Introduction and Summary: So-called “ballen quartz” was first described in 1890, in impact melt rock from the Mien impact structure [1]. “Ballen quartz” has since been reported from about one in seven of the known terrestrial impact structures [2]. The first detailed study of these features was reported by [3], who concluded that the ballen texture represented pseudomorphs after cristobalite that had replaced lechatelierite initially formed by shock-induced thermal transformation of quartz. Then Bischoff and Stoeffler [4] found that ballen represent recrystallized diaplectic quartz glass that had undergone the transition to cristobalite and then to α-quartz. Three types of “ballen quartz” were recognized by [4], based on optical characteristics: ballen with optically homogeneous extinction, ballen with different crystallographic orientations, and ballen with intraballen-recrystallization. Recently, optical and electron microscopic observations, as well as Raman spectroscopy (Fig. 1) and transmission electron microscopy (TEM) investigations, have indicated that five types of ballen silica can be distinguished [2]: α-cristobalite ballen with homogeneous extinction (type I); α-quartz ballen with homogeneous extinction (type II), with heterogeneous extinction (type III), and with intraballen-recrystallization (type IV); and chert-like recrystallized ballen α-quartz (type V). In addition, ballen with a “toasted appearance”, similar to what has been described for shocked quartz grains (e.g., [5]), were reported from Popigai [6], from Wanapitei [7], and from Dhala [8] craters.

Ballen, with either α-quartz or α-cristobalite structure, occur as independent clasts or enclosed in diaplectic quartz glass or lechatelierite inclusions (Fig. 2), mostly in impact melt rock and, more rarely, in suevite [2]. Ballen are more or less spheroidal in shape or in some cases elongate (ovoid), and range in size from about 10 to 220 µm [2]. Furthermore, for the first time, coesite was identified by [2] in the form of tiny inclusions exclusively within ballen cristobalite (type I) from the Bosumtwi crater (Fig. 1).

Regarding the formation of ballen, we have recently [2] suggested that two genetic processes are possible: (a) an impact-triggered solid-solid transition from α-quartz to diaplectic quartz glass, followed by the formation at high temperature of ballen of β-cristobalite and/or β-quartz, and finally back-transformation to α-cristobalite and/or α-quartz; and (b) a solid-liquid transition from quartz to lechatelierite followed by nucleation and crystal growth at high temperature.

Figure 1. MicroRaman spectra of different silica phases characteristic or associated with ballen silica. a) Minute intra-ballen inclusion; b) α-cristobalite ballen (type I); c) α-quartz (ballen of types II–V); d) Aggregate of coesite for reference (sample LB-44B from the Bosumtwi crater).

According to [2], the different types of ballen silica are interpreted to be the result of retrogression/back-transformation of β-cristobalite and/or β-quartz to α-cristobalite and/or to α-quartz with time. Furthermore, because ballen silica has been so far only observed in
impactites, these features have been added to the list of impact-diagnostic criteria [2].

**New Observations and Discussion:** In addition to the 28 impact structures listed by [2] in which ballen silica have been described, we have recently observed ballen in impact melt rock from the Logoisk (ballen of types I, II, and III) and Puchezh-Katunki (ballen of types III, IV, and V) craters.

![Figure 2. Microphotographs of: a) α-quartz ballen (type II) in impact melt rock from Wanapitei crater; b) “Toasted” ballen α-quartz (type II) associated with α-cristobalite ballen (type I) in the same lechatelierite inclusion in impact melt rock from the Popigai crater.](image)

Furthermore, we were able to characterize the different types of ballen silica that occur at Dellen (types I-IV), El'gygytgyn (type I), Jänisjärvi (types III and IV), Sääksjärvi (types II-V), Ternovka (types III and IV), and Wanapitei (types I-V) craters. Surprisingly, no coesite inclusions were observed within α-cristobalite ballen from these structures. However, interestingly, cristobalite ballen (type I) were observed together with ballen quartz (types II and III), associated in the same inclusions, in impact melt rocks from Wanapitei and from Popigai crater. Additionally, some of the ballen quartz from Popigai has “toasted” appearance (ballen cristobalite associated within the same inclusions are not “toasted”; Fig. 2). “Toasted” ballen quartz was also observed for the first time in impactites from the Rochechouart, Sääksjärvi, and Ternovka craters. However, based on our Raman spectroscopy investigations, these “toasted” ballen show only the typical α-quartz signature. Consequently, the origin for this “toasting” is still somewhat mysterious (further analyses are ongoing).

In addition, we were able to investigate ballen of α-cristobalite and α-quartz structure occurring within the same silica inclusion using TEM. As already recognized by [2], α-cristobalite ballen are composed of numerous tiny individual crystals with sizes up to ~2 µm. And we show that, similarly, α-quartz ballen are composed of numerous tiny crystals of α-quartz.

**Conclusions:** Our observations of: a) α-cristobalite ballen occurring together with α-quartz ballen in the same inclusion, b) similar micro-texture under the TEM for α-cristobalite and α-quartz ballen, and c) the occurrence of α-cristobalite ballen only in the “youngest” impact structures, confirm that α-quartz ballen are the result of back-transformation of β-quartz and/or α-cristobalite with time, as suggested by [2-4]. We should also consider that if α-cristobalite ballen were rapidly quenched, the conversion of α-cristobalite to α-quartz would have been inhibited. Furthermore, α-cristobalite ballen from Bosumtwi, with coesite occurring as tiny intraballen inclusions, is so far unique, as we were not able to detect coesite in α-cristobalite ballen from any other impact structure. It is likely that with time, coesite inclusions in materials from much older structures could have been transformed back to α-quartz; note the Bosumtwi structure is, at 1.07 Ma age, by far the youngest impact structure investigated by us.

**Acknowledgments:** This work is supported by the Austrian Science Foundation (FWF), grant P18862-N10, the Austrian Academy of Sciences, and a grant by SYNTHESYS. Dieter Stöffler is gratefully acknowledged for allowing investigation of thin sections from his impactite collection. Thanks to Roald Tagle for providing thin sections from Popigai.

**References:**