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Search for traces of the late heavy bombardment on Earth—Results from high precision chromium isotopes

Robert Frei [a],*, Minik T. Rosing [b]

[a] Geological Institute, University of Copenhagen, Øster Voldgade 10, DK 1350 Copenhagen K, Denmark
[b] Geological Museum, Øster Voldgade 5-7, DK-1350 Copenhagen K, Denmark

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Abstract

High precision mass spectrometric analyses of the chromium isotopic composition of metamorphosed turbiditic and pelagic sedimentary rocks and banded iron stones from the ~3.7 Gyr Isua Supracrustal Belt (ISB) in West Greenland cannot be distinguished from the standard terrestrial $^{53}Cr/^{52}Cr$ ratio at our present level of resolution. As a consequence, our search for chemical traces of possible impact-derived meteoritic components (asteroidal and/or cometary material, or accreted cosmic dust) in the Earth's oldest chemical and detrital sediments was negative. Our results, based on the ^{53}Mn–^{53}Cr short-lived radionuclide system (half-life of 3.7 Myr), cannot confirm the recent findings by [1] [R. Schoenberg, B.S. Kamber, K.D. Collerson, S. Moorbath. Tungsten isotope evidence from approximately 3.8-Gyr metamorphosed sediments for early meteorite bombardment of the Earth. Nature 418 (2002) 403–405.] of tungsten isotope anomalies (based on the ^{182}Hf–^{182}W short-lived radionuclide system; half-life of 9 Myr) in these sediments, which were interpreted as indicating a component derived from meteorites. Possible reasons for the failure to trace cosmic material in the ISB metasediments are various: 1. The samples studied are not representative; 2: The sedimentation period did not overlap with the period of late heavy bombardment of the Moon; and 3. The potential chromium anomalies, if present, are too small to be traceable by our present levels of detection. Unequivocal evidence of a late heavy bombardment on the early Earth therefore remains elusive and uncertain.

Keywords: chromium isotopes; lunar bombardment; West Greenland; Isua; impacts

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1. Introduction

The Moon experienced an interval of intense bombardment peaking at ~3.85 ± 0.05 Ga [2,3], also termed Late Heavy Bombardment (LHB). The Earth must have been subjected to a significantly greater bombardment than the Moon, as it has a larger diameter and a much larger gravitational cross-section. It has been estimated [4] that the mass accretion rate during the LHB was in the order of $(1–2) \times 10^{15}$ gyr^{-1}, or $(2–4) \times 10^{-4}$ g cm^{-2}. Over a 100 Myr

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* Corresponding author.
E-mail address: robertf@geol.ku.dk (R. Frei).

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period of LHB, a total of (1–2) × 10^{23} g of material would have accumulated, which if distributed continuously over the entire planet, would correspond to 200 t m^{-2} [1]. The consequences for the hydrosphere, atmosphere, and even lithosphere of Earth at this time must have been devastating [5].There is evidence that the Earth's upper mantle had already undergone some differentiation at the time of formation of the oldest igneous rocks, suggesting the prior existence of a chemically evolved crust [6–8]. It has also been suggested that the absence of any rocks older than about 3.9–4.0 Ga is the result of the ancient heavy bombardment, during which impact-induced mixing recycled early crustal fragments back into the upper mantle [9]. It is likely that any large-scale early impacts had some polluting influence on the development of the continental crust at this time and, assuming that such crust persisted and survived large scale rehomogenisation with the upper mantle in the period just before the deposition of the oldest sediments in Western Greenland, it would be conceivable that either contaminated continental detritus with remobilized respective chemical signatures or co-deposited cosmic dust, in one way or another, should be traceable in these oldest rocks.

The effect of impacts on the Earth's geological history, its ecosphere and the evolution of life has become a major topic of current interdisciplinary interest since publication of the Alvarez et al. idea that the Cretaceous/Tertiary (K/T) mass extinction was caused by the impact of an asteroid or comet ~10 km across [10]. The existence of an LHB would certainly have prevented the environmental tranquillity necessary for life to gain a foothold [11,12]. In a recent study, [1] presented tungsten isotope evidence from ~3.8 Gyr metamorphosed sediments for an early meteorite bombardment of the Earth. Four of six analyzed early Archean metasediment samples from the Isua Supracrustal Belt (ISB, western Greenland), thought to have been deposited during the waning stages of the LHB, revealed resolvable less radiogenic W than the accessible Earth, and were interpreted to indicate that a proportion of W in these sediments was of extraterrestrial origin. These authors favoured a scenario whereby weathering of meteoritic debris caused preferential liberation of certain elements, depending on the stability of the host minerals in the Hadean atmosphere and hydrosphere.

Our study is based on the successful application of the ^{53}Mn–^{53}Cr isotope system to K–T boundary samples from Stevns Klint, Denmark and Caravaca, Spain [13] and to Late Archean impact-contaminated sediments (spherule beds) from the Barberton Mountain Land (South Africa; [14]), in which the composition of chromium was shown to be different from that of Earth, indicating an extraterrestrial source. One of the key implications of these studies was that the chromium isotopic signatures of various meteorite classes can serve as a diagnostic tool for deciphering the nature of impactors that have collided with Earth during its history.

The radioactive nuclide ^{53}Mn decays to stable ^{53}Cr with a half-life of 3.7 Myr. Although present in the early solar system, ^{53}Mn has fully decayed because of its short half-life and is now extinct in the solar system. Excess ^{53}Cr was detected in various ancient solar system objects [15–17]. The former presence of ^{53}Mn during the formation of these objects is indicated by variations in the relative abundance of the radiogenic daughter ^{53}Cr, and variations are measured as deviations of ^{53}Cr/^{52}Cr ratios from the standard terrestrial ^{53}Cr/^{52}Cr ratio, which are usually expressed in ε units (1 ε unit is one part in 10^4). All terrestrial samples exhibit the same ^{53}Cr/^{52}Cr ratio (~0 ε) regardless of their origin, because Earth homogenized long after ^{53}Mn had fully decayed, and therefore no variations in ^{53}Cr/^{52}Cr is expected. In contrast, all meteorite classes studied so far have excess ^{53}Cr relative to the terrestrial value, with the exception of carbonaceous chondrites (Allende CV, Orgueuil CI, Murray CM, and Kainsaz C0), which show pronounced negative ε^{53}Cr values of between -0.30 to -0.43 [13,14,18]. This particular signature is mainly due to an excess of ^{54}Cr, interpreted as presolar in origin, in excess to ^{53}Cr [18,19], and mainly results from a second order mass bias correction necessary for high precision Cr isotopic analyses.

There are few studies of Cr isotopic compositions in iron meteorites. Indigenous Cr concentrations in metals are low (from a few ppm to around 200 ppm; e.g., [20]). If exposure ages of metals are long, production of spallation ^{53}Cr is predominant compared to radiogenic ^{53}Cr [16,21]. Since Fe is the main target for Cr production, the magnitude of the spallation contribution is proportional to the Fe/Cr ratio. Consequently, in order to obtain spall-