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Early solar system events and timescales

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Abstract–Some recent information on the Mn-Cr and Al-Mg systems is reviewed. This information is used to derive constraints on the timing of processes and events, which took place in the early solar system. Using reasonable assumptions, a timeline is constructed where the estimated age of the solar system is ~4571 Ma. This age is taken to mark the time when most calcium-aluminum-rich inclusions (CAIs) were starting to form, a process that may have lasted for several 10^5 years. Almost contemporaneously small planetesimals have accreted that served to store these CAIs for later dispersal among larger planetesimals. By the time large numbers of planetesimals of several tens of kilometers in size had formed, the interior of these objects started to melt through the decay of ^{26}Al. Collisional disruption of these planetesimals allowed gases, dust, and melt to escape into the surrounding space. The fine droplets of melt reacted with gas and dust to form chondrules, which, after rapid cooling, were partially re-accreted onto the residual rubble pile. This process of *primary* chondrule formation, in most cases involving several generations of planetesimals, most plausibly lasted only for ~2 Ma. Towards the end of this period and during the following 3 to 4 Ma planetary objects of several hundred kilometers in size were formed. They still stored enough energy to continue melting from the inside to finally differentiate into chemically stratified layers, with basaltic volcanism occurring within a few million years.

MANGANESE–CHROMIUM SYSTEMATICS OF SOLAR SYSTEM OBJECTS

The Relative Manganese-53–Chromium-53 Chronometer and Absolute Timescales

The study of early solar system processes requires a time resolution of at least 1 Ma. Among chronometers that are based on long-lived radionuclides only the Pb-Pb isotope method has the demonstrated potential of providing this precision. The drawback of this method lies in the fact that the U-Pb isotopic system can be easily disturbed by natural phenomena such as shock or reheating, which can compromise the age information obtained with this method. In contrast, some isotope chronometers that are based on short-lived radionuclides can provide an experimental precision sufficient to achieve the required time resolution. One of these chronometers is based on the decay of ^{53}Mn to ^{53}Cr ($t_{1/2}$ = 3.7 Ma). Unfortunately, because short-lived radionuclides are now extinct in the solar system they permit to obtain only relative ages, while for many scientific goals the knowledge of absolute ages is essential. On the rare occasion where a reliable absolute Pb-Pb age can be acquired on the same sample in which the effects of the decay of a short-lived radionuclide, which was still extant at the time of crystallization, can be detected, the relative abundance of this nuclide at that time can be determined. A good example for a successful application of this method is that of the angrite Lewis Cliff (LEW) 86010 (Lugmair and Shukolyukov, 1998).

The angrites are early equilibrated planetary differentiates which cooled fast and do not show any signs of later disturbance. The Pb-Pb ages of the angrites LEW 86010 and Angra dos Reis are known with high precision (4557.8 ± 0.5 Ma) and are indistinguishable from one another (Lugmair and Galer, 1992). The large range of ^{55}Mn/^{52}Cr ratios between their various constituent minerals facilitated a precise determination of the ^{53}Mn/^{55}Mn ratio of $(1.25 \pm 0.07) \times 10^{-6}$ at the time of isotopic closure (Lugmair and Shukolyukov, 1998). This value is similar to $(1.44 \pm 0.07) \times 10^{-6}$ obtained by Nyquist *et al.* (1994). The fact that the angrites cooled fast (Störzer and Pellas, 1977) suggests that both the U-Pb and the Mn-Cr isotope systems

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closed approximately at the same time. Thus, the obtained value of $(1.25 \pm 0.07) \times 10^{-6}$ represents the $^{53}Mn/^{55}Mn$ ratio at the absolute time of 4557.8 Ma ago.

Eucrites and the Howardite, Eucrite, Diogenite Parent Body

One of the major groups of early planetary differentiates are the basaltic achondrites, consisting of the howardites, non-cumulate and cumulate eucrites, and diogenites (HED). The antiquity of some non-cumulate eucrites is indicated by the former presence in these meteorites of the short-lived radionuclides ^{60}Fe ($t_{1/2}$ = 1.5 Ma) (Shukolyukov and Lugmair, 1993) and ^{26}Al ($t_{1/2}$ = 0.73 Ma) (Srinivasan *et al.*, 1999). This is in apparent contradiction with the most recent results of Galer and Lugmair (1996) who have shown that the absolute Pb-Pb ages of several eucrites are comparatively low. However, it is well known that most non-cumulate eucrites are highly brecciated. This indicates that the U-Pb system most probably is very sensitive to brecciation events and has been severely disturbed or even totally reset during such an event, rendering the obtained Pb-Pb ages as non-representative of the true time of formation of these meteorites. Thus, the only recourse for determining the original time of formation of eucrites appears to be the method used by Lugmair and Shukolyukov (1998), where the angrites serve as absolute time markers (see above) and are combined with the relative ^{53}Mn-^{53}Cr ages of the eucrites. A necessary prerequisite for this method to yield valid absolute ages is that both the material of the absolute time marker and that of the meteorite to be dated come from an isotopically uniform reservoir.

Figure 1 illustrates several examples of internal ^{53}Mn-^{53}Cr isochrons. The ^{53}Mn-^{53}Cr system in the moderately brecciated eucrite Chervony Kut (CK) indicates that ^{53}Mn was still extant at the time of CK solidification. The slope of the best-fit line yields the $^{53}Mn/^{55}Mn$ ratio of $(3.7 \pm 0.4) \times 10^{-6}$ at the time of isotopic closure. The difference between this value and that from the angrites corresponds to a time difference of 5.8 ± 0.8 Ma. By adding this relative age to the absolute Pb-Pb age of the angrites, we obtain an absolute age for CK of 4563.6 ± 0.9 Ma. In contrast to CK, the mineral fractions from the eucrite Caldera (CAL) exhibit totally equilibrated $^{53}Cr/^{52}Cr$ ratios (Fig. 1) (Wadhwa and Lugmair, 1996), which indicates that ^{53}Mn had practically fully decayed by the time when the ^{53}Mn-^{53}Cr system closed in this meteorite. With an upper

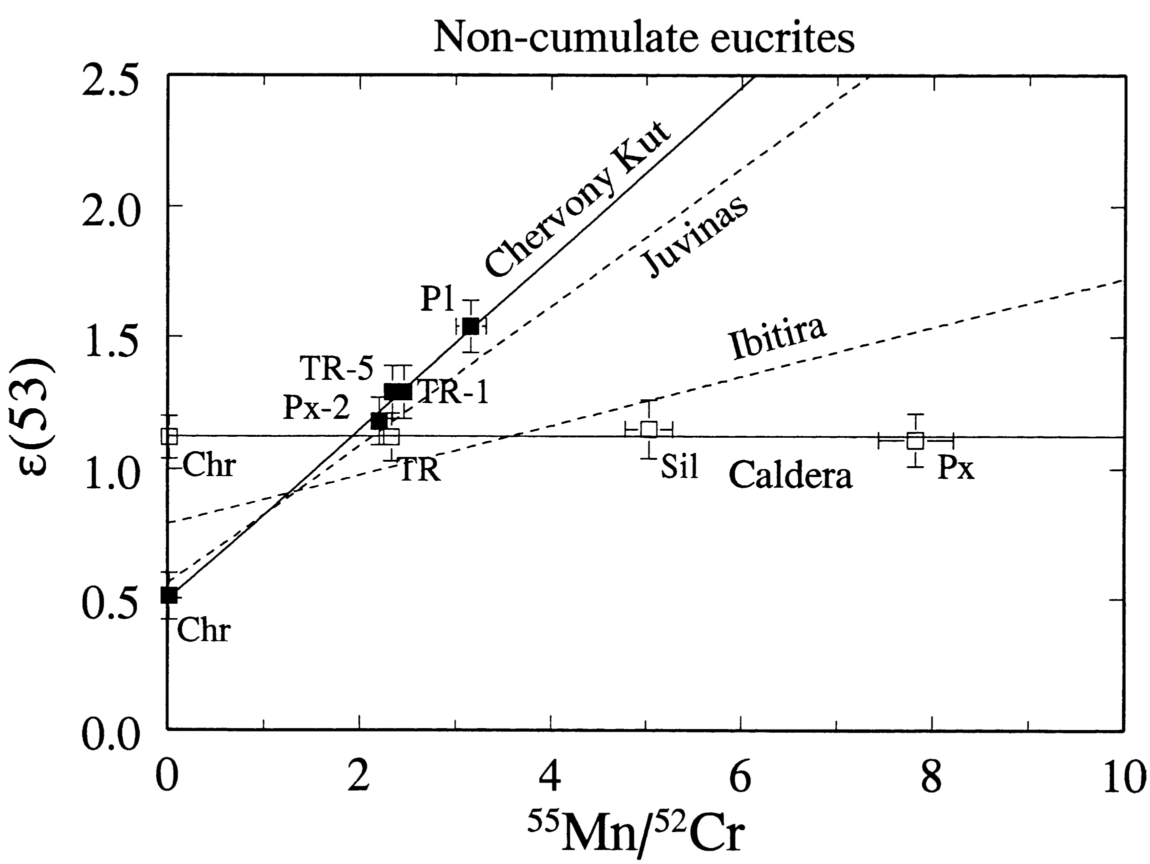

FIG. 1. Mn-Cr internal isochrons for several non-cumulate eucrites. The oldest is Chervony Kut (filled squares), clearly showing the presence of live ^{53}Mn at the time of crystallization. At the other extreme is Caldera (open symbols), which had isotopically equilibrated at a time when ^{53}Mn was no longer extant. $\epsilon(53)$ denotes the deviation of $^{53}Cr/^{52}Cr$ relative to the terrestrial normal in parts in 10^4. Isochrons for Juvinas and Ibitira are shown schematically for comparison. See text for more details. Data from Lugmair and Shukolyukov (1998) and Wadhwa and Lugmair (1996).

limit for the $^{53}Mn/^{55}Mn$ ratio of 1.2×10^{-7} this implies that the age of CAL is ≤4545 Ma. This young age may correspond either to a "cooling age", or more likely, is the result of impact melting that re-equilibrated the Cr isotopes, or possibly a combination of both. Similar re-equilibration of the Cr isotopes is reflected in the mineral fractions of other non-cumulate eucrites such as Pomozdino ($t \leq 4554$ Ma) and Elephant Moraine (EET) 87520 ($t \leq 4549$ Ma). The slopes of the Juvinas and Ibitira isochrons, shown schematically for comparison (dashed lines in Fig. 1), fall between these two extremes resulting in absolute ages of 4562.5 ± 1.0 Ma and 4557^{+2}_{-4} Ma, respectively. Since Ibitira is unbrecciated (and probably also an impact melt) this age is in good agreement with the Pb-Pb ages of 4556 ± 6 Ma (Chen and Wasserburg, 1985) and 4560 ± 3 Ma (Manhès *et al.*, 1987). The diogenites Shalka and Johnstown and the cumulate eucrite Moore County (not shown here) also exhibit a flat $^{53}Cr/^{52}Cr$ isotopic pattern, which most likely reflects slow cooling in the deeper zones of the HED parent body (see Lugmair and Shukolyukov, 1998).

Figure 2 summarizes the results obtained for the *bulk* samples of all studied constituents of the HED parent body (most likely the asteroid Vesta 4) (Lugmair and Shukolyukov, 1998). All data points form a well-defined correlation line. Because this best-fit line is a *bulk* meteorite isochron it contains no information on the time of crystallization or cooling of individual meteorites. Instead, the slope of the line, corresponding to the $^{53}Mn/^{55}Mn$ ratio of $(4.7 \pm 0.5) \times 10^{-6}$, dates the *last Mn/Cr fractionation* and *Cr isotope equilibration* in the HED mantle and, thus, the most likely time of *core formation*. At that time the $^{53}Cr/^{52}Cr$ ratio in the HED parent body was already significantly elevated (~0.25 ϵ) relative to the terrestrial value (≡ 0 ϵ). The absence of a resolvable scatter of the data points from the line implies that the source reservoirs of all these meteorites were formed contemporaneously and that the Mn-Cr systems of the bulk samples of these meteorites remained closed since their formation. From this $^{53}Mn/^{55}Mn$ ratio for the HED parent body and that of the angrites we calculate a relative age for the HED parent body mantle fractionation of 7.1 ± 0.8 Ma prior to angrite crystallization, yielding an absolute age of 4564.8 ± 0.9 Ma. This clearly indicates that planetary differentiation processes must have occurred very early in solar system history.

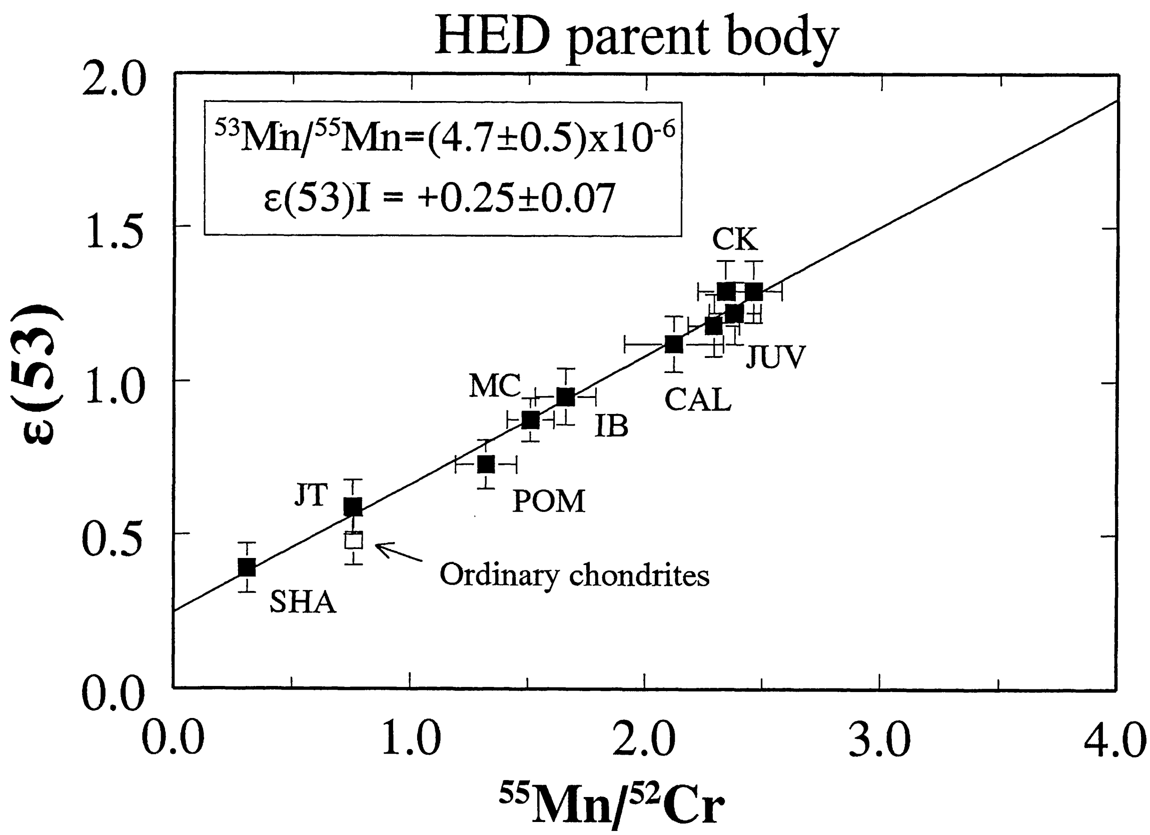

FIG. 2. Bulk rock Mn-Cr isochron for the HED parent body (most likely the asteroid Vesta 4). The average data point for some ordinary chondrites (open symbol) is shown for comparison. The slope of the isochron corresponds to a common $^{53}Mn/^{55}Mn$ ratio in the HED parent body of $\sim 4.7 \times 10^{-6}$. The $^{53}Cr/^{52}Cr$ ratio in the HED parent body material had already evolved at that time to ~25 ppm above the present-day terrestrial value. This isochron indicates that on the HED parent body global melting and differentiation had occurred at a very early time (*i.e.*, ~4565 Ma ago). Data from Lugmair and Shukolyukov (1998).

Radial Gradient in the Relative Abundance of Chromium-53

It has been shown earlier (Lugmair and Shukolyukov, 1998) that bulk samples from ordinary chondrites exhibit both uniform $^{55}Mn/^{52}Cr$ ratios of around 0.76 with an average $^{53}Cr/^{52}Cr$ excess of ~0.48 ϵ relative to the terrestrial standard value. It is generally agreed that chondrites are rather primitive meteorites. Their parent planetesimals experienced no planet-wide Mn/Cr fractionation during their evolution. Therefore, any excesses in $^{53}Cr/^{52}Cr$ ratios in large *bulk* samples of chondrites should be characteristic of their whole parent bodies and for the region where these parent bodies formed.

In contrast, a lunar sample has a $^{53}Cr/^{52}Cr$ ratio indistinguishable from that of the Earth (Lugmair and Shukolyukov, 1998). The martian meteorites Allan Hills (ALH) 84001 and Shergotty have the same $^{53}Cr/^{52}Cr$ ratios of ~0.23 ϵ. The subsequent study of the martian meteorites EETA79001 and Nakhla has yielded a ^{53}Cr excess of ~0.26–0.27 ϵ which seems to be only marginally, but in all measurements consistently higher (Shukolyukov and Lugmair, 2000a). However, for the present discussion this small difference is not important and we take the characteristic ^{53}Cr excess for Mars to be ~0.24 ϵ. In Fig. 2 we note that the HED bulk isochron passes close to the ordinary chondrite data (~0.48 ϵ at 0.76). Hence, the Mn/Cr ratio of the entire HED parent body is consistent with the chondritic Mn/Cr ratio and the original $^{53}Mn/^{55}Mn$ ratios in the ordinary chondrites and in the HED parent body precursors were similar.

Thus, small but clear differences are observed in the relative abundance of ^{53}Cr among inner solar system bodies: the Earth–Moon system has a $^{53}Cr/^{52}Cr$ ratio of ~0 ϵ, samples from the asteroid belt (Vesta and the ordinary chondrites) exhibit a ^{53}Cr excess of ~0.5 ϵ, while Mars is characterized by an intermediate ^{53}Cr excess of ~0.24 ϵ. If these ^{53}Cr variations are viewed as a *function of heliocentric distance* then the data points appear to be well correlated (Fig. 3). No assumptions are involved other than assigning the SNC meteorites to a martian origin and the HED parent body as Vesta. This gradient of $\epsilon(^{53}Cr)$ appears to be close to linear between 1 and ~2.4 AU. We do not know the form of this function outside this range. What can be assumed, however, is that it must have a maximum somewhere at >2.4 AU, either still within the asteroid belt or further outside.

We have suggested that the observed radial gradient in the ^{53}Cr relative abundances is due to an original radially heterogeneous ^{53}Mn distribution, although this gradient could also be explained by an early Mn/Cr fractionation in the nebula with an originally homogeneous ^{53}Mn distribution (Lugmair and Shukolyukov, 1998; Cassen and Woolum, 1997; Birck *et al.*, 1999). Recent studies on enstatite chondrites have shown that the former scenario is more plausible (Shukolyukov and Lugmair, 1999). However, further discussions regarding the

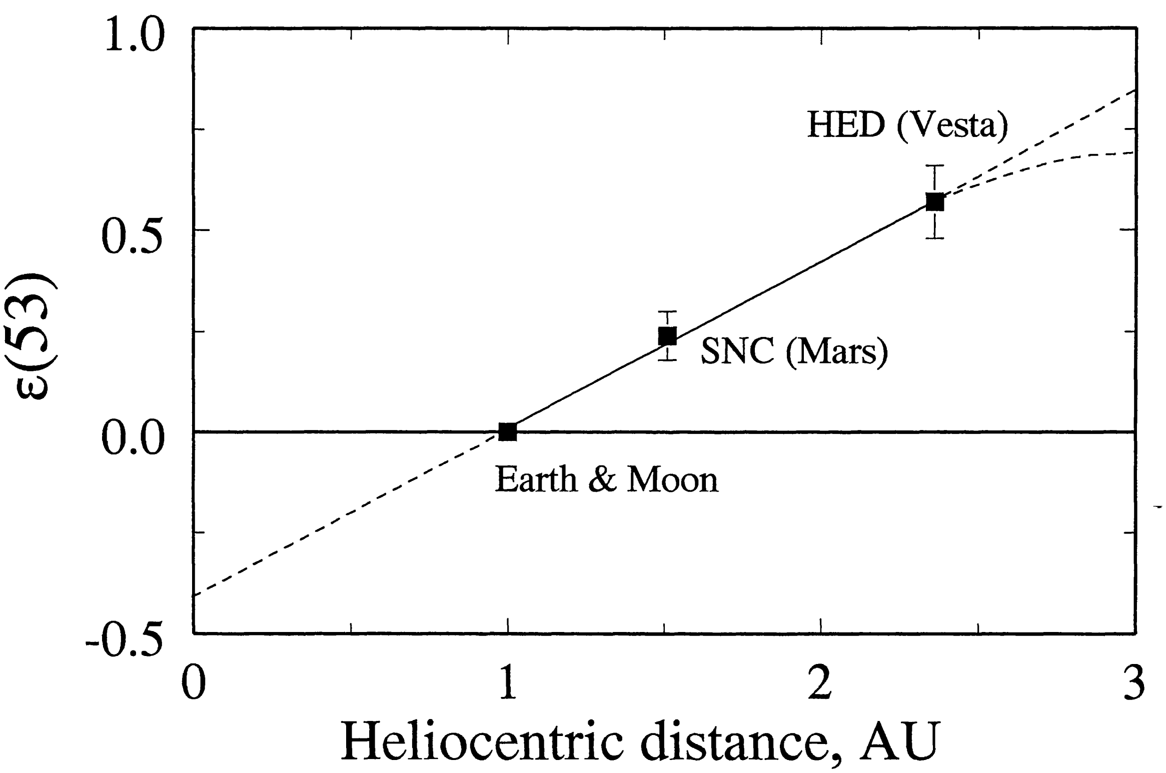

FIG. 3. The $^{53}Cr/^{52}Cr$ variation with heliocentric distance. The terrestrial value of $^{53}Cr/^{52}Cr$ and the extrapolated value to zero AU are used as reasonable estimates for the solar system initial $^{53}Cr/^{52}Cr$ ratio (see text). These two values in turn allow the range for the age of the solar system to be estimated as 4568 to 4571 Ma.

possible cause for the observed gradient are beyond the scope of this paper. Nevertheless, a variation of $^{53}Cr/^{52}Cr$ in the inner solar system is clearly observed and, thus, the question arises: is the use of the $^{53}Mn/^{53}Cr$ system as a chronometer (see Upper Limit of the Solar System Age below) justified? Obviously, the obtained ages would bear chronological meaning only if the original relative ^{53}Mn abundances were the same in the objects under investigation.

Figure 4 shows schematically the internal isochrons for angrites, pallasites, and three primitive achondrites (Wadhwa *et al.*, 1998; Zipfel *et al.*, 1996; Bogdanovski *et al.*, 1997; Lugmair and Shukolyukov, 1998). The bulk meteorite isochron for the HED parent body and the average data point for the bulk ordinary chondrites are shown for comparison. All isochrons pass close to the data point for the bulk ordinary chondrites. This suggests that the Mn/Cr ratios of the *undifferentiated* parent bodies of primitive achondrites are close to chondritic and that their bulk $^{53}Cr/^{52}Cr$ ratios (~0.5 ϵ) are indistinguishable within present resolution. The same holds true for the differentiated angrites and a pallasite. Consequently, the absence of detectable variations of the $^{53}Cr/^{52}Cr$ ratios among several bulk asteroid belt bodies implies that their *original* ^{53}Mn abundance was essentially the *same* and that the use of the ^{53}Mn-^{53}Cr system as a chronometer is justified.

AGE OF THE SOLAR SYSTEM

It has to be noted that we imply here that the formation of the solar system was concurrent with the onset of ^{53}Mn decay within (more or less well mixed) solar system matter. If ^{53}Mn and ^{26}Al (and other short-lived nuclei) were produced by solar particle irradiation (*e.g.*, Shu *et al.*, 1996) then our "age of the solar system" would indicate the time of this relatively short duration event and that of isotopic equilibration of the freshly produced nuclei with the rest of solar system matter. On the other hand, if the short-lived nuclei, originating from stellar sources, were injected into the molecular cloud from which the solar system formed, then the "solar system age" would indicate the time of this episode.

Lower Limit of the Solar System Age

The oldest high-precision absolute ages among solar system objects were obtained for calcium-aluminum-rich inclusions (CAIs), which are regarded as the first condensates of matter in the solar system. A model Pb-Pb age of CAIs from the Allende CV3 chondrite is 4566 ± 2 Ma (Göpel *et al.*, 1991). This age is often considered as the best estimate for the solar system age. However, if this average CAI age reflects processes

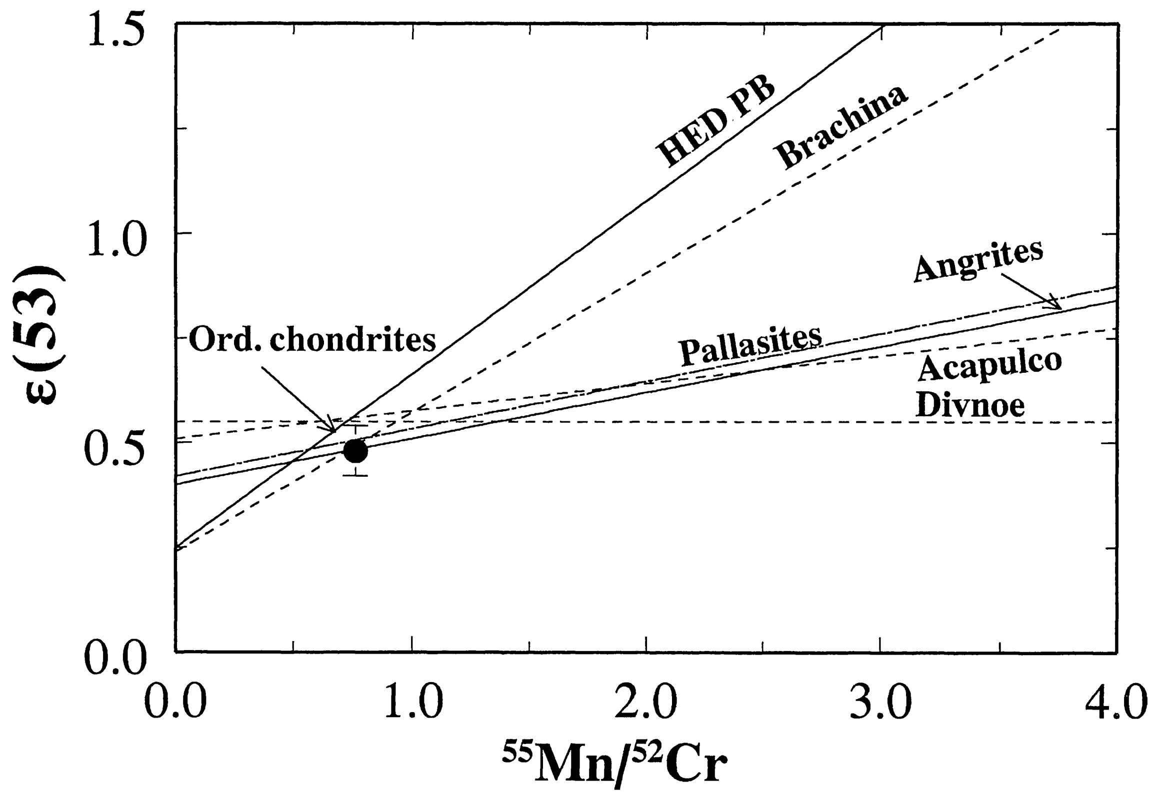

FIG. 4. Comparison of Mn-Cr isochrons for several meteorite types with the average ordinary chondrite data point. The fact that the chondrite point falls at or very close to the intercept of these isochrons indicates that all these meteorites are compatible with a chondritic origin. Their original ^{53}Mn abundance was basically the same, an essential condition for the use of the ^{53}Mn-^{53}Cr system as a chronometer. (Data from Bogdanovski *et al.*, 1997; Wadhwa *et al.*, 1998; and Lugmair and Shukolyukov, 1998.)

of alteration or late re-equilibration rather than the true crystallization age, which cannot be excluded, this value would represent just a lower limit for the time of CAI formation.

The ^{53}Mn-^{53}Cr system offers additional constraints for the solar system age. It is obvious that the solar system initial value for the ^{53}Cr/^{52}Cr ratio cannot be higher than the present-day terrestrial ^{53}Cr/^{52}Cr. Assuming the terrestrial ^{53}Cr/^{52}Cr of 0 ϵ = solar system initial value and using the HED parent body ^{53}Mn-^{53}Cr systematic (initial value = 0.25 ϵ and chondritic ^{55}Mn/^{52}Cr) we calculate a minimum solar system age of ~4568 Ma (Lugmair and Shukolyukov, 1998). This value agrees with the upper limit for the Pb-Pb age of CAIs. Alternatively, using the same solar system initial value and the present-day ratios for chondritic ^{53}Cr/^{52}Cr ≈ 0.48 ε and ^{55}Mn/^{52}Cr ≈ 0.76 yields a similar result (Lugmair and Shukolyukov, 1998).

A further constraint comes from measurements by Hutcheon *et al.* (1999). These authors have shown that carbonates from the Kaidun carbonaceous chondrite formed contemporaneously. The ^{53}Mn/^{55}Mn ratio at the time when these carbonates formed was ~9.4×10^{-6}, indicating a time of ~4569 Ma ago. Since carbonate formation in a meteorite parent body must obviously postdate the formation of the first solids one again is led to the conclusion that 4568–4569 Ma can only be a lower limit for the solar system age.

Upper Limit of the Solar System Age

A linear extrapolation to zero heliocentric distance of the correlation line in Fig. 3 yields a ^{53}Cr/^{52}Cr ratio of about –0.42 ϵ. For the case where the gradient in ^{53}Cr abundances is due to original ^{53}Mn heterogeneity, this value may represent a realistic initial ^{53}Cr/^{52}Cr ratio in the solar nebula. When using a solar system initial value = –0.42 ϵ and the HED parent body parameters from above this yields an initial ^{53}Mn abundance of $(^{53}\text{Mn}/^{55}\text{Mn})_I \sim 1.34 \times 10^{-5}$ and an upper limit for the solar system age of ~4571 Ma (Lugmair and Shukolyukov, 1998).

Thus, using reasonable assumptions the ^{53}Mn-^{53}Cr systematic suggests rather narrow limits for the age of the solar system: 4568–4571 Ma. At face value, an age for CAIs of ~4568 Ma would be supported by the Pb-Pb age of phosphates, 4562.7 ± 0.6 Ma (Göpel *et al.*, 1994), and the ^{26}Al data from feldspars in the H4 chondrite Ste. Marguerite (Zinner and Göpel, 1992). When the ^{26}Al/^{27}Al ratio of $(2.0 \pm 0.6) \times 10^{-7}$ is compared with the canonical ^{26}Al/^{27}Al ratio of 5×10^{-5} in CAIs, a time difference between the isotope closure of the ^{26}Al-^{26}Mg system in Ste. Marguerite and CAIs of 5.6 Ma is calculated, yielding a CAI age of 4568.3 ± 0.7 Ma. If, however, the feldspars in Ste. Marguerite pre-date the phosphates by 3–4 Ma, as is suggested by their I-Xe age of ~4566 Ma (Brazzle *et al.*, 1999; Gilmour, 2000), the CAI age would be close to 4571 Ma. The recently obtained metamorphic Mn-Cr age for Ste. Marguerite of 4565.0 ± 0.7 Ma (Polnau and Lugmair, 2001) agrees very well with the I-Xe age and suggests that between major mineral phases the last isotopic equilibration had occurred at that time.

Can the Upper Limit be Higher?

Early Mn-Cr measurements on inclusions from Allende (Birck and Allégre, 1985; Birck and Lugmair, 1988; Loss and Lugmair, 1990) and more recently from Efremovka by Nyquist *et al.* (1999) suggest a considerably lower initial ^{53}Cr/^{52}Cr ratio for CAIs at around –1 to –2 ϵ. If this value is taken as the initial ^{53}Cr/^{52}Cr ratio in the solar system then its "age" would be greater by another ~3 to 5 Ma (*i.e.*, ~4574 to 4576 Ma). However, as extensively discussed in Lugmair and Shukolyukov (1998), the Cr isotopic composition in CAIs may reflect a superposition of the product of *in situ* ^{53}Mn decay and a mixture of at least two isotopically anomalous Cr components. Thus, it is not clear at present that a simple comparison of Cr data from CAIs with Cr isotopic compositions from well-mixed solar system materials can be made. Much more work is needed in this area to resolve these ambiguities. Longer timescales based on the early estimates of the ^{53}Mn/^{55}Mn ratios in CAIs of ~4.4×10^{-5} (Birck and Allègre, 1988) pose some other problems. For example, (1) they are not consistent with the presence in the HED parent body of live ^{26}Al (Srinivasan *et al.*, 1999), (2) they would require an unknown heat source for planetary melting and differentiation, other than ^{26}Al; and (3) necessitate a storage mechanism for CAIs which was effective over an excessively long period of time (see below).

Additional constraints on the upper limit of the solar system age come from the study of bulk samples of carbonaceous chondrites. The Mn/Cr ratios in bulk carbonaceous chondrites decrease in the sequence CI—CM—CV. Most likely, this is due to nebular fractionation caused by volatility controlled Mn loss from hot regions. If so, the ^{53}Cr/^{52}Cr ratios in bulk carbonaceous chondrites should constrain the ^{53}Mn/^{55}Mn ratio at the time of nebular fractionation (assuming that the initial Cr isotopic composition and the ^{53}Mn abundance were originally the same in the region where these objects formed). Based on the Cr isotopic composition in the bulk samples of Orgueil, Murchison, and Allende, Harper and Wiesmann (1992) calculated an upper limit for the ^{53}Mn/^{55}Mn ratio at the time of nebular fractionation of less than or equal to ~2×10^{-5}, which yields less than or equal to ~4573 Ma on an absolute timescale. Our recent, more precise measurements of bulk Orgueil and Allende (Shukolyukov and Lugmair, 2000b) suggest an upper limit for ^{53}Mn/^{55}Mn of less than or equal to ~1.4×10^{-5} or less than or equal to ~4571 Ma.

Manganese-Chromium and Aluminum-Magnesium in Chondrules: Manganese-Chromium and Aluminum-Magnesium Time Lines

In a recent report Nyquist *et al.* (1999) discussed Mn-Cr correlation lines for data from individual bulk chondrules from the unequilibrated ordinary chondrites Chainpur and Bishunpur. The slopes of these lines correspond to a ^{53}Mn/^{55}Mn ratio of ~9.5×10^{-6}. If this value corresponds to the time when these chondrules were formed then this time would be ~11 Ma prior to the crystallization of LEW 86010, or ~4569 Ma ago. (Strictly speaking, if the Mn/Cr fractionation in chondrule precursors were decoupled from the actual chondrule-formation process, then this time would correspond to that of the fractionation process.) This value is the same or slightly higher than our lower limit for the age of the solar system but roughly 2 Ma younger than the more reasonable upper limit of 4571 Ma. Thus, in our preferred scenario *primary* chondrule formation must have occurred within the first ~2 Ma years of solar system history. These relationships are shown in the upper part of Fig. 5, which represents an early solar system timeline as derived from the Mn-Cr system.

We now consider recent information from the Al-Mg system and compare this with the Mn-Cr systematics. Primary CAIs, whether found in carbonaceous chondrites (see MacPherson *et al.*, 1995 for a review) or in unequilibrated ordinary chondrites (*e.g.*, Russell *et al.*, 1996), appear to have had a remarkably uniform $^{26}Al/^{27}Al$ ratio of ~5×10^{-5} at the time of their formation. Several recent studies of ^{26}Mg excesses in Al-rich chondrules (Russell *et al.*, 1996), Mg-rich chondrules (Kita *et al.*, 1998), and ferromagnesian chondrules (McKeegan *et al.*, 2000) have shown that the inferred $^{26}Al/^{27}Al$ ratios at the time of their formation (or last isotopic equilibration) were > $(3–7) \times 10^{-6}$. This indicates, that the time span between CAI formation and formation of these chondrules was only on the order of ~2 Ma or less.

From the Mn-Cr discussion above it becomes evident that the Pb-Pb ages of CAIs of 4566 ± 2 Ma, as measured by Göpel *et al.* (1991), cannot be the primary ages of CAIs. Rather, we assume here that the primary formation time of CAIs coincides with our upper "solar system age" limit of ~4571 Ma ago. The lower part of Fig. 5 shows the Al-Mg timeline anchored at ~4571 Ma. Both, the Mn-Cr and the Al-Mg systems are consistent in that *primary* chondrule formation mostly occurred within the first ~2 Ma of solar system history and would have been largely concluded ~4569 Ma ago. Most chondrules with inferred $^{26}Al/^{27}Al$ ratios significantly lower than $(3–7) \times 10^{-6}$ and CAIs with $^{26}Al/^{27}Al$ ratios much lower (by a factors of greater than ~2) than the canonical value of ~5×10^{-5} most likely have been metamorphosed, metasomatically altered, or may have even been totally re-crystallized (*i.e.*, no clear indication of metamorphism; see Marhas *et al.*, 2000 for a different interpretation) in the deeper layers of early or intermediate generations of planetesimals. Later disruption of these planetesimals distributed these objects to their ultimate

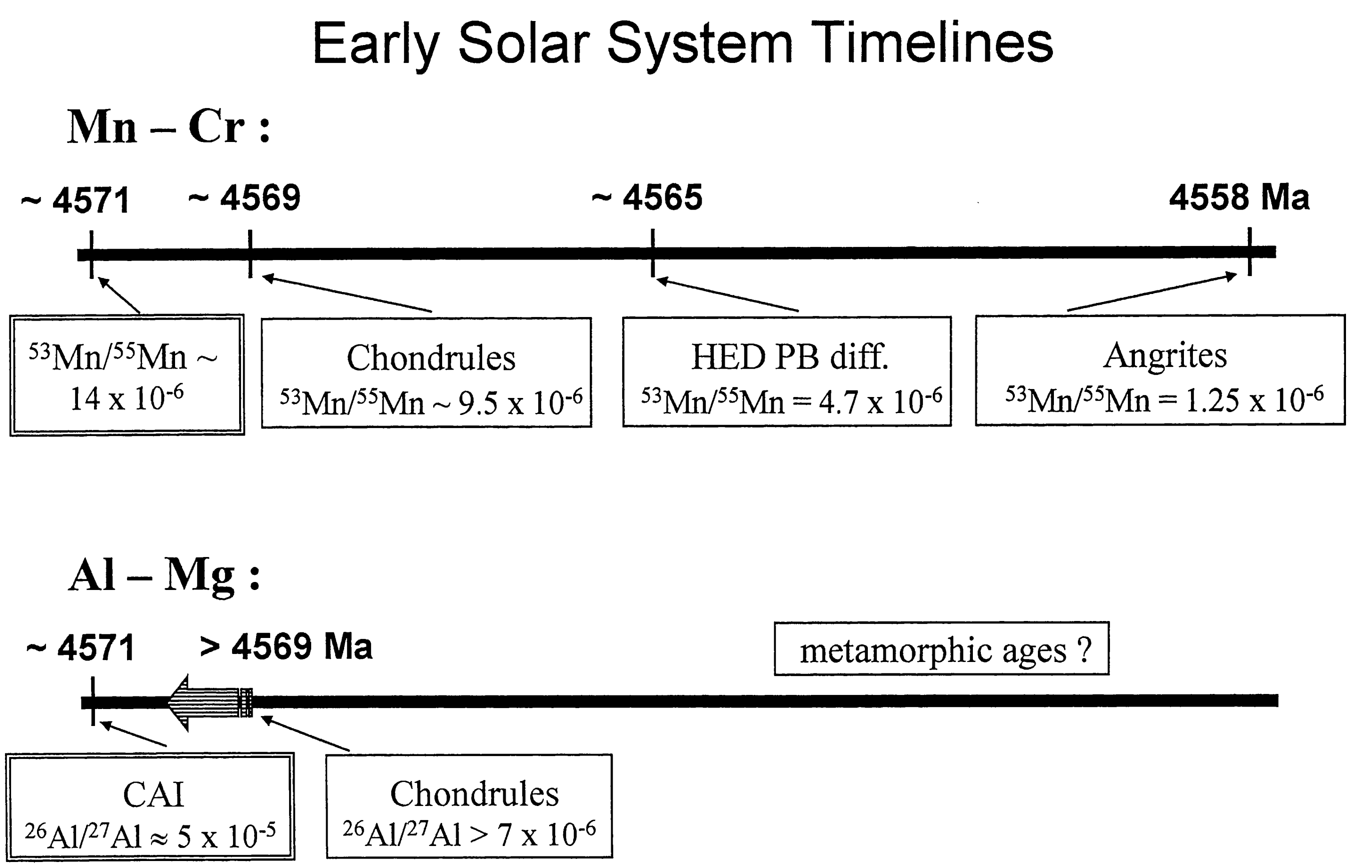

FIG. 5. Mn-Cr and Al-Mg early solar system timelines. The Al-Mg system is anchored at the Mn-Cr estimate for the age of the solar system of 4571 Ma. This time is considered as the time when most refractory meteorite inclusions were starting to form. Within a time span of about 2 Ma most *primary* chondrules have formed on and around small planetesimals, which were melting through the decay of ^{26}Al. For a discussion of the *local* chondrule-formation process scenario, see text.

meteorite parent bodies. In this way, the simultaneous occurrence of "primary" chondrules as well as chondrules devoid of excess ^{26}Mg in meteorites such as Chainpur (Russell *et al.*, 1996), which as such was not heated to temperatures much in excess of ~400 °C (Sears *et al.*, 1991), can be explained. The same is envisioned to be true for CAIs that were altered at different temperatures. It is also important to note that ^{53}Cr/^{52}Cr initials, as would be derived from CAIs (see discussion above), and the resulting higher solar system age (*i.e.*, ~4574 – 4576 Ma) would not permit sufficient amounts of ^{26}Al to remain at ~4569 Ma ago to provide enough heat for substantial melting to take place within planetesimals of intermediate size.

Some Constraints on Calcium-Aluminum-Rich Inclusion Evolution

As discussed above, CAIs have formed very early in solar system history with a remarkably uniform ^{26}Al/^{27}Al ratio. Considering the recently measured variation of ^{26}Al/^{27}Al between petrographically distinct components within the same Allende CAI (Hsu *et al.*, 2000), it appears that CAI formation may have persisted for several 10^5 years.

It is well known that "normal" CAIs with ^{26}Mg excesses also usually possess isotopic anomalies in at least the iron peak elements with reasonably uniform excesses in the neutron-rich isotopes. In contrast, a small subset of CAIs, which are called fractionated and unknown nuclear isotope anomalies (FUN) inclusions, have very large nuclear anomalies but show no or, at most, very small effects on ^{26}Mg. Because of these large isotopic anomalies, it appears most plausible that the FUN inclusions have formed very early, before their highly anomalous components were extensively diluted by mixing with average solar system material. Thus, the most likely reason for their lack of ^{26}Mg excess is that these inclusions have formed within a short time before ^{26}Al was injected into (or produced within) the solar system, a view that has been discussed over the years by several colleagues and has been recently argued by Sahijpal and Goswami (1998).

Because of their old age, the scarcity of FUN CAIs is most probably due to their relatively low chance for survival. At and during some period (several 10^5 years) after injection (or local production) of ^{26}Al (and other short-lived radioactive nuclei) "normal" CAIs were formed. Most FUN type CAIs were reworked and their highly anomalous components were further diluted with average solar system material. Nevertheless, this mixing with average solar system material can only have occurred on a limited scale for the anomalous isotopic signatures to survive. Although the isotopic anomalies in "normal" inclusion are fairly uniform, a brief review of literature data will show that a relative scatter on the order of, say, 30% to 50% still exists. Thus, it is unlikely, that formation of "normal" CAIs occurred within planetesimals (by a mechanism as later considered for the formation of most chondrules), since melting within larger bodies would be expected to erase these residual heterogeneities.

At any rate, after their formation (by whatever process) CAIs had to be stored within rapidly forming (several 10^3 years) small planetesimals (several hundred meters to kilometers in size) in order to prevent their rapid loss into the Sun by gas drag (Weidenschilling, 1977). It also appears reasonable and necessary that formation of CAIs and the small planetesimals took place contemporaneously for the duration of CAI formation. Mutual disruption of the small planetesimals and already larger objects caused further mixing of different types of CAIs. Eventually, these objects were the vehicles by which CAIs were later disseminated among chondrule-bearing planetesimals. Much of those metasomatic alterations, which were acquired later without involving any gas-phase, would then have occurred in the outer layers of these larger bodies. In the deeper regions CAIs ought to have been assimilated by the surrounding chondritic material.

ORIGIN OF CHONDRULES —AN ALTERNATIVE SCENARIO

We are now considering larger planetesimals, already grown to several tens of kilometers in size. The first generation of these bodies probably formed already within the first several 10^5 years after ^{26}Al injection. Because of their high ^{26}Al and volatile element content, these bodies start to melt rapidly from the interior outward. Heat loss most likely is minimal since the exterior of these bodies consists of relatively fluffy material with very low heat conduction. Eventual migration of melt to the surface probably is also of minor importance. Collisional encounters with other planetesimals are occurring at a faster rate than melt migration when typical number densities of these bodies are considered (Weidenschilling, 2000).

During these collisional encounters, the planetesimals are disrupted and some may be fragmented. The (pressurized) melt from the interior will spray into the surrounding space as finely dispersed droplets. (Their size will depend largely on the viscosity of the melt—chemical composition, temperature.) There will be droplets of silicate melt and presumably of Fe-Ni, which may have been expelled from the silicate melt (Connolly *et al.*, 1994). In the very early stages of droplet ejection, at still higher ambient pressures, some volatile loss and even partial evaporation of droplets could be expected to occur. Volatiles from the interior will escape and form a transient atmosphere or cloud of gas mixed with dust from the near-surface layers of the disrupted planetesimals. Chemical reactions of these gases with the droplets may occur, which can account for some so-called "nebular" features observed in chondrules. Dust grains attaching to or becoming embedded into droplets may serve as crystallization nuclei for the droplets. Along their trajectories, while partially cooling, the droplets will sweep up dust to form rims. Within a short time (hours), most of the rapidly cooling droplets will fall back onto and reassemble with the remaining rubble pile. Here they become embedded into the dust, may acquire further rim material, and cool to ambient temperature.

However, some of the newly formed chondrules will have velocities high enough to escape the system to be captured by other planetesimals. The volatiles in the dust cloud surrounding the system may partially be re-condensed on the dust grains, which then settle down onto a yet again accreting planetesimal. Nevertheless, a large portion of the volatile-rich cloud could be transported away from the system by, for example, interaction with solar wind. It is important to note that this process would ensure that the overall system remains largely chemically closed, with the exception of some volatile depletion and exchange of some chondrules with and transport to chemically similar as well as chemically distinct planetesimals.

Over the ensuing ~2 Ma there will be many generations of these chondrule-producing planetesimals. After this period the production of chondrules would taper off rapidly because of the declining supply of ^{26}Al. Mutual disruptions of planetesimals will further re-distribute previously formed chondrules. CAIs from still available early small planetesimals will be embedded and mixed into younger planetesimals. In such a violent environment, one certainly can expect that fracturing of chondrules and CAIs would be a common feature. Pieces of chondrules or CAIs could easily become embedded in newly formed chondrules or chondrule assemblages. CAI material ending up in the deeper layers of these planetesimals will also become part of a newly forming melt.

Towards the latter part of this chondrule-forming epoch, a crop of highly volatile depleted planetesimals may have evolved. These may serve as building blocks capable of assembling to larger highly volatile depleted asteroids such as Vesta. They still would contain sufficient heat and ^{26}Al in addition to gravitational energy to again begin to melt from the inside to eventually differentiate on a global scale, some 3 to 4 Ma later (*i.e.*, ~4565 Ma ago in the case of Vesta).

The surviving chondrule-bearing planetesimals will retain a hot interior for some time so that the observed thermal metamorphism of chondrite material can occur for >10 Ma. In the outer layers of these planetesimals one would expect to find a mixture of products from a variety of temperature regimes, while the assemblage itself may remain at low temperatures for ever after.

It should be understood that we do not wish to imply that this "local" (as opposed to "nebular") chondrule-producing process must be the only one—true nebular processes may also be important, but to a much lesser extent. In addition, some chondrules or chondrule-like assemblages, some even with basaltic characteristics, could have formed by the same process some time later than the main ~2 Ma production period through the disruption of larger, already partially differentiated objects. It could be expected that some of the droplets may have formed from partial melt originating from the outer regions of the melt zone. In general, however, chondrules consisting of partial melts are envisioned to be rare since zones of partial melt would not have a viscosity low enough to take part in the ejection process as indicated above.

Here we have attempted to paint a picture of an alternative scenario for the formation of chondrules, a hitherto unsolved problem, which is as old as meteorite research itself. Several aspects of this scenario have been discussed before by various authors (*e.g.*, Urey, 1955; Wänke *et al.*, 1981; Zook, 1981; Sanders, 1997; Chen *et al.*, 1998), some detailed and some less so. Although the brush we were using in this synthesis may also appear to be a little too broad for some, the intention was to persuade the reader to perhaps start thinking in these terms when considering available data and constraints.

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