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Research Paper

The Puesto Piris Formation: Evidence of basin-development in the North Patagonian Massif during crustal extension associated with Gondwana breakup

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A R T I C L E I N F O

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A B S T R A C T

The Marifil Volcanic Complex, exposed in the eastern North Patagonian Massif, Argentina, includes up to 550 m of red conglomerates, sandstones, black siltstones, limestones, and reworked tuff of the Puesto Piris Formation. The basal part of this unit, which was deposited in high-gradient topographic relief, is composed of conglomerates and sandstones with thin layers of reworked tuffs. The lithofacies associations of the basal part indicate that the depositional mechanisms were mantled and gravitational flows. The middle part of the unit consists of fine sandstones, limestones, and black siltstones that were deposited in low-energy fluvial and lacustrine environments. The outcrops are located along the NE–SW direction and the major thickest units represented by limestones and siltstones, occur near the southeastern border of this NE–SW depocenter. Since the rhyolitic and trachytic lava flows and tuffs of the Marifil Volcanic Complex are interbedded with the sedimentary sequences of the Puesto Piris Formation, both units are coeval. Zircon U–Pb age was obtained for a trachytic lava flow (193.4 ± 3.1 Ma) suggesting that sedimentation and volcanism are Sinemurian. This extensional episode was recorded in the eastern, western, and southwestern sectors of the North Patagonian Massif, and is possibly associated with the Gondwana supercontinent breakup.

1. Introduction

There is ample evidence from studies within South Africa, Antarctica, Australia-New Zealand, and South America for an important magmatic province that developed prior to and during the breakup of the Gondwana supercontinent (Cox, 1992; Encarnación et al., 1996; Riley and Knight, 2001; Storey et al., 2013). One of the major outcrops of these volcanic rocks is located along the Atlantic coast of Patagonia and is known as the Chon Aike province (Pankhurst et al., 1998). Magmatism is thought to be related to the presence of mantle plumes located beneath South Africa and Antarctica at ~182 Ma (Riley and Knight, 2001). The first results from the Chon Aike province were obtained by Rapela and Pankhurst (1992) for the Marifil Formation (188–178 Ma). Other results for this unit and the Chon Aike Formation indicate ages from 168 Ma to 187 Ma (Pankhurst et al., 1993; Airic et al., 1995). Radiometric studies in other regions of Patagonia allowed Pankhurst et al. (2000) to establish the existence of three defined magmatic periods (V). V_1 extends between 188 Ma and 178 Ma and includes the Marifil Volcanic Complex. According to the geochemical data (Pankhurst and Rapela, 1995), this volcanism was generated as a result of lower crust anatexis in an extensional environment, which was possibly related to the breakup of the Gondwana supercontinent (Cox, 1992). V_2 corresponds to volcanism that developed between 172 Ma and 162 Ma and includes rocks of the Nesocratón del Deseado, which is further south of the

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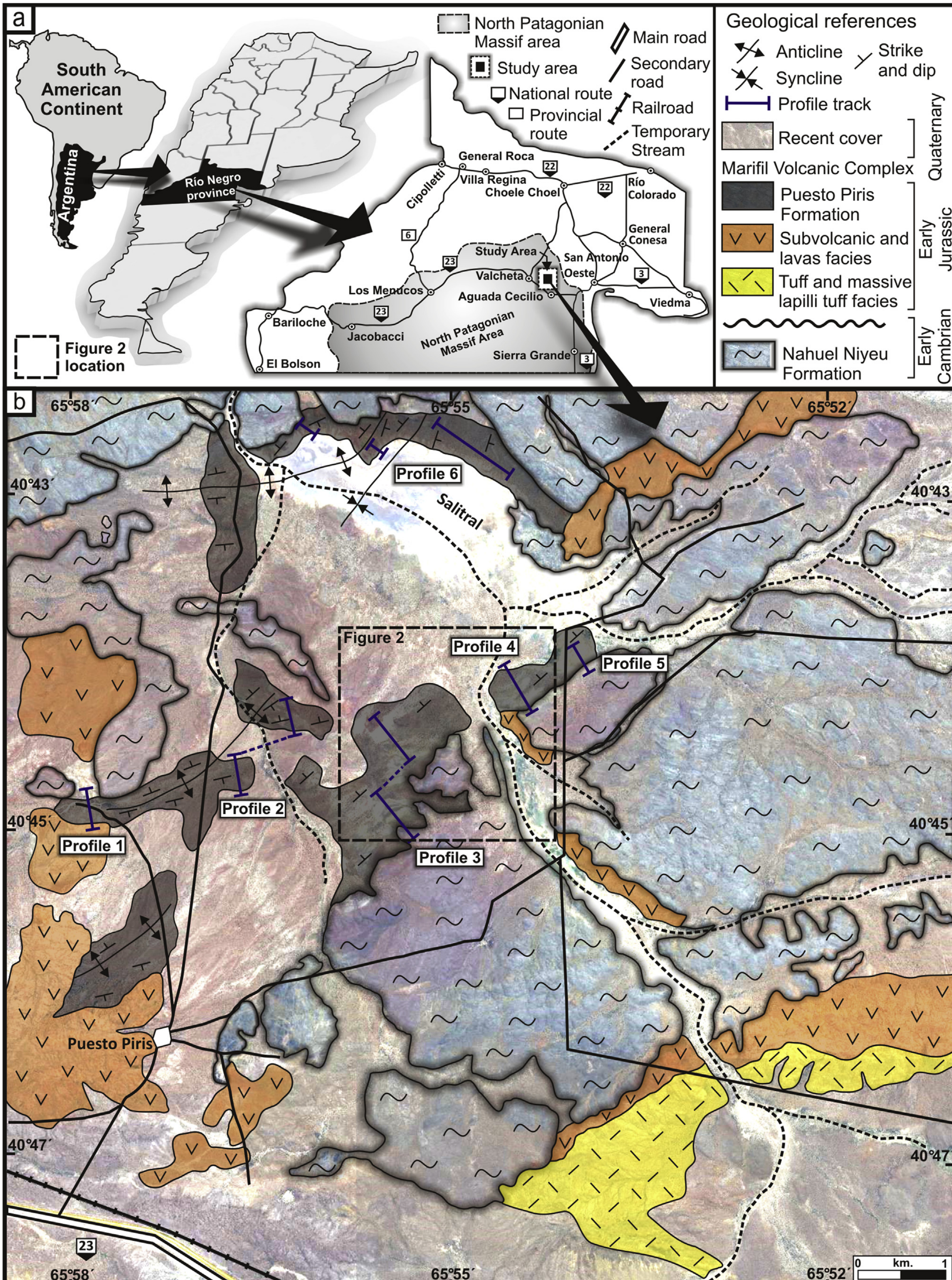

Figure 1. (a) Location of the study area in the North Patagonian Massif (Río Negro Province); (b) geological sketch showing the outcrops of the Puesto Piris Formation, the Marifil Volcanic Complex and other units between 65°51′W and 65°58′30″W and 40°42′S and 40°48′S according to our own field observations. Location of profiles is also displayed.

area studied here. V_3 (157–153 Ma) represents rocks located in the western margin of Patagonia.

The V_1 episode of volcanism is widely represented in the eastern part of the North Patagonian Massif where there are vast outcrops of Jurassic volcanic rocks with minor sedimentary facies. Among the volcanic rocks are thick volcaniclastic associations and subvolcanic bodies that form extended outcrops. Malvicini and Llambías (1974) named these sequences the Marifil Formation. Cortés (1981) later established the Marifil Volcanic Complex, which is composed of three units. The basal unit is the Puesto Piris Formation, formed of conglomerates, agglomerates, and ignimbrites, which yielded a K–Ar age of 189 ± 5 Ma. The following unit is the Aguada del Bagual Formation, represented by orange-red subvolcanic porphyritic bodies. The youngest unit is the La Porfía Formation that is formed of agglomerates, tuffs, tuffaceous sandstones, and ignimbrites. There have been several studies regarding the development, chemistry, and age of the Marifil Volcanic Complex (e.g., Pankhurst and Rapela, 1995; Pankhurst et al., 1998, 2000; Márquez et al., 2010, 2012).

The sedimentary basal section (Puesto Piris Formation), which possibly represents the beginning of the entire complex, has not yet been studied in detail. To the best of our knowledge, there is no information in the literature regarding sedimentary facies, environments, ages, and basin evolution. In this study, we present several detailed stratigraphic sections of the Puesto Piris Formation in the north-eastern region of the North Patagonian Massif at 65°51′–65°58′30″W and 40°42′–40°48′S (Fig. 1b).

The goal of this study is to explain the significance of the Puesto Piris Formation in relation with other Jurassic units of the eastern North Patagonian Massif during the breakup of the western

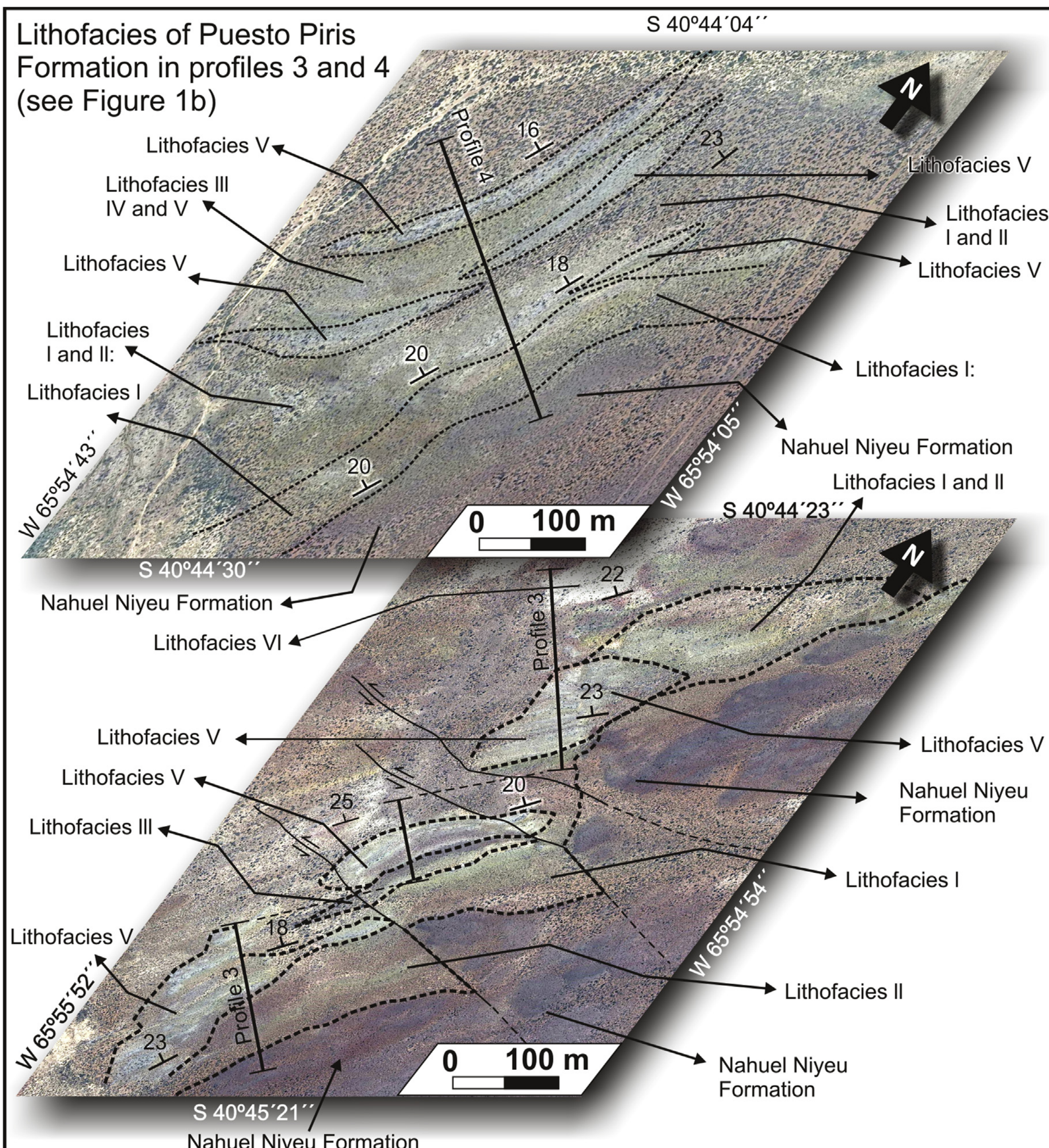

Figure 2. Distribution of outcrops of the Puesto Piris Formation and organization of the lithofacies. Locations of profiles 3 and 4 and strike-slip faults are shown.

Gondwana continent. We aim to establish the age of this unit and its relationship with the Marifil Volcanic Complex since it is believed to represent the base of the volcanic sequence. Our purpose is also to establish the facies associations for the reconstruction of sedimentary environments, shape, and basin type. These findings improve the understanding of local and regional stratigraphy during the Jurassic that is required in order to develop a more refined model of the eastern North Patagonian Massif during Gondwana breakup.

2. Geological setting

The geological configuration of the North Patagonian Massif, 20 km southeast of Valcheta locality is represented in Fig. 1b.

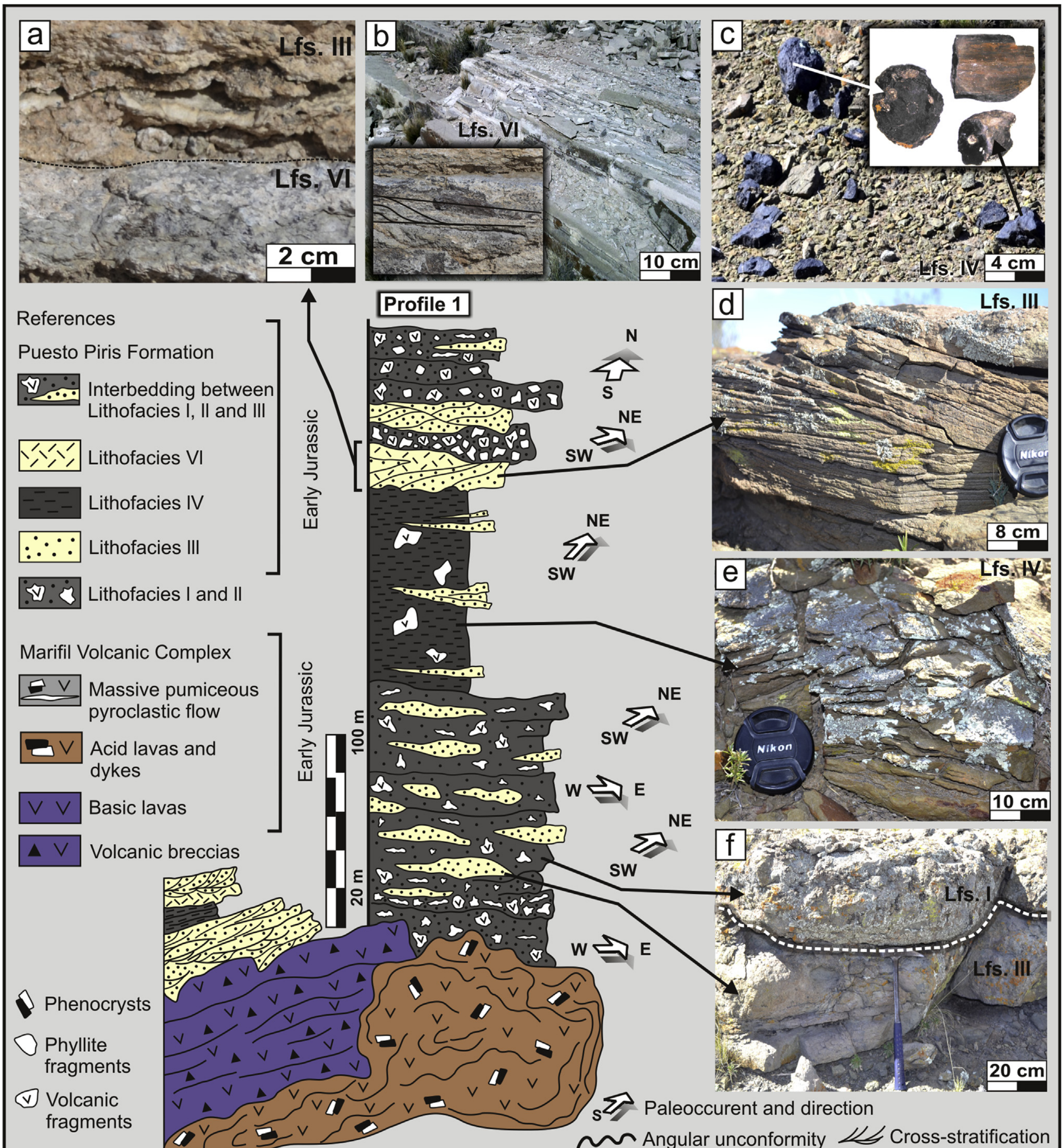

Figure 3. Profile 1 of the Puesto Piris Formation. (a) Interbedding of coarse red sandstones (lithofacies VI) and reworked tuffs (lithofacies VI). (b) View of the reworked tuffs with cross-stratification. (c) Interbedding of fine-grained sandstones and black siltstones (lithofacies IV) with fine conglomerates carrying carbonized wood fragments. (d) Fine-grained sandstones with cross-stratification. (e) View of fine-grained sandstones and black siltstones of lithofacies IV. (f) Contact between coarse red sandstones (lithofacies III) with red to gray matrix-supported conglomerates (lithofacies I).

Basement outcrops are represented by the Nahuel Niyeu Formation, which is composed of alternating beds of phyllites, quartz-feldspathic metagreywackes, and minor intercalations of metasandstones, metaconglomerates, and basic igneous rocks (Nuñez et al., 1975; Caminos, 1983, 2001; Giacosa, 1994a,b; Chernicoff and Caminos, 1996a,b; Greco et al., 2015). The depositional U–Pb age, obtained from detrital zircon using SHRIMP, yielded ages of 515 Ma (Pankhurst et al., 2006) and 507 Ma (Rapalini et al., 2013), while ultramafic to felsic meta-igneous rocks intercalated in the metasedimentary sequence show a SHRIMP U–Pb zircon age of 513 ± 3 Ma (Greco et al., 2015).

The Nahuel Niyeu Formation is intruded by small granitoid bodies and narrow dykes of the Ordovician Punta Sierra and Permian Navarrete plutonic complexes (Caminos, 2001; Pankhurst et al., 2006; López de Luchi et al., 2008; Gozalvez, 2009a,b; Rapalini et al., 2013). The Nahuel Niyeu Formation and granitoid bodies both represent ascended blocks that are slightly eroded. The Ordovician to Devonian sandstones and quartzites of the Sierra Grande

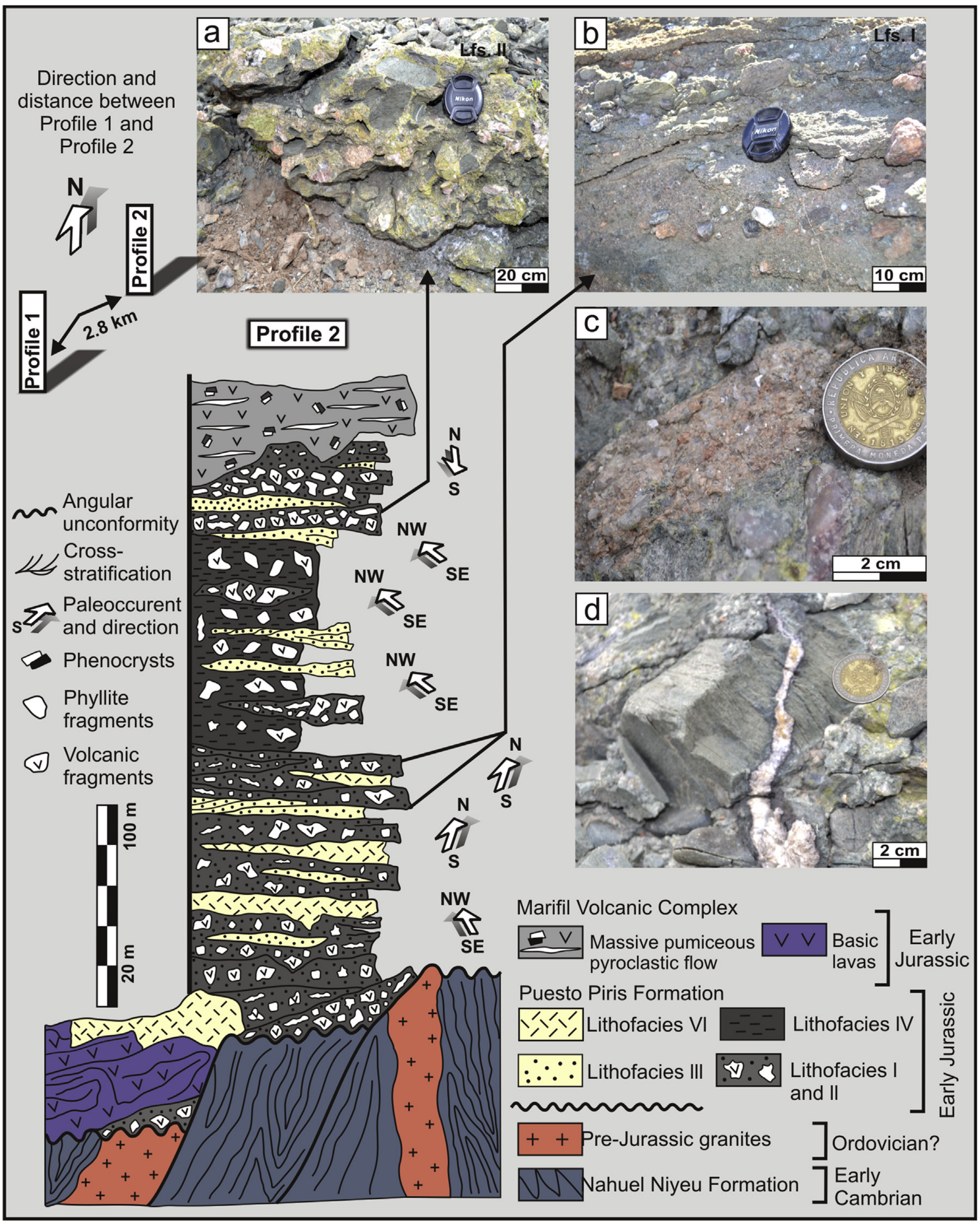

Figure 4. Profile 2 of the Puesto Piris Formation. (a) View of the lithofacies II represented by red clast-supported conglomerates. (b) View of the lithofacies I represented by red to gray matrix-supported conglomerates. (c) Granite fragment included in lithofacies II. (d) Low-grade metamorphic fragment of the Nahuel Niyeu Formation included in lithofacies I.

Formation do not outcrop in the area, but clasts in the basal conglomerate of the Puesto Piris Formation could be derived from that unit.

The Jurassic is represented by the Marifil Volcanic Complex (Malvicini and Llambías, 1974; Cortés, 1981; Pankhurst and Rapela, 1995; Márquez et al., 2010, 2012) that unconformably covers the Nahuel Niyeu Formation (Fig. 1b). The basal section is composed of sedimentary and volcaniclastic rocks of the Puesto Piris Formation. This unit was first described by Nuñez et al. (1975) who reported a succession of alternating gray and red beds of conglomerates with thick pyroclastic flow deposits in the upper part of the unit, 20 km east of the Valcheta locality (Fig. 1a,b). The upper part of the Marifil Volcanic Complex is represented by widespread rhyolitic to andesitic magmatism forming beds and dykes. Vertical flows bands are common in the boundaries of the bodies, while inwards, the texture is massive and columnar joints are common. Unconsolidated Quaternary sedimentary rocks unconformably cover the above units.

3. Results

3.1. Lithology of the Puesto Piris Formation

Outcrops in the study area (Fig. 1) are mainly located in the lower topographic sections and along temporal creeks (Fig. 2). Here, the Puesto Piris Formation consists of sedimentary sequences

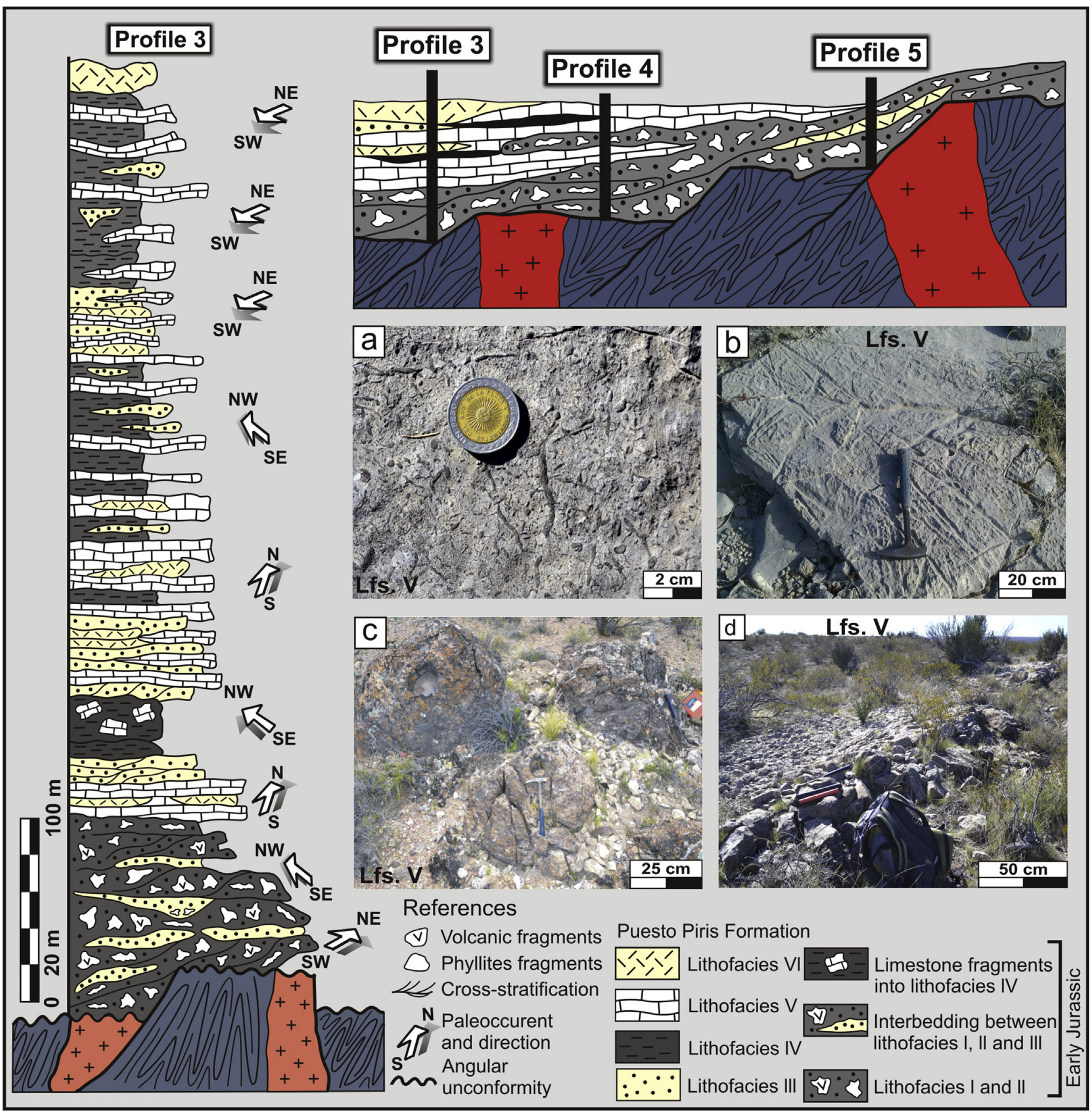

Figure 5. Profile 3 of the Puesto Piris Formation located in the southern side of the depocenter. (a) Bioturbation, burrows marks, bioclasts and fossils such as fragmentary algae are common in the stratification planes of the black limestones. (b) Elephant skin like textures developed on the top of limestone beds. (c) Stromatolite bodies around 1 m diameter. (d) View of the tabular banks in black limestones (lithofacies V).

composed of red, green, and gray conglomerates, with some clasts up to 20 cm in diameter, interbedded with red to brown sandstones up to 3 m thick. Layers of gray and black limestones of 10 m thickness are interbedded in the sandstones. Among the limestones are thin beds of black cherts and fine sandstones with tuffaceous material.

3.2. Facies description of the Puesto Piris Formation

Six detailed profiles (150–550 m thick) were carried out in order to determine facies association and environments (Figs. 1–7). Profiles 1 and 2 (Figs. 3 and 4) are located 3 km north of the Puesto Piris (Fig. 1b), while profiles 3, 4, and 5 (Figs. 4–6) are located 4 km northeast of the Puesto Piris (Figs. 1b and 2). Profile 6 (Fig. 7) is located on the northern margin of the Salitral (Figs. 1b and 7g).

During the analysis of the Puesto Piris Formation profiles, six lithofacies were recognized and are listed in Table 1. Lithofacies I is composed of red to gray matrix-supported conglomerates (Figs. 2, 3f, 4b, 10b,f) forming a coarse stratification with blocks up to 30 cm thick. Lithofacies II is represented by red clast-supported conglomerates (Figs. 2, 4a, 10a,e), which form 5-m wide channels and lenticular bodies. In both lithofacies I and II, the clast composition changes according to the source area. In profiles 1 and 2 (Figs. 3, 4, 10a,e), clasts are predominantly (90%) porphyry volcanic fragments of rhyolites of the Marifil Volcanic Complex, and the remaining 10% are phyllites of the Nahuel Niyeu Complex (Figs. 4c,d, 6a, 10a). In contrast, profiles 2, 3, and 6 (Figs. 4, 5 and 7) contain fragments of phyllites, schist and rhyolites from the Nahuel Niyeu Complex (80%) and Marifil Volcanic Complex (20%) (Fig. 10b,f).

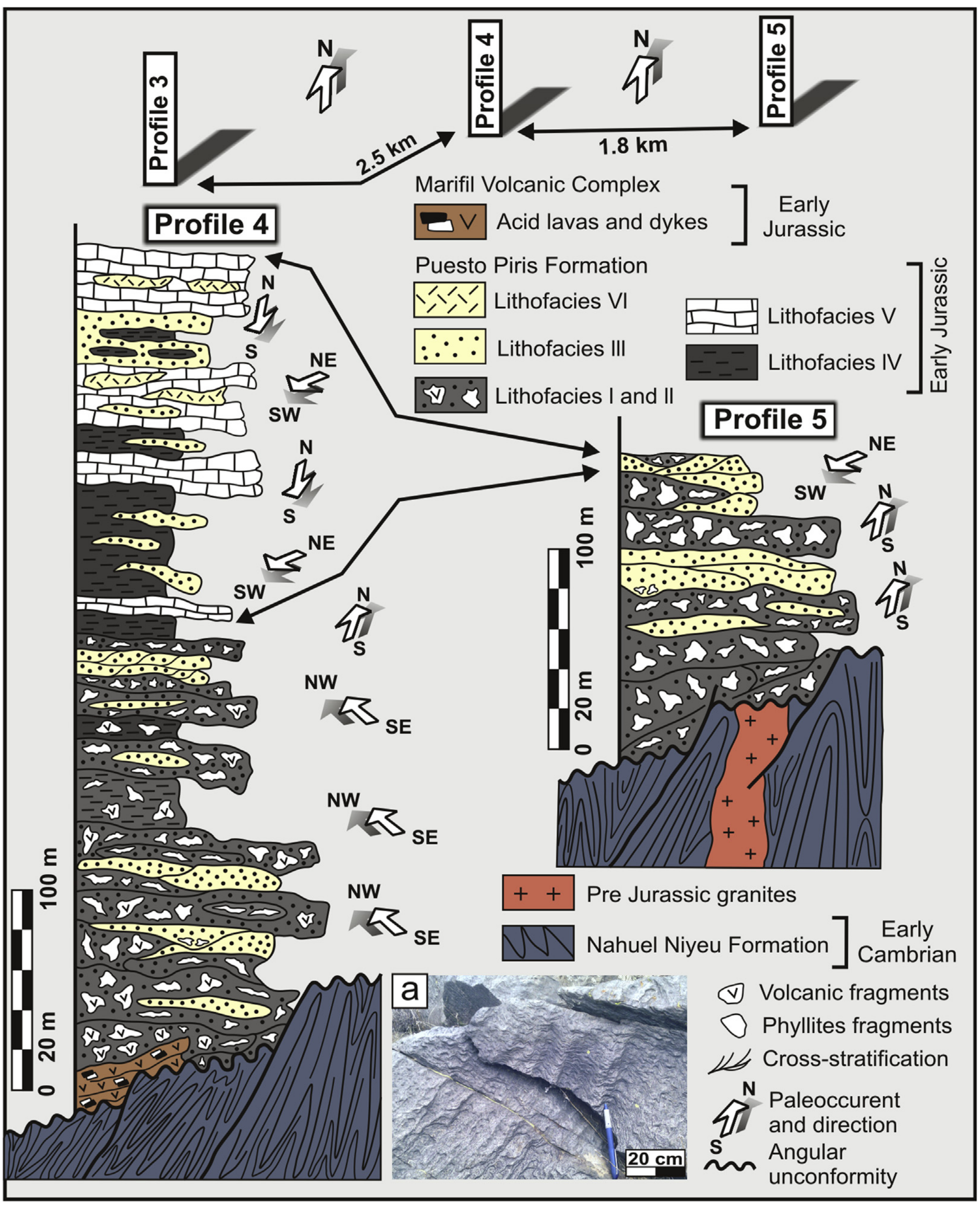

Figure 6. Profiles 4 and 5 of the Puesto Piris Formation. (a) Low-grade metamorphic rock of the Nahuel Niyeu Formation cropping out in the study area.

Paleocurrent measurements in profiles 1, 2, 3, 4, 5, and 6 (lithofacies I and II) indicate that flows came from the S, SE, and SW (Fig. 3a, b). There are also paleocurrents from the N and NE, as indicated by imbricate clasts.

Some carbonized woods that appear as clasts in conglomerates (Fig. 3c) belong to the ferns-like trees *Filicophyta* (Fig. 7c) and *Araucarites* (Fig. 7d). Leaf imprints are found in some stratification planes (Fig. 7b) and belong to the class *Equisetopsida*.

Lithofacies III contains shallow and wide channelized coarse red sandstones (Figs. 2, 3a,d,f) that gradually transition into lithofacies IV. Lithofacies IV includes tabular fine-grained sandstones and black siltstones (Figs. 2, 3c,e, 5–7). The paleocurrents measured in fine sediments indicate flows from the W, SW, NE, and SE.

Lithofacies V is composed of thick black limestones interbedded with lithofacies IV that were recognized from the middle to the upper parts of profiles 3, 4, and 6 (Figs. 2, 5–7, 10g,h). A rough texture, like elephant skin, is common in the stratification surfaces, which indicates surface exposure and sub-air erosion (Fig. 5a,b). The composition of this lithofacies, obtained using X-ray diffraction (Fig. 9a), shows that the principal component is calcite, while the dominant mineralogy of the black siltstones is kaolinite and quartz with minor calcite (Fig. 9b).

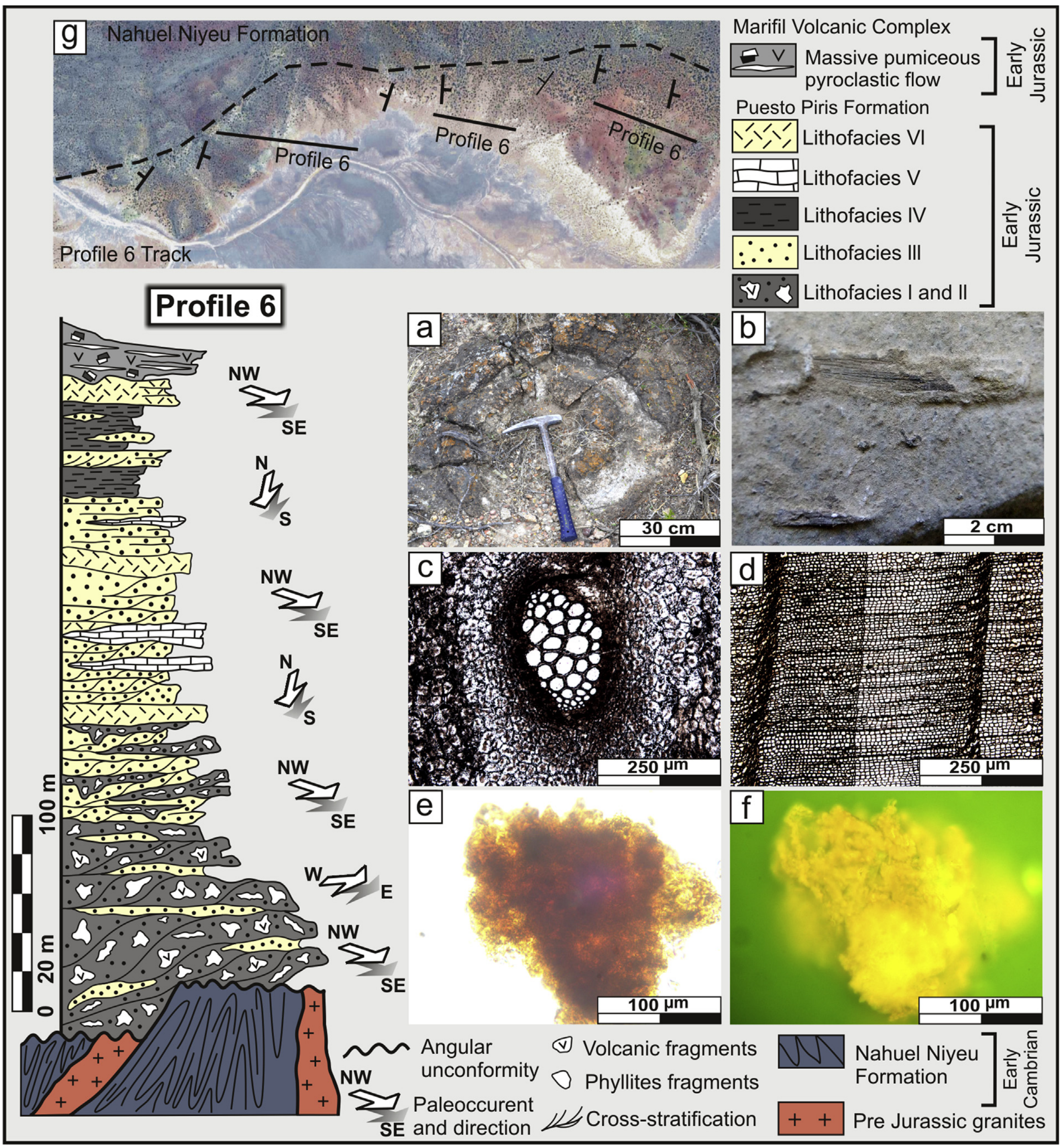

Figure 7. Profile 6 of the Puesto Piris Formation. (a) Surface view of the domal stromatolites (around 1 m diameter). (b) Leaf imprints found in some stratification planes belonging to the Class *Equisetopsida*, Order *Equisetaes*. (c) Photomicrographs of carbonized wood fragments belonging to *Filicophyta* like tree ferns. (d) Photomicrographs of carbonized woods fragment belonging to *Gymnopermofhytae*, Order *Coniferae Araucarites*. The growth rings show marked climatic changes between different seasons. (e) Photomicrographs of algae colonies of the genus *Botryococcus* using transmitted light microscopy. (f) Photomicrographs of algae colonies of the genus *Botryococcus* using blue light fluorescence microscopy. The mounting medium used to prepare palynological slide was glycerine/jelly.

Table 1
Lithofacies I to VI of the Puesto Piris Formation.

Lithofacies	Name	Shape	Relation clast/ groundmass	Clast dimensions and compositions	Groundmass compositions	Flow directions	Lithofacies association
I	Matrix-supported conglomerates	5–10 m Clastic wedges	20%/80%	10–20 cm up to 50 cm. phyllites, quartzites, granites and porphyritic volcanic fragments	Coarse sandstone and white quartz	Imbricate clasts and cross stratification from SE–SW (profiles 1–5) and from N and W (profile 6)	I: Coarsening-upward sequences: High-density alluvial flows that pass transitionally to fining-upwards mantled flows
II	Clast-supported conglomerates	1–2 m Tabular bodies	90%/10%	5–20 cm up to 50 cm. Schists, quartzites, granites and porphyritic volcanic fragments	Greywackes and quartz	Imbricate clasts and cross stratification from SE (profiles 1–5) and from N–NE (Profile 6)	
III	Coarse sandstones	0.5–1 m Tabular beds	60%/40%	1–2 cm. Milky quartz, quartzites and phyllites. Shards of glass	Quartz, micas, K-feldspar	Cross stratification from N–NW and S–SE	II: Low-energy channelized flows
IV	Fine-grained sandstones and siltstones	20–40 cm Tabular beds	40%/60%	0.5–1 cm. Milky quartz quartzites and phyllites. Shards glass. Stem wood fragments	Quartz, micas	Cross stratification from N–NW	
V	Limestones	1–3 m Lenticular shape	10%/90%	Shard glass and printing plant in bedding planes	Dark fine-grained limestones	Bodies are thinned toward NW and NE –SW	III: Offshore and lacustrine deposits
VI	Reworked tuff	5–10 cm Massive lenticular beds	10%/90%	1–2 cm. Volcanic porphyritic rocks and shards glass. Leaf imprints in bedding planes	Shards glass	Bodies are thinned toward NW and NE –SW	

The limestones were classified, using a microscope, as wackestone (Dunham, 1962) with grain contents exceeding 10%, and boundstone (Dunham, 1962), in which lamination due to organic materials was preserved (Fig. 10d,g). This lamination is related to microbial carbonates produced by the interaction between microbial growth and mineral precipitation with grain trapping (Fig. 10g). Early lithification, which is essential for the accretion and preservation of benthic microbial carbonates, generated domal stromatolites around 1 m thick (Figs. 5c, 7a and 10g).

Lithofacies VI form massive lenticular beds of reworked tuff and epiclastic deposits that are interbedded in the conglomerates of lithofacies I, II, and in the coarse sandstone of lithofacies III. Lithofacies VI is also very similar in association to lithofacies V; they are usually at the top of profiles 3, 4, and 6 (Figs. 3a,b, 4, 5, 7, 10c). These beds represent active volcanism coeval with sedimentation (Fig. 8), which is also supported by the presence of massive lapilli-tuff at the top of profiles 2 and 6 (Figs. 4 and 7).

3.3. Lithofacies associations and paleoenvironments of the Puesto Piris Formation

Three lithofacies associations were recognized in the Puesto Piris Formation. Lithofacies I and II (Table 1) represent the first lithofacies association; they correspond to high-density alluvial

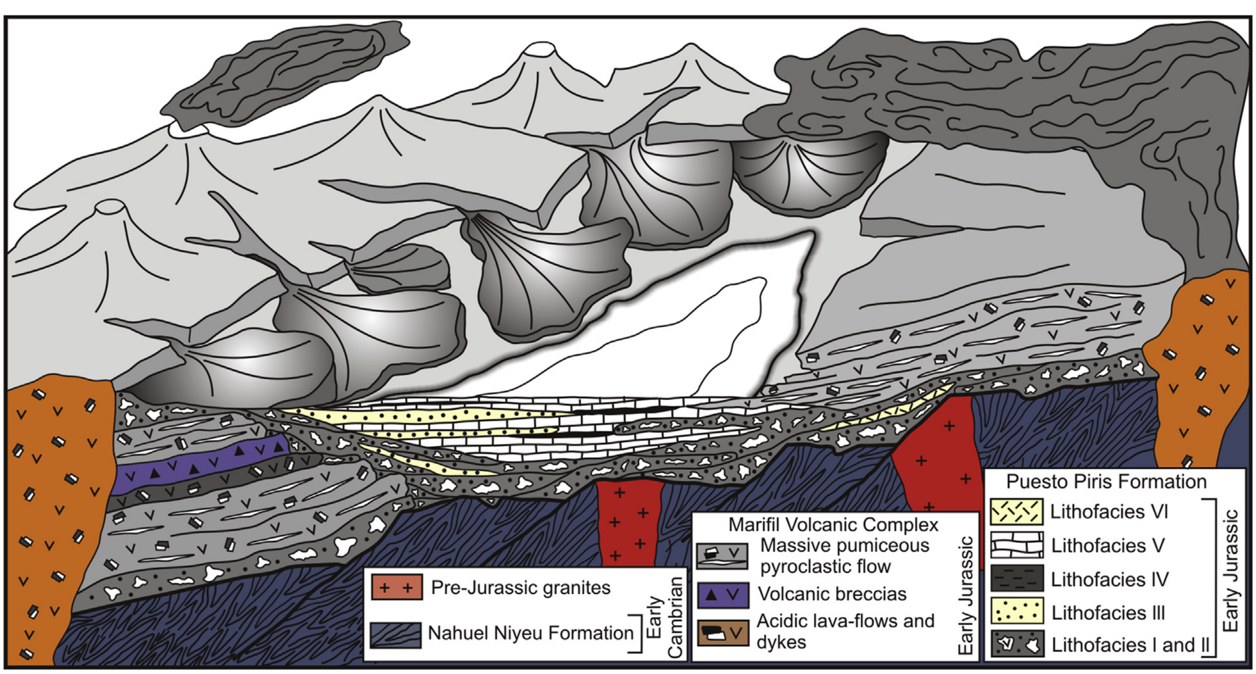

Figure 8. Schematic representation of the facies associations, source areas and paleoenvironments of the Puesto Piris Formation. The basement of the depocenter is the Nahuel Niyeu Formation and the Gondwana granitoids. The depocenter seems to be an elongated structure in NE–SW direction.

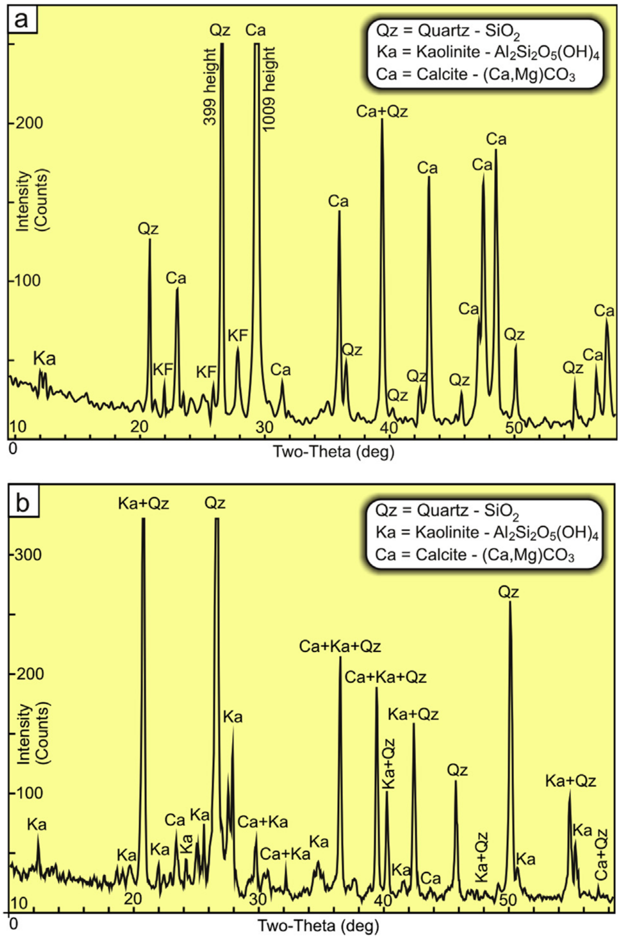

Figure 9. X-ray diffraction patterns diagram (XRD). (a) Representative XRD diagram of the black limestone (lithofacies V). (b) Representative XRD diagram of black siltstone (lithofacies V).

flows and massive bodies, 5–10 m thick, constituted by rough coarsening-upward sequences (Figs. 2, 3f, 4b, 5–7). The transition from lithofacies I to II indicates decreasing energy in the fining-upwards mantled flows (Figs. 2, 4a, 5–7).

Lithofacies association I represents alluvial fans, which suggest minimal participation of an aqueous phase and sedimentation in a high-gradient topographic scenario located near the sediment source (Fig. 8). The alluvial fans recognized in profiles 1–5 show imbricated clasts and cross-stratification, indicating a paleocurrent coming from the SE, while in profile 6, the paleocurrent came from the NW or W (Figs. 3–7). The absence of fluvial reworking on the top of the banks indicates a short time between each sedimentary event.

The upper section in profiles 1, 2 and 5 (Figs. 3, 4 and 6) shows interbedding of coarse sandstones, siltstones, and fine conglomerates, up to 1 m thick, that represent lithofacies association II, typical of low-energy channelized flows.

The middle and upper sections of profiles 3, 4, and 6 (Figs. 5–7), formed by lithofacies V and VI, were grouped into facies association III. This association indicates very low energy during sediment deposition. Tabular banks of fine-grained sandstones, muds, and limestones form the offshore sedimentary deposits of a lacustrine environment system (Fig. 8). Bioturbation, burrows marks, and bioclastic fragmentary fossils, such as algae (*Botryococcus*), are common in the stratification planes of the tabular beds (Fig. 5a). Deeply sculptured surfaces (Fig. 5b) are very common in the bedding planes of the limestones. Thin layers (10 cm thick) composed of volcanic ash are interbedded in lithofacies V and VI (not shown in the figures).

3.4. Lithological description of the Marifil Volcanic Complex

According to the mineral associations and textures, the volcanics rocks that outcrop in the study area are classified as rhyolites and trachytes (Fig. 11a, b). The trachytes (Fig. 11a) are orange-brownish in color and form single intrusion-like dykes and lava flows up to 2 m thick. The trachytes display porphyritic textures defined by euhedral phenocrysts of K-feldspar, plagioclase, and small amounts biotite and quartz (Fig. 11a). These phenocrysts are set in a fine groundmass, formed by K-feldspar, plagioclase, and amphiboles (Fig. 11a).

The rhyolites (Fig. 11b) are orange-brownish to reddish-pink in color and occur mostly as lavas and massive lapilli-tuff or ignimbrites (Fig. 10h). They are also found as subvolcanic bodies and dykes. The rhyolites exhibit porphyritic textures defined by euhedral phenocrysts of quartz, perthitic K-feldspar, plagioclase, and small amounts of biotite, set in a felsitic groundmass (Fig. 11b). Plagioclases are sericitized, and quartz show reaction rims with the groundmass (Fig. 11b). The ignimbrites show porphyritic and eutaxitic textures. Subrounded perlitic textures are common at the base (Fig. 11c, d). Both trachytes and rhyolites underlay the Puesto Piris Formation (Figs. 3, 4 and 8) and fragments of these rocks are recognized in the basal conglomerates (Fig. 10a,e).

3.5. New radiometric dating of the Marifil Volcanic Complex

In order to establish the depositional age of the Puesto Piris Formation and eruptive age of the Marifil Volcanic Complex, we analyzed a sample of the volcanic rocks in the MultiLab of the Departamento de Geologia Regional e Geotectônica at Rio de Janeiro State University. An ICP-MS laser ablation Neptune Plus was used following the procedures developed in this lab.

The measured sample was collected from a trachytic lava flow with porphyritic texture located at 40°44′59.5″S and 65°54′12.5″W. The rock is fresh, orange pale in color, with K-feldspar phenocrysts, plagioclase, and quartz embedded in a glassy groundmass. Individual zircons are prismatic and euhedral (Fig. 12), most of which exhibit typical igneous zoning. 27 zircons were analyzed and 11 were used to construct a concordia diagram. The other results were discarded because they plot outside of the concordia line. Additionally, analysis 002 C, with one age of 397 Ma, was discarded because it was completely outside of the crystallization range of this unit.

Table 2 lists the Pb and U isotopic relationships in the analyzed zircons. Fig. 12 is a $^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$ concordia diagram displaying a U–Pb crystallization age of 193.4 ± 3.1 Ma (Fig. 12 insert). This age suggests that the emplacement and crystallization of the Marifil Volcanic Complex in this area took place in the Early Jurassic (Sinemurian age, Fig. 12). The sedimentation of the Puesto Piris Formation is coeval or later than the Marifil Volcanic Complex, and does not represent the first event of this complex.

3.6. Structural features of the Puesto Piris Formation

The unit in the northern and western parts of the study area is folded (Fig. 1b). Axial planes are W–E and NE–SW with 20–30 m wavelengths. Dips vary between 25° and 30° to the N–NW or S–SE. A soft compression in the N–S or NW–SE direction seems to have developed after deposition of the unit. Folds were not recognized in the southern part, but the observed structure may represent tilted

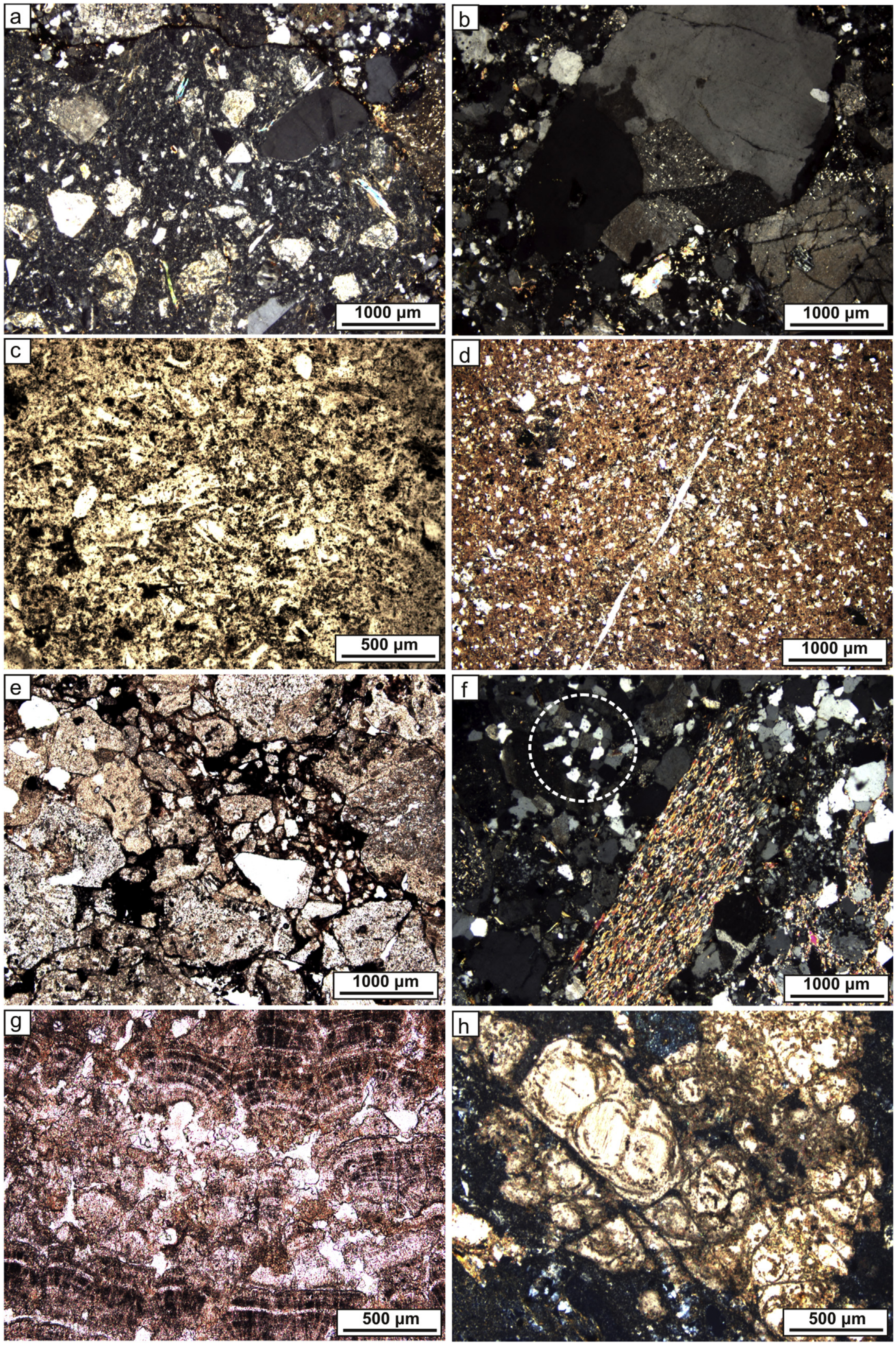

Figure 10. Photomicrographs of the Puesto Piris Formation. (a) Photomicrographs with crossed nicols (CN) of a porphyritic fragment included in clast-supported conglomerates (lithocacies II). (b) Photomicrographs (CN) of a granitic fragment included in matrix-supported conglomerates (lithofacies I). (c) Photomicrographs with parallel nicols (PN) of fine to medium reworked tuff (lithofacies VI) composed of large glassy shards with incipient rounding. (d) Photomicrographs (PN) of the black limestones (lithofacies V) classified as wackestone according to Dunham (1962). (e) Photomicrographs (PN) of porphyritic fragments included in clast-supported conglomerates (lithofacies II). Matrix composed of fine-grained sandstone and ferruginous cement. (f) Photomicrographs (CN) of a fragment of low-grade metamorphic rock of the Nahuel Niyeu Formation. Dotted line shows a quartzite fragment, probably belonging to the Devonian Sierra Grande Formation. (g) Photomicrographs (PN) of stromatolites with calcite fascicular crystals levels (compare with Freytet and Verrecchia, 1998). (h) Photomicrographs (CN) of a well-preserved perlitic groundmass development at the base of massive lapilli tuff of the Marifil Volcanic Complex.

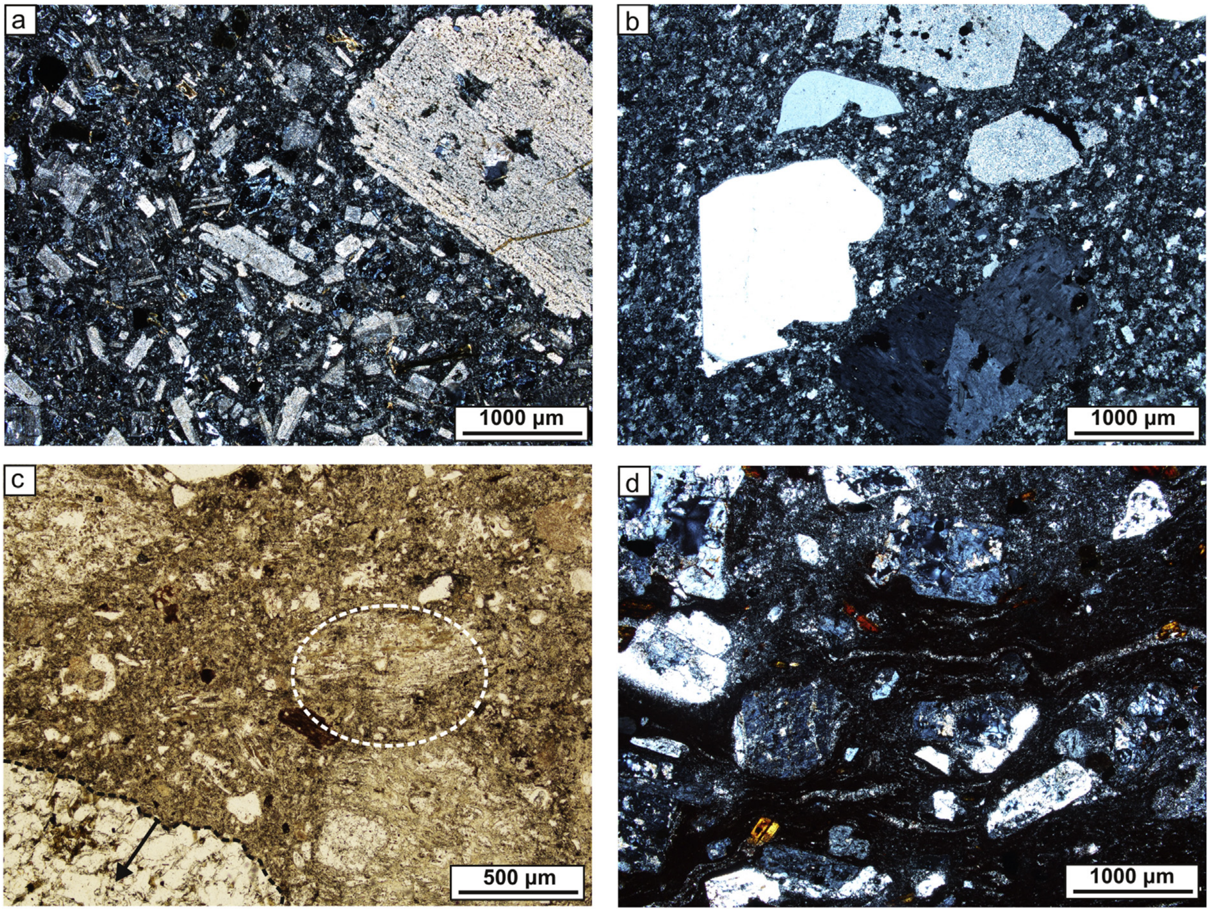

Figure 11. Photomicrographs of the Marifil Volcanic Complex. Parallel nicols (c). Crossed nicols (a, b and d). (a) Photomicrographs (CN) showing petrographic features of a trachytic lava with porphyritic textures, defined by euhedral phenocrysts of K-feldspar, plagioclase and scarce biotite and quartz. Phenocrysts are set in groundmass compound of K-feldspar, plagioclase and amphibole. (b) Photomicrographs (CN) showing petrographic features of the porphyritic texture of a rhyolite defined by euhedral phenocrysts of quartz, perthitic K-feldspar, plagioclase and scarce biotite set in a felsitic groundmass. Plagioclases normally are sericitized and quartz is surrounded by reaction rims due to interaction with the groundmass. (c) Photomicrographs (PN) showing petrographic features of the massive lapilli tuff. Black dotted line shows the border of a low-grade metamorphic fragment of the Nahuel Niyeu Formation picked up by the pyroclastic flow. White dotted line shows non-deformed glassy shards. (d) Photomicrographs (CN) of massive lapilli tuff with deformed vitroclasts. The fragments belong to low-grade metamorphic and porphyritic rocks.

basement blocks. This structure likely allowed the deposition of a thicker sedimentary sequence in this section of the basin. The general disposition of outcrops and maximum thicknesses of the sedimentary sequences indicates the existence of a depocenter developed in the NE–SW direction (Figs. 1 and 2).

4. Discussion

4.1. Paleoenvironmental and paleogeographic reconstruction of the Puesto Piris Formation

The presence of conglomerates with volcanic and metamorphic clasts over tilted and eroded blocks of the Marifil Volcanic Complex and Nahuel Niyeu Formation (lithofacies I and II) indicates very proximal alluvial fans due to tectonic subsidence on a local scale. The presence of volcanic fragments, reworked tuff, and glass shards identified in these conglomerates suggests that the Puesto Piris Formation deposition is coeval with the volcanic activity of the Marifil Volcanic Complex (Fig. 8).

The thickness variations and lateral changes in channelized and mantled flow deposits, and the analyses of lithofacies associations, suggest an irregular topography of the basin (Fig. 8). The sections with substantial thicknesses of fine-grained sandstones, limestones, and muds are interpreted as playa lake environments (Fig. 8). In general, playa lakes are found in arid to semi-arid regions because the average rate of evaporation is higher than precipitation, however, no halite or gypsum layers were found.

The presence of *Botryococcus* sp. in fossil phytoplankton is common in lacustrine basins (Fig. 7e,f). This organism is found worldwide and occasionally in salt water. Although *Botryococcus* sp. has a long geological history, having been recorded as an organic-walled microfossil from the Carboniferous to the present. It was relatively common during the Triassic of the Gondwana continent (Zavattieri, 1991; Brenner and Foster, 1994).

4.2. Correlation of the Puesto Piris Formation

The interbedding between volcaniclastic facies of the Marifil Volcanic Complex and the basal section of the Puesto Piris Formation indicate that both units are closely related. It seems that sedimentation and volcanism started as early as the Sinemurian in the eastern North Patagonian Massif.

A few kilometers south of Sierra Grande, Zanettini (1980) described a 60-m thick sedimentary sequence that includes 18 m of a conglomerate with angular clasts and blocks, 0.2–1.0 m in diameter, that is interbedded with 20-cm thick layers of sandstone. Upwards, there is a 2.7-m thick section of silicified tuff, followed by 7 m of dark gray limestone that includes layers of pale yellow chert. Sandstones and tuffaceous sandstones of 30 m thickness are found at the top. This succession was assigned to the Puesto Piris

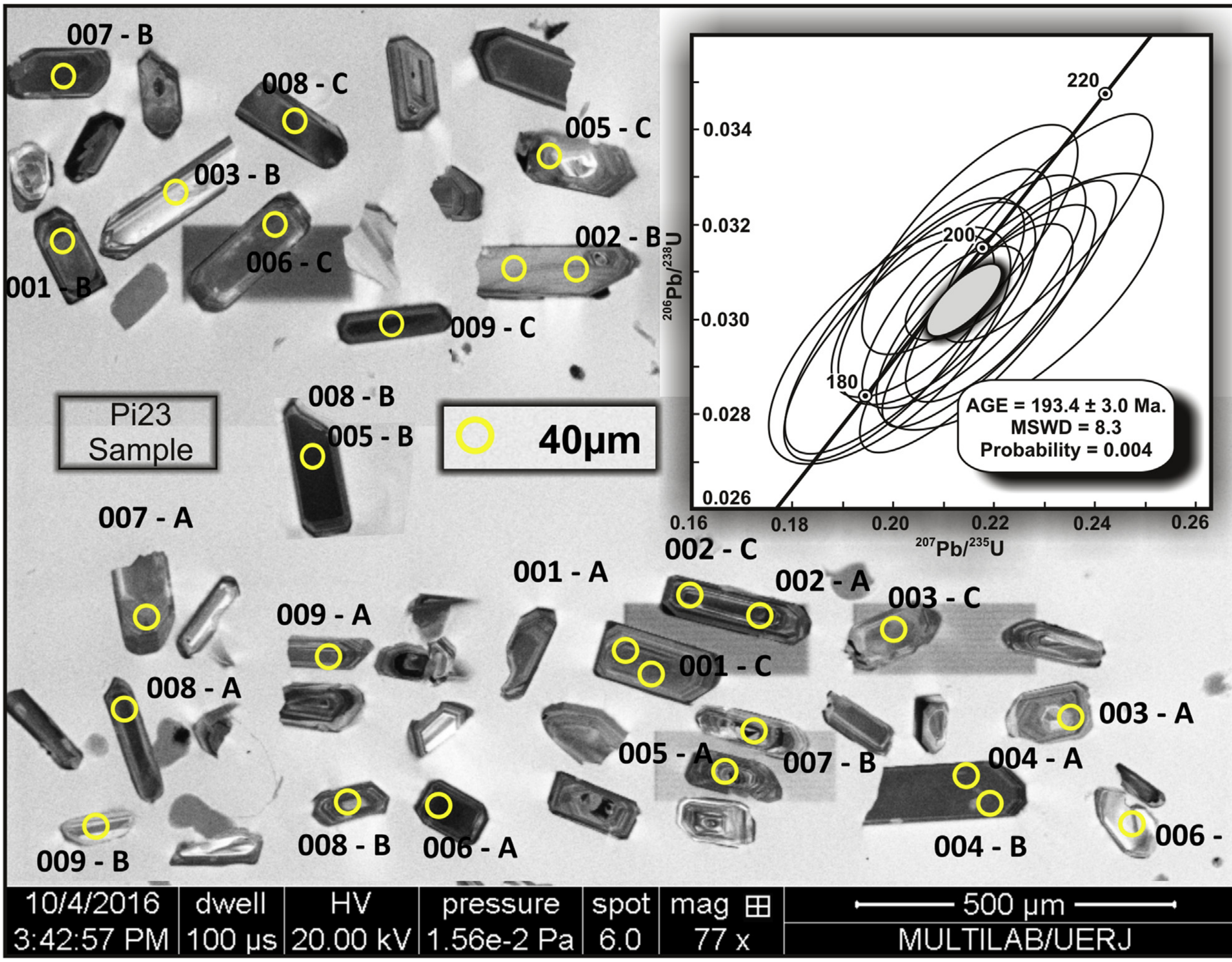

Figure 12. CL images of the dated zircon crystals used for the determination of the U–Pb age of a phenotrachytic lava-flow of the Marifil Volcanic Complex. They are typically prismatic indicative of an igneous origin with magmatic zoning. Green circles indicate points where U–Pb isotope relationships were measured by laser ablation. Data obtained in the MultiLab of the Rio de Janeiro State University using an ICPMS Laser-Ablation Neptune Plus. Inset: $^{206}Pb/^{238}U$ versus $^{207}Pb/^{235}U$ concordia diagram showing individual ages for the analyzed zircons yielding an average age of 193.4 ± 3.0 Ma.

Formation and is considered to have been deposited as alluvial fans that passed upwards to fluvial systems with episodes of lacustrine environments.

A similar unit to Puesto Piris Formation was described by Cortés (1981) in the Estancia El Refugio, located 25 km south of Estancia Marifil in the province of Chubut. Here, 1-m thick red conglomerates formed by clasts of metamorphic rocks, quartz, granites, quartzites, tuff, and porphyrites in a sandy groundmass, were found. The upper part is 170-m thick and includes tuffaceous sandstones, lapillitic tuff, and vitroclastic tuffs. The sequence ends with reddish fluidal rhyolitic ignimbrites. A K–Ar age from these rocks yielded 189 ± 5 Ma. It is therefore possible to conclude that, along 200 km in a N–S direction between Valcheta and the northern part of the Chubut province, several continental depocenters that included alluvial fans, fluvial, and lacustrine systems developed and were active during the Sinemurian in the eastern part of the North Patagonian Massif.

Rocks with a similar age to that of the Puesto Piris Formation can be recognized in Neuquén province. Near the Piedra del Aguila locality (350 km westwards), Spalletti et al. (2010) dated a volcanic tuff in the Piedra del Aguila Formation and obtained a U–Pb age of 191.7 ± 2.8 Ma. This unit includes a succession of reddish conglomerates and conglomerate sandstones interbedded in coarse grain sandstones. Red and reddish mudstones and siltstones that pass upwards to whitish siltstones are also found. The first facies is interpreted to have been deposited by fluvial channels with flooding areas. The second facies is interpreted as lacustrine environment deposits.

In the Alicurá dam, 90 km southwest of Piedra del Aguila, the Nestares Formation (Arrondo et al., 1991) is composed of feldspathic sandstones, red mudstones, carboniferous siltstones, and pelites deposited in low-gradient anastomosed fluvial channels, crevasse splays, flooding areas, and swamp environments. There are some marine influences, according to Volkheimer et al. (1981). Since the fossil flora of the Nestares Formation shares an important number of genera with the Piedra del Águila Formation, it is believed that both represent Sinemurian times.

There are several Jurassic depocenters along the Chubut River in the Chubut province, 380 km southwest from the study area. The depocenters form the Somuncurá-Cañadón Asfalto rift basin (e.g., Piatnitzky, 1936; Stipanicic and Methol, 1980; Cortiñas, 1996), composed of fluvial, volcanic, volcaniclastic, and lacustrine deposits of the Las Leoneras, Lonco Trapial, Cañadón Asfalto, and Cañadón Calcáreo formations. These units were dated by Cúneo et al. (2013), who obtained ages between 189 Ma and 157 Ma. Specifically, the age of the Las Leoneras Formation (189 Ma) seems to be coeval and

Table 2
Geochronological analyses of sample Pi 23, Marifil Volcanic Complex.

Spot (analysis)	U (ppm)	Pb (ppm)	Th (ppm)	Th/Ub	f_{206}	Isotope ratios							Ages (Ma)						Best age (Ma)	± (Ma)
						$^{207}Pb/^{235}U$	1σ (%)	$^{206}Pb/^{238}U$	1σ (%)	Rho	$^{207}Pb/^{206}Pb$	1σ (%)	$^{206}Pb/^{238}U$	1σ abs	$^{207}Pb/^{235}U$	1σ abs	$^{207}Pb/^{206}Pb$	1σ abs		
001 A	94	3.6	93	1.0	0.035164	0.1991	8.66	0.0294	6.6	0.76	0.0491	5.6	186.7	12.3	184.3	16.0	154.1	8.7	186.7	12.3
002 A	182	7.2	195	1.1	0.023548	0.2152	8.12	0.0317	6.2	0.77	0.0493	5.2	201.0	12.5	197.9	16.1	160.7	8.4	201.0	12.5
003 A	90	3.5	90	1.0	0.042618	0.1998	10.01	0.0294	6.8	0.68	0.0493	7.4	186.9	12.7	184.9	18.5	160.2	11.8	186.9	12.7
004 A	141	5.4	132	0.9	0.019442	0.2101	8.39	0.0307	6.3	0.76	0.0496	5.5	195.2	12.4	193.6	16.2	174.0	9.6	195.2	12.4
005 A	145	5.5	125	0.9	0.015058	0.2303	7.54	0.0319	6.1	0.81	0.0523	4.4	202.5	12.4	210.4	15.9	300.1	13.1	202.5	12.4
006 A	179	6.6	127	0.7	0.024509	0.2161	8.29	0.0306	6.5	0.78	0.0513	5.1	194.2	12.6	198.7	16.5	252.2	13.0	194.2	12.6
007 A	98	4.0	75	0.8	0.067952	0.2189	7.86	0.0300	6.5	0.83	0.0529	4.4	190.5	12.4	201.0	15.8	325.6	14.3	190.5	12.4
008 A	129	5.0	128	1.0	0.025672	0.2279	9.09	0.0306	6.5	0.72	0.0541	6.3	194.2	12.6	208.5	18.9	373.5	23.7	194.2	12.6
007 B	155	6.8	281	1.8	0.013134	0.2032	10.14	0.0298	7.3	0.72	0.0494	7.1	189.3	13.7	187.9	19.0	169.2	12.0	189.3	13.7
008 B	139	5.7	193	1.4	0.023699	0.2143	8.11	0.0296	6.6	0.81	0.0525	4.7	188.0	12.4	197.2	16.0	309.1	14.6	188.0	12.4
004 C	384	12.8	259	0.7	0.004492	0.2142	4.41	0.0305	2.7	0.61	0.0509	3.5	193.9	5.2	197.1	8.7	235.5	8.3	193.9	5.2

Measured at MultiLab of the Rio de Janeiro State University using an ICPMS Laser-Ablation Neptune Plus. Rho: correlation coefficient, a measure of the correlation between two continuous random variables. Gehrels et al. (2008) indicated that $^{206}Pb/^{238}U$ ages younger than 1600 Ma have the best precision, while $^{207}Pb/^{206}Pb$ ages older than 1600 Ma have the best precision. Therefore $^{206}Pb/^{238}U$ ages are considered to be best ages.

comparable with those of the Puesto Piris and Piedra del Aguila formations.

The Las Leoneras Formation is 180-m thick and includes a lower section of white, poorly to moderately sorted sandstones, interbedded with purple, massive, and sandy mudstones. They represent amalgamated channelized fluvial systems. Upwards, 63 m of reddish, sandy mudstone with thin intercalations of coarse- to medium-grained sandstone are found. This sequence is interpreted as flood-plain deposits associated with ephemeral channel deposits. The upper member comprises greenish gray, tuffaceous pelites. There are tuff and limestones, 20–60 cm thick, associated with conglomerates of volcanic clasts and tuffaceous matrix. This member is interpreted as lacustrine deposits associated with pyroclastic and debris flow deposits.

As a result, extensional conditions were developed not only in the eastern but also in the western and southwestern parts of the North Patagonian Massif during the Sinemurian. This sedimentary and volcanic episode seems to be a few million years earlier than that which is generally considered for volcanism related to extensional conditions during the pre-breakup of the Gondwana supercontinent.

A lacustrine environment similar to the Puesto Piris Formation was described by Cabaleri and Benavente (2013) in the Las Chacritas member of the Cañadóan Asfalto Formation. The unit is 79 m thick and includes facies of wackestones and packstones that were interpreted as lacustrine and palustrine limestones. However, the age of the Cañadón Asfalto Formation (178–176 Ma), obtained by Cúneo et al. (2013), precluded any temporal correlation between both units. Regardless, all units in the Somuncurá-Cañadón Asfalto rift basin (189–158 Ma) indicate a prolonged period (30 Ma) of extensional conditions in the western part of the North Patagonian Massif.

4.3. The age of the Marifil Volcanic Complex in relation with other radiometric ages

The volcanic activity of the Marifil Volcanic Complex (Malvicini and Llambías, 1974; Nuñez et al., 1975; Cortés, 1981) was considered to be Jurassic (Pankhurst and Rapela, 1995; Pankhurst et al., 1998; Féraud et al., 1999). Previous radiometric dating of the volcanic rocks indicates ages a range of 178–188 Ma (Pankhurst et al., 2000). Rb–Sr ages for the volcanic rocks in the Sierra de Pailemán (located 40 km south of the study area) indicate ages of 188 Ma, 174 Ma in Sierra Grande (100 km south of the study area), and 183 Ma in Estancia Marifil (140 km south of the study area) (Rapela and Pankhurst, 1993; Pankhurst and Rapela, 1995). Airic et al. (1995) reported Ar–Ar ages of 186 Ma and 187 Ma in Estancia Marifil. This indicates that our refined age (193 ± 3 Ma) is partially concordant with the previous ages obtained in the Marifil Volcanic Complex.

During the breakup of the Gondwana supercontinent (∼183 Ma, Encarnación et al., 1996; Riley and Knight, 2001; Storey et al., 2013), intraplate magmatism was related to extensional conditions associated with plate-margin forces and asthenospheric plume ascent. Accordingly, an extensional regime was temporally active and local basin depocenters were generated along a 200 km N–S belt in the modern day Atlantic border of the North Patagonian Massif. Although the sediments of the Puesto Piris Formation apparently settled in a NE–SW depocenter, other depocenters of the area indicate a W–E extensional stress field, probably related to the Gondwana supercontinent breakup.

5. Conclusions

The Puesto Piris Formation, part of the Marifil Volcanic Complex, is composed of red conglomerates, sandstones, black siltstones, limestones, and reworked tuff, with thickness varying between 150 and 550 m. The basal conglomerates unconformably overlie the Early Cambrian rocks of the Nahuel Niyeu Formation. The lithofacies associations recognized in the sedimentary sequence of the Puesto Piris Formation indicate that the depositional mechanism was mantled and gravitational flows developed in a high-gradient topographic landscape located near the sediment source. These high-energy fluvial currents evolved to low-energy fluvial and lacustrine environments where layers of limestones, domal stromatolites, and black siltstones were deposited. The main accumulation of sediments occurred along a NE–SW elongated depocenter. In the study area, the Marifil Volcanic Complex is composed of rhyolitic and trachytic lava flows and subvolcanic bodies with an U–Pb age of 193.4 $\pm$ 3.1 Ma (Sinemurian). The absence of an unconformity with the Puesto Piris Formation, and the presence of interbedded volcaniclastic levels in this unit, indicate that both units are coeval. This extensional episode was recorded in the eastern, western, and southwestern sectors of the North Patagonian Massif and is possibly associated with the Gondwana supercontinent breakup.

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