A systematic review of geological evidence for Holocene earthquakes and tsunamis along the Nankai-Suruga Trough, Japan

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ABSTRACT

The Nankai-Suruga Trough, the subduction zone that lies immediately south of Japan's densely populated southern coastline, generates devastating great earthquakes (magnitude > 8) characterised by intense shaking, crustal deformation and tsunami generation. Forecasting the hazards associated with future earthquakes along this >700 km long fault requires a comprehensive understanding of past fault behaviour. While the region benefits from a long and detailed historical record, palaeoseismology has the potential to provide a longer-term perspective and additional crucial insights. In this paper, we summarise the current state of knowledge regarding geological evidence for past earthquakes and tsunamis along the Nankai-Suruga Trough. Incorporating literature originally published in both Japanese and English and enhancing available results with new age modelling approaches, we summarise and critically evaluate evidence from a wide variety of sources. Palaeoseismic evidence includes uplifted marine terraces and biota, marine and lacustrine turbidites, liquefaction features, subsided marshes and tsunami deposits in coastal lakes and lowlands. While 75 publications describe proposed evidence from more than 70 sites, only a limited number provide compelling, well-dated evidence. The best available records enable us to map the most likely rupture zones of twelve earthquakes occurring during the historical period. This spatiotemporal compilation suggests the AD 1707 earthquake ruptured almost the full length of the subduction zone and that earthquakes in AD 1361 and 684 may have been predecessors of similar magnitude. Intervening earthquakes were of lesser magnitude, highlighting the variability in rupture mode that characterises the Nankai-Suruga Trough. Recurrence intervals for ruptures of the same seismic segment range from less than 100 to more than 450 years during the historical period. Over longer timescales, palaeoseismic evidence suggests intervals between earthquakes ranging from 100 to 700 years, however these figures reflect a range of thresholds controlling the of creation and preservation of evidence at any given site as well as genuine earthquake recurrence intervals. At present, there is no geological data that suggest the occurrence of a larger magnitude earthquake than that experienced in AD 1707, however few studies have sought to establish the relative magnitudes of different earthquake and tsunami events along the Nankai-Suruga Trough. Alongside the lack of research designed to quantify the maximum magnitude of past earthquakes, we emphasise issues over alternative hypotheses for proposed palaeoseismic evidence, the paucity of robust chronological frameworks and insufficient appreciation of changing thresholds of evidence creation and preservation over time as key issues that must be addressed by future research.

Key words: Paleoseismology; paleoearthquake; paleotsunami; Nankai Trough; seismic hazard; rupture zone; recurrence interval; supercycle

1. Introduction

The unexpected magnitude of the 2011 Tōhoku, Japan, earthquake and ensuing tsunami triggered a rapid reassessment of approaches to seismic hazard assessment in Japan (Goto et al., 2014). Responding to the failure of hazard assessments to adequately evaluate the potential for earthquakes and tsunamis exceeding the magnitude of those experienced in the region over the last 400 years, the Central Disaster Management Council (CDMC) of the Japanese Cabinet Office issued revised hazard assessment guidelines. These call for all available evidence to be used to define the maximum possible magnitude of earthquake and the largest potential tsunami for any given coastline (CDMC, 2011, 2012). The new guidelines pay close attention to the Nankai-Suruga Trough, where the Philippine Sea Plate descends beneath the Eurasian Plate (Fig. 1a). This subduction zone lies adjacent to the densely populated and highly industrialised coastline of south central Japan. Earthquakes and tsunamis along the Nankai-Suruga Trough have been historically documented from as early as the 7th century AD (Ando, 1975b; Ishibashi, 1999, 2004), with the most recent great earthquakes occurring in AD 1944 and 1946.

Geological records of past earthquakes and tsunamis provide alternative lines of evidence, complementing historical approaches (e.g. Atwater et al., 2005; Cisternas et al., 2005; Sawai et al., 2012; Shennan et al., 2014a). Previous reviews by Komatsubara et al. (2006a) and Komatsubara and Fujiwara (2007) summarise the spatial and temporal distribution of proposed palaeoseismic evidence along the Nankai-Suruga Trough. While these studies conclude that geological evidence is generally consistent with historical data, they note the difficulties in accurately dating evidence and in reconstructing past earthquake or tsunami characteristics from individual sites. Further field studies undertaken after the publication of these reviews, and particularly since the 2011 Tōhoku earthquake, has fuelled continued discussion of rupture modes and recurrence intervals (e.g. Satake, 2015; Seno, 2012).

In this paper, we substantially expand on previous reviews, providing a critical examination of all available geological evidence for past earthquakes and tsunamis along the Nankai-Suruga Trough. This evidence comes from uplifted intertidal biotic communities, liquefaction features, tsunami deposits and turbidites in marine and lacustrine settings. We seek to 1) summarise the current state of knowledge concerning geological evidence for Holocene great earthquakes and tsunamis along the Nankai-Suruga Trough; 2) constrain the rupture zones of earthquakes occurring during the historical period; 3) assess the contribution of palaeoseismic records to defining earthquake recurrence over longer intervals and 4) discuss maximum magnitude and variability in rupture modes. Additionally, we outline the major issues involved with the interpretation of palaeoseismic records from the Nankai-Suruga Trough and make recommendations on how further geological studies may better contribute to understanding future seismic hazards.

2. Tectonic setting

The Nankai-Suruga Trough, lying to the south of Kyushu, Shikoku and western Honshu, marks the subduction of the north-westward moving Philippine Sea Plate beneath the Eurasian Plate. In the centre of the subduction zone, in the vicinity of the Kii Peninsula, the plates converge at a rate averaging 40 – 55 mm yr^{-1} along an azimuth of ~305° (Fig. 1) (DeMets et al., 2010; Loveless and Meade, 2010; Mazzotti et al., 2000; Seno et al., 1993, 1996). The subduction zone displays along-strike variability in the geometry of the subducting plate, with regions of steeper dip beneath Kyushu, the Kii Peninsula and Suruga Bay separating shallow dipping regions beneath Shikoku and the Enshu-nada coastline (Baba et al., 2002; Hirose et al., 2008; Nakajima and Hasegawa, 2007). Thermal modelling along profiles off the Kii Peninsula and Shikoku is consistent with a seismogenic zone extending from 8 km to 25 km depth, with transitional zones down to 33 km and up to the trench (Hyndman et al., 1995; Mazzotti et al., 2000). At its eastern end, the Fujikawa-Kako Fault Zone constitutes an on-land extension of the interface between the Philippine Sea and Eurasian Plates (Fig. 1). This 2 – 5 km wide fault zone, consisting of a number of parallel to sub-parallel active faults, extends for ~ 40 km and meets the Itoigawa-Shizuoka Tectonic Line at a triple junction between the Philippine Sea, Eurasian and Okhotsk Plates (Lin et al., 2013; Maruyama and Saito, 2007). South of Kyushu, the western extremity of the Nankai-Suruga Trough meets the Ryukyu Trench, where the Philippine Sea Plate subducts beneath the Ryukyu Arc.

Geodetic data suggests the plate interface is highly coupled, with accumulated strain episodically released through major and great earthquakes with magnitudes exceeding 7 and 8 respectively (Aoki and Scholz, 2003; Mazzotti et al., 2000; Ozawa et al., 1999; Sagiya, 1999). Splay faults, subsidiary faults within the overriding plate that branch off the main interface, may slip concurrently with rupture of the plate boundary (Cummins et al., 2001; Moore et al., 2007; Park et al., 2002), contributing to tsunami genesis. The earliest historical records of seismic activity along the Nankai-Suruga Trough describe the occurrence of an earthquake in AD 684 which caused widespread damage and was accompanied by landslides, vertical land-level changes and tsunami inundation, particularly along coastlines of the western region of the subduction zone (Ando, 1975b; Ishibashi, 2004; Sangawa, 2009; Usami, 1996). This, and eleven subsequent earthquakes, are generally accepted as magnitude 8-class megathrust earthquakes, with part or all of the plate boundary rupturing in AD 684, 887, 1096, 1099, 1361, 1498, 1605, 1707, 1854 (twice), 1944 and 1946 (Fig. 1c). Additional undocumented great earthquakes may have occurred during the historical period; this is less likely from the 17th century onwards due to good documentary preservation and the detailed records produced at the domain and village level in Tokugawa society. Japan's classical and medieval periods (AD c.700 – 1185 and 1185 – 1600) are relatively well represented documentarily, though periods of civil war such as the late fourteenth and sixteenth centuries are more sparsely represented.

Instrumental records and the long historical catalogue suggest the subduction zone is characterised by along-strike segmentation, with a series of persistent seismic segments that may rupture individually or in a range of multi-segment combinations (Imamura, 1928; Ando, 1975b; Ishibashi, 2004). Hyodo and Hori (2013) suggest that, in addition to along-strike segmentation, the subduction zone is characterised by variability in slip depth, with larger megathrust earthquakes featuring slip up-dip of the main seismogenic zone.

The most recent pair of great Nankai-Suruga Trough earthquakes occurred on adjacent but not overlapping rupture zones possibly separated by a change in dip or a tear in the downgoing Philippine Sea Plate in the vicinity of the Kii Peninsula (Baba et al., 2002; Baba and Cummins, 2005; Cummins et al., 2002; Tanioka and Satake, 2001a, b). While the AD 1946 rupture was confined to segments A and B (the *Nankai* region), the AD 1944 earthquake ruptured segments C and D (the *Tōnankai* region; Fig. 1). Unlike the preceding AD 1854 earthquake, the 1944 rupture did not extend east into segment E, the *Tōkai* region (Ando, 1975a, Baba and Cummins, 2005).

3. Source of information and data analysis approach

Our compilation incorporates 75 papers, doctoral theses and professional reports, including 52 Japanese language and 23 English language publications. We do not include conference abstracts, but note that these suggest ongoing development of further chronologies of Nankai earthquake and tsunami occurrence from additional sites (e.g. Chiba et al., 2015; Matsuoka and Okamura, 2009; Namegaya et al., 2011; Okamura et al., 2003; Shishikura et al., 2011, 2013; Tanigawa et al., 2015). Publications derive evidence for the occurrence of past earthquakes from a range of different types of site; these fall into three categories, focussing on evidence for intense shaking (through liquefaction or turbidite deposits), deformation (through identifying biotic, facies or geomorphic changes in coastal locations or rupture of onshore faults) or tsunami occurrence (through evidence for erosion and/or deposition at coastal sites). Figure 2 provides representative photographs of some of these palaeoseismic approaches. A comprehensive overview of the utility, applicability and limitations of many of these lines of evidence is provided by McCalpin (2009) and chapters therein. Starting at the western end of the subduction zone, we critically review evidence from each seismic segment, noting where alternative non-seismic hypotheses should be considered for the origin of the evidence presented.

Where publications use radiocarbon dating to provide a chronology for past earthquakes and tsunamis, we recalibrate available data to take advantage of the latest radiocarbon calibration curves, IntCal13 and Marine13 (Reimer et al., 2013). Dates from marine samples must be corrected for the marine radiocarbon reservoir effect; however, appropriate corrections for locations along the southern coast of Japan remain uncertain at present. The Kuroshio current provides water that is well-mixed with the atmosphere, resulting in low ΔR values (Nakamura et al., 2015). Hideshima et al. (2001) and Yoneda et al. (2007) report values ranging between 135 ± 48 and -15 ± 64 years for the Ryukyu Islands, southwest of Kyushu. On coastlines facing the Nankai Trough, Nakamura et al. (2007) report ΔR values of -11 ± 103 years from Yoshigo and -201 ± 77 years from Kuzubasama, while Yoneda et al. (2000) report a ΔR value of -7 ± 0 years for the Kii Peninsula. Shishikura et al. (2008) note that this estimate represents a single measurement on a museum sample and that it cannot be confirmed that the sample was collected alive. Nevertheless, as the ΔR values derived by Nakamura et al. (2007) are from older (mid Holocene) terrestrial and marine samples with the potential for an unknown offset in absolute ages, we prefer Yoneda et al.'s (2000) value. Shishikura et al. (2007) propose a ΔR value of 82 ± 33 years for the Miura Peninsula, east of the Nankai Trough. As it remains the best estimate from the Nankai-Suruga Trough region and is consistent with a well-mixed Kuroshio Current, we follow Yoneda et al. (2000) and use a ΔR value of -7 ± 0 years to correct all marine samples. We report calibrated dates as 2 σ age ranges in years before present (cal. yr BP), rounded to the nearest 10 years, and additionally in years AD where beneficial for comparison with historical dates. Where appropriate, Bayesian age modelling approaches further constrain the timing of past earthquakes and tsunamis. We develop P_sequence (Bronk Ramsey, 2008, 2009) and Sequence (Bronk Ramsey, 1995; Lienkaemper and Bronk Ramsey, 2009) models using the OxCal program v.4.2 (Bronk Ramsey, 2009).

4. Palaeoseismic records from the Nankai-Suruga Trough

Published literature describes geological records of coseismic displacement, intense shaking and tsunami inundation from 72 sites along the Nankai-Suruga Trough (Fig. 3). We divide this section into the proposed seismic segments: the Hyūga-nada (Z), western (A) and eastern (B) Nankai segments, western (C) and eastern (D) Tōnankai segments and the Tōkai (E) segment.

4.1 The Hyūga-nada (Z) segment

Potential palaeoseismic evidence from the westernmost segment of the subduction zone comes from a single coastal lake, Ryūjin Pond, located on the southern edge of the Tsurumi Peninsula, eastern Kyushu (Fig. 3, site 1). This brackish water body, fronted by a beach ridge of approximately 10 m in height, exchanges water with the sea through a narrow channel at its eastern end (Furumura et al., 2011). The lake contains a continuous sedimentary record spanning the last 3500 years, with organic-rich muds intercalated with approximately 40 sand sheets (Okamura and Matsuoka, 2012). Citing a decline in deposit thickness from the seaward to the landward side of the lake and the presence of marine shells, Okamura and Matsuoka (2012) interpret eight of these sand layers as evidence for tsunami inundation. The authors link the uppermost three layers with historically recorded tsunamis in AD 1707 (Hōei), 1361 (Shōhei) and 684 (Tenmu), with the older coarse-grained deposits dating to approximately 1600, 1900, 2600, 3000 and 3300 cal. yr BP. The authors discuss the possibility that erosion by later tsunamis may remove evidence for earlier inundations. A lack of published radiocarbon results precludes recalibration with current calibration curves or further assessment of the age of potential tsunami evidence at Ryūjin Pond. Furthermore, currently published evidence cannot unequivocally link the sand sheets at the site with tsunamis. Typhoon-driven storm surges are also known to produce analogous coarse-grained deposits in coastal lakes in southwest Japan (e.g. Woodruff et al., 2009, 2014). The sedimentary signatures of tsunamis and storm surges may be difficult to distinguish (Engel and Brückner, 2011; Kortekaas and Dawson, 2007; Morton et al., 2007; Shanmugam, 2011) and insufficient evidence has been published to ascertain the causal mechanism for the sand sheets in Ryūjin Pond..

4.2 The Western Nankai (A) segment

Two low lying coastal lakes on the southern coast of Shikoku may provide palaeoseismic evidence for the segment bounded by Cape Ashizuri to the west and Cape Muroto to the east. Tadasu Pond (Fig. 3, site 4), set back approximately 800 m from the current coastline and lying behind a 5 m high beach ridge, holds a sedimentary record covering the period from 4800 to 1300 cal. yr BP (Okamura and Matsuoka, 2012; Okamura et al., 1997, 2000, 2003; Tsukuda et al., 1999). Okamura and Matsuoka (2012) recognise 14 coarse-grained washover deposits which may relate to breaching of the beach ridge by tsunamis. Plant fragments, wood or shells from within the uppermost seven of these sand layers provide limiting oldest dates for each layer. Calibration of dates from Okamura et al. (2000) using the IntCal13 calibration curve for terrestrial samples and the Marine13 curve and a ΔR value of -7 ± 0 years for shells (Yoneda et al., 2000) provides limiting oldest dates for sand deposition of 1070 – 1290, 1290 – 1520, 1400 – 1690, 1710 – 1950, 1830 – 2110 and 2010 – 2310 cal. yr BP. The most recent of these layers, deposited after AD 660 – 880, may correlate with the tsunami associated with the AD 684 Tenmu earthquake. Anthropogenic disturbance may have removed more recent tsunami evidence, including deposits relating to the 1707 Hōei earthquake, which historical records suggest also inundated the lake (Okamura and Matsuoka, 2012).

Approximately 16 km east of Tadasu Pond, Kani Pond (Fig. 3, site 5) holds a 2000-year sedimentary record (Okamura and Matsuoka, 2012). The pond, which lies 400 m inland from the current coastline and behind a 5 m high beach ridge, contains six coarse-grained washover deposits. Okamura and Matsuoka (2012) interpret these layers as evidence for tsunamis associated with the AD 1854 Ansei-Nankai, AD 1707 Hōei, AD 1361 Shōhei and AD 684 Tenmu earthquakes, in addition to two prehistoric tsunamis 1350 – 1650 cal. yr BP and ~1950 cal. yr BP. A lack of published radiocarbon data impedes recalibration of these dates and detailed comparison of the timing of sand layer deposition at Kani Pond with other sites.

As at Tadasu Pond, the alternative hypothesis of inundation during storm surges cannot yet be discounted.

Sangawa (2001, 2009, 2013) suggests that archaeological sites in southwestern Shikoku may preserve evidence for shaking during megathrust earthquakes. At Azono and Funato approximately 30 km north of Cape Ashizuri (Fig. 3, sites 2 and 3), cultural horizons constrain the timing of liquefaction features to the 15th century AD. Such features may have resulted from intense shaking during the AD 1498 Meiō earthquake (Sangawa, 2009). Without more precise dating, it is difficult to unequivocally attribute liquefaction evidence to a specific historical rupture of the subduction interface, rather than activity on an upper plate fault.

Encrusting masses of sessile organisms, including annelid worms, corals, bryozoans, foraminifera, barnacles and coralline algae, occur at the southern tip of Cape Muroto (Fig. 3, site 6), the proposed boundary between segments A and B (Iryu et al., 2009; Maemoku, 1988, 2001). While Iryu et al. (2009) identify emerged encrustations up to 9.18 m above present sea level, the relation between their elevation and the timing and frequency of past episodes of coseismic uplift is uncertain.

4.3 The Eastern Nankai (B) segment

As in segments Z and A, low-lying coastal lakes may provide evidence for past tsunamis from segment B. Lying at Shikoku's eastern tip, Kamoda Lake is separated from the sea by a beach ridge of less than 100 m width and 5 m height (Fig. 3, site 8). Despite the short distance to the sea, there are no historical accounts of inundation during the historically documented tsunamis associated with the AD 1707 Hōei, 1854 Ansei-Nankai and 1946 Showa-Nankai earthquakes (Okamura and Matsuoka, 2012). A 3500-year record of sediment accumulation recovered from the lake does, however, include a single coarse-grained washover deposit, for which Okamura and Matsuoka (2012) provide a calibrated age range of 2000 – 2300 cal. yr BP. Tsunami inundation provides one hypothesis for the deposition of this sand layer.

Komatsubara et al. (2007a) report preliminary investigations at Hidaka Marsh, a largely infilled coastal pond at the western extremity of the Kii Peninsula (Fig. 3, site 20). While the seaward of two cores (measuring 2.2 m in length) contains two sand layers, the absence of evidence for lateral continuity or a marine origin precludes linking these to tsunami inundation at present.

Archaeological sites in Itano-chō, Awaiji Island (Shimonaizen) and on the western side of the Kii Peninsula (Kosaka-tei-ato, Ikeshima Fukumanji, Iwatsuta Shrine, Sakai-shi Shimoda, Tainaka, Hashio, Sakafuneishi, Kawanabe and Fujinami) feature traces of liquefaction that are dated by their stratigraphic relationships with archaeological remains (Fig. 3, sites 9 – 19). Sangawa (2001) summarises evidence from these sites, plotting occurrences of liquefaction broadly coincident with the AD 1946 Showa-Nankai, AD 1854 Ansei-Nankai, AD 1707 Hōei, AD 1605 Keichō, AD 1498 Meiō, AD 1361 Shōhei and AD 684 Tenmu earthquakes (see Fig. 1 in Sangawa, 2001). As liquefaction results from intense and long duration shaking (Obermeier, 2009), the existence of historical records suggesting no discernable shaking occurred in the nearby city of Kyoto in AD 1605 (Ishibashi, 2004) may, however, preclude the occurrence of liquefaction features associated with this earthquake. Further liquefaction features dated to the 14th, 3rd and 2nd centuries AD and the 1st and 3rd centuries BC precede or do not coincide with historically documented megathrust earthquakes.

Iwai et al. (2004) report a sequence of 31 turbidites in a 4.2 m long core from the Tosabae Trough, southeast of Cape Muroto (Fig. 3, site 7). The turbidites, which display erosional bases and fining upward sequences, are interpreted by the authors as evidence for intense shaking during megathrust earthquakes along the Nankai Trough. Recalibrated radiocarbon dates from mixed assemblages of planktonic foraminifera provide a chronology, with the youngest three turbidites postdating 690 – 900 cal. yr BP (AD 1050 – 1260). Iwai et al. (2004) suggest that the sequence records evidence for the AD 1498 Meiō, 1361 Shōhei and 1099 Kowa earthquakes, along with the AD 1233 Tenpuku earthquake, the occurrence of which is disputed (Ishibashi, 1998). The paucity of chronological information for the section of core that relates to the last ~700 – 900 years suggests that such precise correlation between the three most recent turbidites and known earthquakes cannot be made. We employ a *P_sequence* model to constrain the age of 23 turbidites, which lie between 750 – 940 cal. yr BP and 5450 – 5780 cal. yr BP (Supp. Info. S1.1). Five further turbidites are older than the latter age range. The lack of a detailed chronology for the historical period makes it difficult to assess the intensity of shaking required to generate turbidites at the site and the potential for the sequence to also record turbiditic flow generated by non-seismic processes. As with all turbidite records in marine and lacustrine settings, the potential for equifinality must be assessed, with storms, hyperpycnal river discharge and shaking during smaller crustal earthquakes also potential triggers for turbidite generation (Talling, 2014; Shirai et al., 2010).

Sites at the southern tip of the Kii Peninsula, the proposed boundary between the Nankai (segments A and B) and Tōnankai (segments C and D) earthquake rupture zones, provide evidence for repeated abrupt occurrences of uplift. At Kuchiwabuka, Ameshima, Shionomisaki, Izumozaki, Arafunezaki, Ikeshima, Yamamibana, Taiji and Suzushima (Fig. 3, sites 21 – 29) the age, elevation and structure of colonies of emerged sessile organisms point towards the occurrence of repeated episodes of abrupt coastal uplift (Shishikura et al., 2008; Shishikura, 2013). The rocky shorelines of the peninsula support encrusting masses of the intertidal annelid worm *Pomatoleios kraussii* (synonymous with *Spirobranchus kraussii*). The duration of tidal inundation controls the upper growth limit of this species; consequently, when abruptly uplifted, the cessation of tidal inundation results in mass colony mortality. Radiocarbon ages from the outermost layer of each encrustation therefore provide limiting oldest ages for uplift. Furthermore, each encrusting mass may consist of several discrete layers, with each outer edge potentially reflecting additional episodes of uplift. While rapid postseismic uplift has previously been documented in other regions, including the Kuril subduction zone (Sawai et al., 2004), Shishikura et al. (2008) interpret the uplift of the Kii Peninsula as coseismic due to the location of the sites with respect to the trench and the occurrence of historically recorded episodes of coseismic uplift. Radiocarbon ages derived from the outer layers of the youngest encrustations at Izumozaki, Ikeshima and Yamamibana are consistent with historically recorded uplift during the AD 1707 Hōei earthquake (Shishikura et al., 2008). The Yamamibana encrustation displays two older mortality layers, with recalibrated radiocarbon age ranges overlapping with the AD 1605 and 1498 earthquakes. An uplifted colony at Shionomisaki provides a calibrated age consistent with the AD 1361 earthquake, while the age of the youngest encrustation at Kuchiwabuka may indicate uplift during the AD 887 Ninna earthquake. Dates from Ameshima and Suzushima could reflect uplift during the AD 684 Tenmu earthquake. Shishikura et al. (2008) propose further episodes of uplift around 1700, 2200, 3000, 4500 and 5200 cal. yr BP.

4.4 The western Tōnankai (C) segment

Palaeoseismic records from segment C come from lakes on the eastern coastline of the Kii Peninsula and from offshore and lacustrine turbidite records. Ōike Pond (Fig. 3, site 33), separated from the sea by a 4 – 5 m high beach ridge, contains nine coarse-grained layers within a 2500 year long sedimentary sequence (Tsuji et al., 2002). The lateral continuity and origin of these layers remains equivocal as only two piston cores of between 2 and 3.5 m are currently reported. Tsunami inundation remains only one of the potential causal mechanisms, with inundation during storm surges yet to be discounted. Radiocarbon dates from within eight of the sand layers constrain the oldest possible timing of each deposit, providing calibrated age ranges of 550 – 690, 790 – 980, 1080 – 1290, 1420 – 1700, 1820 – 1990, 1890 – 2150, 2340 – 2700 and 2360 – 2720 cal. yr BP (Tsuji et al., 2002). The fourth most recent sand layer remains undated, but a sequence model (Supp. Info. S1.2) constrains the timing of deposition to 1260 – 1520 cal yr BP. Age ranges for the three youngest sand layers (AD 660 – 870, AD 970 – 1160 and AD 1260 – 1400) overlap with historically documented tsunamis in AD 684, 1096 and 1361.

Tsuji et al. (2002) also report seven coarse-grained deposits in piston cores from Suwa Pond (Fig. 3, site 35), a 200 m wide water body separated from the sea by sand dunes with a minimum height of 5 m. Correlation of the layers between the four obtained piston cores is not straightforward, however in the core closest to the sea, three sand layers are located above organic material dated to AD 1410 – 1470 (no uncalibrated data provided). Tsuji et al. (2002) link the layers with the AD 1498 Meiō, AD 1707 Hōei and AD 1854 Ansei-Tōkai tsunamis; however, as at Ōike Pond, their origin remains uncertain. Further information is required to establish that these layers reflect tsunami inundation rather than other processes, such as storm surges. Four further sand layers lie below the 15th century date, with the oldest two layers containing material with calibrated age ranges of 2310 – 2680 and 2350 – 2700 cal. yr BP.

Reconnaissance studies reported by Komatsubara et al. (2007a) did not reveal conclusive evidence for tsunami inundation at lakes and coastal lowlands at Kii-Sano, Atawa, Shihara, Umino Pond, Katagami Pond, Kogare Pond, Funakoshi Pond or Kō, all located on the eastern coast of the Kii Peninsula (Fig. 3, sites 30, 31, 32, 34, 36, 40, 41 and 43 respectively). The limited number of cores (three or fewer per site) and shallow coring depth (less than 1.5 m at three of the sites) suggests that the potential of these sites may not have been exhausted by this single preliminary study.

Sequences of turbidites characterise the stratigraphy of the northern basin of Lake Biwa, the largest lake in Japan (Fig. 3, site 45) (Inouchi et al., 1996; Shiki et al., 2000). Ranging from a few millimetres to several centimetres in thickness, the turbidites feature erosive bases, lateral thinning and fining and two distinct subunits: a thin sand or sandy silt overlain by a thicker silt layer (Shiki et al., 2000). Inouchi et al. (1996) identify 20 turbidite layers within the uppermost 3 m and develop an age model based on average sedimentation rates since the deposition of the Kikai-Akahoya tephra, dated to 7165 – 7303 cal. yr BP by Smith et al. (2013), which occurs in all cores at a depth of 10 – 15 m. Inouchi et al. (1996) use this chronology to link turbidites with historically documented earthquakes, highlighting turbidite age ranges overlapping with the AD 1944 Showa-Tōnankai, AD 1854 Ansei-Tōkai, AD 1707 Hōei, AD 1498 Meiō, AD 1361 Shōhei and AD 887 Ninna megathrust earthquakes. The occurrence of many active faults close to Lake Biwa and the substantial chronological uncertainties resulting from a lack of radiometric dating make the correlations between turbidites and megathrust earthquakes highly questionable. Furthermore, the possibility of non-seismic triggers for turbidite generation must also be considered.

Ikehara (1999) reports the occurrence of 22 turbidites within background hemipelagic muds in a single 4.8 m long core from the Kumano Trough, southeast of the Kii Peninsula (Fig. 3, site 37). Recalibration of radiocarbon dates from planktonic foraminifera indicates the uppermost five turbidites postdate 2460 – 2790 cal. yr BP. Further dates that could link the deposits to intense shaking during historical earthquakes are lacking. A sequence model

(Supp. Info. S1.4) constrains the timing of five turbidites to between 2400 – 2670 and 4050 – 4460 cal. yr BP. The oldest 12 turbidites predate 4230 – 4530 cal. yr BP (Ikehara, 1999). With reference to the Kumano Trough, Omura and Ikehara (2006, 2010) and Omura et al. (2012) highlight the importance of understanding submarine morphology, sediment provenance and changing sea level. They suggest that turbidites may also reflect storms, tidal currents and coastal changes linked to sea-level rise. Investigating the last century of sediment accumulation at Kumano Trough sites approximately 30 km southeast of Ikehara's (1999) core (Fig. 3, site 38), Shirai et al. (2010) further support the hypothesis of both seismic and non-seismic turbidite triggers. The authors identify a well-sorted fine sand layer with an inferred depositional age of AD 1940 – 1945 and link this layer with turbiditic flow resulting from the AD 1944 Showa-Tōnankai earthquake. The chronology suggests other turbidites within the uppermost 30 cm relate to known historical floods and typhoons, confirming that shaking during earthquakes is not the sole process responsible for triggering turbidite deposition in the Kumano Trough.

Sakaguchi et al. (2011) hypothesise that intense shaking was responsible for the formation of mud-breccia units found at the Integrated Ocean Drilling Program (IODP) site C0004, located on the accretionary complex downslope of the Kumano Trough (Fig. 3, site 39). The five mud-breccia units occur within the uppermost 0.8 m, reach up to 17 cm in thickness and are intercalated with laminated muds. A ^{210}Pb decay curve suggests the uppermost breccia unit formed very recently, perhaps during the AD 1944 Showa-Tōnankai earthquake. Radiocarbon dating of planktonic foraminifera from immediately above the second breccia unit provides a limiting youngest date of 3480 – 3550 cal. yr BP, while the fourth and fifth units predate 10580 – 10670 cal. yr BP (Sakaguchi et al., 2011). The presence of brecciated units on the hanging-wall slope of a megasplay fault but absence on the footwall slope suggests slip on the megasplay and stronger ground motion above the hanging wall (resulting from the significant upward motion) are required to generate mud-breccia units at ODP site C0004.

4.5 The eastern Tōnankai (D) segment

Coastal marsh deposits on the Shijima Lowlands (Fig. 3, site 42) contain thin, discontinuous sand layers which are found up to several hundred metres inland from the modern coastline (Komatsubara and Okamura, 2007; Fujino et al., 2008). The height of the beach ridge is unknown, however an artificial coastal dike built on this ridge reaches ~ 6 m, suggesting the natural ridge was probably not higher than this elevation (Fujino et al., 2008). The sand layers are each typically several millimetres to several centimetres thick and contain marine and brackish organisms including gastropods and foraminifera. In most of the drilled and hand-driven cores, the sand layers have sharp basal contacts, while some also display rip-up clasts and stratification (Komatsubara and Okamura, 2007; Fujino et al., 2008). These features are consistent with, though not exclusively characteristic of tsunami deposition. Radiocarbon dating of seeds, leaves and charcoal indicates that the sand layers have been deposited over the last 4500 years (Fujino et al., 2008). The thin and fragmentary nature of the sand layers makes correlation between cores and determination of the number and timing of potential tsunamis problematic at present.

The coastal lowlands at Ōsatsu (Fig. 3, site 44) lie at an elevation of less than 1 m and preserve a sedimentary record spanning the last 7000 years (Hirose et al., 2002; Okahashi et al., 2001, 2002, 2005a, 2005b; Yasuhara et al., 2002). A sequence of up to twelve marine overwash events have overtopped a barrier beach – currently 2.5 m high – and deposited laterally continuous sand or sandy gravel layers of up to 22 cm thickness. The identification of landward thinning, fining upward sequences, marine macro- and microfossils, erosional lower contacts and rip-up clasts in geoslicer samples of up to 6 m in length supports the hypothesis that Ōsatsu records a sequence of tsunamis (Okahashi et al., 2005b). The presence of the sublittoral zone foraminifera species *Heterolepa haidingeri* and *Rectobolivina raphana* in the sand layers suggests reworking of sediments from water depths deeper than would be expected during typhoons (Okahashi et al., 2002; Uchida et al. 2010). The corresponding transport distance, derived from the offshore bathymetry, is 8 – 14 km and transport from such a depth and distance would require a tsunami with an amplitude of 6 m and a period of 60 minutes (Uchida et al., 2010). Radiocarbon dates obtained from plants and wood fragments indicate that the youngest tsunami deposit predates 1550 cal. yr BP (Okahashi et al., 2005b). The lack of evidence for tsunamis during the historical period at Ōsatsu may reflect anthropogenic drainage and cultivation of the site. A sequence model (Supp. Info. S1.3) constrains the timing of the deposition of the five youngest sand sheets to 1540 – 1620, 1560 – 1680, 1590 – 2870, 1990 – 3230 and 3180 – 3990 cal. yr BP (Fig. 3).

The archaeological site of Nagaya Moto-Yashiki (Fig. 3, site 47) contains centimetre to decimetre-thick coarse-grained layers that may attest to the occurrence of repeated tsunamis along the Enshu-nada coastline (Kumagai, 1999; Nishinaka et al., 1996; Takada et al., 2002). The uppermost three of eight sand layers are laterally continuous over tens of metres, with five older sand layers identified from a single 6.5 m long core. The two most recent sand sheets overlie strata dated to the 16th and 17th centuries AD, with Takada et al. (2002) linking these deposits with the AD 1707 Hōei and AD 1605 Keichō tsunamis. Recalibration and sequence modelling of the radiocarbon dates (Supp. Info. S1.5) suggests the oldest sand layer was deposited between 800 and 900 cal. yr BP (AD 1050 – 1150), with five sand layers in the range 540 – 840 cal. yr BP (AD 1110 – 1410). Tsunamis, storm surges and terrestrial mass movements remain plausible sources of sand deposition at this site.

Fujiwara et al. (2006b) and Komatsubara et al. (2006b; 2008) describe seven coarse grained sand sheets in a marshy lowland behind a beach ridge – currently 5 – 10 m high – close to Shirasuka, approximately 500 m east of Nagaya Moto-Yashiki (Fig. 3, 48). The mineralogy and grain size distribution of the lowermost and uppermost sand units suggests a terrestrial origin, while a marine origin is inferred for the remaining five units. These sand sheets are 5 – 50 cm in thickness, laterally continuous over tens of metres and display sedimentary features associated with abrupt marine inundations, including fining upward sequences, current ripples, intraclasts and draping mud caps (Komatsubara et al., 2006b; 2008). On the basis of sedimentary structures within the deposits, Komatsubara et al. (2008) argue that four of the sand sheets reflect tsunami inundation, while one layer results from a storm surge. Recalibration and sequence modelling of radiocarbon dates (Supp. Info. S1.6) constrains the timing of the inferred tsunami deposits to 40 – 280, 150 – 360, 290 – 480 and 490 – 560 cal. yr B.P. (AD 1670 – 1910, 1590 – 1800, 1470 – 1660 and 1390 – 1460), with Komatsubara et al. (2008) correlating them with the AD 1854 Ansei-Tōkai, AD 1707 Hōei, AD 1605 Keichō and AD 1498 Meiō tsunamis. The presence of sand layers at Shirasuka attributed to mechanisms other than tsunami inundation suggests that the nearby site of Nagaya Moto-Yashiki, discussed above, may also record storm or terrestrially-derived deposits.

Geological and geomorphological data support historical records in describing the effects of the AD 1498 Meiō tsunami on the floodplain of the former Hamana River in the vicinity of Arai (Fig. 3, site 49) (Fujiwara et al., 2010b, 2013a). An abrupt change from an estuarine to a backmarsh environment, coincident with the deposition of a ~90 cm thick sand layer, reflects the closure of the river mouth. The sand layer, found only in one 7.5 m long drilled core, contains a mixed assemblage of marine, brackish and freshwater diatoms. A sequence model (Supp. Info. S1.7) suggests the abrupt facies change occurred around 430 – 650 cal. yr BP (AD 1300 – 1520). The age range is consistent with the interpretation of the closure of the river mouth and abandonment of the channel following the AD 1498 Meiō tsunami and/or subsequent storm surges in AD 1498 and 1499 (Fuijwara et al., 2013a). A further sand bed contains marine and brackish diatoms and displays multiple layers of sand alternating with silt drapes: a feature consistent successive tsunami waves separated by periods long enough to allow silt to fall out of suspension. The sand layer, dated to after 10 – 270 cal. yr BP (AD 1680 – 1940), may reflect deposition during the AD 1707 Hōei or AD 1854 Ansei-Tōkai tsunamis (Fujiwara et al., 2010b, 2013a).

Nishinaka et al. (1996) and Kumagai (1999) report a well-sorted blue-grey sand layer overlying the ruins of a 17th century AD palace at Goten-ato, approximately 1.5 km east of the Arai coring sites described above (Fig. 3, site 50). The site lies 750 m from the contemporary coastline, close to the present day mouth of Lake Hamana. The laterally extensive sand layer reaches a thickness of 20 – 30 cm. While historical records indicate the palace was destroyed by a storm in AD 1699, Nishinaka et al. (1996) suggest the sand layer reflects deposition by the tsunami that followed the AD 1707 Hōei earthquake. A storm surge in AD 1699 provides an alternative explanation for the deposit, however Kumagai (1999) suggests the extensiveness of the deposit and the historically documented heights of the two marine inundations favours the tsunami hypothesis.

Lake Hamana, a large brackish lagoon on the Enshu-nada coastline (Fig. 3, site 51), contains a sedimentary record extending back over the last 10,000 years (Ikeya et al., 1990; Morita et al., 1998; Okamura et al., 2000). Investigating cores from the flood-tide delta of up to 2 m in length, Tsuji et al. (1998) interpret gravel and marine shell layers as evidence for up to eight tsunamis, with radiocarbon dates providing limiting oldest age ranges for the 2nd, 3rd and 4th most recent deposits. Our recalibration provides age ranges of 50 – 400, 290 – 490 and 470 – 640 cal. yr BP (AD 1550 – 1900, 1460 – 1660 and 1310 – 1480). While typhoons and channel migration remain plausible explanations for the deposits, Tsuji et al. (1998) link the four youngest deposits with tsunami inundation in AD 1854 or 1707, 1498, the 13th century and 1096. Two older deposits are younger than 3050 – 3530 and 3600 – 4060 cal. yr BP respectively. Examining a 3.5 m long core from the main basin of Lake Hamana, Sato et al. (2016) identify an older potential marine inundation, interpreting a spike in the abundance of a diatom species indicative of sand-rich tidal flats as evidence for a tsunami or storm surge redistributing sediment within the lake. Radiocarbon dating of bulk sediment suggests this occurred after 4790 – 4420 cal. yr BP. Sato et al. (2016) additionally infer an increase in lake salinity coincident with the AD 1498 earthquake, a trend also noted in previous investigations (Honda and Kashima, 1997; Kashima et al., 1997; Morita et al., 1998), though yet to be precisely dated. Nishinaka et al. (1996) identify two organic layers, each overlain by sand, in the channel that presently links the lake to the sea. A radiocarbon date from the upper organic layer provides an age range of 280 – 0 cal. yr BP (AD 1670 – 1950), suggesting the overlying sand layer may relate to a recent historical tsunami or storm. Without further sedimentological and chronological information, other causal mechanisms including channel migration cannot be discounted. The palaeotsunami record contained within Lake Hamana remains an ongoing focus for the *QuakeRecNankai* project (De Batist et al., 2015).

An extensive survey of the Rokken-gawa Lowlands to the east of Lake Hamana (Fig. 3, site 52), undertaken using hand-driven coring and a handy geoslicer, mapped a fine sand sheet that reaches 25 cm in thickness and extends for over 600 m (Fujiwara et al., 2013b; Sato et al., 2011; Sato, 2013). The deposit, the sole coarse grained unit found in cores in excess of 3 m long, displays cross-stratification, landward thinning and fining, internal mud drapes and marine diatom assemblages, strongly suggesting a tsunamigenic origin. Deposition of the sand layer coincides with an abrupt environmental change from a brackish to a freshwater marsh environment, suggesting the closure of a tidal inlet. A sequence model (Supp. Info. S1.8), incorporating radiocarbon dates from Sato et al. (2011), suggests the sand layer was deposited around 3410 – 3790 cal. yr BP.

A series of beach ridges of approximately 3 m height that formed after the mid-Holocene sea-level highstand occupies the broad coastal lowlands south and west of the city of Hamamatsu (Fig. 3, site 53) (Ishibashi et al., 2009; Matsubara, 2000; Sato, 2013). Swales between the beach ridges preserve sand sheets which Fujiwara (2013) interprets as evidence for tsunamis that inundated the Hamamatsu Lowlands. The oldest of these tsunami deposits is found in the swale furthest from the modern shoreline, more than 3 km inland. As at the Rokken-gawa Lowlands, which are located at a similar distance from the contemporary coastline, this swale does not preserve any potential tsunami deposits younger than the ~3150 cal. yr BP Kawagodaira pumice horizon (Fujiwara, 2013). Swales closer to the contemporary shoreline contain sand sheets interpreted as evidence of more recent tsunamis.

Sites in the vicinity of Tadokoro (Fig. 3, site 46) contain evidence for liquefaction, dated by stratigraphic relationships with archaeological remains (Sangawa, 2001, 2009, 2013). The derived ages overlap with historically documented earthquakes in AD 1944 (Showa-Tōnankai), AD 1498 (Meiō), AD 1361 (Shōhei), AD 887 (Ninna) and AD 684 (Tenmu). Due to uncertainties regarding the precision of the dating approach, rupturing of upper plate faults rather than the megathrust cannot be discounted as the source of liquefaction-inducing intense shaking.

4.6 The Tōkai (E) segment

Construction trenches exceeding several hundred metres in width and percussion cores of 2 – 4.5 m in length reveal the stratigraphy of the Ōtagawa Lowlands, the floodplain of the Ōta River (Fig. 3, site 54). A facies succession consisting of deltaic sands, intertidal muds, peat and flood plain silt is interrupted by extensive and laterally continuous sand sheets containing brackish microfossils (Fujiwara et al., 2008; Fujiwara, 2013, 2015). The sand sheets display thinning and fining in both the landward direction and away from the river, suggesting this channel is the primary route of sediment transport during extreme marine inundations (Fujiwara, 2013). Sedimentary evidence, which also includes multiple fining upward beds, landward-oriented current ripples and internal mud drapes suggests a tsunami origin. The youngest radiocarbon sample underlying the second youngest sand sheet yielded a calibrated range of 760 – 920 cal. yr BP (AD 1030 – 1190) and, while radiocarbon ages constraining the timing of the other sand sheets have yet to be published, Fujiwara (2013, 2015) suggests that the site records evidence of the AD 684 Tenmu, AD 887 Ninna, AD 1096 Eichō and AD 1498 Meiō tsunamis.

Fujiwara et al. (2007a) report an abrupt change in depositional environment in a former lagoon on the Yokosuka Lowlands, approximately 7 km west of the Ōtagawa Lowlands (Fig. 3, site 59). Thirty-five geoslicer samples of up to 3 m in length map the sedimentary infill. The sudden transition from estuarine muds to organic marsh deposits suggests abrupt coseismic uplift of the site, with a laterally extensive sand and gravel layer with an erosional base potentially suggestive of tsunami deposition coincident with uplift. A sequence model incorporating five radiocarbon dates (Supp. Info. S1.9) yields an age range for the facies change of 170 – 410 cal. yr BP (AD 1540 – 1780). While coseismic uplift is historically documented in this area in AD 1707, there is no record of tsunami inundation and a storm surge in AD 1680 provides an alternative candidate for the sand layer (Fujiwara et al., 2007a).

Sand boils disrupt the remains of residential buildings from the mid 7th century at the archaeological site of Sakajiri (Fig. 3, site 56) (Sangawa, 2001, 2009, 2013). The emplacement of buildings of the early 8th century on top of these features suggests intense shaking affected the site before this time. As at Tadokoro in the Western Tōnankai segment, the AD 684 Tenmu earthquake is a plausible source of this shaking. Additional liquefaction features at Sakajiri and the nearby sites of Tsurumatsu and Harakawa (Fig. 3, sites 57 and 58) imply shaking also occurred in the 2nd and 4th centuries AD and the 2nd century BC (Sangawa, 2001, 2013).

Azuma et al. (2005) and Fujiwara et al. (2010a) describe a series of four uplifted marine terraces, each mantled by intertidal and aeolian sands, on the southwestern coast of Cape Omaezaki (Fig. 3, site 60). Radiocarbon data suggest the lower three terraces emerged above marine influence before 540 – 650, 2140 – 2310 and 4830 – 4960 cal. yr BP respectively; Fujiwara et al. (2010a) consequently infer an uplift rate averaging 1.1 – 1.5 m kyr^{-1}. The disparity between rapid emergence at the tip of Cape Omaezaki and much lower rates a few kilometres to the northwest leads Fujiwara et al. (2010a) to propose the activation of a high-angle splay fault, rupturing concurrently with slip on the megathrust. Chronological constraints are insufficient to link the youngest emerged terrace to a historically documented earthquake.

Initial reconnaissance studies of the stratigraphy of the Yaizu Plain (Fig. 3, 61) have not revealed evidence for tsunami inundation or coseismic deformation (Kitamura et al., 2015), despite historical records suggesting the plain was inundated by both the AD 1498 Meiō and

AD 1854 Ansei-Tōkai tsunamis (Tsuji et al., 2013). Cores of up to 9 m in length taken between 1 and 2 km inland of the contemporary coastline do contain gravel layers within otherwise fine-grained deposits, however these are likely to reflect the lateral migration of river channels rather than abrupt marine incursions (Kitamura et al., 2015). The absence of recent historical tsunami deposits suggests a lack of preservation, perhaps due to anthropogenic reworking, or may reflect the small number of cores and the fragmentary nature of tsunami deposits in coastal lowland environments (cf. Brill et al., 2012; Garrett et al., 2013; Szczuciński, 2012).

Sangawa (2001, 2009, 2013) describes liquefaction features uncovered at the archaeological sites of Agetsuchi and Kawai on the western coast of Suruga Bay (Fig. 3, sites 62 and 63). Dated by their stratigraphic relationships with the remains of buildings of known periods, the features suggest intense shaking occurred in the late 7th century and the 13th century AD. The earlier of these two periods includes the AD 684 Tenmu earthquake, while the later period does not overlap with the timing of any major known megathrust earthquake.

The Ōya Lowlands (Fig. 3, site 64) preserve a sedimentary record exceeding 7300 years (Kitamura and Kobayashi, 2014b; Kitamura et al., 2011, 2013a). Seven cores of up to 9 m in length map the stratigraphy at the site. Three layers of well-sorted, well-rounded beach sand interrupt the otherwise fine-grained sediment accumulation at the site. Erosional basal contacts, rip-up clasts, internal mud drapes and multiple graded structures –features consistent with a tsunami origin – characterise the sand layers. The lateral extent of the coarse-grained deposits remains uncertain, in particular for the youngest and oldest layers which are each found in only one core. An increase in freshwater diatom species across the middle sand layer is suggestive of coseismic uplift, however the magnitude of this change is not quantified and Kitamura et al. (2013a) base their interpretations on a limited number of widely spaced samples with low total diatom count numbers. The youngest sand layer contains a peach seed radiocarbon dated to 790 – 930 cal. yr BP (AD 1020 – 1160), as well as a 6th century AD pottery fragment. Kitamura et al. (2013a) correlate this deposit with the AD 1096 Eichō tsunami. The two older sand layers are bracketed by radiocarbon dates, allowing the development of a sequence model (Supp. Info. S1.10), which provides depositional age ranges of 3580 – 3950 cal. yr BP and 3920 – 4070 cal. yr BP.

Kitamura and Kobayashi (2014a) report sedimentological and biostratigraphic evidence from the Shimizu Plain (Fig. 3, site 65). At one of their 12 coring locations, a transition from sand containing marine diatoms to clay containing brackish and freshwater diatoms may reflect a decline in marine influence due to historically documented uplift during the AD 1854 Ansei-Tōkai earthquake. While the radiocarbon-dated maximum age for the transition, 20 – 260 cal. yr BP (AD 1690 – 1930), does not preclude this possibility, the lateral extent and continuity of the transition are yet to be established. Kitamura and Kobayashi (2014a) hypothesise that sand layers found in selected cores from the Shimizu Plain may be evidence for earlier tsunamis. The four sand layers reach a maximum thickness of 70 cm and are characterised by erosional bases, normal grading and rip-up clasts. Sequence modelling of radiocarbon dates, primarily from marine bivalves and gastropods, indicates that the four potential tsunami deposits were deposited at 3260 – 3580, 4010 – 4370, 5560 – 5720 and 5630 – 6070 cal. yr BP (Supp. Info. S1.11).

At the head of Suruga Bay, the Fujikawa-Kako Fault Zone constitutes the on-land extension of the Nankai-Suruga subduction zone (Fig. 3, site 66). Lin et al. (2013) review slip rates from trench and outcrop data and present evidence for repeated fault rupture during the Holocene. In the central section of the fault zone, trenches across the Shibakawa, Kubo and Kamiide Faults suggest a rupture within the last 1300 years. To the north, offset of the AD

864 – 865 Aokigahara lava also suggests fault activity within the last ~1150 years. Citing historically recorded push-up structures and liquefaction along the southern section of the fault zone, Lin et al. (2013) conclude that the AD 1854 Ansei-Tōkai is the most likely candidate. Taking the fault scarp heights generated by the most recent displacement, Lin et al. (2013) suggest the average slip rate of 5 – 8 m kyr^{-1} reflects an average recurrence interval of 150 – 500 years.

The Ukishima-ga-hara coastal lowlands lie at the head of Suruga Bay, immediately adjacent to and on the Philippine Sea Plate side of the Fujikawa-Kako Fault Zone (Fig. 3, site 67). The stratigraphy of the site displays alternating layers of organic-rich peat and inorganic clay (Fujiwara et al., 2006a; 2007b; 2016; Komatsubara et al., 2007b; Shimokawa et al., 1999). The contacts between peat and overlying clay layers are abrupt and laterally continuous over tens to hundreds of metres, discounting local causal mechanisms such as channel migration. Analysis of diatom assemblages associated with two of the facies changes indicates abrupt increases in marine influence, suggesting the site records multiple episodes of coseismic subsidence (Fujiwara et al., 2007b; 2016). Six abrupt peat – clay transitions overlie the ~1500 cal. yr BP Obuchi scoria; Fujiwara et al. (2016) suggest that the most recent transition may reflect the expansion of rice cultivation on the lowlands, but infer a coseismic origin for the remaining four contacts. A sequence model (Supp. Info. S1.12) constrains the timing of the five inferred episodes of coseismic subsidence to 610 – 660, 1080 – 1120, 1190 – 1280, 1350 – 1380 and 1360 – 1410 cal. yr BP (AD 1290 – 1340, 830 – 870, 670 – 760, 570 – 600 and 540 – 590). One of these age ranges is consistent with the historically documented AD 684 Tenmu earthquake, while another is slightly older than the AD 1361 Shōhei earthquake. Fujiwara et al. (2016) note that caution must, however, be exercised when linking the evidence from Ukishima-ga-hara with documented earthquakes as independent, undocumented ruptures of the Fujikawa-Kako Fault Zone or the Tōkai segment could also provide a plausible hypothesis. The absence of evidence for the AD 1707 Hōei and 1854 Ansei-Tōkai earthquakes may reflect cultivation and land reclamation.

Sawai et al. (2015) report the occurrence of a laterally continuous sand layer interbedded within organic muds indicative of a freshwater wetland environment on the Ita Lowlands, northern Suruga Bay (Fig. 3, site 68). The 10 to 30 cm thick layer extends at least 200 m from the present shoreline and grades upwards from medium-coarse sand to sandy mud. The few diatoms encountered are of mixed salinity preference, with brackish-marine and freshwater species present. The authors identify elevated concentrations of magnesium and calcium in the upper part of the sand. The sedimentary characteristics, mixed diatom assemblages and geochemical data suggest a high energy marine flow. Noting the lack of sandy deposits associated with nine exceptionally large storms over the last 1200 years, Sawai et al. (2015) conclude tsunami inundation is a more likely origin. A comprehensive dating approach, incorporating radiocarbon samples from above and below the sand layer, constrains the timing of deposition. Combining these data in a sequence model (Supp. Info. S1.13) yields an age range of 630 – 830 cal. yr BP (AD 1120 – 1320). Sawai et al. (2015) suggest possible correlations with historically documented tsunamis in AD 1096, 1099, 1293 or 1361. The AD 1293 Einin or Kamakura earthquake occurred along the Sagami Trough (Fig. 1), with evidence of tsunami inundation also proposed from the Miura Peninsula (Shimazaki et al., 2011). Gaps in the historical record may also allow the deposit to be correlated with an as-yet unknown tsunami.

An immense sand dome underlies part of the coastal village of Iruma on the southern tip of the Izu Peninsula (Fig. 3, site 69) (Asai et al., 1998; Sugawara et al., 2005). The dome, which reaches more than 10 m in height, 250 m in length and 140 m in width, is situated immediately behind the contemporary beach at the head of the V-shaped Iruma Bay.

Historical reports and numerical modelling of wave amplification in an enclosed bay lead Sugawara et al. (2005) to interpret the entire dome as nearshore sands reworked and deposited by the AD 1854 Ansei-Tōkai tsunami. Fujiwara et al. (2009) provide a different interpretation, based on sedimentary analysis of a 20 m-long core. The authors suggest the dome is an aeolian dune, but note that five decimetre to metre-scale gravelly sand beds may indicate tsunami or storm surge deposition. Fujiwara et al. (2009) suggest the timing of deposition of uppermost bed, a metre-thick sand and gravel layer approximately 3.5 m below the present surface, is broadly consistent with the AD 1854 tsunami. A marine shell within the layer provides an oldest limiting age of 10 – 60 cal. yr BP (AD 1890 – 1940) and we note that uncertainties over the marine reservoir correction (Yoneda et al., 2000) may explain this age discrepancy.

Kitamura et al. (2013b) and Kitamura and Kawate (2015) report the findings of coring surveys on the Minami-Izu and Kisami Lowlands, two fluvial valleys on the southern tip of the Izu Peninsula (Fig. 3, sites 70 and 71). While the authors encountered sedimentary sequences exceeding 5000 years in length and indicative of a range of environments including floodplain, back marsh, dune and shoreface, neither site has yet produced evidence for tsunami inundation.

The presence of sessile intertidal organisms attached to a boulder on a wave cut platform at Shimoda (Fig. 3, site 72) may provide evidence for transport during an extreme wave event (Kitamura et al., 2014). Radiocarbon dates from the emerged barnacles, oysters and annelid worms, killed when the boulder was moved out of the intertidal zone, provide five age estimates. The youngest of these suggests the transport of the boulder occurred after 260 cal. yr BP. Kitamura et al. (2014) propose the AD 1854 Ansei-Tōkai tsunami as the most likely mechanism, however a number of storm surges and other tsunamis from sources along both the Nankai-Suruga Trough (e.g. AD 1944 Showa-Tōnankai tsunami) and the adjacent Sagami Trough (e.g. AD 1923 Kantō tsunami) would also be consistent with the radiocarbon dating results.

5. Discussion

The combined evidence from the 72 sites summarised in section 4 constitutes the current state of knowledge regarding geological records of past earthquakes and tsunamis along the Nankai-Suruga Trough. Only a limited subset of these sites provide compelling evidence for coseismic deformation, shaking or tsunami inundation and we discuss the limitations of the palaeoseismic catalogue further in section 6. In this section, we highlight the best available geological evidence for earthquakes and tsunamis over the last ~1350 years, summarise the rupture zones of historical earthquakes and discuss recurrence intervals and variability in rupture modes.

5.1 Rupture zones of historical earthquakes

The rupture zones of the AD 1944 Showa-Tōnankai and 1946 Showa-Nankai earthquakes are well constrained by inversion of tsunami waveforms, geodetic data and seismic wave data (e.g. Ando, 1975b; Baba and Cummins, 2005; Baba et al., 2002; Kanamori, 1972; Tanioka and Satake, 2001a, b). Slip during the 1944 earthquake occurred to the east of the Kii Peninsula, but did not extend to segment E (Fig. 4a). Two years later, a non-overlapping rupture released strain in segments A and B to the west of the Kii Peninsula (Fig. 4b). Geological records are sparse for both earthquakes, however shaking in 1944 may be recorded in turbidite and mud-breccia records from the Kumano Trough (Sakaguchi et al., 2011; Shirai et al., 2010) and in liquefaction deposits at Tadokoro (Sangawa, 2009). Archaeological sites on the western side of the Kii Peninsula and in eastern Shikoku may record liquefaction resulting from the 1946 earthquake (Sangawa, 2009). The scarcity of published records of sedimentary and geomorphological evidence for tsunami deposition or coseismic deformation may reflect anthropogenic reworking on heavily cultivated and industrialised coastlines.

Separated by just 32 hours, the AD 1854 Ansei-Tōkai and Ansei-Nankai earthquakes together ruptured segments A to E (Figs. 4c and 4d). Compelling evidence for tsunami deposition at Shirasuka (Komatsubara et al., 2008) as well as potential evidence for boulder transport at Shimoda (Kitamura et al., 2014), rupture of the Fujikawa-Kako Fault Zone (Lin et al., 2013) and uplift at Shimizu (Kitamura and Kobayashi, 2014a) are consistent with the first earthquake rupturing the three segments east of the Kii Peninsula (Fig. 4d). The following day, the Ansei-Nankai earthquake ruptured segments A and B (Ando, 1975b; Ishibashi, 2004). Palaeoseismic evidence for this second earthquake is limited (Fig. 4c), with Okamura and Matsuoka (2012) proposing a sand layer at Kani Pond as evidence of tsunami inundation and Sangawa (2009) making reference to liquefaction at Itano-chō. Uplifted sessile organisms reported by Shishikura et al. (2008) at three locations on the southern tip of the Kii Peninsula may also reflect coseismic deformation during either of the AD 1854 earthquakes.

With extensive reports of coseismic deformation (both uplift and subsidence), tsunami inundation and intense long-duration shaking, historical records suggest the AD 1707 Hōei earthquake included both of the regions that ruptured in the two 1854 earthquakes (Ando, 1975b; Ishibashi 2004). The inferred rupture zone, comprising segments A to E, exceeds 600 km in length (Fig. 4e). Geological evidence for the earthquake and accompanying tsunami also spans much of the length of the Nankai-Suruga Trough, with possible evidence for tsunami inundation at Ryūjin Pond in segment Z (Okamura and Matsuoka, 2012) and at Nagaya Moto-Yashiki and Shirasuka in segment D (Komatsubara et al., 2008; Takada et al., 2002). Also in segment D, uplift may be recorded by a change in facies on the Yokosuka Lowlands (Fujiwara et al., 2007a), while in the centre of the subduction zone, sessile organisms suggest coseismic uplift of the southern Kii Peninsula (Shishikura et al., 2008). While we have been unable to confirm the robustness of the evidence or the chronology of marine inundations at Ryūjin Pond, Furumura et al. (2011) argue that evidence from this site favours the westwards extension of the rupture zone to include at least part of the Hyūga-nada segment (Z). Modelled tsunami run-up heights from ruptures excluding this segment are insufficient to inundate the pond or to match documented run-up heights in eastern Kyushu and western Shikoku. No geological evidence for the AD 1707 earthquake has yet been proposed from segment E.

Historically documented shaking and coseismic land-level change associated with the AD 1605 Keichō earthquake is notably scarce (Ando, 1975b; Ishibashi, 2004). Yamamoto and Hagiwara (1995), however, report documentary evidence for tsunami run-up heights exceeding 5 m at locations in segments A to D. The discrepancy between the low intensity of shaking and the large tsunami implies the occurrence of a tsunami earthquake, with Ando and Nakamura (2013) consequently suggesting a rupture zone located along a shallow portion of the plate interface, up-dip of the main seismogenic zone in segments A to D (Fig. 4f). Published geological evidence for tsunami inundation and vertical land-level change is scarce, but consistent with this rupture zone. Potential tsunami deposits are reported from coastal lowlands at Shirasuka (Komatsubara et al., 2008) and Nagaya Moto-Yashiki (Takada et al., 2002), both in segment D. Age ranges from emerged sessile organisms at Yamamibana (Shishikura et al., 2008) and liquefaction features at Itano-chō (Sangawa, 2001) also overlap with this earthquake.

Sites in segment D are posited to record evidence for tsunami inundation following the AD 1498 Meiō earthquake (Fig. 4g). Along the Enshu-nada coastline, sand sheets at Nagaya Moto-Yashiki (Takada et al., 2002) and Shirasuka (Komatsubara et al., 2008) and environmental change recorded at Arai (Fujiwara et al., 2013a) and Lake Hamana (Honda and Kashima, 1997) support historical records of a damaging tsunami (Fujiwara et al., 2013a). Emerged sessile organisms at Shionomisaki may indicate coseismic uplift of the southern Kii Peninsula at this time (Shishikura et al., 2008). Proposed liquefaction features from segments A and B (Sangawa, 2001, 2009) could imply a rupture zone extending further west than previously suggested, however further historical and geological evidence is required to test this hypothesis.

With evidence proposed from all six segments of the Nankai-Suruga Trough, the distribution of sites recording the AD 1361 Shōhei earthquake and tsunami is similar to that of the AD 1707 Hōei earthquake (Fig. 4h). Okamura and Matsuoka (2012) suggest inundation of coastal lakes in segments Z and A, with potential tsunami inundation also recorded at Ōike Pond in segment C (Tsuji et al., 2002). We note that the occurrence of tsunami evidence at a site does not necessarily imply that the adjacent segment ruptured; further modelling efforts, combined with detailed sea-level and shoreline reconstructions, are required to link palaeotsunami evidence with the rupture zone (cf. Furumura et al., 2011). Subsidence at Ukishima-ga-hara in segment E may relate to the AD 1361 earthquake (Fujiwara et al., 2007b; 2016), while Shishikura et al. (2008) document evidence for uplift of the Kii Peninsula at the boundary between segments B and C. As in AD 1707, this episode of uplift was not followed by reoccupation of sessile organism encrustations, suggesting a larger magnitude of uplift or a lack of subsequent interseismic subsidence. Turbidite occurrence in Lake Biwa (Inouchi et al., 1996) and liquefaction at sites on the western side of the Kii Peninsula and at

Tadokoro (Sangawa, 2001, 2009) has also been linked to shaking during this earthquake, however more robust chronologies are required for these sites. A rupture zone incorporating segments Z to E supersedes earlier interpretations incorporating segments A and B only (Ando, 1975b). While the similarity in the distribution of evidence with the AD 1707 earthquake and the comparable permanent uplift of the Kii Peninsula (Shishikura et al., 2008) points towards a single large rupture, the potential for two smaller temporally closely spaced ruptures of segments east and west of the Kii Peninsula (c.f. Ishibashi, 2004) cannot be conclusively discounted on the basis of geological evidence alone.

Ishibashi (1999, 2004) suggests the occurrence of one or more great earthquakes during the 13th century AD. While Ishibashi (1998) dismisses an earthquake in AD 1233 reported by Usami (1996) as fictitious, evidence of liquefaction from archaeological sites in segments B and E (Sangawa, 2001) does support the occurrence of intense shaking in the interval between the historically documented earthquakes in AD 1099 and 1361. While other processes cannot be discounted for their deposition, sand layers at Nagaya Moto-Yashiki could reflect tsunami deposition during this time (Takada et al., 2002). The number, timing and rupture zones of earthquakes occurring during the 12th and 13th centuries AD remain unknown and should be the focus of further historical and geological investigation.

Despite the lack of a historically documented tsunami, Ando (1975b), Ishibashi (1999, 2004) and others list the AD 1099 Kowa earthquake as a megathrust earthquake rupturing segments A and B (Fig. 4i). The absence of a tsunami and restricted evidence for intense shaking suggests the rupture zone may not have been analogous to the later AD 1854 and 1946 Nankai earthquakes. Instead, the 1099 earthquake may have ruptured a smaller area of the plate interface or an upper plate fault. Geological evidence for this earthquake is severely limited. While turbidites are proposed from the Tosabae Trough (Iwai et al., 2004) and Lake Biwa (Inouchi et al., 1996), neither site is underpinned by a chronology that is robust enough to discount other possible earthquakes. Consequently, there is currently insufficient evidence to consider the AD 1099 Kowa earthquake as a magnitude 8-class subduction megathrust earthquake.

The rupture zone of the AD 1096 Eichō earthquake, derived from historical records, incorporates segments C and D (Ishibashi, 1999, 2004). Evidence for potential tsunami inundation at Ōike and Suwa Ponds in segment C (Tsuji et al., 2002), Nagaya Moto-Yashiki in segment D (Takada et al., 2002) and the Ōtagawa Lowlands (Fujiwara et al., 2013a) and Ōya Lowlands (Kitamura et al., 2013a) in segment E support this interpretation (Fig. 4j).

Historical records suggest the AD 887 Ninna earthquake ruptured segments A and B (Ando, 1975b; Ishibashi, 1999). Palaeoseismic evidence from these segments is limited (Fig. 4k). Our age-depth model (Supp. Info. S1.1) suggests turbidite emplacement in the Tosabae Trough in segment B may have occurred around this time, while ages from sessile biota at Ameshima and Suzushima on the Kii Peninsula are also consistent with coseismic uplift in AD 887 (Shishikura et al., 2008). Ishibashi (2004) suggests concurrent rupture of segments C and D based on historical records. Evidence for shaking at Tadokoro (Sangawa, 2009) could support this eastwards extension. Further dating is required to confirm the association of a proposed tsunami deposit on the Ōtagawa Lowlands in segment E with this earthquake (Fujiwara et al., 2008).

Ando (1975b) maps the AD 684 Tenmu earthquake as a rupture of segments A and B, with Ishibashi (1999, 2004) tentatively extending the rupture zone into segments C, D and E. Palaeoseismic evidence supports this larger rupture zone (Fig. 4l), with possible evidence for coseismic subsidence of the Ukishima-ga-hara lowlands at the eastern end of the subduction zone (Fujiwara et al., 2007b; 2016). Sangawa (2001, 2009) additionally attributes liquefaction features in segments D and E to this earthquake, while Shishikura et al. (2008) provide evidence for the abrupt uplift of the southern tip of the Kii Peninsula. To the west of the peninsula, sand sheets in Ryūjin, Tadasu and Kani Ponds suggest tsunami inundation (Okamura and Matsuoka, 2012). As in AD 1707 and 1361, inundation of Ryūjin Pond may support rupture of at least part of segment Z during the 684 earthquake, however further shoreline reconstructions and modelling efforts are required (Furumura et al., 2011). Temporally closely spaced ruptures of more limited spatial extent provide an alternative hypothesis for the evidence that has been linked to the AD 684 earthquake.

5.2 Recurrence intervals

Historical records suggest earthquakes ruptured part or all of the Nankai-Suruga Trough twelve times between AD 684 and 1946, yielding an average recurrence interval (± 1 σ) for major or great earthquakes occurring anywhere along the subduction zone of 115 ± 89 years. Recurrence intervals range from 32 hours between the two AD 1854 earthquakes to 262 years between the AD 1099 and 1361 earthquakes. Looking at the intervals between ruptures of the same area of the plate interface (rather than the subduction zone as a whole), the shortest intervals are 92 years for the Hyūga-nada and Nankai segments (Z, A and B) and 90 years for the Tōnankai and Tōkai segments (C, D and E). If we reject the AD 1099 earthquake as a great interplate earthquake due to the lack of records of tsunami occurrence and the paucity of geological data, the longest interval between two ruptures of the same segment is the 474 years that separated the AD 887 Ninna and 1361 Shōhei earthquakes. If the AD 1605 earthquake occurred solely at the shallowest portion of the interface (Ando and Nakamura, 2013), the main seismogenic zone may not have ruptured for the 209 years between AD 1498 and 1707. Furthermore, if the AD

1498 earthquake did not extend into the Nankai region (segments A and B), this interval may be extended further back to encompass the 376 years between AD 1361 and 1707. Shorter recurrence intervals may, however, be inferred if additional great earthquakes occurred during periods with fragmentary and incomplete documentary records. Further geological and historical research is required to resolve these uncertainties.

Palaeoseismic records have the potential to yield information on earthquake recurrence over timescales longer than the historical record; however, at present, few sites along the Nankai-Suruga Trough display suitably long, well-dated sequences. Okamura and Matsuoka (2012) suggest Tadasu Pond records 14 tsunamis at consistent intervals averaging 270 years, while Ryūjin Pond records longer and more variable intervals of between 300 and 700 years. The authors note that later tsunamis may erode evidence for earlier inundations, resulting in longer apparent intervals. Our modelling of the timing of sand sheet emplacement on the Ōsatsu Lowlands (Mitamura et al., 2001; Okahashi et al., 2005b) suggests the eight intervals average 400 – 600 years (2 σ). P_sequence modelling of the Tosabae Trough record (Iwai et al., 2004) indicates an average interval between turbidites of 200 – 230 years over the last 5500 years. Sequence modelling of the timing of five episodes of coseismic subsidence on the Ukishima-ga-hara Lowlands (Fujiwara et al., 2016) suggests intervals of less than 100 years, with an average of 180 – 200 years. The recurrence interval for each site reflects both the true interval between megathrust earthquakes and also site-specific thresholds. A site's palaeoseismic record only includes the earthquakes or tsunamis that exceed both creation and preservation thresholds (Nelson et al., 2006; McCalpin and Nelson, 2009). Consequently, a single site may underrepresent the number of earthquakes or tsunamis within a given period if a subset of these events fail to exceed the site's thresholds. A site may also potentially overestimate earthquake frequency due to misidentification of features of a non-seismic origin as palaeoseismic evidence (discussed further in section 6).

5.3 Maximum earthquake and tsunami size

As discussed in section 5.1, historical records suggest that the six proposed segments of the Nankai-Suruga Trough ruptured together during a single great earthquake in AD 1707. No geological evidence for this earthquake has yet been proposed from segment E; whether the rupture extended this far east remains equivocal and future investigations should focus on the coastal lowlands fringing Suruga Bay and on the Fujikawa-Kako Fault Zone to resolve this question. Geological evidence suggests that the earthquakes of AD 1361 and 684 may have been of similar rupture length. There is no published geological evidence that currently suggests that earthquakes with longer rupture lengths have occurred along the Nankai-Suruga Trough; however, few attempts have been made to use geological evidence to compare the absolute or relative magnitudes of different historical or prehistoric earthquakes in this region (Komatsubara and Fujiwara, 2007; Komatsubara et al., 2006a).

Several attempts have been made to address the related question of the relative sizes of tsunamis to have impacted coastlines facing this subduction zone. Investigating records of tsunami deposition in coastal lakes, Okamura and Matsuoka (2012) link the presence or absence of sand layers and their characteristics to variation in the height of tsunamis striking western Kyushu and southern Shikoku. While Ryūjin Pond preserves evidence for the AD 1707 tsunami, the absence of sand layers relating to the subsequent AD 1854 and 1946 tsunamis suggests they were not of comparable height and did not inundate the lake. The presence of deposits related to the AD 1361 and 684 tsunamis at Ryūjin and Kani Ponds, suggests that these tsunamis may have been of comparable size to 1707 in this location. The potential for variation in the threshold for evidence creation must be considered, with changing relative sea level, shoreline progradation, the height of the tide at the time of tsunami impact and the availability of erodible sediment also important factors.

The compilation of assessments of the maximum inland extent of tsunami deposits with detailed reconstructions of shoreline positions over time may facilitate comparison of the relative inundation distances of past tsunamis. While further chronological and stratigraphic information is required, initial findings suggest no tsunami during the historical period has inundated the most landward regions of the lowlands to the east of Lake Hamana (Fujiwara, 2013; Fujiwara et al., 2013b). On the Rokken-gawa and Hamamatsu Lowlands, swales 3 – 5 km inland from the present coastline only preserve evidence for tsunamis older than 3150 cal. yr BP. More recent tsunami deposits are confined to swales closer to the current coastline, suggesting that over the last few thousand years, no tsunami has inundated the whole of the Hamamatsu coastal plain (Fujiwara, 2013). The continued development of this approach and its replication in other regions along the Nankai-Suruga Trough may provide additional constraints on the largest inundation distances associated with past tsunamis. Such studies and associated modelling of source fault ruptures must, however, acknowledge that true inundation distances may considerably exceed the inland extent of identifiable coarse-grained deposits (Abe et al., 2012; Goto et al., 2011; Shi et al., 1995).

While the maximum amplitude of tsunami waves in far-field locations (those located separated by ocean basins from their source earthquakes) correlates with earthquake magnitude, this relationship beaks down in locations close to the source (Abe, 1979). Consequently, the largest tsunamis to have struck locations along the Nankai-Suruga Trough may not have been generated by the largest earthquakes. Further field evidence for maximum tsunami run-up heights, inundation distances and their along-strike distribution should be sought to address the question of the maximum size of Holocene tsunamis.

5.4 Rupture modes, segmentation and supercycles

Historical records, supported by geological data, suggest the Nankai-Suruga Trough is characterised by six segments, with earthquakes rupturing the subduction zone in a range of different multi-segment combinations (see section 5.1). The occurrence of full-length ruptures in AD 1707, 1361 and 684, with lesser magnitude earthquakes rupturing smaller areas of the fault during the intervening periods, suggests the existence of supercycle behaviour (cf. Cisternas et al., 2005; Goldfinger et al., 2013; Herrendorfer et al., 2015; Sieh et al., 2008). Such fault behaviour is currently difficult to identify over the longer timescales afforded by geological evidence. Nevertheless, the repeated reoccupation of sessile biotic encrustations on the southern tip of the Kii Peninsula before final, permanent abandonment, could support this hypothesis (Shishikura et al., 2008; Shishikura, 2013). Within each encrusting mass, up to three or four mortality events are each followed by colony reoccupation, before a final uplift episode with no subsequent reoccupation. Shishikura et al. (2008) suggest this could reflect a series of moderate episodes of coseismic uplift, each followed by interseismic subsidence, before a final episode of outsized coseismic uplift. Whether such outsized uplift is associated with a larger earthquake incorporating a greater number of segments and/or variation in the depth of slip on the plate interface remains unresolved. Hyodo and Hori (2013) provide a potential mechanism for variation in coseismic deformation between different earthquakes, with their numerical model suggesting that larger earthquakes could feature slip to the trench, while smaller ruptures are restricted to the main seismogenic zone.

The AD 1605 earthquake stands out as dissimilar from other Nankai-Suruga Trough ruptures, with historical records suggesting an extensive and damaging tsunami despite a lack of strong ground motion (Ando, 1975b; Ishibashi, 2004). As discussed in section 5.1, these characteristics are consistent with a tsunami earthquake, with slip restricted to the shallowest portion of the interface. With a plate convergence rate of 50 mm yr^{-1}, just 100 years are required to accumulate sufficient slip to explain the historically documented tsunami run-up heights (Ando and Nakamura, 2013). The lack of other proposed tsunami earthquakes, inferred from records of intense shaking associated with the other historical ruptures (Ando, 1975b; Ishibashi, 2004), may provide further support for shallow slip occurring simultaneously with ruptures of the main seismogenic zone or could indicate that the shallow portions of the interface are only partially locked. Geological records are currently insufficient to identify the occurrence of prehistoric tsunami earthquakes along the Nankai-Suruga Trough.

Ando (1975a) and Ishibashi (1976; 1981) identified the Tōkai region (segment E) as a mature seismic gap, a finding that contributed to the implementation of the 1978 Large Scale Earthquake Countermeasures Act by the Japanese Government and the intensive and ongoing monitoring of the region by the Japanese Meteorological Agency (Rikitake, 1979). The frequency of ruptures of the Tōkai segment and the simultaneity with ruptures of the Tōnankai region (segments C and D) remain poorly understood. Geological or historical records support rupture of both regions in AD 1854, 1707, 1361 and 684, while instrumental records suggest the 1944 earthquake ruptured only the Tōnankai segments and did not extend eastwards into the Tōkai segment. An episode of coseismic subsidence identified from the Ukishima-ga-hara Lowlands does not correlate with any major historically documented earthquake (Fujiwara et al., 2007b; 2016) and could reflect an undocumented rupture of the Tōkai segment or of the Fujikawa-Kako Fault Zone. A lack of further palaeoseismic evidence for independent rupture of segment E could reflect the magnitudes of coseismic deformation, shaking and tsunami inundation being insufficient to surpass thresholds for evidence creation, rather than the absence of single segment earthquakes in this location.

6. Problems and potentialities

Despite the breadth of sites investigated and the length of some of the resulting palaeoearthquake records, a complete and coherent picture of the timing, recurrence, rupture zones and magnitudes of past earthquakes along the Nankai-Suruga Trough cannot currently be derived from geological data. This is in contrast to other subduction zone settings, where the integration of records from multiple sites has yielded a more comprehensive understanding of prehistoric great earthquakes, including in Alaska (Shennan et al., 2014a, b), Cascadia (Goldfinger et al., 2012; Nelson et al., 2006) and Chile (Moernaut et al., 2014). We identify four key issues that currently limit the contribution of palaeoseismic records to understanding seismic hazards along the Nankai-Suruga Trough: 1) alternative hypotheses for proposed palaeoseismic evidence; 2) insufficient chronological control to correlate between evidence at different sites; 3) research designs insufficient to address maximum earthquake and tsunami magnitudes and 4) incomplete appreciation of the variation in palaeoseismic thresholds over time and between sites. These issues are not unique to the Nankai-Suruga Trough and the identified difficulties and subsequent recommendations presented here have implications for palaeoseismic research globally.

6.1 Alternative hypotheses

Geological records may overrepresent the frequency of earthquakes or tsunamis when features of a non-seismic origin are incorrectly identified as palaeoseismic evidence. Misidentification arises from equifinality, the principle that dissimilar processes can produce similar sedimentary or geomorphic signatures (Chorley, 1962; McCalpin and Nelson, 2009).

Along the Nankai-Suruga Trough, we illustrate this issue with reference to the most widely investigated lines of evidence: turbidites, liquefaction features and tsunami deposits. The limitations of other paleoseismic approaches are detailed briefly throughout section 4 and at length in comprehensive reviews, including those by Dura et al. (2016), Carver and McCalpin (2009), Nelson et al. (1996) and Pilarczyk et al. (2014).

Marine and lacustrine sediment sequences have the potential to preserve long, continuous records of intense shaking during multiple great earthquakes. While Lake Biwa records turbidites at closely spaced intervals, storms, hyperpycnal river discharge and shaking during smaller, more local crustal earthquakes may also induce turbidity currents (Talling, 2014; Shirai et al., 2010). Such alternative hypotheses are yet to be conclusively discounted for either the Lake Biwa record or offshore turbidite records from the Kumano and Tosabae Troughs. Indeed, the presence of turbidites in the Kumano Trough that cannot be linked to recent historical earthquakes indicates that local seismicity or non-seismic processes must also be active (Shirai et al., 2010). The issue of equifinality affects turbidite palaeoseismology globally and key ways forward include establishing site sensitivity through calibration of deposits with the historical record, correlation of multiple cores using independent marker horizons, sedimentary provenance analysis, and confluence tests (Goldfinger et al., 2012; Moernaut et al., 2014; Pouderoux et al., 2014; Van Daele et al., 2015).

Similarly considered a record of intense shaking during great earthquakes, liquefaction features may also suffer from overrepresentation caused both by shaking during smaller earthquakes and the misidentification of similar sedimentary features of non-seismic origin (Obermeier, 1996, 2009). With earthquakes with magnitudes as low as 5 capable of generating peak ground accelerations large enough to cause liquefaction (Ambraseys, 1988), the occurrence of local upper plate earthquakes could explain some liquefaction features at sites along the Nankai-Suruga Trough. Particularly in sediments with very high liquefaction susceptibility, rapid sedimentation, landsliding, permafrost and artesian springs may also generate analogous sedimentary features. Along with judicious site selection to avoid the influence of some of these processes, the identification of liquefaction features at multiple locations within a few kilometres, combined with geotechnical testing, can assist in determining a seismic origin (Green et al., 2005; Olson et al., 2005).

While the papers discussed in this review frequently invoke tsunamis to explain sand sheets found in coastal lakes and lowlands adjacent to the Nankai-Suruga Trough, storm surges may also deposit coarse-grained sand sheets with similar features to the sedimentary imprints of tsunamis. Typhoon-driven storm surges occur along the Nankai-Suruga Trough and there are few seismically active regions where major storms do not occur, at least on geological timescales. The consistent and reliable differentiation between storm and tsunami deposits remains an ongoing issue for the community (Engel and Brückner, 2011; Kortekaas and Dawson, 2007; Morton et al., 2007; Shanmugam, 2011). Careful application of detailed sedimentological criteria (e.g. Komatsubara et al., 2008; Fujiwara and Tanigawa, 2014) and multi-proxy approaches (e.g. Chague-Goff et al., 2011; Goff et al., 2012; May et al., 2015a) may assist in avoiding misidentification. Further in-depth characterisation and comparison of the deposits left by recent tsunamis (e.g. Abe et al., 2012; Brill et al., 2012; Goto et al., 2014; Szczuciński, 2012) and storms (e.g. Hawkes and Horton, 2012; May et al., 2015a, b; Williams, 2009) in a wide range of depositional settings remains crucial. Novel methods of sedimentary analysis, such as micro-computed tomography (May et al., 2015a), anisotropy of magnetic susceptibility (Schneider et al., 2014; Wassmer et al., 2010) and microfossil analysis (Uchida, 2010) may also assist in discriminating between the origins of different extreme wave event deposits.

6.2 Chronological control

The issues surrounding the use of radiocarbon dating to discriminate between closely-spaced events are well-documented (Atwater et al., 1991; Nelson et al., 1995). The short recurrence intervals between Nankai-Suruga earthquakes, known from the historical record to include periods of just hours to a few years, prevent the use of radiocarbon dating to establish unequivocal correlations between palaeoseismic evidence at different sites. Such issues are less often encountered where intervals exceeding several centuries separate recorded palaeoearthquakes, as appears to be the case in Alaska (Shennan et al., 2014b), and where earthquake timing is constrained by very high resolution chronologies, such as those based on annual varves (e.g. Moernaut et al., 2014). More precise constraints on the timing of palaeoseismic evidence are clearly desirable, particularly to assist with characterising the sedimentary fingerprint of historical earthquakes. Komatsubara and Fujiwara (2007) highlight the issue of ambiguous relationships between radiocarbon dated samples and proposed palaeoseismic evidence. We advocate for this information, including sample depth, context, material, conventional radiocarbon age and isotopic fractionation, to be routinely reported in future. Advances in radiocarbon analyses can be gained through the use of age modelling, particularly when combined with strategically planned sampling approaches (c.f. Bronk-Ramsey, 2009; Lienkaemper and Bronk Ramsey, 2009). Additionally, the use of alternative dating methods, including annual varves, short lived radionuclides (^{137}Cs and ^{210}Pb), luminescence dating techniques, tephrochronology and other chronohorizons (pollen, pollution markers), may help to improve correlations between sites and between palaeoseismic evidence and historically recorded earthquakes. Both age modelling and the application of a diverse suite of complementary dating approaches may serve to enhance chronological control on the sedimentary evidence for earthquakes and tsunamis along the Nankai-Suruga Trough and in other seismically impacted regions around the world.

6.3 Research design

The Central Disaster Management Council of the Japanese Cabinet Office emphasizes the need for greater understanding of the maximum magnitude of earthquakes and the largest possible tsunamis (CDMC, 2011, 2012). This deterministic approach to hazard assessment provides an alternative and complementary approach to probabilistic assessments. Nevertheless, the majority of currently published research has not been designed with questions of magnitude as a central focus. Accurate assessment of the run-up and inland extent of past tsunamis depends on detailed mapping and characterisation of tsunami deposits, as well as comprehensive understanding of palaeoshorelines and sea levels (Fujiwara, 2013). At present, these complementary data are not consistently explored when interpreting tsunami deposits. While the extent of identifiable deposits may remain a minimum estimate of inundation distance, this still constitutes a valuable constraint for testing models of tsunami inundation and fault rupture (e.g. Sugawara, 2014; Witter et al., 2012). Future coastal studies should, therefore, seek to better understand palaeoshoreline positions and coastal evolution and combine mapped tsunami deposit distributions with inundation and fault slip models.

Turbidite records also have the potential to provide information on the rupture extents and magnitudes of past earthquakes (e.g. Goldfinger et al., 2003; Howarth et al., 2014; Moernaut et al., 2014; Poderoux et al., 2014). While existing publications identify both lacustrine and marine basins as having the potential to hold records of shaking during past Nankai-Suruga Trough earthquakes, these sites have not been exploited to their full extent and reanalysis, combined with investigations of new locations, could yield additional insights into the largest magnitude earthquakes that have struck this subduction zone. As discussed in the preceding paragraphs, the current lack of high resolution chronologies and issues over the differentiation between seismoturbidites and those generated by other processes currently limits the utility of turbidite records. Renewed efforts should attempt to fingerprint the sedimentary record of known historical earthquakes, establish the defining characteristics of seismoturbidites and use this understanding to exploit longer sedimentary records in marine and lacustrine settings.

Additional palaeoseismic approaches, used successfully elsewhere but previously only rarely if at all along the Nankai-Suruga Trough, may supplement existing methods and provide further insights into past earthquake and tsunami occurrence. Sugawara and Goff (2014), for example, propose that beach ridges may respond to seismic forcing and could provide a geomorphic record of the timing of past earthquakes along the Japan Trench. The presence of beach ridge systems on coastal plains facing the Nankai-Suruga Trough (Matsubara, 2005) raises the possibility for the application of analogous approaches along this subduction zone.

6.4 Palaeoseismic thresholds

The presence of evidence for past earthquakes and tsunamis depends on thresholds of both creation and preservation (Nelson et al., 2006; McCalpin and Nelson, 2009). For example, for a tsunami-deposited sand sheet to be discovered in the sub-bottom stratigraphy of a coastal lake, the tsunami must have been of sufficient height to overtop the lake's sill with sufficient energy to transport sand (a creation threshold) and the sand layer must have withstood subsequent taphonomic alteration, for instance through bioturbation (a preservation threshold). The sensitivity with which a site preserves evidence for earthquakes or tsunamis should be explicitly assessed, principally through calibrating historic earthquake and tsunami deposits with their causal events (c.f. Moernaut et al., 2014; Van Daele et al., 2015). At present, few studies from the Nankai-Suruga Trough have addressed site sensitivity and corresponding palaeoseismic thresholds. Furthermore, such thresholds may vary over time, for example the relative elevation of a lake's sill decreasing or increasing due to sea-level rise or fall, complicating the relationship between the initial process and the resulting stratigraphic or geomorphic evidence. When comparing evidence for repeated tsunamis or earthquakes, the impact of changes in these thresholds must be considered if the relative magnitude of each event is to be discerned.

7. Conclusions

A critical examination of proposed palaeoseismic evidence from 72 sites along the Nankai-Suruga Trough reveals the current state of knowledge regarding geological evidence for past earthquakes and tsunamis along this subduction zone. Sites include marine, coastal, lacustrine and terrestrial locations that record evidence for intense shaking, coseismic deformation and/or tsunami inundation. A minority of sites provide compelling, well-dated evidence, with issues including the differentiation of seismic and non-seismic evidence and insufficient chronological control limiting the contribution of many locations to understanding past fault behaviour.

We use the best available evidence to constrain the most likely rupture zones of eleven earthquakes for which historical records also exist. This spatiotemporal compilation suggests the AD 1707 earthquake might have involved slip on at least five of six proposed seismic segments; an along-strike distance in excess of 600 km. The distribution of geological evidence suggests earthquakes in AD 1361 and 684 possibly ruptured all six segments, although further research is required to conclusively discount the possibility of closely temporally spaced ruptures of adjacent segments. Intervening earthquakes probably involved smaller areas of the subduction interface, including at least one rupture potentially confined to the area up-dip of the main seismogenic zone, highlighting a high degree of variability in rupture mode. We find insufficient geological evidence to consider the AD 1099 earthquake a great interplate event, but note that additional previously undocumented subduction megathrust earthquakes may have occurred during the historical period.

The combined historical and geological record suggests intervals between ruptures of the same seismic segment ranged from 90 to 474 years over the last ~1350 years. Over the longer timescales afforded by palaeoseismic data, individual sites suggest recurrence intervals of 200 to 700 years. These figures do not just reflect the recurrence of great earthquakes, however, and future assessments must consider thresholds of evidence creation and preservation when assessing recurrence intervals from palaeoseismic data.

While the Central Disaster Management Council of the Japanese Cabinet Office has called for historical and geological data to be used to define the largest magnitude of past earthquakes (CDMC, 2012), few attempts have yet been made to use palaeoseismic data to compare relative sizes or quantify absolute magnitudes of past earthquakes along the Nankai-Suruga Trough. As such, there is currently no evidence for the occurrence of a larger magnitude earthquake or greater tsunami inundation than that experienced in AD 1707. Future research efforts should address the question of maximum magnitude through combined field and modelling efforts. Amongst the diverse range of palaeoseismic evidence types available, records of turbidite emplacement in marine and lacustrine settings and tsunami inundation from coastal lowlands and lakes appear best placed to provide new insights into the dimensions of past fault ruptures. These approaches and complementary methods will also be crucial to future attempts to answer a range of additional questions pertinent to probabilistic seismic hazard assessments. These include uncertainties over the permanence of segment boundaries over time, the simultaneity of ruptures of the Nankai, Tōnankai and Tōkai regions and the occurrence, frequency and characteristics of tsunami earthquakes.

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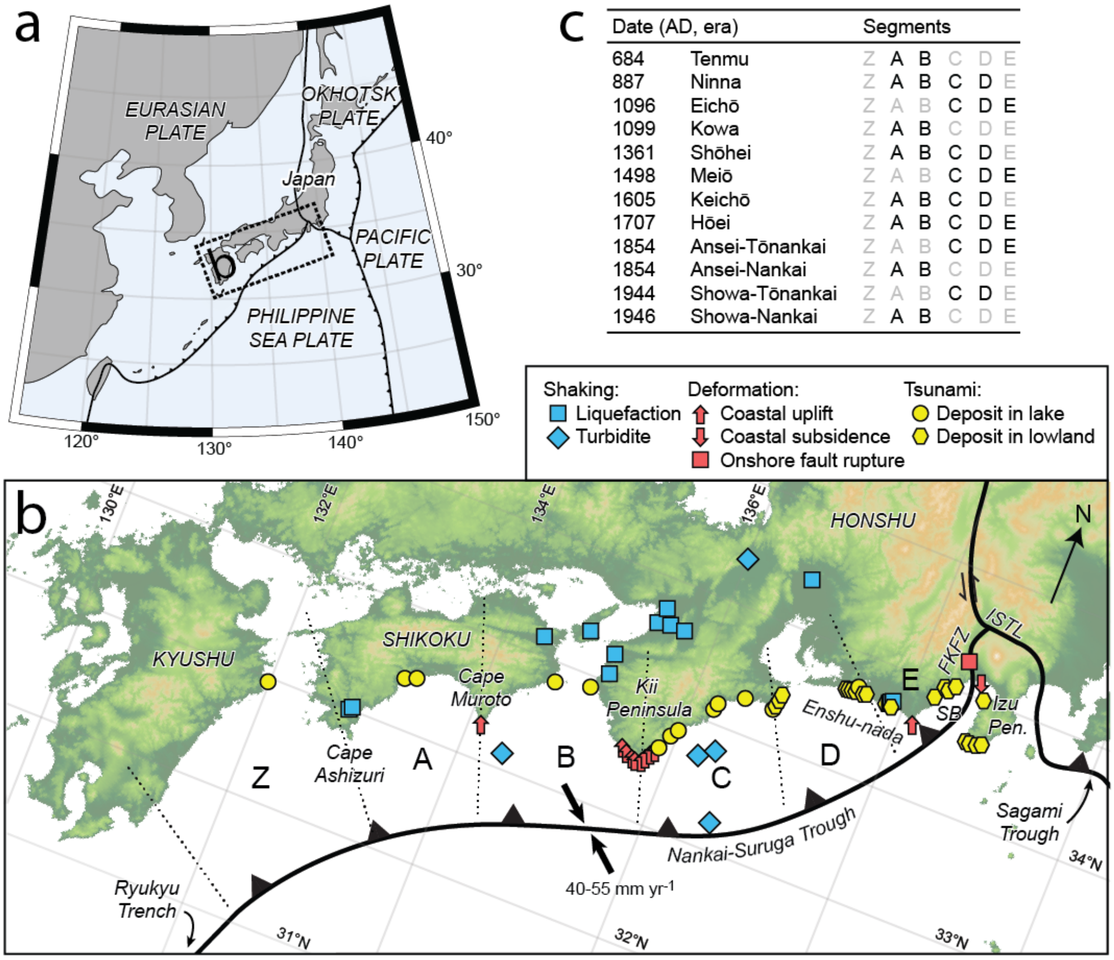
Figures



Date (AD, era)		Segments
684	Tenmu	Z **A** **B** C D E
887	Ninna	Z **A** **B** **C** **D** E
1096	Eichō	Z A B **C** **D** **E**
1099	Kowa	Z **A** **B** C D E
1361	Shōhei	Z **A** **B** **C** **D** E
1498	Meiō	Z A B **C** **D** **E**
1605	Keichō	Z **A** **B** **C** **D** E
1707	Hōei	Z **A** **B** **C** **D** **E**
1854	Ansei-Tōnankai	Z A B **C** **D** **E**
1854	Ansei-Nankai	Z **A** **B** C D E
1944	Showa-Tōnankai	Z A B **C** **D** E
1946	Showa-Nankai	Z **A** **B** C D E

Figure 1: a) Tectonic setting of Japan, including the location of b) The Nankai-Suruga Trough, with the distribution and classification of sites discussed in this paper. Abbreviations: SB: Suruga Bay, FKFZ: Fujikawa-Kako Fault Zone, ISTL: Itoigawa-Shizuoka Tectonic Line; letters Z, A, B, C, D and E refer to seismic segments. Segment Z is also known as "Hyūga Nada"; segments A and B are collectively "Nankai"; segments C and D are collectively "Tōnankai"; segment E is "Tōkai". c) Summary of historical Nankai-Suruga Trough earthquakes, including calendar year, era name (nengō) and proposed rupture zone segments from historical records (following Ando, 1975b; Ishibashi, 2004).

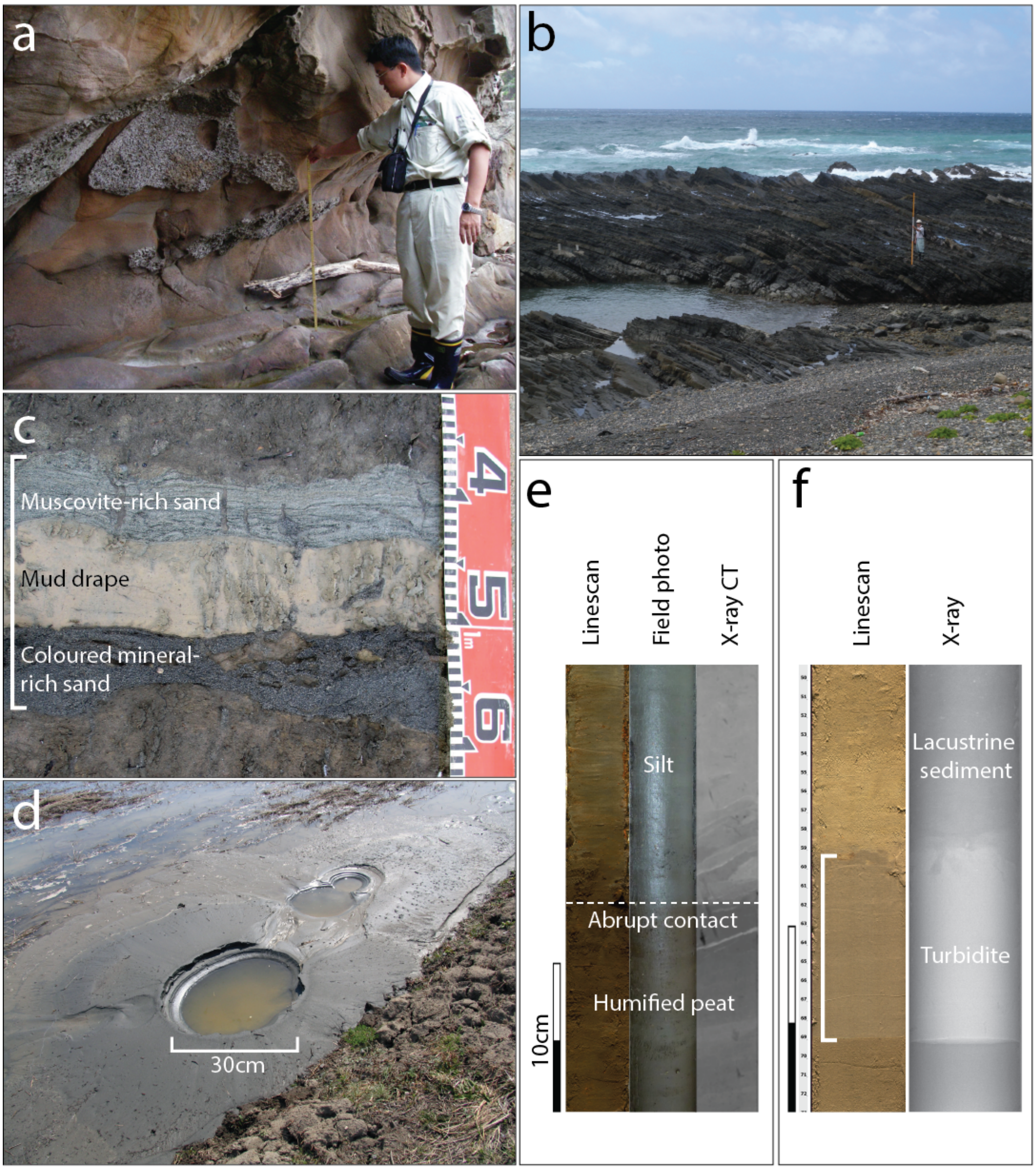


Figure 2: Representative photographs of different lines of palaeoseismic evidence that have been employed along the Nankai-Suruga Trough. a) Emerged sessile organisms at Suzushima close to the boundary between segments B and C. Mass mortality of colonies of intertidal annelid worms reflects coseismic uplift during an earthquake approximately 2000 cal. yr BP (Shishikura et al., 2008). b) An emerged wave cut platform near Cape Ashizuri. The platform lies at an elevation of approximately 1 – 1.2 m above present mean sea level and may reflect uplift during the AD 1946 earthquake (M. Shishikura, unpublished data). c) Layers of sand and mud probably left by the AD 1605 tsunami at Shirasuka (Fujiwara et al., 2006). d) An

abrupt transition from humified peat to inorganic silt that may reflect abrupt subsidence of a coastal lowland in segment D (E. Garrett, unpublished data). e) Liquefaction features (sand blows) induced by intense shaking during the 2011 Tohoku earthquake (O. Fujiwara, unpublished data). f) A lacustrine turbidite from a lake in segment E possibly caused by intense shaking during an earthquake (L. Lamair, unpublished data).

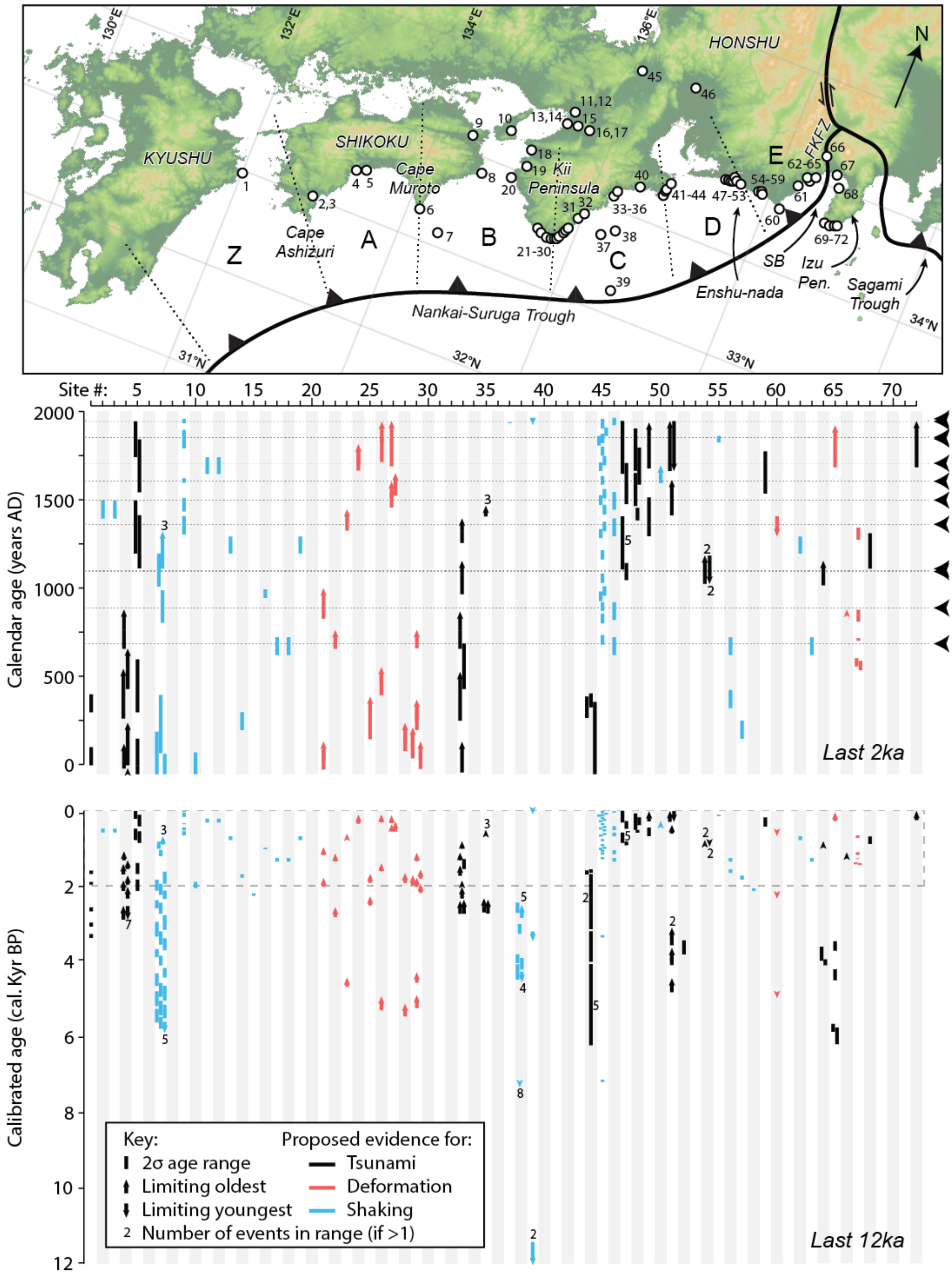


Figure 3: Summary of the spatial and temporal distribution of proposed evidence for past megathrust earthquakes along the Nankai-Suruga Trough. We emphasise that for many of the records summarised here, alternative, non-seismic formation mechanisms are yet to be discounted. Upper panel displays site locations, lower panels give age ranges and limiting

dates for proposed palaeoseismic evidence. Site numbers: 1. Ryūjin Pond*; 2. Azono*; 3. Funato*; 4. Tadasu Pond†; 5. Kani Pond*; 6. Cape Muroto; 7. Tosabae Trough‡; 8. Kamoda Lake*; 9. Itano-chō*; 10. Shimonaizen*; 11. Kosaka-tei-ato*; 12. Ikeshima Fukumanji*; 13. Iwatsuta Shrine*; 14. Sakai-shi Shimoda*; 15. Tainaka*; 16. Hashio*; 17. Sakafuneishi*; 18. Kawanabe*; 19. Fujinami*; 20. Hidaka Marsh §; 21. Kuchiwabuka†; 22. Ameshima†; 23. Shionomisaki†; 24. Izumozaki†; 25. Arafunezaki†; 26. Ikeshima†; 27. Yamamibana†; 28. Taiji†; 29. Suzushima†; 30. Kii-Sano §; 31. Atawa §; 32. Shihara §; 33. Ōike Pond†‡; 34. Umino Pond §; 35. Suwa Pond†; 36. Katagami Pond §; 37. Kumano Trough W*; 38. Kumano Trough E†‡; 39. IODP core C0004†; 40. Kogare Pond §; 41. Funakoshi Pond §; 42. Shijima Lowlands §; 43. Kō §; 44. Ōsatsu Town‡; 45. Lake Biwa*; 46. Tadokoro*; 47. Nagaya Moto-Yashiki‡; 48. Shirasuka‡; 49. Arai‡; 50. Goten-ato*; 51. Lake Hamana†; 52. Rokken-gawa Lowlands‡; 53. Hamamatsu Lowlands§; 54. Ōtagawa Lowlands†; 55. Fukuroi-juku*; 56. Sakajiri*; 57. Tsurumatsu*; 58. Harakawa*; 59. Yokosuka Lowlands‡; 60. Omaezaki; 61. Yaizu Plain §; 62. Agetsuchi*; 63. Kawai*; 64. Ōya Lowlands†‡; 65. Shimizu Plain‡; 66. Fujikawa-Kako Fault Zone; 67. Ukishima-ga-hara‡; 68. Ita Lowlands†‡; 69. Iruma §; 70. Minami-Izu §; 71. Kisami §; 72. Shimoda†. Sites with calibrated ages taken from original publications marked *, sites with ages recalibrated in this publication marked †, sites with ages modelled in this publication marked ‡ (see also Supp. Info.), sites with no chronological data or where chronological data cannot be related to palaeoseismic evidence marked §. Abbreviations: SB: Suruga Bay, FKFZ: Fujikawa-Kako Fault Zone, letters Z, A, B, C, D and E refer to seismic segments.

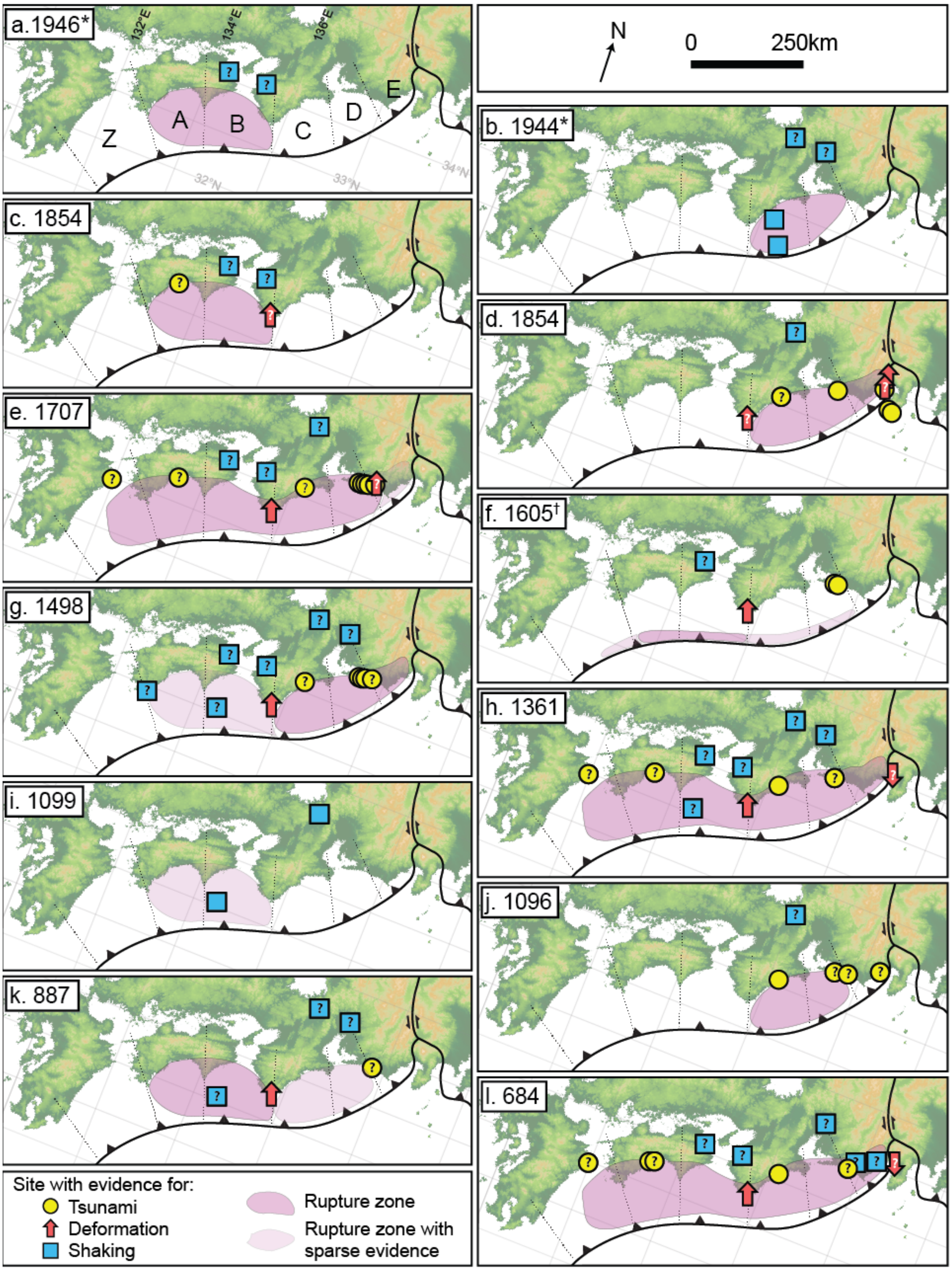


Figure 4: Summary of inferred rupture zones of historical great Nankai-Suruga Trough earthquakes and the distribution of associated geological evidence. Question marks indicate uncertainty over the chronology or the origin of evidence at a site. * Rupture zones of the AD 1946 and 1944 earthquakes are approximated from Baba and Cummins (2005) and

Tanioka and Satake (2001a, b). † Rupture zone of the AD 1605 earthquake following Ando and Nakamura (2013) and Park et al. (2014).