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Discovery of a large resurgent caldera at Incahuasi, southern Ayacucho Province, Peru

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1. Introduction

The Central Volcanic Zone (CVZ) of the Andes is well known for its intense silicic volcanism, with emplacement of large-volume plinian fall deposits and ignimbrites in Cenozoic to Quaternary times (de Silva and Francis, 1991). The CVZ hosts a number of silicic calderas (super-volcanoes) that are preserved in nowadays topography or have been inferred from volcanological studies (e.g. calderas concealed beneath younger stratovolcanoes). While source calderas of several CVZ ignimbrites have been identified, many others are still unknown because they experienced later volcanism, fluviatile and glacial erosion, as well as tectonic dismantling. This is the case in Southern Peru where successions of voluminous ignimbrites with unknown sources are exposed in 2–3.5 km-deep canyons of Ica, Ayacucho, Arequipa, and Moquegua provinces (Sébrier and Soler, 1991; Thouret et al., 2007; 2016; Schildgen et al., 2009; de La Rupelle, 2013). In this note we describe for the first time a large resurgent caldera in Southern Ayacucho province, where geothermal and epithermal economic potentials might exist.

2. Geological context and methods

The structure described below occurs in the region between Coracora, Jaqui and Pauza (Olchauski, 1998; Diaz and Milla, 2001). To the south of the studied area the coastal batholith exposes gneisses and associated younger silicic intrusives of Cretaceous-Paleogene ages, overlain by thick successions of deformed and slightly metamorphised Triassic and Jurassic sediments. Younger Cenozoic successions rest discordantly on top of the folded Mesozoic sediments and chiefly consist of Neogene to Quaternary andesitic to dacitic lavas and domes, as well as conspicuous volcaniclastic and epiclastic deposits. These sequences also include thick and widespread rhyolitic ignimbrite units, which crop out with non to strongly welded facies in local canyons and hills, and over vast tabular surfaces of the region (Schildgen et al., 2009; de La Rupelle, 2013; Thouret et al., 2016). On the eastern side of the studied area the Sara Sara volcano (5522 m above sea level, asl., Fig. 1) grew up in Pleistocene times through extrusion of voluminous silicic lavas and domes, with repeated violent rhyolitic plinian events. The whole region witnessed intense tectonic and magmatic activity during the Andean orogenic uplift and major folds and faults of different directions are common in the area (Sébrier and Soler, 1991).

We conducted several field surveys in the region located between Coracora and Pauza cities (Fig. 1) by investigating stratigraphic, lithologic, and structural features of the area, with emphasis on volcanic, pyroclastic and epiclastic successions. We carried out geological mapping, rock sampling and tephra studies, along with petrographic determinations (e.g. mineralogical assemblages, pumice textures, degree of welding in ignimbrites, etc.). We also inspected 1/100000 topographic documents as well as geological maps of INGEMMET (quadrangles Coracora 31-o, Chaparra 32-o, Caraveli 32-p, Pauza 31-p). In addition, we scrutinized freely public-accessible web-based satellite resources, as Google Earth-handled LANDSAT images and ASTER images. This approach proved extremely helpful to infer the geology of remote and hardly accessible areas, particularly in high altitude localities and steep-sided canyons.

3. Ignimbrite volcanism around Ocoña-Cotahuasi-Maran (OCM) canyons

Previous works in the OCM area have documented thick ignimbrite units in the so-called Huaylillas and Barroso formation (Sébrier and Soler, 1991). Recently dated ignimbrite sheets (Thouret et al., 2007; de La Rupelle, 2013; Thouret et al., 2016) include the Nazca (~24 Ma), Alpabamba (~18 Ma), Huaylillas-Chuquibamba (~14 Ma), and Caraveli (~ 9 Ma) units, each with a bulk volume exceeding 100 km^3. Other younger units of smaller volumes are also present.

Two major ignimbrite sheets are largely exposed in the region between Coracora and Pauza. The ~18 Ma-old Alpabamba unit crops out in valley walls as a thick (200-400 m) light-toned indurated tuff, and it bears yellowish to whitish fibrous rhyolitic pumice clasts which host plagioclase and sanidine, biotite, as well as some quartz, oxides and zircon crystals. The ~9 Ma-old Caraveli unit occurs as a 30-100 m-thick reddish- to orange-toned crudely jointed sheet that coats the landscape in many places of the area between Coracora and Pauza. It displays strongly welded facies with ample recrystallization in the region north of Caraveli village (located out of Fig. 1 to the southeast), while non to incipiently welded, beige- to pinkish-toned sillar-type facies are widespread south of Caraveli village. Where preserved the whitish rhyolitic pumice clasts display sub-fibrous textures and bear 10-15 vol.% phenocrysts with similar amounts of plagioclase and alkali feldspars, as well as pyroxene and biotite plates (commonly corroded and circled by oxide rims), and some quartz and zircons (de La Rupelle, 2013). Lateral variations of the welding intensity and the dendritic, rill-like drainage patterns observed around Caraveli village clearly support an ignimbrite source somewhere in the highlands above the village.

The area between Coracora and Pauza was already suspected to host some volcanic collapse structures. For example, based on examination of satellite images and field work, Diaz (2004) proposed a 55 km-large caldera system whose limits mainly coincided with local canyons. Anisotropy of Magnetic Susceptibility (AMS) data also pointed to a vent region for the Caraveli ignimbrite around Sara Sara volcano (Bréard, 2011), while Laguna de Parinacochas was as well suggested as a potential source (Thouret et al., 2016). Nevertheless, none of these works identified the structures and typical features that define a silicic caldera.

4. Evidence for a large caldera system at Incahuasi

The Caraveli ignimbrite crops out extensively across a vast area south and north of Caraveli village and can be followed up in the field and satellite images to a depressed area where it is unexposed. This low and flat area hosts Laguna de Parinacochas (3278 masl, Fig. 1), a ~10 x 8 km-wide salar (salt lake) located between the villages of Incahuasi, Yuracwasi, Incuyo, and Sallasalla (Fig. 1). The salar is roughly crescent-shaped in map view and is surrounded on its western side by a ridge of hills that culminate at about 3500-3700 masl, i.e. ~200-400 m above the level of the salt lake (Fig. 2). These hills mainly expose an altered whitish and yellowish non-welded ignimbrite unit (possibly the Alpabamba unit) capped by a 20-50 m-thick, loosely jointed, reddish- to dark-toned welded ignimbrite unit (most likely the Caraveli unit). Near Incahuasi the eastern side of the hills shows sliding structures towards the salt lake, and strong sulfur smell (from hydrothermal circulation and/or weathering of pyrite?) is perceived in a nearby extremely weathered site. South of the lake the upper red-tinted ignimbrite unit rests upon a wide and low-angle pass that separates the main drainage system towards Caraveli village and the Pacific Ocean from that oriented to the north towards Laguna de Parinacochas (Figs. 1 and 2). In the southern vicinity of Laguna de Parinacochas light-toned sediments lying on top of the red-tinted ignimbrite are exposed; they comprise regularly bedded clastic layers with marl intercalations and all bend gently towards Laguna de Parinacochas (Figs. 1 and 2). These sediments occur only in the topographic low near Laguna de Parinacochas, but not on the pass mentioned above (Fig. 1). On the eastern side of Laguna de Parinacochas conspicuous successions of quaternary dacitic to rhyolitic pumice flow, block-and-ash flow, and tephra fall deposits are exposed and hide older sequences. Thickness and directional data indicate they belong to nearby young Sara Sara volcano (whitish fan-shaped area near Sara Sara in Fig. 1). However, a set of older curved normal faults exist north of the fan and consist of large steps with collapse towards Laguna de Parinacochas lowlands.

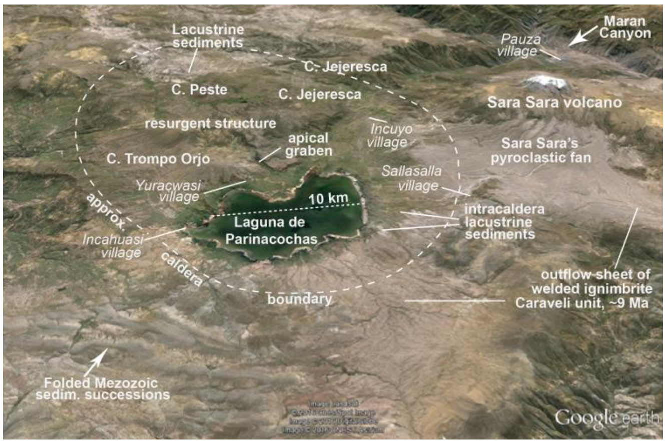

Figure 1. Oblique Google Earth view from the SW of the Incahuasi caldera system. The North is toward the upper-left corner of the image. The caldera boundary (visible and inferred) is indicated with a dashed line. The dendritic drainage south of Laguna de Parinacochas is cut within the welded outflow sheet of the ca. 9 Ma Caraveli ignimbrite unit.

We interpret these topographic and structural features around Laguna de Parinacochas as the southern part of a larger caldera system. The western caldera rim is particularly well preserved with relatively steep-sided walls, while the gently inclined to sub-horizontal borders on the southern side recall a hinged line described at other downsag-type calderas in the world. Nicely preserved slide features on the western side and normal stepwise fracturing on the eastern side point to a wide collapse structure between Incahuasi, Sallasalla and Incuyo, while lacustrine deposits south of Laguna de Parinacochas suggest a much larger lake in the depression after caldera collapse (Figs. 1 and 2). Similar sedimentary successions form 200-300 m-thick hills north of the volcanic massif of Cerro Trompo Orjo and Cerro Peste (Fig. 1). They consist of micro-conglomerates, sands and gravels, silts and clays, with some marls layers, which point to sedimentation in a lacustrine environment. We similarly interpret that these sequences were emplaced into a caldera lake. A steep-sided crescent-shaped scarp is observed 6-7 km north of Cerro Peste summit and may represent the norther rim of the collapsed structure, where hot springs are also present (e.g. Aguas Calientes site). Strongly altered areas with kaolin and silicified fields, fluid circulations, hot springs, bubbling, and sulfur smells occur mainly on and near the edge of the structure (Bellavista, Incahuasi, Chacaray east of Incuyo, etc.) and all evidence a major ~25x35 km-wide elliptical collapse caldera in the area. In this interpretation, the wide plain around Laguna de Parinacochas can be regarded as an intra-caldera moat, while the fine grained detritic and marl sequences support long-lived intra-caldera sedimentation, and the now-emerged deposits were either upheaved by later (volcano-?) tectonic processes, or appeared after drainage of a wider lake, or both. The presence of nearby rhyodacitic Sara Sara volcano and the existence of typical hydrothermal activity inside the caldera suggest that the intra-crustal silicic system feeding the caldera and the young Sara Sara volcano might still be active, thus raising questions about volcanic risks in the area.

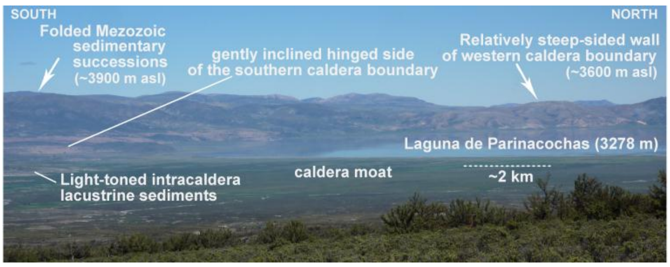

Figure 2. A west-looking view of the southern part of the Incahuasi caldera, showing the Laguna de Parinacochas (salar) and the surrounding moat, along with other features of the caldera boundary. The picture is taken from the western side of Sara Sara volcano (see Fig. 1).

5. Evidence for a central resurgent dome

A large massif sits North of Laguna de Parinacochas and culminates at Cerro Peste (4353 m asl., Fig. 1). It comprises several hills and summits that essentially expose a light-toned and strongly altered ignimbrite deposit (Alpabamba unit?) overlain by a 30-60 m-thick, densely welded and crudely jointed ignimbrite sheet, which we correlate to the Caraveli unit.

Several structural and volcanological lines of evidence indicate that a large part of this massif has undergone a significant uplift that cannot be fully explained by local or regional tectonic processes. The western massif called Cerro Trompo Orjo (4087 masl.) is a roughly low-angle cone cut in its central part by a noticeable ~N-S-trending depression (Fig. 1). The latter is about 1.6 km in width near Yuracwasi and it extends 8 km northward of the village and widens to 3-4 km in the center of the Trompo Orjo massif. Field examination of the depression near Yuracwasi (the "white village" in Quechua language) reveals that it does not result solely from erosion, but instead from local collapse of the center of the Cerro Trompo Orjo massif. The strongly welded ignimbrite that blankets most of the massif offers an excellent key marker horizon: it defines the low-cone shape of the massif, but occurs 100-200 m below the level of that cone inside the southern part of the depression, notably near Yuracwasi village. Moreover, well preserved landslide structures on the eastern side of the depression indicate that the latter resulted from local collapse of the central upper part of the Cerro Trompo Orjo massif. In addition, extremely altered ignimbrite materials are exposed along intensely fractured exposures near the village of Yuracwasi, where hetero-lithologic breccia and highly silicified and kaolinitized ignimbrite products crop out on both sides of the depression and within it. A hot spring and sulfurous smells are noticed along the western fault and in the eroded graben and the coeval detritic material sourced in the depression forms a small delta in Laguna de Parinacochas (Fig. 1). Noticeably, the lower whitish non-welded ignimbrite exposed within the graben displays sub-proximal facies with lithic concentration zones (and clasts above 1 m in diameter), which recall near-vent lag breccia documented at other silicic calderas in the world. The other massifs of Cerro Peste and Cerro Jejeresca (4206 masl., Fig. 1) are equally coated by the welded Caraveli ignimbrite, and locally show similar evidence of uplift. Tilted sedimentary sequences are exposed on the flanks of these massifs, whose eastern base almost meets the rim of the Incahuasi caldera.

We interpret the whole massif as a large resurgent dome structure located roughly in the center of the Incahuasi caldera. The size (16x18 km) and height (> 1 km) of the resurgence compares with those of other calderas worldwide. In addition, the strongly welded Caraveli ignimbrite key marker reveals that the central part of massif collapsed and formed an apical graben at Cerro Trompo Orjo that is a typical feature of resurgent calderas in the Andes and elsewhere. The size and shape of this apical graben are similar to those of summit depressions observed at many other resurgent calderas. Hydrothermal alteration, hot springs and sulfurous exhalation in the apical graben support a volcanic origin for this uplifted structure, although the orientation of the edging pull-apart-shaped faults may have been controlled by tectonic processes. The northern and eastern Peste-Jejeresca massifs may as well have been upheaved by intra-caldera processes, but we also suspect some tectonic effects related to a local compressive strain regime at some time after the formation of the Incahuasi caldera. On the other hand, the initial development of the caldera may have been promoted by local extensional regime during Miocene uplift of the northern part of the CVZ.

6. Conclusion

Analyses of stratigraphic, lithological, petrological and structural characteristics yield ample evidence for a large ~25x35 km-wide caldera system in the studied area (Incahuasi, Incuyo, Breapampa, Fig. 1) and the noticeable Laguna de Parinacochas lies in the southern sector of this 650 km^2 collapse structure, which we call the Incahuasi caldera. In addition, structural features as well as alteration patterns and hydrothermal manifestations bring robust indications for a large up-doming resurgence in the center of the Incahuasi caldera. Beyond this volcanological interpretation, the hot springs that occur in the area suggest the presence of heated aquifers at deeper levels inside the caldera; they may be of interest for geothermal exploitation, even if the volcanic system seems fairly old. Similarly, the epithermal deposits exploited in the Breapampa gold mine on the NW side of the structure confirm the strong link between caldera context and ore formation. Additional works on the Incahuasi caldera system are needed to decipher the probably complex history of its development and to disclose the associated economic potentials. Our study at Incahuasi illustrates the importance of conducting volcanological research for potential economic applications, and with this work we discovered the first large resurgent caldera of the whole Peruvian territory.

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