



## A calderas field at the Marifil Formation, new volcanogenic interpretation, Norpatagonian Massif, Argentina

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**Abstract** — Major volcanogenic structures within the Marifil Formation allowed to determine the location of a calderas field that spreads along 400 kilometers. This field has at least three large calderas with diameters near to 100 kilometers, recognizable by regional distribution of associated dikes and rhyolite lava flows present at the caldera border that separates a monotonous ignimbritic plateau from a depressed (150 meters) inner volcanic collapsed caldera. The Marifil ignimbritic plateau cover more than 50,000 square kilometers with thicknesses that reach 800 meters. Associated with these plateau ignimbrites there is an important fluorite mineralization. Copyright © 1996 Elsevier Science Ltd & Earth Sciences & Resources Institute

**Resume** — Las principales estructuras volcanogénicas de la Formación Marifil, han permitido ubicar un campo de calderas que se extiende por unos 400 kilómetros. En dicho campo se han reconocido al menos tres grandes calderas con diámetros próximos a los 100 kilómetros, identificables por la distribución regional de la asociación dikes y flujos lávicos riolíticos que indican el borde que separa al plateau ignimbritico monotono de la depresión (150 metros) con las vulcanitas del interior colapsado. Los plateaux ignimbriticos de la Formación Marifil, cubren un área mayor a los 50.000 kilómetros cuadrados, con espesores que alcanzan los 800 metros y al que se asocia una importante mineralización de fluorita.

### INTRODUCTION

The Northpatagonian Massif at southernmost South America is an igneous-metamorphic morpho-structural unit with a protracted igneous history, from plutonic emplacements through Paleozoic times, to epizonal and volcanic activity during Mesozoic and Cenozoic times (Table 1). The distribution of the igneous activity affects both margin (to the west), to intraplate settings (central-eastern patagonia, Figure 1), with a general arrangement for the Mesozoic of shallow plutons and stratovolcanoes to the central and western side of the massif to large ignimbritic plateaus to the east, in at least two distinctive intraplate cycles — Triassic and Jurassic. The extent of each igneous cycle has produced enormous volumes of magma traceable by hectokilometric outcrops that follow NW-SE or N-S or seldom NE-SW trends. Sediments from neighboring basins invade the massif surface usually as thin covers and locally as tectonic valley fills, either as marine or continental sedimentation. Paleozoic to Lower Mesozoic deposits are isolated outcrops over crystalline basement. A Jurassic transgression (lower to middle toarcian) reaches the southern central part of the massif, but it is not until Cretaceous-Tertiary times that sedimentation seems to be able to make a continuum of any great extent.

The early to middle Mesozoic igneous activity has been genetically related to crustal anatexis which relates to an increased heat flow during crustal extension at the early stages of Gondwana rifting.

About one quarter of the patagonian massif holds the Jurassic intraplate igneous cycle. It includes plutons of the Central Patagonia Batholith (Rapela et al., 1992) and middle to upper Jurassic volcanism.

Immediately after the Toarcian transgression (Osta Arena Formation, outside south-eastern limit of Fig. 1),

volcanic activity includes at least two andesitic stratovolcanic belts to the west (Lonco Trapial Formation), an extended andesitic-rhyolitic ignimbritic plateau to the East (Marifil Formation), and minor alkaline basalt's (basalts at the base of Cañadon Asfalto Formation) at both settings (Figure 1). Sedimentary fill of local volcanogenic basins belongs to Cañadon Asfalto Formation and Santa Antia Formation, continues through a low angle unconformity with Chubut Group (Cretaceous), followed by a transgression (Roca Formation, Danian) and tertiary tuffs. Positive relief for middle to late Mesozoic times at this part of The Massif was controlled by a Comallo-Gastre rise and a Nahuel Niyeu-Sierra Grande rise of complex nature.

The knowledge of the andesitic-rhyolitic ignimbritic field goes back to Windhausen (1921) who called it Porphyritic Rock Series. Later, Feruglio (1949) named them as the Prophyryc-Porphyritic Complex of Extra-Andean Patagonia.

The term Marifil Formation was created by Malvicini and Llambias (1972). At that time they introduced the concept of the Ignimbritic Plateau of the Norpatagonian Massif as the volcanogenic feature characteristic of this Formation. As for their origin these authors suggest the hypothesis of a probable fissure extrusion. In a recent work Ciccirelli (1990) describes a group of small intrusive bodies towards the southeast of Sierra Grande, interpreting one of them as a 4 kilometer caldera, and the whole as an eruptive complex.

Compositionally it is rhyolitic with minor andesitic, rhyodacitic, trachitic and trachibasaltic flows, Haller *et al.*, (1990) classified it as high potassium alkaline but Rapela and Pankhurst, (1993) prefer to use transalkaline, placing emphasis on the transitional nature to subalkalic.

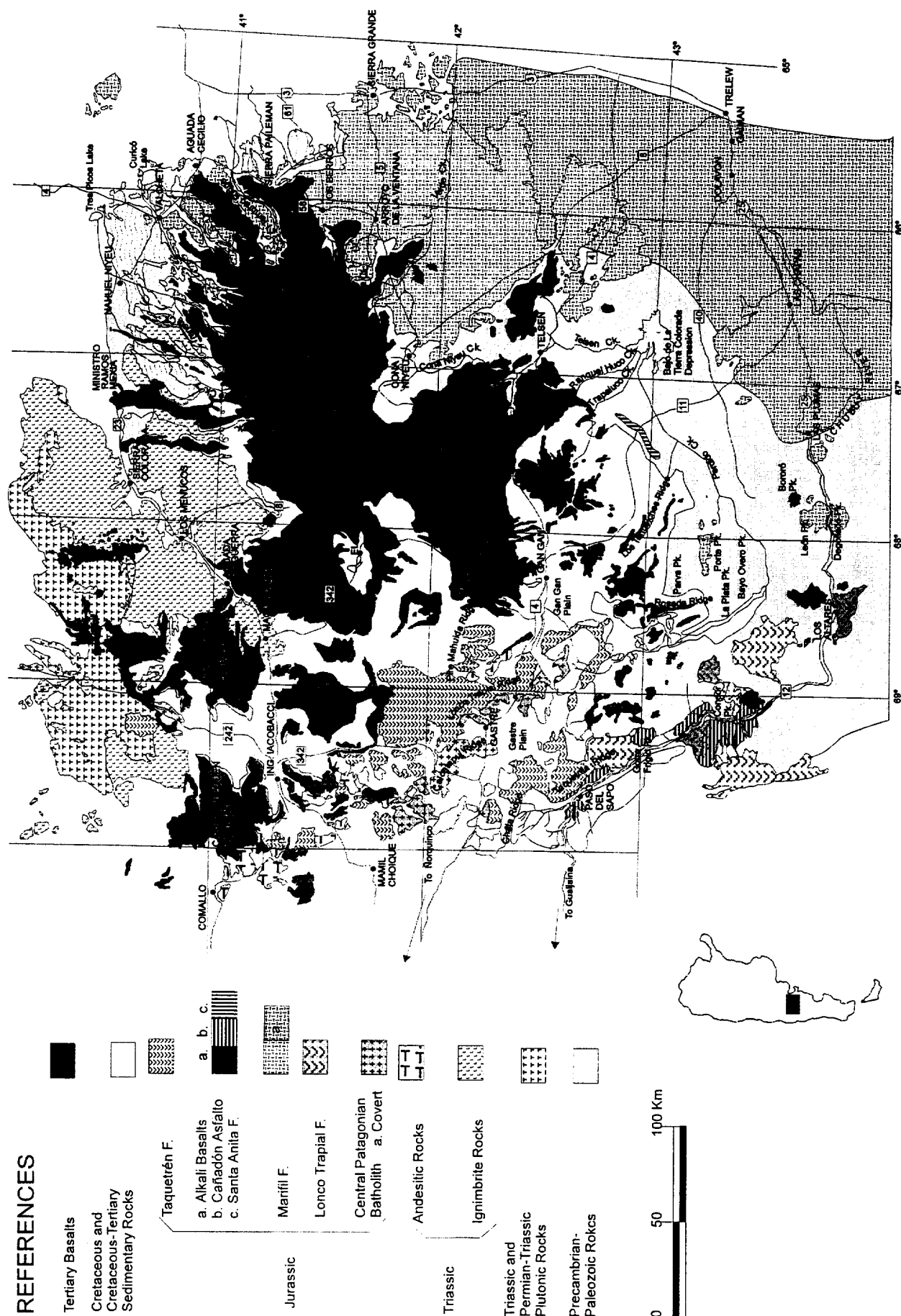
Table 1.

| AGE      | CENTRAL MASSIF                                          | EASTERN MASSIF                                                             | ROCK TYPE                                             |
|----------|---------------------------------------------------------|----------------------------------------------------------------------------|-------------------------------------------------------|
| Tc       |                                                         |                                                                            | Basalts                                               |
| K-T      | Arroyo Barbudo F.                                       | Roca F.                                                                    | Marine sediments                                      |
| K        | Chubut Group                                            |                                                                            | Continental sedim.                                    |
| J-K      | Taquetren F.                                            |                                                                            | Andesites                                             |
| Upper J  | <i>Oxfordian</i><br><i>Calovian</i><br><i>Bathonian</i> | Cañadon Asfalto F.<br>Santa Anita F.                                       | Alkaly Basalts and<br>contin. Sediments               |
| Middle J | <i>Bajocian</i><br><i>Aalenian</i>                      | Lonco Trapial F.<br>Marifil F.                                             | Andesites and<br>rhyolites                            |
| Lower J  | <i>Toarcian</i>                                         | Osta Arena F.                                                              | Marine sediments                                      |
| Lower J  | Central Patagonia<br>Batholith                          |                                                                            | Granitoids                                            |
| TR       | Andesitas de Comallo                                    | Ignimb. los Menucos                                                        | Andesites and<br>rhyolites                            |
| Pm-TR    | Dos Lomas and La<br>Esperanza Complex                   |                                                                            | Granitoids                                            |
| Pz       | Mamil Choique and<br>Yaminue Complex.                   | Jaguelito and Mina<br>Gonzalito Complex.<br>Paileman F. Nahuel<br>Niyeu F. | Metamorphic and<br>related granitoids.<br>granitoids. |

The time span of this particular volcanic cycle of strato-volcanoes to the west (Lonco Trapial Formation) and ignimbritic plateau to the east (Marifil Formation) is restricted to a 10 Ma period. Ignimbrites of Marifil Formation age range from  $178 \pm 1$  Ma or  $183 \pm 2$  Ma (Rapela and Pankhurst, 1993) from four well defined sets of Rb-Sr isochrones, concluding that these rocks were formed during a short and well-defined igneous event, becoming younger from north to south. Andesites of the Lonco Trapial Formation overlie Osta Arena Formation, with ammonite fossils of Toarcian age (Riccardi in Musachio and Riccardi, 1971), and are overlaid by alkali

basalts (base of Cañadon Asfalto Formation) with a K/Ar age of  $173 \pm 4$  Ma (Stipanovic and Bonetti, 1970). Andesitic volcanic rocks are also present beneath Osta Arena Formation to the south (El Cordoba Formation), and over Cañadon Asfalto Formation to the North (Taquetren Formation), indicating that besides Lonco Trapial Formation, several andesitic cycles have affected central patagonia, and that there is a spatial-temporal migration from south to north (Nulo and Proserpio, 1975), opposite to that of Marifil Formation but in a wider time span.

The Marifil Formation volcanic topography is an



extended repetition of very low hills that usually resemble gentle egg-box shapes, made by monotonous ignimbrite sequence of pheno-rhyolitic to andesitic composition, reaching up to 800 meters in thickness, with a regional distribution of more than 50,000 square kilometers. Emplaced in the ignimbrites, are a great number of hydrothermal fluorite deposits of economic value, which have been mined for a long time. Scarce erosive processes have taken place since Jurassic times, leading to residual kaolin deposits on the ignimbritic plateau surface. Other sedimentary deposits overlying the Marifil Formation are restricted to marine sediments to the east, with scarce outcrops of the Roca and Arroyo Verde Formations on the Cretaceous-Tertiary limit, and westward, to fluvial and lake deposits assigned to Santa Anita Formation (Callovian-Oxfordian) and Chubut Group (Cretaceous).

The present contribution deals with the finding of a group of unusually large calderas in this continuous volcanic field. Difficulties in identifying these structures in the past are attributed to: 1) their unusual size; 2) poor exposures due to little erosion and partial covering; 3) The rim between the plateau and collapsed areas are placed to the western limits of the outcrops. The collapsed areas have been flooded by Cretaceous sediments and Tertiary volcanic materials, therefore most outcrops belong to the ignimbritic plateau outside the calderas limit; 4) The unusual thickness of the ignimbritic sequence outside the caldera limits, with large cooling units that mask not only the original flow units but also the textural and structural relationships.

### METHODOLOGY, OBSERVATIONS AND CONSIDERATIONS

Field work has enabled the recognition of three volcanogenic morphological-lithological features within the Marifil Formation. From the spatial arrangement of these features the source and type of the eruptive center is established.

The mapped morphological-lithological features are: 1) flat extended ignimbritic plateau with gentle egg-box like surfaces, spreading almost continuously for more than 50,000 square kilometers. This monotonous sequence of ignimbrites is horizontal, dips gently to the east, or is controlled by local topography showing synclinals of varying shapes and trends. It has completely flooded the pre-existing topography leaving the bedrock outcrops to the east and northern limits of this unit observable; 2) to the west of the ignimbritic plateau, there is a group of outcrops where the ignimbrites are cut by dikes and covered by rhyolitic lava flows. Such outcrops follow a half circle distribution coincident with regional dike alignment. Detected fractures towards the west change the ignimbrite slopes in that direction; 3) further to the west continues an area that in most cases is flooded by Upper Jurassic-Cretaceous sediments and Tertiary volcanic materials. In some places this area is partly free of sediments exposing the Marifil Formation at 150 meters

below the level of the ignimbritic plateau. In these areas the sedimentary fill consist of tuffs, breccias and volcanoclastics, and belongs to a fluvial and shallow lake depositional environment. The sediments at the walls of the volcanic depression rules out the possibility of its origin by post-Jurassic faulting.

The source and type of the eruptive center is established following the arrangement of dikes and lava-flows that mark the existence of at least three large half-circle structures that separate an eastward ignimbritic plateau with respect to a westward depressed volcanic surface with sedimentary fill. Such volcanic-structural arrangements are interpreted as calderas or cauldrons (for simplicity we will refer to them as calderas from now on).

The above morphological-lithological features have been mapped in Figs. 2 and 3. From these figures it can be observed that the key feature mapped is represented by the dike and rhyolite lava flow patterns. Note that most dikes have not been mapped individually since scale does not allow it, but caldera borders are drawn following local alignment of dikes and lava-flows. Going towards the east of this feature the ignimbritic plateau spreads, and to the west, the collapsed volcanic materials with sediment flood can be observed.

The southernmost structure (Fig. 2) is cut by the Chubut River at Las Plumas, continuing northward for 35 kilometers. At this point the structure is cut by the second large structure that surrounds the Tierra Colorada Depression and continues toward Cona Niyeu with NNW trend. At this locality it intercepts the third large structure that can be followed along the upstream of creeks Verde, Ventana and finally Valcheta. Each structure is part of at least one large caldera.

The intercepting unusually large calderas near to 100 kilometers in diameter spread along 400 kilometers as a calderas field with a NNE-SSW trend. Exposures are best observed on the northern caldera, and decrease towards the south as sedimentary fill of the collapsed areas tend to overflow and cover the plateau. Even though present, the possibility of morphological complications caused by post Jurassic faulting, does not interfere with the calderas major features.

In spite of the fact that we do not discharge the idea of the existence of nested calderas, at present we observe that the three large structures contour three unusually large calderas, where the superposition or nesting possibility is to be cleared by much more detailed future works.

The northernmost caldera is the most well exposed, and we named it Llumdeuñ, the local word means hidden volcano. The extracaldera area has a slightly periclinal tilt (eastward) with respect to the caldera's rim, and flatten toward distal outcrops (Fig. 3). The rim area has lava flows and dikes (10 to 70 meters wide) that align in an almost 100 kilometer diameter half-circle, indicating the caldera's ring fractures. There are also minor radial dikes at the extracaldera area. The half-ring area stands slightly

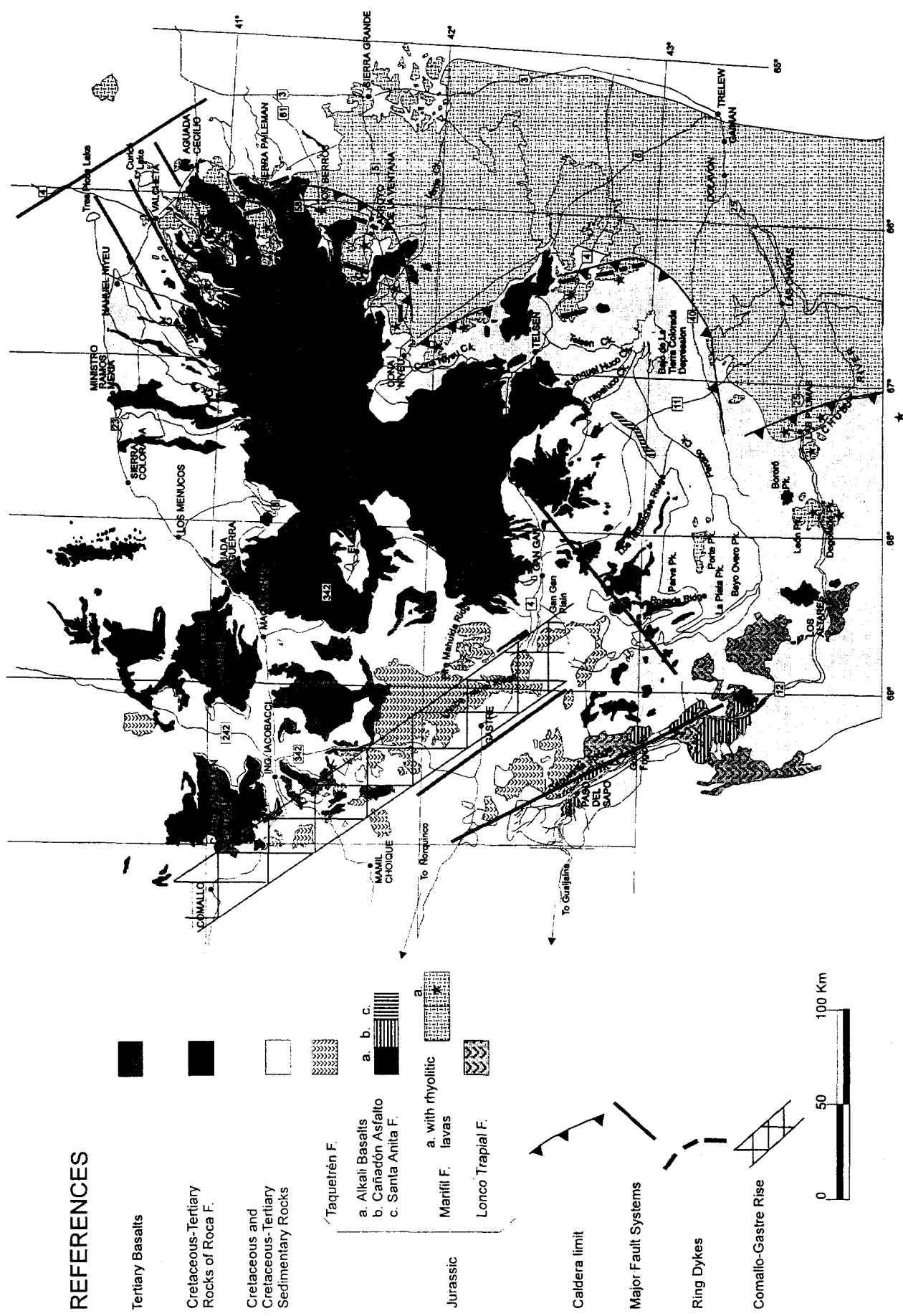


Fig. 2. Distribution of Jurassic volcanism at central and eastern North Patagonian Massif with calderas field.

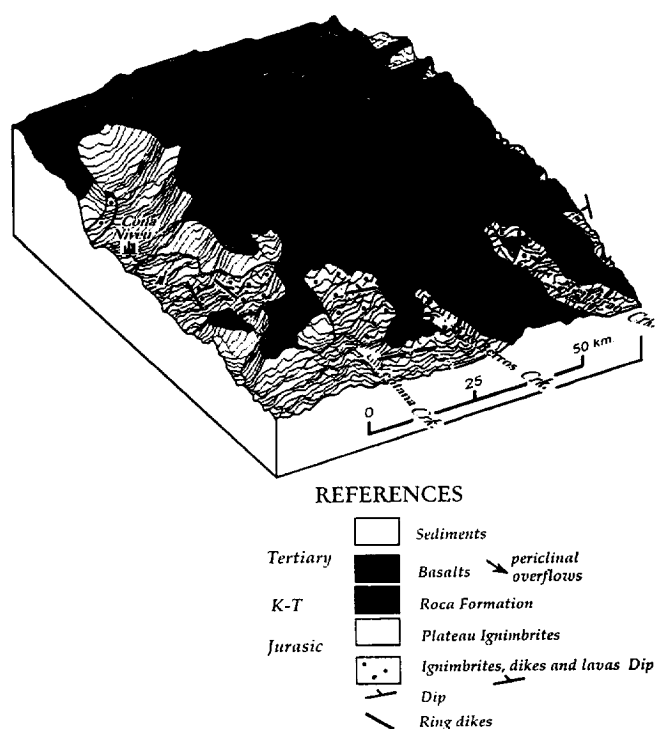


Fig. 3. Block diagram of Sierra de Somun Cura, showing the main morphological features at caldera Llumdehuin rim area.

above the extracaldera surface. Inward the ignimbritic sequence change dip opposite to extracaldera dips in a narrow moat with few small rhyolite lava domes. Further in, thick highly welded ignimbrite lobes with few rhyolite lava flows on top, build up a probable resurgence that is covered in part by a thin sediment blanket and completely by tertiary basalts. The sudden end of rim dikes (at Valcheta creek) toward paleozoic rocks (phyllites) controlled by old NE faults suggest a trap-door caldera type. Furthermore, these NE faults must have had controlled magma rise. The role of phyllites as local host rocks is evident by abundant phyllite lithoclast at ignimbrites in Paja Alta Ck. area.

Even though eroded, the calderas paleogeography controlled local sedimentation up to tertiary times. Tertiary basalts of the Somun Cura Plateau have overflowed the calderas collapsed area, spilling through the eroded rim as fingers that spread in a periclinat design onto the extracaldera ignimbritic plateau (Fig. 3). Basalt fingers cover the marine sediments of the Roca Formation. These sediments have a carbonate platform facies model that is controlled by the calderas paleogeography, with ramp deposits along the periclinat extracaldera plateau (off-shore deposits of Spalletti *et al.* 1993), and a rimmed shelf at the inner-calderas rim (moat), with coral covered by dunes resembling an atoll reef. Exceptional outcrops can be observed upstream of Tembrado creek.

The second large structure continues southward (Fig. 2), which encircles at least one caldera that we have called Bajo de la Tierra Colorada. The major difference with the previous one is that in this caldera the collapsed

area is exposed at the Tierra Colorada Depression. The rim and moat area with rhyolitic lava flows and breccia dikes stands eastward of the Tierra Colorada Depression, the walls of the caldera have remnants of lake deposits, and breccias made of volcanoclastic sediments and tuffs. The volcanic rock outcrops of the floor are 150 meters below the neighboring extracaldera ignimbritic plateau of rhyolitic composition.

The southernmost structure (Fig. 2) has been named Los Mártires Caldera. Even though much covered by sediments, it can still be recognized an intracaldera area with important lava flows at Los Mártires Valley with respect to the extracaldera ignimbritic plateau towards the ESE. The caldera rim and moat is best exposed at Las Plumas showing a collapse of more than 170 meters with respect to the eastward ignimbritic plateau of dacitic-andesitic to rhyolitic compositions.

The extended ignimbritic plateau is mapped as one, since at many places is not possible to distinguish from which structure the flow units came from. The nature of these rocks is mainly ignimbritic with phenocrysts (from 5 to 35%) of alkali feldspar and/or plagioclase and quartz, volcanoclasts and eutaxitic structures are almost always present, but at thick outcrops flammes may be almost erased accompanied by increased phenocryst size and abundance, reaching the appearance of a granitoid with uncertain relations to neighboring flows. Other areas show a fine grained texture with internal vertical or twisted flow and dike relationships. The size of these features is small (seldom kilometric) and has lead to the idea that these are related to eruptive centers (Malvicini and Llambias 1972; Cicciarelli 1990).

Fluorite mineralization has a widespread distribution mainly through the north-eastern area of the plateau (41° 15' to 42° 15' SL), but not so at the border or intracaldera settings where it is totally absent. There are more than 150 mineralized structures. Veins are sub vertical, the strikes are mainly east-west to N 55°E, exceptionally NW-SE, with lengths up to 600 meters (few reach 1100 meters), and 0.8 to 3 meters thickness (seldom 25 meters).

Sedimentary fill of the caldera is best observed at the Tierra Colorada Depression. Here Santa Anita Formation of Callovian-Oxfordian age (Ardolino and Franchi 1995) stands at the base of the profile and is covered by a low angle unconformity with the Chubut Group (Cretaceous). These belong to fluvial and shallow lake environments with great amounts of inter stratified breccias at the caldera's inner rim. In this area there are small isolated alkaline basalt outcrops that correlate with Santa Anita Formation, since further east in the andesitic stratovolcano environment of Lonco Trapial Formation, Santa Anita's Formation equivalent is the Cañadon Asfalto Formation, and at this unit base there are alkaline basalts. These basalts have a much more restricted extent compared to Marifil or Lonco Trapial Formations, and have a probable NE-SW trend.

## DISCUSSION

The total absence of either inter stratified sedimentary-volcanic sequences or morphologies of cone-like volcanic buildings along an extended (50.000 square kilometers) volcanic field made up of a monotonous sequence of sub-horizontal ignimbrites, rule out the participation of strato-volcanoes at any stage of development of this particular volcanic area.

The presence of rhyolitic lava-flows and dikes are evidence of an underlying magma chamber. Most dikes and lava flows are restricted to a half-ring arrangement of regional extent (and far away from the stratovolcanic belts) that separates an external ignimbritic plateau from an inner depressed volcanic surface (moat). Such lithological-structural arrangements are indicative of collapsed caldera or cauldron type eruptions.

At Llumdehiñ Caldera several stages of caldera development (After Smith and Bayley 1968) are recognized. A) Regional periclinal disposition of ignimbritic plateau around the caldera rim, may be due to Stage 1 of regional swelling. B) The presence of unusually large volumes of ignimbritic flows are evidence of stages 2 and 3 (eruption and collapse). C) Major ring-fracture volcanism, rhyolite lava flows and domes are indicative of stages 5 and 6 (ring fractures and probable resurgence).

Extensive fluorite mineralization through the plateau, is indicative of a high fluorine content in the magma. This component must have been partly responsible for the unusually low viscosity of the crystal-rich rhyolitic magmas and aid the ignimbritic type eruption. The lack of fluorite at intracaldera settings suggests that fluorine left the chamber during eruption with the magma shards and fluids, further crystallization in the unusually thick cooling units may have led to fluorite segregation as a new fluid phase. Yet a second possibility suggests that the shallow magma chamber may extend as great sheets sills beneath the ignimbritic plateau, in this case slow cooling and crystallization could also produce fluorine rich fluids that intrude the overlying ignimbrites and country rock. Sparse small dikes through the plateau and fluorite deposits outside volcanic rocks seem to support the second hypothesis.

At present there is no strong evidence for resurgence, except for some rhyolite lavas at Llumdehiñ caldera to the north, and outcrops along Chubut river (Leon and Degollado Peaks) at the southernmost caldera. Most activity is related to the caldera's rim and moat. The moats can be observed at the eastern side of Tierra Colorado Depression, at Las Plumas, and upstream of Valcheta Creek.

The presence of minor outcrops of alkaline basalts immediately after ignimbrites of Marifil Formation and andesites of Lonco Trapial Formation at Rio Chubut, mark the end of this wide upper Jurassic igneous cycle with an extension signature.

Major volcanogenic alignments, NW-SE for andesitic

stratovolcanoes to the west, NNE-SSW and NE-SW for ignimbrite calderas field to the east, and NE-SW for alkaline basalts, obey early paleozoic to early Mesozoic fault systems.

From the finding of at least three unusually large (100 kilometers) calderas, there still is to be studied the existence or not of superimposed or nested calderas (difficulties arise from exposure limitations); age variation between them and detailed structural and compositional information of each, to explain the unusual size and related fluorite mineralization at the extracalderas plateau.

Finally, considerations on the geotectonic setting have been made by Page and Page (1993) for volcanism within Jurassic times. This important work recognizes at regional scale three volcanic belts (Cordilleran, Central and Atlantic), showing temporal variation from east to west (Cordilleran being younger than Atlantic), where the Central belt (Taquetren and Lonco Trapial Formations. Andesitic stratovolcanoes in this work) is a branch of the Cordilleran belt and therefore they interpret it as a part of the volcanic area related to subduction and described by Baker *et al.* (1991) and Haller and Lapido (1992). On the other hand, the Atlantic belt that deals with the ignimbritic plateau of this work has been studied by Bruhn *et al.* (1978); Baker *et al.* (1981); Gust *et al.* (1985) and Kay *et al.* (1989), whom have interpreted these ignimbrites as the product of cortical anatexis under an extension strain. Ciciarelli (1990) suggests that the structures that cut the Marifil Formation belong to a hemigraben system parallel to the passive margin in a traction system. Rapela and Pankhurst (1993) consider that these volcanics were derived from an isotopically uniform source such as enriched lithospheric upper mantle or a lower crustal source much less evolved isotopically than the middle and upper crust.

This new interpretation has significant economic implications since mineralizations and ornamental rocks are closely related to the model previously described, and is on this basis that detailed studies are being carried out under the auspices of the project PID-BID 0123-CONICET "Geology and mineral resources of the Norpatagonian area".

**Acknowledgments** — In particular to Dr. E. Llambias for his invaluable field observations and constructive discussions. Also to Dr. M.M. Mazzoni for the critical review of the manuscript.

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