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Fast and Slow Subduction Earthquakes in Latin America

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earthquakes, slow slip events, subduction, seismic gap, Latin America

Abstract

Most seismicity in Latin America is controlled by the subduction process. Different zones have hosted earthquakes of magnitudes larger than Mw 8.5 that repeat every several centuries. Events around Mw 8.0 are more frequent; since the beginning of the twentieth century, some collocated earthquakes have occurred with differences of decades, which allows for comparison of old and modern seismological records. The rupture zones that have hosted mega-earthquakes continue to produce smaller earthquakes after three centuries. Therefore, the process of unlocking in the Latin America subduction zone occurs by giant ($\geq$Mw 9.0), mega- ($9.0 >$ Mw ≥ 8.5), and large ($8.5 >$ Mw ≥ 7.5) earthquakes, and interaction between these events is not yet fully understood. We have less understanding of the earthquakes that occurred in the oceanic plates, which have not been correctly recorded due to poor seismological instrumentation and lack of knowledge about subduction during the first half of the twentieth century in Latin America. Slow earthquakes have been observed in some zones of Latin America, several of them with recurrence periods of a few years, as well as tectonic (nonvolcanic) tremors and low-frequency and very low-frequency earthquakes. How do these slow slip manifestations relate to ordinary earthquakes? This question is still difficult to answer for Latin America given the lack of dense geodetic and seismic networks that allow identification of all the slow earthquakes that likely occur more frequently than currently reported.

- Latin America subduction zones share similar seismic characteristics. They can host large-magnitude earthquakes and exhibit a variety of slow earthquakes.

- Giant earthquakes, with a magnitude greater than 9, have occurred so far in Chile, and mega-earthquakes have occurred in several Latin American countries.
- Additional slow earthquakes will be detected in Latin America as seismic and geodetic networks become denser.

1. INTRODUCTION

Understanding the seismicity of Latin America is a challenge. This region has hosted the largest earthquakes in the world, events of magnitudes larger than 8.5, such as the 1960 Mw 9.5 Valdivia earthquake (e.g., Kanamori & Cipar 1974, Cisternas et al. 2005, Ruiz & Madariaga 2018, Salazar et al. 2022, Ramírez-Herrera et al. 2024). These extreme events have occurred because of the subduction of the Cocos and Nazca plates under the North and South American plates. Additionally, events of magnitudes close to 8.0 are common; during the twentieth century, an event larger than 8.0 occurred approximately once every 5 years. **Figure 1** shows large ruptures in the western seaboard of Latin America. The relative scarcity of very large events in some places may be due to long return periods that extend beyond the beginning of instrumental seismology around 1900, a situation similar to that in the Cascadia subduction zone (Satake et al. 1996). Evaluating the current seismicity rate in Latin America is difficult due to the sparseness of the seismological stations managed by national seismological centers (Barrientos & Pérez-Campos 2018). These sparse geodetic and seismic networks have prevented the identification of slow earthquakes, events that generate seismic waves inefficiently relative to ordinary earthquakes (e.g., Beroza & Ide 2011) but that have begun to be identified in a more systematic way during the last decade due to geodetical and seismological stations recording for a long time and temporary dense network deployments (e.g., Dascher-Cousineau & Bürgmann 2024). In the past 20 years, observations associated with slow earthquakes have been reported in Mexico, Costa Rica, Ecuador, and Chile (e.g., Kostoglodov et al. 2010, Ide 2012, Jiang et al. 2012, Vallée et al. 2013).

Latin American countries share a common history associated with the arrival of the Spanish and Portuguese at the end of the fifteenth century and the beginning of the sixteenth. The Europeans did not preserve the culture and history of the native peoples, so there is information only since the period of European conquest (approximately five centuries). Earthquake information before the fifteenth century has become available based on paleoseismological studies (e.g., Cisternas et al. 2005, Ramírez-Herrera et al. 2020, Easton et al. 2022) and archaeology (e.g., Rodríguez-Pascua et al. 2020, Salazar et al. 2022, Pérez-López et al. 2024). Since the end of the fifteenth century, information about earthquakes can be found in books, newspapers, and letters sent to the kings by Spanish settlers, preserved to this day in the General Archive of the Indies in Granada, Spain (Giesecke et al. 2004, Udías et al. 2012). At the beginning of the twentieth century, seismologists began to compile the first historical seismic catalogs. For Central America and Chile, Montessus de Ballore did much of this work (Montessus de Ballore 1912, Cisternas 2009). These initial catalogs were improved and complemented during the twentieth century in different countries (e.g., Lomnitz 1970, Silgado 1978, White 1984, Giesecke et al. 2004, Egred 2009, Beauval et al. 2010, Suárez et al. 2020). From these first catalogs, it was possible to identify areas where earthquakes seemed to repeat themselves periodically and where earthquakes had not occurred for many decades, which were designated as seismic gaps by Kelleher (1972) and Kelleher et al. (1973). These pioneering works also identified areas with a higher probability of breaking in future events (Lay & Nishenko 2022). The main challenge with the identification of gaps was to have adequately long catalogs and good earthquake characterization (e.g., Husker et al. 2023).

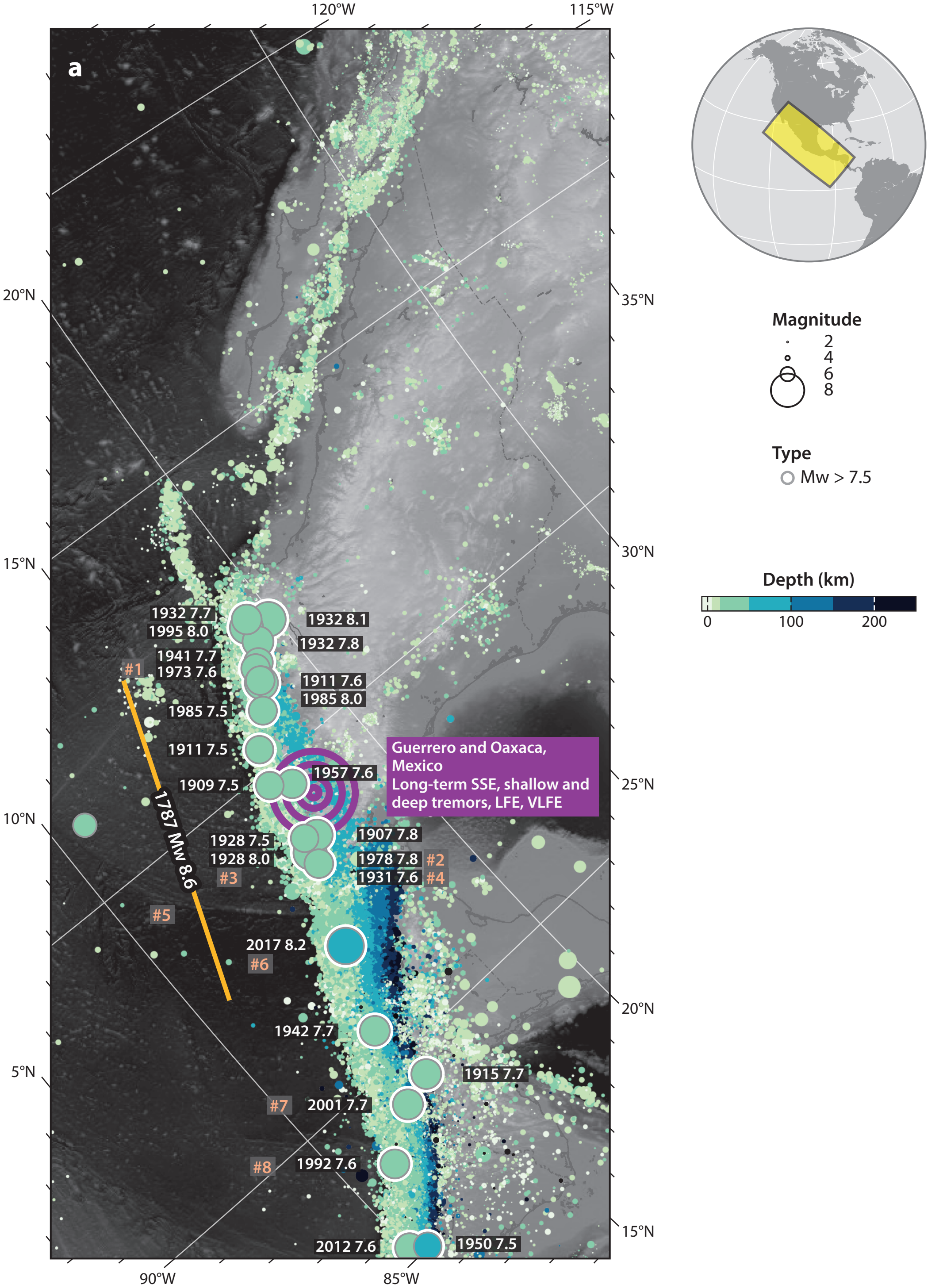

Figure 1

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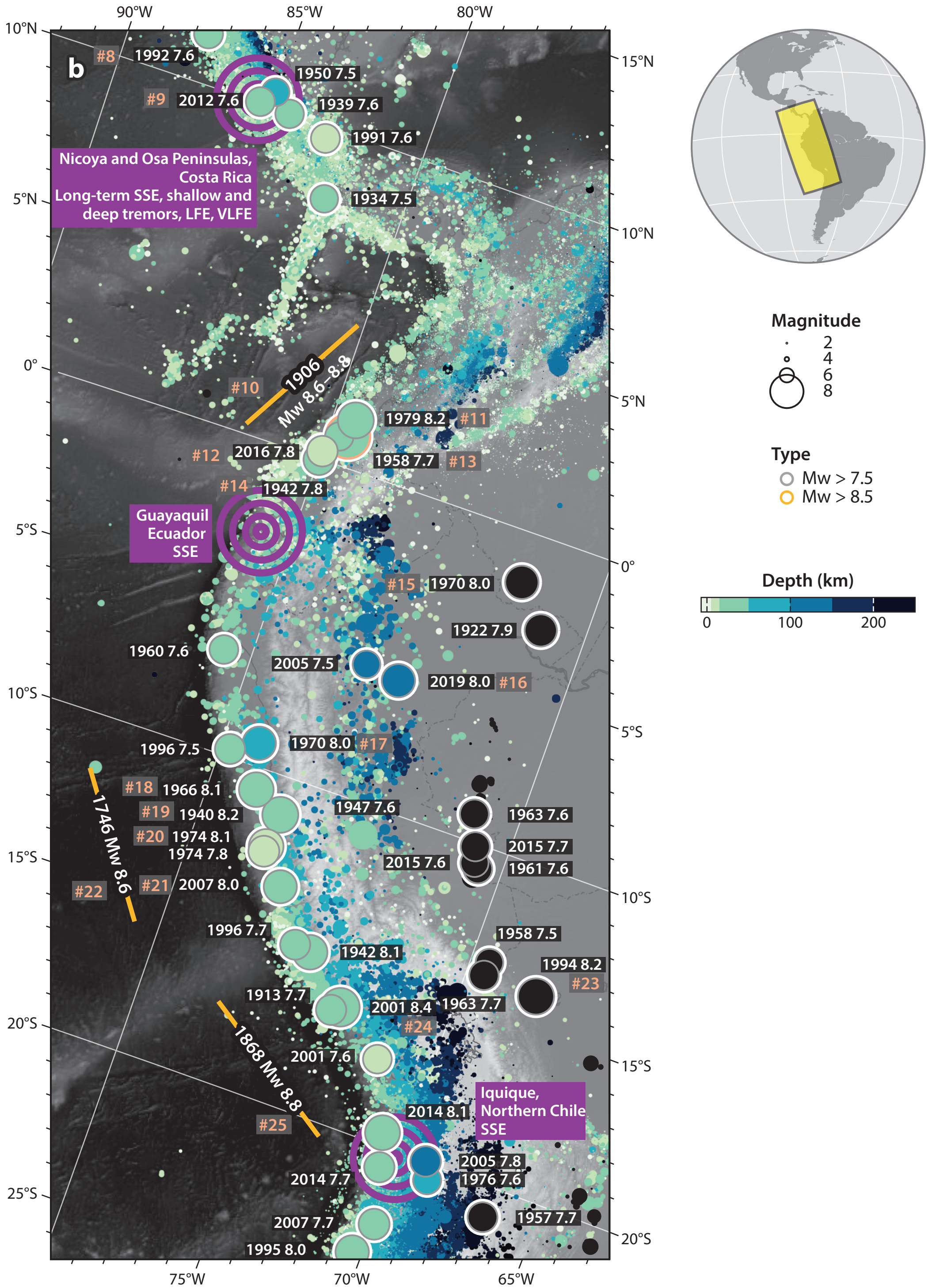

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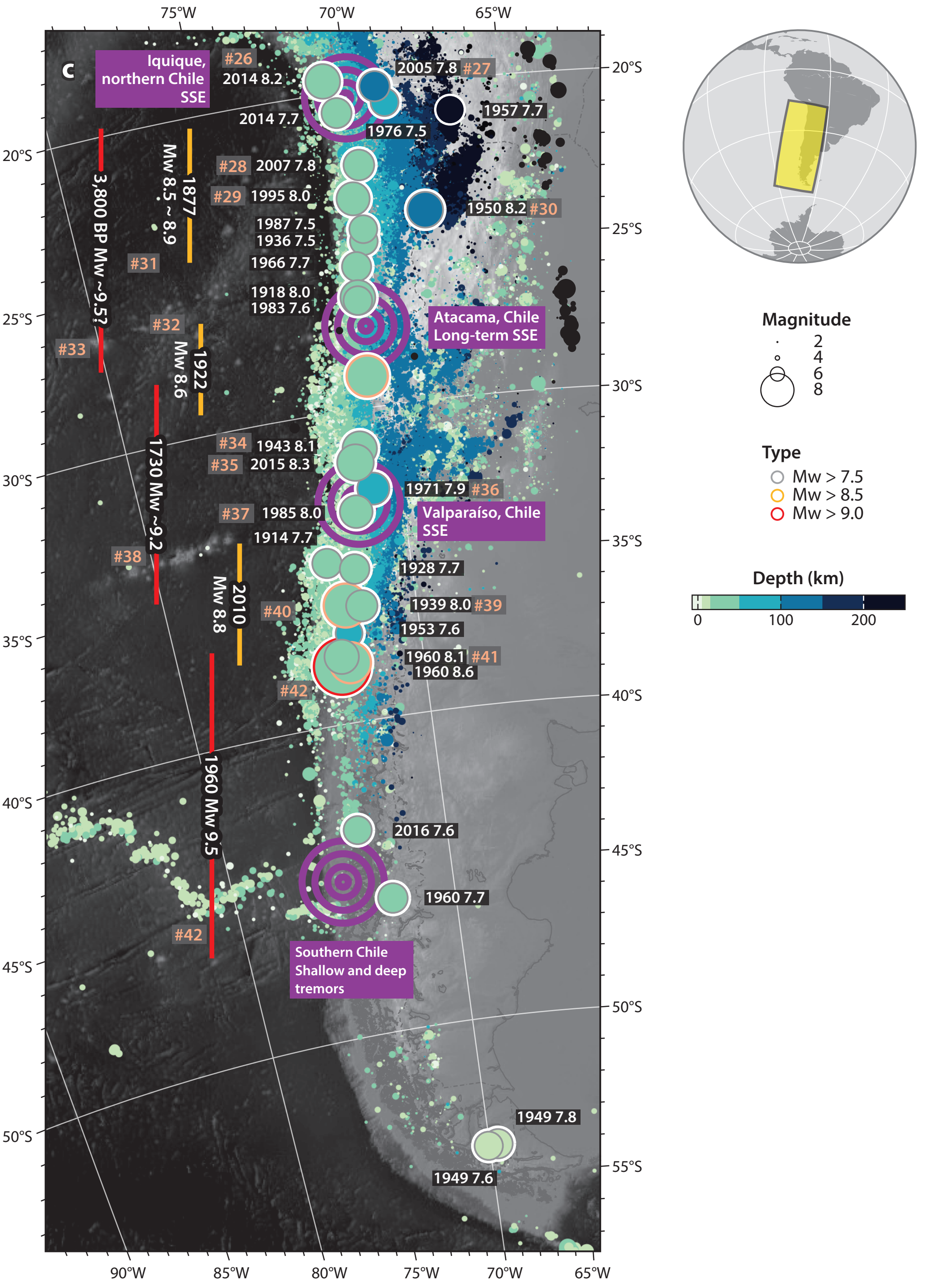

(Caption appears on following page)

Figure 1 (*Figure appears on preceding page*)

Giant, mega-, and large earthquakes in (*a*) northern, (*b*) central, and (*c*) southern Latin America. Red and yellow lines are the estimated length ruptures of giant and mega-earthquakes, respectively. Dots are epicenters of the events reported in the ISC catalog from 2010 to 2022, and dot size represents magnitude; circled dots indicate events with magnitudes larger than 7.5 from 1904 to 2020, reported by the ISC-GEM catalog (Di Giacomo et al. 2018, Int. Seismol. Cent. 2024). Dot colors relate to earthquake depth. Purple concentric circles indicate where the most important slow earthquakes, nonvolcanic tremors, LFEs, and VLFEs have been located. Events identified with a number are mentioned in the text. Abbreviations: GEM, Global Earthquake Model; ISC, International Seismological Centre; LFE, low-frequency earthquake; SSE, slow slip event; VLFE, very low-frequency earthquake. Topography comes from Tozer et al. (2019).

In recent decades, the catalogs have been extended and completed from the work of paleoseismologists and archaeologists. The reanalysis and better classification of some events have allowed us to improve locations, magnitudes, and identification of event types (e.g., inter- or intraplate). In Kelleher's early works (Kelleher 1972, Kelleher et al. 1973), most of the large events were attributed to subduction when in fact these zones present a diversity of types of earthquakes (Ruiz & Madariaga 2018). The recent discovery of slow earthquakes (Beroza & Ide 2011) also raises the challenge of how these slow movements are connected to ordinary earthquakes (Obara & Kato 2016). The first observation from GPS data of a slow earthquake in Latin America was made in 2001 in Mexico when an event of magnitude 7.5 with a duration close to 7 months took place in the Guerrero seismic gap (Lowry et al. 2001, Kostoglodov et al. 2003). This short observation window from the first report of slow earthquake in Latin America in 2001 until now prevents us from fully understanding what role these events play in the occurrence of large earthquakes in Latin America.

Here we review the largest Latin American earthquakes and the slow earthquakes reported so far. First, we describe the giant earthquakes, events with a magnitude larger than 9.0, where we highlight the Valdivia 1960 Chilean earthquake of magnitude 9.5 (Kanamori & Cipar 1974) and two additional giant earthquakes proposed by the interpretation of chronicles and paleoseismological studies in central Chile in 1730 (Udías et al. 2012, Dura et al. 2015) and the paleoseismological and archeological identification of the Atacama social disruption that occurred 3,800 years ago, possibly triggered by a giant earthquake of ∼Mw 9.5 (Salazar et al. 2022). Next, we study the most recent mega-earthquakes in Latin America, events of magnitudes larger than 8.5 and lower than 9.0. From north to south, a mega-earthquake of 450 km in rupture length of magnitude 8.6 was reported in Mexico in 1787 (Núñez-Cornú et al. 2008, Suárez & Albini 2009). To the south, we have the Ecuador-Colombia mega-earthquake in 1906 with a magnitude of Mw 8.8 estimated by Kanamori & McNally (1982). In central Perú, a mega-earthquake with a rupture length of 350 km occurred in 1746 that triggered a catastrophic tsunami that devastated the port of Callao (Dorbath et al. 1990, Okal et al. 2006); other tsunamigenic mega-earthquakes of magnitude Mw 8.8 occurred in 1868, and another one of magnitude Mw 8.5 occurred in northern Chile in 1877 (Dorbath et al. 1990, Comte & Pardo 1991, Vigny & Klein 2022). Next, we summarize the mega-earthquake of 1922, Mw 8.6 in Atacama in north-central Chile (Kanamori et al. 2019), and the recent event of magnitude Mw 8.8 that occurred in south-central Chile in 2010 (Vigny et al. 2011, Moreno et al. 2012). We then review the large earthquakes that occurred in Latin America, events of magnitude around Mw 8.0 collocated after a few decades (e.g., Singh et al. 2024), and the characteristics of large events that have begun to occur in areas where giant earthquakes or mega-earthquake took place a few centuries ago. In the last part of this article, we briefly discuss some relevant earthquakes that have occurred within oceanic plates. Crustal earthquakes are not described in this review. Finally, we report the slow earthquakes that have occurred in Latin America, such as slow slip events (SSEs), tectonic tremors, low-frequency earthquakes (LFEs), and very low-frequency earthquakes (VLFEs), that have been detected in well-instrumented areas by dense networks of seismographs, such as Mexico, Costa Rica, Ecuador, and Chile.

2. GIANT EARTHQUAKES

In this section, we review the giant earthquakes, which we define as those events with Mw greater than 9.0. These occur very rarely, and during the instrumental period (that starts approximately since 1900) only 3 events have exceeded the magnitude of 9.0: Mw 9.2 Alaska in 1964, Mw 9.1 Sumatra in 2004, and the Mw 9.5 1960 Valdivia earthquake in Chile (Bilek & Lay 2018, Wirth et al. 2022). Even the proposal of such large events from paleoseismology studies and historical data is rare worldwide, so here we also highlight the only two ancient events that occurred in Latin America that are proposed as giant: the giant earthquake in 1730 in central Chile that is inferred from historical evidence and the giant event that occurred 3,800 years ago in Atacama, Chile, that is inferred from paleoseismological and anthropological data. These giant earthquakes are shown in **Figure 1**.

2.1. The Mw 9.5 Valdivia Earthquake of 1960 in South-Central Chile

The only giant earthquake recorded by geophysical instruments is the 1960 Valdivia earthquake of Mw 9.5 (**Figure 1*c***, #42) hosted in the southern Chile subduction zone (Kanamori & Cipar 1974, Cifuentes 1989, Ho et al. 2019). This event broke the entire locked part of the subduction interface over a length of almost 1,000 km, triggering a trans-Pacific tsunami and significant uplift and subsidence along the Chilean coast. These coastal level changes were measured by Plafker & Savage (1970) who proposed the first slip distribution. Their data allowed more recent works to expand upon their results by incorporating improved numerical modeling and inversion (Barrientos & Ward 1990, Moreno et al. 2009, Ho et al. 2019). The 1960 event suggests that contrary to what was assumed in the 1970s, giant earthquakes do not repeat every ~100 years but occur instead every several centuries, with smaller-magnitude earthquakes (~8.0–8.5) between them (Cisternas et al. 2005, 2017; Garrett et al. 2015; Ruiz & Madariaga 2018). Interestingly, the unlocking process of this sequence began one day before the giant event with a magnitude 8.1 foreshock (**Figure 1*c***, #41) located in the deepest part of the plate interface (Cifuentes 1989, Ojeda et al. 2020) that triggered a sequence of major foreshocks that ended with the May 22, 1960, Mw 9.5 mainshock (Cifuentes 1989). Immediately before the mainshock, Kanamori & Cipar (1974) detected a slow slip precursor in the long-period strain seismogram recorded at Pasadena.

2.2. The 1730 Valparaíso Earthquake in Central Chile (Mw Close to 9.2)

On July 30, 1730, a giant earthquake occurred in central Chile (**Figure 1*c***, #38) in a zone that since that event has presented a high level of seismic activity with many large earthquakes of Mw close to 8.0. Udías et al. (2012) analyzed all the historical information available about the 1730 earthquake in the Indian Archive of Spain and estimated from the reported damage the enormous extent of this event. Carvajal et al. (2017a) also reinterpreted the historical information and the local and trans-Pacific tsunami inundations simulating different rupture scenarios. They proposed a rupture length between 600 and 800 km and a magnitude range between Mw 9.1 and 9.3. However, paleoseismological studies of ancient tsunamis observed in trenches indicate a recurrence period ranging from 200 to 500 years for these kinds of events in this zone (Dura et al. 2015). In the last three centuries, a diversity of earthquakes of magnitude around 8.0 have been hosted in the 1730 rupture zone, the last of which—Illapel 2015 Mw 8.3 (**Figure 1*c***, #35), Valparaíso 1985 Mw 8.0 (**Figure 1*c***, #37), and La Ligua 1971 Mw 7.9 (**Figure 1*c***, #36)—broke only a part of the almost 1,000 km of rupture produced by the 1730 earthquake (Udías et al. 2012, Carvajal et al. 2017a, Ruiz & Madariaga 2018, Easton et al. 2022).

2.3. A Possible Atacama M9.5 Earthquake, 3,800 Years B.P. in North-Central Chile

A possible Atacama M9.5 earthquake occurred in a desert area that had poor coverage by the national seismic network until recently (Pastén-Araya et al. 2022, González-Vidal et al. 2023, Potin et al. 2025). However, the zone hosted a great earthquake of magnitude 8.6 on November 11, 1922 (**Figure 1*c***, #32) (Carvajal et al. 2017b, Kanamori et al. 2019). In addition, a study of paleoseismological records of boulder deposits and correlation with historical information of tsunamis reported in Japan suggest that a mega-earthquake occurred in 1420 a few years before the arrival of the Spaniards in Chile, with a magnitude that would range between 8.8 and 9.4, although more studies are necessary to confirm these estimations (Abad et al. 2020). Salazar et al. (2022) proposed an even larger earthquake than these megathrust events, a giant event occurring 3,800 years ago with a length of almost 1,000 km and a magnitude of around 9.5 (**Figure 1*c***, #33). This study was based on paleoseismic evidence along the coast and general social disruption in the native peoples who lived there. This is the third event that might be classified as a giant earthquake in Latin America.

3. MEGA-EARTHQUAKES ALONG LATIN AMERICA DURING THE PAST TWO CENTURIES

Since the 1960s, there have been important improvements in seismological instrumentation with GPS and satellite images completed in the 1990s (Segall & Davis 1997, Hu et al. 2014). This is what we call the modern instrumental period. Since then, the earthquakes in Japan in 2011 with a magnitude of 9.0 and the 2010 Maule mega-earthquake of Mw 8.8 in Chile were recorded with these modern data (e.g., Ruiz et al. 2012, Uchida & Bürgmann 2021) and the 2004 Mw 9.1 Sumatra earthquake that unfortunately was not well-recorded with local seismic instruments (Shearer & Bürgmann 2010). These data allowed us to better understand the characteristics of the rupture of the events that occurred in Latin America with magnitudes between 8.5 and 9.0, as well as better understand the differences with earthquakes of lower magnitude (<Mw 8.5) (Lay et al. 2012).

3.1. March 28, 1787, Mw 8.6 San Sixto Earthquake, Guerrero-Oaxaca, Mexico

Recent works by Ramírez-Herrera et al. (2020, 2024) have examined tsunami records along the coast of Mexico. From these observations, they suggest that ancient tsunami deposits are related to mega-earthquakes, even though no such event has been observed in the central Mexico subduction interface in the past 120 years. Mega-earthquakes have also possibly left imprints as damage to ancient Mexican structures such as the pyramids of Teotihuacan (Pérez-López et al. 2024). The last tsunamigenic earthquake with an estimated length of 450 km and a magnitude of 8.6 occurred on March 28, 1787 (**Figure 1*a***, #5), in the Oaxaca-Guerrero subduction zone (Núñez-Cornú et al. 2008, Suárez & Albini 2009). This event had a large area of intensity greater than VIII, from which its rupture extent was deduced by Suárez & Albini (2009). The event of 1787 is the largest reported in Mexico in the last five centuries (Ramírez-Herrera et al. 2020) and is several times larger than the earthquakes that occurred since 1900 (Nishenko & Singh 1987, Kostoglodov & Pacheco 1999, Sawires et al. 2019), of which the 2017 Mw 8.2 (**Figure 1*a***, #6) intraplate event in the oceanic Cocos plates is the largest (Suárez et al. 2019). In the regions of Guerrero and Oaxaca where the 1787 earthquake took place, the interseismic coupling maps show significant variations along the strike, and Maubant et al. (2022) suggest that the high and low coupling values are related to the occurrence of transient signals such as the aseismic slip events that have occurred in the Oaxaca region (Cruz-Atienza et al. 2021, Dominguez et al. 2022).

3.2. January 31, 1906, Mw 8.8 Ecuador-Colombia Earthquake

A January 31, 1906, mega-earthquake in Ecuador and Colombia had a large rupture extent of around 500 km, and a moment magnitude of Mw 8.8 as determined by Kanamori & McNally (1982) or Mw 8.6 (**Figure 1*b***, #10) as was proposed more recently by Ye et al. (2016). Okal (1992) proposed a lower size due to the small trans-Pacific tsunami and the mantle magnitude between 8.3 and 8.5. Like other mega-earthquakes in Latin America, cores of turbidites obtained from the Colombian coast suggest that one or two similar mega-earthquakes occurred in the last 600 years (Migeon et al. 2017). After this event, a sequence of earthquakes occurred in the years 1942, Mw 7.8 (**Figure 1*b***, #14); 1958, Mw 7.7 (**Figure 1*b***, #13); and 1979, Mw 8.2 (**Figure 1*b***, #11) (Kanamori & McNally 1982, Mendoza & Dewey 1984, Sennson & Beck 1996); recently, the 2016 Mw 7.8 Pedernales earthquake (**Figure 1*b***, #12) took place in the same area as the 1942 event (**Figure 1*b***, #14) (Ye et al. 2016, Nocquet et al. 2017). These events show a complex sequence of ruptures that partially overlap each other, demonstrating the heterogeneity of the megathrust and the variability of ruptures along the dip (Kanamori & McNally 1982, Ye et al. 2016, Nocquet et al. 2017, Yoshimoto et al. 2017). Nocquet et al. (2014) show a heterogeneous high interseismic coupling that may have generated a slip deficit in the smaller area that recently broke in the 2016 Mw 7.8 Pedernales earthquake. Finally, Nocquet et al. (2017) hypothesize that the 1906 earthquake did not release all the strain accumulated before it, due to the slip deficit observed during the 2016 Pedernales earthquake.

3.3. October 29, 1746, Mw 8.6 Central Perú Earthquake

The 1746 central Perú mega-earthquake (**Figure 1*b***, #22) was one of the most destructive earthquakes in Perú, strongly shaking the city of Lima and generating a tsunami that destroyed the port of Callao (Silgado 1978, Dorbath et al. 1990, Okal et al. 2006). The rupture length of this earthquake was about 350 km, and the magnitude proposed by Dorbath et al. (1990) was Mw 8.6. No major earthquakes occurred from 1746 until the 1940 event of magnitude 8.2 (**Figure 1*b***, #19) (Di Giacomo et al. 2018); the earthquake of 1966, a tsunamigenic event of magnitude 8.1 (**Figure 1*b***, #18); the 1974 earthquake in front of Lima of magnitude Mw 8.1 (**Figure 1*b***, #20); and the 2007 Mw 8.0 Pisco earthquake (**Figure 1*b***, #21). In addition, there was a 1970 Mw 8.0 (**Figure 1*b***, #17) intraplate earthquake (Beck & Ruff 1989, Beck & Nishenko 1990, Dorbath et al. 1990, Pulido et al. 2015). At present, the 1746 rupture zone is highly coupled, which led Villegas-Lanza et al. (2016) to propose that subduction mega-earthquakes in central Perú have a recurrence of the order of 305 years.

3.4. August 13, 1868, Mw 8.8 Southern Perú Earthquake

The damage caused by an August 13, 1868, mega-earthquake (**Figure 1*b***, #25) was described by Montessus de Ballore (1912), and more recently, in the 1990s, its magnitude was revised considering the zone of intensities greater than VIII by Dorbath et al. (1990) and Comte & Pardo (1991) who proposed a magnitude of Mw 8.8 in agreement with its rupture length of 500 km and trans-Pacific tsunami (Okal et al. 2006). The previous event in this region that triggered a trans-Pacific tsunami was in 1604 and seems to have had a length similar to that of the 1868 event (Dorbath et al. 1990). Okal et al. (2006) highlight the similarity between the structural damage of these events in coastal towns and the tsunamis observed along the Perúvian coast. The southern part of this event broke in the year 2001 with an event of Mw 8.4 (**Figure 1*b***, #24) (Perfettini et al. 2005). The 2001 earthquake was the only large event recorded in southern Perú since 1868 (Tavera et al. 2006). This zone shows heterogeneous coupling values (Villegas-Lanza et al. 2016, Lovery et al. 2024), and Lovery et al. (2024) consider these observations when proposing that this area is a seismic gap, that is, an area that could host a mega-earthquake in the future.

3.5. May 9, 1877, Mw 8.7 Northern Chile Earthquake

The mega-earthquake of May 9, 1877 (**Figure 1*c***, #31), took place in northern Chile with a rupture length estimated at 400 km (Comte & Pardo 1991). Considering the area of Modified Mercalli Intensity up to VIII and tsunami observations, different magnitudes were proposed, varying from 8.7 to 8.9 (Ruiz & Madariaga 2018). Recently, Vigny & Klein (2022) inferred from damage reports that the magnitude could be considerably lower than previously proposed, as low as 8.5, with a size larger than Illapel in 2015 at Mw 8.3 but smaller than Maule in 2010 at Mw 8.8. Similar to other mega-earthquakes in the region, during the last 100 years, northern Chile has had several earthquakes of magnitude around 8.0 located in different places along dip: 1967 Mw 7.4 and 2007 Mw 7.8 (**Figure 1*c***, #28) Tocopilla earthquakes in the deepest zone of plate interface, depths between 35 and 60 km, 1995 Mw 8.0 (**Figure 1*c***, #29) Antofagasta, and 2014 Mw 8.2 (**Figure 1*c***, #26) Iquique in the middle of plate interface, depth between 20 and 40 km (Ruiz & Madariaga 2018) (**Figure 2**). Métois et al. (2013) proposed that the zone is highly coupled and bounded by narrow barriers of weak coupling, and Michel et al. (2023) proposed that a possible Mw 8.8 event could occur there, where the potential barrier has a limited impact considering uncertainties.

3.6. November 11, 1922, Mw 8.6 Atacama North-Central Chile Earthquake

On November 11, 1922, a magnitude 8.6 mega-earthquake occurred in the Atacama region in the north-central area of Chile (**Figure 1*c***, #32). Initially this event was poorly located, and in some catalogs it appeared mistakenly as a deep event within the oceanic plate. Kanamori et al. (2019) analyzed old paper seismograms of the 1922 earthquake to confirm that it was a Mw 8.6 mega-earthquake with a rupture length of a few hundred kilometers. The zone shows high and heterogeneous values of coupling, less coupled in areas where the oceanic plate has ridges and fracture zones (Métois et al. 2016, Yáñez-Cuadra et al. 2022, González-Vidal et al. 2023, Vigny et al. 2024). In this zone several earthquakes, swarms, and SSEs have occurred recently (Ojeda et al. 2023; Klein et al. 2021, 2023). Similar to other mega-earthquake zones, events of magnitudes around 7.5 have occurred in recent decades (Ruiz & Madariaga 2018), and as discussed in Section 2.3, other past mega-earthquakes have been identified, such as the one proposed by Abad et al. (2020) in 1420 and the giant earthquake of 3,800 years ago (**Figure 1*c***, #33) (Salazar et al. 2022).

3.7. February 27, 2010, Mw 8.8 Maule South-Central Chile Earthquake

The most recent mega-earthquake in Latin America is the February 27, 2010, Mw 8.8 Maule south-central Chile earthquake (**Figure 1*c***, #40). This event was well-recorded by GPS stations (Vigny et al. 2011, Moreno et al. 2012) and by some accelerometers in the near field (Ruiz et al. 2012). Several groups made inversions of the slip distribution of this event using teleseismic and near-field data or both (e.g., Delouis et al. 2010, Vigny et al. 2011, Moreno et al. 2012, Ruiz et al. 2012). In general, they propose a heterogeneous rupture pattern along the strike and the dip with a rupture length of approximately 400 km (Ruiz & Madariaga 2018). In the past, other large earthquakes have been reported in the area such as the 1835 earthquake of approximate magnitude between 8.0 and 8.5 according to Lomnitz (2004), which broke the southern part of the Maule rupture and was described by Charles Darwin in his travels to Chile (Fitzroy 1839, Darwin 1851), and the 1751 mega-earthquake, which appeared to be very similar to the 2010 earthquake (Udías et al. 2012, Ruiz & Madariaga 2018). Before the 2010 earthquake, GPS data showed high coupling, which led Ruegg et al. (2009) to propose that the zone had a high potential for an earthquake of magnitude as large as 8.0 to 8.5. Madariaga et al. (2010) and Moreno et al. (2010) confirmed that the mega-earthquake occurred in the zone of higher coupling values.

4. THE LARGE EARTHQUAKES, MAGNITUDES LESS THAN Mw 8.5

In the previous sections, we reported the few giant and mega-earthquakes that have occurred in Latin America in the last centuries. Here, we present the most frequent earthquakes with magnitudes less than 8.5. We do not discuss them in detail but just highlight some observations that we consider important to understand the evolution of large subduction earthquakes. For example, unlike the giant events and the mega-earthquakes that break the entire megathrust, the events of magnitude around 8.0 usually break only a part of the plate interface along dip (Lay et al. 2012, Ruiz & Madariaga 2018). Lay et al. (2012) proposed four different domains along dip, where moderate earthquakes can be located. Here we represent this idea in **Figure 2**, schematizing giant or mega-earthquakes that broke the entire plate interface, as opposed to moderate earthquakes that are located only in a part of the plate contact. With a size slightly smaller than a mega-earthquake, in Latin America there were two large events that almost broke the entire megathrust: the 2001 Mw 8.4 Arequipa earthquake in Perú and the 2015 Mw 8.3 Illapel earthquake in Chile (Giovanni et al. 2002, Ruiz et al. 2016). Another important difference with mega-earthquakes is that the smaller-magnitude events present shorter return periods (Ruiz & Madariaga 2018). This characteristic may allow us to better understand the similarity of collocated large events comparing seismograms from different earthquakes recorded by the same stations (Singh et al. 2024). So far, examples of repeat or quasi-repeat events of magnitudes around 8.0 have been found using old paper

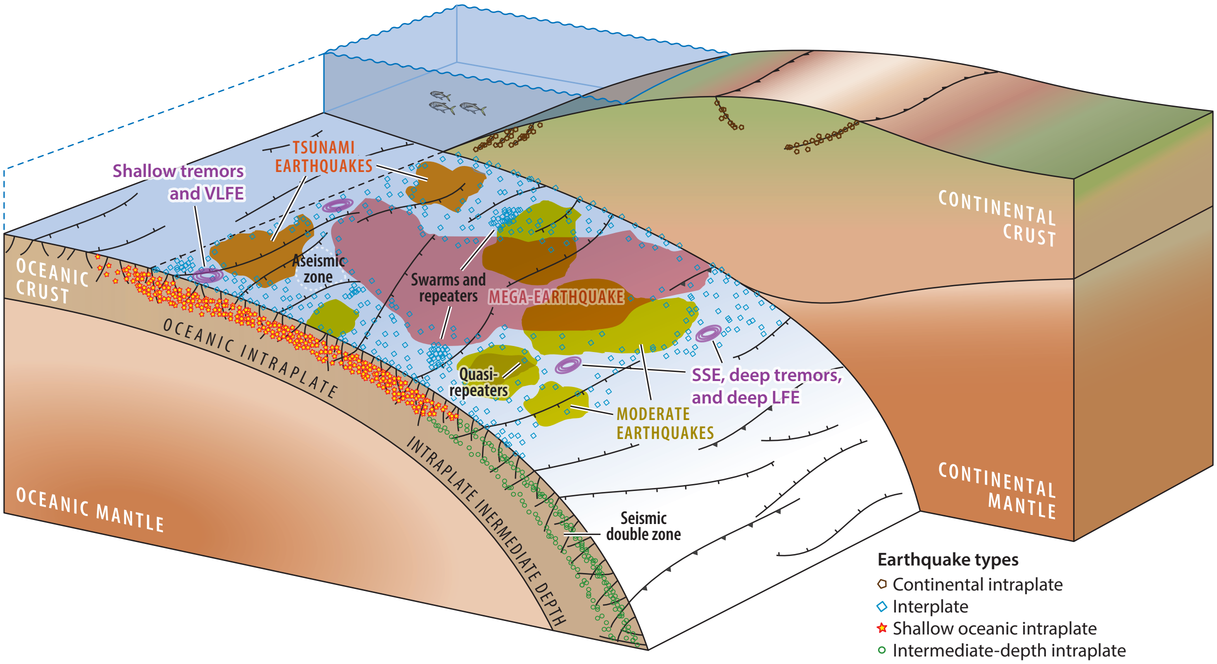

Figure 2

Diagram of subduction in Latin America showing events at the plate interface and within the oceanic plate, and the diversity of fast and slow earthquakes occurring at different depths. Abbreviations: LFE, low-frequency earthquake; SSE, slow slip event; VLFE, very low-frequency earthquake.

seismograms: e.g., in Ecuador, the 2016 (**Figure 1*b***, #12) and 1942 (**Figure 1*b***, #14) earthquakes (Ye et al. 2016, Nocquet et al. 2017); and in Chile, the 2015 (**Figure 1*b***, #35) and 1943 (**Figure 1*b***, #34) Illapel earthquakes (Ruiz et al. 2016, Tilmann et al. 2016). In Mexico, several sequences have been proposed as repeat or quasi-repeat earthquakes (Iglesias et al. 2022, Liu et al. 2023, Singh et al. 2024). However, we observe that some zones that hosted mega-earthquakes in the eighteenth century [Mexico 1787 (**Figure 1*a***, #5), Perú 1746 (**Figure 1*b***, #22), and Chile 1730 (**Figure 1*c***, #38)] are still, after almost three centuries, rupturing in smaller earthquakes. Finally, in Latin America, several large earthquakes have broken the subducted oceanic plate, causing great destruction, such as the 2017 Mw 8.2 (**Figure 1*a***, #6) Tehuantepec, Mexico, earthquake (Suárez et al. 2019) or the 1939 Mw 8.0 (**Figure 1*c***, #39) Chillán, Chile, earthquake (Ruiz & Madariaga 2018).

4.1. Almost Mega-Earthquakes of 2001 in Perú (Mw 8.4) and 2015 in Northern Chile (Mw 8.3)

The June 23, 2001, Arequipa earthquake in southern Perú (Mw 8.4) (**Figure 1*b***, #24) and the September 16, 2015, Illapel earthquake in north-central Chile (Mw 8.3) (**Figure 1*c***, #35) occurred in a zone where mega-earthquakes had previously occurred (Villegas-Lanza et al. 2016, Ruiz et al. 2016). The Arequipa earthquake was located in the northern part of the 1868 mega-earthquake (**Figure 1*b***, #25) with a unilateral rupture to the south-southeast of around 200 km in length (Giovanni et al. 2002). This event produced a regional tsunami that was more destructive than the earthquake itself, and an uplift in the coast close to the Camana town was proposed by Okal et al. (2002). This description is similar to that of the 2015 Mw 8.3 Illapel event (**Figure 1*c***, #35), which had a rupture length of 200 km and in some areas reached the deepest part of the plate contact (around 50 km depth) (**Figure 2**), generating a local coastal uplift; in other areas, it reached the trench, generating a regional tsunami (Melgar et al. 2016, Ruiz et al. 2016, Tilmann et al. 2016, Easton et al. 2022). In both cases, the limit of rupture in depth coincided with the coastline, producing the uplifts. After the mainshock, both events show in some part of the coseismic rupture a short recovery and a longer post-seismic deformation in the boundaries of the rupture (Villegas-Lanza et al. 2016, Hormazábal et al. 2023). Another characteristic of the Arequipa earthquake is the possible precursory phase observed in the GPS time series by Ruegg et al. (2001), and its rupture probably stopped at the Nazca fracture zone (Robinson et al. 2006). For the 2015 Illapel earthquake, it has been suggested that there was a post-seismic SSE lasting a few days (Tissandier et al. 2023).

4.2. Mega-Earthquakes Fragmented into Smaller Events

From the previous sections, we conclude that mega-earthquakes have not occurred in the same rupture area in less than 300 years. However, these large rupture zones, in general longer than 300 km, host lower-magnitude events that break only a part of these large areas (**Figures 1** and **2**).

In Mexico, the rupture area of the 1787 mega-earthquake (Section 3.1; **Figure 1*a***, #5) in the last 100 years has hosted several events of magnitudes less than 8.0; these occurred in the years 1965, 1968, 1978, 1982, 1995, 1996, 2012, 2018, and 2020 (Chael & Stewart 1982, Tajima & McNally 1983, Suárez & Albini 2009, Graham et al. 2014, Melgar et al. 2021). Some of these ruptures could overlap or be located very close to each other: the 2012 Mw 7.5 Ometepec earthquake and the 1982 doublet earthquakes of magnitudes close to 7.0 (Astiz & Kanamori 1984, Melgar et al. 2021), the 2018 Pinotepa and 1968 earthquakes of magnitudes close to 7.4 (Singh et al. 2024), and the 2020 La Crucecita and 1965 earthquakes of magnitudes close to 7.5 (Melgar et al. 2021). Since 1787, no interplate events greater than 8.0 have occurred in the Oaxaca region, which differs from other seismic sequences of Latin America, where events of magnitudes between 8.0 and 8.4 occur in the same zone where mega-earthquakes previously occurred. In central Perú, for instance, after the Mw 8.6 mega-earthquake of 1746 (**Figure 1*b***, #22), several events of magnitudes as large as 8.0 have occurred (Section 3.3). In central Chile, after the giant Mw ∼9.1 to 9.3 earthquake of 1730 (Section 2.2; **Figure 1*c***, #38), several large events were reported by Greve (1964) with the largest ones with magnitudes close to 8.0 in 1822 and 1880. The 1880 earthquake was similar to the 1943 Mw 8.1 (**Figure 1*c***, #34) and 2015 Mw 8.3 (**Figure 1*c***, #35) Illapel earthquakes (Ruiz et al. 2016). The 1822 earthquake of magnitude between 8.0 to 8.5 (Lomnitz 2004) that occurred in front of Valparaíso is a quasi-repeat event of the 1906 Mw 8.2 and 1985 Mw 8.0 (**Figure 1*c***, #37) earthquakes (Ruiz & Madariaga 2018). In addition, other large events occurred in the rupture area of 1730, such as the 1971 Mw 7.9 (**Figure 1*c***, #36) La Ligua earthquake (Malgrange & Madariaga 1983).

4.3. Earthquakes Studied with Analog and Modern Seismograms

The conversion from analog to digital seismograms began in the 1970s (Okal 2015), and the use of analog instruments ended in the 1980s and 1990s in Latin America. This revolutionized seismology, leaving paper records forgotten or eliminated (Okal 2015). However, today these paper records are the only way to compare large earthquakes with repeat times of tens of years that occurred in the same place or nearby (see schematic in **Figure 2**). The 2016 Mw 7.8 (**Figure 1*b***, #12) and 1942 Mw 7.8 (**Figure 1*b***, #14) Pedernales sequence in Ecuador was revisited by Ye et al. (2016) who concluded, comparing old and modern seismograms, that there were similar motions of the aligned waveforms but a discrepancy in duration from the onset to the peak motion and a shorter signal interval for the 1942 event, suggesting that the main slip area of the 2016 event overlaps with that of the 1942 event. The 1943 Mw 8.1 (**Figure 1*c***, #34) and 2015 Mw 8.3 (**Figure 1*c***, #35) Illapel earthquakes in Chile were analyzed by Tilmann et al. (2016) who compared the modern 2015 seismograms with those published by Beck et al. (1998) for the 1943 earthquake and suggested that the 1943 event is smaller than the event of 2015. Finally, Singh et al. (2024) identified waveforms nearly identical of several sequence of earthquakes of magnitudes larger than Mw 7.0 in Mexico comparing the old seismograms recorded at De Bilt, Netherlands. They studied repeat earthquakes in eastern Oaxaca in 1928, 1965, and 2020 with magnitudes of ∼7.5, in western Oaxaca in 1928, 1968, and 2018 with magnitudes of ∼7.2, and in the Acapulco area in 1962 and 2021 with magnitudes of 7.0 (Iglesias et al. 2022). In addition, they found quasi-repeat earthquakes in central Oaxaca on June 17, 1928 (**Figure 1*a***, #3), and November 29, 1978 (**Figure 1*a***, #2), with magnitudes close to 8.0 and Michoacán-Colima earthquakes of 1973 (**Figure 1*a***, #1) and 2022 with magnitudes close to 7.5, the latter of which was also studied by Liu et al. (2023).

4.4. Oceanic Intraplate Earthquakes

Here we define oceanic intraplate events of those earthquakes that occur within oceanic plates below the plate contact, i.e., at depths less than ∼60 km (**Figure 2**). This is in contrast to intraplate intermediate-depth events, which are generally defined as occurring between depths of 60–70 km and 300–350 km, as proposed by Gutenberg & Richter (1954) (**Figure 2**). These oceanic intraplate events are gaining worldwide relevance after the large-magnitude earthquake that occurred in Mexico, the 2017 Mw 8.2 Tehuantepec earthquake located below the plate interface in the Cocos plate (**Figure 1*a***, #6). Suárez et al. (2019) proposed that the Tehuantepec event is the consequence of the tensional stresses caused by a highly coupled megathrust. Okuwaki & Yagi (2017) propose that the tension occurs due to slab bending, while Meng et al. (2019) argue that it is due to reactivation of subducted outer-rise faults. Several other intraplate oceanic events of large magnitude have occurred in Latin America; in Mexico, the 1903 Mw 7.4 event occurred in the northern part of the rupture of the 2017 Mw 8.2 earthquake, and further north two other events occurred in 1931 (**Figure 1*a***, #4) and 1999 with magnitudes of Mw 7.8 and Mw 7.5, respectively (Suárez 2021). Two other destructive earthquakes were reported in El Salvador in 2001 (**Figure 1*a***, #7) where a Mw 7.7 event took place in the subducting Cocos plate at a depth of ~50 km (Vallée et al. 2003) and in Perú in 1970 (**Figure 1*b***, #17) with a magnitude of Mw 8.0 that broke the Nazca plate (Beck & Ruff 1989) that could be related to the presence of the Mendaña Fracture Zone (Jiménez et al. 2023). Smaller-magnitude oceanic intraplate earthquakes occur along many of the subduction zones of Latin America. Unfortunately, the presence of the seismological stations only on the continent and the use of 1D velocity models for location prevent having good hypocenters for the events below the ocean (Potin et al. 2025), making it difficult to distinguish events located in the plate interface from those within the plates.

4.5. Intraplate Intermediate-Depth and Deep Events

Intraplate intermediate-depth (60–70 km to 300–350 km) and deep events (>300–350 km) are well-studied events that frequently occur in subduction zones (Green & Houston 1995, Astiz et al. 1988, Hacker et al. 2003, Zhan 2020). These earthquakes are different from interplate earthquakes, presenting differences in their rupture mechanisms, fewer aftershocks, and a spatial distribution controlled by the characteristics of pressure, temperature, and age of the subducted plate.

Large-magnitude intraplate intermediate-depth events are less common than the earthquakes that occur in the plate interface. No events of this type with magnitudes greater than 8.5 have been reported worldwide, and Latin America has recorded some of the largest reported in the world: in Chile, 1939 Mw 8.0 Chillán (99.8 km depth) (**Figure 1*c***, #39), 1950 Mw 8.2 Calama (113.9 km depth) (**Figure 1*c***, #30), and 2005 Mw 7.8 Tarapacá (105.0 km depth) (**Figure 1*c***, #27) (Ruiz & Madariaga 2018, depths from ISC-GEM catalog Bondár et al. 2015); in Perú, 2019 Mw 8.0 Loreto (122.6 km depth) (Vallée et al. 2023, depth from NEIC catalog); and in Mexico, 1902 Mw 7.8 Chiapas central (170 km depth) (Suárez 2021). Several of these events were erroneously reported in the early catalogs (e.g., Kelleher 1972) of the 1960s and 1970s, mainly due to errors in location using paper seismograms and the fact that the concept of subduction was just beginning to be accepted. For example, the 1939 Mw 8.0 Chillán earthquake, the most destructive event in Chile, was at first identified as an interplate event filling part of the Maule seismic gap (see Kelleher 1972). A similar error occurred for the 1902 Mw 7.8 Chiapas central earthquake in Mexico, an event located at 170 km depth on the Cocos plate (Suárez 2021). Other historical earthquakes are probably misclassified in the seismic catalogs because there are no intraplate intermediate-depth earthquakes reported in the catalogs prior to 1900, which is inconsistent with the abundance observed in modern catalogs.

Deep intraplate events (>300–350 km depth) appear to be concentrated in South America in the northern areas of Argentina, on the Perú-Brazil border, and in Bolivia and Colombia (see **Figure 1*c***). The largest so far are the 1994 Mw 8.2 Bolivia (**Figure 1*b***, #23) and 1970 Mw 8.0 Colombia (**Figure 1*b***, #15) earthquakes (Okal & Geller 1979, Kikuchi & Kanamori 1994). Several Mw 7.0 deep events in Latin America appeared during 1921–1922, 1961–1963, 1989–1990, 2002–2003, and 2015 (Ruiz et al. 2017). However, an explanation of why this clustering occurs remains to be studied (Zhan 2020).

5. SLOW EARTHQUAKES

Since around 2000, a new type of earthquake-like phenomena, underground shear deformation without strong shaking, has started to become frequently detected in well-instrumented subduction zones such as Cascadia, Japan, and New Zealand (Gomberg & Cascadia 2007 Beyond Work.

Group 2010, Beroza & Ide 2011, Wallace 2020, Nishikawa et al. 2023). Through the use of geodetic instruments, they are recognized as aseismic episodic slip motions on a part of the plate interface and thus are called SSEs. Generally, SSEs last for several days, months, or even years and repeat in similar places at intervals of several weeks to years, with magnitudes of Mw 5.5 to 7.5. SSEs are often accompanied by weak seismic signals, which can be explained as radiation from tiny and successive slip events. Each small slip event is regarded as an LFE with durations of 0.2–0.5 s with Mw less than 2.0, and its successive occurrence is termed a tectonic (nonvolcanic) tremor. While LFEs and tremors are detected by short-period seismometers at frequencies higher than 1 Hz, sometimes broadband seismometers simultaneously observe very low-frequency signals in the range of 0.01–0.05 Hz. These signals are considered as radiation from VLFEs with durations of 10–100 s and magnitudes of Mw 3.0 to 4.0. Although LFEs and VLFEs are usually separately observed, continuous signals are observed from 0.01 to 10 Hz when the noise level is extremely low (e.g., Kaneko et al. 2018). Therefore, LFEs, tremors, and VLFEs are considered to be different manifestations of single very broadband phenomenon that we may call slow earthquakes. The seismic moment and duration of these seismic events share a common scaling relation with SSEs (e.g., Ide & Beroza 2023), which may be considered as a geodetic manifestation of these slow earthquakes, or "geodetic slow earthquakes" (Nishikawa et al. 2023).

Most slow earthquakes occur near the source area of large to giant earthquakes. However, the distributions of slow and regular earthquakes have little overlap (Nishikawa et al. 2023). In other words, slow earthquakes occur near the edge of the source area of regular earthquakes. Therefore, the depth ranges from 0–10 km at very shallow plate interfaces to 30–50 km near the deep limit of megathrust earthquakes (see **Figure 2**). While some SSEs were thought to occur before giant earthquakes (e.g., Ruiz et al. 2014, Kato et al. 2012, Obara & Kato 2016), temporal correlations between them are yet enigmatic.

In Latin America, in general, seismological and geodetic networks are not dense enough to regularly record slow earthquakes. Most of those discovered have been based upon observations made by stations recording in the same place for a long time and for the temporary deployment of dense networks of instruments (e.g., Kostoglodov et al. 2003, Klein et al. 2023, Perry et al. 2023). Various kinds of slow earthquakes have been observed in Mexico, Costa Rica, Ecuador, and Chile. This section is divided into two sections related to the different manifestations of slow earthquakes: geodetic slow earthquakes or SSEs and slow earthquakes observed only in seismograms (i.e., LFEs, tectonic tremors, and VLFEs), which we call seismic slow earthquakes. In this review, we highlight the clearer account of slow earthquakes reported in Latin America; we do not include the observed swarms and/or sequences of repeating events.

5.1. Slow Slip Events or Geodetic Slow Earthquakes

5.1.1. Mexico. In Mexico, the first observation of an SSE was made by Lowry et al. (2001) in a continuous GPS site in Guerrero that slipped slowly for a few months in 1988 (**Figure 1*a***). The same GPS station and others deployed in the area captured a new SSE of magnitude Mw 7.5 that began in October 2001 and lasted for 6–7 months (Kostoglodov et al. 2003). This SSE was repeated in 2006 (Larson et al. 2007), showing a return period of 4 years (Cotte et al. 2009, Vergnolle et al. 2010). Then, these SSEs were observed in the Guerrero zone in 2009/2010 (Walpersdorf et al. 2011), 2014 (Radiguet et al. 2016), and 2017/2018 (Maubant et al. 2020). Some SSEs appear to have a causal relationship with nearby ordinary earthquakes via the change of stress state: The 2014 SSE triggered the Mw 7.3 Papanoa earthquake, and the 2017/2018 SSE deformation interacted with the 2017 Mw 8.2 (**Figure 1*a***, #6) Tehuantepec afterslip (Cruz-Atienza et al. 2021). In the Oaxaca region, SSEs have also been identified with smaller magnitudes (from Mw 6.5 to Mw 7) and shorter recurrence intervals of 1.5 years (Graham et al. 2017, Cruz-Atienza et al. 2021).

5.1.2. Costa Rica. In Costa Rica, several SSEs have been observed beneath the Nicoya and Osa Peninsulas, on a part of the plate interface shallower than the typical source area of ordinary earthquakes (**Figure 1*b***). The first SSE was observed in mid-September 2003 and lasted about 4 weeks, as documented by Protti et al. (2004), and later in May 2007, a new SSE was observed by Outerbridge et al. (2010). A recurrence period for SSEs below the Nicoya Peninsula was observed to be 21.7 ± 2.6 months based on data from 33 GPS stations between 2002 and 2020 (Jiang et al. 2012, Xie et al. 2020) with magnitudes around Mw 7.0 (Xie et al. 2020). Among the SSEs reported, the 2012 SSE preceded the Mw 7.6 earthquakes, with an increase of slip rate within 1 week of the Mw 7.6 event (Voss et al. 2018). At the Osa Peninsula, Perry et al. (2023) observed five shallow SSEs in 2013, 2018, and 2022 indicating a preliminary recurrence interval of 4–5 years.

5.1.3. Ecuador. A 1-week-long duration SSE has been reported in Ecuador with an equivalent Mw of 6.0–6.3 in August 2010 below La Plata Island (Vallée et al. 2013). Another SSE of longer duration, 6 weeks, was reported from December 2013 to January 2014 in the northern part of the 2016 Mw 7.8 Perdernales earthquake rupture (Vaca et al. 2018) (**Figure 1*b***). Unlike Costa Rica's reported SSEs, these events have occurred in isolation.

5.1.4. Chile. In the Atacama region of Chile, GPS stations recorded SSEs during the years 2014 and 2016, and a re-examination of data from a subset of these stations installed years earlier observed a similar transient in the years 2005 and 2009, suggesting a 5-year recurrence period (Klein et al. 2018). Later, a new SSE was observed in the year 2020, confirming the previous recurrence observation (Klein et al. 2023) (**Figure 1*c***). The Atacama SSEs had several-month-long durations, longer than those observed in Mexico (Klein et al. 2023). Recently, smaller-magnitude SSEs have been identified in northern Chile and south Perú by Jara et al. (2024) that do not show signs of recurrence as in the case of the SSE of Atacama. Finally, two well-documented SSEs preceded large ordinary earthquakes. In northern Chile, an SSE began several weeks before and ended with the 2014 Mw 8.2 Iquique (**Figure 1*c***, #26) earthquake (Ruiz et al. 2014, Socquet et al. 2017), and in central Chile (**Figure 1*c***), another SSE began some days before the 2017 Mw 6.9 Valparaíso earthquake (Ruiz et al. 2017, Caballero et al. 2021). Finally, Tissandier et al. (2023), examining the post-seismic phase of the 2015 Mw 8.3 Illapel earthquake in northern central Chile, proposed that an SSE started 67 days after the main shock, with a duration of approximately 4 days, and an equivalent moment of ~Mw 6.1–6.2.

5.2. Seismic Slow Earthquakes

5.2.1. Mexico. In Mexico, tectonic tremors were detected downdip of the deep SSEs reported in the Guerrero-Oaxaca regions (**Figure 1*a***), using the broadband seismographs from the National Seismological Center of Mexico and the MASE (Meso America Subduction Experiment) temporary deployment of the years 2005 to 2007 (MASE 2007, Payero et al. 2008). Frank et al. (2013, 2015) recognized these tremors as LFEs and found strong temporal correlations between the LFEs and SSEs. Nevertheless, the spatial correlation is not perfect, and tremors delineate the deeper edge of the wider SSE slip area. Different researchers have confirmed these observations showing tectonic tremors in two main zones of the Guerrero and Oaxaca regions (e.g., Brudzinski et al. 2010, 2016; Husker et al. 2012; Cruz-Atienza et al. 2015, 2021; Yousfi et al. 2023). Maury et al. (2016, 2018) detected VLFEs corresponding to these tremors and confirmed that their focal mechanisms are low-angle thrusts, which is consistent with the regional plate subduction direction. In the Jalisco-Colima-Michoacán region, tectonic tremors were also detected by Ide (2012) using temporary observations of the Mapping the Rivera Subduction Zone Project (Yang et al. 2009). Although tectonic tremors are observed along the Mexican coast from Jalisco to Oaxaca, there are some differences in the characteristics of the tectonic tremors and their relation to SSEs among regions. The current deep tremor distribution is very patchy, separated by gaps of tens to hundreds of kilometers, and this might be due to detectability, which is strongly controlled by the quality of seismological observation networks.

In addition to these inland tremor observations at the deeper edge of the locked plate interface, episodic activities of shallow tremors repeating at 1–3 months were proposed for the first time using onshore and ocean bottom seismometer (OBS) stations in the Guerrero seismic gap by Plata-Martinez et al. (2021). This finding suggests that the shallow part of the Guerrero gap is not fully locked.

5.2.2. Costa Rica. The temporary seismic network deployed at the Nicoya Peninsula (Outerbridge et al. 2010) allowed the identification of tectonic tremors at the downdip of the seismogenic zone (Outerbridge et al. 2010, Walter et al. 2011), where Brown et al. (2009) identified LFEs located in almost the same area (**Figure 1*b***). The location of these LFEs/tremors corresponds to the low slip area of SSEs. Later, Walter et al. (2013) found that VLFEs temporally correlated with tremors in the period of the 2008 SSE. Baba et al. (2021) determined the hypocenter distribution of VLFEs that occurred in 2004–2005 at very shallow depth near the trench axis, where SSE slip has not been well-resolved. Thus, the spatial relation among the different slow earthquakes is not well-understood yet. Nevertheless, after Walter et al. (2015), who determined tectonic tremors preceding the 2012 Mw 7.6 earthquake (**Figure 1*b***, #9), no tremor catalog has been published in this decade. We therefore hope that future studies will clarify whether these events are persistent in this area.

5.2.3. Chile. For the Chile Ridge Subduction Project from 2005 to 2007 (Gallego et al. 2010), up to 63 broadband seismic stations were deployed north of the Chile Triple Junction (CTJ), which led to the first observation of tectonic tremors in Chile (Gallego et al. 2006, 2013; Ide 2012; Idehara et al. 2014) (**Figure 1*c***). Tectonic tremors were located beneath the Chonos Archipelago, close to the plate boundary between the Nazca and South America plates. These tremors share common characteristics with those in other regions (Beroza & Ide 2011), such as fast (~10 m/s) migration along the slab dip or slip direction, slow (~0.1 m/s) or diffusive migration in the direction parallel to the trench axis, and clear modulation by tidal stress (**Figure 3**). From February 2009 to March 2010, five OBSs were deployed near the subducting ridge of the CTJ. Using the records of these OBS data, Sáez et al. (2019) detected tremor events right beneath the OBS stations. Until now no other clear evidence of seismic slow earthquakes has been discovered in Chile.

5.3. Other Phenomena

5.3.1. Triggered tremors. Tectonic tremors have often been triggered by stress disturbances due to large distant earthquakes (e.g., Miyazawa & Brodsky 2008). Tectonic tremors were first reported as triggered tremors before the discovery of ambient tremor activity in New Zealand (Fry et al. 2011) and Taiwan (Tang et al. 2010). In Latin America, there are four regions where only triggered tremors were discovered, although there are more areas where ambient tectonic tremors have been observed (see Section 5.2). Those are Cuba (Peng et al. 2013), Haiti (Aiken et al. 2016), Colombia, and Ecuador (Chao et al. 2019). Most of these observations were made at stations located far from the areas where tectonic tremors usually occur (see Section 5.2; **Figure 2**), so that it is unlikely that these are subduction-related tectonic tremors. In other places the triggered tremors were reported collocated with tectonic tremors zones, in southern Chile (Chao et al. 2019), and in Guerrero and Jalisco in Mexico (Zigone et al. 2012, Miyazawa & Santoyo 2021).

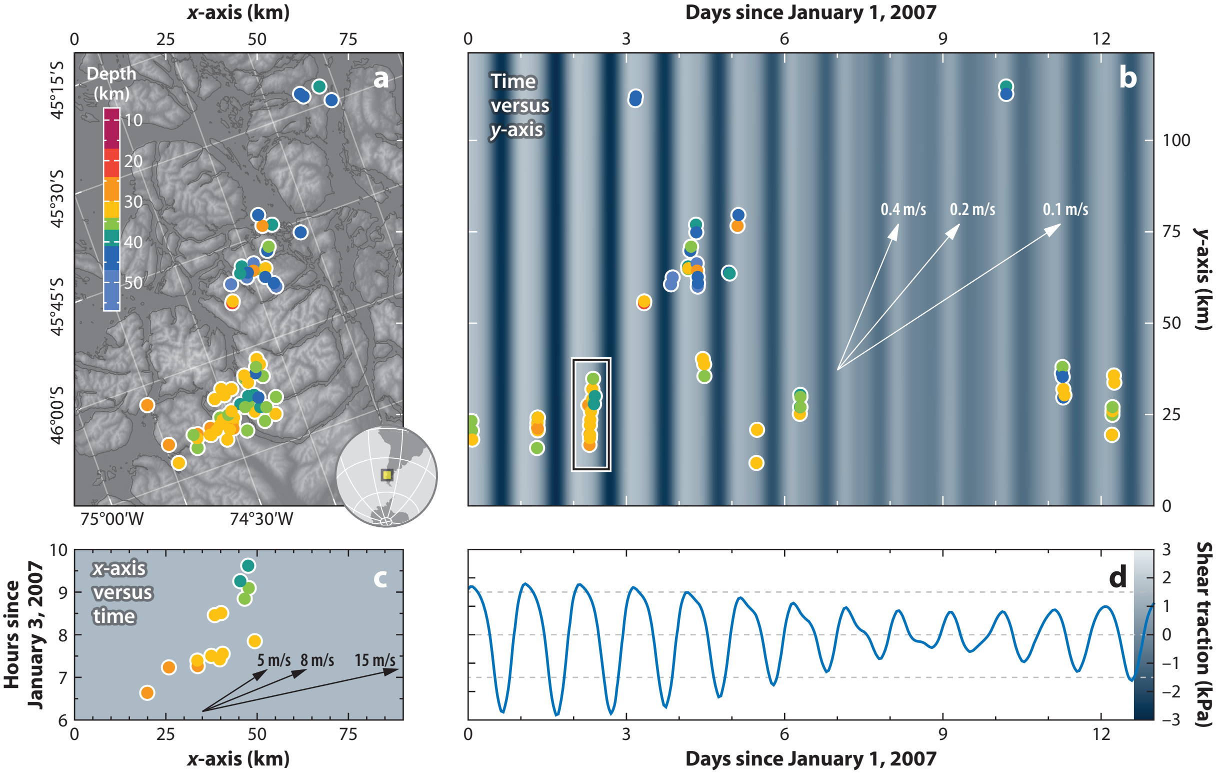

Figure 3

Tremor distribution during the January 1–14, 2007, period, color coded with depth. (*a*) Map view. (*b*) Space-time plot with gray shading showing shear traction on the plate interface shown in panel *d*. The vertical axis corresponds to the vertical axis of the map in panel *a*. Vectors show migration velocities for 0.1–0.4 m/s. (*c*) Space-time plot, 4 h starting at 6 AM on January 3, 2007. The horizontal axis corresponds to the horizontal axis of the map in panel *a*. Vectors show migration velocities for 5–15 m/s. (*d*) Shear traction on the plate interface, calculated using the code of Yabe et al. (2015) with a focal mechanism of (strike, dip, slip) = (10°, 30°, 90°). Topography comes from Eur. Space Agency (2024).

5.3.2. Tsunami earthquakes. Unlike megathrust earthquakes that break a large part of the plate contact including areas close to the trench, tsunami earthquakes are smaller and concentrate their rupture in the shallowest part of the contact (see **Figure 2**). Tsunami earthquakes are a type of rare event observed in this region that excites larger tsunami than what is expected from its surface magnitude (Kanamori 1972). In addition to a tsunami earthquake of Mw 7.6 in 1992 (**Figure 1*a*,*b***, #8) off the coast of Nicaragua (e.g., Ide et al. 1993, Kanamori & Kikuchi 1993), several events of moderate magnitude with relatively deficient high-frequency waves were reported offshore of Mexico (Iglesias et al. 2003). Before 2000, tsunami earthquakes were often called slow earthquakes. However, the rupture propagation speed and slip rate of tsunami earthquakes are faster by orders of magnitude than those of slow earthquakes, and therefore they are grouped as regular or fast earthquakes (Ide & Beroza 2023). Nevertheless, the source regions of tsunami earthquakes are close to those of shallow slow earthquakes observed in Mexico and Costa Rica (see Sections 5.1 and 5.2), and the interaction between regular, tsunami, and slow earthquakes should be important for the comprehensive understanding of the events that take place in the shallow subduction zone (**Figure 2**).

6. SUMMARY

6.1. Giant, Mega-, and Large Earthquakes

We define giant earthquakes as those with magnitudes larger than 9.0, mega-earthquakes as those of magnitudes larger than 8.5 and lower than 9.0, and large earthquakes as those with magnitudes between 8.0 and 8.5. Giant earthquakes are rare around the world. In Latin America, only one has been recorded with seismograms (Valdivia 1960, Mw 9.5); another one (Valparaíso 1730, with an estimated magnitude in the range 9.1–9.3) was reported in historical documents; and a last possible event, 3,800 years ago in Atacama of magnitude Mw 9.5, was inferred from paleoseismology and anthropology (Kanamori & Cipar 1974, Udías et al. 2012, Salazar et al. 2022). Mega-earthquakes, events of magnitudes between 8.5 and 9.0, are more frequent, and we observe that they repeat in the same region after a few centuries (Ruiz & Madariaga 2018). We cannot rule out that mega-earthquakes occurred in regions where they have not been reported because of lack of historical information or paleoseismology studies. Large earthquakes, events of magnitudes around 8.0, are more frequent and can be found in almost all the Latin America subduction zones.

6.2. Uncertainty in the Rupture Zone of Earthquakes Occurred Before the Availability of Seismograms

Before modern seismology based on seismic recordings (analog or digital), it was very difficult to evaluate the rupture area of earthquakes. We detected two assumptions frequently made in Latin America to resolve this problem: first, to consider that earthquake damage, floods, tsunamis, or other effects are associated with interplate events (e.g., Lomnitz 2004), and second, that the zone of greatest intensity (usually about VIII) is equivalent to the rupture zone (e.g., Dorbath et al. 1990, Comte & Pardo 1991). We believe that these a priori assumptions produce a large bias; for example, it is difficult to find oceanic intraplate earthquakes in the history of Latin America, and the dimensions of the earthquakes have a large uncertainty. The recent mega-earthquake (2010 Mw 8.8 Maule, Chile) (**Figure 1*c***, #40) had an area of intensity greater than VIII, much smaller than the well-defined rupture area (Astroza et al. 2012), so that if its rupture area was inferred from the intensity reports, its rupture zone would be half of the real one.

6.3. Repeat Time of Large Earthquakes

In Section 4.3, we showed examples of repeat and quasi-repeat earthquakes that occurred in Mexico, Ecuador, and Chile. A careful study is required to find out whether the same asperities broke every time and if the rupture process is similar for these events. Considering the few examples reported so far, we believe that the same zones or nearby zones could rupture almost regularly every few decades but that their rupture processes are different every time (e.g., Tilmann et al. 2016, Ye et al. 2016). This is what we expect from the strong nonlinearity of earthquake rupture dynamics, due to the combined effects of dynamic stress geometry (asperities) and fault geometry (barriers), as discussed by Aki (1984).

6.4. Different Slow Slip Manifestations in Latin America

All types of slow earthquake manifestations have been observed in Latin America (Beroza & Ide 2011), and we expect that additional slow earthquakes will be detected in other parts of Latin America due to the increasing number and density of seismological and geodetic instruments available. While slow earthquakes often delineate the source regions of ordinary fast earthquakes (Nishikawa et al. 2023), their manifestations are diverse, depending on regional tectonic environments as demonstrated in Japan (Nishikawa et al. 2023). Despite their spatial proximity, the interaction or temporal causality between slow and fast earthquakes has not been clearly understood. Latin America has several good examples to tackle this problem, such as the complex interactions observed in Mexico by Cruz-Atienza et al. (2021) or the slow earthquake precursor of the 2014 Mw 8.2 (**Figure 1*c***, #26) Iquique earthquake in Chile (Ruiz et al. 2014). Dense and long-term continuous monitoring in this region will allow figuring out the conditions for the interaction between slow and fast earthquakes.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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