TERRESTRIAL COSMIC-RAY EXPOSURE HISTORY OF A 23-GRAM MOLDAVITE AND EVIDENCE FOR THE PRESENCE OF METEORIC BERYLLIUM-10.

F. Serefiddin[1,2], G.F. Herzog[1], and C. Koeberl[3], [1]Dept. Chemistry and Chemical Biology, Rutgers U., Piscataway, NJ 08854-8087, [2]Space Si. Lab., U. Cal., Berkeley, Ca 94720-7450 <feride@ssl.berkeley.edu>, [3]Dept. Geological Sciences, U. Vienna, A-1090 Vienna, Austria.

Introduction: Impact-associated melting of near-surface materials such as soils or loess probably produced the four main groups of tektites [1,2]. Measurements of cosmogenic nuclides in Australasian and Ivory Coast tektites support this view. In particular, both types have appreciable concentrations of ^{10}Be ($t_{1/2}$=1.5 My) [3,4] and, in a few cases, very low levels of the cosmogenic nuclides ^{26}Al ($t_{1/2}$=0.70 My) and ^{53}Mn ($t_{1/2}$=3.7 My) [5,6]. The relative and absolute concentrations indicate that cosmic rays produced the ^{10}Be mainly in the Earth's atmosphere rather than *in situ*. That these tektites incorporated relatively high levels of meteoric ^{10}Be implies that they formed from small (<1 mm) precursor grains, a conclusion consistent with other petrographic and geochemical evidence [7-9]

To extend these arguments, we decided to search for meteoric ^{10}Be in a third major group of tektites. The Central European tektites formed ~ 15 My ago as a result of the Ries-Steinheim impact event into a region capped by a discontinuous layer of sand, clay, and limestone [10,11]. Assuming that the ^{10}Be concentrations in this region resembled those inferred for Australasian tektites, we estimated that even after the passage of ten half-lives, enough ^{10}Be might remain - a fraction of ~0.001 - for a measurement. To control for the possibility of recent, *in situ* production of ^{10}Be, we decided to analyze for ^{36}Cl ($t_{1/2}$=0.3 My), certain that none of any original ^{36}Cl ($<10^{-15}$) would be detectable.

Experimental methods: We obtained a moldavite with a mass of 23.1985 g from the Natural History Museum in Vienna. Wary of the possibility of meteoric contamination, we removed surface material in several steps. First we abraded ~ 3 g from the surface with a Dremel tool, recovering 1.2120 g of powder (J2388ZA) and several chips. The chips, which we reserved, consisted of what appeared to be colorless glass and of orange material resembling iron oxide. Next, we carried out 6 etches of J2388Z as follows: B, 20 mL 1M HCl, low heat for 15 min; C, 1 M HF for 15 minutes at 20°C; D-F, 1 M HF for 20 minutes at 20°C; G, 1 M HF for 30 minutes. The masses of the etched samples were determined by difference. At the end of the etching procedures a sample mass of 19.95 g remained of which we took 19.14 g for the analysis of ^{10}Be.

To each sample we added a known mass of Be carrier. In addition, to sample H we added ~10 mg of Cl$^-$ ion as NaCl for a determination of ^{36}Cl. Samples A and H were dissolved in HF and HNO$_3$. We separated Cl from sample H and isolated ^{10}Be from all samples as described by [12]. The concentrations of ^{10}Be and ^{36}Cl were measured by accelerator mass spectrometry (AMS) at PRIME Lab of Purdue University. In calculating the concentrations of ^{10}Be and ^{36}Cl, we made small corrections for the native concentrations of Be (2 ppm) and Cl (10 ppm) [9].

Results: Results of the ^{10}Be measurements appear in Table 1 and Figure 1. Uncertainties are relatively large for all samples except J2388H because of the small number of atoms of ^{10}Be in the samples. For sample J2388ZB, the uncertainty of the mass, which was ~1 mg, increases the total uncertainty further.

We calculated nominal depths (data points in Figure 1; 'Depths' in Table 1) and layer thicknesses (hori-

Table 1. ^{10}Be concentrations in samples from a 23-gram moldavite.

Sample	Mass (g)	'Depth' (cm)	^{10}Be (10^6 atom/g)
J2388ZA	2.9471	2.72×10^{-2}	9.6±4.8
J2388ZB	0.0009	5.43×10^{-2}	565±565
J2388ZC	0.0466	5.48×10^{-2}	12.1±5.0
J2388ZD	0.0689	5.59×10^{-2}	24.2±9.9
J2388ZE	0.0565	5.71×10^{-2}	5.9±4.2
J2388ZF	0.0654	5.83×10^{-2}	2.6±3.6
J2388ZG	0.0579	5.95×10^{-2}	3.0±3.9
J2388ZH	19.9552	64.34×10^{-2}	0.8±0.1

Figure 1
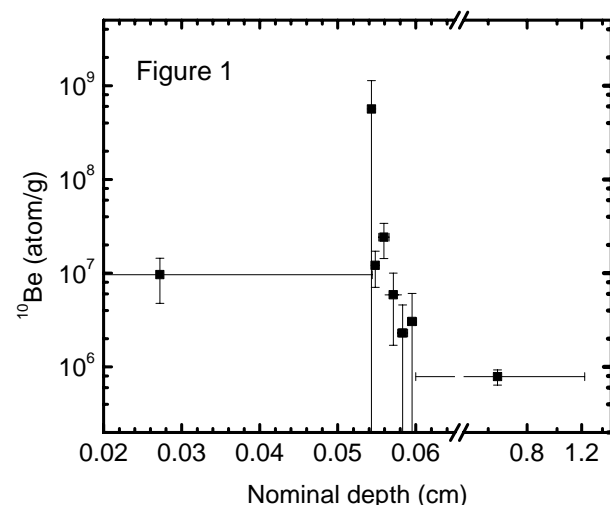
zontal error bars) from the sample masses by treating the tektite as a spherical object with a total initial mass of 23.2 g and a density of 3.0 g/cm^3.

The AMS determination of the $^{36}Cl/Cl$ atom/atom ratio in J2388ZH yielded a value equal to the blank, 15×10^{-15}. Based on this result, we attributed to the sample an upper bound of 1/3 the blank, i.e., $^{36}Cl/Cl=5\times10^{-15}$, which corresponds to a ^{36}Cl concentration of $<2\times10^4$ atom/g.

Discussion: In our preferred, but non-unique interpretation, Figure 1 shows two layers: a surface layer < 1 mm thick with a ^{10}Be concentration of about 10×10^6 atom/g and an interior region relatively unaffected by meteoric contamination with a ^{10}Be concentration about 10 times smaller. In this picture sample E is transitional. The measured concentration of ^{10}Be of 0.8×10^6 atom/g in J2388ZH, the main mass, corresponds to a concentration of 800×10^6 atom/g at the time of formation. This concentration is 2 to 3 times the maximum value of 280×10^6 atom/g reported for Australasian tektites and about 5 times the average [3]. Given the size of the correction for radioactive decay, 1000, we regard this agreement as promising. On the other side, although we doubt that contaminating meteoric ^{10}Be penetrated recently (<<15 My) into J2388ZH, we cannot rule it out.

We consider next the possible contributions of *in situ* production, which depend on composition. Masarik and Reedy [13] give a production rate for ^{10}Be of 5.97 [atom yr^{-1} (g $SiO_2)^{-1}$]. From Masarik and Reedy (1994) [14], we take the production rate ratio $P_{10}(O)/P_{10}(Si)\sim4.7$ and infer $P_{10}(O)\sim9.5$ [atom yr^{-1} (g $O)^{-1}$] and $P_{10}(Si)\sim2.0$ [atom yr^{-1} (g $Si)^{-1}$]. With the approximation that the production rates for all elements other than oxygen equal that of Si, we obtain for the average composition of a moldavite (50 wt% O; [8,15]), $P_{10}=5.8$ [(atom ^{10}Be) yr^{-1} (g moldavite)$^{-1}$] or 13×10^6 atom ^{10}Be/g at saturation. Chlorine-36 is produced from Ca (73 [atom yr^{-1} (g $Ca)^{-1}$]), K (154 [atom yr^{-1} (g $K)^{-1}$]), and Cl (0.081 [atom yr^{-1} (ppm $Cl)^{-1}$]) [16]. With a composition of 1.41 wt% Ca, 2.56 wt% K, [8,15] and a geometric mean chlorine concentration of 5 ppm adopted from Australasian tektites [9] we find a production rate of 5 [(atom ^{36}Cl) yr^{-1} (g moldavite)$^{-1}$]. At saturation then, the expected concentration of ^{36}Cl is 2×10^6 [atom ^{36}Cl/g].

If both ^{10}Be and ^{36}Cl were produced only in a recent surface irradiation (an important assumption), then surface exposure ages calculated from the measured activity, R=concentration/λ, and production rate of each nuclide should be the same. In particular,

application of the relation $T_{exp}= -Ln(1-R/P)/\lambda$ gives $T_{10}=140$ ky and $T_{36}=4$ ky. The small sizes of both these ages relative to the 15-My formation age of the Central European tektites indicate that our sample was well shielded (buried) during most of its history. We conjecture that their small magnitudes imply that exposed moldavites weather and decompose quickly. The larger value of T_{10} suggests that a major portion of the ^{10}Be came from the atmosphere and not from exposure *in situ*. Specifically, a surface exposure lasting ~4 ky would produce a ^{10}Be concentration of only 0.03×10^6 atom/g, implying that most of the ^{10}Be measured in the moldavite is meteoric. Complex histories with exposures occurring more than 4 half-lives of ^{36}Cl ago might also explain our results.

Conclusions: Low ^{36}Cl and ^{10}Be concentrations show that the moldavite studied was buried at a depth of several meters for most of the time since it formed 15 My ago. 2) We interpret a measured depth profile of ^{10}Be as showing that after the moldavite formed, meteoric ^{10}Be did not penetrate to an average depth much grater than 1 mm. 3) At the time of moldavite formation, the source material contained up to 800×10^6 atom/g of meteoric ^{10}Be. Allowance for some prior exposure *in situ* and re-burial of the moldavite would reduce this value to one more typical of Australasian and Ivory Coast tektites. The presence of a substantial meteoric component of ^{10}Be in this moldavite indicates that the precursor material was near the surface and loosely consolidated at the time of formation.

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