

HOW HOMOGENEOUS WAS THE EARLY SOLAR SYSTEM? THE CHROMIUM STORY. C. M. O'D. Alexander and R. W. Carlson. DTM, Carnegie Institution of Washington, Washington D.C. 20015, USA (alexande@dtm.ciw.edu and carlson@dtm.ciw.edu).

Introduction: An isotopically homogeneous early Solar System is a prerequisite if short-lived radionuclides are to be used as chronometers. Shukolyukov and Lugmair [1] pointed out that there is a correlation between $\epsilon^{53}\text{Cr}$ and $\epsilon^{54}\text{Cr}$ excesses in bulk carbonaceous chondrites. Excesses in ^{53}Cr are generally ascribed to the decay of ^{53}Mn ($T_{1/2}=3.7$ Ma), while ^{54}Cr excesses are generally assumed to be nucleosynthetic in origin. Sequential leaching of bulk chondrites has shown that they are composed of several isotopically distinct Cr components, and that the ^{53}Cr and ^{54}Cr excesses are carried in separate components [1-4]. Hence this apparent correlation between the two Cr isotopes in the bulk compositions is a puzzle. In addition, correlations have also been reported between $\epsilon^{54}\text{Cr}$ and Mn/Cr ratio, and between $\epsilon^{54}\text{Cr}$ and $\Delta^{17}\text{O}$ [2]. A correlation between $\Delta^{17}\text{O}$ and ^{63}Cu excesses has also been reported [5]. The variations in O isotopes are not due to radioactive decay, but the ^{63}Cu excesses have been attributed to the decay of ^{63}Ni ($T_{1/2}=100$ yrs). Thus, in carbonaceous chondrites there appears to be a correlation between two possibly radiogenic nuclides (^{53}Cr and ^{63}Cu) with very different half-lives, a nucleosynthetically derived anomaly (^{54}Cr excess), and what is generally thought to be a photochemical derived variation in $\Delta^{17}\text{O}$.

The non-radiogenic anomalies point to significant nebular heterogeneity. The evidence for nebular heterogeneity is emphasized when the ordinary and enstatite chondrites, achondrites, Earth-Moon and Mars are included. They do not fall on the same correlation lines as the carbonaceous chondrites in plots of $\epsilon^{54}\text{Cr}$ vs. Mn/Cr, ^{63}Cu or $\Delta^{17}\text{O}$. In these bodies, but not the carbonaceous chondrites, it has been suggested that $\epsilon^{54}\text{Cr}$ and $\epsilon^{62}\text{Ni}$ are correlated [6]. The compositional distinction of carbonaceous chondrites is further displayed by their nucleogenic isotope anomalies in Ba, Nd and Sm compared to ordinary chondrites, differentiated meteorites, and Earth [7, 8].

The key to understanding the causes of the observed correlations in the bulk meteorites is to identify the various components responsible for the range of isotopic compositions observed. Several studies have shown that the ^{54}Cr carrier is resistant to acid attack at low temperatures [1-4]. Shukolyukov and Lugmair [1] suggested that the ^{54}Cr carrier may be a presolar grain preserved in the matrix, and that the range of $\epsilon^{53}\text{Cr}$ and $\epsilon^{54}\text{Cr}$ isotopes in carbonaceous chondrites is the result of variable abundances of matrix and chondrules. Alexander [9] has suggested that the matrices of all chondrites are dominated by a CI-like component and that

this component is responsible for the abundances of presolar grains and organic matter, as well as highly volatile elements, in chondrites – e.g., in the most primitive members of each chondrite class the matrix-normalized abundances of presolar grains [10] and organic matter are CI-like.

If all chondrites accreted the same presolar material in their matrix, the $\epsilon^{54}\text{Cr}$ carrier should have been present in all chondrites, including the ordinary chondrites and ECs. Since the $\epsilon^{54}\text{Cr}$ carrier is somewhat acid resistant, it should be possible to concentrate the carrier and determine whether it has the same composition in all chondrite classes. A common carrier in all carbonaceous chondrites is suggested by the results of Alexander [11] who reported similar $\epsilon^{54}\text{Cr}$ compositions for hot HCl (6N HCl, 80°C for ~12 hrs) leaches of acid residues of Orgueil, Tagish Lake and Murchison (201±23, 177±6 and 236±6, respectively). Ion probe mapping of the Orgueil residue failed to identify the ^{54}Cr carrier, but showed that it is not in $\geq 1\mu\text{m}$ grains with isotopically anomalous O (or S) compositions [12, 13], deepening the mystery about why there is an apparent correlation between $\epsilon^{54}\text{Cr}$ and $\Delta^{17}\text{O}$ in the bulk carbonaceous chondrites.

Methods: Following up on this, we have measured the Cr isotopic compositions of new residues for Murchison, the CVs Leoville and Mokoia, and the LL3.05s QUE97008 and MET00452. The residues were prepared using the relatively gentle CsF technique [e.g., 14] at room temperature. Since almost all chondrule and CAI material is either destroyed or physically removed during the preparation of these residues, they are essentially concentrates of the acid-resistant matrix material, including the presolar grains. The residues were leached with 6N HCl at 80°C for ~12 hrs. A small aliquot of each solution was retained so that the amount of Cr in the leachates could be estimated by ICP-MS. The Cr was then isolated from the remainder of the solutions following standard column chemistry [e.g., 3, 4], and analyzed by TIMS with the Carnegie's Triton.

Results: The results are given in Table 1. As can be seen, large ^{54}Cr anomalies were found in all the leachates, including the ordinary chondrites. The ^{54}Cr excesses for the new Murchison residue are not as large as previously reported by [11] for this meteorite, but it is possible that the new much larger residue is not as pure as the previous one. The ^{54}Cr excesses found in the CVs and ordinary chondrites are not as large as in Murchison, but they are larger than any previously reported values for meteorites from these

classes. As previously noted, the ^{54}Cr anomalies are accompanied by small, to not significant, ^{53}Cr anomalies.

Table 1. The isotopic compositions of 6N HCl leaches of acid residues and the estimated fraction of the bulk meteorite Cr in the leaches.

	% Cr	$\epsilon^{53}\text{Cr}$	$\epsilon^{54}\text{Cr}$
CM			
Murch 2	0.0075	-0.60±0.26	111.5±0.6
Murch 2b	0.0075	-0.28±0.21	103.0±0.5
CV			
Leoville	0.0171	-0.42±0.17	26.6±0.4
Mokoia	0.0140	0.15±0.15	9.1±0.4
LL			
MET00452	0.0075	-0.65±0.08	39.6±0.3
QUE97008	0.0077	-0.35±0.10	39.1±1.3

Discussion: Two factors may have caused the smaller excesses in the CV and ordinary chondrite leachates than in the Murchison leachates: the residues from these meteorites have more leachable isotopically normal Cr, and/or the metamorphism these meteorites have experienced has destroyed some of the ^{54}Cr carrier. Nevertheless, the most striking feature of our new results is that the two ordinary chondrite residues produced higher ^{54}Cr excesses than the two CVs despite the fact that, in bulk, the CVs have significant ^{54}Cr excesses and the ordinary chondrites have significant depletions [1, 2].

Table 2. Comparison of the predicted and measured bulk $\epsilon^{54}\text{Cr}$ compositions [2].

	Predicted	Measured
CM		
Murch 2	0.75	1.01
CV		
Leoville	0.67	0.86
Mokoia	0.54	0.86
LL		
MET00452	0.29	-0.44
QUE97008	0.30	-0.44

To test whether the leachates account for all the ^{54}Cr excesses in the bulk meteorites, it was assumed that the bulk meteorites are a mix of the leachate and material with a bulk $\epsilon^{54}\text{Cr}$ isotopic composition of 0. For the carbonaceous chondrites, this simple model is able to explain between 62 and 78% of the bulk ^{54}Cr anomaly. The ordinary chondrite bulk compositions cannot be explained by this simple model and require that the bulk of their Cr has a large $\epsilon^{54}\text{Cr}$ depletion (~-0.7). Nevertheless, these results are consistent with the bulk of the ^{54}Cr being carried in an acid-resistant phase that is concentrated in the matrix and is presolar. Su-

pernova-derived Si_3N_4 is a possible candidate as in should be soluble in hot HCl.

The bulk of the Cr in ordinary chondrites is presumably in chondrules. Trinquier et al. [2] reported $\epsilon^{54}\text{Cr}$ compositions for two Chainpur chondrules of only -0.41±0.14 and -0.48±0.12, suggesting that there is an even more depleted component that has yet to be identified. The $\epsilon^{54}\text{Cr}$ composition of one chondrule from Qingzhen (EH3) is similar (-0.46±0.14) to those in Chainpur, but a chondrule from Allende has a composition that is significantly different (-0.08±0.11), suggesting that chondrules from different chondrites formed from different materials. Chondrules also exhibit a wide range of $\Delta^{17}\text{O}$, wider than bulk meteorites, within and between chondrite classes that could also indicate a range of precursors. If, as seems possible from the reported $\epsilon^{54}\text{Cr}$ - $\Delta^{17}\text{O}$ correlation in bulk carbonaceous chondrites, these precursors had different Cr isotopic compositions, dating of chondrule formation based on bulk chondrule isochrons is questionable. If the CI composition is similar to that of the bulk Solar System, the fact that the chondrules are depleted in ^{54}Cr relative to CI suggests that at least one of their precursors formed from material that was depleted in the presumably presolar ^{54}Cr carrier.

Conclusions: Our results are consistent with the bulk of the ^{54}Cr excesses being carried in an acid-resistant presolar phase that is present in the matrices of all chondrites. The range of bulk Cr compositions and the reported correlations with $\Delta^{17}\text{O}$, Mn/Cr ratio, $\epsilon^{62}\text{Ni}$, and $\epsilon^{65}\text{Cu}$ requires at least 2 additional components in chondrites that are relatively depleted in ^{54}Cr . Thus, the Solar System was not isotopically homogeneous, potentially making the use of short-lived radionuclides as chronometers more difficult. Further studies of residues and other chondritic components are underway and will be presented at the meeting.

References: [1] Shukolyukov A. and Lugmair G.W. (2006) *EPSL*, 250, 200-213. [2] Trinquier A. et al. (2007) *ApJ*, 655, 1179-1185. [3] Podosek F.A. et al. (1997) *M&PS*, 32, 617-628. [4] Rotaru M. et al. (1992) *Nature*, 358, 465-470. [5] Luck J.M. et al. (2003) *GCA*, 67, 143-151. [6] Bizzarro M. et al. (2007) *Science*, 316, 1178-1181. [7] Carlson R.W. et al. (2007) *Science*, 316, 1175-1178. [8] Andreasen R. and Sharma M. (2007) *ApJ*, 665, 874-883. [9] Alexander C.M.O'D. (2005) *M&PS*, 40, 943-965. [10] Huss G.R. and Lewis R.S. (1995) *GCA*, 59, 115-160. [11] Alexander C.M.O'D. (2002) *LPS*, XXXIII, #1872. [12] Nittler L.R. and Alexander C.M.O'D. (2003) *M&PS*, 38, A129. [13] Zinner E. et al. (2005) *GCA*, 69, 4149-4165. [14] Cody G.D. et al. (2002) *GCA*, 66, 1851-1865.