Influence of the Yucatan earthquake event

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In recent years, seismic wave effects caused by meteorite impacts have been widely observed. The meteorite impact event that occurred 66 million years ago is one of the most famous impact events in Earth's history. The influences of the seismic wave field generated by this collision event on the solid Earth itself is worth exploring. Therefore, this study initially estimated the seismic source parameter information based on the multiring structure of the meteorite crater, and then simulates the seismic event. The results of this study provide a possible explanation for the formation of the Earth's tectonic plates. The findings of this study suggest that the seismic wave field generated by the meteorite impact event 66 million years ago may have caused the destruction of the Solid Earth, leading to the formation of the boundary between the Indian Ocean and the Pacific Plate. Simultaneously, this study has important significance for inspiring the development of new geoscientific methods.

KEYWORDS

solid earth, seismology, seismic source, meteorite impact, plate tectonics

1 Introduction

Collisions between objects, such as those that occur in nuclear reactions and due to the generation of gravitational waves, widely occur in nature. Moreover, collisions between meteorites and planets are common in solar systems (Bierhaus et al., 2022; Mark et al., 2022; Kimi and Vijayan, 2023). Among the many previous celestial collision events, the Chicxulub impact event that occurred 66 million years ago has been widely studied (Alvarez et al., 1980; Goderis Steven et al., 2021; Ross et al., 2022; Nixon et al., 2022). The present results show that the main reason for the extinction of dinosaurs is that a change in the Earth's environment was triggered 66 years ago when a meteorite impacted the Earth (Kring, 1997; Schulte et al., 2010; Kunio et al., 2016; Morgan et al., 2022). In addition to causing volcanic eruptions, tsunamis (Hull Pincelli et al., 2020), worldwide wildfires (Venkatesan and Dahl, 1989) and other secondary disasters, this meteorite impact also directly produced strong seismic effects (Kim et al., 2022).

A weak seismic wave field can be used to study the internal structure of a planet (Stahler et al., 2021), while a strong seismic wave field usually results in intense damage (Caglar et al., 2023). The seismic wave field is primarily affected by the physical parameters of the source and the underground medium. For seismic sources, the seismic energy, source type, source direction, depth and source time function are important components to consider.

Regarding the source energy of the Chicxulub event, previous studies have shown that the source energy released by the impact was approximately 5×10^{23} joules (Morgan et al., 1997). Regarding the source direction, numerical experiments show that the meteorite impacted the Yucatan Peninsula at an angle of approximately 45–60 degrees, approaching from the northeast (Collins et al., 2020). However, the source depth and source time function are still unclear.

Nevertheless, the source depth and source time function can be estimated. The method of estimating the seismic time function using near-field seismic waveform information is widely used in the field of seismology (Isadora et al., 2020). For most meteorite impact events, the source time function can normally be approximated as a delta function (Holsapple and Schmidt, 1987). However, due to the seismic wave absorption and attenuation by the existing underground medium, the seismic source time function can generally be approximated as a Ricker wavelet or a triangular function (Ricker, 1977). The dominant frequency of the function is the parameter to be determined. The frequency of large impact events is usually concentrated in low-frequency components (Teanby and Wookey, 2011). To obtain this parameter, we analyzed the multiring structure of the crater and found that this structure reflects a regular ground wave phenomenon due to the presence of excessive energy during the seismic body wave propagation. In this study, two adjacent rings are considered to be the density extremum caused by the same peak frequency. Usually, the corresponding seismic parameters can be determined by solving the body wave equation in the frequency space domain, then setting different parameters, and conducting comparative tests. Basic equations in the field of natural science, such as the acoustic wave equation, light wave equation and seismic body wave equations, they usually have the same form. Li and Chen., 2021 efficiently solved this equation.

After obtaining the above approximate source parameter information, we can conduct research on global seismology to quantitatively explore the influence of the seismic effect generated by this event on both the interior and exterior of the Earth.

2 Data acquisition

An important difficulty in the study of events 66 million years ago is the acquisition of actual data. The direct evidence of meteorite impact mainly comes from meteorite craters.

Since the Chicxulub event occurred, 66 million years have elapsed, and there exists no current seismic data available that can be used to extract the source information from that event. However, geophysical exploration shows that the area retained a multiring structure with a diameter of approximately 180 km (Campos et al., 1997, Morgan et al., 2011; Gulick et al., 2013; Sweeney, 1978). The diameter of the inner ring of the multiring structure is approximately 70 km, and the diameter of the second ring is approximately 100 km at its widest point (Hildebrand et al., 1991). The multiring structure is mainly attributed to variations in the existing medium density caused by the propagation of the compressional wave. The two adjacent peak loops can be regarded as a wave cycle. The exact amplitude of the multiring structure will have changed over 66 million years due to gravity and other effects, but the wavelength information of the multiring structure can be used to estimate the frequency of the seismic source time function of the collision event.

The extraction of data on the multiring structure of meteorite craters in this study are based on previous measurements of gravity data (Hildebrand et al., 1991). The gravity data results mainly reflect changes in the density of the medium. To obtain
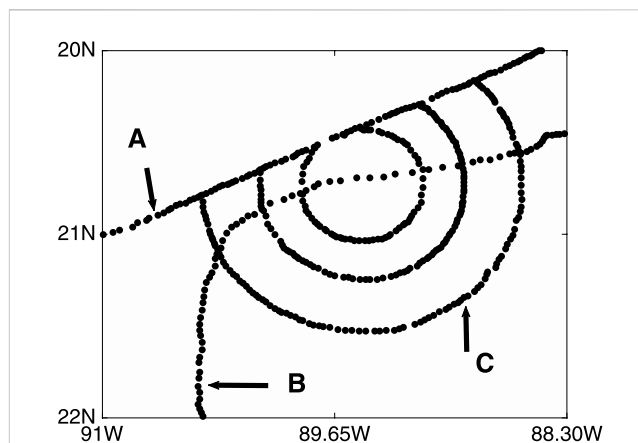

FIGURE 1
Schematic diagram of the crater multi-ring structure of the crater (Hildebrand et al., 1991), in which (A) represents the waveform data acquisition system, (B) represents the fracture caused by meteorite impact, and (C) represents the crater multi-ring structure, there are three multiring structures here, the first ring has a diameter of approximately 70 km, and the second ring has a diameter of approximately 100 km. These two circles represent wave peaks and can be considered as a waveform cycle.
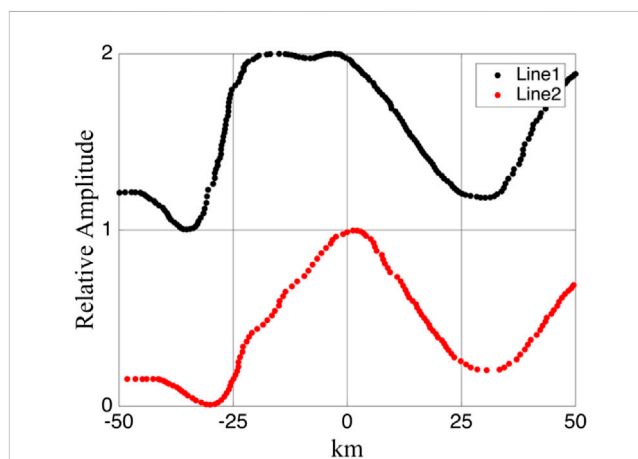

FIGURE 2
Waveform maps of the same region extracted from the survey lines obtained in different articles (Sweeney, 1978; Hildebrand et al., 1991), the wavelength values of Line1 and Line2 are basically the same.

relatively large amounts of reliable data, this study mined corresponding multiring structures and waveform diagrams from previous articles. Here, the ginput function of MATLAB is Primarily used for data extraction.

The multiring structure and waveform of the crater are shown in Figures 1, 2.

In addition to the multiring structure of the crater, the waveform results of the crater can also be used as an additional source of information in order to constrain the source information. The waveform results obtained from previous data are as shown in Figure 2.

Based on the above information, we can perform wave field simulations to obtain the source information.
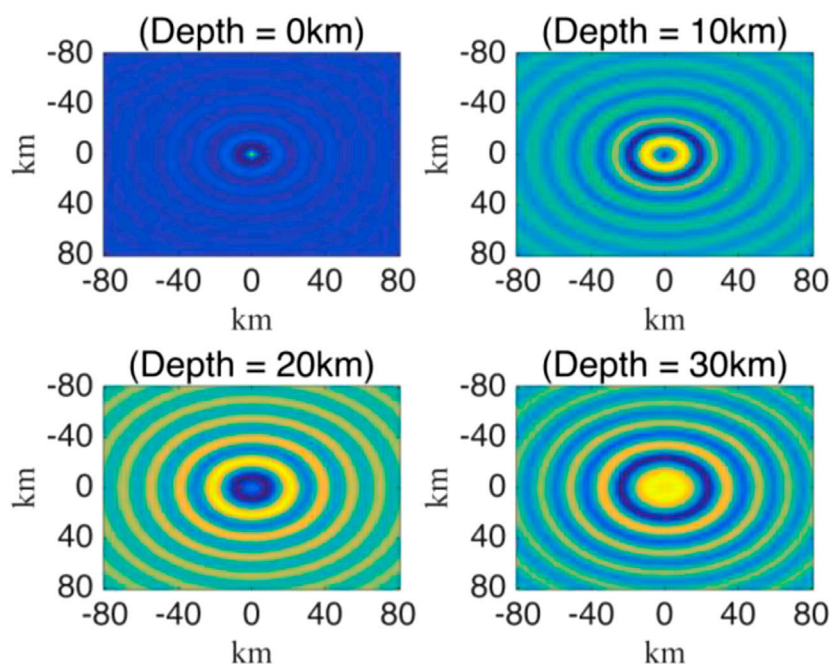
FIGURE 3
Influence of different source depths on multiring structure.

3 Source parameter estimation

Generally, we can use the waveform inversion method to invert the source parameters (Simute et al., 2023). However, due to the limitations of the actual data that is available, and the risk of multiple solutions for parameters with limited data constraints, we use the data fitting method to study this problem. During the data fitting process, the wavelength information of the multiring structure of the meteorite crater is mainly affected by the source depth, dominant frequency, and of the medium wave velocity. The simulation of the multi-ring structure of a meteorite crater is shown below.

Firstly, we can approximate the corresponding wavelength range based on the relationship between wavelength, wave velocity, and frequency as follows.

$$\lambda = v/f,$$

Where λ represents the wavelength information of the multiring structure, v represents the wave speed, and f represents the corresponding wave field frequency. The specific results are as follows.

In order to further estimate the relatively accurate source information, we can discuss the results. The rock structure of shallow surface craters is complex (Riller et al., 2018), but this study mainly focuses on low-frequency large-scale structure. To obtain the corresponding source depth. Here, we set the medium velocity to 1,500 m/s and the frequency to 0.1 Hz. Then, set different source depths for calculation. The source depth changes from 0 km to 30 km. The calculation result (Figure 3) shows that when the source is set at the surface, the first ring appears at the source, and as the depth increases, the diameter of the first ring gradually increases.

Therefore, we can use the first ring diameter information to constrain the source depth information.

Next, we consider the influence of frequency on the multi-ring structure. At this time, we set the medium velocity to 5,000 m/s, change the frequency from 0.1 Hz to 0.25 Hz, and set the source depth to 20 km. The calculation result (Figure 4) shows that as the calculation frequency gradually increases, the multi-ring structure becomes increasingly dense, which manifests as a shorter wavelength. This information can be used to extract the approximate source dominant frequency information more accurately from the waveform information shown in Figure 2.

Finally, considering the impact of the wave velocity on the circular structure, the dominant frequency was set to 0.1 Hz, and the wave velocity was changed from 1,500 m/s to 3,000 m/s, and the source depth was set to 20 km. The calculation result is shown in Figure 5.

After discussing the influence of different source parameters on the structure of the crater, we compared the crater multiring structure, actual waveform information, and theoretical simulation results. In the actual simulation, the determined medium velocity of the formation was 5 km/s, based on the actual crustal velocity model (Dziewonski and Anderson, 1981). The comparison results are shown in Figure 6. The research results show that when the source depth is 20 km and the calculated frequency is 0.15 Hz, the simulated theoretical wavelength results are closest reconstruction of the actual results. At the same time, some scholars believe that this density change is due to the different thicknesses of the layers of deposited caused by fluctuations in the seismic shear wave, which resulted in a change in density (Morgan et al., 2022). For seismic shear
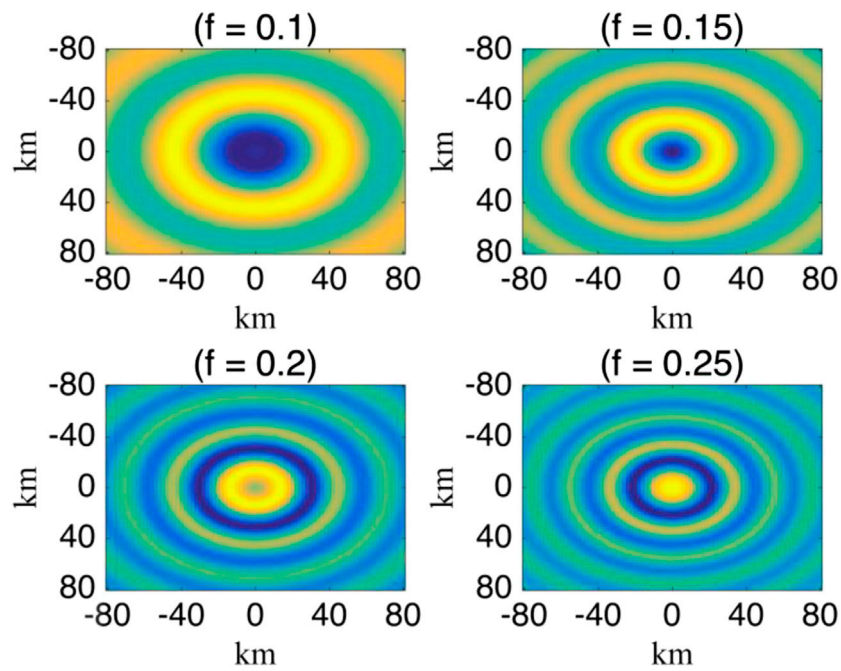
FIGURE 4
The impact of different frequencies on the structure of the multiple circles of the crater.
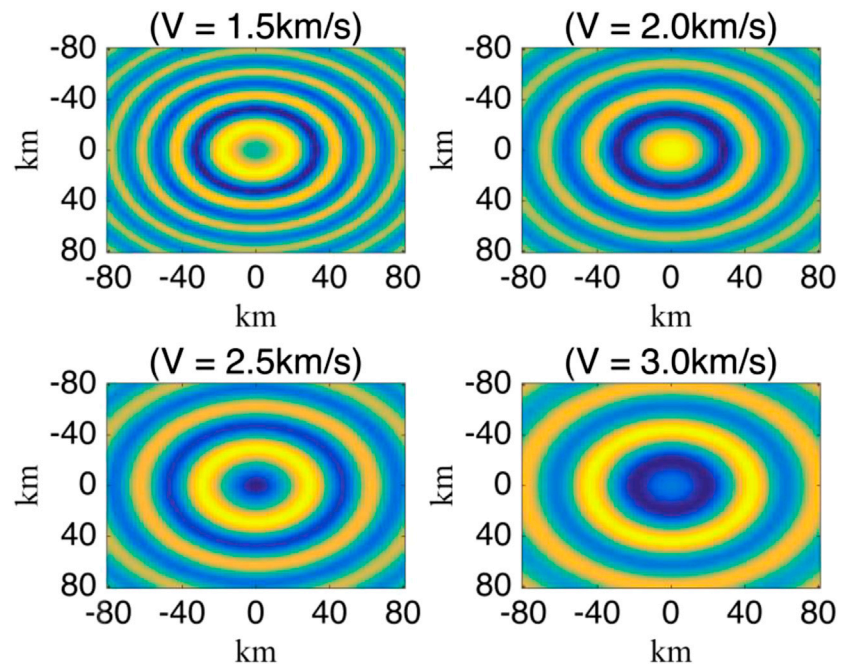
FIGURE 5
Effect of different wave velocities on the multi-ring structure of the crater.

waves, the main difference is that the wave velocity can vary to some extent, but for the simulated global impact of seismic fluctuations caused by meteorite impacts, such as those that are generated from a purely natural phenomena, this source parameter has little influence on the results.

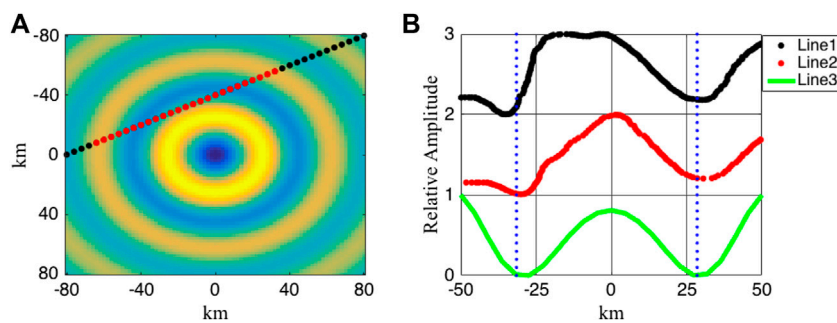Then, the corresponding source time function can be calculated.

FIGURE 6
(A) Simulated crater multiring structure, **(B)** Simulated waveform, noted as Line3 and the actual waveform comparison results.
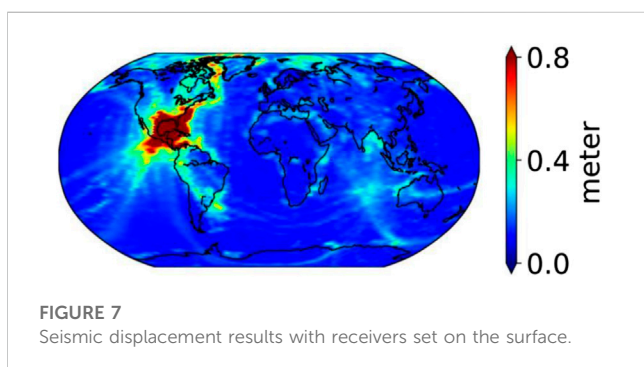

FIGURE 7
Seismic displacement results with receivers set on the surface.

4 Seismic wave effects on the solid earth

To estimate the harm caused by this event, relevant research was conducted on the source. For the meteorite impact process, previous theoretical analysis shows that the process is an external force impact problem (Yang and Chen., 2022). Therefore, the process is discussed first. For a force source, it can be expressed as $\vec{f} = F\overrightarrow{e_f}\delta(x - x_s)S(t)$, where F represents the amplitude, $\overrightarrow{e_f}$ represents the direction of the force, x_s represents the source position, and $S(t)$ is a source time function. The dominant frequency of the earthquake primarily has a specific impact on the amplitude value of the calculated results. The phenomenon of the presence of multiple circular fluctuations in meteorite craters indicates that this problem is a low-frequency seismological problem (Hildebrand et al., 1991). Considering the impact of the actual calculation amount and numerical accuracy, the half duration of the source time function in the following study is 15 s, and the calculated maximum frequency is approximately 0.11 Hz.

For the impact external force impact problem, we can use the impulse theorem to solve it. During the impact process, meteorites are mainly affected by the formation reaction force and the gravitational force of the Earth. The product of the gravitational force and time are negligible relative to the product of the impact velocity and mass of the meteorite, so it is approximately written as follows:

$$\int_0^t Fdt = mv,$$

If the Rake wavelet is approximated to a triangular function, the external force is approximately $F = 1.5 \times 10^{19}$ N. After obtaining the source information, we can conduct Seismic wave field simulation (Komatitsch and Tromp, 2002) to estimate the impact of this event on Solid earth.

In the process of using seismological methods to explore the influence of a meteorite impact on solid earth, we accidentally found that the area located beneath the impact of the Hiksurub meteorite would break due to the action of seismic waves, and the break showed clear similarities with the boundary between the Indian plate and the African plate (Figure 7).

As one of the four fundamental theories in the field of natural science in the 20th century, plate tectonics are as important to earth science as the theory of relativity, quantum mechanics, and molecular biology are to the fields of physics and biology (Zheng, 2018). Its development is of great significance to the further development of geology, geochemistry, seismology, geodynamics, rock physics, and other disciplines (Holder et al., 2019). Exploring its initiation mechanism and the timing period of events have always been one of the most innivative of questions to investigate in the field of earth science (Wan et al., 2020).

The theory of plate tectonics originated from the hypothesis of continental drift and the theory of seafloor spreading (Cwojdzinski, 2017). According to the theory of plate tectonics, the lithosphere is rigid relative to the asthenosphere, beneath which lies the low viscosity asthenosphere (Conrad and Lithgow-Bertelloni, 2002). The lithosphere is not a uniform entity, but contains directionally heterogeneous characteristics and is divided into large and small blocks by many active zones, such as mid-ocean ridges, trenches, transform faults, Earth sutures, and continental rifts. The interior of the plates are stable, while the edges and joint zones of the plates are active zones on the Earth's surface, with strong tectonic movement (Ouchi, 1985), magmatic activity (Pilger, 1984), volcanic activity (Canon and Walker, 2004), metamorphic rock (Holder et al., 2019), and seismic activity (Maouche et al., 2019). These active zones are also very favorable mineralization zones (Yang et al., 2022). Second, the lithospheric plates are themselves active. During continental drift, some plates move

away from each other, and some collide with each other to form various geological structures, such as the Mid-Ocean Ridge (Macdonald et al., 1988) and the Alpine Himalayan Fold Belt (Ali et al., 2019). Major volcanic activity zones and major deep seismic zones around the world are also mainly distributed in these plate fractures zones (Barrier et al., 2021).

Plate tectonics are important for the field of seismology. The vast majority of earthquakes in the world are mainly concentrated in the seismic zones. Seismic zones refer to regular banded areas where earthquakes are concentrated, and these seismic zones principally coincide with the tectonic plate edges (Dewey, 1972). There are three main seismic zones on the Earth, namely, the Pacific Rim seismic zone (Yin et al., 2019), the Eurasian seismic zone (Tang et al., 2020), and the oceanic ridge seismic zone (Kagan, 2003). The Pacific Rim seismic belt (Wu et al., 2019) is mainly distributed on the continental margin of the Pacific Ocean. This seismic zone is the primary earthquake area of occurrence area on Earth, where most catastrophic earthquakes with magnitude 8 or above and global earthquakes are concentrated (Yin et al., 2019). In addition, seismic zones are also the main volcanic activity zones in the world. The second largest seismic zone in the world is the Eurasian seismic zone (Wu et al., 2019). There is also much volcanic activity in this area. Historically, many large earthquakes have occurred in this area. This seismic zone is widely distributed and basically covers the Eurasian and African continents. Ocean ridge seismic zones (Wu et al., 2019) are mainly distributed in the Pacific, Atlantic, and Indian oceans, including almost all of the ocean ridge tectonic regions.

Therefore, the theory of plate tectonics involves almost all topics that exist in the field of solid earth science. The plate structure is a sign that the Earth is different from other planets. Due to plate tectonics, materials within the Earth can interact and circulate between circles. This process is beneficial to Earth becoming the current blue livable planet (Stern and Leybourne, 2016). Exploring the initiation mechanisms and timing of events are of great significance to the development of the geosciences.

Regarding the starting time of plate tectonics, based on geological rocks, the possibility that plate tectonics began 4.44 billion to 1 billion years ago has been analyzed (Stern and Leybourne, 2016; Johnson et al., 2017; Weller and Stonge, 2017; Stern, 2018). According to the paleomagnetic evidence, this time period of initiation was advanced to having occurred 800 to 600 million years ago (Piper, 2013). Therefore, it can be considered that the of the global movement plate tectonics do not necessarily start at the same time, and varying start times of different plate tectonic may accompany different time periods of the Earth's evolution. However, there is currently no detailed study on what forces caused the initiation of plate tectonics.

Currently, it is generally believed that there are two possible mechanisms for the initiation of plate tectonics, one is spontaneous generation, and the other is that they were induced by external factors (Zhang, 2022). Regarding spontaneous generation, the possibility of this situation was discussed through numerical simulation experiments (Gerya, 2014). However, this situation needs to reflect the existence of different densities that exist between different plates, and there are also weak zones between plates, which gradually evolve into subduction boundaries.

FIGURE 8
Seismic displacement results with receivers set at a depth of 50 km.
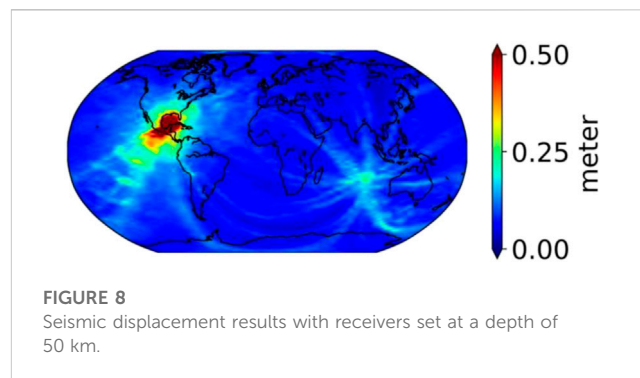
Regarding the theory that tectonics were induced by external factors, some scientists have considered the possibility of early meteorite impacts on the Earth leading to meteorite impacts inducing plate tectonics. By explaining the origin of the Tarsi uplift on Mars, they have speculated on the possibility of meteorite impacts leading to the origin of the Earth's plate tectonics (Yin, 2012; Maruyama et al., 2018). However, the above theory lacks quantitative constraints and corresponding direct evidence.

Figure 8 shows that due to the destructive effect of the strong seismic wave field energy on the solid earth, an obvious fault anomaly occurs in the Indian Ocean region, and the location of this fault anomaly is very consistent with the boundary of the earth plate. Therefore, we think that the meteorite impact event 66 million years ago may be the cause of this plate formation. To demonstrate that this fracture affects the entire lithosphere, we calculated seismic displacement results at different depths (Figure 8).

The research results show that this kind of fault has almost spread to the entire lithosphere, which may induce the formation of plates in the region. Of course, in addition to being affected by the seismic source, this calculation result can also be influenced by the Earth model. Here, the S362ANI model is used. Sixty-five million years ago, except for the Atlantic region, the Earth model was basically consistent with the current model (Merdith et al., 2021).

5 Conclution and discussion

Based on seismological methods, this study quantitatively explored the impact of seismic wave effects that were generated by meteorite impacts over 66 million years ago on the solid Earth itself. The research results show that this event promoted the formation of the Indian Ocean plate. This result is of great significance for improving our understanding of spatial distribution patterns of the globe disaster risk from outer space, as well as for the development of plate tectonics theory.

This study has also highlighted some unresolved issues in the field of earth science.

1. In addition to the formation of plate tectonics, meteorite impacts can also form some special internal and external anomalies of the Earth, but existing theories cannot well describe the dynamic formation process of these phenomena. In theory, the best mathematical and physical description method for this study

should be the application of geodynamics, which describe the process of meteorites impacting the Earth from the perspective of earthquake sources and geodynamics, as well as their infulence on the progression of future tectonic changes on Earth. However, the existing geodynamic methods mainly describe the Earth's change process on a large time scale. For the rapid external force effect of meteorite impact, further research may be needed. This method will have an important role in studying the past and present, and predicting the future of the Earth, and can also help us accelerate the evolution of exoplanets to make them more suitable for human beings.

2. The direct evidence for meteorite impacts primarily comes from the multi-ring structure of the crater. This study is generally aimed at extracting source parameter information from the multi-ring structure of a meteorite crater to conduct global seismic wave field simulation, without involving the dynamic formation process of the meteorite crater itself. The further development of elastoplastic wave theory in the future can better help us better understand the formation process of meteorite craters.

3. Among the numerous tectonic plate divisions, the most obvious is the boundary that exists between the American plate and the African plate. The continental drift hypothesis suggests that the two plates originally belonged to the same plate. Based on the comparison of similarities and differences between strata and rocks, it is theoretically possible to predict when the plate split in the past. For the development of the fracture mechanism, concurrent meteorite impacts may further verify this view.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

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Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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