On the recurrence of great subduction zone earthquakes

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The last decade has witnessed two unusually large tsunamigenic earthquakes. The devastation from the 2004 Sumatra–Andaman and the 2011 Tohoku-Oki earthquakes (both of moment magnitude ≥ 9.0) and their ensuing tsunamis comes as a harsh reminder on the need to assess and mitigate coastal hazards due to earthquakes and tsunamis worldwide. Along any given subduction zone, megathrust tsunamigenic earthquakes occur over intervals considerably longer than their documented histories and thus, 2004-type events may appear totally 'out of the blue'. In order to understand and assess the risk from tsunamis, we need to know their long-term frequency and magnitude, going beyond documented history, to recent geological records. The ability to do this depends on our knowledge of the processes that govern subduction zones, their responses to interseismic and coseismic deformation, and on our expertise to identify and relate tsunami deposits to earthquake sources. In this article, we review the current state of understanding on the recurrence of great thrust earthquakes along global subduction zones.

Keywords: Andaman–Nicobar, earthquake recurrence, subduction zone, tsunami geology.

Introduction

SUBDUCTION zones are convergent plate boundaries where the world's largest earthquakes originate, contributing to a substantial part of the seismic moment released, worldwide. Because they are shallow and very large in terms of energy release and rupture areas, these great plate boundary earthquakes constitute hazard not only from ground shaking but also from tsunamis that are likely to follow them[1] (see also, Satake and Atwater[2], and references therein). History is punctuated with devastating tsunamis caused by earthquakes, the 1755 Lisbon tsunami being the largest historical event ever described[3]. Among the great earthquakes of the last century, the Chile (1960) and Alaska (1964) earthquakes are noted for their large magnitudes (M 9.5 and 9.2 respectively, USGS) and their transoceanic tsunamis which travelled across the Pacific Ocean. Other notable tsunamigenic earthquakes in recent times are the (M_w 9.2) 26 December 2004 Sumatra–Andaman[4]; the (M_w 8.0) 29 September 2009 Samoa-Tonga; the (M_w 8.8) 27 February 2010 Chile and the (M_w 9.0) 11 March 2011 Tohoku-Oki[5–7] (Figure 1, Table 1). In their efforts to understand the factors that control the size of megathrust subduction zone earthquakes, seismologists have attempted to relate various properties of subduction zones to seismic productivity, such as plate convergence rate, slab age and fault zone temperature. Given that the rupture of any one contiguous segment of several hundred kilometres length of the >40,000 km of global subduction boundaries is sufficient to produce an $M_w \geq 9$ event, possibilities for great earthquakes existing along every subduction zone have been recognized[8].

History of large subduction-zone earthquakes during the past century suggests that some subduction zones are more active than the others. Thus, Cascadia, southern Chile, and the Marianas, appear to be relatively less active compared to Java, Sumatra, Japan, South America, the Aleutians and the Kurile trenches. What factors control the intrinsic character of a subduction zone, leading to the century-scale differences in their seismic productivity is not very well understood. It was believed that if a young subducting plate was plunging fast along a shallow trajectory, the higher resistance at the plate interface would lead to larger earthquakes[9]. Indeed, many of the largest twentieth-century earthquakes have occurred at zones of fast subduction[10], favouring this argument (Figure 2). Later studies however suggest this relation to be less compelling, arguing that non-mechanical factors are also to be accounted for[8]. Thus, it may be noted that the 2004 Sumatra–Andaman earthquake occurred on a subduction zone where old lithosphere subducts at slow rates, not complying with the Ruff and Kanamori relationship mentioned above[11].

The next important question is about the recurrence of great earthquakes. Since we relate great earthquakes to transoceanic tsunamis, and an $M \sim 9$ event is about the largest earthquake that can occur on a given segment of a plate boundary, recurrence estimates are typically discussed for such events[2]. The largest earthquake ($M \sim 9$) that can occur within a given segment of the plate boundary is typically considered to be one that ruptures the entire length of the segment. A first-order estimate of an M 9 earthquake recurrence can be obtained from the basic premise of moment conservation that underlies plate
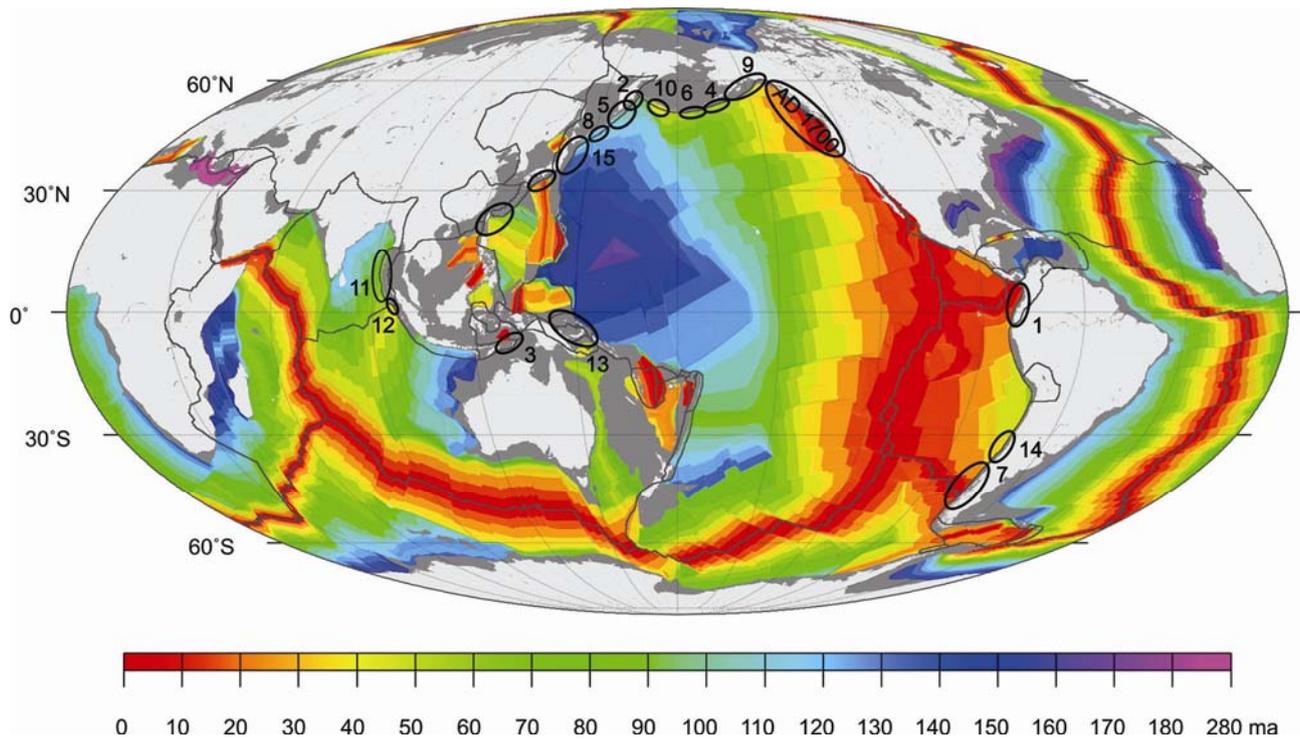
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Figure 1. World map centred along the 180th meridian, marking the ruptures of interplate earthquakes ($M \geq 8.5$) from 1906 to 2012, numbered chronologically and listed in Table 1 (data source for earthquake ruptures: NEIC, IRIS; ocean floor age data modified from Muller *et al.*[65]).

Table 1. A list of (mostly $M \geq 8.5$) interplate earthquakes from 1906 to 2012, marked in Figure 1

Sl. no.	Region	Year	Magnitude
1	Ecuador	1906	8.5
2	Kamchatka	1923	8.5
3	Banda Sea	1938	8.5
4	Unimak Island	1946	8.5
5	Kamchatka	1952	9.0
6	Andreanof Islands	1957	8.6
7	Chile	1960	9.5
8	Kuril Islands	1963	8.5
9	Alaska	1964	9.4
10	Rat Islands	1965	8.7
11	Sumatra	2004	9.2
12	Sumatra	2005	8.7
13	Samoa-Tonga	2009	8.0
14	Chile	2010	8.8
15	Japan	2011	9.0

Data source: NEIC, IRIS.

motions[8]. Thus, if an M 9 earthquake on a plate boundary of convergence rate v accounts for u metres of average slip, then the long-term average time between two consecutive events will be u/v (assuming that all the slip is by M 9-type earthquakes). Plate convergence rates on different boundaries might vary from $v = 25$ to 100 mm/yr, suggesting repeat times of the order of 250–1000 years if $u = 25$ m, a reasonable estimate for an M 9 earthquake. If some fraction of the convergence is taken up by other

means such as creep, slow slip events, or smaller earthquakes, this repeat time may increase[8]. Validation of this hypothesis would require some knowledge of the long-term history of subduction zones. Reliable records date back only to a few centuries and for most regions this is much shorter than the average recurrence period of great earthquakes. Information derived from written and geologic records however suggest that the interval between great earthquakes is irregular, not necessarily following the convergence rate–slip relation postulated by plate motions. For example, Cascadia is noted for its AD 1700 earthquake and at least 13 events at intervals of about 300–900 years, with an average of 570–590 years, but it has not generated any great earthquakes during the last >300 years[12].

Well-known examples (like Cascadia) suggest that many other factors could affect the productivity of a subduction zone. The unexpectedness of the 2004 and 2011 earthquakes, both in terms of their sources and magnitudes is partly due to the incomplete knowledge about the past seismicity as well as a lack of understanding of the long-term behaviour of subduction zones. For example, there was no historical precedent for an M 9-type earthquake along the Sumatra–Andaman plate boundary. Similarly, there was no historical record for any massive earthquakes near the 2011 source, except for the AD 869 Jōgan earthquake and its resulting tsunami, which devastated the Mutsu province of Japan[13]. These two earthquakes, however, have invigorated discussions on the
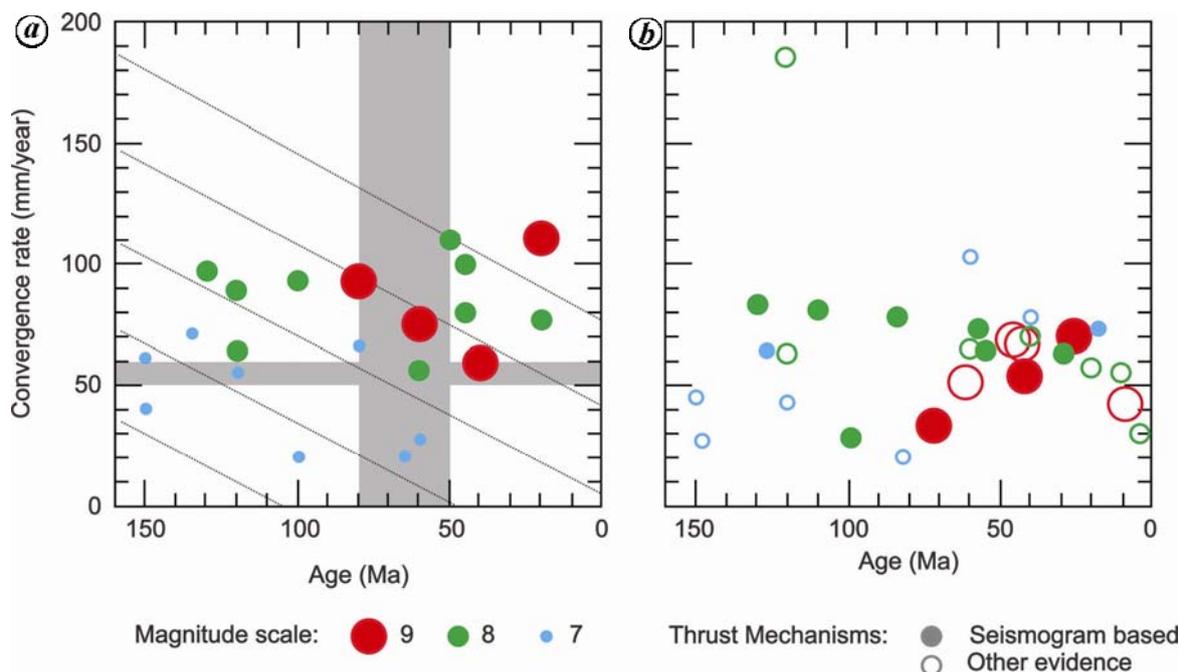
Figure 2. *a*, Ruff and Kanamori[10] using the then existing data suggested that maximum earthquake size at subduction zones is a function of plate age and convergence rate. Grey bands depict the plate age and convergence rate across the Sunda Trench marking the limiting values associated with the 2004 earthquake. *b*, Updated datasets analysed by Stein and Okal[11] (modified after refs 2 and 11).

recurrence of giant megathrust earthquakes and the use of tsunami deposits as proxies of past earthquake rupture sizes. In fact, the field evidence left by both these earthquakes has helped in improving tools like tsunami geology[14,15].

Tsunami geology studies are based on geological data such as ground deformation from great earthquakes and sand deposits from their ensuing tsunamis. While working with great subduction zone earthquakes, their recurrence and tsunamigenic potential, there are three important questions that need to be addressed. These are about the time window of the earthquake, its magnitude and rupture extent, and location on the plate boundary. Answers to these questions can only emerge from a perceptive understanding of the nature of the seismic cycle. In this article, we discuss tsunami geology as a tool in addressing these issues. Dependence of great earthquakes on the age of the subducting plate, rate of convergence, and working models of earthquake recurrence are briefly reviewed to place this study in context.

A brief overview of subduction zone processes and recurrence models

Seismicity, deformation and rupture characteristics at subduction zones vary from one to another, as well as along the same zone[2,10,16,17]. While some margins are known to produce frequent moderate to large earthquakes (e.g. the South American subduction zone), there are others that have not experienced any great earthquakes during

recent history times, but have produced great earthquakes in the past (e.g. Cascadia). As for the Sumatra–Andaman subduction zone, the southern Sumatra region has generated several large and great earthquakes, but the overall seismicity of the Andaman and Nicobar segments is comparatively low, involving a few large earthquakes and rupture lengths of 200–300 km (ref. 18).

Basic models of plate motions suggest that the forces required to drive lithospheric plates essentially originate at mid-oceanic ridges where they start to spread (ridge push); these forces are complemented by slab pull and slab suction[19,20] (Figure 3). A great thrust earthquake is believed to occur when the ridge push and slab pull forces exceed the strength of the locked interface of the thrust zone and this would imply an increased stress at the plate boundary prior to a great thrust earthquake[20]. Early models of recurrence, such as the elastic rebound, that also assume some sort of periodicity could be justified using these models[21]. If indeed earthquakes repeat and if they are presumed to be periodic, information derived on past earthquakes serves to make predictions on future earthquakes. Instrumental records of earthquakes or tsunamis are available only for a couple of hundred years or less and the average recurrence interval between great tsunamigenic earthquakes is much longer. There are exceptions like southwestern Japan where historical records are available for more than a 1000 years, and where the geologic and historical data can be combined[22]. Models of earthquake recurrence as discussed below are based on these fundamental attributes of subduction zone and
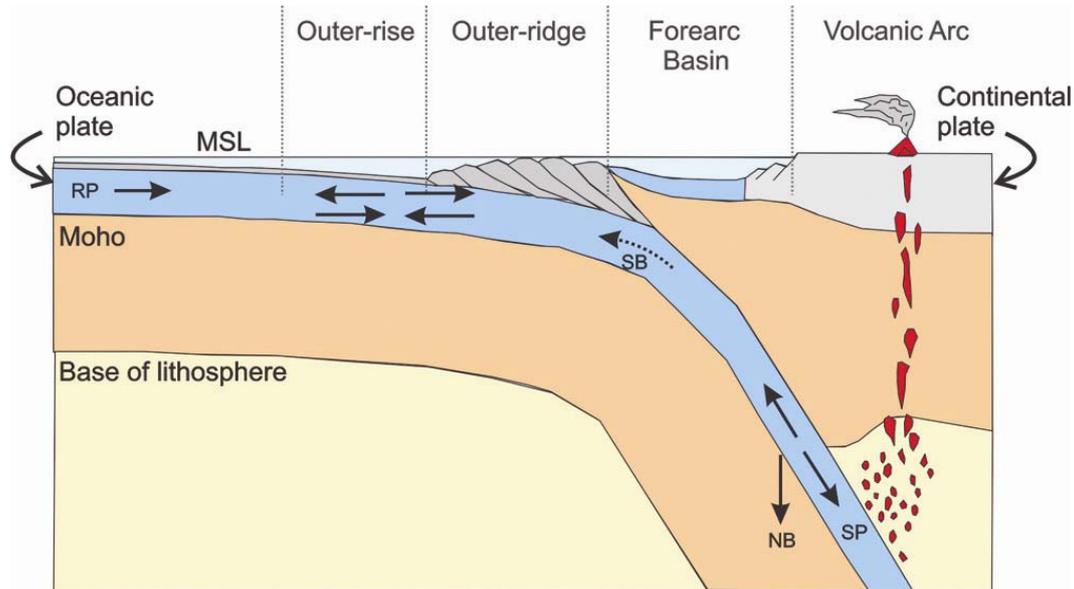
Figure 3. Schematic showing the structure and main seismogenic provinces of a subduction zone. The driving forces responsible for plate motions are also shown. RP, Ridge push; SP, Slab pull; NB, Negative buoyancy and resistive SB, Slab bending forces (modified after refs 19 and 22).

information derived from geological, historical and recent seismicity.

Time and slip predictable models

The elastic rebound theory, developed after the great 1906 San Francisco earthquake, presents a simple concept that describes the behaviour of faults and fault systems[21]. Plate tectonics provides a compelling, steady source of the strain energy that drives the elastic rebound, suggesting that occurrence of large earthquakes must be separated by intervals long enough for reloading. Early models have used this simple theory for describing earthquake behaviour, popular among them being the time-predictable and the slip-predictable models[23,24]. As implied by their names, the time-predictable model predicts the time (not size), and the slip-predictable model predicts the slip (and not time) of the next event. The time-predictable model assumes that each earthquake occurs at a critical stress level, but that the stress drop (slip) varies, and that the time to reach that critical stress level can be predicted. The slip-predictable model makes the opposite assertion, that there is a constant minimum stress, whereby all the strain accumulated since the previous earthquake is released in the next event.

Some early studies that used these models and their variations claimed predictive power[25], but their applications were over fault systems and large regions, overlooking the assumption that the time- and slip-predictable models consider earthquakes as a point source process. Several other studies have found that both these models are inadequate to explain earthquake behaviour and argue

instead for spatial/temporal clustering[26]. For example, neither time- nor slip-predictable models fit with the best-dated geologic records of the great Cascadia earthquakes, that show marked variation, not just in earthquake size but also in recurrence interval, which averages close to 500 years but ranges from a few centuries to a millennium[2]. Modern-day examples provide opportunities to review these models, based on more observations. It has been shown that events that form part of the super cycle can have a long recurrence interval (300–1500 yrs) and release extremely high seismic moment ($M_w > 9$), as was the case of the 1960 Valdivia (Chile) earthquake[27]. It follows that the seismic moment of the next great earthquake within such a super cycle might not be predictable from the slip deficit of the previous great earthquake. The latter point has been observed in the 2004 Sumatra–Andaman[28] and the 2011 Tohoku-Oki[7] earthquakes; both events released less than the theoretically predicted slip based on linear extrapolation of interseismic coupling.

Characteristic earthquakes and seismic gaps

The concepts that rupture zones tend to abut rather than overlap, and that large events occur in regions with histories of both long- and short-term seismic quiescence form the basis of the seismic gap hypothesis[29]. If much of the stress from plate motion is to be released seismically, then it intuitively follows that long-lived, unbroken segments of plate boundaries form gaps, and are most likely to rupture in future. Nishenko[30] published a list of 13 earthquakes endorsing the seismic gap hypothesis and since then it has been used for long-term forecast of

earthquakes in many regions (see Jackson and Kagan[26] and references therein). The seismic gap hypothesis holds that most long-term geologic slip on faults or plate boundaries are accomplished by characteristic earthquakes[31]. Important underlying assumptions are that faults and plate boundaries are segmented, that each characteristic earthquake reduces the stress to a uniform base level and that the time to the next earthquake depends almost entirely on the time of the previous event, ignoring the non-elastic stress redistribution and other causes that take place during the intervening period. Both the gap and the characteristic earthquake continue to be questioned in the context of recent global examples. For example, the 2010 Chile earthquake, discussed later in this article, had limited overlap with the previous 1928 rupture and only partially filled the gap, as predicted by the gap theory[32]. However, the gap theory was challenged by the great Tohoku-Oki earthquake, which occurred in a region where only an M 7.5-type earthquake was anticipated[33].

Both the characteristic and gap hypothesis need to be understood in the context of global examples that suggest substantial variations between earthquake ruptures within an individual subduction zone as well as from one zone to another. Some subduction zones are known to generate thrust events of $M_w > 9$, whereas some others host only earthquakes of magnitude 7–8. For example, the subduction zones of southern Chile, Cascadia, southern Alaska, Sumatra–Andaman and Japan have generated $M > 9$ earthquakes in the recent history. In contrast, other subduction zones in the southwest Pacific Island arcs have generated earthquakes of magnitude ≤ 7.5; others, such as the Makran subduction zone, are associated with earthquakes of magnitude ~8 (refs 1 and 34). Since the magnitude of an earthquake is related to its rupture area, it may be intuitively inferred that subduction megathrust earthquakes of $M \leq 7.5$ may lead to smaller rupture areas (tens of kilometres across). On the other hand, $M \sim 9$ earthquakes may be associated with ruptures ~1000 km alongstrike and a few tens of kilometres down-dip, as in the case of 1960 Chile[35], 1964 Alaska[36] and 2004 Sumatra–Andaman earthquakes[4]. The great plate boundary-breaking earthquakes mentioned above have also led to significant permanent ground deformation and tsunami inundation that remain preserved in the coastal stratigraphy, which are used by tsunami geologists to develop the chronology of past earthquakes.

Tsunami geology as a tool for earthquake recurrence studies

Tsunami geology has helped identify past events along several subduction zones; the South American, North American and Japanese among them. Along the Cascadia subduction zone (North America), palaeoseismological evidence such as tsunami deposits, coastal subsidence

and deep-sea turbidites suggests a recurrence interval of ~500 years and the most recent event (AD 1700) was around 300 years ago[22]. The M 9.5 1960 Chile earthquake, the largest in the 20th century, was preceded by similar earthquakes in 1837, 1737 and 1575. Historical and tsunami geology data show evidence for the 1575 earthquake and similar events comparable to the 1960 event following a ~300 year cycle[27]. Studies in eastern Hokkaido, Japan show that the southern Kuril trench repeatedly produced earthquakes and tsunamis larger than those recorded in the region's 200 years of written history[16]. Thus, realistic assessment of time windows of previous great earthquakes seems plausible using tsunami geology, but obtaining estimates of the rupture area and modelling the inundation limits are far more challenging. Here we discuss observations that have led to identification of past earthquakes in some subduction zones.

Coseismic land deformation preserved in stratigraphy

The complex processes that govern subduction zones often manifest in the coseismic deformation of the coastal regions. For example, the sudden coseismic slip during an earthquake leads to perceptible deformation, expressed as submergence or emergence of land. Convergence prior to great earthquakes causes bending and buckling of the crust, producing a flexural bulge farther inland. These processes are known to cause gradual uplift on the leading edge of the overriding plate and thrust faulting earthquakes[20] (Figure 4). As the rupture releases the stored elastic energy, the seaward edge of the continent springs back and moves upward, and the bulge collapses leading to subsidence of land. The most compelling evidence of past tectonic movements along the plate margins comes from such ground deformation preserved in the geological records. For example, the coseismic deformation observed during great earthquakes as in the 1960 Chile and 1964 Alaska events, demonstrates these effects[35,36]. Geomorphic changes following sudden submergence, such as dead vegetation, peat/mud couplets and landward deposits of tsunami sand sheets are considered as direct evidence of a tsunamigenic earthquake[37,38].

Uplift of land is usually expressed as coral platforms or tidal mudflats, raised above the pre-earthquake shoreline, as observed during the 1960 Chile and 1964 Alaska earthquakes. Regions of subsidence during both these earthquakes included vegetated coastal lowlands, which subsequently turned into intertidal flats leading to the formation of peat used for dating the subsidence event[39]. Observations of ground subsidence expressed as two generations of dead red cedar trees were used to obtain evidence of penultimate coseismic subsidence along the Cascadia subduction zone (Figure 5). Besides establishing the seismic history during the Holocene, subsequent
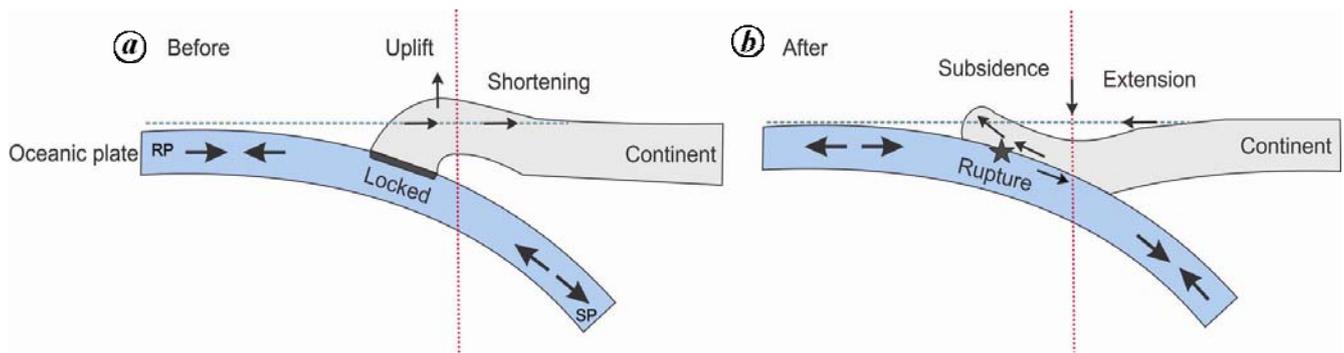
Figure 4. Deformation across the plate boundary before and after a megathrust earthquake showing uplift and subsidence on the leading edge of the overriding plate, figure modified from Hyndman and Wang[45]. Plate driving forces modified after refs 19 and 20. RP, Ridge push; SP, Slab pull.

Figure 5. Subsided marshes showing two palaeo-root zones of red cedar trees, from the AD 1700 earthquake and one of its predecessors, at the Redtail locality of the Niawiakum River, a tidal arm of the Willapa Bay at Washington, along the Cascadia subduction zone (photograph courtesy: Brian Atwater, USGS).

studies in North America and Japan yielded the exact time (the evening of 26 January 1700) and approximate size (M 8.7–9.2) of the most recent of Cascadia's great earthquakes (Atwater et al.[22] and references therein). Since this pioneering study, submergence of land along coastal regions of subduction zones is considered as a useful proxy to identify past tectonic events[14].

Tsunami deposits

Most literature on tsunami geology deals with Holocene tsunami sands deposited on coastal lowlands along seismically active continental margins, the work that began in the mid-1980s, along Cascadia[40] and Japan[41]. Tsunami inundation limits are obtained from the inland extent of tsunami deposits, which occur as sand sheets, coral or organic debris, often associated with marine organisms[42]. For example, studies of Holocene tsunami deposits in Japan have used deposits of prehistoric tsunamis to infer the infrequent occurrence of larger earthquakes[16]. Repeated occurrences of palaeotsunami sand sheets, making sharp contacts with the underlying peaty soil layers within the rupture zone of the 1960 Chile earthquake (Figure 6) have been used to identify its predecessors[27].
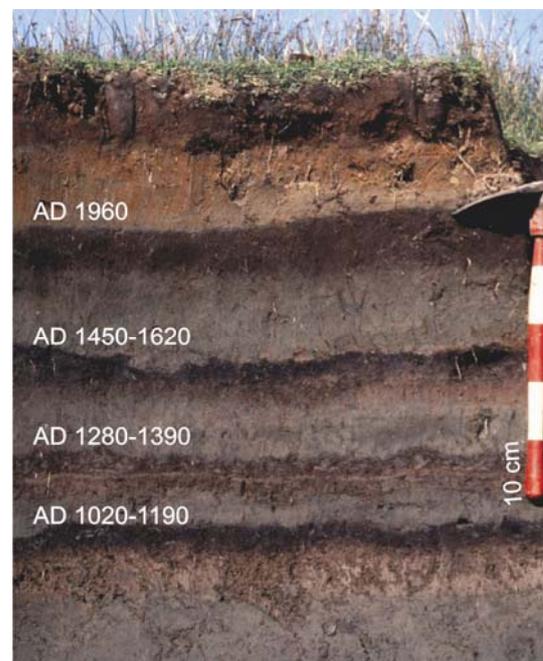

Figure 6. Stratigraphic section showing episodes of co-seismic subsidence associated with tsunami deposition. The topmost sand deposit corresponds to the 1960 tsunami and the lower deposits are from earlier events discussed by Cisternas et al.[27] (photograph courtesy: Brian Atwater, USGS).

It has been widely recognized that the thickness of tsunami deposits and their landward extent are controlled by the morphology of the coast and the availability of the source sand. Further, at the limits of inland inundation, deposition is marked by thin veneers of sand or mud, which are poorly preserved. Thus, models of inundation and rupture based on the extent of palaeotsunami deposits need more refinement, based on recent examples. The rupture of the AD 869 Jōgan earthquake (M 8.4), modelled based on the extent of its palaeotsunami deposits[13,43] has been found to be an underestimate following the observations during the 2011 Tohoku-Oki earthquake. Tsunamis of both these earthquakes affected the same region, but there were significant differences between the
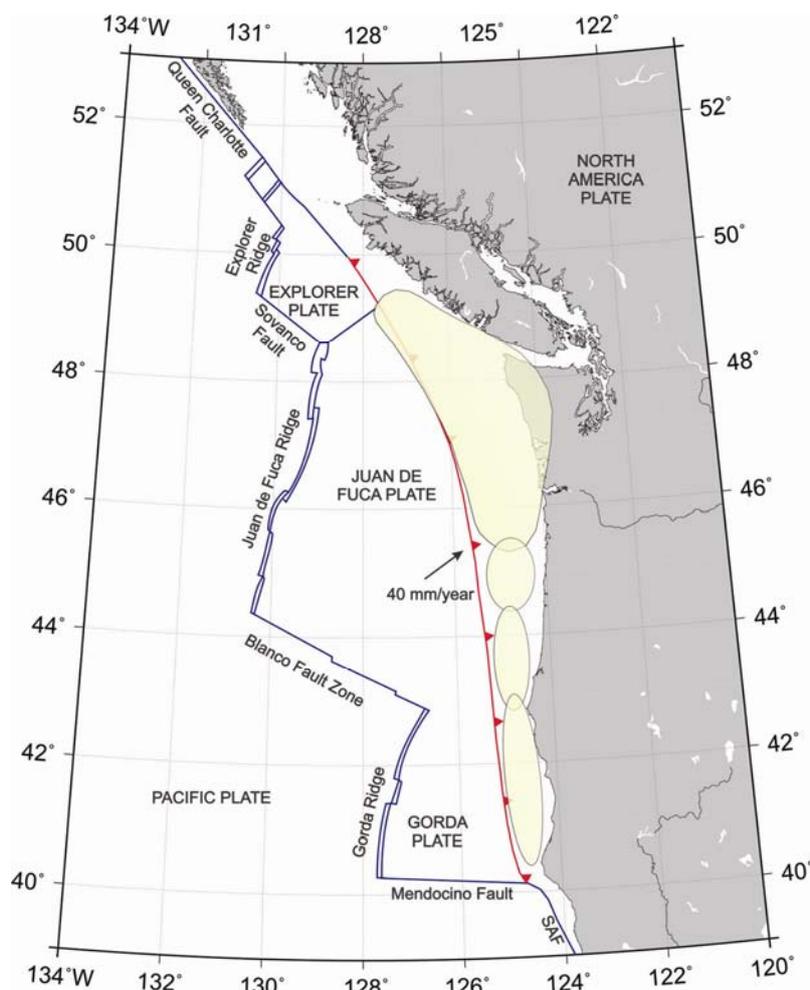
Figure 7. Seismotectonic setting of the Cascadia subduction zone (after Nelson *et al.*[37]) showing the modelled rupture of the AD 1700 earthquake (after refs 37 and 66). SAF, San Andreas Fault.

inland extent of palaeo-tsunami deposits and the limit of inundation during the 2011 event. Such discrepancies could possibly arise from incomplete mapping of palaeo-deposits or poor deposition/preservation of inland deposits and/or inadequacies of the inverse models. However, the ability to identify appropriate rupture extents from the spatial distribution of palaeo-tsunami deposits has been demonstrated by the study of the Jōgan tsunami. The under-predicted size of the 2011 tsunami in the same region suggests that additional research is needed to improve deposit-based estimates of the magnitudes of past tsunamis[44].

Earthquake recurrence at selected subduction zones

Cascadia

The Cascadia subduction zone, which extends along the west coast of North America from northern California to southern British Columbia, is a unique plate boundary with no history of recent great earthquakes (Figure 7). Three possibilities have been suggested for the lack of plate boundary seismicity. One, there is no convergence at present; two, the convergence is accommodated through aseismic slip, and three, large earthquakes occur, but the last one was more than 300 years ago[45]. The perceptions of low seismic hazard, based exclusively on historical seismicity, began to change after researchers started to document crustal strain consistent with that of a locked subduction zone[46]. Thus, it is only during the last two decades of the 20th century that the potential of the Cascadia subduction zone to generate great earthquakes has been recognized.

The search for geological evidence of past great earthquakes in the Cascadia subduction zone began in the mid-1980s, which established the repeated occurrence of great earthquakes and tsunamis along the Washington coast[40]. Studies that followed provided evidence for a great subduction zone earthquake, mostly from buried remains of former forests and subsided marshes along the

coast. Studies along the coastal regions bordering the Cascadia subduction zone have helped evolve several diagnostic criteria to identify archives of coseismic deformational features. For example, suddenness and amount of subsidence, lateral extent of buried soils, coincidence with tsunami deposits and synchrony at spatially separated sites suggest coseismic subsidence followed by deposition. Based on multiple proxies, the time window of the past subsidence event and great rupture in southern Washington and northern California was dated at AD 1690–1720 (refs 37 and 47). Turbidite proxies of contemporaneous origin, provided supplementary evidence for earthquake-related ground shaking[48].

Several decades of onshore palaeoseismology and offshore turbidite palaeoseismology work have now established the record of repeated great earthquakes and tsunamis along the Washington coast[49] suggesting an apparent clustering of larger events (rupture lengths >600 km, $M_w \sim 8.7$–9.0) during time gaps of ~700 to 1200 years[12]. Based on the time history of the Cascadia subduction zone, it has been suggested that the energy release is not uniform, and occurs through supercycles and super earthquakes[49].

The next important question is how many giant earthquakes have occurred along the Cascadia subduction zone. Based on a coast-wise comparison of radiocarbon ages for coseismic subsidence and palaeo-tsunami deposits, it has been suggested that two-thirds of Cascadia's great earthquakes in the past 5000 years may have resulted from full-length ruptures or from sequences of shorter ruptures[50]. Other earthquakes during the past 5000 years have produced a variety of geological evidence that is spatially restricted to the northern, central, or southern part of the subduction zone. Thus, Cascadia seems to behave like the southwest Japan, Colombia and Ecuador, south-central Chile and Sumatra–Andaman subduction zones, where ruptures vary in size, and smaller and larger ruptures alternate and overprint[2].

Chile

The Chile subduction zone is part of the South America margin, where the Nazca and the South America plates converge at a relatively fast rate of ~68 mm/yr. Many earthquakes with magnitude >7.5 have occurred on this plate boundary during the 20th and 21st centuries and historical records that go back to the 1500s suggest additional great ($M > 8$) earthquakes along this margin (Figure 8). Because of its fast convergence rates, its relatively simple structure and shorter inter-event intervals, the Chile subduction zone provides a good example to test recurrence models. The 1960 Chile and the 2010 Maule earthquakes are the two significant earthquakes to have occurred on this plate boundary in recent history. Much of the plate margin has broken in great earthquakes

and among them is the 1960 M_w 9.5 (Valdivia) Chile earthquake, the largest to have ever been recorded globally (see Bilek[17] for a review). Tsunami geology studies along the coast of Chile suggest that the fault rupture of the 1960 earthquake spanned two to three seismic segments along the trench[27]. The Maule earthquake of 27 February 2010 (M_w 8.8) ruptured the segment to the north of the 1960 rupture area, with some overlap with the 1960 rupture. Seismic activity preceding the 1960 and 2010 great earthquakes was very low over their respective aftershock areas, suggesting almost 100% coupling along the subduction zone and existence of seismic gaps[51]. Other studies support this view and argue that the source zone of the 2010 earthquake is an area of high interseismic coupling, a 'seismic gap', which is either undergoing permanent aseismic creep or is fully locked[52].

An important question is whether the rupture segment of the 1960 Chile event generated great earthquakes in the past, with similar slip. Historically known earthquakes preceded the 1960 earthquake in 1575, 1737 and 1837, and geologic evidence suggests an average interval of ~300 years, which is more than double the historical average of 128 years, and their rupture extent are not known. If all of these earthquakes were similar in size, they would have expended about twice the plate-motion budget. Thus, to accommodate the plate-motion budget, the Chile earthquakes of 1575, 1737, 1837 and 1960 had to be associated with variable slip, and thus the 1960-type earthquake need not repeat after ~128 years. Rupture along the South American subduction zone may be considered as one example of variability in rupture mode[2].

Sumatra–Andaman

The ~1300 km long rupture associated with the 2004 earthquake and its transoceanic tsunami challenged the understanding of the subduction zone earthquakes based on plate age and convergence rates (Figure 2)[11]. The historic seismicity along the Sumatra–Andaman subduction front can be divided into the regions north and south of the 2004 source zone. The region south of the 2004 rupture has been relatively more active in recent history, generating several large earthquakes. The maximum magnitude earthquake known from this region occurred in 1833 (M 8.9) and there were smaller earthquakes in 1797, 1861 and 1935 (ref. 53). In comparison, the northern (and longer) part of the plate boundary has generated fewer earthquakes and none of them was of magnitude >8.0. Important among them are the 1847 M 7.5 earthquake off Great Nicobar, and the 1881 M 7.9 event was located off Car Nicobar. The latter also generated a small tsunami, which was recorded across the Bay of Bengal, along the east coast of India[18]. The 1941 M 7.7 earthquake, offshore South Andaman is reported to have caused localized subsidence but did not generate a tsunami. Very little
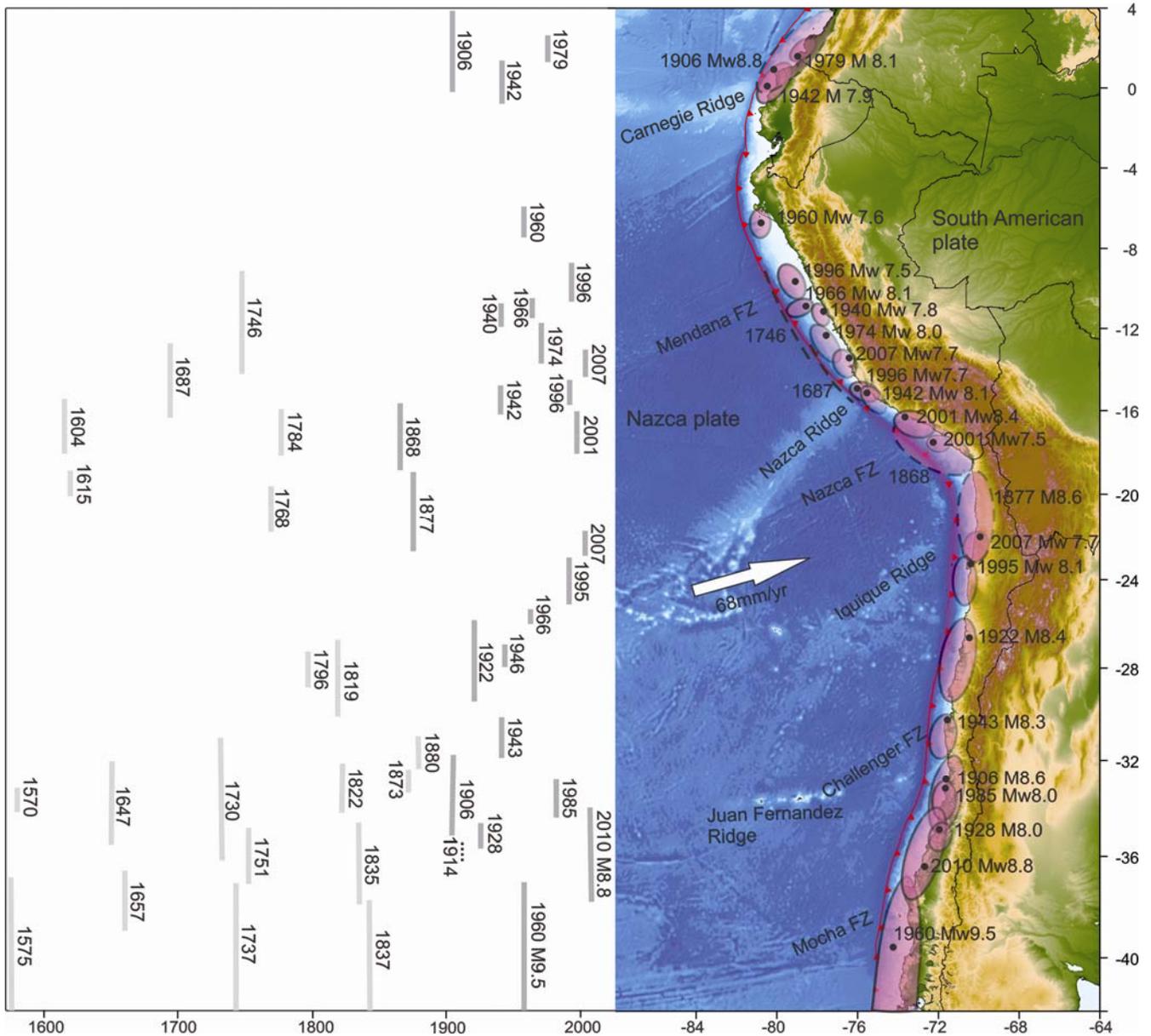
Figure 8. (Right) Seismotectonic setting of the South American subduction zone showing locations (filled black circles) and rupture areas (ellipses) of significant earthquakes. (Left) Their spatial and temporal rupture estimates (modified after refs 17 and 52).

is known about the 1679 earthquake that occurred off the northern Andaman Islands, which was reported to have been felt in Myanmar (Burma) and in parts of India[54].

The 2004 rupture stripped through all previous ruptures to the north of its source, and thus may be considered as a super-earthquake with a longer recurrence interval. The Sumatra–Andaman plate boundary was not explored much prior to the 2004 earthquake, but researchers are now using the 2004 coseismic deformational features and transoceanic tsunami deposits to develop its history. The 2004 earthquake caused significant uplift and subsidence along the islands as defined by the hinge line. The maximum subsidence on the Indian territory was at Campbell Bay (~3 m) and the maximum uplift was at East Island

(~1.5 m), the northern terminus of the 2004 rupture[55] (Figure 9). Tsunami deposits mostly consisted of sand sheets deposited in low-lying areas and coral and organic debris, transported as far as 500 m inland along the creeks and streams of the islands. Tsunami sand sheets were found in far-off locations, like the coasts of Thailand, Sri Lanka and the east coast of India. These deformational and depositional features have led to the identification of older deposits at transoceanic locations. Chronological constraints based on palaeotsunami deposits from two locations on the east coast of India, from the Andaman and Nicobar Islands, the Aceh coast of Indonesia and the Phra Thong coast of Thailand[56] suggest that two events could have occurred during the last
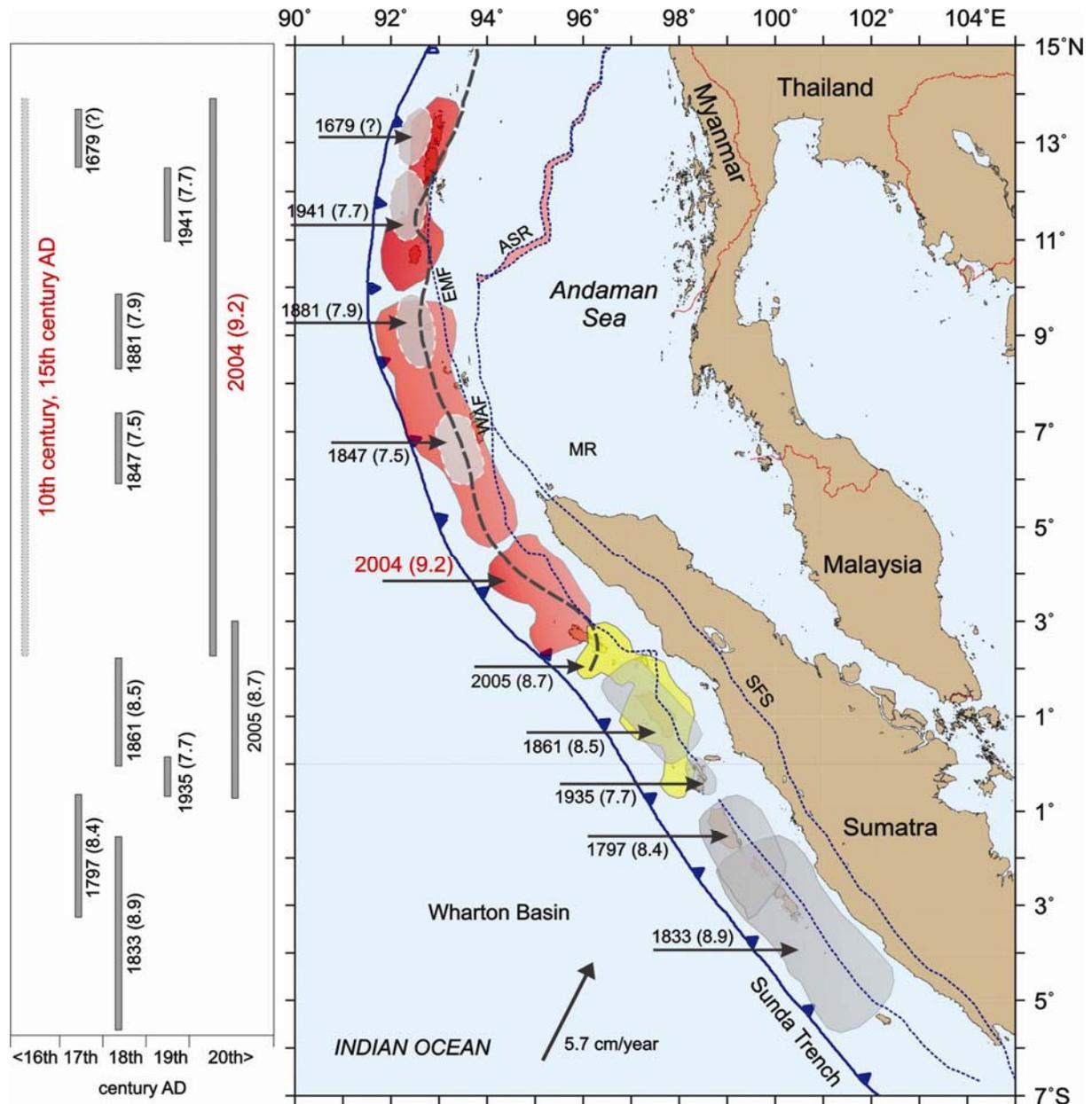
Figure 9. (Right) Seismotectonic setting of the Sumatra–Andaman subduction zone showing rupture areas (shaded) of significant earthquakes. (Left) Their spatial and temporal rupture estimates. Faults marked on the overriding plate are EMF, WAF, SFS and ASR (from Natawidjaja[53]). Historical earthquake ruptures are shaded in grey (from refs 18, 53 and 55); the 2004 and 2005 ruptures are in red and yellow respectively (from Chlieh *et al.*[67]). EMF, Eastern Margin Fault; WAF, West Andaman Fault; ASR, Andaman Spreading Ridge; SFS, Sumatra Fault System.

millennium, during an approximate interval of about 500 years[55–61].

The event dated between 800 and 1040 years ago appears to be comparable to that in 2004, both in its rupture extent and tsunami reach, but it is unclear if this earthquake is its true mimic in terms of its rupture. For example, the rupture could have originated in the middle and propagated bilaterally or it could have originated in the northern part and propagated southward. The spatial consistency of evidence at far-off locations, including those on the east coast of India and East Island, located at

the northern terminus of the 2004 rupture. Thus, Rajendran *et al.*[59] consider it as a true predecessor in the rupture extent, although a bilateral rupture cannot be ruled out. However, the rupture dimension of the ~500-yr-old earthquake seems less certain, because of the limited spatial extent for its evidence on the east coast of India and also at the northern limits of the 2004 rupture. However, the synchronous ages reported from Indonesia and Thailand suggest this to be another true predecessor of the 2004 rupture. Thus, we have represented the approximate rupture dimensions of both these earthquakes in Figure 9,

and at this point consider that both these earthquakes were possibly associated with similar rupture dimensions as their rupture areas are comparable.

Discussion and comments

Occurrence of two great tsunamigenic earthquakes during the last decade, the 2004 Sumatra–Andaman and the 2011 Tohoku-Oki events demonstrate the underestimated hazard potential along some subduction zones. As for the 2004 earthquake, it occurred on a subduction zone that had no precedents of great tsunamigenic earthquakes during recent history. A few historically documented earthquakes broke smaller segments (100–300 km) of the plate boundary, but a super earthquake of $M > 9$ that could unzip ~1300 km of the locked subduction zone was not anticipated. The slower convergence rates, age (50–80 Ma) and the relatively low-level historic seismicity of the subduction zone are the other factors that gave the perception of a lower seismic hazard. However, in retrospect Satake and Atwater[2] argue that this plate rupture could have been anticipated because the Sunda subduction zone extends for several thousand kilometres southward and great earthquakes have occurred here during the preceding centuries. The 2004 earthquake broke through previous ruptures (1881, 1941), and it appears to be a part of a super cycle. The history of smaller ruptures remains incomplete, but geological evidence suggests that at least two such great events have occurred in the past millennium, with an approximate inter-event interval of 500 years, which appears to be longer than what is reported for most other subduction zones discussed here.

Whilst the 2004 earthquake occurred in a region with no comparable history and therefore was a surprise, the 2011 Tohoku-Oki earthquake occurred at the Japan trench, which has a long, well-documented history, but the hazard was vastly underestimated. The national seismic hazard map of Japan had identified the Tohoku area as one of significantly lower hazard, following the prevalent view that M 9 earthquakes were unlikely[62]. The largest future earthquakes along this part of the Japanese trench were expected to be in the magnitude range 7–8. That the different segments of the trench are unlikely to break simultaneously, as it happened during the 2011 super earthquake, was probably the basis of this assumption. Perhaps the lack of any such super earthquakes in written records must have led many to believe that the Japan trench is not capable of generating an M 9-type earthquake. The occurrence of the 2011 Tohoku-Oki earthquake and its associated tsunami points to the incompleteness in our understanding of subduction zone processes.

Examples from other subduction zones suggest that it may be possible to estimate the maximum credible size of future events, at least in some subduction zones. For example, near-real-time measurements of strain/stress accumulation in seismic gaps seem possible with the advent of space geodesy[63]. With more observations, concepts such as seismic gaps can be better tested. For example, the 2010 M_w 8.8 earthquake that struck Maule in south-central Chile was a gap-filling event, which was captured by modern space-geodetic monitoring networks. A locked plate interface that accumulated significant stresses and the high seismic potential of the region were indicated by geodetic measurements, decades before the event. Thus, the 2010 earthquake appears to have ruptured a mature seismic gap referred to as Constitución gap (consistent with the predictions of the seismic gap theory, to some extent predictable by pre-seismic observations)[64].

We conclude this discussion with a reference to the Cascadia subduction zone, where no significant earthquakes have occurred in recent history, and yet today, the knowledge of a 300-yr-old M 9 earthquake forms the basis for engineering design and tsunami evacuation plans[2]. The Sumatra experience tells us that the super cycle can be independent of the smaller, historically known ruptures. Advances in space technology have been useful in identifying locked segments, and at least in some cases, seismic gaps may be construed as holding larger potential for future ruptures. Following the paradigm of plate tectonics and the fundamental assumption that locking and slip form part of the same physical processes, seismic gaps could be visualized as harbingers of future ruptures. While no single recurrence model may apply to all subduction zones, through the advances in seismometry, space-based geodesy, tsunami and earthquake geology, our understanding of the subduction processes is improving. As we use more observational data to strengthen these observations, the recurrence models should become more realistic, leading to more accurate predictions of the related hazards.

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