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Hawaiian and Strombolian style monogenetic volcanism in the extra-Andean domain of central-west Argentina

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Abstract

In the provinces of Mendoza and La Pampa (central-western Argentina), retroarc volcanism was active from the Miocene through historic times. There are approximately 40 basaltic eruptive centers between 36°S and 37°30′S to the East of 68°40′W. These centers were studied in order to define their volcanological evolution. The vents are constituted of seven lithofacies: i.e., (A-1) weakly welded lapilli and bomb beds; (A-2) agglutinated spatter and bomb beds; (A-3) agglutinated spatter beds; (B) ash beds; (C) lava flows; (D) conduit fill; and (E) dikes. Three eruptive episodes (phases) were identified. The first one generated agglutinated spatter and bomb beds (lithofacies A-2), which constitute the internal part of the edifices. These are followed by weakly welded lapilli and bomb beds (lithofacies A-1) and agglutinated spatter beds (lithofacies A-3). The final episode includes lava flows (lithofacies C), minor agglutinated spatter deposits (lithofacies A-3) and isolated lapilli and bomb clasts. We postulate Hawaiian style fountaining activity as responsible for the generation of agglutinated spatter and bombs beds, and variations between Strombolian and Hawaiian activity for the formation of successions of weakly welded lapilli and bomb beds and agglutinated spatter beds. The vent features and the homogeneity of the erupted magma suggest that the studied volcanoes were monogenetic.

Keywords: monogenetic volcanoes; basalts; Argentina; Hawaiian; Strombolian

1. Introduction

Retroarc basalts (Paleocene–Holocene) from Patagonia in Argentina form one of the largest Cenozoic continental basaltic provinces on earth (Kay et al., 2004). They constitute the Patagonian Basaltic Province (Llambías, 2003) that covers a surface of c. 200,000 km^2, stretching between 36°S and 52°S. The origin of these basalts has been related to mechanical perturbations of the subcontinental mantle, as a consequence of subduction of the oceanic lithosphere under the South American continental plate (Skewes and Stern, 1979). On the other hand, retroarc magmatism of northern Patagonia (Somuncurá Plateau) has been related to changes in the age of the subducted oceanic crust (Ramos and Barbieri, 1989) and to the presence of transitory hot spots (Kay et al., 1993). An explanation of the origin of the heat necessary to produce the large volume of molten rock

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outcropping in Patagonia was proposed by Kay (2002) and Kay et al. (2004), who suggested the possibility that the subpatagonian mantle may have been near melting temperature since the breakup of Gondwana in the Mesozoic and that younger tectonic perturbations may have acted as triggers in the melting of an already hot mantle. Several studies have dealt with the chemical features of these rocks (eg. Muñoz Bravo et al., 1989; Stern et al., 1990; Kay and Gorring, 1999), however, less attention has been paid to the volcanological aspects of the eruptive centers generating the lava (Bermúdez et al., 1993; Inbar and Risso, 2001). In this paper we present the results of research carried out on the basaltic vents located along the northeastern margin of the Patagonian Basaltic Province in the provinces of La Pampa and Mendoza (Fig. 1). These basalts have been considered as indicators of extensional events produced after the main compressive phase during the Tertiary and may have been generated by subduction-related mechanical and thermal modifications of the upper mantle (Bermúdez et al., 1993). Kay (2002) and Kay et al. (2004) related the eruption of the extensive lava plateau of northern Neuquén and southern Mendoza (35°S to 38°S) to the melting of hydrated mantle after a temporary low angle subduction episode in the late Miocene, which was postulated by Kay and Mancilla (2001).

The aim of this study is to infer the volcanological evolution of the eruptive centers located between 36°S and 37°30′S to the East of 68°40′W, i.e., within the Argentinean retroarc volcanic zone in the provinces of La Pampa and Mendoza (Fig. 1).

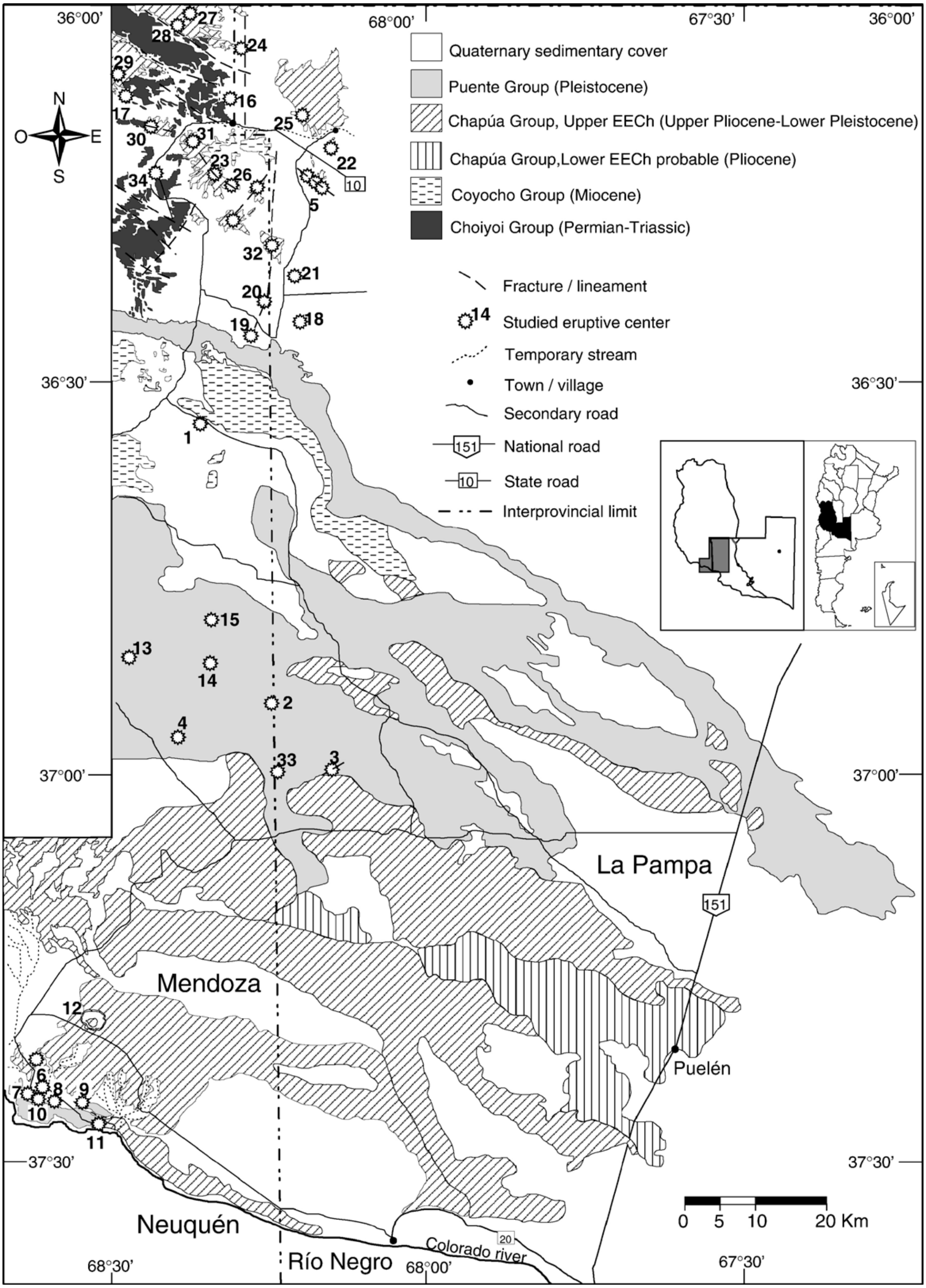
When locality names are repeated, these will be identified with an additional number (e.g., Negro 1, Negro 2 and Negro 3).

2. Geological setting

The volcanoes of the northern sector of the area included in this study are in the northwestern part of the Las Matras Block (Sato et al., 2000), while the eruptive centers of the southern area are along the eastern margin of the Neuquén Basin (Jurassic–Paleogene). The Las Matras block is composed of basement igneous and metamorphic rocks of middle Proterozoic age (Sato et al., 2000). The units of the Las Matras Block are intruded and covered by rocks of the Permian to Early Triassic Choiyoi Group (Llambías et al., 2003), which are widespread in the northern part of the study area (Fig. 1). The rocks of the Choiyoi Group exposed in our study area are mainly rhyolitic in composition and show NW–SE structures. In the southern area of this study, the rocks of the Choiyoi Group constitute the basement of the Neuquén Basin. There, the exposed rocks are mainly sandstones with reptile bones and silicified wood assigned to the Late Cretaceous by Holmberg (1962). Widespread over all the area there are evaporites, alluvial, and principally aeolian deposits of Holocene age.

Volcanism in the extra-Andean retroarc zones of Mendoza and La Pampa has been active since the Miocene (González Díaz, 1979) up to prehistoric times (Groeber, 1946; Inbar and Risso, 2001). During the Pliocene–Holocene – between 35°S and 38°S – large volumes of basalt generated the volcanic fields of Llancanelo, Payún Matru, Chachahuén and Auca Mahuida. These were the most important lava flow-fields in Patagonia during this period (Kay, 2002). The products of these flows in Llancanelo and Payún Matru were grouped in the Andino–Cuyana Basaltic Province (ACBP) by Bermúdez and Delpino (1989). Their outcrops cover an area of approximately 15,900 km^2 (Bermúdez et al., 1993) in the provinces of Mendoza and La Pampa. Llancanelo and Payún Matru fields are formed by two large Tertiary andesitic–trachytic composite volcanoes (Nevado and Payún Matru), with widespread lava flows, and numerous cinder cones mostly concentrated around the volcanoes. Bermúdez et al. (1993) recognized – for the Pliocene/Holocene time span – three periods of highest activity, calling them Chapualitense (upper Pliocene–lower Pleistocene), Puentelitense (Pleistocene) and Tromenlitense (Holocene) eruptive epochs. Based on cone morphology and type of material erupted, these authors suggested that the eruptions involving the cinder cones in Payún Matru and Llancanelo Fields could be considered of Hawaiian type and in some cases Strombolian. Inbar and Risso (2001) studied the morphology of several cinder cone clusters around the Tertiary Payún Matru and Nevado volcanoes, to the West and North of the area considered in this study. They recognized a high density of cones in several sectors and made detailed relative age determinations. They concluded that most (>90%) of the studied volcanic centers were less than 1 Ma and also noted that these monogenetic centers were active in different periods, the oldest one during the Plio-Pleistocene and the youngest one during the Holocene. The peak of activity was concentrated in the late Pleistocene, when c. 75% of the cinder cones were formed.

The vents considered in this study are located along the eastern margin of the ACBP, on the area along the border between the provinces of La Pampa and Mendoza. This area is covered by lava flows which flowed in a NW–SE general direction and numerous pyroclastic cones. The outcrops of this lava field represent the easternmost manifestations of the extra-Andean retroarc volcanism north of the Colorado River. This basaltic


36°00'
68°00'
67°30'
36°00'
N
O
E
S
Quaternary sedimentary cover
Puente Group (Pleistocene)
Chapúa Group, Upper EECh (Upper Pliocene-Lower Pleistocene)
Chapúa Group, Lower EECh probable (Pliocene)
Coyocho Group (Miocene)
Choiyoi Group (Permian-Triassic)
Fracture / lineament
14 Studied eruptive center
Temporary stream
Town / village
Secondary road
151 National road
10 State road
Interprovincial limit
36°30'
36°30'
37°00'
37°00'
37°30'
37°30'
La Pampa
Mendoza
Neuquén
Río Negro
Puelén
Colorado river
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68°30'
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volcanism is associated with a widespread tensional tectonic regime developed in response to the steepening of the subducting oceanic slab in Pliocene to Recent times (Kay et al., 2004).

This work is based on the analysis of 34 eruptive centers. Although most of them are isolated, some are aligned. For example, the De Díaz (1–3), Los Corrales–Lindero–Peludo and Del Chivo centers (Fig. 1). The alignments probably represent Paleozoic fractures reactivated during the Pliocene–Pleistocene volcanism (González Díaz, 1972). In the southern area, Holmberg (1962) identified two vent lineaments along the northern margin of the Colorado River. These comprise the El Pozo, La Yegua and La Blanca centers, with a N70°W direction, and El Águila, Rial and Carrizo centers, with a N65°W direction (Fig. 1). These two patterns coincide with the direction of the Colorado River valley in that area, suggesting a possible relationship between the faults responsible for the volcanic lineaments and the development of the Colorado River valley. Three eruptive centers (De Díaz 1–3, Agua Poca and El Pozo) evidence that local fissures controlled the eruptions, with the fissure at De Díaz (1–3) probably linked to major Paleozoic faults.

Geochemical characterization of the basaltic rocks that form the cones studied herein was carried out by Bertotto et al. (2005). These authors stated that the rocks show a variation in silica content from 42.3 to 51.7 wt.%, therefore classifying mainly as basic. Exceptions are those corresponding to the Negro 1 and De la Laguna volcanoes, which are ultrabasic. The rocks are, in order of abundance, trachybasalts, basalts and basanites all of them alkaline (fields of Macdonald, 1968). These rocks may have originated through low degrees of partial melting from enriched or primitive mantle sources. They present a trace element pattern with variable enrichment of incompatible elements ($La_N/Yb_N = 17.8 - 7.4$). The oceanic plate that subducts beneath South America may have been responsible for the presence of these elements, which vary according to the geographic location of the studied rocks. The enrichment in incompatible elements decreases from the northern towards the southern and central areas (Bertotto et al., 2005).

3. Terminology

The nomenclature used in the description of pyroclastic components of the eruptive centers is based on that of Fisher (1961, 1966) and Schmid (1981). However, we should note that for the basaltic pyroclasts we frequently use the term spatter, which is used herein to compare the field observations and interpretations based on the material studied, with the descriptions of active volcanoes. The term spatter, depending on the individual pyroclasts, is a synonym of bomb or lapilli agglutinate. Macdonald (1972) defined spatter as “accumulation of flattened and welded fragments”. Vergniolle and Mangan (2000) stated that the spatter bombs are glassy pyroclasts with fluidal shapes. Sumner et al. (2005) defined spatter as an accumulation of hot, fluid pyroclasts, which agglutinate on landing. Wolff and Sumner (2000) and Sumner et al. (2005) considered the term to be a synonym of agglutinate, stating that the deposit is an agglutinate or pile of spatter in which the particle contours are partially retained.

4. Volcanology

4.1. Volcanic lithofacies

4.1.1. Lithofacies A

The characteristics of pyroclastic deposits are influenced by accumulation rate and by the amount and rate of cooling (Head and Wilson, 1989; Sumner et al., 2005). Capaccioni and Cuccoli (2005) demonstrated that welding and agglutination can occur at distances of a few kilometres from the vent. This will depend on: (a) eruptive parameters such as exit velocity, ejection angle, accumulation rate; (b) particle characteristics, size, shape, density, chemical composition and initial temperature; and (c) wind velocity. Variations in these parameters will produce deposits ranging from brittle, unwelded lapilli and bombs (equivalent to type 1 clasts of Sumner et al., 2005) to highly welded spatter with coalescence of clasts (like type 4 clasts of Sumner et al., 2005). Among the different eruptive centers studied here, there are great variations in the degree of welding of pyroclasts, showing a gradation from lower temperature deposits (weakly welded lapilli and bomb beds) to high temperature ones (agglutinated spatter beds) (Figs. 2 and 3). An intermediate state very frequent in the studied centers is represented by agglutinated spatter and bomb beds, with the bombs showing unflattened shapes (Fig. 3A). Within this gradation, we identified three subtypes (A-1, A-2 and A-3) of deposits with different degree of welding, which are

Fig. 1. Geological map of study area (modified from Bertotto, 2003). Volcanoes studied: 1 = La Parva, 2 = Del Nido, 3 = Agua Poca, 4 = Ñire Co, 5 = De Díaz, 6 = El Pozo, 7 = El Águila, 8 = La Yegua, 9 = La Blanca, 10 = Rial, 11 = Morado (3), 12 = Huanul, 13 = Tapa, 14 = Morado (1), 15 = Los Carrizales, 16 = Chato, 17 = Chato segundo, 18 = La Negra, 19 = Tordillo, 20 = Amarillo, 21 = Puntudo, 22 = Agua de Torres, 23 = El Lindero, 24 = Negro (2), 25 = Negro (1), 26 = El Peludo, 27 = El Oscuro, 28 = Negro (3), 29 = Morado (2), 30 = Del Chivo, 31 = Los Corrales, 32 = Loma Jagüel del Moro, 33 = Escorial, 34 = De la Laguna.

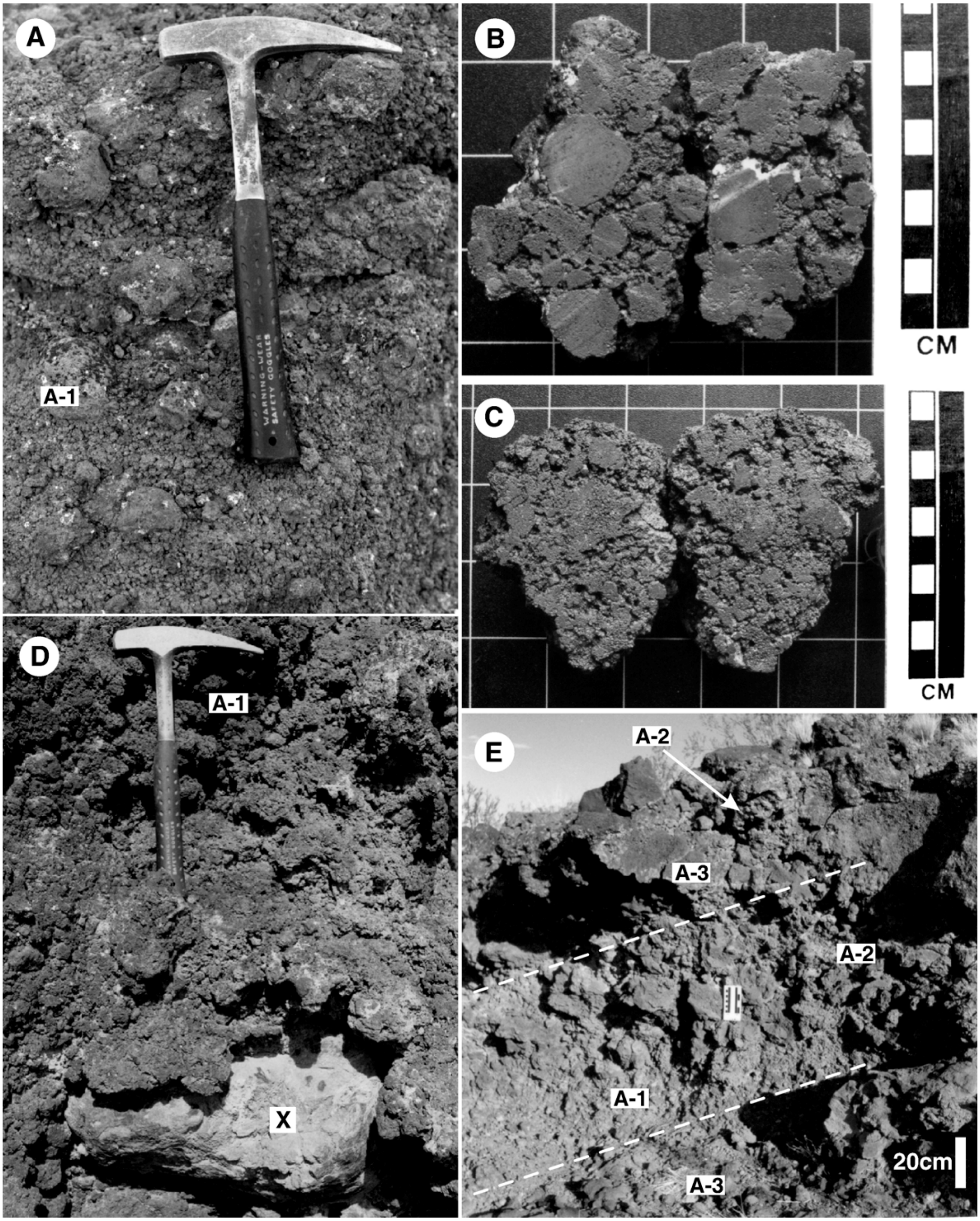

Fig. 2. Volcanic lithofacies A. (A) Lithofacies A-1, weakly welded lapilli and bomb bed (El Oscuro volcano). The major clasts are rounded. (B–C) Sawed samples of lithofacies A-1, moderately welded lapilli-size scoria (Negro 2 volcano); with rounded (B) and irregular (C) clasts. (D) Lithofacies A-1 at La Blanca cone, moderately welded lapilli and bomb bed. Note the crustal xenolith (X) of more than 20 cm long. (E) Beds of lithofacies A-1, A-2 and A-3 at Agua Poca hill. Note the change from A-3 to A-2 (arrow) on the upper bed, and from A-2 to A-1 in the central bed.

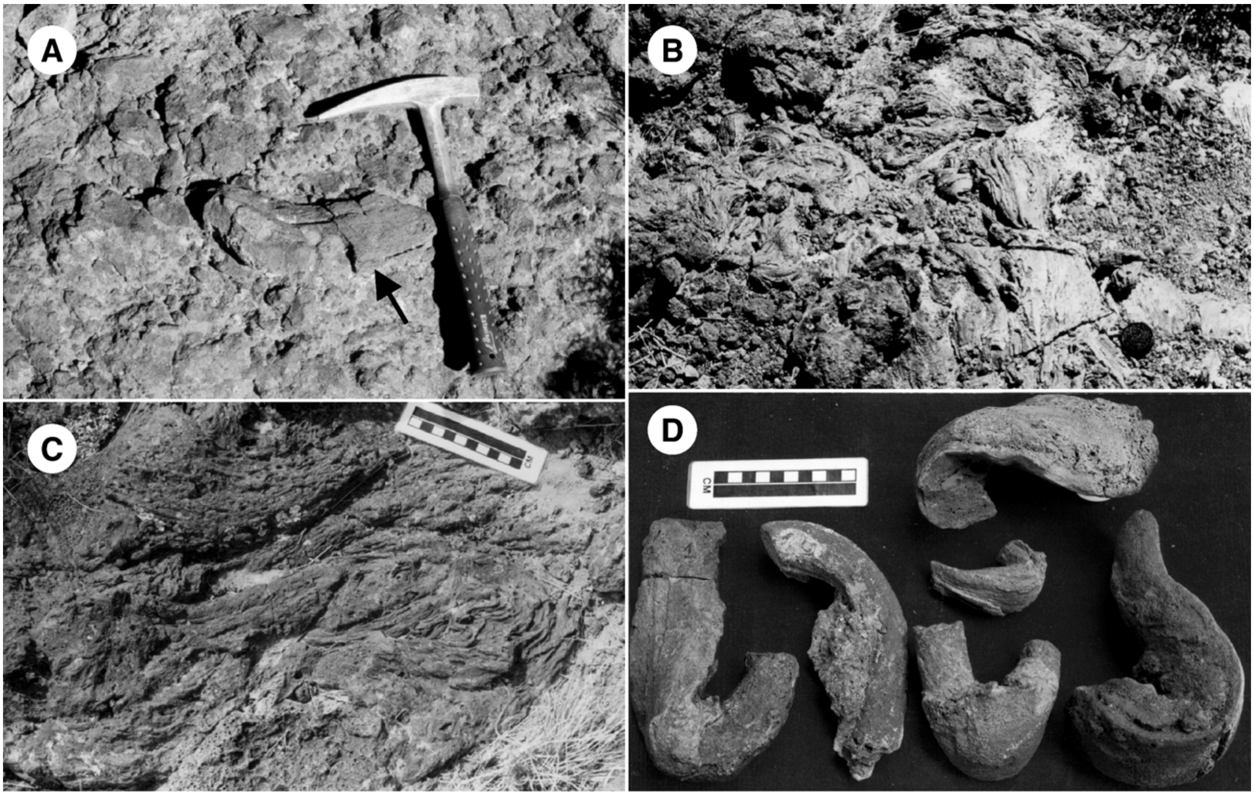

Fig. 3. Volcanic lithofacies. (A) Lithofacies A-2, agglutinated spatter and bomb bed, at Del Chivo cone. Arrow indicates a bomb-sized clast. (B–C) Lithofacies A-3, flattened spatter on Agua Poca volcano. Lens cape for scale in (B). (D) Isolated unwelded pyroclasts (bombs probably folded on landing). The continuous black lines for scale in (C) and (D) are of 10 cm.

described below. An important feature observed in several volcanic edifices (e.g., Agua Poca, El Pozo, La Blanca) from proximal to distal sectors of the vents, is that a single bed of agglutinated spatter change gradually to a deposit of weakly welded lapilli and bombs.

Clasts of the three subtypes (A-1, A-2 and A-3) are vesicular, with subcircular and irregularly shaped vesicles. Crystal textures are also common to all three, with porphyritic texture predominant, followed by glomeroporphyritic, with hyalophitic to hyalopilitic, intergranular, and intersertal groundmasses, in decreasing order of abundance. The most frequent association of phenocrysts is olivine–plagioclase–clinopyroxene, followed by olivine and olivine–clinopyroxene. The olivine phenocrysts in pyroclasts of lithofacies A are mainly subhedral, accompanied to a lesser degree by euhedral individuals, with a maximum length of 6.8 mm. In same cases, pyroclasts contain skeletal olivine, with embayed and partial to total replacements by iddingsite (±bowlingite) and rarely carbonates. Plagioclases are mainly subhedral, with albite and albite–Carlsbad twins, and a maximum length of 1.5 mm. Clinopyroxenes are mainly subhedral, with a maximum diameter of 2.8 mm, and frequent oscillatory and sectorial (hourglass) zoning. The groundmass of several samples contained more than one kind of glass (tachylite and sideromelane) or its alteration product (palagonite). The varieties found were tachylite, sideromelane + palagonite and tachylite + palagonite.

Olivine xenocrysts (with kink bands and reaction rims) were found in rocks of the Negro 1, El Tordillo and Loma Jagüel del Moro centers. Likewise, xenocrysts of quartz, feldspar and plagioclase, and felsic xenoliths (from acid to intermediate volcanic rocks and quartzose metasedimentites) occur as inclusions in rocks from several volcanoes (e.g. Negro 3, Morado 2, Agua Poca, Ñire Co, Amarillo and Loma Jagüel del Moro). Plagioclase xenocrysts show reaction rims and sieve texture. The quartz and feldspar show reaction rims.

4.1.1.1. Lithofacies A-1: weakly welded lapilli and bomb beds. These are formed mainly by brittle lapilli clasts with irregular shapes (non-fluidal), and to a lesser degree fluidal bombs and blocks (equivalent to type 1 clasts of Sumner et al., 2005) (Fig. 2). They lie in beds constituting the fundamental part of the slopes of the volcanoes. The beds reach up to 6 m thick and show a coarse internal stratification. The degree of welding is variable, but generally ranges from none to medium. Beds are always clast-supported and in most instances lacking matrix. Lapilli forming the beds are mainly scoriaceous and red, except at La Yegua, where they are black.

4.1.1.2. Lithofacies A-2: agglutinated spatter and bomb beds. These are constituted by poorly to highly vesicular spatter (lava-like) matrix and bombs (Figs. 2 and 3) (clasts type 1, 2 and 3 of Sumner et al., 2005). The latter are generally fluidal bombs 5 cm to 2.2 m long, which can be of spindle, ribbon, spherical or cylindrical type. They show similar characteristics as those of the isolated non-welded pyroclasts described below. The deposits lie in the upper and central sectors of the volcanoes, in beds ranging from 2 cm to 2 m thick, which by superposition may reach up to 8 m thick (e.g., Morado 3, La Blanca). In all the eruptive centers they are always matrix-supported, although the matrix appears in variable percentages. In some sectors, especially in the central portions of the volcanoes, this lithofacies contains basaltic angular blocks of up to 35 cm long, produced by vent erosion. This lithofacies predominates in the summit zone of some volcanoes.

A remarkable feature of the spatter matrix is the presence of felsic xenoliths of up to 20 cm diameter. These show a metamorphic halo at the contact with the basalt. In addition, within this lithofacies and in the volcanoes near the Colorado River, there are gravels from the sedimentary country rock.

4.1.1.3. Lithofacies A-3: agglutinated spatter beds. This lithofacies is formed entirely of highly-welded and coalesced spatter clasts (type 4 clasts of Sumner et al., 2005), lying on the perimeter of the vents and constituting the walls of the volcanic edifices. They lie in beds 20 cm to 2 m thick, intercalated with weakly welded lapilli and bomb beds (lithofacies A-1) (Figs. 2 and 3). The spatter clasts of this lithofacies become less welded and fluidal, grading to a weakly welded lapilli and bomb bed (lithofacies A-1) (Fig. 2E). This is evident in some volcanoes (Agua Poca, El Pozo and La Blanca) on a profile from the inner to the outer walls of their volcanic edifices.

4.1.2. Lithofacies B: ash beds

Ash was found only in two eruptive centers (El Oscuro and Morado 3), where it lies in beds 20 to 50 cm thick. It forms unconsolidated deposits, with very poor welding (in some sectors partially cemented by secondary carbonate material). At both volcanoes the ash is interstratified with weakly welded lapilli and bomb beds (lithofacies A-1). We think that the reasons for the lack of ash in the studied volcanoes are: (1) Hawaiian and Strombolian eruptive styles are characterized by low degree of fragmentation (Vergniolle and Mangan, 2000; Chester et al., 1985); (2) ash-fall is quickly eroded after the eruption (e.g. Mount Etna, Chester et al., 1985); (3) evidences of initial phreatomagmatic phases were recongnized only in two of the studied eruptive centers (Morado 3 and El Oscuro).

4.1.3. Lithofacies C: lava flows

The studied lava flows are of the pahoehoe type. In most of the volcanoes they are terminal (i.e. discharged at the end of the eruption), but at El Tordillo a flow on the northern slope probably represent a lava flow discharged at the beginning of the eruption. Measured thickness range between 30 cm and 5 m for each flow. In some instances (Loma Jagüel del Moro, Chato segundo, Tapa and Huanul) flows represent the largest volume of the eruptive center. In type 2 volcanoes (refer to Section 4.2), lava flows show spheroidal weathering, which generated boulders (1.5 to 2 m diameter) of poorly to non-vesicular basalt. Other lava flows show slab or columnar erosion. Several lava flows contain felsic xenoliths and the terminal ones at Huanul and Agua Poca carry ultramafic xenoliths (Bertotto, 2000, 2002a).

The lava flows are dark-grey to black in colour with vesicularity varying from very high on the surface (upper crust) to absent in the middle sector. In the central zone (cores) of some of the flows there are vesicle sheets and vesicle cylinders. At several localities (Morado 1, Ñire Co, Tapa) there are lava toes about 35 cm wide and lava tubes of up to 1.5 m wide. The “Cueva de Halada” lava tube near Agua Poca, comprise a system of underground galleries with an aggregate length of 295 m, a maximum height of up to 2.5 m and a width ranging between 4 and 15.6 m (Bertotto, 1996).

Lava flows show a variation in groundmass texture; the cores are porphyritic with intergranular groundmass, while at the top of the flows the groundmass is intersertal to pilotaxitic and at the base of the flows, it is pilotaxitic. The main phenocrysts phase in the upper (crusts) zones and in the base of the flows is olivine. In the internal sectors (cores) olivine, olivine–plagioclase, olivine–plagioclase–pyroxene, and olivine–pyroxene are the phenocrysts phases. Phenocrysts of olivine are mainly subhedral and to a lesser extent euhedral, with a maximum size of 3 mm. They are commonly replaced partially or completely by iddingsite (±bowlingite), and also show skeletal shapes and resorption embayments. Plagioclase crystals are subhedral and reach a maximum length of 7.6 mm. They show albite and albite–Carlsbad twins, and in several thin sections we observed individuals with oscillatory zoning. Clinopyroxenes (titanoaugites) are subhedral, attaining a maximum size of 2.4 mm and showing frequent development of oscillatory and sectorial (hourglass) zoning.

In addition to the described lava flows that form part of the volcanic edifices, several eruptive centers have emitted pahoehoe lava flows that extended far away from the vent. The lava flows of Tapa volcano cover approximately 650 km^2, those of Huanul 515 km^2, Morado 3 up to 130 km^2 and 70 km^2 those of Negro 1.

4.1.4. Lithofacies D: conduit fill

Vent-filling deposits of La Parva and De la Laguna (Bertotto, 2002b) volcanoes were studied. The rocks are massive, and weakly vesicular (less than 5% of vesicles), at times this grades into amygdaloidal because of the infilling of carbonates in the vesicles. Textures are subophitic to intergranular and porphyritic (to glomeroporphyritic) with intergranular groundmass. The assemblages of phenocrysts include plagioclase–olivine–clinopyroxene–opaque minerals, and olivine alone. The mineral assemblage of the groundmass is plagioclase–clinopyroxene–olivine–opaque minerals±nepheline; in addition apatite was observed as an accessory mineral. Olivines are subhedral to euhedral, with margins frequently reabsorbed by the groundmass and they are partially or completely replaced by pseudomorphic iddingsite. The maximum size attained is 2.3 mm. Plagioclases are subhedral to euhedral and reach a maximum length of 3.6 mm. Clinopyroxenes are subhedral to anhedral, brown to weakly purplish and show poorly developed hourglass zoning, reaching a maximum size of 1.1 mm. Opaque minerals are polygonal (equidimensional and prismatic), in many cases with jagged edges and some of them showing acicular ends. We also observed clusters of opaque minerals forming glomerocrysts. In several thin sections we recognized xenocrysts of feldspar, which developed reaction coronae along their edges.

4.1.5. Lithofacies E: dikes

Dikes are formed of basalt with varying vesicularity. They show variable directions, although at some of the localities the radial ones are predominant. They generally intrude lithofacies A-1 and A-2; in some cases (Morado 1 and Los Carrizales), because of erosion, dikes comprise most of the remaining volcanic edifice. They show a minimum thickness of 5 cm but in many volcanoes they coalesce to form thicker packs by multiple intrusions. These dikes are only in the vent constructs, not in the country rock.

4.1.6. Isolated lapilli and bomb clasts

The volume of isolated and unwelded lapilli and bomb clasts is not significant in any of the vents. They are red to black (depending on the degree of oxidation of the iron minerals) with sizes ranging from 2 cm to 2 m, although the most frequent size range is 5 cm to 1 m. They are usually located on the outer slopes of the volcanic edifices. Most of them show aerodynamic shapes, the largest part of the bombs being the unipolar and bipolar fusiform, ribbon and cylindrical ones (clasts type 1 and 2 of Sumner et al., 2005; Fig. 3D). Some of the recognized features are: longitudinal striae, folds and discoidal projections, which are normally acquired as they turn during motion in a plastic state; transverse cracks (in several directions), formed when the pyroclasts still have a plastic core while the surface has already hardened (corresponding to type 2 clasts of Sumner et al., 2005); and curvatures, possibly caused by the impact of the bombs against the ground (Fig. 3D).

The lapilli and bomb clasts are vesicular, and the vesicles are normally elongated and concentrated at different levels, defining highly and poorly vesicular zones. They commonly develop a chilled margin with smaller crystals and vesicles compared with the rest of the pyroclast. Texture in the bombs is porphyritic with pilotaxitic and intergranular groundmasses; olivine either is the only phenocryst or is accompanied by clinopyroxene. Lapilli show porphyritic and glomeroporphyritic textures in hyalophitic groundmass with an assemblage of phenocrysts including olivine–plagioclase and olivine–plagioclase–clinopyroxene. Olivines are subhedral, frequently altered (iddingsite and bowlingite) and with a maximum diameter of 1.6 mm. Plagioclases are subhedral of up to 1.2 mm long, with albite and albite–Carlsbad twins; those of the groundmass show swallow-tail terminations. Clinopyroxenes are subhedral, reaching a maximum length of 1.3 mm and showing oscillatory and sectorial zoning (hourglass).

4.2. Edifice characteristics

The 34 eruptive centers were arranged in 5 groups (types) according to their degree of erosion, lithofacies association and deposits geometry.

4.2.1. Type 1 (La Parva type)

La Parva and De la Laguna eruptive centers are type 1 edifices. They are located in the northern sector of the study area (Fig. 1). These are almost circular edifices

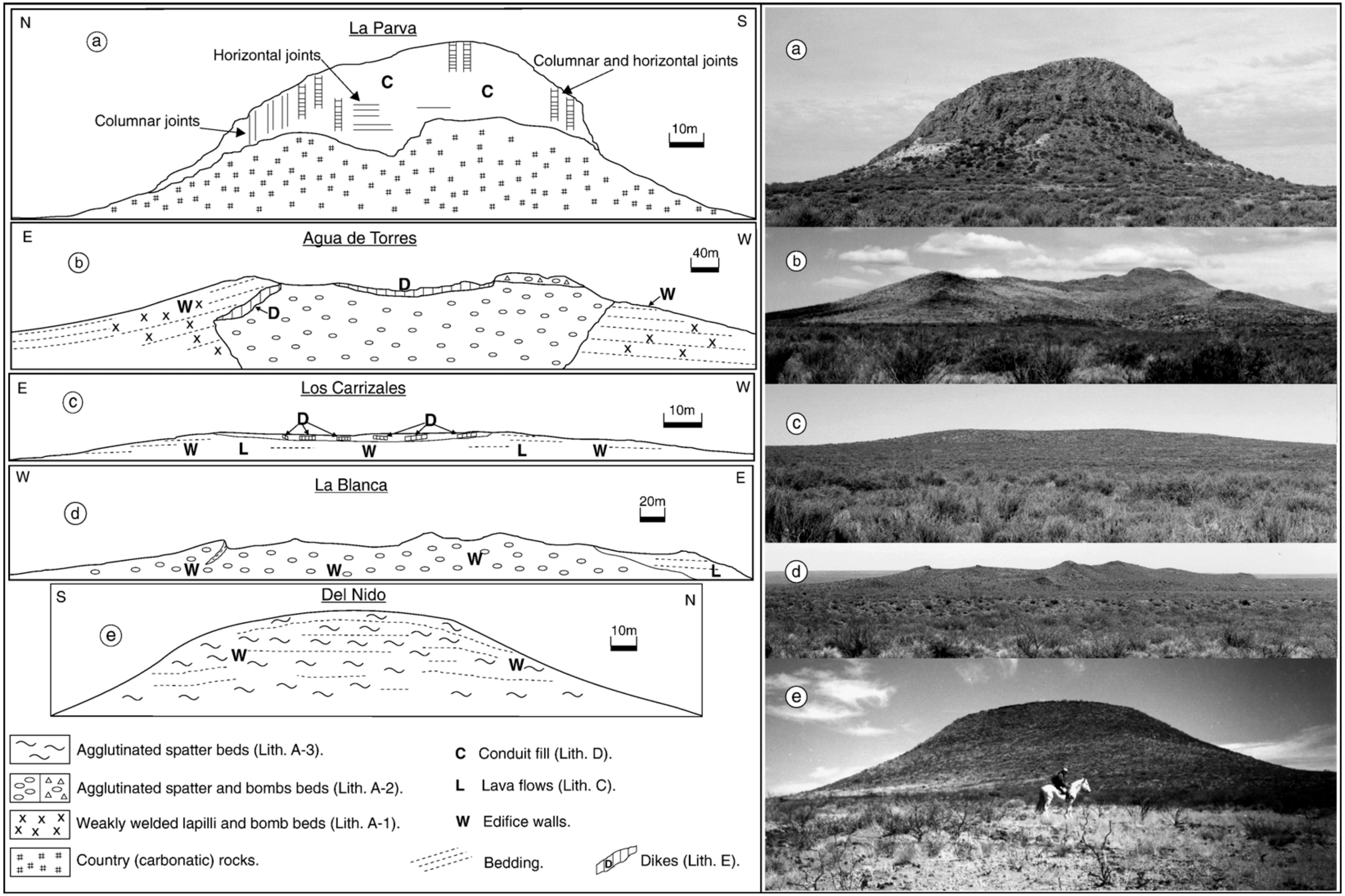

Fig. 4. Typical erosion profiles, lithofacies and photographs of some edifice types. Volcanoes: (A) La Parva (type 1); (B) Agua de Torres (type 2); (C) Los Carrizales (type 3); (D) La Blanca (type 5); (E) Del Nido (type 6).

rising approximately 50 m above the surrounding terrain, with strongly inclined slopes (90° at several sectors). They intrude Cretaceous–Paleogene fossil-bearing limestone or rhyolitic rocks of the Choiyoi Group (De la Laguna eruptive center), and are formed of massive, dark grey aphanitic basalt (lithofacies D), affected by several sets of joints, that at places intersect to originate columnar jointing (Fig. 4). These bodies are interpreted to be the eroded necks of volcanic edifices.

4.2.2. Type 2 (Agua de Torres type)

This type includes the following volcanoes: Escorial, Los Corrales, Del Chivo, Morado 2, El Oscuro, Negro (1, 2 and 3), El Peludo, El Lindero, Agua de Torres, Puntudo, Amarillo, Tordillo, La Negra, Chato segundo, Chato, Morado 3 and Rial. Except Morado 3, Rial (southern zone) and Escorial (central zone), the eruptive centers of this type are placed in the northern zone of the study (Fig. 1). Edifices are 30 to 50 m high, have no central depression or crater and are composed of weakly welded lapilli and bomb beds, agglutinated spatter and bomb beds, agglutinated spatter beds, dikes and lava flows. In the cuspidal zone (upper central) of the edifices, the predominant rocks are agglutinated spatter and bomb beds (lithofacies A-2). Weakly welded lapilli and bomb beds (lithofacies A-1) occupy the perimeter of the volcanoes. They are generally up to 4 m thick, and weakly bedded (e.g. Los Corrales, El Oscuro). At the base of two centers (El Oscuro and Morado 3), the size of the pyroclasts in lithofacies A-1 is smaller than in the rest of the volcanoes, sometimes grading into ash. In these cases, lapilli and ash individuals show glass altered to palagonite, and at Morado 3 there are accidental lithic fragments. Agglutinated spatter and bomb beds include bombs with aerodynamic shapes and among these, ribbon, fusiform, spherical and cylindrical types, reaching up to 1.5 m in diameter, are frequent. In the central portions of the volcanoes, instead of bombs there are basaltic angular blocks of up to 35 cm long, produced by vent erosion. Dikes (lithofacies E) are constituted by variously vesiculated lava and they show variable directions, but generally are radial intruding the beds of lapilli and bombs, and agglutinated spatter and bombs. The lava flows are of the pahoehoe type, showing jointing in several orientations and, in the majority of volcanoes, they were discharged at the vanishing stages of the eruption.

4.2.2.1. Sub-Type 2-a (Loma Jagüel del Moro type). It includes only the Loma Jagüel del Moro volcano (northern sector; Fig. 1) and comprises the same lithofacies observed in type 2 eruptive centers. The difference lies in the greater proportion of lava compared to the other lithofacies (i.e. 90–10). The basal diameter of this volcano is 3.2 km, reaching a height of 100 m and slopes dipping at 3° to 7°. Its morphology suggests it is a Scutulum-type shield volcano (nomenclature of Walker, 1993, 2000).

4.2.3. Type 3 (Los Carrizales type)

Included in this type are Los Carrizales and Morado 1 volcanic centers, located in the central zone (Fig. 1). These are craterless, circular mesetiform elevations about 20 m high with basal diameters of 200–250 m. They are constituted by lava flows (lithofacies C) and vesicular dikes (lithofacies E). The lava flows are of the pahoehoe type with thickness ranging from 3 m to 6 m, arranged around the flanks. Their central part (core) carries vesicle sheets and vesicle cylinders. Other features associated with these pahoehe flows are lava toes and tubes. Lava dikes are 10 cm thick and cluster to form thicker packs by multiple intrusions. We assume that the present form of these edifices is the result of erosion of mainly weakly to non-welded lapilli and bomb beds (lithofacies A1), due to the presence of scattered lapilli and bomb clasts in the proximities and on top of the elevations.

4.2.4. Type 4 (Huanul type)

This type includes Tapa (central zone) and Huanul (southern zone) volcanoes (Fig. 1). These eruptive centers are semicircular rings of lava flows (lithofacies C), in the internal area of which outcrop dikes, unwelded lapilli and bomb clasts (Tapa), agglutinated spatter and bomb beds and lava flows (Huanul). The lava flow rings measure 450 m in diameter at Tapa and 3.9 km at Huanul, and are up to 20 m high. The lava flows are of the pahoehoe type. Lapilli and bomb clasts of Tapa are irregularly shaped and the majority measures 2 to 6 cm in diameter. Superficially oxidized dikes (lithofacies E) are at least 5 cm thick. Agglutinated spatter and bombs (lithofacies A-2) of Huanul lie in beds at least 2 cm thick; these beds overlie each other and are welded together. We infer that Tapa edifice was formed by collapse, i.e. is a collapsed lava rise (Walker, 1991). The edifice of Huanul is a pit surrounded by lava rises.

4.2.5. Type 5 (La Blanca type)

In type 5 belong the La Blanca, La Yegua and El Águila eruptive centers, all located in the southern sector of the study area (Fig. 1). These are edifices about 40 m high. Although their walls are partly destroyed, a central depression or crater can still be observed. They are composed mainly by weakly welded lapilli and bomb beds, agglutinated spatter and bomb beds, agglutinated spatter beds and to a lesser degree by lava flows.

The lapilli, bomb and spatter clasts form poorly (lithofacies A-1) to highly (lithofacies A-2 and A-3) welded layers at least 2.5 cm thick. Successive layers form beds up to 10 m thick. The bombs are aerodynamically shaped, mainly fusiform and up to 50 cm long. Flows are terminal and of the pahoehoe type (lithofacies C).

4.2.6. Type 6 (Agua Poca type)

In this type belong the De Díaz (northern zone), Ñire Co, Agua Poca, Del Nido (central zone) and El Pozo (southern zone) volcanoes (Fig. 1). These edifices are 40 to 70 m high, conical and breached (except Ñire Co), with few signs of erosion (scarce destruction and "parasol" ribbing erosion), and their craters are perfectly recognizable. Local faulting was identified in the De Díaz (N53°W), Agua Poca (N61°E) (Bertotto, 2000) and El Pozo (N70°W) centers. The faulting is possibly related to magma ascent. The volcanoes mainly consist of alternating layers of weakly welded lapilli and bomb beds (lithofacies A-1), agglutinated spatter and bomb beds (lithofacies A-2) and agglutinated spatter beds (lithofacies A-3). In addition, they show pahoehoe terminal lava flows (lithofacies C), isolated unwelded lapilli and bomb clasts and vesicular dikes (lithofacies E). The lithofacies A-1, A-2 and A-3 are arranged in 0.1 to 2 m thick layers and comprise: solely spatter (lithofacies A-3); a vesicular to lapillitic lava-like matrix with aerodynamically shaped bombs (lithofacies A-2); and scoria alone, mainly of lapilli size (lithofacies A-1). The isolated unwelded lapilli and bombs clasts vary in size from 4 to 200 cm long (mainly <40 cm), are fusiform, ribbon-shaped, or spherical and are accompanied by scarce angular basalt blocks of a similar size.

4.3. Volcanic evolution

According to Head and Wilson (1989), the classic Hawaiian lava fountain consists of three different parts: a) inner or central incandescent portion, with a high density of very hot clasts, most of which fall within the cone that surrounds the emission aperture and accumulate contributing to the formation of the central lava lake; b) intermediate fountain, with hot pyroclasts that can fall over the rim of the cone and form a rootless flow or remain at the top of the volcano as a welded spatter deposit; c) outer fountain, composed of clasts that cooled sufficiently during flight to behave in a brittle way when they hit the ground. The edifices resulting from the activity of Hawaiian lava fountains are typically a welded spatter cone. Over the spatter cone there is a cinder cone consisting of interstratified lava, and pyroclastic deposits, with an agglutinated rim (Sparks et al., 1997).

Based on the observations of Head and Wilson (1989), from considerations of Sparks et al. (1997) and Wolff and Sumner (2000), and following the volcanic activity units nomenclature of Fisher and Schmincke (1984), we established an eruptive sequence for the studied volcanoes.

4.3.1. Initial eruptive phase

It comprises the several early pulses that we infer existed because of the deposits stratification. During this phase, agglutinated spatter and bomb beds (lithofacies A-2) were deposited (Fig. 5). Deposits generated by this phase are those identified in centers of types 2, 3 and 4 (Fig. 4).

Regarding the formation of agglutinated spatter and bomb beds, we postulate that the spatter matrix fell from the intermediate parts of a lava fountain and the bombs included in it came from slightly higher parts, allowing them to cool enough during flight and thus retain their shape (not coalescing) as they fell. In any event, the two components could still weld strongly together because they fell simultaneously. This welding indicates a high temperature and rapid accumulation, albeit not so high that pyroclasts would lose their identity (cf. with the deposits of lithofacies A-3).

It is possible that at volcanoes Morado 3 and El Oscuro the first phases were of phreatomagmatic character because the presence of palagonitized and accidental lithic deposits.

4.3.2. Middle or main eruptive phase

This includes the array of pulses responsible for the volumetrically largest deposits made up of successive layers of weakly welded lapilli and bombs (lithofacies A-1) and agglutinated spatter (lithofacies A-3) (Fig. 5). The rocks originated during this phase were found in type 5 and 6 edifices (Fig. 4).

At most of the localities the weakly welded lapilli and bomb layers were probably deposited from the external part of a Hawaiian lava fountain, and the agglutinated spatter deposits from the intermediate part, analogous to what occurs in modern eruptions (Head and Wilson, 1989; Sumner et al., 2005). Another possibility for the formation of successions of weakly welded lapilli and bomb beds and agglutinated spatter beds would be variations from Strombolian to Hawaiian eruption style, in a similar way to the Strombolian changing to fire-fountaining activity during the 2001 eruption of Etna, documented by Lautze et al. (2004). However, in some of the localities (Los Corrales, El

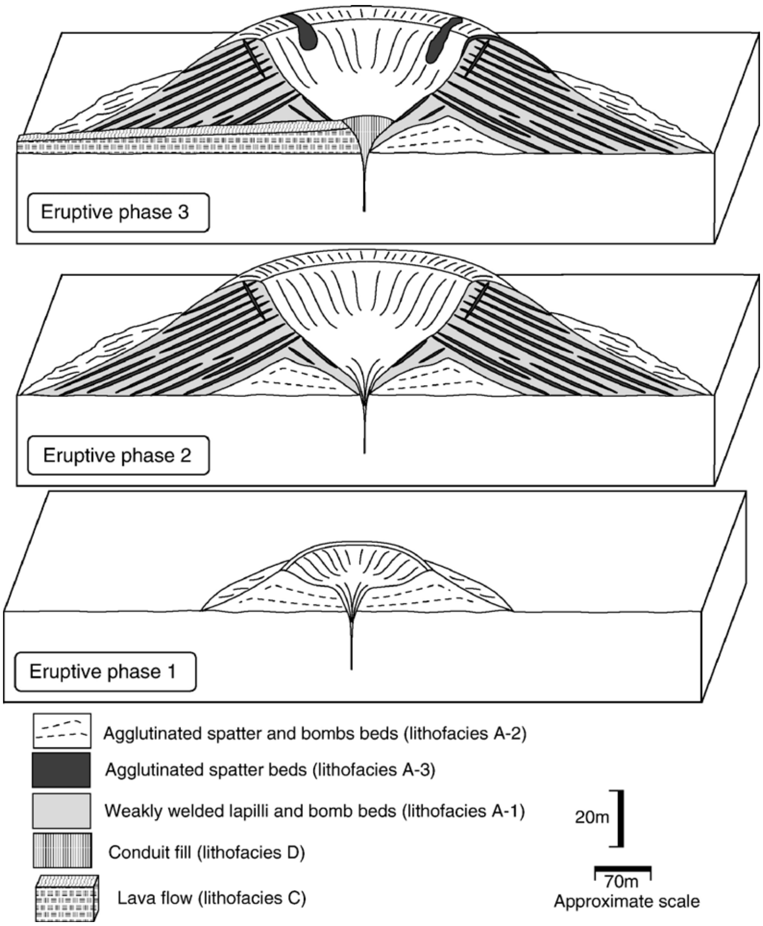

Fig. 5. Block diagrams of deposits generated from inferred eruptive phases.

Oscuro and La Yegua) we observed weakly welded lapilli and bomb layers several meters thick which could have been formed by isolated Strombolian eruptions. Furthermore, in Agua Poca, El Pozo and La Blanca edifices there is lateral variation in degree of welding from proximal to distal sectors of the vents, i.e. a single bed of agglutinated spatter grades to a deposit of weakly welded lapilli and bombs, suggesting fire-fountaining activity.

4.3.3. Final eruptive phase

Includes the final pulses that formed lava flows (lithofacies C), minor spatter deposits (lithofacies A-3) and isolated unwelded lapilli and bombs. These rocks could represent the eruption wanning (Fig. 5). Examples of this phase are observable at Huanul, Agua Poca and Del Nido cones.

Fisher and Schmincke (1984) defined a nomenclature to be applied to volcanic eruptions and pointed out that an eruption can be divided into different units of volcanic activity. Based on these units of volcanic activity, the characteristics of the erupted magma, and the vent morphology (Cas and Wright, 1987), volcanoes could be classed as monogenetic and polygenetic. The volcanoes described herein are monogenetic, as suggested by the homogeneity of the erupted magma and the simple features of the eruptive vents. In addition, there are no traces of erosion or soil formation among the units, i.e., the time span from one eruptive cycle to the next was very short. They probably formed during a sole eruption comprising several pulses.

4.3.4. Considerations on the Hawaiian and Strombolian eruptive styles

Strombolian eruption deposits differ from Hawaiian ones by the absence of small glass fragments called tears and hair of Pele, by the greater dispersion and fragmentation of pyroclasts, and by the abundance of fine-grained tephra (Fisher and Schmincke, 1984; Cas and Wright, 1987). Likewise, Hawaiian activity produces a significantly larger proportion of spatter because of the mechanism called lava fountaining, generating cones and mounds of spatter at vents. The cinder cones formed by Strombolian eruptions are typically composed of unwelded clasts, as most of them are already cold when they fall (Vergniolle and Mangan, 2000; Parfitt, 2004). However, some basaltic eruptions show both Hawaiian and Strombolian features. This is typical of the so-called "transitional eruptions" (Parfitt and Wilson, 1995; Parfitt, 2004). The transition from the Hawaiian to the Strombolian style depends mainly on magma ascent speed. The "transitional style" originates when the ascent speed is intermediate between the typical Strombolian and Hawaiian ones (Parfitt and Wilson, 1995). A well-documented example of varying welding in a cinder cone is that of the Monterosso cone at Etna, the early phase of eruption produced a large amount of spatter bombs which agglutinated on landing. The upper inner part of the cone consists of bedded ash, scoria and spatter, and the external flanks are composed of bedded glassy ash and scoria (Chester et al., 1985).

Variations between Strombolian and Hawaiian activity can be assumed at majority of volcanoes. However, is important to note that: (1) at Los Corrales, El Oscuro, La Yegua and Morado 3 the weakly welded lapilli and bombs layers were probably formed by Strombolian eruptions; (2) for volcanoes Agua Poca, El Pozo and La Blanca, where lateral variation in degree of welding occur, Hawaiian style activity can be supposed; (3) in Huanul, Tapa, Morado 3, Negro 1 and Loma Jagüel del Moro we assume predominance of effusive eruption, because of the presence of lava flows.

At Morado 3 it is possible to infer a greater variability of eruption style: first phreatomagmatic activity (lapilli-ash beds with palagonite plus accidental lithic fragments), followed by Strombolian (thick beds of weakly welded lapilli and bombs) and Hawaiian style eruptions (pahoehoe lava flows).

In the eruptive centers with inferred effusive activity, the volcanic units may have been generated through Hawaiian lava fountains such as those described by Vergniolle and Mangan (2000). The presence of mantle xenoliths in rocks from several of these volcanoes indicates that speed of magma ascent was very high (otherwise xenoliths would never have reached the surface due to their high density compared to the hosting lava), a typically Hawaiian feature according to Parfitt and Wilson (1995).

5. Conclusions

Seven lithofacies can be recognized in the studied area, which are inferred to be the result of three eruptive phases.

The field evidence indicates that lava fountaining activity was responsible for the formation of agglutinated spatter and bombs beds, and variations between Strombolian and Hawaiian activity led to the formation of successions of weakly welded lapilli and bomb beds and agglutinated spatter beds. Typical Hawaiian style activity is evidenced by volcanoes that emitted lava flows, in several cases hosting mantle xenoliths, which indicates magma generation at deep levels in the mantle and very high rates of magma ascent.

Uniformity of erupted magmas and characteristics of the vents indicates that the studied volcanoes were monogenetic.

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