Promotion of Circum-Pacific Earthquakes on Plate Movement

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Abstract

The dynamic mechanism of plate movement remains a mystery till today. To explore the mystery we calculated the large-scale deformations caused by two great circum-Pacific earthquakes, using the dislocation theory in a spherical Earth model. The result showed that the displacement and strain caused by the two events gradually expand from the area surrounding the epicenter to distant places after the earthquake. The steady-state tensile strain covers most of the Pacific Ocean, reducing the difficulty of mid-ocean ridge spreading, thereby promoting plate movement. This study confirms for the first time that there is a two-way relationship between the circum-Pacific earthquake and tectonic plate, and the viscous mantle of Earth plays a vital role in the relationship.

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Key Points

- Defromations caused by great earthquake gradually expand from the area surrounding the epicenter to distant places after the event.
- Steady-state tensile strain caused by circum-Pacific subduction earthquake promotes the lateral spreading of the East Pacific Rise.
- We propose a new seafloor spreading model, which confirms a two-way relationship between circum-Pacific earthquakes and tectonic plate.

Abstract

The dynamic mechanism of plate movement remains a mystery till today. To explore the mystery we calculated the large-scale deformations caused by two great circum-Pacific earthquakes, using the dislocation theory in a spherical Earth model. The result showed that the displacement and strain caused by the two events gradually expand from the area surrounding the epicenter to distant places after the earthquake. The steady-state tensile strain covers most of the Pacific Ocean, reducing the difficulty of mid-ocean ridge spreading, thereby promoting plate movement. This study confirms for the first time that there is a two-way relationship between the circum-Pacific earthquake and tectonic plate, and the viscous mantle of Earth plays a vital role in the relationship.

Plain Language Summary

The theory of plate tectonics demonstrated significant progress in the last century. The motion law and variation characteristics of tectonic plate have long been well understood, but its dynamic mechanism remains a mystery. To explore the relationship between circum-Pacific earthquakes and tectonic plate, we calculate the steady-state deformations caused by the Tohoku-Oki Mw9.0 earthquake in 2011 and the Chile Mw8.8 earthquake in 2010 using the spherical dislocation theory, analyze the temporal and spatial evolution characteristics of the co- and post-seismic deformations, and find that the two strong earthquakes produce steady-state tensile strain of 100 n , as well as horizontal displacement of more than 20 cm, in the East Pacific Rise. The tensile strain, covering most of the Pacific ocean, caused by the circum-Pacific earthquakes, leads to the lack of material on the ocean floor, which reserves space for the generation and lateral movement of new material at the mid ocean ridge, thus reducing the difficulty of seabed expansion. Our result confirms a two-way relationship between circum-Pacific earthquakes and tectonic plate.

1 Introduction

The theory of plate tectonics demonstrated significant progress in Earth science in the last century. Its motion law and variation characteristics have long been well understood, but its dynamic mechanism remains a mystery (*Chen et al.*, 2020). The dynamic hypotheses of plate movement include Earth rotation and celestial dynamic action hypothesis, Earth expansion hypothesis, inrush structure hypothesis, meteorite induced hypothesis, and mantle convection hypothesis, among which the mantle convection hypothesis is the most famous (*Wan*, 2011). The mantle convection hypothesis holds that the movement of the Lithospheric plate depends on the convection ring of the deep mantle. The plate is driven by the cold, heavy, and downward moving mantle to produce subduction, which causes the expansion of the ocean floor under the influence of the hot and upward moving mantle. The horizontal movement of the upper mantle drives the plate migration. However, high-precision Global Navigation Satellite System (GNSS) observations and ocean floor hot spot studies show that the migration rate of lithospheric plates is generally one order of magnitude higher than that of the mantle (*Raymond et al.*, 2000). The low-speed "conveyor belt" (mantle) cannot make the "goods" (plate) move rapidly, and the mantle convection hypothesis is difficult to be established. Therefore, scientists put forward the dynamic model of plate-driven mantle. Specifically, mantle material is extruded upward and cooled in the mid-ocean ridge to form a new ocean crust, driving the ocean crust on both sides of the ridge to move laterally. At the trench, the cold plates sink under the action of negative buoyancy (i.e., gravity is greater than buoyancy), resulting in mantle convection. However, the simulation shows that the lateral driving force of the new oceanic crust on the mid-ocean ridge and the negative buoyancy of the trench plate is limited, which is not enough to promote the lateral movement of the oceanic crust (*Wan*, 2011; *Forsyth and Uyeda*, 1975). Therefore, there should be another form of forces large enough to match the movement of the ocean floor up to thousands of kilometers.

There is a seismic zone around the Pacific Ocean, also known as the Baileov seismic zone. A large number of earthquakes occurred in this seismic zone, of which subduction earthquakes account for the vast majority (Fig. 1a). It is well known to us for a long time that the circum-Pacific earthquakes are the result of the plate movement. But whether circum-Pacific earthquakes affect the tectonic plate has not been deeply addressed till today. Recently, based on the GNSS observations on Anatolian plate, *Hornyak* (2022) speculated that there may be a two-way feedback relationship between earthquake and micro plate tectonic movement, and predicted that mantle viscous structure can modulate plate migration and seismic cycle. Therefore, the possible role and mechanism of earthquake on plate movement is a scientific problem that needs to be further studied.

Earthquake is a natural phenomenon, usually lasting less than 120 seconds (*Watts*, 2001). However, a great number of studies show that large earthquakes will not only cause significant co-seismic deformation, but will also be accompanied by post-seismic deformation (*Ozawa et al.*, 2011; *Vigny et al.*, 2011; *Wang et al.*, 2012). Generally speaking, post-seismic deformation can be divided into three parts: after-slip, poroelastic rebound and mantle viscosity relaxation effects, of which the latter will exist for a long time after the earthquake (*Sun et al.*, 2018). In fact, for the Earth with viscous mantle structure, large earthquakes should be organically composed of two parts: instantaneous co-seismic elastic rupture and long-term post-seismic viscous relaxation. Therefore, each large earthquake should be regarded as a persistent natural phenomenon rather than an instantaneous completion one. In view of this, this paper takes the steady-state deformation caused by typical strong earthquakes in the circum-Pacific seismic belt as the research object, and studies the temporal and spatial evolution of the deformation field caused by the mantle viscosity relaxation effect after strong earthquakes, discusses the feedback mechanism of the mantle viscosity relaxation effect on the ocean bottom strain field, and tries to reveal the mystery of the force of the Pacific plate movement.

2 Calculation method of steady-state seismic deformation

Dislocation theory gives the theoretical connection between the fault model of an earthquake and the corresponding seismic deformations the earthquake causes. Based on a fault slip model, the deformations on the earth's surface or inside the earth caused by the earthquake can be calculated by using dislocation theory (*Sun*, 2012). The correctness of relevant calculations has been confirmed by many GNSS and gravity observations (*Imanishi et al.*, 2004; *Xu et al.*, 2017; *Zhao et al.*, 2018). The spherical dislocation theory proposed by *Tang and Sun* (2019) can be used to accurately calculate the co-seismic deformation field and post-seismic mantle viscosity effect caused by any type of earthquake around the world.

Steady-state deformation refers to the accumulation of co-seismic deformation caused by an earthquake and the relaxation effect of mantle viscosity after the earthquake for a very long time. The spherical dislocation theory proposed by *Tang* (2020) can be used to quickly and accurately calculate the steady-state deformation. Considering that the viscoelastic relaxation effect persists for a long time (*Suito and Freymueller*, 2009), the steady-state seismic deformation can converge only after a long time after the earthquake.

To study the post-seismic deformation in a realistic gravitational viscoelastic earth model, *Tang and Sun* (2019) constructed the seismic deformation control equation based on the viscoelastic earth model, on basis of the consistency principle and the basic equation of elastic seismic deformation. According to the consistency principle, the deformation problem in linear rheological medium can be solved indirectly by a way of solving the deformation problem of equivalent elastic medium in complex domain. When considering the deformation problem of viscoelastic media, a usual method is to transform the constitutive relationship of viscoelastic media into a similar form of elastic media, then solve the equivalent elastic problem in Laplace domain to obtain the complex domain solution, and finally carry out the inverse Laplace transform to get the solution of viscoelastic deformation problem in time domain (*Pollitz* 1997; *Tanaka et al.*, 2006). However, when considering the steady-state problem of viscoelastic deformation caused by external forces in the time domain, the corresponding inverse Laplace transform cannot be calculated because the time scale is infinite, so the solution of the steady-state deformation problem cannot be obtained through the consistency principle. In view of this difficulty, *Tang* (2020) used the liquid mantle medium to replace the viscoelastic mantle medium of the actual earth, constructed an earth model of "solid core - liquid outer core and liquid mantle - elastic crust" to solve the problem of steady-state deformation. In this way he directly obtained the steady-state solution of viscoelastic deformation caused by earthquakes in the time domain. The above dislocation theories (*Tang and Sun*, 2019; *Tang*, 2020) provide a theoretical basis and calculation tool for this study.

Taking the 2011 Tohoku-Oki Mw 9.0 earthquake and the 2010 Chile Mw 8.8 earthquake as examples, this paper studies the deformations caused by earthquakes in the circum-Pacific seismic belt. Specifically, based on the slip models of the above two great earthquakes and the spherical dislocation theory (*Sun and Okubo*, 1993; *Tang and Sun*, 2019; *Tang*, 2020), we calculate the large-scale co-seismic, post-seismic and steady-state deformations caused by them with high precision, and discuss their contribution to plate movement.

In our process of calculating seismic deformation, the thickness of the earth's elastic layer is set as 50 km, the viscosity of the mantle is set as 10^{19} Pa s, the elastic medium parameters refer to the PREM *(Dziewonski and Anderson*, 1981), and the fault model comes from published researches (*Wei et al.*, 2012; *Yue et al.*, 2014). When calculating the steady-state deformation, the viscoelastic mantle of the actual Earth is replaced by liquid medium, and the solution is obtainable directly. The steady-state deformation mainly depends on the thickness of the elastic layer rather than the viscosity distribution, which can only change the time to reach the steady-state deformation. In addition, when the focal depth exceeds the thickness of the elastic layer, there is no shear fracture in the liquid mantle of the new earth model. Therefore, when calculating the steady-state deformation, it is necessary to abandon the dislocation signal in the viscoelastic layer of the actual Earth and only retain the dislocation information in the fully elastic medium. The rupture of the 2011 Tohoku-Oki Mw 9.0 earthquake is completely concentrated in the elastic layer, and the fault model does not need special treatment. However, the depth of part rupture of the 2010 Chile Mw 8.8 earthquake reaches 80 km, and the dislocation signal below 50 km needs to be discarded when calculating the steady-state deformation. Finally, the far-field deformation caused by an Earthquake is linearly related to the seismic moment, and is little affected by the slip distribution of fault plane (*Zhao et al.*, 2018).

3 Steady-state deformation caused by two great earthquakes

According to the slip models of the 2011 Tohoku-Oki Mw 9.0 earthquake (*Wei et al.*, 2012) and the 2010 Chile Mw 8.8 earthquake (*Yue et al.*, 2014), we calculated the steady-state horizontal deformation caused by the two great events in the whole Pacific region with high accuracy, using the spherical dislocation theories established by *Tang and Sun* (2019) and *Tang* (2020). Steady-state deformation refers to the accumulation of co-seismic deformation caused by an earthquake and the relaxation effect of mantle viscosity after the earthquake for an infinitely long time. The above two earthquakes were located in the circum-Pacific seismic belt. Both of them were typical trench subduction strong earthquakes, and the seismic displacement field and strain field are representative.

Figure 1a shows the steady-state horizontal displacements caused by the above two great earthquakes in the Pacific and surrounding area. The yellow isolines represent the magnitude of horizontal displacement. The red and blue arrows denote the directions of horizontal displacement caused by the Tohoku-Oki Mw 9.0 earthquake and the Chile Mw 8.8 earthquake, respectively. Taking the eastern boundary of the Pacific plate as the dividing line, we draw the steady-state displacement fields of the above two earthquakes (Fig. 1a). The steady-state horizontal displacement field covers the Pacific Ocean, which is significantly different from that the co-seismic displacement field which is mainly distributed around the source (*Wei et al.*, 2012; *Suito and Freymueller*, 2009). In other words, within the entire Pacific plate, the Tohoku-Oki Mw 9.0 earthquake caused significant northwest horizontal displacements. At the East Pacific Rise, about 10000 kilometers away from the epicenter, the Tohoku-Oki Mw 9.0 earthquake caused a horizontal displacement of about 5 cm. The Chile Mw 8.8 earthquake, relatively closer to the East Pacific Rise, caused a steady-state horizontal displacement of nearly 20 cm around the seamount.

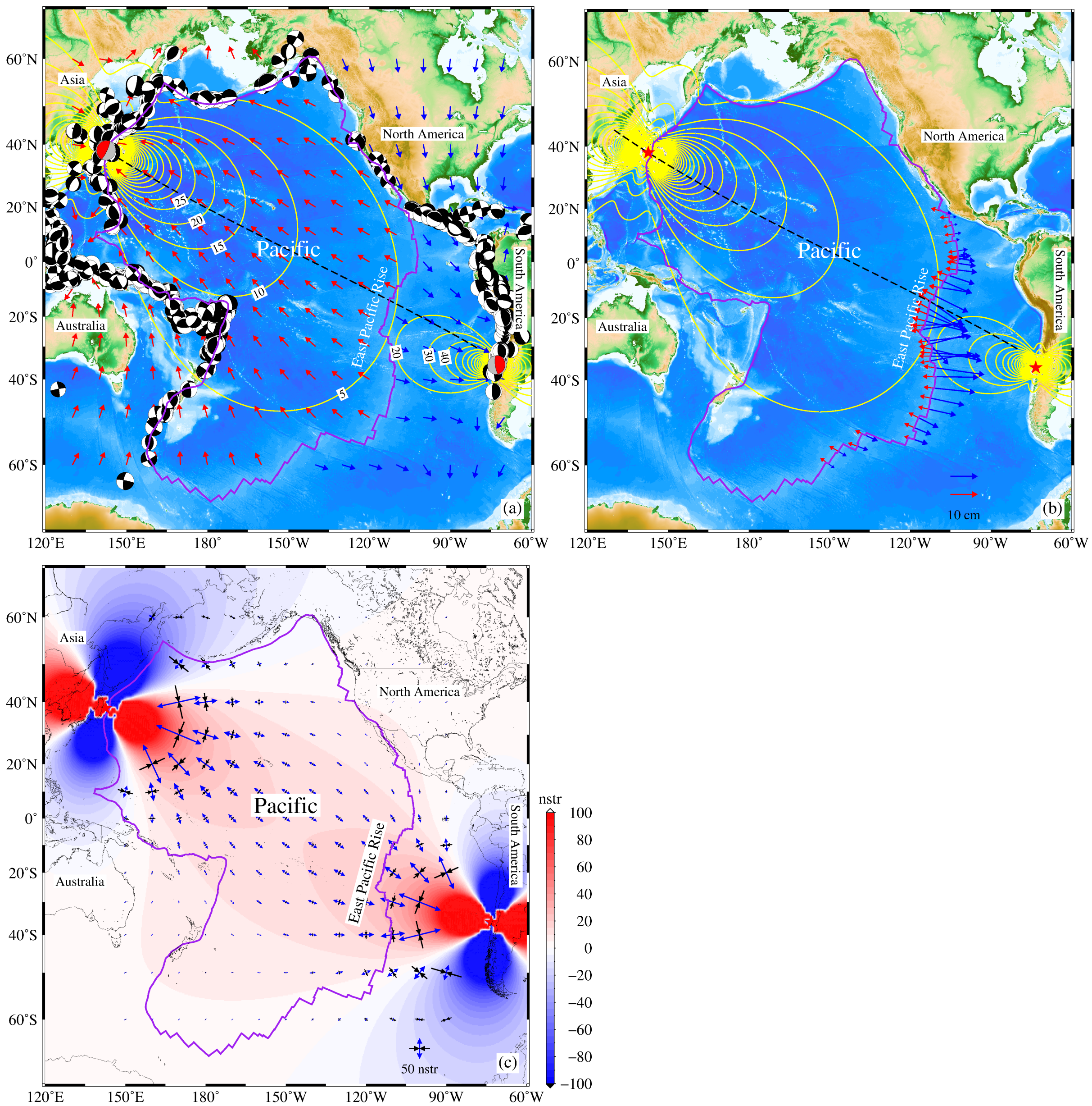

Figure 1. Steady-state deformations caused by the 2011 Tohoku-Oki Mw 9.0 earthquake and the 2010 Chile Mw 8.8 earthquake. (a) Steady-state displacements. The unit is cm. Black-and-white spheres denote the focal mechanism solutions of earthquakes with M 7.0 around the Pacific Ocean since 1970. (b) Expansion of normal direction caused by the two earthquakes in the East Pacific Rise. (c) Steady-state strain field. The color gives the magnitude of surface strain. The double arrows indicate the direction of horizontal strains.

Taking the mid-ocean ridge as a weak boundary, we show the component of the steady-state horizontal displacement caused by the two great earthquakes in the normal direction of the East Pacific Rise (Fig. 1b), which is roughly the same as the direction of expansion there. The two great events expanded the East Pacific Rise by 5 cm and 20 cm, respectively.

Figure 1c shows the steady-state horizontal strain produced by the two earthquakes in the whole Pacific region. Around the epicenter of the two great earthquakes, the strain field presents a four-quadrant distribution pattern, with compressive strain in the direction parallel to the trench and tensile strain in the direction perpendicular to the trench. The whole Pacific plate presents an apparent state of tensile strain, and the magnitude gradually decreases with the increase of epicentral distance. The strain in the East Pacific Rise reaches 100 n . The tensile strain direction is very similar to the overall normal direction of the East Pacific Rise, that is, the direction of the expansion of the mid-ocean ridge. The results show that owing to the two great earthquakes, the crust of the entire Pacific plate has undergone continuous tension, which makes the transverse expansion of the mid-ocean ridge easier. The new material produced in the mid-ocean ridge only needs to naturally fill the material loss associated with the tension and does not need a substantial transverse pushing force. In other words, the tensile strain covering the entire Pacific plate has reserved space for the generation and lateral movement of new materials in the mid-ocean ridge, reducing the difficulty of seafloor spreading. Therefore, the circum-Pacific earthquakes are not only the result of plate movement but also an important driving force of plate movement and seafloor spreading.

Figure 2 shows the temporal and spatial evolution of co-seismic and post-seismic cumulative horizontal displacements caused by the Tohoku-Oki Mw 9.0 earthquake. The profile position corresponds to the dotted line in Fig. 1a. The horizontal displacement in the southeast direction is positive, and the one in the northwest direction is negative. Figure 2a shows the near-field horizontal displacement caused by the great earthquake. The co-seismic displacement is dominant in the near field. The subsequent post-seismic deformation is only adjusted based on co-seismic deformation, but does not change the overall distribution. Figure 2b shows the seismic deformation with an epicentral distance of 12 to 60 degrees. In this interval, the co-seismic signal is very small, but the cumulative deformation after the earthquake is relatively significant, up to 0.6 m. Figure 2c shows the evolution of deformation with an epicentral distance of 60 to 140 degrees, in which the vertical dotted line corresponds to the location of the East Pacific Rise. In this range, the co-seismic displacement is close to 0. Still, the cumulative amount of post-seismic displacement can reach the decimeter scale, much greater than the co-seismic deformation. Figure 2 shows that the steady-state displacement caused by the Tohoku-Oki Mw 9.0 earthquake in the near field is mainly controlled by the co-seismic signal, but the far-field displacement is mainly controlled by the post-seismic mantle viscosity relaxation effect. In other words, the impact of the earthquake in the initial stage was mainly limited to the area around the epicenter, but with time, due to the existence of the mantle viscosity relaxation effect, the impact range of seismic deformation gradually expands to the surrounding area. From the perspective of far-field seismic deformation, the Tohoku-Oki Mw 9.0 earthquake was not a natural phenomenon completed in a short time, but a natural event lasting more than 10000 years. As a result, in a strictly scientific sense, the great earthquake should be regarded as a persistent natural phenomenon rather than an instantaneous one.

In addition, it can be seen from Fig. 1a that the Tohoku-Oki Mw 9.0 earthquake and the Chile Mw 8.8 earthquake produced significant convergence near the oceanic trench, which will undoubtedly promote the downward insertion of trench plates. Therefore, the dynamic source of the downward movement of the trench plate confirmed by numerous observations and studies (*Chen et al.*, 2020; *Zahirovic et al.*, 2015) should partly come from the co-seismic deformation of the earthquake and the viscous relaxation effect of the mantle after the earthquake, but not only the negative buoyancy of the plate material. The subduction earthquake near the oceanic trench can generate enough energy to promote the plate insertion under the support of the viscous mantle of the Earth.

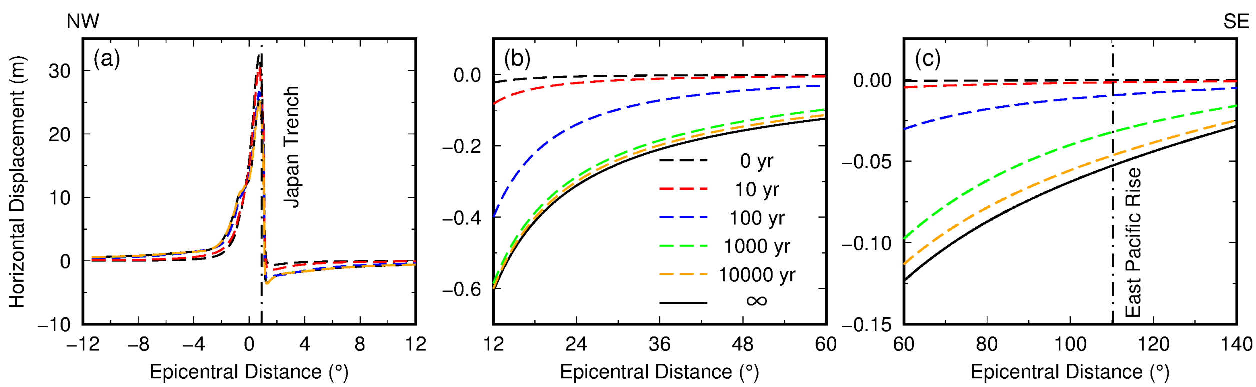

Figure 2. Evolution of co- and post-seismic horizontal displacements caused by the 2011 Tohoku-Oki Mw 9.0 earthquake.

4 A new Pacific seafloor spreading model

We construct a new model of Pacific plate movement and seafloor spreading (Fig. 3). There is a two-way feedback between the circum-Pacific earthquake and plate movement at the trench. On the one hand, plate movement makes the crust on both sides of the oceanic trench converge, which promotes the occurrence of earthquakes. On the other hand, the circum-Pacific earthquake causes the subduction plate of the trench to undergo downward movement, and the viscous structure of the mantle ensures that this downward movement continues a long time after the earthquake. The continuous convergence will modulate the plate movement and promote the occurrence of new earthquakes. On the Pacific Ocean, the circum-Pacific earthquake promoted the expansion of the oceanic floor. The trench subduction earthquake makes the Pacific plate generate co-seismic displacement in the trench direction (Fig. 3a). Subsequently, the relaxation effect of mantle viscosity makes the oceanic crust continuously move in the trench direction. With time, the influence range of the earthquake becomes larger and larger so that tensile strain is generated on the whole Pacific plate. Under the action of this tensile strain, the mantle material at the bottom of the East Pacific seamount rises to form a new crust and then moves laterally to fill the material loss associated with the tensile strain of the ocean floor (Fig. 3b). In other words, the lack of ocean floor material, accompanied by the extensional action of the earthquake on the entire Pacific Ocean floor, is filled by the lateral extrusion of new material from the mid-ocean ridge so that the whole Pacific plate shows a northwest movement of 70.1mm/yr (*Jin and Zhu*, 2002). The movement mode is similar to an instantly elongated rubber band. One end is slowly released to return to its natural state gradually, and the released end is connected with a new rubber band.

This study shows a two-way feedback relationship between the circum-Pacific earthquake and the Pacific plate movement. The core element of this relationship lies in the existence of viscous mantle structure on the Earth, which leads to the long-term deformation after the earthquake. The effect gradually expands out from the area around the epicenter. The results confirm the prediction that the viscous mantle structure can modulate the plate movement (*Hornyak*, 2022). The spatial irregularity of earthquake distribution can explain the plate movement in different directions (*Faccenna et al.*, 2013), and the migration of earthquakes can explain the temporal change of plate movement. The internal relationship between circum-Pacific earthquakes, mantle viscous structure and plate movement lays a foundation for unraveling the century mystery of the dynamic source of plate movement.

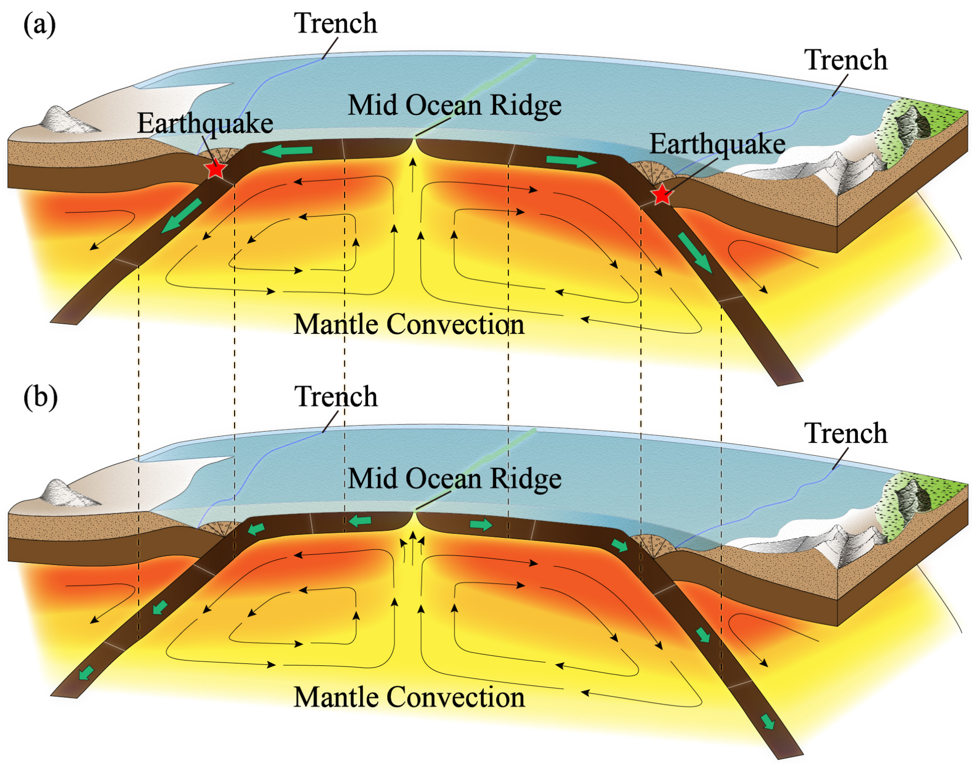

Figure 3. Schematic diagram of Pacific seafloor spreading and plate movement. (a) Co-seismic crustal deformation. (b) Crustal deformation after an earthquake (post-seismic mantle viscosity relaxation effect plus mid-ocean ridge spreading).

Finally, the mid-ocean ridge spreading also plays a vital role in filling the material loss caused by tensile strain at the ocean floor. Considering the long duration of steady-state deformation, the displacement caused by earthquakes is lower than the displacement converted by the observed crustal expansion rate of the East Pacific Rise (>10 cm/yr). The difference between them is mainly filled by the generation and lateral expansion of new materials of the mid-ocean ridge.

5 Conclusion

For the Earth with viscous mantle structure, a large earthquake is organically composed of instantaneous co-seismic elastic rupture and long-term post-seismic viscous relaxation. Therefore, each large earthquake should be regarded as a persistent natural phenomenon rather than an instantaneous completion one. In view of this, we calculated the large-scale steady-state deformations caused by the 2011 Tohoku-Oki Mw 9.0 earthquake and the 2010 Chile Mw 8.8 earthquake using the spherical dislocation theory, and analyzed the temporal-spatial evolution characteristics of the co- and post-seismic deformations. The co-seismic deformation is mainly distributed around the epicenter, but the post-seismic deformation gradually expand to distant places. The above two strong earthquakes produce steady-state horizontal displacement of more than 20 cm and tensile strain of 100 n in the area as far as the East Pacific Rise. The tensile strain covers most of the Pacific Ocean, resulting in the lack of material on the ocean floor and reserves space for the generation and lateral movement of new crust on the East Pacific Rise, thus reducing the difficulty of seafloor spreading. The above result confirms the promotion of circum-Pacific earthquakes on tectonic plate.

Data Availability Statement

The co-seismic and post-seismic displacement and strain data supporting this article are provided in the Supporting Information (Tables S1a, S1b, S1c and S2) and are uploaded in the open-access repository Zenodo for sharing purpose (https://doi.org/10.5281/zenodo.6809507).

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