EARLY VOLATILE DEPLETION AND RAPID CORE FORMATION IN THE EARTH: EVIDENCE FROM THE ^{53}MN-^{53}CR SYSTEM. H. Palme[1], T. Kleine[2], D.C. Rubie[3], [1]Forschungsinstitut und Naturmuseum Senckenberg, Senckenberganlage 25, D-60325 Frankfurt am Main, Germany, [2]Institut für Planetologie, Westfälische Wilhelms-Universität Münster, Wilhelm-Klemm-Strasse 10, D-48149 Münster, Germany; thorsten.kleine@uni-muenster.de, [3]Bayerisches Geoinstitut, University of Bayreuth, D-95440 Bayreuth, Germany, dave.rubie@uni-bayreuth.de

Introduction: The Earth is depleted in volatile elements. The extent of depletion increases with decreasing condensation temperatures similar to the depletion pattern in CV chondrites, although the absolute concentrations of volatile elements are significantly below those of CV-chondrites. The depletion of Mn, a moderately volatile element, decreases from CI through CM and CO to CV chondrites and the primitive mantle (PM) appears to continue the trend to still lower Mn contents (Fig. 1), whereas ordinary chondrites (OC) are only slightly depleted relative to CI [1].

The variations in Mn/Cr ratios of carbonaceous chondrites have been used to date the depletion of Mn and by inference other moderately volatile elements in carbonaceous chondrites using the short-lived ^{53}Mn-^{53}Cr system ($t_{1/2}$~3.7 Myr). [2] reported the first bulk rock Mn-Cr isochron for carbonaceous chondrites, showing that the depletion of moderately volatile elements occurred contemporaneously with CAI formation. These results were later confirmed by [3], but more recent studies show more scatter and a less well defined isochron [4, 5] resulting in slightly younger ages (Fig. 2). The reason for this discrepancy is currently unclear, but the data are still consistent with an early volatile element fractionation between chondrites within the first few Myr of the solar system. Earth's mantle is characterized by lower ^{53}Cr/^{52}Cr ratios than chondrites, reflecting its lower Mn/Cr ratio. Here we attempt to interpret the terrestrial Cr isotopic composition within the framework of the meteorite data.

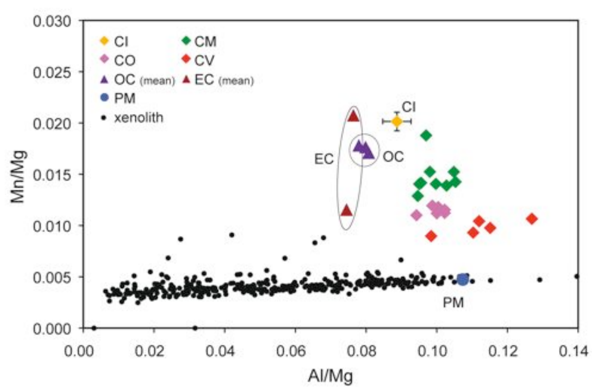

Fig. 1: Mn/Mg ratios of chondritic meteorites and upper mantle rocks. PM is the primitive mantle of the earth. The Mn-depletion sequence from CI to CV and Earth is clearly visible. Data from [1,7].

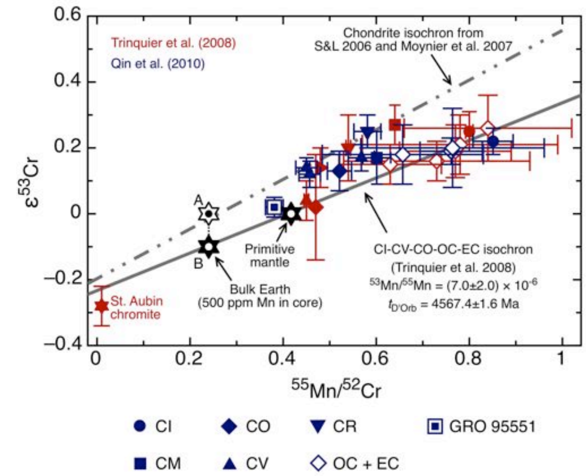

Fig.2: Cr-isotope plot of chondrites and Earth's primitive mantle (PM). If bulk Earth has the same Cr isotopic compostion than PM (point A), it would not plot on the isochron defined by chondrites. It is more likely that the bulk Earth is at point B, implying different Cr isotopic compositions of the core and mantle.

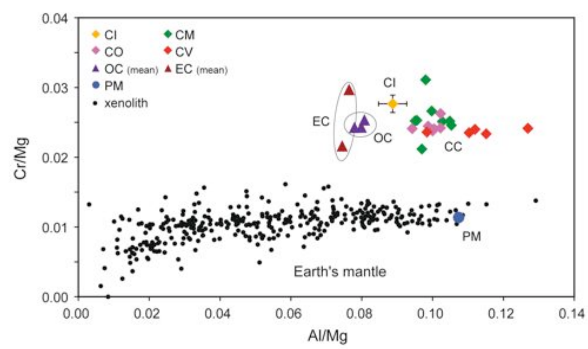

Fig. 3: Cr/Mg of chondritic meteorites and Earth's primitive mantle (PM). The low ratio in PM reflects the presence of about 60% of the Earth's Cr residing in the core (data sources as in Fig. 1).

The Cr and Mn contents of the bulk Earth: The Mn/Cr ratio of the primitive mantle (PM) of the Earth is 0.417 [1], similar to the ratio in CV-chondrites (0.42), despite a significantly lower Mn/Mg ratio in the Earth's mantle (Fig. 1). The higher-than-expected Mn/Cr ratio of the PM is the result of the low Cr content of the Earth's mantle, which is generally explained by a major fraction of Cr residing in the Earth's core. Using a CI bulk Earth Mg/Cr ratio a Cr content of 7444 ppm is calculated for the core, implying that about 60% of the total terrestrial Cr is in the core. This is similar to estimates by [7].

The bulk Earth Mn/Cr ratio depends on the amount of Mn in the core. There is no doubt that Mn depletion in the Earth is largely volatility related. But as Mn is slightly siderophile, some Mn may have partitioned into the core, increasing the bulk Earth Mn/Cr ratio. However, the amount of Mn in the core is not expected to be large, because Mn is much less siderophile than Cr [8]. A second reason for the low Mn contents of the core is the absence of volatile elements during the early stages of accretion, when conditions are reducing enough that a large fraction of Cr partitions into the core [9]. We thus conclude that the Mn content in the core is very low, in agreement with [7]. New numerical accretion simulations following the procedures of [9] typically give a maximum of 500 pppm Mn in the core. The basically chondritic Na/Mn ratio of the Earth's mantle supports the absence of Mn in the core, as Na does not partition into metal [10]. A maximum core Mn content of 500 ppm yields a maximum bulk Earth Mn/Cr ratio of 0.21 (^{55}Mn/^{52}Cr = 0.24), assuming a bulk Earth Cr content of 4120 ppm, derived from a CI-chondritic Mg/Cr ratio (see Fig. 2).

Cr isotope evolution of the Earth: In Fig. 2 we have plotted the ^{55}Mn/^{52}Cr ratios of the Earth's primitive mantle (0.42) and that of the bulk Earth (0.24), calculated by assuming 500 ppm Mn in the core. If it is assumed that the bulk Earth has the same ^{53}Cr/^{52}Cr than its primitive mantle (point A in Fig. 2), then bulk Earth would not plot on the chondrite isochron. This is unlikely, however, because the major process responsible for the low Mn content of the Earth is the depletion of volatile elements, which is thought to have happened very early. It thus is more likely that the bulk Earth plots on the chondrite isochron, at lower Mn/Cr and ^{53}Cr/^{52}Cr than the primitive mantle (point B in Fig. 2).

Chondrites do not only have different ^{53}Cr/^{52}Cr ratios compared to the Earth but also show pronounced anomalies in ^{54}Cr. The latter were interpreted to be nucleosynthetic in origin. This raises the question as to whether the different ^{53}Cr/^{52}Cr of the Earth and chondrites could also be nucleosynthetic rather than reflecting an early Mn/Cr fractionation. Several lines of evicnence suggest that this is unlikely, however. There is a small but distinct difference in the ^{54}Cr abundance between carbonaceous, ordinary and entstatite chondrites. For example, carbonaceous chondrites have larger excesses of neutron-rich isotopes than OC and EC, while the ^{54}Cr/^{52}Cr of the Earth is similar to that of ordinary and enstatite chondrites but distinct from the values of carbonaceous chondrites (e.g., [11]). However, as can be seen in Fig. 2 there is no difference between ordinary and carbonaceous chondrites in their ^{53}Cr/^{52}Cr ratios. Thus nucleosynthetic effects in ^{53}Cr, if present at all, are certainly much smaller than in ^{54}Cr. We thus conclude that at the beginning of the solar system Earth-forming planetesimals and chondritic meteorites had the same initial ^{53}Cr/^{52}Cr ratio. In this case the bulk Earth should plot on the chondrite isochron indicated by point B in Fig. 2.

The Mn-Cr systematics, therefore, imply a lower ^{53}Cr/^{52}Cr ratio of the Earth's core compared to its mantle, indicating that Cr was partitioned into Earth's core during the lifetime of ^{53}Mn. Moreover, no later re-equilibration had occurred, that would have homogenized the Cr isotopes in the bulk Earth. The higher ^{53}Cr/^{52}Cr of the Earth's mantle most likely reflects later addition of (chondritic) material, after the complete decay of ^{53}Mn.

Conclusions: The Mn-Cr systematics of the Earth and chondrites are most readily explained by an early Mn/Cr fractionation during volatile element depletion in the inner solar system. During early core formation in the Earth Cr partitioned into Earth's core while ^{53}Mn was still extant. As a result, bulk Earth has lower Mn/Cr and ^{53}Cr/^{52}Cr than its mantle, and plots on the Mn-Cr isochron defined by chondrites. The Earth's mantle acquired its higher ^{53}Cr/^{52}Cr during late accretion of oxidized and volatile-rich embryos and planetesimals with chondritic ^{53}Cr/^{52}Cr.

This model has two important consequences: (1) Some core formation in the Earth must have occurred within the first million years of the solar system, when ^{53}Mn was still alive, consistent with evidence from the Hf-W system [12]. Once Cr was in the metal core it remained there. (2) The volatile element depletion was established very early, within the first few million years, defined by the slope of the chondrite isochron. Either Mn was lost by early heating of small planetary bodies or it is incompletely condensed, as the solar nebula dissipated before full condensation of Mn. The depletion of volatile elements in chondritic meteorites and in the Earth reflects early nebular processes and are unlikely to be the result of late evaporation during collisions.

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