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Meteoritic impact in volcanic flows of the Serra Geral Formation, Paraná Basin

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ABSTRACT - The Vista Alegre circular structure, in the county of Coronel Vivida (State of Paraná), represents the erosion remnant of a meteorite impact crater formed on basaltic lavas of the Serra Geral formation of the Paraná Basin. The astrobleme, discovered in 2004, has a diameter of 9.5 km and is one of the few examples of this type of geologic structure known in Brazil, and one of the very rare impact craters formed on basalt on Earth. The morphologic expression of the structure is remarkable, with its near perfect circular outline and steep borders, exhibiting topographic gradients of up to 120 m between the exterior and the interior. The identification of the impact nature of Vista Alegre came after the recognition of shock deformation features in impact breccias found within the structure. These features, comprising shatter cones and planar deformation features in quartz, are exclusively formed due to impact metamorphism and corroborate the occurrence of a meteorite impact event. With the discovery of this new astrobleme, the impact record in Brazil comprises currently six confirmed impact craters, four of them located in the Paraná Basin (Araguainha Dome, Vargeão Dome, Vista Alegre and Cerro Jarau) and two in the Parnaíba Basin (Serra da Cangalha and Riachão).

Keywords: astrobleme; meteorite impact crater; Serra Geral Formation; Paraná Basin.

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INTRODUCTION

The formation of meteorite impact craters is a geologic phenomenon that, although relatively common during the history of the Earth, mainly in its early stages, did not leave an apparent abundant record on its surface. The reason for this apparent lack on impact craters on the Earth´s surface is related to the dynamics of the Earth's crust, which caused this record to be progressively obliterated, differently from what happened in other solid planetary bodies, such as the Moon, Mars, Venus, among others, which have numerous craters on their surfaces. Therefore, craters formed by the impact of extraterrestrial bodies of large dimensions (which are generically called "meteorites") are rare geological features on Earth. The current number of known impact craters is around 180 (Earth Impact Database: www.passc.net/EarthImpactDatabase/index.html, accessed in December 2010).

Proposed by Dietz (1961), the term "astrobleme" is employed to designate craters which have been eroded, and encompasses the vast majority of the meteorite craters known on Earth.

In Brazil there are currently only six structures whose origin by meteorite impact has been confirmed: Araguainha Dome (GO-MT), Serra da Cangalha (TO), Riachão (MA), Vargeão Dome (SC), Cerro Jarau (RS) and Vista Alegre (PR) (Crósta 2004; Crósta 2010a). There is also Colônia Astrobleme (SP) (Riccomini *et al.*, 2005), whose impact nature is still to be determined.

With a diameter of 9.5 km, the Vista Alegre Astrobleme (Figs. 2, 3 e 4) represents an erosion remnant of a meteorite crater with a maximum age attributed to the Cretaceous, formed on basalt of the Serra Geral Formation of the Paraná Basin, in a similar way as the Vargeão (with a diameter of 12.4 km) and Cerro Jarau (13.5 km) astroblemes.

The discovery of Vista Alegre occurred from the observation, in satellite remote sensing images, of a conspicuous geomorphologic and structural circular anomaly circular which, after field work verification, revealed the presence of impact breccias and other features which are diagnostic of this type of phenomenon (Crósta *et al.* 2004, 2010b).

LOCATION

Vista Alegre Astrobleme is located in the southeastern portion of Paraná State (Fig. 1), with its center at 25^{0}57' S and 52^{0}41' W. The structure is part of Coronel Vivida County, and the Vista Alegre rural village is located in the interior of the astrobleme.

The interior of the structure can be easily reached by road PR-562, which links Coronel Vivida to the neighbor town of Itapejara D'Oeste, going through Vista Alegre village. This paved road cuts the entire structure from east to west, giving easy access to its interior

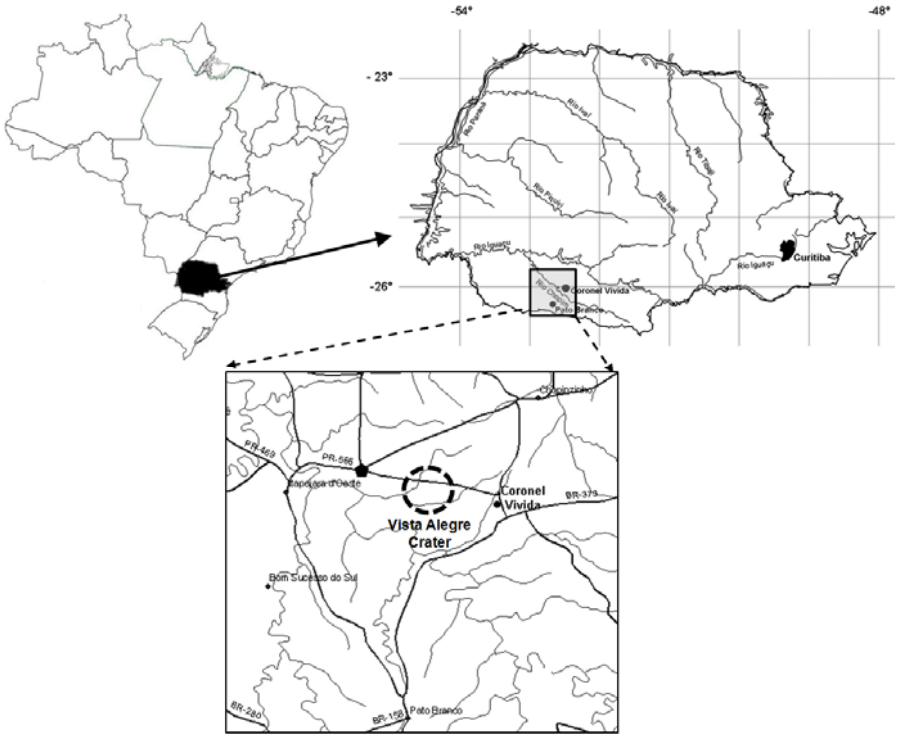

Figure 1. Location of Vista Alegre Astrobleme, Coronel Vivida County, Paraná State.

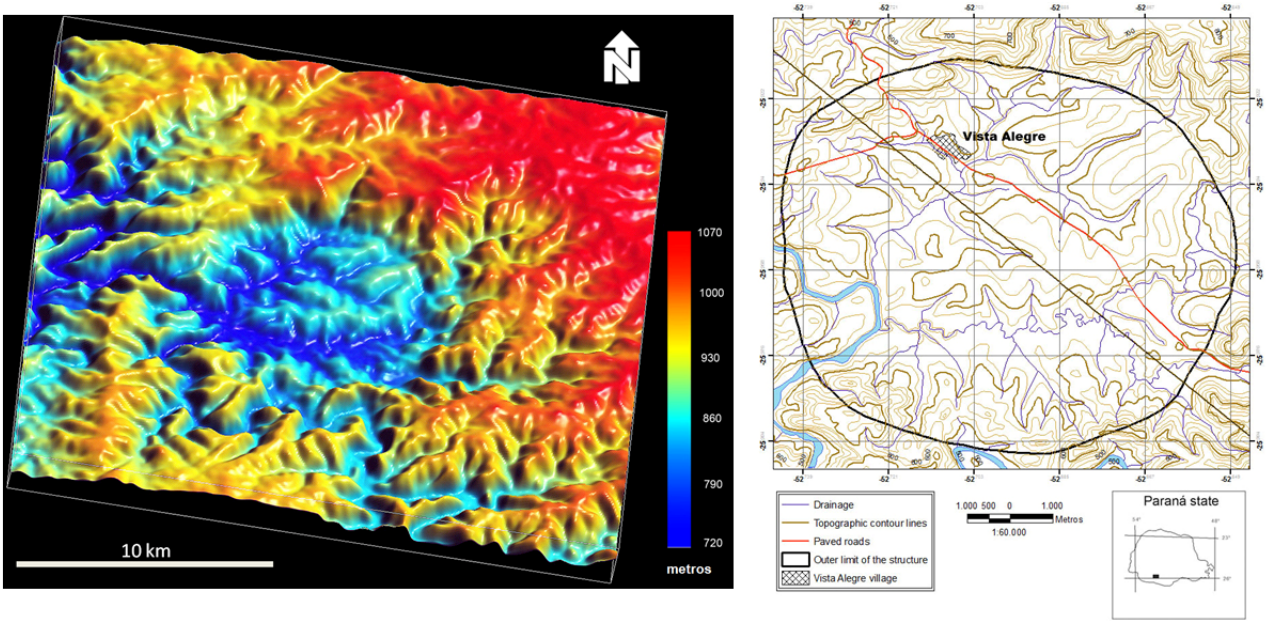

Figure 2 – Morphology of the Vista Alegre Astrobleme. Left: 3-dimensional perspective view of the SRTM digital elevation model *(Shuttle Radar Topographic Mission)* depicting the near-circular depression and its steep inner rim. Right: map with elevation contours (vertical spacing of 10m) of the structure; the southern and southwestern portions were eroded by the Chopim river, which enters the structure in its southwestern portion, flowing towards outside in its western rim.

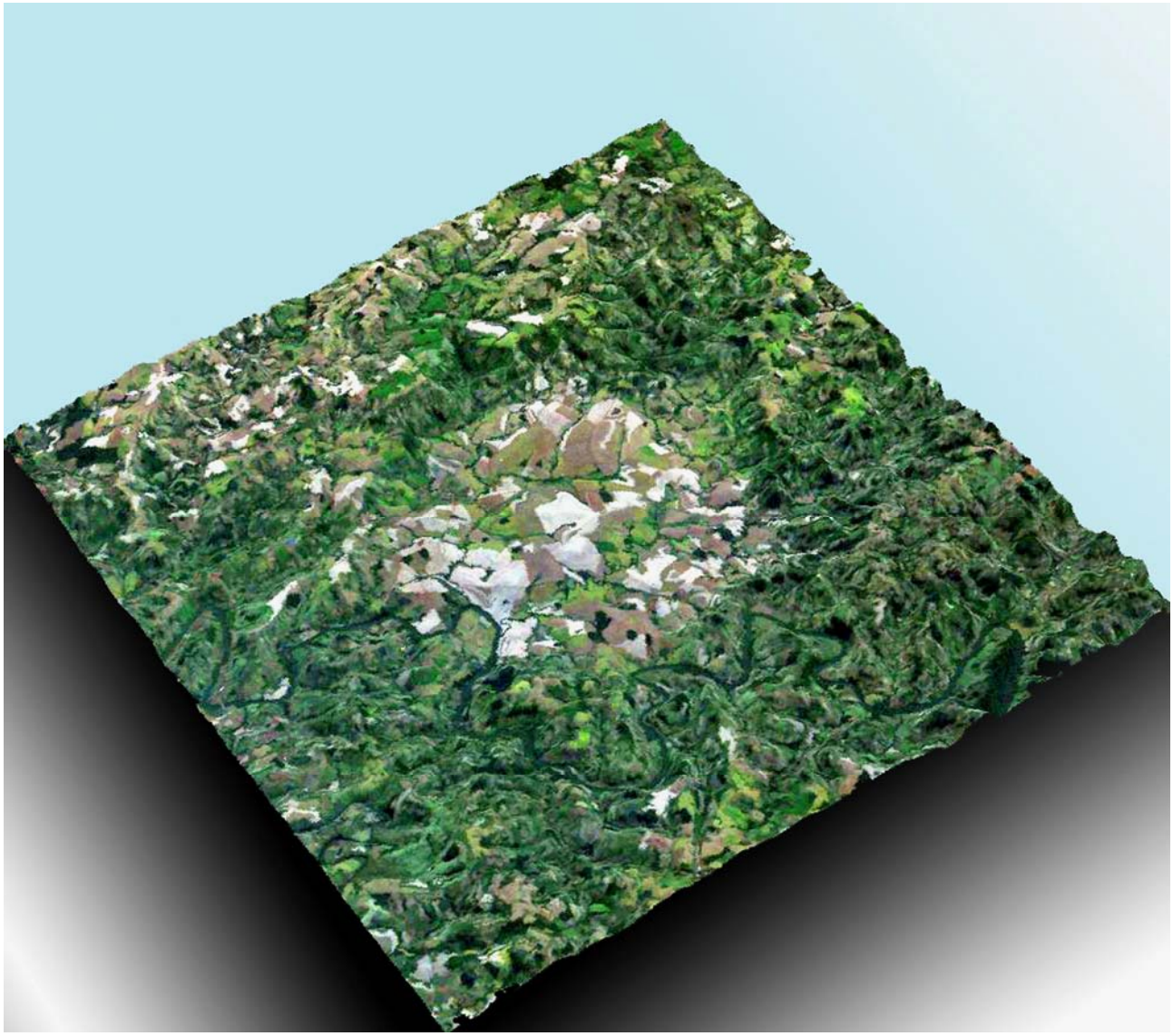

Figure 3 – 3D perspective view of theVista Alegre Astrobleme based on Landsat5/Thematic Mapper data combined with SRTM digital elevation model, exhibiting the contrasting morphological patterns between the interior and the exterior of the structure, as well as the steep inner rim and the gentle undulating relief in its interior.

Figure 4. Panoramic view of the interior of the Vista Alegre astrobleme taken from its northern rim, looking towards south. On the right hand side, in the background, the steep slopes of the inner rim of the crater can be seen, as well as the gentle undulating hills in the center.

DESCRIPTION OF THE SITE

The Vista Alegre Astrobleme was formed on basaltic lava flows of the Serra Geral Formation, which have ages in the range 139-125 Ma (Renne *et al.*, 1992; Turner *et al.*, 1994; Mantovani *et al.*, 1995).

These flows formed the extensive plateaus of the western region of Paraná State, which are dissected by the main rivers of the region (Iguaçu, Chapecó and Chopim, as well as their tributaries).

The structure forms a near-circular depression, with around 2/3 of its perimeter marked by a steep rim, with topographic gradients of up to 120 m between the ridges along the rim and the interior of the structure. The remaining 1/3, in the south and southwestern portions, has been removed by the erosion of the Chopim river, whose meanders enter part of the structure in its southwestern portion (Fig. 2).

In the western rim of the structure there are five distinct lava flows exposed, giving to the internal part of the rim a multi-step aspect resulting from the differential erosion along the contact between the different flows.

The morphology associated with Vista Alegre Astrobleme differs noticeably from the morphology of the region outside the structure. The interior is a topographically depressed area in comparison with the exterior, being characterized by gently rolling hills and topographic gradients up to 50 m (Fig. 3). The external part exhibits a very irregular relief, with topographic gradients of around 200 m between the top of the higher hills and the valleys.

Drainage patterns in the interior of the structure, represented by the Surubim and Quieto streams, are radial/dendritic and centripetal, flowing from the scarps of the inner rim towards the interior, and then flowing towards west, until they meet the Chopim river. In the external portion the drainage is dendritic.

Figure 4 is a panoramic view of the interior of the astrobleme, taken from its northern rim looking towards south. The inner slopes of the rim are marked by numerous exposures of the basaltic flows. However, the interior of the structure contains mostly soils up to several meters thick which are used all year round for intensive agriculture, with very little bedrock exposure

The schematic geological map of Vista Alegre Astrobleme is presented in Figure 5, based on the reduced number of rock outcrops found in its interior. In the inner slopes of the rim the only rock type observed is represented by fractured basalt. Fracturing is particularly intense in the annular zone around the rim, when compared with the typical fracture patterns seen on the Serra Geral basalt outside the structure.

The central portion of the structure contains impact polymictic breccias (impactites), which outcrop as slabs along the Quieto and Surubim streams, and which are exposed in a small abandoned quarry at Vista Alegre village (Fig. 6).

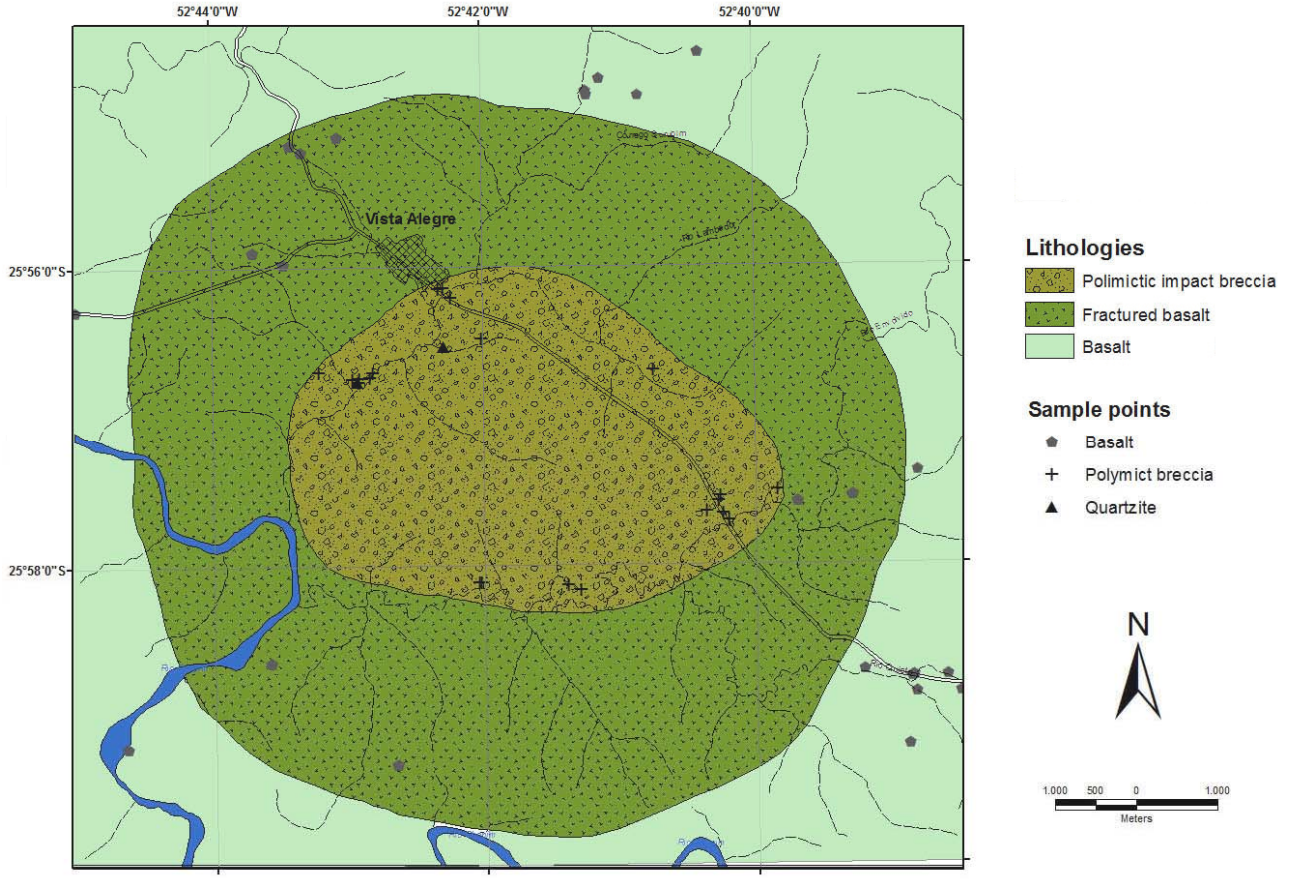

Figure 5. Schematic geologic map of the Vista Alegre Astrobleme.

Figure 6. Quarry located in Vista Alegre village, containing the best exposures of the polymict impact breccia (impactites) of the interior of the Vista Alegre Astrobleme.

This quarry exhibits the best exposures of the impactites of Vista Alegre. The impact breccia layer that can be seen in the front of the quarry has a thickness of 7-8 m. As this layer extends up to the bed of the nearby Surubim stream, a minimum thickness of 10-12 m can be estimated for the breccias at this part of the structure. However, its lower contact is not known, and the breccias can have a greater thickness.

The discontinuous outcrops of the polymict breccias suggest an area of occurrence of around 20 km^2 in the central portion of the structure (Fig. 5). These outcrops occur mainly along the drainage channels in the central area of the crater, suggesting that they form a presumable continuous and sub-horizontal layer, which is currently covered by residual soils, and only exposed at places where the drainage channels have cut through the layer of soil.

The polymict breccias from Vista Alegre exhibit, when fresh, a very characteristic steel-grey color (Fig. 7). After being exposed to the air for relatively short periods (a few months), this color changes to light grey-brown, indicating quick chemical weathering. The matrix of the breccias comprises a mass of very fine fragments, apparently derived from the Serra Geral basalt, with a powdery texture.

Larger fragments within the breccia, with dimensions in the range between few millimeters and several decimeters, are largely of basaltic composition, with a minor contribution from sedimentary rocks (sandstones and siltstones). Some exhibit ballistic shapes and black color (Fig. 8), suggesting the contribution of melt which might have solidified in contact with the air after being excavated from the crater site by the impact and ejected into the air, and later re-deposited into the newly-created crater to form the breccia.

Another rock type that occurs in the interior of the Vista Alegre Astrobleme is white quartzose sandstone with recrystallized portions and exhibiting intense cataclasis (Fig. 9). This rock occurs as sub-metric sized blocks, found within residual soils in at least two sites near the course of the Surubim stream (Fig. 5). As the Serra Geral Formation does not contain rocks similar to this sandstone, it might have originated from lower stratigraphic units, such as the Botucatú and/or Pirambóia formations. These two units contain white sandstones which, if subject to high pressure and temperature conditions, could have resulted in the quartzites now found in the central regions of the Vista Alegre structure. In this portion of the Paraná Basin, these two stratigraphic units are positioned several hundred meters (~700 m) below the present surface, and underneath the volcanic package of the Serra Geral Formation.

The occurrence of these sandstones very close to the surface in the central area of the structure suggests the existence of a central uplift, which is typical of meteorite craters of the complex type (French, 1998). This mechanism would explain the uplift of these rocks from depths of several hundred meters towards the surface, similarly to what happens in the Vargeão Dome, another meteorite crater formed in the same stratigraphic set up (Crósta *et al.,* 2005). However, the fact that the few quartzitic blocks found in Vista Alegre do not seem to be *in situ*, combined with the absence of adequate sub-surface information in the interior of the structure, leaves the issue of the central uplift pending upon further investigations of the sub-surface.

Although the precise age of the formation of the

Vista Alegre crater is yet undetermined, the fact that it formed on basaltic layers of the Serra Geral Formation, apparently already solidified, allows to estimate a maximum age in the order of 125 Ma, which is the minimum age of these basalts (Renne *et al.*, 1992; Turner *et al.*, 1994; Mantovani *et al.*, 1995). However, there is a possibility of establishing the precise age of the impact based on geochronological analysis of material melted by the impact and subsequently incorporated into the polymictic breccia, such as the one shown in Figure 8. Establishing the age of formation of meteorite impact craters is an important issue, since it allows them to be associated with other significant evolution events that shaped the Earth's surface, including the catastrophic life mass extinction events, in a local, regional or global scales (which depend on the dimension of the impacting body), and/or high-energy sedimentary depositions events (e.g., tsunamites), among others.

Figure 7. Polymictic impact breccia (impactite) formed mainly by fragments of diversified sizes of basalt, with secondary contribution from sandstone and siltstone. The matrix comprises extremely fine material derived from basalt. When fresh, this rock exhibits a peculiar steel-grey color, as seen in the central portion of the breccia depicted in this picture; after weathering, this color changes to grey-brown, as seen in the outer portion.

Figure 8. Polymict breccia with a ballistic-shaped glass fragment. The fragment has vesicles and amigdules, suggesting material melted as a consequence of the impact, which solidified in contact with air during its ballistic trajectory, being later deposited together with other fragments to form the breccia.

Figure 9. Quartzitic sandstone: (a) sub-metric block of white quartzose sandstone amid residual soil; (b) quartzose sandstone exhibiting intense cataclasis.

SINOPSIS ON THE ORIGIN, GEOLOGIC EVOLUTION AND IMPORTANCE OF THE SITE

The determination of the origin of terrestrial circular structures suspected of being of meteorite impact nature depends fundamentally on the identification of rocks which were formed or deformed by the impact process, and which contain one or more of the features which are diagnostic of this type of geologic process. French (1998) and French & Koeberl (2010) detailed the complete set of diagnostic shock features, which in turn require very specific and peculiar pressure and temperature conditions to form, and are generically named "shock features". These features are found exclusively in impactites.

In the Vista Alegre Astrobleme the polymictic breccias that occur in its interior represent the main rock type formed as a result f the impact process. These breccias comprise fragments of the rocks which existed at the time and at the site of the event, which are the basaltic lavas of the Serra Geral Formation and, possibly, the underlying sandstones, belonging to the Botucatú and Pirambóia formations. The analysis of these breccias by Crósta *et al.* (2004, 2010b) allowed the identification of the specific shock features in fragments that form the breccias.

The first shock feature observed in Vista Alegre comprises small fragments of shatter cones immersed in the polymictic breccias (Crósta *et al.*, 2004) (Fig. 10). They are striated features with conical shape that usually occur as aggregates, with dimensions of the individual cones ranging from a few centimeters to several meters in length. Shatter cones are formed as a consequence of the passage of the shock waves created by the meteorite impact through the rocks. They represent the main macroscopic feature diagnostic of meteorite impact (French, 1998; French & Koeberl, 2010).

Subsequently, Crósta *et al.* (2010b) found larger fragments and aggregates of shatter cones formed in basalt; these aggregates contain up to hundreds of cones, with dimensions ranging between 0.5 and 20 cm (Fig. 11). The shatter cones from Vista Alegre have significant historic and scientific importance attached, due to the fact that this is possibly the first occurrence of basaltic shatter cones found on Earth.

The second type of shock features identified in Vista Alegre is a set of microscopic deformation features that occur in quartz crystals. They are called planar deformation features (PDFs), also known as shock lamellae. PDFs are crystallographic deformation features developed in some minerals as a consequence of the interaction with the shock waves produced by the impact. They form sets of planar features parallel to some specific crystallographic axes, formed under pressure conditions ranging between 40 and 500 kbars. In the Vista Alegre Astrobleme PDFs were found in quartz grains from sandstone fragments within the polymictic breccias (Fig. 12). Although relatively rare, some of these grains exhibit PDFs in up to two distinct crystallographic directions.

The importance of the Vista Alegre Astrobleme is due not only to the fact that it is one of the few meteorite impact craters in Brazil and also in South America, but mainly because the specific type of rock in which it was formed (basalt). Although common in other planetary bodies, basaltic craters are very rare on Earth. There are currently only two examples known. The first is Lonar Crater in India (Fredriksson *et al.* 1973; Fudali *et al.* 1980; Osae *et al.* 2005), a young and relatively small (d=1.9 km) crater formed on basaltic rocks of the Deccan Plateau in southern India; its interior if filled with lake water, which restricts the exposure of the shocked basalt. Besides Lonar, the only other basaltic crater previously known is

Logancha in Siberia, Russia, also formed on basalt (Feldman *et al.* 1983; Masaitis 1999), but in advanced stage of erosion, with the basalt almost completely eroded. In Brazil, besides Vista Alegre, there are other two meteorite craters formed on basalt, both in the domains of the Serra Geral Formation in the Paraná Basin: Vargeão Dome (Crósta *et al.*, 2005) and Cerro do Jarau (Crósta *et al.*, 2010a).

The basaltic craters on Earth, and particularly the Brazilian craters, may boast significant value for planetary research, as they may provide important information for the study of impact effects on basaltic targets, serving as analogue features to the craters in other planetary bodies with basaltic crusts, as Mars and Venus (Hagerty & Newsom, 2003; Maloof *et al.,* 2010). Furthermore, the conditions of easy access, reasonable exposure and adequate local infrastructure favor considerably the development of scientific, educational and cultural activities at the Vista Alegre Astrobleme. Currently, this crater has the first known occurrences of basaltic shatter cones on Earth.

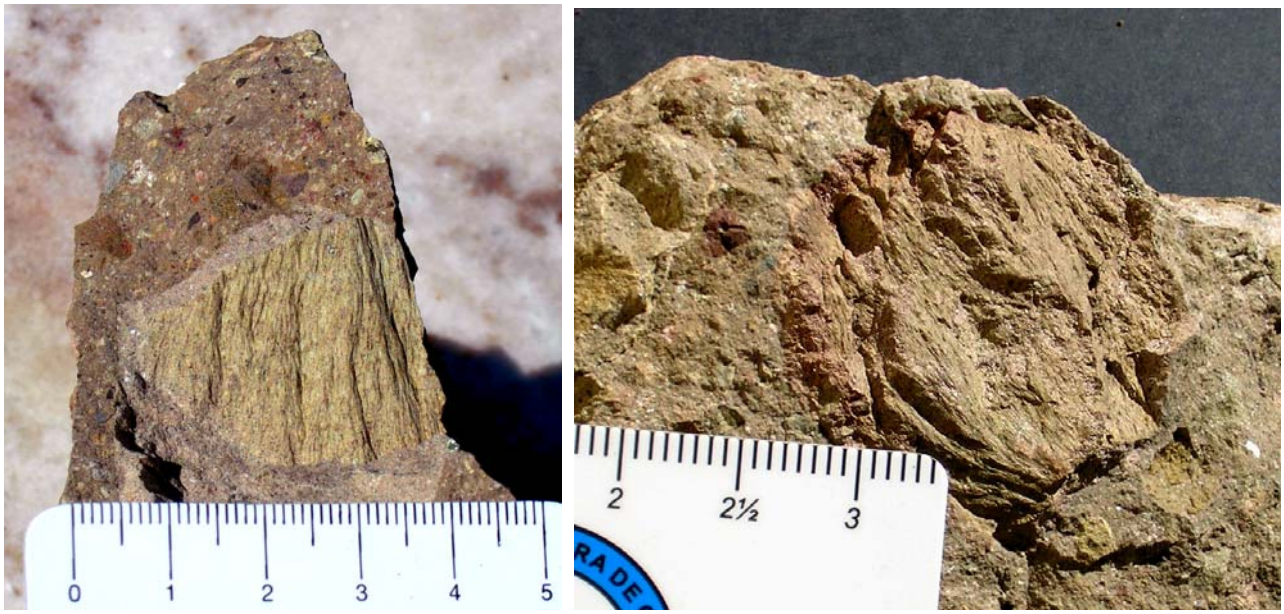

Figure 10. Fragments of shatter cones within polymict breccias, found in the small quarry near the Vista Alegre village.

Figure 11. Shatter cone aggregates formed in basalt fragments within the polymict breccia found in the small quarry near Vista Alegre village.

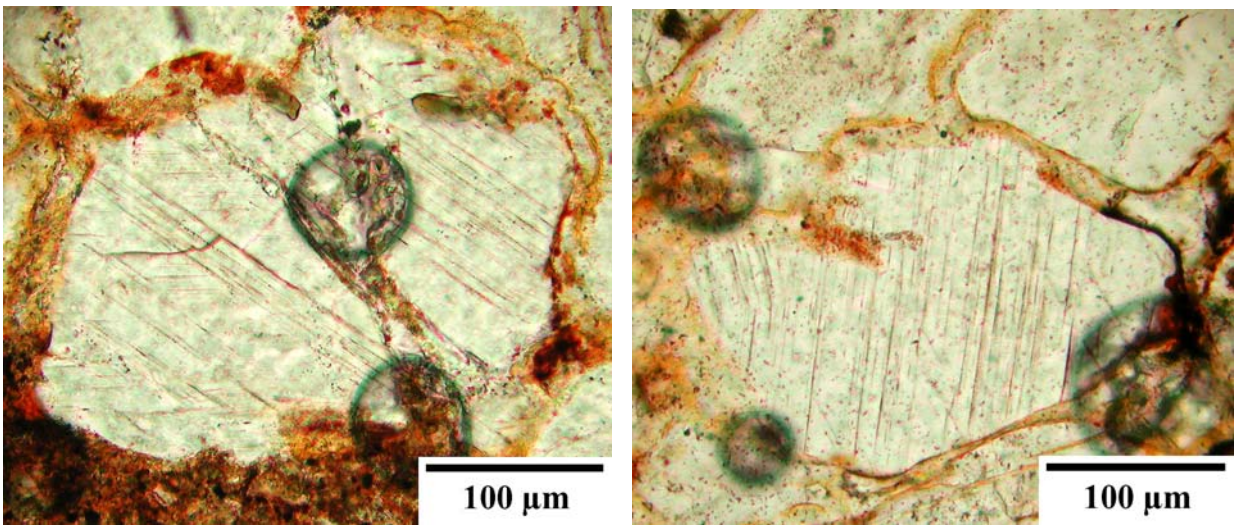

Figure 12. Photographs of thin sections of sandstone fragments embedded in polymict breccia from Vista Alegre. Some rare quartz grains exhibit planar deformation features (PDFs) in up to two sets of crystallographic planes.

PROTECTION MEASURES

Vista Alegre Astrobleme also stands out with respect to protection measures aiming at preserving its important geological heritage. By means of a collaboration between Mineropar-Minerais do Paraná S.A. (a State of Paraná-owned mining company), the University of Campinas-Unicamp and the local administration of Coronel Vivida County, a series of protection measures have been implemented since 2006.

After the discovery of the meteorite crater in 2004 (Crósta *et al.,* 2004) , the authors, in collaboration with Mineropar, proposed its inclusion in the index of the geological sites of touristic interest of Paraná State in 2006, as part of the Geotourism Program of Paraná State maintained by Mineropar. As a consequence, promotional materials were prepared containing geo-scientific information related to Vista Alegre Astrobleme. These materials comprise flyers with information, maps, images and photographs, printed in three languages (Portuguese, English and Spanish) (Fig. 13). They are distributed by Mineropar and by the city of Coronel Vivida to residents and visitors. In addition to the flyers, panels with similar content were produced by Mineropar, and installed in downtown Coronel Vivida, in the Vista Alegre village and in the quarry where the breccias are exposed (Fig. 14).

Another important measure for protecting the geological heritage of Vista Alegre was the official declaration by the State of Paraná which transformed the quarry at Vista Alegre village into a protected area. This declaration was proposed by Mineropar and carried out by the State of Paraná Secretary of Culture, encompassing an area of 10 thousand m^2 in the area of the quarry and surroundings which contain the rocks exhibiting the best records of the meteoritic nature of the structure. The declaration was officially announced in a ceremony held at the Coronel Vivida Council, on December 21, 2008. The Brazilian Post Office (ECT) marked the event by issuing a commemoration stamp depicting the topographic image of the Vista Alegre Astrobleme (Fig. 15).

Currently, the facilities for a viewpoint are under construction in an elevated area located at the northern rim of the crater. When completed, the viewpoint will allow visitors to have a panoramic view of the entire structure, similar to the one depicted in Figure 4. The viewpoint will have another panel, similar to the ones already installed in Coronel Vivida and Vista Alegre.

These initiatives have contributed significantly to publicize this important geological site and the subject of meteorite impact, leading to the awareness of the local population and visitors about the importance and the need of preserving this unique geological heritage site.

Figure 13. Folder written in three languages (Portuguese, Spanish and English) with the basic facts about Vista Alegre, for distribution to visitors and residents; the figure shows the Portuguese version.

Figure 14. Panel with the basic facts about Vista Alegre meteorite crater. The opening of the panel happened in December 2006, and the picture shows (from left to right) Mr. Pedro Mezomo (Mayor of Coronel Vivida during the period 2005-2008), Prof. Alvaro P. Crósta (IG-Unicamp) and Dr. Eduardo Salamuni (President of Mineropar).

Figure 15. Postal stamp celebrating the declaration of State of Paraná natural heritage status of the Vista Alegre Astrobleme, in December 2008. The picture depicts Mr. Pedro Mezomo, the representative of the Brazilian Post Office (ECT), Ms. Vera Mussi Augusto, the State of Paraná Secretary for Culture, and Prof. Alvaro P. Crósta. The stamp exhibits the digital elevation model of the Vista Alegre Astrobleme also shown in Figure 2.

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