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# PETROGRAPHY AND GEOCHEMICAL CHARACTERISATION OF THE PERMO-TRIASSIC IN THE SIERRA DE VARELA, SAN LUIS, ARGENTINA

*Caracterización petrográfica y geoquímica del Permo-Triásico en la Sierra de Varela, San Luis, Argentina*

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**Abstract:** *The Choiyoi Group reflects the initial breakdown of Gondwana in the Permo-Triassic. The group outcrops over large areas of the Andes and the centre of Argentina. In this regard, the pyroclastites of the Sierra de Varela, in the province of San Luis, were recognised as an integral part of the Choiyoi Group. Knowledge about the physical and chemical characteristics of this unit in San Luis is scarce. The paper presents results about the stratigraphy, petrography and geochemistry of the Cerro Varela formation, in the hill of the same name, and investigates the possible depositional environment for the sequence. The bulk of the rocks correspond to welded and non-welded tuffs of rhyolitic composition. The welded tuffs would represent the transition towards an intraplate complex of alkaline character. In contrast, non-welded tuffs exhibit a predominant calc-alkaline signature of variable $K_2O$ contents, possibly related to their formation in a volcanic-arc environment. Distinctive rock populations are also evidenced by the content of traces and rare earth elements. Deposition would have resulted from pyroclastic flows in a Plinian explosion. It is argued that the welded tuffs correspond to basal ignimbrites, whilst the unconsolidated fraction is indicative of fallout deposits moved to the distal parts of the flow.*

**Keywords:** *Pyroclastic flow, petrography, geochemistry, Choiyoi Group, San Luis, Argentina.*

**Resumen:** *El Grupo Choiyoi refleja los comienzos de la ruptura de Gondwana en el Permo-Triasico. El Grupo aflora en una vasta región de los Andes y el centro de Argentina. En relación con ello, las piroclastitas de la Sierra de Varela, en la provincia de San Luis, han sido reconocidas como una parte integral del Grupo Choiyoi. Sin embargo, el conocimiento acerca de las características físico-químicas de esta unidad en San Luis continua siendo escaso. Este artículo presenta nuevos resultados relacionados con la estratigrafía, petrografía, y geoquímica de la Formación Cerro Varela, en la sierra del mismo nombre, e investiga el posible ambiente de deposición de dicha secuencia. El grueso de las rocas se vincula con tobas soldadas y tobas no consolidadas de composición riolítica. Las tobas soldadas representarían la transición hacia un complejo de intraplaca de carácter alcalino. Por el contrario, las tobas no soldadas presentan características calco-alcalinas con contenido variable en $K_2O$, posiblemente relacionadas con un ambiente de arco volcánico. El contenido de elementos traza y tierras raras pone en evidencia la existencia de grupos diferenciales entre las rocas analizadas. La deposición habría tenido lugar a partir de flujos piroclásticos en una explosión Pliniana. Las tobas soldadas son atribuidas a depósitos basales de ignimbritas, mientras que la fracción no soldada se relacionaría con materiales de caída en las zonas distales del flujo.*

**Palabras clave:** *Flujos piroclásticos, petrografía, geoquímica, Grupo Choiyoi, San Luis, Argentina.*

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The Permo-Triassic period in South America, in particular the area between 23º and 42º latitude was characterised by an extensive magmatic activity interpreted as the first signs of breakdown of the Gondwana continent. In this regard, the Permo-Triassic Choiyoi rhyolite province of Chile and Argentina is by its extension, volume and geological significance, indicative of one of the most important magmatic events of the southwestern margin of Gondwana (Rocher and Valecillo, 2014). Products of this magmatism are found to outcrop between the Pastos Blancos Group in northern Chile, to the Cordillera del Viento in northern Patagonia. Furthermore, related deposits are exposed in the Andean Cordillera of La Rioja, San Juan and Mendoza, together with deposits found in the provinces of San Luis and La Pampa, in the centre of Argentina. Based on oil exploration boreholes the extension of the Choiyoi volcanites in Argentina may be up to 500,000 km$^2$ in area (Llambias et al., 2003).

According to Stipanicic et al. (1968), the Choiyoi Group can be divided into two major units; a lower member of basic to intermediate composition and an upper member comprising a succession of rhyolites and felsic volcanites. The lower member is estimated to have developed between 272 Ma and 260 Ma in association with the final stages of a subduction process, whilst the rocks of the upper member could be described as post-orogenic siliceous deposits from an intraplate setting, mainly from 259 Ma to 247 Ma (Kleiman and Japas, 2009). The current consensus ascribes the magmatism to a transitional calc-alkaline series in an extensional geotectonic setting. Nevertheless, the regional areal extent of the event, its heterogeneous chemistry and the discontinuity of the outcrops are still open to debate (Martinez, 2005). Most of the recent investigations of the Choiyoi Group were undertaken on the mountain ranges of the Cordillera Frontal within the provinces of Mendoza and San Juan where the sequence is better represented (e.g. Strazzere et al., 2006; Kleiman and Japas, 2009; Martinez, 2009; Valecillo et al., 2010; Poma et al*.,* 2014; Rocher and Vallecillo, 2014). Further inland and especially in San Luis, the number of studies of this geological group is more limited. The first analysis of the Choiyoi Group in the region of the mid-west of Argentina was conducted by Flores (1969) who described the porphyries and pyroclastites of the Sierra de Varela as lithologically connected to other units in the west. Further studies led Flores and Criado Roque (1972) to assign the rocks in the Sierra as an independent succession named Cerro Varela Formation. A description of the formation was carried out by Romero (1987) who characterised the basement as a sequence of schists, granites and diverse tuffs. The structural setting of the area was later investigated by Costa and Cortes (1993) who thought of an extensional environment with a tectonic style coincident with the general features that characterised the Mesozoic geology of the region. Furthermore, Martinez et al. (2012) hypothesised that rocks in the Sierra de Varela would have been originated in a convergent boundary transitioning towards an intraplate setting and could thus be compared to the middle and upper sections of the Choiyoi Group in the Andes. Unlike its counterpart in the Cordillera Frontal, the magmatism in the province of San Luis has not been fully understood yet and its physical and chemical characteristics remain relatively obscure. This paper describes the main findings from an investigation that combined geological observations with petrographic and geochemical analysis to better characterise the pyroclastites of the Cerro Varela Formation within the Sierra de Varela of San Luis. The possible environment of deposition of the Cerro Varela Formation is also discussed. This study also aims to advance the knowledge regarding the Choiyoi volcanic province in the mid-west of Argentina, together with contributing to a more detailed understanding of the geodynamics of the region during the Permo-Triassic period.

## Analytical techniques

Geological data and rock samples were collected over two field campaigns (the investigation) which were conducted in the Sierra de Varela. Tens of specimens were first examined by standard light microscopy to enable a systematic description of the stratigraphic succession in the study area. This examination was followed by observations with an ore microscope using thin-polished sections on typical samples from each of the identified lithologies. The petrographic study was conducted at the Department of Geology of the San Luis National University using a Leica polarizing microscope and digital scanner.

Mineral and rare earth elements (REE) analyses were conducted using X-ray fluorescence (XRF) and ICP-MS (inductively coupled plasma-mass spectrometry) techniques at ACTLABS Ltd in Canada. The REE analyses incorporated international geostandards for calibration purposes. Finally, plotting of whole-rock geochemical results was carried out using GCDkit (Janoušek et al., 2003) and Petrograph (Petrelli et al., 2005) software packages.

## Study area

### *Geological Setting*

The investigation covered an area of about 10 km$^2$ within the Sierra de Varela on the southern margins of the Sierra de San Luis, in the San Luis Province of Argentina (Fig. 1). The Sierra of Varela comprises a series of isolated hills extending north-south for about 14 km, before being overlain by Quaternary cover which extends towards the Patagonia region. Lithologically the area is dominated by a variety of felsic tuffs and pyroclastics flows from the Permo-Triassic period. The geological setting, chemical composition and age of the rocks investigated suggest a good correlation between the volcanic units of the Sierra

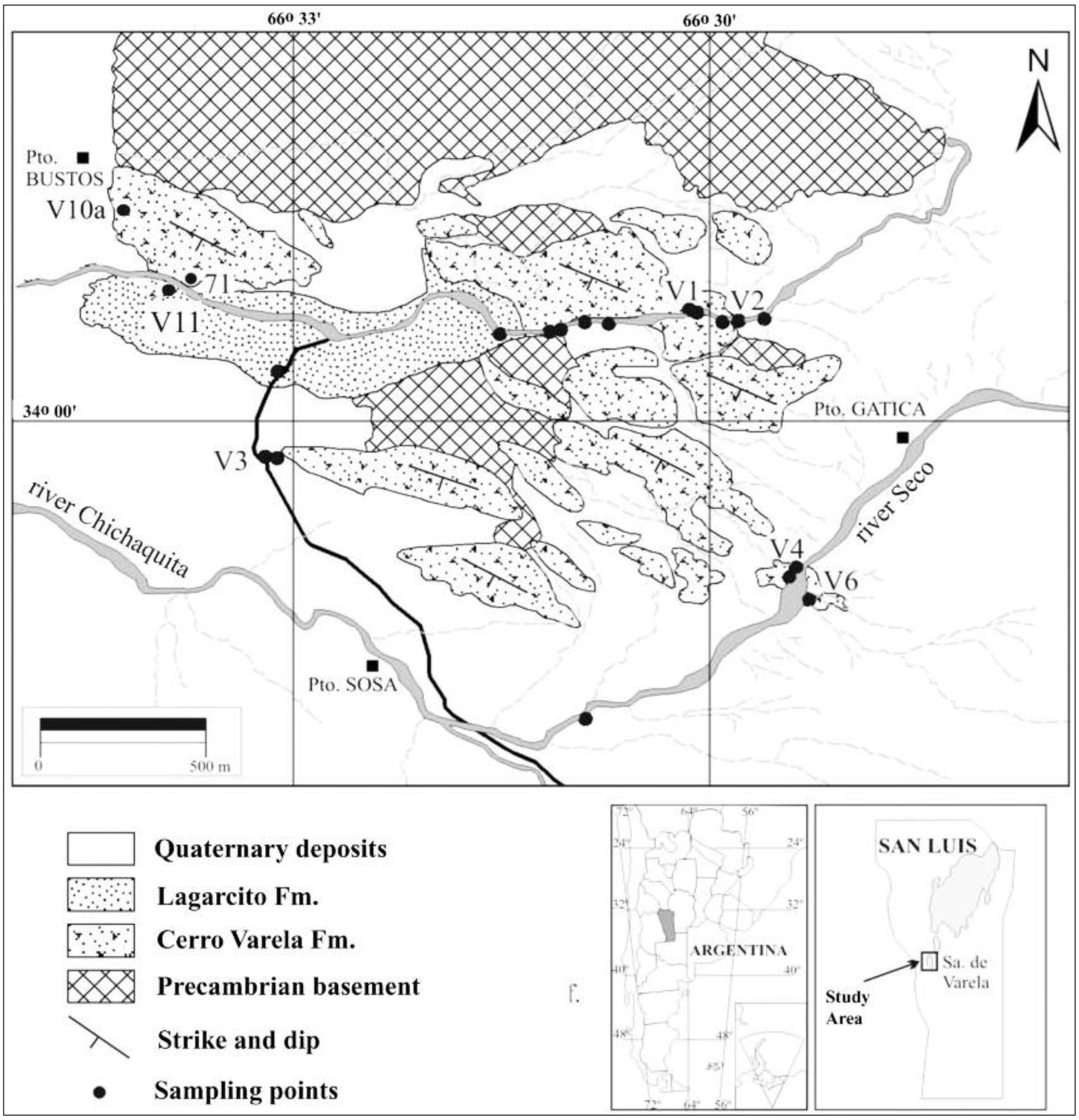


**Figure 1.-** Location and geology of the southern margin of the Sierra de Varela.

de Varela and those of the Choiyoi Group found in the Cordillera Frontal of Mendoza and San Juan provinces (Martinez et al., 2012).

At a regional scale, the Sierra de Varela is situated on the southern margins of the Beazley basin. This basin is part of a major complex of Triassic rift basins found within the mid-west of Argentina (Stipanicic and Marsicano, 2002). These basins form elongated valleys and were created by the amalgamation of isolated depocentres, which were originally a product of pull-apart activity (Uliana and Biddle, 1988). Many of these basins are located above presumed boundaries of terranes accreted during Palaeozoic era (Ramos and Kay, 1991). Following the accretionary period, the western margin of Gondwana was affected by an extensional regime that led to the reactivation of Palaeozoic faults and the formation of a series of rift systems with an overall NNW trend (Uliana et al., 1989). In this regard the geographical distribution of the basins and the granite - rhyolites of the Choiyoi Group would suggest a sinistral strike-slip or transtensional tectonic environment that lasted from Carboniferous period to the Triassic period (Simpson et al., 2001).

More specifically the Beazley basin comprises a rhomboidal area of about 4,000 km$^2$ filled with continental sediments over 4,000 m thick. Similar to the other basins of western Argentina, the Beazley basin is bounded by a network of faults with variable degree of activity during the sedimentation process. In this context the Varela Fault (Flores, 1969) is a thrust of northeast to south strike that defines the western boundary of the Sierra de Varela. The Beazley basin also hosts the pyroclastites of the Cerro Varela Formation which are regionally and chronologically related to the Choiyoi Group (Martinez et al., 2010). It must be noted however that the basin developed after the peak of magmatic activity and therefore the first sedimentary deposits, are coincident with the final manifestations of volcanism in the region (Spalletti, 1999; Martinez, 2004). This hypothesis is supported by the presence of pyroclastites and volcanites interfingered with the lower members of Triassic sedimentary deposits. According to Costa et al.

(1998), Triassic sediments occur in asymmetric slopes which have a NNW orientation and are bounded by normal faults of general strike between 290º and 310º and dipping 60º to 70º NE.

*Stratigraphy*

The stratigraphy of the study area is summarised in Table I. The crystalline basement of the Sierra de Varela is mainly constituted by migmatites from the Upper Precambrian to the Lower Palaeozoic. These rocks are made up of bands and lenses and display a variety of types with nebulitic, stromatolitic and ophthalmic textures. The nebulite texture reflects diffuse relics of pre-existing structures as opposed to the stromatolitic texture which is layered. The core minerals found in these units are quartz, alkali feldspar (microcline), plagioclase and biotite. The microcline crystals found in ophthalmic specimens can be up to 5 cm in diameter (Costa et al., 1998). Accessory minerals include apatite, epidote, zircon and iron oxides. Gneisses and alkali feldespar granites were identified towards the central and northern parts of the Sierra. These units are characteristically massive with porphyry outcrops where the microcline crystals align with the general structure of the ridges.

The southeast section of the Sierra of Varela comprises schist complexes of limited areal distribution. The schistosity texture consists of anhedral quartz, muscovite, biotite, plagioclase, garnets and feldespars (Romero, 1991). Furthermore, red granites have been described to occur in outcrops that range from 150 $m^2$ to 1,600 $m^2$ throughout the central and northern parts of the region. The contact between the migmatites and the granites would be transitional with a slight foliation parallel to the general structure observed in the southern margins of the Sierra (Costa et al., 1998).

The basement is unconformably overlain by a pyroclastic sequence of rhyolitic composition that outcrops predominantly in the south. This unit is referred as the Cerro Varela Formation and has an estimated thickness of about 500 m (Flores and Criado Roque, 1972). Based on lithology, age and regional context these pyroclastites can be considered to be part of the Permo-Triassic magmatism of the Choiyoi Group (Flores, 1969). Radiometric dating by $^{40}Ar/^{39}Ar$ indicates an age of 239.9 ± 0.6 Ma for the unit, which can therefore be assigned to the Ladinian stage in the Middle Triassic.

The basins experienced limited to no deposition between the Triassic and the Cretaceous periods. The first evidence of sedimentation reappears with the Lagarcito Formation (200 to 350 m thick), which is mainly composed of fluvial and eolian deposits from the late Cretaceous period (Rivarola and Spalletti, 2006). This unit comprises sandstones, loams and red to orange clays grading to siliciclastic materials and evaporites towards the top of the sequence. According to Flores (1969), the sediments were deposited in a lacustrine environment with some effects of streamflow. More recently, Yrigoyen et al. (1989) suggested a paleoenvironment that combined high-energy streams with alluvial plains in arid zones and potential ephemeral lakes at a local scale. In the Sierra de Varela, the Lagarcito unit has a thickness of about 290 m and lies unconformably on the volcanites of the Cerro Varela Formation.

## Results

The petrographic characteristics of the tuffs in the Cerro Varela Formation have been assessed and the findings combined with geochemical analysis of selected rocks. This has enabled further definition of the tectonic setting that contributed to the emplacement of the formation. The mineralogical examination revealed two main pyroclastics facies, namely welded tuffs and non-welded tuff units. Minor breccias of variable composition were also observed at some localities although analysis of these is not included in this paper.

*Welded Tuffs*

As shown in Figure 1, the welded tuffs or ignimbrites (Marshall, 1935) of the Cerro Varela Formation comprise the majority of the outcrops in centre of the study area. In general, these units are characterised by reddish to orange coloration, crude bedding, relatively good sorting and fine to very fine grains. The dense welding is shown by the prismatic columnar disjunction exposed on the Sierra de Varela slopes. Furthermore, the presence of fiammes and the development of eutaxitic textures (banding due to compaction of glass shards and pumice fragments) confirm an ignimbrite composition. As previously mentioned, outcrops are predominantly orientated in a WNW-ESE direction and are frequently bounded by normal faults with a general strike between 290º and 310º. Discontinuous joints and shear fractures with a WNW strike have also been identified in the uppermost part of the sequence. It has been proposed that the joints were formed as a consequence of volumetric contraction and vertical compaction during tuff cooling and welding (Wohletz, 2006). The fractures are commonly filled with jaspilite and complex anastomosing veinlets of calcite which suggests a late-stage deposition for

| Stratigraphy | Age | Thickness (m) | Lithology |
|---|---|---|---|
| Alluvium - colluvium | Quaternary - recent | 60 | Unconsolidated sands, silts, clays |
| Lagarcito Fm | Early Cretaceous (Aptian-Albian?) | 290 | Sandstones, loams, mudstones |
| Cerro Varela Fm. | Permo-Triassic (Ladinian) | 500 | Pyroclastites – ignimbrites - breccias |
| Basement | Precambrian - Lower Palaeozoic | ? | Migmatites, gneisses, alkali-feldspar granites |

**Table I.-** Overview of the stratigraphy in the Sierra de San Luis.

these minerals. Based on the types of material observed, and following the classification of Pettijohn (1975) and Schmidt (1981), the welded tuffs of the Cerro Varela Formation form two major groups of rhyolitic composition, namely lapilli lithic tuffs and lapilli crystal tuffs.

Microscope examination of the lapilli lithic tuffs reveals a clast-supported porphyroclastic texture with a clast to matrix ratio of 60:40. The predominant minerals are quartz and sanidine and to a lesser extent plagioclase, micas and opaques (Table II). The quartz – sanidine relationship is highly variable establishing a full range of compositional zonation. The porphyroclasts' grains range from 0.1 mm to 3 mm with an average size about 1 mm. The quartz appears euhedral to subhedral, with fractures and ragged boundaries suggesting a second episode of growth. The sanidine is also subhedral, often displaying the characteristic Carlsbad twinning (Figs. 2a, b). Grains reach up to 2 mm in diameter and are commonly altered to sericite. In some cases alteration products completely replace the entire phenocrysts. Relatively fine grains (<0.5 mm diameter) of imbricated biotite are abundant and their presence also helps to distinguish these tuffs from other units in the area. Finally, microcline xenocrysts with crosshatched twinning were observed to be irregularly distributed within the tuff matrix. The corroded outlines of the microcline could reflect partial albitization and the subsequent replacement of microcline by albite (Fig. 2c, d).

Approximately 20 % of the rock is constituted both by accidental lithoclasts and juvenile lithic fragments. These fragments reflect a granite-basement origin. In general, the lithics range from 0.1 mm to 1.5 mm in diameter. The reddish and yellowish-green coloration of the samples suggest that the opaque minerals dispersed in the rock matrix correspond to iron oxides, namely; hematite and goethite. Additionally, the accidental lithics are sometimes obliterated by calcite veins with rhombohedral cleavage. As previously mentioned, irregular calcite dykes are common features which cut across the welded tuff facies. Locally, the

| | Primary Minerals % | | | | | | Secondary Minerals | | Lithics % | | | Vitroclasts % | Matrix % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Quartz | Sanidine | Plagioclases | Micas | Opaques | Zircon | Calcite | Jaspilite | Juveniles | Accidentals | Xenocrysts | | |
| Welded lithic tuffs | 10 | 10 | 5 | 5 | 5 | - | Yes | - | 10 | 10 | 5 | - | 40 |
| Welded crystal tuffs | 15 | 20 | - | - | 15 | 5 | - | Yes | 5 | - | - | 10 | 30 |
| Non-welded crystal tuff | 10 | 10 | 5 | 5 | 5 | - | Yes | Yes | 5 | - | - | - | 6 |

**Table II.-** Typical mineralogical composition of the analysed tuffs in the Cerro Varela Formation.

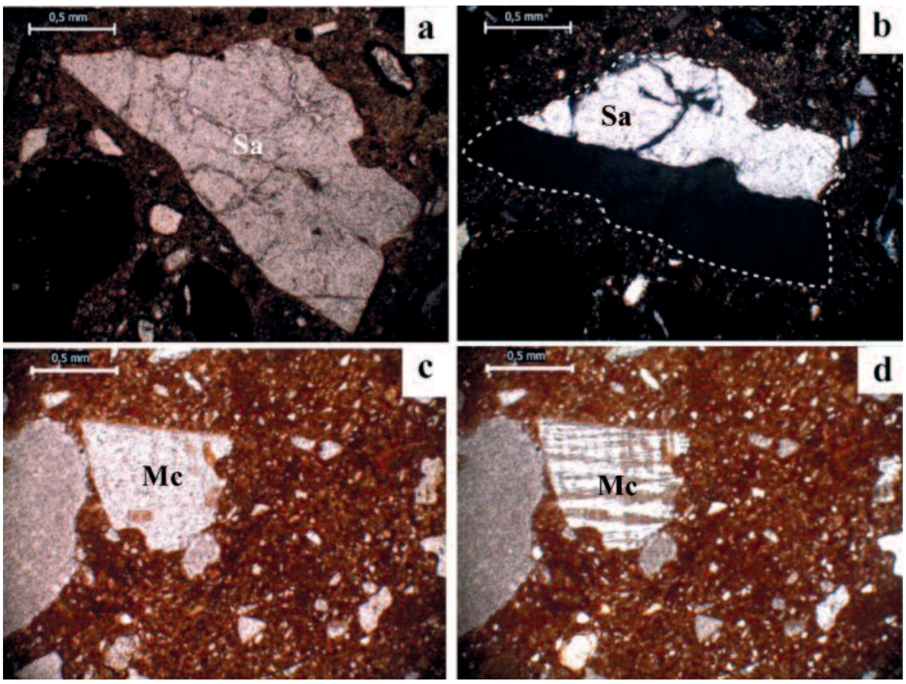


**Figure 2.-** a) Plane-polarised light image of subhedral sanidine with irregular edges in the welded tuffs; b) Crossed polars image of typical Carlsbad twinning in sanidine; c) microcline with irregular edges under plane- polarised light; d) crossed polars image of crosshatched twinning in the microcline

original fabric of the rock show signs of devitrification which led to the formation of ultrafine felsic textures.

Based on the grains size and mineralogical composition, the second group of welded pyroclastites was classified as lapilli crystal tuffs. This group is characterised by a porphyroclastic texture with a general relationship of 70 % phenocrysts and 30 % matrix. Similar to the lithic tuffs, the main components were identified as quartz (15 % by volume), sanidine (20 %) and ubiquitous opaque minerals (15 %). The quartz is represented by euhedrals to anhedral grains often showing embayment and irregular outlines. Crystals (up to 2 mm in diameter) are sometimes broken or cut by subparallel fractures filled with ultrafine matrix minerals and iron oxides. About 10 % of the fragments correspond to red-blackish pyroclasts (up to 2.5 mm in diameter) which comprise anhedral quartz and subhedral zircon within an iron-oxides dominated groundmass (Fig. 3a, b). In addition, the vitroclastic fraction (~ 10 %) is mainly characterised by highly deformed and coalescent pumices with their borders replaced by iron oxides. Some pumices also display axiolitic intergrowths radiating from quartz and feldspar (Fig. 3c, d).

*Non-welded Tuffs*

Geological mapping indicates that non-welded crystal tuffs are ubiquitous on the eastern margin of the study site along the rivers Agua de Las Piedras and Seco. The somewhat friable nature of these rocks enhances erosion rates and consequently reduces the likelihood of preservation near the surface. The mineralogy of these deposits reflects a rhyolite to alkali composition.

These tuffs beds generally extend in an East-West direction, dipping about 10º to the South. The units exhibit a crude layering with fine to very fine grains and are moderately to well sorted. Pore spaces sometimes contain abundant carbonates that post-date the tuffs deposition. Microscope observations reveal a matrix-supported porphyroclastic texture with an approximate composition of 60 % matrix and 40 % phenocrysts. The fine microcrystalline groundmass and the abundance of iron oxides make identification of minerals in thin sections problematic. However, the primary constituents of the non-welded crystal tuffs have been estimated as quartz (10 %), sanidine (10 %) and plagioclases (~5 %). Accessories include muscovite and biotite (5 %), opaques (5 %) and ubiquitous cognate lithoclasts (Fig. 4a, b). Quartz phenocrysts vary from subhedral to anhedral, are faintly fragmental and have poorly defined cribated contacts. Similarly, sanidine and plagioclases form subhedral to locally anhedral crystals and may exhibit polysynthetic twinning due to deformation. Biotite occurs in minor amounts commonly displaying a pleochroism from pale to dark brown, which might be attributed to the release of structural iron. Both muscovite and biotite are seen to be imbricated with occasional signs of flexuration (Fig. 4c).

Cognate lithic fragments are generally up to 2 mm in size and mostly related to iron oxides. The lithoclasts exhibit a pyroclastic texture with crystals of anhedral quartz embedded in an ultrafine groundmass, with a high content of opaques. Finally, it is important to note that this unit contains abundant microbreccias with jaspilite-type as cement or as voids infill. Fine-grained calcite cuts across the jaspilite, which indicates that it was deposited at a later stage (Fig. 4d).

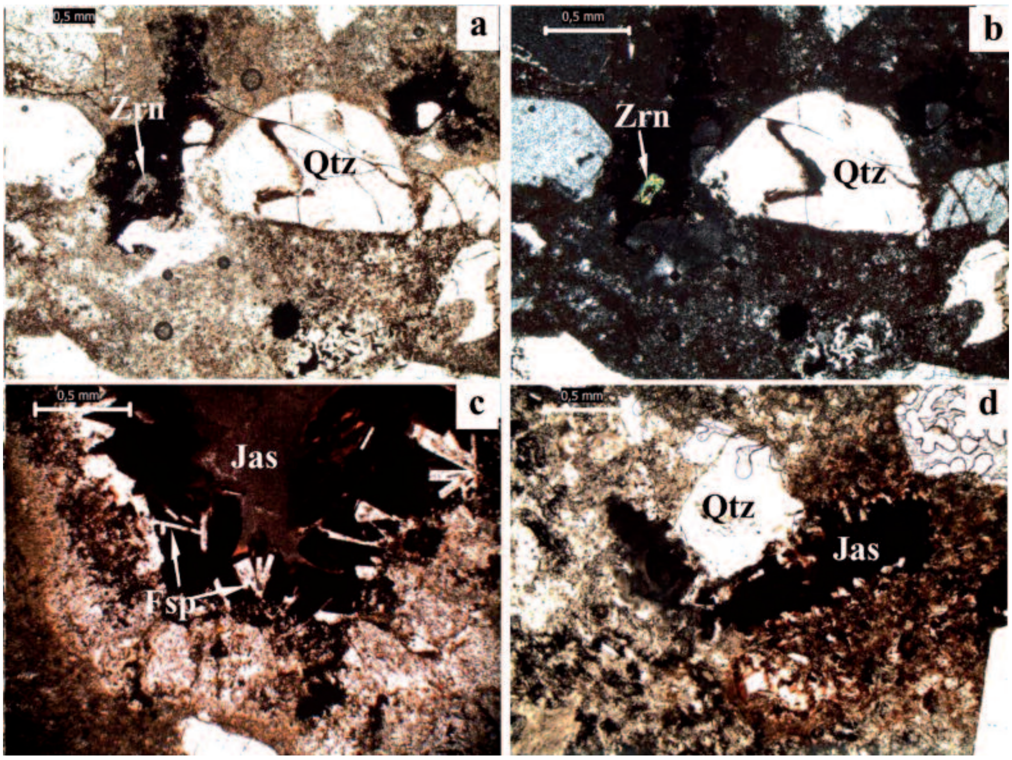


**Figure 3.-** a) Plane-polarised light image of quartz and subhedral zircon in a finer grain groundmass including deformed pumices; b) Crossed polars image of 3a, with signs of devitrification; c) Plane-polar light image showing axiolitic texture of feldspar and quartz along the walls of an open space; d) Jaspilite within distorted pumices (plane-polarised light)

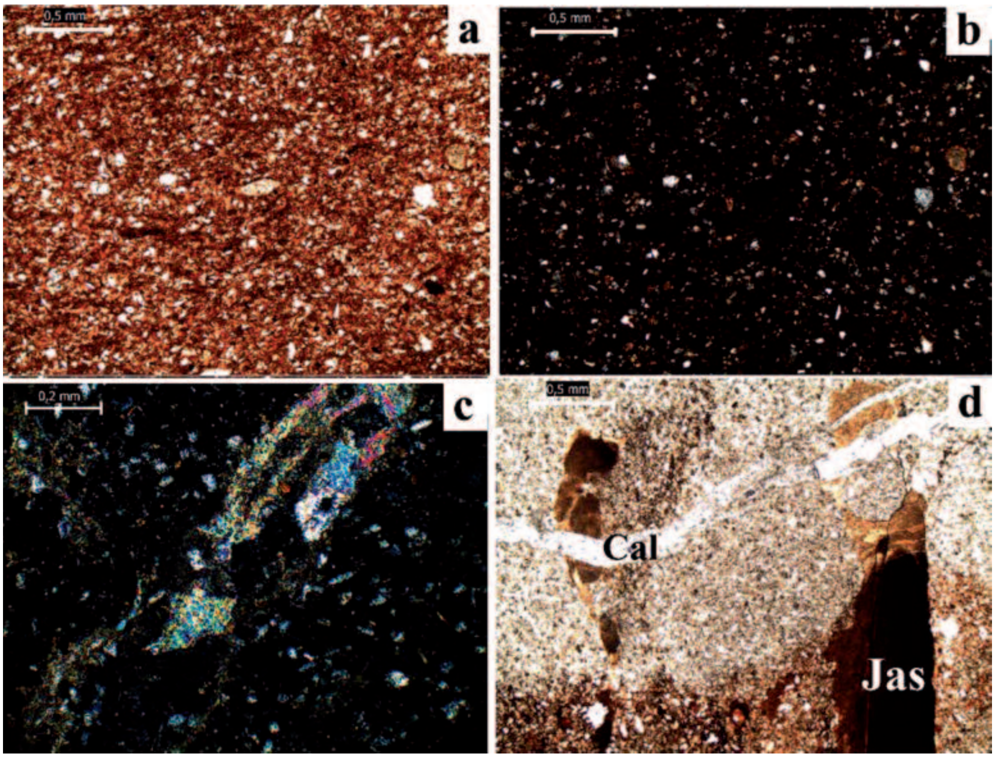


**Figure 4.-** a) Crossed polar image of unwelded tuffs, showing phenocryst of quartz and feldspar in a fine groundmass; b) Plane polarised light image of 4a; c) Crossed polar photo showing imbricated muscovite and biotite dispersed within the matrix; d) Plane-polarised light image showing calcite veinlets cutting the jaspilite.

*Geochemical Analysis*

Geochemical analysis was performed on both welded and non-welded tuffs from the Cerro Varela Formation (Appendix I).

On the basis of the silica vs. total alkalis (TAS) criterion of Middlemost (1994), all samples are sub-alkaline with a strong rhyolite composition (Fig. 5). The felsic character of the rocks is also indicated by the relationship $SiO_2$ vs. $TiO_2$ according to Winchester and Floyd (1977). In this regard, all the samples plot as rhyolite-dacite, with the exception of one specimen (V6) which plots close to a rhyodacite – dacite with almost 70 % of silica. A predominant rhyolitic composition is therefore consistent with the mineralogy observed under microscope. Furthermore, Figure 6 shows that all the rocks can be incorporated in the rhyolite field which is associated with high potassium. As the samples all plot within a cluster in the same field within the diagram, this indicates limited compositional variations in terms of immobile trace elements. The Co-Th diagram was designed as a proxy for the standard $K_2O$ – $SiO_2$ used for unaltered rocks and enables further insight into the composition of altered tuffs.

All samples appear to be a part of a transition across the Sierra of Varela, with calc-alkaline, low-K rocks in the east (samples V1, V2, V4, V6), to shoshonitic lapilli crystal tuffs (V3, V71, V10a) in the west. Based on the Y+Nb/Rb plot of Pearce et al. (1984), it is observed that the first group of samples would be associated with the volcanic arc environment, whilst K-rich samples V3, V71 and V10a present affinity with an intraplate continental setting (Fig. 7). Normalising the samples according to the values proposed by Sun and McDonough (1989) for OIBs (Ocean Island Basalts) indicates a contrast between less differentiated tuffs to the east and rocks with higher fractionation to the west (Fig. 8a). The welded crystal tuffs (V3, 71, V10a) are particularly depleted in Ti, which along with negative anomalies in P and Sr can be ascribed to the effects of continental crust melt. This is typical of the intraplate granites type-A described by Condie (1989). In contrast the depletion of Ba, Nb and Sr for the remaining rocks would be typical of a volcanic arc environment.

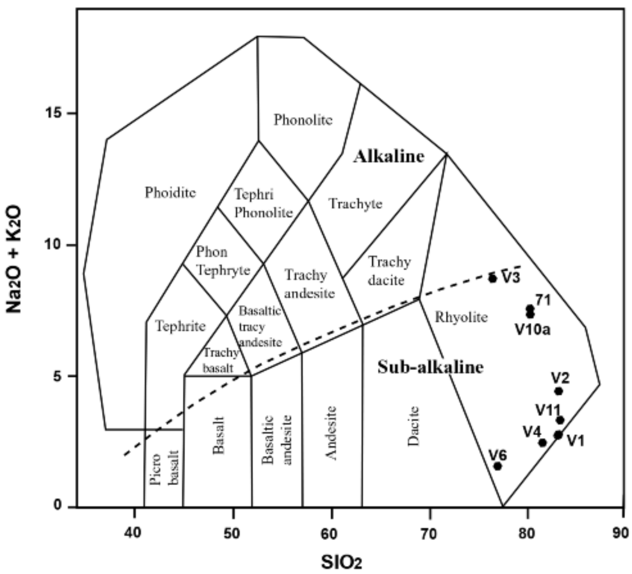


**Figure 5.-** Total alkali-silica (TAS) diagram for the pyroclastites of the Cerro Varela formation.

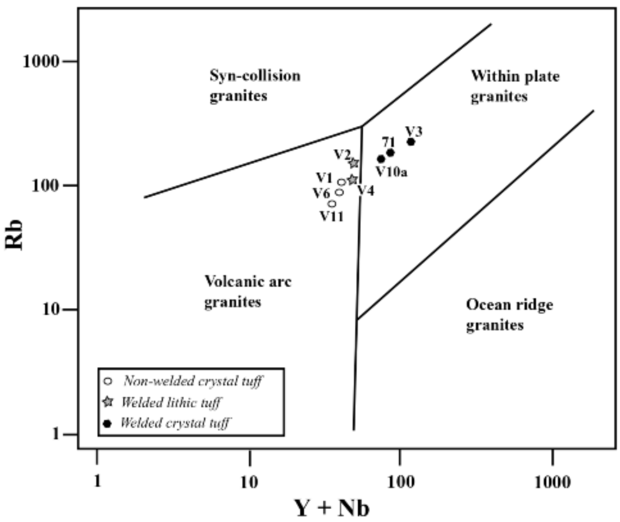


**Figure 6.-** Y+Nb vs Rb after Pearce et al. (1984) showing both the volcanic arc and intraplate character of the studied rocks.

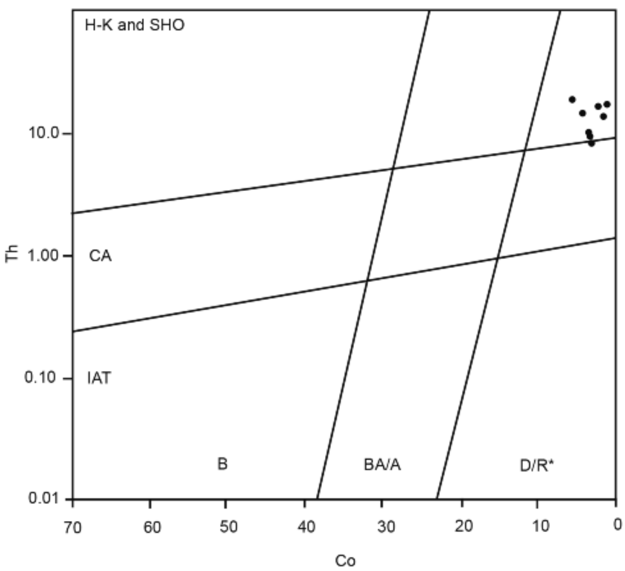


**Figure 7.-** Diagram of Hastie (2007) for the vulcanites of the Sierra de Varela. B: basalts; BA/A: basaltic andesites and andesites; D/R*: dacites and rhyolites*; IAT: island arc tholeiites; CA: calc alkaline series; H-K and SHO: high calc alkaline and shoshonitic series.

Chondrite-normalised rare element (REE) patterns for the samples of the Cerro Varela Formation support the hypothesis of two rock populations with distinctive sources and petrogenic history (Fig. 8b). The first group is coincident with the calc-alkaline series and is characterised by a slight declining trend in light rare earth elements (LREE) and relative uniformity for the high rare earth elements (HREE). These rocks are also characterised by a low Eu anomaly (Eu/Eu*: 0.18). In contrast, samples V10a and especially V71 define a second group of shoshonitic tuffs enriched in LREE and exhibiting a notorious depletion of europium (Eu/Eu*: 2.07). The europium anomaly can therefore be used as an indication of the amount of fractionation that magma has undergone. The HREE pattern is flat suggesting a plagioclase fractionation from a low-pressure magmatic source (Kay et al., 1991). In this context, the variability in the tuffs' $K_2O$ content could be attributed to their formation under a crust of average thickness (~30 km) in a magmatic arc within a convergent plate boundary. This setting would be transitional to a rifting, alkali-dominated continental environment where a second group of rocks highly depleted in Eu would have formed in a thin crust subject to lower pressures.

## Discussion

Compositional data in combination with petrographic analysis permit to make further inferences about the tectonic environment of the Cerro Varela rocks.

The rhyolitic composition of the rocks, along with their calc-alkaline to alkaline magma signature, indicates that the studied units are the result of pyroclastic flows associated with the collapse of an eruption column in a high-energy Plinian explosion. The collapse of the eruption column is understood to occur due to an exhaustion of its upward momentum (Sparks and Wilson, 1976; Kaminski and Jaupart, 2001).

In line with typical characteristics of the ignimbrites, sediments of the Cerro Varela Formation are poorly sorted and have crude to indistinct stratification. This can be explained as a result of a dense and poorly expanded flow, together with the gravitational settling of particles. Poor sorting in ignimbrites is attributed to high particle concentrations in a laminar flow, not turbulence (Sparks, 1976). The eutaxic fabric, deformed vitroclasts and the subparallel arrangement of biotite flakes in the groundmass provide further evidence for pyroclastic flows as the source of the sedimentation in the area. In addition, the well developed oblique and parallel cleavage in the quartz crystals can be interpreted as shear deformation during the transport process (Fisher and Schminke, 1984). In this regard, Sparks et al (1973) distinguished three layers in a typical section of pyroclastic flow deposits:

*layer 1*, which corresponds to the dilute surge preceding the main flow;

*layer 2*, the deposit of the main flow and;

*layer 3*, an ash-fall deposit at the end of the pulse.

Layer 2 forms the pyroclastic-flow deposit sensu stricto and was further subdivided into layer 2a, a coarse-depleted basal layer and layer 2b, the main flow (Legros and Marti, 2001). Based on the textural and petrographic characteristics described above, the highly vitrified ignimbrites of the Cerro Varela are considered to be equivalent to the coarser main unit of a pyroclastic flow (layer 2b).

Non-welded tuffs with a low proportion of phenocrysts would be part of the end member deposits in distal parts of the ignimbrite flow. As transport proceeds in medial to distal runout, the rheological characteristics of the flow evolve becoming less able to abrade substrate and entrain material. Pumice rich portions are moved to the margins and distal parts of the flow so that distal deposits are lithic poor and non-erosive (Calder et al., 2000). Thus, the fine-grained non-welded beds of the area of study are interpreted as ash sediments suspended by the wind or derived by

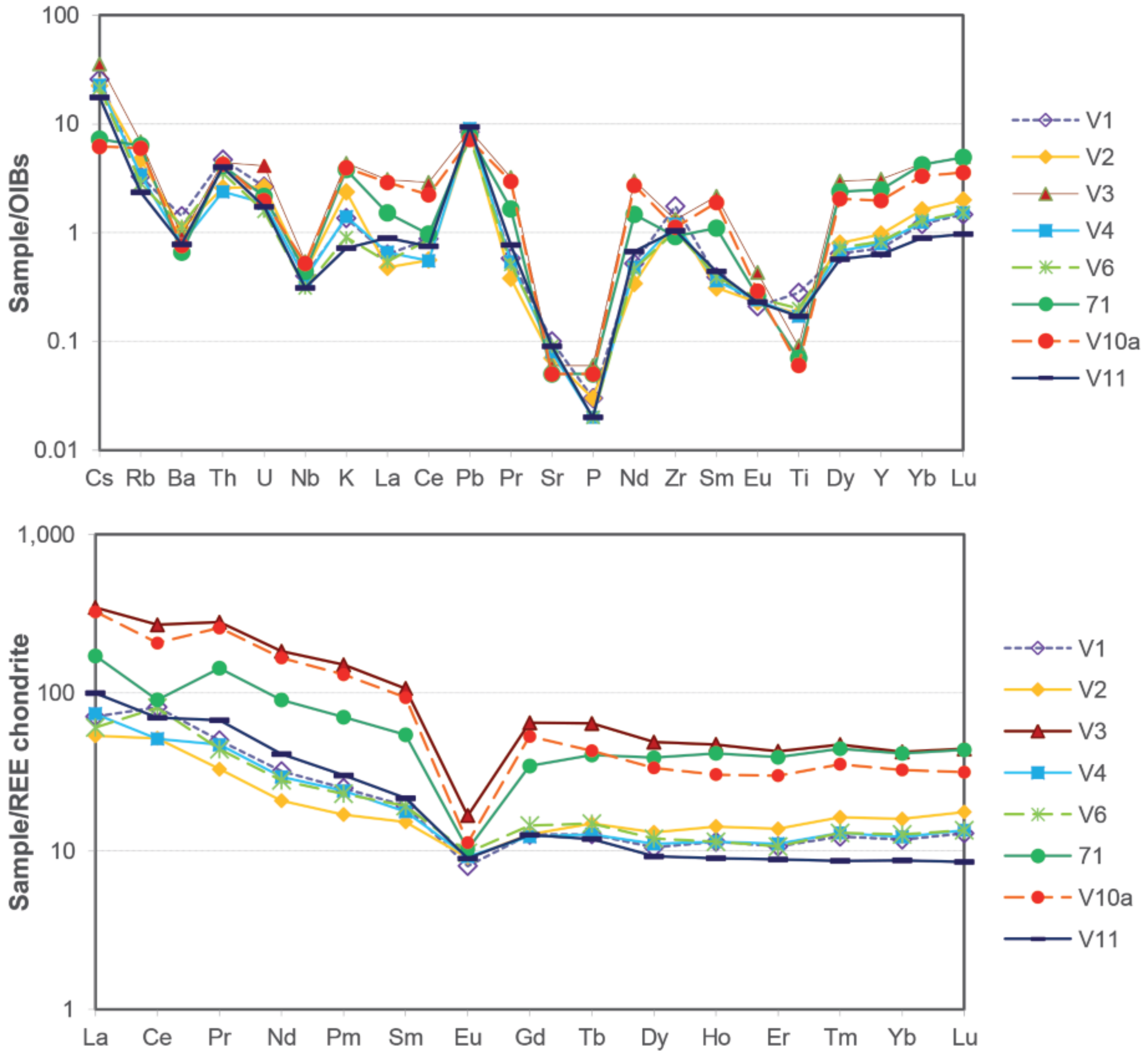


**Figure 8.-** a) Mantle-normalised trace element plot (after Sun and McDonough, 1989). Samples can be discriminated in two groups based on negative anomalies of Ti, P (continental setting) and Ba, Nb and Sr (volcanic arc); b) Chondrite-normalised rare earth elements patterns (Nakamura, 1974) for the investigated tuffs.

elutriation from the ignimbrite flow which subsequently settled as fallout at the end of the pulse. These facies would correspond to the layer 3b of the system described by Sparks et al., (1973), a pyroclastic air-fall deposit depleted in lithics and crystal fragments above the flow unit (Sheridan, 1979).

The emplacement of the tuffs in the Sierra de Varela would follow a similar pattern to the progressive aggradation model proposed by Branney and Kokelaar (1997). This model assumes that in areas of crustal extension, the paleotopography of the basement (controlled by successive tilted fault blocks and scarps) determines the character and geometry of the pyroclastic deposits. Thus, thick massive ignimbrites would accumulate in valleys proximal to the eruption centre while on topographic highs the net rate of deposition would be much lower and/or the onset of deposition would be significantly delayed. This downcurrent transport of selected clast types produces a decrease in clast density with distance from dense constituents in the proximal breccia to low density pumice and ash in distal ignimbrites (Wright and Walker, 1981).

The deposits of the study area closely resemble and are therefore correlated to the final stages (Late Permian – Late Triassic) of the Choiyoi magmatism in the Cordillera Frontal of Mendoza and San Juan. This period was characterised by the formation of extensional basins that led to block faulting and magma ascent and the consequent deposition of terrigenous sediments and pyroclastites from concomitant vulcanism. Low contents of hydrated minerals such as amphiboles and biotite suggest that the pyroclastic flows evolved from a dry parental magma (Martinez, 2004). Therefore, the compositional zonation of the Cerro Varela Formation could be explained as syn-rift infilling with denser basal deposits evolving into welded tuffs in half-graben depressions, whilst fine-ash fallout deposited more widely over the terrain to generate the non-welded tuffs.

## Conclusions

The petrographical and geochemical data presented in this study enabled a more detailed characterisation of pyroclastic deposits in the Sierra de Varela and provided new insights about the Permo-Triassic magmatism in the mid-west of Argentina.

Thin sections of selected samples led to the recognition of two main type deposits of rhyolitic composition; highly welded tuffs and non-welded tuffs. Minor breccia with abundant blocks of welded/glassy tuffs and lithics were also mapped in a few isolated outcrops. These breccias might be co-ignimbrite deposits in proximity to the eruption vent. The bulk of the sequence is believed to have evolved from a high-energy flow that followed a felsic Plinian eruption. The dense pyroclastic current would have first deposited massive to poorly bedded clast-supported sediments composed of varying proportions of felsic and lithic fragments. As the flow momentum subdued, pumice and ash would have been accumulated in suspension as a consequence of fallout overlying the basal deposits.

The tuffs showed distinctive geochemical signature on a set of trace-elements diagrams. Differences between calc-alkaline and alkali groups suggest that rocks in the Sierra de Varela would have been emplaced in a convergent boundary transitioning towards an intraplate setting. The magmas developed at this stage would have developed an alkali character. Additionally, the bimodal characteristics of the rocks assemblage could be interpreted either as two pulses within the same volcanic event, or as the result of independent eruptions.

It is estimated that the deposition and distribution of pyroclastites was influenced by the tectonic features of the basin. Thus, the basal layers of tuff would have accumulated in valleys and depressions constrained by half-grabens, unlike non-welded beds which would have been widely deposited as ash-fall at the end of the flow pulse.

This work represents a pioneering approach to further assess the Gondwana magmatism and the extent of the Choiyoi Group of central Argentina. It also provides the basis for future studies in the region of San Luis. Further work is necessary to validate the proposed interpretations of the ignimbrite-generating events and to better define the tectonic evolution of the region.

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**APPENDIX I.**

Major and trace elements for the tuffs in the study area

| | | Non-welded tuffs | | | Welded tuffs | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Crystal | | | Lithic | | Crystal | | |
| | | V1 | V6 | V11 | V2 | V4 | V3 | 71 | V10a |
| Major % | $SiO_2$ | 77.0 | 68.6 | 75.0 | 77.9 | 73.4 | 73.2 | 77.9 | 75.9 |
| | $Al2O_3$ | 10.6 | 15.9 | 13.2 | 10.7 | 11.6 | 13.2 | 11.6 | 11.5 |
| | $Fe_2O_3$ (T) | 3.3 | 3.4 | 3.4 | 3.0 | 3.5 | 3.3 | 2.2 | 2.9 |
| | MnO | 0.031 | 0.031 | 0.01 | 0.055 | 0.03 | 0.014 | 0.009 | 0.02 |
| | MgO | 0.3 | 0.4 | 0.5 | 0.3 | 0.3 | 0.05 | 0.04 | 0.11 |
| | CaO | 1.1 | 1.7 | 0.6 | 0.3 | 1.5 | 0.4 | 0.2 | 0.2 |
| | $Na_2O$ | 0.6 | 0.1 | 0.1 | 0.6 | 0.3 | 2.1 | 1.8 | 1.3 |
| | $K_2O$ | 2.0 | 1.3 | 1.0 | 3.4 | 2.0 | 6.3 | 5.5 | 5.7 |
| | $TiO_2$ | 0.8 | 0.6 | 0.5 | 0.5 | 0.5 | 0.2 | 0.2 | 0.2 |
| | $P_2O_5$ | 0.02 | 0.01 | 0.01 | 0.02 | 0.01 | 0.04 | 0.03 | 0.03 |
| | LOI | 5.0 | 7.8 | 4.9 | 3.2 | 5.2 | 1.5 | 1.3 | 1.3 |
| | Total | 100.6 | 99.9 | 99.5 | 100.1 | 98.2 | 100.4 | 100.7 | 99.3 |
| Traces ppm | Sc | 12 | 13 | 9 | 6 | 5 | 5 | 4 | 4 |
| | Be | 2 | 4 | - | 4 | 3 | 5 | 3 | - |
| | V | 74 | 61 | 96 | 59 | 58 | 19 | 11 | 16 |
| | Cr | 30 | - | 120 | - | 60 | - | 70 | - |
| | Co | 5 | 4 | 2 | 3 | 3 | 1 | 1 | 1 |
| | Cu | 40 | - | 8 | 20 | - | 10 | 20 | 7 |
| | Zn | 40 | 40 | 38 | 70 | 50 | 30 | - | 28 |
| | Ga | 13 | 18 | 21 | 18 | 19 | 25 | 21 | 24 |
| | Ge | 2 | 2 | 5 | 2 | 3 | 3 | 2 | - |
| | As | 18 | - | 6 | - | - | - | - | 4.9 |
| | Rb | 102 | 88 | 73.5 | 146 | 105 | 212 | 196 | 185 |
| | Sr | 63 | 59 | 57 | 47 | 56 | 41 | 36 | 35.9 |
| | Y | 21 | 24 | 18 | 28 | 23 | 90 | 72 | 57 |
| | Zr | 489 | 289 | 291 | 358 | 336 | 369 | 258 | 315 |
| | Nb | 19 | 15 | 15 | 21 | 18 | 26 | 21 | 25.1 |
| | Mo | - | - | 1 | - | 5 | - | 7 | 1 |
| | Ag | 1.2 | 0.8 | 0.5 | 0.9 | 0.9 | 0.9 | 0.7 | 0.5 |
| | Sn | 4 | 4 | 4 | 6 | 4 | 5 | 8 | 4 |
| | Sb | 1.4 | 0.9 | 0.4 | 1 | 1 | 0.5 | 0.5 | 0.2 |
| | Cs | 10 | 8.3 | 6.8 | 8.7 | 8.8 | 13.8 | 2.8 | 2.4 |
| | Ba | 497 | 401 | 273 | 379 | 278 | 329 | 231 | 267 |
| | Hf | 10.2 | 7.4 | 7.2 | 9.4 | 8.6 | 10.1 | 7.7 | 9.7 |
| | Ta | 1.2 | 1 | 1.2 | 1.2 | 1.1 | 1.4 | 1.3 | 1.5 |
| | W | 2 | 1 | 3 | 3 | 3 | 2 | 2 | 3 |
| | Tl | 0.6 | 0.4 | 0.2 | 0.7 | 0.5 | 0.8 | 0.6 | 0.04 |
| | Pb | 27 | 24 | 30 | 27 | 29 | 28 | 25 | 23 |
| | Th | 18.8 | 14.2 | 16 | 10.3 | 9.5 | 17.7 | 16.6 | 17 |
| | U | 2.7 | 1.6 | 1.8 | 2.7 | 1.9 | 4.2 | 2.2 | 2.0 |

| | | Non-welded tuffs | | | Welded tuffs | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Crystal | | | Lithic | | Crystal | | |
| | | **V1** | **V6** | **V11** | **V2** | **V4** | **V3** | **71** | **V10a** |
| **REE ppm** | La | 23.3 | 19.9 | 32.8 | 17.6 | 24.3 | 114 | 56.3 | 107 |
| | Ce | 70.2 | 69.5 | 60.1 | 44.6 | 44.2 | 232 | 78 | 178 |
| | Pr | 5.6 | 4.9 | 7.5 | 3.7 | 5.3 | 31.2 | 16 | 28.7 |
| | Nd | 20.1 | 17.6 | 25.8 | 13.1 | 18.5 | 115 | 56.7 | 104.5 |
| | Sm | 3.9 | 3.9 | 4.3 | 3.1 | 3.6 | 21.6 | 11 | 18.9 |
| | Eu | 0.6 | 0.8 | 0.7 | 0.7 | 0.7 | 1.3 | 0.8 | 0.8 |
| | Gd | 3.5 | 4 | 3.5 | 3.5 | 3.4 | 17.8 | 9.5 | 14.6 |
| | Tb | 0.6 | 0.7 | 0.6 | 0.7 | 0.6 | 3 | 1.9 | 2.0 |
| | Dy | 3.6 | 4.1 | 3.2 | 4.5 | 3.8 | 16.7 | 13.3 | 11.5 |
| | Ho | 0.8 | 0.8 | 0.6 | 1 | 0.8 | 3.3 | 2.9 | 2.1 |
| | Er | 2.4 | 2.4 | 1.9 | 3.1 | 2.4 | 9.6 | 8.8 | 6.7 |
| | Tm | 0.4 | 0.4 | 0.3 | 0.5 | 0.4 | 1.4 | 1.3 | 1.1 |
| | Yb | 2.6 | 2.8 | 1.9 | 3.5 | 2.8 | 9.3 | 9.1 | 7.2 |
| | Lu | 0.4 | 0.5 | 0.3 | 0.6 | 0.5 | 1.5 | 1.5 | 1.1 |