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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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ABSTRACT

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.

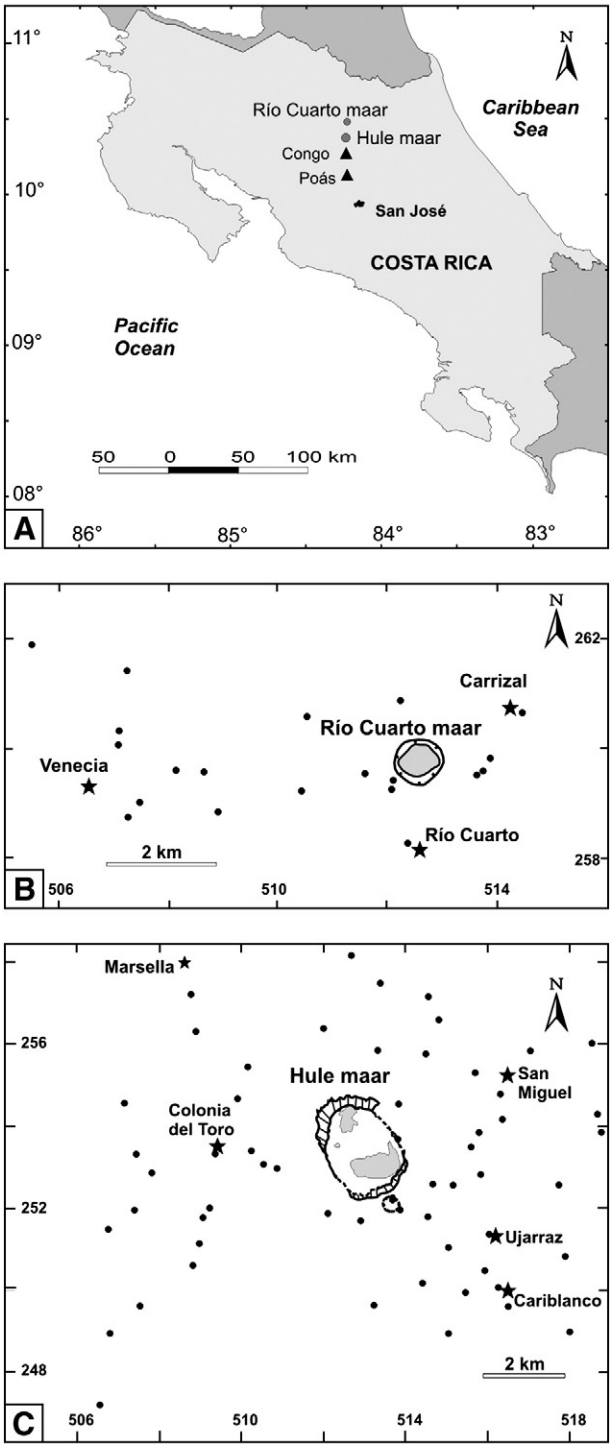

Fig. 1. A. Location of the two maars and main stratovolcanoes of the Poás massif. B. Río Cuarto maar, nearby towns (stars) and location of studied sections (dots). C. Hule maar, nearby towns and location of studied sections. Coordinates in figures hereafter are local *Lambert Costa Rica Norte*.

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