^{53}Mn-^{53}Cr CHRONOLOGY OF ORDINARY CHONDRITES DERGOAN (H5) AND KAMARGAON (L6).

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Introduction: Ordinary chondrites are among the solar system's most primitive materials, containing early formed solids, including chondrules, calcium-aluminum rich inclusions (CAIs), metallic Fe-Ni grains and fine-grained matrix. Ordinary chondrites are metamorphosed to different degrees but their parent bodies never experienced global melting and differentiation. They are divided into different petrological types ranging from petrological type 3 (unequilibrated, low thermal overprint) to types 4–6 (equilibrated, higher metamorphic grade) [1]. Critical time information regarding the formation of the ordinary chondrite parent body and onset and progressive metamorphism on these bodies can be acquired from chronological studies using short-lived chronometers such as ^{182}Hf-^{182}W and ^{53}Mn-^{53}Cr [2, 3]. One of the advantages of using the ^{53}Mn-^{53}Cr chronometer ($t_{1/2} \approx 3.7$ Ma [4]) is that Mn and Cr are abundant elements in ordinary chondrites and their components have variable and/or high Mn/Cr ratios, which makes them suitable for dating by constructing an isochron. Alternatively, the Cr-isotopes can be used to obtain precise ''model ages" for minerals with a Mn/Cr ratio near zero, which is the case for chromite, a mineral that occurs in samples from all ordinary chondrite groups. Chromite preserves an initial ^{53}Cr/^{52}Cr ratio corresponding to the time of isotope closure of the ^{53}Mn-^{53}Cr system and this isotope ratio can be measured with high precision. A model age can be obtained by comparing the Cr-isotopic composition of the chromite with the Cr-isotope evolution of its assumed reservoir (such as chondritic reservoir). The present study reports isochron and chromite model ages for the two ordinary chondrites Dergaon (H5) and Kamargaon (L6). These ages provide new constraints on the metamorphic history of the ordinary chondrite parent body. Both these samples are observed falls (W0) from the Indian state of Assam.

Methods: For both chondrite samples, 1.5 g of whole-rock material was crushed and subjected to a mixture of HF-HCl-HNO$_3$ to chemically split the samples into a less resistant metal-sulphide-silicate fraction (hereafter 'silicates') and a highly resistant chromite fraction, following the procedure described in [3]. After separation, chromite fractions were completely digested at elevated temperature and pressure in a Parr® bomb. Additionally, a separate ca. 50 mg whole-rock powder for each sample was also digested in the Parr® bomb. The three digested fractions, i.e., silicates, chromite and whole-rock, from both meteorite samples, were divided into two aliquots. The first aliquot was used for the determination of ^{55}Mn/^{52}Cr and ^{56}Fe/^{52}Cr ratios [3]. The second aliquot was used for chemical separation of Cr and measurement of Cr isotopes on a Triton Plus thermal ionization mass spectrometer (TIMS) in the isotope laboratory at the University of Bern [3]. The Cr isotopes for each sample fraction were measured multiple times ($\geq$3) to obtain higher precision. The Cr isotope compositions of all the fractions were corrected for spallogenic Cr contributions using the ^{53}Cr and ^{54}Cr production rates obtained for the interior of the iron meteorite Grant (2.9×10^{11} atoms/Ma, [5]); the relation is described in [6], and a similar depth dependency was assumed as used in [7]. The cosmic ray exposure (CRE) age is 9.7 Ma for Dergaon [8] and 7.03 Ma for Kamargaon [9].

Results and Discussions: The Cr isotopic composition (spallogenic Cr contribution corrected and uncorrected) and ^{55}Mn/^{52}Cr and Fe/Cr ratios for the studied chondrites are given in Table 1. The correction for spallogenic Cr contribution is insignificant for all fractions, given reported uncertainties. This small spallogenic Cr contribution, even in silicate fractions with high Fe/Cr ratio ($\geq$500) is primarily due to the low CRE age of both the samples. The spallogenic Cr contribution corrected ε^{54}Cr composition of both the chondrites (whole-rock) and their fractions are in good agreement with the average ε^{54}Cr composition of ordinary chondrites (whole rock and components) reported in the literature [3 and ref. therein].

In order to obtain ^{53}Mn-^{53}Cr cooling ages for the samples, the analyzed fractions: whole rock, silicates, and chromite are plotted on the spallogenic Cr corrected ε^{53}Cr vs. ^{55}Mn/^{52}Cr diagrams as shown in Fig. 1. The slope of the ε^{53}Cr vs. ^{55}Mn/^{52}Cr correlation line for Dergaon (^{53}Mn/^{55}Mn $= 4.56 \pm 1.49 \times 10^{-7}$), yields an age of 14.4 (+2.2/-1.6) Ma after CAI formation, when anchored to the D'Orbigny angrite (Pb–Pb age of 4563.37 ± 0.25 Ma [10] and initial ^{53}Mn/^{55}Mn ratio of $3.24 \pm 0.04 \times 10^{-6}$ [11]. In case of Kamargaon, no correlation of ^{53}Cr/^{52}Cr with the ^{55}Mn/^{52}Cr ratios for different fractions is observed and hence, no isochron age can be determined. However, this result shows that ^{53}Cr/^{52}Cr was equilibrated in the L6 chondrite Kamargaon after the radionuclide ^{53}Mn had essentially decayed, which for all practical purposes can be considered as five half-lives of the short-lived radioactive decay system, i.e., ~18 Ma after CAIs for the ^{53}Mn-^{53}Cr system.

In addition to the isochron age, a model age of 12.26 (+2.86/-1.85) Ma is obtained from the chromite fraction of the Dergaon chondrite relative to the CAI formation age, assuming a chondritic (OC chondrites-like) ^{55}Mn/^{52}Cr = 0.74 [12] of the source reservoir, a solar system initial ^{53}Cr = -0.30 [13] and a canonical ^{53}Mn/^{55}Mn = 6.28×10^{-6} [14]. The chromite model age for Dergaon agrees with its isochron age and hence, gives confidence over the estimates for the initial ^{53}Cr and ^{53}Mn abundances.

The ^{53}Mn-^{53}Cr isochron and chromite model ages for Dergaon (H5) determined in the present study are consistent with the ^{53}Mn-^{53}Cr ages of high petrologic grade (type 5/6) ordinary chondrites, SaU 228 (H6), Dho 1012 (L6) and Finney (L5), reported in the previous studies [3, 15]. These ages also agree with an onion-shell structure of the ordinary chondrite parent body that predicts that higher temperatures are achieved at greater depths and slightly different times during the evolution of the chondrites parent bodies [e.g., 16].

A late (>18 Ma) ^{53}Cr equilibrium in Kamargaon (L6), as inferred from its ε^{53}Cr vs. ^{55}Mn/^{52}Cr diagram (Fig. 1), is most likely due to an impact disrupted cooling history of the sample which is consistent with the high shock stage (S3) of this meteorite. Recent studies have reported shock-induced incongruent melting of olivine as well as vesicular texture in the Kamargaon (L6) chondrite that possibly formed due to localized melting during a shock event and subsequent degassing of volatiles after decompression [17, 18]. Average shock P-t conditions determined in the shock veins of Kamargaon meteorite are ~24-25 GPa and ~2310-2633K, respectively which are much higher than the closure temperature of the ^{53}Mn-^{53}Cr system [3 and ref. therein]. Hence, the equilibration of ^{53}Cr/^{52}Cr can be the result of a shock-event that reset the ^{53}Mn-^{53}Cr system in Kamargaon meteorite occurring much later than the initial thermal metamorphism.

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Table 1. Cr-isotope composition of samples.

	^{55}Mn/^{52}Cr	Fe/Cr	Raw data		Spall. Cr corrected	
			ε^{53}Cr	ε^{54}Cr	ε^{53}Cr	ε^{54}Cr
			Dergaon			
Chr.	0.01	0.55	0.07±0.02	-0.46±0.05	0.07±0.02	-0.46±0.05
WR	0.78	71.98	0.12±0.04	-0.38±0.12	0.11±0.04	-0.39±0.12
Sil.	5.53	600.39	0.31±0.07	-0.18±0.10	0.29±0.07	-0.25±0.10
			Kamargaon			
Chr.	0.01	0.50	0.16±0.05	-0.35±0.03	0.16±0.05	-0.35±0.03
WR	0.81	57.37	0.20±0.02	-0.30±0.10	0.20±0.02	-0.31±0.10
Sil.	5.48	410.29	0.19±0.02	-0.28±0.06	0.18±0.02	-0.32±0.06

Chr.- Chromite, WR- whole rock, Sil.- silicates.

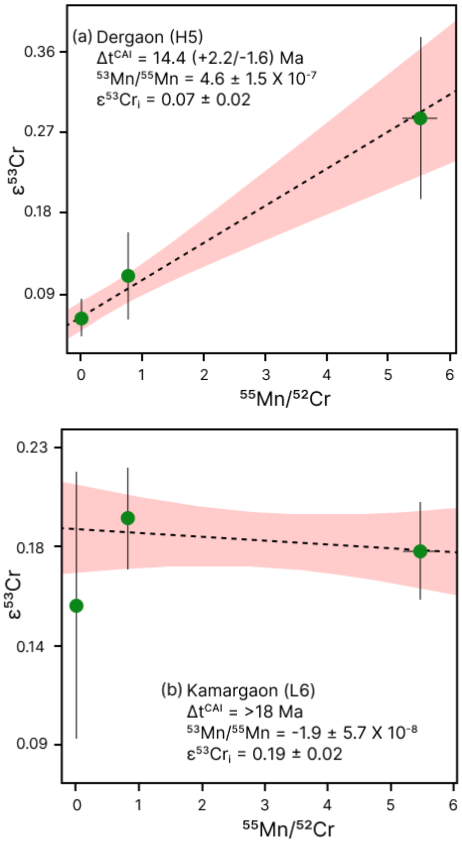

Fig. 1. ^{53}Mn-^{53}Cr systematics in the ordinary chondrites (a) Dergaon and (b) Kamargaon. The spallogenic Cr corrected ε^{53}Cr and ^{55}Mn/^{52}Cr data points for chromite, whole rock and silicate fractions (Table 1) from each sample are used to construct an isochron. Δt_{CAI} refers to time after CAIs formation.