FORMATION OF BALLEN IN SILICA BY THERMAL SHOCK. A. Chanou[1], R. A. F. Grieve[1] and G. R. Osinski[1,2] [1]Dept. of Earth Sciences/Centre for Planetary Science and Exploration and [2]Dept. Physics and Astronomy, Western University, 1151 Richmond St., London, Ontario, Canada N6A5B7, *achanou@uwo.ca

Introduction: Ballen silica is a microscopic textural feature that has been defined and used within the impact cratering community since its first description by Carstens [1]. Since then, "ballen" has been associated exclusively with impacts although, not explicitely stated to be a diagnostic impact indicator [2]. The current working hypothesis for the formation of ballen is the shock-pressure driven back-transformation and recrystallization of β-cristobalite from the amorphous state (i.e., diaplectic glass and lechateliarite melt) [1,3,4]. This mechanism requires multiple stages of phase transformation. In addition, this hypothesis implies that ballen is a shock pressure indicator [3-5]. Here, we present an alternative working hypothesis for the origin of ballen. We propose that ballen is the result of the systematic mechanical failure of quartz under extreme thermal condition, based on petrographic and morphological observations.

Samples and methods: Impact melt-bearing breccias from Mistastin, Deep Bay (Canada) and Popigai (Russia) impact structures were examined using optical microscopy, Raman microscopy and Backscatter Electron imagery in an EPMA. All breccia samples have an impact glass clast population.

Observations: Petrographic investigations revealed that all identifiable ballen-bearing quartz clasts are found exclusively within impact glass particles. Ballen appear to propagate/initiate from pre-existing discontinuities in the crystal, such as, fractures, inclusions (e.g., toasted areas) and clast boundaries. Ballen shape variations were also noted to range in both roundness and circularity (Fig 1). Ballen that is traditionally described as round or ball-like have shapes ranging from circular to polygonal and/or rectangular. Ballen domains also vary in size. Larger ballen are defined by wider cracks and commonly contain a finer network of smaller less well developed ballen fractures (Fig 1).

Most importantly, ballen clasts with planar deformation features (PDFs) were observed in samples from all impact structures (Fig 2). The PDFs appear to be continuous across ballen domains. In some cases, there is more than one set of PDFs. Mineralogically, the majority of the ballen-bearing clasts analyzed with Raman were quartz, with rare exceptions of cristobalite patches and some fully amorphous clasts**.** All examined PDF-bearing clast with ballens, however, were quartz.

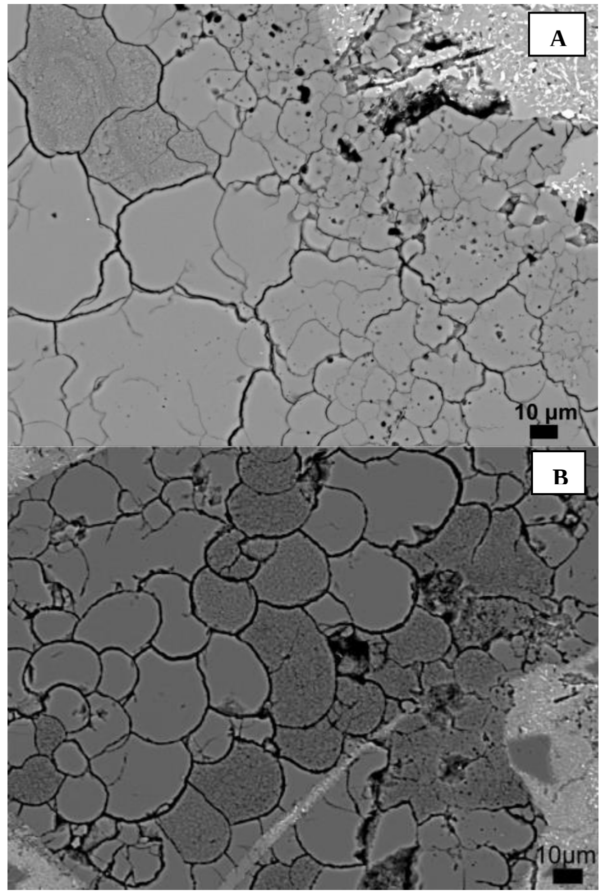

Figure 1 Ballen bearing clasts showing ranging shapes of individual ballen domains. [A] Ballen show angular and polygonal shapes , as well as many "secondary" cracks within the larger domains. In addition, ballen initiation is favored near the clast's boundary resulting to smaller ballen domains. [B] Ballen of higher roundness with some "secondary" cracks.

Discussion: In the literature, "ballen" consistently appears in association with impact melt lithologies [1,3,4] and is absent from parautochthonous target rock lithologies. In addition, ballen-bearing clasts are only found within glassy particles (or formerly glassy) or crypto- to micro-crystalline impact melt rocks. Ballen do not occur in quartz clast in coarser grained melt rocks.

We have documented PDF-bearing ballen from the Mistastin, Deep Bay and Popigai impact structures. PDF-bearing ballen has been reported in the past in both Deep Bay and Dhala impact structures [6,7].

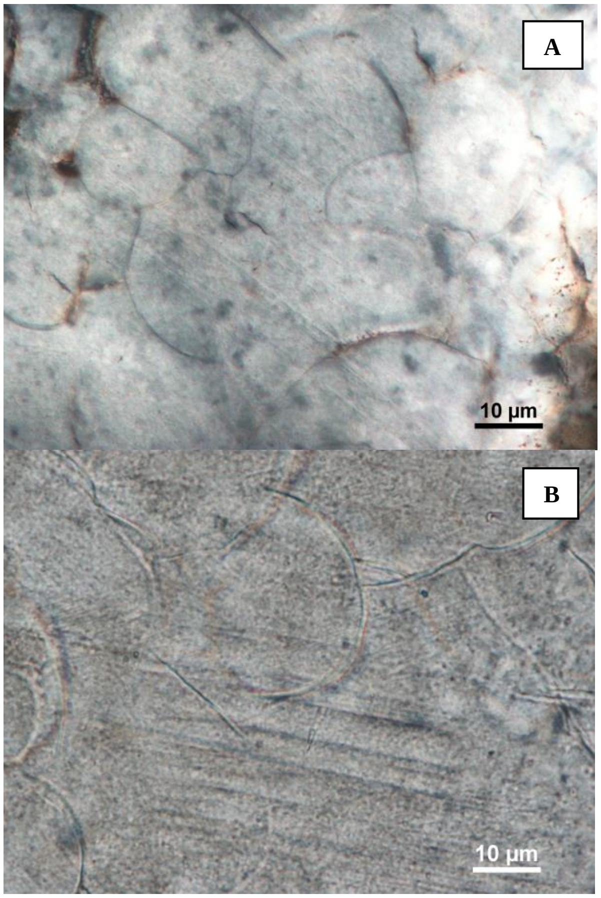

Figure 2 Photomicrographs of ballen clasts showing PDFs under PPL [A] is under conoscpic illuminnation. The PDFs are continuous across ballen cracks**.**

The fact that ballen micro-cracks cross-cut well developed PDFs indicates that ballen is a form of crack and not a growth front [8]. Most importantly, the concurrence of PDFs and ballen indicates that ballen can form without the transitions through an amorphous and/or cristobalite phase(s). The current multi-step formation mechanism would eliminate all traces of PDFs. That is the concurrence of PDFs and ballen leave no doubt that the clasts that display both features have not undergone the phase trasitions described by [1,3,4]

Ballen micro-cracks form networks that have a hierarchical ordering suggests that their formation is successive. The "primary" ballen cracks are wider and the ballen domains larger. "Secondary" ballen cracks develop within the larger ballen domains. Cracks tend to terminate at nearly 90 degrees angles releasing residual stress parallel to previous crack. The ballen network as a whole developes with the successive propagation of new cracks.

Conclusions: We propose that ballen fracture networks develop in quartz clasts when the (cold) clasts undergo extreme thermal shock during their incorporation into super-heated impact melt and the subsequent extremely fast cooling of thatmelt. Based on the restriction of ballen-bearing clasts to essentially vitric melt rocks, we believe that two thermal steps or "shocks" are required for ballen formation: (1) a "hot" shock, when the clast are incorporated in the impact melt and (2) a "cold" shock, when the impact melt cools fast due to the continuous addition of (cold) clastic material, as well melt disaggregation and incorproration into colder lithic breccia material [9]. We suggest that the extreme thermal gradient and fast change of thermal conditions is sufficient to cause enough volumetric change and result to the initiation and development of ballen network. Our observations of PDF bearing ballen also supports this alternative model since there is no requirement of multiple phase changes.

References: [1] Carstens H. (1975), Contr. Min. Petr., *50,* 145-155. [2] French and Koeberl (2010) [3] Ferrière L. et al. (2009) *E. J.Min, 21, 203-217*. [4] Ferrière L. et al. (2010) Geol. Soc. Amer. Spec. Pap., *465,* 609 – 618. [5] Bischoff A. and Stöffler D. (1984) JGR, 89, 645 – 656. [6] Smith J.J. et al. (1999) Meteoritics & Planet. Sci., 34, A110-A111 [7] Kuriyama Y. and Nakamura N. (2011) [8] Short N.M. (1970) *J. Geol., 78, 705 – 732*. [9] Onorato P.I.K. et al.(1978) *JGR, 83,*

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