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Vargeão Dome Astrobleme, State of Santa Catarina

A meteoritic impact record on volcanic rocks of the Paraná Basin

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Vargeão Dome is one of the few examples of astrobleme in the Brazilian territory. Located on the western portion of Santa Catarina State, this conspicuous circular depression has a diameter of 12 km and depicts sharp topographic gradients of up to 150 meters between its borders and inner portions. The geomorphological features seem today represent the erosion remnants of the original crater, formed over volcanic rocks of the Serra Geral Formation (Jurassic-Cretaceous) by the impact of an extra-terrestrial body against the Earth´s surface. Besides the steep borders, it depicts internally a series of topographic elevations and depressions, arranged as concentric rings and also along radial lineaments, formed by brittle faulting associated to the crater formation process. It is a complex crater, with a central uplift comprising impact breccias and sandstones from the Pirambóia/Botucatu (Triassic/Jurassic) formations, vertically displaced by some 700 meters in comparison with their normal position in this portion of the Paraná Basin. Features due to impact metamorphism found at Vargeão include shatter cones in sandstones and basalts, impact breccias in basalts and sandstones and PDFs in quartz and plagioclase.

Key-words: astrobleme, impact crater, impact metamorphism.

INTRODUCTION

There are currently only five known impact craters in Brazil. Another six Brazilian structures are suspected to have been formed by the impact of extra-terrestrial bodies (generic term 'meteorites'), although not enough evidence of their impact origin are available yet (Romano & Crósta, 2003; Crósta, 2004).

Among the proven Brazilian impact craters is Vargeão Dome, located in the western portion of Santa Catarina State, in southern Brazil. Its center is located at 26º49'S e 52º10'W (Figure 1) and it has a diameter of 12,4 km. This formidable circular structure extends over three different municipalities (Vargeão, Faxinal dos Guedes and Passos Maia). The town of Vargeão is located within the crater, more precisely in its southern border (figures 2 e 3).

The occurrence of an anomalous circular feature at Vargeão was first pointed out by Paiva Filho & Scheibe (1978), based on observations of radar imagery from the RADAMBRASIL Project. The name 'Vargeão Dome' was proposed by these authors. They identified a circular depression exhibiting a ring/radial fracture pattern, affecting volcanic rocks of the Serra Geral Formation of the Paraná Basim, with some outcrops of sandstones at the center of the structure. These sandstones were correlated by them to the Jurassic Botucatú Formation. The anomalous stratigraphic position of the sandstones, at least some hundreds of meters above their normal depth of occurrence at this portion of the Paraná Basin, led the authors to point out the existence of a 'stratigraphic window' and to relate its origin to a hidden alkaline intrusion of Cretaceous age, similar to those occurring in other parts of Santa Catarina State, such as the Anitápolis and Lajes intrusives.

The Vargeão Dome was studied in more detail during the 1980´s, when oil/gas exploration surveys were carried out in the region. Barbour Jr. & Corrêa (1981) reported on a survey that resulted in the definition of at least four lava flows between the outer and the inner portions of the depression, the three lower ones of basaltic composition and the upper flow comprising porphyry quartz-latites. The authors proposed a tectonic origin for the sandstone outcrops at the center of the structure, since they were bounded by faults along the contacts with the volcanic rocks of the Serra Geral Fm. The occurrence of breccias in the interior of the structure was also noted by these authors. They considered them to be of tectonic origin and related the brecciation to the same event responsible for the uplift of the sandstones. As to the origin of the entire structure, Barbour Jr. & Corrêa *(op. cit.)* proposed four different hypotheses: faulting (with vertical displacements of up to 500m), cryptovolcanic explosion (either gas explosion or meteorite impact), volcanic explosion with the formation of a caldera or igneous intrusion of alkaline nature. Subsequent work by Crósta (1982) and Paiva Filho *et al.* (1982) pointed out the morphologic and tectonic similarities between Vargeão Dome and other eroded impact craters on Earth, including Araguainha Dome, which was by then the only proved astrobleme in Brazil. These authors also reasoned on the complete lack of evidence to support the tectonic and/or igneous origin for Vargeão.

Crósta (1987) mentioned the occurrence of planar deformation features (PDFs, or shock lamellae) in at least two directions in quartz grains from the sandstones outcrops at the center of Vargeão. This finding, through petrographic analysis carried out by M. V. Coutinho (personal communication to A. P. Crósta), reinforced the impact origin of Vargeão Dome. PDFs are considered one of the best diagnostic features of impact metamorphism, being widely used as criterion for the recognition of impact craters (Carter, 1965; French, 1998).

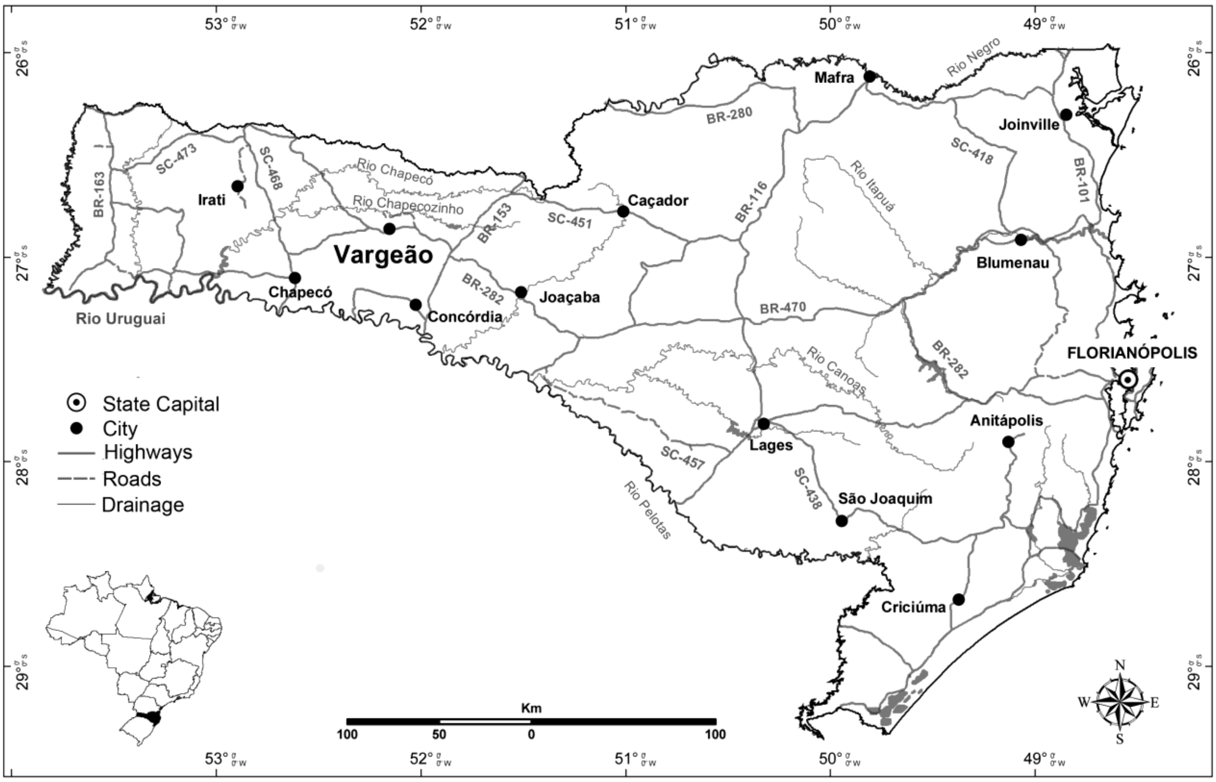

Figure 1: Location and access to Vargeão.

Hachiro et al. (1993) presented petrographic evidences of impact metamorphism found in samples of sandstones and volcanic rocks from the interior of the Dome. In sandstones, they identified PDFs in quartz and feldspar crystals, with directions {0001}, {1013} e {1012}, together with the formation of diaplectic glass (maskelynite). They also found deformation features in feldspar crystals from volcanic rocks of the Serra Geral Fm., such as recrystallization, fracturing, rotation and grinding of crystals, which retained their original external morphology but were converted into mosaics of crystalline fragments welded by microcrystalline material.

Kazzuo-Vieira (2003) and Kazzuo-Vieira *et al.* (2004) analyzed in more detail the impact features associated with Vargeão Dome, some of which are presented in this work.

The set of evidences currently available confers to Vargeão Dome considerable importance, as one of the rare occurrences of impact craters in Brazil and also in the world. This astrobleme has some very favorable conditions as a geological site, such as the easiness of access to the area and to the main representative outcrops, remarkable scenic characteristics and the cooperation of the local population, which has demonstrated particular interest and has been involved in the preservation of the astrobleme as a natural heritage site. In this sense, the transformation of Vargeão astrobleme in a geological site will significantly contribute towards its preservation for scientific studies and also for geoscientific publication.

LOCATION

Vargeão astrobleme is located in the municipalities of Vargeão, Faxinal dos Guedes e Passos Maia, all in Santa Catarina State. The town of Vargeão is located within the crater itself, very close to its southern rim. Access to the interior of the crater is by BR-282 highway, which cuts across the western portion of Santa Catarina State in the east-west direction (Figure 1). From this highway, one can take any of the secondary roads that access the town of Vargeão, descending the scarps marking the southern rim of the crater. From Vargeão, it is possible to travel over most of the crater´s interior by minor unpaved roads, usually in good condition. The main outcrops of rocks representing the deformation events and impact features occur towards the central portion of the crater, mainly within the domains of the central uplift and its surroundings (Figure 2). Good exposures may be found along road cuts and areas of extraction of aggregate materials, common in the area.

SITE DESCRIPTION

Morphologic and Structural Aspects

The first aspect of Vargeão Dome to attract the attention of observers is its remarkable concentric multi-ring morphology (figures 2 and 3). Located in the lava plateaus of the central portion of Paraná Basin, highly dissected by the main fluvial courses of Chapecó, Chapecozinho, Irani and Uruguai rivers, the Vargeão structure stands out due to its circular shape and steep borders, with topographic gradients of up to 150m (figures 3 and 4).

These characteristics, which are visually noticeable from the secondary roads that connect Vargeão to the BR-282 highway, are clearly seen on satellite images and/or digital elevation models such as those shown in figures 2 and 3. The use of these images allows to visualize and to interpret the fault and fracture patterns associated with the structure, as well as its steep rims and inner geomorphologic patterns, characterized by radial and multi-ring elements. The drainage system within the crater is strongly controlled by faults and fractures that enhance the above mentioned patterns.

The Vargeão crater is of the complex type, according to the terminology proposed by Dence (1968). Complex craters differ from the simple ones by the existence of a central uplift. At Vargeão, the surface expression of the uplift is given by the occurrence of the Triassic/Jurassic sandstones at the center of the structure. It should be borne in mind that these sandstones were placed into their present position several hundreds of meters above the normal depth of the Pirambóia/Botucatú formations in this portion of the Paraná Basin. Three of the pioneer wells drilled by Petrobrás (Brazilian Oil Company) for oil/gas exploration in the region around Vargeão indicate minimum depths for these units ranging from 680 to 1,220 meters (wells 1RCH-0001-SC, 1SE-0001-SC e 2AL-0001-SC).

The central uplift of Vargeão was formed during the intermediate stages of the crater formation, by relief of the overload caused by the removal of an enormous amount of rocks, ejected upwards and outwards by the collision of the impacting body. The layers that originally lay beneath the center of the crater were consequently uplifted and these are represented by the lower portions of volcanic rocks of the Serra Geral Fm. and by the sandstones of the Pirambóia and Botucatu formations. The uplift was marked by intense vertical faulting at the central portion of the crater and its surroundings.

Simultaneously, the rocks situated at the margins of the temporary crater, formed at the excavation stage by the action of shock waves generated by the impact, collapsed along concentric gravitational faults, forming depressed rings (ring grabens) and annular highs, thus increasing the crater in its lateral dimension. The dimensions and shape of the final crater were dependent upon the combination of these marginal collapse faults.

The cross sections shown in Figure 4, along the north-south and east-west directions, illustrate the proposed model to explain the formation of the central uplift and the rim of the crater, by means of predominant vertical movements. Despite the current degree of erosion at Vargeão, which significantly modified the original crater morphology, it is still possible to relate the internal morphological pattern seen today to the effect of colapse faulting. As seen in figures 2 and 3, the scarps present in the inner rim of the structure represent the original marginal collapse faults. The central uplift does not stands out topographically as in other complex craters (such as Araguainha Dome), but there are portions of it with topographic gradients of up to 70m in relation to the surrounding terrains within the crater.

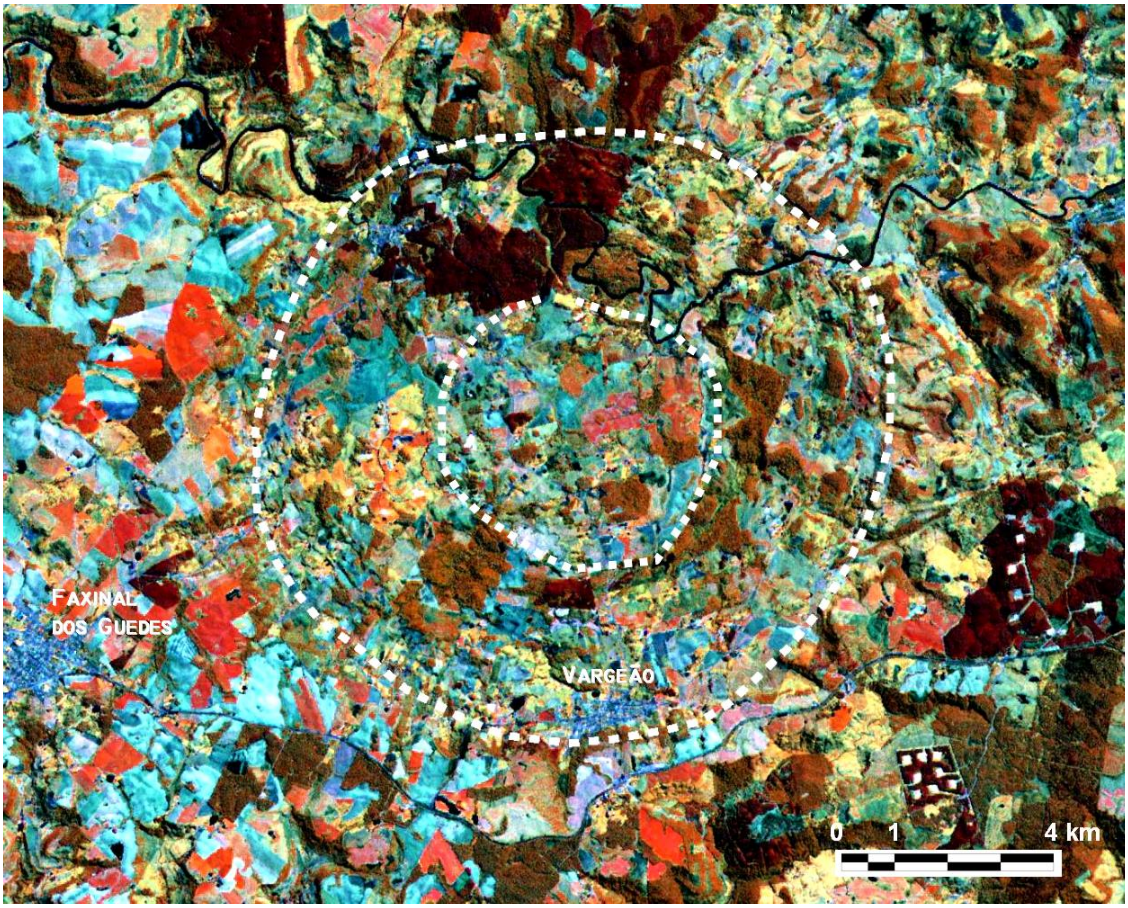

Figure 2: Landsat/ETM+ satellite image (color composite of bands 4, 5 e 3 in RGB) showing the Vargeão astrobleme. The outer dashed line represents the crater rim and the inner line the approximate position of the central uplift. In the interior of the eroded crater there are conspicuous ring and radial features.

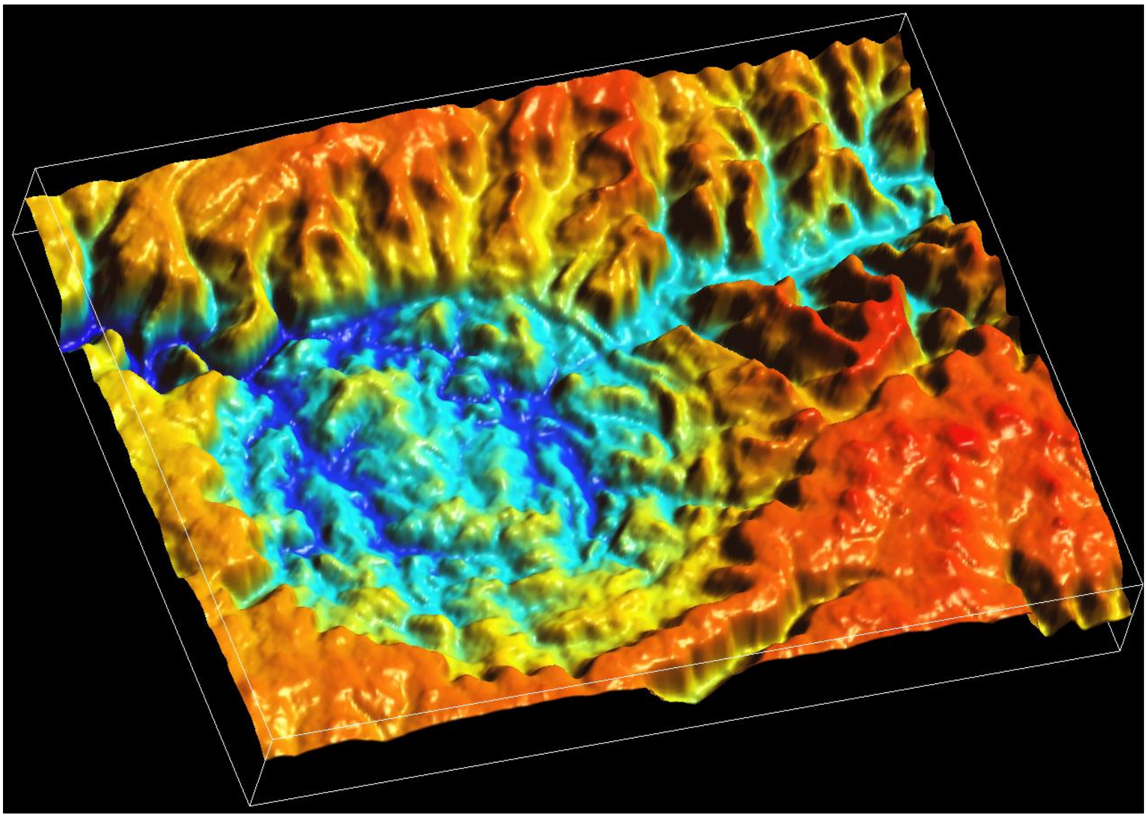

Figure 3: Perspective 3-D view of Vargeão Dome using a digital elevation model from the Shuttle Topography Radar Mission (SRTM).

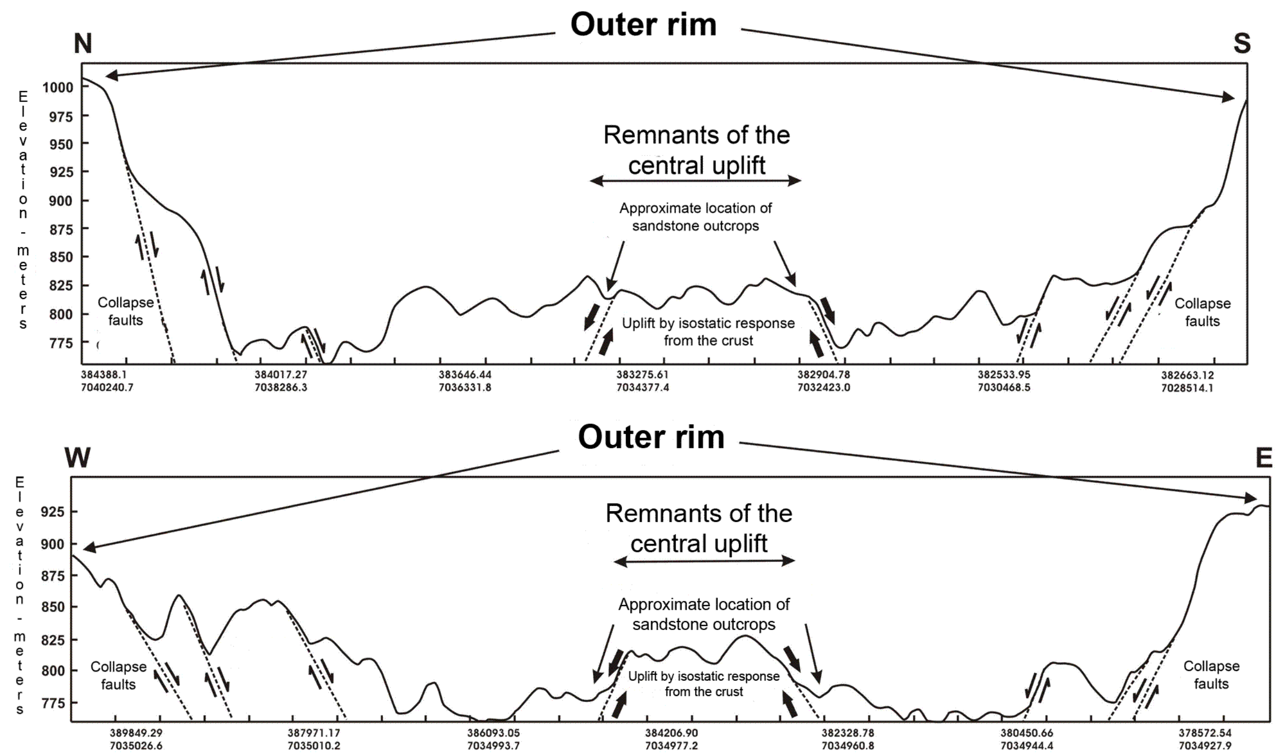

Figure 4: Topographic cross-sections in the N-S and E-W directions showing the steep slopes of the crater rim, the central uplift and the concentric ring features, interpreted as products of the brittle faults associated with the formation of the crater.

Lithologic Aspects

The main lithologic types present at Vargeão Dome are shown in Figure 5. One of the most outstanding characteristics of these rocks is that almost all of them are deformed in some way, varying only the intensity of the deformation. Still, it is possible to relate the lithologies found there to the original litho-stratigraphic units of the Paraná Basin.

The volcanic rocks belong to the Serra Geral Fm., of the São Bento Group, represented by tholeiitic basalts in thick lava flows (up to a few hundred meters) and by quartz-latites (usually with up to some tens of meters in thickness). The two sub-units of the Serra Geral Fm. were named by CPRM (2002) respectively Alto Uruguai Basalts and Chapecó Acidics. Paiva Filho (2000) named these same units respectively as Lower Serra Geral Member and Goio En Member. The quartz-latite unit occurs preferentially at the east and south-east borders of the crater and at some points in its interior, and usually shows a lower degree of deformation. The contact between these two units represents a stratigraphic marker, allowing to infer the relative vertical displacement of the lava layers as a result of the movements induced by the crater formation processes.

The most important deformation feature in the quartz-latites is block collapsing and tilting. These rocks were affected mostly by collapse faulting responsible for the delimitation of the crater rims. They correspond to a layer that was originally placed at higher topographic levels, as it may be seen outside the domains of the Vargeão Dome, having collapsed and tilted downwards and inwards towards the center of the crater.

The unit comprising the basalts is more difficult to separate from the breccias near the center of the crater, alternating portions more or less deformed with strongly brecciated portions. Towards the crater rim the basalts appear in contact with the upper quartz-latite unit.

The sandstones occur at the center of Vargeão Dome, in or near the domains of the central uplift. Considering the high degree of deformation of these rocks, it was not possible to relate them with certainty to the litho-stratigraphic units which probably originated them, represented by the Pirambóia and Botucatu formations. For this reason, these sandstones were not differentiated, being referred to Pirambóia/Botucatú. Some of the main occurrences are exposed due to the extraction of aggregate material for construction purposes, as in the Ghisolfi sand pit, the largest found at the center of Vargeão Dome (Figure 6-D). As shown in Figure 5, the sandstone outcrops are in fact large faulted blocks in tectonic contact with volcanic rocks of the Serra Geral Fm. and/or with breccias derived from them. The sandstones are in general highly deformed, although blocks of metric dimensions are found better preserved from deformation, immersed in fine-grained, highly deformed sandy material. In some of these blocks original sedimentary structures, such as bedding and cross stratification, can still be found (Figure 6-E).

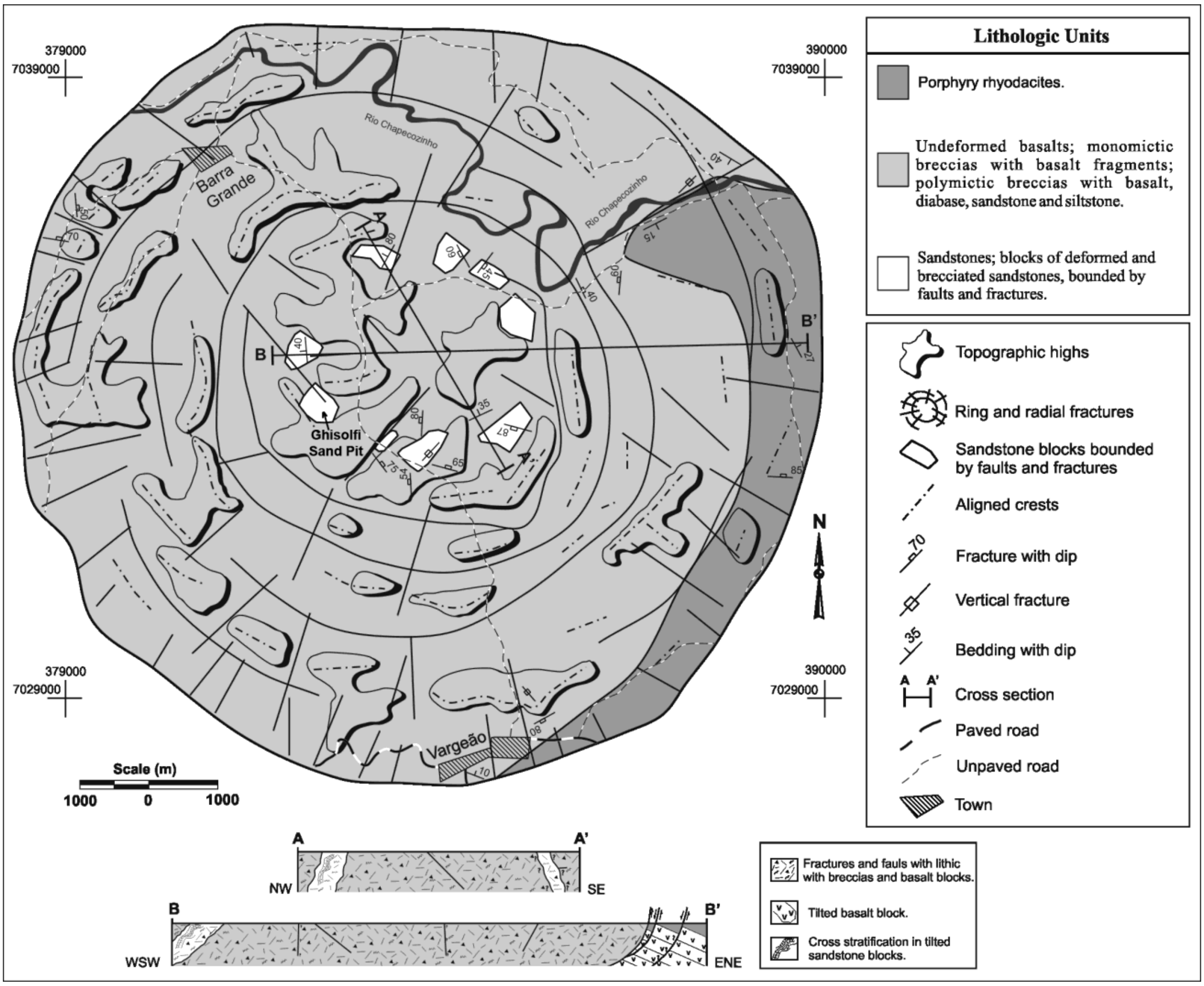

Figure 5: Simplified geologic map of the Vargeão astrobleme.

Impact Metamorphic and Deformation Features

The main impact metamorphism features found at Vargeão comprise impact breccias, partial melting of basaltic rocks, shatter cones in sandstones and basalts, and microscopic deformation features, such as shock lamellae (PDFs).

Impact breccias are rocks formed by the impact event, from pre-existing ones from the target area hit by the meteorite. In the case of Vargeão astrobleme, the pre-existing rocks include basalt, quartz-latite and sandstone. These breccias, with very peculiar characteristics, show multi-granulometric comminution, from clay to pebble-sized granulommetry, with thickness ranging from few millimeters to ten meters. The degree of development of the breccias increase towards the central portion of the crater, where they may form sequences interlayered with less deformed rocks. In the interior of the crater, the contacts between lava layers do not conform to the original stratigraphic contacts. Another characteristic of the breccias is the conspicuous oxidation of the clay portions, producing purple-reddish colors independently of the lithology.

At Vargeão Dome, breccias occur mainly at the concentric plateaus in the central portion of the crater, which in turn are located at the central uplift and its surroundings. These breccias may be divided into two main types. The first type comprises monomict breccias from igneous rocks, usually with fragments of basalt and possibly diabase in a fine grain, poorly sorted matrix (figures 6-A, 6-B, 6-C, 7-A, 7-B and 7-C). The second type includes the sandstone monomict breccias (figures 6-F, 7-E and 7-F).

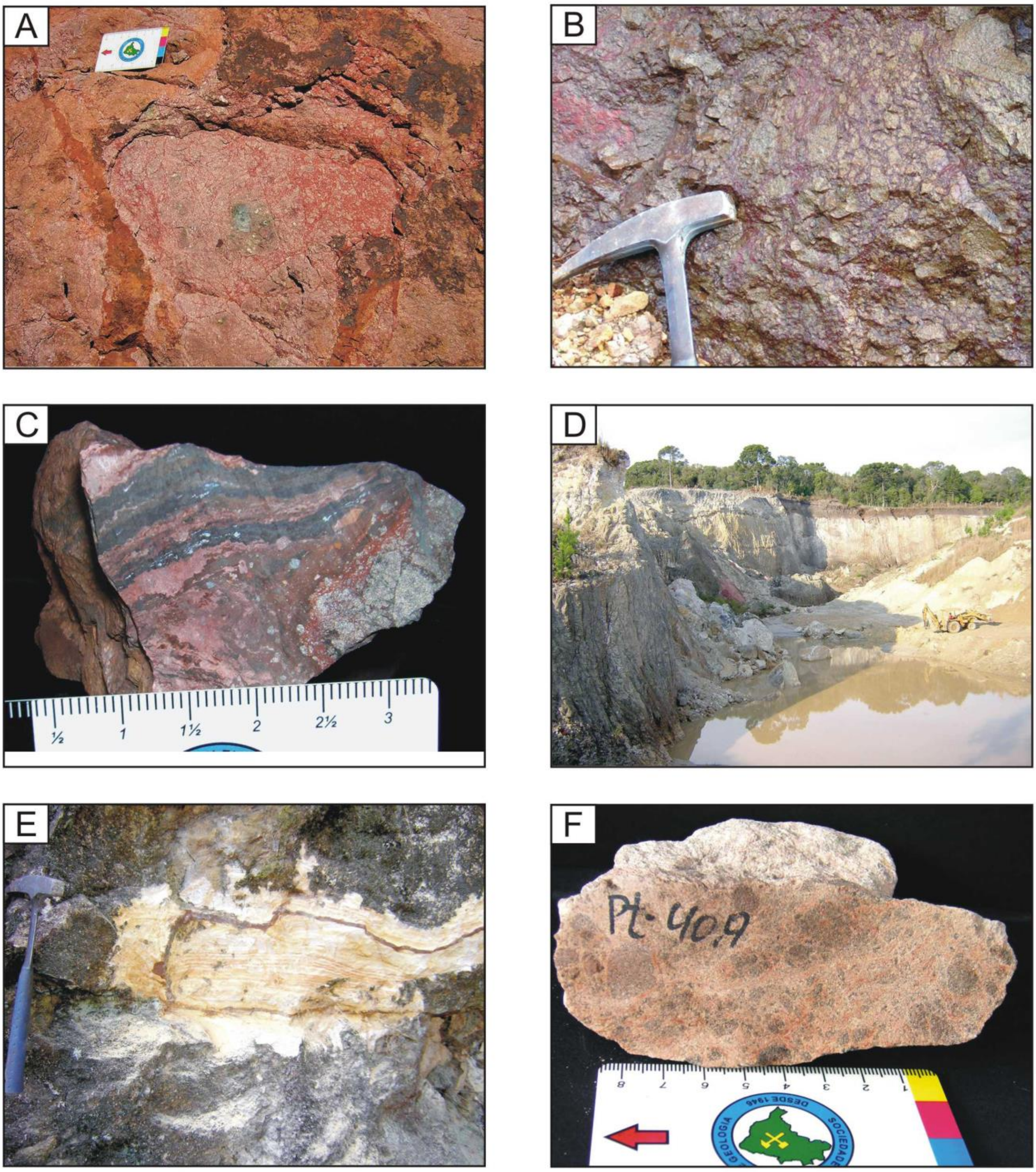

Figure 6: A) veins and veinlets (reddish colors) in polymictic breccias comprising sandstones and basalts; B) basalt monomict breccia showing a detail of angular fragments of basalt in a mycrocrystalline matrix; C) clast with fluidal structure in basalt monomict breccia; D) view of Ghisolfi sand pit, the main sand extraction area within Vargeão Dome; E) sandstones with cross stratification cut by dark red vein of mycrocristalline material; F) sandstone monomict breccia with sandstones clasts immersed in a matrix of fractured and shattered grains..

Examples of partial melting in basalt are shown in figures 6-C and 7-C, in which a breccia is cut by a portion with fluidal texture (dark color), comprising glass originated by partial melting of pre-existing rocks. Although uncommon in Vargeão astrobleme, this type of structure occurs at same places, always associated with the breccias. Shatter cones are tridimensional aggregates of conical striated structures, generated by deformation produced by the passage of the shock waves through the target rocks after the impact. Known occurrences of shatter cones in Brazil are previously limited to Araguainha and Serra da Cangalha (Romano & Crósta, 2003). At Vargeão, four different sites of occurrence were identified, all of them located near the center of the structure, within the domains of the central uplift.

The rocks in which shatter cones developed are sandstones (figures 8-A, 8-B and 8-C) and also basalts (Figure 8-D). Individual cones show dimensions ranging from 12cm up to 35cm, with the larger ones having been found in the sandstones exposed at the Ghisolfi sand pit.

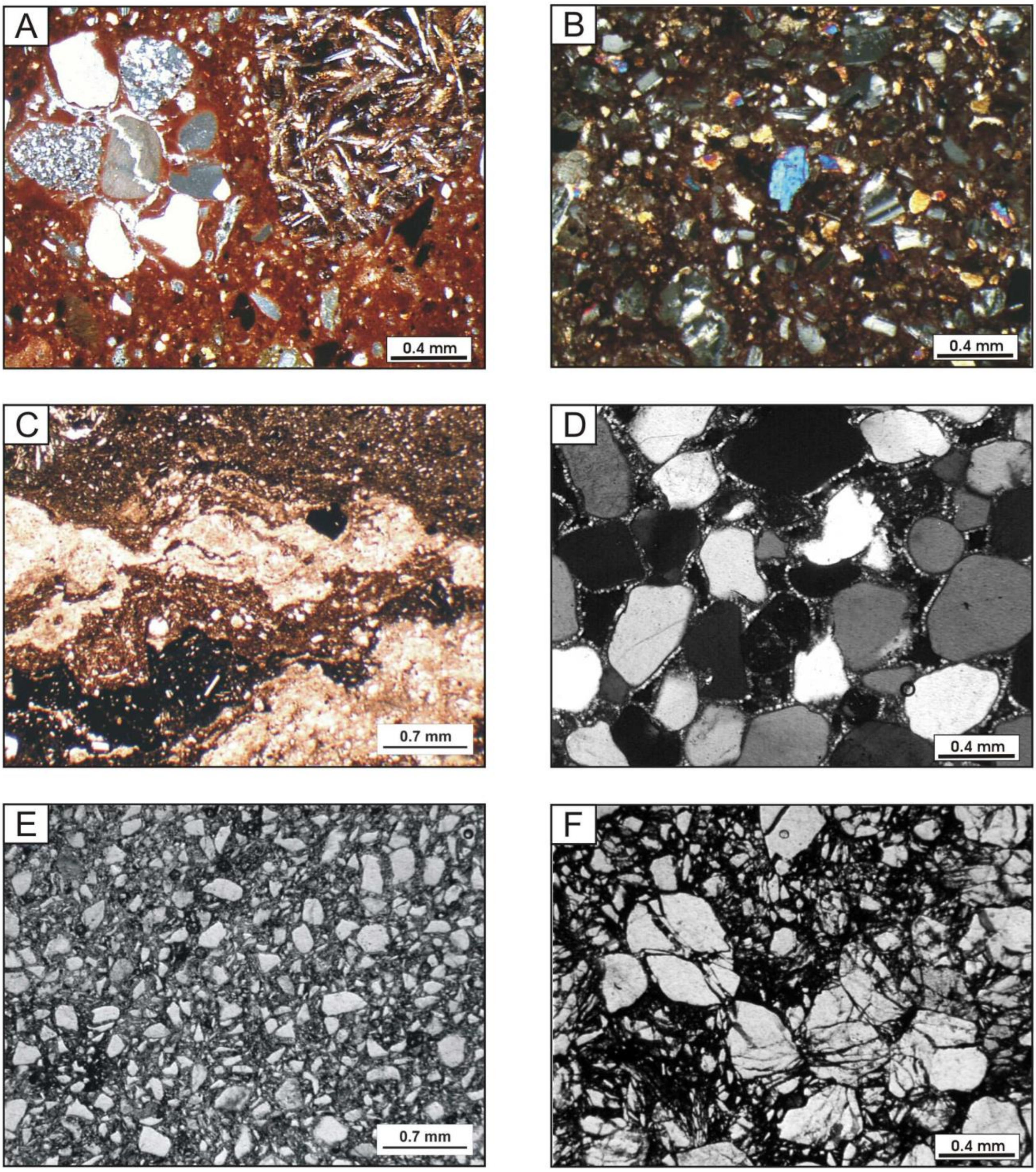

Figure 7: A) basalt polymict breccia with strongly fractured plagioclase grain within a basalt fragment with sub-ophitic texture and incipient fracturing – X nicols; **B)** a more advanced fracturing stage of the breccia seen in 7-A, in which fragments of piroxene, plagioclase and opaque minerals constitute the matrix – X nicols; **C)** detail of fluidal structure in which the bright portions are microbreccia comprising quartz fragments and the dark ones comprise mainly glass, eventually with the presence of plagioclase microlites – X nicols; **D)** sandstone fragment from the sandstone monomict breccia with undeformed, sub-rounded to sub-angular quartz grains, with microcrystalline sílica cementation preserved – X nicols; **E)** fractured and shattered quartz grains forming a mosaic, together with undeformed quartz grains – parallel nicols; **F)** detail of the mosaic of quartz grains with fractures crossing several grains, suggesting that there was no post-deformation movement – X nicols.

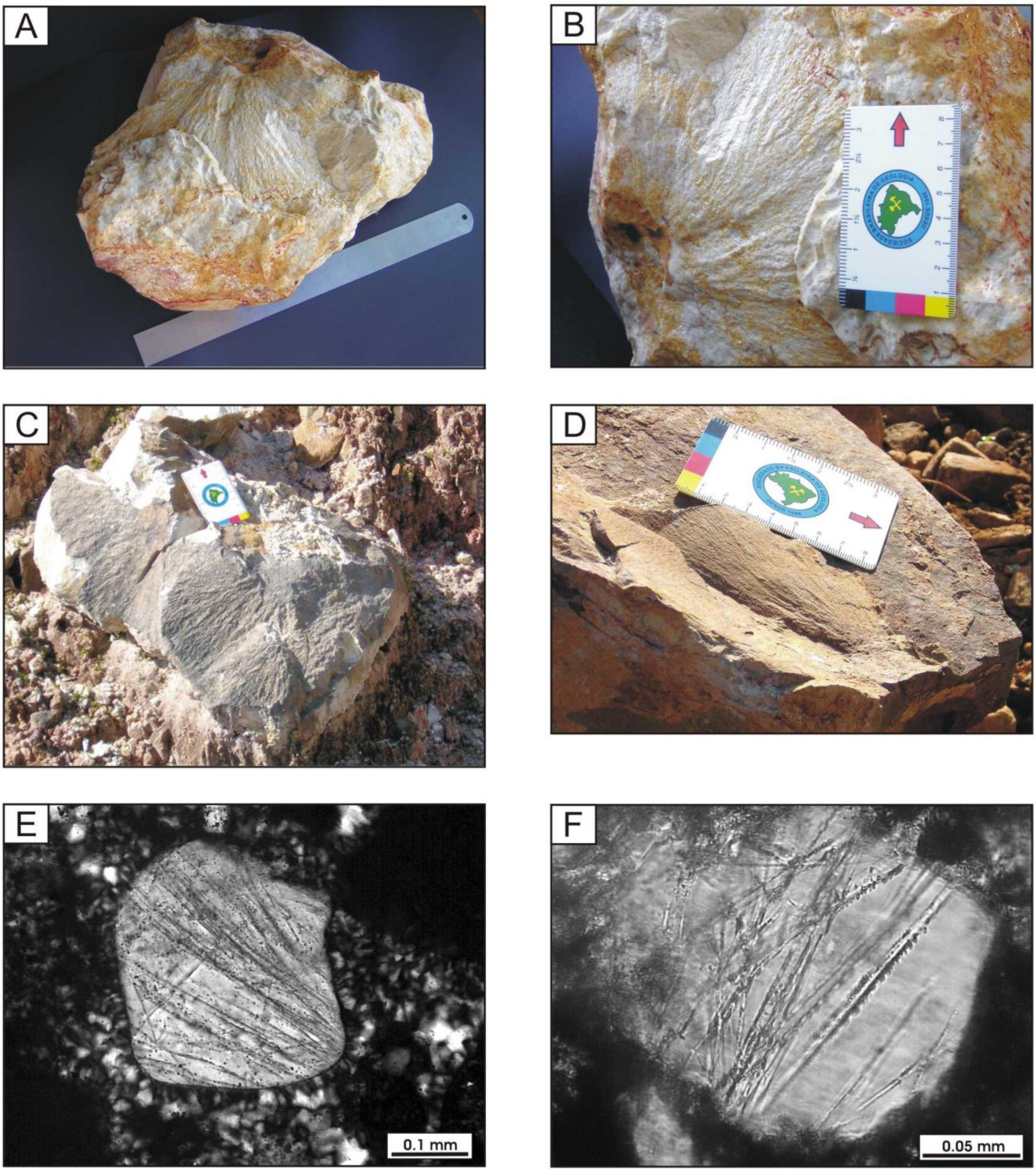

Figure 8: A) shatter cones in sandstones; B) detail showing the apex of a striated shatter cone; C) sandstone exhibiting tri-dimensional aggregates of shatter cones; D) shatter cone in basalt with dimensions of 15x10cm; E) planar deformation features (PDFs) in quartz in four crystallographic directions; F) PDFs in plagioclase in five directions.

Microscopic deformation features identified include planar deformation features (PDFs or shock lamellae) and mechanical deformation of minerals, both caused also by the passage of the shock waves. PDFs constitute, together with shatter cones, diagnostic features for impact events (Carter 1965; Stöffler & Langenhorst, 1994; Grieve *et al.,* 1996; French, 1998). At Vargeão, PDFs were found in both, quartz and plagioclase grains. Almost all the sandstone samples collected at the center of the structure exhibit PDFs and at least three different crystallographic directions have been identified in a single grain (Figure 8-E) (Hachiro *et al.,* 1993; Kazzuo-Vieira, 2003). Measurements of these directions on universal stage suggest peak shock pressures of up to 20 GPa (Kazzuo-Vieira, 2003). In plagioclase, up to five crystallographic directions were observed, as shown in Figure 8-F.

The most common mechanical deformation features at microscopic scales are fracturing, shattering, splintering and crushing of mineral grains, frequently forming mosaics of fractures grains (figures 7-A, 7-E and 7-G). Quartz grains which were originally round-shaped were deformed into aggregates of angular and sharp shards. The most deformed grains occur usually along preferential directions, thus forming 'deformation corridors', close to which undeformed grains are common. These deformation features, clearly post-depositional and post-diagenetic in the case of the sandstones, are frequent in all the rocks found at the interior of Vargeão Dome, in particular in those occurring close to its central zone.

PROTECTION MEASURES

The region of Vargeão Dome has been intensely developed for agriculture and cattle farming for more than a century. Over this period, the original forest-type vegetation has been replaced by crops, pasture and reforestation with pine trees and eucalyptus, significantly changing the landscape. The current status is of relative stability as to the conservation of the remnants of original vegetation.

In relation to the preservation of the outcrops of the most representative rock types and impact features that occur at Vargeão crater the situation is more critical. Almost all the sandstone occurrences at the center of the structure were or are still being exploited for sand extraction for construction purposes, without the adoption of measures for mitigating the impact. A few of these areas were exploited for decades and nowadays are totally abandoned and subject to collapse, with most of the old pits filled with water. The main area still in activity is the Ghisolfi sand pit, where excavation has reached some tens of meters (Figure 6-D; see also Figure 5 for location). The areas of occurrence of basalt and quartz-latite, as well as of impact breccias, are subject to small scale extraction of aggregate materials for surface revetment of unpaved roads.

A positive factor that contributes towards future preservation of this site is the relatively high level of awareness of the local community about the origin of the structure, as well as its importance and singularity. The city of Vargeão has recently adopted the motto "The City of the Meteor", as a result of the publicity of the geological history and origin of the astrobleme. Initiatives for the development of studies and scientific awareness programs, as well as for touristic exploitation of the crater, have been supported by the city administration. In 2004 an observation tower located along BR-282 highway was opened to the public, offering a scenic view of the entire rim of the crater, as well as of its interior. These initiatives will certainly contribute towards the future preservation of this Brazilian geological site.

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