THE COMPLEX COSMIC RAY EXPOSURE HISTORY OF JESENICE (L6): POSSIBLE EVIDENCE FOR EJECTION FROM PARENT BODY BY TIDAL DISRUPTION OR YORP RELATED EFFECTS. K. C. Welten, M. W. Caffe, and K. Nishizumi, Space Sciences Laboratory, University of California, Berkeley, CA 94720-7450 (e-mail: kwelten@ssl.berkeley.edu; kuni@ssl.berkeley.edu), Department of Physics, Purdue University, West Lafayette, IN 47907-2036 (mcaffe@purdue.edu).

**Introduction:** Cosmic-ray exposure (CRE) ages of meteorites represent the ground-level truth against which models for the delivery mechanisms of meteorites from the asteroid belt to Earth are tested [1,2]. As a first-order approach, it is generally assumed that most objects were buried deep enough (more than 5 m) on their parent body and thus avoided any CRE before their ejection into space as a small object and thus that the CRE age of a meteorite represents the transit time of a small object from its parent body to Earth. This assumption is a good starting point for more than 90% of all chondrites and for most irons and achondrites (except lunar meteorites). This seems at odds with model calculations of the orbital evolution of meteoroids [3], which suggest that ~30% of all chondrites should have a two-stage CRE history i.e., these meteorites were exposed to cosmic rays under two (or more) different shielding conditions. Measurements of cosmogenic nuclides in hundreds of chondrites have shown that a small fraction of these meteorites show clear evidence of complex CRE histories [4-12], but the number represents only a few% of all chondrites studied. It is possible that many complex CRE histories have not been identified yet, or have not been convincingly proven [13,14], since this generally requires measurement of both cosmogenic noble gases as well as several long-lived cosmogenic radionuclides, which has only been done on a limited number of samples.

Recently, a complex CRE history was proposed for the Jesenice L6 chondrite [15]. Jesenice has a nominal CRE age of 4 Myr, but shows evidence of a first-stage with high shielding conditions and a second stage in an object less than 20 cm in radius [15]. However, the nature of its exposure history is not well constrained, due to the lack of long-lived radionuclide data. In this work, we measured the cosmogenic radionuclides $^{10}$Be (half-life=1.36 Myr), $^{26}$Al (0.705 Myr) and $^{36}$Cl (0.301 Myr) in the metal and stone fractions of Jesenice to better constrain its CRE history.

**Experimental methods:** We separated the magnetic (metal) and non-magnetic (“stone”) fractions from a 2 g fragment of Jesenice #1 [13]. We dissolved 66.9 mg of purified metal in dilute HNO$_3$, along with a few mg of Be, Al, Cl and Ca carriers. After dissolution of the metal, we took a small aliquot for chemical analysis by ICP-OES. The Mg concentration in the aliquot shows that the metal contains <0.1 wt% silicates, which implies that contributions of $^{10}$Be and $^{26}$Al from silicates are negligible (<1%). We dissolved 116 mg of the stone fraction in concentrated HF/HNO$_3$, along with a few mg of Be and Cl carrier. We separated and purified the Be, Al and Cl fractions from the dissolved metal and stone samples, and measured the concentrations of cosmogenic $^{10}$Be, $^{26}$Al and $^{36}$Cl by accelerator mass spectrometry (AMS) at Purdue University [16]. Results are summarized in Table 1.

<table>
<thead>
<tr>
<th>Type</th>
<th>$^{10}$Be</th>
<th>$^{26}$Al</th>
<th>$^{36}$Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>metal</td>
<td>3.14±0.10</td>
<td>2.89±0.15</td>
<td>22.8±0.5</td>
</tr>
<tr>
<td>stone</td>
<td>13.1±0.2</td>
<td>49.0±1.3</td>
<td>8.8±0.3</td>
</tr>
</tbody>
</table>

**Radiocline results:** The $^{36}$Cl concentration of 22.8 dpm/kg in the metal fraction of Jesenice is consistent with the saturation value in small to medium sized meteorites, thus indicating a minimum CRE age of ~1.5 Myr under low shielding conditions. The $^{10}$Be concentration of ~3.1 dpm/kg in the metal fraction is lower than typical concentrations of ~5 dpm/kg in small to medium-sized objects. The high ratios of $^{26}$Al/$^{10}$Be (0.92) and $^{36}$Cl/$^{10}$Be (7.3) in the metal fractions as well as the low $^{10}$Be and $^{26}$Al concentrations are consistent with a recent CRE age of 1.5-2.0 Myr. If we take into account small contributions of $^{10}$Be and $^{26}$Al from the first stage, then a CRE age of ~1.6 Myr provides the best agreement with measured values.

The $^{10}$Be and $^{26}$Al concentrations in the stone fraction are lower than typical saturation values of 20 and 60 dpm/kg. Assuming typical $^{10}$Be and $^{26}$Al production rates, yields contributions of 11 (10$^{10}$Be) and 47 dpm/kg (26$^{26}$Al) for a CRE age of ~1.6 Myr. The $^{26}$Al value is within error consistent with the measured AMS value, suggesting that the first-stage irradiation either happened more than a few Myr ago or was deep enough that $^{26}$Al contribution from the first-stage is insignificant. On the other hand, the measured $^{10}$Be concentration shows a small excess, suggesting a contribution of ~2 dpm/kg from the first stage irradiation, corresponding to a production rate of 4-5 dpm/kg. Based on this production rate and a $^{21}$Ne contribution of ~0.45 x 10$^{-5}$ cc/g from the second stage, we can calculate the $^{10}$Be/$^{21}$Ne age for the first-stage. Assuming a $^{10}$Be/$^{21}$Ne production ratio of ~0.12 at/at, we calculate a CRE age of ~15 Myr for the first stage irradiation.

Finally, the measured $^{36}$Cl concentration in the stone fraction is significantly higher than the value of 7.0±0.5 dpm/kg expected for production by spallation reactions on K, Ca, Fe and Ni. This elevated $^{36}$Cl con-
centration is most likely due to $^{36}$Cl production by capture of thermal neutrons on $^{35}$Cl. Thermal neutrons are only produced in objects large enough to attenuate the secondary neutrons (which are produced by GCR interactions with the meteoroid) to thermal energies before they escape the meteoroid. It is clear that the pre-atmospheric radius of Jesenice (R<20 cm) was too small to produce a significant thermal neutron flux, so the neutron-capture $^{36}$Cl must have been produced under high shielding in the first-stage irradiation, either near the center of a object of ~3 m diameter (based on $^{10}$Be production of ~5 dpm/kg) or 50-100 cm below the surface of a larger (10 m to km) object [10]. Given the short half-life of $^{36}$Cl, this implies that this first stage irradiation must have occurred immediately before the recent irradiation. Since ~97% of the $^{36}$Cl produced in the first stage has already decayed (since ejection from its parent body), we estimate a first-stage neutron-capture $^{36}$Cl contribution of ~60 dpm/kg. The presence of neutron-capture $^{36}$Cl is at least qualitatively supported by the elevated $^{36}$Ar/$^{38}$Ar ratios, which indicate excess $^{38}$Ar from the decay of neutron-capture produced $^{36}$Cl [15]. However, we note that we would expect larger $^{38}$Ar losses compared to such a high neutron-capture $^{36}$Cl component, although this discrepancy can be due to inhomogeneous distribution of Cl. Unfortunately, no Kr-isotopic compositions are available to further verify the neutron-capture component.

**Discussion:** The complex CRE history of Jesenice is similar to that of other chondrites, i.e., it involves a long irradiation (>10 Myr) near the surface of a larger parent body (2π exposure), followed by a short irradiation (~10^6 yr) at a small object in space (4π exposure). These long first-stage CRE ages are often interpreted to represent the orbital drift times of small (10 m to a few km) asteroid fragments from the main belt to the chaotic resonance zones [1,2]. These chaotic resonances result in eccentric orbits, and thus turn the asteroid fragments into near-Earth asteroids (NEA). The short second-stage CRE ages represent the delivery times of meteoroids ejected from these NEA’s to Earth.

Until a few years ago, the ejection of meteoroids from asteroids was generally assumed to involve impacts, but recent modeling efforts have suggested that tidal disruption [17,18] and the spinup of small asteroids due to the YORP effect [19,20] should also be considered as ejection mechanisms. It may be possible to distinguish these different ejection mechanisms for meteorites with complex CRE histories based on their noble gas record if some ejection mechanisms result in shock-induced helium loss, while others don’t. In some chondrites with complex CRE histories, such as the large Jilin (H5) chondrite, the noble gas record shows evidence of cosmogenic helium loss due to the ejection process [6,21]. Depth profiles of cosmogenic and radio-