**FORMATION TIME OF CHELYABINSK BRECCIA AND ITS SUBSEQUENT THERMAL HISTORY.**

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**Introduction:** The ages determined by different radioisotopic dating techniques for the Chelyabinsk meteorite range from 4558 Ga [1] down to ~28 Ma [2]. Radioisotopic ages identified for this genomict breccia [3] are usually considered as geochronologically meaningful and are ascribed to distinct impact events [4,5] creating the impression of a strongly heterogeneous material that experienced a large variety of impact events [4,6]. In an attempt to clarify the thermal history of the Chelyabinsk meteorite we performed high-resolution $^{40}$Ar-$^{39}$Ar dating of its different lithologies [7]. The review of recent petrological data on this meteorite resulted in a revised interpretation of $^{40}$Ar-$^{39}$Ar data yielding a reasonable sequence of impact events affected the Chelyabinsk parent body.

**Samples:** Three samples of the Chelyabinsk meteorite were selected for $^{40}$Ar-$^{39}$Ar dating: a sample from a less shocked portion of the light-colored chondritic lithology, a sample from the shock-darkened chondritic lithology (65.5 and 31.1 mg, respectively) and impact melt of a shock vein adjacent to light chondritic material (71.4 mg).

**Results and discussion:** *Argon release.* A remarkable feature is that all measured samples are different in the degassing behavior of $^{39}$Ar [7]. Although light and dark lithologies are of LL5 origin, their different shock level leads to different retentivity and diffusion properties of Ar, most likely because of the sensitivity of plagioclase to shock metamorphism. The $^{39}$Ar release pattern of the impact melt can be explained by the presence of variably shocked material.

*$^{40}$Ar-$^{39}$Ar chronology.* All measured samples contain trapped argon determined by three-isotope diagrams. The presence of excess argon was not reported by other Ar-Ar labs in Chelyabinsk samples measured by laser systems or its composition was determined with huge uncertainties [4], as it is not always easy to measure precisely $^{36}$Ar and $^{38}$Ar in gas-poor samples by laser degassing techniques, that degas only very low amounts of material yielding low amounts of $^{36}$Ar and $^{38}$Ar. The composition of trapped argon of low temperature (LT) extractions is air-like or slightly higher. The high temperature (HT) extractions of dark and light lithologies contain trapped argon of extraterrestrial compositon with $(^{40}Ar/^{36}Ar)_{tr}$ ratio of 1900 and 20-50, respectively, pointing out to distinct sources of trapped argon in these samples. Depending on selection of HT extractions, $(^{40}Ar/^{36}Ar)_{tr}$ ratio in impact melt ranges between 1 – 30, i.e. similar to adjacent light material. We relate the origin of these extraterrestrial components in Chelyabinsk and other asteroidal meteorites [e.g., 8] to Ar mobilization from host and/or neighboring lithologies during thermal processes accompanying impact events.

The age spectra of light and dark materials with standard correction for trapped primordial argon with $(^{40}Ar/^{36}Ar)_{trapped}=1\pm1$ (Fig. 1a) look similar to the age spectra reported by [2]. The age spectrum of impact melt material is somewhat intermediate between the age spectra of light and dark lithologies (Fig. 1a).

After correction for identified HT trapped argon compositions the dark lithology displays a high temperature age plateau of 2.0±0.1 Ga ( about 60% of fractional $^{39}$Ar release) and the impact melt sample yields a plateau age of 1.71±0.04 Ga (~35% of fractional $^{39}$Ar release) (Fig. 1b). Within 2σ errors, these two ages are indistinguishable and can be explained by a single impact event 1.7±0.1 (2σ) Ga ago. The significance of HT apparent ages of the small segment (~5% of fractional $^{39}$Ar release) of light lithology age spectrum (Fig. 1b) is debatable.

LT ages of the light and impact melt lithologies are 28±41 and 35±30 Ma (Fig. 1b), respectively, and likely represent the ~28 Ma event identified by [2]. Despite the large errors, these values point to a significant heating event during the last tens of million years. This event apparently reset the LT reservoirs of the three lithologies almost completely (Fig. 1b), and left the argon inventory of the HT phases largely unaffected. Hence, the lithologies with the highest proportion of HT argon display the most pronounced HT age plateau, as they are most resistant against thermal reset.

*Ar chronology in the petrological context.* Recent petrological observations [9,10] suggest that the formation of the Chelyabinsk breccia is likely the result of one highly energetic impact event. Textural similarity of the Chelyabinsk fragments with a large mass of melt to terrestrial impactite [9] indicates that a single impact cratering event inducing various shock wave pressures and peak/post-shock temperatures may explain the diversity of shock features in Chelyabinsk. This is also supported by [10] demonstrating that the black veinlets, veins and dikes of impact melt in

Chelyabinsk were simultaneously generated, and the heating of material around the dikes induced mobilization of troilite–metal liquid, filling of open fractures and blackening of the surrounding rock. Uneven distribution of shock metamorphic features in the Chelyabinsk meteorite was related to rapid shock wave dissipation and/or peak pressure heterogeneity within the parent body of the meteorite**.** Finally, although individual shock veins are crosscutting both light and darkened chondritic material [10-12] it was not observed that the same shock veins extend from one to another lithology.

Thus, one energetic impact event apparently led to formation of the Chelyabinsk genomict breccia of S4 level. Afterwards the Chelyabinsk breccia was buried shallow inside the parent body and cooled fast at near-surface conditions [9,10,13]. Since formation the Chelyabinsk breccia was unaltered by shock events [13] and poorly consolidated, so it broke up into numerous fragments during atmospheric entry [11,14].

We interpret the high temperature ages of ~1.7 Ga for the Chelyabinsk dark amd impact melt lithologies as the age of breccia formation, related to a large impact event that caused major impact metamorphism. This is the latest event resulting in light-dark structure formation on the LL chondrite parent body reported so far [15,16]. At the same time, HT phases were formed in strongly shocked material, i.e., the dark lithology and the melt, thereby changing the diffusion properties, making the Ar system more retentive and more resistant to subsequent impact event(s). Our results are consistent with the detailed studies comparing Ar retentivity in lithologies with different shock levels by [17]. Preexisting radiogenic $^{40}Ar$ and primordial $^{36}Ar$ from host and/or neighboring lithologies were mobilized, but not lost completely and equilibrated resulting in the presence of trapped argon.

More recently, strong but mere thermal effects of an energetic impact event about 30 Ma ago reset the LT phases of all three lithologies to varying degrees, mostly affecting the least retentive light lithology. According to petrological observations [13], this impact event caused no mineralogical or textural shock metamorphism, but only resulted in partial loss of radiogenic argon. This could have happened during tempering in the vicinity of an impact melt sheet.

Finally, mild ejection from the parent body (or a parent body fragment) occurred 1-1.5 Ma ago [e.g., this study, 4,14], but did not leave recognizable thermal or mineralogical shock effects.

**Summary:** We conclude the following sequence of events: An intense impact event ~1.7±0.1 Ga ago formed the light-dark structured and impact veined Chelyabinsk breccia. Such a one-stage breccia formation is consistent with petrological observations and was recorded by the strongly shocked lithologies (dark and impact melt). A young reset event ~30 Ma ago particularly affected the light lithology due to its low argon retentivity. Finally, the breccia was ejected 1-1.5 Ma ago from the asteroid.

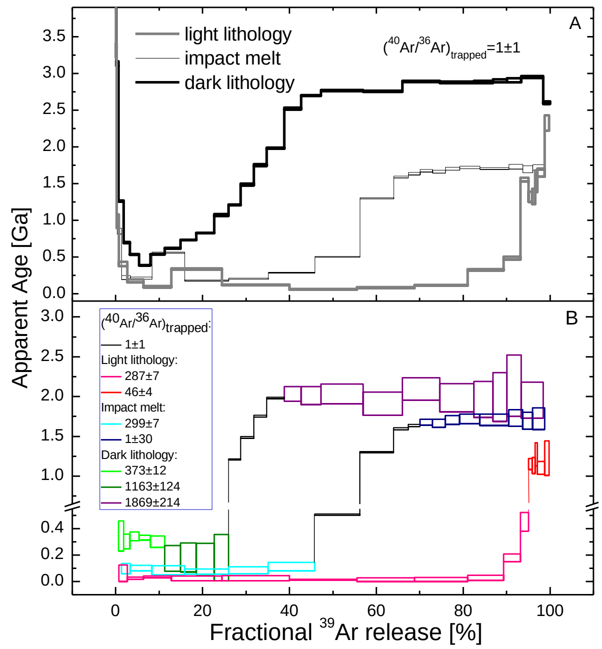


Fig. 1. The age spectra of Chelyabinsk samples corrected for primordial argon with $(^{40}Ar/^{36}Ar)_{trap}$=1±1 (a) and for $(^{40}Ar/^{36}Ar)_{trap}$ ratios determined by three isotope diagrams (b).

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