

McGuire *et al.*³ provide a detailed look at seismic behaviour on an oceanic ridge transform fault, using the latest generation of ocean-bottom seismometers. Enhanced fluid circulation could cause parts of the fault to act as a barrier to fault rupture and could facilitate slow, aseismic slip that may ultimately trigger a main rupture on an adjacent fault section. Identification of similar

rupture-preparation zones in faults on land could provide an early warning tool for large earthquakes. □

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PLANETARY SCIENCE

Earth's ancient catastrophes

During the collision-filled early years of the Solar System, the rocky planets accreted, the Moon formed and the frequency of large impacts decayed over time. Several hundred million years later, the rocky planets were once again bombarded by asteroids in an episode termed the Late Heavy Bombardment. Evidence for a spike in large impacts can be seen on less geologically active planetary bodies, such as the Moon, where the majority of the youngest large impact basins all date to this time interval. The Late Heavy Bombardment was thought to have ended abruptly about 3.7 billion years ago.

However, geologic evidence implies that the Earth was subject to similarly large asteroid impacts beyond this date.

Although impact craters this old have not yet been found on Earth, some of the oldest known stratigraphic sequences reveal the last gasp of this ancient bombardment. Large impact events produce rapidly expanding plumes of vaporized impactor and target rock material, which cool and condense into spherical droplets. The spherules from large impacts can be distributed across great distances — even globally — before falling back to the Earth's surface. Widespread spherule layers as old as 3.5 billion years have been found in otherwise quiescent marine depositional environments. Although the source craters of these ancient impacts remain unknown, the spherule layers themselves tell a story about the asteroid impactors that caused them, as evidenced in two recent papers published in *Nature*.

Brandon Johnson and Jay Melosh deduce the size and impact velocity of the asteroids that generated the known spherule layers on Earth using measurements of spherule layer thickness and a spherule formation model (*Nature* <http://dx.doi.org/10.1038/nature10982>; 2012). According to the resultant impact chronology, the asteroid flux was higher



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than expected 3.5 to 2.5 billion years ago, long after the Late Heavy Bombardment was thought to have ended.

The reason for this extended bombardment is explained by William Bottke and colleagues (*Nature* <http://dx.doi.org/10.1038/nature10967>; 2012). Using numerical simulations of asteroid behaviour during the Late Heavy Bombardment, they show that shifts in the orbits of the giant planets around that time would have pushed asteroids onto planet-crossing orbits, putting some on a collision course with Earth. Although the bulk of the resulting impacts would have occurred by 3.7 billion years ago, they find that asteroids from a now largely extinct portion of the asteroid belt would have been driven onto planet-crossing orbits over a more extended period of time. The asteroids surviving this orbital shake-up may now be represented by an asteroid group called the Hungarias that is tracked by astronomers today, whereas some of the victims may have produced the ancient spherule layers seen on Earth.

The simulations of Bottke *et al.* indicate that the main Late Heavy Bombardment continued for over 400 million years on the Moon. This is consistent with the best available ages of lunar and meteorite samples, many of which were reset by heating events between 3.5–3.7 and

4.1 billion years ago. The models predict that the Moon was subject to only a few large impacts after the conventional end of the Late Heavy Bombardment, consistent with lunar basin ages. However, the Earth is a much larger target than the Moon, and the findings show that the ancestral Hungaria asteroids continued to enter Earth-crossing orbits well after that. They calculate that about 70 impactors capable of producing Chicxulub-sized craters hit the Earth between 3.7 and 1.7 billion years ago, which was enough to reproduce the known spherule layers.

Interestingly, these late large impacts occurred during the time when life was just taking hold on Earth. Could these ancient catastrophes have aided life by delivering organic molecules or providing habitats in long-lasting hydrothermal systems under the resulting craters? Of course, the Earth's terrestrial cratering record is incomplete, owing to erosion and plate tectonics. But the combination of the cratering records of the Earth and Moon, together with observations of asteroid populations, allow scientists to begin piecing together the impact history of the inner Solar System. Meanwhile, the search for more spherule layers hidden in the Earth's stratigraphy continues.

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