The Earth-Moon system during the Late Heavy Bombardment period
– geochemical support for impacts dominated by comets.

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Abstract.

The solid planets assembled 4.57 Gyr ago during a period of less than 100 Myr, but the bulk of the impact craters we see on the inner planets formed much later, in a narrow time interval between 3.8 and 3.9 Gyr ago, during the so-called Late Heavy Bombardment (LHB). It is not certain what caused the LHB, and it has not been well known whether the impactors were comets or asteroids, but our present study lend support to the idea that it was comets. Due to the Earth’s higher gravity, the impactors will have hit the Earth with \( \sim \) twice the energy density that they hit the Moon, and the bombardment will have continued on Earth longer than on the Moon. All solid surface of the Earth will have been completely covered with craters by the end of the LHB.

However, almost nothing of the Earth’s crust from even the end of this epoch, is preserved today. One of the very few remnants, though, is exposed as the Isua greenstone belt (IGB) and nearby areas in Western Greenland. During a field expedition to Isua, we sampled three types of metasedimentary rocks, deposited \( \sim \)3.8 billion years ago, that contain information about the sedimentary river load from larger areas of surrounding land surfaces (mica-schist and turbidites) and of the contemporaneous seawater (BIF). Our samples show evidence of the LHB impacts that took place on Earth, by an average of a seven times enrichment (150 ppt) in iridium compared to present day ocean crust (20 ppt). The clastic sediments show slightly higher enrichment than the chemical sediments, which may be due to contamination from admixtures of mafic (proto-crustal) sources.

We show that this enrichment is in agreement with the lunar cratering rate and a corresponding extraterrestrial LHB contribution to the Earth’s Hadean-Eoarchean crust, provided the bulk of the influx was cometary (i.e., of high velocity and low in CI abundance), but not if the impactors were meteorites (i.e. had velocities and abundances similar to present day Earth crossing asteroids). Our study is a first direct indication of the nature of the LHB impactors, and the first to find an agreement between the LHB lunar cratering rate and the Earth’s early geochemical record (and the corresponding lunar record). The LHB comets that delivered the iridium we see at Isua will at the same time have delivered the equivalent of a \( \sim \)1 km deep ocean, and we explain why one should expect a cometary ocean to become roughly the size of the Earth’s present-day ocean, not only in terms of depth but also in terms of the surface area it covers. The total impacting mass on the Earth during the LHB will have been \( \sim \)1000 t/m².

**Keywords:** comets; meteorites; geological processes; ices
Introduction.

While the lunar craters could in principle represent the end of the planetary accretion, most evidence point to the planetary accretion epoch and the lunar crater formation as being two different events in the history of the solar system, separated in time by several hundred million years. Comparison of the relative age and size distribution of craters throughout the solar system, indicates that the event that created the ancient lunar craters during the LHB period, (i.e. the crater-rich highlands and the basins that later became the Mare regions) also formed the craters on Mars, asteroids, Mercury, and elsewhere in the solar system; in other words that the LHB was unique, heliocentric, and the most violent independent event that has happened during the whole history of our solar system since the formation of the planets (e.g., Gomes et al. 2005, Martin et al. 2006, Hartmann et al. 2000, Kring & Cohen 2002, Ryder 2002, Pater & Lissauer 2001).

Very little, however, is known about its effect on the Earth. Several studies have searched for signs of the LHB on the Earth, throughout many years, without conclusive evidence and often with seemingly contradictory results. It is often assumed that the traces of the LHB on Earth has been erased due to Earth’s dynamic geology. However, the LHB was so intense, in particular on the Earth, that it has radically affected the bulk composition of the atmosphere and hydrosphere, and probably the crust and mantle, too. Judging from the size of the lunar craters, the largest LHB impacts on Earth will have evaporated the ocean and stripped off a major fraction of the atmosphere (e.g., Zahnle & Sleep 1997, Chyba 1991). There will have been $\sim 3000$ impacts comparable with or larger than the K/T event, and $\sim 1000$ tons of cosmic material fell on each $m^2$ of the Earth’s surface (see calculations below). A few pieces of the Earth’s present-day crust is formed from material that was part of the Earth’s solid surface during the end of the LHB period. The problem of identifying what happened on Earth during the LHB is therefore not the amount of accessible material, but rather difficulties in interpreting the available data, and very uncertain, or completely lacking, knowledge about the basic astronomical, physical and chemical properties of the various possible impactors.

We have collected and analysed three different types of sedimentary rock samples from the Earth’s oldest well preserved sedimentary crust; the $\sim 3.8$ Gyr old Isua greenstone belt (IGB) north-west of Nuuk in Greenland. The sediments were deposited during the end of the LHB period, and we are here presenting the direct geochemical evidence they show of what we interpret as a cometary nature of the LHB impactors.
Interpretations of possible atmospheric and crustal signals of the LHB.

The most obvious signal of the LHB, but also one of the most difficult to interpret, may lie in the Earth’s atmosphere, and we may in fact breathe the gases from the LHB impactors through our lungs every day, and we may sip a piece of the impactors every time we drink a glass of water. Marty & Meibom (2007) compared the relative noble gas abundances in the Earth’s atmosphere with that of carbonaceous chondrites and comets, and concluded that up to 6% of the nitrogen content in our present-day atmosphere may have originated from the LHB impactors. They concluded that the bulk of the impactors must have been of a composition similar to carbonaceous chondrites, and that a mixture with as little as 0.5% cometary material could explain the difference between the relative noble gas abundances in the Earth’s mantle and atmosphere. In order to translate these differences into percentage of cometary contribution to the LHB, one, however, has to make assumptions about the relative noble gas abundances interpreted from a few present-day cometary out-gassing spectra. This exercise involves estimating the noble gas content, not of the possible cometary LHB impactors where they formed (which can be difficult enough), but of the noble gas abundances in the fractured pieces of such comets after they have been disrupted and heated by approaching the Sun typically several times before impact. On top of this, “comets” is a concept that hide many different classes of objects, formed from close to the orbit of Jupiter, and anywhere out to far beyond the orbit of Neptune, where the noble gas capture rate, as well as the isotopic ratio of individual types of molecules, differ widely. The estimates of the LHB cometary contribution percentage to the present-day composition of the atmosphere of the Earth, therefore still include so many unknown parameters that the results, in our opinion, mainly should be understood as an interesting hint that the LHB contribution to the Earth’s atmosphere may be mainly chondritic, as concluded by Marty & Meibom (2007). A number of other papers have dealt with the possible cometary contribution to the origin of the Earth’s present atmosphere and hydrosphere in general (without specific concern of whether the cometary volatiles were necessarily related to the LHB or other epochs of the Earth’s evolution), but a general consensus is still lacking (e.g., Pepin 1991, Owen et al. 1992, Owen & Bar-Nun 2001, Dauphas 2003, Zahnle 2006). The conclusions are strongly dependent on the detailed assumptions about the nature of the impacting cometary pieces.

One could hope that the study of solid rocks would give a more straightforward picture than the volatile atmosphere, but also here the interpretation has been more difficult than anticipated. Lunar rocks should in principle be the simplest rocks to interpret in terms of LHB, because the bulk of the lunar craters are formed by the LHB impactors and only little has changed on the Moon since the end of the LHB. Therefore also the bulk of the sampled lunar impact melt rocks are due to these impacts, and could be expected to be a mixture of lunar
crust and representative cosmic LHB impact material. However, the interpretation of the lunar rock measurements have been far from simple. A recent example is the work by Kring & Cohen (2002). By measuring the abundances of Au, Ge, and Ir in Apollo impact melt samples, they found that 2 of the 6 melts plotted in a 3-element abundance diagram of these elements fell in the region of iron meteorites, 3 fell in the region of enstatite meteorites, while one fell outside the region of any known meteorites. Based on these results, they concluded that asteroids were the cause of the LHB (as opposed to comets). In earlier studies (Gros et al. 1976, Hertogen et al. 1977) based on a 3-element abundance diagram of other elements, it was concluded that the resemblance was largest not with iron meteorites as in Kring & Cohen’s work, but with ordinary chondrites (and enstatites) and with CI carbonaceous chondrites, respectively. However, only relatively little is known about the abundances in the comets that can have bombarded the Earth-Moon system during the LHB, and even more important is (as we will show below) that the bulk of impacting comets will leave no chemical trace on the Moon. This is because the high ratio of cometary impacting velocity to lunar escape velocity, will make all the cometary material being re-ejected into space. The fact that some studied melts fall in the same region as some meteorite-types in a 3-element diagram, therefore give no information about the cometary contribution.

Alternatively to studying the lunar material from the LHB period, one could sample the oldest rocks on Earth, closest in time to the LHB period. As opposed to on the Moon, a considerable fraction of the cometary material will stay on the Earth after impact. Koeberl et al. (1999) looked for shock impacted material in the ∼3.8 Gyr old Isua region and searched for material with CI-type relative abundances. In spite of the relatively high detection limit in their measurements, they did notice excess iridium in a few of the samples, but because of a failure to find shocked material and a relative abundance pattern matching CI composition, they concluded that the material was not contaminated with LHB impactors, without giving any alternative explanation of the enhanced iridium. However, neither cometary nor asteroid impacts will necessarily result in CI abundance patterns (since various types have widely different relative abundances), and shocked impact material, if identified, is concentrated toward the impact site, whereas the non-destructive LHB enrichment of the proto-Isua crust is more likely to have been in the form of stratospheric dust fall-out.

A very illustrative example of how unexpected the composition of impacting material can be, is the largest known impact (∼100 m diameter or ∼10^6 tons) in historic time (the Tunguska event in 1908). The most pronounced evidences of its cosmic nature are: a 30 fold increase (relative Earth’s present-day upper crust) in the peat ash iridium abundance in some of the surrounding swamp peat layers (Korina et al. 1987, Hou et al. 1998), a strongly non-terrestrial Pb isotopic pattern (Kolesnikov et al. 2005), a very peculiar C/Ir ratio (unknown from any other cosmic body but interpreted as indicating cometary origin; Rasmussen et al. 1999), weak
CI abundance correlation, and no shocked material. There is no doubt that the impact was a cosmic event, although there are still strong disputes about whether it was a carbonaceous-like chondrite or a comet (e.g. Turco et al 1982, Vasiljev 1998, Bronshten 2000, Jopek et al. 2008). The Tunguska event did result in a local dust cloud, but did not result in a traceable global fall-out (Rasmussen et al. 1995), but its mass corresponds to only the lower end of the LHB mass distribution. A more typical LHB impactor (in terms of the total mass contribution) will have corresponded to the well studied Cretaceous-Tertiary (K/T) Chicxulub impactor that fell, in the region of present-day Mexico, 65 million years ago. It is likely to have been a cosmic body of approximately 10 km in diameter, and there will have been several thousands of such impacts on the Earth during the LHB. A mixture of material from the Chicxulub impactor itself and the impacted crust was whirled into the stratosphere, where it was transported worldwide and over the following several years fell as a cm-thick layer of dust all over the globe. The enhanced iridium abundance in this dust layer was the most important proof that it was due to a cosmic impact (Alvarez et al. 1981, Hansen et al. 1988, Frei& Frei 2002). There were no associated Pb isotopic anomalies, no reported extreme C/Ir anomaly, but CI-like PGE abundances. Shocked quartz and feldspar have been reported, but their abundances relative to the rest of the fall-out material varies with orders of magnitude between the different K/T sites at various distances from the impact location (Bohor et al. 1987, Cisowski 1990). Other studies of early major impacts on Earth include those of Glikson (2008), Simonson & Glass (2004), and Lowe et al. (2003).

We envision that the Earth’s atmosphere by the end of the LHB period must have been rich in cosmic dust that slowly settled over most of the globe, in analogy to the Tunguska and K/T-events, but not necessarily identical in composition to any of the two.

Anbar et al. (2001) searched for cosmic traces of Ir and Pt in samples from the Akilia island near Nuuk, approximately 150 km south-west of Isua. Nutman et al. (1996, 1997), and later Mojzsis & Harrison (2000), found the age of the Akilia suite to be close to 3.85 Gyr, thus being older than the Isua samples we analyse here and closer in age to the peak of the lunar LHB. However, this depositional age determination was later questioned by Kamber & Moorbath (1998, 2000) who found an age of 3.65 Gyr. Apart from the discussion regarding the depositional age constraints, also the nature of the rocks was disputed. Fedo & Whitehouse (2002) found that what was at first interpreted as sediments in ancient seawater (BIF), were rocks of ultramafic igneous origin that only superficially resembled BIF. The criticism of the dating and the nature of the rocks was summarised by Moorbath (2005) together with critical remarks about Anbar et al.’s interpretation of possible carbon-isotopic traces of life in the Akilia rocks. Nevertheless, Anbar et al.’s results are interesting for the present analysis in two respects: (1) These old rocks are depleted in iridium relative to the present-day upper crust, and (2) the lower iridium abundance with a factor 10 or more compared to our Isua measurements is
consistent with an exponentially decaying LHB impact rate only if Kamber & Moorbath’s age
determination of 3.65 Gyr is correct instead of Anbar et al’s of 3.85 Gyr.

W, Hf, and Cr versus iridium.

Two relatively recent studies searched for signs of the LHB in sediment samples from the
Isua greenstone belt area, with seemingly contradicting results, and therefore needs particular
attention and comparison with the present study. Both of the studies aimed at searching for
signs of the LHB by use of short-lived radiogenic tracers (the $^{182}\text{Hf}$–$^{182}\text{W}$ system; Schoenberg
et al. 2002, and the $^{53}\text{Mn}$–$^{53}\text{Cr}$ system; Frei & Rosing 2005).

$^{182}\text{Hf}$ decays to $^{182}\text{W}$ with a half-life $\tau_{\text{Hf}}$ of only 9 Myr. W is siderophile, while Hf is lithophile.
After the Earth melted, W therefore mixed with iron and became concentrated in the Earth’s
core, while Hf became concentrated in the mantle and crust. If the accretion and separation
took place on short time scales (relative to $\tau_{\text{Hf}}$), Hf would still have been radioactive after
the core-mantle separation, and the final $^{182}\text{W}/^{183}\text{W}$ ratio in the mantle would be higher than
the corresponding $^{182}\text{W}/^{183}\text{W}$ ratio in the original material (often represented by carbonaceous
chondritic material, for example the Allende meteorite), and considerably higher than in the
Earth’s core and in iron meteorites. Several people have estimated the Earth’s accretion history
based on the $^{182}\text{Hf}/^{182}\text{W}$ system. Jacobsen (2005) concluded that the Earth assembled in
$\sim 10$ Myr, and by comparing with the slightly higher $^{182}\text{W}/^{183}\text{W}$ in the lunar material than
in the present-day reachable part of the Earth’s mantle, he found that the Earth’s core and
mantle must have separated (and the Moon formed due to an impactor of mass ratio relative
the Earth of $\sim 1:9$) already $\sim 30$ Myr after the Earth’s formation. In agreement with these
formation ideas, un-processed chondritic material, such as Allende, show a $^{182}\text{W}/^{183}\text{W}$ ratio
slightly lower than standard terrestrial samples, and iron meteorites even lower. In principle,
material can therefore be identified as extra-terrestrial if it has a lower $^{182}\text{W}/^{183}\text{W}$ than the
Earth’s crust. In a study of $^{182}\text{W}/^{183}\text{W}$ in samples from Isua, Schoenberg et al. (2002) found
$^{182}\text{W}/^{183}\text{W}$ values two to four sigmas below the standard terrestrial samples, and interpreted
it as evidence of impact contamination of the Isua crust. However, the CI (and also the iron
meteoritic) $^{182}\text{W}/^{183}\text{W}$ value is only a few times $10^{-4}$ smaller than the crustal Earth; $\epsilon_{\text{W}} =
[(^{182}\text{W}/^{183}\text{W})_{\text{met}} - (^{182}\text{W}/^{183}\text{W})_{\oplus}] / (^{182}\text{W}/^{183}\text{W})_{\oplus}$ is $-2.1\times10^{-4}$ for the Allende meteorite, and
is $-3.7\times10^{-4}$ for iron meteorites (and zero for the Earth’s present-day crust, $^{182}\text{W}/^{183}\text{W})_{\oplus}$).
This means that the contamination with cosmic material has to be very large before it will
be measurable in terrestrial samples. The $^{182}\text{W}/^{183}\text{W}$ values reported by Schoenberg et al.
(2002) correspond to a mixture of approximately 50% of the measured tungsten coming from
Allende-like meteoritic material and 50% from terrestrial standard crust (and 1:3 if the cosmic
material was iron meteorites).

While the negative $\epsilon_{\text{W}}$ values do point at identified extraterrestrial contamination of the
measured material, it is not straightforward to use as a quantitative measure of the LHB contamination, for the following reasons: Bulk cosmic material (asteroids or comets) is always associated with a strong enrichment of iridium (because iridium is so strongly siderophile that from a cosmic perspective the Earth’s crust has basically zero iridium abundance). If the tungsten mixing rate of the extraterrestrial and the Isua material is representative for the CI to Isua material mixing ratio, then the mixed material would end up with an iridium abundance approximately half that of CI, or well above 200,000 ppt, which is more than 1000 times above measured values at Isua (see below). Since the measured iridium abundance relates directly to the total amount of LHB impacts, such high Ir abundance would also mean that the LHB bombardment on Earth should have been ∼1000 times stronger than on the Moon, which has no bearings in dynamics. The meteoritic tungsten would therefore have to mix extremely selectively with the proto crust in order to in general reach the high mixing values reported. While this is not impossible, it would leave us with little possibility to quantify the impact rate or verify that the measured $\epsilon_W$ actually represented a general LHB inflow.

Also the chromium isotopic pattern is valuable in identifying extraterrestrial matter. Different types of meteorites have distinctly different chromium isotopic patterns, notably the $^{53}\text{Cr}/^{52}\text{Cr}$ ratio which is caused by the decay of $^{53}\text{Mn}$ which has a half-life of only 3 Myr. This fact was used by Shukolyukov & Lugmair (1998) to show that the K/T impactor was likely to be of CI-type material (i.e. a carbonaceous chondrite or a comet). However, just as for the $^{182}\text{W}/^{183}\text{W}$ ratio, also the $^{53}\text{Cr}/^{52}\text{Cr}$ ratio in meteorites is only a few sigma different from the terrestrial standard. In order to identify extraterrestrial contamination in terrestrial material, it is therefore necessary that the amount of extraterrestrial and terrestrial material in the mixture are of the same order of magnitude (or at least that the amount of extraterrestrial chromium in the sample is a large fraction of the total amount of chromium). This is certainly the case in the K/T dust layer, where $\epsilon_{\text{Cr}}$ is almost identical to the carbonaceous chondritic value ($\epsilon_{\text{Cr}} \approx -0.410^{-4}$), and where the chromium abundance itself is close to the chondritic value (in particular in the K/T dust in Caravaca in Spain where the Cr abundance is only a factor 2 to 3 below the value in Orgueil and Allende carbonaceous chondrites). Frei & Rosing (2005) searched for extraterrestrial $^{53}\text{Cr}/^{52}\text{Cr}$ anomalies in Isua sediments by use of high precision chromium abundance analysis, but found no deviation from the terrestrial standard. This result is only contradicting the corresponding $^{182}\text{W}/^{183}\text{W}$ results reported in Schoenberg et al. (2002) in the sense that one study found meteoritic contribution to some of the samples studied, and the other didn’t. With respect to analysing the possible LHB contribution to the Isua proto-crust, both methods are not very sensitive to the contamination, and difficult to quantify in terms of how much cosmic material might have impacted the area.

Schoenberg et al. (2002) suggested that some kind of weathering processes could have been responsible for the up-concentration of tungsten. If a similar process didn’t affect the chromium
abundances, the two studies could in principle be in agreement with one another. We, however, conclude that the uncertainties and the low sensitivity in the terrestrial material to cosmic contamination associated with both methods, make them infeasible to quantify the possible LHB contribution to the Earth’s Hadean-Eoarchean crust.

In contrast to the tungsten and chromium systems, the abundance of iridium in the terrestrial crust and in meteorites are widely different from one another. CI-type meteoritic material, for example, is approximately 20,000 times richer in iridium than the Earth’s upper crust, and even very small contaminations of cosmic material to terrestrial rocks, will therefore be identifiable. Hence, we focused specifically on analysis of iridium in this first study of our samples, and in the analysis of the results we focused in particular on finding a unified explanation of the iridium abundances in the Isua and lunar surfaces (because the same cosmic LHB has affected the Moon and the Earth, but given rise to widely different iridium abundances), and on relating this to the amount of impacting material that can be inferred from the lunar crater counting (because the scaled lunar impact rate must have been accompanied by the corresponding amount of iridium that the impacting bodies contained).

**Our Isua rock samples.**

The Isua greenstone belt comprises the oldest known major pieces of Earth’s supracrustal rocks, with an age of $\approx 3.8 \text{ Gyr}$ (Nutman et al. 1996, Jenner et al. 2008). The greenstone belt consists of extensive basaltic pillow lava flows with intercalated beds of iron-formation, felsic volcanogenic rocks, pelitic mica schists and a conglomerate. Intruded into these rocks are mafic and ultramafic sills and dykes. The whole belt has been repeatedly metamorphosed under amphibolite facies conditions and suffered several phases of deformation. The belt has furthermore been intruded by extensive tonalite sheets. In spite of intense deformation, low strain domains are frequently seen (Appel et al. 1998). In these domains primary sedimentary and volcanic structures are often seen, such as conglomerate, well preserved pillows with ocelli, pillow breccias and debris flows. The samples for this study were collected from banded iron formation, mafic mica schists and from turbidite.

Cosmic impacts completely re-shaped the lunar surface during the short LHB period, but the contemporary Isua region has revealed no impact structures at all. The fact that the Isua sediments represent the oldest known sedimentary crust, may indicate that it and its surrounding proto-crust can have been a special place on Earth, relatively quiet and remote from major impact craters during the end of the LHB, but Isua may also be a completely representative and ”normal” piece of crust, that just happened to be the only place not completely re-molten by geodynamical processes during the subsequent evolution of the Earth until the present day. The fact that no craters and shock material have been identified may lend support to the idea that the Isua proto-crust was particularly far from major LHB impact craters, at least in the
final LHB period. Whatever the reason is for the lack of impact structures and shocked material at Isua, such structures and material would not be the focus for understanding the LHB impact on Earth, because they would contain information about specific events, and not the sought statistical information about the bulk LHB impacting on the Earth in general. Instead, rock types that represent erosion from larger areas of surrounding land surface, and subsequent sedimentation, will contain the bulk mixture of original crust and atmospheric fall-out of LHB impacted material from the time prior to and during the sedimentation, which is precisely what one would be most interested in selecting when trying to understand the influence of the LHB on the early Earth. By sampling sediments potentially ”contaminated” by atmospheric fall-out and erosional material of the land-masses in the hinterlands of the Isua basin (which likely acted as sediment feeders through weathering and subsequent transport of dissolved and particulate matter by rivers (river loads)), we therefore do not sample a local phenomenon, but are likely to catch the global effect of the last part of the LHB on Earth. The sediments of the Isua greenstone belt are therefore the most likely reservoirs on the Earth to potentially reveal representative traces of elements that were once part of the LHB impactors.

Chemical sediments that precipitated from the water (i.e. part of the BIFs), on the other hand, are not affected by dentrital material transported as river loads. If the late heavy bombardment had still not quite finished while the Isua sediments were deposited, large impacts will still have brought a mixture of crust and impactor material into the stratosphere in the form of dust that later will have rained out of the atmosphere. Dust from this fall-out will mechanically have mixed with any sediments in open waters, including material from chemically precipitated sediments. If sediments from both river load erosion and chemical precipitation include traces of cosmic material, it will therefore be an indication that the LHB was still in its final phases on the Earth 3.8 Ga ago, in agreement with what we should expect from scaling of the Apollo dating of lunar impact melts to the conditions on Earth.

We have therefore sampled three different types of metasedimentary rocks: (1) shallow water pelagic sediments (garnet-bearing mica-schists) with detrital input from both mafic volcanic and intrusive rocks (Bolhar et al. 2004), (2) clastic sediments (turbidites) deposited in deep water (Rosing 1999), and (3) detritus-free oxide-facies banded iron stones (BIF) characterised by alternating magnetite-rich and silica-rich microbands (Polat & Frei 2005; Frei & Polat 2007) Age determinations of the region constrain the deposition of the sediments to \( \sim 3.8 \) Ga ago (Nutman et al. 1996). The sediments are composed of eroded material derived from the contemporaneous surrounding land surface as well as possible atmospheric fall-out.

Trace element systematics of Isua greenstone belt metasediments show strong resemblance to other well-documented Archean clastic sediments, and are consistent with a provenance consisting of ultramafic, mafic and felsic igneous rocks (Bolhar et al. 2005). Major element systematics document incipient-to-moderate source weathering in the majority of metasedi-
ments, while signs of secondary K-addition are rare. Detailed inspection of \( \text{Eu}/\text{Eu}^* \), \( \text{Fe}_2\text{O}_3 \) and CIW (chemical index of weathering) relationships revealed that elevated iron contents (when compared to average continental crust) and strong relative enrichment in Eu may be due to precipitation of marine Fe-oxyhydroxides during deposition of diagenesis on the sea-floor (Bolhar et al. 2005).

The voluminous mafic volcanic rocks are composed primarily of pillow basalts intercalated with ultramafic units. Banded iron formation, cherts, conglomerates and siliciclastic turbidites are intercalated. The geochemical characteristics and features represent a coherent mafic to ultramafic suite, comparable to those of Phanerozoic boninites (Polat et al. 2002). Given the observation that in the Tertiary, boninites are exclusively associated with intra-oceanic subduction environments (e.g. Izu-Bonin-Mariana subduction system), this suggest that the Isua metabasalts were formed in intra-oceanic subduction zone-like geodynamic processes (Polat et al. 2002), although there is still an ongoing debate as to the existence of subduction zones this early in the Earth’s history (Glikson 2004).

Geochemical, lithological, and structural data from the Isua greenstone belt are all collectively consistent with a convergent margin geodynamic setting. The Isua BIFs are spatially and temporally associated with boninitic and island arc picritic pillow basalts. Given the observations that Cenozoic boninites and picrites tend to form in an intra-oceanic arc-forearc setting, Polat & Frei (2005) suggested that the Isua BIF-boninite and BIF-picrite associations were also deposited in a similar geodynamic setting. The high-temperature hydrothermal alteration of the oceanic crust produced significant hydrothermal discharge with large quantities of Fe necessary to contribute to the deposition of the Isua BIFs. The hydrothermal alteration may have resulted from the opening of an asthenospheric window developed as a consequence of ridge subduction beneath an early Archean arc-forearc region (Polat & Frei, 2005). The ridge subduction model can also explain the origin of the contemporaneous tonalite-trondhjemite-granodiorite (TTG) intrusions in the Isua region. Partial melting of laterally accreted and thickened oceanic crust under amphibolite to eclogite metamorphic conditions by upwelling of asthenospheric windows may have produced TTG melts.

**The iridium abundance analyses.**

In Table 1 we report our results of high-precision iridium abundance measurements in 37 individual samples, grouped according to rock type. Mica-schists and turbidite samples were crushed in an agate mortar from whole rocks chips. BIF samples from quartz- and magnetite-rich mesobands were separately crushed and analysed. When possible, we divided our samples into two or more sub-samples, which were then measured separately in order to trace possible larger inhomogeneities in the sample. The iridium abundance in the sub-samples were typically within a factor of two from one another. One of the turbidity current samples, however,
Table 1: Measured iridium concentration in ppt in three types of sediments from the Isua greenstone belt, Western Greenland. A '(2)' after the sample-name means that two separate sub-samples were measured individually, and the average is reported here.
seemingly had a nugget resulting in an extremely high iridium concentration of 13700 ppt in one of the sub-samples, and the reported value is an average (6850 ppt) of this and a successive measurement of the other sub-sample of this same sample. The listed average of the turbidites is calculated without including the nugget value. Regrettably, we obviously know nothing more about this assumed nugget, since nothing particular was noticed during the mortaring of this particular sample. Also listed is the weighed average (by weight) of the individual samples.

Mortared samples were irradiated at the JAEA’s research reactor, JRR-3, without prior chemical separation. Gamma-gamma coincidence spectroscopy (Oshima et al. 2002, Hatsukawa et al. 2002, Toh et al. 2001, Oshima et al. 2008), of multiple γ-rays from the radio-isotopes produced by the neutron capture reactions, were then performed with an array of twelve Ge detectors equipped with BGO Compton suppressors GEMINI-II (Oshima et al. 2008). Each sample was typically of 50–100 mg, and were measured for about 24 hours after 4 weeks of radiation. This method has previously been demonstrated to be capable of measuring iridium concentrations as low as a few ppt with a relative accuracy of a few percents (Oshima et al. 2002, Hatsukawa et al. 2002, Toh et al. 2001, Oshima et al. 2008, Hatsukawa et al. 2003, Hatsukawa et al. 2007).

It is seen that the mica-schists and turbidites consistently have a bit higher Ir enrichment than the BIFs, and we take their value as representative for the surrounding solid crust prior to the erosion and following deposition of the sediments. Magnetite-rich BIF samples are more difficult to measure than the silica-rich BIF, because they give rise to a higher Ir-detection limit. We envision that the BIF has formed as chemical precipitate in the ocean with addition of a cosmic fall out (analogue to the K/T-fall out) during the period of sedimentation. We therefore conclude from Table 1 that the pre-existing Hadean-Eoarchean crust just prior to the depositional period that led to the sedimentations we now see at Isua, had an iridium abundance close to the value of the mica-schists and turbidites, and that there still was an atmospheric cosmic fall out in the ocean at the time of BIF sedimentation – all in qualitative agreement with our expectations from a declining LHB and its lunar records prior to the formation of the Isua sediments. We therefore conclude from Table 1 that a rough round number for the cosmic iridium contribution seen in the sediments is 150±25 ppt.

The source of the iridium in the sediments.

In order to test to which extent the iridium concentrations in the metasediments of the IGB are controlled by detrital (i.e., particle-controlled) components, we need to distinguish between chemical sediments (BIF microbands) and clastic sediments (mica-schists, turbidites). Based on chemical (major and trace element) and isotope geochemical (Pb isotope) characterisation of ancient clastic and chemical sediments from the IGB (and TTG intrusions emplaced within the IGB) Kamber et al. (2005) and Bolhar et al. (2005) concluded that the Isua protocrust
probably had a mafic character and showed a slightly enriched signature which these authors attributed to an earlier (i.e., pre-3.8 Ga) differentiation-recycling event. In the view of this scenario, and based on the exposure itself of mafic volcanic rocks (i.e., boninitic and picritic basalts; Polat et al., 2002; Polat et al., 2003) within the IGB, we discuss the measured Ir concentration in the samples presented herein as follows:

Chemical sediments (BIFs)

BIFs from within the IGB are characterised by low detrital components as shown by Frei & Polat (2007). These authors used scandium concentrations to monitor the lithogenic element concentrations in IGB BIFs. Similar to other such studies which used Sc concentrations of <20 ppm to reflect very low detrital components in BIFs (e.g., Alexander et al., 2008), Frei & Polat (2007) argued that Sc concentrations smaller that 1 ppm in the Isua BIFs indicate very pure chemically precipitated sediments, which they support by REE patterns which resemble present-day seawater. These values are in agreement with very low Al₂O₃ contents of <0.5 wt% (our unpublished data). On the basis of these investigations, the Ir concentrations in silica-rich BIF mesobands given in Table 1, are interpreted to reflect an extraterrestrial contribution to the sediment. It is difficult to assess in which form this Ir may have co-sedimented, i.e., whether Ir is hosted by minor particles or precipitated from an initially dissolved form. The very low Al₂O₃ and MgO concentrations (both <0.5 wt%; our own unpublished data) in these BIFs argue against a small mafic particulate component (either eroded from the continental hinterland or direct fall-out from the atmosphere) that could have co-sedimented with the silica-rich bands. Even if we assumed that as much as 0.5wt% MgO derived from basaltic precursors (such as boninites and picrite typical of the IGB) with Ir concentrations comparable to Archean komatiites, mafic komatiites and basalts (MgO from 5-20 wt%) with up to 1 ppb Ir (Hong et al., 2006; Puchtel and Humayun, 2000; Maier et al., 2003; and others), then the Ir concentrations in such mesobands should not exceed ~25 ppt. We therefore interpret the elevated Ir concentrations in these BIF mesobands to derive from extraterrestrial sources (mainly as atmospheric fall-out) with high Ir concentrations. The iron-rich mesobands of the BIFs studied herein, despite the elevated analytical detection limits for Ir, are characterised by Ir concentrations that are similar or lower than the respective concentrations in the silica-rich mesobands (cf. Table 1). Since these mesobands are demonstrably dominated by hydrothermal (vent-derived) input (high Eu anomalies; Frei & Polat, 2007) with presumably very low dissolved PGE, the average limit of detection around 80 ppt is regarded as a maximum for the Ir levels in these horizons, which compares well with the ~100 ppt average of the silica-rich mesobands, and consequently interpreted by us to indicate admixture of the same extraterrestrial component into the chemical sediment.
Clastic metasediments

Similar calculations for the interpretation of Ir levels measured in the clastic metasediments from the IGB may indicate a smaller mafic proto-crustal addition to the source of PGE in these lithologies. Bolhar et al. (2005) showed that trace element systematics of IGB metasediments strongly resemble other well-documented Archean clastic sediments, and trace elemental signatures are consistent with a provenance from mixed ultramafic, mafic and felsic igneous rocks. In particular, based on Ti/Zr vs. Ni concentration diagrams, these authors propose that IGB metasediments are broadly consistent with approximately equal proportions of average basalt and boninite admixed to average felsic volcanogenic sediment and TTG. Minor additional mixing of a komatiite-derived clastic components with Ir concentrations as high as 1.0−1.5 ppb Ir (Puchtel & Humayun, 2000; Anbar et al., 2001; Maier et al., 2003) cannot be excluded without future additional extensive studies of isotopic (in particular osmium) and elemental abundances. However, the most important observation at this place from the results presented in Table 1, is: (1) the remarkable similarity in the iridium abundance in the three completely different types of sediments, (2) the rough average of a factor seven iridium excess compared to present day ocean crust and upper continental crust, and (3) that none of the sediment types have an iridium excess much higher than the rough average of 150 ppt. The last point is very important, as will become clear from the following discussion, because an asteroidal dominated LHB would have resulted in considerably higher iridium excesses in the Isua sediments, so even if smaller amounts of iridium-rich komatiite-like clastic components would have mixed into the measured clastic metasediments, this could admittedly add a complication in the understanding and quantifying of the derived average iridium excess, but it would not change the conclusion about a cometary dominated LHB impact.

Iridium and the Earth-Moon formation.

A standard theory for the formation of the Earth-Moon system (Martin et al. 2006), is that most of the Earth accreted rapidly from 4.57 Ga to 4.5 Ga ago. Near the end of this period the core and the mantle had separated, when a Mars-sized object collided with the proto-Earth, and resulted in the Moon forming from expelled mantle material (Jacobsen 2005, Martin et al. 2006). At this time the upper Earth and the Moon obviously had an identical abundance of iridium (and all other refractive elements). The Moon never totally differentiated, but the upper ∼100 km melted and homogenised to form the present feroan anorthosite surface. The oldest Moon dust is 4.42 Ga (Snyder et al. 2000, Ryder 2002), and the outermost lunar crust must therefore have been solid since that time. Almost all the craters we see on the Moon today were, however, formed during the narrow LHB period from ≈3.9 Ga to 3.8 Ga ago. The iridium abundance in the present lunar surface is therefore coming from material of composition close to the Earth’s early mantle (i.e., very low in Ir) mixed with cosmic impacts from the LHB.
period (plus possible impacts from the period from 4.42 to 3.9 Ga ago). Likewise the Earth’s proto-Isua crust is a mixture of this same first Earth-mantle material and material from the same kind of impactors that formed the lunar craters. The lunar anorthosite has < 10 ppt Ir (Lodders & Fegley 1998, Wedepohl 1969) (while unprocessed meteoritic material such as Allende have 465,000 ppt, and the Earth’s present-day upper crust and ocean crust have 20 ppt). The fact that we find that the Isua proto-crust had an Ir abundance higher (15 times or more) than the lunar anorthosite, shows that the cosmic impactors that hit both the Earth and the Moon during the LHB, were of such a character that they deposited their Ir on the Earth but essentially not on the Moon. This might at first seem intuitively impossible, but in fact it instead contains crucial information about the impactors and, in particular, their velocity. Our numerical models, described below, show that the measured difference in Ir deposition would occur if the impactors were comets, but not if they were asteroids (“meteorites”). The basic theory and assumptions are similar to what has been adopted by others (e.g. Chyba 1991, and Melosh & Vickery 1989), but here applied to estimate the expected abundance of iridium.

**Asteroid versus comet crater formation and crustal enrichment.**

The total mass that impacted the Moon during the period in which today’s visible craters were formed, can be calculated by transforming the observed crater sizes to impact mass. The transformation depends on several parameters, noticeably the energy per impacting mass unit, which is proportional to the impacting velocity squared, $v_i^2 = v_{\infty}^2 + v_{esc}^2$, where $v_{\infty}$ is the impactor velocity far away from the Earth-Moon, and $v_{esc}$ is the escape velocity (from Earth or Moon). Since $v_{\infty}$ is higher for comets than for asteroid impactors, the total impact mass necessary to form the lunar craters, is somewhat smaller if they were comets than if they were asteroids, but typical values reached in the literature are around $10^{20}$ kg (Martin et al. 2006, Chyba 1991, Hartmann et al. 2000).

The impacting mass on the Moon can be scaled to corresponding impacting mass on the Earth. The effective gravitational area, $A_{eff}$, that an approaching impactor will see, is related to the geometrical area, $A_{geom} = \pi r^2$, by

$$A_{eff} = A_{geom}(1 + 2\theta)$$

(1)

where the proportionality factor, or gravitational enhancement factor, $(1 + 2\theta)$, is given by the Safronov number

$$\theta = \frac{Gm}{rv_{\infty}^2} = \frac{E_{pot}}{2E_{kin}} = \frac{1}{2} \left( \frac{v_{esc}}{v_{\infty}} \right)^2$$

(2)

While the escape velocity, $v_{esc}$, the target mass, $m$, and the geometrical radius, $r$, (of Earth and Moon) are known, it is not obvious what $v_{\infty}$ was, and it depends on the assumption of the nature of the impactors. Comets will, as a group, have more elliptical orbits, and cross the Earth’s orbit with higher velocities than asteroids. By assuming that typical asteroids had
∞ ≈ 12 km/s (as present-day Earth-crossing asteroids) and typical comets had \( v_\infty \approx 20 \) km/s (as present-day short-period comets), we can express the ratio of impacting mass per m\(^2\) on the Earth and the Moon, \( m_\oplus/m_\text{moon} \), as

\[
m_\oplus/m_\text{moon} = \left( \frac{A_\text{eff}}{A_\text{eff}_\text{moon}} \right) \left( \frac{r_\text{moon}}{r_\oplus} \right)^2
= \left( \frac{v_i^\oplus}{v_i^\text{moon}} \right)^2
= 1.8 \text{ for asteroids and 1.3 for comets}
\]

We see that with the appropriate data for Earth and Moon used in Eq. 2 and 3, and the velocity estimates given above, we can scale the lunar cratering rate to Earth impacts, and conclude that 1.8 times more mass must have hit the Earth than the Moon per m\(^2\) surface if the impactors were asteroids, and 1.3 times more if the impactors were comets.

The corresponding ratio, \( f_\oplus/f_\text{moon} \), of impacting energy per m\(^2\) of the Earth \( (f_\oplus) \) and the Moon \( (f_\text{moon}) \) is,

\[
f_\oplus/f_\text{moon} = \frac{m_\oplus}{m_\text{moon}} \left( \frac{v_i^\oplus}{v_i^\text{moon}} \right)^2
= \left( \frac{v_i^\oplus}{v_i^\text{moon}} \right)^4
= 3.2 \text{ for asteroids and 1.7 for comets}
\]

As a side remark we see that the ratio of total impacting mass hitting the Earth and Moon is

\[
\left( \frac{m_\oplus}{m_\text{moon}} \right) \left( \frac{r_\oplus}{r_\text{moon}} \right)^2 \approx 24 \text{ for asteroids and 18 for comets}
\]

(since \((r_\oplus/r_\text{moon})^2 = 13.5\)).

In reality, \((m_\oplus/m_\text{moon})\) may well have been \( \approx \) a factor two larger than given by Eq.3 because the calculations leading to Eq.3 only includes the effect of impactors of the same size hitting the Earth and Moon, while considerations about small number statistics of the very largest impactors, show that the larger probability of a body hitting the Earth, implies that the few very largest impactors (larger than the one that formed Mare Imbrium on the Moon) will most likely have hit the Earth and added considerably to the ratios in Eq.3.

The enrichment the impacting material will create in the crust depends not only on the total impacting mass and its composition, but also on the ratio between mixed and re-emitted material during the impact. It happens that this ratio is very different for Earth and Moon, and different if the impactors were comets or asteroids. This is basically because the LHB impactor velocities were comparable to the escape velocity of Earth, but much larger than the
escape velocity from the Moon. This is a situation very different from that of the accreting proto-planets, where the relative velocities of the accreting and accreted material were small. The quantification of the different ratios between accreted and re-emitted material contain important clues to understanding what type of impactors were causing the LHB. The ratio of escaping to mixing material scales with the number of impactors that form plumes of high speed material (i.e. with $v > v_{esc}$), relative to those that don’t, which is a function of impactor composition, impactor velocity distribution ($v_\infty$), and target escape velocity ($v_{esc}$).

In order to create a vapour plume that expands with more than the escape velocity, obviously the impacting energy must exceed the energy required to evaporate the impactor (and other material to be included in the plume) plus accelerate this mass of material to above the escape velocity. By assuming that such a plume-creating impact will evaporate and carry away the impactor itself plus an identical amount of target mass, and that the downward absorbed energy is identical to the upward released energy in the gas expansion (Melosh 1989, Melosh & Vickey 1989), we can express the minimum impact velocity, $v_{min}$, required from

$$\frac{1}{2} \left( \frac{1}{2} m v_{min}^2 \right) = 2 \left( \frac{1}{2} m v_{esc}^2 \right) + 2 m H_{vap} \Leftrightarrow$$

$$v_{min}^2 = 4 \left( v_{esc}^2 + 2 H_{vap} \right)$$

where $H_{vap}$ is the vaporisation energy (the enthalpy of vaporisation), which, expressed in MJ/kg ($=\text{km}^2/\text{s}^2$), is

$$H_{vap} = 13\text{MJ/kg for silicates} \quad H_{vap} = 3\text{MJ/kg for ice}$$

which with $v_{esc}^{\text{moon}}=2.4 \text{ km/s}$, and $v_{esc}^{\oplus}=11.2 \text{ km/s}$ gives

$$v_{min}^{\text{moon}} = 11 \text{ km/s for asteroids, and 7 km/s for comets}$$

$$v_{min}^{\oplus} = 25 \text{ km/s for asteroids, and 23 km/s for comets}$$

With the velocity distributions from Earth crossing asteroids and Earth-crossing short-period comets, one concludes from Eq.8 that on the Moon approximately 50% of asteroids and 100% of comets will create Moon-escaping plumes, while the corresponding numbers for the Earth are 10% and 50%. On the Moon the plumes will result in that all the plume mass is lost, while on Earth this is only the case if the plume mass (with velocity above $v_{esc}$) is larger than the mass of the "hat" of atmosphere above and tangentially to the side of the impact (which is then also lost into space).

Apart from the mass that is lost with the plume, also direct ejecta from the impact crater can be lost. Chyba (1991) found that the mass of the crater material, $M_{ejc}(v > v_{esc})$, ejected with velocity $v$ above $v_{esc}$ expressed as function of density $\rho$ and mass $m$ of the impactor, and density $\rho_t$ of the target, can be expressed as

$$M_{ejc}(v > v_{esc}) = 0.11 \left( \frac{\rho}{\rho_t} \right)^{0.2} \left( \frac{v}{v_{esc}} \right)^{1.2} m$$
Introducing for the Moon \((\rho_t = 2.9 \text{ g/cm}^3)\) \(v_{med} = 12 \text{ km/s}\) and \(\rho = 2.2 \text{ g/cm}^3\) for collisions with asteroids and \(v_{med} = 20 \text{ km/s}\) and \(\rho = 1.0 \text{ g/cm}^3\) for comets, we find the mass of material ejected with velocity larger than \(v_{esc} (= 2.4 \text{ km/s})\) to be \(M_{ejc}(v > v_{esc}) = 0.7m\) for asteroids and 1.1m for comets. I.e., for asteroids 70% the impact mass is escaping the Moon in the form of directly ejected lunar surface rocks, and for typical comets the same amount (i.e., \(\approx 1.1m\)) of crater material escapes the Moon as the mass of the impacting comet.

An “average” asteroid of mass \(m\) colliding with the Moon, will therefore (according to the above formulas and numbers introduced) cause the Moon to accrete half of the asteroid mass, lose the other half in a plume, lose additional 0.5m worth of lunar material in the plume, plus loosing 0.7m of lunar material in crater ejecta material. Net, we therefore see that the Moon will become 0.7m lighter for each heavy bombardment asteroid impact of mass \(m\).

An “average” comet of mass \(m\) colliding with the Moon, will cause the Moon to lose all the comet mass in a plume, lose additional 1m worth of lunar material in the plume, plus loosing 1.1m of lunar material in crater ejecta material. Net, we therefore see that the Moon will become 2.1m lighter for each heavy bombardment cometary impact of mass \(m\).

While we see from the above that a typical comet will leave no traces apart from the crater (because all the cometary material escapes the Moon in the plume), the crust will change composition if the impacts were asteroids, because net the Moon will accrete 0.5m of (chondritic) meteoritic material (100% enriched in chondritic material), while it will lose 1.2m lunar material enriched with (today) 2% chondritic material, so net gaining at least 0.5m-0.02×1.2m=0.48m≈0.5m chondritic material per \(m\) chondritic impact. The net loss of material is therefore in agreement with an increase of chondritic material in the crust during the late heavy bombardment with asteroids.

The corresponding numbers for the Earth give that 10% of asteroids and 50% of comets will create a plume, implying that on average 0.2m will leave the Earth in plumes per asteroid impacts of mass \(m\), and 1m crater and comet material will on average be ejected when a 1m comet impact the Earth. An ”average” speed asteroid (i.e., \(v = v_{med} = 15 \text{ km/s}\)) of mass \(m\) will accelerate 0.14m crater material to velocities above the Earth’s escape velocity, while a corresponding comet (i.e., \(v = v_{med} = 23 \text{ km/s}\)) will eject 0.20m crater material. On average therefore \(m\) mass asteroids will leave 0.9m chondritic material on Earth and eject 0.1m asteroid plus 0.25m Earth mantle material, thereby making the Earth 0.55m heavier. A cometary impact of mass \(m\) will inject 0.5m cometary material into the Earth’s crust, return 0.5m comet to space together with 0.7m terrestrial material, thereby making the Earth 0.2m lighter.

As opposed to the Moon, the Earth is likely to accrete some of the ejected material again later in a new collision, possible at lower encounter velocity, while the ejected material from the Moon has a higher probability to be accreted by the Earth than by the Moon after entering an Earth crossing heliocentric orbit.
In summary, we find that on the Moon only half of the impacting asteroids, but almost all of the comets, will form high-velocity plumes. On Earth the corresponding numbers are 10% for asteroids and 50% for comets (taking into account also that on Earth the plume energy has to be large enough to blow away the atmosphere above it before it can disappear into space).

For typical comets, the above numbers therefore show that 50% of their impact mass would mix with the terrestrial crust (and 50% being lost in plume ejection), while on the Moon all of a comet would be lost into space in plume ejection. Therefore an impacting comet will leave Ir on Earth but not on the Moon. In contrast, we have seen that typical asteroids hitting the Earth and the Moon will leave respectively 90% and 50% of their mass mixed with the crust. Therefore asteroids will leave Ir on Earth as well as on the Moon.

The final iridium abundance of course also depends on how long time this impacting took place on solid crust, and how stiff the crust was relative to the impacting energy, as function of time. If the Moon and Earth were identical bodies in this respect, an impacting asteroid (of a certain impact energy) would leave $9/5 = 1.8$ times more Ir on the Earth than on the Moon. Several factors contribute to lowering this number (lower volume to surface ratio and smaller impact energy contribute to a faster cooling and solidification of the lunar crust, and higher escape velocity on Earth contributes to deeper mixing of impactors in otherwise identical crusts). In spite of this, we do not find a smaller Ir abundance, or even a comparable Ir abundance, but rather a substantially higher (a factor 15 or more) Ir abundance in our Isua samples than what is known from the lunar anorthosite. We therefore conclude that the impactors cannot have been asteroids.

Comets, on the other hand, are in qualitative agreement with finding almost no Ir in the lunar anorthosite (because of 100% plume escape), and at the same time enhanced Ir in the Isua samples. We have therefore shown above that the relative lunar and Isua iridium abundances are in qualitative agreement with a cometary LHB, but not with an asteroid LHB. We will now argue that the amount of Ir we list in Table 1, within reasonable basic assumptions, not only is in qualitative, but also in quantitative, agreement with the expectations from cometary dominated LHB impacts.

**The LHB iridium deposition on Earth.**

In order to quantify the effect of the LHB impacts, we first need to quantify what is meant by the LHB, which has come to have a rather diffuse meaning in the literature. Strictly speaking, the transformation from lunar crater counts to impact mass only gives us a lower limit for the total mass of the LHB impactors. The lunar surface is saturated with craters, and the age of the oldest measured impact melts therefore gives us the age at which the impacting energy density for the last time dropped below the saturation point. Any impact melted rock older than this age will per definition have been hit by a new impact later, thereby being re-melted.
and having its melting age reset. The peak of the LHB is defined as this saturation age. The fact that the energy density of impacts could have been even larger before the LHB peak, is the root of the well known discussion of whether there at all were a late heavy bombardment (or we just see the post-saturation declining part of a much stronger impact flux that possibly was the tail of the accretion that formed the planets and moons). The reasons for believing that there was an LHB include: (1) that the $\approx 10^{13}$ comets estimated to now be in the Oort-cloud must have been perturbed in random directions from their formation place in the plane between Jupiter and Neptune some time after the formation of the solar system (and some of these must necessarily have hit the inner planets and moons in some kind of time-limited bombardment at that time), (2) that it is theoretically difficult to envision that the planetary accretion process could have taken as long as 700 million years until the end of the LHB, and (3) that the impacts that created the basins on the Moon may have been as abundant as $\sim 1$ per 10 Myr around the LHB peak, but then abruptly ended $\sim 3.8$ Gyr ago.

The amount of iridium one would expect to have mixed into the proto-Isua crust as a result of the LHB, obviously depends on the assumption that there actually was a LHB, and it also depends on how long time such a bombardment took place with the capacity to mix material into the surface rocks. While the first assumption (that there was a LHB) is very likely to be correct (among other things for the 3 reasons given above), the latter is unknown and not likely to be answerable, at least in the foreseeable future. We will assume that the cosmic material which mixed into the original crust material, both on the Moon and on the proto-Isua crust, came from the LHB peak and onward in time. While this assumption affects the quantification of the expected iridium abundance at Isua, it does not affect the question of whether the impactors were comets or asteroids.

The Apollo dating of the lunar impact melts has been fitted in the literature with an exponentially decaying impact rate,

$$N(t) = N(t_0)e^{-\frac{t-t_0}{\tau}} = N(t_0)e^{-\frac{\ln(2)(t-t_0)}{\tau}} $$

(10)

with a half life, $\tau_{1/2}$, between 30 and 100 Ma (Chyba 1991). In Eq. (10) $t$ and $t_0$ could in principle be any two times during the LHB, but we will conveniently think of a normalisation such that $t_0$ is the time of the LHB peak (and hence $N(t_0)$ the number density of impacts at the LHB peak) and $t$ any time later than $t_0$. The LHB peak (in the way it was defined above) occurred somewhat later on the Earth than on the Moon (but the decay rate, $\tau$ or $\tau_{1/2}$, will have been the same). This is because the energy per mass unit impactor per m$^2$ is higher on Earth than on the Moon, and the craters are explosion features, such that their diameters scale roughly with the 3$^{rd}$ root of the impacting kinetic energy density, $f$ in Eq. (4) (not the mass density $m$ in Eq. (3)), such that the saturation point will have occurred on the Earth (i.e. the terrestrial LHB peak) only when the terrestrial impacting flux, $f^\oplus(t)$, had fallen to the value $f^{moon}(t_0)$ it
had at the Moon during the lunar LHB peak. As the kinetic energy depends on whether the impactors were asteroids or comets, the time of the terrestrial LHB peak also depends on the nature of the impactors, and has to be evaluated independently in the two cases. If large areas of terrestrial crust from the time of the LHB still existed, the time of the terrestrial LHB peak could have been defined empirically from crater counts and crater dating, just as it is done for the Moon. It is because such pieces of the terrestrial crust do not exist, that we are forced to scale the lunar LHB peak instead, and introduce the associated additional challenges.

The impacting mass flux as function of time can be calculated from Eq.10 and the kinetic energy flux ratio on the Earth and Moon at any given time can be computed from Eq.4. We can therefore find the delay, \( \Delta t = \frac{(t - t_0)}{\tau_{1/2}} \), in the terrestrial LHB peak compared to the lunar LHB peak, by expressing the demand of \( f_\oplus(t) = f_{\text{moon}}(t_0) \) from these two equations, such that

\[
\frac{N(t)}{N(t_0)} = \left( \frac{v_i^{\text{moon}}(t_0)}{v_i^{\oplus}(t)} \right)^4 = \left( \frac{v_i^{\text{moon}}(t)}{v_i^{\oplus}(t)} \right)^4 \Leftrightarrow e^{-\ln 2(t-t_0)/\tau_{1/2}} = \left( \frac{v_\infty^2 + (v_{\text{esc}}^{\oplus})^2}{v_\infty^2 + (v_{\text{esc}}^{\text{moon}})^2} \right)^2 \Leftrightarrow \frac{(t - t_0)}{\tau_{1/2}} = \ln \left( \frac{v_i^{\oplus}/v_i^{\text{moon}}}{\ln 2} \right)^4 = 1.7 \text{ for asteroids and 0.75 for comets}
\]

If the lunar LHB peak (\( t_0 \) in Eq.11 usually just referred to as the LHB peak) was at \( t_0 = 3.9 \) Ga and the half life was 100 Ma, then the terrestrial LHB peak was at 3.825 Ga for a cometary LHB and at 3.73 Ga for an asteroidal LHB. It would then be very surprising that we find no impact structures and shocked material at Isua (in particular if the impactors were asteroids). If the lunar LHB peak was at 3.95 Ga and the half life 30 Ma, then the terrestrial LHB peak was at 3.93 Ga for a cometary LHB and at 3.90 Ga for an asteroidal LHB. There would then have been almost no more impactors left at the time the sedimentation occurred that would become Isua, and in that case at least the chemically precipitated minerals (i.e., part of the BIF) would show no trace of enhanced iridium. The correct values of \( t_0 \) and \( \tau_{1/2} \) therefore must be somewhere in-between, in order to agree with both the morphological and the geochemical data (and the corresponding lunar data).

The fraction \( F_{12} \) of material that fell in a given time interval, \( t_1 - t_2 \) after \( t_0 \), relative to the amount that fell during the full declining part of the impact curve, \( t = t_0 \) to \( t \to \infty \), can be calculated from Eq.10 as

\[
F_{12} = \int_{t_1}^{t_2} e^{-(t-t_0)\ln 2/\tau_{1/2}} dt / \int_{0}^{\infty} e^{-\ln 2/\tau_{1/2}} dt = \left[ e^{-\ln 2(t)/\tau_{1/2}} \right]_{t=t_2}^{t=t_1} / \left[ e^{-\ln 2(t)/\tau_{1/2}} \right]_{t=0}^{t=\infty} = e^{-\ln 2(t_1-t_0)/\tau_{1/2}} - e^{-\ln 2(t_2-t_0)/\tau_{1/2}} \quad (12)
\]
If we let $t_1$ be the time of the terrestrial peak, and the impactors were comets, then $t_1 - t_0 = 0.75\tau_{1/2}$ in accordance with Eq. 11 and Eq. 12 simplifies to

$$F_{12} = 0.6 - e^{-\ln2(t_2-t_0)/\tau_{1/2}}$$  \hspace{1cm} (13)

We will now assume that the cosmic material we find in the Isua sediments is a result of mixing into an Isua proto-crust that existed from the time of the terrestrial LHB peak until 3.8 Ga when the sediments formed. Then $t_2 = 3.8$ Ga in Eq. 13 (and 11) and $t_0$ is the lunar LHB peak. For reasonable choices of $t_0$ and $\tau_{1/2}$ (e.g., 3.9 Ga/50 Ma, 3.85 Ga/30 Ma, 3.95 Ga/75 Ma), Eq. 13 then gives us that $F_{12} \approx 0.3$. Since the gravitational focusing of comets toward Earth was found to be 1.3 times the focusing toward the Moon ($N(t_0)_{\oplus}/N(t_0)^{moon} = 1.3$), the total amount of cometary mass that fell on the proto-Isua crust was $\sim 1.3 \times 0.3 = 40\%$ of what fell on the Moon (and gave rise to the craters we see today), under the above assumptions. Half of this mass fell onto the Earth (and half to escape the Earth in high-velocity plumes). Since the lunar crater density showed us that the impacting mass on the Moon was $\approx 10^{20}$ kg, or $2.6 \times 10^6$ kg/m$^2$, the amount of material that will have mixed with the proto-Isua crust was $0.2 \times 2.6 \times 10^6 \approx 5 \times 10^6$ kg/m$^2$ (and the total amount that fell onto it was twice this number, giving the 1000 t/m$^2$ stated in the abstract and introduction).

In order to estimate which abundance of iridium this amount of cometary mass would give rise to in the Isua sediments, we will need to know the abundance of iridium in comets, and we will need to know how deep the material mixed into the proto-Isua crust, both of which can at present unfortunately only be a rough estimate. The concept “comets” represent a wide class of objects, that are likely to have widely different compositions. However a reasonable estimate of a representative “standard cometary composition” could be 80% ice, 10% CI material, and 10% other kinds of dust (Festou et al. 1993). If this material mixed homogeneously with the $\approx 50$ km upper layer of the Earth, we reach a fraction of $(5 \times 10^4$ g/cm$^2)/(5 \times 10^6$ cm)/(3.5 g/cm$^3$)/10 = $2.86 \times 10^{-4}$ g CI-material per g crust (assuming $\rho_{crust} = 3.5$ g/cm$^3$). With an abundance of 465,000 ppt Ir in CI, this finally leads to an estimated $2.86 \times 10^{-4} \times 4.65 \times 10^5 \approx 130$ ppt iridium concentration in the Isua proto-crust; a value which is in close agreement with our measured average concentration of $\approx 150$ ppt.

Our assumed mixing depth of $\approx 50$ km seems likely in the light of the high impact kinetic energy, and is in good agreement with what has been argued for by others (e.g. Sleep et al. 1989 argues for a 35 km mixing depth on the Moon), but even $\approx 25$ or 100 km mixing would obviously be in agreement with our measurements (predicting $\approx 260$ respectively 65 ppt cometary iridium, still in good agreement with our measured 150 ppt within the theoretical uncertainty). In order to test our assumption about a relatively deep mixing, we also measured the iridium abundance in 6 samples of metabasaltic rocks collected at Isua. The results of these measurements are contained in Table 2 and show elevated iridium concentrations in these metabasalts,
averaging 230±50 ppt. This implies that impact-derived iridium, potentially deposited on a mafic proto-crust, was transported down into the mantle where it was imparted to the melts that later on produced the boninitic and picritic basalts now exposed in the Isua greenstone belt. Such a recycling scenario is compatible with the intra-oceanic geotectonic setting (opening of an asthenospheric window developed as a consequence of ridge subduction beneath an early Archean arc-forearc region) proposed by Polat & Frei (2005) to explain the geochemical features of these metabasalts.

If the LHB impactors had been asteroids instead of comets, the focusing factor would have been 1.8 instead of 1.3, the fraction that had mixed into the proto-Isua crust would have been 0.9 instead of 0.5, and the amount of CI material relative the amount of impacting material would have been 1 instead of 0.1. Under the same assumptions used for the estimates regarding cometary impactors above, this would therefore have lead to an estimated iridium abundance of \((1.8/1.3)\times(0.9/0.5)\times(1.0/0.1)\times130\text{ ppt} = 3,200\text{ ppt}\) which obviously is much further from our measured 150 ppt than the cometary 130 ppt. Assuming 35 km mixing depth on the Moon (as in Sleep et al. 1989) and 50 km on the Earth, the predicted iridium abundance in the lunar soil due to an asteroidal LHB would be \(3,200\text{ ppt}/1.8\times(0.5/0.9)\times(50/35) = 1,400\text{ ppt}\). Even though this is still smaller than the predicted terrestrial iridium abundance for an asteroidal LHB, it is obviously in severe disagreement with the very low measured lunar value of <10 ppt.

As for the Earth, a cometary LHB is, however, in quantitative agreement also with the lunar iridium value, because the calculations above showed the amount of impacting material to accumulate on the Moon during a cometary LHB would be (close to) zero, in good agreement with the very low lunar value measured. Accepting a longer mixing history than from the LHB peak and onward, would not affect the expected lunar Ir abundance if caused by comets, but would increase it further beyond an already unrealistically high value if the impactors were asteroids.

We therefore see that only comets would be able to explain the profound difference in lunar and terrestrial iridium abundances, and that in addition reasonable estimates for the period

| Identification | Concentration in ppt |
|----------------|----------------------|
| 462906         | 600±50               |
| 462948         | 120±40               |
| 463418         | 210±50               |
| 463428         | 290±40               |
| 2000 4         | 140±40               |
| 2000 6         | < 50                 |
| simple average | 230±50               |
| average excl. sample | 190±40               |

Table 2: Measured iridium concentration in ppt in six samples of Isua metabasalt rocks.
of LHB mixing, the crustal mixing depth, etc, can lead to a quantification in good agreement with the actually measured iridium abundance both on Earth and on the Moon.

Implications for extraterrestrial delivery of water to the Earth.

There exist an extensive literature on the question of whether the Earth’s oceans (and its atmosphere) originated from geological out-gassing or from late extraterrestrial impacts by volatiles (and if so, then by which type of objects). The debate has been summarised recently by e.g. Delsemme (2006). It is beyond the goal of the present paper to enter into this discussion, but our results have two novel inputs to the debate that we will explain in this section: (1) in order to explain our measured iridium abundances, an amount of water corresponding to a substantial fraction (or all) of the water in the Earth’s present-day oceans will have been delivered to the Earth during the LHB in the form of cometary ice; (2) the simple formulas derived for the ratio between mixed and re-emitted material as function of impactor type, may indicate the existence of a feed-back mechanism that in a simple way explains why the combined size of the Earth’s oceans is approximately the size it is.

None of the theories that have been proposed (neither out-gassing nor delivery by any single type of cosmic object) is in agreement with the bulk of all the isotopic and elemental ratios in the ocean and the atmosphere. However, it has often been seen as a strong argument against a cometary origin of the oceans that three comets (Halley, Hale-Bopp, and Hayakutake) all have been measured to have a D/H ratio twice the value of the ocean water. Several papers have summarised the D/H problematics; e.g. Robert et al. (2000), Morbidelli et al. (2000), Delsemme (1999, 2006). We will therefore here only very shortly summarise the relevant numbers for D/H before proceeding to the explanation of the implications of our Isua iridium measurements for the delivery of cometary water to the Earth during the LHB.

The D/H ratio in the present-day standard mean ocean water (SMOW) is 156 ppm (Lodders & Fegley 1998), the D/H ratio in the proto-solar nebula (out of which the Earth formed) is inferred to have been 25 ppm from observations of the present-day D/H ratio in the atmosphere of Jupiter and Saturn (26±7 ppm and 25±10 ppm for respectively Jupiter and Saturn; Lodders & Fegley 1998), and the proto-ices (i.e., comets) in the Neptune region is inferred to have been between 70 ppm and 250 ppm (Lecluse et al. 1996, Mousis et al. 2000) based on models and measured values (120 ppm; Lodders & Fegley 1998) of Neptune’s atmosphere. The water on Mars is inferred from SNC meteorites to have a D/H ratio of 300 ppm (Leshin 2000). Most CI, CM, and CV meteorites have values between 130 and 170 ppm (i.e., close to SMOW), CR meteorites and ordinary chondrites have values around 250 ppm (with large variations) (Robert 2003). The three measured values of comets (Halley, Hale-Bopp, and Hayakutake) was found to ∼300 ppm (e.g. Bockelée-Morvan 1998). Based on these numbers, a ”cometary value of D/H” has been assigned to be twice the SMOW value, and is often seen as an evidence that the
oceans of the Earth cannot have had a cometary origin but must be either from carbonaceous chondrites or intrinsic. However, as we already pointed out in the beginning of this paper (in relation to which PGE abundance ratios to expect from impacts) "comets" is not a homogeneous type of objects, and it is not obvious which type of comets may have contributed to the LHB. Delsemme (1999) estimated that with a reasonable mix of comets from different regions of the outer solar system, the measured D/H in ocean water could be explained by cometary impacts, and he found that the statistical probability of yet having measured the class of comets that were most likely to have contributed to the delivery of the Earth’s oceans was quite small.

We argued above that our iridium measurements at Isua was in agreement with an estimated total of $10^{20}$ kg of cometary material having impacted the Moon since the time of the (lunar) LHB peak, and that this corresponded to $2.6 \times 10^6 \times 1.3$ kg/m$^2$ of cometary impacts on Earth. If water could be treated the same way as our estimates of the iridium enrichment (i.e., very iridium-rich impactor material hitting a very iridium-poor target), then half would have remained in the Earth’s crust and half would have been re-emitted to space in high-velocity plumes. Hence, $1700 \times (2600 \times 1.3/2 = 1700)$ of cometary material would have mixed with each m$^2$ of Earth’s dry crust. If comets are 80% water, as assumed in the calculations above, this would correspond to the equivalent of a 2 km deep present-day-area ocean ($1.7 \times 0.8/0.7 = 2$).

However, the Earth will obviously not stay dry (i.e., a water-poor target) forever once it is impacted with km-layers of ice. Interestingly, this causes a feedback mechanism that prevents the Earth from being completely transformed into an ocean planet, independently of how many comets impacted the Earth during the LHB. This is because the ratio between delivery and expelling of water during impact depends on whether comets (of the assumed velocity distribution) hits ocean or dry land. In the simple theory outlined above, we argued that it happens to be so that the meridian velocity of Earth crossing comets is roughly equal to the velocity required to form a high velocity plume (Eq. 6–8). When such a plume forms, all the cometary mass escapes back into space, together with a similar amount of target mass. On top of this, a typical impact accelerates additional (surrounding) target mass equivalent to $\sim 20\%$ of its mass into escape velocity (Eq. 9 with $p_t \approx \rho \approx 1$ g/cm$^3$ and $v \approx 2v_{esc}$). For comets hitting an ocean, the target mass is water, and therefore 50$\%$ of the LHB comets that hit the ocean will not only disappear back into space in the plume, but they will drag a similar amount of ocean water into space, plus a minor amount of surrounding target mass (usually also ocean-water). In summary, the impact in the ocean of a high velocity (i.e., $v > v_{esc}$ in Eq. 9) comet of mass $m$ will cause the Earth to lose $\sim 1.2m$ of water. A similar comet of too low velocity to cause an Earth-escaping plume, will deliver $(0.8 - 0.2)m = 0.6m$ worth of water. For comets hitting dry land, the corresponding budget is zero water delivery for the high velocity comets, and 0.8m for the low-velocity ones. When most of the Earth is still dry land, the delivery budget is therefore that 40$\%$ of the impacting cometary mass will stay in the form
of delivered water. Once the created ocean covers ~50% of the Earth’s surface, the budget will have become: The ocean hitting comets subtract \( \sim (0.6/2 - 1.2/2) \) \( m = -0.3 \) \( m \) of water, and the 50% land hitting comets will add \( \sim (0.4/2) \) \( m = 0.2 \) \( m \) water. Hence, when the Earth’s ocean-covered increases beyond 50%, more water will be subtracted than added on average, until the cover again decreases below ~50%. This feedback mechanism would therefore result in that the Earth is covered with oceans on ~half of its surface, in rough agreement (within the estimates given) with the actual present-day ocean cover. In summary, this simple estimate would reduce the delivered present-day-area ocean from the 2 km depth calculated above to, say, ~1 km depth, but still, obviously, being a considerable amount.

Chyba (1990) computed the effect of cometary impacts in a static ocean (and therefore obviously didn’t reach conclusions about a possible maximum extend). Under the assumption of a more restricted interaction between the ocean and the impactor (including that no direct ejecta is created and that only water initially in front of the impactor on its passage through the ocean will escape the Earth), he reached the conclusion that only up to 15% of the ocean could be eroded away because of high-velocity cometary impacts. A more thorough analysis, beyond the scope of the present work, would have to take into account the statistics of the distribution of the few highest mass impacts, the effect of ocean-evaporating impacts, the loss of water with atmosphere-stripping impacts, a more precise estimate of the abundance of water in the LHB comets, an estimate of the topography of the early Earth, etc. However, it is clear from the very simple estimates above that there may be a natural upper limit of the size of an impact delivered ocean, and that the water associated with the iridium enrichment we have measured at Isua will have been a substantial fraction of the present-day ocean mass, if our interpretation, that the iridium in the 3.8 Ga old Isua rocks represents a cometary LHB impact, is correct.

In this way, our measurements are the first results to bring a conceptual and quantitative agreement between the lunar LHB cratering records and the geochemical records on the part of the Earth’s crust that existed during the LHB period. The results are in good qualitative agreement with recent models (Gomes et al. 2005) for the solar system formation, which predict a large fraction of the LHB to be comets perturbed onto collision course with the Earth and Moon when Jupiter and Saturn migrated through a 1:2 orbital resonance 3.9 Ga ago, but which also predict that a large fraction could be asteroids (in contradiction with our measurements). Our results would be in disagreement with the expected Isua proto-crustal (and lunar) Ir abundance if the LHB impactors were asteroids, unless some unknown mechanism would be able to remove the iridium from the solid crust (on Earth as well as on the Moon) in which the asteroids impacted.
Conclusions.

We have sampled 3 different types of sedimentary rocks from the Isua greenstone belt in Greenland, which with an age of \( \sim 3.8 \) Ga is the oldest known major piece of the Earth’s crust. We argued that the 3 types of metasediments potentially contain an average proto-crustal signature transported by rivers to the site of deposition (in case of clastic sediments) and likely reflect a contemporaneous dissolved seawater inventory in case of the chemical metasediments (BIFs). 37 individual samples were mortared and neutron-radiated in a nuclear research reactor. Subsequent \( \gamma - \gamma \) coincidence spectroscopy of the radiated samples revealed an average iridium abundance of \( \approx 150 \) ppt. This is an enhancement of the Isua proto-crust relative to the Earth’s present-day ocean and upper crust of a factor 7, and relative to the lunar crust with a factor of more than 15.

We argued that this enrichment is in qualitative agreement with a cometary LHB, but in qualitative disagreement with a LHB caused by asteroids.

In order to also see which quantitative restrictions the measured iridium abundances could impose on various impact scenarios, we developed the theoretical basis for how the lunar crater counts can be scaled to LHB impact mass on the Isua proto-crust. We first toughened the concept of LHB peak up a bit and quantified the delay in the terrestrial LHB peak relative to the lunar LHB peak (usually just called the LHB peak), and explained how the shift in the time of the peak, as well as the whole terrestrial LHB energy density flux curve, depends on whether the impactors were comets or asteroids. We then quantified how impacts caused by asteroids differ from impacts caused by comets, in terms of the amount of iridium they will have imposed into the Isua proto-crust and into the lunar surface. By use of the developed framework and selection of reasonable values for the relevant parameters (such as mixing depth, mixing duration, etc), we estimated under which conditions a cometary LHB on Earth would give rise to roughly the measured iridium abundance in the sampled Isua sediments, and at the same time also to the measured value in the lunar surface material. As far as we know, it is the first time that a self-consistent scenario has been presented in the literature, which rigorously quantifies the scaling of a cometary lunar LHB to the conditions on the Earth, and is able to find agreement between the lunar cratering counts and elemental abundances measured in the lunar soil as well as in the early terrestrial crust.

A similar calculation based on the assumption that the LHB impactors were asteroids (i.e., "meteorites") lead to a predicted Isua iridium abundance approximately a factor 20 higher than we measured, and a factor of several hundreds too high for the lunar abundance. Therefore comets but not asteroids can quantitatively account for the measured values of both the lunar and Isua iridium abundances, as well as the impacting mass that have given rise to the lunar craters.

The quantification made it possible for us to estimate the total (cometary) mass that have
hit the Earth, and the (impactor-dependent) balance between impacting and re-emitted material. We therefore finally estimated what effect a cometary LHB impact can have had on the formation of the Earth’s oceans. We discovered that there is a feedback mechanism that will prevent the oceans caused by cometary impacts to cover more than approximately 50% of the Earth’s surface, and calculated that the LHB cometary impactors that can have caused the craters we see on the Moon today and explain the iridium abundances measured in the Isua sediments and in the lunar soil, will have covered the Earth with a km deep ocean over ~50% of its surface.

**Acknowledgements:**
Valuable comments from S.Moorbath, A.Polat, B.Reipurth, R.Gwozdz, and the two referees, are greatly acknowledged. This work was supported by the Danish Natural Science Research Council (FNU) and the Isua Multidisciplinary Research Project (IMRP).
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