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Note

Asteroidal source of L chondrite meteorites

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ABSTRACT

Establishing connections between meteorites and their parent asteroids is an important goal of planetary science. Several links have been proposed in the past, including a spectroscopic match between basaltic meteorites and (4) Vesta, that are helping scientists understand the formation and evolution of the Solar System bodies. Here we show that the *shocked* L chondrite meteorites, which represent about two thirds of all L chondrite falls, may be fragments of a disrupted asteroid with orbital semimajor axis $a = 2.8$ AU. This breakup left behind thousands of identified 1–15 km asteroid fragments known as the Gefion family. Fossil L chondrite meteorites and iridium enrichment found in an ≈467 Ma old marine limestone quarry in southern Sweden, and perhaps also ∼5 large terrestrial craters with corresponding radiometric ages, may be tracing the immediate aftermath of the family-forming collision when numerous Gefion fragments evolved into the Earth-crossing orbits by the 5:2 resonance with Jupiter. This work has major implications for our understanding of the source regions of ordinary chondrite meteorites because it implies that they can sample more distant asteroid material than was previously thought possible.

1. Introduction

The ordinary chondrites (OCs) are the most common group of meteorites in our collections with a relative fall frequency of 79.9% (Keil et al., 1994). According to their iron content, these meteorites are divided into H (high total Fe), L (low total Fe) and LL (low total Fe, low metallic Fe) groups, with 42.8%, 47.4% and 9.8% of OC falls belonging to each group, respectively. These meteorite groups are closely related because the chondrules in H, L and LL chondrites are similar. This probably indicates that H, L and LL chondrites collected chondrules from a common source region.

Oxygen isotope analysis shows that the OC groups most likely represent different parent bodies (Clayton, 1993). For example, asteroid 6 Hebe has been suggested as the probable parent body of H chondrites (Gaffey, 1996; Gaffey and Gilbert, 1998) and the Flora region was proposed to be the asteroid source of LL chondrites (Vernazza et al., 2008). Here we study the asteroid source of L chondrites. Note that, despite their related formation, the H, L and LL groups may sample different regions in the present asteroid belt, because dynamical processes have significantly altered the orbits of asteroids since their formation (e.g., Petit et al., 1999).

About two thirds of L chondrite meteorites (hereafter L chondrites) were heavily-shocked and degassed with ^{39}Ar–^{40}Ar ages near 470 Myr (Korochantseva et al., 2007) suggesting that the L chondrite parent body suffered a major impact at ≈470 Myr ago and catastrophically disrupted (see also Heymann, 1967; Haack et al., 1996 and the references therein). The measured slow cooling rates moreover imply that the original parent body had diameter $D \gtrsim 100$ km (Haack et al., 1996). Strikingly, the timing of the shock event coincides with the stratigraphic age (467 ± 2 Myr) of the mid-Ordovician strata where abundant fossil L chondrites, meteorite-tracing chromite grains and iridium enrichment were found in the active marine limestone quarry in southern Sweden (Schmitz et al., 1997, 2003; Greenwood et al., 2007). The recent shocked and fossil L chondrites may thus apparently record the same event, a catastrophic disruption of a large main-belt asteroid that produced an initially intense meteorite bombardment of the Earth and at least ≈30% of the OCs' falls today.

Catastrophic breakups of $D \gtrsim 100$ km main belt asteroids leave behind groups of km-sized and larger asteroid fragments known as asteroid families (Hirayama, 1918). We analyzed all existing asteroid families for their potential relationship with the 470-Ma event. Most of the asteroid families identified by us are older than 1 Gy and/or have a taxonomic classification that is clearly incompatible with them being the source of L chondrites (Mothé-Diniz et al., 2005). Also, the measured short Cosmic Ray Exposure (CRE) ages of fossil L chondrites and narrow interval of sediment depths in which they were found indicate very short delivery times ($\lesssim$1–2 Myr) of meteoroid-sized fragments from the breakup orbital location to Earth (Heck et al., 2004). Clearly, at least one resonance in the main belt is capable of transferring meteoroids from a nearby family to Earth on this timescale.

A possible candidate is the prominent Flora family located near the ν_6 secular resonance in the inner asteroid belt (Nesvorný et al., 2002, 2007). To produce the most extreme CRE ages of the collected fossil meteorites (∼50–200 kyr; Heck et al., 2004) from the Flora family, however, the meteoroid-sized fragments would have to be launched with very large ejection speeds ($\Delta V \gtrsim 1$ km/s) to reach the fast-acting core of the ν_6 resonance (Nesvorný et al., 2007). Also, it is not clear whether the Flora family may have the formation age that is compatible with the 470-Ma event (or it is instead ∼1 Gy old; Nesvorný et al., 2006). Moreover, the Flora family is probably olivine rich and has olivine/pyroxene composition more similar to the LL chondrites (Vernazza et al., 2007, 2008; Binzel et al., 2008). According to Vernazza et al., the main-belt asteroid analogs of the L-chondritic olivine/pyroxene composition may instead be located beyond $a = 2.5$ AU. In the view of these results, in this note we investigate the possibility that the shocked recent and fossil L chondrites originated in the outer part of the main asteroid belt.

2. The Gefion family

We identified and analyzed all known asteroid families with $a > 2.5$ AU. We found that only one resonance, the 5:2 mean motion resonance with Jupiter at 2.823 AU, is capable of transporting meteorites to the Earth on timescales comparable with the most extreme CRE ages of the fossil meteorites (∼50–200 kyr; Heck et al., 2004). There are only two known large asteroid families close to the 5:2 resonance, the Gefion family at 2.7–2.82 AU and Koronis family at 2.84–2.96 AU, with a spectroscopic type in the taxonomic S complex that is broadly compatible with OC-meteorite mineralogy. [Immediate after-breakup deposition of meteoroids

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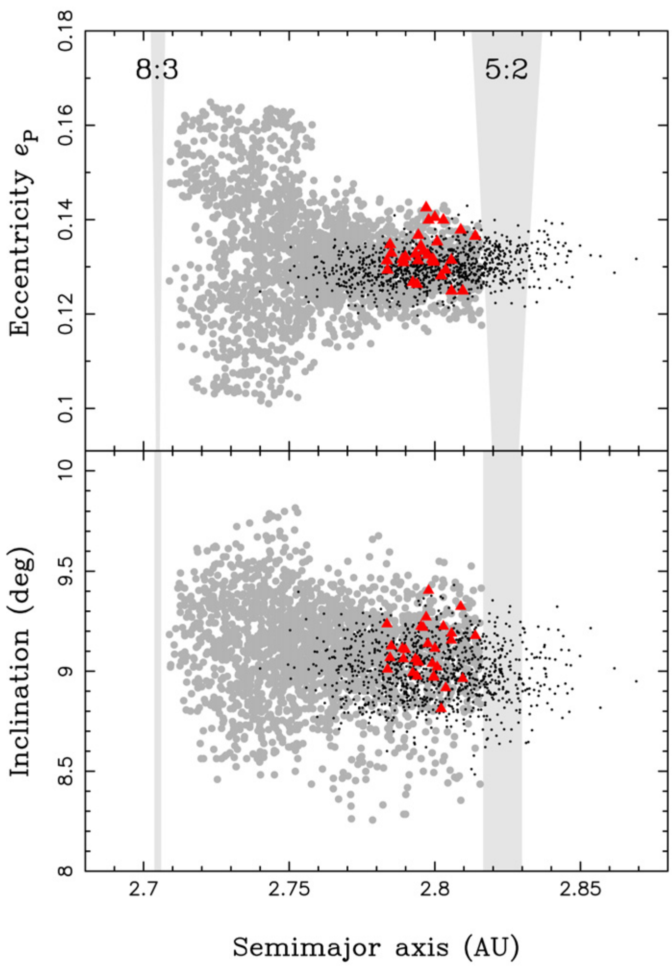

Fig. 1. The Gefion family is located at the edge of the 5:2 mean motion resonance (denoted by the wide light-gray strip) which provides a fast escape route from the main belt. Grey dots: 2240 dynamical members of the Gefion family identified with $d_{\mathrm{cutoff}} = 60$ m/s. The eccentricity distribution is wider below $a \approx 2.75$ AU due to effects of several secular and mean motion resonance located near 2.75 AU (Carruba et al., 2003). Red triangles: 31 large Gefion family members belonging to the taxonomic type S. These members are located near $a \approx 2.8$ AU indicating that the breakup occurred near that semimajor axis value. Black dots: Gefion fragments launched with $\langle v_{\mathrm{ej}} \rangle = 63$ m/s. About 25% of these fragments fall into the 5:2 resonance, have their orbital eccentricity rapidly pumped up by resonant effects and end up in Earth-crossing space.

into the 5:2 resonance from other S-complex type asteroid families would require large ΔVs.] The Koronis family is probably Gys old (Bottke et al., 2001), leaving the Gefion family as a single remaining candidate in the outer main belt for the source of fossil and shocked recent L chondrites. Interestingly, this family, having the estimated olivine fraction of 62–68%, was identified by Vernazza (personal communication) as one of the best compositional main-belt analogs for the L chondrites which typically have the olivine fraction in the 60–70% range.

To identify the dynamical members of the Gefion family, we applied the Hierarchical Clustering Method (HCM; Zappalà et al., 1990) to search for asteroids near (1272) Gefion in 3D proper element space: proper semimajor axis a_P, proper eccentricity e_P and proper inclination i_P. The proper orbital elements, being more constant over time than instantaneous orbital elements (Milani and Knežević, 1994), provide a dynamical criterion of whether or not a group of asteroids has a common ancestor. We used the AstDyS[1] proper element catalog from October 2007 which includes 268,524 objects. The result of HCM is a group of asteroids with member objects connected by a chain in (a_P, e_P, i_P) space with the length of each link smaller than parameter d_{cutoff}. We tested d_{cutoff} values between 40–100 m/s. The best results were obtained with $d_{\mathrm{cutoff}} = 60$ m/s.

The Gefion family has 2240 dynamical members with $d_{\mathrm{cutoff}} = 60$ m/s (Fig. 1). After excluding several known large interloper asteroids from the list (93, 255, 527, 2559; Mothé-Diniz et al., 2005), we found that the largest S-type family members are asteroids 2911 and 5622 both having absolute magnitude $H = 11.3$. To convert H into D we assumed albedo $A = 0.2$ derived as the mean albedo value for the S-complex type asteroids. The Size Frequency Distribution (SFD) of the Gefion family starts at $D \approx 15$ km, steeply rises down to $D \approx 3$ km and flattens for $D \lesssim 3$ km because these faint main-belt asteroids are difficult to detect by current observational surveys. A slightly convex shape of the SFD for $D = 3$-10 km (Durda et al., 2007) was probably produced by the dynamical removal of small Gefion objects by the neighbor 5:2 and 8:3 resonances. The SFD corrected for this effect is nearly flat in the $D = 3$–10 km range with the cumulative power index $\alpha \approx -4$ and shows no clear signs of being altered by collisions since the family's birth.

To estimate the size of the parent body of the Gefion family, we used a standard Smooth Particle Hydrodynamic (SPH) code capable of modeling asteroid collisions (Benz and Asphaug, 1999) and followed the phase of fragment gravitational reaccumulation with PKDGRAV (Richardson et al., 2000). Various impact parameters, including the parent body and impactor sizes, collision speed and angle, were set to provide the best fit to the Gefion's SFD at $D = 3$–15 km. Based on these tests we estimate the parent body diameter $D_{\mathrm{pb}} = 100$–150 km. The Gefion family was apparently produced by a super-catastrophic breakup with the largest fragment to parent body mass ratio $M_{\mathrm{lf}}/M_{\mathrm{pb}} \approx 0.001$–0.004. These results clearly fulfill the basic requirements (discussed above) on the parent body breakup inferred from the analysis of the shocked L chondrites.

To determine when this breakup occurred we used a code developed in our previous works (e.g., Vokrouhlický et al., 2006). The code starts by launching asteroid-sized fragments from the assumed impact site with speeds following a Maxwellian distribution with the specified mean ejection speed, $\langle v_{\mathrm{ej}} \rangle$. It then tracks the dynamical spreading of fragments via radiation effects known as the Yarkovsky drag (Bottke et al., 2006), and adjusts the family age, t_{age}, so that the best fit is obtained to the observed H and orbit distributions of the Gefion family. Using the code we found that t_{age} scales nearly linearly with $\rho/\sqrt{A}$, where ρ is the assumed asteroid bulk density. With $\rho = 2.0$ g/cm^3 and $A = 0.2$, the best fit occurs for $t_{\mathrm{age}} = 485^{+40}_{-10}$ Myr and $\langle v_{\mathrm{ej}} \rangle = 63 \pm 7$ m/s. Therefore, the formation time of the Gefion family can plausibly coincide with the 470-Ma shock event of L chondrites. Our age estimate, however, is sensitive to the exact semimajor axis location of the breakup, a_{break}. Here we assumed that a_{break} coincided with the mean semimajor axis of the large Gefion family members ($a_{\mathrm{break}} = 2.979$ AU). Other plausible values of a_{break} produce somewhat larger t_{age}. The assumed $\rho = 2.0$ g/cm^3 to have t_{age} near 47 Myr is lower than that of Ida and Eros ($\rho = 2.7$ g/cm^3; Hilton, 2002) possibly hinting on the larger porosity of the small Gefion family asteroids. For a comparison, the rubble pile asteroid Itokawa has $\rho = 1.9$ g/cm^3 and ≈ 40% porosity (Fujiwara et al., 2006).

3. Cosmic ray exposure ages

To match the short CRE ages of fossil meteorites (0.05–1.5 Myr; Heck et al., 2004), Gefion fragments must rapidly evolve from the main belt to Earth-crossing orbits. Interestingly, the nearby 5:2 resonance at 2.83 AU was previously noted to provide very short transfer times (Gladman et al., 1997). To estimate the expected CRE ages of meteorites delivered from the Gefion family location by the 5:2 resonance, we placed test particles in the 5:2 resonance and used an efficient N-body integrator known as Swift (Levison and Duncan, 1994) and an Öpik-based algorithm (Wetherill, 1967) to determine the timing and expected number of impacts on the Earth. Note that speeds of only ≈ 50 m/s are required to reach the resonant orbits at $a \approx 2.82$ AU from the core of the Gefion family at $a \approx 2.8$ AU.

We found that the first Gefion meteorites arrive on Earth only about 50 kyr after they had been placed in the 5:2 resonance (Fig. 2). The produced peak in the impact rate lasts about 1–2 Myr when $\sim 10^{-4}$ Myr^{-1} impacts occur per test particle. Therefore, most Gefion meteorites are expected to have CRE ages between 50 kyr and ≈ 1–2 Myr and be spread over ≈ 1–2 Myr of terrestrial sediments. These findings fit very nicely the measured CRE and stratigraphic ages of fossil meteorites (Heck et al., 2004). Based on this result, the Gefion family's formation near 500 Ma and its L-chondritic olivine/pyroxene mineralogy we propose that the Gefion family can be the asteroidal source of fossil L chondrites.

The CRE ages of most recent OC meteorites are between ~ 5–100 Myr (Marti and Graf, 1992). Because resonant delivery generally takes only <10 Myr, most recent OC meteorites must be slowly delivered to resonances via the Yarkovsky effect (Vokrouhlický and Farinella, 2000), a thermal radiation force that causes objects to undergo semimajor axis drift. We used our code known as TrackMet to estimate the expected CRE ages of recent Gefion meteorites. In addition to the Yarkovsky-driven drift in a, TrackMet also follows the collisional cascade of 10-cm to 10-km-diameter fragments as they break by collisions with background objects. Their collisional lifetimes were set according to Bottke et al. (2005).

Upon reaching the ν_6, 3:1 or 5:2 resonances, the TrackMet objects can be trapped on resonant orbits with size-dependent capture probability values that we previously determined from our test N-body simulations. Trapped particles are removed from the main belt and produce terrestrial impacts with overall rates that were set individually for each resonance (1×10^{-2} for ν_6, 2×10^{-3} for 3:1 and 2×10^{-4} for 5:2; e.g., Morbidelli and Gladman, 1998). We start the CRE clock when a meteoroid first becomes smaller than 3 m in diameter and stop it upon its impact on the Earth.

[1] http://hamilton.dm.unipi.it/cgi-bin/astdys/astibo.

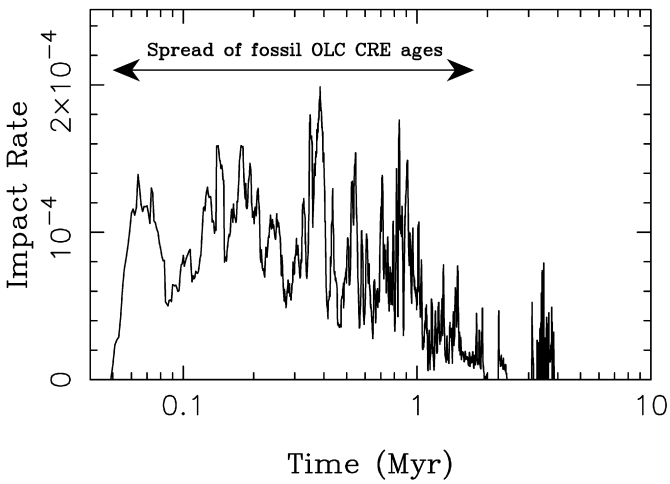

Fig. 2. The impact rate of meteorites from the 5:2 resonance nicely corresponds to the CRE age range of fossil L chondrites (0.05–1.5 Myr; shown by the two-headed arrow; Heck et al., 2004). To obtain the impact rate we placed test particles in the 5:2 resonance (see Fig. 1) and let their orbits evolve by resonant effects. The Earth-impact probability was determined using an Öpik-algorithm-based code (Wetherill, 1967). The number of impacts per Myr per active particle is shown, where we defined the active particle as the one which reaches an Earth-crossing orbit over the integration time span (10 Myr). The overall impact probability per one active particle in the first 2 Myr after the start of simulation was 2×10^{-4}. Thus, on average, one out of ∼500 fragments inserted into the resonance impacts Earth within 2 Myr after the Gefion family breakup. [The jagged appearance of the impact rate line is due to the small statistics obtained from our simulations. In reality, the mean impact rate is a smooth function of time.]

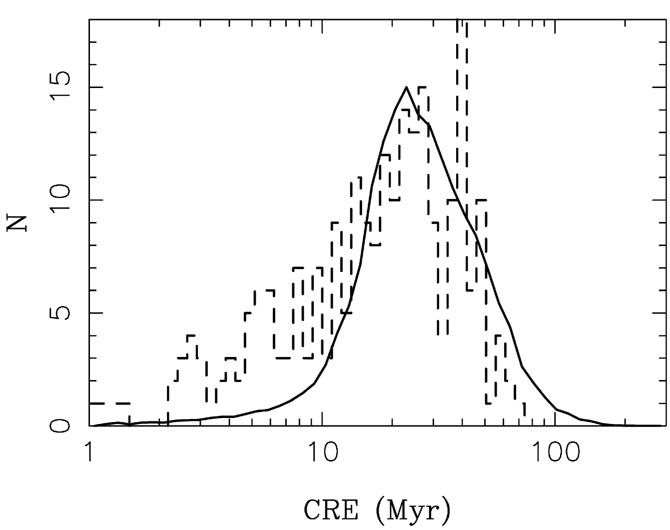

Fig. 3. The comparison between the CRE ages of Gefion meteorites obtained with TrackMet and measured CRE ages of recent L chondrites (lab data taken from Marti and Graf, 1992). The overall agreement is good. Our model produces a slightly deficient number of meteorites with CRE ages < 10 Myr. This result was obtained with assumed surface thermal conductivity $K = 0.01$ W/(m K), which would correspond to porous or fragmented rocks. Larger K values would imply slower drift rates of 1–10 m meteoroids. With $K \approx 1$ W/(m K), a value more typical for 'bare' meteoritic rocks, our model shows an excess of meteorites with CRE ages 100–200 Myr. This is due to the fact that the slow-drifting Gefion meteoroids with $K \approx 1$ W/(m K) must travel a large semimajor axis distance before they can reach the 3:1 resonance at $a = 2.5$ AU, and acquire long CRE ages along the way. The delivery of recent Gefion meteorites to Earth through the neighbour 5:2 resonance is inefficient relative to the 3:1 resonance.

The distribution of CRE ages of Gefion meteorites that we obtain from TrackMet is broad with nearly all CRE ages occurring between 5 and 100 Myr, and most common CRE ages falling near 30–40 Myr. The distribution closely matches that of measured CRE ages of the recent L chondrites (Fig. 3). We also note that the most efficient route for Gefion meteoroids to reach Earth at the present time is to evolve down to $a = 2.5$ AU and be delivered via the 3:1 resonance. This may be consistent with the previous work suggesting that one out of two bolides capable of dropping meteorites should reach the Earth-crossing orbit by the 3:1 resonance (Morbidelli and Gladman, 1998). Conversely, most meteorites produced from sources in the inner main belt ($a = 2.1$–2.5 AU; including the Flora family region) should reach Earth via the ν_6 resonance due to the larger terrestrial impact rates obtained from this resonance.

4. Discussion

Our work has several important implications for the origin of OC meteorites, Near-Earth Asteroids (NEAs), and the terrestrial impact record. It was previously thought that the OC meteorites are sampling the inner asteroid belt, the same source region that provides the basaltic meteorites and most NEAs (Bottke et al., 2002). We showed here, however, that most L chondrites can instead represent asteroid material from beyond $a = 2.5$ AU. This gives support to claims of Vernazza et al. (2007, 2008) who argued that the 'olivine-poor' ordinary L (and H) chondrites should be sampling outer parts of the asteroid belt. The gradual change of the olivine/pyroxene mineralogy with heliocentric distance that our study implies has yet to be explained by properties of protoplanetary disk from which asteroids formed.

A potential problem with this result is the low relative efficiency of meteorite delivery from the Gefion family location. As discussed above, dynamical models indicate that meteoroids exiting the main belt via the 3:1 resonance have a factor of ≈5 lower probability of striking the Earth than those coming out of the ν_6 resonance. All things being equal, this would suggest that meteoroids from the ν_6 resonance should dominate meteorite fall statistics. Strangely, though, observations suggest that all things may not be equal. According to Vernazza et al. (2007, 2008), the most likely source of the LL chondrites is the large Flora family located near the efficient ν_6 resonance. The fraction of LL falls is ≈3 times smaller than the shocked L chondrites, which we predict are coming from the 3:1 resonance. This raises the question; why are LL chondrites so under-represented in our meteorite collections relative to the shocked L chondrites?

One way to resolve this problem is to assume that ∼50 times more Gefion meteoroids are currently reaching the 3:1 resonance than the number of Flora meteoroids reaching the ν_6 resonance. This would imply that: (i) the Gefion breakup produced a much larger number of sub-km fragments than the Flora breakup; and/or (ii) the sub-km precursor objects to Flora meteoroids have been efficiently depleted over the Flora family age. Unfortunately, we lack sufficient constraints to resolve this issue at this time. This will hopefully change once Pan-STARRS data allows the SFDs of the Gefion and Flora families to be determined in the sub-km size range.

On a more speculative note, we suggest that item (i) may have something to do with the fact that the Gefion family was produced in an exceptionally super-catastrophic breakup with $M_{\rm lf}/M_{\rm pb} \approx 0.001$–$0.004$, while $M_{\rm lf}/M_{\rm pb} \approx 0.3$ for the Flora family (Nesvorný et al., 2006). The difference in impact energies between the two events might also explain (assuming here that the Gefion and Flora families are sources of L and LL chondrites, respectively) why L chondrites register the pervasive shock event while LL chondrites do not, because exceptional impacts (in terms of the projectile's size and/or impact speed) may be needed to produce the required shock levels.

By extrapolating the currently known SFD of the Gefion family (Durda et al., 2007) down to $D = 1$ km, we estimate that the Gefion family formation event produced as many as 10^5 $D \gtrsim 1$-km-sized fragments. Some 25% of these objects were placed directly into the 5:2 resonance (assuming $\langle v_{\rm ej}\rangle = 63$ m/s). With the Earth-impact probability of 2×10^{-4} (Fig. 2), we find that ∼5 large terrestrial impacts should have been produced within ≈2 Myr after the family-forming breakup. Therefore, we predict that some of the identified terrestrial craters with ages around ∼470 Ma, possibly including craters Ames and Strangways, may have been produced by the Gefion L-chondrite impactors. The composition of impactors that produced these craters can be checked by the analysis of the crater melts.

Our study, while primarily motivated by issues related to asteroid-meteorite connections, may also have potentially important implications for the Earth's biosphere because large quantities of cosmic material accreted by the Earth at 470 Ma may have altered the climatic/biologic conditions on the Earth, possibly causing the explosion in biodiversity during the Ordovician Period (Schmitz et al., 2007).

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