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The formation and evolution of Hule and Río Cuarto maars, Costa Rica

Guillermo E. Alvarado [a,b], Gerardo J. Soto [a,b,c,*], Flavia M. Salani [d], Pablo Ruiz [e], Luis Hurtado de Mendoza [f]

[a] Área de Amenazas y Auscultación Sísmica y Volcánica, Instituto Costarricense de Electricidad, Apdo. 10032-1000, San José, Costa Rica
[b] Escuela Centroamericana de Geología, Universidad de Costa Rica, Apdo. 214-2060, Ciudad Universitaria Rodrigo Facio, Costa Rica
[c] Terra Cognita Consultores, Apdo. 360-2350, San Francisco de Dos Ríos, Costa Rica
[d] CONICET–Departamento de Ciencias Geológicas, Universidad de Buenos Aires, Pabellón 2, Ciudad Universitaria, C1428EGA, Buenos Aires, Argentina
[e] Department of Earth and Planetary Sciences, Rutgers University, NJ, USA
[f] Proyecto Hidroeléctrico Toro 3, Instituto Costarricense de Electricidad, Costa Rica

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A B S T R A C T

The Hule and Río Cuarto maars are respectively located 11 and 18 km northward of the active crater of Poás volcano, on the Caribbean side of the Central Volcanic Range of Costa Rica. They lie on the northern part of Poás volcano massif, along a N–S trending, ~27 km-long volcanic fracture crossing the Poás volcano. The volcanic products from Hule maar (2.3 km × 1.8 km, area ~3.5 km^2) are mainly pyroclastic surges (poorly vesiculated andesites with very small plagioclases), silica-rich andesitic pumice flows, air-fall deposits, ballistic blocks, and reworked deposits that overlie the regional Pleistocene volcanic basement. They were produced during three main explosive phases. Two overlapping pyroclastic cones have developed within the Hule maar, and at least three lava fields are related to them (high-Al basalt to basaltic andesite). Another maar, Pata de Gallo (400 m across), is located less than 1 km off the SE rim of Hule. Río Cuarto is a nearly circular maar (700–850 m across) with a surface area of 0.33 km^2. Río Cuarto products include surges, ballistics and air-fall tephra, produced during three main explosive phases. These deposits show a narrow fan oriented westward, according to westerly wind direction. They indicate a westerly-directed surge (first 2 km), followed by air-fall deposits (up to 5 km away). Radiocarbon dating has shown that Hule was formed ~6.2 ka ago and Pata de Gallo probably formed ~2.8 ka ago, while the intra-maar products could have ages of ~1.7 ka or ~0.7 ka, indicating that Hule is a polygenetic maar. There are no radiocarbon ages yet for dating the formation of Río Cuarto maar, but archaeological data suggest that it erupted between 3–4 ka ago. The volume of pyroclastic deposits associated to Hule maar is estimated to be 0.51–0.53 km^3, from which ~20% is juvenile material, therefore 0.07–0.08 km^3 of new dense rock equivalent (DRE) magma, after subtracting 20–30% of porosity. The tephra from Río Cuarto is estimated to be 4.4×10^7 m^3, of which 0.008 m^3 correspond to DRE magma. The Hule and Río Cuarto maars are occupied by lakes and, in the last decades, several lake-overturn events have taken place, with a repeat cycle of six to seven years. The main outcome of these events has been the mass death of fish accompanied by changes in the lake color. In these systems, the hazard related to the possible occurrence of Nyos-type gas eruptions can be considered negligible or very local, but significant for tourists who camp by the lakes.

1. Introduction

Maar is a German-derived word that means *crater lake*, which origin is from the Latin word *mare* (sea). It was first and widely used by Ollier (1967) and Lorenz (1970, 1973, 1986), who put it into the scientific literature as an important volcanic landform related to phreatic and phreatomagmatic eruptions. The site is in the Eifel area of Germany, where the craters are usually occupied by pounded lakes. Now the term is applied to similar craters everywhere, whether or not they contain lakes.

A maar is a large volcanic crater cut into country rocks, with a low-height rim composed of pyroclastic deposits (up to 50 m in thickness). It may reach a few meters or tens of meters above the pre-existing ground surface, forming one type of tuff ring. Maars host depressions of up to 3.2 km wide, several tens to 250 m deep, in which the crater floor lies well below the surrounding ground level, frequently exhibiting near-vertical scarps below the crater rim (Lorenz, 1970, 1973, 1986; Verpermann and Schmincke, 2000).

Most maars are located in older fluvial valleys, lowland areas, plateaus or plains, or in areas once occupied by a lake or covering aquifer-bearing rocks. Maars generally lack or have only minor inward dipping beds, and are surrounded by low ramparts of well-bedded tephra dipping <25° outwards that decrease rapidly in thickness away from the rim. Their deposits, mainly composed of base surges and tephra fallout, differ from those of true tuff rings/tuff cones by the abundance of non-juvenile components (up to 80%).

Historic maar eruptions are rare and poorly documented (Lorenz, 1973, 1986; Cas and Wright, 1987; Verpermann and Schmincke,

* Corresponding author. Área de Amenazas y Auscultación Sísmica y Volcánica, Instituto Costarricense de Electricidad, Apdo. 10032-1000, San José, Costa Rica. Tel.: +506 8369 3126.
E-mail address: katomirodriguez@yahoo.com (G.J. Soto).

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2000), with some exceptions as Ukinrek maars in Alaska in 1977 (i.e., Kienle et al., 1980). In America, maars are common volcanic features in flat and relatively dry areas, with local aquifers such as in Nicaragua (van Wyk de Vries et al., 2007, Freundt et al., 2010), the highlands of Bolivia (Francis and Oppenheimer, 2004), the Argentinean Puna (Petrinovic et al., 2005, 2006), Argentinean Patagonia (Corbella, 2004; Haller and Németh, 2006; Németh et al., 2007), and Andean Chile (Moreno and Lara, 2009). On the other hand, they are infrequent, not reported or poorly documented in some countries with Holocene volcanism in wetter areas, like Guatemala, Panama, Colombia and Ecuador.

In Costa Rica, the only relatively well studied maars are Hule and, to a lesser degree, Río Cuarto (Melson et al., 1988; Soto and Alvarado, 1989; Malavassi et al., 1990; Soto, 1990, 1999; Horn, 2001; Alvarado and Salani, 2002, 2004; Alvarado, 2006). There is another volcanic depression interpreted as a maar (called La Legua, 1620 m a.s.l.), on the northern flank of Barva volcano in a densely vegetated area (Soto, 1999), as well as a series of poorly studied explosion craters on the northern flank of Tenorio volcano (ICE-ENEL, 1990).

The aim of this paper is to revisit and reinterpret all previous work on Hule and Río Cuarto maars, based on the description of new volcanological, radiocarbon and archaeological data, for synthesizing the Holocene volcanic history of both maars. In addition, the records of occasional lake water overturns in both lakes are discussed. These events are characterized by sudden changes in water color (turning from blue to a reddish hue) and resulting in mass death of fish fauna, probably due to chemical and physical processes. Both crater lakes are a growing tourist attraction, and therefore a hazard approach is a relevant issue.

2. Methodology

Following the location and mapping of maar-related deposits in the field, a detailed description and measurement of stratigraphic sections was performed. Data on their internal structure, petrography, and texture were recorded. Seventy four stratigraphic sections of tephra deposits were measured (fifty four in Hule, twenty in Río Cuarto: Fig. 1). Most of the detailed stratigraphic sites are on roads, and artificial and natural erosional channels in an area that is covered by rainforest or pastures, and have developed thick soils.

Existing raw radiocarbon ages from publications and unpublished internal reports have been calibrated using the methodology of Stuiver and Reimer (1993), Bronk Ramsay (1995, 2001), Hughen et al. (2004) and Van der Plicht et al. (2004), according to their different age ranges.

As a novelty in Central America, the geographic and geomorphological parameters (i.e. length, maximum and minimum height of volcanic rims, area, perimeter and volumes) of the different volcanic features were obtained using a set of high resolution LiDAR images. These images were obtained during the course of an airplane flight in April 2009 by the Spanish company STEREOCARTO with an ALS50-II LEICA system. The resolution of these LiDAR images is three points per m^2, which is enough to create a digital elevation model (DEM) with a resolution of 50 cm in the x and y axis, and 15 cm in the z. The differences in altitude from the images and the benchmarks of the topographic maps are less than 11 cm. The high resolution of these data has allowed unprecedented resolution to identify volcanic features that were previously not recognized using standard photogrammetric techniques. These images were processed using the following commercial software packages: Quick Terrain Modeler, SURFER 9.0 and GLOBAL MAPPER 10.0.

A compilation of previous chemical analyses of rocks from Hule area has been done. The data have been plotted in a geochemical diagram for interpretations based on the stratigraphy, and to be compared to new petrographical analyses.

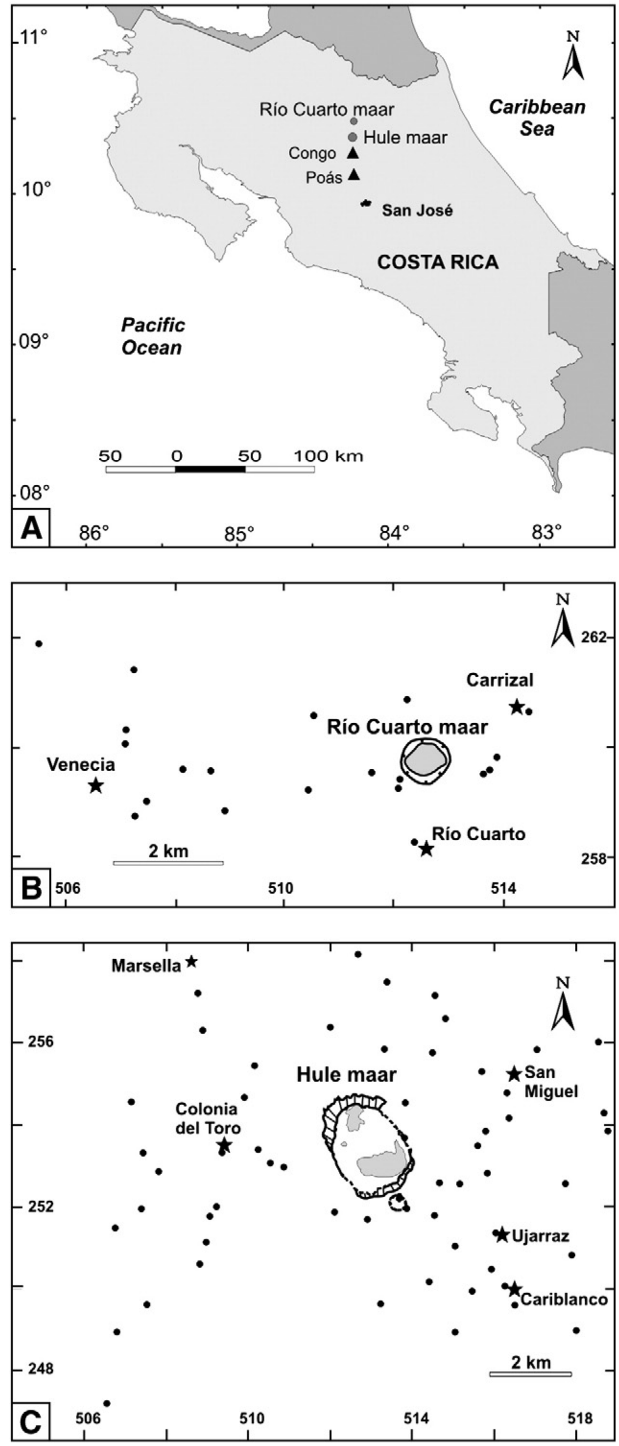

Fig. 1. A. Location of the two maars and main stratovolcanoes of the Poás massif. B. Río Cuarto maar, nearby towns (stars) and location of studied sections (dots). C. Hule maar, nearby towns and location of studied sections. Coordinates in figures hereafter are local *Lambert Costa Rica Norte*.

3. Geological setting

Hule and Río Cuarto lakes are located into maars, which are 11 and 18 km northward of the active crater of Poás volcano, respectively, on the Caribbean watershed of the Central Volcanic Range of Costa Rica (Fig. 1). The whole Poás massif has evolved, at least, in two stages (Paleo- and Neo-Poás) spanning about for the last 700 ka (Soto, 1999; Ruiz et al., 2010). Along the rift, basaltic andesitic to andesitic aphyric lavas have erupted during the last 200 ka, some of which formed smooth, flat lava fields with well-preserved lava flow fronts, around the Río Cuarto maar (Carr et al., 2007; Ruiz et al., 2010).

Hule and Río Cuarto maars lie on the northern part of Poás massif, along the 27-km-long fracture zone cutting Poás. This fracture zone starts with the Sabana Redonda cinder cones on the southern flank of Poás massif, through Botos cone, Poás active crater, Von Frantzius cone, and Congo stratocone, ending with the two maars (Fig. 2). The prominent N70ºW scarp of San Miguel, 200 m high, is located between Hule and Río Cuarto maars, which is interpreted as a thrust propagation fault-fold (Borgia et al., 1990; Soto, 1999). The original land surface around both lakes is rather flat, gently dipping northward from Hule before acutely dropping due to the presence of the San Miguel scarp toward the northern part. Slumping and debris sliding from crater walls have slightly changed the shape of both craters.

Both maars and their respective diatremes cut the mid to distal facies of volcanic sequences (aphyric lavas, pyroclastic and epiclastic rocks). The steep inner walls of the maars around the lakes are still covered by rainforest, while the outer areas beyond the rim of the basins, are mainly covered by coffee and sugar plantations and cattle fincas.

There have been several hypotheses on their origin. Sapper (1925) interpreted the Río Cuarto lake as an explosion crater. Besides, speculative information was printed in a local newspaper claiming a meteorite-impact origin for the round-shaped basin of the Río Cuarto lake (Salguero, 1978). Bergoeing and Brenes (1978), and Madrigal and Rojas (1980) proposed the term 'maar' for the Río Cuarto lake. Indeed, there is little obvious volcanic tephra present around of Río Cuarto crater lake, and therefore it was not described before. On the other hand, the Hule lake depression was originally interpreted as the result of the subsidence of a cone into a collapse caldera (Bergoeing and Brenes, 1978; Madrigal and Rojas, 1980; Tournon, 1984), and later interpreted as a maar (Soto and Alvarado, 1989). However, if we use the general definition of caldera, which means a volcanic depression larger than 1.5 km (Macdonald, 1972; Williams and McBirney, 1979), the Hule depression should be also referred as a maar caldera or as an explosion caldera.

There are some works dealing on the stratigraphy and age of Hule. Melson et al. (1988) dated a wood-bearing pyroclastic flow, which they interpreted as originated from the Congo volcano (southward from Hule maar; Fig. 2), in 5140 ± 110 ^{14}C yr B.P. Malavassi et al. (1990) extracted a sample of carbonized material supposedly associated to the last eruption of Hule maar, dated at 2730 ± 50 ^{14}C yr B.P. Soto (1990, 1999) mapped the surge deposits of Hule and surrounding volcanic deposits. Further research took upon such works, mainly to chronology (Horn, 2001), chrono- and tephra-stratigraphy (Alvarado and Salani, 2004; Alvarado, 2006), that included preliminary isopachs of tephra fall and surge deposits, and therefore sustaining that some deposits thought to belong to Congo, instead belong to Hule. Radiocarbon dates included in those words were better matched to the newly reconstructed tephra-stratigraphy.

Other studies on these lakes, such as on morphological, geochemical and limnological topics have been carried out by Kohkemper (1954), Umaña (1993), Gocke et al. (1987, 1990), Haberyan and Horn (1999), and Tassi et al. (2009).

4. The Hule maar

Hule is a subcircular volcanic depression (Fig. 3), with the major axis of 2.3 km and the minor axis of 1.8 km, for a total area of ~3.5 km^2. The walls range from 230 m high in the northern rim (978 m a.s.l.) to only 20 m high (777 m a.s.l.) in the southern rim, with variable slopes (27–45°). Two intra-maar pyroclastic cones are present, called Bosque Alegre, since it was thought to be only one

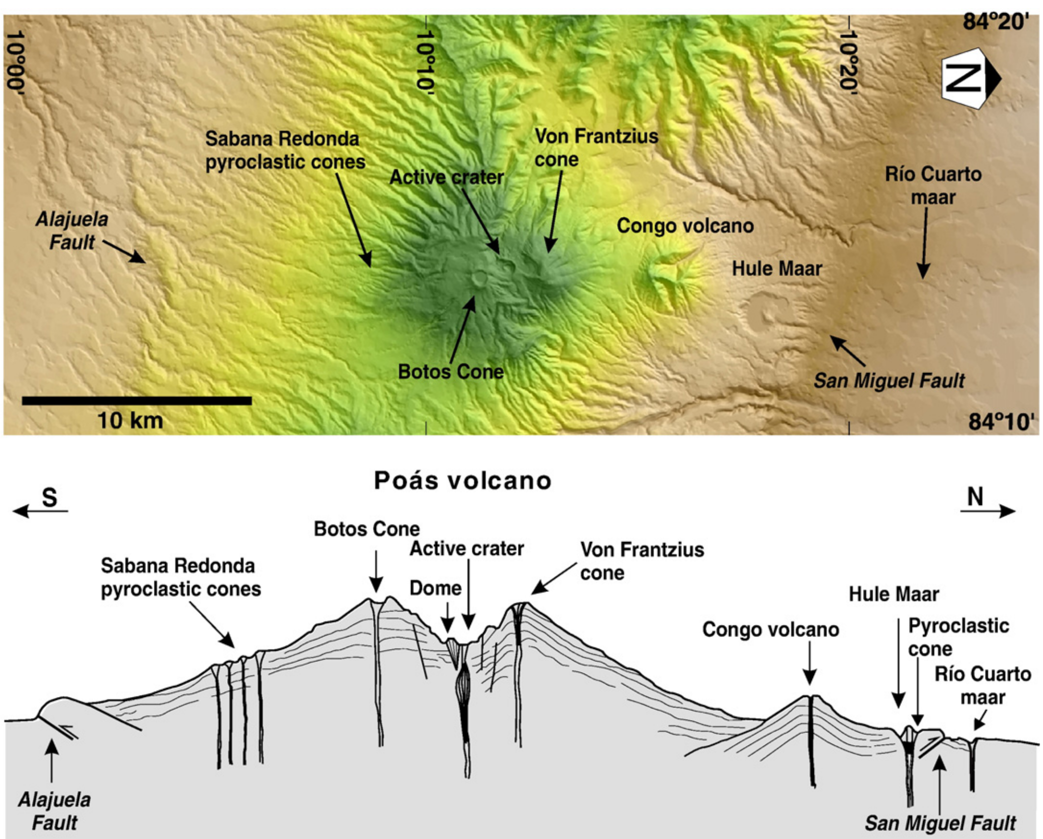

Fig. 2. Above: Map of Poás volcano massif showing the main structures. Below: Cartoon not to scale of the volcanic and main tectonic structures of the Poás massif, along a south-north profile.

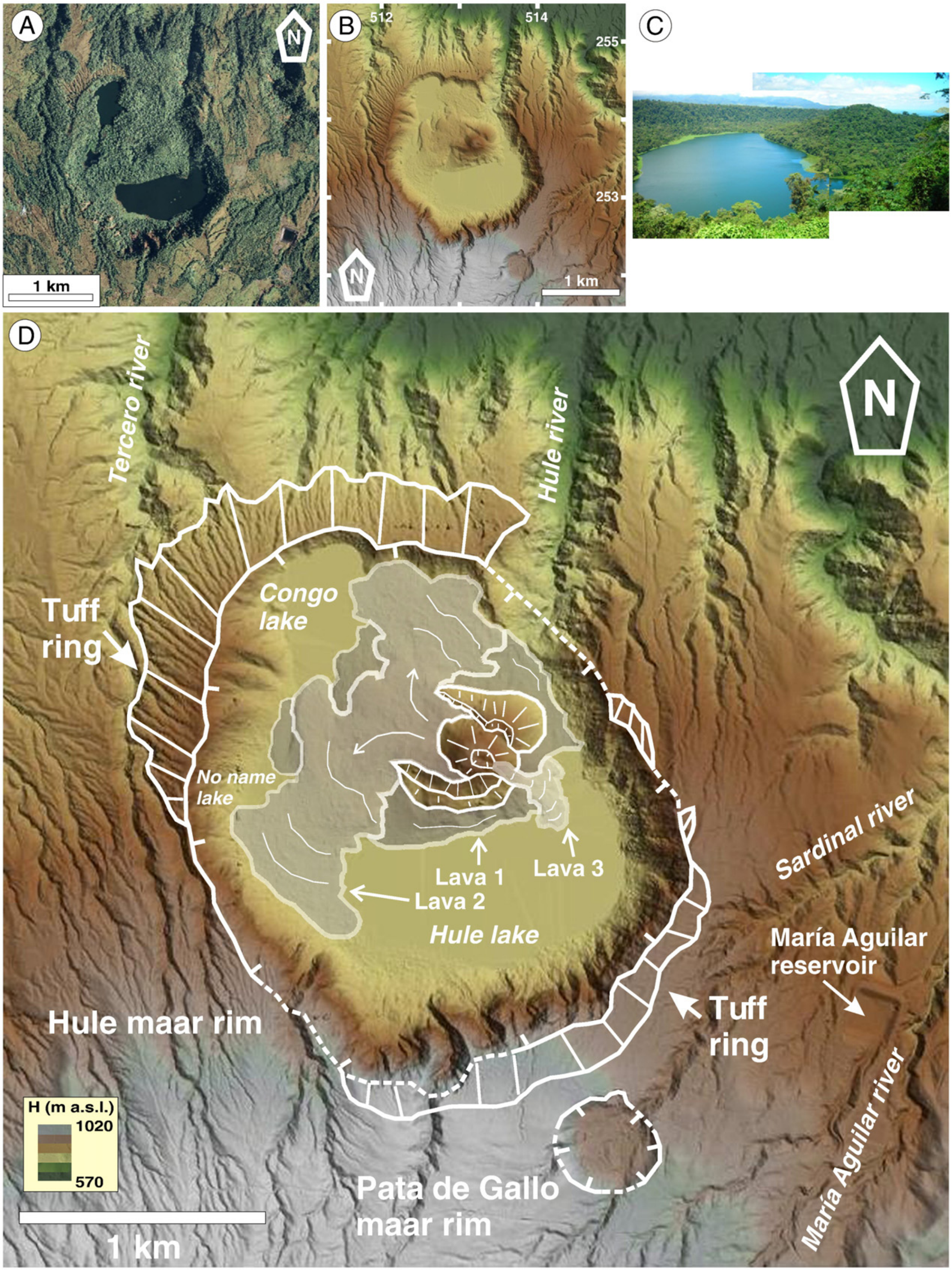

Fig. 3. Hule maar. A) Aerial photograph taken on April 2009. B) DEM from LiDAR images from April 2009. C) Photograph from the eastern rim, showing the densely-forested cones and lava fields. D) Interpretation of geological features.

cone. The detailed features have just been recognized with the new LiDAR images, and are clearly younger than the maar itself, because they are growing into it. The older cone shows part of the crater preserved, into which the younger cone, which shows a relatively well preserved crater (ca. 138 m high, 878 m a.s.l.) grew and one lava flow from it breached the eastern rim of the first cone. At least one lava field appears to be related to the first cone (Lava 1 in Fig. 3) and two lava fields to the second cone (Lavas 2 and 3 in Fig. 3).

Another maar (25–50 m deep), called Pata de Gallo or Los Ángeles, is 400 m in diameter and is located less than one kilometer of the southeastern rim of Hule maar (Fig. 3).

The Hule basin is presently occupied by three lakes (740 m a.s.l.; Fig. 3): Hule (54.7 ha, 26.5 m deep), Congo (14.9 ha, 14.6 m deep) and an unnamed one (0.6 ha, 4 m deep) (Horn and Haberyan, 1993). Hule lake overflows at its northeastern end, through the Hule river. Despite similarities in size and depth, Hule is stratified with elevated CO_2 in the lower part, while Congo is freely mixing from top to bottom and contained very little CO_2 when sampled in 1993 (Haberyan and Horn, 1999). In repeated measurements at Hule Lake, Umaña (1993) found surface water temperatures to vary between 22.2 and 26.5 °C, while temperature at 25 m depth varied between 20.9 and 21.4 °C, indicating a thermal stratification. He estimated a water volume of 6.9×10^6 m^3.

4.1. Tephrastratigraphy of Hule maar

The best exposures of the Hule deposits are on the rural routes between the villages of Ujarraz, San Miguel and Colonia del Toro (Fig. 4). The volcanic products from the maar explosion are mainly pyroclastic surges, silica-rich andesitic pumice flows, air-fall deposits, ballistic blocks, and reworked deposits that overlie the regional Pleistocene volcanic basement. A composite stratigraphic sequence is given in Fig. 4 (location of all sections is given in Appendix A). The stratigraphic exposures allowed to distinguish seven main different explosive facies, and two minor facies. The stratigraphy is described from base to top.

4.1.1. Basal organic debris (BOD)

It overlies the regional, well-developed, thick orange to brown soil. The first layer product of the Hule eruption is a black organic debris soil, rich in branches and big trunks (up to 20 m long × 1.5 m in diameter) partially charcoaled. It represents the original heavy-forested surface destroyed and covered by thick explosive deposits. The thickness varies from 0 to 2 m.

4.1.2. Sequence of pyroclastic flow and base surges 1 (SFS-1)

It overlies the BOD or the old paleosol. It is a complex sequence of coarse pumice lapilli and subordinate tuffs. The lowermost levels correspond to a brown tuff, followed by andesitic lapilli layers and a polymictic (pumice and blocks) breccia. The upper levels comprise block and ash deposits with vesiculated juvenile components, slightly vesiculated pumice and vesiculated or hydrothermally altered andesitic lithic fragments (10–30%) in a light gray ash matrix (30–65%). These upper levels show a coarse stratification defined by up to 5 layers.

Pumice flows were recognized 2.5 km away from the crater at Berros creek (section Rc27 in Fig. 4), composed by sub-rounded white and gray juveniles (DMax = 4 cm), immersed in a brown matrix, separated by a bed 4 cm-thick of medium to coarse ash. The lower section presents accretionary lapilli (1–3 cm) and lesser juvenile content. The upper

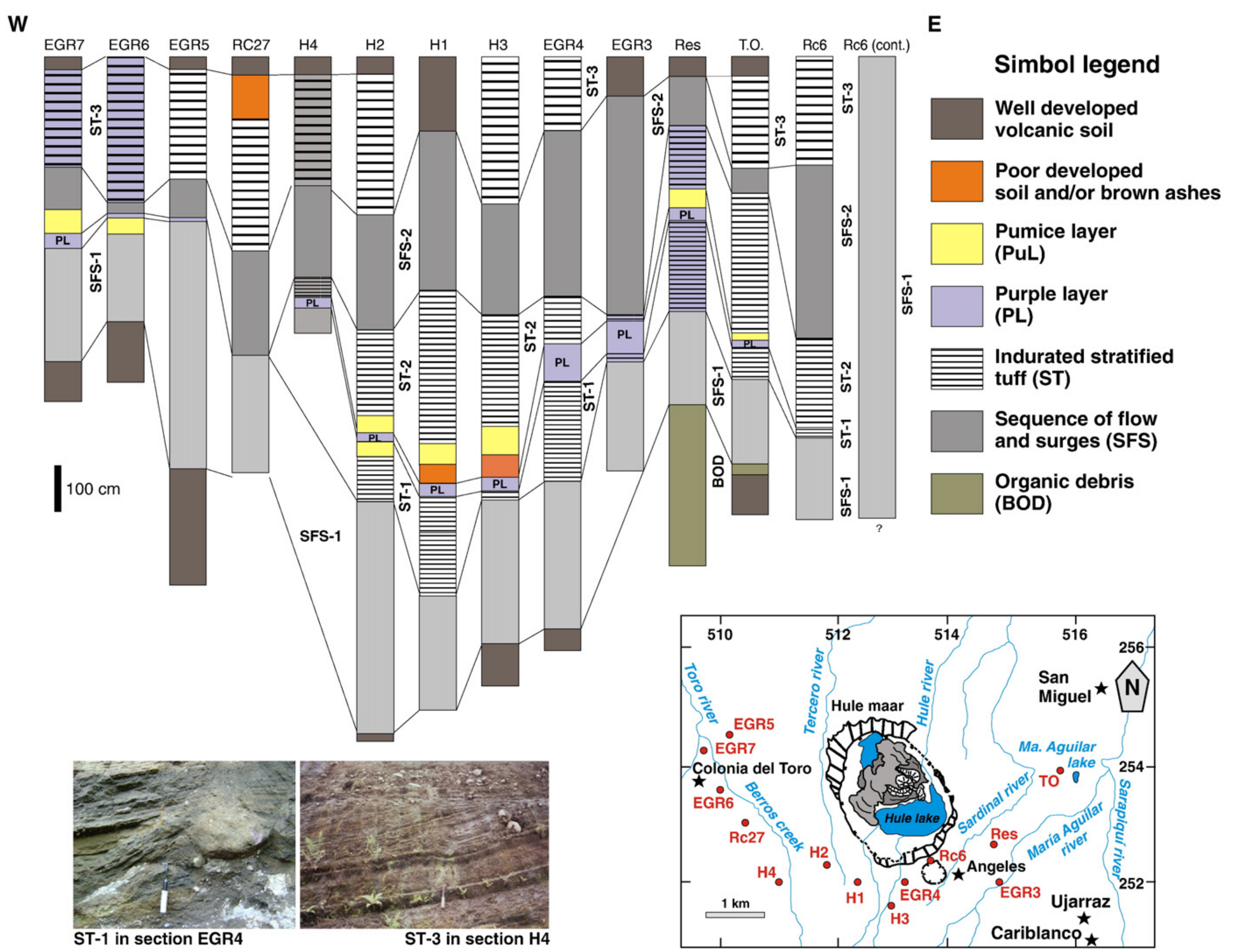

Fig. 4. Main Hule maar sections (coordinates in Appendix A) showing their correlation. Two facies are exemplified in the pictures.

section is light-gray to purple, followed by 1.5 m of a brown deposit with juveniles (DMax = 3 cm) and lithics (D = 3–8 cm), particularly at its base.

On the basis of the textural features, the juvenile lapilli layer with an open framework texture, rapid lateral thickness variation, and the presence of charcoal, can be interpreted as a dry and hot pumice pyroclastic surge (blast type) associated to pyroclastic flows. The explosion breccia in some sections resembles debris flows, while in other resembles pyroclastic flows, like an explosion breccia related to the opening of the maar.

4.1.3. Stratified tuff 1 (ST-1)

This deposit is only found toward the southern outskirts of the maar. It is composed of interstratified fine ash and lapilli tuff, with centimetric lithic fragments. Locally, a black ash layer with lithic fragments (10 cm maximum), and a strong lateral variation in thickness, can be found. The maximum thickness is 1.4 m. These characteristics suggest a genesis due to the lateral dilution of pyroclastic flows coeval with a dry pumice surge, maybe a blast.

4.1.4. Purple layer (PL)

It is a good strata marker, composed by a fine-grained plastic tuff to coarse-grained less plastic tuff, purple to pink-reddish color (therefore the informal name “purple layer”) and light brown lapilli tuff, containing some accretionary lapilli. It shows a diffuse normal lamination and stratification, oscillatory gradation and good sorting. It comprises of juvenile clasts, forming frequent ballistic impact structures. Its genesis is interpreted as a base surge.

4.1.5. Stratified tuff 2 (ST-2)

It is restricted to a narrow tephra fan, 3 km wide, extending less than 1.5 km SW of Hule Lake. It is a dark- to light-brown, medium to coarse tuff, with subangular lithics with locally parallel stratification and lenses of juvenile dense andesitic lapilli. It forms an indurated, stratified tuff with accretionary lapilli. Its thickness varies from 2 to 0.6 m, and varies laterally and upward to the overlying pyroclastic flow unit. It presents dune structures with wavelengths of 0.6–2 m. These features suggest pyroclastic flows, which locally grade into more diluted density currents or surges.

4.1.6. Sequence of pyroclastic flow and base surges 2 (SFS-2)

This deposit is composed of juvenile andesites (amphibole bearing) and sub-angular andesitic lithics, partially in grain-to-grain contact (60–75%). The matrix is poorly-sorted, fine lapilli and ash, reddish-brown to gray. The unit is interpreted as pyroclastic flows. At the base of some sections, there are ballistic blocks (35–85 cm in diameter). A medium size lapilli layer is present above, with pumice fragments, grain to grain texture and thickness ranging from 6 to 56 cm. This block and ash flow is partly overlain by another block and ash deposit, 60–300 cm thick. Coarse facies are massive or poorly stratified, grain-supported, white to gray and 1.7 to 5 m thick. The deposits show a wide granulometric and compositional span, different structures and thicknesses. These features can be interpreted as the coeval occurrence of block and ash flows, pumice flows, surges and possibly air and ballistic fall as simultaneously occurring processes.

4.1.7. Stratified tuff 3 (ST-3)

It is a widely extended sequence of fine to coarse tuff, densely compacted. It also has some vesiculated tuff and angular to subrounded, coarse to medium basaltic-andesitic lapilli. Stratified lapilli tuff shows planar, low angle and cross stratification, and erosion and filled structures, partially enriched in accretionary lapilli. Near Hule, the deposits show coarse grain and block sag structures, as large as 80 cm × 50 cm × 40 cm. Its thickness varies from 2.5 m in filled erosive channels, to less than 35 cm. These stratified tephras, interpreted as a sequence of surges, are cut by the same stratified tephra due to sin-eruptive or almost post-eruptive slides, tilted blocks, and slumps.

There are two additional minor deposits associated.

4.1.8. Pumice layer (PuL)

It is a light brown, well sorted, grain-supported deposit, composed of gray to white pumiceous lapilli. Some reddish and white isolated lithic fragments occur in the lower part. The proximal facies show isolated ballistic lithics (7–20 cm in diameter). This deposit is interpreted as an air-fall layer, and could have a minor lateral component as a blast. It is genetically associated to the “Purple layer”.

4.1.9. Lahar

A massive and chaotic deposit composed of andesitic cobles, rounded dark-gray vesiculated and poorly vesiculated juvenile andesitic fragments and charcoaled trunks in a volcanic sand, silt, and dark gray clay matrix. It could be interpreted as a hot lahar triggered by the Hule eruption. It is found in more distal sections.

The whole sequence is overlain by a well-developed brown volcanic soil with a thickness of several decimeters.

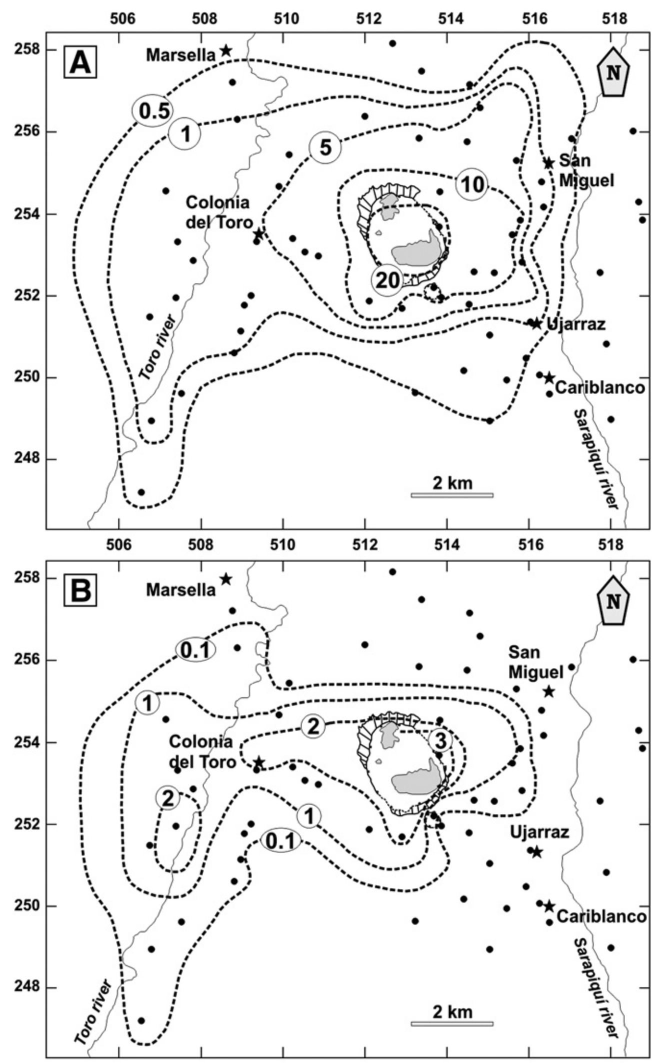

Fig. 5. Isopach maps of Hule maar deposits. A) The whole pyroclastic deposits, in meters. B) The pyroclastic surges, in meters. Main towns are shown by stars. The dots are the sections used for thickness measurements and stratigraphy.

4.2. Tephra map and volume estimation of Hule products

The outcrops around Hule maar have allowed drawing isopach maps. Isopleth maps were not made, because there is a mixture of dense blocks and broken juvenile clasts in the different gradational (lateral and vertical) facies.

The thickness distribution of the Hule tephra shows a clear radial and western pattern with minor lobes near the major rivers as Toro, and to a lesser extent in Sarapiquí (Fig. 5). Two maximum thicknesses in the upper surge deposit were identified in the isopach map (Fig. 5B). They are interpreted as being due to thicker pyroclastic surges near the source in the first case. The second and smaller case is interpreted as ash cloud-related surge deposition, displaced downwind and uphill along the canyon of the Toro river and tributaries. This latter case is typical for strong winds running upward into the valleys.

The minimum volume of pyroclastic deposits associated with Hule maar is estimated to be 0.37 km^3, which is the volume of the volcanic depression (calculated using the DEM), equivalent to the non-juvenile material erupted over the magma cap. The calculations obtained by the isopachs give a volume of eruptive products (flow, surge and fall) of around 0.51–0.53 km^3. The volume of the depression is hence ~0.7 of the total tephra volume for Hule, roughly meaning 70% of non-juvenile material. The last stratified layer (ST-3), related to the base surge and ash cloud fall-related deposit, represents about 0.1 km^3. Assuming 20–30% of porosity, thus 0.36–0.40 km^3 corresponds to dense rock equivalent (DRE), from which about ca. 20% are juvenile material, therefore 0.07–0.08 of new DRE magma.

4.3. Petrochemistry of Hule area products

Based on earlier chemical analyses, we present a wider appraisal of the maar formation. There are few petrographic and chemical analyses available of the Hule area (Fig. 6; Table 1). There are 4 analyses from the Hule intra-maaric cones and lavas (McBirney and Williams, 1965; Tournon, 1984; Prosser and Carr, 1987; Malavassi, 1991), and one from the juvenile andesitic pumice of the Hule tephras (Soto, 1999). There are eight other samples from this area, although without precise locations (Malavassi, 1991), of which five appear to be from the intra-maaric cone-lavas, one from the silica-rich andesites of Hule tephra, and two from the walls of the maar.

Hule's juvenile tephras are mainly poorly vesiculated andesites, showing blocky grains, with very small crystals of plagioclase. Some particles are characterized by planar and curviplanar surfaces. In the

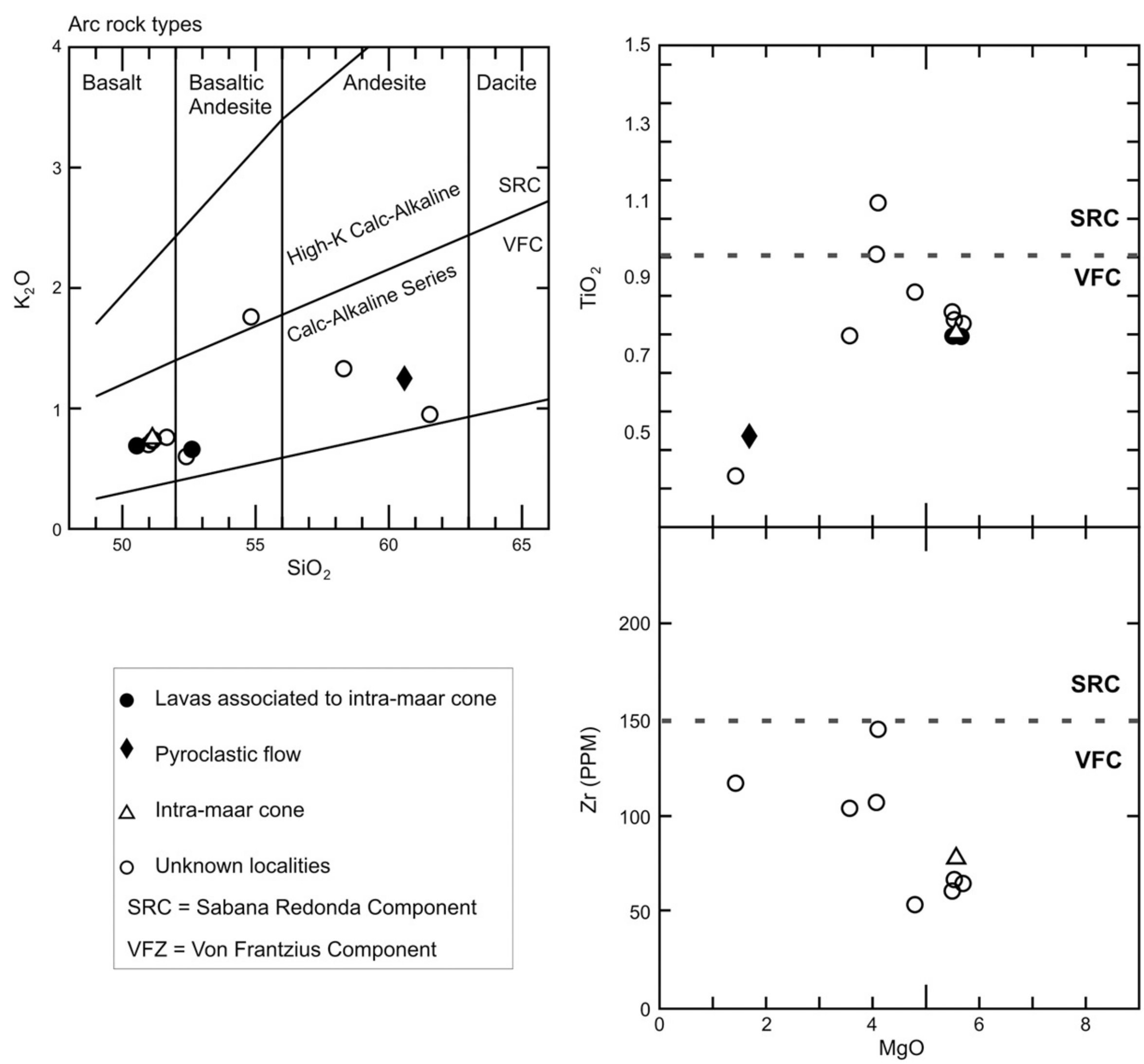

Fig. 6. Rock classification diagram for rocks from volcanic arc (based in Peccerillo and Taylor, 1976) for the Bosque Alegre Unit (Hule maar deposits and intra-maar cones), and variation of TiO_2, and Zr in function of Mg for series characterization. Major elements in %, trace elements in ppm.

Table 1
Chemical analyses. Major elements in%.

Sample	PO2	P001	2	3	PO9	69	123	68	244	150	592	182	141
SiO_2	51.13	50.54	51.18	52.61	60.59	51.56	51.67	51.13	50.98	54.83	52.4	58.31	61.64
TiO_2	0.75	0.73	0.82	0.74	0.47	0.77	0.78	0.8	0.85	1.08	0.95	0.74	0.38
Al_2O_3	19.64	18.83	18.89	18.44	17.65	19.16	18.97	19.18	19.05	16.64	20.74	17.85	19.46
FeO	8.99	5.35	5.11	5.16	5.43	–	–	–	–	–	–	–	–
Fe_2O_3	–	4.62	4.01	4.12	–	–	–	–	–	–	–	–	–
Fe_2O_{3T}	–	–	–	–	–	10.14	9.96	10.28	11.36	10.32	11.41	8.26	6.05
MnO	0.18	0.19	0.17	0.17	0.18	0.17	0.17	0.18	0.18	0.17		0.15	
MgO	5.55	5.55	5.33	5.47	1.63	5.64	5.48	5.44	4.74	4.06	4.04	3.54	1.42
CaO	9.61	9.39	9.61	9.43	5.99	9.61	9.49	9.8	9.69	8.22	7.76	7.03	6.24
Na_2O	2.89	2.35	2.57	2.47	3.80	2.46	2.57	2.33	2.3	2.66	2.2	2.65	3.56
K_2O	0.75	0.69	0.94	0.66	1.25	0.74	0.76	0.73	0.7	1.76	0.6	1.33	0.95
P_2O_5	0.16	0.3	0.24	0.44	0.27	0.14	0.16	0.14	0.15	0.27	0.25	0.12	0.39

PO2: intra-maar cone, Prosser and Carr (1987).
P001: intra-maar lava, McBirney and Williams (1965).
2 and 3: lava cone, Tournon (1984).
PO9: Hule pyroclastic flow, Soto (1999).
Samples from unknown localities (69, 123, 68, 244, 150, 592, 182, 141), Malavassi (1991).

same fraction are euhedral crystals of mafic minerals (amphibole) and minor amounts of magnetite.

The dense (poorly vesiculated) “pumice” from Hule pyroclastic flows is an amphibole-bearing andesite (60.59% SiO_2), with plagioclase and clinopiroxene phenocrysts, immersed in a glassy matrix with tiny plagioclase and apatite microlites. Levels of fine tephras from Hule also constituted of andesite juveniles and glassy fragments with planar and curviplanar surfaces, euhedral crystals of mafic minerals and minor amount of oxides represented by magnetite.

On the other hand, the intra-maaric lava flows are high-Al basalts to basaltic andesites (50.54–52.61% SiO_2; 18.44–19.64% Al_2O_3) with plagioclase as dominant phenocryst (17–25%), followed by olivine and clinopyroxene in the same proportions (2–4%), and less abundant opaques (1–2%). The groundmass (65.5–75%) ranges from intergranular to intersertal, dominant in microlites of plagioclase and Fe-Ti oxides, and less abundant clinopyroxene, olivine, hematite and interstitial brown glass.

The rocks classify as low to medium in K in the calc-alkaline series, ranging from basalts to andesites (Fig. 6). Two samples (150 and 182 in Table 1) from unknown localities (Malavassi, 1991) may be from the maar wall, and are also plotted in the diagram for comparison. They fit in the basalt–andesite trend defined by intra-maar rocks and pyroclastic flows and partially cover the compositional gap in between these rocks.

Based on the geochemistry of rocks from the Poás massif, Ruiz et al. (2010) defined the Von Frantzius Component (VFC) and the Sabana Redonda Component (SRC). According to the geochemistry of the Bosque Alegre Unit (deposits from Hule maar and intra-maar cones), it is part of the VFC. Some of the characteristics present in these lavas are: the levels of $TiO_2 < 1\%$, P_2O_5 contents $<0.2\%$, low values for trace elements like Ba, Nb and Zr compared to SRC, which presents higher values of these elements (Fig. 6).

4.4. Age constrains on the formation and activity of Hule maar

Thirteen radiocarbon dates related to Hule maar events and one to Congo volcano have been published (Table 2; Fig. 7). According to Malavassi et al. (1990) and Horn (2001), the most plausible age for the Hule maar formation is around 2.7 ka. We disagree with that age interpretation. Our own research results suggest that no significant pyroclastic activity from Congo volcano occurred since 35.6 ka and, most remarkable, it has been clarified that the pumiceous pyroclastic

Table 2
Radiocarbon ages of Hule, including core sediment ages from Hule and María Aguilar lakes.

Source, sample number	Sample description and location	Radiocarbon age (a)	Calibrated age (b)	Average CAL age (c)	Calibrated age (d)	Average CAL age (f)
Malavassi et al. (1990)	Charcoal, Congo tephra	30 580 ± 660	–	–	35600 ± 600 (e)	35600
Horn (2001) A-5129	Bulk sediment, base of Core 1, Hule lake	7580 ± 90	8190–8550	8370	8193–8545	8369
Horn (2001) B-34039	Bulk sediment, base of Core 3, Hule lake	6910 ± 90	7590–7940	7765	7594–7879	7737
Hurtado de Mendoza (2006) A-13649	Wood, Los Higuerones site, base of Holocene explosive sequence	5390 ± 45	6170–6290	6230	6172–6289	6230
Soto (1999)	Wood, pyroclastic deposit, Berros creek	5330 ± 130	5750–6400	6075	5886–6355	6120
Melson et al. (1988)	Wood, pyroclastic deposit, Higuera creek	5140 ± 110	5650–6200	5925	5653–6182	5917
Alvarado and Salani (2004)	Wood in lahar deposit, presumed to be associated to andesitic pyroclastic flow	5110 ± 80	5650–6200	5925	5651–6004	5827
Horn (2001), ß-30430	“Surface sediments” Hule	3230 ± 80	3320–3650	3485	3321–3641	3481
Horn (2001), ß-56233	Wood at 2.66 m in Core 3, Hule lake	3080 ± 70	3450–3070	3260	3136–3445	3290
Malavassi et al. (1990)	Wood, Hule tephra deposit	2730 ± 50	2750–2950	2850	2753–2929	2841
Horn (2001), ß-73925	Leaf, at 1.45 m in Core 3, Hule lake	1250 ± 60	1050–1300	1175	1056–1293	1174
Horn (2001), ß-73926	Leaf, at 2.94 m in Core 3, Hule lake	2230 ± 60	2100–2350	2230	2112–2350	2231
Horn (2001), OS-4412	Leaf above ash at 0.5 m from base of Core 1, María Aguilar lake	2520 ± 30	2650–2480	2560	2488–2644	2566
Horn (2001), ß-56234	Wood fragments at base of Core 3, María Aguilar lake	2610 ± 70	2870–2460	2665	2470–2864	2667

(a) ^{14}C years B.P.
(b) CAL years B.P. 2-sigma range (Bronk Ramsay, 1995, 2001).
(c) years B.P.
(d) CAL years B.P. 2-sigma range (Stuiver and Reimer, 1993; Hughen et al., 2004).
(e) using the graph of Van der Plicht et al. (2004).
(f) years B.P.

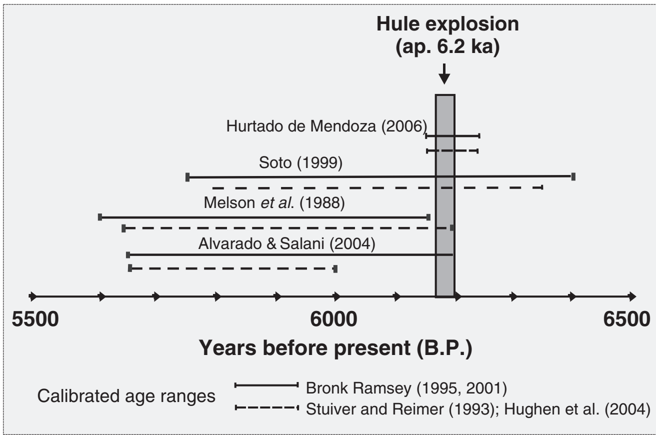

Fig. 7. Summary of the ages for Hule explosion according to the reinterpretation of data from different authors. The graph shows calibrated ages and the associated uncertainties and the best fit from all, for the age of the maar formation.

flow sequence previously attributed to Congo volcano (Melson et al., 1988; Malavassi et al., 1990; Soto, 1999), is rather associated to the Hule explosive events, according to the distribution and isopachs of the deposits. The calibrated ages are around 6.2 ka, obtained from wood fragments and charcoal into the pyroclastic flows of Hule, or in epiclastic deposits related to them (see Table 2 and Fig. 7). The oldest sediments into Hule lake give ages slightly older than Hule lake formation (calibrated ages of 7.7–8.4 ka from C-14 ages from Horn, 2001). It is speculated that these ages are affected by gases or some other process into the lake, changing the ^{14}C ratios (Horn, 2001). The samples dated by Malavassi et al. (1990) and then calibrated at 2.8 ka, were obtained in the surroundings of Pata de Gallo maar, and therefore, it seems that this crater would be well correlated to this age. Thus, the age formerly attributed to Hule maar actually corresponds to the younger Pata de Gallo maar, which in fact cut the Hule tephras. Younger thin pyroclastic layers obtained from drilled cores into the Hule lake, dated in 1.7 and 0.67 ka by Horn (2001), would be related to eruptions from the intra-maaric cones. These ages are in agreement with the geoarchaeological data presented in Section 5.3.

5. The Río Cuarto maar

The Río Cuarto lake (361 m a.s.l.) is also known as the *Laguna de los Misterios* ("Lake of Mystery", probably due to its relative seclusion and its characteristic periodic and unexplained phenomena of mass fish death), *Laguna Kopper* (after the landowner's family name), *Laguna Yurro Hondo* or *Río Hondo* ("Deep Ravine"). It is into a crater with a rim that reaches some 52 m above the water level (412 m a.s.l.; Fig. 8). The crater rim has an E–W axis of 847 m, a mean width of 707 m, and the lake has an E–W axis of 758 m, a mean width of 581 m, and a surface of 0.33 km^2.

The lake has a maximum depth of 66 m, making it the deepest natural lake in Costa Rica (Horn and Haberyan, 1993). A bathymetric study by Gocke et al. (1987) showed a mean depth of 45.5 m, corresponding to a water volume of 15×10^6 m^3. Surface water temperature has been observed to vary between 24.6 and 29.9 °C, whereas the temperature of the hypolimnion at 60 m fluctuates only between 24.2 and 24.4 °C (Gocke et al., 1987, 1990; Haberyan and Horn, 1999). The depth of the boundary layer between the oxic and anoxic water bodies varies between 25 m (January–February) and 20 m (May–June). About 55% (mean value) of the total lake water body is permanently anoxic (Gocke et al., 1987).

5.1. Tephrastratigraphy of Río Cuarto maar

Río Cuarto's juvenile tephras are poorly vesiculated andesites with plagioclase microlites, and phenocrysts of euhedral amphiboles and magnetite. The fragments show angular shapes and irregular surfaces.

The Río Cuarto deposits have been found in the flatlands extending from the Río Cuarto town towards the city of Venecia, and some neighboring areas (Fig. 9). At Río Cuarto maar and surroundings, the stratigraphical sections allowed distinguishing two main facies related to the maar: a surge and coeval ballistic blocks area and an air-fall area (Fig. 9). The composite stratigraphic sequence is given in

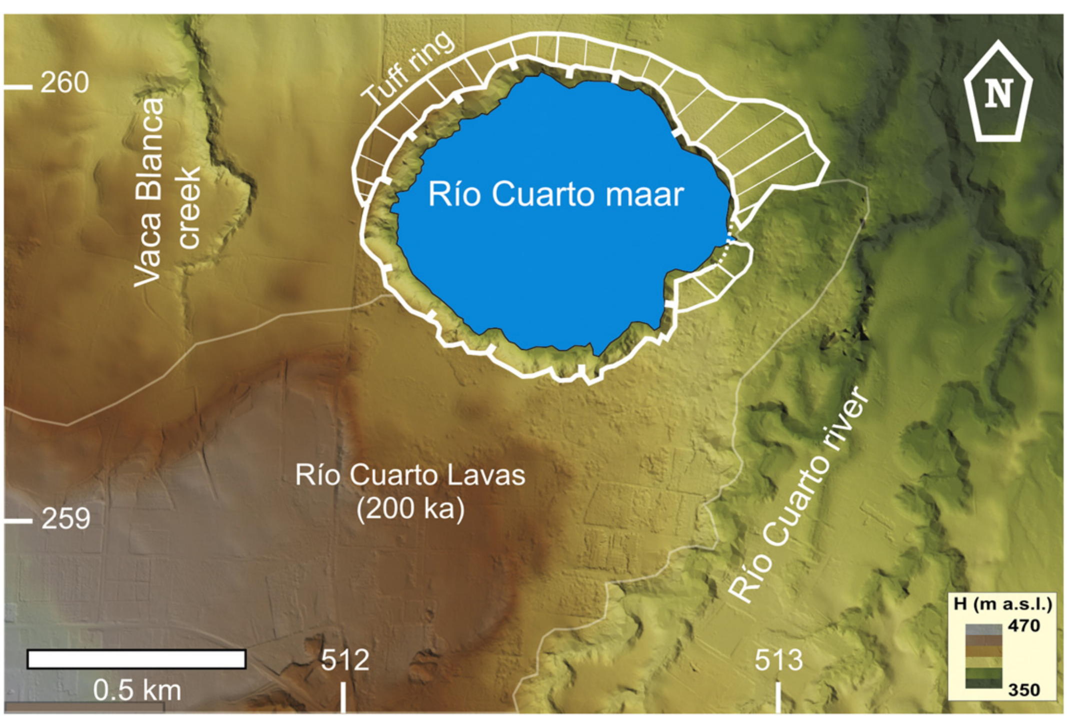

Fig. 8. Río Cuarto maar. DEM from LiDAR images from April 2009. The geological features are shown, as well as their relationship to the Río Cuarto Lavas (200 ka), which front is marked by the thin white line.

Fig. 10 (location of all sections is given in Fig. 9 and in Appendix A), and shows three different explosive phases, subdivided in several other sub-phases.

The near-crater proximal facies (Figs. 9 and 10), overlie a brown paleosol. The lowermost sequence comprises the air-fall lapilli, minor ballistic blocks and ash, and surge ashy layers relatively rich in lithics. It is overlain by a grain supported volcanic breccia, composed of coarse lapilli and large andesitic ballistic blocks from the country rock (up to 3 m across), that is inter-layered with both base surge and air-fall (including minor ballistics) clasts. The uppermost sequence mainly comprises the air-fall layers of lapilli and blocks, a minor layer of pumice, and subordinated and alternating planar and cross bedding base surge layers.

There is a transition between the proximal and distal area. In this latter (Figs. 9 and 10), only air-fall deposits can be recognized, characterized by an inter-layering of at least three gray hardened ashes and lapilli, and three brown loose ash-and-lapilli layers.

5.2. Estimation of tephra volume of Río Cuarto products

The tephra deposits related to Río Cuarto show a clear narrow fan oriented westward (Fig. 9), according to westerly trade winds, indicating as well, a laterally-directed surge (first 2 km, as discussed above). It has not been possible to draw isopach maps for Río Cuarto deposits. Isopleth maps were not made either, because there is a mixture of dense blocks and broken juvenile clasts in the different facies.

The volume of the Río Cuarto depression is about 3.1×10^7 m^3. As we have no isopach volume for Río Cuarto, using the same proxy as for Hule (volume of depression is 0.7 the total tephra volume), we could have 4.4×10^7 m^3 of total tephra, of which about ~25% corresponds to porosity (3.3×10^7 m^3) and 25% of that total is juvenile, which makes 0.008 km^3 of new DRE magma.

Using the empirical formula of Sato and Taniguchi (1997) for estimating the volume of erupted tephra on the basis of crater diameter, we obtain 2.2 km^3 and 0.1 km^3 for Hule and Río Cuarto, respectively, 3–5 times larger than the volume deduced by the isopachs in both cases. It could be that crater diameters have been enlarged during multistage subsidence phases along nested ring fractures and so, the actual diameters are larger than the original ones. Alternative explanations are that the deposits have been significantly eroded, or soils have made them unidentifiable. However, since all possibilities are unlikely in the way that only one third to one fifth of the tephra produced would have been preserved, such empirical formula seems not to be applicable in these two cases.

5.3. Geoarchaeology age constrains on the formation and activity of Río Cuarto maar

There are no ages available yet for dating the formation of Río Cuarto maar. However, important clues are provided by archaeological settlement pattern data.

Using archaeological data for deciphering volcanological age uncertainties or vice versa has been a matter treated by several researches, and have shown to be very useful in tropical areas of the Olmec and Mayan areas in Mexico and Central America (e.g., Ford and Rose, 1995; Delgado et al., 1998; Siebe, 2000).

Archaeological research in the Hule-Río Cuarto area has been performed since the 1960 s. Such research was mainly based on the study of single sites, some of them of substantial importance. These sporadic efforts have been complemented by undergoing research, initiated in 2003, linked to the construction of two hydroelectric power plants (called Cariblanco and Toro 3) by the Costa Rican Institute of Electricity (ICE). This has allowed for the discovery and compilation of stratigraphic evidence from an important number of new archaeological sites. Archaeological discoveries, in most of these sites, are underlain, separated or sealed by natural layers, some erosional in origin, others of volcanic origin. Although it is not possible to discard the implications of other natural and socio-cultural factors, it seems that both the burial of archaeological deposits and the regional arrangement of human settlements in the region, are linked to the history of volcanic activity of Río Cuarto and Hule maars.

Most cultural components of prehispanic age in the Hule-Río Cuarto region are well known. Their relative chronological position does not differ significantly from the cultural sequence of the Caribbean watershed of Costa Rica (i.e. Hurtado de Mendoza, 2004). Also, each cultural phase is marked by distinct material remains.

The correlation between archaeological settlement patterns data and the volcanic activity of Río Cuarto is examined under the rationale that people in the past have tended to colonize and settle areas around a volcano in the absence of eruptive activity. Counter-wise, in the face of volcanic violent activity, people would move away from the erupting source. Another possibility is that indurated pyroclastic deposits such as those produced by maars, would prevent the land use for long periods, since the soils are slowly developed and would be less fertile for long periods than others not affected by such kind of phenomena. It seems reasonable to expect then, that the response to eruptions would be archaeologically registered as increasing distances of human settlements from volcanic sources.

The archaeological record for this area includes 49 sites. Most of these are multi-component (i.e. occupied over two or more cultural

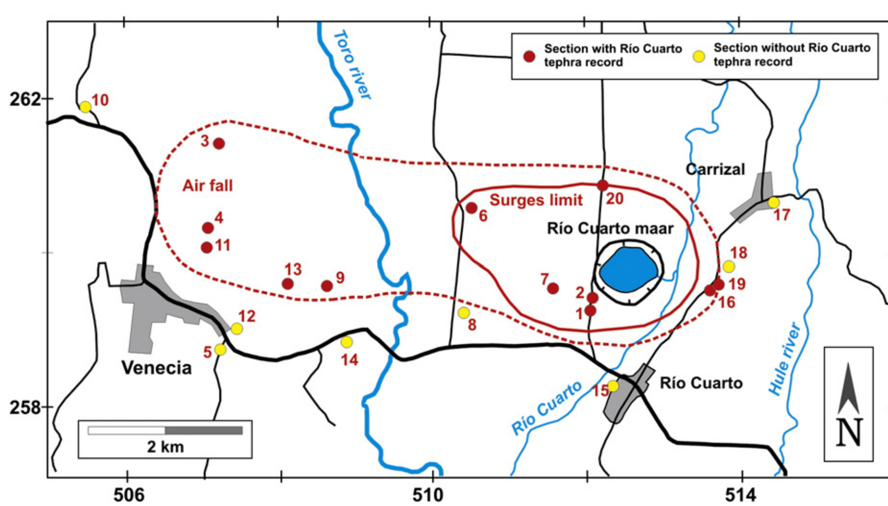

Fig. 9. Río Cuarto maar, main villages in the surroundings, the tephra sections studied (coordinates in Appendix A, LRC 1-20) and interpreted limits of the surge and air-fall deposits.

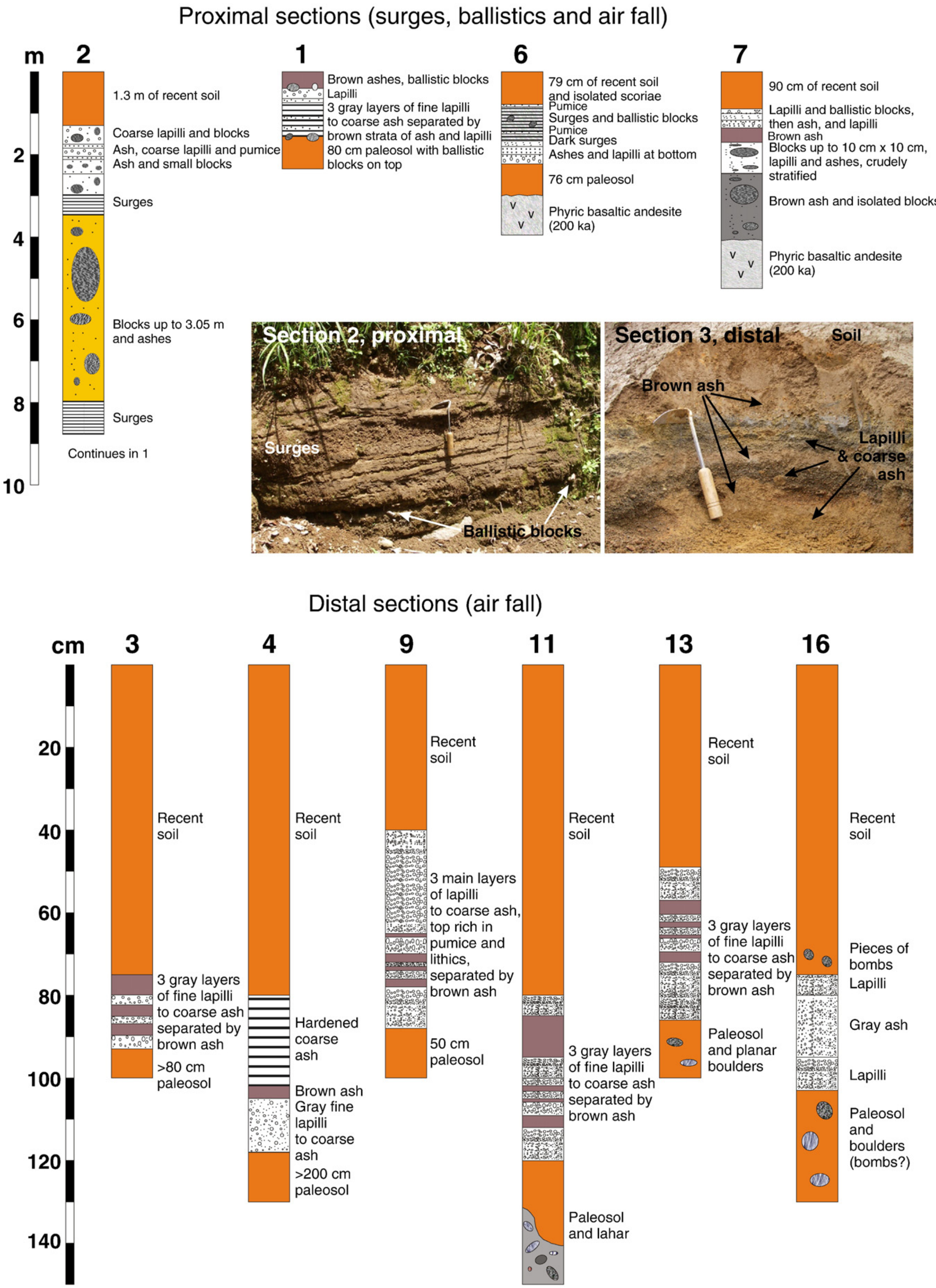

Fig. 10. Main Río Cuarto maar sections. Numbers refer to localities in Fig. 9.

Table 3
Cultural phases exemplified in the Río Cuarto - Hule region by ceramic complexes and their chronology.

Cultural phase	Ceramic complexes	Chronology* (yrs B.P.)
Late Chiefdoms	La Isla/Ujarrás-2	1200–500
Early Chiefdoms	La Selva/Ujarrás-1	2200–1200
Late Formative	Burío/Cariblanco	3000–2200
Middle Formative	La Montaña/Chaparrón	4000–3000

* From Hurtado de Mendoza (2004).

phases). They belong to both pre-ceramic and ceramic times. For the purposes of this work, only sites of the ceramic stage (4.0 ka B.P. and younger) will be considered. Pre-ceramic evidence around the neighboring Hule region is scarce, mainly due to their burial by the thick 6.2-ka-Hule deposits, or because they were precluded to settle by the hard consolidated deposits. The settlement patterns corresponding to four pre-hispanic ceramic phases are now better understood. These cultural phases, together with their respective ceramic markers and their corresponding chronological spans are herein detailed (Table 3, Fig. 11). The sites are ranked A or B according to the higher or lower quality of archaeological remains, respectively.

The available sample of settlements from the Middle Formative period (4000–3000 years B.P.), includes 13 sites. Settlements associated to Río Cuarto are located at an average distance of 4.7 km from it, whereas those in the Hule area of influence are at an average distance of 3.1 km from the maar. These differences could be interpreted as evidence of confidence on the part of human settlers regarding Hule, while avoidance was the case with respect to Río Cuarto during Middle Formative times. Seemingly, this trend became more emphatic during the Late Formative (3000–2200 years B.P.). Hule still enjoyed the former confidence projected on human settlers (average distance of 2.7 km), while those in the area of influence of Río Cuarto became scarce and much more distant (average distance of 5.9 km).

This would suggest that an episode of volcanic activity originating in Río Cuarto took place sometime around 3 ka B.P. or earlier (3–4 ka).

Río Cuarto maar appears to have become dormant afterwards, since colonization of its neighboring area occurred during the Early Chiefdoms phase (2200–1200 B.P.), while the occupation of areas close to Hule continued and increased, but still not westward. It is remarkable that the areas westward from both maars were less settled, something that seems to be logical since most hard tephras were directed westward and hence, were less susceptible to develop into fertile soils for a while.

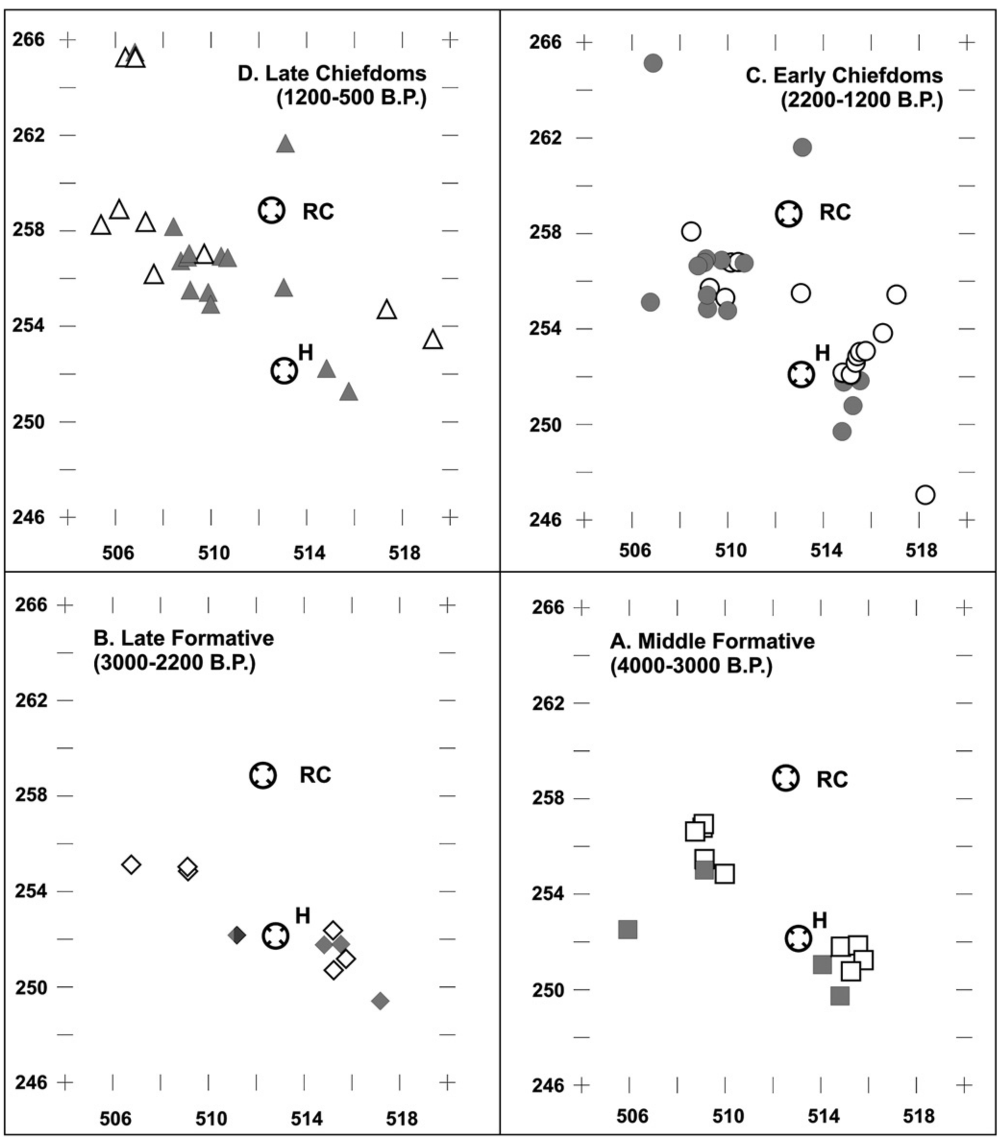

Fig. 11. Archaeological settlements according to cultural phases in the Hule-Río Cuarto (A to D in chronological order). RC is Río Cuarto maar; H is Hule maar; open symbols are Rank B sites; filled symbols are Rank A sites (see text for explanation of A and B). Local coordinates (*Costa Rica Lambert Norte*), ticked every two kilometers. North is upward.

During the Late Chiefdoms phase (1200–500 B.P.), an important change in settlement patterns is registered. While sites in the area of influence by Río Cuarto appear to maintain their traditional locations, this is not the case for Hule. Here, the number of sites is drastically reduced and the remaining A-ranked sites take a considerable longer distance from the Hule source. This might correspond to mild volcanic activity in which Hule was involved, as calibrated radiocarbon dates also suggest, with eruptions around 1.7 and 0.67 ka B.P., maybe during the emplacement of the lava fields and cones into the maar.

6. Intra-maar lake overturn events: volcanic and/or limnological origin?

Local people have reported the occurrence of fish killing and changes in the color of the Hule and Río Cuarto lakes since the first published mention of these phenomena at Río Cuarto by Sapper (1925). He reported that in 1924 the lake had a temperature of 23 °C, and that a local informant sustained that on Sunday 30th, May of 1920 at 1 p.m., a black and then white smoke rose from the central part of the lake.

It seems that in Río Cuarto lake, at the beginning of some years, the green water adopted a yellow-reddish coloration accompanied by massive fish mortality. As Gocke et al. (1987, 1990) pointed out, the wind cannot play a larger role, but only a minor role in the mixing process, since the lake is well sheltered by its relatively high and steep rims. They proposed that a possible explanation could be that long periods of anomalously cold weather (in December-January-February), combined with extremely strong winds, favored in cooling the surface and making it denser, and then the lake overturned. As a result, hypolimnetic Fe^{2+} mixed into the epilimnion, which was then oxidized to insoluble yellowish $Fe(OH)_3$, producing a very low oxygen concentration. The lake waters may have overturned at least once between 1978 and 1991 (Haberyan and Horn, 1999). Recent oral communications from the owner of the land where the lake sits reveal that such events occur every 6–7 years. The most recent event has been witnessed in February of 2010.

According to local inhabitants around Hule lake, at least 4 or 5 events of lake overturn likely occurred during the last four decades: prior to 1989, sometime between 1991 and 1996, in January 1996, and the last between December 2001 and January 2002. These lake overturn events are marked by sudden color changes (from dark blue to red), turbid water, odorous, and large-scale fish-death events (Gocke et al., 1987, 1990; Soto, 1999; Alvarado, 2006). Seemingly, even birds become eventual victims (Tassi et al., 2009). At Laguna Hule, episodes of lake turnover are likely to occur when the air temperature is relatively cold and the weather is rainy and windy, so it is expected for the lake to mix deeply between December to February. A deeper mixing of the water column was observed in Hule lake during February 1991. The red coloration at that time was due to the presence of dense purple clumps or masses floating of *Merismopedia* cf. *chondroidea*, which grow in the upper surface of the anoxic layer. At Hule and Congo lakes, the pH varies between 6.22–7.31 and 5.40–6.47, respectively, being slightly acid almost all the time, even at the surface. The low pH might be in part the result of the volcanic origin of the lake and its catchment area (Umaña, 1993; Haberyan and Horn, 1999; Tassi et al., 2009).

Hule was stratified at 5.1 m and its deep water was more concentrated in CO_2 (65 ppm) than any other lake tested, though levels were not high (Umaña, 1993; Haberyan and Horn, 1999; Tassi et al., 2009). The relative small increase of CO_2 with depth suggests that the lake is stratified, and it could be ascribed to degradation of organic material in agreement with the relative high concentration of N-compounds along the whole vertical profile, typically produced by bacterial activity (Gocke, 1997). However, the interpretation of radiocarbon dating of bulk surface sediments and core samples indicates that isotopically dead carbon entered into the lake (Horn, 2001), suggesting that CO_2 is released into the lake from a deep source, although at relatively low amounts when considering the low percentage of the measured CO_2. This hypothesis is consistent with the lack of CH_4, whose production by bacteria is favored at reducing conditions, such as those dominating the Hule deep water strata (Tassi et al., 2009). In fact, around Hule lake, there are several reports of CO_2 bubbling in cold and hot springs, and caverns with high concentrations (Sarapiquí, Sardinal and Toro rivers, see Fig. 4), or even in sufficient volumes to be extracted commercially through boreholes. At Recreo Verde hot spring (some 4 km southwest from Río Cuarto and 5 km northwest from Hule), the gas chemistry indicated variable quantities of CO_2 and other volcanic gases (Zimmer et al., 2004). In addition, under the construction of the tunnel of the Cariblanco hydroelectrical project (~6 km to the southeast of Hule), 21 workers were temporally affected (September 19 to October 8, 2004) with the gases, particularly CO, and variable quantities of SO_2, HCl, and CH_4 (Alvarado et al., 2007). The accumulation and emanation of those gases in some periods, could be an additional factor for the mortality of animals during these events.

Thus, the question that arises is whether massive fish mortality is due to the mixing of oxygenated and anoxic waters and/or accumulation or sudden emission of volcanic gases. In any case, the dimensions of these reservoirs are limited by the continuous gas dispersion through the lake surface, which is favored by the dominant convective regime resulting in frequent mixing of water strata. Therefore, in these systems the hazard related to the possible occurrence of Nyos-type gas eruptions (i.e. Kusakabe, 1996) can be considered negligible or very local (see Table 4 for comparison), but important if tourists camp in or near the lake shoreline.

7. The generation of Hule and Río Cuarto maars

The eruptive history of Hule maar began ~6.2 ka when a silica-rich andesitic magma ascending through a weak crustal zone reached the regional groundwater table, 200–300 m deep (~500–600 m a.s.l.). The interaction of this volatile rich magma with the water table generated phreatomagmatic eruptions.

Three different eruptive stages are identified. The first eruptive phase is represented by the opening of the crater with the simultaneous formation of a pumice blast, pyroclastic flows and phreatomagmatic fall breccias. This phase destroyed the heavy dense rain forest and, as a result, an organic debris level was formed at the base (BOD), covered later by the thick explosive deposits (ST-1 and SFS-1). Later, at the beginning of the second phase, a minor explosive

Table 4
Comparative characteristics between Hule and Río Cuarto (Costa Rica), and Nyos (Cameroon) lakes.

Characteristic	Hule	Río Cuarto	Nyos (Camerún)
Volcano type	Maar	Maar	Maar
Lake area (km^2)	0.46	0.33	1.58
Lake depth (m)	26.5	66	208
Age (ka)	6.2	3–4?	>100?
Petrography	Basalt-andesite	Andesite?	Basalt
Tectonics	Fissure	Fissure	Fissure
Geotectonic setting	Subduction	Subduction	Intraplate
Predominant gas	CO?, CO_2 ?	CO?, CO_2?	CO_2
pH	0 m: 5.40–7.31 >4 m: 6.19–6.96	0 m: 6.40–6.75 (9.26)	0 m: 8,0 208 m: 5.1
HCO_3 zonation level (aerobic/anoxic) (m)	5–10	13–25	7–44
Estimate recurrence (years)	~ 6–7 (up to 10?)	~ 6–7	30 ± 8
Last event	2001/2002	At least once between 1978 and 1991; 2010	1986
Water color change during the overturn	Reddish to brown	Yellow to reddish	Reddish to brown

eruption, originated a widely distributed "purple" ash bed (PL) as the product of a wet pyroclastic surge. It was followed by pyroclastic flows and associated surges, alongside ballistic fall, resulting in the explosive levels of ST-2 and SFS-2. The third phase deposited extensive stratified base and ash cloud surges of the ST-3 unit, enhanced by wind direction.

The previous age determination of 2800 B.P., obtained from a location near the small town of Los Ángeles, and originally associated to the formation of Hule (Malavassi et al., 1990), appears to be instead related to the formation of the Pata de Gallo maar, that cuts through the Hule tephras.

In a later and relatively quieter phase, a new high-Al, basaltic andesitic/basaltic magma reached the surface inside the maar, producing two strombolian phases. This activity built at least two scoria cones (the Bosque Alegre composite scoria cone) and at least three lava fields. Minor ash events recorded in the Hule lake sediments ranging from 1700 B.P. to 670 B.P. (Horn, 2001), could be associated with these events, and archaeological data support this hypothesis.

Río Cuarto maar appear to have formed sometime between 4 and 3 ka. Three main successive explosive phases constructed a low-angled asymmetric tuff ring elongated to the west that overlies the Río Cuarto lavas (200 ka old). The ash fall deposits are also distributed westward in a narrow tephra apron. Both facies are strongly influenced by westerly trade winds.

The abundance of juvenile clasts is higher in Hule than in Río Cuarto, which could mirror the amount of magma involved, that is an order of magnitude higher in Hule compared to Río Cuarto (0.08 and 0.008 km^3, respectively).

For comparative purposes, a compilation of data on 119 maar diameters in the world is presented graphically as a histogram showing Hule among the largest, Río Cuarto as mid-sized, and Pata de Gallo being smaller (Fig. 12). From an empirical point of view, based on historical cases, comparative crater dimensions and tephra deposits, Lorenz (1986) found that the longer the duration of explosive activity, the larger the diameter and depth of the maar. In that way, Hule maar would have been active much longer than Río Cuarto, perhaps for weeks or months, or even intermittently for years, and then generating a second phase of activity with a much different chemistry, several millennia later, inside the maar. On the other hand, a small maar like Pata de Gallo would have had an ephemeral life, as it is shown by its single and restricted ejecta.

Usually, but not always, the maars are monogenetic centers, and include multiple-erupting or polygenetic maars (Ollier, 1967). Hule is one of them, illustrating at least two phases separated by a significant quiescence period. There are other examples of polygenetic maars such as in Deception island (Antarctica), where a maar displayed more than one explosive episode in a short period of time during 1967, 1969 and 1970 (Baker et al., 1969). Also, in Galunggung volcano (Indonesia) a small scoria cone with a lava flow were built in November 1982 inside the May 1982 maar (Gourgaud et al., 2000). Another fine example is in Chile, where the Carrán and Riñinahue maars have had reactivation episodes (Moreno and Lara, 2009).

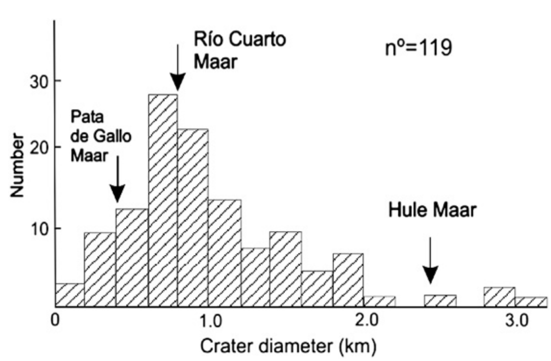

Fig. 12. Histogram of frequency of crater diameter of maars in the world (119 data, reformed from Wood, in Cas and Wright, 1987), showing the size of the studied maars. Hule is one of the largest, while Río Cuarto is in the median and Pata de Gallo is amongst the smaller maars.

Because of the polygenetic characteristics of Hule maar, the emplacement of Hule and Río Cuarto along a rift during the Holocene, and especially because of the overturn events in both lakes, in an area with a growing tourist industry, further hazard assessments would be necessary in the Hule-Río Cuarto area.

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Appendix A

Coordinates (local *Lambert Costa Rica Norte*) of the stratigraphic sections around Hule and Río Cuarto maars, studied and referred in Figs. 4, 9 and 10.

Section	North	East
EGR 7	254200	509750
EGR 6	253650	510000
EGR 5	253450	510140
EGR 4	252000	513180
EGR 3	252000	514850
Rc27	253180	510480
H4	252000	511000
H2	252350	511780
H1	252000	512350
H3	251760	512950
Res	252651	514830
Rc6	252150	513680
TO	253940	515760
LRC1	259255	512049
LRC2	259420	512078
LRC3	261416	507227
LRC 4	260321	507084
LRC 5	258748	507246
LRC 6	260569	510352
LRC 7	259542	511564
LRC 8	259225	510406
LRC 9	259573	508629
LRC 10	261890	505493
LRC 11	260066	507069
LRC 12	259018	507459
LRC 13	259602	508120
LRC 14	258846	508886
LRC 15	258274	512343
LRC 16	259516	513601
LRC 17	260650	514430
LRC 18	259847	513822
LRC 19	259591	513715
LRC 20	260873	512209

References

Alvarado, G.E., 2006. Estudio Complementario y de Actualización del Peligro Volcánico para el Proyecto Hidroeléctrico Toro 3. Internal Report ICE. 42 pp.

Alvarado, G.E., Salani, F.M., 2002. Evaluación del Peligro y Riesgo Volcánico para los Proyectos Hidroeléctricos Cariblanco y Toro III.— I Internal report ICE. 72 pp.

Alvarado, G.E., Salani, F.M., 2004. Tefroestratigrafía (40 000–2000 a.P.) en el sector Caribe de los volcanes Barva, Congo y Hule, Cordillera Central, Costa Rica. Rev. Geol. Am. Cent. 30, 59–72.

Alvarado, G.E., Soto, G.J., Pullinger, C.R., Escobar, R., Bonis, S., Escobar, D., Navarro, M., 2007. Volcanic activity, hazards, and monitoring. In: Bundschuh, J., Alvarado, G.E. (Eds.), Central America: Geology, Resources and Hazards, vol. 2. Taylor & Francis, London, pp. 1155–1188.

Baker, P.E., Davis, T.G., Roobol, M.J., 1969. Volcanic activity at Deception Island in 1967 and 1969. Nature 224, 553–560.

Bergoeing, J.P., Brenes, L.G., 1978. Laguna Hule, una caldera volcánica. Inf. Semestral, Inst. Geogr. Nacional de Costa Rica, pp. 59–63.

Borgia, A., Burr, J., Montero, W., Morales, L.D., Alvarado, G., 1990. Fault-Propagation folds induced by gravitational failure and slumping of the Costa Rica volcanic range: implications for large terrestrial and Martian edifices. J. Geophys. Res. 95 (B9), 14,357–14,382.

Bronk Ramsay, C., 1995. Radiocarbon Calibration and Analysis of Stratigraphy: The Oxcal Program. Radiocarbon 37 (2), 425–430.

Bronk Ramsay, C., 2001. Development of the radiocarbon calibration program OxCal. Radiocarbon 43 (2A), 355–363.

Carr, M.J., Saginor, I., Alvarado, G.E., Bolge, L.L., Lindsay, F.N., Milidakis, K., Turrin, B.D., Feigenson, M.D., Swisher III, C.C., 2007. Element fluxes from the volcanic front of Nicaragua and Costa Rica. Geochem. Geophys. Geosyst. 8, Q06001. doi:10.1029/2006GC001396.

Cas, R.A.F., Wright, J.V., 1987. Volcanic Successions. Modern and Ancient. Unwin Hyman, London. xvi + 528 pp.

Corbella, H., 2004. Structural Control of the Pali-Aike Lavas and Maars. Second International Maar Conference. IAVCEI, Budapest, Hungary, p. 49. Abstract Volume.

Delgado, H., Molinero, R., Cervantes, P., Nieto-Obregón, J., Lozano-Santa Cruz, R., Macías-González, H.L., Mendoza-Rosales, C., Silva-Romo, G., 1998. Geology of Xitle volcano in southern Mexico City—a 2000-year old monogenetic volcano in an urban area. Rev. Mex. Cienc. Geológicas 15 (29), 115–131.

Ford, A. And, Rose, W.I., 1995. Volcanic ash in ancient Maya ceramics of the limestone lowlands: implications for prehistoric volcanic activity in the Guatemala highlands. J. Volcanol. Geoth. Res. 66, 149–162.

Francis, P., Oppenheimer, C., 2004. Volcanoes2nd ed. University Press, Oxford. xii + 521 pp.

Freundt, A., Hartmann, A., Kutterolf, S., Strauch, W., 2010. Volcaniclastic stratigraphy of the Tiscapa maar crater walls (Managua, Nicaragua): implications for volcanic and seismic hazards and Holocene climate changes. Int. J. Earth Sc. 99 (6), 1453–1470.

Gocke, K., 1997. Basic morphometric and limnological properities of Laguna Hule, a caldera lake in Costa Rica. Rev. Biol. Trop. 44/45, 537–548.

Gocke, K., Bussing, W., Cortés, J., 1987. Morphometric and basic limnological properties of the Laguna de Río Cuarto, Costa Rica. Rev. Biol. Trop. 35 (2), 277–285.

Gocke, K., Bussing, W., Cortés, J., 1990. The annual cycle of primary productivity in Laguna de Río Cuarto, a volcanic lake (maar) in Costa Rica. Rev. Biol. Trop. 38 (2B), 387–394.

Gourgaud, A., Thouret, J.-C., Bourdier, J.-L., 2000. Stratigraphy and textural characteristics of the 1982–83 tephra of Galunggung volcano (Indonesia): implications for volcanic hazards. J. Volcanol. Geoth. Res. 104, 169–186.

Haberyan, K.A., Horn, S.P., 1999. Chemical and physical characteristics of seven volcanic lakes in Costa Rica. Brenesia 51, 85–95.

Haller, M.J., Németh, K., 2006. Architecture and pyroclastic succession of a small Quaternary(?) maar in the Pali Aike Volcanic Field, Santa Cruz, Argentina. Z. Dtsch Geol. Ges. 157 (3), 467–476.

Horn, S.P., 2001. The age of the laguna Hule explosion crater, Costa Rica, and the timing of subsequent tephra eruptions: evidence from lake sediments. Rev. Geol. Am. Cent. 24, 57–66.

Horn, S., Haberyan, K.A., 1993. Physical and chemical properties of Costa Rican lakes. Natl. Geogr. Res. Explor. 9 (1), 86–103.

Hughen, K.A., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Kromer, B., Mccormac, F.G., Manning, S.W., Bronk Ramsay, C., Reimer, P.J., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, J.R., Talamo, S., Taylor, F.W., Van Der Plicht, J., Weyhenmeyer, C.E., 2004. Marine04 Marine radiocarbon age calibration, 26–0 ka B.P. Radiocarbon 46, 1059–1086.

Hurtado de Mendoza, L., 2004. Guayabo, Historia Antigua de Turrialba. Litografía e Imprenta Lehmann, San José, Costa Rica. 147 pp.

Hurtado de Mendoza, L., 2006. Investigaciones Arqueológicas en el Proyecto Hidroeléctrico Cariblanco, Sarapiquí de Alajuela. Internal report, Instituto Costarricense de Electricidad.

ICE-ENEL, 1990. Estudio de reconocimiento y prefactibilidad geotérmica en la República de Costa Rica, Fase II: estudio de prefactibilidad del área de Tenorio. Internal report Project COS/83/t01.

Kienle, J., Kyle, P.R., Self, S., Motyka, R.J., Lorenz, V., 1980. Ukinrek Maars, Alaska, I. April 1977 eruption sequence, petrology and tectonic setting. J. Volcanol. Geoth. Res. 7, 11–37.

Kohkemper M.J., 1954. Bosquejo limnológico de la Laguna del Misterio. Thesis, Universidad de Costa Rica 184 pp.

Kusakabe, M., 1996. Hazardous Crater Lakes. In: Scarpa, R., Tilling, R.I. (Eds.), Monitoring and Mitigation of volcano Hazards. Springer, pp. 573–598.

Lorenz, V., 1970. Some aspects of the eruption mechanism of the Big Hole Maar, Central Oregon. Geol. Soc. Am. Bull. 81, 1823–1829.

Lorenz, V., 1973. On the formation of Maars. Bull. Volcanol. 37 (2), 183–204.

Lorenz, V., 1986. On the growth of maars and diatremes and its relevance to the formation of tuff rings. Bull. Volcanol. 48 (5), 265–274.

Macdonald, G.A., 1972. Volcanoes. Prentice-Hall, Inc. xii + 510 pp.

Madrigal, R., Rojas, E., 1980. Manual Descriptivo del Mapa Geomorfológico de Costa Rica (escala 1:200 000). SEPSA, Imprenta Nacional, San José. 79 pp.

Malavassi, E., 1991. Magma sources and crustal processes at the terminous of the Central American Volcanic Front. PhD. Thesis, University of California at Santa Cruz, xxii + 435 pp.

Malavassi, E., Gill, J.B., Trimble, D., 1990. Nuevas Dataciones Radiométricas del Alineamiento Volcánico de Poás (Costa Rica): Contribución a la Evaluación de Peligros Volcánicos. Programa y Resúmenes de Ponencias. VII Congreso Geológico de América Central, 19–23 November 1990. San José, p. 37.

McBirney, A.R., Williams, H., 1965. Volcanic history of Nicaragua. Univ. Calif. Publ. Geol. Sci. 55, 1–65.

Melson, W.G., Sáenz, R., Barquero, J., Fernández, E., 1988. Edad relativa de las erupciones del Cerro Congo y Laguna Hule. Bol. Vulcanología OVSICORI Univ. Nac. Heredia 19, 8–10.

Moreno, H., Lara, L., 2009. The polygenetic Carrán and Riñinahue Maar eruption in the 20th Century: historic cases of reactivation in young Arc Volcanism, Southern Andes (40.2° S), Chile. Abstract, IAVCEI-CVS-IAS 31 MC Conference, Malargüe, Argentina.

Németh, K., Martin, U., Haller, M.J., Alric, V.I., 2007. Cenozoic diatreme field in Chubut (Argentina) as evidence of phreatomagmatic volcanism accompanied with extensive Patagonian plateau basalt volcanism. Episodes 30 (3), 217–223.

Ollier, C.D., 1967. Maars, their characteristics, varieties, and definition. Bull. Volcanol. 31 (1), 45–73.

Peccerillo, A., Taylor, T.S., 1976. Geochemistry of Eocene calc-alkaline volcanic rocks from Kastamonu area, Northern Turkey. Contrib. Mineralog. Petrol. 58, 63–81.

Petrinovic, I., Arnosio, J.M., Alvarado, G.E., Guzmán, S., 2005. Erupciones freáticas sintectónicas en el campo geotérmico de Tocomar, Salta. Rev. Asoc. Geol. Argent. 60 (1), 142–158.

Petrinovic, I.A., Riller, U., Brod, J.A., Alvarado, G., Arnosio, M., 2006. Bimodal volcanism in a tectonic transfer zone: evidence for tectonically controlled magmatism in the southern Central Andes, NW Argentina. J. Volcanol. Geoth. Res. 152, 240–252.

Prosser, J., Carr, M.J., 1987. Poás volcano, Costa Rica: geology of the summit region and spatial and temporal variations among the most recent lavas. J. Volcanol. Geoth. Res. 33, 131–146.

Ruiz, P., Gazel, E., Alvarado, G.E., Carr, M., Soto, G.J., 2010. Caracterización geoquímica y petrográfica de las unidades geológicas del macizo del volcán Poás, Costa Rica. Rev. Geol. Am. Cent. 43, 37–66.

Salguero, M., 1978. Un aerolito formó la Laguna de Río Cuarto. Gentes Paisajes 47 (VII-78), 17B.

Sapper, K., 1925. Los Volcanes de la América Central. Max Niemayer, Halle (Saale). 144 pp.

Sato, H., Taniguchi, H., 1997. Relationship between size and ejecta volume of recent magmatic and phreatomagmatic eruptions: implications for energy partitioning. Geophys. Res. Lett. 24 (3), 205–208.

Siebe, C., 2000. Age and archaeological implications of Xitle volcano, southwestern Basin of Mexico City. J. Volcanol. Geoth. Res. 104, 45–64.

Soto, G.J., 1990. Consideraciones Volcanológicas y Tectónicas Preliminares del Área de Laguna Hule. Internal report ICE. 8 pp.+ 6 figs.

Soto, G.J., 1999. Geología Regional de la hoja Poás (1: 50 000). In: Alvarado, G.E., Madrigal, L.A. (Eds.), Estudio Geológico-Geotécnico de Avance a factibilidad del P. Laguna Hule. Inf. Interno ICE, San José, pp. 15–45.

Soto, G.J., Alvarado, G.E., 1989. Procesos Volcánicos Asociados con el Agua Subterránea. El Caso de los Volcanes Arenal y Poás, Costa Rica. Memoria del III Congreso Nacional de Recursos Hídricos, 15–17 November 1989, pp. 249–261.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C database and revised CALIB radiocarbon calibration program. Radiocarbon 35, 215–230.

Tassi, F., Vaselli, O., Fernández, E., Duarte, E., Martínez, M., Delgado Huertas, A., Bergamaschi, F., 2009. Morphological and geochemical features of crater lakes in Costa Rica: an overview. J. Limnol. 68 (2), 193–205.

Tournon, J., 1984. Magmatismes du Mesozoique a l'actuel en Amérique Centrale: l'exemple de Costa Rica, des ophiolites aux andésites. Mém. Sci. Terre Univ. Curie París 84–49 335 pp.

Umaña, G., 1993. The planktonic community of Laguna Hule, Costa Rica. Rev. Biol. Trop. 41 (3), 499–507.

Van der Plicht, J., Beck, J.W., Bard, E., Baillie, M.G.L., Blackwell, P.G., Buck, C.E., Friedrich, M., Guilderson, T.P., Hughen, K.A., Kromer, B., McCormac, F.G., Bronk Ramsay, C., Reimer, P.J., Reimer, R.W., Remmele, S., Richards, D.A., Southon, J.R., Stuiver, M., Weyhenmeyer, C.E., 2004. NotCal04-Comparison/Calibration ^{14}C Records 26–50 cal kyr BP. Radiocarbon 46 (3), 1225–1238.

van Wyk de Vries, B., Grosse, P., Alvarado, G.E., 2007. Volcanism and volcanic landforms. In: Bundschuh, J., Alvarado, G.E. (Eds.), Central America: Geology, Resources and Hazards, vol. 1. Taylor & Francis, London, pp. 124–154.

Verpermann, D., Schmincke, H.-U., 2000. Scoria cones and tuff rings. In: Sigurdsson, H. (Ed.), Encyclopedia of Volcanoes. Academic Press, pp. 683–694.

Williams, H., McBirney, A.R., 1979. Volcanology. Freeman Cooper & Co., San Francisco. 397 pp.

Zimmer, M.M., Fisher, T.P., Hilton, D.H., Alvarado, G.E., Sharp, Z.D., Walker, J.A., 2004. Nitrogen systematics and gas fluxes of subduction zones: insights from Costa Rica arc volatiles. Geochem. Geophys. Geosyst. 5 (5), 1–19. doi:10.1029/2003GC000651.