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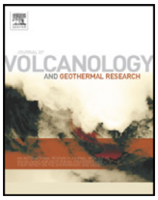

La Peligrosa caldera (47° 15′S, 71° 40′W): A key event during the Jurassic ignimbrite flare-up in Southern Patagonia, Argentina

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ABSTRACT

Pyroclastic and lava vent-facies, from the Late Jurassic El Quemado Complex, are described at the southern Lake Ghío, in the Cordillera Patagónica Austral. Based on the comprehensive study of lithology and structures, the reconstruction of the volcanic architecture has been carried out. Four ignimbrites and one rhyolitic lava unit, affected by oblique-slip normal faults have been recognized. The evolution of La Peligrosa Caldera has been modeled in three different stages:1) initial collapse, consisting of a precursory downsag subsidence, related to a dilatational zone, which controlled the location of the caldera, 2) main collapse, with the emplacement of large volume crystal-rich ignimbrites and megabreccias, under a progressive subsidence controlled by a pull-apart structure related to a transtensional regime and 3) post-collapse, in which lava flows and associated domes were emplaced under an oblique-extensional regime. The caldera records a remarkable change from transtension to oblique extension, which may represent an important variation in regional deformation conditions during Jurassic times. La Peligrosa Caldera may be considered a key event to understand the eruptive mechanisms of the flare-up volcanism in the Chon Aike Silicic Province.

1. Introduction

Ancient calderas offer exceptional insight into those lithofacies and structures commonly buried in modern calderas. In particular, collapse-related breccias may be exposed in deeply eroded cases, giving the opportunity to explore both mechanisms and timing of the caldera collapse. In addition, the role of regional tectonics in controlling the caldera inception may be assessed.

Unlike other ancient and large-volume ignimbrite fields, where collapse calderas are commonly recognized (Lipman, 1975; Steven and Lipman, 1976; Busby-Spera, 1984; Lipman, 1984; Swanson and McDowell, 1984; Aguirre-Díaz et al., 2008), only a few well-documented calderas were assumed to be associated with Jurassic Patagonian volcanism (Sruoga, 1994; Aragón et al., 1996; Fernández et al., 1996; Chernicoff and Salani, 2002; Guido, 2004; Echavarría et al., 2005; Sruoga et al., 2010). Several factors may be considered responsible for the poor preservation of structural or lithological evidence which may be undoubtedly related to caldera-forming eruptions. Particularly, the overlapping of many successive large-volume ignimbrite events during ~35 Ma along the southwestern margin of Gondwanaland (Fig. 1a), combined with a low post-Jurassic erosion rate in the extra-Andean domain, led to the concealment of eruptive centers.

On the northeastern flank of the Sierra Colorada at 47°S (Fig. 1b), Tertiary Andean thrusting and Cenozoic strong glacial erosion permitted the exhumation of the roots of the deeply dissected La Peligrosa caldera (Sruoga, 1994; Sruoga et al., 2008, 2010). Moreover, it is a unique window from where the eruptive mechanisms prevailing throughout the Jurassic ignimbrite flare-up in the southwestern margin of Gondwana might be examined.

The aim of this paper is to describe complex intracaldera stratigraphy and structures, and to propose a model for the evolution of La Peligrosa caldera. Key pieces of evidence have been taken into account to reconstruct the volcanic center and to unravel the collapse mechanisms leading to the caldera formation. Particularly, the megabreccia, herein described and interpreted as a collapse breccia deposit for the first time, provides relevant evidence for the caldera reconstruction. In addition, the role of previous structures in controlling the caldera development is discussed. As the original dimensions are no longer preserved no volume calculation has been carried out.

2. Geological setting

In Patagonia, the Jurassic (188 to 153 Ma, Pankhurst et al., 2000) silicic magmatic rocks are known as the Chon-Aike Province, one of the two Gondwana Granite–Rhyolite Provinces defined by Kay et al. (1989). The Chon-Aike Province (Fig. 1a) was emplaced in the first

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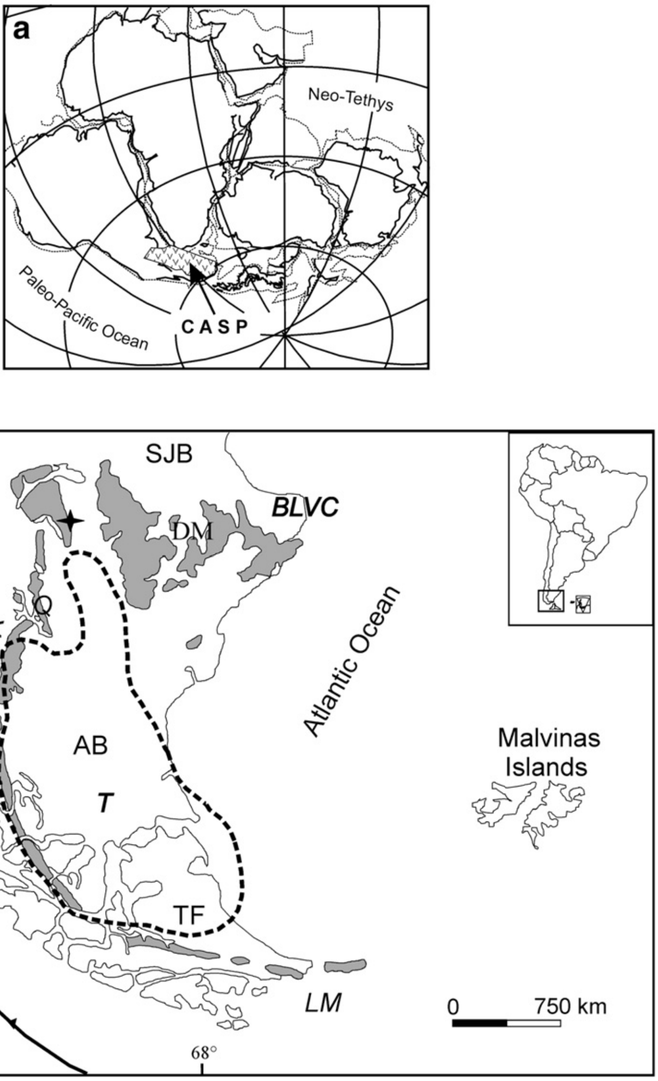

Fig. 1. a) Location of the Chon Aike Silicic Province (CASP) in Gondwanaland adapted from Vaughan et al. (2005). b) Sketch map of Southern Patagonia showing the main outcrop areas of South CASP. SJB: San Jorge Basin. AB: Austral Basin. DM: Deseado Massif. CPA: Cordillera Patagónica Austral. TF: Tierra del Fuego. Main local stratigraphic names are included (BLVC: Bahía Laura Volcanic Complex, Q: El Quemado Complex, I: Ibáñez Formation, T: Tobífera, LM: Lemaire Formation). The study area is indicated with a star.

stages of Gondwana breakup, within a complex and dynamic tectonic setting. A combination of slow subduction rates at the proto-Pacific margin with the activity of the Karroo mantle plume and a clockwise rotation of the axes of the Pacific magmatism since the Triassic has been proposed (Storey et al., 1992; Rapela et al., 2005). The province covers an area of *ca*. 700,000 km^2, including the subsurface of the San Jorge and Austral oil-productive basins, the Continental Platform and the Antarctic Peninsula. A minimum volume of 235,000 km^3 has been estimated (Pankhurst et al., 1998). Based on its huge size and monotonous silicic composition, it was defined as a silicic LIP by Pankhurst et al. (1998) and renamed as the Chon-Aike Silicic Province (CASP) by Sruoga et al. (2010). It extends from the Atlantic to the Pacific coast and it is better exposed in the North Patagonian and Deseado massifs and along the Andean Cordillera, where it has local stratigraphic names (Fig. 1b). Distinctively, the volcanic province includes either silicic-dominated monotonous series or bimodal assemblages. It encompasses large-volume ignimbrite plateaus and granites, with subordinated lavas, domes and dykes, and interbedded epiclastic rocks. Locally, andesites and trachyandesites are relatively abundant (Sruoga, 1989; Pankhurst and Rapela, 1995; Pankhurst et al., 1998).

In the southern CASP, the volcanic rocks are remarkably similar in their lithology and geochemical composition and they may be distinguished only on the basis of post-Jurassic tectonic deformation.

In the Deseado Massif, where many low sulfidation gold and silver deposits are associated with the Bahía Laura Volcanic Complex (Schalamuk et al., 1999; Guido and Schalamuk, 2003), the volcanic rocks are predominantly flat-lying and relatively undeformed. They overlie Early Paleozoic to Early Jurassic sedimentary and igneous rocks. In contrast, the silicic rocks in the Andean Cordillera have been variably deformed during the Cenozoic Andean orogeny. Locally known as El Quemado Complex (Riccardi, 1971), Tobífera (Thomas, 1949) and Lemaire Formation (Borrello, 1969) they extend from the province of Chubut (42° S) to Tierra del Fuego and Isla de los Estados (51° S) (Fig. 1b). This unit overlies a Paleozoic low-grade metamorphic basement, known as Río Lácteo Formation. It consists of black shales, interbedded metagreywackes and quartz phyllites and it was tentatively assigned to the Devonian–Carboniferous (Riccardi and Rolleri, 1980). During the Permian, the basement was deformed (Ramos, 1982) resulting in a NNE to N–S structural grain (Giacosa and Franchi, 2001). In Jurassic times, a regional and long-lasting extensional regime resulted in a system of grabens and half-grabens, controlled by NW–SE trending faults (Ramos, 1989; Kraemer et al., 2002). According to Homovc et al. (1996) the main NNW trending structures show evidence of transtensional behavior since the Early Jurassic. Elsewhere, Japas et al. (2007, 2013a) and Sruoga et al. (2010) studied the close relationship between the Chon-Aike silicic volcanics and the normal faulting system and identified strike-slip components associated with these faults. The rifting tectonics prevailed until the Early Cretaceous and ultimately led to the opening of the Atlantic Ocean. In the early stages of the Gondwana break-up, a dominantly mafic to bimodal volcanism, probably related to the activity of the Karroo plume, took place (Pankhurst et al., 2000). Subsequently, the volcanic activity became essentially silicic and shifted episodically towards the Pacific margin (Storey et al., 1992). Based on SHRIMP U–Pb zircon dating, Pankhurst et al. (2000) defined three main episodes: V1 (188–178 Ma), V2 (172–162 Ma) and V3 (157–153 Ma). The youngest episode of this westward migration corresponds to the emplacement of the volcanic rocks belonging to El Quemado Complex and the Ibañez Formation, in Argentina and Chile, respectively. At Sierra Colorada, Rb–Sr data for ignimbrites gave an errorchron of 136 ± 6 Ma (Pankhurst et al., 1993) and a SHRIMP age of 154.1 ± 1.5 Ma (Pankhurst et al., 2000). A similar age of 156.5 ± 1.9 Ma was reported by Iglesia Llanos et al. (2003) on ignimbrites from the nearby location of Lago Posadas.

Cretaceous near-shore marine sandstones of the Springhill Formation and continental deposits of the Río Tarde Formation overlie the El Quemado Complex (Giacosa and Franchi, 2001). In the Tertiary, the Andean deformation developed a fold and thrust belt within a triangle zone and associated back thrusts (Ramos, 1989). During this orogenic cycle, the rift system was locally inverted along the main extensional and/or transtensional fault zones (Giacosa and Franchi, 2001).

El Quemado Complex encompasses rhyolitic ignimbrites, volcanic breccias, tuffs, andesitic, dacitic and rhyolitic lavas and domes, conglomerates and sandstones (Giacosa and Franchi, 2001). Sruoga (1989) described several detailed sections in the pre-Andean area of Sierra Colorada and in the nearby Andean region of the Oro River and Lake Belgrano, in order to correlate the different volcanic events and to identify the eruptive centers. Even though El Quemado Complex is very similar to its equivalent in the Deseado Massif (Fig. 1b), some important features may be pointed out: a) the minor but significant participation of andesitic lavas in the sequence, b) the presence of interbedded hyaloclastites and peperites in the proto-Pacific margin (Hanson and Wilson, 1993), c) the intense and pervasive chloritic/propylitic alteration, and d) the geochemical evidence indicating a continental volcanic arc signature (Sruoga, 1989; Pankhurst et al., 1998; Riley et al., 2001).

Chon-Aike rocks belong to rhyolite-dominated calc-alkaline suites. They are low and high-silica, high-K and slightly peraluminous. Taking into account the behavior of certain trace elements, several subgroups may be recognized. However, most of the rocks plot in the low-Zr (75–206 ppm)/low-Nb (2–10 ppm) field (Pankhurst et al., 1998), similar to the subalkaline subduction-related magmatic series. A common and distinctive feature is the high degree of post-emplacement alteration, which leads to unrealistic contents in many mobile elements. Particularly, K- enrichment is due to deuteric feldspar dissolution and recrystallization during the protracted ignimbrite cooling history (Sruoga et al., 2004; Sruoga and Rubinstein, 2007).

A suitable petrogenetic model includes basalt underplating and partial melting of Grenvillian age mafic lower crust, which resulted in an isotopically homogeneous magma after long-term storage (Pankhurst and Rapela, 1995; Riley et al., 2001). Rhyolites should have equilibrated at shallow depth, under low temperatures (<800 °C), in high-level reservoirs (<5 km). They may be derived from silicic andesites within a two-step fractional crystallization model (Sruoga, 1989). In addition, minor upper-crustal contamination may be invoked to account for some geochemical variation (Riley et al., 2001).

3. Stratigraphy of La Peligrosa caldera

On the northeastern flank of Sierra Colorada two main ignimbrite-dominant sequences, La Peligrosa and Sierra Colorada, may be distinguished (Figs. 2, 3a). With no base exposed, La Peligrosa sequence may be subdivided into five caldera-related lithofacies (Sruoga et al., 2008, 2010). They crop out from the lowest part of the Sierra Colorada to the southern margin of Lake Ghío (Fig. 2). Overlying them, the Sierra Colorada volcaniclastics make up more than 800 m thickness of the highest peak. They constitute a flat-lying pile of thin high-grade and thick non-welded ignimbrites with interbedded laminated epiclastic rocks (Fig. 3a). Glacial erosion has strongly polished these rocks, which are partially covered by drift deposits (Fig. 2).

La Peligrosa volcanic sequence represents the main scope of this study and it includes five units, from base to top: La Peligrosa Ignimbrite, La Salina Breccia, Los Acantilados Ignimbrite, Cerro Ghío Ignimbrite, and Cerro Las Cuevas Rhyolite.

3.1. La Peligrosa Ignimbrite

Although poorly exposed near the main house of La Peligrosa ranch (Fig. 2), this unit is relevant to the model of the caldera evolution, as it will be further discussed. With no base exposed, it underlies the Cerro Ghío Ignimbrite, whereas eastwards, both pyroclastic units rest on a fault contact.

La Peligrosa Ignimbrite is a complex volcaniclastic sequence, encompassing dominant pyroclastic and minor interbedded epiclastic deposits. Light green in color, due to pervasive chloritic replacement, it makes up the lowest ~100 m thickness of the northeastern flank of the Sierra Colorada (Fig. 3a).

The sequence begins with a pumice- and lithic-rich ignimbrite deposit, ~30 m thick and partially welded. Volcanic and metamorphic clasts, up to 20 cm in size, are concentrated in crudely stratified layers. The pumice fragments are dark green and variably flattened due to welding. Only locally, eutaxitic zones may be observed. Crystals, commonly broken, compose up to ~40 vol.% with quartz > sanidine > plagioclase > biotite, opaques and zircon. Vitric shards are rarely observed and slightly deformed, while pumices are thoroughly devitrified into granophyric textures. A distinctive feature of this unit is the presence of tiny euhedral crystals of quartz, alkali-feldspar and albite, hosted by relict phenocrysts, vesicles and other pore spaces. This deuteric vapor-phase crystallization is very common in many non-welded to partially welded ignimbrites elsewhere in the CASP (Sruoga et al., 2004; Sruoga and Rubinstein, 2007).

Overlying the lowest ignimbrite deposit, accretionary-lapilli beds and planar laminated to thin-bedded sedimentary rocks are recognized. The best exposure is located 1,000 m southwards of the main house. The 38-m-thick epiclastic deposit, includes 1-to-5-cm laminated tuffaceous accretionary lapilli-bearing layers, thin black shales, a 20-cm-thick non welded ignimbrite deposit, pale gray shales displaying occasional mud cracks and raindrop marks and, at the top, greenish pink tuffaceous beds. This sequence would indicate a deposition in non-permanent lagoons or lakes, developed under a depth fluctuation regime with periodic subaerial exposure, coeval with the volcanic activity.

The upper ~20 m of the section consists of partially welded ignimbrites and thin cross-bedded lithic-poor pyroclastic surges. The ignimbrites are very similar to the ones at the base of the sequence.

Propylitic alteration is ubiquitous in La Peligrosa Ignimbrite. Typically, chlorite + calcite + sericite paragenesis, in a variable proportion, either replaces crystals and groundmass, or infills open spaces as vesicles or fractures (Sruoga et al., 2010).

The Cerro Ghío Ignimbrite overlies the sequence, showing a remarkable thinning in comparison to nearby equivalent outcrops, like Cerro Ghío itself, where the ignimbrite reaches a thickness of hundreds of meters.

3.2. La Salina Breccia

The main outcrops surrounding La Salina ephemeral lagoon (Figs. 2, 3b, 4a) constitute a 40-to-60-m-thick chaotic deposit, with blocks of as much as 300 m across, immersed in a pyroclastic matrix (Fig. 4b). The breccia includes different types of lithics: Paleozoic basement schists, phyllites, quartzites and granites belonging to the Río Lácteo Formation, Jurassic (?) andesites, rhyolites and ignimbrites, and laminated and

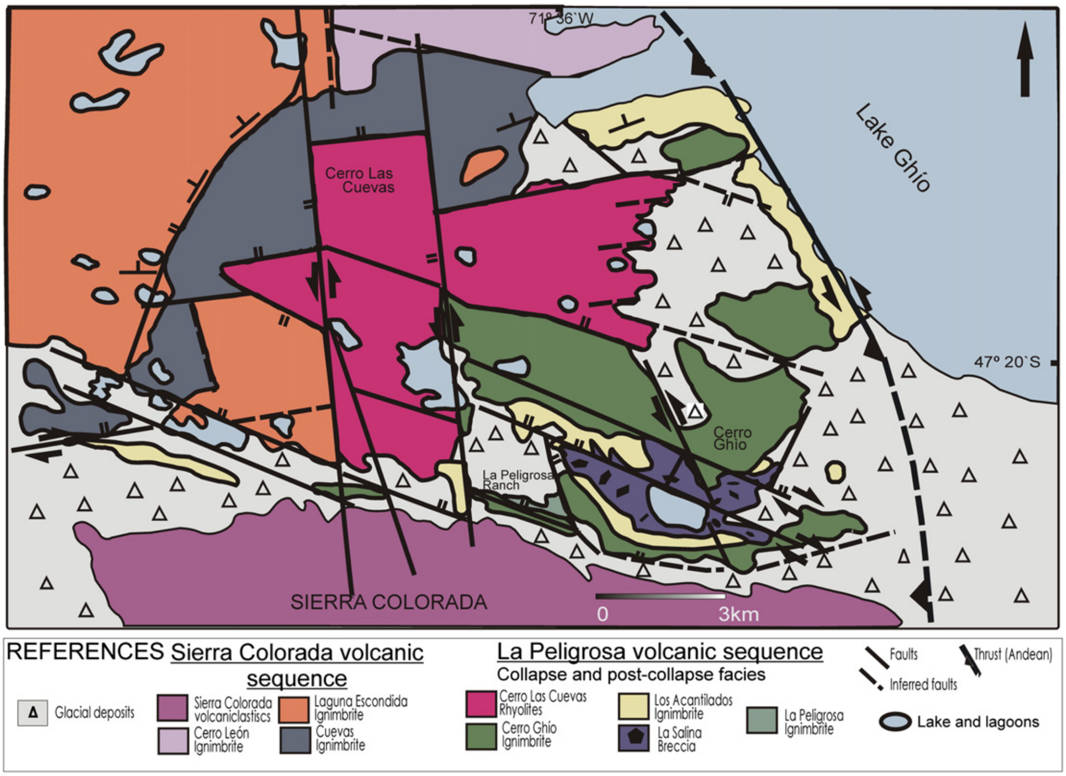

Fig. 2. Geologic map of the La Peligrosa caldera region. The Sierra Colorada volcanic sequence is included in the map to show its distribution relatively to the La Peligrosa volcanic sequence. It is not described in the text because it is out of the scope of this paper.

deformed lacustrine sediments tentatively correlated to La Peligrosa Ignimbrite (Fig. 4c). This mega-to-meso breccia (Lipman, 1976) pinches out to the west, accompanied by strong variation in lithic size and content. In the upper part, a transition to the overlying unit may be recognized, based on lithic depletion and a considerable reduction in their size. The matrix is pyroclastic in origin, with very high crystal content (~60%) of mostly broken quartz, sanidine, plagioclase and strongly bent biotite, suggesting a very high degree of fragmentation during the emplacement of the pyroclastic breccia deposit (Fig. 4d, e).

Most of the vitric shards are partially obscured by spherulitic devitrification and chloritic alteration. However, some stretched and highly deformed shards may be observed next to the biggest crystals. Fiamme, up to 2 mm in length, are totally recrystallized into axiolitic aggregates around chloritized nuclei (Fig. 4d). Although propylitic alteration is dominant, silicic replacements, crystal overgrowth and small quartz veins are common.

3.3. Los Acantilados Ignimbrite

Poorly to moderately welded ignimbrite, this whitish and massive deposit is characterized by a high content of lithics, up to 0.50 m in size. The best exposures of this unit are found on the southwestern margin of Lake Ghío, where it makes up 350 m of the cliff, on the northeastern flank of the Sierra Colorada, where it thins to 140 m, and to the south of the Escondida lagoon (Fig. 2). The contact with the underlying La Salina Breccia is transitional, marked by a gradational lithic depletion, both in content and size (Fig. 3b). Pumices show a slight deformation and the upper part of the unit displays a vertical zonation, with green fiamme layers developing eutaxitic textures. High crystal content (~50%) consists of quartz, up to 2.2 mm in size, partially sericitized sanidine, plagioclase and biotite. Abundant crystal fragments coexist with large euhedral phenocrysts. Non-deformed vitric shards are poorly preserved, whereas chloritized fiamme are frequent. A lithic population includes strongly propilitized andesites, welded and silicified crystal-rich ignimbrites, porphyritic rhyolites, black shales, quartzites and oxidized volcanics. In the upper part of this deposit two lithic-rich lensoid layers are recognized. They are clast-supported and carry large lithics, with an average size of 0.40 m and exceptionally reaching up to 0.90 m.

3.4. Cerro Ghío Ignimbrite

This unit corresponds to a *ca*. 400 m thick, massive, dark green, crystal-rich and densely welded cooling unit. A spectacular exposure may be observed at Cerro Ghío (Fig. 5b), with an estimated thickness of *ca*. 360 m. A few kilometers to the west and south, it shows an order of magnitude decrease in thickness, where the ignimbrite deposit thins to *ca*. 40–60 m (Fig. 5a)

The Cerro Ghío is an ignimbrite rhyolite (71.86% SiO_2), characterized by very high crystal content (~60%) and extremely deformed vitric components. Mineral assemblage consists of quartz > sanidine > plagioclase > biotite accompanied by apatite, zircon and opaque minerals. Quartz crystals, of up to 3 mm in size, are commonly embayed or broken into small angular fragments. Plagioclase and K-feldspar, of up to 2 mm in size, are partially sericitized and carbonitized. Biotite is completely replaced by chlorite and carbonates. Vitric shards and pumices are remarkably stretched against the largest phenocrysts, developing conspicuous eutaxitic texture and local pseudo flow-banding (Fig. 5c). Spherulitic and axiolitic devitrification textures are commonly observed. Typically, the fiamme display chloritized nuclei with axiolitic envelopes. Scarce less-deformed pumices are recrystallized into felsophyric and granophyric aggregates.

The lithic content is relatively low, consisting of small fragments of andesites and quartz phyllites.

3.5. Cerro Las Cuevas Rhyolites

This ~40 km^2 lava field encompasses clusters of domes and associated lava flows extending from the southwestern margin of Lake Ghío to La Misteriosa lagoon (Fig. 2). The Cerro Las Cuevas represents the largest rhyolitic lava dome (Fig. 5d). Lavas are massive and homogeneous,

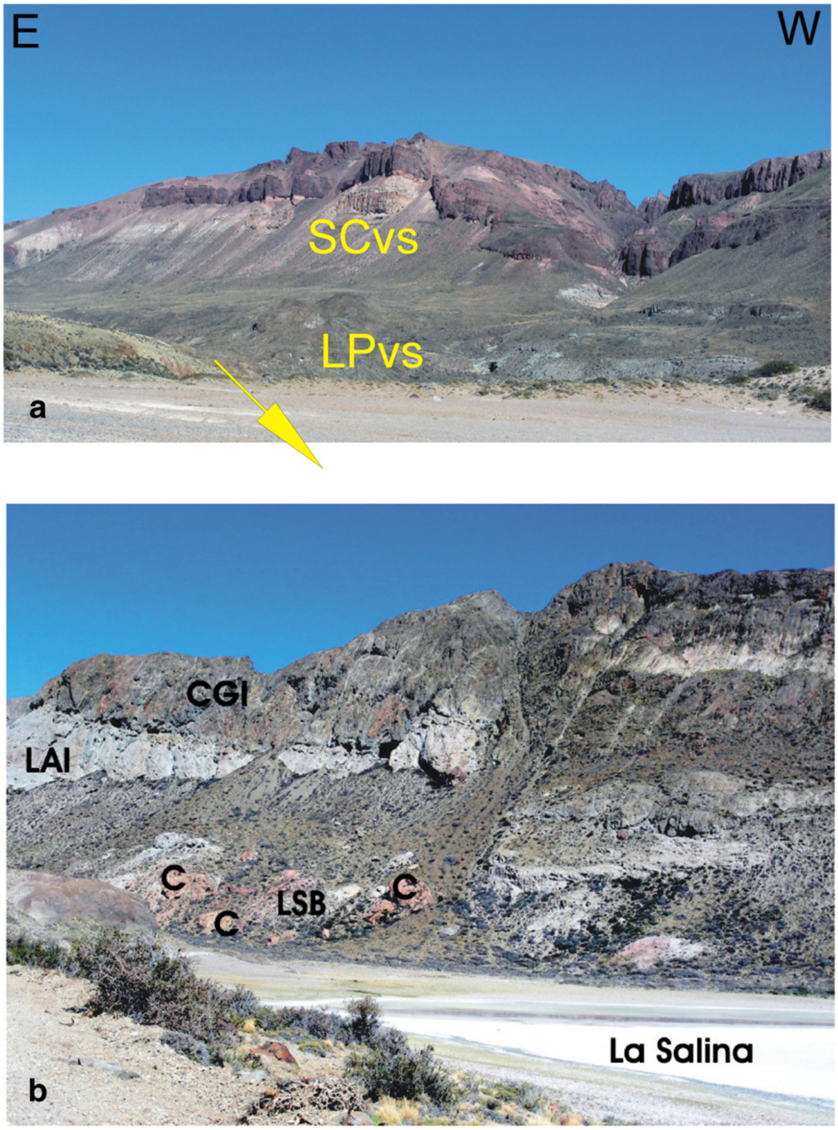

Fig. 3. a) On the northeastern flank of the Sierra Colorada two volcanic sequences may be distinguished: SCvs (Sierra Colorada volcanic sequence) and LPvs (La Peligrosa volcanic sequence). b) At the base of the Sierra Colorada the main collapse facies are well-exposed. LSB: La Salina Breccia, C: lithic clasts. LAI: Los Acantilados Ignimbrite. CGI: Cerro Ghío Ignimbrite.

exhibiting planar and convolute flow banding. Autoclastic facies are locally associated.

Under the microscope, the rhyolites (73.52–78.07% SiO_2) are porphyritic. They carry ~30 vol.% crystals, including quartz, up to 3 mm in size, partially sericitized sanidine and scarce biotite. The matrix is completely devitrified into spherulitic aggregates. Flow banding is highlighted by opaque dissemination along millimeter-thick layers. Silica alteration is present as coarse anhedral quartz.

4. Structure

Structural analyses were carried out in La Peligrosa area, involving field mapping of the main structures as well as kinematic and strain analyses at different scales. This study pursues a two-fold purpose i.e. to identify the main extensional structures which controlled the caldera location and geometry, and to characterize both deformation and kinematics in order to constrain the caldera evolution.

The dominant structures recognized in the study area are faults and brittle–ductile to brittle shear zones (Fig. 6a–e), revealing heterogeneous deformation.

4.1. Main structures

Typically, the area exhibits a block-faulted structure, developed during Jurassic times and dominated by oblique-slip normal faults that would represent reactivated structures affecting the pre-Jurassic basement. Main structures are normal–sinistral NNW- and N-trending faults as well as normal–dextral WNW faults. Subordinate normal–dextral and normal–sinistral ENE faults are also present (Figs. 2, 7). These brittle transtensional structures are commonly arranged following *en-échèlon* patterns at different scales.

La Peligrosa volcanics are presently exposed on a tilted block bounded by the NNW-striking west-dipping Cerro Colorado fault (Figs. 2, 6a). As the main Andean structure of this area, it shows transpressional reactivation due to tectonic inversion during Cenozoic shortening (Giacosa and Franchi, 2001). This 45-km-long fault exhibits the largest displacement at the Sierra Colorada (Giacosa and Franchi, 2001). Minor related structures, such as R and R′ Riedel shears as well as extensional and contractional structures, reveal an Andean transpressional fabric overprinting the Jurassic transtensional one (Fig. 6b).

The WNW oblique-slip fault in northern Sierra Colorada is nearly coincident with a dramatic decrease in thickness of the Cerro Ghío and Los

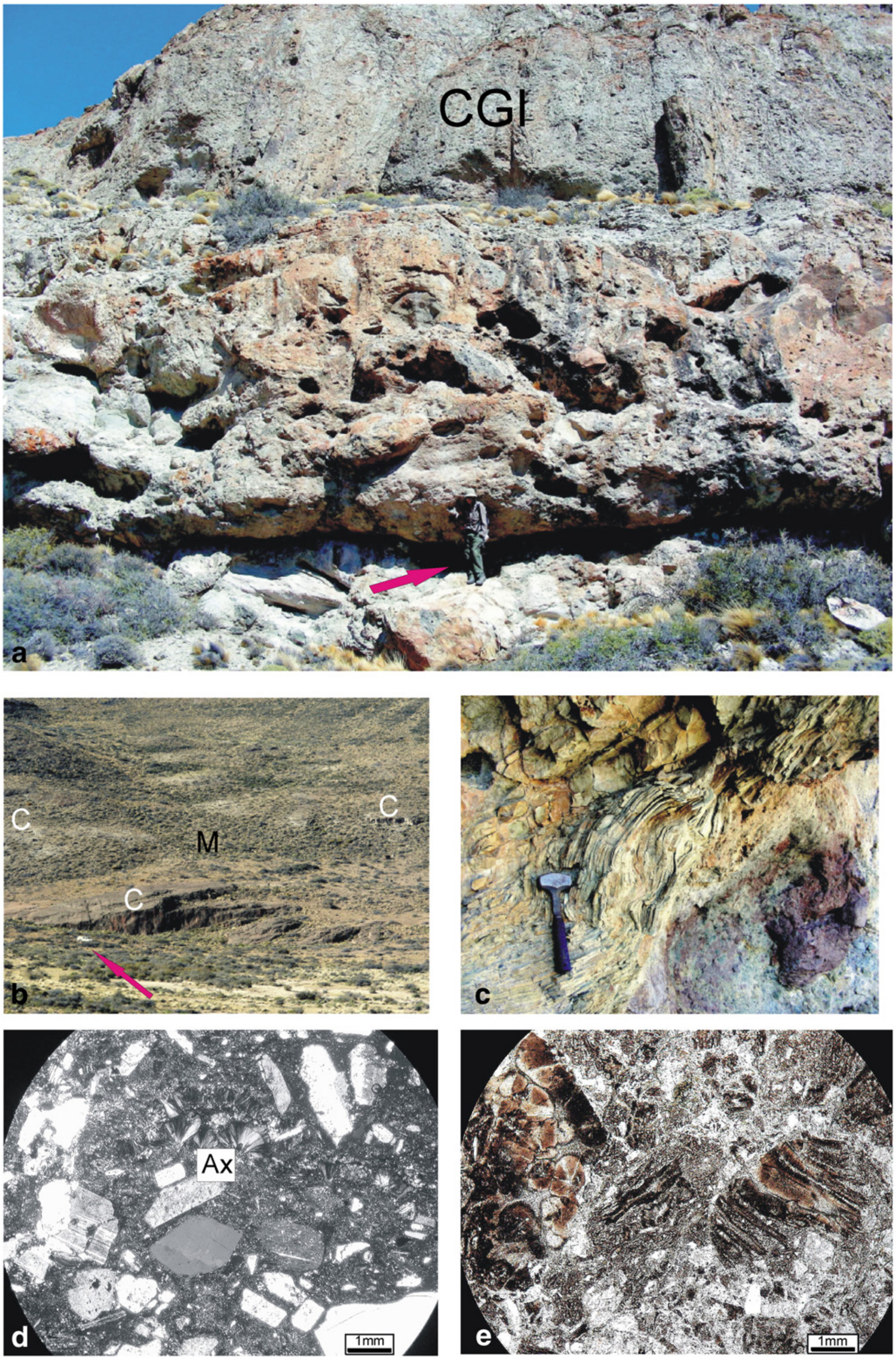

Fig. 4. La Salina Breccia: a) General view of the unit underlying Cerro Ghío Ignimbrite (CGI) in La Peligrosa ranch, the arrow points out a person for scale, b) Large clasts (C) immersed in pyroclastic matrix (M), the arrow points out a vehicle for scale, c) Laminated pelitic block of lacustrine origin, d) Highly fragmented matrix under the microscope: broken quartz and feldspar crystals are abundant and small axiolitic-devitrified fiamme (Ax) may be observed. 5×, e) Breccia texture due to syn-eruption fragmentation. 5×.

Acantilados Ignimbrites, and it also represents the southern limit of La Salina Breccia outcrops (Fig. 2).

4.2. Minor structures

The main sets showing sinistral–normal and dextral–normal motions trend N/NNW and WNW, respectively (Fig. 7a, c). Both groups of shear extensional structures show a subordinated population characterized by opposite strike-slip motions. Tensional structures strike dominantly NW (Fig. 7b) although a second NE-trending population was also recognized (Fig. 7b).

4.3. Kinematic analyses

In order to define the incremental strain field of the Jurassic deformation event, a kinematic analysis has been carried out. At several

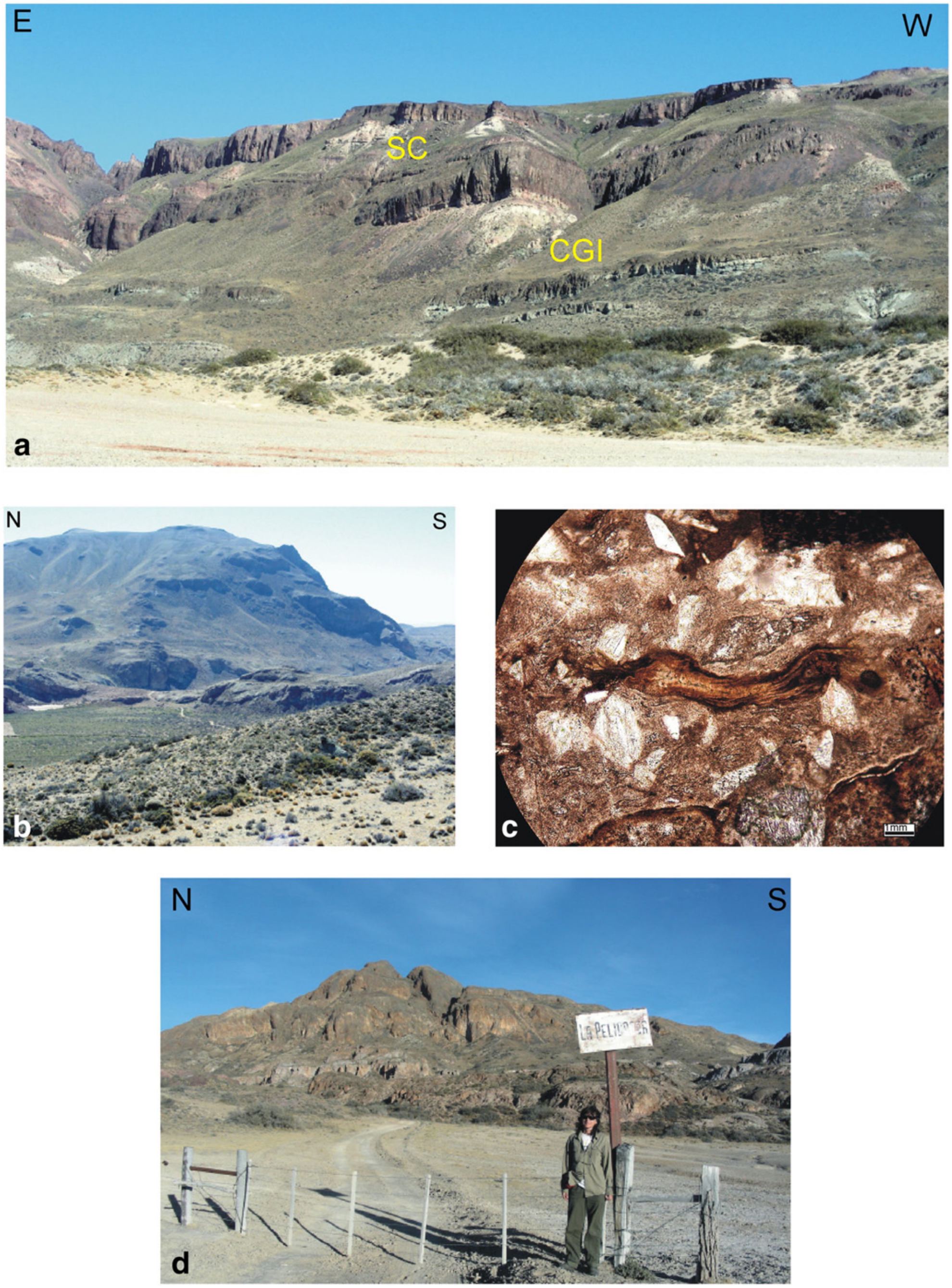

Fig. 5. Cerro Ghío Ignimbrite: a) Cerro Ghío Ignimbrite (CGI) thins southwards, under the Sierra Colorada volcanic sequence (SC), b) At Cerro Ghío, the ignimbrite yields its maximum thickness, c) partially oxidized fiamme and vitric shards are highly deformed. 5× d) Cerro Las Cuevas rhyolitic dome.

sites, and following Japas et al. (2008, 2013b), kinematic indicators were measured for different lithofacies groups: a) La Salina Breccia–Los Acantilados and Cerro Ghío Ignimbrites, b) Cerro Las Cuevas Rhyolites, and c) Sierra Colorada volcaniclastics. T-axes (incremental extension direction) were calculated using the *FaultKinWin* software (Allmendinger, 2001) and represented on an equal area stereographic plot. Fig. 8 shows the resulting T-diagrams for each group. All these plots show a main and a subordinated T-population. A NE-trending main T-axes cluster define the extension direction for both the caldera-related ignimbrites and the Sierra Colorada volcaniclastics (Fig. 8a,c), whereas a principal set of NW-trending T-axes is representative of the rhyolitic lithofacies (Fig. 8b). Additionally, a secondary T-axes population could be also defined for all the three lithofacies groups (Fig. 8a,b,c). There are also some scarce, isolated NNW-trending T-axes that represent WNW extensional–transtensional structures linked to transpressional deformation. These data were discarded for further analysis because they were interpreted as Cenozoic structures, since they are consistent with Andean kinematics.

In order to improve kinematic results, a kinematic fault-plane solution plot for the main population of each lithofacies group was performed (Fig. 8d, e, f). These diagrams confirm a NE extension direction for the caldera-related ignimbrites (Fig. 8a, d) and the Sierra Colorada volcaniclastics (Fig. 8c, f). On the other hand, a NW direction of extension was linked to the rhyolitic lithofacies (Fig. 8b, e). Overprinting relationships and the presence of a second set of NE-trending tensional fractures affecting the older lithofacies (close to the contact with Las Cuevas Rhyolites) confirm that this kinematic change occurred during the rhyolitic emplacement. Furthermore, ENE and NNE transtensional

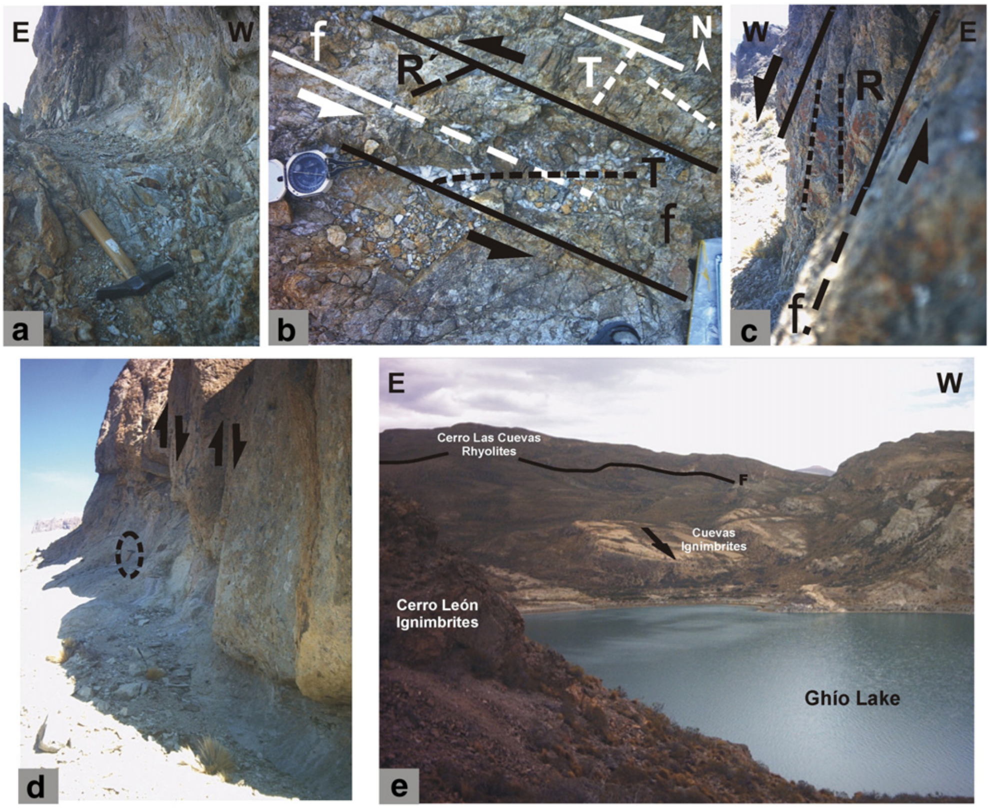

Fig. 6. a) Cerro Colorado fault at Lake Ghío, b) Andean fabric (white) overprinted on Jurassic transtensional fabric (black), R and R′: Riedel shears, T: Tensional fractures, f: margin of the brittle–ductile shear zone, c) Brittle–ductile shear zones (same references as in b), d) Normal meso-faults (hammer for scale), e) Post-collapse fault.

faults and fractures are the main structures controlling rhyolitic emplacement (Figs. 7 and 8e).

The extension axes for the rhyolitic lithofacies event lie at nearly 90° to that for the other lithofacies (Fig. 8), confirming the observations shown in Fig. 7. Intermediate incremental strain axes (2-axes, Fig. 8d) are nearly vertical for caldera-related ignimbrites, revealing significant strike-slip displacements for the structures, whereas the attitude of 2-axes obtained for the rhyolites and the Sierra Colorada volcaniclastics (Fig. 8e, f) would indicate oblique-extension conditions.

5. Discussion

Based on the comprehensive interpretation of lithofacies and structures, the reconstruction of the volcanic architecture has been made and a model for the caldera evolution is proposed. In addition, in order to explore the role of regional structures, the results from analogue models as well as from field studies of similar tectonic settings are discussed.

5.1. Caldera evolution

The formation and development of La Peligrosa caldera can be modeled in three stages: initial, main, and post-collapse. Fig. 9 summarizes the evolution model, taking into account the volcanic activity, the subsidence dynamics, and the associated extensional regime.

5.1.1. Initial collapse stage

The high proportion of andesitic and ignimbrite lithics immersed in La Salina Breccia records persistent volcanic activity prior to the onset of the caldera collapse. However, only the isolated outcrops of La Peligrosa Ignimbrite may be considered as the remnants of the caldera floor. Particularly, the lacustrine deposits interbedded in the volcaniclastic sequence indicate an initial subsidence, prior to the main collapse stage. The laminated sedimentary large clasts are tentatively correlated to La Peligrosa Ignimbrite. They exhibit planar and convolute syn-depositional deformation, due to the rapid incorporation of water-saturated sediments into the chaotic breccia deposit. In addition, base-

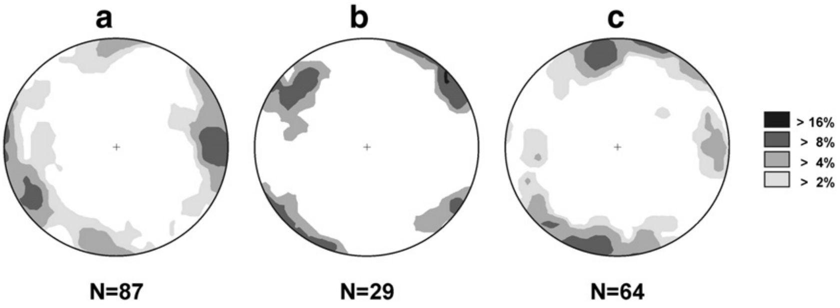

Fig. 7. Lower-hemisphere plots on equal-area stereonets. a) Poles of faults and brittle–ductile shear zones that show normal–sinistral motions, b) Poles of tensional fractures, c) Poles of faults and brittle–ductile shear zones that show normal–dextral motions. *GEORIENT* software (Holcombe, 2005).

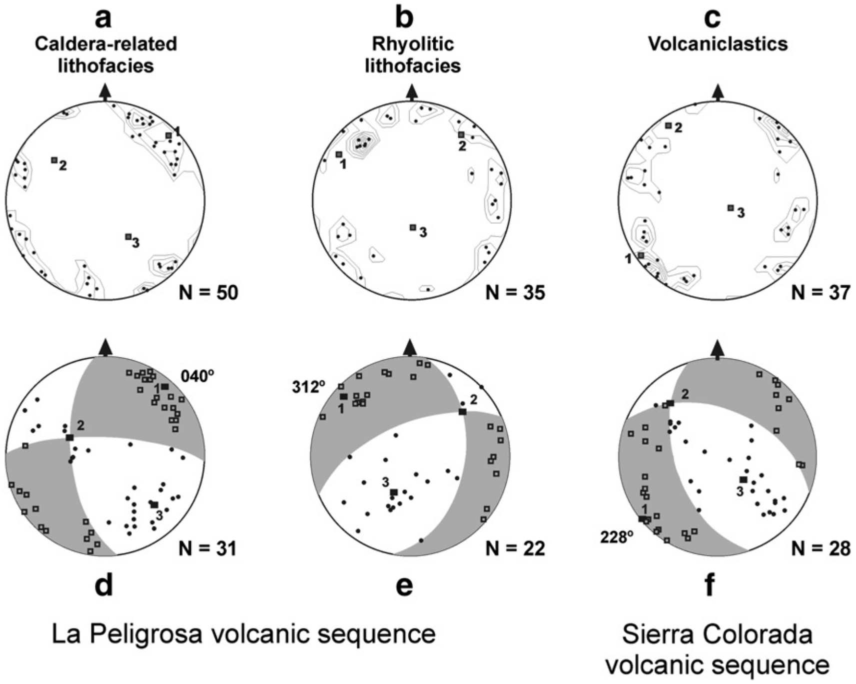

Fig. 8. a), b), c) Kinematic T-axes plots. Black circles represent individual T-axes. Gray squares refer to the three principal kinematic axes: extension (1), intermediate (2) and shortening (3). d), e), f) Kinematic fault-plane solution plots for the main population in a, b and c. Black circles represent P-axes whereas squares indicate T-axes. Black squares refer to the main kinematic axes. Azimuth refers to the extension direction obtained for the main kinematic event that controlled the emplacement of the different lithofacies. *FaultKinWin* software (Allmendinger, 2001).

surge and fluvial deposits and accretionary-lapilli layers, which are interbedded in the pyroclastic sequence of La Peligrosa Ignimbrite, show evidence of water participation, either as magma–water interaction leading to discrete phreatomagmatic eruptive events or meteoric supply.

Tentatively, the caldera formation might have started at this stage, when subsidence anticipating the collapse may be inferred (Fig. 9a). A downsag type of collapse, without ring-fault inception, is invoked (Walker, 1984; Cole et al., 2005), similar to the southern part of Bolsena Caldera (Italy, Acocella et al., 2012) or Rotorua and Taupo calderas (New Zealand, Milner et al., 2002)

Location of the caldera was strongly controlled by regional structures. A dilatational zone, related to a releasing step-over, is defined by two left-lateral NNW regional transtensional faults displaying a left-hand *en-échèlon* pattern (Cerro Colorado fault and the main fault to the west; Figs. 2 and 10). This structural fabric reveals a pull-apart system associated to the early stage of La Peligrosa caldera evolution.

5.1.2. Main collapse stage

Based on the gradational contact between La Salina Breccia and Los Acantilados Ignimbrite and on the absence of epiclastic deposits between this unit and Cerro Ghío Ignimbrite, these three pyroclastic units are believed to have recorded the main collapse stage during the evolution of La Peligrosa caldera. Although they display variation in the degree of welding, they show similar petrographic features. Besides, the absence of temporal gaps suggests a rapid ignimbrite emplacement, concurrent with the main phase of caldera collapse.

In particular, La Salina Breccia represents the onset of this collapse stage. Even though the polimictic breccia lenses are not fully exposed, they pinch out drastically away from the caldera wall. Chaotic and extremely poorly sorted, this deposit carries lithic fragments ranging from millimeters to hundreds of meters in size. Most of them are fragments of country rocks (granites, metamorphic and pre-caldera volcanic rocks); however, the relatively scarce lacustrine clasts provide meaningful evidence of a catastrophic phenomenon. Moreover, the ash-bearing matrix significantly indicates that La Salina Breccia cannot be considered as a typical landslide deposit. Its origin must have been closely related to the collapse, occurring simultaneously with the ignimbrite eruption.

Similar breccia deposits, associated with deeply dissected calderas, have been described in the western United States (Lipman, 1984; Fridrich et al., 1991; Tucker et al., 2007). Lipman (1976) defined caldera-collapse breccias and highlighted their usefulness as guides to the roots of deeply eroded and/or structurally complex calderas. Their emplacement mechanism involves large-scale slumping and sliding of the over-steepened caldera walls during the early stages of collapse. Highly unstable along the ring-faults, the caldera walls provide a full range of clast sizes, including huge blocks which are catastrophically engulfed by the pyroclastic eruption.

The overlying lithic-rich Los Acantilados Ignimbrite is considered to record the initial infill of the caldera. Compared to La Salina Breccia, it shows a gradational lithic depletion and a strong reduction in size. Two distinctive lithic-rich lenses, in the upper part of this deposit, may record minor local incremental adjustments during the rapid collapse (Lipman, 1984).

The uppermost and thickest Cerro Ghío Ignimbrite may be envisaged as the main intracaldera facies, emplaced shortly afterwards. Its main features, such as the high degree of welding, the high crystal content and the remarkable thickness strongly support its emplacement in a deep depocenter. To the south and west, it shows an order-of-magnitude decreasing thickness, which might indicate a piecemeal type of subsidence, resulting in a highly irregular caldera floor. In addition, the Cerro Ghío ignimbrite is highly deformed to the west of La Salina lagoon, which would suggest that the ignimbrite emplacement was accompanied by progressive subsidence.

According to the above-mentioned kinematic analysis, the caldera evolved during the main collapse stage under a transtensional regime linked to a NE direction of extension. The blocks of the caldera floor were controlled by NNW and WNW transtensional faults (Figs. 10, 11). These structures might have resulted in a polygonal array of blocks resembling the structural grain described by Sibson (1986) for implosion breccias formed at dilatational sites.

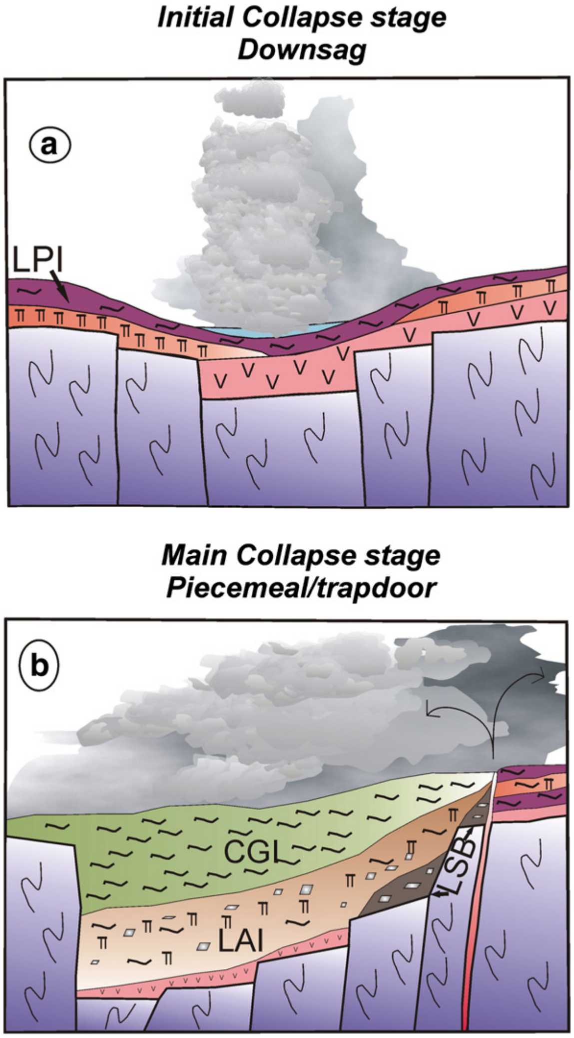

Fig. 9. Schematic evolution model of La Peligrosa caldera. LPI: La Peligrosa Ignimbrite. CGI: Cerro Ghío Ignimbrite, LAI: Los Acantilados Ignimbrite, LSB: La Salina Breccia. See Section 5.1 for discussion.

Tentatively, a piecemeal (Lipman, 2000; Cole et al., 2005) type of subsidence may be invoked at this stage (Fig. 9a). The combination of major structures, like the Cerro Colorado fault with other NNW and WNW minor faults, defines a system of discrete blocks. A good example is the NNW-normal fault between La Peligrosa and Cerro Ghío Ignimbrites (Fig. 2), which may be considered as the eastern side of a block among the multiple independent blocks of the caldera floor. Field evidence, however, is insufficient to assess the amount of displacement experienced by individual blocks; consequently, if piecemeal collapse occurred, it cannot be evaluated. On the other hand, a trapdoor-type collapse (Lipman, 2000; Cole et al., 2005) (Fig. 9b) is well supported by maximum local depths, as at Cerro Ghío, where the intracaldera ignimbrite is thickest. This type of subsidence may be due to either a particular stress field or an asymmetric shallow magmatic chamber (Lipman, 2000; Acocella, 2007), or even a combination of both.

Several classifications of collapse calderas have been proposed, according to morphological and/or genetic criteria (Williams and McBirney, 1979; Walker, 1984; Lipman, 2000; Acocella, 2006; Aguirre-Díaz et al., 2008; Martí et al., 2009). Particularly, Martí et al. (2009) approached the issue from the physical volcanology point of view, taking into account the pressure variation inside the magma chamber and the timing of ring-fault formation. Two end-members are distinguished: overpressure calderas (OC) and underpressure calderas (UC). Even though La Peligrosa caldera is only partially preserved, it may be classified as an underpressure caldera, in which the main collapse was preceded by a significant eruptive episode. La Peligrosa Ignimbrite does not include fallout deposits, which are characteristic of the UC initial plinian phase (Martí et al., 2009). However, the pyroclastic sequence includes several ignimbrite and surge deposits which suggest that depressurization of the magma chamber occurred before the main collapse.

5.1.3. Post-collapse stage

During this final stage, progressive degassing rhyolitic magmas were emplaced as dome clusters and associated lava fields. Strain fabric and kinematic analyses carried out on these lithofacies indicate not only a relevant and transient change from NE to NW extension regime but also the onset of oblique extension (according to Morley et al., 2004) conditions as well.

Our proposed evolution model agrees fairly well with most of the analogue models (Acocella, 2007 and references therein) and particularly, with those which examine the influence of regional tectonic

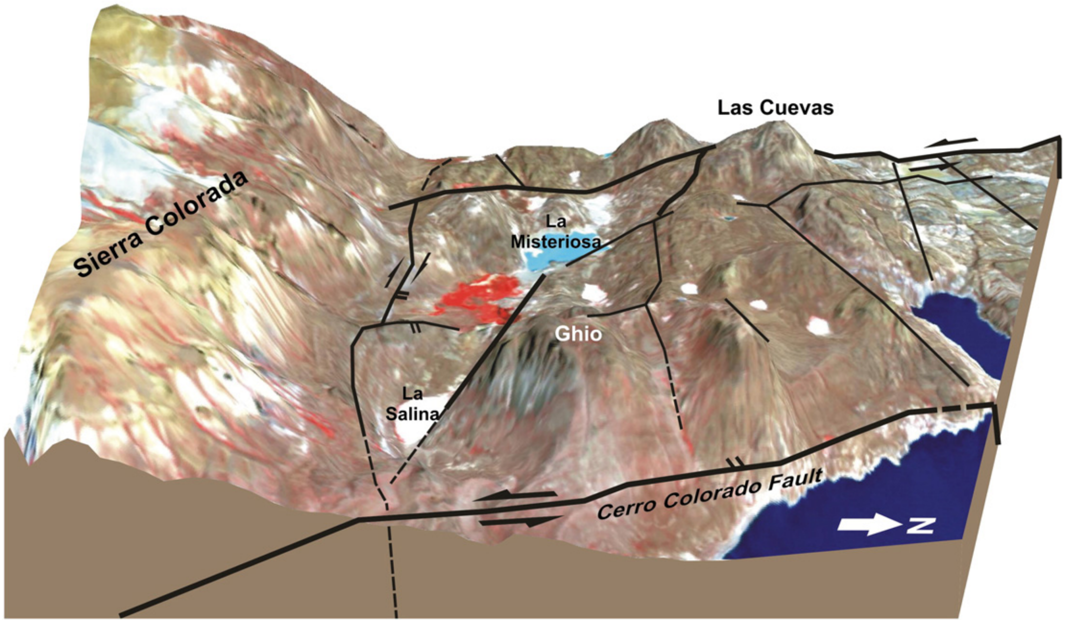

Fig. 10. DEM showing the releasing step-over defined by two NNW-trending regional transtensional faults that display a left-hand *en-échélon* pattern.

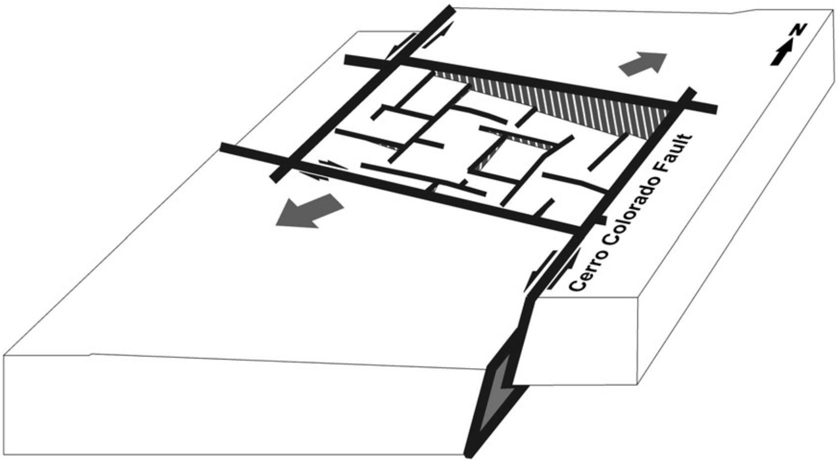

Fig. 11. Schematic block diagram of the pull-apart structure. Arrows indicate the direction of extension during caldera collapse.

structures on collapse calderas (Acocella et al., 2004; Girard and van Wyk de Vries, 2005; Holohan et al., 2006, 2008). The experiments considering strike-slip tectonics predict that evacuation of elliptical chambers go through sequential downsag, reverse fault formation and asymmetric trapdoor subsidence. Holohan et al. (2008) highlight the difficult task of distinguishing the relative contributions of volcano–tectonic and regional tectonic subsidence to the final caldera structure. Moreover, the authors consider that piecemeal collapse could be mistaken with pre-collapse tectonic block disruption, and that in the absence of evidence of syn-eruptive growth faulting, ignimbrite thickness variation is not enough to assess the difference. In consequence, without definitive evidence, our proposed piecemeal mechanism remains tentative and a major contribution of tectonic faults on La Peligrosa caldera subsidence cannot be discarded.

Furthermore, the experiments performed by Holohan et al. (2006) show that the main faults in pull-apart systems exert a strong influence not only on the magma chamber shape at depth but also on the caldera geometry. This seems to be the case for the La Peligrosa caldera, where the Cerro Colorado pull-apart eastern fault might have controlled trapdoor subsidence during the main stage of caldera evolution. On the other hand, there are examples of volcano–tectonic complexes, which resulted from a combination of ductile magmatic intrusion and transtensional deformation (Girard and van Wyk de Vries, 2005).

5.2. La Peligrosa: a graben-type caldera?

Aguirre-Díaz et al. (2008) coined the name "graben-caldera" to refer to those volcano-tectonic structures wherein the graben master faults and the intra-graben block faults play the role of ring-faults resulting in the collapse and the fissure ignimbrite eruptions. The best examples are those well-documented calderas in the Sierra Madre Occidental (SMO), in México (Aguirre-Díaz et al., 2008 and references therein). The Tertiary SMO is comparable to the Jurassic CASP and main similarities may be highlighted: 1) both volcanic provinces have been subject to an ignimbrite flare-up, during which large-volume dacitic/rhyolitic ignimbrites were emplaced, 2) in both cases a prevailing regional extensional regime produced dominant graben and half-graben systems, where the major faults strongly controlled the location of vents and collapse calderas (=graben-calderas), 3) as a consequence, the morphology of the calderas is rectilinear or polygonal, instead of the typical subcircular or elliptical shape and 4) the facies architecture and caldera evolution is similar in both widespread volcanic fields. In particular, La Peligrosa caldera shares with many of the calderas of the SMO an initial subsidence stage, the subsequent piecemeal subsidence, the absence of an initial plinian fallout deposit and the presence of lithic-ignimbrite breccias close to the graben/ring-faults. However, it is worth pointing out that the common pyroclastic/lava dykes, closely related to the main normal faults in the SMO calderas, were not recognized at the studied area.

Despite the remarkable similarities, the tectonic setting is not totally equivalent. As it was described in detail, a transtensional regime exploiting previous structural grain provided suitable dilatational conditions which favored both location and geometry of La Peligrosa caldera. As a consequence, we prefer to consider it as a pull-apart sub-type (Fig. 11) of the wide graben-caldera type proposed by Aguirre-Díaz et al. (2008).

Likely, the regional and long-lasting extensional regime which prevailed in the southern CASP in Jurassic times was suitable for the development of pull-apart systems, which in turn played a major role in the emplacement of silicic volcanism and the formation of collapse calderas. Whether it was magmatism or deformation, what triggered initial rifting is out of the scope of this study. However, it might contribute to a long-lived and open debate.

6. Conclusions

- The comprehensive study carried out at La Peligrosa caldera represents the first attempt to understand the eruptive mechanisms which took place during the Jurassic flare-up in Southern CASP.
- A three-stage model evolution is proposed, combining lithological and structural evidences. It is consistent with the types of subsidence predicted by the analogue models.
- Among the 5 lithofacies, La Salina Breccia turned out to be the most significant as it offered insight into mechanisms and timing of the caldera collapse.
- Tentatively, La Peligrosa caldera may be classified as an underpressure caldera (Martí et al., 2009).
- Pre-existing structures exerted a first-order control on the caldera formation and they played the role of ring-faults, in a similar way as the graben-calderas of Aguirre-Díaz et al. (2008). However, a pull-apart sub-type is herein proposed because it is considered to be more suitable to the local stress field which influenced the caldera formation.
- The evolution of La Peligrosa caldera involved a relevant kinematic change. During caldera collapse, a NE extension prevailed, whereas NW extension dominated during the post-collapse stage. Moreover, a change from transtensional to oblique extension conditions occurred.
- La Peligrosa caldera may be considered as a key event for the Southern CASP. It might be useful to explore other potential calderas, either in

the less-eroded extra-Andean Patagonia, or in the better-exposed and structurally more complex Cordillera Patagónica.

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