draped over a 2009 SPOT5 image (2.5 m pixel), display 12 edifices as well as the Chachani Base lavas and Pre-Chachani bedrock. The color characterizing each edifice is used in all figures to refer to the same edifice (e.g. green for Nocarane volcano).

A classification scheme was used to distinguish several units that have built up as many as 12 edifices, divided into three main groups: (1) the oldest Pre-Chachani lavas underlay the Yura Tuffs dated at 1.278 Ma. (2) The Old edifices group, built up between ~1 Ma and 642 ka, consists of Chachani Base lavas, Chingana, Estribo, El Angel and Nocarane composite cones, and El Colorado two dome coulees. (3) Young edifices encompass El Rodado composite cone, La Horqueta cumulo dome, the Airport Domes cluster, Uyupampa lava flow field, Chachani stratocone, and Cabrería and Volcancillo domes coulees. Based on stratigraphic contacts, mapping and thirteen 40Ar/39Ar ages (Table 1) we divided each of the edifices in lower, middle and upper units. Erosional and angular discordances, morphological similarities and the location of vents allow us to define each unit.

2. GROWTH AND VOLUME ESTIMATE OF THE CVC

The Chachani volcanic complex, with an area about 600 km2 (measured on the GIS embedded geological map), is characterized by lava flows, PDC and tephra ranging in composition from basaltic andesite to dacite. Some lava flows extend as far as ~ 10 km from their source, but most of them are shorter, stubby "aa" or block-lava flows. The bulk of this volcanic complex is made up of an overwhelming amount of lava flows, which have built 12 volcanic edifices in a relatively short time period (~1 Ma). Geometrical and geomorphic parameters, together with the outlined contact between CVC and its bedrock, have helped us to compute the volume of each individual edifice based on one 2009 SPOT5 image and Google Earth images (Table 2). The volume of pyroclastic deposits has not been taken into account.

Table 2. Estimated volumes for each volcanic edifice composing the CVC.

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Stratigraphy	Type	Sub-Edifice	Area (km²)	Subarea	Max thickness (m)	Min thickness m	Rounded volume km³
YOUNG EDIFICES							
12. VOLCANCILLO	Dome coulee	Dome	0.95	0.53	380	250	0.20-0.30
		Lava flow		0.42	200	150	
11. CABRERIA	Domes coulees	Dome	20.20	6.20	1000	800	2.80-3.80
		Lava flows		14.00	100	50	
10. CHACHANI	composite cone	Lava cone	44.85		2000	1600	20.60-25.70
9. UYUPAMPA	Lava flows (aa)	Lava field	15.89		130	100	1.60-2.10
8. AIRPORT	Cumulo domes	West cluster	67.84	43	1000	800	7.60-9.70
DOMES	Domes coulees	East cluster		24.84	750	550	
7. LA HORQUETA	Cumulo dome	Dome coulée	39.9	7.85	1000	500	2.20-5.00
		Lava flows		32.05	80	30	
6. EL RODADO	Composite cone	Cone	50.50	11.50	1000	800	4.25-7.10
		Lava flows		39	120	60	
OLD EDIFICES							
5. COLORADO	Dome coulee	Upper dome	12.26	5	400	300	2.80-3.70
		Lower dome		7.26	200	150	
4. NOCARANE	Composite cone	Eroded	121.02		2200	1760	44.50-97.50
3. EL ANGEL	Composite cone	Eroded	12.95	7.65	1100	900	3.30-4.30
		lava flows		5.3	120	80	
2. ESTRIBO	Composite cone	Eroded	120.50		2300	1900	40.30-48.80
1. CHINGANA	Composite cone	Eroded	44.17		1400	130	21.80-36.70
BASE CHACHANI	Lava flows	Upper LF	27	13	50	30	0.90-2.80
		Lower LF		14	150	30	
						YOUNG EDIFICES	**40-54**
						OLD EDIFICES	**114-194**
						TOTAL VOLUME	**154-248**

The preserved bulk volume of the entire CVC was computed between 154 and 248 km3, and as much as 289 km3 based on DEM and a bedrock slope of 4-5% from NE to SW. The preserved old edifices group has produced a volume range of 114-194 km3, although glacial erosion and flank landslides have decreased at least one fourth of the original built volume of the old edifices. CVC is one the largest volcanic complexes in the Central Volcanic Zone and arguably in the Andes (Fig. 2). Computed volume of 40–54 km3 for the young edifices represent one-fourth of the volume estimate of the CVC old edifices. Young edifices are volumetrically similar to young, un-eroded composite cones of the Pleistocene volcanic range in south Peru (e.g. Ubinas, Misti; Thouret et al., 2001).

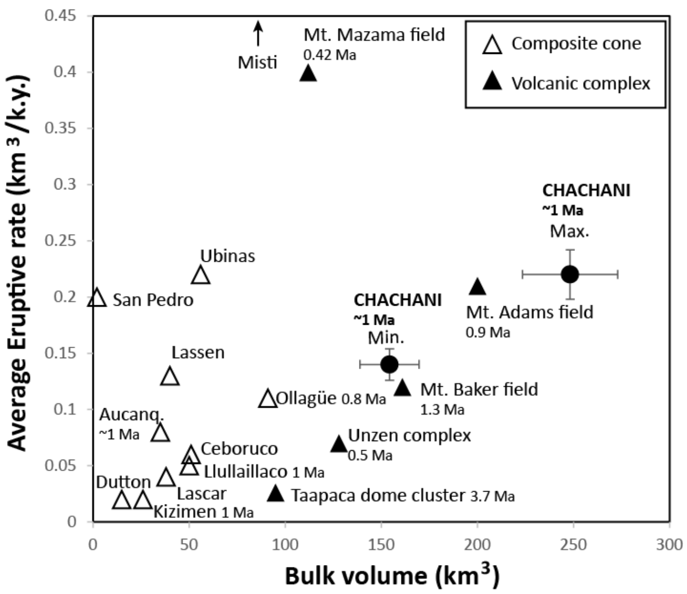

Figure 2. Bulk volume versus average eruptive rate for major dacite and andesite volcanoes worldwide compared to composite cones.

The entire CVC estimated volume, however, is not at odds with volumes computed by other authors who have described large regional volcanic complexes or clusters. The volume of the Mount Mazama massif with a 450 ka-long eruptive history is estimated to be 58 – 112 km3 (Bacon & Lanphere, 2006). The Mount Adams regional field, which has erupted 200 km3 during ~0.9 Ma (Hildreth & Lanphere, 1994), is comparable with the CVC volume.

3. TEMPORAL AND COMPOSITIONAL EVOLUTION OF THE CVC

Major elements of 74 samples indicate that CVC lavas belong to a high-K calc-alkaline suite.
Detailed stratigraphy for each of the individual edifices of the CVC allows us to rank all samples according to relative chronology supported by 40Ar/39Ar

age determinations. This temporal sample distribution enables to follow up the compositional variations across the CVC eruptive history. As a result, SiO2 contents show that the three groups identified in CVC exhibit different compositional behaviors (Fig. 3):

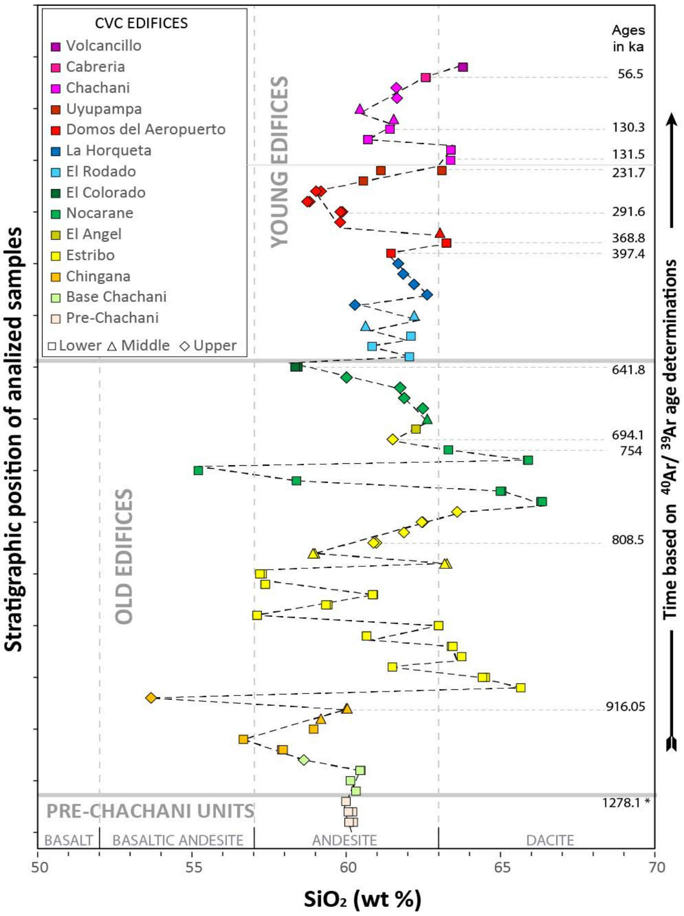

Figure 3. Variations in magma compositions as a function of time for all CVC edifices. The vertical position of samples follows a relative stratigraphic position based on 40Ar/39Ar ages. The vertical dimension of diagram is not intended to be proportional to time.
* Age of Yura Tuffs (this study) emplaced between Pre-Chachani lavas and Chachani edifices.

(1) the oldest Pre-Chachani lava units (>1.28 ka) show homogeneous andesite compositions close to 60 wt.% SiO2. (2) Old stratovolcanoes (~1000 - 640 ka) aligned along N130° and N160° trends in the northeast side of the CVC show a wide compositional range from basaltic andesite to dacite (53–67 wt.% SiO2). (3) Young edifices (640–56 ka), aligned along a N70° direction in the central part of the complex, show a narrower compositional range (59–64 wt. % SiO2). Our additional study of trace elements (Ba/Th versus La/Yb) also shows that the CVC and the Arequipa Airport Ignimbrite stem from the same magmatic system. This supports the hypothesis that the potential source of the Pleistocene ignimbrites that filled the Arequipa basin is to be found beneath the CVC (Paquereau-Lebti et al., 2008).

CONCLUSION

The eruptive history evolution of the Chachani Volcanic Complex in south Peru has been described through detailed mapping, stratigraphy and Ar/Ar chronology of 12 edifices composing the long-lived (1 Ma) magmatic system (Fig. 1, Table 1). The three groups comprise: (1) the oldest Pre-Chachani consisting of andesitic lavas (>1.28 Ma), (2) the old edifices (<1000 – 640 ka) exhibiting a wide range of basaltic andesite to dacite compositions (Chachani Base, Chingana, Estribo, El Angel, Nocarane composite cones, and El Colorado dome coulees), and in contrast (3) the young edifices (>400 – 56 ka) which are characterized by a more restricted range of andesite and dacite compositions (El Rodado and La Horqueta cumulo domes, the Airport Domes, Uyupampa lava flows, Chachani stratocone, and Cabrería and Volcancillo domes). The temporal-compositional evolution of the CVC lavas suggest homogenization of magmas through time as expressed by the narrow compositional range of Young edifices despite a variety in mineral assemblages.

The bulk volume of each of the CVC edifices has been estimated despite a number of uncertainties due to the poor knowledge of structures and thicknesses of deep units. Taking the contact between CVC and bedrock and several morphometric parameters, we obtained a range of minimum total volume between 154 and 248 km3. Old edifices represent 75% whereas young edifices represent about 25% of this volume. The CVC is a singular, fast growing, post-caldera magmatic system due to its large volume attained in 1 Myr-long eruptive activity, compared to other volcanic complexes in the Central Andean Volcanic Zone.

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