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Neoproterozoic subaqueous extrusive–intrusive rocks in the Playa Hermosa Formation in Uruguay: Regional and stratigraphic significance

Leda Sánchez-Bettucci [a,*], Magdalena Koukharsky [b], Pablo J. Pazos [b], Santiago Stareczek [a]

[a] *Facultad de Ciencias, Universidad de la República, Departamento de Geología, Area Geofísica-Geotectónica, Iguá 4225, Malvin Norte, CP 11400, Montevideo, Uruguay*
[b] *CONICET — Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Ciudad Universitaria, Pabellón II, piso 1, CP 1428, Ciudad Autónoma de Buenos Aires, Argentina*

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ABSTRACT

Volcanic rocks in southern Uruguay are linked to an extensional tectonic regime related to the post-collisional Brasiliano–Pan African orogenic cycle. The ca 580 Ma magmatic event is recorded in the Playa Hermosa Formation. In the upper section of this formation several units were defined. The basal unit is a quartz–syenite brecciated deposit, interpreted as the result of explosive episodes of shallow plutonic quartz–syenite intrusion with signs of hydrothermal alteration. Sedimentary and basaltic lithoclasts are occasionally present in the breccia, implying the emplacement of basalts before of that magmatic event. The middle unit is composed of trachytic hyaloclastites. Local distribution and textural evidence indicate that trachytic volcanic pulses have been followed by an explosive event that produced brecciated deposits. The upper unit of the studied sequence is composed of basalts with thin sedimentary intercalations. Most of the outcropping basalts display the typical micro- and macro-features of hyaloclastites; distinctive of extrusions occurred in wet sediments previous to lithification. Basaltic feeder dikes are common in the lower unit. The study of flow structures in the quartz–syenite brecciated deposits led to the recognition of two basaltic inputs. Such differences are related to the intensity of chloritic alteration, which would be related to water contamination. Basaltic peperites are one of the most impressive features of the Playa Hermosa Formation. Hyaloclastites and peperites largely represented among the studied volcanic rocks, and devitrification textures are all evidences of magma/seawater interactions. In the basaltic fragments of the peperites well preserved orange palagonite appears, while the sandstone fractions have lithic clasts of felsic volcanic rocks, such as rhyolitic lavas with perlitic cracks and lithophysae-like structures. Palagonite chemical analyses suggest marine environment and, at the same time, it proves that the studied section lacks of regional metamorphism. The felsic volcanic lithoclasts contained in sandstones could be related to the felsic volcanic lobes intercalations. The studied magmatic event is important in order to formulate correlations with other Neoproterozoic units distributed around the Dom Feliciano belt, like Camaquã and Campo Alegre basins (Brazil), and in the Kaoko belt (NW Namibia) in Africa. Also, Playa Hermosa Formation presents glacigenic features that are well documented, and reinforce the volcanism around 580 Ma in the Rio de la Plata Craton.

1. Introduction

The recognition of peperites and hyaloclastites (magma/wet sediment and/or water interaction, White et al., 2000) in the geological record is common and unequivocal way of confirming the simultaneous nature of sedimentation and volcanism. The Precambrian record has few references about these conspicuous structures, since they are generally affected by metamorphism and deformation, obliterating the original textures. There are examples in Paleoproterozoic rocks of Australia (Koongie Park Formation), where Orth and McPhie (2003) described interaction of magma (rhyolitic sills) and wet sediments (sand and mudstones). Calver et al. (2004) in Tasmania describes rhyodacite flows underlying deposits related to glacigenic episode around 580 Ma. In the Campo Alegre Neoproterozoic basin, southern Brazil, Citroni et al. (2001) mentioned a hyaloclastic fragmentation and possible peperites, and Janikian et al. (2003) described peperites in the Cerro da Angélica Formation (Bom Jardim Group) of the Camaquã Supergroup (sensu Fragoso Cesar et al., 2003) with an age ca. 590 Ma (Remus et al., 1999; Janikian et al., 2003, and references therein).

The present study is focused on the Playa Hermosa Formation (Playa Verde Basin), located in southern Uruguay near Piriápolis City, at 34°49′41″ S/55°19′00″ W (Fig. 1), which integrate the sedimentary cover of the Rio de la Plata craton. This Basin contains three units: the Playa Hermosa, Las Ventanas, and San Carlos Formations. Well preserved hyaloclastites and peperites are an evident feature of the Playa Verde Basin in Southern Uruguay (Figs. 2 and 3).

The Playa Hermosa Formation was defined by Masquelin and Sánchez Bettucci (1993) as a turbiditic sequence containing conglomerates

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* Corresponding author. Tel.: +598 2 5258617.
E-mail addresses: leda@fcien.edu.uy (L. Sánchez-Bettucci), mkou@gl.fcen.uba.ar (M. Koukharsky).

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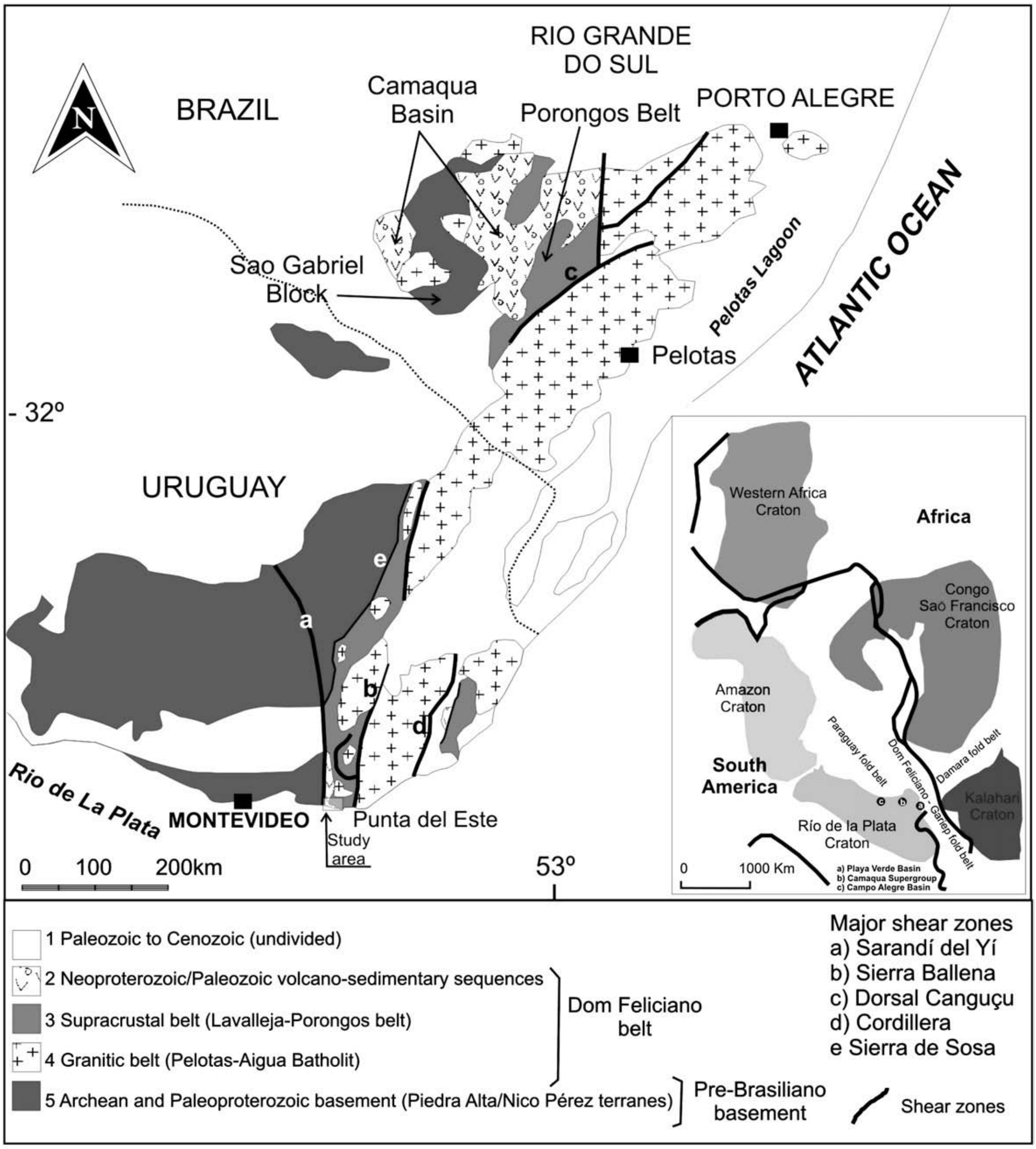

Fig. 1. Simplified geological sketch of Uruguay and Rio Grande do Sul, showing the distribution of Neoproterozoic/Paleozoic volcano–sedimentary sequences.

deposited in submarine fans and canyons. Pazos et al. (1998, 2003) suggested a fan delta system with subaqueous and sub-aerial facies related to a glacial input. According to Sánchez Bettucci and Pazos (1996), the Playa Verde Basin started the infilling in the late Neoproterozoic and it may have ended in the early Ordovician (e.g. San Carlos Formation). The Playa Hermosa Formation is divided into a lower and upper members (Sánchez Bettucci and Pazos, 1996). Pazos et al. (1998, 2003, 2008) described glacial influence in the lower member based on features like dropstones, diamictites, and rhythmites. Sánchez Bettucci and Pazos (1996) mentioned that the upper member of the Playa Hermosa Formation is composed of sandstones and conglomerates, and is cut by numerous dikes and sills. The upper part of the lower member, which is contemporary with the glacial-related deposits of the Playa Hermosa Formation, was developed during the volcanic event that conform the Sierra de Las Animas Complex (Sánchez Bettucci, 1997, 1998; Sánchez Bettucci et al., 2003). It consists of a bimodal volcanic and subvolcanic suite exposed close to Piriápolis City (Fig. 2). This magmatism is assigned to an extensional event that marks the end of the late Neoproterozoic Brasiliano–Pan African orogenic cycle (Sánchez Bettucci, 1997, 1998; Sánchez Bettucci et al. 2001, 2003; Sánchez-Bettucci et al. 2004). The volcanic complex consists of trachytes, rhyolites, ignimbrites, basalts and intercalated sediments. Conduits for these volcanic eruptions have not been identified, but the existence of numerous north–south trends of basic and acidic dikes suggests that the feeder fractures could have an equivalent orientation.

Isotopic ages for different rock types from the Sierra de Las Animas Complex range from 615 to 490 Ma (Sánchez Bettucci, 1997, and references therein; Sánchez Bettucci and Rapalini, 2002; Oyhantçabal et al., 2007).

The aim of this paper is the description of the products that resulted from the interaction between magmas and wet sediments and/or water. Also, the study of an important breccia deposit related

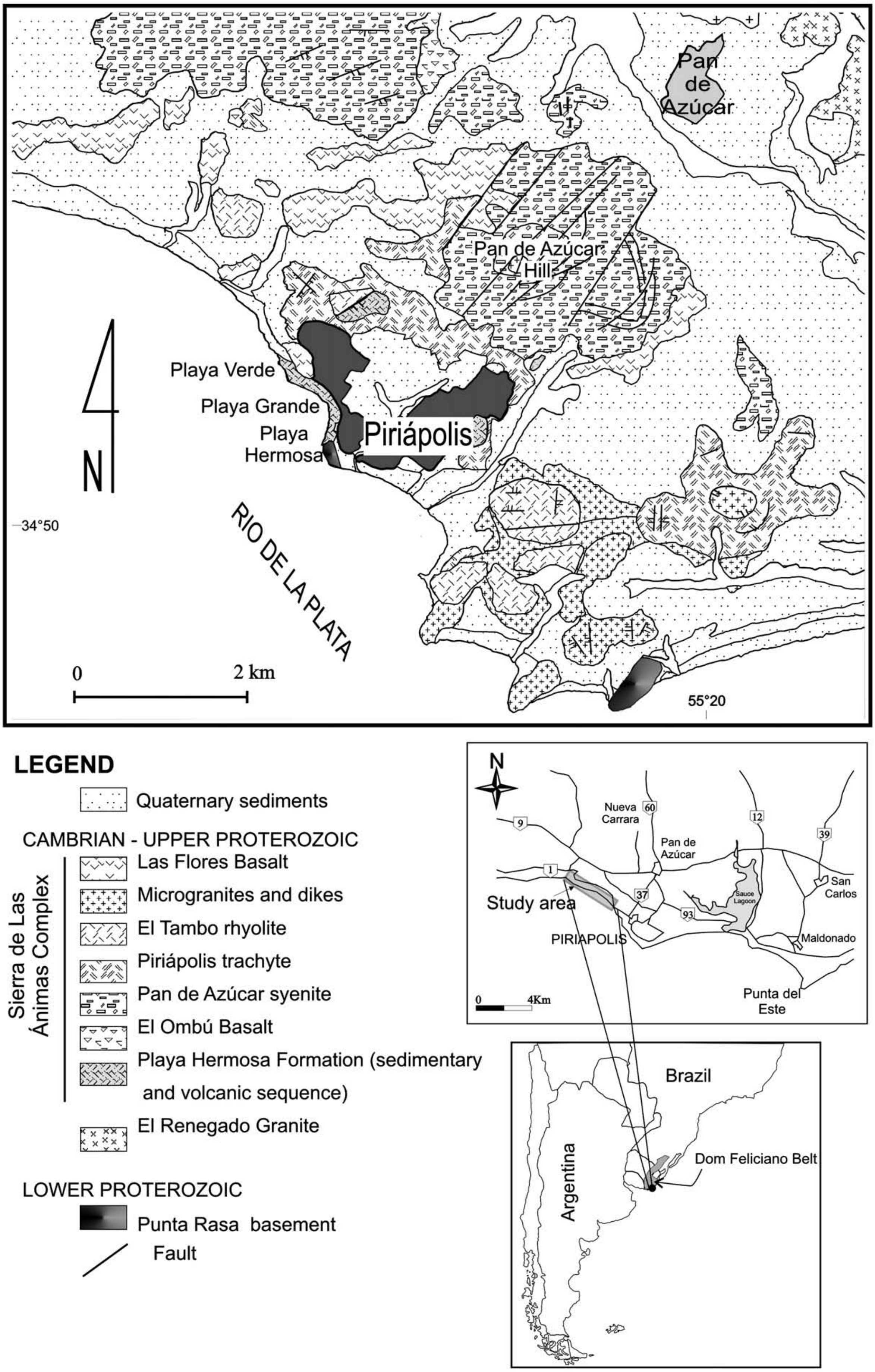

Fig. 2. Location map and simplified geological map of the study area.

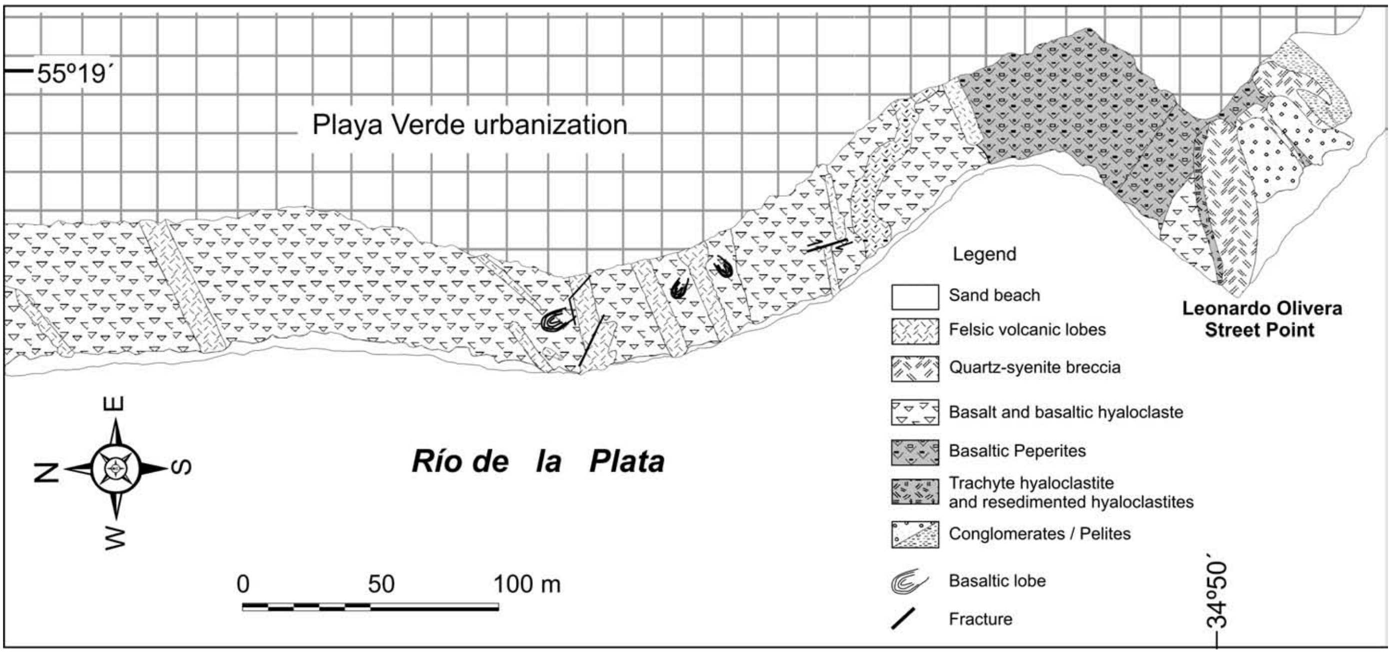

Fig. 3. Geologic map of study area, located at the Upper member of Playa Hermosa Formation.

to these rocks and their interpretation in the geological context. This is crucial in order to generate new evidence for further stratigraphic correlations.

2. Geological setting

The geological framework of Uruguay during Neoproterozoic–Early Paleozoic shows a great similarity with that observed in southern Brazil (Rio Grande do Sul) and eastern Argentina (Buenos Aires Province) because all form part of the Rio de la Plata Craton. Cordani et al. (2000) suggested that during the Neoproterozoic, the Río de la Plata Craton (Argentina and Uruguay) may have been integrated within a single plate with the Luis Alves block of southern Brazil. The Río de la Plata Craton consists in part of Paleoproterozoic nucleus overprinted by Late Proterozoic orogenic events (Dalla Salda et al., 1988; Cingolani and Dalla Salda, 2000).

At the margin of the Río de la Plata craton, the Brasiliano–Pan African orogenic cycle is well documented along the Dom Feliciano Belt developed in southern Brazil and Uruguay (Fragoso Cesar, 1980). The studied area contains units that represent the final stage of the Brasiliano–Pan African orogenic Cycle, in southern Uruguay (Fig. 1). The post-collisional setting (sensu Bonin, 2004) was characterized by magmatism, rapid sedimentation (e.g. molassic sequences) and episodes of significant movements and reactivations along shear zones.

The Playa Verde Basin (Sánchez Bettucci and Pazos, 1996) was developed and filled at the end of the Neoproterozoic, starting with the deposition of the Playa Hermosa Formation (Masquelin and Sánchez Bettucci, 1993), and ending in Cambrian–Ordovician times with the deposition of Las Ventanas (Midot, 1984) and San Carlos formations. Nevertheless, Las Ventanas Formation was assigned to the Neoproterozoic by Gaucher et al. (2008) and Pecoits et al. (2008).

Sánchez Bettucci and Pazos (1996) defined this basin as a transtensional type with a north–south axis, which could be related to the transtensional phase at ca. 600 Ma proposed for the granitoids of the Eastern Dom Feliciano Belt in Southern Brazil (Frantz and Botelho, 2000).

The Sierra de Las Animas Complex (Fig. 2) is composed of intrusive syenites, micro-syenites, and granites; with trachytes constituting the more evolved extrusive rocks. Others components are rhyolites, basalts, and pyroclastic deposits. The Complex has a subalkaline to alkaline trend marked by the presence of pyroxenes and amphiboles (Sánchez Bettucci, 1997, 1998). Geochemically, this Complex have alkaline nature, volatile elements and LILE enrichment, indicating that are derived from a mantle enriched source, and record crustal contamination in its ascent. All of these are in agreement with the features proposed by Bailey (1983) for the extensional setting. Also, it shows enrichment in Th, product of the mobility of this element, during the fusion processes of the crust (Sánchez Bettucci, 1997). Some basalts are tholeiitic and probably represent the first stage of basic magmatism related to extensional event (Sánchez Bettucci, 1997, 1998) at the Playa Verde Basin.

The Sierra de Las Animas Complex was developed in Neoproterozoic and Cambrian times, apparently during a long period from 615 to 490 Ma, according to isotopic data (Sánchez Bettucci, 1997, and references therein; Oyhantçabal et al., 2007). The available geological, structural, and geochronologic data suggest the presence of at least two main magmatic phases (Sánchez Bettucci, 1997; Sánchez Bettucci and Rapalini, 2002). The older phase generated intrusive syenites (Pan de Azúcar Formation) and related bodies with ages ranging from 580 Ma to 559 Ma (Sánchez Bettucci and Linares, 1996; Oyhantçabal et al., 2007). In addition, the extrusive basaltic lavas (El Ombú Formation) that have a computed mean age of ca. 547 (K–Ar and Rb–Sr). Recently, an Ar–Ar age on amphibole of 579 ± 1.5 Ma was determined for the Pan de Azúcar syenite (Oyhantçabal et al., 2007). The youngest phase of the Sierra de Las Animas Complex is represented by trachytes, rhyolites, and mafic dikes with ages ca. 520 Ma (see Sánchez Bettucci and Rapalini, 2002). The long period spanned by the Sierra de Las Animas Complex is supported by paleomagnetic results (Sánchez Bettucci and Rapalini, 2002). These authors determined a low to intermediate paleolatitude and a congruent polar wander path, through the 600 Ma, age for the Neoproterozoic lower member of Playa Hermosa Formation. Based on the available data it is considered that 580–570 Ma is the most plausible age for Playa Hermosa Formation.

2.1. The Playa Hermosa Formation

This formation crops out along the coastline from the Playa Hermosa to the Playa Verde beaches, located few kilometers to the west of Piriápolis (Figs. 2 and 3). The top of the upper member is not exposed, but the base (lower member) is clearly discordant with tonalitic gneisses (Fig. 4) dated at 1.7 Ga (Sánchez Bettucci et al., 2003; Oyhantçabal et al., 2007). The Playa Hermosa Formation consists of an epiclastic succession with volcanic intercalations. This Formation is subdivided into two members. The lower one is composed of conglomerates, sandstones, diamictites, and siltstones of brown to greenish colors. A 53 m-thick section was studied by Sánchez Bettucci and Pazos (1996) and Pazos et al. (1998, 2003, 2008). Pazos et al. (2003) recognized rhythmites, diamictites and dropstones, interpreted as evidence of glacigenic processes during sedimentation. Pazos et al. (2003) conclude that the sedimentary succession lacks evidences of a marine environment and only a subaqueous depositional setting can be assured. However, Fambrini et al. (2003) suggested a glacimarine setting, based on the occurrence of massive conglomeratic sandstone facies formed by rain-out processes, presence of micro-hummocky cross-stratification (sensu Dott and Bourgeois, 1982) and occurrence of dropstones in fine-grained sediments indicative of a hydrodynamic paradox. However, as pointed out by Pazos et al. (2003, 2008) hummocky is not present and it is drift cross lamination with high input form suspension and neither conglomerates or rain-out is per se indicative of a marine depositional setting because it is common in fjord lakes, lakes and marine glacial influenced basins (see Pazos et al., 2008). At the top of the lower member occurs the first evidence of magma/wet sediment interaction in an interval where faint rhythmically lamination and embedded conglomerates can be recognized. From there begins the upper member.

2.1.1. *Playa Hermosa Formation — upper member*

This member is represented by breccias, hyaloclastites, peperites and sedimentary rocks (pelites, sandstones and conglomerates). In many cases the contact between volcanic and sedimentary rocks is irregular suggesting that sedimentary material was unconsolidated.

The base of the studied section, 220 m-thick (Figs. 3 and 4), is represented by breccias constituted by fragments of fine grained quartz–syenite. Their matrix is mostly finely crushed quartz–syenite material with few clasts of sedimentary rocks and basalts. Quartz–syenite rock fragments with irregular borders and jigsaw-fit textures are common (Fig. 5), suggesting explosive mechanism for their fragmentation. Conglomerates with a pelitic matrix, and pelite intercalations are interpreted as boulders included in the quartz–syenite breccias. This part of the section ends in a narrow, in part faintly laminated level of fragmented vitrophyric trachyte, interpreted as reworked hyaloclastites and hyaloclastites based on their microscopic characteristics. Thin dikes with a sinuous outcrop pattern, composed of fine grained trachyte displaying granophyric textures, cut the lower and medium sections of the breccia. They represent trachytic fillings of fractures interpreted as feeder dikes. Overlying those reworked hyaloclastic trachytes; highly fractured basaltic lavas (hyaloclastic) with thin sedimentary intercalations are exposed. At this position excellent examples of peperites are recognized.

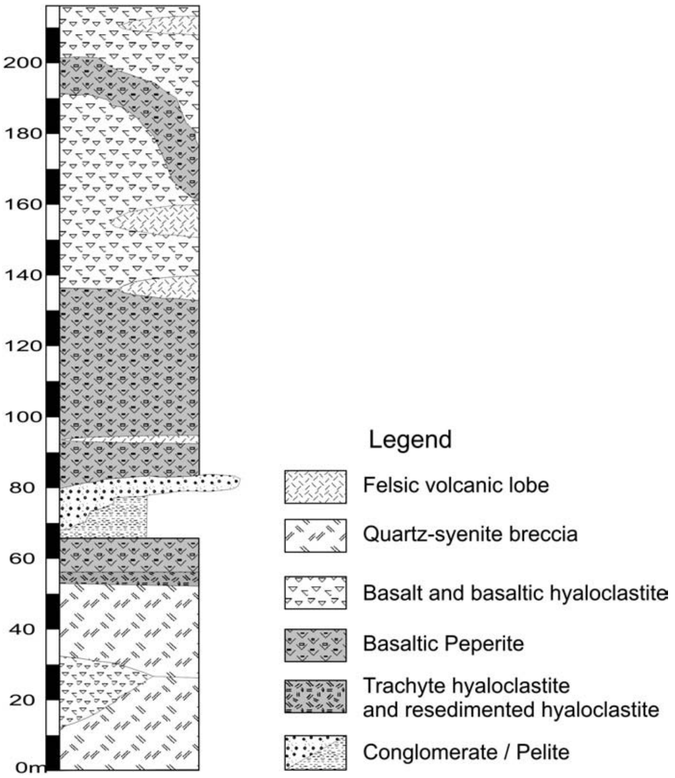

Fig. 4. Stratigraphic column of the studied section.

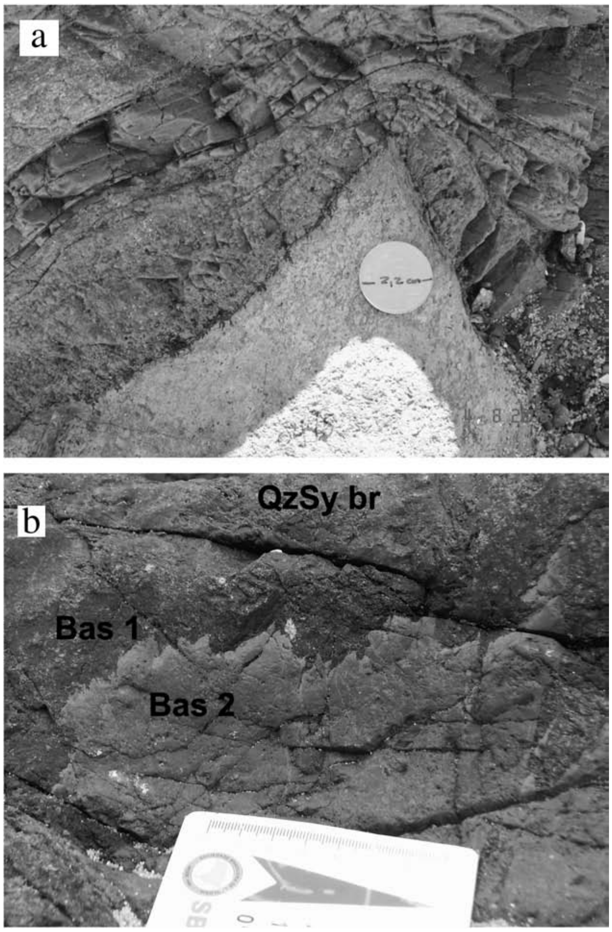

Fig. 5. a) Basal contact between flows laminated rhyolite lobe and altered basalt. The coin has 2.2 cm length, b) Basaltic pocket intruded the quartz–syenite breccia. QzSy br: quartz–syenite breccia fragment; Bas 1: relatively anhydrous basalt; Bas 2: chloritized (originally highly hydrated) basalt. The arrow of the scale represents 5 cm.

Rhyolite lobes are intercalated with basalts near the top of the upper member of the Playa Hermosa Formation (Fig. 5b). Thin dikes and concordant lenses (sills?) of basaltic composition are present locally. Its massive appearance contrasts with the typical contraction cracks of "in situ" hyaloclastites.

2.1.1.1. *Quartz–syenite breccia.*

The breccias are poorly sorted, with fragments dominantly made of fine-grained reddish or whitish gray colored quartz–syenite, immersed in a dark gray aphanitic matrix. The common fragment size varies from 3 to 30 cm, but near its lower section includes some boulders of grayish green massive pelites and conglomerates that can be related to the lower member of the Playa Hermosa Formation, and some minor dark gray basaltic fragments.

Quartz–syenite clasts frequently have very irregular open borders and jigsaw disposition in a “false peperitic texture”. Under the microscope, quartz–syenite clasts (Fig. 6) have a fine-grained (1–2 mm) texture, with subhedral patchy perthitic alkaline feldspar as dominant component, scarce or absent euhedral altered plagioclase, and about 7% interstitial quartz. It is remarkable, in some quartz–syenite fragments, the presence of partly euhedral quartz grains showing secondary enlargement, as a border of thin prisms developed normal to the nucleus. This texture represents the typical quick quartz enlargement under hydrothermal environments. Crystalline clasts of the breccia are derived from the quartz–syenite. They are composed of alkaline feldspar with irregular patchy perthites and minor altered plagioclase, quartz with homogeneous or slightly heterogeneous optical extinctions, opaque minerals and zircon.

A representative chemical analysis (EDS-SEM) from alkaline feldspar is shown in Table 1. Similar proportions of Na and K indicate sanidine or anorthoclase as original minerals, suggesting hypabyssal (ca. 1 km?) emplacement for the quartz–syenite intrusive. Sectors of intense crushing inside the breccia have similar previous microbreccia clasts, revealing two fragmentation episodes. The matrix has the same crystalline fragmental composition, accompanied by scarce felsitic or near trachytic finely devitrified glass and extremely fine dusty probably sedimentary components, with secondary chlorite, carbonates and opaque granules.

2.1.1.2. Trachyte hyaloclastites and reworked hyaloclastites. Trachyte hyaloclastites, with scattered quartz–syenite lithic clasts, are recognized as a narrow level at the top of the quartz–syenite breccia. They are composed of massive aphanitic gray rocks, which in detail contain some sub-oriented whitish gray irregular aphanitic aggregates up to 1.5 cm long and 0.4 cm high (which are fragmented feldspar crystals) looking like “false ignimbritic” textures. In thin section, we can observe that, these rocks are fragmented and composed by felsitic (formerly glassy) fragments cemented by scarce chlorite minerals accompanied by few little pyrite nodules. Perlitic fractures are common; the same as jigsaw-fit feldspar phenocrysts and incipient spherulitic textures. A faint sediment-like planar lamination developed at the upper 30 cm of the outcrops, which are overlain by basalt lavas, led to classify that sector as reworked hyaloclastites.

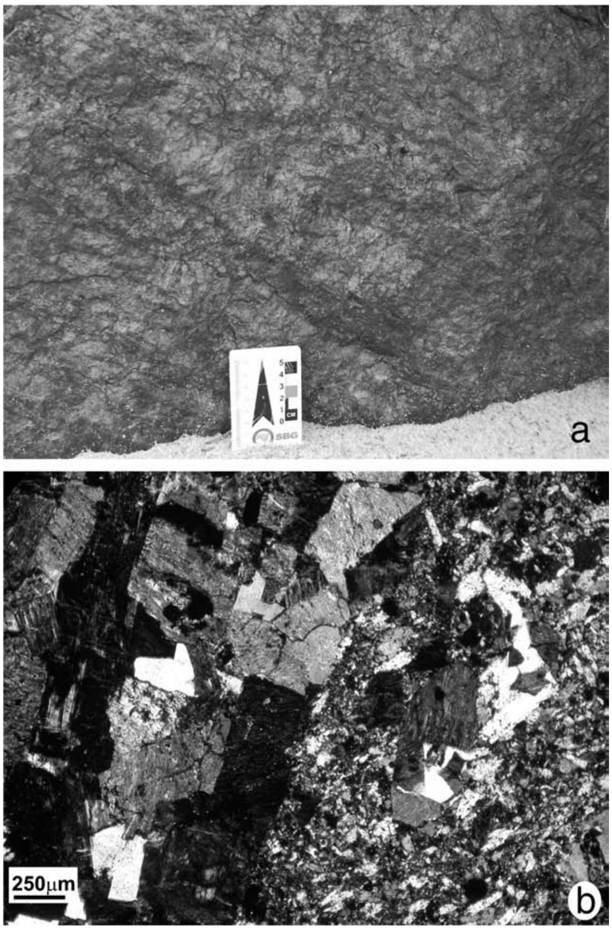

Fig. 6. a) Quartz–syenite breccia: note the jigsaw texture and false peperitic texture, b) Photomicrography of quartz–syenite clasts in the quartz–syenite breccia (cross polarized light).

Table 1
Representative EDS-SEM analysis of minerals from different rock samples: 04-12 quartz–syenite breccia, 04-8a basaltic peperite and 05-4 chloritized basalt lens in quartz–syenite breccia.

Sample/ Composition	Alkaline Feldspar 04-12(23)	Plagioclase 04-8a(2)	Plagioclase 05-4	Palagonite 04-8a(8)	Palagonite 04-8a(4)	Apatite 05-4
SiO_2	67.00	67.10	67.90	40.29	38.59	–
Al_2O_3	18.10	20.12	19.14	18.76	18.65	–
FeO	0.37	–	–	19.32	21.48	1.12
MgO	–	–	–	21.62	20.79	–
CaO	0.80	0.66	–	–	–	48.57
Na_2O	7.57	12.12	12.96	–	–	–
K_2O	6.14	–	–	–	0.47	–
P_2O_5	–	–	–	–	–	44.98
F	–	–	–	–	–	5.32

2.1.1.3. Trachyte feeder dikes. Dark greenish gray colored fine-grained dikes of tabular outcrop patterns about 0.30 m to 0.70 m wide were observed in the lower member of the quartz–syenite breccia. In thin section these rocks are characterized by the presence of granophyric textures developed at the borders of altered plagioclases, and by the abundance of alkaline feldspar crystals. Some dark brown, strongly pleochroic relicts of primary biotite, are preserved associated with secondary chlorite minerals. Pale green amphibole (actinolite) is present in some samples. Quartz occurs in interstitial positions. Accessory minerals are opaque grains with frequent skeletal form (probable ilmenite), prismatic apatites and scarce zircons, which sometimes have thin and long prismatic habits, mentioned for alkaline rocks (Pupin, 1980). Carbonate, sphene and epidote granules are common secondary minerals.

2.1.1.4. Basalts and basaltic hyaloclastites. Basalts are dark gray to light yellowish brown aphiric or finely porphyritic altered rocks, which constitute some massive lava levels and lobes. They present in situ fragmentation (Fig. 7) grading from mega- to micro-breccias interpreted as hyaloclastites based on their tiny normal or/and polyhedral contraction joints and microscopic glassy textures (Yamagishi, 1994; McPhie et al., 1993). Lobe structures are sometimes recognized from flow-lines defined by the orientation of tabular plagioclase crystals. In hand specimens, plagioclase phenocrysts with seriated sizes (reaching 6 mm in length) can be observed. These basalts have irregular vesicles and zoned amygdules (up to 1 cm in diameter) made of quartz, chalcedony, calcite and chlorite. Vesicles are especially common towards the top of the studied section.

Most of the basalts are porphyritic and frequently micro-brecciated as a consequence of hyaloclastitization (Fig. 7b). Plagioclase is always altered to clay minerals and/or replaced by albite and calcite. Sometimes, serpentine and chlorite pseudomorph of olivine phenocrysts can be identified. The groundmass texture, which probably was hyalophitic, now is seriated. It is composed by plagioclase microlites, occasionally in variolitic disposition, set in brown or black isotropic interstitial material, with scarce orange palagonite remnants, and opaque aggregates (iron oxides and pyrite). Inside the basaltic fragments of the peperites (see below), clear plagioclase microlites and orange palagonitized glasses

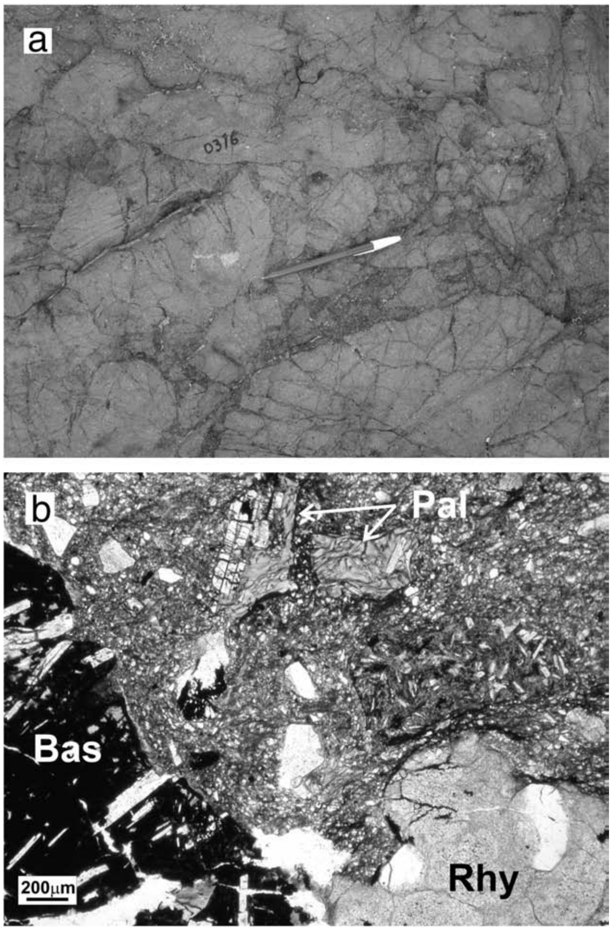

Fig. 7. a) Detail of an outcrop of basalt hyaloclastite, b) Thin section of a peperite showing palagonite (Pal) replacement of basaltic glass shards, plagioclase microlites, rhyolitic lithoclast (Rhy) from the sediment, and (Bas) basaltic oxidized dark groundmass eject.

occurs and were analyzed for this study (see Table 1). For the plagioclase microlites, compositions of near pure albite (An_3 to An_0) suggest an important sodium replacement. Palagonites are of crystalline type, probably with the development of Mg rich di-octahedral smectite in a network of submicrometer-sized bent flakes, similar to that mentioned by Zhou and Fyfe (1989) for marine palagonites (Fig. 8). They have a low silica content, similar MgO and FeO proportions, sometimes a little K content, and lack of Ca and Na, as is expected for the mature stages of this material in marine environments (Zhou and Fyfe, 1989; Ramanaidou and Noack, 1987; Stroncik and Schmincke, 2001).

2.1.1.5. Feeder dikes and associated lenses or pockets of basaltic composition. Short dikes and lenses or "pockets" of basaltic composition are very common near the top of the breccia deposit. Their appearance is sometimes peculiar with "peperitic-like" structures (see Fig. 5). At least two pulses of basaltic dikes were recognized, some at the same place, resulting in complicated mingling textures. The older lenses or "pockets" are composed of near greenish gray aphyric basalts, occasionally foliated. Under the microscope they show scarce clean plagioclase (albite) and apatite grains immersed in a dense chloritic aggregate with very fine carbonate granules marking flow lines. These basaltic rocks are interpreted as the result of highly hydrated basaltic lavas, where former palagonite was completely transformed in chlorite, following a normal evolution as it was suggested by Fisher and Schmincke (1984). Plagioclase, chlorite and apatite chemical analyses are shown in Table 1. The other recognized pulse of basaltic dikes, relatively anhydrous in relation to that previously described, occurs as 0.50 m irregular dikes that are short running or form "pockets". They are mostly emplaced into the lowest basaltic lava levels. In hand specimens, they are near aphyric micrograined dark gray rocks with microamygdules filled by chlorites and calcite. Microscopically the well preserved intergranular primary textures are composed of altered plagioclase containing acicular apatite inclusions, mafic crystals replaced by chlorite mineral aggregates, and opaque granules. Accessory minerals are opaques and apatite.

2.1.1.6. Basaltic peperites. Blocky peperites were defined by Busby and White (1987) as composed by angular, polyhedral juvenile clasts, and they infered that development is more favorable in coarse-grained wet or unconsolidated or poorly consolidated sediments. The jigsaw-fit texture corresponds to blocky clasts generated by in situ fragmentation. The generation of blocky and tapered clasts is due to brittle fragmentation of magma (Busby and White, 1987; Skilling et al., 2002). This type of fragmentation is favored by high viscosity magma and/or high strain-rate. Steam-driven explosion can form in magmas that engulf pore fluid-sediment combination, fragmenting the magma into blocky clast that may be dispersed by rapidly expanding superheated pore fluids (Kokelaar, 1986; Busby and White, 1987; White et al., 2000). These processes generate dispersed blocky clasts in the host sediment. Micro and mega-blocky peperites are common in the studied area. At least three levels with micro and mega blocky peperites are observed, associated with basalts in the study area. The Fig. 9 illustrates close-packed blocky peperites in a fine to medium-grained conglomerate in contact with basalt. Some blocky peperites consist of lobes or irregular protrusions of basaltic lavas. Those features indicate that the deposits were formed by eruptions in a shallow-water to emergent eruptive setting. They provide some of the most conspicuous and impressive evidence of lava-pelite interactions in the study area. Globular peperites (McPhie et al., 1993) are related to pelitic sediments. In thin sections, sedimentary and basaltic components can be identified. Sedimentary components consist of poorly sorted angular volcanic clasts in a fine brownish-gray matrix. Inside them, lithic clasts of micro-porphyritic rhyolitic to trachytic compositions are frequent. Sometimes they have perlitic fractured groundmasses. The quartz and plagioclase microphenocrysts are set in an alkali feldspar dominant mosaic, or feathery or spherulitic textures, as well as fragmented spherulitic, welded tuffs and litophysaes (tiny tabular feldspars aggregates linearly disposed on clean quartz bases). Plagioclase and quartz are the crystalline fragments. The basaltic components appear among the biggest and smallest fragments. The biggest ones are porphyritic with elongate and invariably albitized plagioclase and chloritized/serpentinized olivine phenocrysts, in an originally hyalopilitic or hyalophitic groundmass. The glass has been altered into opaque material and/or palagonite. The smaller fragments

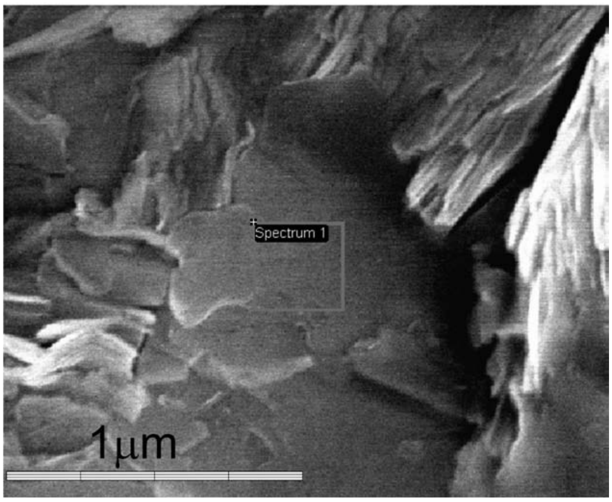

Fig. 8. EDS image of palagonite from a basaltic peperite.

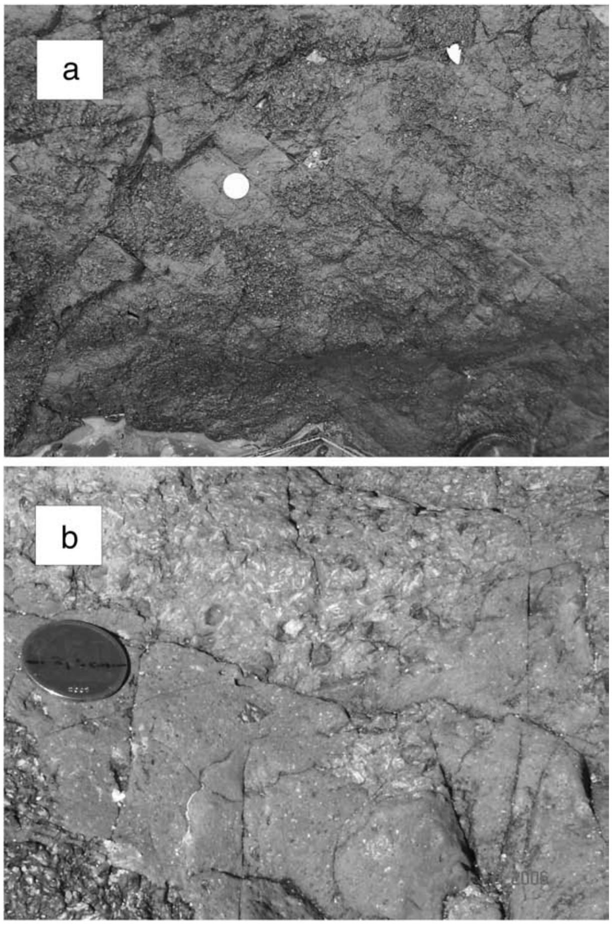

Fig. 9. Peperites. a) Close packed blocky peperite in conglomerate at the contact with basalt, the coin is 3.2 cm length; b) sectors of globulitic peperite in contact with basalt, the coin is 2.2 cm length.

are palagonite shards and drop-like palagonitized, sometimes vesiculated groundmasses, with skeletal plagioclase microlites. The palagonite, orange in color, is always devitrified with some passages to chlorite. The thin section shows that the sediment had a rhyolitic to trachytic source. Palagonite is considered as an evidence of the interaction between water and incandescent lava. The combination of palagonite, dispersed peperite, and vesicular fragments suggest shallow emplacement at relatively small water depths.

2.1.1.7. Felsic volcanic lobes. Felsic volcanic rocks crop out as lobes or bodies from tens of meters to less than 10 m thick intercalated with the basalts. Their disposition (NE) is concordant with the attitude of basaltic and trachyte hyaloclastic levels (Fig. 3). They are reddish brown, light gray, or greenish gray near aphanitic or porphyritic rocks, with phenocrysts of quartz and altered feldspar of up to 2 mm in diameter. Most of them are massive, and near the contacts the presence of banded flow suggests that the former were vitrophyric lavas or domes. Irregular, mostly fine-grained primary autobreccias can be seen at the surface of some lava bodies and sometimes as sectors inside them. Scarce basaltic lithoclasts are seen in the felsites near the contact. In thin sections, the primary fluidal structures are appreciated by alignment of crystallites, which are argillized microlites or crystallites replaced by opaque material, in microgranular groundmasses, which are converted into mosaics of quartz enclosing different proportions of sericite flakes. Devitrified structures are in great part obliterated by silicification, but relict spherulites replaced by quartz are still clearly visible in some clusters. Quartz phenocrysts can be abundant (near 8%). They indicate secondary enlargement, detected through similar optical orientation with the groundmass mosaic grains around them. Former feldspar (plagioclase) phenocrysts are replaced by carbonate, sericite-clay and fluorite aggregates, accompanied by scarce clean quartz grains.

3. Correlations

The studied volcanic rocks belong to an alkaline bimodal magmatism with magma/wet sediment or water interaction associated processes that clearly occurred previous to the lithification of the Playa Hermosa Formation. In the same way it brings new tools for the correlation with equivalent sections in basins from Brazil (see Fig. 1). In southern Brazil Neoproterozoic magma/water or wet sediments were mentioned for Camaquã Basin. Janikian et al. (2003) had mentioned basic peperites in the Cerro da Angélica Formation (Bom Jardim Group) of Camaquã Supergroup (sensu Fragoso Cesar et al., 2003) with an age ca. 590 Ma (Remus et al., 1999; Janikian et al., 2003, 2005, and references therein). Geochemical data indicate that the lithologies of the Camaquã Basin are bimodal and present an alkaline-trend (Almeida et al., 2002, and reference therein). Sander et al. (2005) described a drill core and superficial outcrops from the Hilario Formation with peperites related to basalts and andesites (sic), with ages around 590 Ma (Janikian et al., 2003 and references therein). Citroni et al. (2001) describes the Campo Alegre Basin (Paraná and Santa Catarina states, Brazil) developed during Proterozoic–Fanerozoic. In this basin, anorogenic alkaline to peralkaline rocks with an age ca. 595 Ma, basic to acidic magmatism and lacustrine sediments can be found. Citroni et al. (2001) suggest shallow intrusions intercalated with unconsolidated sediments, hyaloclastites and possible peperites. The volcanic rocks of the Playa Hermosa Formation are considered to be a part of the oldest portion (ca. 580 to 570 Ma) of the igneous alkaline Sierra de Las Animas Complex. Both units present features which support a correlation with the stratigraphic scheme of the Bom Jardim Group and Acampamento Velho Formation and Campo Alegre Basin.

All these units mentioned before are related with post-orogenic Brasiliano event. The basins were formed in the late stages and they were coeval with volcanism. This extensional post-orogenic relaxation phase occurs after collision between Kalahari and Rio de la Plata cratons in a foreland tectonic setting. On the other hand, evidences of glacially influenced sedimentation were described in Playa Hermosa Formation (Pazos et al., 2003, 2008) and in Picada das Graças Formation – Bom Jardim Group – (Erola and Uutela, 2008). The ages of Camaquã Supergroup range from 605 to 574 Ma (Janikian et al., 2008). On the other hand glacial deposits occur in the Kaoko Belt, NW Namibia (Campanha et al., 2008; Goscombe and Gray, 2008) which can be correlated with Uruguayan and Brazilian records. These deposits are assigned to the Gaskiers glaciation recorded in high to low latitudes (Kawai et al., 2008; Meert and Liebarman, 2008; Schmitt et al., 2008). Combination of paleoclimatic indicators (glacial related origin) and a characteristic type of volcanism, including compositional similarities and magma — wet sediments/water interactions, reinforce the tendencies to correlate the successions of southern Brazil with those recorded in Uruguay.

4. Discussion and conclusions

The studied section of approximately 220 m of Playa Hermosa Formation (upper member) confirmed volcanism with bimodal composition. This section is represented by basalts and felsic rocks. The most conspicuous lithology is the hypabyssal quartz–syenite intrusion and the brecciated quartz–syenite (Fig. 10). The breccia deposit, previously considered of trachytic composition (Sánchez Bettucci, 1997) is the basal unit in the section. Nevertheless, the present study reveals that almost all its clasts are composed of a fine equigranular quartz–syenite, pointing out an origin by fragmentation parts of a shallow plutonic body. Shallow conditions are supported by

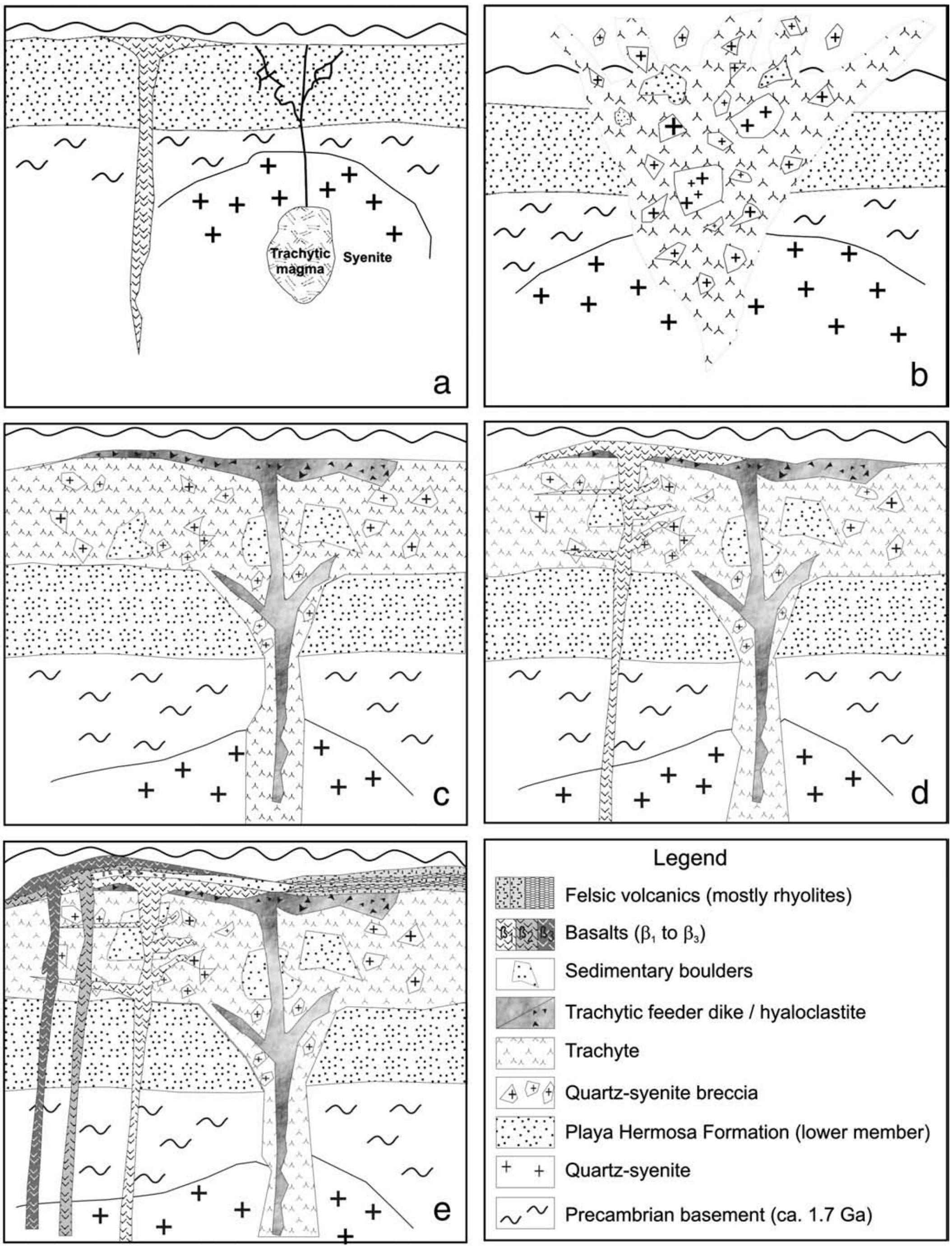

Fig. 10. Cartoon illustrating the sequence of processes inferred in the upper member of Playa Hermosa Formation. a) Basaltic magma ($\beta 1$) ascends toward the top of sediments of Playa Hermosa Formation and trachytic magma enters in a shallow quartz syenite body along fractures that reach the sea bottom. b) An important explosive event occurs at the top of the quartz syenite giving origin to the quartz syenite breccia with minor sedimentary boulders and basaltic fragments. c) Trachytic magma cuts the quartz syenite breccia and form the trachytic hyaloclastite level. d) Basaltic lavas and hyaloclastites ($\beta 2$) are deposited over the trachytic hyaloclastites. Basaltic lenses and pockets are emplaced into the quartz syenite breccia. e) A new level of basaltic lavas and hyaloclastites is deposited interacting with sedimentary lenses to form peperites ($\beta 3$). Felsic volcanic lobes come from the western region.

alkali feldspar's chemical composition, which suggests sanidine or anorthoclase as original phase. Both minerals are present only in extrusive or shallow (subvolcanic or hypabyssal) environments.

The jigsaw-fit fragments arrangement, as well as very irregular and opened borders of the mentioned quartz–syenite clasts are interpreted as the result of expansive forces, like those expected because of an explosive origin. Recurrence of explosive episodes is indicated by the common presence of similar breccia clasts in the quartz–syenite breccia. Absence of any type of juvenile volcanic clast inside the breccia, and identification of final hydrothermal textures in quartz from the quartz–syenite fragments, led to consider a geothermal system disruption associated to the cooling of the hypabisal body, as the probable principal cause of the explosivity.

Conglomerates and sandstones, similar to those of the Lower Member of Playa Hermosa Formation, occur as boulders enclosed in the quartz–syenite breccia.

Sedimentary and basaltic lithoclasts are occasionally present in the breccia, as evidences of previous basaltic magmatism. They can be related to peperitic basalts from the Lower Member of Playa Hermosa Formation which were already mentioned (Sánchez Bettucci, 1998), implying that basalt was erupted at the beginning of the magmatic event.

Stratigraphical evidences indicate that a trachytic volcanic pulse followed the explosive event that produced the breccia deposit. This interpretation is supported by the presence of trachyte dikes (feeder dikes), which cut across sedimentary rocks through the Lower Member of the Playa Hermosa Formation (Sánchez Bettucci, 1998) and the quartz–syenite breccia deposit (Fig. 10). The Upper section of the studied sequence consists of basalts with some narrow sedimentary intercalations. Minor decametric rhyolite lobes crop out near the top with conspicuous flow foliation near the borders.

Basalt lavas are highly altered (chloritized, albitized, silicified, argillized, etc.), but their textures, in general, are perfectly preserved, documenting the absence of local or regional tectonic deformation. Some strike–slip minor faults are related to the volcanic setting. Most of the basalt outcrops show the pattern of jointing or fragmentation with irregular, but normal fractures, typical of hyaloclastites, visible in macro and microscopic scales. Variolitic textures are commonly seen in thin sections. All these features are distinctive of an extrusion in water rich sceneries.

The study of flow structures in basaltic lenses or pockets, located in the quartz–syenite deposit, led to the recognition of two basaltic inputs. Between both are differences in the intensity of chloritic alteration.

Basaltic peperites are one of the most impressive features of the Playa Hermosa Upper Member. Blocky types are commonly developed along contacts with sedimentary lenses. In the finer basaltic fragments of the peperites, orange crystallized palagonite is still preserved. Palagonite represents the first alteration of basaltic glass in contact with water. Metamorphism or intense diagenesis always transforms palagonite to chlorite (Fisher and Schmincke, 1984). Thus, its presence proof that pervasive metamorphism did not occur in the studied sequence. This is an important feature, because other units within the same basin show ductile deformation and low grade regional metamorphism, as well as superimposed dynamic metamorphism and hydrothermal activity (such as the Las Ventanas Formation).

The MgO and K_2O contents, obtained from EDS analyses of the palagonites, are similar to those from other palagonites whose origin was considered in gains from seawater after the lost in a first alteration stage (Ramanaidou and Noack, 1987). Hyaloclastites and peperites are significant elements of the studied volcanic rocks, and devitrification textures are all evidences of magma/ seawater interactions.

Felsic altered and silicified rocks crop out in contact with the basaltic lavas and hyaloclastites near the top of the studied section. A primary flow-banding was observed in most of them at their basal and top contacts. The porphyritic textures and the presence of spherulites or crystallites in the groundmass, led us to classify them as altered rhyolitic to dacitic (latitic?) vitrophyre lobes. They are additional evidence of, already mentioned, volcanic bimodality (basic and acidic). Sandstones lenses participate in peperites, in association with basalts, having lithic clasts of felsic volcanic rocks, such as rhyolitic lavas with perlitic cracks and lithophysae. It is probable that they are related to the same source as felsic lobes intercalated near the top of the studied section. These rock types are equivalent with rhyolites and ignimbrites described together with basalts and syenites in the nearby Sierra de Las Animas Complex (Sánchez Bettucci, 1997, 1998).

A generalized alteration in the volcanic rocks, having a paragenetic sequence of albite–chlorite–sericite–calcite (epidote–clay) in basaltic lavas; quartz–sericite–alkaline feldspar (fluorite–calcite) in rhyolites; and alkaline feldspar–actinolite–chlorite–epidote (biotite) in trachytic dikes, is considered to be the result of local hydrothermal systems, commonly developed in volcanic rocks of marine environments. As it was already mentioned, the presence of crystallized palagonite precludes the consideration of a metamorphic green schist facies.

The sequence of rock types present in the Playa Hermosa Formation Upper Member and their generation processes inferred in this study is synthesized in Fig. 10.

The attributed age of this volcanism and magma/water or interaction with unconsolidated sedimentary sequence and glacial deposits is ca. 580–570 Ma, based on a correlation scheme with Ar–Ar ages in syenites of the Pan de Azúcar Formation.

The studied magmatic event related to the Brasiliano–Pan African orogenic cycle (Fig. 1) is important in order to formulate correlations with other Neoproterozoic units distributed around the Dom Feliciano belt like Camaquã and Campo Alegre (Brazil) Basins and the Kaoko Belt (NW Namibia) in Africa.

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