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RESEARCH ARTICLE

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The 322 ka Tiribí Tuff: stratigraphy, geochronology and mechanisms of deposition of the largest and most recent ignimbrite in the Valle Central, Costa Rica

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Abstract The Tiribí Tuff covered much of the Valle Central of Costa Rica, currently the most densely populated area in the country (~2.4 million inhabitants). Underlying the tuff, there is a related well-sorted pumice deposit, the Tibás Pumice Layer. Based on macroscopic characteristics of the rocks, we distinguish two main facies in the Tiribí Tuff in correlation to the differences in welding, devitrification, grain size, and abundance of pumice and lithic fragments. The Valle Central facies consists of an ignimbritic plateau of non-welded to welded deposits within the Valle Central basin and the Orotina facies is a gray to light-bluish gray, densely to partially welded rock, with yellowish and black pumice fragments cropping out mainly at the Grande de Tárcoles River Gorge and Orotina plain. This high-aspect ratio ignimbrite (1:920 or 1.1×10^{-3}) covered an area of at least 820 km^2 with a long runout of 80 km and a minimum volume outflow of 25 km^3 (15 km^3 DRE). Geochemically, the tuff shows a wide range of compositions from basaltic-andesites to rhyolites, but trachyandesites are predominant. Replicate new $^{40}Ar/^{39}Ar$ age determinations indicate that widespread exposures of this tuff represent a single ignimbrite that was erupted 322±2 ka. The inferred source is the Barva Caldera, as interpreted from isopach and isopleth maps, contours of the ignimbrite top and geochemical correlation (~10 km in diameter). The Tiribí Tuff caldera-forming eruption is interpreted as having evolved from a plinian eruption, during which the widespread basal pumice fall was deposited, followed by fountaining pyroclastic flows. In the SW part of the Valle Central, the ignimbrite flowed into a narrow canyon, which might have acted as a pseudo-barrier, reflecting the flow back towards the source and thus thickening the deposits that were filling the Valle Central depression. The variable welding patterns are interpreted to be a result of the lithostatic load and the influence of the content and size of lithic fragments.

Keywords Tiribí Tuff · Ignimbrite · Welding facies · Channelized · $^{40}Ar/^{39}Ar$ geochronology · Barva caldera · Costa Rica

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Introduction

The Valle Central (Central Valley) in central Costa Rica, a volcanic plateau underlain mainly by the Tiribí Tuff, constitutes the most densely populated area of the country, hosting more than 2.4 million people. Until now, little was known about stratigraphy, precise age, source area, transport and, depositional characteristics of this tuff.

Since it forms terraces that have been displaced by active faults, the Tiribí Tuff is important for its implications in the volcanic history of the region and its utility in neotectonic studies (Borgia et al. 1990; Marshall et al. 2003). Also, due to its relatively low-permeability, the Tiribí Tuff protects the Valle Central aquifers, located in the underlying Colima lavas (Fernández 1968; Echandi 1981), from urban contamination. It also is an important source of construction and road aggregate producing about 1.9 million tons of aggregates per year (Berrangé et al. 1990).

Despite its economic and scientific importance, as well as the presence of well-exposed artificial and natural outcrops, there have been virtually no studies on its eruptive and emplacement history, and a precise age has not been firmly established.

This work, which focuses on stratigraphic and geochronologic aspects of the Tiribí Tuff, complements a geochemical and petrological study made by Hannah et al. (2002). The Tiribí Tuff comprises pyroclastic deposits that crop out in the lower SW flanks of Barva volcano, in deep gorges into the Valle Central plateau, and distal exposures along the Grande de Tárcoles River, including the Orotina plain near the Pacific coast (Fig. 1). We use the term "Tiribí Tuff" to denote only the youngest and most widespread of the Valle Central ignimbrites, which is part of the Tiribí Formation of Fernández (1968) and Echandi (1981) or of what has been also referred to as "Glowing Avalanche Deposits" by other authors (Williams 1952; Kussmaul and Sprechmann 1982). Several older ignimbrites have also been identified in the Valle Central region and are described elsewhere (Gans et al. 2003; Vogel et al. 2004).

The main purpose of this investigation is to clarify the eruptive and transport history of this unit, which constitutes perhaps the most explosive pyroclastic event of central Costa Rica. In addition, we present the results of a detailed $^{40}Ar/^{39}Ar$ dating investigation of the tuff and units directly underlying and overlying it. We also describe the interaction of a widespread ignimbrite with a variable forested area and determine the effect of a canyon system during a rapid aggradation of an ignimbrite deposit. Finally, based on geological and geomorphological mapping, contours of the height of the top, isopleth and isopach maps, as well as geochemical and geochronological analyses, we propose that the Barva caldera was the source of this ignimbrite.

Methods

The Tiribí Tuff, as well as the overlying and underlying volcanic units of the Valle Central and Cordillera Central, were examined in detail at 76 localities and 7 boreholes, in an area of about 900 km^2. Sizes of the five largest fragments (pumice and lithic), percentage of components (ash to block/bomb size, juvenile and lithic fragments) and thickness were measured. In addition to the outcrops and boreholes examined, we also used the well logs of 233 water-supply boreholes from the database of the SENARA (National Service of Waters, Irrigation and Draining) to determine thickness and locate the top of this unit. Isopach and ignimbrite top-height maps, as well as lithic and juvenile-fragment isopleth maps, were made for the Tiribí Tuff in order to assess its volume and source area. Bulk densities of whole-rock and juvenile fragments were measured in the laboratory. Petrographic examination of 50 samples from a broad spectrum of positions in the tuff were conducted to document lateral and vertical variations in the modal mineralogy and textural characteristics. Seven samples from widely separated sections of the tuff, representing the entire range of facies, were dated by the $^{40}Ar/^{39}Ar$ method, using both step heating and total-fusion experiments on high-purity plagioclase separates to establish its precise age.

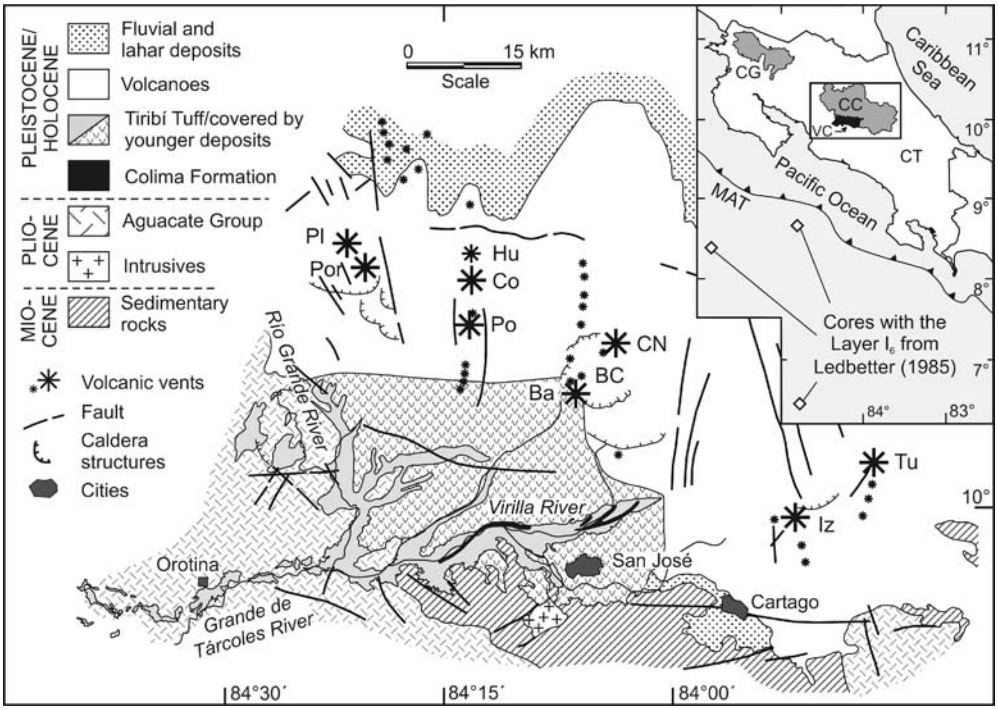


Fig. 1 Geologic map of the Valle Central and Cordillera Central, including volcanic structures and faults. The Tiribí Tuff is exposed mainly along the canyons of the Virilla and Grande de Tárcoles rivers, while in the southwestern slope of Barva volcano, it is shown only in the area where it has been detected in water-supply boreholes. The inset shows the location of Ledbetter (1985) piston cores where the layer I_6 was found (correlated with the Tiribí Tuff). *MAT* Middle America Trench, *CC* Cordillera Central, *VC* Valle Central, *CG* Cordillera de Guanacaste, *CT* Cordillera de Talamanca, *Pl* Platanar volcano, *Por* Porvenir volcano, *Po* Poás volcano, *Co* Congo volcano, *Hu* Hule Maar, *Ba* Barva volcano, *BC* Barva Caldera, *CN* Cacho Negro volcano, *Iz* Irazú volcano, *Tu* Turrialba volcano

Geological setting

Since at least 80 Ma, Costa Rica, located on the Central America isthmus, hosts a mature volcanic arc formed as the result of the subduction of the Cocos Plate beneath the Caribbean Plate (Alvarado et al. 1992; Tournon and Alvarado 1997). Subduction of the Cocos Plate is responsible for active volcanism in Costa Rica, mainly in northern and central Costa Rica (Cordillera de Guanacaste and Cordillera Central). The Cordillera Central has been built up by several andesitic shield volcanoes and stratovolcanoes, some of which have erupted during historical time (e.g., Poás, Irazú and Turrialba), and Holocene time (e.g., Hule and Barva; Fig. 1).

The Valle Central is an elongated volcanic plateau, 50 km long by 20 km wide, limited to the north by the Cordillera Central, and to the south by a Tertiary volcano-sedimentary range. Quaternary volcanic activity began around 1.0 Ma in the Cordillera Central, whose Middle Pleistocene history was characterized by alternating periods of andesitic effusive volcanism (constructional) and short-lived silicic pyroclastic eruptions (Alvarado et al. 1992; Gans et al. 2003).

Inside the Valle Central, the Tiribí Tuff commonly overlies brecciated andesitic lava flows of the Pleistocene Colima Formation (Echandi 1981; Kussmaul 1988), which are separated by a well-sorted trachytic pumice deposit, the Tibás Pumice Layer (see section Stratigraphy and facies distribution). To the south, the Tiribí Tuff overlies sedimentary Tertiary rocks and older local ignimbrites, and towards the western boundary it overlies older lava flows related to the Aguacate Group. At the Orotina plain, the Tiribí Tuff overlies sedimentary rocks of the Punta Carballo Formation, breccias of the Tivives Formation and ancient fluvial deposits. It is overlain by basaltic andesite lava flows (Barva Formation) at the southern slope of Barva volcano, debris flow and debris avalanche deposits at the easternmost area, and ash-fall deposits from Late Pleistocene-Holocene eruptions of active volcanoes.

Previous geologic studies of the Tiribí Tuff

The first study of these rocks was made by Romanes (1912), who interpreted them as banded lavas, sometimes brecciated and with columnar jointing. Alfaro (1913) was the first to recognize their fragmental and pyroclastic nature, while the German volcanologist K. Sapper (in Alfaro 1913) believed they were products of accumulation of volcanic material from the volcanic range. Dengo and Chaverri (1951) described the deposits as a volcanic tuff made up of pumice and scoriaceous blocks, elongated black glass in an ashy matrix. Williams (1952) described the deposits in great detail, and was the first to propose a pyroclastic flow origin, interpreting them as an extensive Mt. Pelée nuée ardente-type eruption. Fernández (1968) defined the Tiribí Formation and Echandi (1981) divided it into three members: Nuestro Amo, Electriona and La Caja, but Pérez (2000) found that the division in Electriona and La Caja Members corresponds with different degrees of welding, while Nuestro Amo Member is a non-related debris flow deposit. Kussmaul and Sprechmann (1982) suggested a new formal name of “Formación Depósitos de Avalancha Ardiente” (Glowing Avalanche Deposits Formation). Madrigal (1970) defined the Orotina Formation consisting of ignimbrites close to the Pacific coast. Marshall et al. (2003), based in geologic mapping, correlation columns and new ^{40}Ar/^{39}Ar dating, established that what they call “Snake Flow Member” of Orotina Formation can be traced from Orotina plain to the Valle Central, where it merges with the Tiribí Tuff. Geological mapping of the Tiribí Tuff was done by Madrigal (1970), Echandi (1981), Denyer and Arias (1991) and Tournon and Alvarado (1997), among others. The first chemical analysis was made by Schaufelberger in 1935 (Dengo and Chaverri 1951), and a detailed petrologic study was made by Hannah et al. (2002).

Characteristics of the Tiribí Tuff

The Tiribí Tuff is the most widespread, recent and well exposed ignimbrite in Central Costa Rica. The distribution of this moderate-grade tuff is established by morphological continuity from an extensive plateau gently dipping to the SW in the Valle Central to isolated small plateaus along the Grande de Tárcoles River Gorge and Orotina alluvial plain (Fig. 1).

The proximal deposits of the Tiribí Tuff are not accessible or exposed anywhere, the closest known outcrop is 13 km SW of Barva volcano, the inferred source (see section Source of the ignimbrite). In the outcrops inside the Valle Central, the ignimbrite is usually presented as a massive indurated non-welded tuff with an increasing degree of welding toward the bottom, especially where the tuff fills in paleodepressions. The upper, non-welded portion of the ignimbrite is poorly sorted and consists of 5–20 vol% lapilli or bombs of black, gray, white, and banded pumices, commonly with a bulk density of 1.2 g cm^{-3} to 1.5 g cm^{-3}, 1–5 vol% of lithic fragments, varying in diameter from 40 cm to ≤1 cm and dominated by andesitic lavas (most are similar to the Colima Formation lavas) with subordinate plutonic (gabbro) clasts. The clasts are set in an ashy matrix of broken crystals, glass shards and lithic fragments. The lowermost portions of the tuff are densely welded, with well-developed columnar jointing and eutaxitic texture with obsidian fiamme. The deposits at the Grande de Tárcoles River Gorge and Orotina plain are relatively thin sheets of a grayish light blue, moderately welded columnar devitrified ignimbrite, with scarce fiamme or yellowish elongated juvenile fragments, varying from 3 to 0.5 cm in size, and very few small (<2 mm) lithic fragments.

Geochemically, the tuff shows a wide range of compositions, but trachyandesite is the predominant composition. There are also more evolved rocks like trachytes and mafic compositions like basaltic-andesites and andesites. High emplacement temperatures are likely as shown by welding, granophyric crystallization, gas-escape structures, columnar jointing, and burned paleosols directly underlying the tuff.

Stratigraphy and facies distribution

Tibás Pumice Layer

In the eastern part of the Valle Central, there is a pumice deposit underlying the Tiribí Tuff, the Tibás Pumice Layer (Madrigal 1967; Echandi 1981). It is a 0.5–3 m thick, inversely graded deposit of white pumiceous lapilli and scarce andesite lithic fragments (<1 vol%). The deposit crops out mainly in quarries along the Virilla River Canyon and its tributaries and locally in some road cuts in the western part of the Valle Central, and was also found in water supply wells (Echandi 1981; Fig. 2). This pumice layer shows features more consistent with a primary fall origin, it mantles the topography (observed in extensive quarries), is inversely graded and well sorted. This layer locally shows cross-bedding at the base.

An estimate of the volume for the Tibás Pumice Layer is a difficult task, since it is covered by the thick Tiribí Tuff and outcrops only in a few quarries, mainly in the margins at Virilla River. In order to obtain a minimum volume for the Tibás Pumice Layer, we reconstructed and mapped the thickness over the known area. Although the isopach map is not well constrained (due to the lack of good exposures), it indicates that the source of the tephra was to the north, toward Barva volcano (Fig. 2). Extrapolating the isopachs to the Barva caldera and using the method of Pyle (1989), a bulk tephra volume for the Tibás Pumice Layer of about 0.6 km^3 (~0.3 km^3 dense rock equivalent, DRE) was estimated.

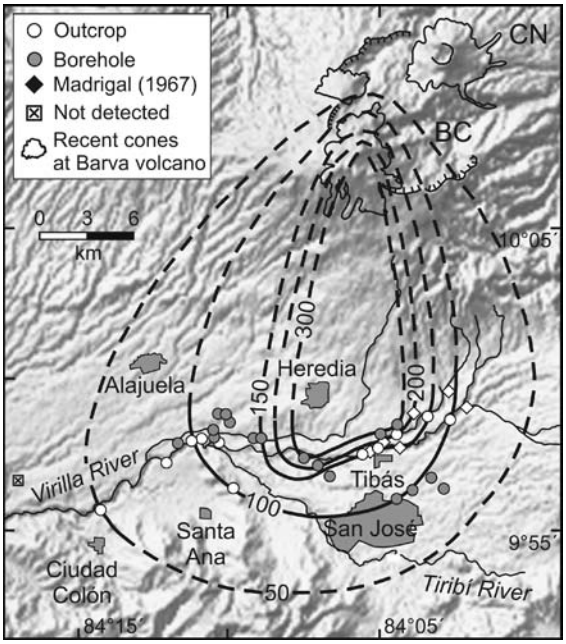


Fig. 2 Distribution and isopachs (in centimeters) of the Tibás Pumice Layer. Almost all of the localities where the thickness data were collected come from surroundings of the Virilla River and its tributaries. Discontinuous lines are used for the extrapolation of the isopachs to the Barva caldera

Pyroclastic flow deposits

Based on macroscopic lithologic characteristics of the rocks, we distinguish two main facies in the Tiribí Tuff: the Valle Central and the Orotina facies (Fig. 3). These facies also correspond with differences in welding degree, devitrification (Streck and Grunder 1995, McPhie et al. 1993), maximum grain size and abundance of pumice and lithic fragments. Moreover, lateral gradations from one lithofacies to the other have been observed in the same outcrop.

The Valle Central facies

The Valle Central facies is a non-welded to densely welded tuff exposed in the Valle Central basin. This facies exhibits great variation in degree of welding and associated textures, and accordingly can be subdivided into three zones: non-welded, intermediately welded and densely welded (Figs. 3, 4). These three zones can be present in one single exposure and the contact between them is gradational. The change from non-welded to welded ignimbrites corresponds with an average increase in density from around 1.2 to 2.4 g cm^{-3} (Fig. 4). There are also variations in the shape of the pumice fragments, from rounded to completely collapsed (strain ratio from 1 to 0.04, respectively); color of the whole rock, from bluish gray to black; as well as in luster (from opaque granular rock to a shiny vitric rock).

Non-welded This consists of a massive poorly sorted ignimbrite composed of non-deformed highly vesicular black (Fig. 5a), gray, white and banded pumice lapilli and lithic fragments, set in an ash matrix. It is usually present in the upper portions of the deposit with a thickness over 50 m.

Partially welded The partially welded portion presents normally as a compact bluish gray tuff with vitroclastic texture with flattened pumice fragments or fiamme with sizes ranging from 2 to 74 cm and a strain ratio from 0.15 to 0.40. Deformed and flattened colorless to brown glass shards are visible in thin section. Sometimes it shows slight devitrification, especially in the bluish gray tuffs similar to the Orotina distal facies.

Densely welded Found in the lower part of the tuff, in sites where the tuff is thicker because it had filled topographic lows or paleodepressions, this portion consists of a dense black vitrophyre (Fig. 5b) to a fiamme-rich pale-gray dense tuff, with a lithic content of 1–2%, well-developed columnar jointing and a maximum density of 2.35 g cm^{-3}.

At the NW margin of the Valle Central, in the vicinity of La Garita and Atenas (Fig. 3), two non-welded to slightly

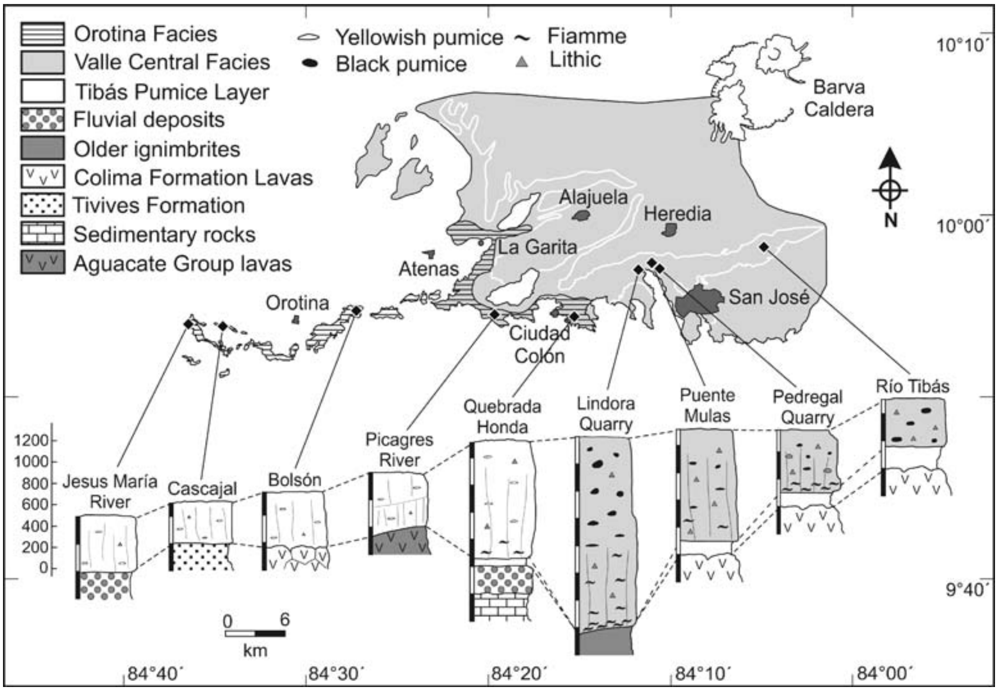
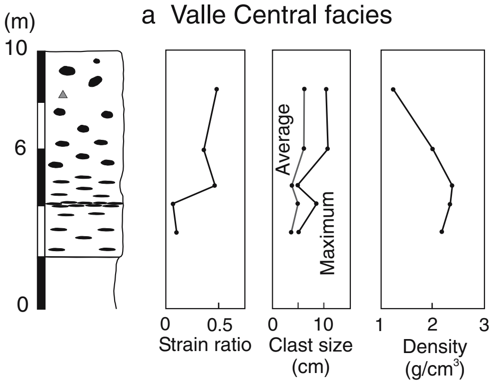


Fig. 3 Distribution of the Tiribí Tuff facies (Valle Central and Orotina), including an east–west correlation profile of localities inside the Valle Central and along the Grande de Tárcoles River Canyon. The different lithologies underlying the tuff are also shown

compacted units of the Tiribí Tuff crop out. It is coarse-grained and rich in black lapilli and bombs (20–150 cm size), with some white to gray lapilli. Here it is common to find large black pumice lumps (up to ~150 cm in diameter) concentrated mainly in the upper portions of the deposit. The lithic abundance ranges from 1 to 10%, with sizes ranging from 0.1 to 10 cm.

An immature epiclastic deposit lies between the two flow units, consisting of a clast-supported pumice gravel with a flat upper contact and an irregular lower contact. This unit lacks internal stratification but contains fines-depleted pumice swarms, lenses, and pods. These lenses are poorly sorted and consist mainly of rounded to sub-rounded pumice (black, banded and scarce white), 5–50 cm in diameter. Gas pipes come from these pumice-concentration zones and cross into the overlying ignimbrite, suggesting that the pumice-rich sediment was deposited hot (perhaps a hot debris flow) or that it was heated by the overlying ignimbrite.

a Valle Central facies



b Orotina facies

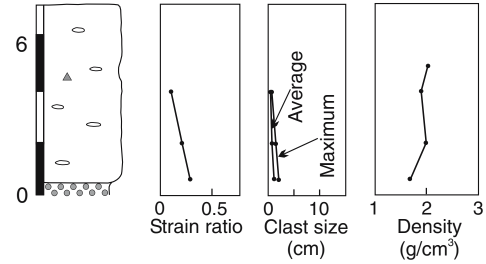


Fig. 4 Representative measured sections of the two facies, including the vertical variation in strain ratio, clast size (maximum and average) and density. The symbols used for the columns are the same as in Fig. 3. **a** Valle Central facies at the Ramírez-Crexpo quarry. Note that the lower half of the section shows the lowest strain ratios and higher densities. **b** Orotina facies at the Jesús María River in Orotina. The strain ratio and clast size decrease toward the top, whereas the density increases slightly

The Orotina facies

The Orotina facies is characterized by moderately welded, homogeneous and devitrified, light bluish-gray tuff, showing well to intermediate development of columnar jointing. It contains 1–5% fiamme and yellowish stretched pumices (strain ratio from ~0.10 to 0.40), as well as scarce lithic fragments (less than 1 vol% of the bulk deposit; Figs. 3, 4). The presence of fine-grained quartz, feldspar and sericite in a micropoikilitic texture, detected in thin sections, are evidence of devitrification (Fig. 5c, d).

Most of the distal finger-like deposits of Orotina facies flowed westward in the paleocanyon of the Grande de Tárcoles River, probably reaching the Pacific coast. The outcrop pattern of the ignimbrite inside the Grande de Tárcoles River Canyon consists of isolated plateaus, massive cliffs or small volcanic tables, as high as 60 m

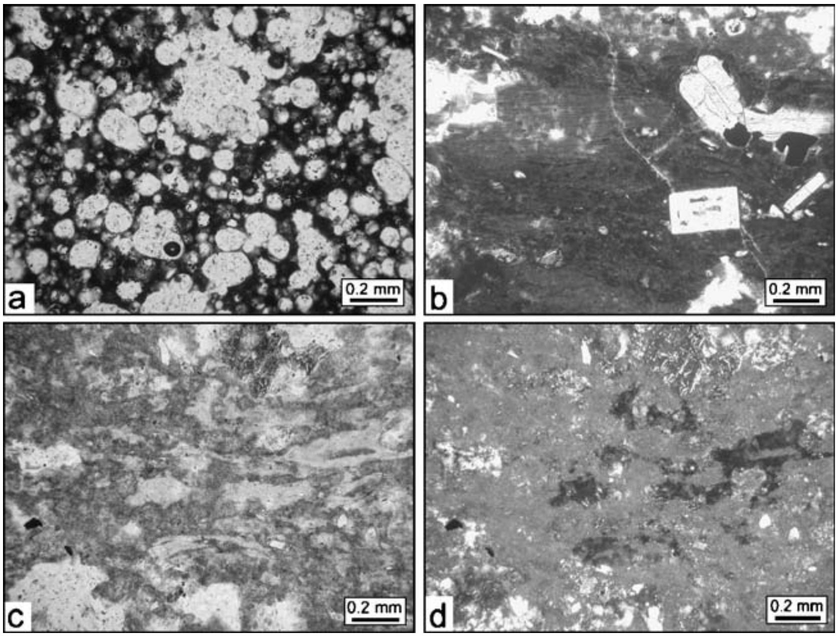


Fig. 5 Microscopic photographs of the Tiribí Tuff facies. **a** Highly vesicular black pumice of the non-welded portions of the Valle Central facies, showing abundant *small spheric vesicles*, **b** Densely welded portion of an ignimbrite of the Valle Central facies at the Electriona Power Plant (eastern Valle Central). The rock is a vitrophyre of fresh dark brown glass and euhedral plagioclase and clinopyroxene crystals. **c** Devitrified ignimbrite of the Orotina facies, showing still fresh glass shards surrounded by a devitrified groundmass altered to sericite and microcrystalline quartz. **d** Same sample as **c** but with crossed polarized light

in the gorge. In the Orotina plain, they have formed a plateau which has been eroded, therefore showing inverted relief above the surrounding landscape. Marshall et al. (2003) called the Orotina facies the "Snake Flow Member" and suggested it followed an incised meandering stream system.

In the Orotina plain, where the tuff overlies fluvial deposits, there is a deposit of generally less than 0.5 m thick at the base of some exposures of the Orotina facies. It consists of medium to fine-grained layers that locally exhibit internal truncation surfaces and cross-laminations. There are sand-wave structures with low angle (up to 10°), moderate wavelength (1.5 m) and low amplitude (0.25 m), giving the deposits a pinch-and-swell pattern. These cross-stratified deposits are fines depleted and appear to have a gradational contact with the overlying ignimbrite, suggesting they are ground-surge deposits (cf. Sparks and Walker 1973).

The Valle Central facies can be interpreted as valley-pond facies, which forms the Valle Central plateau, whereas the Orotina facies are the channelized facies exposed mainly along the Grande de Tárcoles River Canyon and at the southwest margins of the Valle Central.

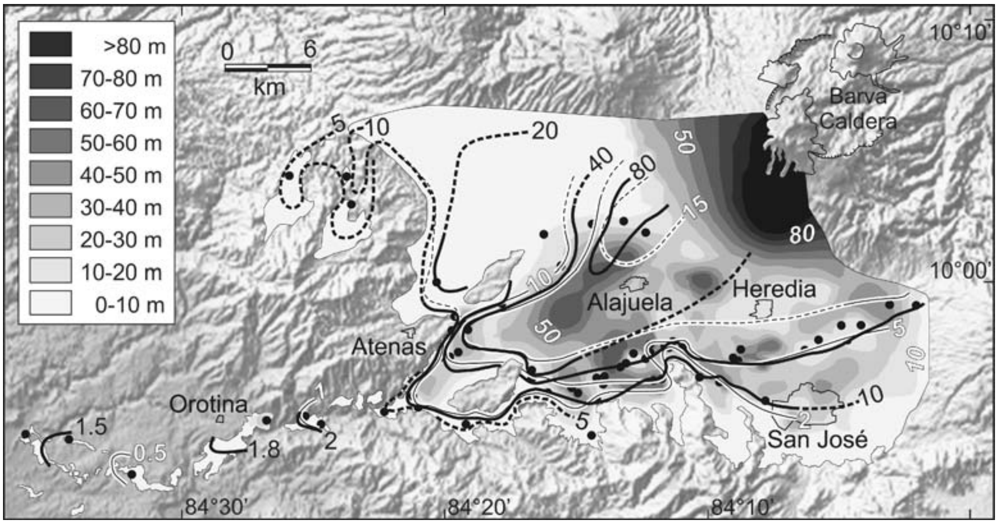


Fig. 6 Isopachs and isopleths of the Tiribí Tuff. The *color scale* indicates the isopachs every 10 m, and some values are given in *italic numbers*. The thickest deposits are located toward Barva volcano (>80 m) and at the middle portion of the basin, where the ignimbrite covered a rugged topography. The *black lines* are the isopleths in centimeters of juvenile fragments. Note that large fragments are concentrated at the narrow canyon entrance (near Atenas). The *black and white lines* are the isopleths (also in centimeters) of the lithic fragments, which follow a pattern similar to the juvenile ones. The *black filled circles* are the localities where measures of juvenile and lithic maximum sizes were carried out for the construction of the isopleths

Distribution, volume and aspect ratio

It is challenging to make an estimate of the dispersal area and volume of Tiribí Tuff because proximal deposits are apparently buried under more recent volcanic rocks. Also the summit of the volcano is located in the densely forested area with rough topography. Moreover, using geological maps (Madrigal 1970; Echandi 1981; Denyer and Arias 1991), 76 stratigraphic sections and 7 borehole cores studied in detail, as well as 233 geologic records from the SENARA water-supply boreholes database, we estimated a minimum dispersal area for the Tiribí Tuff of 820 km^2. This area comprises the Valle Central basin and the channelized deposits in the Grande de Tárcoles River, and also includes the minimal area in Barva volcano's southern slope where the Tiribí Tuff is covered by recent deposits and has only been detected by boreholes (Fig. 3).

The thickness distribution of the deposits is highly variable (Fig. 6), ranging from more than 80 m in a borehole at Barva volcano's southern slope, to less than 2 m at the Orotina plain. Inside the Valle Central, the thickness variations are stronger, with areas where the ignimbrite can be as thick as 60 m, representing valley-filling deposits, to areas with less than 10 m and areas where there was no deposition at all or the deposits have been eroded. These are two ridges aligned NE–SW towards the southwestern end of the Valle Central and near Atenas. This is an indication that the ignimbrite was deposited over a rugged topography that was left after deposition of lava flows of the Colima Formation in part of the valley.

Integrating the thickness from the isopach map, a volume of at least 25 km^3 was estimated (~15 km^3 DRE) for the Tiribí Tuff. This is only a minimum estimate, not considering possible deposits bordering and filling the caldera, now covered by recent lavas and fallout tephra and/or obscured by dense tropical rain forest, or distal co-ignimbritic ash.

The minimum erupted magma mass is estimated as 3.5×10^{13} kg, thus the cataclysmic eruption had a magnitude ≥6.6 and a volcanic explosivity index (VEI) ≥V, following the adaptation of Pyle (2000) from Newhall and Self (1982). This magnitude is similar to that of the Valley of Ten Thousand Smokes ignimbrite eruption in 1912, Krakatoa in 1883 and Pinatubo in 1991.

The aspect ratio for the Tiribí ignimbrite (average thickness/diameter of a circle equal in area to the deposit, cf. Walker 1983) is relatively high, 1:920 or 1.1×10^{-3}. High-aspect ratio flows respond passively to the topography, following and infilling pre-existing valleys such as the Río Caliente Ignimbrite (México) with 1:300, Valley of Ten Thousand Smokes Ignimbrite in Alaska (USA) with 1:400, and Pinatubo (Phillipines) from 1:480 to 1:1200 (Wright 1981; Walker 1983; Scott et al. 1996).

Petrography and chemistry

A detailed geochemical and petrological study of the Tiribí Tuff was carried out by Hannah et al. (2002). In this work, we present a summary of all the geochemical data that are available on the Tiribí Tuff, including the Tibás Pumice Layer, all of them analyzed with X-ray fluorescence (XRF). We also make a comparison between the chemistry of the Tiribí Tuff with that of Barva, Irazú and Poás volcano lavas, as well as with Barva volcano-related rocks, older and younger than the tuff. For the Tiribí Tuff data presented here, we used the 87 chemical analysis from Hannah (2000) as well as data compiled from previous workers (Dengo and Chaverri 1951; Williams 1952; Kussmaul 1988; Bergoeing 1982; Paniagua 1984; Tournon 1984; Appel 1990). For Barva, Irazú and Poás volcano rocks, the data were taken from Kussmaul et al. (1982), Tournon (1984), Alvarado (1990), Malavassi (1991), Soto (1999) and mostly from M.J. Carr's database http://www.rci.rutgers.edu/~carr/index.html).

Tibás Pumice Layer

The pumices from the Tibás Layer are poorly phyric with phenocrysts of plagioclase (1–2%), clinopyroxene, magnetite, and rare biotite in a fibrous hyaline matrix. According to their chemical composition they can be classified as trachytes and rhyolites, with alkali content between 8.1 and 8.8 wt%, and only a slight variation in silica content from 65.2 to 68.4 wt% SiO_2 (Fig. 7). They have similar chemistry to the most evolved pumice clasts of the Tiribí Tuff, showing high SiO_2 and K_2O contents and low Al_2O_3, FeO, MgO and CaO, and in the trace elements high Rb, Y, Nb, Ba and low Sr.

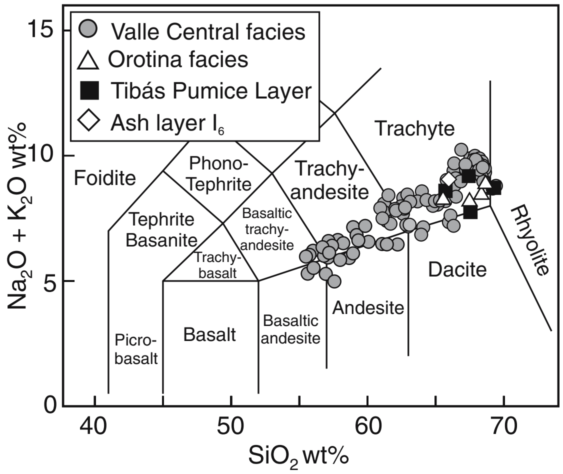


Fig. 7 Total alkali-silica (TAS) diagram for Tiribí Tuff facies Valle Central and Orotina, including Tibás Pumice Layer (classification according to Le Maitre et al. 1989). Note the chemical similarity of the Tibás Pumice Layer, the Orotina facies and the high silica pumices of the Valle Central facies. The open rhombus is the average chemical composition of the ash layer I_6 of Ledbetter (1985), see section Co-ignimbrite ash fall deposit for explanation

Tiribí Tuff

The non-welded parts from the Valle Central facies consist of white (0–5%), gray (0–10%), banded and black pumices (5–35%) and lithic fragments (0–20%) set in a crystal-lithic-rich ash matrix (40–84%). Petrographically, the juvenile fragments contain about 1–10% phenocrysts of plagioclase ($An_{34–76}$), clinopyroxene (<1–5%), orthopyroxene (0–1%), opaques (<1–2%), and rare olivine, amphibole, apatite, zircon, and sanidine. The groundmass consists of dark to pale brown glass and, in banded pumices, it is possible to distinguish glass stripes of both colors. The preservation of fragmental textures includes shards, lithic fragments, and broken crystals. Crystal-poor to crystal-rich black pumices with a characteristic crimped, fibrous vesicle texture and numerous schlieren of crystal fragments, occur in different quantities but show the same chemical composition. Dark and light color pumice samples have similar mineralogy, but different modal proportions; also, as was noted by Hannah (2000), the black pumices show rounded globular vesicles (Fig. 5a), while the white or pale-gray ones show stretched vesicles.

The total pumice fragments range in chemical composition from 55.1 to 69.2 wt% SiO_2 and 4.5 to 10.2 wt% alkali (Fig. 7). Hannah et al. (2002) distinguished three chemical groupings: a low silica group (55.1–65.6 wt% SiO_2) represented by the black pumice, a silicic group (66.2–69.2 wt% SiO_2) of white pumices, and a mingled group (58.6–67.7 wt% SiO_2), represented by the banded pumices with intermediate compositions.

The moderately welded deposits of the Orotina facies have plagioclase phenocrysts in a devitrified groundmass with micropoikilitic textures, with quartz patches and sericite (Fig. 5c, d). They include traces of biotite as an accessory component, which has not been identified in the Valle Central facies and only in the Tibás Pumice Layer. This deposit has a trachytic composition, and the major element and trace element compositions are very similar to those of the Tibás Pumice Layer and to the white pumice fragments of the Valle Central facies (the silicic group of Hannah et al. 2002; Fig. 7). One plausible interpretation could be that the Orotina facies represent the first more evolved and/or water-rich magma that was erupted after the plinian event of the Tibás Pumice Layer, followed by the less evolved/water-poor Valle Central facies.

Comparison of the Tiribí Tuff with the Cordillera Central volcanoes

Chemical analysis from M.J. Carr's online database of the nearest volcanoes of the Cordillera Central—Barva, Irazú and Poás—were compared with those of the Tiribí Tuff (Fig. 8). In major and trace element compositions, it is possible to differentiate the tuff clearly from the Poás rocks. Irazú lavas are more basic, with silica contents mainly between 51 and 57 wt%, and although they show similar trends to the Tiribí Tuff rocks, can also be distinguished by some chemical compositions such as SiO_2-MgO or Sr-Rb (Fig. 8). The Barva volcano case is more complicated as some of the rocks have a very similar chemistry to that of the tuff, but others are more similar to Irazú and Poás chemical trends (Fig. 8). However, when comparing the chemistry of different units of Barva volcano, older and younger than the Tiribí Tuff, it is apparent that the Tiribí Tuff is quite similar to Barva volcano. In particular, older units like the Paleo-Barva and the Colima Formation lavas show similar trends of major and trace elements with those of the Tiribí Tuff, whereas younger rocks (Neo-Barva, Barva Formation lavas and Cacho Negro volcano) are more mafic (Fig. 8). The geochemical similarity between lavas from Paleo-Barva, Colima lavas and the Tiribí Tuff are consistent with a common source.

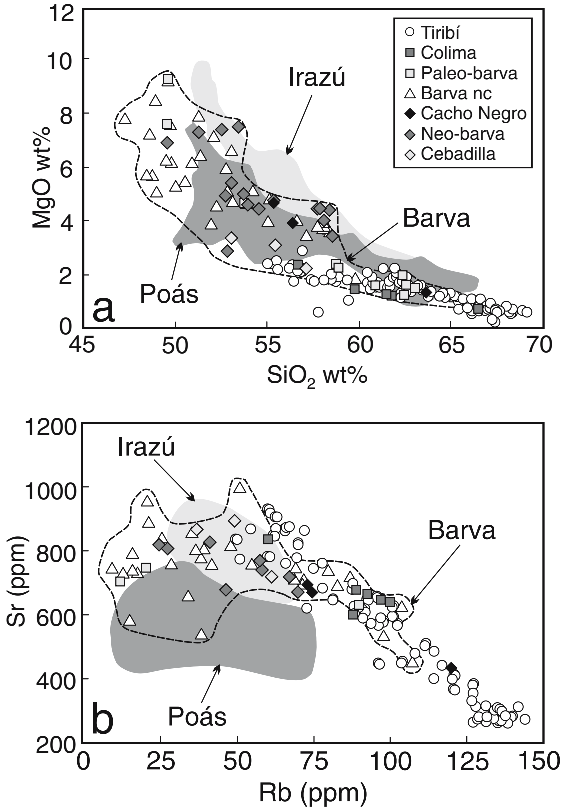


Fig. 8 Diagrams comparing the chemistry of the Tiribí Tuff with that of the nearest volcanoes of the Cordillera Central (Barva, Irazú and Poás, given as fields) and with rocks related to Barva volcano, older and younger than the tuff. **a** Plot of major elements MgO-SiO_2 and **b** trace elements Sr-Rb. Cebadilla is a particular lava flow grouped into the Barva Formation that overlies Tiribí. Barva *nc* (not classified) are samples of rocks of Barva volcano for which no genetic classification has been given, but according to the chemistry they must be of both groups, Paleo- and Neo-barva. Cacho Negro is a small stratovolcano located north of Barva volcano, which grew at the caldera rim (see section Source of the ignimbrite). Note the close similarity between the tuff and the older rocks like Colima Formation and Paleo-barva, while the younger rocks show more mafic compositions. Data taken mainly from M.J. Carr's database, among others

Age of the Tiribí Tuff

Previous geochronologic studies

Previous investigators (e.g., Fernández 1968; Echandi 1981) concluded that the Tiribí Tuff was formed by several different units because of striking differences in color, degree of welding, and lithic and pumice content. In addition, a number of ^{40}K/^{39}Ar age determinations (Bellon and Tournon 1978; Bergoeing 1982; Alvarado et al. 1992) spanned a broad range from 0.2 to 1.4 Ma, also suggesting a number of different flows. However, many of the ^{40}K/^{39}Ar ages were done on whole rock (including lithic fragments).

Recent ^{40}Ar/^{39}Ar age determinations (Gardner and Turrin in Alvarado et al. 1992; Woodward-Clyde 1993; Marshall et al. 2003; B. Turrin, 2002, personal communication) give a much smaller range of ages (201–399 ka) but still do not clarify if there is more than one tuff present, or which is the precise age of the main Tiribí ignimbrite. The work by Marshall et al. (2003) provides the first reliable estimate for the age of the tuff, and confirms that the Orotina ignimbrite (Snake Flow Member) is the same as that in the Valle Central (Tiribí Tuff). They dated six different samples of the tuff (from the Valle Central basin and Orotina plain) and obtained ages ranging from 320 to 390 ka (Fig. 9), yielding a weighted mean age of 340± 13 ka. Not all of their ages overlap within error (2 sigma) of each other, and they report a preferred age of 330 ka.

Analytical methods for the new ^{40}Ar/^{39}Ar dates

The Tiribí Tuff is a difficult unit to date, as it is both very young (relative to the ^{40}K/^{40}Ar decay constant) and is a crystal-poor ignimbrite that lacks a high-K phenocryst phase (i.e., sanidine). Indeed, much of the scatter in the existing geochronology on the unit can be attributed to these difficulties, perhaps compounded by either xenocryst contamination (which would tend to give older ages) or incomplete removal of the groundmass glass (which would tend to give ages that are too young). The strategy used here was to date relatively large splits of highly purified plagioclase separates, taking great care to remove any potential xenocrystic or glass contamination, and to perform replicate analyses on different samples and on different size ranges in order to improve the statistics of the analyses and to critically assess the isotopic homogeneity of the unit.

Approximately 10 different samples of the Tiribí Tuff from sections geographically separated and representing different textural facies of the unit were collected for ^{40}Ar/^{39}Ar dating purposes (Fig. 9). In the field, care was taken to remove as many of the accidental andesitic lithic fragments as possible and to collect either pure pumice fragments (if they were large enough), or pumice concentrates. After petrographic examination, seven of these samples were selected for detailed geochronologic work (Table 1). Two of the samples (CR-56 f.g., CR-56 c.g.) were obtained from the same locality but different parts of the section. In addition, underlying and overlying lavas in several locations were collected to provide independent brackets on the age of the tuff (Table 1).

All mineral separations and isotopic analyses were carried out in the Argon Geochronology Laboratory at the University of California, Santa Barbara. The samples were first coarsely crushed and hand picked to remove any additional small lithic fragments that might contribute xenocrystic contamination. For one sample (CR-56 c.g.) the pumice fragments were sufficiently large so that it was possible to obtain plagioclase from a pure pumice separate. The purified concentrates were then finely crushed, sieved, and ultrasonically cleaned. High-purity plagioclase separates of different size fractions were obtained using

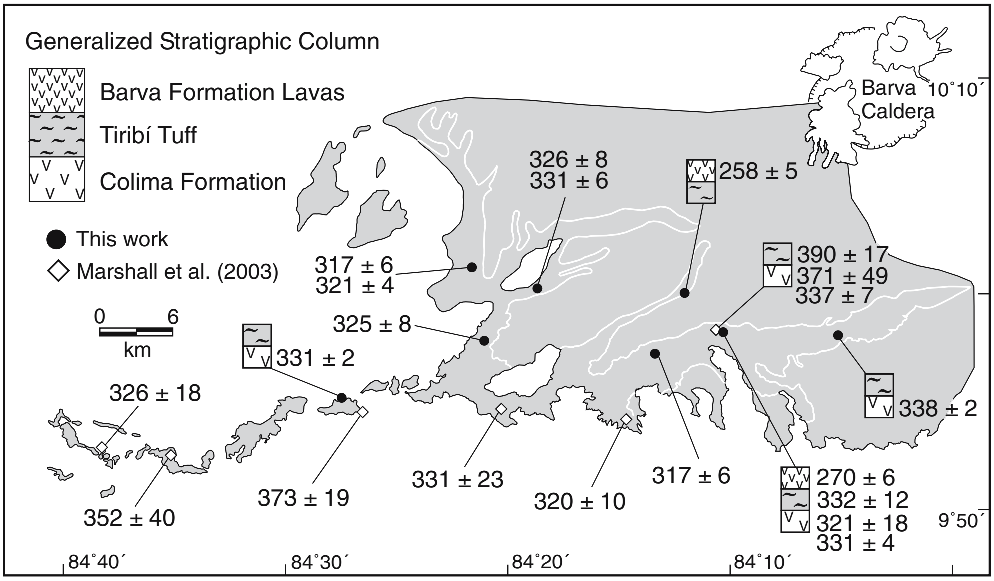


Fig. 9 Map showing the location of the Tiribí Tuff samples dated with ^{40}Ar/^{39}Ar by Marshall et al. (2003) (*white rhombus*) and in this work (*dark circles*) with its preferred age in ka. A small schematic stratigraphic column is provided when the dating was not carried out in the Tiribí Tuff but in over- or underlain units

Table 1 Tabulated $^{40}Ar/^{39}Ar$ geochronological data from the Tiribí Tuff and immediately overlying and underlying units

Barva Formation Lavas

Sample	Latitude	Longitude	Mineral	Experiment	Pr. Age	Est±2s	TFA	WMPA	IsoA	K/Ca	%Rad	Comments
CR–052	09°59.89′	−84°12.82′	WR	8 step heat	**0.258**	**0.005**	0.264	0.258±0.004	0.255±0.008	0.8–1.1	24–47	Slight recoil but nice flat spectrum
CR–038	09°58.53′	−84°11.99′	WR	5 step heat	**0.27**	**0.006**	0.267	0.270±0.006	0.273±0.010	0.5–0.68	8 to 21	Excellent flat spectrum

Tiribí Tuff

Sample	Latitude	Longitude	Mineral	Experiment	Pr. Age	Est±2s	TFA	WMPA	IsoA	K/Ca	%Rad	Comments
CR–56Af.g.	10°01.029′	−84°21.54′	PLAG	7 step heat	**0.317**	**0.006**	0.316	0.317±0.006	0.320±0.012	0.11	26–48	Excellent flat spectrum
CR–101A	09°57.39′	−84°13.43′	PLAG	5 step heat	**0.317**	**0.006**	0.316	0.317±0.006	0.322±0.016	0.075–0.092	19–36	Nice flat spectrum
CR–56A c.g.	10°01.03′	−84°21.54′	PLAG	5 step heat	**0.321**	**0.004**	0.323	0.321±0.004	0.313±0.010	0.1	26–48	Excellent flat spectrum
CR–067	09°57.78′	−84°20.95′	PLAG	3 step heat	**0.325**	**0.008**	0.333	0.325±0.008	0.290±0.024	0.12–0.13	36–61	Flat spectrum, looks good
CR–053–1	10°00.18′	−84°18.62′	PLAG	5 step heat	**0.326**	**0.008**	0.325	0.326±0.008	0.331±0.014	0.12	40–75	Excellent flat spectrum
CR–053–2	10°00.18′	−84°18.62′	PLAG	5 step heat	**0.331**	**0.006**	0.337	0.331±0.006	0.328±0.016	0.12	36–70	Flat spectrum, but possible transmission
CR–021	09°58.21′	−84°10.73′	PLAG	5 step heat	**0.332**	**0.012**	0.329	0.332±0.012	0.337±0.026	0.1	22–58	Excellent flat spectrum

Colima Formation Lavas

Sample	Latitude	Longitude	Mineral	Experiment	Pr. Age	Est±2s	TFA	WMPA	IsoA	K/Ca	%Rad	Comments
CR–019	09°58.21′	−84°10.73′	PLAG	6 step heat	**0.321**	**0.018**	0.365	0.321±0.018	0.290±0.050	0.058	22–49	Irregular U shape with small plateau
CR–039	09°54.978′	−84°27.594′	WR	5 step heat	**0.331**	**0.002**	0.336	0.331±0.002	0.332±0.004	1.1–2.1	63–74	Recoil with excellent flat
CR–019	09°58.21′	−84°10.73′	WR	7 step heat	**0.331**	**0.004**	0.336	0.331±0.004	0.330±0.006	1.1–2.1	34–65	Recoil with excellent flat
CR–011	09°58.05′	−84°05.20′	WR	7 step heat	**0.338**	**0.002**	0.343	0.338±0.002	0.337±0.008	0.5–1.4	40–63	Recoil with good flat

Grand weighted mean plateau age of the Tiribí Tuff=322.8±2.3 ka
Grand weighted mean isochron age of the Tiribí Tuff=320.2±5.4 ka

Explanatory notes: **WR** = Whole rock, **PLAG** = Plagioclase, **Pr. Age** = Preferred age, **TFA** = Total fusion age, **WMPA** = Weighted mean plateau age, **IsoA** = Inverse isochron age, **%Rad** = Typical radiogenic yields over most of the step heating experiment standard heavy liquids and magnetic separation techniques. Purified plagioclase separates were treated in 5% HF for 5 to 10 minutes, cleaned in an ultrasonic bath, and remaining contaminant minerals were removed by hand under reflected light. Separates ranging from ~50 mg up to several hundred mg and in size ranges of 150–300 mm and 300–600 mm were packaged in copper foil, loaded in a quartz vial, and irradiated in a cadmium-lined tube at the TRIGA reactor at Oregon State University. The analyses we present here were obtained from three separate irradiations (two of 40 min each and one of 20 min) performed over a span of 2 years. The flux monitor used in all three irradiations was Taylor Creek Rhyolite Sanidine, with an assigned age of 27.92 Ma (Duffield and Dalrymple 1990). For reference, we obtained ages of 747±4 ka on Bishop Tuff Sanidine and 27.6 ka on Fish Canyon Tuff Sanidine using this standard.

The results, including total gas ages, weighted mean plateau ages, inverse isochron ages, and our preferred ages are summarized in Table 1, as are the results on selected underlying and overlying bracketing lavas. All errors on our estimated (preferred) ages of the different samples as reported throughout the text and in Table 1 are ±2 sigma (95% confidence). Representative age spectra and inverse isochron plots for 2 of the samples are illustrated in Fig. 10.

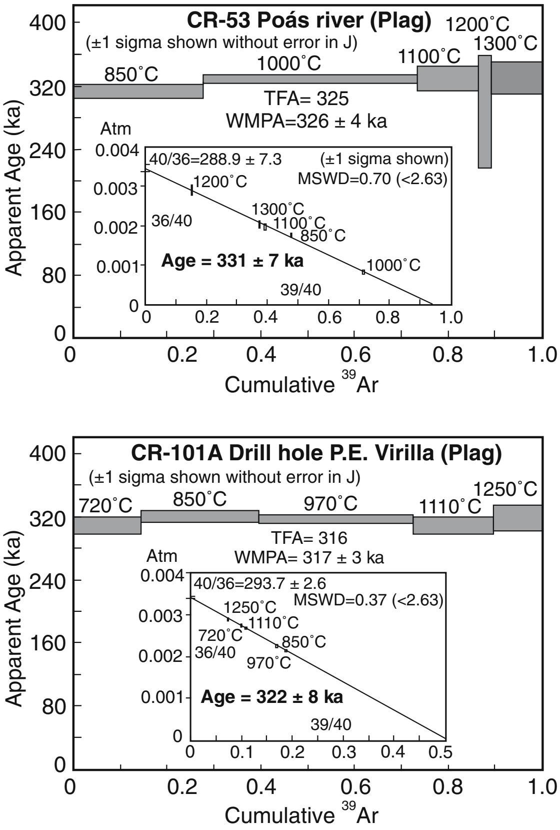


Fig. 10 Selected representative ^{40}Ar/^{39}Ar age spectra and inverse isochron plots for 2 of the samples for the Tiribí Tuff. *TFA* total fusion age, *WMPA* weighted mean plateau age, *MSWD* mean squared weighted deviate

Discussion of analytical results

The new ^{40}Ar/^{39}Ar results on the Tiribí Tuff tightly constrain its age. All of the samples yielded concordant results at the 2 sigma (95%) uncertainty level, with errors on individual analyses as low as ±1.5%. All but one of the samples yielded reasonably flat age spectra (Fig. 10) with well-defined plateau ages that are concordant with the associated isochron ages and give close to atmospheric ratios for the trapped component. Individual samples yielded ages ranging from 317 to 332 ka (Table 1) and no statistically significant age differences could be detected between different facies of the tuff, as a function of grain size of the separate, or stratigraphic position within the tuff. The grand-weighted mean plateau age for all the samples is 322.8±2.3 ka (2 sigma), indistinguishable from its weighted mean inverse isochron age of 320.2±5.4 ka. Combining these yields, a new estimated age of 322±2 ka for the Tiribí Ignimbrite could be obtained (Fig. 11). Radiogenic yields of up to 70% were obtained from several of the samples, which is impressively high for such a young plagioclase. K/Ca ratios ranged from 0.07 to 0.14 in the plagioclase-rich black pumices of the tuff, yielding the lower K/Ca ratios. The concordance of this data set together with the fact that we see no difference in age between small handpicked splits, and bulk plagioclase for the same samples, suggests that we successfully eliminated any xenocrystic contamination. As further evidence of the robustness of this data set, we see no systematic correlation between the ages we obtain on individual heating steps and apparent K/Ca ratio, signal size, or radiogenic yield.

An independent assessment of the age of the Tiribí Tuff is provided by the ages of andesitic lavas that directly

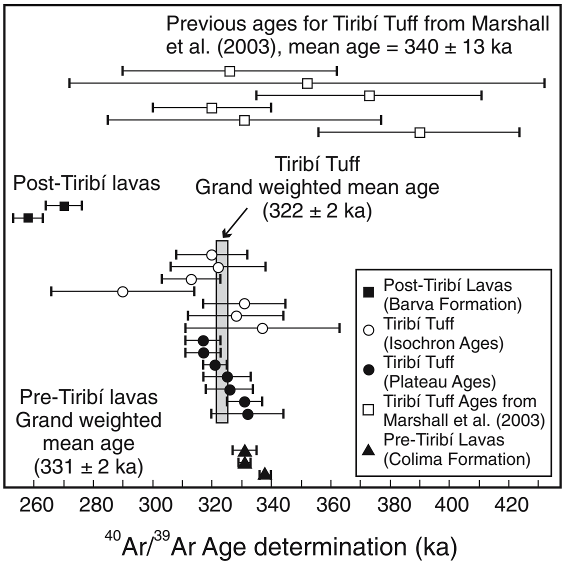


Fig. 11 Diagram showing the determination of age of the Tiribí Tuff from the weighted mean plateau ages and the mean inverse isochron ages. The resultant age (322±2 ka) it is also concordant with the constraints given by the ages of the immediately underlying and overlying units. Marshall et al. (2003) data are also provided for comparison

underlie and overlie the tuff. The Upper Colima Formation lavas directly underlie the tuff in many parts of the Valle Central, and in all exposures we examined, it appeared that the basal pumice fall (Tibás Pumice Layer) was deposited directly on the rubbly vesicular top of the underlying lava flow. This observation is in accord with our geochron data that indicates that these lavas are 331±2 ka, and thus only a few thousand years older than the Tiribí Tuff. Basaltic andesite lavas from the Barva Formation locally overlie the Tiribí Tuff and these have yielded ages of 270±6 ka and 258±5. Taken together, the bracketing units indicate that the Tiribí Tuff must be between 330 and 258 ka, with geological evidence that its deposition must have closely followed the older unit.

Our new 322±2 ka age for the Tiribí Tuff represents a substantial refinement and improvement over the previous geochronology. Most of the dates obtained by Marshall et al. (2003) lie within 2 sigma uncertainty of our weighted mean age, but they have much larger errors. According to the geological time scale of Gradstein et al. (2004), this age places the Tiribí Tuff in the Middle Pleistocene.

Source of the ignimbrite

Previous workers have suggested different sources for the Tiribí Tuff, including: the Aguacate Range for the ignimbrites in Orotina (Dengo 1961), several small calderas aligned NW–SE (Denyer and Arias 1991; Marshall et al. 2003), old fissures located at the present sites of the Cordillera Central (Tournon 1984; Protti 1986; Kussmaul 1988), or even from Poás and Barva volcanoes (Dengo and Chaverri 1951; Williams 1952; Madrigal 1970; Echandi 1981).

We defined the source as Barva caldera (Barva volcano) based in several lines of evidence:

1. The gradient of the ignimbrite top increases eastward toward the Barva volcano (Fig. 12) with an slope of 1.4°.
2. The size of lithic and juvenile clasts increase toward the Barva caldera (Fig. 6).
3. According to the geologic data from boreholes, the ignimbrites can be continuously traced from the Valle Central to the southwest flank of the volcano, where they are covered by more recent lava flows and deposits. The nearest borehole is just 3.5 km to the SW of the caldera rim.
4. Comparing the chemistry of the Tiribí Tuff with that of the nearest major volcanoes of the Cordillera Central, they are most similar to the Barva volcano rocks. Older units than Tiribí show similar trends of major and trace elements with those of the Tiribí Tuff, whereas younger rocks are more mafic. Thus, the geochemical similarity between some lavas from Barva volcano and the Tiribí Tuff is consistent with a common petrogenetic source (see Fig. 8).
5. Although the isopachs of the Tibás Pumice Layer are not well constrained, they are consistent with a source to the north where Barva volcano is located (Fig. 2).

The most proximal studied exposures (between 13 and 15 km) contain large (20–30 cm) lithic fragments floating in the matrix, but no typical lithic lag breccias have yet been found. This suggests the vents lay at least a few kilometers away from these localities and nearer to the source where no outcrops exist due to the more recent thick lava cover and the rain forest.

Barva volcano (2,906 m a.s.l.), the proposed source, is a composite, dormant, andesitic shield volcano (slope gradi-

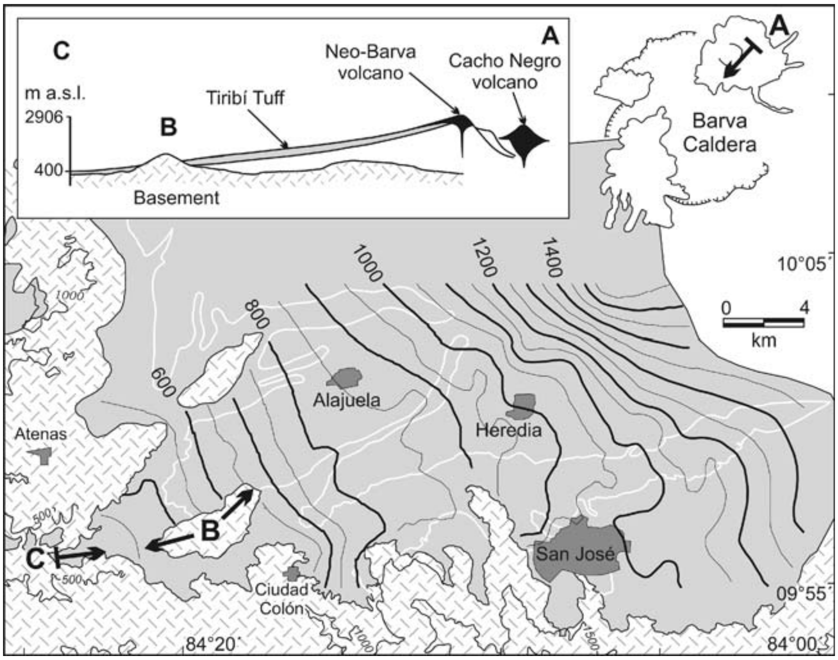


Fig. 12 Contours of the top of the Tiribí Tuff in meters above sea level. Note the decrease in slope from Barva volcano towards the southwest. A schematic longitudinal cross section (*A-B-C*, with no horizontal scale) from Cacho Negro volcano to the Grande de Tárcoles River Canyon is shown in the upper left corner

ent of 4–20°). The volcanic edifice covers an area of 1,500 km^2 with a dozen small vents at the summit, parasitic vents on its slopes and at least two major caldera structures (Fig. 13). Barva caldera is the youngest of these structures (ca. 10 km in diameter; Fig. 13) and rim and erosion scarps 140–320 m high above the floor. The rim is poorly defined in the east and northeast parts, where erosion may have substantially enlarged and erased the original topographic depression. Younger andesitic cones and lava flows obscure the southwestern rim and Cacho Negro volcano has grown in the NNE rim. This caldera is one of the two major caldera structures that can be recognized in the Barva volcano edifice. The other important caldera structure is at least 15 km in diameter, which appears to be older than the Barva caldera based on the degree of erosion (Fig. 13). The rim of this caldera is also open to the NE and the eastern rim is affected by faulting. There are some accounts of the presence of Tertiary sedimentary rocks inside this depression, which can be related to a resurgent caldera, however there is still much work to carry out in this densely forested and tropical jungle area (Fig. 13).

Co-ignimbrite ash-fall deposit

Until now, there are no accounts of co-ignimbritic deposits for the Tiribí Tuff inland, at the Pacific or Caribbean flanks of the magmatic arc. Nevertheless, Ledbetter (1985) reported 11 tephra horizons in the last 300,000 years at the Gulf of Mexico, Caribbean Sea and Pacific Ocean. Few of them could be correlated with deposits on land (e.g., Los Chocoyos ignimbrite, Guatemala), but for most of them just a possible origin area could be addressed. Comparing the mean chemical composition of the Ledbetter ash layers with our Tiribí compilation data, results in a correlation of the major element chemistry of the tuff with the ash layer I_6. This layer was found in three piston cores at depths between 2.4 and 5.2 m, and was dated in 300±4 ka by assuming a constant sedimentation rate between dated tephra horizons (Fig. 1). There is a very good correlation between the Tiribí Tuff and the ash layer I_6 in major element chemistry (Fig. 7), distribution, and age. If we would take into account these distal outcrops of the Tiribí Tuff, located between 200–400 km from the Valle Central, the volume would be much more than the 25 km^3 bulk volume calculated in this work; unfortunately, the thickness data of this distal deposit is unknown.

Discussion

Channeling of pyroclastic flows

The near lack of different flow units (except in the La Garita–Atenas–Río Grande area), the homogeneity of the deposits and their considerable thickness, are consistent with a high and continuous mass discharge rate and a sustained fountain of eruption columns that were low in altitude.

The pyroclastic flows that formed the Tiribí Tuff first filled the Valle Central and then overflowed the wide basin (~20 km wide) through a single outlet: the deep (50–100 m), narrow (~2 km in average), and rough canyon of the Grande de Tárcoles River. This channeling or sudden reduction of ~90% of the cross-section, must have produced an increase in the velocity and decrease in the pressure, known as “Venturi effect” in fluid dynamics (cf. Erismann and Abele 2001). In the Garita–Río Grande area, where the Tiribí is present at the canyon entrance, large black pumice lumps (up to ~150 cm in diameter) are concentrated in the upper portions of the deposit. This is related to shear stress at the base of the flow, with the upward concentration of light particles, which were transported by laminar flow into a pronounced vertical variation

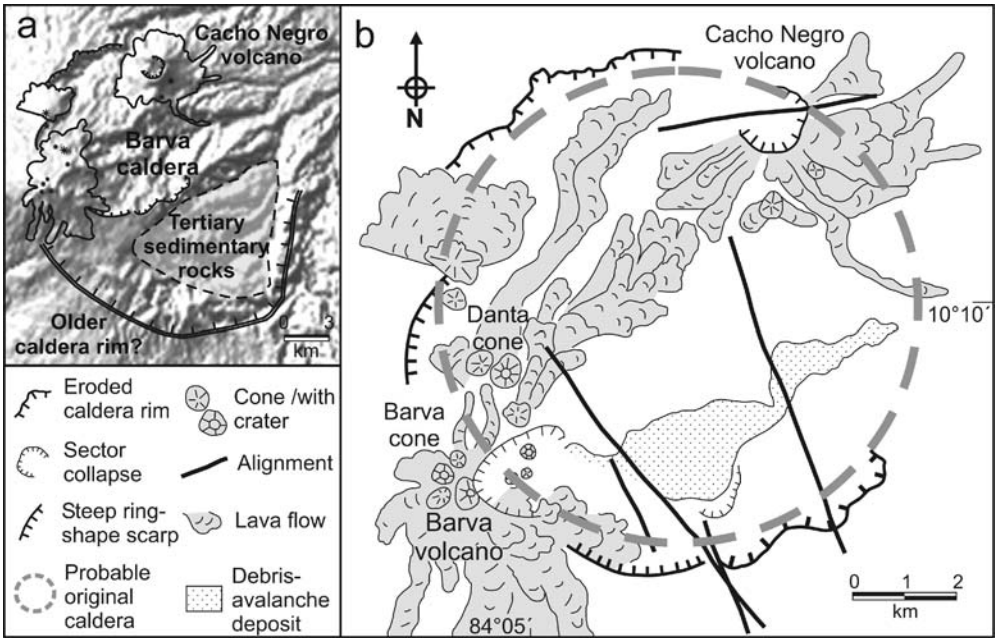


Fig. 13 Photogeologic sketch of Barva volcano. **a** General sketch showing at least two large calderas, an older previous one and the youngest Barva caldera. **b** Detail from Barva caldera, showing the location of more recent volcanic edifices like Cacho Negro volcano and Barva volcano summit that cover the caldera rim in some places. The western portion of the caldera is highly eroded

(e.g., Walker and Wilson 1983; Cole et al. 1993) and an enrichment of vitric fines in the lower portion of the deposit where temperatures were higher.

The canyon could also work as a partial barrier, reflecting the flow back towards the source in the form of a bore (e.g., Woods et al. 1998), gradually filling the Valle Central depression and thickening the deposit. When the flow moved through the canyon, it reached shallower slopes and, as a consequence, began to decelerate (e.g., Hoblitt 1986). Fluidization decreased with the rapid deceleration (e.g., Beget and Limke 1989), causing a sudden thinning of the deposits (from 40 to 10 m in a distance of 10 km) inside the canyon (Fig. 6). Finally, the flows reached the Orotina plain following a meandering pattern (Marshall et al. 2003). The last outcrop is 3.5 km from the Pacific coast, thus it is likely that the Tiribí Tuff reached the Pacific Ocean.

The distance traveled by the Tiribí ignimbrite flows (long-runout) was greatest along the Grande de Tárcoles River Gorge, reaching 80 km. This long distance was reached because the flows were channeled into a single outlet paleocanyon, after filling the Valle Central depression, but not as result of highly energetic flows. The low-aspect ratio Taupo ignimbrite reached the same long-runout of 80 km but in a radial pattern from the source (Wilson 1985).

Welding patterns and devitrification

The most densely welded facies occur in the Valle Central basin, usually in the lower portions of the deposits and particularly where the thickness is greatest (e.g., Electriona Power House in the eastern part of the Valle Central, 80 m thick). This indicates that at least inside the Valle Central basin, the most important factor that controlled the welding pattern was the lithostatic load. Nevertheless, in the distal Orotina facies, the tuff is moderately welded even when the thickness is normally less than 10 m. That could be related to some degree of post-deposition erosion and to the amount and size of lithics, which in the lower welded zones of the Valle Central facies and Orotina facies are less than 1% and between a few mm and cm in diameter, respectively; whereas at the non-welded sections, the content could be as high as 10% and the size up to 40 cm. This could be explained because lithic fragments incorporated at the vent could drastically cool the pyroclastic mixture, helping to inhibit welding (Eichelberger and Koch 1979, Martí et al. 1991).

Ground-surge deposits and its possible relationship with the environment

Ground-surge deposits were only observed at the bottom of the ignimbrite where the tuff overlies fluvial deposits (conglomerates, sandstones and diatomite) in the Orotina plain. At other localities where it overlies Tertiary rocks, mainly toward the western end of the Valle Central and at the Grande de Tárcoles River Canyon, some plant rests and a well-developed ground layer have been found; whereas, the tuff and the Tibás Pumice Layer immediately overlie the Colima Formation lava flows inside the valley, with no paleosol, fluvial or epiclastic deposits in between. One explanation could be that the short time between the eruption of previous widespread lava flows (Colima Formation, 331±2 ka) and the Tiribí Tuff (322±2 ka) and its precursory Tibás Pumice Layer, did not permit significant growth of vegetation, in a Malpais lava plateau, as suggested by the absence of paleosol. The lack of fluvial or epiclastic deposits between the Colima lavas and ignimbrites also suggest there was no time to develop a fluvial system on the high-permeability lava plateau. Thus, the ground surge was developed in places where water from fluvial systems, and dense forest were present, like in the Orotina plain. The ingestion of cold air and water from underlying alluvial deposits and vegetation at the front of a pyroclastic flow (e.g., Fisher 1979) could cause a violent expansion producing turbulent surge clouds, the deposits of which would be immediately overridden by the parent pyroclastic flow.

In southern Central America, regional climatic oscillations during Quaternary were less dramatic, relative to middle and northern latitudes, but they still affected some areas, especially the high lands (e.g., Cordillera de Talamanca in Costa Rica). A glacial period (e.g., 350–130 ka, Zubakov and Borzenkova 1990) could have influenced the weather and vegetation on hill slopes at the time when the Tiribí Tuff and the Colima lavas were formed (between 331 and 322 ka). In the case of the Colima lava plateau, the lack of paleosols suggests that the weather was not favorable for developing a thick soil and vegetation in approximately 10,000 years or even less. Such a climate change may also generate a sediment load in the lower reaches of a fluvial channel network, as was described in detail by Marshall et al. (2003) in the Orotina plain.

Conclusions

Our new age determination of 322±2 ka for the Tiribí Tuff represents a dramatic improvement of the previous geochronology and nicely illustrates the type of precision that can be obtained from Quaternary volcanic rocks, even though they lack a high-K mineral phase. It concretely establishes that the Tiribí Tuff represents a single large volume ignimbrite that blanketed most of the Valle Central region, supporting the field evidence.

The isopach-calculated minimum volume for the ignimbrite of 25 km^3 (~15 km^3 DRE) does not include possible intracaldera deposits and co-ignimbritic ash. Correlation with the major element chemistry, distribution and age of the marine ash layer I_6 of Ledbetter (1985), found between 200 and 400 km offshore Costa Rica, indicates the volume must be much larger.

We propose Barva caldera (ca. 10 km in diameter) as the source of the Tiribí Tuff, based on several lines of evidence such as isopleths, isopachs, contours of the ignimbrite top and chemical similarity with Barva volcano's rocks. The caldera-forming eruption of the Tiribí Tuff is the most explosive event registered up to now in the geological history of central Costa Rica. The eruption is interpreted as starting with a plinian event, which released ~0.3 km^3 DRE and originated the Tibás Pumice Layer.

A fountain of a pyroclastic material (mass ~3.5×10^{13} kg) formed a high-aspect ratio (1:920) ignimbrite. The pyroclastic flows filled the Valle Central basin and overflowed it to the narrow canyon of the Grande de Tárcoles River. This reduction in cross-sectional area probably caused the flows to experience the Venturi effect, and the canyon also worked as a partial barrier, reflecting the flows back and helping the gradual filling of the Valle Central depression and thickening of the deposit. As the ignimbrite was deposited over an area with rugged topography in the central part of the Valle Central, this allowed drastic variations in thickness and, as a consequence of lithostatic load, resulted in different degrees of welding. The content and size of lithic fragments also influences the degree of welding as these fragments cool the deposits and inhibit welding.

Ground surges are present only where the Tiribí ignimbrite overlay paleosols of Tertiary rocks and a former fluvial system, but not over the previous underlying and similar age (331 ka) lava plateau. This suggests that these surges were formed by the interactions of the flow with water bodies, forest and wet soils from the surrounding hills. The Cordillera Central, as well as several areas inside and outside the Valle Central are also currently covered by a dense rainforest, which could also behave in a similar way in the case of a pyroclastic density current-forming eruption.

It is important to recognize high-magnitude events such as the Tiribí Tuff eruption, in the geological record of Barva volcano, which would now pose a very serious threat for the about 2.4 million people living at its foot and southern slope.

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