

THE 1723 A.D. VIOLENT STROMBOLIAN AND PHREATOMAGMATIC ERUPTION AT IRAZÚ VOLCANO, COSTA RICA

LA ERUPCIÓN ESTROMBOLIANA VIOLENTA Y FREATOMAGMÁTICA DE 1723 EN EL VOLCÁN IRAZÚ, COSTA RICA

Guillermo E. Alvarado^{1*} & Hans-Ulrich Schmincke²

¹Área de Amenazas y Auscultación Sísmica y Volcánica, ICE,
Apdo. 10032 San José, Costa Rica

²Geomar, Wishhofstrass. 1-4, Kiel, D-24148 Kiel, Germany

*Autor para contacto: galvaradoi@ice.go.cr

(Recibido: 14/02/2013; aceptado: 11/06/2013)

ABSTRACT: The largest of the recorded historic eruptions at Irazú volcano began on February 16, 1723 and lasted until at least December 11. We here critically examine deposits of this eruption exposed on the summit of Irazú. Our reconstruction of the eruption is based on the unique chronicle of the Spanish governor Diego de la Haya. The eruption began with a < 10 cm thick surge deposit of phreatic origin showing block sag structures. The deposit is overlain by 6 m-thick coarse-grained basaltic andesitic non-graded juvenile fallout tephra consisting of highly vesicular (22-59 vol.%) bombs and lapilli with minor hydrothermally altered lapilli (1-7 vol.%) and rare light colored andesitic vesicular lapilli (< 1%). These fallout deposits are interpreted as strombolian, possible generated during a short-lived scoria cone at the end of February 1723, dominate volumetrically in the proximal facies. Overlying <1.2 m thick phreatomagmatic deposits of finely laminated lapilli-bearing gray ash (fallout and surge deposits) some with contorted bedding and sag structures, are in turn overlain by a 1.2 m thick bed of ash matrix-rich bomb/block deposit. The 1723 eruption was accompanied by shallow volcano-tectonic earthquakes (Modified Mercalli scale Intensity MMI VI-VII, magnitude $M_L \sim 5.5$) that possibly facilitated magma/water interaction. Phenocrysts in the basaltic andesite (~53-55 wt.% SiO_2) bombs comprise plagioclase (6.1-21.6 vol.%, An_{52-35}), clinopyroxene (2.5-10 vol.%), orthopyroxene (0.7-2 vol.%), olivine (0.1-2.2 vol.%; Fo_{76-88}) and Fe/Ti-oxides (0.1-1%), in a groundmass (66.5-90.3 vol. %), dominated by plagioclase (An_{69-54}), clinopyroxene and opaques in brown and black glass with the same range of chemical composition ($\text{SiO}_2 = 57-64$ wt.%). Rare white pumiceous lapilli in the scoria deposits are high-K, hornblende andesite (SiO_2 : 58-60 wt.%), geochemically unrelated to the scoria deposits. Thus, two different magmas co-existing in the magma chamber were mingled shortly before, and during, the eruption, suggesting that the eruption was triggered by magma mingling between hornblende andesite and basaltic andesite magma.

Keywords: Strombolian/phreatomagmatic eruptions, proximal lithofacies, volcano-tectonic seismicity, magma mingling, Irazú volcano, Costa Rica.

RESUMEN: La erupción histórica más grande registrada en el Irazú, se inició el 16 de febrero de 1723 y se extendió por lo menos hasta el 11 de diciembre de ese año. El presente trabajo analiza críticamente los depósitos expuestos en la cima del Irazú, y se comparan con el relato del gobernador español, don Diego de la Haya, la única crónica de dicha erupción. La erupción se inicia con un depósito de oleada piroclástica freática (< 10 cm de espesor), con estructura de impacto por bloques. Está sobreyacida por un depósito de escorias andesítico basálticas (6 m de espesor), no gradadas, altamente vesiculares (22-59 vol. %), conformado mayoritariamente por bombas y lapilli, con algo de lapilli alterado hidrotermalmente (1-7 vol. %) y poco lapilli andesítico vesicular blancuzco (< 1%). Estos depósitos se interpretan como del tipo estromboliano, volumétricamente dominantes en las facies proximales, que debieron de construir un cono de escorias efímero al finales de febrero de ese año. Sobreyaciendo se presenta un depósito freatomagmático (<1,2 m de espesor) de cenizas grises de caída y de oleada, finamente estratificado y laminado, algunas con pliegues sinvolcánicos y estructura de impacto. La erupción fue acompañada por temblores volcano-tectónicos someros (MMI VI-VII, magnitud $M_L \sim 5,5$) que posiblemente facilitaron la interacción magma/agua. Las bombas andesítico-basálticas (SiO_2 : ~53-55 wt.%) contienen fenocristales de plagioclasa (6,1-21,6 vol.%, An_{52-35}), clinopiroxeno (2,5-10 vol. %), ortopiroxeno (0,7-2 vol. %), olivino (0,1-2,2 vol. %; Fo_{76-88}) y óxidos de Fe-Ti (0,1-1%), en una matriz (66,5-90,3 vol. %), dominada por plagioclasa (An_{69-54}), clinopiroxeno, opacos y vidrios café y negro con el mismo rango de composición química (SiO_2 : 57-64 wt.%). Las pómez casuales de lapilli blancas, presentes dentro del depósito de escorias negras, corresponden con andesitas hornbléndicas (SiO_2 : 58-60 wt. %) ricas en K, geoquímicamente no relacionadas con el depósito escoriáceo. Así, dos diferentes magmas coexistieron en la cámara magmática, que se mezclaron poco tiempo antes de la erupción, pudiendo haber sido un mecanismo disparador.

Palabras clave: Erupciones strombolianas y freatomagmáticas, litofacies proximales, sismicidad volcano-tectónica, mezcla de magmas, volcán Irazú, Costa Rica.

INTRODUCTION

Description of historic violent “strombolian” eruptions, involving relatively viscous magma, repeated clogging of the vent, or the influence of groundwater, are rarely described (Macdonald, 1972; Walker, 1973, 1982). A famous example is Parícutín (Mexico), which erupted between 1943 and 1952 (Segerstrom, 1950; Foshag & González, 1956), or Etna between July and August, 2011 (Behncke & Neri, 2003), or even the prehistoric eruption AR-19 (=ET-3) about 930 B.P. (Soto & Alvarado, 2006).

The case of the 1723 violent eruption of Irazú is particularly interesting to better understand this type of eruption because of the existence of an accurate narrative of the volcanic events that, together with our new detailed field and laboratory data, allow to reconstruct the evolution and dynamics of several phases of the eruption. Magmatic and phreatomagmatic explosive events characterized different stages of this eruption. These two contrasting styles of fragmentation dynamics have been recognized in eruptions of many other volcanoes (e.g., Fisher & Schmincke, 1984; Barberi et al., 1988; Houghton & Schmincke, 1989).

Finally, a comparison of the contrasting styles of the 1723 eruption compared with the predominantly phreatomagmatic eruptions at Irazú in the past century (Alvarado, 1993; Alvarado and Schmincke, 1994), allows to better understand the behavior of this volcano helping to constrain its hazard potential.

GENERAL GEOLOGIC AND GEOGRAPHIC ASPECTS

Irazú volcano, the highest (3 432 m a.s.l.) and one of the largest volcanoes (~600 km³) at the southern end of the Central American Volcanic Front, is a shield volcano located in the Cordillera Central of Costa Rica, 150 km NW of the Middle America Trench (Fig. 1). Large lava flows, strombolian and phreatomagmatic (vulcanian) eruptions occurred during the past 50 000 years, but there is no evidence for plinian eruptions in the last 11 000 years. Irazú experienced several eruptions, since its earliest reported historic eruption in 1723, principally during the 20th century (1917-1921, 1924, 1928, 1930, 1933, 1939-1940 and 1963-1965). The vo-

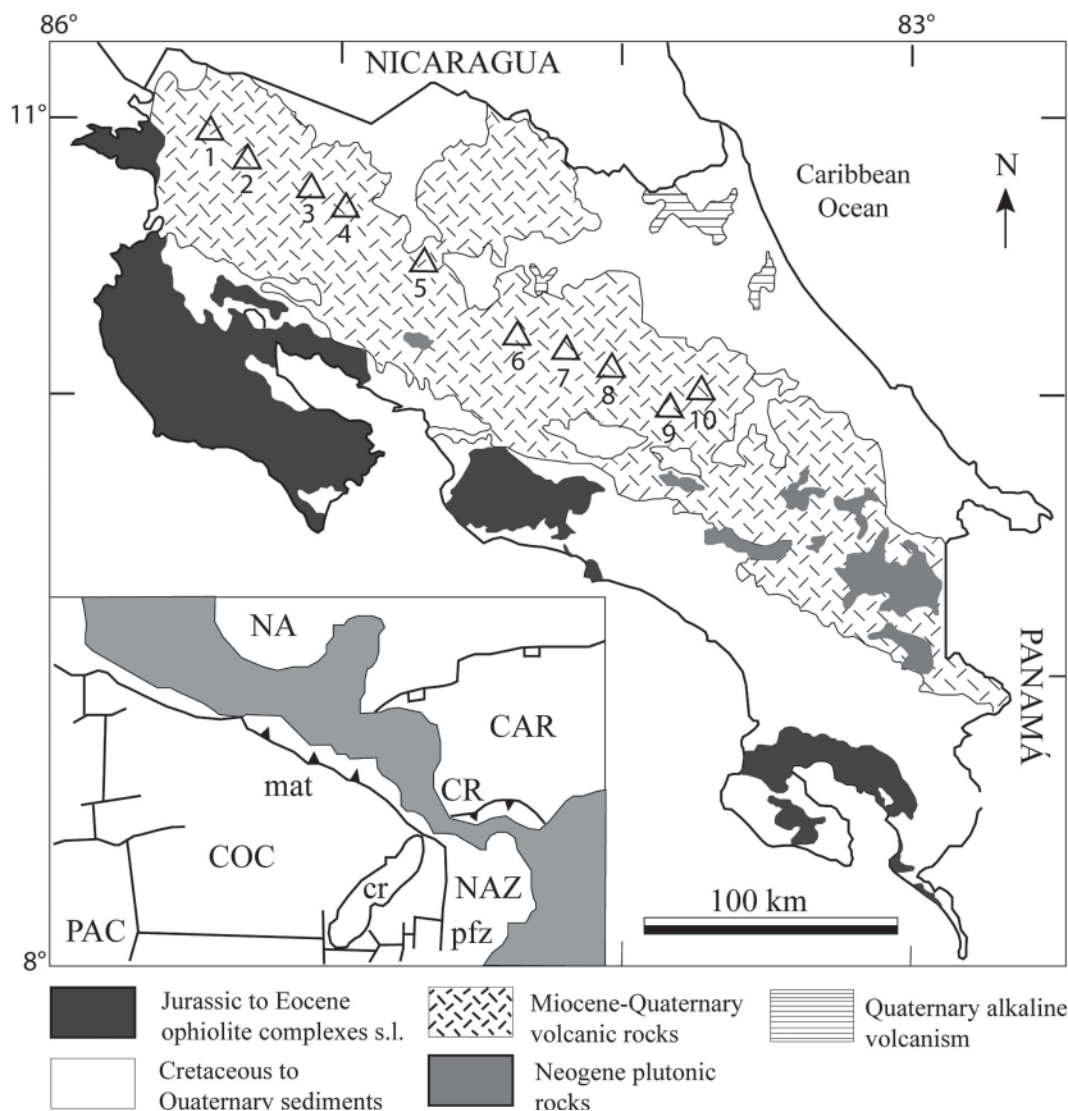


Fig. 1: Simplified geological map of Costa Rica showing the 10 Quaternary volcanoes. Irazú is the number 9. The inset map illustrated the plate tectonic setting of Costa Rica: subduction of the Cocos Plate and Middle America Trench (mat) is limited to the south by the Cocos ridge (cr), and Panama fracture zone (pfz). Key of the tectonic plates: NA: North American Plate, CAR: Caribbean Plate, COC: Cocos Plate, NAZ: Nazca Plate.

Irazú is notorious for its most recent vulcanian eruption (1963-1965), characterized by the production of copious very fine ash that affected several towns of the Central Valley, the heartland of Costa Rica. One of the largest cities in its vicinity, Cartago city, 15 km southwest of Irazú's summit, was founded in 1563 by Juan Vásquez de Coronado and Juan de

Cavallón was the first Spaniard in this area in 1561. Irazú volcano also generated rain-induced lahars that have hurt the economy of this small country (Alvarado and Schmincke 1994). Detailed stratigraphic, petrological and chronological aspects of Irazú volcano are described in detail by Alvarado (1993) and Alvarado et al. (2006).

METHODS

Stratigraphically controlled granulometric analyses of tephra samples in the interval -6 to 6.50 phi (64 mm-10 μm) were performed first with a set of sieves with half phi intervals in the range from -6 to +3 phi (64-125 mm). After desiccation, the coarser material was hand-sieved to prevent breakage of vesicular fragments. The grain size analyses of the fraction finer than 125 μm were carried out using a Coulter Counter Ta II^o particle size counter instrument which provides data in volume and not in weight %. Since the size classes < 125 μm have a constant density (the quantity between the different component is quite constant) an equivalent of % in weight and % in volume exists. The data obtained using the two different analytical techniques were integrated to form a complete grain size distribution with half phi intervals. The conventionally used statistical parameter Md phi and sorting were calculated. Using these two parameters, one need to be aware that these two are significant only in the case of Gaussian distribution and this is not the case in many samples of Irazú. However, to interpret the grain size, one has to use these parameters combined with a visual study of the distribution form which provides useful information in the case of non-ideal Gaussian samples. The terminologies of the parameter of skewness in grain size distribution, the class intervals suggested by Fisher & Schmincke (1984) for tephra in grade scales (millimeters or in phi units), and the range of classification of sorting in pyroclastic deposits (Cas & Wright, 1987, p. 473) were applied. Representative samples of the different types of deposits were selected for microscopic study. Following the method of Sheridan and Marshall (1983), the most representative grain size classes were first examined by stereomicroscope to distinguish glass, lithics, and crystals, and subsequently were cleaned by a weak 30 second ultrasonic treatment in distilled water, which did not modify the original features of the clasts. Finally, particles were analyzed by scanning electron microscope (SEM), using a Cambridge Stereoscan 360 system joined with an energy dispersive system (EDS) device. Scoriaceous lithic ash, for

example, was distinguished from juvenile glassy ash on the base of EDS analyses. Tephra samples were selected for thin section and modal analysis. Modal compositions were determined by count pointing. The number of points in each sample ranged from 300 to 1000 depending on grain size and relative proportion of phenocrysts; the size boundary between phenocrysts and microphenocrysts was taken at 0.3 mm (Wilcox, 1954). The data base used for this study includes 11 new chemical analyses of the 1723 tephra deposits (hereafter referred to as '1723 scoria') obtained by X-ray fluorescence (XRF) analysis on glass pellets with a Philips PW 1480 spectrometer measured in Bonn and Kiel. The analytical program is Oxiquant with a calibration program for geological samples based on 270 standards with synthetic standards and International Certified standards (cf. Govindaraju, 1989). Data are given in files located at M.J. Carr's Web site, www-rci.rutgers.edu/~carr/index.html.

NARRATIVE OF THE ERUPTION AND PREVIOUS WORK

The 1723 eruption of Irazú has been almost completely neglected in the scientific literature although it was the first recorded historic eruption in Costa Rica. This violent eruption took place from February 16, 1723 to at least December 1723. The Spanish governor Diego de la Haya wrote a remarkably detailed record of the seismic and volcanic phenomena of this eruption in his diary (the first volcanological historic record in Costa Rica). The chronicle was reproduced by the Official Newspaper of Costa Rica, "La Gaceta", in 1852. De la Haya correlated the violent explosions with the lunar phases, but he did not record the end of the eruption. Montessus de Ballore (1888) mentioned eruptions of scoria in May, 1726. Pedro Nolasco, during the XX century, mentioned eruptions and earthquakes between 1723 and 1726 at Irazú; and those large earthquakes occurred between September 1723 and February 1724 (González, 1910; Díaz, 1930). González (1910), Tristán (1923), and Peraldo & Montero (1994) did not find any primary data

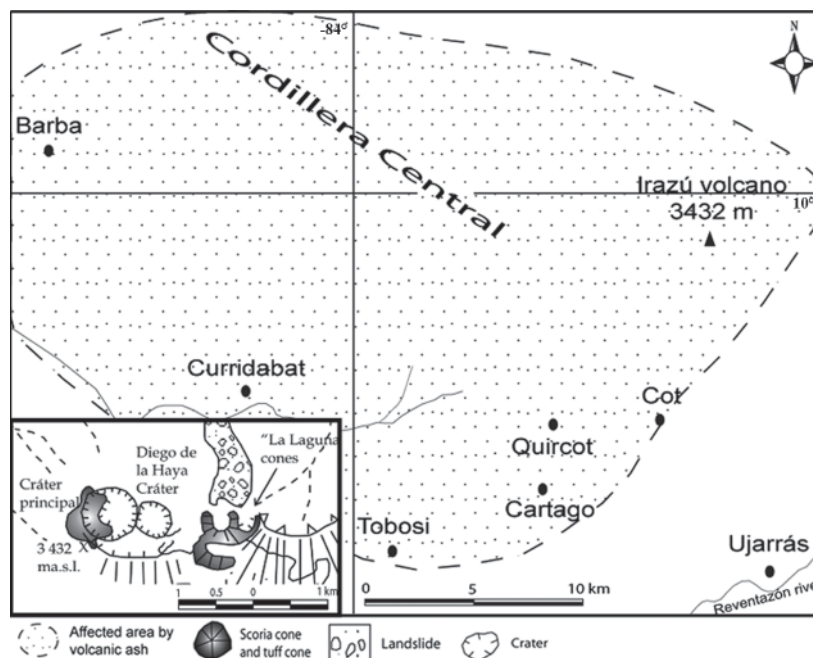


Fig. 2: Generalized map of the principal (seriously to lightly affected area) distribution of volcanic ash from Irazú in 1723, and villages present at that time. Inset, present situation of craters and cones at the summit in the XXI century.

or specific documents in Costa Rica or Spain concerning the last presumable volcanic phase between 1724 and 1726. Sapper (1925, 1926) concluded that the 1723 eruption occurred in the Diego de la Haya crater based on the size of large bombs. A complete reproduction of De la Haya's letter is included in González (1910), Tristán (1924), Mata (1930), and Alvarado (2000), and translated also into English in Alvarado (2005).

According to the diary of Diego de la Haya, the eruption started at 3 p.m. (all data local time, LT+6 hours= GMT) on February 16, 1723 with the formation of an eruption column. Ash fell southwest and west of the volcano on the towns of Curridabat, 22 km to the SSW and Barba, 32 km to the WNW; explosions began at 5 p.m. (*"thunder every half hour"*) [for localities see Fig. 2]. At 4 a.m. in the morning of February 17, a strong explosion (*"thunder"*) was followed by flames, ... and the rumbling continued ever louder, one clap of thunder following close on another.

Afterwards, the *"thunders"* became more frequent. A first expedition to the area surrounding

the volcano reported ash and finer scoria. During the night of the same day, there were strong explosions with large incandescent bombs, continuing to 4 a.m. of the next day (see also Tristán, 1924):

At nightfall flames were seen shooting up from the highest part of the mountain, and within the flames large balls of fire and other burning fragments, all accompanied by great blasts, thunder and rumbling which continued to be heard until four in the morning of the 18th when, at dawn, the flames subsided but not the columns of smoke, which continued.

On this day (February 18) the observers (perhaps located between Cartago and Curridabat) saw that a new cone (?) may have been built on the summit (Fig. 3). At the end of this day, the eruptive activity was intense, and continued to February 20:

We could all see that on the summit of the plateau great quantities of ash and sand had been spewed creating a hill there, and as we were watching, listening to the stupendous thunder and crackling, we saw, around three in

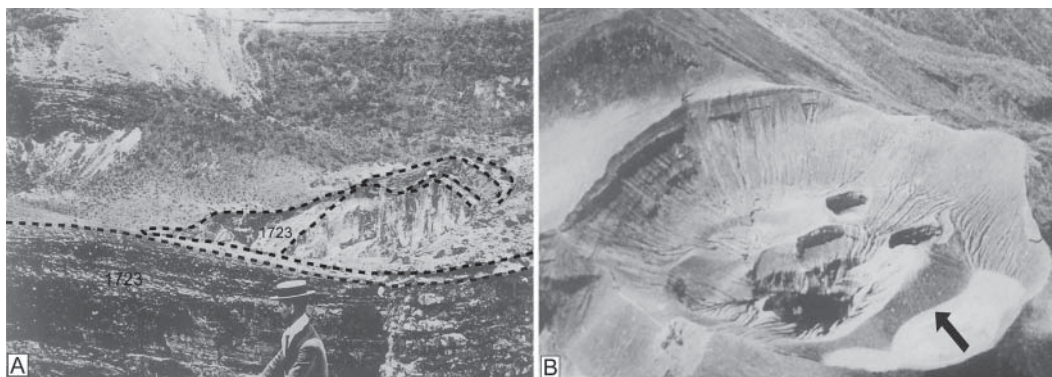


Fig. 3: A) Old photograph taken in 1897 (Tristán, 1923) from the internal part of the main crater (Cráter Principal) showing the small pit craters and the superficial scoria bomb and lapilli deposits correlated to the 1723 eruption, which overlie older phreatic deposits. B) Aerial view of the summit of Irazú in 1946, including part of Diego de la Haya crater (left) and in the background (left) the Playa Hermosa rim. On the right side, the Cráter Principal with several small pit craters and the rest of a pyroclastic cone (1723 cone?). Now, this area is occupied by the Cráter Principal after its progressive size increase during the eruptions in the XX century.

the afternoon, an arc about a yard [as seen from Cartago] wide appearing amid the smoke seemingly made up of cotton or snow balls such was their whiteness, and about four fingers thick and about two pike-lengths in height; it went straight up separating itself from the smoke where it remained for a moment then continued upward, decreasing in size, throwing off from time to time the material of which it was made until it disintegrated. A similar arc of vapor was observed at 6 p.m. on February 19.

De la Haya (1852) thought that perhaps the crater grew in size:

...but later as night fell it was seen to throw up great fire with increased amounts of great burning rocks, the mouth seemingly having opened wider...

During this time, an incessant roaring sound (explosive quakes and tremor) was felt and heard in Cartago:

The night of the 19th till the morning of the 20th the dull roar under the earth continued throughout the city which, putting one's ear to ground, sounded like rivers rushing through its veins, which caused great terror in everyone; from time to time the said volcano threw out great balls and burning stones in greater abundance than heretofore.

During the morning on February 20 (4 a.m.) the volcano was shaken by one strong earthquake

and at 6 p.m. a strong “resound” (shallow volcano-tectonic earthquake?) was felt strongly in Cartago, opening doors and windows, followed by other similar ones. A similar situation occurred on day 21. At 10 p.m. a strong explosion with incandescent bombs occurred, and ash fell in Cartago city:

At four o'clock in the morning of the 20th there was an earthquake felt in the entire city, its valleys and surrounding areas, which was quite strong though it caused no great damage but moved the people to set up shelters for sleeping in their patios; and at six the volcano exploded with such a report that it sounded like a discharge of heavy artillery, and shook the city and opened the doors and windows that were closed; the shots continued hour by hour with increasing loudness and lasted until nightfall, there having been another earthquake.

At one o'clock in the morning of the 21 there was an earthquake greater than the ones that came before and another greater than the ones that came before and another at five in the afternoon which again opened the doors and windows of the houses of the city.

During February 23 to 26, the explosive volcanic activity was more or less constant. On the morning of February 27, heavy ash fall on Cartago delayed the daylight until 10 a.m. and extensive sediment-water flooding of the rivers was reported:

From one o'clock in the morning of the 27th great amounts of ash began to fall on this city and its surrounding area, and at four o'clock a great explosion was heard throughout the region, and it was not until ten o'clock that the sun was seen on account of the rain of ash; this ash was so fine that it got into the eyes, nose and mouth, causing people to sneeze and cough. The water of the rivers and streams was turned to mud.

The morphology of the summit at Irazú at the start of the 1723 eruption or before is unknown. On March 3 a second expedition went to the summit (De la Haya, 1852) and:

..., they reported that they had gone up the mountain to a plateau on the north slope of about one quarter league where it faces the western side, which is where the volcano began to open its mouth broadening it on the lower part below the said plateau, so much so that it may be two leagues in circumference; that the flames continued in the lower portion, toward the North, as when a large pot of tar catches fire, with constant bubbling and spurting as if water were being thrown onto it; that it occasionally threw up ash, sand and small rocks of the type that covered the whole surrounding region, as well as large rocks which could have filled a hundred ships.

This expedition found a large composite crater of "two leagues in circumference". Because one league is about 5.5 km, the diameter should be about 3.5 km. The diameter was probably overestimated by the frightened Spaniards, completely lacking experience with volcanic eruptions. It could represent the present Playa Hermosa "caldera" rim, with a constructed diameter of about 1.2 km, in which the Diego de la Haya crater and the 'new' active crater (Cráter Principal ?) was located in the western part with a lava lake (Fig. 2).

The ashfall, accompanied by small earthquakes, continued during March, affecting Curridabat and Barba. On April 3, a strong earthquake (between 10 and 11 p.m.) was followed by violent explosions with high projection of incandescent bombs:

On the third day of the month, between ten and eleven at night, there was a strong earthquake which was felt mostly in the roofs of the houses and in their patios; shortly afterwards

the volcano began a kind of ferment, as if fifty forges were working their bellows, punctuated by periodic loud reports; the summit could not be seen because it was covered by a black mass. Then a large fire was seen which lasted until two in the morning of the 4th and which threw up rocks and other burning fragments very high, so high that one could say four times the Apostles.

The activity continued until 2 a.m. on April 4 but ended abruptly. The third and last expedition to the summit on April 8, 1723 reported abundant ash covering the rocks and no "sands" like in previous reports that suggests a continuously high degree of fragmentation since March 27:

On April 8 I sent Lieutenant Marcos Chinchilla, Sergeant Manuel Barboza and Cayetano Orozco to explore the volcano. They returned and informed me that the mouth of the volcano was continuously throwing up fire and ash in such quantities that all the rocks in the surrounding area were covered with it.

Finally, De la Haya concluded:

Since then until the present day (December 11) we have seen a continuation of fires, ashes and sands which increase in volume during lunar conjunctions and oppositions and on the days immediately before and after, there being days with four, six and eight earthquakes, though without damage to houses. The fields have been fertilized by the ash that has fallen on them, and the volcano continues its activity to this day.

THE 1723 ERUPTION

We now attempt to correlate and interpret the deposits with the narrative of the 1723 eruption. According to Diego de la Haya, the 1723 eruption lasted at least ten months with the projection of "large balls of fire" and "burning stones" during the first days, followed by fine ashfall, bombs and lahars, suggesting a more efficient fragmentation. Sapper (1925, 1926) concluded that the 1723 eruption took place in the Diego de la Haya crater based on the size of the fragile fusiform bombs. We thus expected to find a thick strombolian sequence overlain by phreatomagmatic tephra de-

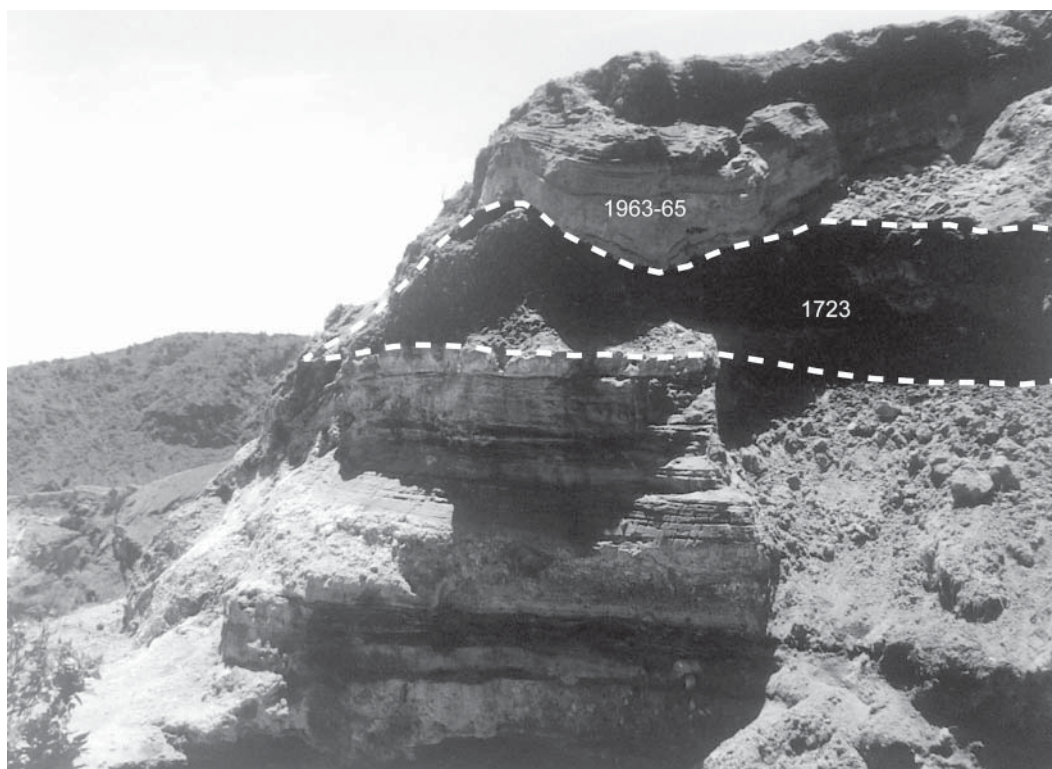


Fig. 4: Contacts between pyroclastic surges and fallout from 1963-65 tephra deposits which overlie (erosive contact) the 1723 scoria lapilli deposits. Photo at the Cráter Principal rim.

posits around Diego de la Haya crater, but this was not the case. In the summit area of Irazú (SW part of the Cráter Principal), however, a 6 m-thick coarse tephra deposit, consisting principally of scoria lapilli and bomb deposits, unconformably overlies phreatic breccia deposits with minor to pronounced erosion surfaces separating the deposits (Fig. 4). This scoriaceous deposit underlies the tephra sequence of the main eruptions of this century (i.e. 1917-1921, 1939-1940, and specially 1963-1965) in the southwestern part of the Cráter Principal. This scoria bomb deposit, however, is thinner (< 1 m) surrounding the Diego de la Haya crater. Other eruptions reported between 1723 and 1917 are doubtful (Tristan, 1923), and they have no stratigraphic record (Alvarado, 1993). Additionally, no report of the eruptions between 1561 and 1723 exists.

The remains of the 1723 scoria deposits in the inner wall of the Cráter Principal have been

intensely oxidized due to post-depositional alteration. The scoria bomb and lapilli deposits may correspond to the 1723 volcanic eruption. Furthermore, a comparison between the historic documents, the tephrostratigraphic record, the increasing thickness of tephra deposits toward the WSW part of Cráter Principal, the size of blocks and bombs and the orientation of asymmetric ballistic impact sags, all indicate that Cráter Principal was the source. The scoria cone “La Laguna” on the eastern part of the summit was not the source of the 1723 eruption because the second expedition (March 3, 1723) did not mention anything about an active pyroclastic cone (Fig. 2).

Other strombolian deposits exposed in the summit area cannot be correlated with the 1723 eruption because the overlying tephra layers do not show any correlation with historic volcanic eruptions (including the doubtful reports in the last century), its type of fragmentation or erup-

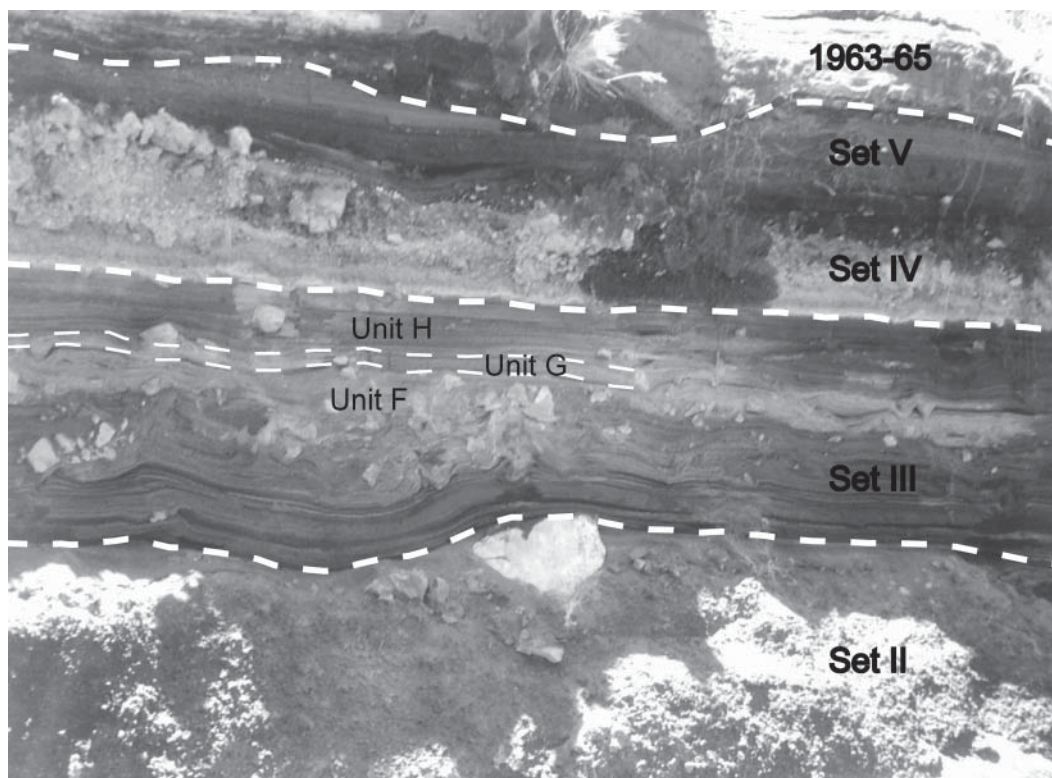


Fig. 5: General exposure showing bedforms and textures of 1723 tephra deposits. The Cráter Principal rim is about 125 m to the left. See text for explanation. Set III is about 1 m thick.

tive mechanism. The study of old photographs taken between 1897 and 1917 from the summit of Irazú, included in Tristán (1923), show that a thick strombolian-style scoria fall deposit was not covered by other tephra deposits at that time and was widely exposed on the floor of the Cráter Principal (Fig. 3). These photographs show that the scoria (bombs and lapilli) deposits erosionally overlie a light colored tephra deposit correlated to the Alfaro unit (Alvarado et al., 2006). Other thick strombolian deposits, called the Tristán unit, exposed in the south wall of the Cráter Principal, are overlain in the photographs by a thick sequence of light colored tephra deposits, correlated to the Alfaro unit. Thus, the Tristán unit cannot be correlated with the 1723 eruption. All this evidences strongly suggest that the Cráter Principal, and not the Diego de la Haya crater as proposed by Sapper, was the vent of the 1723 eruption, and further supports the hypothesis that the scoria

fall and the phreatomagmatic deposits exposed on the SW part of the Cráter Principal represent the 1723 eruption deposits.

Stratigraphic section, type of beds and eruption style

The most complete stratigraphic section is exposed in the upper southern part of the Cráter Principal and in some small outcrops in the summit at 3432 m high. The principal tephra units are listed below (Figs. 5 and 6) with their maximum thicknesses found in the crater rim.

Set I (9 cm): Unit A, a pink to violet fine ash and lapilli deposit showing block sag structures between parallel-laminated, hydrothermally altered coarse to fine ash.

Set II (6 m): Three coarse-grained, highly vesiculated bomb and lapilli-bearing subunits B, C

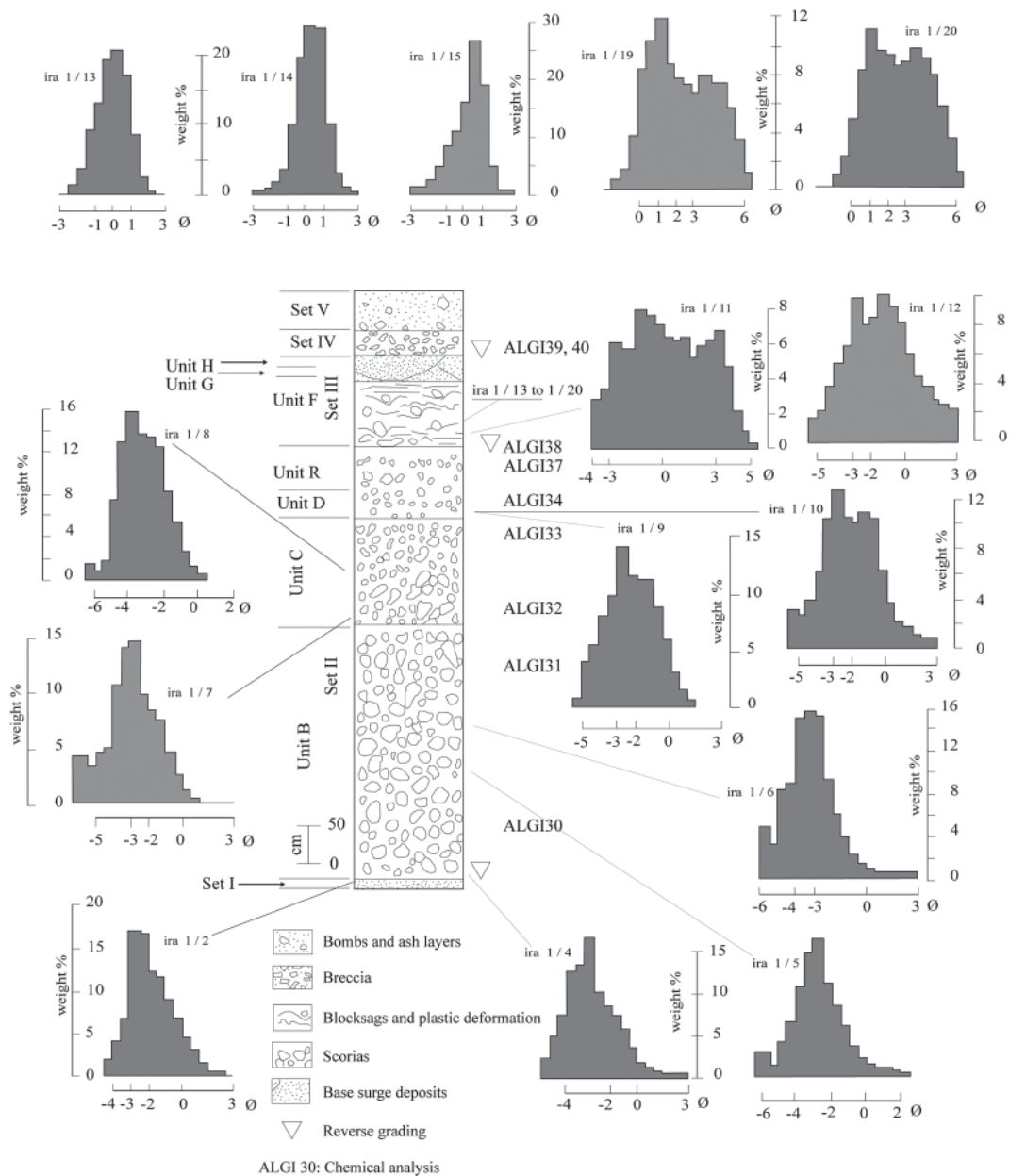


Fig. 6: Generalized stratigraphic section showing the 1723 eruption sequence and representative grain size analyses, and samples location for chemical analyses.

and E.

Unit B (3.6 m): Black, ungraded, scoriaceous bomb-bearing lapilli (without ash) with rare pumiceous andesite (< 1%) and few (1-4%) hydrothermally altered lapilli.

Unit C (1.5 m): Deposits of black bombs with lapilli matrix and few hydrothermally altered lapilli (1-3%). The lower part, 30 cm thick, contains isolated horizons of hydrothermally altered lapilli and small bombs (6-10 cm diameter).

Unit D (24 cm): Brown scoriaceous bombs and lapilli with crude reverse grading, and an irregular horizon of hydrothermally altered lithics and small brown scoria (3-10 mm).

Unit E (70 cm): Brown lapilli-bearing coarse ash and some pumice lapilli.

Set III (≤ 1.2 m): This unit includes phreatomagmatic subunits F, G and H:

Unit F (94 cm) Deposit of gray laminated lapilli-bearing coarse ash layers showing plastic deformation, numerous block sags, and few scoriaceous bombs ($< 5\%$).

Unit G (< 5 cm): Scoriaceous lapilli, laterally grading into 4 thin layers of lapilli-bearing-ash at some locations.

Unit H (< 30 cm): Laminated layer of lapilli and ash without plastic deformation.

Set IV (< 59 cm): Defined by subsets I and J:

Unit I (5 cm): Normally graded medium- to fine-laminated beige ash and lapilli.

Unit J (< 24 cm): Massive tephra layer with blocks (< 15 cm diameter), scoriaceous bombs (15-25 diameter) and lapilli-bearing (juvenile scoria, xenoliths and hydrothermally altered rocks) coarse ash layer with weak reverse grading.

Unit K: Deposits of scoriaceous lapilli and medium sized ash, rich in bombs, blocks and scoriaceous lapilli.

Set I (< 10 cm) is a pink to violet ash and lapilli deposit, showing block sag (lithic lapilli) structures between poorly defined parallel-laminated, hydrothermally altered coarse to fine ash. The scoria lapilli and bomb deposits consist of non-graded coarse-grained layers, with a maximum observed thickness of 6 m (set II), composed of highly vesicular, black to dark brown bombs and lapilli with a few (1-7 %) hydrothermally altered lapilli, lithics and rare ($< 1\%$) light colored felsic vesicular lapilli. The juvenile lapilli have mm-size vesicles, while the bombs also have larger vesicles up to 3 cm. The vesicularity of these clasts ranges from 22 to 59 vol%, a typical feature for coarse-grained strombolian deposits (cf. Kokelaar, 1986; Houghton and Wilson 1989). Xenoliths (hydrothermally altered lavas) are sparse or locally concentrated in discrete horizons. At other locations, such as around the crater Diego de la Haya, these tephra layers are

replaced by isolated large bombs (e.g. Playa Hermosa terrace and surrounding area), small thin scoria lapilli and bombs lenses (e.g. near highest point of the volcano) or locally by a thin (≤ 80 cm) layer formed by deformed and welded bombs, which are part of agglutinates dipping into the Diego de la Haya crater, very close to the Cráter Principal.

A finely laminated lapilli-bearing gray ash (set III, ≤ 1.2 m in thickness) overlies the strombolian deposits and shows plastic bedding-deformation (contorted stratification) and sag structures. The overlying 1.15 m consists of scoria lapilli lenses, ash layers and bomb and block-bearing coarse ash layers (sets IV and V). Set IV consists of a scoria lapilli bed with normal and reverse grading overlain by fine ash with cross-lamination. The fine ash beds are poorly sorted cohesive ash overlain by well-sorted fine lapilli with some lamination, sandwave and truncation structures forming thin layers composed of unconsolidated, well stratified beds. The coarse ash bands following the cohesive wave morphology, with variations in bed thickness orthogonal to strike, fill the trough part of the thin cohesive deposits.

Features that suggest a phreatomagmatic origin for the sets III, IV, and V include: high degrees of fragmentation, good bedding, abundant cohesive ash, large cauliflower-shaped bombs, penecontemporaneous deformation (cf. Fisher and Schmincke 1984). Sedimentation from turbulent depositional mechanisms (surges) of several fine-tephra layers is indicated by: (1) common wave-like and planar bedforms; (2) flat upper surface and an irregular lower surface of some beds, and; (3) bedding sags in cross-bedding layers. The fine ash beds are interpreted as "wet" surge deposits, based on cohesive ash, internal structure and post-depositional alteration features (cf. Sheridan & Wohletz, 1983; Dellino et al., 1990). Well-sorted ash deposits with subordinate lamination, sandwave and truncation structures, are interpreted as "dry" surge deposits (sensu Fisher & Waters, 1970), and they form thin layers composed of unconsolidated, well-stratified beds.

Table 1

Grain size parameters for representative tephra deposits

Inman parameter	Coarse bombs fall deposit	Lapilli fall deposit	Dry surge deposit	Wet surge deposit
Md ϕ	-4.31 to -2.91	0.19 to 0.30	0.04 to 0.56	2.29 to 2.73
$\sigma\phi$	1.27 to 2.00	0.88 to 0.91	0.76 to 0.98 (2.59)	1.82 to 2.02

Grain size analyses

The deposits resulting from the 1723 eruption vary widely in grain sizes (Fig. 6, Table 1). Since all samples were collected near the rim of the Cráter Principal, this variability may be due to the different type of fragmentation and transportation processes. A total of 8 representative tephra samples (bombs, lapilli, ash, rare lithics) from set II were analyzed for grain size distribution. All samples are coarse-grained and well sorted (1.27-2.00 phi). The grain size distributions are asymmetric with respect to the Gaussian distribution (positive skewness). The coarse bomb and lapilli juvenile deposits may have an irregular (bimodal) distribution. These can be attributed to the fact that the strata were sampled at proximal locations where the selection of the ballistic trajectories is not effective. A similar situation has been observed for the deposits of other volcanic areas (e.g. Mt. Pilato sequence at Lipari, Italy; Dellino, 1991).

The data show that the low-angle laminated (pyroclastic surge) deposits are typically finer-grained and better sorted (usually between 0.88 and 0.98 phi) than the coarse juvenile deposits (1.27-2 phi). This could suggest that at least in near vent locations, a tractive transport is more effective in selecting the grain size with respect to a ballistic fallout process. The poor sorting (1.82-2.59) of some samples taken from cross-laminated deposits, probably result from the presence of some scoria lapilli due to contemporaneous fallout deposits. Some poorly sorted pyroclastic surge deposits (1.82-2.59 phi) result from the incorporation of some fallout lapilli scoria which were deposited contemporaneously. The “dry” surge deposits show a well developed Gaussian form (normal to negative skewness), due to the effective granulometric selection during the trac-

tional movement. In fact, the grain size in a single “dry” surge bed varies with distance from the vent (samples ira 1/13, 14, and 15; Fig. 6), constraining an effective selection during transportation. Instead, “wet” surge deposits have a more abundant finer fraction and some show bimodal distribution. The “wet” surge deposits have a finer grain size in respect to the “dry” ones; they are bimodal and have a higher sorting parameter. This could be due to the presence of condensing water during the transport, which has inhibited an effective tractional process, so preventing a selective transport.

SEM observations

Among the tephtras, five major types of ash were distinguished from SEM images: (1) hydrothermally altered scoria lithics; (2) blocky lithic grains, with more or less equant shapes showing variable proportion of vesicles, small microlites and signs of hydrothermal alteration; (3) non-vesicular juvenile blocky grains; (4) weakly-vesicular blocky pyroclasts; and (5) vesicular blocky grains (angular shaped) or irregularly shaped scoria grains (Fig. 7). The differences between the various types of deposits comprise the different proportions of the five type of ash. The first two types of ash are dominant in set I (pyroclastic surge) that represents the beginning of the 1723 eruption. SEM images and EDS analyses show that the ash from this deposit consist of hydrothermally altered scoria (lithic blocky grains) some with evidence of mechanical abrasion.

Highly vesicular juvenile fragments are abundant in set II, some with linear and short cracks. The abundant vesicle surfaces with thin vesicular walls represent the remnants of exploded bubbles; irregular shapes and the jagged outline of particles suggest that fragmentation was due to the expansion of juvenile gases.

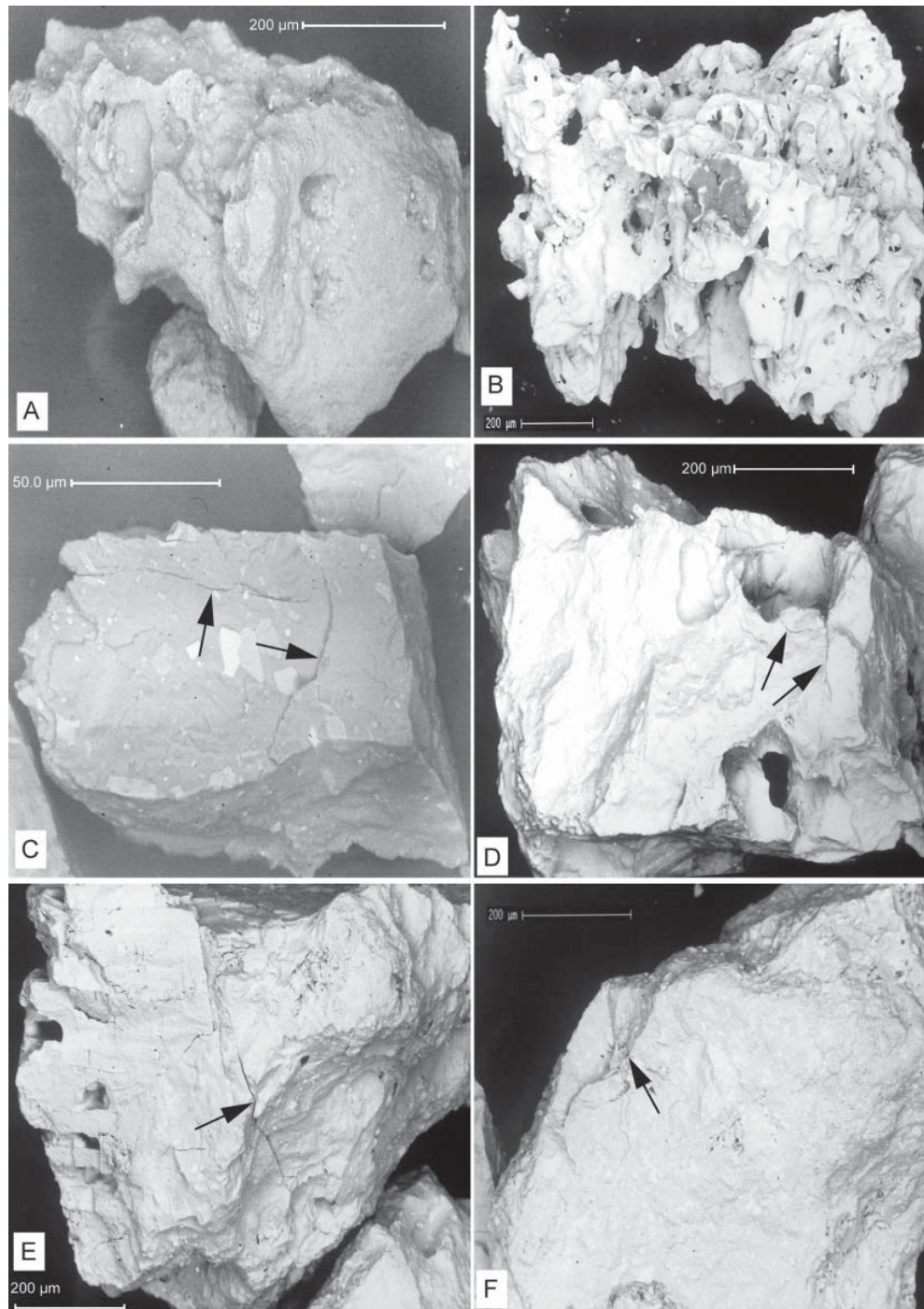


Fig. 7: SEM images from 1723 tephra deposits. A) Hydrothermally altered old scoria (= lithic) showing evidence of mechanical abrasion by pyroclastic surge transport (Set I). B) Vesicular pyroclast from strombolian scoria deposit (Set II, Unit C). C, D and E) Block grains showing hydration cracks, characteristics of phreatomagmatic surge deposits (Set III, Unit F). F) Blocky grain with impact structure on the left hand, from dry surge deposits (Set III, Unit F).

Sets III, IV, and V are consisting of cohesive and non-cohesive ash and lapilli beds with parallel and low angle lamination, in which ash 3, 4 and 5 types are prevalent. At SEM images, the surge deposits show clear evidence of magma/water interaction, for example, poorly vesicular blocky grains and abundant hydration cracks (Fig. 7). Blocky fragments were produced by brittle deformation during quenching and solidification (Wohletz 1983) and the hydration cracks mark the contact between a hot clast with external fluids, probably in a superheated state (a typical situation of phreatomagmatic phenomena). Some grains in the “dry” surge deposits show impact structures, which supports transport in the tractional or saltation zone of a turbulent medium. In general, however, the juvenile components of the “wet” and “dry” surge deposits display similar morphologic characteristics in most of the fragments suggesting that the magma/water interaction was similar for both surge deposits.

Petrography and petrology

The basaltic andesite bombs of the 1723 eruption contain 9.7-23.5 vol% phenocrysts (modal analyses expressed vesicle-free) with phenocrysts of plagioclase (6.1-21.6 vol.%, An_{52-35}), clinopyroxene (2.5-10 vol.%), orthopyroxene (0.7-2 vol.%), olivine (0.1-2.2 vol.%; Fo_{76-88}), opaques (0.1-1%), in an interstitial groundmass (66.5-90.3 vol.%). Zoned (normal or reverse) and unzoned phenocrysts coexist with resorbed, anhedral and perfectly euhedral phenocrysts in the same rocks. The groundmass is dominantly plagioclase (An_{69-54}), clinopyroxene and opaques occur in brown and black glass, both with the same range of chemical composition: basaltic andesite to dacite glass ($SiO_2 = 57-64$ wt.%).

The 1723 scorias are all similar in composition with ~53-55 wt.% SiO_2 and ~16.7-17.6 wt.% Al_2O_3 . Incompatible trace element abundances are relatively high, and LREE elements are enriched. The stratigraphically located samples come from

the basal 6 m (set II) of scoriaceous bombs (ALGI 30 to 38) and from the phreatomagmatic layers (ALGI 39 and ALGI 40). Rock samples from this section show a well defined pattern of slightly increasing SiO_2 , Na_2O , K_2O , Cr and Rb and slightly decreasing TiO_2 , FeO , CaO, Al_2O_3 , Sr and V with respect to its stratigraphic position. The white pumiceous lapilli are high-K andesite (SiO_2 : 58-60 wt. %) included in the scoria from unit E (ALGI 35 and 36). The bombs taken from the phreatomagmatic set IV (samples ALGI 39 and ALGI 40) have slightly higher SiO_2 contents (54.3-55 wt.% vs. 53-53.76 wt.%), and higher Cr (85-99 ppm vs. 66-77 ppm), and lower Al_2O_3 (16.8-17 vs. 17.1-17.6 wt.%), CaO (7.7-7.8 wt.% vs. 8.3-8.6 wt.%), and Sr (765-767 ppm vs. 789-823 ppm) than the lower scoriaceous units (set II: unit B to E) but together they define the same petrochemical trend of fractionation (see Alvarado et al., 2006).

Major and trace element trends of the 1723 scoria provide additional evidence for crystal fractionation. Plagioclase, pyroxene and magnetite are the most abundant phenocrysts controlling fractionation. The linear decrease in FeO/Ti with increase in silica can be explained by the fractionation of magnetite and clinopyroxene. Magnetite fractionation is suggested by the linear decrease in V. The occurrence of magnetite phenocrysts, and especially the existence of magnetite inclusions in plagioclase and clinopyroxene phenocrysts shows that magnetite is in equilibrium with the 1723 parental magma. The decrease in CaO and Al_2O_3 with increasing silica can be explained by removal of calcic plagioclase and lesser calcic clinopyroxene. The decrease of Sr with increasing SiO_2 reflects plagioclase removal at low pressure levels. Using the least-squares technique of Bryan et al. (1969), it is possible to show that the 1723 scoria can be derived from MgO-TiO₂ rich basalts present at Irazú by a moderate degree of fractional crystallization (~28%: 2.1% cpx + 3.6% ol + 0.6% mt + 3.5% plag) consistent with the relatively high-Ti content of the 1723-magma.

The subordinate white pumice lapilli of andesite composition (Fig. 8a), present in the 1723 basaltic andesite scoria deposits, cannot be de-

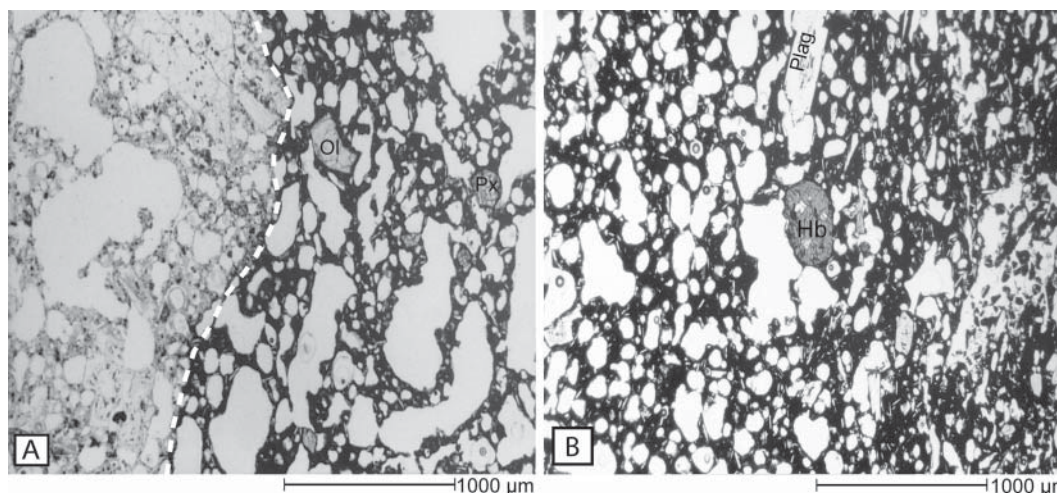


Fig. 8: Vesiculate bombs under the microscope (plane polarized polars). A) The photograph shows the contact between a vesiculate andesite inclusion (left) and the host basaltic andesite bomb (right, sample ALGI30). B) Isolated hornblende (hb) "xenocryst" in the center, in a basaltic andesite scoria bomb (ALGI32). Ol: olivine, Plag: plagioclase and Px: pyroxene.

rived by fractionation from the host basaltic andesite. They can, however, be formed by about 16.5% of fractionation ($\sim 4.5\%$ opx + 2% opx + 0.3% mt + 9.2% plag) from their basaltic andesite of the Tristán layer. The occurrence of pumice inclusions indicate that compositionally distinct magmas (basaltic andesite and andesite) co-existed at different levels in the chamber and were physically mixed shortly before and during the eruption. The andesite component is subordinate ($< 1\%$) with respect to the basaltic andesite. These features suggest that the volume of the andesitic component in the magma chamber was always very small. The pumice inclusions in the scorias could be interpreted as evidence of eruption from shallower depth (< 7 km), since the petrological data suggests a pressure ≤ 2 kbar for the 1723 scoria. Geophysical evidence suggests the existence of shallow and small magma chambers at Irazú volcano (Alvarado et al., 2006). Xenocrysts in the 1723 scoria are unrimmed euhedral hornblende crystals, indicating a rapidly ascended magma of a few days or hours (Fig. 8b; cf. Rutherford, 1993). The contrasting density and temperature of the two magmas (olivine-basaltic andesite and hornblende-andesite: 53-55 vs. 59-60% SiO_2) was probably large.

Seismicity

The strong "resound" or subterranean sounds of the quakes suggest a shallow source (< 15 km) with a maximum intensity MM (Modified Mercalli scale) of VI at Cartago city and possible VII at Irazú. The local magnitude (M_L) can be estimated from empirical relation between magnitudes ML and the epicentral intensity (I_0).

$$M_L = 1 + (2/3) I_0 \text{ (Gutenberg \& Richter, 1956)}$$

$$\text{or } M_L = 1.85 + 0.49 I_0 \text{ (Topozada, 1975).}$$

Assuming that I_0 was VII in the epicenter for the event on February 21, 1723 (1 a.m.), thus $M_L \sim 5.6$ or 5.28, respectively. It is also possible to obtain the magnitudes M_L (local magnitude scale), mb (body wave magnitude) and M_s (surface wave magnitude) using:

$$mb = 1.7 + 0.8 M_L - 0.01 M_L^2 \text{ (Richter, 1958)}$$

$$M_s = -3.197 + 1.653 mb \text{ (Miyamura, 1980).}$$

Thus, the largest volcano-tectonic earthquake could have had a $M_L \sim 4.8-5$, mb ~ 5.3 and $M_s \sim 5.5$. Therefore, the magnitude of the principal earthquakes of this seismic swarm that was felt in Cartago city could have had a M_s between 3.5 and

<5.5. Numerous volcano-tectonic earthquakes of smaller magnitude were also presented. The subterranean ground sounds of February 20, for example, were probably a high energy volcanic tremor or low frequency volcanic quake.

The potential role of earth tidal stress as a potential trigger for the 1723 volcanic explosions and earthquakes was tested, but no clear correlation was found (Alvarado, 1993).

RECONSTRUCTION OF THE VOLCANIC ACTIVITY IN 1723

The various phases of the volcanic activity of the 1723 eruption and the fragmentation and transport processes, resulting in the pyroclastic sequence are reconstructed from the narrative, field observations and laboratory data.

The opening explosive phreatic phase and the construction of a scoria cone

The eruption of Irazú started on February 16, 1723 with a brief phase that is now represented in set I, consisting of a thin (< 10 cm thick) fine grained breccia and phreatic pyroclastic surge deposits with block sag structures, reflecting the opening of the crater by explosions generated due to interactions of magma (heat?) with external water. The initial phreatic phase was followed by a dominantly strombolian eruption (set II) which produced relatively homogeneous and monotonous, very coarse grained, well-sorted, highly vesicular scoria lapilli and bomb deposits of high-K basaltic andesite composition. The form of several bombs, with a flattened base, indicates that they were still plastic on impact.

The eruptive column of ash was more or less constant in height and shape during the first days of the eruption in 1723. The extraneous white-steam arc which formed from the active crater, as observed on February 18 and 19, can be interpreted as a vapor-ring originated from the crater, like those observed at many volcanoes (cf. Perret, 1950; Tazieff, 1988).

During this strombolian phase, a scoria cone was rapidly built at the summit of Irazú during the first two days of the eruption. Part of this cone can be seen in old photographs (1897-1962) and in the cartoons of Tristán (1923) and Sapper (1926). Later, this cone was destroyed by the last large and prolonged eruptive period between 1963 and 1965. The rate of growth for this cone can be estimated by looking at analogies in more recent examples like at Parícutín volcano (México), a similar cone that grew very quickly initially, having achieved a height of 30 m in the first day of activity and 60 m after three days (Foshag & Gozález, 1956). At the Phlegrean Fields (Italy), a pyroclastic cone was built up to a height of 132 m and a 1200 m base diameter during the 1538 A.D. Monte Nuovo eruption, in only two days of continued activity (Barberi et al., 1988; D'Orlando et al., 2005), and more recently, at 2001 Etna eruption, a almost 100 m high symmetrical cone grew mostly in a week (Behncke & Neri, 2003).

The phreatomagmatic phase

A finely laminated phreatomagmatic lapilli-bearing gray ash overlying the strombolian deposits shows plastic bedding-deformation (contorted stratification in the lower part) and sag structures (≤ 1.2 m thick). The following 1.15 m consists of lapilli scoria lenses, ash layers and bomb/block-bearing coarse ash layers (sets IV and V). The phreatomagmatic deposits are rich in wall-rock lithoclasts and nonvesicular to weakly vesicular essential clasts. This lithic-rich breccia deposit (set IV) may have resulted from progressively deeper explosive foci and/or wall-rock collapse and mechanical erosion ("craterization") produced by dense high-pressure, high-velocity volcanic jets (cf. Eichelberger & Koch, 1979). Ballistic and turbulent mechanisms dominated during the deposition of sets III, IV and V. The transition between "wet" and "dry" surge deposits is sharp but without erosional unconformities. "Wet" surge deposits appear to have been cohesive and aggrading rather than erosive. The differences between the two types of pyroclastic surge deposits at Irazú are not due to an inherent difference in

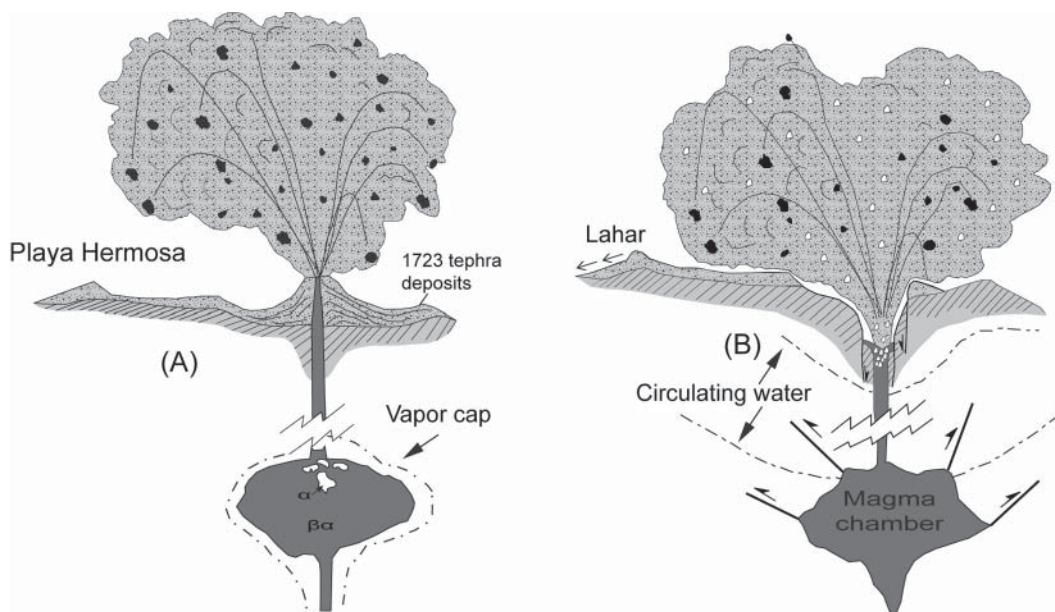


Fig. 9: Cartoons of the 1723 eruption. A) During the first 3 days, magma rises, mixing triggers a violent strombolian eruption. A scoria cone was built within the Cráter Principal. B) On March 1723, continuous shock waves (volcano-tectonic events) help to the interaction magma/water, generating strong phreatomagmatic eruption and collapse of the cone. See text for more details. Not to scale.

the eruptive mechanisms but can probably be correlated to different water contents in the moving cloud preventing the elutriation of the fine ash in the case of wet surge, thus preserving the clast size distribution during the fragmentation.

The reworked tephra deposits and contorted stratification interbedded between primary fallout and ballistic blocks (Figs. 5 and 6) confirm episodes of rainfall during the eruption (sometime between May and December, 1723).

DISCUSSION AND CONCLUSION

The 1723 mafic magma erupted as scoria can be derived from MgO-TiO₂ rich basalts presented at Irazú by a moderate degree of fractional crystallization (~28%) consistent with the relatively high-Ti content of the 1723-magma. The subordinate andesite inclusions (felsic pumice) in 1723 basaltic andesite scoria deposits cannot be derived by fractionation from the host basaltic andesite, but they can be formed by about 16.5% of fractionation from their basaltic andesite magma (see also Alvarado

et al., 2006). The occurrence of pumice inclusions indicate that compositionally distinct magmas (basaltic andesite and andesite) co-existed at different levels in the chamber and were only in part physically mingled shortly before and during the eruption (Figs. 8 and 9).

The eruption resulted from the rise of a small batch of basaltic andesite magma into a small andesitic magma chamber leading to rapid initial contact and final eruption. Because the contrasting density and temperature of the two magmas (53-55 vs. 59-60 wt.% SiO₂) was probably large, the mixing was incomplete. The presumed length of dormancy between the 1723 eruption and the previous prehistoric eruption was possibly more than 162 years, and more than 9 % phenocrysts were present in both magmas; crystallization had thus started prior to the eruption. Hence, a long period of crystallization causing water saturation or oversaturation (cf. Blake, 1984; Tait et al., 1989) is likely and physically an additional mechanism for triggering this eruption. In fact, the structure at Irazú is weakened as the volcano is cut by many faults. Therefore, only minor

crystallization is required to generate the cracking pressure necessary to initiate an eruption, and the extra energy needed to produce deformation of the surrounding area.

A pyroclastic deposit located in the southern part of the Cráter Principal is associated for the first time with the 1723 eruption at Irazú volcano. Its areal distribution, stratigraphy, grain morphology together with eyewitness accounts suggest that this eruption was characterized by an initial phreatic eruption, following by strombolian and finally phreatomagmatic activity. The strombolian activity built an ephemeral scoria cone in the inner part of the Cráter Principal (Fig. 9).

Stratigraphic, historic and laboratory data indicate the final phreatomagmatic phase of the 1723 eruption was accompanied by strong earthquakes. These may have opened fractures leading to a dramatic decrease in discharge rate and thus a drop of the pressure in the magma chamber below the hydrostatic pressure in the aquifer. This caused influx of water into the shallow magma chamber, resulting in the implosion of the chamber roof and walls, generating the phreatomagmatic explosions. The scoria cone was partially destroyed in this phase by a series of collapses and vent-clearing explosions. This phase was possibly linked to the eruption period that started on February 27, 1723, when the existence of abundant fine ash fallout suggests more efficient fragmentation, and lahars were reported in Cartago. In fact, the transition from strombolian to phreatomagmatic eruptions at the Cráter Principal was very rapid, as confirmed by the tephra deposits. The fold structure (contorted stratification) in the deformed horizon that is nearly horizontal was caused by load pressure, high water content and strong earthquakes. Several volcanic explosions during this phase were preceded by volcanic earthquakes and, therefore, could have been triggered by shock waves (Wohletz, 1983; Zimanowski et al., 1991), such as low- and high-frequency volcano-tectonic events, permitting the periodic interaction of magma with water. A nice example for this was probably the

phase on April 3, 1723 when volcanic explosions followed a strong earthquake.

The final eruptive stage is unknown (1724-1726?), but possibly consisted of drastic changes in the appearance of the crater terrace, and in the formation of several small pit vents observable in the old photographs, followed by fumarolic activity.

Magma composition did not change during the eruption. This implies that the main controls on the eruptive style of Irazú are the magmatic gas content, and the interaction between magma and water. Magma/water interaction (i.e. phreatomagmatic eruption) only occurred when discharge rates were low and the fragmentation surface was below the water table (Houghton & Schmincke, 1989) and when the magma was primarily fragmented (Barberi et al., 1988). At Irazú, however, the abrupt change between “dry” to “wet” deposits could also be favored by the continued occurrence of earthquakes.

The lithostratigraphy of the tephra sequence at the summit of Irazú suggests that, commonly, the principal eruptive phases at Irazú began with magmatic or “dry” eruption -in this case as strombolian style- followed by phreatomagmatic eruptions. Therefore, although of very small magnitude (Volcanic Explosivity Index, VEI ~ 3; cf. Newall & Self, 1982), if a similar eruption occurs again it may cause serious losses in agriculture, industry and damage to infrastructure, but also severely affected the international aircraft flying.

ACKNOWLEDGEMENTS

This work is part of G.E.A.'s Ph.D. thesis at the Christian-Albrechts-Universität zu Kiel. Discussions with G. Soto, L. La Volpe, P. Dellino, and M.J. Carr, and financial support by Deutscher Akademischer Austauschdienst (DAAD), Instituto Costarricense de Electricidad (ICE) to G.E.A., the Deutsche Forschungsgemeinschaft (DFG) Leibniz grant to H.-U. S., and Dipartimento Geomineralogico at

Bari are gratefully acknowledged. W. Rojas and W. Montero provided also valuable comments. F. Arias helped in the field and S.M. Garro in the figures. Steffen Kutterolf makes helpful comments on the text.

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