MINERALOGY, PETROLOGY, CHRONOLOGY, AND EXPOSURE HISTORY OF THE CHELYABINSK METEORITE AND PARENT BODY.

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Introduction: The Chelyabinsk meteorite fall on February 15, 2013 attracted much more attention worldwide than do most falls [1-3]. A consortium led by JSC received 3 masses of Chelyabinsk (Chel-101, -102, -103) that were collected shortly after the fall and handled with care to minimize contamination. Initial studies were reported in 2013 [4]; we have studied these samples with a wide range of analytical techniques to better understand the mineralogy, petrology, chronology and exposure history of the Chelyabinsk parent body.

Oxidation and weathering: The samples exhibit little to no oxidation: Mössbauer and Raman spectrometry indicate their fresh character. Mass spectrometry reveals a low but clearly detectable level of terrestrial organics indicating that despite the rapid collection and care of handling some terrestrial contamination is present.

Mineralogy and petrology: Mineralogy, petrology, bulk chemistry and magnetic susceptibility measurements all indicate these masses are LL chondrite material [4]. However, detailed studies show that the masses contain three distinct lithologies (Figure 1). A light colored lithology is LL5 material that has experienced shock at levels near S4, based on mineralogy and textures. A second lithology consisted of shock darkened LL5 material in which the darkening is caused by melt veins, and metal-troilite veins distributed along grain boundaries. A third lithology is an impact melt breccia that formed at high temperatures (~1600 ºC), and experienced rapid cooling and degassing of S_2 gas. Shock level S4 was experienced by the LL5 lithology (<20 to 30 GPa) but slightly higher pressures (up to 38 GPa) are suggested by high resolution imaging of textures in impact melt veins (Figure 2), as compared to results of shock experiments [20].

Chronology: Portions of light and dark lithologies from Chel-101, and the impact melt breccias (Chel-102 and Chel-103) were prepared and analyzed for Rb-Sr, Sm-Nd, and Ar-Ar dating. Results yielded ages that cluster at ~264-312 Ma, 716-1014 Ma, and 1112–1464 Ma thus indicating a complex history of impacts and heating events (Figure 3); these ages are consistent with other studies of Chelyabinsk [1, 5-10]. The wide range of ages indicates the Chelyabinsk parent body did not experience post-shock annealing that other ordinary and R chondrites have experienced [11-14]. In addition, the specific ages do not include a 4.2-4.3 Ga impact event identified in other LL chondrites [15].

Exposure history: Finally, noble gases and Sm isotopic compositions were measured on these same aliquots to determine space exposure history. Most LL chondrites have yielded CRE ages of 6 to 50 Ma [16], but Chelyabinsk yields 1 Ma (also [17-19]). This young age, together with the absence of measurable cosmogenic derived Cr, and a barely detectable neutron capture effect in Sm for Chel-101, indicate that Chelyabinsk may have been derived from a recent breakup event on an NEO of LL chondrite composition.

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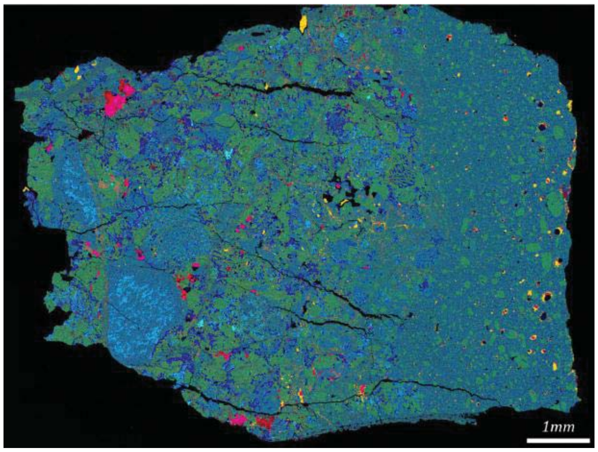

Figure 1: X-ray map of thin section of Chel-102,16. Red = Fe, dark blue / purple = Mg, green = Si, light blue = Ca, magenta = Ni, yellow = S, and white = Ti.

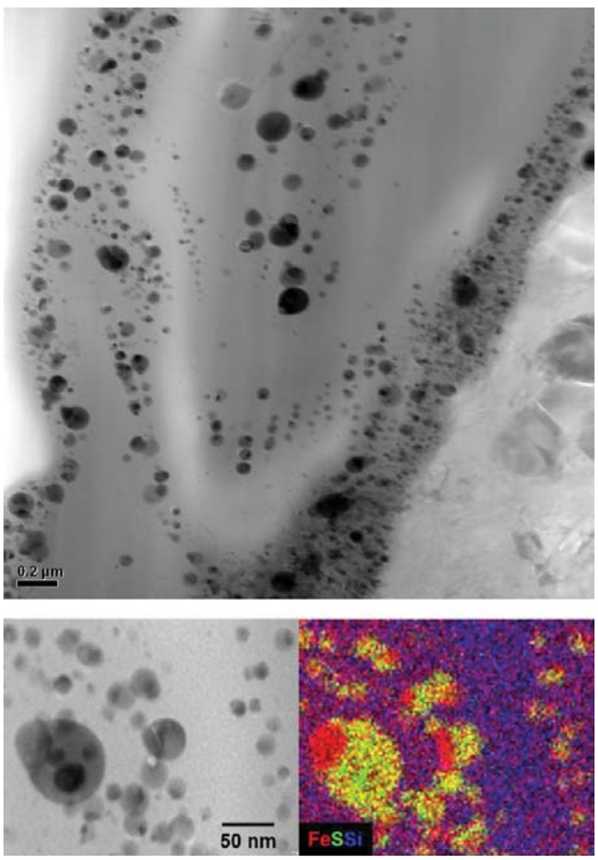

Figure 2 (top): Bright-field STEM image from a FIB section extracted from a region of shock melt in Chelyabinsk. The metal and sulfide inclusions (dark, round grains) are sub-micrometer in size and heterogeneously distributed. Figure 2 (bottom): Bright-field STEM image from a region of shock melt with nanophase inclusions (left) and corresponding composite x-ray map (RGB=Fe S and Si) (right).

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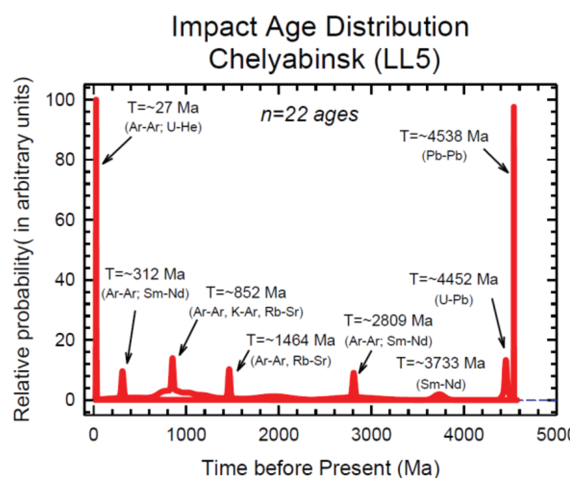

Figure 3: Impact age probability distribution for Chelyabinsk. Red curve represents the summation of the Gaussian distribution of each individual age analysis The age data of Pb-Pb, U-Pb, Ar-Ar (plateau and "integrated" ages), K-Ar, and U-He [1, 5-8, this study] are more precise and are shown by sharp peaks. The less precise Sm-Nd and Rb-Sr isochron [9,10, this study] are shown by broad humps. At least eight impact events (e.g. ~4.53 Ga, ~4.45 Ga, ~3.7 Ga, ~2.8 Ga, ~1.4 Ga, ~312 Ma, and ~27 Ma) are identified for Chelyabinsk. The Sm-Nd and Rb-Sr isotopic systems in Chelyabinsk are very complex and are highly disturbed which is consistent with its having experienced many events of thermal metamorphism and impact resetting after its accretion.