cussed above are more effective than short-period triplication data because short-period data are more prone to scattering.

The model we adopted with a sharp change of anisotropy at about 100 to 250 km depth of the inner core is not unique. For example, models with multiple boundaries may explain the data, as may models with the boundary depth varying laterally. Recent travel-time measurements for NS paths show considerable variation of over 2 s in BC − DF differential times from rays sampling different parts of the inner core (*14*). Large scatter in AB − DF is expected based on the large variation in the lowermost mantle (*28*). Scatter in BC − DF is more difficult to explain without variation in the inner core because the two rays are near each other when crossing the core-mantle boundary. The seismic data that sample the inner core reported here suggest variation of more than 100 km in the depth of the transition boundary over the sampling distance approximately equal to the radius of the inner core. Such large variation, as illustrated schematically in Fig. 1A, could produce the reported scatter of differential BC − DF travel times. This is rather speculative, however, and needs to be substantiated by more NS observations of short-period inner core reflections and modeling of long-period and broadband waveforms.

Naturally, the question of the physical or chemical cause of this inner core structure arises. Three structures of iron—face-centered cubic, hexagonal close-packed (hcp), and the recently discovered (*29*) β structures—are thought to be stable in the inner core. A phase transition from one structure of iron to another would be consistent with the sharp boundary that we have observed, but the depth of such a phase transition may not vary much laterally in the inner core where temperature variation is expected to be small. Alternatively, the observed boundary may mark the separation of randomly oriented anisotropic iron crystals in the upper part and those aligned preferentially NS in the lower part. If we assume hcp iron for the inner core, the velocity change across the boundary along the NS direction from the upper part of randomly oriented iron crystals to the lower part with iron crystals preferentially aligned, NS is expected to be two to three times the velocity change across the boundary along the EW direction, making the boundary more evident along NS paths as we reported here.

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Isotopic Evidence for the Cretaceous-Tertiary Impactor and Its Type

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High-precision mass spectrometric analysis of chromium in sediment samples from the Cretaceous-Tertiary (K-T) boundary coincident with the extinction of numerous organisms on Earth confirms the cosmic origin of the K-T phenomenon. The isotopic composition of chromium in K-T boundary samples from Stevns Klint, Denmark, and Caravaca, Spain, is different from that of Earth and indicates its extraterrestrial source. The chromium isotopic signature is consistent with a carbonaceous chondrite–type impactor. The observed differences in the chromium isotopic composition among various meteorite classes can serve as a diagnostic tool for deciphering the nature of impactors that have collided with Earth during its history.

The discovery of high concentrations of Ir and other noble metals in K-T boundary sediments (*1, 2*) led to the hypothesis that the worldwide enrichment of this and some other siderophile elements in the K-T boundary layer is due to an impact of asteroidal or cometary material 65 million years ago (Ma). This suggestion was based on the fact that the terrestrial crust is highly depleted in the noble metals as compared to the concentrations of noble metals in meteorites and because the terminal Cretaceous extinctions of terrestrial organisms occurred at the K-T boundary (*3*). However, the hypothesis on the cosmic origin of Ir and the concept of the extraterrestrial cause of the Cretaceous extinctions have not been unanimously accepted. Some researchers have argued that excess Ir and other phenomena observed at the K-T boundary can be explained by enhanced volca-

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nic activity that occurred near the end of the Cretaceous (4). They have related the K-T boundary features to the formation of one of the most extensive continental flood basalt provinces of the world—the Deccan Traps in India. Extensive volcanism could provide a transport of noble metals from the mantle which, similarly to meteorites, has high concentrations of noble metals. On the other hand, the age of the recently discovered Chicxulub impact structure (180 km in diameter) on the Yucatan Peninsula, Mexico (65 Ma), is coincident with the K-T boundary and suggests an extraterrestrial cause for the K-T event (5). The global occurrence of magnesioferrite spinel and shocked quartz (6) in the K-T boundary sediments has also strengthened the impact hypothesis. However, direct isotopic evidence is still missing.

Several isotopic systems have been used to search for an extraterrestrial signal in the K-T sediments. The study of the ^{187}Re-^{187}Os isotope system (7) has shown that the low ^{187}Os/^{186}Os ratio of the sediments is inconsistent with that in the crust and could be of extraterrestrial origin. This, however, can also be explained by volcanic transport of material with low ^{187}Os/^{186}Os from the mantle. The Pb isotopic composition in K-T boundary samples (8) does not resemble meteoritic Pb and probably has a terrestrial origin. The isotopic signature of noble gases in the K-T samples is indistinguishable from that of the terrestrial atmosphere (9). The elemental patterns in the K-T samples bear a certain resemblance to the cosmic elemental abundances (1, 2, 10). However, various chemical fractionation processes such as diagenetic mobilization in sediments, variable residence times in and precipitation from seawater, and possible input of terrestrial ejecta material make the determination of the type of a possible impactor complex.

We used the results from our recent studies of the ^{53}Mn-^{53}Cr isotope systematics in various solar system objects (11) to shed light on the K-T boundary phenomenon. The radioactive nuclide ^{53}Mn decays to stable ^{53}Cr with a half-life of 3.7 Ma. Although present in the early solar system, ^{53}Mn has now fully decayed because of its short half-life and is now extinct in the solar system. However, it was present at the time of formation of the first solids in the early solar system and even during the formation of early planetesimals. After vestiges of ^{53}Mn were found in refractory inclusions from the carbonaceous chondrite Allende (12), excess ^{53}Cr was detected in various ancient solar system objects (11, 13). The former presence of ^{53}Mn is indicated by variations in the relative abundance of the radiogenic daughter ^{53}Cr. These isotopic variations are measured as the deviations of the ^{53}Cr/^{52}Cr ratios from the standard terrestrial ^{53}Cr/^{52}Cr ratio, which are usually expressed in ε units (1 ε is one part in 10^4).

We developed a technique for high-precision mass spectrometric analysis of the Cr isotopic composition of terrestrial and extraterrestrial rocks and minerals (11). This technique allows us to measure small ^{53}Cr/^{52}Cr variations of less than 1 ε with an uncertainty of 0.05 to 0.10 ε units. All terrestrial samples exhibit the same ^{53}Cr/^{52}Cr ratio ($\sim$0 ε) regardless of their origin: Earth homogenized long after ^{53}Mn had fully decayed, and thus no variation in ^{53}Cr/^{52}Cr ratios is expected for any terrestrial samples (Table 1). The lunar anorthosite 60025 has ^{53}Cr/^{52}Cr ratios that are the same as in the terrestrial samples, which indicates a close genetic relationship between Earth and the moon. In contrast, all meteorite classes studied so far have excess ^{53}Cr relative to the terrestrial value. The ordinary chondrites show a characteristic ^{53}Cr excess of $\sim$0.48 ε. Although the ^{53}Cr/^{52}Cr ratios of individual eucrites and diogenites vary because of an early planet-wide Mn/Cr fractionation (11), their parent body (the asteroid Vesta) is characterized by the close-to-chondritic ^{53}Cr excess of $\sim$0.57 ε. The Mn-Cr isotope systematics of the angrites, primitive achondrites, and

Table 1. ^{53}Cr/^{52}Cr ratios and Cr concentrations in various terrestrial and extraterrestrial samples. ND, not determined.

Sample	Cr (ppm)	^{53}Cr/^{52}Cr (ε units)
Terrestrial minerals, rock, and sediment		
Laboratory shelf standard		$\equiv$0
KH-1 Px, Kilbourne Hole, USA (pyroxene)	2500	-0.01 ± 0.08
JAG 89-9, Jagersfontein, South Africa (garnet)	ND	0.04 ± 0.08
SC Ol, San Carlos Volcanic Field, USA (olivine)	202	-0.03 ± 0.11
MB 81-14, Deccan Traps, India (basalt)	112	-0.04 ± 0.06
ODP 31-302-5-5, Western Pacific (clay)	34	-0.02 ± 0.09
*Bulk meteorites and meteorite parent bodies**		
Ordinary chondrites (H, L) and their parent bodies	$\sim$3900	$\sim$0.48
Eucrites	1600–3200	0.7–1.3
Diogenites	6000–12700	0.4–0.6
Howardite-eucrite-diogenite parent body (Vesta)		$\sim$0.57†
Primitive achondrites and their parent bodies	3400–8000	$\sim$0.53
Angrites	800–1800	0.4–0.7
Angrite parent body		$\sim$0.48†
Pallasite parent body		$\sim$0.52†
Martian (SNC) meteorites	1600–1800	$\sim$0.22
Enstatite chondrites (EH) and their parent body	2900–3900	$\sim$0.17
Lunar anorthosite 60025	$\sim$240	0.00 ± 0.09

*From (11). †Calculated on the basis of the Mn-Cr isotope systematics.

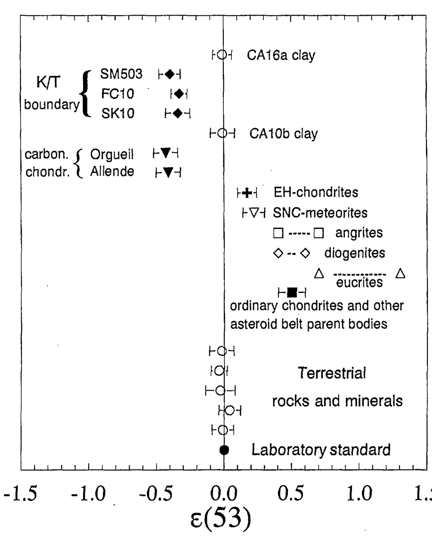

Fig. 1. ^{53}Cr/^{52}Cr ratios in K-T boundary sediments and in various terrestrial and meteoritic samples. Note the difference in ^{53}Cr/^{52}Cr between terrestrial samples, the control sample clays, and the K-T boundary clays. The isotopic signature in the latter is nonterrestrial and is very similar to that in carbonaceous chondrites.

Table 2. ^{53}Cr/^{52}Cr ratios and Cr concentrations in the K-T boundary samples, background samples, and carbonaceous chondrites Allende and Orgueil.

Sample	Cr (ppm)	^{53}Cr/^{52}Cr (ε units)
K-T boundary and background clays		
SK10, Stevens Klint, Denmark	204	-0.34 ± 0.09
FC10, Stevens Klint, Denmark	133	-0.33 ± 0.04
SK503, Caravaca, Spain	991	-0.40 ± 0.08
CA10b, Caravaca, Spain, 10 to 15 cm below K-T (clay)	40	-0.01 ± 0.07
CA16a, Caravaca, Spain, 16 to 20 cm above K-T (clay)	69	-0.01 ± 0.09
Bulk carbonaceous chondrites		
Allende (CV3)	3540	-0.41 ± 0.09
Orgueil (CI)	2530	-0.43 ± 0.09

pallasites is also consistent with $^{53}Cr/^{52}Cr$ ratios of $\sim 0.5\ \varepsilon$ in their bulk parent bodies. The ^{53}Cr excesses of the martian meteorites ($\sim 0.22\ \varepsilon$) and of the EH-chondrites ($\sim 0.17\ \varepsilon$) are intermediate between those of Earth and the chondrites. The observed distribution of radiogenic ^{53}Cr may not be due to differences in the bulk Mn/Cr ratios of the parent bodies. Instead, this distribution may reflect an original spatial heterogeneity of ^{53}Mn in the early solar system, which is now manifest as a radial gradient in the radiogenic ^{53}Cr abundances (*11*). Regardless of the scenario, this observed difference is a direct experimental fact that does not involve any models or assumptions and allows us to distinguish extraterrestrial material on the basis of the Cr isotopic composition.

Chromium concentrations in K-T boundary sediments are commonly 20 to 30 times higher than those in background sediments (*2, 10*). Chromium is depleted in Earth's crust as compared to the Cr concentration in many types of meteorites. The average Cr concentration in the bulk continental crust is 185 parts per million (ppm) (*14*), whereas that in bulk meteorites is usually several thousand parts per million (Table 1). If a considerable part of the Cr in the K-T samples is indeed of cosmic origin (rather than mostly from terrestrial ejecta material or volcanic ash), high-precision measurements of the Cr isotopic composition can provide direct isotopic evidence for the impact hypothesis. We have measured the Cr isotopic composition and Cr concentrations of the K-T boundary samples FC10 and SK10 from Stevns Klint, Denmark (*2, 10*), of SM503 from Caravaca, Spain (*10*), and of two background sediments from Caravaca, CA10b (10 to 15 cm below the K-T boundary) and CA16a (16 to 20 cm above the K-T boundary) (Table 2).

The $^{53}Cr/^{52}Cr$ ratios of the background clays are indistinguishable from those of other terrestrial samples, whereas those of the K-T samples (Table 2 and Fig. 1) are different from that of Earth and indicate that much of the Cr must clearly be of extraterrestrial origin. The Cr concentrations in the K-T samples vary from 133 to 991 ppm, whereas the $^{53}Cr/^{52}Cr$ ratios are the same within uncertainties. This suggests that cosmic Cr is predominant in all these samples and that the measured $^{53}Cr/^{52}Cr$ ratios reflect the Cr isotopic composition of the K-T impactor (*15*). We note, however, that none of the meteorite classes studied so far in our laboratory [(Table 1) (all have excess ^{53}Cr)] have a Cr isotopic composition similar to that of the K-T samples (which have a deficit of ^{53}Cr). Furthermore, it is not clear at present whether the obtained deficit of ^{53}Cr is real or if it is the result of an elevated $^{54}Cr/^{52}Cr$ ratio in the samples, which is tentatively indicated. In our method (*11*), the $^{54}Cr/^{52}Cr$ ratio is used for a second-order fractionation correction (*16*). All meteorite samples studied so far (*11*) were found to have, within error, a normal $^{54}Cr/^{52}Cr$ ratio. However, carbonaceous chondrites contain Cr of a presolar origin, and this Cr is characterized by mostly elevated but sometimes lower than normal $^{54}Cr/^{52}Cr$ ratios (*17*). There are indications (*18*) for an elevated $^{54}Cr/^{52}Cr$ ratio even in the bulk samples of carbonaceous chondrites. For this reason and as an attempt to establish the type of K-T boundary impactor material, we measured the Cr isotopic composition in large (1 to 2 g) bulk samples of the carbonaceous chondrites Allende and Orgueil. When treated in the same way as the K-T samples (that is, using the $^{54}Cr/^{52}Cr$ ratio for the second-order fractionation correction), the results for Allende and Orgueil (Table 2 and Fig. 1) show that their Cr isotopic signature is similar to that of the K-T samples. Thus, regardless of what the "negative" ε values will actually translate into (that is, a deficit of ^{53}Cr or an excess of ^{54}Cr and an excess of ^{53}Cr), the results suggest that the K-T boundary impactor was composed of carbonaceous chondrite–type material (*19*). All other measured meteorite types listed in Table 1 can be excluded. Thus, a probable candidate for the impactor is a carbonaceous asteroid similar to those that supplied Earth with carbonaceous chondrites of different metamorphic types. The alternative is a comet. Comets are considered to be composed of material similar to that of carbonaceous chondrites (*20*). Massive interstellar clouds or passing stars could gravitationally perturb the inner reservoir of comets and the surrounding Oort cloud and cause a flux of comets in the inner solar system (*21, 22*). For example, the enhanced flux of extraterrestrial ^{3}He in late Eocene pelagic limestones 36 million years old, coincident with the Popigai and Chesapeake Bay craters, most likely indicates a cometary source (*23*). On the other hand, recent data on a fossil meteorite from the K-T boundary favor an asteroid over a cometary source (*24*). However, with the limited set of our present Cr data and the total lack of Cr isotopic data from cometary material, it would be premature to choose between these two possibilities for the K-T impactor.

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