SHATTER CONES IN BASALT: A NATURAL EXAMPLE FROM THE VISTA ALEGRE IMPACT STRUCURE, BRAZIL. L. Pittarello[1,2], F. Nestola[3], C. Viti[4], A.P. Crósta[5], and C. Koeberl[2,6], [1]Analytical, Environmental & Geo-Chemistry (AMGC), Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium (lidia.pittarello@vub.ac.be), [2]Dept. of Lithospheric Research, University of Vienna, Althanstraße 14, A-1090 Vienna, Austria, [3]Dept. of Geosciences, University of Padova, via Gradenigo 6, I-35131 Padova, Italy, [4]Dept. of Physics, Earth and Environmental Sciences, University of Siena, Via Laterina 8, I- 53100 Siena, Italy, [5]Institute of Geosciences, Unicamp, R. Joao Pandía Calógeras 51, 13083-970 Campinas SP, Brazil, [6]Natural History Museum, Burgring 7, A-1010, Vienna, Austria.

Introduction: Shatter cones, multiple sets of penetrative striated conical fractures that can occur individually or in clusters roughly resembling conical structures [1,2], are considered to be the only macroscopic evidence of an impact event (e.g., [3]). The variety of shapes and features observed in natural samples cannot be fully explained by the existing models about shatter cone formation, so far (e.g., [4]). However, some of the features observed in nature have been recently reproduced in experiments [5], suggesting that a definitive interpretation of the phenomenon is close.

Shatter cones formed in fine-grained basalt in the Vista Alegre impact structure (Brazil) exhibit features that have not been described before [6]. Even though a clear interpretation of these features was not possible, this finding provides an exceptional natural example of shatter cones in basalt, which should be considered for further studies and modeling about shatter cone formation process.

Methods: Shatter cones have been discovered in the Vista Alegre impact structure by C. Koeberl and A.P. Crósta during field work in 2009. A sample showing striation on opposite surfaces has been selected for this study. A polished thin (35 µm thick) thin section has been prepared from this sample and investigated by optical and electron microscopy (FEI Inspect S50 scanning electron microscope). A foil from a selected location within the thin section was cut with focused ion beam (FEI Quanta 3-D FEG) and studied with transmission electron microscope (TEM; JEOL 2010, with 200 kV accelerating voltage, LaB6 electron source, ultrahigh-resolution pole piece, and point-to-point resolution of 1.9 Å, equipped with EDS detector). Bulk chemical characterization of the sample was done using X-ray fluorescence and Instrumental Neutron Activation Analysis. In-situ chemical analyses have been obtained with electron microprobe (Cameca SX100). Raman spectroscopy, to characterize the investigated phases, has been done with a confocal LabRAM HR Evolution HORIBA instrument. Except for Raman spectroscopy, performed at the Dept. for Materials and Chemistry of the Vrije Universiteit Brussel (Brussels, Belgium) and the TEM, performed at the Dept. of Physics, Earth and Environmental Sciences of the University of Siena (Italy), all measurements have been done at the Dept. of Lithospheric Research of the University of Vienna (Austria).

Fig. 1 *Shatter cone clast in the suevite from Vista Alegre. Field of view ca. 5 cm.*

Results: The Vista Alegre impact structure, Brazil, is 9.5 km in diameter and is centered at 25°57'S and 52°41'W [7,8]. The target rock mostly consists of tholeiitic basalts of the Paraná Basin. Shatter cones have been found as clasts in polymict breccia (Fig. 1) that largely fills the crater depression, in a quarry close to the village of Vista Alegre [8].

The selected sample consists of a clast of basalt in the polymict breccia, showing striations on opposite surfaces and, therefore, interpreted as shatter cone (Fig. 1a). The basalt in the selected sample mainly consists of plagioclase (An_{53}), augitic pyroxene, and magnetite, with average grain size of 50-70 µm. The chemical composition of the basalt in this sample is consistent with that of unshocked target rock collected outside the crater. The sample is crosscut by fractures, sub-parallel to the striated surfaces, which contain a fine-grained cataclasite. The cataclastic layers are ca. 30 µm in thickness, have sharp margin with the host basalt, locally show a possible offset, and consist of 10 µm in size pyroxene clasts embedded in a very fine-grained (<50 nm) clastic matrix. Pyroxene clasts have sub-rounded surface, are generally slightly elongated, are oriented sub-parallel to the cataclasite margin, and have a composition consistent with that of the pyroxene in the host basalt.

The striated surface in the selected sample is locally decorated with a thin (50 µm thick) continuous film of melt rock. The melt rock film has sharp margin with the host basalt, but displays a local embayment where next to magnetite that shows effects of thermal breakdown. The melt rock film is mostly crystallized in nm-sized, acicular phase with composition mixed between plagioclase and augite. The identification of this phase was not possible, neither by TEM diffraction pattern, which resembles that of pigeonite but this is not consistent with the chemical composition, nor by micro-Raman spectroscopy. A small amount of mica and amorphous material has also been observed in the melt rock film.

Discussion: Cataclastic layers and the melt rock film have some characteristics in common, such as orientation with respect to the striated surfaces, sharp margins with the host basalt, and similar thickness, even though they also show quite different internal microstructures. This suggests a coeval formation, by cold, brittle deformation for the cataclastic layer and localized melting for the melt rock film [6]. Cataclastic layers and the melt rock film are limited to the shatter cone sample and do not extend into the host breccia, supporting the hypothesis of a unique formation process. They clearly did not result from post-impact tectonic deformation of the area.

The occurrence of a continuous melt rock film on the striated surface of shatter cones is quite rare in the literature. Siliceous melt on the surface of shatter cones has been described in samples from the Vredefort and the Sudbury impact craters, which are both large structures [9-11], and more recently a melt film has been reported on shatter cone surfaces from the Santa Fe, New Mexico [12], and the Keurusselkä, Finland [13], impact structures. A vesicular melt film has been preliminarily described also in experimentally produced shatter cones [14].

The identification of the crystalline phase dominating the melt rock film in the Vista Alegre sample would have provided information for constraining the conditions of melting formation. Despite the effort, our attempts failed. This phase is likely a high-temperature polymorph of pyroxene, enriched in alkali and Al, which quenched from the melt.

The formation of shatter cones, including possible local melting effects, is not yet completely understood (e.g., [4]). The most credible models for shatter cone formation seem to agree on (i) the generation of tensile fracturing at the tail of fast propagating shock waves and (ii) the formation of the roughly conical shape fractures due to the presence of heterogeneity in the host rock [4,14-17]. The occurrence of cataclastic layers and melt rock film decorating the striated surfaces in shatter cones from the Vista Alegre impact structure is consistent with this general theory. On the other hand, the lack of clear evidence of a frictional component and the missing identification of the phase crystallized from the melt do not allow the discrimination between proposed models.

Tensile stress at the tip of a fast propagating shear fracture has been invoked for gouge formation during a seismic event [18]. This can locally result in pulverization or even melting of the fault rock, depending on the propagation velocity. Considering the high speed of shock wave propagation and the tensile stress that generates at the tail of the shock front, this mechanism is very likely consistent with shatter cone formation and the observed features. The process probably occurs with the first trail of shock waves emanating at the contact stage, consistent with the general belief that shatter cones formed during the early stages of impact cratering and with their occurrence as clasts in the suevite in the Vista Alegre impact structure.

Conclusion: The Vista Alegre impact structure, Brazil, is one of the few impact structures excavated in basalts where shatter cones have been found. This offers the unique opportunity to investigate natural shatter cone in this lithology. Features that are related to these shatter cones, such as cataclastic layers subparallel to the striated surfaces and a melt rock film decorating the striated surfaces, have been compared with previous similar findings in natural [12,13] and experimental [5,14] samples. Our observations are consistent with the general hypothesis about shatter cone formation, involving tensile stress at the tail of fast propagating shock waves during the early stage of impact cratering. The following step for a complete understanding of the process would be performing experiments on shatter cone formation in basalts, to provide a comparison, under known conditions, with the features observed in this natural occurrence.

References: [1] Dietz R.S. (1947) *Science, 105,* 42-43. [2] Dietz R.S. (1960) *Science, 131,* 1781-1784. [3] French B.M. and Koeberl C. (2010) *Earth-Science Reviews, 98,* 123–170. [4] Wieland F. et al. (2006) *Meteoritics & Planet.Sci., 41,* 1737–1759. [5] Wilk J. and Kenkmann T. (2015) *LPSC XLVI,* Abstract#2637. [6] Pittarello et al. (2015) *Meteoritics & Planet.Sci.* doi:10.1111/maps.12466. [7] Crósta A.P. et al. (2004) *Meteoritics & Planet.Sc., 39,* A28. [8] Crósta A.P. et al. (2010) *Meteoritics & Planet.Sc., 45,* 181-194. [9] Gay N.C. et al. (1978) *EPSL, 41,* 372-380. [10] Gibson H.M. and Spray J.G. (1998) *Meteoritics & Planet.Sc., 33,* 329-336. [11] Nicolaysen L.O. and Reimold W.O. (1999) *JGR, 104,* 4911-4930. [12] Fackelmann S.P. et al. (2008) *EPSL, 270,* 290-299. [13] Hasch M. et al. (2015) *LPSC XLVI,* Abstract#1376. [14] Kenkmann T. et al. (2012) *Meteoritics & Planet. Sci., 47,* Abs.5092. [15] Sagy A. et al. (2002) *Nature, 418,* 310-313. [16] Sagy A. et al. (2004) *JGR 109,* B10209. [17] Baratoux D. and Melosh H. (2003) *EPSL, 216,* 43-54. [18] Reches and Dewers (2005) *EPSL, 235,* 361–374.