Icarus 252 (2015) 347–365

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Hydrothermal alteration in basalts from Vargeão impact structure, south Brazil, and implications for recognition of impact-induced hydrothermalism on Mars

Elder Yokoyama [a,b,*], Anne Nédélec [b], David Baratoux [b,d], Ricardo I.F. Trindade [a], Sébastien Fabre [c], Gilles Berger [c]

[a] IAG, University of São Paulo, 05508-090, São Paulo, Brazil
[b] GET-OMP, CNRS-University of Toulouse, 31400 Toulouse, France
[c] IRAP-OMP, CNRS-University of Toulouse, 31400, Toulouse, France
[d] Institut de Recherche pour le Développement & institut Fondamental d'Afrique Noire, Dakar, Sénégal

ARTICLE INFO

Article history:
Received 18 March 2014
Revised 12 January 2015
Accepted 1 February 2015
Available online 7 February 2015

Keywords:
Impact processes
Earth
Mars, surface
Infrared observations

ABSTRACT

The 12-km-wide Vargeão impact structure was formed 123 Myr ago in the Paraná basaltic province (southern Brazil). At this time the province region had a dry climate, although a large brackish aquifer had been formed in the underlying sandstones. It is therefore one of the best terrestrial analogs for studying impact-related products on a dry martian surface environment with preserved ice-rich ground. The basalts within the impact structure display cm-sized breccia veins filled with lithic clasts, glassy remnants, newly formed Fe-oxyhydroxides and secondary phases, such as calcite, phyllosilicates and, subordinately quartz and zeolite. The textural and mineralogical study of these phases demonstrate their hydrothermal origin. Although the very center of the structure has experienced the highest pressures and temperatures, the most developed hydrothermal changes are recognized in an inner collar surrounding the central depression. This inner collar is also the location of major modifications of the rock magnetic properties. These magnetic signatures are related to the distribution of impact-related faults and to the formation of new iron oxides. Geochemical modeling indicate that hydrothermal phases formation required low water/rock ratios. Our observations therefore suggest that hydrothermal alteration took place following the perturbation of the aquifer by the impact, but evidence for hydrothermal circulation is limited in comparison with other impact-related hydrothermal systems. This situation may be explained by the presence of the aquifer below the heat source, such a setting being exceptional for the Earth, but common on Mars. However, the spectroscopic signatures in visible/near infrared images suggest that this kind of impact-related hydrothermal alteration may be still indentified in large impact craters on Mars by orbital instruments. These results does not exclude the possibility that more developed alteration took place in breccias that are today eroded.

1. Introduction

Impact-induced hydrothermal systems are relatively common on the Earth (Osinski et al., 2013) and the development of similar systems on Mars has received particular attention as they could have hosted temporal oases for life (Cabrol et al., 2001). The formation and emplacement of impact melt and hot breccias following shock compression can provide sufficient thermal gradients to drive a hydrothermal system, provided H_2O is available in the environment. Although present surface conditions on Mars are cold and dry, hydrated minerals appear to be associated to some impact craters, suggesting that impact-related hydrothermalism was involved in their formation (*e.g.*, Marzo et al., 2010; Carter et al., 2013; Tornabene et al., 2013). However, there is a debate on their origin and significance, as these phyllosilicates may alternatively represent exhumed older, *i.e.* Noachian (>3.6 Ga), sediments formed under wet/warm conditions (Fairén et al., 2010; Barnhart and Nimmo, 2011). Field observations and mineralogical data on impact-induced hydrothermal systems affecting basaltic rocks on Earth may therefore provide clues regarding this controversial issue. Analogous structures are rare on Earth. Basaltic surfaces

* Corresponding author now at: IG, University of Brasília, 70910-900, Brasília, Brazil.
E-mail addresses: eyokoyama@unb.br, elder.yokoyama@gmail.com (E. Yokoyama).

http://dx.doi.org/10.1016/j.icarus.2015.02.001
0019-1035/

are largely represented by the oceanic crust, and such surfaces are young (paucity of large impact craters), difficult to access, and would provide a submarine context different to subaerial martian contexts. The terrestrial impact cratering record is largely dominated by structures affecting the continental crust, that is dominated by sedimentary or crystalline but acidic compositions. Few exceptions to this situation are provided by impact structures into continental basaltic provinces, such as Lonar in the Deccan Traps (India), Lochanga in the Siberian trap and Vargeão and Vista Alegre in the Paraná Traps (Brazil).

The 20-km Lochanga structure formed into basalt, pyroclastics deposits and Permian sediments (Feldman et al., 1983), Little is known about this structure (Mironov and Lagyduin, 1988) and despite the presence of basalts, the mixed nature of the shocked material limits its interest for martian analog studies. The Lonar structure is only 1.8 km wide (*e.g.*, Fredriksson et al., 1973; Wright et al., 2011). Hydrothermal alteration of its basaltic impact breccias has been studied from core samples by Hagerty and Newsom (2003). A well developed hydrothermal systems has been identified within the impact breccia. The presence of calcite as the main late stage mineral in the Lonar samples is consistent with alteration by meteoric water, and supports the use of Lonar as an analog for craters on Mars if water was supplied by abundant rainfall (or snowfall). In contrast, the surface conditions during the formation of the Vargeão impact, compare more favorably with a dry and cold Mars. Indeed, the crater formed under a dry climate (lack of or very minor precipitation), but host rocks hosted a large aquifer (analogous to the presence of ground ice). The structure is also much larger than Lonar, with frequent occurrence of outcrops of basalts within the crater cavity that have been affected by impact deformation.

The aim of this study was to search for evidence of hydrothermal alteration and document the alteration assemblages within the basaltic target rocks, if present. We show that hydrothermal phenomena resulted in limited alteration of the basaltic disturbed basement and under low water/rock ratio, but did not occur in polymict breccia deposits. The water may have been provided by the dehydration of the basats, or has been made available as the result of the perturbation of the aquifer at the time of impact. Spectroscopic analyses of the samples suggests that this kind of limited impact-related hydrothermal alteration may be detected from the orbit.

2. Geological setting

2.1. The Vargeão impact structure

The 12-km-wide Vargeão complex impact structure is located on the Santa Catarina state (center at 26°49′S and 52°10′W), south Brazil (Fig. 1A). The impact event took place in the central part of the Paraná Basin, affecting the Early Triassic-Cretaceous rocks of the São Bento Group (Fig. 1B) (Kazzuo-Vieira et al., 2004; Crósta et al., 2012). The São Bento Group, from the base to the top, is formed by Piramboia, Botucatu and Serra Geral formations (*e.g.*, Milani et al., 2007). The Piramboia Formation is composed of sandstones that can be separated into two major systems that comprise a wet aeolian record (wet interdune facies) in the lower part and a dry aeolian record (dunes facies) toward the upper part (*e.g.*, Caetano-Chang and Wu, 1994). The Botucatu Formation consists of aeolian deposits that are dominantly sets and cosets of cross-strata (*e.g.*, Scherer, 2000). According to Scherer (2000), the Botucatu Formation records a dry aeolian system formed by the accumulation of aeolian dunes without the development of a wet interdune facies. The Botucatu Formation is made of fine- to medium-grained well-sorted sandstones of aeolian origin, whereas the Piramboia Formation is more clayish and comprised both aeolian and restricted fluvial sediments. The Botacatu sandstones contain >90% quartz with dominant hematite coatings and rare calcareous cements. Feldspars and micas are minor or accessory phases. The thickness of the formation ranges from 100 to 700 m, depending on the location within the basin. The Serra Geral Formation belongs to the Paraná-Etendeka Large Igneous Province and is mainly composed of tholeiitic flood basalts (90% of the volume) and minor felsic volcanics (Piccirillo and Melfi, 1988). The sandstones were deposited during Jurassic times under an arid climate. The Botucatu desert was then covered by the thick basaltic flows of the Serra Geral Formation at ca 134 Ma (Scherer, 2002).

Stratigraphic relationships suggest that the impact affected about 1 km of the volcanic rocks from the Serra Geral Formation reaching the deeper sandstones of the Pirambóia and Botucatu Formations (Kazzuo-Vieira et al., 2004; Crósta et al., 2012) (Fig. 1B). Morphologically, the Vargeão structure is characterized by a well-preserved rim and an eroded central uplift (*e.g.*, Kazzuo-Vieira et al., 2009; Crósta et al., 2012). The central uplift can be divided into two domains. The first domain is characterized by topographic highs (inner collar), consisting of intercalated blocks with a few hundred meters of basalts from the Serra Geral Formation and aeolian sandstone strongly deformed from the Pirambóia/Botucatu Formations. The second domain is represented by a central depression that is formed by basalts and rare polymict impact breccia deposits. According to Crósta et al. (2012), the rim area is affected by concentric normal faults penetrating through the hundreds of meters thick tholeiitic basalt flows and the few tens of meters thick rhyodacites. Networks of breccia veins containing oxidized material and lithic fragments occur in association with these faults (Nédélec et al., 2013). In situ U/Pb ages obtained on zircons from these veins indicate that the impact event occurred at 123 ± 1.4 Ma (Nédélec et al., 2013). In addition to these veins, macroscopic impact features include shatter cones in sandstones and basalts. Microscopic evidence of impact-related shock metamorphism has been also reported in the form of planar deformation features (PDFs) in quartz grains (Crósta et al., 2012).

2.2. The Guarani aquifer

The Guarani aquifer system, also called Mercosul aquifer system, is the most important aquifer of the Paraná basin. It extends into the Botucatu and Piramboia formations and provides a major source of fresh water for southern Brazil and bordering countries and represents one of the world's largest freshwater reservoirs. Three geochemical regions were identified from east to west by Meng and Maynard (2001), namely: the recharge area, the mid-region, characterized by high Ca^{2+} and HCO_3^- contents due to calcite dissolution, and the central region, where leakage of evaporites from the Piramboia Formation add Na^+, Cl^- and SO_4^{2-} to the water. Detailed water compositions from several wells scattered in São Paulo state can be found in Sracek and Hirata (2002) and are representative of the whole system. At the time of formation of the basaltic flow of the Serra Geral Formation (134 Ma) and until 110 Ma *i.e.*, including the time of the Vargeão impact event, the aquifer water was only slightly saline or brackish (Araujo et al., 1999). Flushing by increased rainfall and the creation of a hydraulic gradient due to the uplift of Serra do Mar along the present-day Brazilian coast occurred after mid-Cretaceous times (ca 100 Ma).

3. Material and methods

3.1. Field observations, sampling and optical microscopy

Fifty-three sites within or around the impact structure were visited (Fig. 1). At each site at least one hand sample for petrographic or geochemical study was collected. The field-based description was complemented by the observation of 60 polished thin sections, both in transmitted and reflected light.