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THE AREQUITA FORMATION (LOWER CRETACEOUS): PETROGRAPHIC FEATURES OF THE VOLCANIC FACIES IN THE LAGUNA MERÍN BASIN, EAST URUGUAY

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Abstract: The southeastern border of the Laguna Merín Basin (Rocha Department, East Uruguay) consists of Mesozoic volcanic deposits of the Puerto Gómez and Arequita formations, overlain by a sedimentary cover of Cenozoic and recent deposits. Well-preserved lava flow and pyroclastic deposits have been identified in the Arequita Formation after detailed mapping (1.50.000) in Sierra de los Ajos region. The present study focuses on the petrographic characterization of this felsic volcanism, with special emphasis on the pyroclastic units. Differences in the structural and petrographic distribution of these volcanic units are related to the N20ºE trending India Muerta Lineament. East of this lineament, SiO_2-rich rhyolites and pyroclastic deposits (ignimbrites) are present whereas to the west, the volcanic rocks are mainly represented by basic to felsic lavas. Based on petrographic features and regional distribution, explosive mechanisms have been assigned to some of the volcanic units, interpreted as pyroclastic flow and pyroclastic surge deposits.

Resumen: El extremo sureste de la Cuenca Laguna Merín (Departamento de Rocha, Uruguay) está constituido por depósitos volcánicos mesozoicos, correspondientes a las Formaciones Puerto Gómez y Arequita, cubiertos por sedimentos Cenozoicos y de edad reciente. Los trabajos desarrollados en la región de Sierra de los Ajos permitieron identificar en la Formación Arequita flujos de lava y depósitos piroclásticos bien preservados, cuyas características petrográficas son presentadas en este trabajo. La distribución espacial y estructural de este volcanismo en la región de estudio está relacionada con el Lineamiento India Muerta de dirección N20ºE. Al este del mismo, se encuentran depósitos piroclásticos (ignimbritas) y derrames riolíticos ricos en SiO_2 mientras que hacia el oeste la región está constituida fundamentalmente por flujos de lava básicos y ácidos. En función de las características petrográficas y de la distribución espacial que presentan los depósitos piroclásticos se interpretan a los mismos como depósitos de flujo y oleada piroclástica.

Keywords: petrography, rhyolites, ignimbrites, Mesozoic, Uruguay.
Palabras clave: petrografía, riolitas, ignimbritas, Mesozoico, Uruguay.

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INTRODUCTION

Mesozoic magmatism related to the opening of the South Atlantic Ocean is widely known since the studies of Bellieni *et al.* (1986), Piccirillo *et al.* (1988), Peate *et al.* (1992) and Hawkesworth *et al.* (1992), among others. The remnants of this volcanic episode in the South American platform are represented by the Paraná Magmatic Province (PMP), one of the greatest continental magmatic provinces in the world (Peate, 1997). Silicic rocks related to the southern portion of the PMP and their correlatives in the Etendeka Province have been the focus of several investigations over the past two decades (Bellieni *et al.*, 1986; Milner *et al.*, 1992; Peate *et al.*, 1992, Garland *et al.*, 1995; among other authors). In the PMP, this felsic volcanism is mainly composed of rhyolites and rhyodacites that were chemically subdivided into two groups (Bellieni *et al.*, 1986): the Palmas-type and the Chapecó-type volcanic rocks. The first type prevails in the southern portion of the PMP while the second one crops out in the central and northern region. After Peate *et al.* (1992) the Palmas-type was divided into the Santa María and Caxias do Sul chemical subtypes whereas the Chapecó rhyolites were separated as the Guarapuava, Ourinhos and Sarusas varieties in the Etendeka province (Umann *et al.*, 2001).

Evidence of pyroclastic activity has been mentioned by different authors regarding the Palmas type and the Etendeka silicic units (Milner *et al.*, 1992; Garland *et al.*, 1995; Umann *et al.*, 2001). The difficulty in the characterization of these pyroclastic deposits arises from the fact that little well preserved textural evidence of this kind of facies had been found. However, some inferences for the mode of eruption and emplacement based on pyroclastic textures were made by Umann *et al.* (2001) and Marsh *et al.* (2001).

In Uruguay, the Mesozoic magmatism of felsic composition was first described as the “Aiguá Series” by Walther (1927) and later as the “Lascano Series” by Caorsi and Goñi (1958), including in these nomenclatures all the felsic outcrops present in the southern-southeastern region of the country. These geological units (comprising rhyolites, rhyodacites, dacites and granophyres) were later defined as the Arequita Formation by Bossi (1966). Kirstein *et al.* (2000) identified two different chemical types of rhyolites, the Lavalleja and the Aiguá types, within the Arequita Formation in Uruguay. These rhyolites were interpreted as either the results of extensive fractional crystallization and assimilation processes or residual melts of pre-existing lower crust with subsequent extreme fractionation (Kirstein *et al.*, 2000; Lustrino *et al.*, 2003a). The texture and chemical composition of these rhyolites are different from other PMP felsic rocks. According to Kirstein *et al.* (2000) the Lavalleja and Aiguá rhyolites constitute chemical subdivisions of the Arequita Formation with no petrologic equivalents in other parts of the PMP.

The Early Cretaceous Valle Chico igneous complex (VCIC; Muzio, 2000; Muzio *et al.*, 2002) is also temporally linked to the PMP and to the early stages of the South Atlantic rifting. It is composed of felsic plutonic bodies and subordinated volcanic rocks, crosscut by rhyolitic dykes of the Arequita Formation. These rocks of the VCIC bear many petrological similarities with Mesozoic igneous complexes from the Etendeka province, particularly with the Messum Complex (Lustrino *et al.*, 2003b; Lustrino *et al.*, 2005).

The presence of pyroclastic facies in the Arequita Formation has been formerly mentioned by Bossi *et al.* (1966); Bossi *et al.* (1998); Kirstein *et al.* (2000) and Kirstein *et al.* (2001a). However, field descriptions and detailed petrography of these rocks are still scarce not only for outcrops in Uruguay but also for the PMP and even for the African counterparts.

The aims of this article are: a) to elaborate the first petrographic account of the felsic volcanic deposits of the Arequita Formation located in the southern extreme of the Laguna Merin Basin, east Uruguay; b) to present a detailed petrographic characterization of its pyroclastic deposits; c) to contribute to the better understanding of the local and regional eruption mechanisms involved with the PMP event.

GEOLOGIC SETTING

In Uruguay, the Mesozoic felsic volcanic rocks extend from the eastern border of the Santa Lucia Basin to the Laguna Merín Basin, along the tectonic corridor traced by the Santa Lucia-Aiguá-Merín Lineament (SaLAM lineament, after Rossello *et al.*, 2000; Fig. 1). These silicic rocks dominate the landscape forming remarkable hills with structural trends around NE to SW, from Arequita to San Miguel regions (Muzio, 2003). The study area presents around 160 km^2 of volcanic exposures located

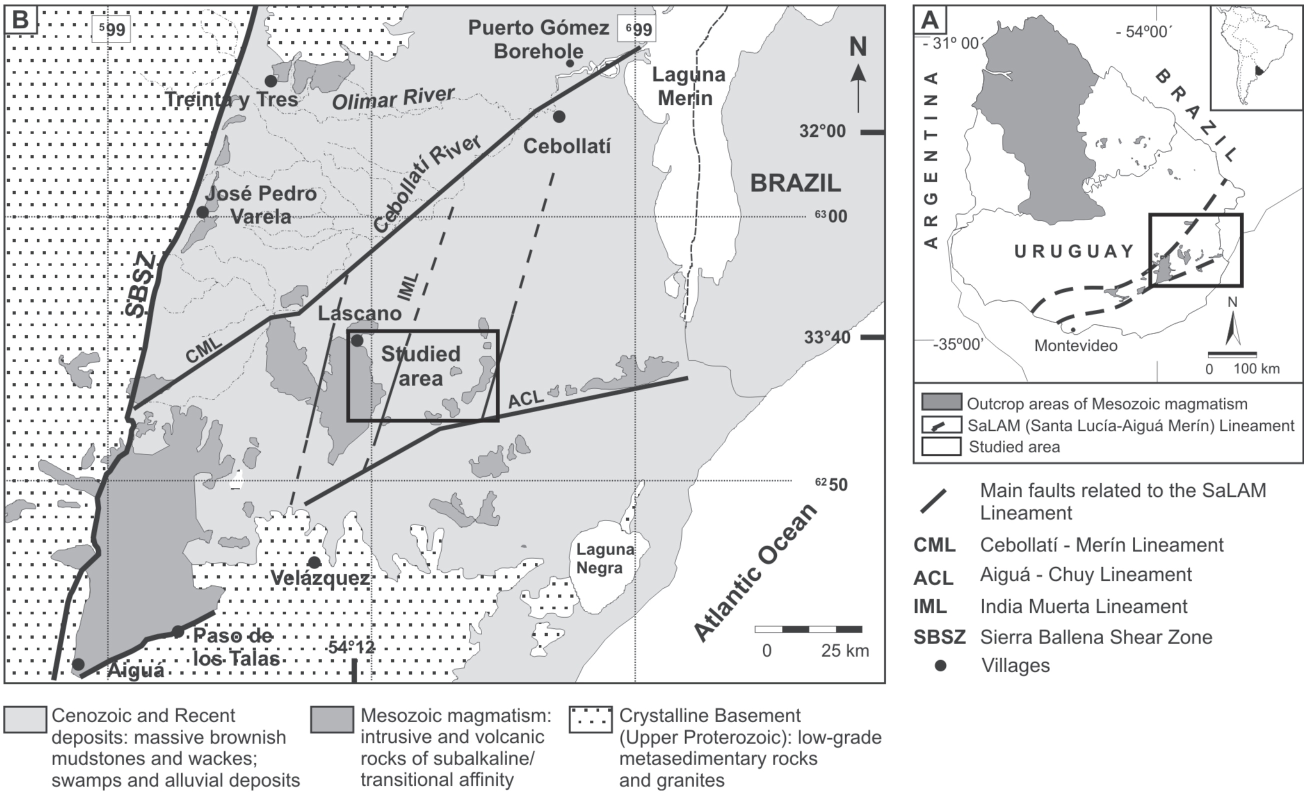

Figure 1. a) Location map. b) Structural framework and regional distribution of the main Mesozoic plutonic-volcanic occurrences related to the Santa Lucía-Aiguá- Merín lineament, after Veroslavsky *et al.* (2003).

between Sierra de los Ajos and Lascano localities (Figs. 1, 2) which correspond to the easternmost Mesozoic felsic volcanic outcrops in Uruguay. These rocks are formally grouped in the Arequita Formation (Bossi, 1966) and comprise, according to available chemical data, from dacites to rhyodacites, rhyolites and granophyres (Kirstein *et al.*, 2000; Muzio *et al.*, 2002; Muzio *et al.*, 2004). They overlie basaltic and andesitic lavas of the Puerto Gómez Formation (Bossi, 1966) but no clear contact has been observed between this unit and the Arequita Formation in the studied area. Recently obtained $^{40}Ar/^{39}Ar$ ages and other previous radiometric ages are well constrained around 134-130 Ma for the mafic lavas of the Puerto Gómez Formation and 132-124 Ma for the felsic rocks of the Arequita Formation (Stewart *et al.*, 1996; Kirstein *et al.*, 2001b; Lustrino *et al.*, 2005), supporting their spatial and temporal relationship.

Different authors pointed out the important and widespread distribution of pyroclastic occurrences in the Arequita Formation (Bossi *et al.*, 1966; Bossi and Navarro, 1988; Kirstein *et al.*, 2000; Kirstein *et al.*, 2001a; Lustrino *et al.*, 2003b and Muzio *et al.*, 2004). These deposits are partially covered by sediments of Cenozoic age making difficult to find complete sections where to establish facies associations and to elucidate their spatial distribution.

LAVA FLOW AND PYROCLASTIC DEPOSITS OF THE AREQUITA FORMATION

Petrographic characterization of volcanic facies, following textural categories *sensu* McPhie *et al.* (1993), allow recognizing two main textural groups in the Arequita Formation: (i) lava flow deposits and (ii) pyroclastic deposits. The study area can be divided into two regions crosscut by the India Muerta lineament (IML) and with different distribution of the here described volcanic rocks (Morales, 2006; Fig. 2). The N20ºE IML is one of the tectonic controls of the eastern extreme of the SaLAM Lineament (Rossello *et al.*, 2000; Veroslavsky *et al.*, 2003).

Lava flow deposits

This group is represented by SiO_2-rich rhyolites (mean SiO_2 value of 72%; Kirstein *et al.*, 2000), with porphyritic textures composed either of quartz/K-feldspar or mainly of plagioclase (An_{10-30}) phenocrysts,

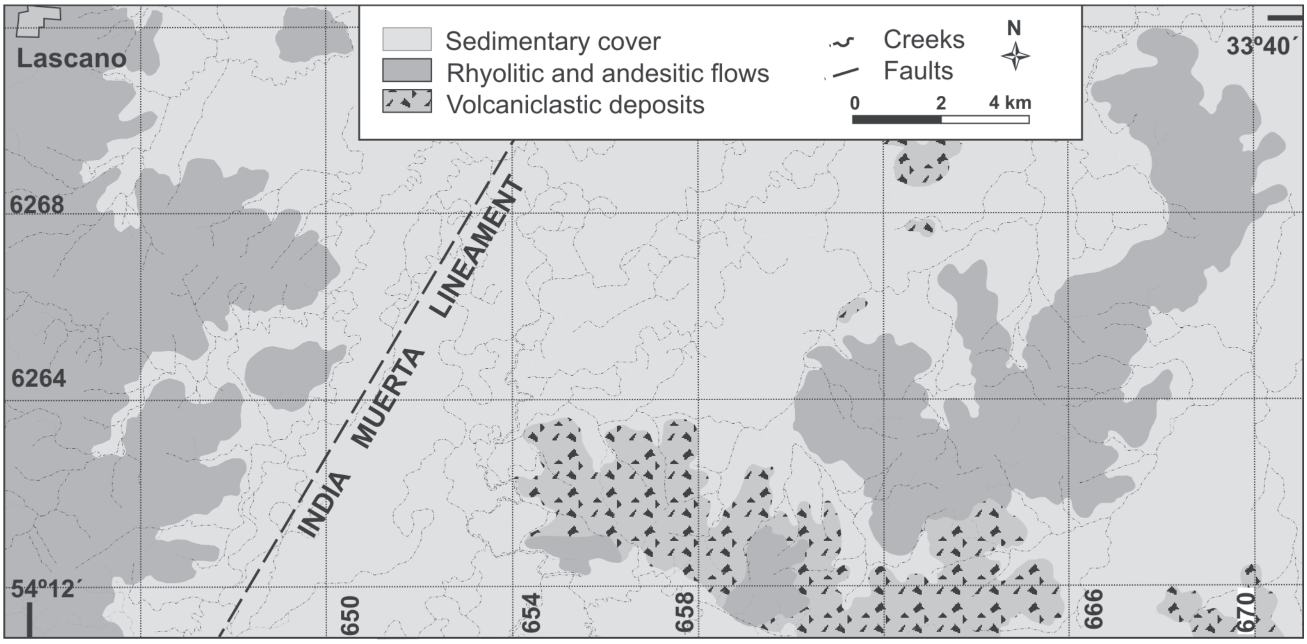

Figure 2. Simplified geological sketch of the area, after Morales (2006). (Planar coordinates related to Jacaré datum projection).

cropping out mainly to the east of the IML. In the western region (west of the IML), porphyritic rhyolites with plagioclase phenocrysts (An_{10-30}) were also recognized, overlying andesites (Puerto Gómez Formation; cf. Bossi, 1966), with both plagioclase (andesine) and augite phenocrysts.

The rhyolitic lava flows are flow banded with autoclastic brecciated surfaces. The contacts between different rhyolitic flows along several exposures indicate the presence of at least three lava flow units, each one of around 1 meter of thickness. The upper part of each flow is characterized by important vesicle contents, often elongated and mainly filled by zeolite group minerals and quartz with crystals ranging in size from a few mm to 2-3 cm. The massive levels of each flow have common porphyritic textures (less than 10% of phenocrysts). The phenocrysts can be represented by subhedral embayed quartz (Fig. 3a, b), subhedral K-feldspar and/or plagioclase ($An_{10–30}$) crystals (Fig. 3c, d). The groundmass, of aphyric felsitic composition, reveals micropoikilitic and recrystallized spherulitic textures. It is composed of a microcrystalline arrange of quartz, alkali feldspar and plagioclase. Scarce mafic minerals are represented by clinopyroxene (augite) and iron oxides. Devitrification processes, due to hydration and vapor phase interactions, such as spherulitic texture and perlitic fractures are present.

The andesitic lava flows, present in the western region of the study area, are texturally glomeroporphyritic with plagioclase and clinopyroxene phenocrysts (Fig. 3e). These rocks show lateral variations either by the increase of the amount of vesicles, partially filled by zeolite minerals, or by the absence of clinopyroxene as a phenocryst phase. They are composed of euhedral to subhedral plagioclase (An_{30}-An_{50}) and clinopyroxene (augite), both in a glassy groundmass, remarked by perlitic fractures (Fig. 3f). Fine-grained opaque minerals are also present. Alteration minerals include both chloritic and sericitic replacements.

Pyroclastic deposits

Pyroclastic rocks occur in the eastern portion of the studied area, eastwards of the IML (Fig. 2). These deposits are always associated with the most evolved lava flow group (porphyritic rhyolites with quartz and K-feldspar phenocrysts) of the here described Arequita Formation. Following descriptive criteria, grain-size based on McPhie *et al.* (1993), three pyroclastic facies have been recognized: pyroclastic breccias, lapilli-tuffs and monomictic breccias.

Pyroclastic breccias. These rocks are poorly sorted, matrix supported breccias composed of angular clasts (lithic fragments and crystal fragments) in a vitroclastic groundmass (Fig. 4a, b). The juvenile clasts comprise around 30% of the whole rock composition, with variable size of up to 80 cm and correspond

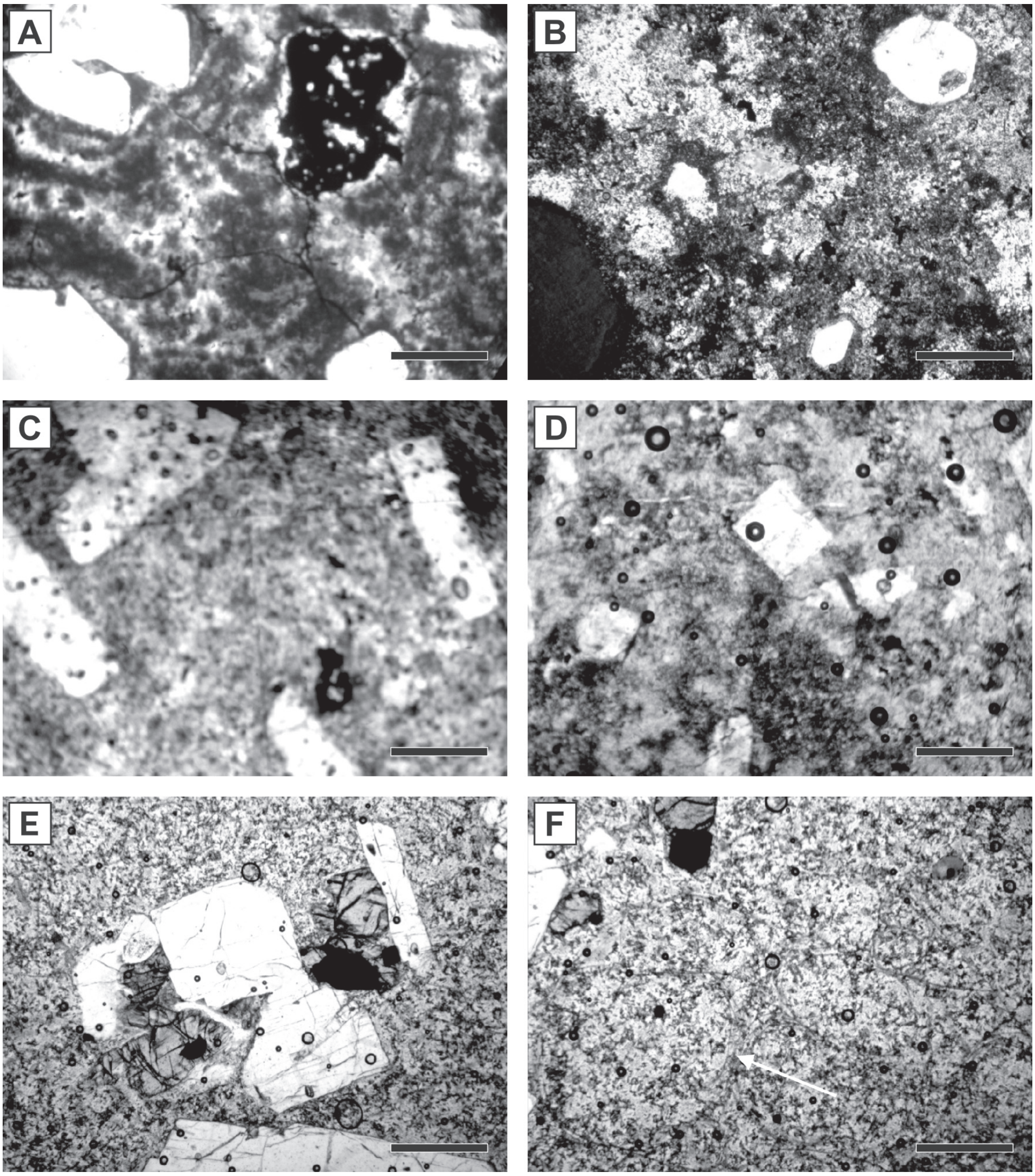

Figure 3. Photomicrographs of the lava flow deposits (scale bar: 1 mm). a) and b) Arequita Formation: rhyolites with quartz phenocrysts and micropoikilitic matrix, showing evidences of reabsorption /disequilibrium processes. c) and d) Arequita Formation: rhyolites with oligoclase ± alkali feldspar phenocrysts and dominantly felsitic matrix partially devitrified. e) and f) Andesites underlying the Arequita Formation, with glomeroporphyritic texture composed by andesine, augite ± opaque mineral phenocrysts, in a very fine groundmass with perlitic fractures.

mainly to porphyritic rhyolites with embayed quartz phenocrysts. In minor proportions (less than 5% of the whole rock), accessory and/or accidental lithic fragments of high welded ignimbrites are also present (Fig. 5a, b). The matrix is mainly composed of glass and sand-size crystal fragments of silicic composition. Some crystal fragments also correspond to plagioclase crystals and opaque minerals. Other relevant textural features include shard-like structures, with mean grain size of around 2 mm and well-preserved cuspate and Y-shaped morphologies (Fig. 5c, d). Occasionally, eutaxitic texture defined by flattened, welded pumices and shards is also present. These pyroclastic breccias present a tabular geometry and are located along the valleys developed among the main topographic highs.

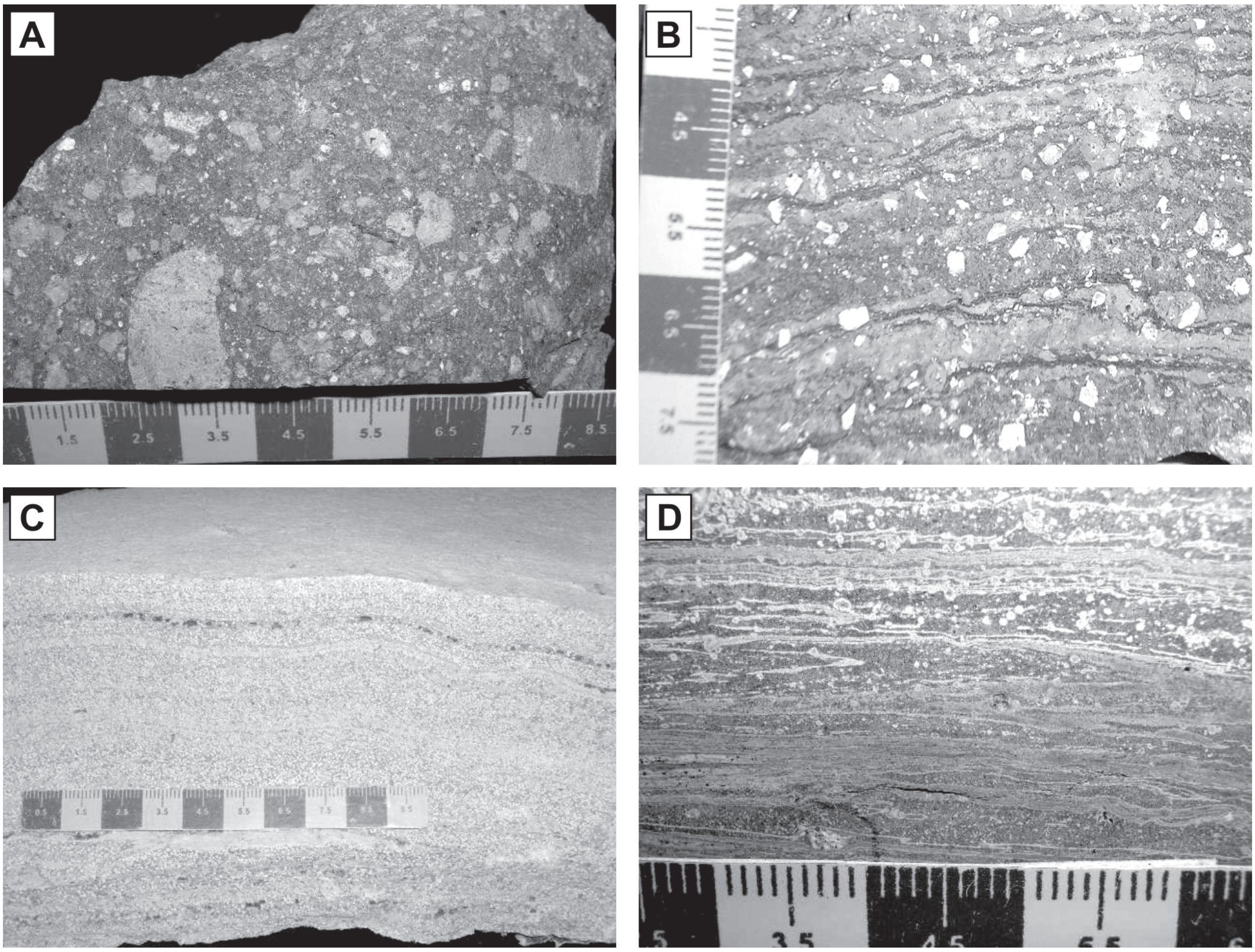

Figure 4. Textural features of the pyroclastic deposits. a) and b) Pyroclastic breccias. c) and d) Lapilli tuffs.

Lapilli tuffs. This facies is composed of fine grained stratified ignimbrites (Fig. 4c, d), comprising sand-grain size particles composed of rounded quartz and feldspar fragments (less than 5%) and glassy devitrified nodules (around 10%) with spherulitic and perlitic fractures (Fig. 5e). These rocks have a moderately sorted, matrix supported fabric. Occasionally, fine layers composed of pores, manganese and opaque minerals, are present (Fig. 5f). Ash-nodules of very fine grained material with quartz and opaque minerals, spatially oblique to the lamination, have also been identified.

An outstanding feature of these deposits is the presence of a distinct planar lamination (< 2 mm), almost parallel to gently undulated, although some micro-folds contouring crystal fragments are observed. Subordinately, thin sections allowed the recognition of incipient development of cross lamination.

Monomictic breccias. They are laterally discontinuous levels of autoclastic breccias, mainly composed of irregular rhyolitic fragments with sizes around 5-10 cm and quartz crystals fragmented *in situ*, with variable grain size between 2 mm and 3 centimeters. The matrix is also of rhyolitic composition and has been affected by post-emplacement fractures partially filled by quartz. These breccias are related to the previously described rhyolitic lava flows, occurring at the top/base of the silicic porphyritic lavas containing quartz/alkali feldspar phenocrysts.

The identification of the here described textural features in some deposits related to the Mesozoic lava flows of eastern Uruguay allowed the interpretation of genetic aspects related to these rocks. The monomictic breccias are interpreted as autoclastic breccias, resulting from lava flow fragmentation. They are always associated with the porphyritic and high silicic lava flows. These breccias are composed of porphyritic fragments of rhyolitic composition and quartz fragments within a rhyolitic groundmass. No pumice or other fragmented features related to

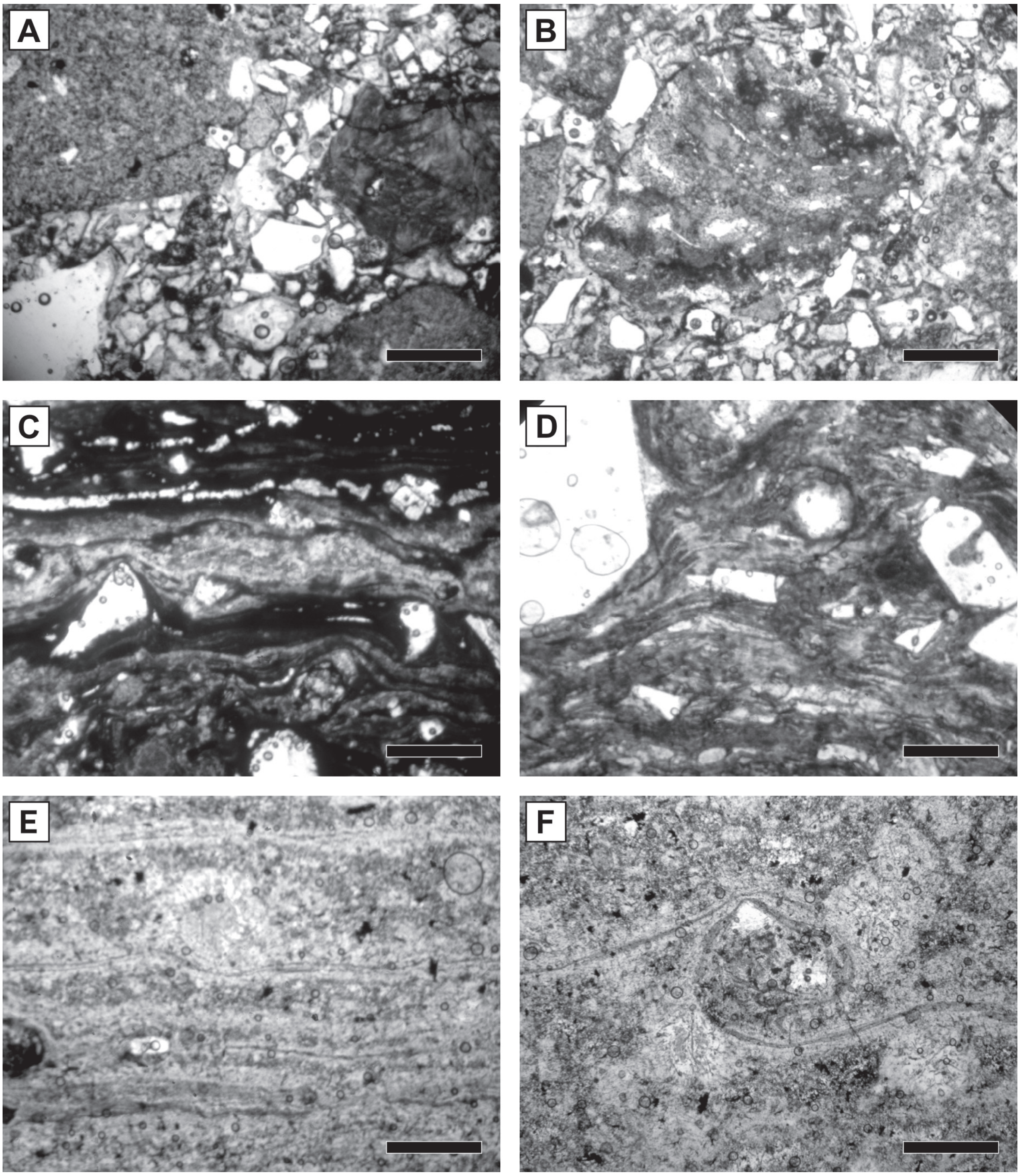

Figure 5. Photomicrographs of the pyroclastic deposits (scale bar 1 mm). a) and b) Massive pyroclastic breccias composed quartz and lithic fragments unevenly distributed in a vitroclastic groundmass composed by crystal fragments, shards and pumice. c) and d) High welded pyroclastic breccias, composed by quartz fragments in a glassy matrix with abundant shards. Shards are usually deformed around crystal fragments and, rare axiolitic textures due to devitrification are present. e) and f) Lapilli tuffs composed by clasts of feldspar in a banded and very fine grained devitrified matrix. Glassy nodules with perlitic fractures, spherulites and axiolitic devitrified bands are present.

explosive mechanisms have been found. According to these features these deposits are interpreted as primary pyroclastic deposits due to effusive volcanic eruptions.

The pyroclastic breccias and lapilli tuffs, according to their textural features, can be separated in pyroclastic flows and pyroclastic surge deposits. The pyroclastic breccias are interpreted as pyroclastic flow deposits (Fisher and Schmincke, 1984; McPhie *et al.*, 1993) according to the following criteria: (a) components: presence of juvenile pyroclasts (crystals, crystal fragments and shards) and lithic fragments;

(b) lithofaciological features: they constitute massive deposits, poorly sorted with tabular geometry located along the valleys and (c) textural features: they correspond to volcaniclastic deposits composed of block to lapilli grain size pyroclasts, within an ash-lapilli grain sized matrix. Thus, considering the different types of pyroclastic flow deposits they genetically correspond to ignimbrite deposits *sensu* Fisher and Schmincke (1984). The lapilli tuffs are interpreted as primary pyroclastic surge deposits (Cas and Wright, 1987; Martí, 1989; McPhie *et al.*, 1993), based on the following features: (a) they are constituted by a thin set of layers; (b) they present a parallel laminar banding slightly undulated and, occasionally, a fine crossed micro-stratification can be observed; (c) they are composed of very fine grained material. Among the different pyroclastic surge deposits they would correspond to ground surge deposits (McPhie *et al.*, 1993), because of their topographic and stratigraphic relations with the pyroclastic breccias. The pyroclastic breccias and the lapilli tuffs are very similar in composition although the second one are better sorted and present a finer granulometry than the first one. No reworked pyroclasts or epiclastic detritus have been identified in order to assign them a volcanogenic sedimentary origin. Both pyroclastic deposits allow the characterization of explosive eruption mechanisms in the area and can be generically called as ignimbrites *sensu* Fisher and Schmincke (1984).

DISCUSSION

The mapping carried out in the Sierra de los Ajos and Lascano regions allow recognizing in the Arequita Formation both lava flows and the here described pyroclastic rocks. Lava flow facies is represented by porphyritic rhyolites with different amounts and types of phenocrysts, while three kinds of pyroclastic deposits have been distinguished. Lithostratigraphically, the Arequita Formation covers the lava flows of mafic composition assigned to the Puerto Gómez Formation.

The recognition of some textural and field features in rocks of the Arequita Formation, indicating the presence of pyroclastic deposits in eastern Uruguay allow a discussion of some aspects of these rocks and their relation to the felsic volcanic deposits of the PMP and the Etendeka Province. Kirstein *et al.* (2000) pointed out that the porphyritic lavas with quartz phenocrysts from south-eastern Uruguay are petrographycally similar to rheomorphic rhyolites of the Erongo Volcanic Complex (Etendeka Province). If these rhyolites can be considered as lava flows or as high welded pyroclastic flows could lead a controversy. The here presented field-petrographic evidences and previous works (Kirstein *et al.*, 2000; Muzio *et al.*, 2004; Morales, 2006) were used to distinguish lava flows from rheomorphic tuffs and lava-like ignimbrites in eastern Uruguay. Following Umann *et al.* (2001) some of these criteria are: a) the stratigraphy of the volcanic pile with presence of massive and brecciated levels which are common structural features in rhyolitic lava flows; b) petrographycally the absence of pyroclasts like pumice, crystal fragments and/or shards, favors an effusive origin and c) estimated temperature of emplacement (Kirstein *et al.*, 2001a). These authors yielded a temperature of emplacement of around 800º - 900º for the felsic rocks from south-eastern Uruguay. According to the authors, these temperatures would not be enough to obliterate completely an original pyroclastic texture. This situation could be one of the most remarkable differences between, at least, part of the Uruguayan rhyolites and their pyroclastic deposits and the felsic volcanic deposits from southern Brazil which correspond to high temperature lava flows (Umann *et al.*, 2001). However, other hypotheses regarding explosive mechanisms of emplacement have been discussed by many authors for the origin of the siliceous volcanic deposits related to the PMP (Milner *et al.*, 1995; Marsh *et al.*, 2001). Despite the fact that no vents have been identified in this study the presence of sub-circular structures, the continuity of pyroclastic deposits related to the porphyritic rhyolites and the intersection of important lineaments close to the studied area suggest the proximity to possible emission centers.

CONCLUSIONS

The Mesozoic felsic magmatism related to the opening of the South Atlantic Ocean is represented in eastern Uruguay by the Arequita Formation which comprises lava flow and pyroclastic deposits. According to structural and petrographic criteria the area between Lascano and Sierra de los Ajos localities was divided into two regions (western and eastern) in relation to the India Muerta lineament. This lineament, with a N20ºE structural trend, represents one of the most important tectonic controls of the region concerning the tectomagmatic evolution of this portion of the Laguna Merin Basin (Rossello *et al.*, 2000; Veroslavsky *et al.*, 2003). Eastwards this lineament, SiO_2-rich porphyritic lavas with quartz/alkali feldspar phenocrysts and pyroclastic deposits (ignimbrites) are present. To the West, only lava flow deposits have been identified, represented by porphyritic rhyolites, mainly with plagioclase phenocrysts. Regarding the volcanic deposits located to the West of IML, the presence of fragmented lithologies associated with the lava flows can not be ruled out. Several authors, like Bossi *et al.* (1966), Bossi and Schipilov (1998) and more recently Kirstein *et al.* (2000, 2001a) have recognized not only ignimbritic deposits but also occasional agglomerated scoria fragments in a basaltic matrix westwards the IML, near the Lascano locality. Neither in these cases nor in the present study the possible vents have been identified so, detailed studies must be carried out to the western region of the IML.

Taking into account the petrographic features and the chemical subdivision of the Arequita Formation performed by Kirstein *et al.* (2000), the porphyritic lavas and the pyroclastic deposits distributed eastwards the IML correspond to the Type 1 - Quartz-phyric rhyolites or Lavalleja subtype (cf. Kirstein *et al.*, 2000). Petrographycally, they are composed of an anhydrous mineralogy represented by plagioclase (An_{10}-An_{45}), clinopyroxene (augite), quartz, alkali feldspar and opaque minerals.

The presence of alkali feldspars and quartz in the rhyolitic lava flow deposits of the Arequita Formation (as phenocrysts or as felsitic groundmass) reinforces some of the previously mentioned petrologic differences between these rocks and the felsic volcanism of the PMP in south-southeastern Brazil, despite the fact that their share some similar petrogenetic histories.

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