Long-term Indian Ocean tsunami record reveals alternating event clusters punctuated by quiet interludes

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Abstract

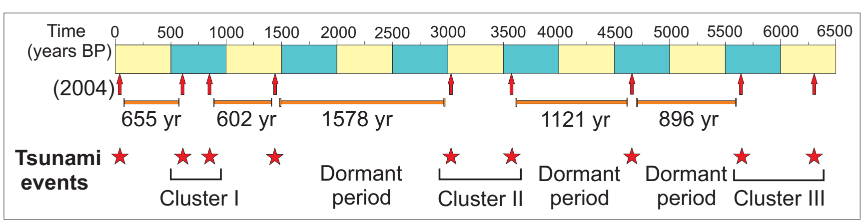
[The analyses of sediment cores retrieved near Port Blair (South Andaman) revealed alternate bands of out-of-sequence layers at various depths identified by their sediment characteristics and microfossil content. The 'out-of-sequence' layers are found to be in the age ranges of 596-606; 819-856; 1358-1522; 2899-3145; 3718-3461; 4584-4837; 5390-5823; and 6239-6472 yr BP, and show a remarkable chronological equivalence with paleo-tsunami deposits identified from far-field locations in the Indian Ocean region. The long-term tsunami record implies temporally clustered sequence of causative earthquakes alternating with interevent gaps and stand-alone events. This variable recurrence pattern of tsunamigenic great earthquakes is supported by the theoretical models espousing the characteristics of long-term stress re-cycling processes active within the subduction zones and transfer processes between the lower viscoelastic layer and the upper seismogenic crust.]

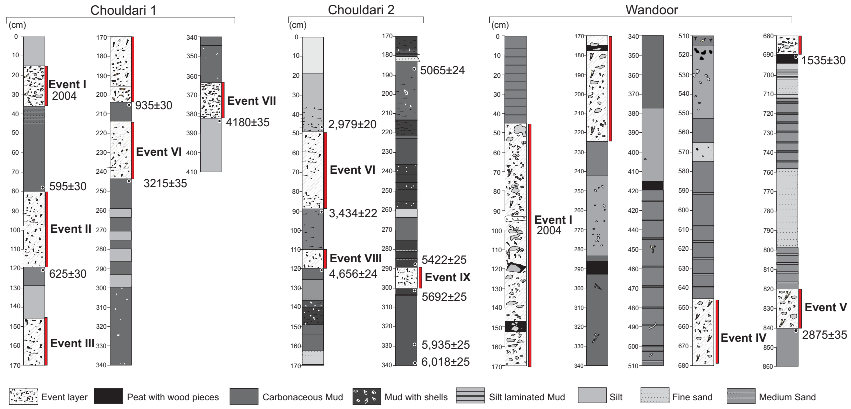
Table 1. Radiocarbon ages of tsunami deposits recorded in Port Blair, South Andaman

Event	Depth from surface (cm)	Thickness of the sediment (cm)	Age above tsunami deposit (μ±2σ calendar yr BP) (Calibrated ages (BCE/CE)	Age below tsunami deposit (μ±2σ calendar yr BP) (Calibrated ages (BCE/CE)	Age within the deposit (μ±2σ calendar yr BP) (Calibrated ages (BCE/CE)	Midpoint age of the tsunami deposits	Sites
Event 1	15	20				**2004**	Chouldari-1
	45	180				**2004**	Wandoor
Event 2 (II)	80	40	595±30 (1298-1410CE)	625±30 (1290-1398 CE)		**1349 CE**	Chouldari-1
Event 3 (III)	147	60	885±30 (1042-1219 CE)	935±30 (1027-1161 CE)		**1113 CE**	Chouldari-1
Event 4 (IV)	645	45			1535±30 (428-592 CE)	**510 CE**	Wandoor

Event	Depth from surface (cm)	Thickness of the sediment (cm)	Age above tsunami deposit ($\mu\pm2\sigma$ calendar yr BP) (Calibrated ages (BCE/CE)	Age below tsunami deposit ($\mu\pm2\sigma$ calendar yr BP) (Calibrated ages (BCE/CE)	Age within the deposit ($\mu\pm2\sigma$ calendar yr BP) (Calibrated ages (BCE/CE)	Midpoint age of the tsunami deposits	Sites
Event 5 (V)	820	20	2725$\pm$35 (967-808 BCE)		2875$\pm$35 (1192-930 BCE)	**1068 BCE**	Wandoor
	835						
	50	30	2840$\pm$30 (1107-917 BCE)	2979$\pm$20 (1262-1127 BCE)			Chouldari-2
Event 6 (VI)	105	20		3434$\pm$22 (1872-1666 BCE)		**1641 BCE**	Chouldari-2
	240	30	3215$\pm$35 (1606-1417 BCE)				Chouldari-1
Event 7 (VII)	365	20			4180$\pm$35 (2888-2635 BCE)	**2762 BCE**	Chouldari-1
Event 8 (VIII)	145	20	4656$\pm$24 (3516-3366 BCE)	5065$\pm$24 (3950-3797)		**3657 BCE**	Chouldari-2
Event 9 (IX)	280	20	5422$\pm$25 (4336-4244 BCE)	5692$\pm$25 (4586-4456 BCE)		**4407 BCE**	Chouldari-2

Note: AMS dating of charcoal samples were conducted at Poznan Radiocarbon Laboratory (Poz), Poland. Radiocarbon ages were calibrated using CALIB (Version 7.0.4) (Stuiver and Reimer, 1993; Reimer et al., 2013). The 2 sigma ranges have maximum area under the probability distribution curve. All samples are taken from organic-rich bulk sediment.




Chouldari 1
Chouldari 2
Wandoor
(cm)
Event I
2004
595±30
Event II
625±30
Event III
935±30
Event VI
3215±35
Event VII
4180±35
2,979±20
Event VI
3,434±22
Event VIII
4,656±24
5065±24
5422±25
Event IX
5692±25
5,935±25
6,018±25
Event I
2004
Event IV
1535±30
Event V
2875±35
Event layer
Peat with wood pieces
Carbonaceous Mud
Mud with shells
Silt laminated Mud
Silt
Fine sand
Medium Sand

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Key Points:

- Established the record of tsunamis in the last 6.5 ka using sediment cores from South Andaman
- Timeline of Indian Ocean tsunamis marked by hiatuses of variable timescales between event clusters
- This data can be used for theoretical models as an independent observational validation

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Abstract

[The analyses of sediment cores retrieved near Port Blair (South Andaman) revealed alternate bands out-of-sequence layers at various depths identified by their sediment characteristics and microfossil content. The 'out-of-sequence' layers are found to be in the age ranges of 596-606; 819-856; 1358-1522; 2899-3145; 3718-3461; 4584-4837; 5390-5823; and 6239-6472 yr BP, and show a remarkable chronological equivalence with paleo-tsunami deposits identified from far-field locations in the Indian Ocean region. The long-term tsunami record implies temporally clustered sequence of causative earthquakes alternating with interevent gaps and stand-alone events. This variable recurrence pattern of tsunamigenic great earthquakes is supported by the theoretical models espousing the characteristics of long-term stress re-cycling processes active within the subduction zones and transfer processes between the lower viscoelastic layer and the upper seismogenic crust.]

Plain Language Summary

[This paper reports tsunami history of the Indian Ocean during the last 6000 years that has bearing on the predecessors of the 2004 tsunami sourced in the Andaman-Sumatra subduction zone. The conclusions are drawn from comparing the results from various sites of the Indian ocean littoral countries with that of the chronologically constrained out-of-sequence layers identified from the sedimentary cores located in the south Andaman, a near-field site. Using the Andaman site as a template, we have identified nine tsunami event layers, including the 2004 deposits. The combined time-series of Indian Ocean sites provide some fresh insights into the recurrence pattern of the 2004-type transoceanic tsunamis. The long-term tsunami record implies temporally clustered events occasionally punctuated by stand-alone events. Using the tsunami record as a proxy to the causative mega-earthquakes, we say that this observational evidence can be used to validate the theoretical models espousing the earthquake cycles marked by long and irregular quiescent intervals between the periods of a succession of earthquake occurrences that are ultimately related to the characteristics of tectonic loading rates and visco-elastic relaxation within the subduction zones.]

1 Introduction

Sourced off Banda Aceh, Sumatra Island, the Mw 9.2 earthquake of December 26, 2004 generated a massive tsunami in the Indian Ocean (Figure 1a). The earthquake rupture unilaterally extended northward and terminated near the northern tip of the Andaman Island chain and the ensued tsunami devastated the shores of littoral countries of the Bay of Bengal (Figure 1a). The waves as high 30 m reached Banda Aceh and the Nicobar (A&N) Islands within 30 minutes. Much reduced in height (5 m), the waves arrived at the Andaman Coast in 40 minutes. The tsunami impacted the distant coasts of Thailand, Sri Lanka, the southeast coast of India, the Maldives Islands and the southeastern coast of Africa, after 2 to 4 hours (Figures 1a and b). The post-tsunami studies from Thailand and Sumatra report a paleotsunami in the range of 1250-1450 CE (Jankaew et al., 2008; Monecke et al., 2008) and is also correlative of well-dated coral uplifts located off Sumatra (Meltzner et al., 2010). A still older tsunami in the range of 770-1040 CE was also construed from the Sumatra (Monecke et al., 2008) as well as from the A&N Islands and southeastern coast of India (C. Rajendran et al., 2011, 2013).

The cores from the coastal lagoons in the far-field regions (Sri Lanka and Maldives) had revealed much older tsunami record (Jackson et al., 2014; Klostermann et al., 2014). From the cave deposits of Sumatra, (Rubin et al., 2017) deciphered a timeline of eleven tsunamis, between 2900 and 7400 years. A 6600-year long record of earthquakes was deciphered from the turbidite sequences, off Sumatra, from the southern part of the 2004 source zone (Patton et al., 2015). Their results are representative of both the mega 2004-type tsunamigenic as well as local slip events. A recent study from South Andaman sug-

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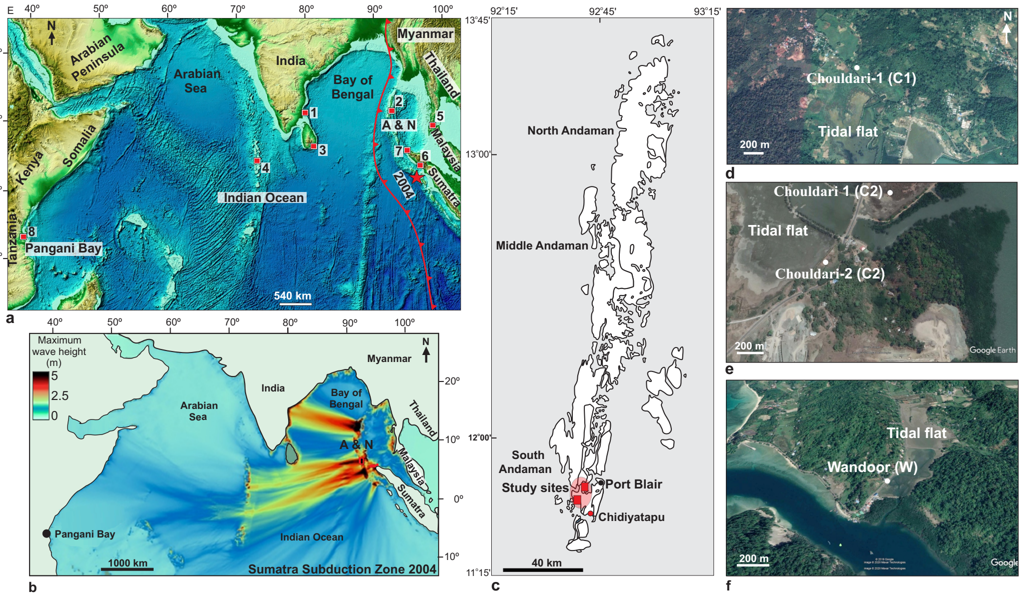

Figure 1. a. Map showing the Indian Ocean region and source region of the 2004 (Mw 9.2) earthquake; A&N: Andaman Nicobar Islands, MA: Maldives and SL: Sri Lanka. Paleotsunami sites: 1.(C. Rajendran et al., 2006, 2011) 2.(C. Rajendran et al., 2013) 3.(Jackson et al., 2014) 4.(Klostermann et al., 2014) 5.(Jankaew et al., 2008) 6.(Monecke et al., 2008) 7.(Rubin et al., 2017) 8.(Maselli et al., 2020). b. Map shows the maximum wave heights during 2004 Tsunami (modified after Maselli et al., 2020). c. Map of Andaman Islands with present study sites (red-filled squares inside the hilighted circle) and an earlier sampling site by (Malik et al., 2019) (red-filled circle). d, e and f. Close-up views of the coring sites: Chouldari-1 (C1); Chouldari-2 (C2) and Wandoor (W) near Port Blair South Andaman.

gests evidence for six tsunami depositions are linked to the historically reported local events of 1881 (Mw 7.9; Car Nicobar), 1762 (Mw $\leq$ 8.5; Arakan Coast, Myanmar) and 1679 (North Andaman?) and older ones (1300-1400 CE, 2000-3000 BCE, 2810-3200 BCE/2892-1895 BCE) (Malik et al., 2019) (Figure 1c). Designed to develop an independent authentication of long-term history ($\sim$ 6,500 years) of the transoceanic tsunamis we use core lithology from the near-field sites in South Andaman (Figures 1c-f) that would also facilitate comparison with the data from distant sites.

2 Materials and Methods

We chose some of the accessible marshes and tidal inlets located in the South Andaman, which lie within the tsunami reach (Figures 1c-f; S 1a-c). We expected that these locales where the land-derived erosive processes are apparently less dominant offer favorable depositional environments for off-shore borne sediment. From the selected three sites near Port Bair, namely, Chouldari-1 (4.1 m), Chouldari-2 (3.4 m) and Wandoor (8.6 m), the sediment cores were collected (Figures 2a-c). Our initial examination of the cores from all the three drill sites, aided by the CAT scan images, helped in demarcating alternating lighter colored layers of coarse materials within dark colored muddy sediments (Figures S3a-c). The lithology of cores that consists of the dark colored mud is representative of in-situ sediment deposited in tidal environment, and intermittent bands of coarser material (Figures S4b-d). The ^{137}Cs concentration provided corroboration for the presence of the 2004 tsunami deposits at the top level of the cores (Figure S5). The intermittent bands of the coarser sediment from the cores comprise silica rich mud, silt and sand, plant debris along with broken shells and coral fragments (Figures S6a-c; 7a-e; 8a-b; 9, 10 and 11). The dominant foraminifers in these layers have affinity with marine shelf environment (Figure S12). The broken shells make $\tilde{3}5\%$ of the total sediment, while the organic-rich debris make $\tilde{4}5\%$ in these deposits (Figures S13b-d). These characteristics help in categorizing the bands of coarse material as a mixture of transported material from the open sea and those incorporated from the landward part of coastal water. The 'out-of-sequence' layers are comparable to the 2004 tsunami deposits identified at the upper levels of the cores in terms of textural and faunal content (Figures S12a-c; 14a and b). Thus, these coarser bands are attributed to the deposition by the previous sea inundation episodes as specified by their sedimentary characteristics, micro-faunal assemblages and the transporting mechanism include either a cyclonic storm or a tsunami (Figures S14a-b; 15a-c; S16).

The inundation limit of storm surge is reported to be minimal in these areas and is authenticated by documentary evidence on near absence of cyclone impacts on the island (Department, 2008). The maximum tsunami inundation limit during the 2004 tsunami is reported to be 1320 m in Wandoor settlement area (Dharanirajan et al., 2007). All the coring sites mentioned here are located within or near narrow bays which have been impacted during the 2004 tsunami. As the 2004 tsunami inundation demonstrated that these narrow bays offered focused pathways for the tsunami waves and facilitated their propagation further inland. We targeted the tidal inlets as they provide the ideal depositional environment from the repeated high energy sea inundations. The core lithology thus retrieved from such environment was expected to reveal out-of-sequence deposition within the low-energy regular sedimentary facies.

3 Chronology of event layers

Event 1: The top levels from the cores recovered from Chouldari-1 and Wandoor contain 20-120 cm-thick bands of shell and plant debris (Figure 2a and c, Figures S4a-d). The deposition of these debris occurred during the 2004 tsunami as confirmed at Wandoor site, indicated by ^{137}Cs concentration from 45 to 150 cm from the top (Figure S5). However, we were not able to obtain similar signal from the site at Chouldari-1, except

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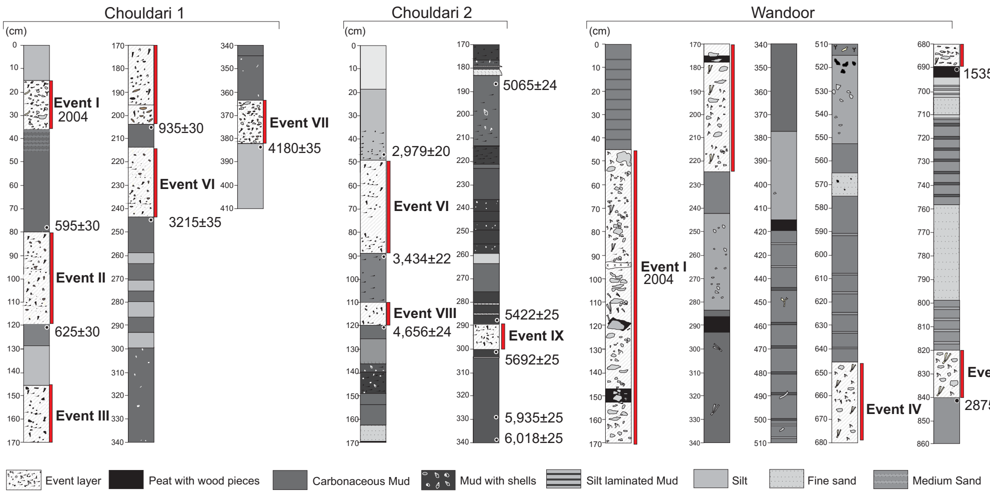

Figure 2. Lithologs from the study sites: a. Chouldari-1 (C1); b. Chouldari-2 (C2) and c. Wandoor (W), near Port Blair, South Andaman.

some modern ages (Figures 2a and c; Table 1 and Table S2 for calibrated ages of event layers).

Event 2: An out-of-sequence band of coarse material was identified at a depth of 80 cm from Chouldari-1 (Figures 2a, Figure S6a to d). The bulk sediment samples collected from above and below this layer are dated at 595±30 and 625±30 yr BP, respectively. This depositional event correlates with the 14th century tsunami inundation reported from Sumatra, Thailand, A&N Islands and the southwest coast of India (Monecke et al., 2008; Jankaew et al., 2008; C. Rajendran et al., 2013; Patton et al., 2015; C. Rajendran, 2019) (Figure 3). Recently,(Malik et al., 2019) reported a subsequent paleotsunami event from North Andaman with minimum and maximum age ranges from 311 to 663 cal yr BP.

Event 3: Characterized by coarse to medium sand with transported coral fragments and broken shells, an out-of-sequence deposit occur at the depth of 147 cm from Chouldari-1(Figure 2a; Figure S7a). The bulk sediment collected from top and the base of this layer is dated at 885±30 and 935±30 yr BP. Within the margins of error, this event between 819 and 856 cal yr BP may correlate with the paleo-tsunami reported near Port Blair and the southeastern coast of India (Monecke et al., 2008; C. Rajendran et al., 2006; K. Rajendran et al., 2008; Fujino et al., 2009; Patton et al., 2015). A contemporary event ranging from 726-984 cal. yr BP is also reported from Maldives, a far-field site located in the southern Arabian Sea (Klostermann et al., 2014) (Figure 3).(Maselli et al., 2020) identified an inundation zone from Tanzanian coast of east Africa that was dated between 802 and 1008 cal. yr BP and was attributed to a transoceanic tsunami source from the Andaman-Sumatra region.

Event 4: Yet another layer of coarse sediment identified from Wandoor site at a depth of 645 cm is dated at 1535±30 yr BP from the organic debris within this layer (Figure 2c; Figure S7b). This is considered to have been deposited by an inundation contemporaneous with the paleo-tsunami sand sheet identified from the southeast coast of India, which is dated at 1,470±70 and 1400±90 yr BP (C. Rajendran et al., 2006; K. Rajendran et al., 2008) (Figure 3).(Klostermann et al., 2014) reported a tsunami event from Maldives with an age range between 1485 and 1956 cal yr BP. with the maximum and minimum ages ranging from 1610±30 and 2000±30 cal yr BP. And, the event may also coincide with an earthquake identified using turbidities as a proxy off Sumatra with a date of 1,500±110 yr BP (Patton et al., 2015).

Event 5: Overlying the undisturbed laminated organic-rich mud another transportation event is identified in the range of 2899 and 3145 cal. yr BP at two sites: Chouldari-2 (C2) (Figures S7b-c) and Wandoor (W) (Figures S8a). The minimum ages of this event derived from bulk sediment of the upper boundary of the undisturbed layer at both sites (C2 and W) are 2725±35 and 2875±35 yr. BP, respectively. The maximum age of this event is dated as 2979±20 yr BP, from the lower boundary of undisturbed laminated mud (Figure 2b and c). The organic debris at the depth 835 cm within the out of sequence layer is dated at 2875±35 yr BP at Wandoor (W). These dates are comparable with the OSL dates of a paleotsunami deposit in the range of 2400-3020 cal. yr BP (2710±310 yr BP) reported from the southern Sri Lankan coast(Premasiri et al., 2015). (Jackson et al., 2014) and(Klostermann et al., 2014) also found an analogous event from the western Sri Lanka and Maldives respectively (Figure 3). A contemporary event is also recognized from a coastal cave in Aceh, Indonesia with the maximum and minimum ages ranging from 2862 to 2975 cal. yr BP and 2772 to 2859 cal. yr BP respectively(Rubin et al., 2017).

Event 6: We obtained evidence of another event from two sites at Chouldari-1 and Chouldari-2 (Figure S8b). The timing of this event ranges from 3461 to 3718 yr BP, estimated using the maximum and minimum ages of 3434±22 and 3215±35 yr BP obtained from the bulk sediment at the lower and top contact zones of the event layer with the organic mud (Figure 2b). This event may correspond to an earlier event dated from Maldives with the minimum and maximum age ranging from 3210±30 and 3280±30 cal. yr BP(Klostermann et al., 2014)(Figure 3). Similar timing for an event is reported with the OSL age of 3170±320 yr BP (2850-3490 yr BP) from the southern coast of Sri Lanka (Premasiri et al., 2015). The tsunami sand sheet recognized from a coastal cave in Aceh, Indonesia constrained between 3068 and 3464 cal. yr BP(Rubin et al., 2017) might be indicative of a regional contemporaneous tsunami (Figure 3).

Event 7: Identified only at Chouldari-1 (C1), the depositional age of event 7 at a depth of 365cm is constrained based on bulk sediment age of 4180±35 yr BP, obtained from the organic debris within the sand sheet (Figure 2a). This may correspond to an earlier event of tsunami dated from Maldives ranging from 4110±30 to 4210±30 cal. yr BP(Klostermann et al., 2014)(Figure 3).(Rubin et al., 2017) also reported the range of 5231-4515 and 5258-4552 cal. yr BP (Figure 3); within the age uncertainty this event may also coincide with the date of a turbidite (5033-3212 cal. yr BP) off Sumatra, as a proxy for an earthquake(Patton et al., 2015)(Figure 3).

Event 8: The minimum and maximum ages of the bulk sediment collected from the undisturbed organic mud above and below the 20 cm thick out-of-sequence deposit from Chouldari-2 is dated at 4656±24 and 5065±24 cal. yr BP (ranging between 5390-5823 cal. yr BP) is ascribed to event 8 that is represented by the coarse sand layer at the depth of 145 cm (Figure 2).(Rubin et al., 2017) also reported a similar event from Indonesia (5331-5583 and 5357-5575 cal. yr BP). Contemporaneously, an earthquake is also reported from the turbidite sequence off Sumatra-Andaman subduction zone (5902-4864 cal. yr BP: 4720±220 yr BP)(Patton et al., 2015)(Figure 3).

Event 9: Sedimentary evidence of an oldest tsunami in this sequence is identified from Chouldari-2 (Figure S8d). The bottom of the event layer is dated at 5692±25 yr BP while the top is dated at 5422±25 yr BP. Using these constraints, the timing of the event 9 can be approximated between 6239 and 6472 cal. yr BP that may correspond with an event dated at 5400±30 cal. yr BP (6121-6287 cal. yr BP) reported from Maldives(Klostermann et al., 2014)(Figure 3). The contemporaneous tsunami deposition dated between 6155 to 6248 and 6248 to 6458 cal. yr BP from Karagan Lagoon, Sri Lanka may also indicate

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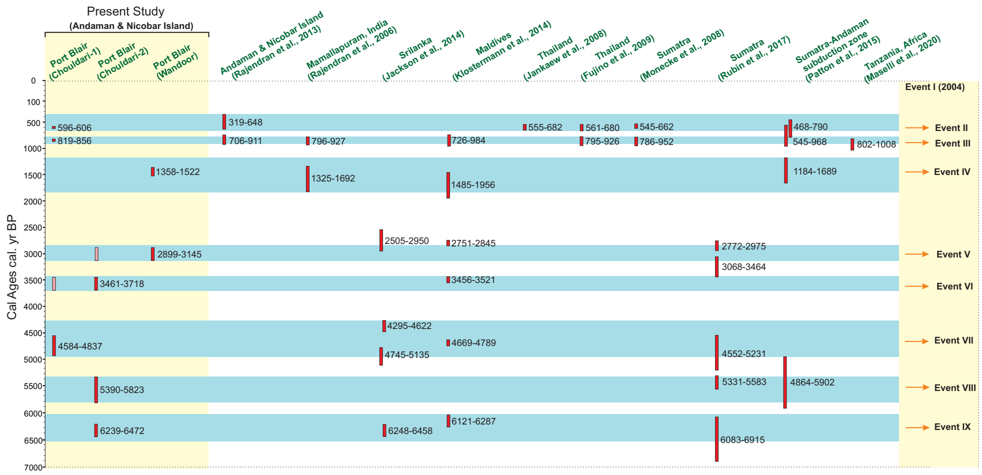

Figure. 3

Figure 3. Comparative space-time correlation of tsunami event ranges from different parts of the Indian Ocean region. For each event, the age data is calibrated using the Calib 7.0.2 with 2 σ range.

contemporaneity(Jackson et al., 2014) (Figure 3). A tsunami has also been constrained between 5857-6680 and 6083-6915 cal. yr BP from a coastal cave in Indonesia(Rubin et al., 2017)(Figure 3). Timings of paleotsunamis reported in the aforementioned age ranges match with an episode of subsidence in South Andaman that is dated at 6643±107 yr BP and 6739±85 yr BP(K. Rajendran et al., 2008). Evidence for an old earthquake in the similar range (6500-7000 cal. yr BP)(Pre et al., 2012) is reported from Aceh, Indonesia that may also correlate with this event.

4 Conclusions and Implications

We have identified nine event layers in the cores collected from the South Andaman Coast including the 2004 tsunami within a timescale of 6500 years (Figures 2a-c). The timeline developed in this study and the chronologically equivalent events identified in the distant sites in the Indian Ocean imply that all those depositions could be attributed transoceanic tsunamis. The timeline suggests hiatuses (intervals longer than the recurrence periods between the events within a cluster) of variable time-intervals between the tsunamigenic earthquake clusters (Figure 4). As shown in Figure 4, two quiet periods of lasting 655 and 602 yr, respectively are estimated, before and after the event clusters I. A long hiatus of about 1578 yr is estimated between a stand-alone event and the cluster II, which is also followed by a long quiet interlude lasting up to 1121 yr. A repeat of hiatus lasting for about 896 yr is estimated between the event cluster III and another stand-alone event. We conclude that the tsunamigenic great earthquakes along the Andaman-

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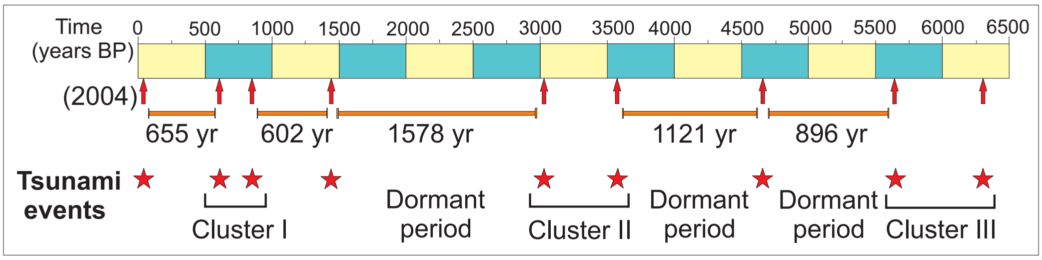

Figure 4. The time series showing the long-term occurrence pattern of earthquakes along the Sumatra-Andaman subduction zone.

Sumatra subduction zone have occurred in pulses separated by either long or short periods of quiescence with stand-alone events occurring in between such cycles (Figure 4). Overall, the pattern of earthquake occurrences suggests non-periodic variability from cycle to the next. Temporal variability in earthquake cycles has been suggested for the southern part of the Sunda megathrust(Sieh et al., 2008) and the Cascadia margin in the northwest United States(Goldfinger et al., 2012).

The numerical models have repeatedly shown that an earthquake cluster is expected to occur when a reservoir of stress is stored in the viscoelastic layer. This scenario promotes dormant periods to last longer until the reservoir of stress is exhausted and yield stress increases leading to reloading of the fault(Weldon et al., 2004; DiCaprio et al., 2008).(Chen et al., 2020) mathematically characterize clusters of earthquakes separated by longer and irregular intervals of quiescence as the 'Devil's staircase pattern'. They conclude that the lengths of the quiescent intervals between clusters are inversely related to tectonic-loading rates, whereas earthquake clustering can be attributed to many factors, including earthquake-induced viscoelastic relaxation and fault interaction. The data presented in this study presents an independent observational validation from an active tectonic regime for the theoretical models.

Acknowledgments

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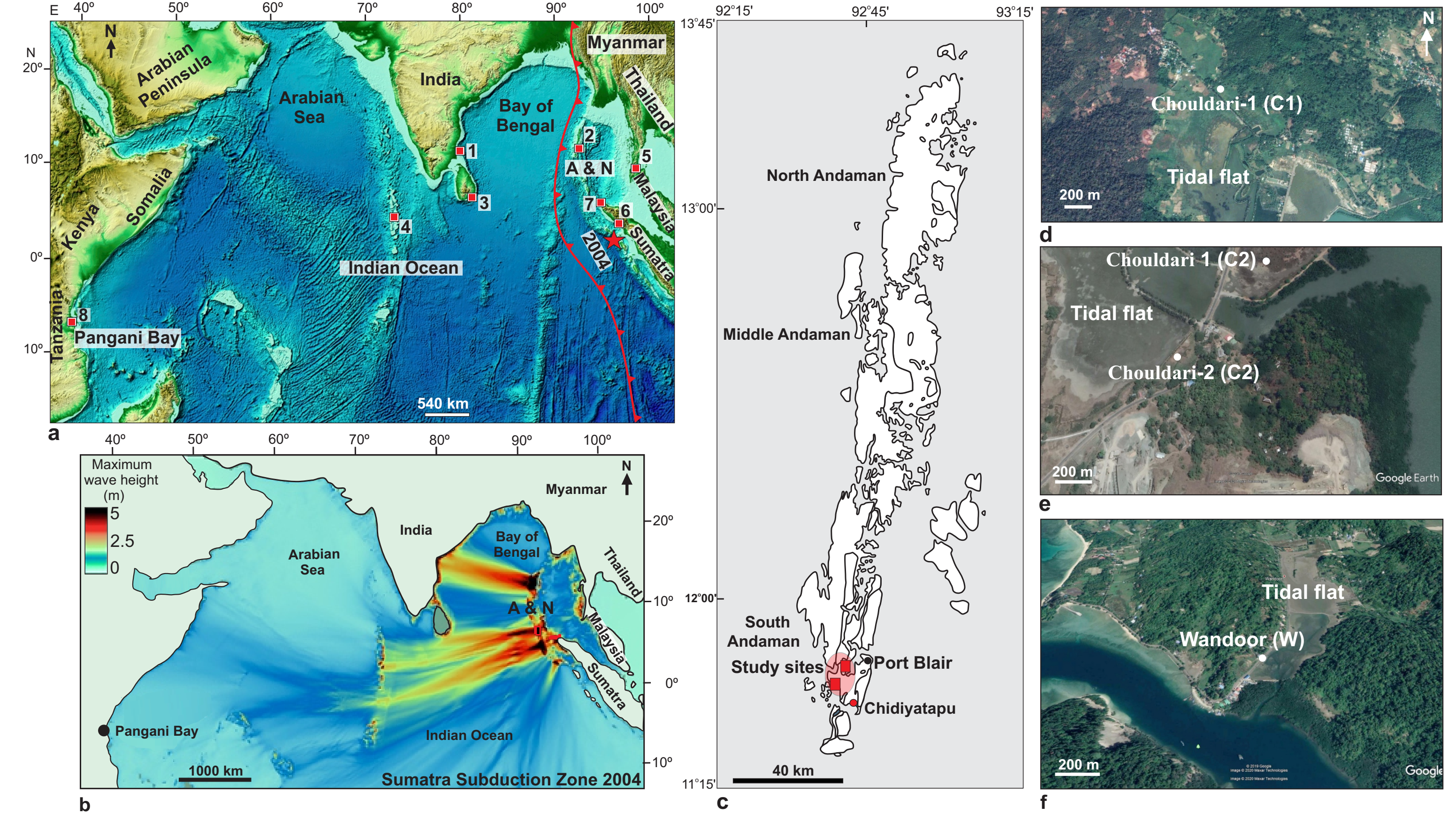
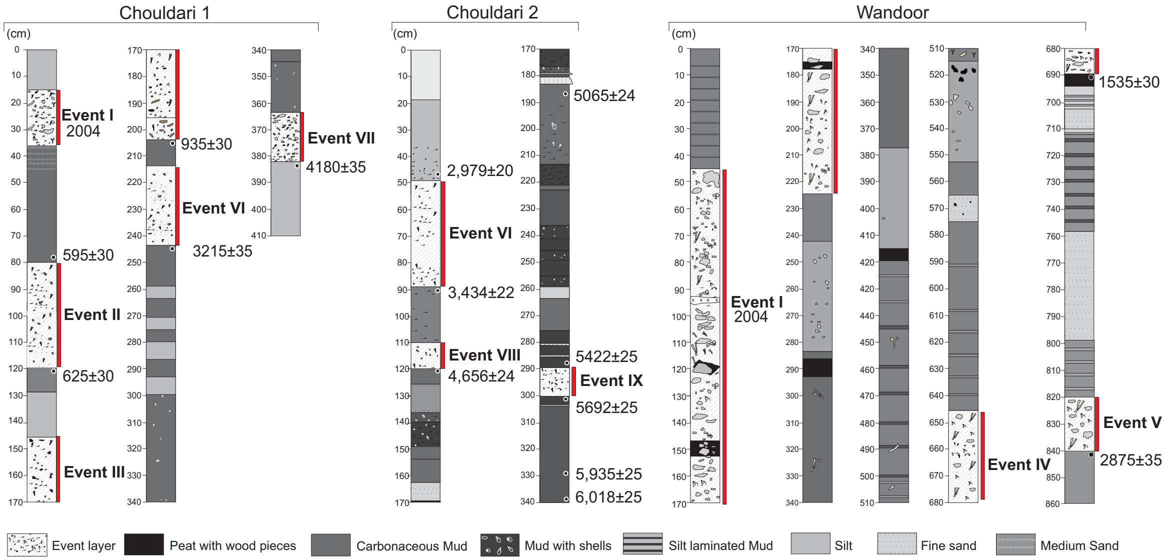
Figure 1.pdf.



E 40º 50º 60º 70º 80º 90º 100º
N 20º 10º 0º 10º
N
Arabian Peninsula
India
Arabian Sea
Bay of Bengal
Myanmar
Thailand
A & N
Malaysia
Sumatra
2004
Somalia
Kenya
Tanzania
Indian Ocean
Pangani Bay
1
2
3
4
5
6
7
8
540 km
a
Maximum wave height (m)
5
2.5
0
Arabian Sea
India
Bay of Bengal
Myanmar
Thailand
A & N
Malaysia
Sumatra
Pangani Bay
Indian Ocean
1000 km
Sumatra Subduction Zone 2004
20º 10º 0º -10º
b
92°15' 92°45' 93°15'
13°45' 13°00' 12°00' 11°15'
North Andaman
Middle Andaman
South Andaman
Study sites
Port Blair
Chidiyatapu
40 km
c
N
Chouldari-1 (C1)
Tidal flat
200 m
d
Chouldari 1 (C2)
Tidal flat
Chouldari-2 (C2)
200 m
Google Earth
e
Tidal flat
Wandoor (W)
200 m
Google
f

Figure 2.pdf.



Chouldari 1
Chouldari 2
Wandoor
(cm)
Event I
2004
595±30
Event II
625±30
Event III
935±30
Event VI
3215±35
Event VII
4180±35
2,979±20
Event VI
3,434±22
Event VIII
4,656±24
5065±24
5422±25
Event IX
5692±25
5,935±25
6,018±25
Event I
2004
Event IV
1535±30
Event V
2875±35
Event layer
Peat with wood pieces
Carbonaceous Mud
Mud with shells
Silt laminated Mud
Silt
Fine sand
Medium Sand

Figure 3.pdf.

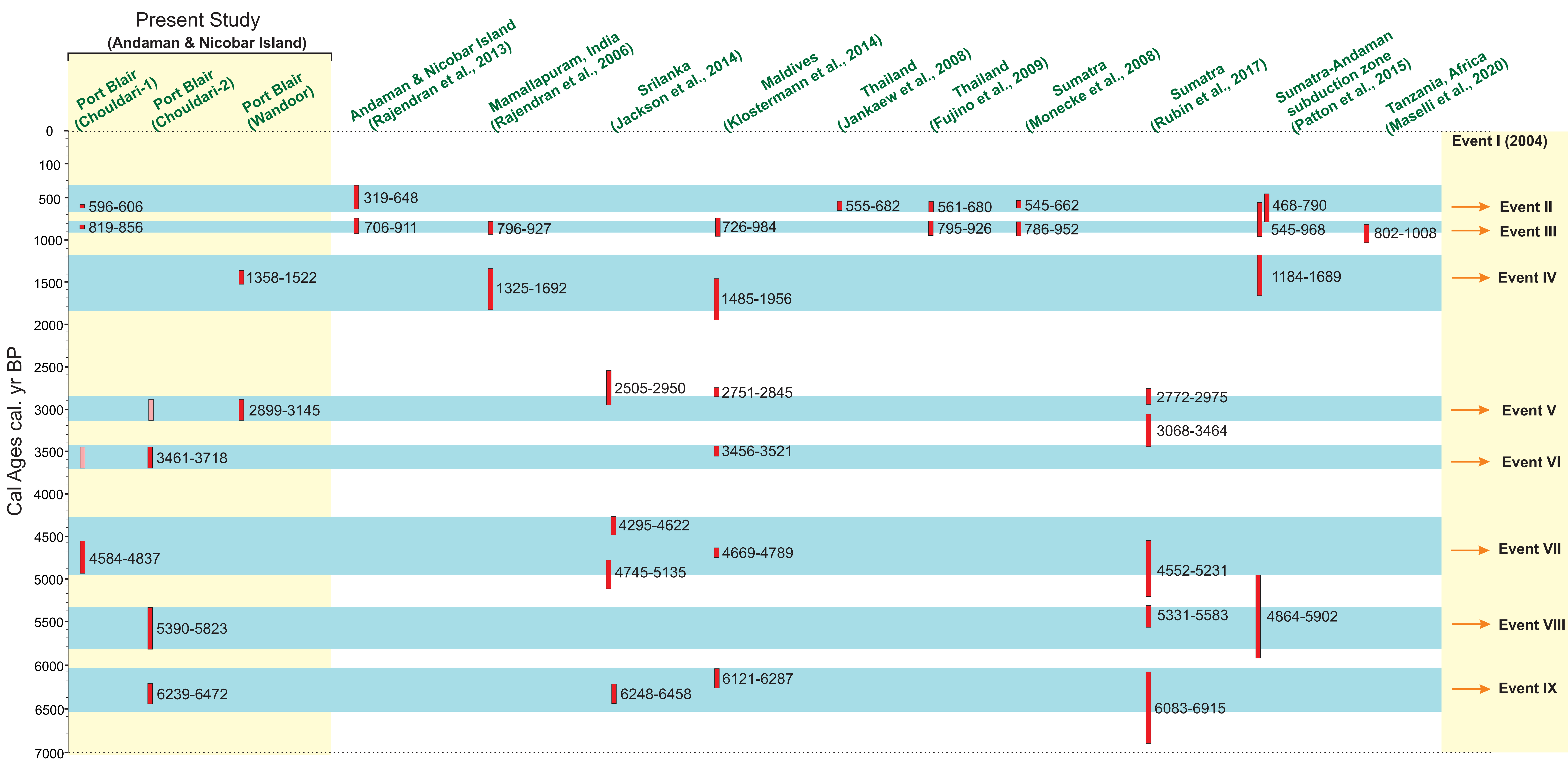

Present Study
(Andaman & Nicobar Island)
Port Blair (Chouldari-1)
Port Blair (Chouldari-2)
Port Blair (Wandoor)
Andaman & Nicobar Island (Rajendran et al., 2013)
Mamallapuram, India (Rajendran et al., 2006)
Srilanka (Jackson et al., 2014)
Maldives (Klostermann et al., 2014)
Thailand (Jankaew et al., 2008)
Thailand (Fujino et al., 2009)
Sumatra (Monecke et al., 2008)
Sumatra (Rubin et al., 2017)
Sumatra-Andaman subduction zone (Patton et al., 2015)
Tanzania, Africa (Maselli et al., 2020)
Cal Ages cal. yr BP
0
100
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
7000
596-606
819-856
319-648
706-911
796-927
726-984
555-682
561-680
795-926
545-662
786-952
468-790
545-968
802-1008
1358-1522
1325-1692
1485-1956
1184-1689
2505-2950
2751-2845
2772-2975
2899-3145
3068-3464
3461-3718
3456-3521
4295-4622
4669-4789
4584-4837
4745-5135
4552-5231
5331-5583
4864-5902
5390-5823
6121-6287
6239-6472
6248-6458
6083-6915
Event I (2004)
Event II
Event III
Event IV
Event V
Event VI
Event VII
Event VIII
Event IX

Figure. 3

Figure 4.pdf.

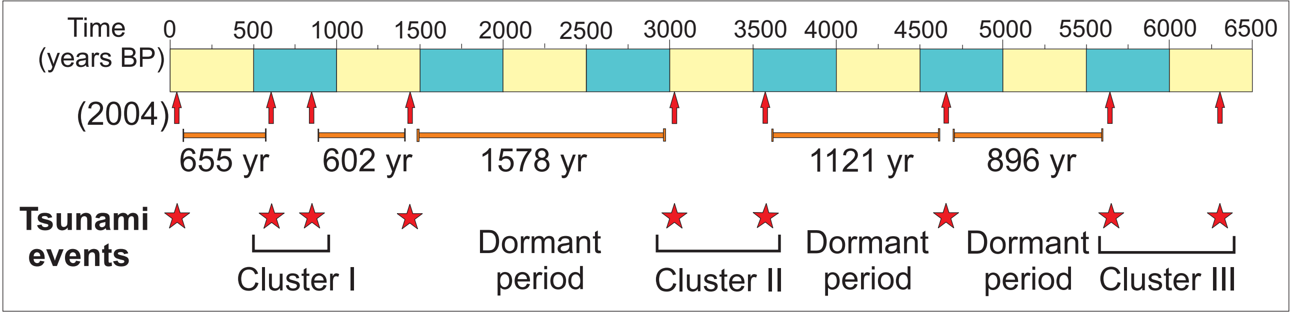

Time
(years BP)
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
6000
6500
(2004)
655 yr
602 yr
1578 yr
1121 yr
896 yr
Tsunami events
Cluster I
Dormant period
Cluster II
Dormant period
Dormant period
Cluster III

Table 1. Radiocarbon ages of tsunami deposits recorded in Port Blair, South Andaman

Event	Depth from surface (cm)	Thickness of the sediment (cm)	Age above tsunami deposit (μ±2σ calendar yr BP) (Calibrated ages (BCE/CE)	Age below tsunami deposit (μ±2σ calendar yr BP) (Calibrated ages (BCE/CE)	Age within the deposit (μ±2σ calendar yr BP) (Calibrated ages (BCE/CE)	Midpoint age of the tsunami deposits	Sites
Event 1 (I)	15	20				**2004**	Chouldari-1
	45	180				**2004**	Wandoor
Event 2 (II)	80	40	595±30 (1298-1410CE)	625±30 (1290-1398 CE)		**1349 CE**	Chouldari-1
Event 3 (III)	147	60	885±30 (1042-1219 CE)	935±30 (1027-1161 CE)		**1113 CE**	Chouldari-1
Event 4 (IV)	645	45			1535±30 (428-592 CE)	**510 CE**	Wandoor
Event 5 (V)	820	20	2725±35 (967-808 BCE)		2875±35 (1192-930 BCE)	**1068 BCE**	Wandoor
	835						
	50	30	2840±30 (1107-917 BCE)	2979±20 (1262-1127 BCE)			Chouldari-2
Event 6 (VI)	105	20		3434±22 (1872-1666 BCE)		**1641 BCE**	Chouldari-2
	240	30	3215±35 (1606-1417 BCE)				Chouldari-1
Event 7 (VII)	365	20			4180±35 (2888-2635 BCE)	**2762 BCE**	Chouldari-1
Event 8 (VIII)	145	20	4656±24 (3516-3366 BCE)	5065±24 (3950-3797)		**3657 BCE**	Chouldari-2
Event 9 (IX)	280	20	5422±25 (4336-4244 BCE)	5692±25 (4586-4456 BCE)		**4407 BCE**	Chouldari-2

Note: AMS dating of charcoal samples were conducted at Poznan Radiocarbon Laboratory (Poz), Poland. Radiocarbon ages were calibrated using CALIB (Version 7.0.4) (Stuiver and Reimer, 1993; Reimer et al., 2013). The 2 sigma ranges have maximum area under the probability distribution curve. All samples are taken from organic-rich bulk sediment.

[Geophysical research Letter]

Supporting Information for

[Long-term Indian Ocean tsunami record reveals alternating event clusters punctuated by quiet interludes]

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2National Institute of Ocean Technology, Chennai 600100,

3 Indian Institute of Science, Bangalore 560012 India]

Contents of this file

Text S1 to S7
Figures S1 to S17
Tables S1

Additional Supporting Information (Files uploaded separately)

Captions for Tables S1

Introduction

The itemized supporting information given here provides additional figures and supporting data refered in the original article.

S1

We chose the tidal inlets inundated by the2004 tsunami for coring work. These sites are located at Chouldari and Wandoor near Port Blair, South Andaman (Figure S1). The observations indicated that the whole region had subsided during the 2004 earthquake (Rajendran et al., 2013).

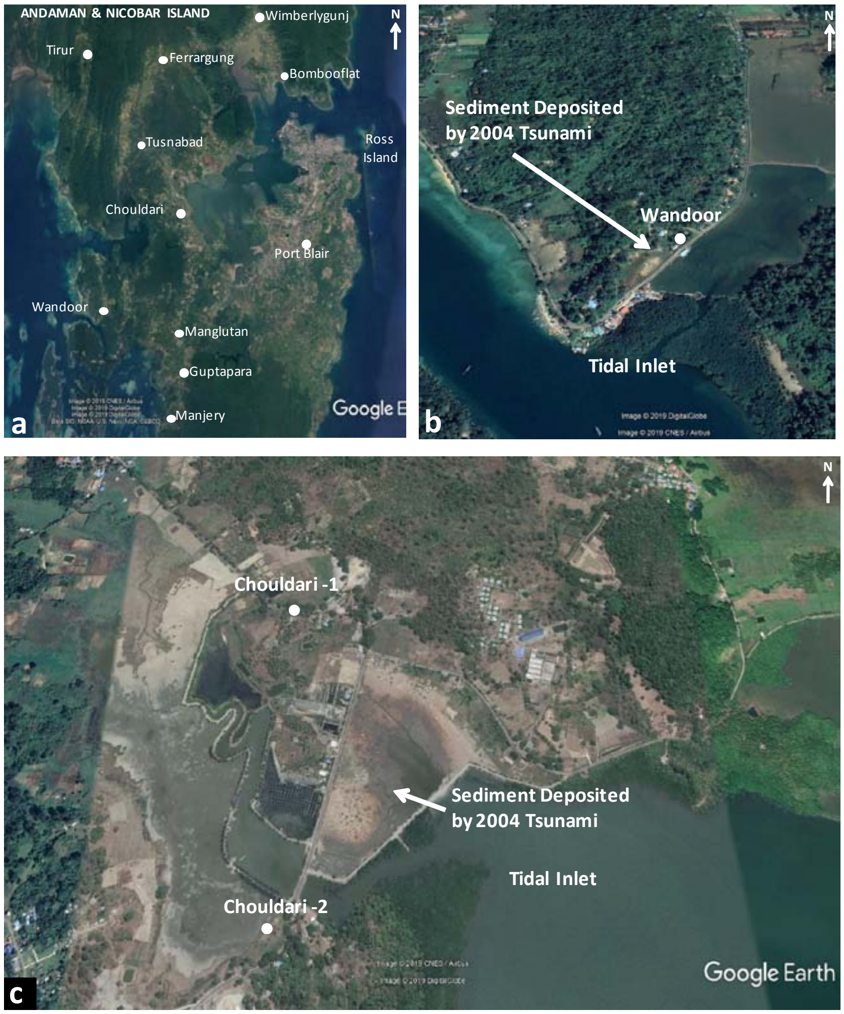

Figure S1 a. Google image of the study areas, near Port Blair, South Andaman. b. Close-up view of the drilling locations at b. Wandoor. c. Chouldari-1 and Chouldari-2

Three drilling campaigns carried out in the year of 2014-2015 during March-April, December and in September 2015. The contracting company Geofoundations Pvt. Ltd. conducted the drilling at three sites: Chouldari-1, Chouldari-2, and Wandooralong the tidal inlet using a weighted tripod system to collect sediment cores (Figure S2). The drilling was conducted using 1.5m long "Chlorinated Polyvinyl Chloride (CPVC)".

Figure S2. Field photographs of coring. a. Chouldari-1; b. Chouldari-2; c. Wandoor. The cores were collected using a weighted tripod system using steel barrel with PVC lining.

The locations were identified based on our survey of the south Andaman coast. The total recovery of sediment cores below the top surface at Chouldari-1, Chouldari-2 and Wandoor was 4.1 m,3.4 m and 8.6 m, respectively (Figure S2c).The recovered cores were bundled together in crates for shipping to Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore (India).Undisturbed cores from all the sites were CT scanned (Figure S3a-c) and later all the cores were split into half and sub-sampled at the interval of 1 cm for multiple analyses. We have categorized the tidal and out-of-sequence sedimentary layers, based on their sedimentary characteristics, grain size variation, organic carbonate concentration and assemblage analysis of foraminifers. These characteristics help in classifying the bands of coarse material as a mixture of transported material from the open sea and those incorporated from the landward part of coastal waters.

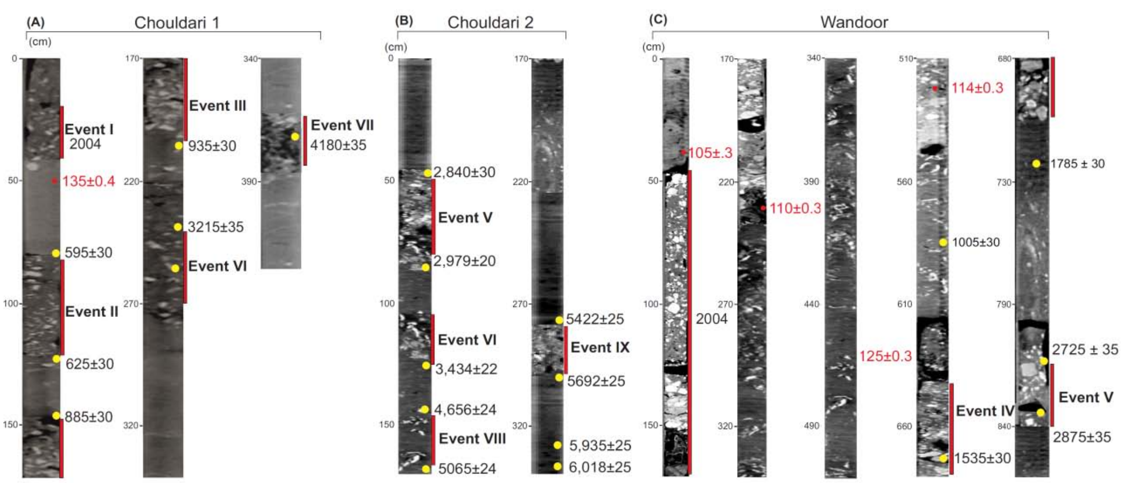

Figure S3. The CAT scan images: a. Chouldari-1; b.Chouldari-2; c. Wandoor. The out-of-sequence layers, sequentially characterized as 'events' are marked by red lines on the margins of core logs.

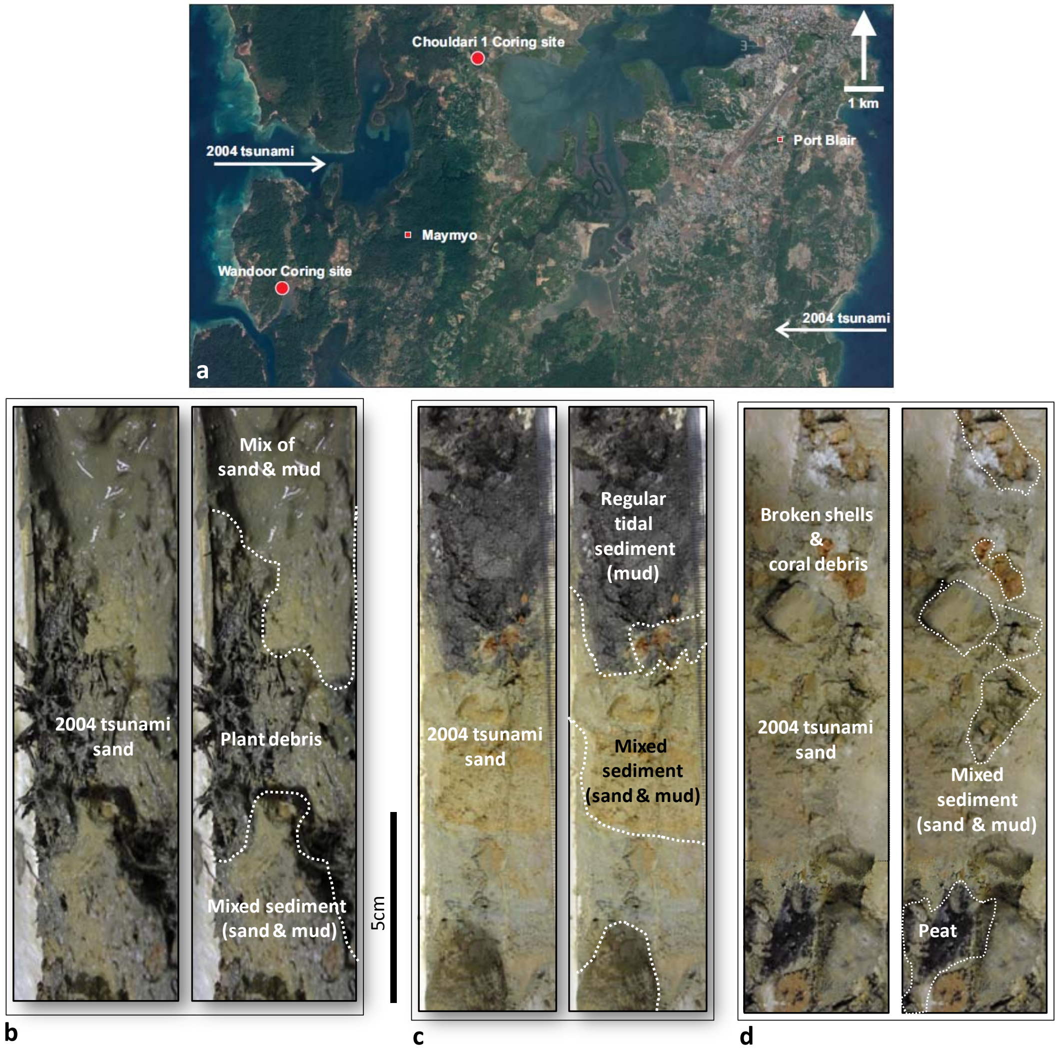

Figure S4. a. Map shows the coring location at Chouldari-1 and Wandoor and the inundation direction of the 2004 tsunami. b. Close-up view of sand mixed with plant debris transported during the 2004 tsunami in Chouldari-1 core. c and d. Photographs show the approximate boundary of regular tidal sediment and out-of-sequence layer during the 2004 tsunami containing broken shells and coral debris recovered from Wandoor core.

S2

Radionuclide Cesium (137 Cs) and Lead (210Pb) dating

The verification of the 2004 tsunami deposit in Wandoor core was done by analyzing137Cs concentration at the depth of 1.45 m from the top surface (Figure S5). The samples were analyzed for 137Cs and 210Pb concentrations - the most widely used method for dating the recent sediments of the age <75 years.Following the standard protocol based on the 1945 nuclear explosion and their testing till 1975. The samples were analyzed at the Physical Research Laboratory, Ahmedabad, India.

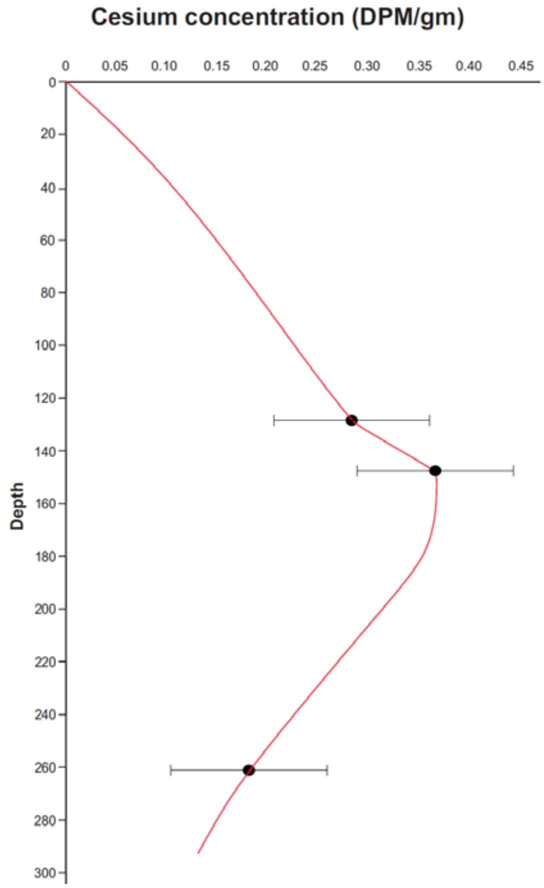

Figure S5. ^{137}Cesium concentration (DPM/gm) in 2004 tsunami deposits from Wandoor core.

S3

Lithological details of the cores:

The overall lithology of sediment cores is represented by the darker colored laminated mud with occasional mollusks, deposited under the regular tidal environment and the intermittent bands of coarser sediment. The grain size and microscopic analyses of the regular tidal sediments suggest that they dominantly consist of clay and silt with occasional thin bands of fine sand. The alternating coarserfractions were identified as 'out-of-sequence' material based on their sediment characteristics and microfossil content. The erosional boundary between the coarser fraction and regular tidal mud can be demarcated at various depths in the cores from all the three locations (Figures S6 a-c; S7 a-e; S8 a and b).

The lithology of these 'out-of-sequence' layers can be described as silica-rich mud, mixed with medium to coarse grain, broken shells, coral debris, micro-fossils with occasional cobbles and plant remains including wood pieces and peat (Figures S6 a-c; S7 a-e; S8 a and b). These presumed 'out-of-sequence' sediment layers feature similar characteristics and grain size distribution as seen in 2004 tsunami deposits recovered at Chouldari-1 and Wandoor, suggesting that these alternating bands correspond to previous sea-borne inundations analogous to the 2004 tsunami.

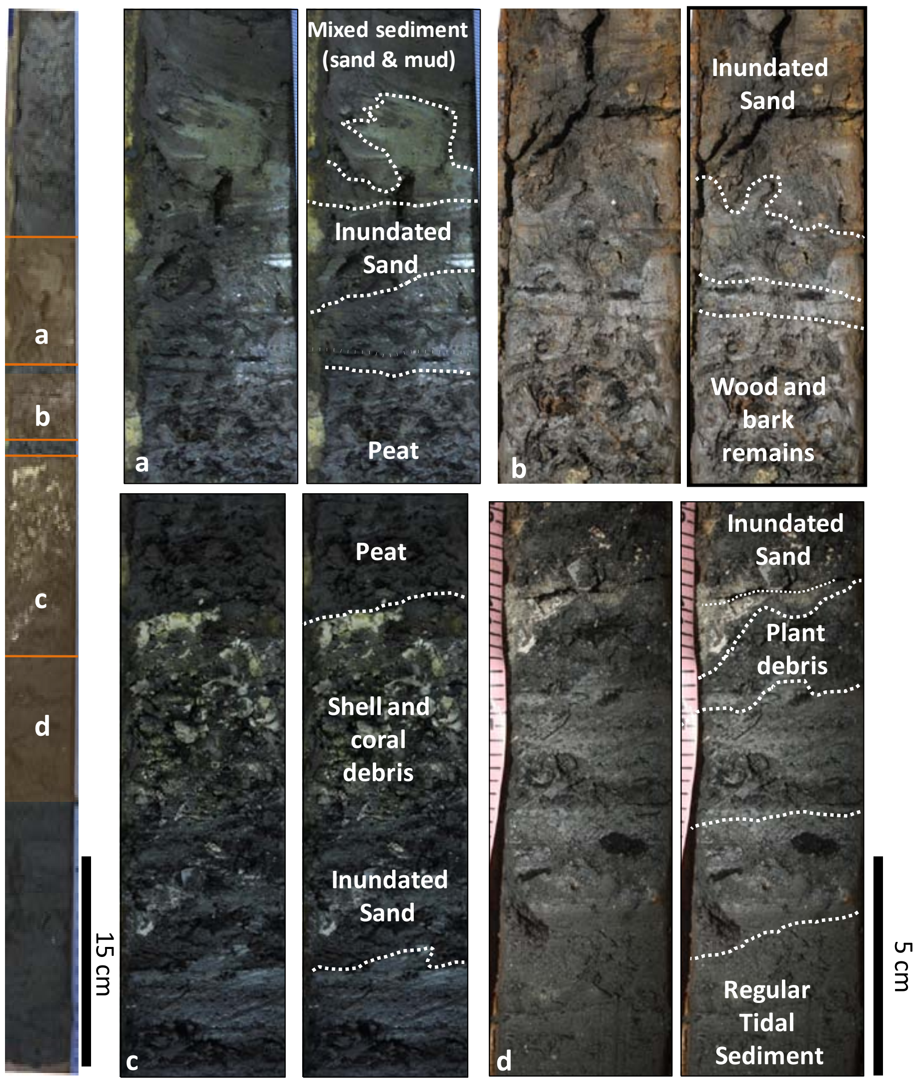

Figure S6 a. Photographs of cores with broken shells and peat from Chouldari-2; b-c. Close-up views of Event II deposition exhibiting peat, shell and coral remains as detritus. d. Close-up views showing boundary between Event II deposition and regular tidal sediment.

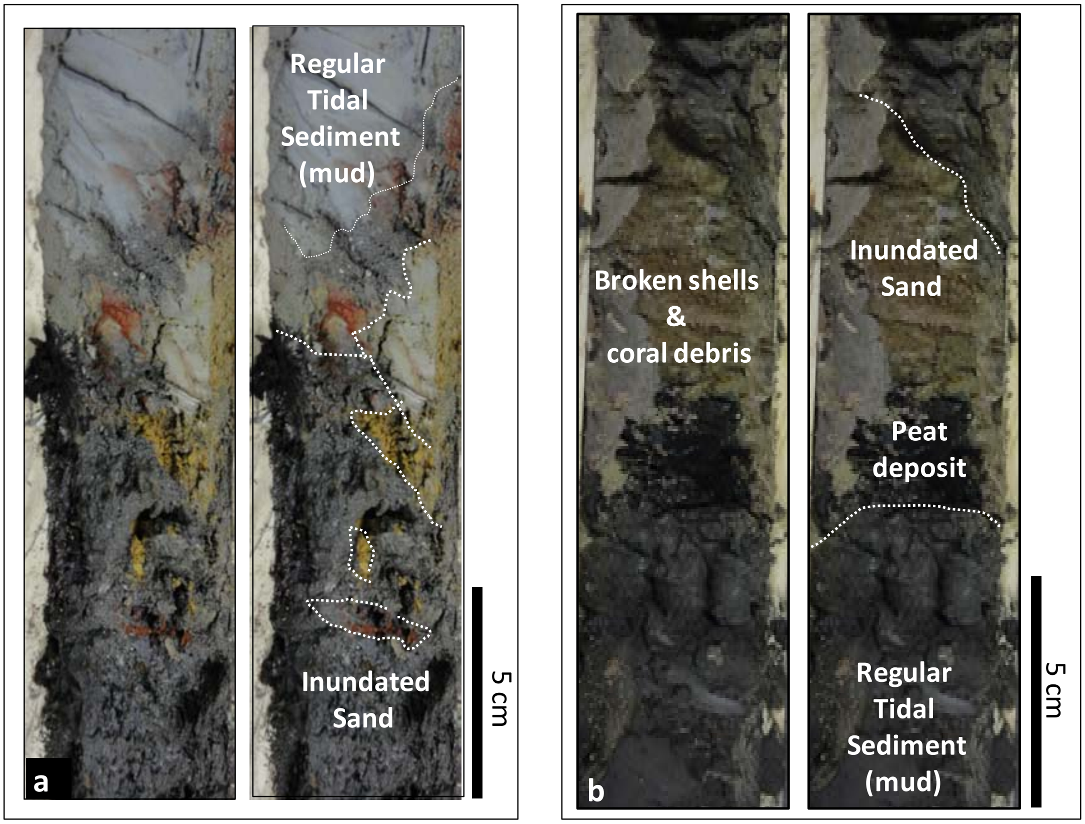

Figure S7 a. Close-up views of the core from Chouldari-1 show boundary between tidal and out-of-sequence deposit belonging to Event III, at a depth of 145cm below the top surface. b. Close-up views of Event IV deposition from Wandoor core at a depth of 680 cm from the top surface.

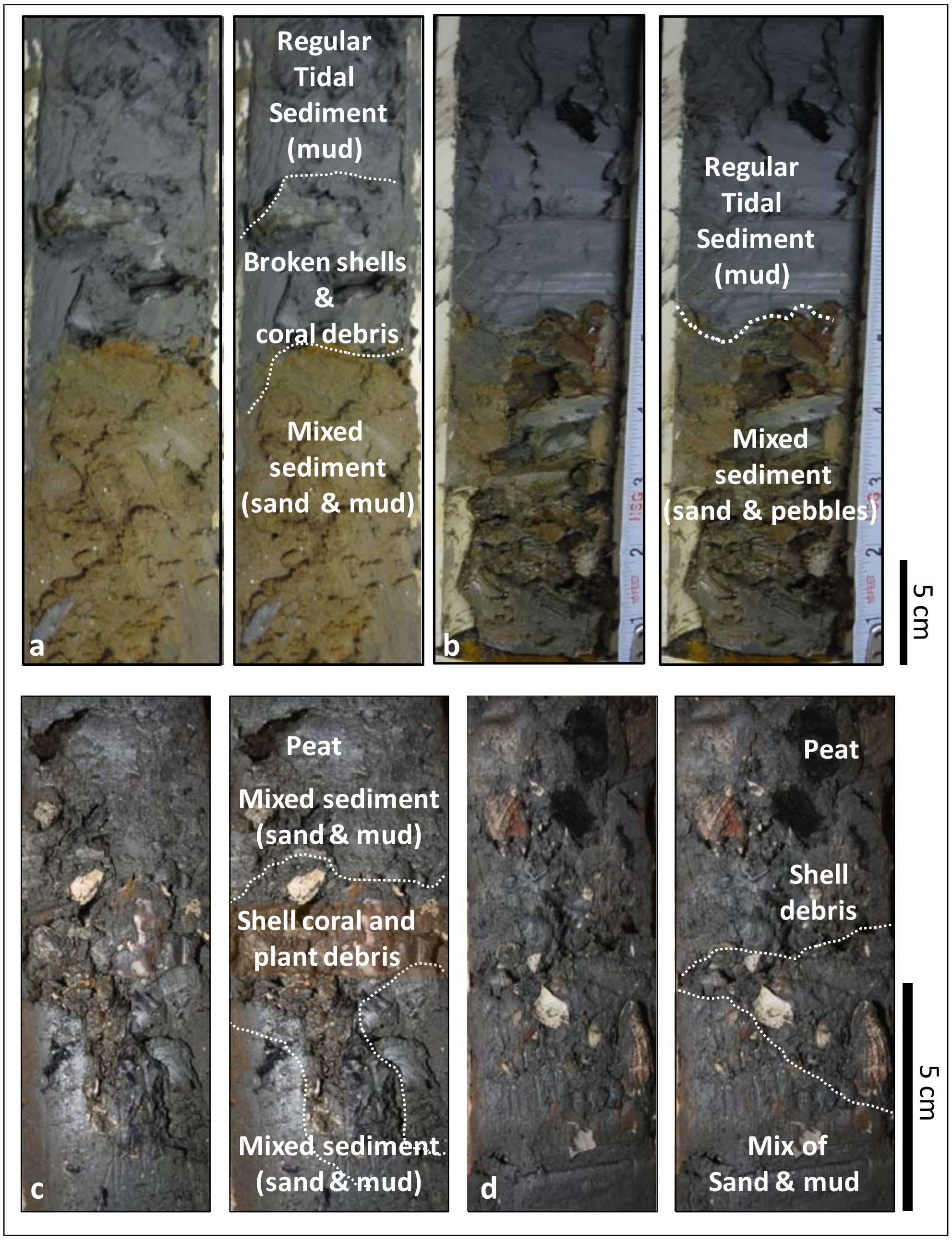

Figure S8 a. Close-up views of Wandoor cores showing boundary between tidal and Event V deposition with shell remains and coral debris, at a depth of ~820 cm from the top surface. b. Close-up views of Event VI deposition with debris at a depth of ~240 cm from the top surface in Chouldari-1 core. c. Close-up views showing Event VIII deposition with shell and plant debris at a depth of 150 cm from the top surface in the core from Chouldari-2. d. Close-up views showing Event IX deposition with shell and peat at a depth of ~290 cm from the top surface in the core from Chouldari-2.

S4

Grain Size Analyses

The grain size analyses were conducted for the sediment cores collected from each site with the resolution of 5-10 cm. The large size pebbles, broken shells, coral and organic debris inthe sediment were removed with the help of forceps.The samples were dried in hot air over about 50oc and samples were treated with HCL (30%) to eliminate the carbonate material and the organic matter was removed with H2O2. Grain size analyses were done following the size classifications as suggested by Folk and Ward (1957). The results obtained from all the three sites (Chouldari-1, Chouldari-2 and Wandoor) illustrate the change from fine grained sediment (silt/clay) to coarse sand across the sharp boundary between the tidal and overlying out of sequence deposit (Figures S9; S10 and S11).

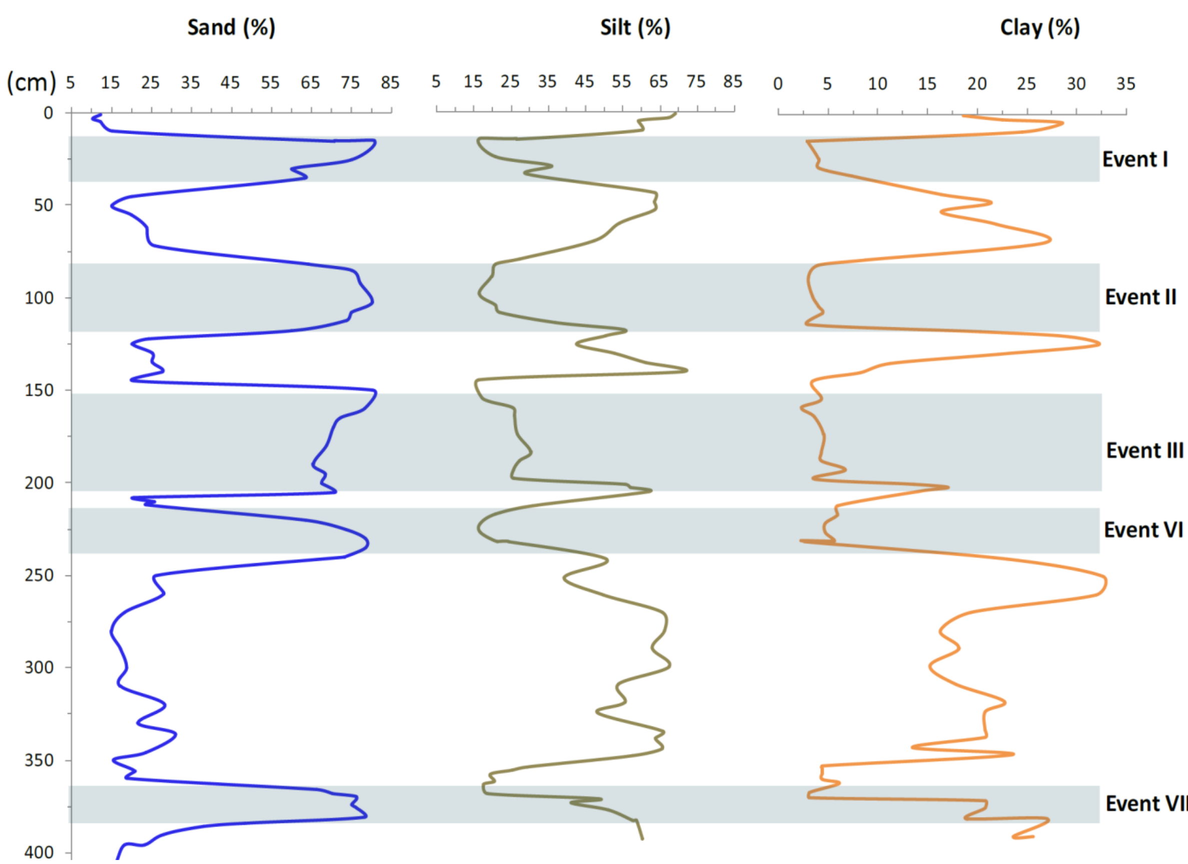

Figure S 9. Percentage of grain-size distributions of the sediment samples estimated from Chouldari-1 cores. Graph shows an increasing trend of sand within the out-of-sequence deposits.

The percentage of sand varies between 10 to 30% in the tidal sediment while in the out-of-sequence sediment 60 to 80% of sand is observed with an upward fining sequence from the lower boundary of the layer (Figures S9; S10 and S11). The out-of-sequence layers consists of fine to coarse sand, dominated by quartz grains, along with intact as well as fragmented shells including occasional carbonate grains.

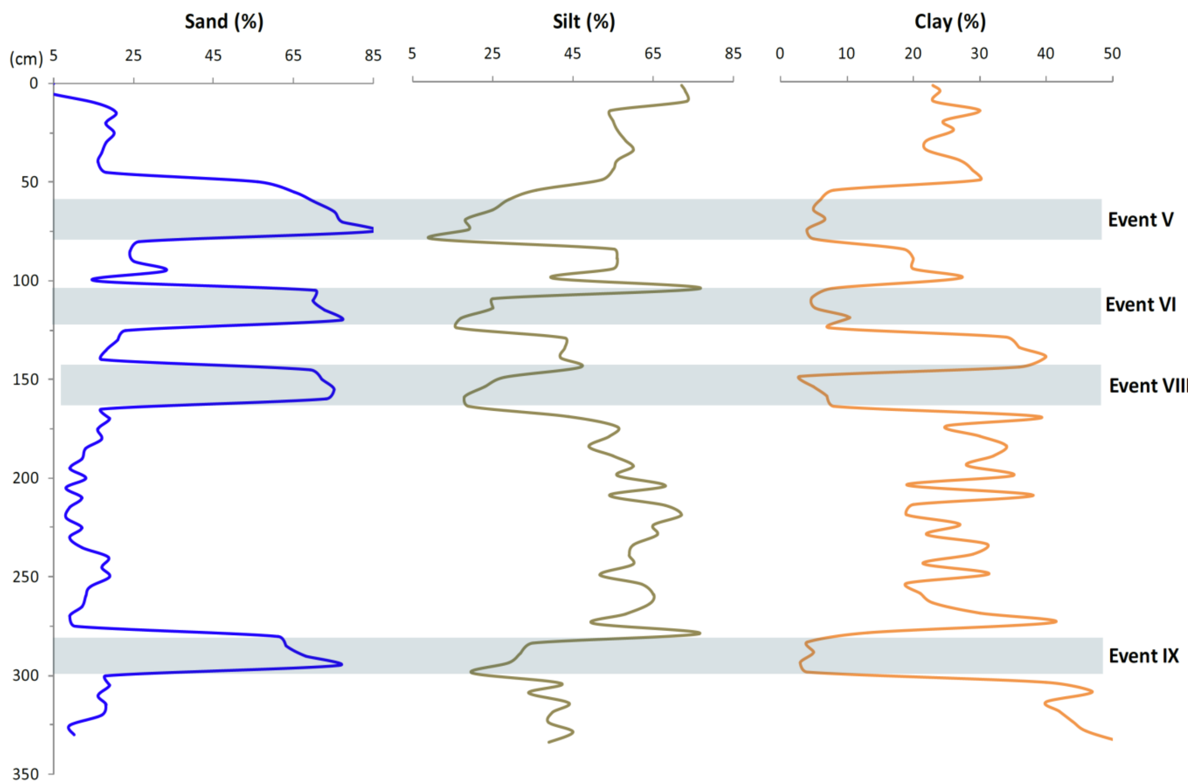

Figure S10. Percentage of grain size distribution of the sediment samples estimated from Chouldari-2 cores. Graph shows an increasing trend of sand within the out-of-sequence deposits.

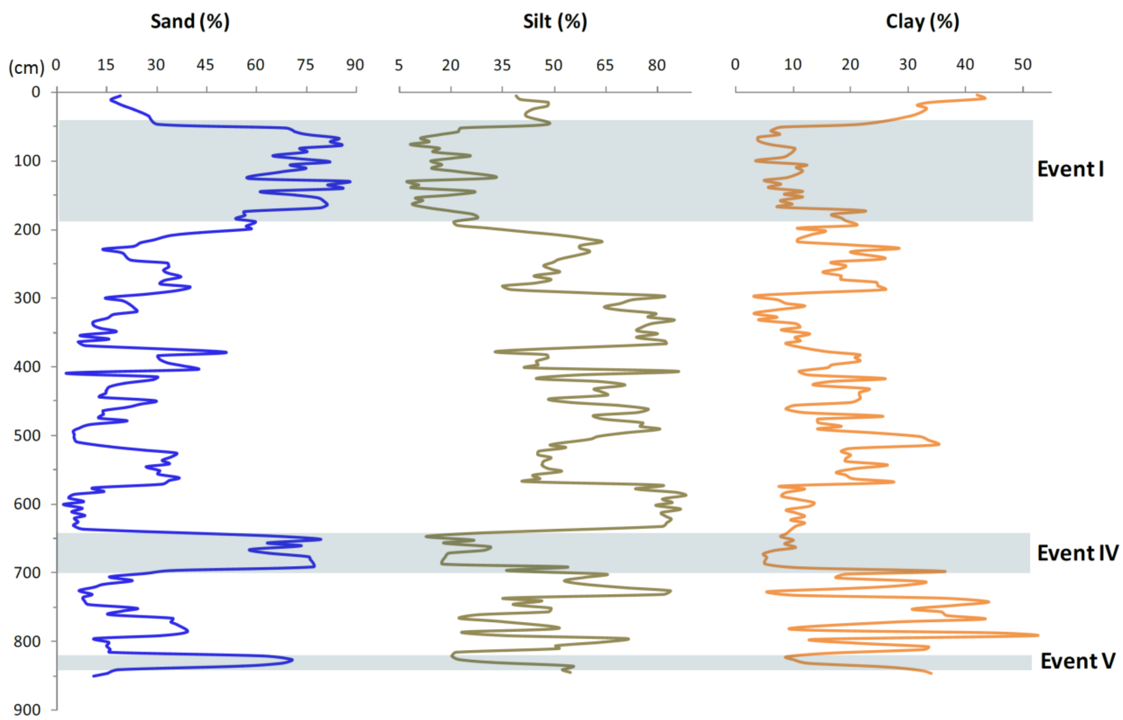

Figure S11. Percentage of grain size distribution of the sediment samples estimated from Wandoor cores, indicating increasing trend of sand within the out-of-sequence deposits.

S5

Textural and faunal content

Assemblage analyses of foraminifers

For foraminiferal assemblage in the core samples were analyzed from the tidal and intermittent bands of the coarser sediment at regular intervals of ~10 cm. The samples were treated with H_2O_2 to remove the organic matter and then sieved with ASTM mesh of 60, 100, 230 sizes. For picking up the foraminifers we have used fractions of 60 and 100 mesh. The dominant foraminifers in the intermittent out-of-sequence bands belong to *Elphidium sp.*, *Quinqueloculina sp*. and *Globigerina sp*., generally associated with marine shelf environment (Figures S12 b-d).

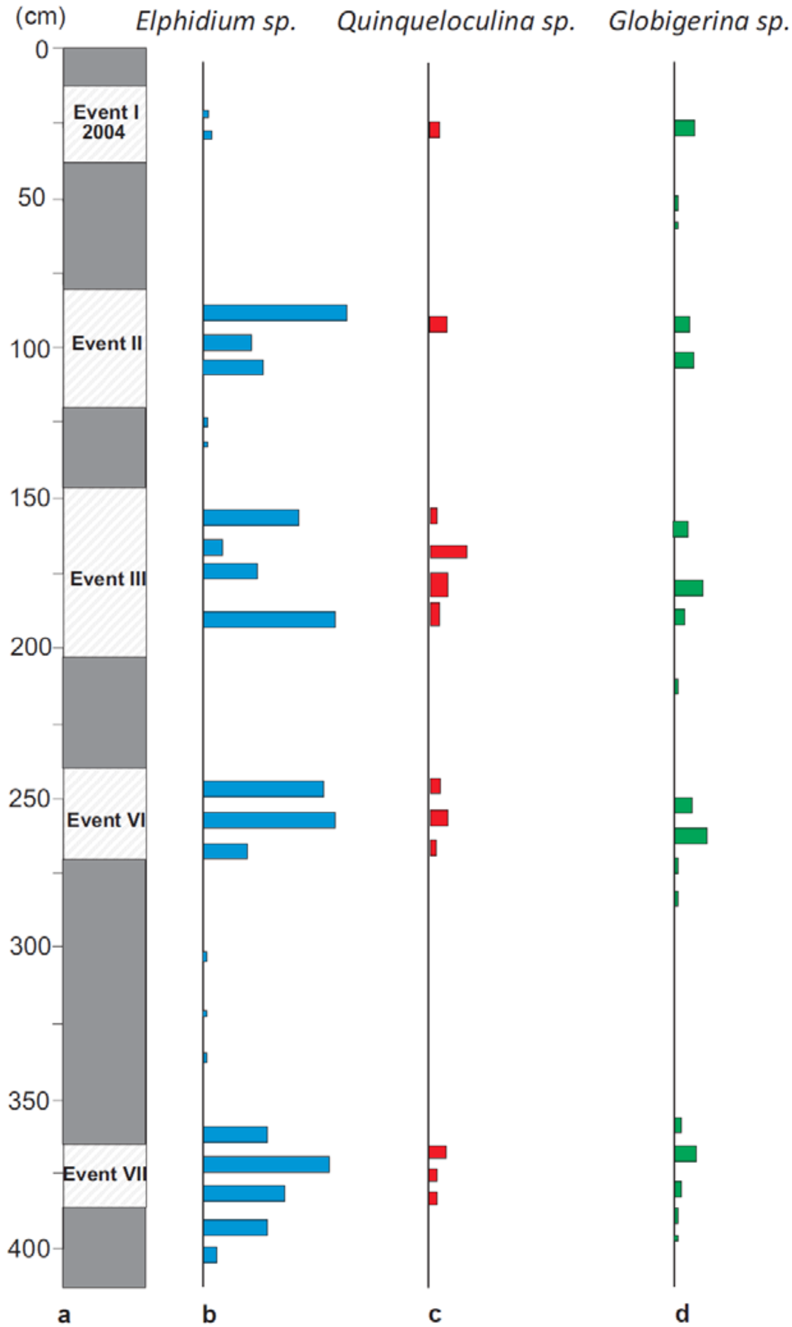

Figure S12 a. Core from Chouldari-1; b-d. Showing the abundance of foraminifera species

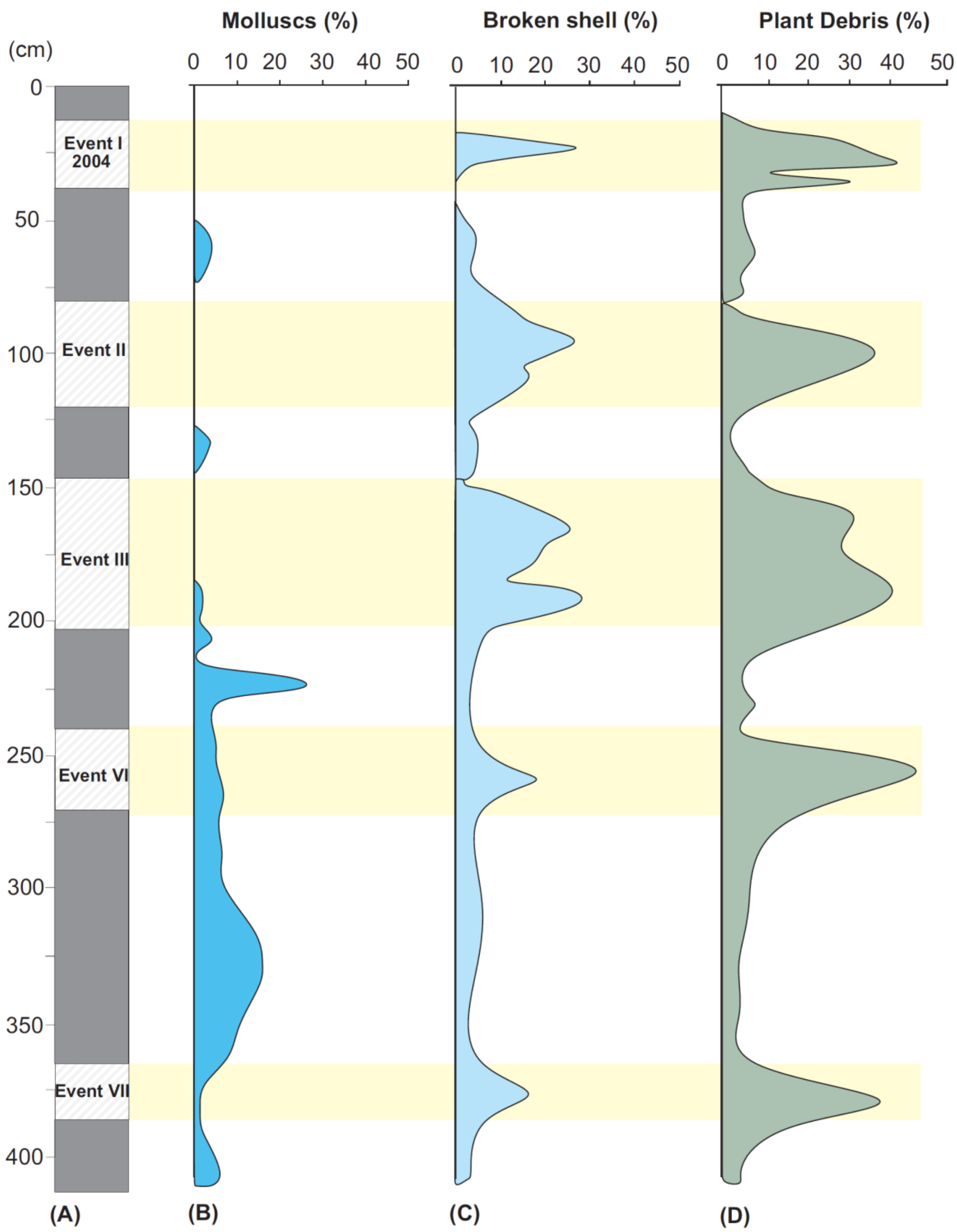

Figure S13 a. Core log from Chouldari-1; b-d. Graph shows the representative percentage of molluscs, broken shells and plant debris in the out-of-sequence deposits from the macro-sieve (>2 mm) fraction.

The coarser sediment within out-of-sequence bands from the cores comprises silica-rich mud, silt and sand, plant debris along with broken shells, coral rubble and unidentified carbonate (Figure S13). In both locations (Chouldari-1 and Wandoor), the 2004 tsunami sand is significantly rich in carbonate shells, coral and plant debris. It also shows occasional upward finning medium to coarse grained sand mixed with mud. The microscopic observation of these bands suggests that the broken shells make ~35% of the total sediment, while the organic-rich debris make ~45% in these deposits (Figures S13; S14 a-b; S15 and S16). In contrast, only few shells (with no plant debris and coral fragments) are found in the regular tidal sediments.

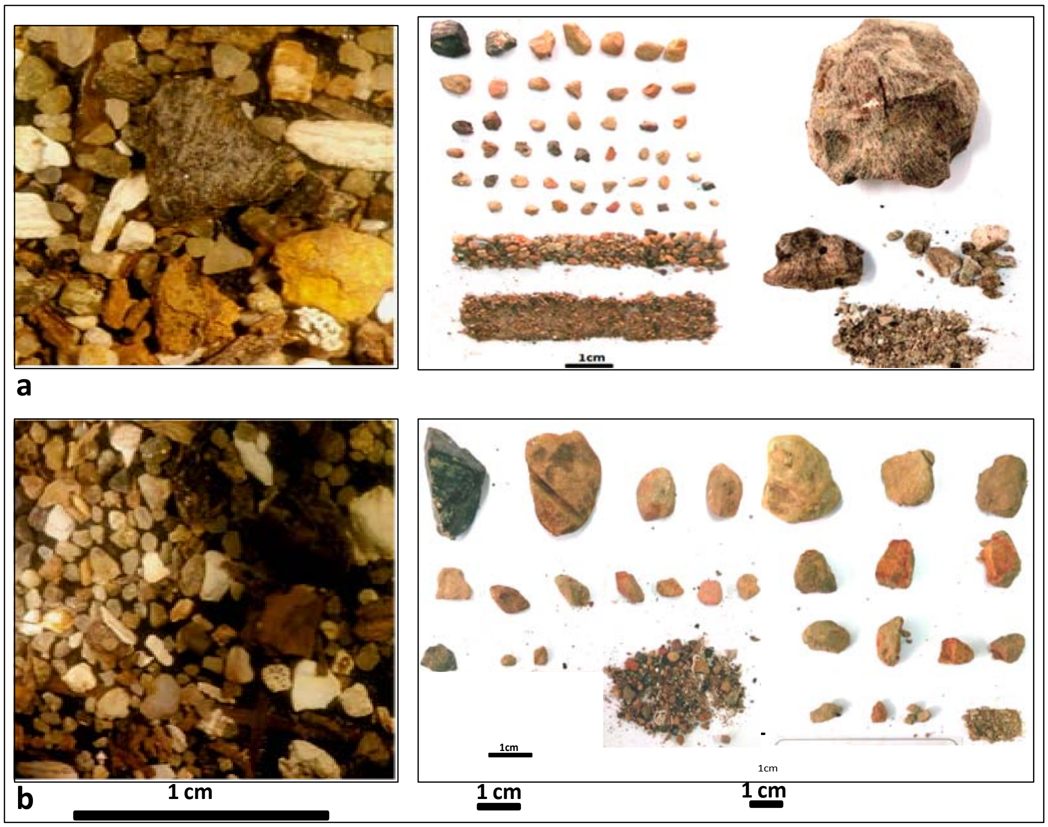

Figure S14 a. Examples of vegetational and carbonate material found in 2004 tsunami sediment observed at Chouldari-1. b. Microscopic view of the coarse-grained fraction from out-of-sequence sediment (Event III) recovered from Chouldari-1. Coarser clasts in out-of-sequence sediments often show the marks of transportation. The particles shown here are part of the macro (>2 mm) fraction.

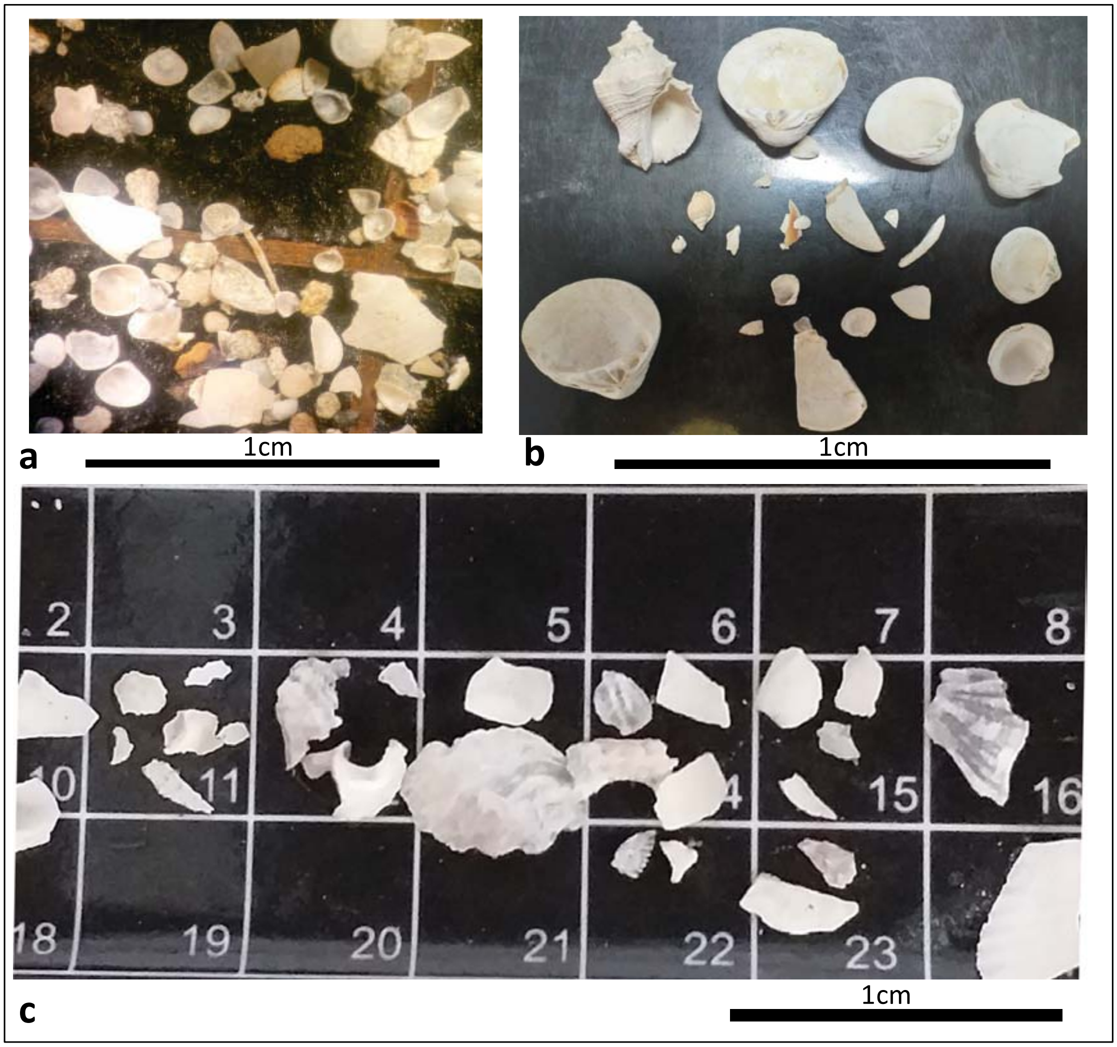

Figure S15. a and b. Microscopic views of the broken and complete shells recovered from 2004 tsunami sediment from Wandoor. c. Microscopic views of the broken shells recovered from out-of-sequence sediment (Event IV) recovered from Chouldari-2.

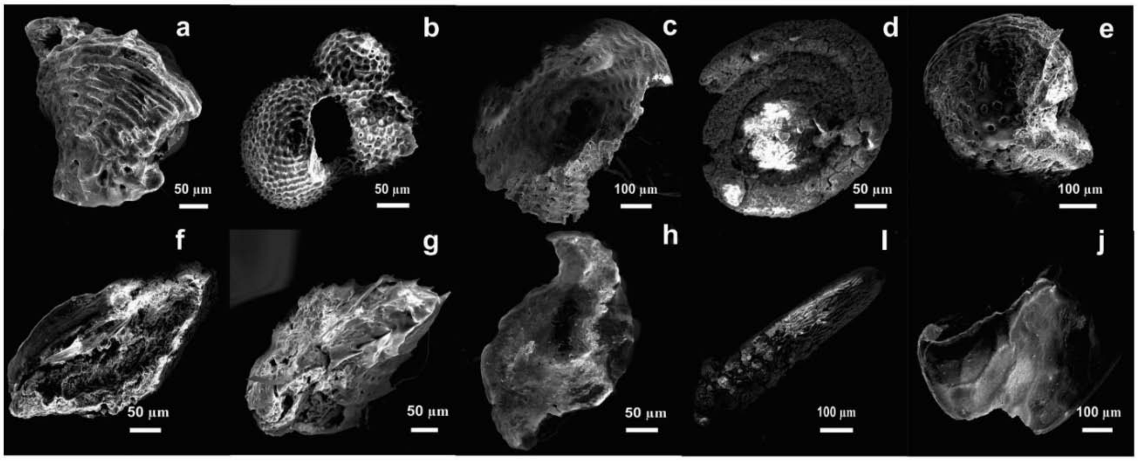

Figure S16. Broken and reworked shells recovered from Wandoor core. a) Broken shell of *Elphidumadvenum*; b) *Globigerina bulloides*; c) *Elphidium carticulatum*; d) *Spriulina sp.* e) *Elphidium advenum*; f) Chemically altered *Spiroloculina sp*. g) *Rusella spinulosa*; h) Broken shell of *Spriloculina bradyi*; i) *Bolivina sp*; j) Broken shell of *Amphistegina radiata*

S6

Chronological constrains

To reconstruct the timing of the out-of-sequence deposits from the cores, we relied on the radiocarbon ages of the organic material obtained from the top and bottom of the layers or from within the layers in question (Table X; Table SX; Figures 2a, b and c). The Accelerator Mass Spectroscopy (AMS) radiocarbon dates thus estimated and were calibrated using calib7.0.2 (Stuiver and Reimer, 1993; Reimer et al., 2013). The age data, in most cases provided maximum and minimum ages of the inferred paleo-tsunami deposits (Figure S17). Excluding the 2004 deposits (at Wandoor and Choudari-1), we have identified eight bands of out-of-sequence deposits in the cores that range in ages between ~600 to ~6500 cal. yr. BP (Figures 2a, b and c). The timings of the out-of-sequence depositions are reported in 2σranges, for our results as well as for those reported from elsewhere in the Indian Ocean region (Figure S3).

AMS Radiocarbon Dating

Buried organic rich bulk sediment were chosen for AMS radiocarbon dating to reduce the likelihood of analyzing detrital material that died a significant time before burial. We have obtained Accelerator Mass Spectrometry (AMS) radiocarbon ages from Poznan Radiocarbon Laboratory, Poland. Total 25 ages were recovered from all the three sites (Chouldari-1, Chouldari-2 and Wandoor), and the timing of soil burial was calculated from calibrated radiocarbon dates. Radiocarbon ages were calibrated using Calib 7.0.2 calibration software

(Stuiver and Reimer, 1993; Reimer et al., 2013). Calibrated age ranges are shown with two standard deviations, expressed as 'before present' (BP) and years before CE and BCE.

S7

Age Estimation of Event Layers

The final estimated ages of the events are captures within the time range of the events, spanning from the youngest possible age (above the deposit) to the oldest possible age (below the deposit), where ages arereported as µ±2σ calendar yr BP and calibrated ages BCE/CE (Tables 1 and SX). The possible age of six tsunami events (Event II, Event III, Event V, Event VI, Event VIII and Event IX) are estimated by taking the average of the time range from the oldest to youngest age. Another two ages of the old tsunamis are calculated by taking the midpoint of the time range from the single age obtained from the sediments within out-of sequence layers. Furthermore, the age data obtained from the top and the bottom of out-of-sequence deposits and within these event deposits show minimum error. Therefore, all the dates obtained from the cores are used in the present study except Á few modern ages (Figure2 a-c; Table X).

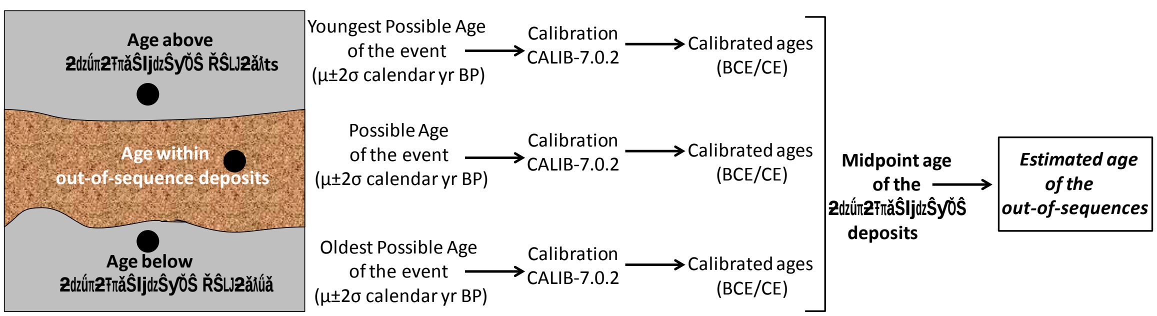

Figure S17. A schematic figure showing how the ages of event layers were estimated by using AMS radiocarbon dating of the bulk tidal sediment from above and below the ÏÕôζÏÆζóÅÑÕÅÎÃÅ sediments. In some cases, contemporary ages were estimated based on the dates from within the event layers. The ages of all event layers are approximated by taking the midpoint between the youngest and oldest age.

References

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Location	Lab no.	Depth of the sediment (cm)	Sample type	^{14}C ages ($\mu\pm2\sigma$ calendar yr BP)	Error (±)	Calib 702 2σ ranges of calibrated ages (BCE/CE)
Wandoor	Poz-70525	38	Charcoal	105	0.3	1696-1918
Wandoor	Poz-70435	230	Charcoal	110	0.3	1694-1919
Wandoor	Poz-70439	520	Charcoal	114	0.3	1693-1920
Wandoor	Poz-70436	290	Peat	125	0.3	1688-1926
Chouldari-1	Poz-17177	45	Charcoal	135	0.4	1683-1930
Chouldari-1	Poz-17181	78	Bulk	595	30	1298-1410
Chouldari-1	Poz-17176	122	Bulk	625	30	1290-1398
Chouldari-1	Poz-88045	145	Bulk	885	30	1042-1219
Chouldari-1	Poz-17175	205	Bulk	935	30	1027-1161
Wandoor	Poz-70438	585	Bulk	1005	30	979-1150
Wandoor	Poz-70440	678	Bulk	1535	30	428-592
Wandoor	Poz-70442	725	Bulk	1785	30	135-331
Wandoor	Poz-70445	818	Bulk	2725	35	967-808
Chouldari-2	Poz-83902	48	Bulk	2840	30	1107-917
Wandoor	Poz-70441	838	Bulk	2875	35	1192-930
Chouldari-2	Poz-70446	82	Bulk	2979	20	1262-1127
Chouldari-1	Poz-17180	240	Bulk	3215	35	1606-1417
Chouldari-2	Poz-17182	125	Bulk	3434	22	1872-1666
Chouldari-1	Poz-17179	370	Bulk	4180	35	2888-2635
Chouldari-2	Poz-17183	145	Bulk	4656	24	3516-3366
Chouldari-2	Poz-17172	268	Bulk	5065	24	3950-3797
Chouldari-2	Poz-17178	279	Bulk	5422	25	4336-4244
Chouldari-2	Poz-17174	302	Bulk	5692	25	4586-4459
Chouldari-2	Poz-17170	330	Bulk	5935	25	4894-4726
Chouldari-2	Poz-17168	338	Bulk	6018	25	4987-4842

Table S1. Radiocarbon ages of core sediments recorded in Port Blair, South Andaman

Note: Radiocarbon AMS ages obtained using the charcoal from the organic-rich bulk sediment samples. The analysis was conducted at Poznan Radiocarbon Laboratory (Poz), Poland. Radiocarbon ages were calibrated using CALIB (Version 7.0.4) (Stuiver and Reimer, 1993; Reimer et al., 2013). The 2 sigma ranges have maximum area under the probability distribution curve.