

REVIEW

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Recent progress in research on source processes of great earthquakes using tsunami data

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Abstract

This paper provides an overview of inverse studies that estimate earthquake source processes using tsunami-related data. Methods and techniques developed with those data associated with the 2004 Sumatra and 2011 Tohoku-oki earthquakes were reviewed. These events significantly impacted subsequent studies that focused on great historical earthquakes. Thus, recent advancements from studies on great historical earthquakes ($M > 8$) using old tsunami data, including documents and non-digital tsunami waveforms, have been reviewed. Another key earthquake was the 1700 Cascadia earthquake, and its source process was revealed using geological tsunami deposit data, which have led to a recent surge in prehistorical earthquake studies using tsunami deposit data. Considering this, the advancements in prehistorical earthquake studies have been reviewed. Finally, expected advancements in earthquake source process studies using tsunami-related data in the near future have been discussed.

Keywords Research on source processes, Great earthquakes, Progress in tsunami research

1 Introduction

In 2004, the Sumatra–Andaman great earthquake (Mw 9.1) occurred along a subduction zone in which the Indian plate is subducting beneath the Sunda plate and generated a devastating tsunami (Fig. 1). Larger tsunami heights than 40 m were observed along the northwestern coast of Sumatra, Indonesia (Tsuji et al. 2006). The tsunami severely damaged coasts not only in Indonesia and India, but also in Thailand, Sri Lanka, the Maldives, and Somalia. Consequently, the 2004 tsunami killed approximately 230,000 people along the Indian Ocean coast (Srivichai et al. 2007). In 2011, the Tohoku-oki great earthquake (Mw 9.0) occurred in a subduction zone along the Japan Trench, where the Pacific plate is subducting beneath the North American or Okhotsk plates

(Fig. 2). The earthquake generated a tsunami that reached heights as large as 40 m along the Sanriku Coast (Mori et al. 2011). The 2011 tsunami killed 19,000 people along Japan's Pacific coast (The Fire and Disaster Management Agency 2014). The 2011 tsunami was observed using various sensors, including GPS buoys, cabled ocean-bottom pressure sensors, DART (Deep-ocean Assessment and Reporting of Tsunamis) buoys, and tide gauges. Many researchers have conducted inverse studies of the source processes of these two earthquakes using tsunami-related data. New methods and techniques for estimating earthquake sources and enhancing existing source-estimation skills have been developed via those studies.

This review specifically focused on the methods and techniques for estimating source processes using observed tsunami-related data. This review is divided into three sections. First, the methods and techniques developed by published studies on the 2004 Sumatra and 2011 Tohoku-oki earthquakes are reviewed. Second, recent advancements in research on great historical earthquakes using document data for tsunami

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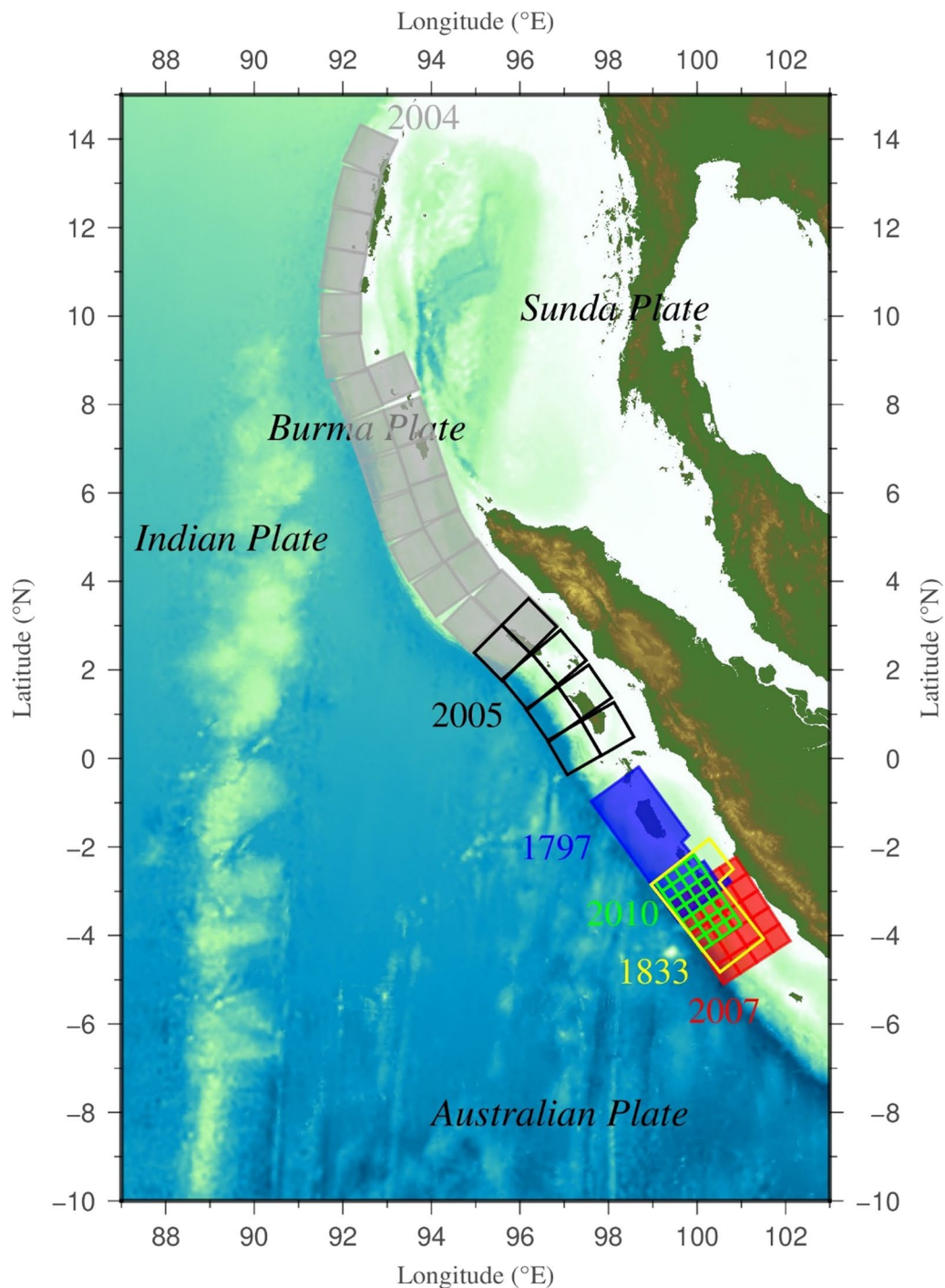


Fig. 1 Earthquake sources off Sumatra in Indonesia in 1797 and 1833 (Natawidjaja et al. 2006), 2004 (Fujii and Satake 2007), 2005 (Fujii et al. 2020), 2007 (Fujii and Satake 2008), 2010 (Satake et al. 2013b)

heights and tsunami waveforms observed at old tide gauges are reviewed. After the source of the 1700 Cascadia earthquake was revealed using geological

data (Atwater et al. 1991; Satake et al. 1996), research on the source processes of prehistorical earthquakes using tsunami deposit data has flourished. Third, the

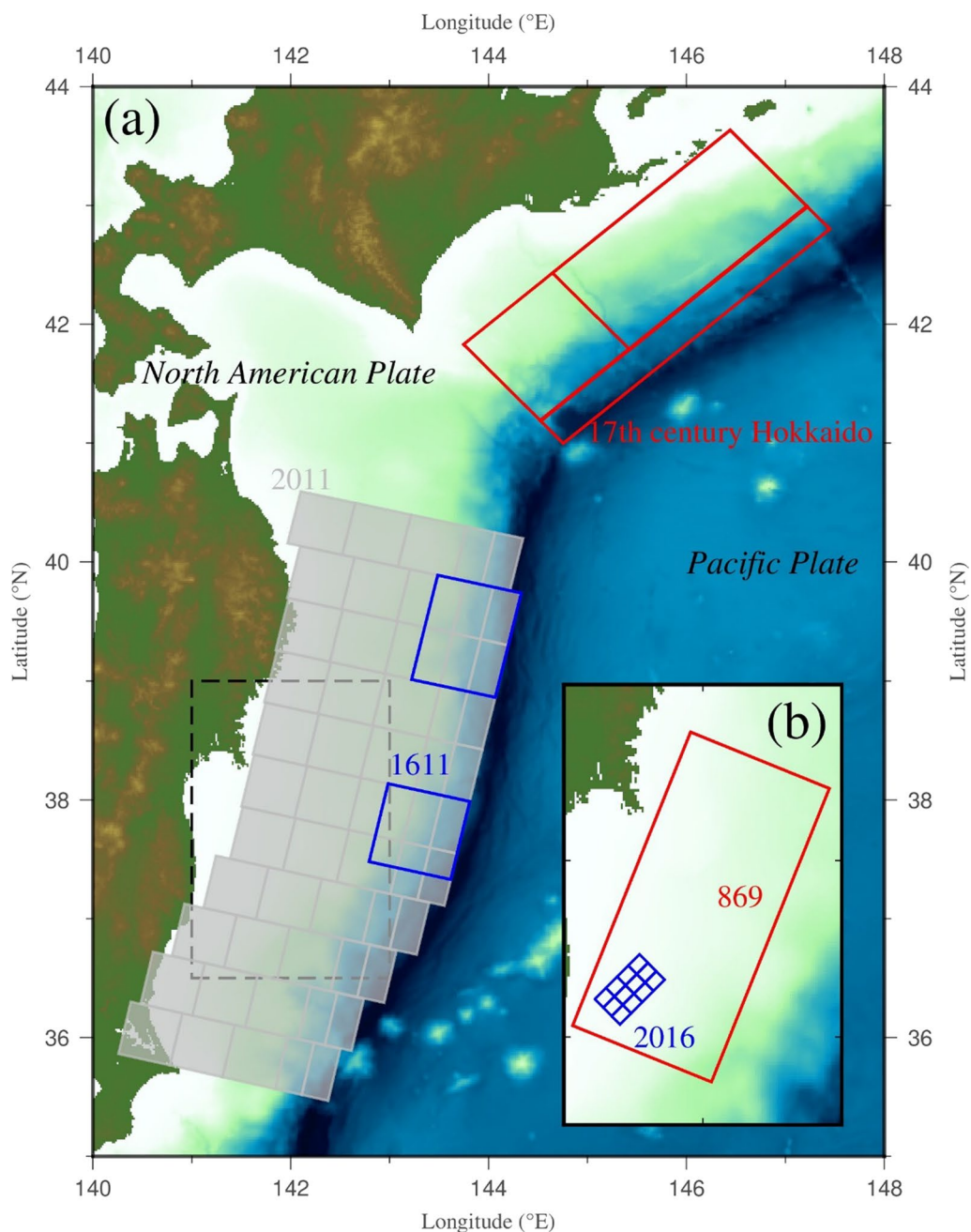


Fig. 2 Earthquake sources off Tohoku and Hokkaido in Japan in 869 (Namegaya and Satake 2014), 1611 (Yamanaka and Tanioka 2022), 2011 (Satake et al. 2013a), 2016 (Gusman et al. 2017) and the seventeenth century (Ioki and Tanioka 2016). Area of panel (b) corresponds to an area specified by black-dashed square in panel (a)

advancements in research on the source processes of prehistorical earthquakes are reviewed. The third part includes key element studies that will lead to source process estimation of prehistorical earthquakes in the future because those tsunami deposit studies have great future potential. Finally, future advancements in these studies using tsunami-related data are discussed.

2 Recent great earthquakes

2.1 The 2004 Sumatra-Andaman, 2007 Bengkulu, and 2010 Mentawai earthquakes

The 2004 Sumatra-Andaman earthquake (Fig. 1) was a key earthquake, and its detailed source process was thoroughly revealed using various available seismological,

geodetical, and tsunami data (Lay et al. 2005). It is worth noting that, the 2004 tsunami was the first tsunami detected by the altimetry of two satellites, “Jason-1” and “TOPEX/Poseidon” along the pass of the satellites (Hirata et al. 2006). Tsunami data from satellites with tsunami waveforms recorded at tide gauges have been used to estimate the source processes of earthquakes (Fujii and Satake 2007; Lorito et al. 2010; Fujii et al. 2021). In addition, the rupture velocity of an earthquake was first determined using tsunami data (Hirata et al. 2006; Fujii and Satake 2007; Tanioka et al. 2006). Because both the resolution of the source processes using tsunami data and the resolution of that using seismic data are increased, the discrepancy of the slip distribution or the rupture velocity among the different data sets was estimated. As a result, it became possible to discuss the frequency-dependent source processes. The sand materials brought by the tsunami into inland areas from the sea (tsunami deposits) have been well surveyed and investigated after the tsunami. A key finding of Gusman et al. (2012a) was that the source process could be constrained by comparing the thickness distribution of tsunami deposits estimated in a numerical simulation with the observed thickness distribution.

Subsequent great earthquakes occurred off Sumatra Island in Indonesia in 2007 and 2010 (Fig. 1). The source process of the 2007 great Bengkulu earthquake (Mw 8.5) was estimated using a joint inversion of tsunami waveforms and InSAR data (Gusman et al. 2010). Gusman et al. (2010) successfully estimated both the slip angle and slip amount of each subfault via joint inversion, although typical tsunami waveform inversion estimates only the slip amount of each subfault with a fixed slip angle. A smoothness factor was introduced in this joint inversion, and its magnitude was quantitatively determined based on the Akaike’s Bayesian information criterion (ABIC) (Akaike et al. 1980). This joint inversion technique has often been used with geodetic and seismological data to estimate the slip distributions of large earthquakes. Using the smoothness factor, a small size of the subfault (25 km × 25 km) can be used to estimate a realistic slip distribution (Gusman et al. 2010). In 2010, the Mentawai earthquake occurred trenchward from the source of the 2007 Bengkulu earthquake and generated large tsunami heights around the Mentawai Islands without strong shaking, and it was likely a tsunami earthquake (Satake et al. 2013b). The source model (Mw 7.9) was estimated from far-field tsunami waveforms; however, the large tsunami heights on the Mentawai Islands could not be explained with the estimated source model (Satake et al. 2013b). Hill et al. (2012) explained the large tsunami on the Mentawai Islands by using a layered crustal structure model instead of a simple elastic half-space

model. Recently, Ratnasari et al. (2020) estimated the source process based on W-phase inversion, assuming a relatively low rigidity of 1.5×10^{10} N/m² near the trench. The source model of Ratnasari et al. (2020) produced a similar tsunami to that observed in the Mentawai Islands. This suggests that the depth-dependent rigidity along the plate interface is the key to estimating the slip amount along the fault model of great earthquakes.

2.2 The 2011 Tohoku-oki earthquake

The 2011 great Tohoku-oki earthquake (Fig. 2) was another key earthquake and its detailed source process was revealed using various tsunami-related data. The tsunami was observed through various systems such as typical tide gauges, ocean bottom pressure gauges connected by cables, GPS buoy systems (operated by the Port and Airport Research Institute in Japan) (Nagai and Shimizu 2009), and DART buoy systems (operated by the National Oceanic and Atmospheric Administration) (Meinig et al. 2005). In addition to those tsunami waveforms, various geophysical observational data, seismic data (including broadband and strong motion waveforms), co-seismic deformation data obtained from GPS data, ionospheric total electron content (TEC) data obtained from GPS data (Kakinami et al. 2012), and ocean bottom electromagnetic data (Ichihara et al. 2013) are available. Therefore, various researchers have investigated the source processes of this earthquake using various data sets. As a result, it became possible to discuss the frequency-dependent source processes. Particularly, the source process of the northern parts of the source area is still controversial.

Maeda et al. (2011) and Fujii et al. (2011) estimated the large near-trench slip by utilizing the data observed at cabled ocean bottom pressure gauges. Yamazaki et al. (2018) tried to reconcile the discrepancy between the slip estimation from seismic data and that from tsunami data. The rupture process of the 2011 Tohoku-oki earthquake and the temporal evolution of slip were determined by an inversion of tsunami waveform data observed at tide gauges, cabled ocean bottom pressure gauges, GPS buoys, and DART buoys (Satake et al. 2013a). Although static slip distributions of earthquakes have been estimated using tsunami waveforms by various researchers since 1987 (Satake 1987), the time-dependent slip distribution was first estimated for the 2011 Tohoku-oki earthquake. Gusman et al. (2012b) determined a slip distribution of the earthquake by using a joint inversion of co-seismic deformation data from GPS observations and tsunami waveforms observed at various station types. Gusman et al. (2012b) were the first study to incorporate aseismic deformation of unconsolidated sediment near the trench due to a large horizontal co-seismic displacement

into tsunami inversion, which was originally suggested by Tanioka and Seno (2001). Yokota et al. (2011) estimated the source process of the earthquake using joint inversion with strong motion, teleseismic waves, near-field tsunami waves, and geodetic data. Because they successfully estimated source processes using various observational data, Yokota et al.'s (2011) study was regarded as one of the most important studies on earthquake source processes. Saito et al. (2011) found that the tsunami waveforms observed at one DART station had dispersive characteristics; they used a linearized Boussinesq model for tsunami propagation simulation to compute Green's functions for their inversion. Yamazaki et al. (2013) also modeled dispersive effects using a non-hydrostatic evolution of the ocean wave model (NEOWAVE) to compute the tsunami propagation. Both models are based on the depth-integrated theory with weak dispersive characteristics and successfully improved the accuracy of the simulation of the 2011 tsunami. Based on these results, it is suggested that weak dispersive characteristics should be considered in tsunami simulations for the source process determination of great earthquakes.

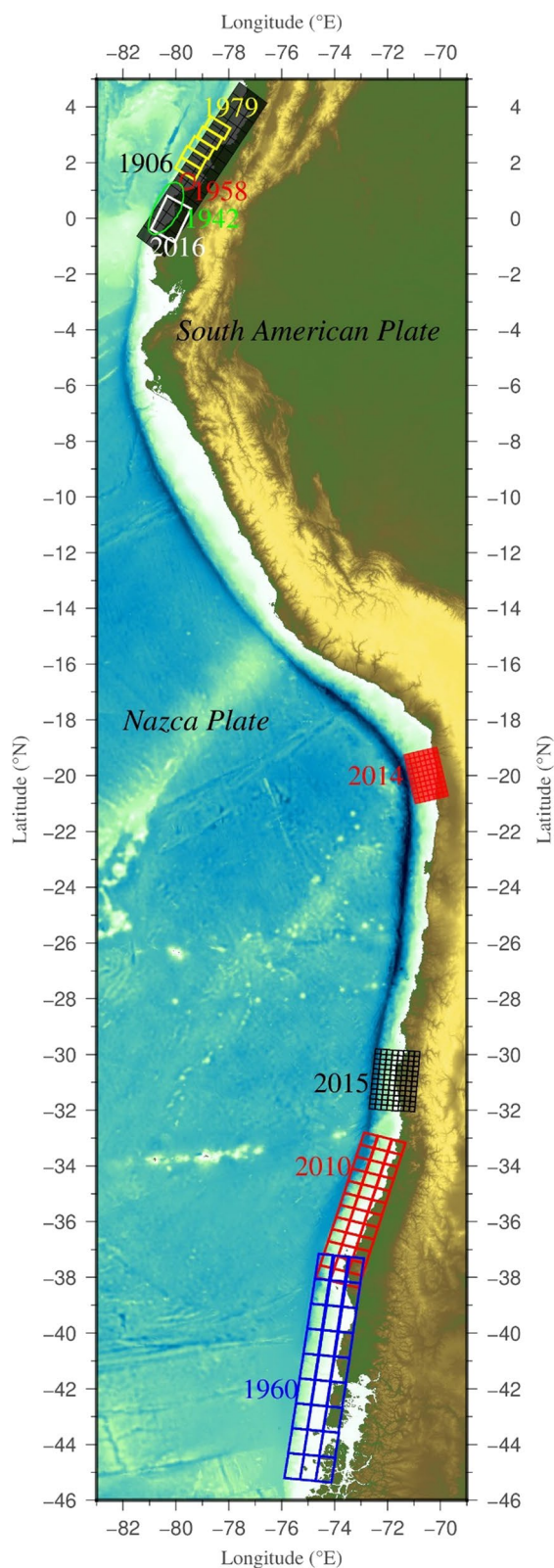
Furthermore, the 2011 tsunami was observed using far-field DART buoys and tide gauges along the Pacific Ocean. Watada et al. (2014) investigated these far-field tsunami waveforms and found that the tsunami propagated not only with the wave dispersion itself, but also with dispersion effects associated with the self-gravitating elastic earth. Watada et al. (2014) also developed a method to account for these effects using a theoretical dispersion curve. Baba et al. (2017) developed a method for directly incorporating these effects into tsunami propagation simulations. The dispersion effects associated with a self-gravitating elastic earth are not negligible for tsunamis propagating over long distances. Thus, the method developed by Watada et al. (2014) to account for dispersion effects has been key for investigating the source processes of great earthquakes using far-field tsunami waveforms. The method was used to investigate the source process of the recent great earthquakes: the 2004 Sumatra–Andaman earthquake (Mw 9.2) (Fujii et al. 2021), the 2005 Nias earthquake (Mw 8.6) (Fujii et al. 2020), the 2010 Maule, Chile, earthquake (Mw 8.8) (Yoshimoto et al. 2016), the 2014 Iquique, Chile, earthquake (Mw 8.0) (Gusman et al. 2015), the 2015 Illapel, Chile earthquake (Mw 8.4) (Heidarzadeh et al. 2015), and the 2020 Shumagin, Alaska earthquake (Mw 7.8) (Mulia et al. 2022). The details of these advancements in far-field tsunami computations have been reviewed by Watada (2023).

Ichihara et al. (2013) showed that ocean bottom electro-magnetometers near the 2011 Tohoku-oki earthquake source detected the 2011 tsunami. Using these

data, the tsunami source could be constrained. A detailed theoretical study (Minami et al. 2017) concluded that the tsunami waveform with dispersive characteristics was reproduced well from observed ocean-bottom electromagnetic data. Especially, it is important that the flow speeds during the 2011 tsunami can be reproduced from the ocean bottom electromagnetic data. The tsunami was also detected as an ionospheric disturbance by analyzing GPS data (Kakinami et al. 2012). The Total Electron Content (TEC) along the slanted path between the satellite and receiver was obtained from GPS data and represents the ionospheric disturbance 300 km above the sea level. Because there are more than 1000 GNSS stations in Japan, the ionospheric disturbance caused by the 2011 Tohoku-oki tsunami was detected using the TEC time series obtained from GPS stations in Japan (Kakinami et al. 2012). If tsunami amplitudes are precisely estimated from TEC time series data, such highly dense observations of tsunami wave fields will be key for investigating the source process of great earthquakes in the future.

The characteristics of the sediments deposited by the 2011 tsunami along Japan's Pacific coast were thoroughly surveyed. Jaffe et al. (2012) showed that inundated flow speeds along a survey line during a tsunami can be estimated by modeling sandy tsunami deposit layers at the survey points. Gusman et al. (2018) shows that not only the thickness of the tsunami deposits but also grain sizes of the tsunami deposits were key to reproduce the 2011 tsunami behavior along the steep coastal valley. Mitra et al. (2020) developed an inverse method to estimate tsunami characteristics, inundated flow depth, and velocity from tsunami deposit conditions in one-dimensional flat bathymetry using a deep learning neural network. These results indicate that a detailed tsunami deposit distribution is a key element that will lead to estimating the source processes of historical and pre-historical great earthquakes in the future.

After the 2011 Tohoku earthquake, a dense cabled observation network called the seafloor observation network for earthquakes and tsunami around the Japan Trench (S-net) was installed. In this network, 150 observation stations consisting of ocean-bottom pressure sensors and seismometers are connected by cables at 30-km intervals (Aoi et al. 2020). The first earthquake event with a tsunami after the installation of the S-net was the 2016 Fukushima earthquake (Mw 7.1) (Fig. 2). The 2016 tsunami was observed by pressure sensors of the S-net (Kubota et al. 2021), five ocean bottom pressure sensors offshore Kamaishi, and tide gauges (Gusman et al. 2017). The source process of the 2016 earthquake has been well studied using those tsunami data. Kubota et al. (2021) estimated the stress drop of an earthquake and discussed the stress regime of the source region. Moreover,



◀ **Fig. 3** Earthquake sources off South America in 1906 (Yamanaka and Tanioka 2021), 1942 and 1958 (Collot et al. 2002), 1979 (Adriano et al. 2017), 2016 (Gombert et al. 2018), 2014 (Gusman et al. 2015), 2015 (Heidarzadeh et al. 2015), and 1960 and 2010 (Fujii and Satake 2012)

Mizutani and Yomogida (2021) developed a back-projection imaging method for tsunami waveforms, applied it to the observed ocean bottom tsunami waveform data, and estimated the tsunami source of the 2016 Fukushima earthquake. These advancements in techniques will be a key for understanding the source processes of great earthquakes in the future.

3 Historical great earthquakes

Research on source processes of great historical earthquakes using tsunami data has recently made significant progress. As presented previously, Watada et al. (2014) found that far-field tsunami propagation is largely affected by self-gravitating elastic earth. Considering this effect has become essential for investigating historical tsunamis propagating over a long distance (far-field tsunamis). The source processes of the 1960 great Chile earthquake (Mw 9.3–9.4) were accurately estimated by computing the far-field tsunami waveforms with this effect and computed near-field co-seismic deformation (Ho et al. 2019) (Fig. 3).

The source of the 1854 great Ansei Tokai earthquake (Mw 8.5) that occurred in the Nanakai Trough subduction zone (Japan) was estimated using tsunami waveforms from San Francisco and San Diego along the California coast (USA) (Kusumoto et al. 2020) (Fig. 4). In 1854, tsunami waveforms observed at tide gauges were only available in California, but not in Japan. Those results obtained by including the dispersion effects for far-field tsunamis showed that far-field tsunami waveforms contribute to the estimation of earthquake source processes. The source process of the 1707 great Nankai earthquake (Mw 8.7) was estimated using a large number of historical documents of tsunami heights along the coast of Shikoku, Kii Peninsula, and Tokai area and a key tsunami deposit site data in the Kyusyu region of Japan (Furumura et al. 2011). To explain the key tsunami deposit data, the source of the earthquake needed to be extended about 70 km west from the Ashizuri Peninsula, at the westernmost end of the Shikoku region.

The slip distribution of the 1906 Colombia-Ecuador great earthquake (Mw 8.7) (Fig. 3) was estimated from an old tide-gauge record from Naos Island in Panama, located relatively near the source (Yamanaka and

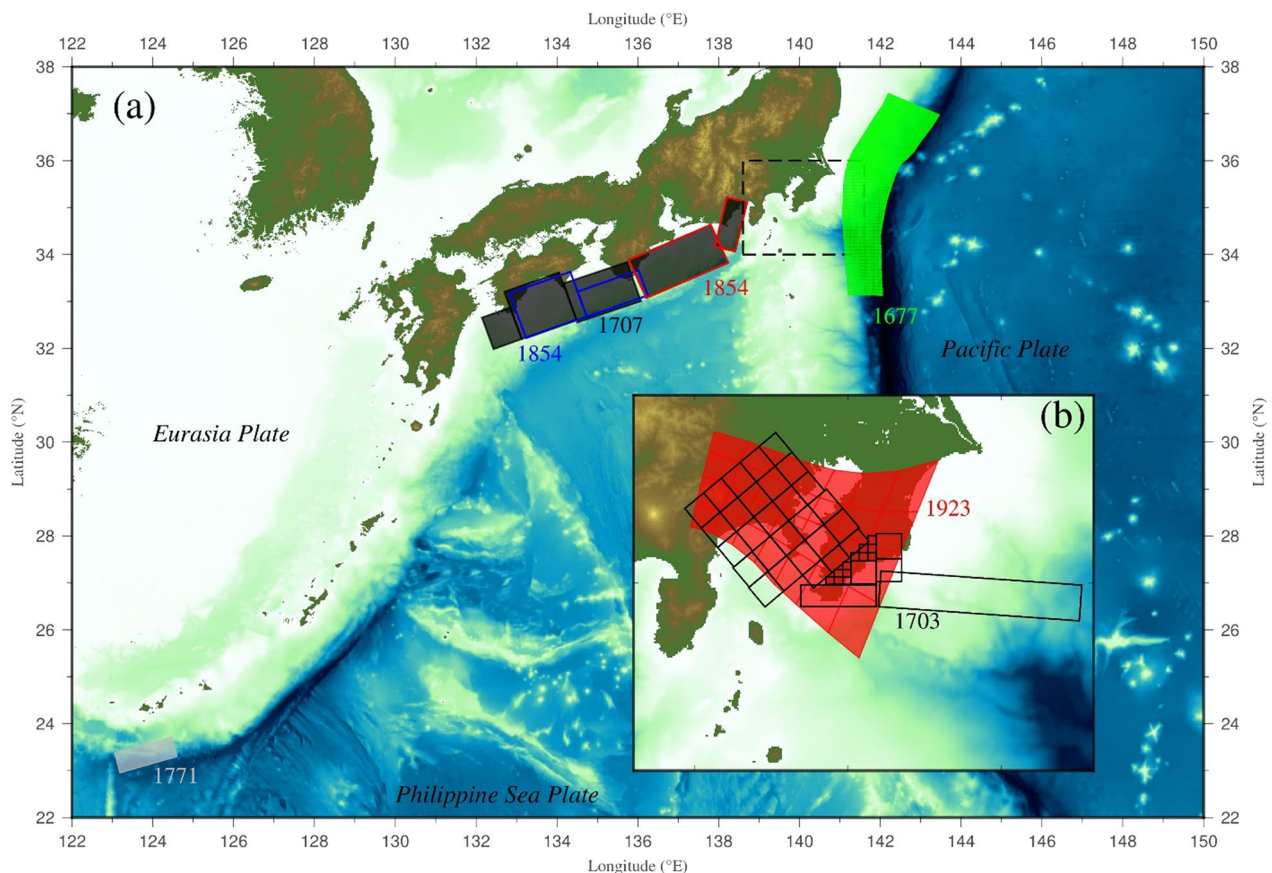


Fig. 4 Earthquake sources off Kanto and western parts of Japan in 1677 (Cabinet Office 2013), 1703 (Yanagisawa and Goto 2017), 1707 (Furumura et al. 2011), 1771 (Nakamura 2009), 1854 (Tokai: Kusumoto et al. 2020; Nankai: Ando 1975), 1923 (Nakadai et al. 2023). Area of panel (b) corresponds to an area specified by black-dashed square in panel (a)

Tanioka 2021). Old tide gauge data occasionally remain uncertain and are associated with various unknown factors such as absolute time and absolute amplitude. To resolve this problem, by comparing the astronomical tide level changes in the tide gauge record with estimated ones, Yamanaka and Tanioka (2021) validated the old tide gauge record for the 1906 tsunami and used it in their inversion with synthetic waveforms simulated based on a linearized Boussinesq model. Although a single tsunami waveform was used for the tsunami waveform inversion, the slip distribution was well resolved. The estimated slip distribution of the 1906 earthquake was compared with the source areas of the recent sequence of great earthquakes, namely the 1942 (Mw 7.9), 1958 (Mw 7.8), 1979 (Mw 8.1), and 2016 (Mw 7.8) great earthquakes that occurred in the Colombia-Ecuador subduction zone (Fig. 3). Consequently, the stress-release conditions at the plate interface were discussed by Yamanaka and Tanioka (2021).

The source processes of the 1923 Kanto earthquake (Mw 8.0) that occurred beneath the Metropolitan

Tokyo area (Fig. 4) were re-estimated using tsunami waveforms observed at tide gauges in Tokyo Bay and the Ibaraki Prefecture, tsunami height survey data along the Izu Peninsula, and co-seismic vertical deformation survey data (Nakadai et al. 2023). The source processes were estimated using seismic wave data and co-seismic vertical deformation data (e.g. Kobayashi and Koketsu 2005; Matsu'ura et al. 2007). Nakadai et al. (2023) modified digital topography data to be consistent with the topography in 1923 for a tsunami computation and estimated a slip distribution of the earthquake. According to Nakadai et al. (2023), a large slip along the plate interface near the Sagami Trough was responsible for the large tsunami observed along Izu Peninsula. The results of Nakadai et al. (2023) demonstrate that the use of detailed bathymetric and old topographic data is essential for tsunami analysis of historic great earthquakes.

Historical documents on the tsunami at several locations in Choshi City are available for the 1703 Genroku Kanto earthquake (Mw > 8.3) (Fig. 4), which was another

great earthquake that occurred beneath the Metropolitan Tokyo area before the 1923 earthquake (Yanagisawa and Goto 2017). Yanagisawa and Goto (2017) investigated the source process of the 1703 Genroku earthquake using these data and found that a trenchward extent of the fault model was necessary. The slip amount of the 1677 Enpo Tsunami earthquake (Mw 8.3–8.6) that occurred off Boso peninsula was estimated using historical document data and tsunami deposit data at Choshi (Yanagisawa et al. 2016). The sub-fault model located near the Japan Trench that was originally used by Cabinet office (2013) (Fig. 4) was used to estimate the slip amount by Yanagisawa et al. (2016).

Detailed historical documents are important in determining the source processes of great earthquakes, and for the 1611 Keicho earthquake (Mw 8.5) (Fig. 2), the tsunami disaster along the Sanriku Coast is well documented. One reported that the tsunami overflowed the Koyadori pass, with an elevation of 26 m, inside the Funakoshi Peninsula from south to north. At three locations several kilometers away from the Koyadori pass, the tsunami reached an elevation of less than 4 m. Yamanaka and Tanioka (2022) found that this significant local concentration was only produced when the source area was located relatively close to Koyadori. They also suggested resonance in the southern bay of Koyadori as a potential mechanism for producing local concentration. Thus, Yamanaka and Tanioka (2022) proposed that two large slip areas at the plate interface near the Japan Trench were necessary to excite the resonance of the bay.

4 Great pre-historical earthquakes

Source processes of great pre-historical earthquakes have been determined by geological studies, including tsunami deposits, diatoms, coastal tree fossils, coral microatolls, and turbidites. Influential results based on geological studies were present for the 1700 Cascadia earthquake (Fig. 5). The occurrence of the 1700 Cascadia earthquake was suggested from the analysis of tsunami deposits and coastal tree ring dating (Atwater et al. 1991; Atwater and Yamaguchi 1991) or the presence of turbidites at the ocean bottom (Adams 1990; Goldfinger et al. 2003). The source process of the 1700 Cascadia earthquake was revealed using historical tsunami height information without shaking in Japan and the coastal subsidence distribution from coastal tree death and tsunami deposit data in Cascadia (Satake et al. 1996, 2003). Those studies concluded that the 1700 Cascadia earthquake with a magnitude range of 8.7–9.2 ruptured the entire Cascadia subduction zone.

An earthquake in Hokkaido in the seventeenth century (the seventeenth century Hokkaido earthquake) was a great prehistoric earthquake (Mw 8.8) in which the

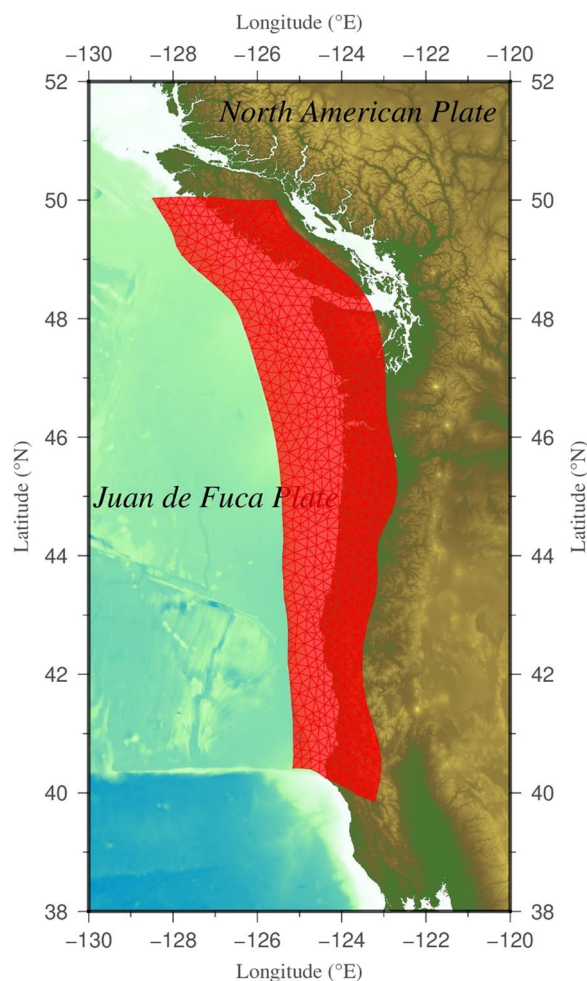


Fig. 5 Potential Cascadia earthquake source area (Melgar et al. 2022). This source area can be comparable to the area of 1700 Cascadia earthquake

source process was well determined from geological data (Fig. 2). The earthquake source model was first estimated by Nanayama et al. (2003) and Satake et al. (2008) based on the tsunami deposit distribution along the Pacific coast of Hokkaido. Ioki and Tanioka (2016) re-estimated the source model of the earthquake using all available tsunami deposit data and suggested that the earthquake ruptured the plate interface near the Kuril trench. This indicates that the source process of the seventeenth century Hokkaido earthquake may have been similar to that of the 2011 Tohoku-oki earthquake. In addition to the earthquake itself, pre- and post-earthquake deformations along the Hokkaido coast were first determined by Sawai et al. (2004) using the diatom distribution in coastal sediment layers above or below tsunami deposits. This result shows that these sediment analyses are key for understanding earthquake generation processes.

The 869 Jogan earthquake (Fig. 2), which was likely a predecessor of the 2011 earthquake, was another event in which the source process was well studied using tsunami deposit data. Minoura et al. (2001) surveyed tsunami deposits in the Sendai Plain, in the Tohoku region of Japan, and suggested that a great earthquake with a large tsunami occurred off the Sendai Plain in 869. Namegaya et al. (2010) estimated a source model for this earthquake (Mw 8.5) using tsunami deposit data from the Sendai Plain and Ishinomaki City. The 2011 event provided valuable insights into tsunami deposits, as previously reviewed. As a result, after the 2011 Tohoku-oki earthquake, studies on the tsunami deposit distribution associated with the 869 event accelerated (Sawai et al. 2012; Sugawara et al. 2013). Namegaya and Satake (2014) suggested that the rupture of the 869 earthquake extended over at least 200 km, resulting in a moment magnitude of 8.6. An additional important finding by Namegaya and Satake (2014) was that the flow depths and velocities of the 2011 Tohoku-oki tsunami at most sites where the deposits associated with the 2011 tsunami were found to be approximately 1 m and 0.6 m/s, respectively. This result indicates that there is the required flow depth and velocity to produce a tsunami deposit at the site. The required flow depth and velocity are key elements that will lead to understanding the source processes of prehistorical earthquakes in the future.

Studies on coral microatolls along the Sumatra coast (Natawidjaja et al. 2004, 2006) are important to find the sources of great earthquakes. Microatolls are very sensitive to sea level changes. Since their growth produces annual coral bands, historical sea level changes have been recorded in them. Then, co-seismic, pre-earthquake, and post-earthquake vertical deformations can be analyzed from these data. The sources of the Great Sumatra megathrust earthquakes of 1797 and 1833 were estimated using these data (Natawidjaja et al. 2006) (Fig. 1).

Sources of great earthquakes can be investigated via coral boulder distribution along the coasts as a geological study. The 1771 great Yaeyama tsunami killed more than 10,000 people on the Ishigaki and Miyako Islands in Okinawa, Japan. Many large coral boulders are distributed along the coasts of Ishigaki and Miyako Islands. These are considered to have been caused by a large tsunami (Goto et al. 2010a). Further, the 1771 tsunami is considered to have been caused by a large submarine landslide, accounting for large local tsunami heights ranging from 30 to 80 m. Okamura et al. (2018) suggested that the tsunami was caused by an accretionary prism collapse from seismic profiles and geomorphological evidence. By contrast, Nakamura (2009) suggested that the tsunami was generated by a great earthquake (Mw 8.0) (Fig. 4). Goto et al. (2010b) showed that small boulders

found off the coasts of the Okinawa Islands along the northeast of the Ryuku Trench could be moved by coastal waves under storm conditions; however, large boulders off the Ishigaki or Miyako Islands along the southwest of the Ryuku Trench could not be moved by such waves. Therefore, all large boulders off the Ishigaki and Miyako Islands must have been moved by large tsunamis. By dating the coral boulders, a tsunami was found to have occurred in 1600–1630, and a big wave was documented in 1625 at Ishigaki Island (Araoka et al. 2010). Even before this event, many events had been identified to have occurred in the previous 2000 years (Goto 2017). This indicates that large tsunamis generated by great earthquakes repeatedly occurred along the southeastern part of the Ryuku Trench, but not along the northwest part of Ryuku Trench.

5 Discussion

Since the great 2004 Sumatra–Andaman and 2011 Tohoku-oki earthquakes, research on earthquake source processes using various tsunami-related data has advanced intensively, as shown in this review. However, future improvements are still needed in source process studies of historical and pre-historical great earthquakes. One expected advancement is the development of nonlinear inversion methods using tsunami waveforms or heights. The observation data of tsunamis associated with great historical earthquakes are based solely on historical documents or tsunami waveforms observed by old tide gauges. That is, offshore tsunami observational data are unavailable for such events. Nearshore tsunami dynamics of large amplitude waves are strongly influenced by nonlinear effects. To use observational data for historical large tsunamis in the estimation of earthquake source processes, nonlinear inversion techniques are required. For seismological studies, nonlinear inversion methods have been already developed (e.g., Tarantola 2005; Brossier et al. 2010). For geodetical data, such as GNSS measurements, the Markov chain Monte Carlo (MCMC) method has been used for source process analysis of earthquakes (Ito et al. 2016; Yamada et al. 2022). In tsunami analysis, forward tsunami modeling is still occasionally used to determine the source processes of historical earthquakes through trial and error although Nemoto et al. (2019) proposed a weekly nonlinear inversion method. Nonlinear inversion methods for estimating earthquake source processes from tsunami data must be developed and applied to various events to assess their performances.

Tsunami deposits provide key data for understanding the source processes of prehistorical earthquakes. In general, tsunami inundation areas estimated from tsunami deposit data are used to estimate the source

Table 1 Important progress in source studies of great earthquakes reported in this review

Section	Name of earthquake	Mw	References	Important progress (*data, #parameter, and \$method)	
Recent great earthquakes	2004 Sumatra–Andaman	9.1	Hirata et al. (2006) Tanioka et al. (2006) Fujii and Satake (2007) Lorito et al. (2010) Gusman et al. (2012a) Fujii et al. (2021)	satellite data*, rupture velocity# satellite data*, rupture velocity# satellite data*, rupture velocity# satellite data*, GPS data*, slip angle#, rupture velocity# deposit (thickness data)*\$ far-field (Watada et al. 2014)\$	
	2007 Bengkulu	8.5	Gusman et al. (2010)	InSAR data*, slip angle#	
	2010 Mentawai tsunami	7.9	Satake, et al. (2013b) Hill et al. (2012) Ratnasari et al. (2020)	detail survey* layered crustal structure\$ depth-dependent rigidity\$	
	2011 Tohoku-oki	9.0	Satake et al. (2013a) Gusman et al. (2012b) Yokota et al. (2011) Saito et al. (2011) Yamazaki et al. (2013) Watada et al. (2014) Baba et al. (2017) Ichiyama et al. (2013) Minami et al. (2017) Kakinami et al. (2012) Jaffe et al. (2012) Gusman et al. (2018) Mitra et al. (2020)	temporal evolution slip\$ deformation of sediments near the trench\$ seismic wave + geodetic + tsunami\$ dispersive wave equations\$ dispersive wave equations\$ dispersion effects with the self-gravitating elastic earth\$ dispersion effects with the self-gravitating elastic earth\$ electro-magnetometer data*\$ electro-magnetometer data*\$ TEC data from GPS data*\$ sedimental data by tsunami*\$ sedimental data by tsunami*\$ sedimental data by tsunami*\$	
	2005 Nias (Sumatra)	8.6	Fujii et al. (2020)	far-field (Watada et al. 2014)\$	
	2010 Maule (Chile)	8.8	Yoshimoto et al. (2016)	far-field (Watada et al. 2014)\$	
	2014 Iquique (Chile)	8.0	Gusman et al. (2015)	far-field (Watada et al. 2014)\$	
	2015 Illapel (Chile)	8.4	Heidarzadeh et al. (2015)	far-field (Watada et al. 2014)\$	
	2020 Shumagin (Alaska)	7.8	Mulia et al. (2022)	far-field (Watada et al. 2014)\$	
	2016 Fukushima	7.1	Kubota et al. (2021) Mizutani and Yomogida (2021)	S-net data*, stress drop#\$ S-net data*, back-projection imaging\$	
	Historical Great Earthquakes	1960 Chile	9.3–9.4	Ho et al. (2019)	far-field (Watada et al. 2014)\$
		1854 Ansei Tokai	8.5	Kusumoto et al. (2020)	old tide gauges* far-field (Watada et al. 2014)\$
		1707 Nankai earthquake	8.7	Furumura et al. (2011)	historical document*, tsunami deposit sites*
		1906 Colombia-Ecuador	8.7	Yamanaka and Tanioka (2021)	old tide gauges* dispersive wave equations\$
		1923 Kanto	8.0	Nakadai et al. (2023)	old tide gauges*, geodetic data document*, old maps*
1703 Genroku Kanto		> 8.3	Yanagisawa and Goto (2017)	historical document*, tsunami deposit sites*	
1677 Enpo (Boso)		8.3–8.6	Yanagisawa et al. (2016)	historical document*, tsunami deposit sites*	
Pre-Historical Earthquakes	1611 Keicho Sanriku	8.5	Yamanaka and Tanioka (2022)	historical document*, resonance of the bay\$, dispersive wave\$	
	1700 Cascadia	8.7–9.2	Atwater and Yamaguchi (1991) Goldfinger et al. (2003) Satake et al. (1996) Satake et al. (2003)	tsunami deposit sites* tree ring dating* turbidites* historical documents (Japan)* geological evidence (USA)* historical documents (Japan)*	
	Seventeenth century Hokkaido	8.8	Nanayama et al. (2003) Satake et al. (2008) Ioki and Tanioka (2016) Sawai et al. (2004)	tsunami deposit sites* tsunami deposit sites* tsunami deposit sites* diatom distribution in sediment*#\$	

Table 1 (continued)

Section	Name of earthquake	Mw	References	Important progress (*data, #parameter, and \$method)
	869 Jogan (Tohoku)	8.5–8.6	Namegaya et al. (2010) Sawai et al. (2012) Sugawara et al. (2013) Namegaya and Satake (2014)	tsunami deposit sites* tsunami deposit sites* tsunami deposit sites* tsunami deposit sites* flow depth (at deposit limits)#\$
	1797 Sumatra	-	Natawidjaja et al. (2006)	Microatolls (annual coral bands)*#\$
	1833 Sumatra	-	Natawidjaja et al. (2006)	Microatolls (annual coral bands)*#\$
	1771 Yaeyama	8.0	Nakamura (2009) Okamura et al. (2018) Goto et al. (2010b) Goto (2017)	historical document* tsunami deposit sites* prism collapse#, seismic profiles* large coral boulders*\$ large boulders (precise dating)*#\$

processes of great earthquakes (e.g., Namegaya and Satake 2014; Ioki and Tanioka 2016). Recent studies further showed that tsunami deposit characteristics provide information about tsunami propagation that can be used to constrain the source process of the earthquake. Jaffe et al. (2012), Gusman et al. (2018), and Mitra et al. (2020) indicated that tsunami characteristics, flow depth or velocity, could be estimated from tsunami deposit data. The inverse method using a deep-learning neural network developed by Mitra et al. (2020) was assuming one-dimensional flat topography. A problem with the work by Mitra et al. (2020) is that the method only works when the ground gradient can be approximated as zero. The sediment transport model by Gusman et al. (2018) works for two-dimensional horizontal (2D) topography as a forward model although the 2D topography at the time of the earthquake needs to be surveyed before applying the method to pre-historical earthquakes. We eagerly anticipate the development of an inverse method for 2D topography that would allow the extraction of the source processes of major earthquakes from the characteristic data found in tsunami deposits.

6 Conclusions

The 2004 Sumatra–Andaman and 2011 Tohoku-oki great earthquakes were key events that advanced studies on source processes using tsunami-related data. Research on the source processes of historical earthquakes has advanced because these two earthquakes have been extensively studied. After the source process of the 1700 Cascadia earthquake was revealed using geological data near the source and tsunami documents in Japan, tsunami deposit studies rapidly advanced. Those advancements discussed in this review are summarized in Table 1. A nonlinear inversion method using

tsunami waveforms or heights to obtain the slip distribution of great historical earthquakes is expected to be developed in the near future. Inverse methods of tsunami deposit characteristic data in 2D topography must be developed to specifically obtain the source processes of great earthquakes.

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