[Geophysical research Letter]

Supporting Information for

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

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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).

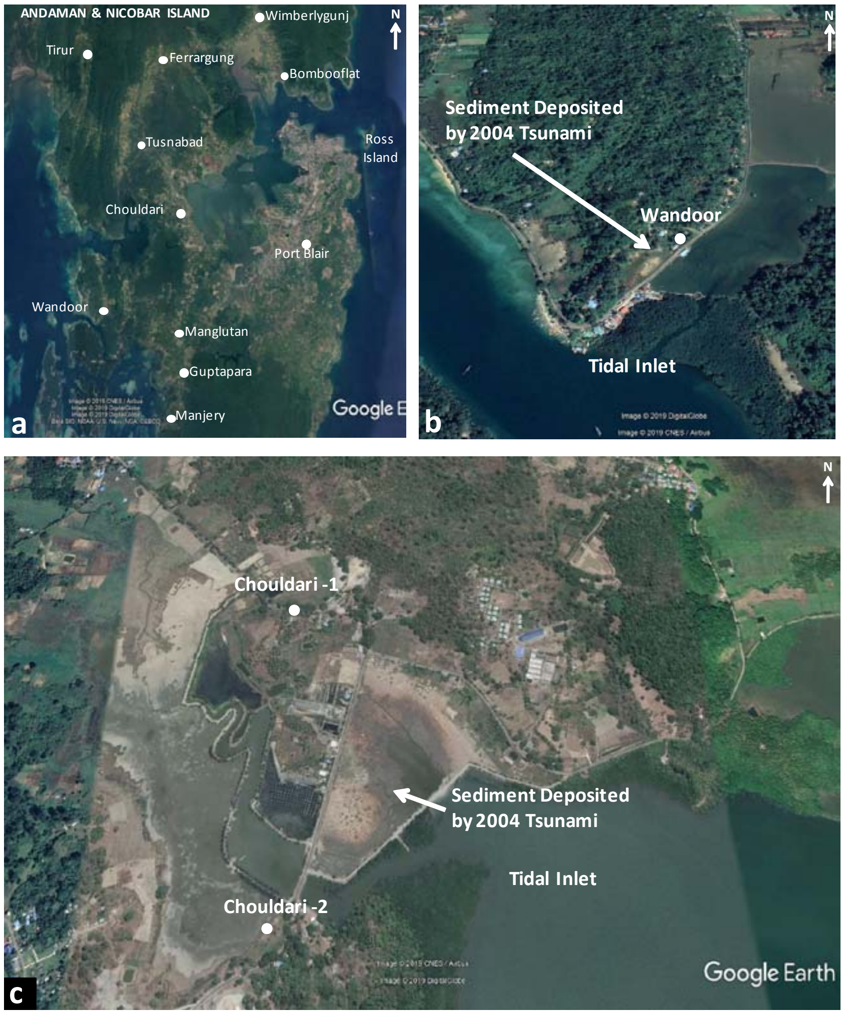

Figure S1 a. Google image of the study areas, near Port Blair, South Andaman. b. Close-up view of the drilling locations at b. Wandoor. c. Chouldari-1 and Chouldari-2

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.

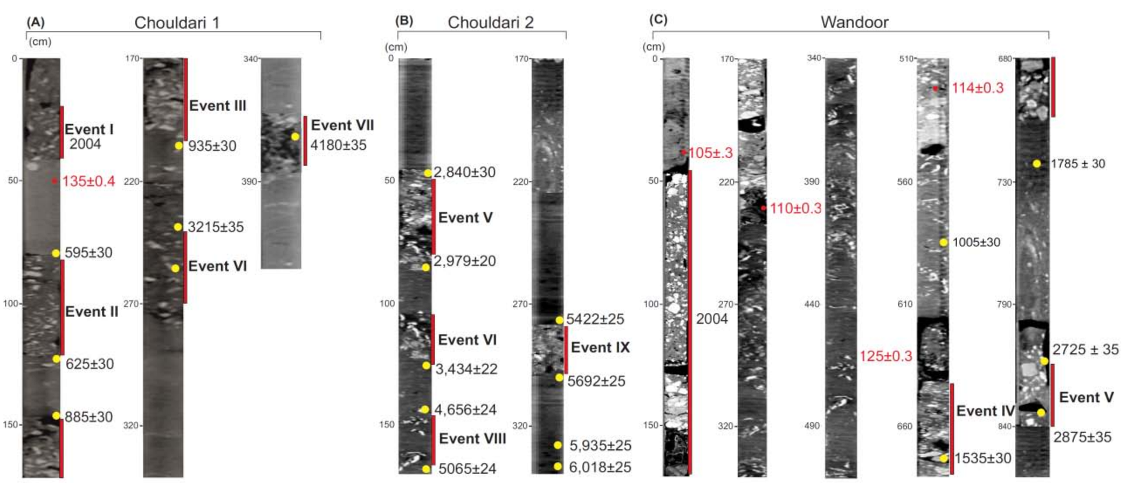

Figure S3. The CAT scan images: a. Chouldari-1; b.Chouldari-2; c. Wandoor. The out-of-sequence layers, sequentially characterized as ‘events’ are marked by red lines on the margins of core logs.

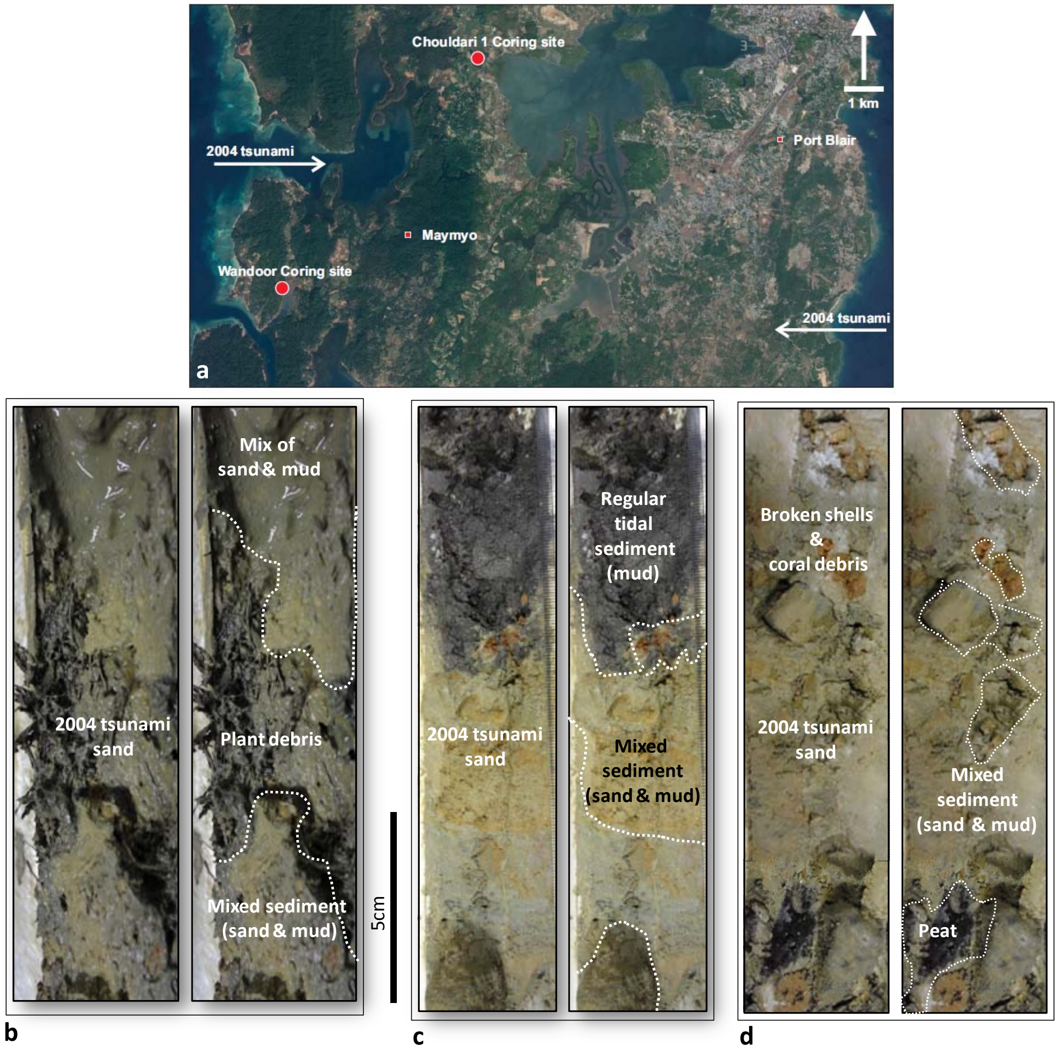

Figure S4. a. Map shows the coring location at Chouldari-1 and Wandoor and the inundation direction of the 2004 tsunami. b. Close-up view of sand mixed with plant debris transported during the 2004 tsunami in Chouldari-1 core. c and d. Photographs show the approximate boundary of regular tidal sediment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

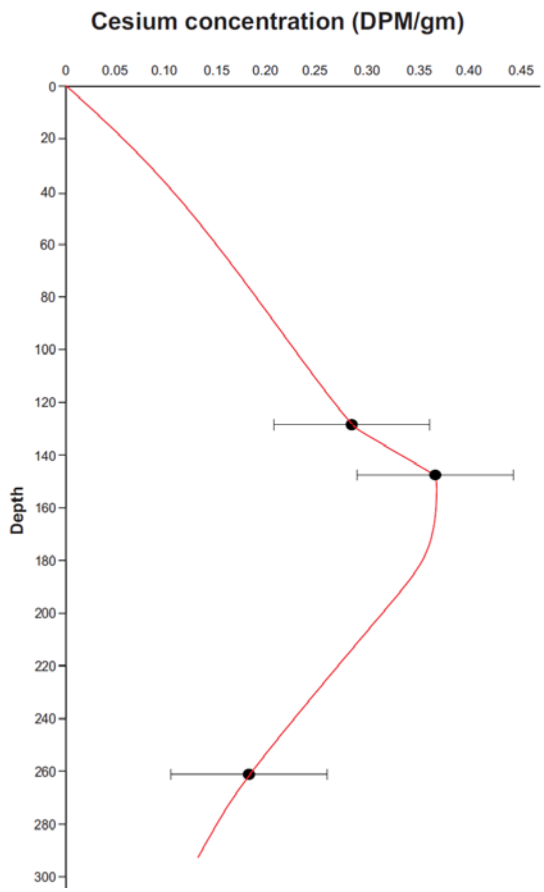

Figure S5. ^{137}Cesium concentration (DPM/gm) in 2004 tsunami deposits from Wandoor core.

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.

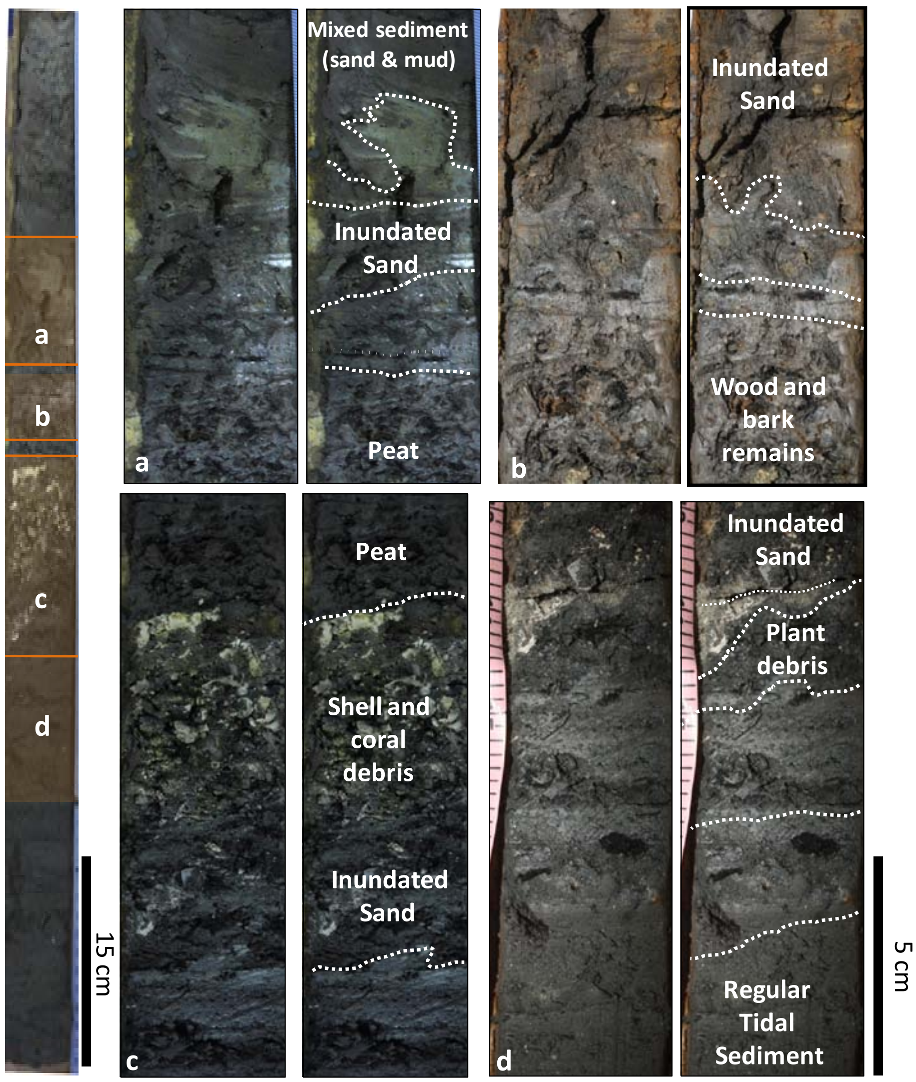

Figure S6 a. Photographs of cores with broken shells and peat from Chouldari-2; b-c. Close-up views of Event II deposition exhibiting peat, shell and coral remains as detritus. d. Close-up views showing boundary between Event II deposition and regular tidal sediment.

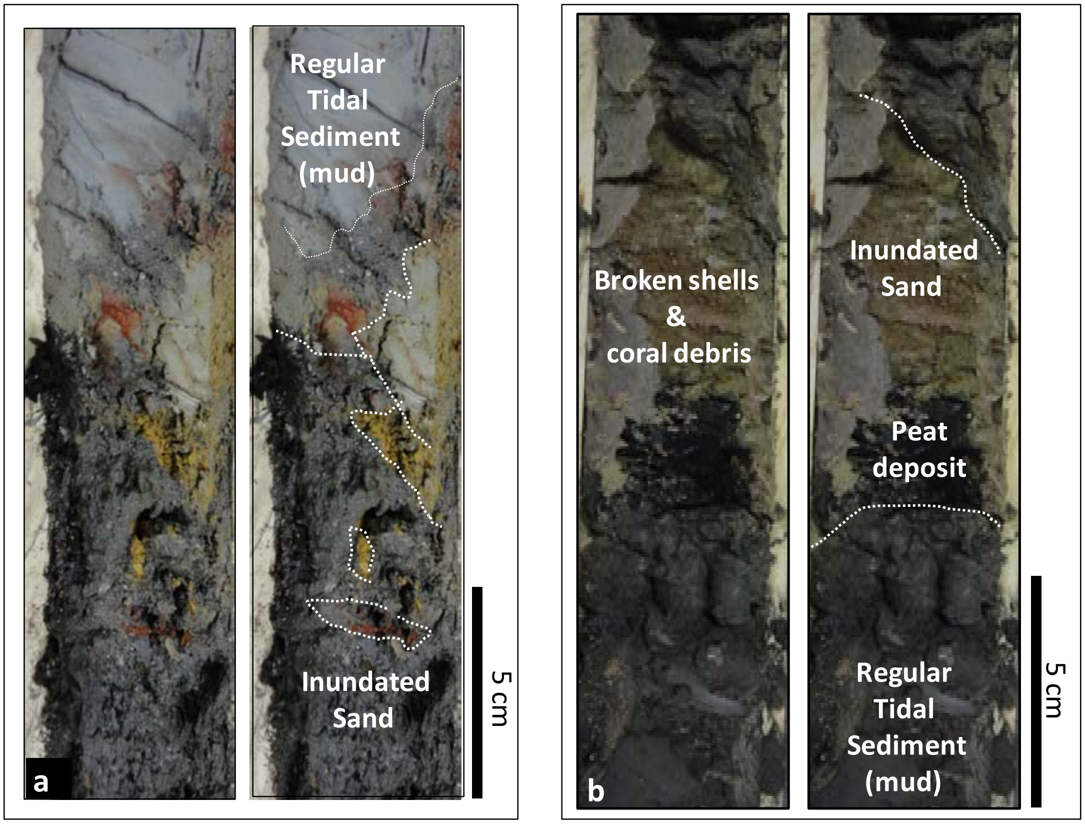

Figure S7 a. Close-up views of the core from Chouldari-1 show boundary between tidal and out-of-sequence deposit belonging to Event III, at a depth of 145cm below the top surface. b. Close-up views of Event IV deposition from Wandoor core at a depth of 680 cm from the top surface.

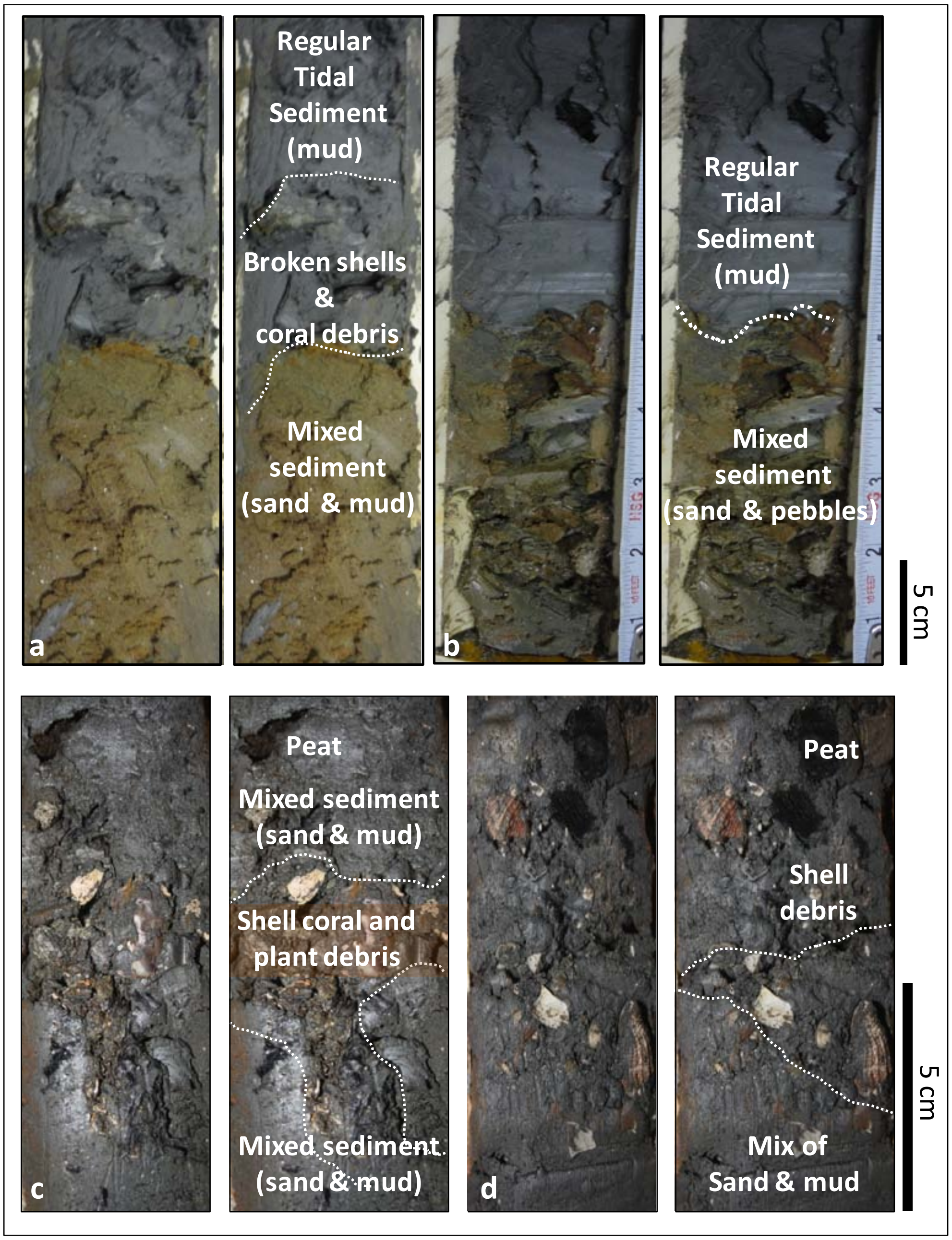

Figure S8 a. Close-up views of Wandoor cores showing boundary between tidal and Event V deposition with shell remains and coral debris, at a depth of ~820 cm from the top surface. b. Close-up views of Event VI deposition with debris at a depth of ~240 cm from the top surface in Chouldari-1 core. c. Close-up 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 H_2O_2. 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).

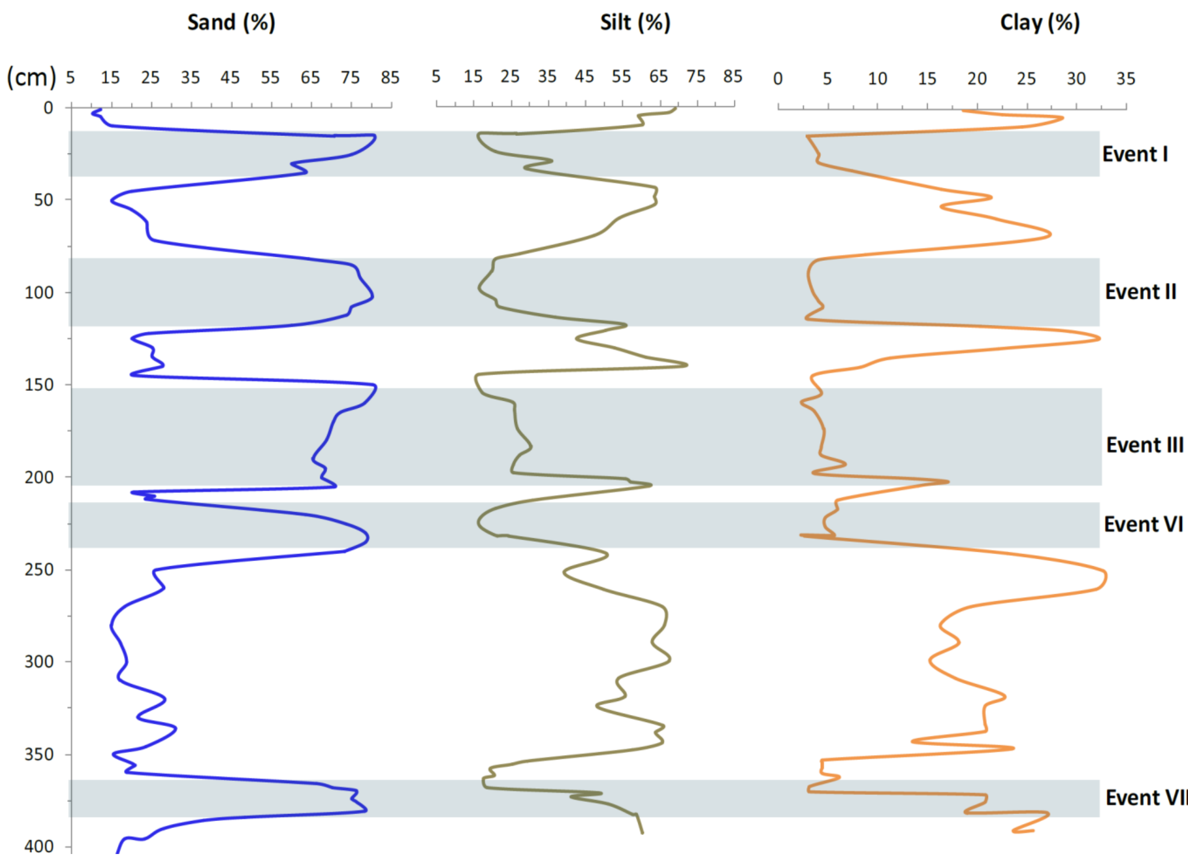

Figure S 9. Percentage of grain-size distributions of the sediment samples estimated from Chouldari-1 cores. Graph shows an increasing trend of sand within the out-of-sequence deposits.

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.

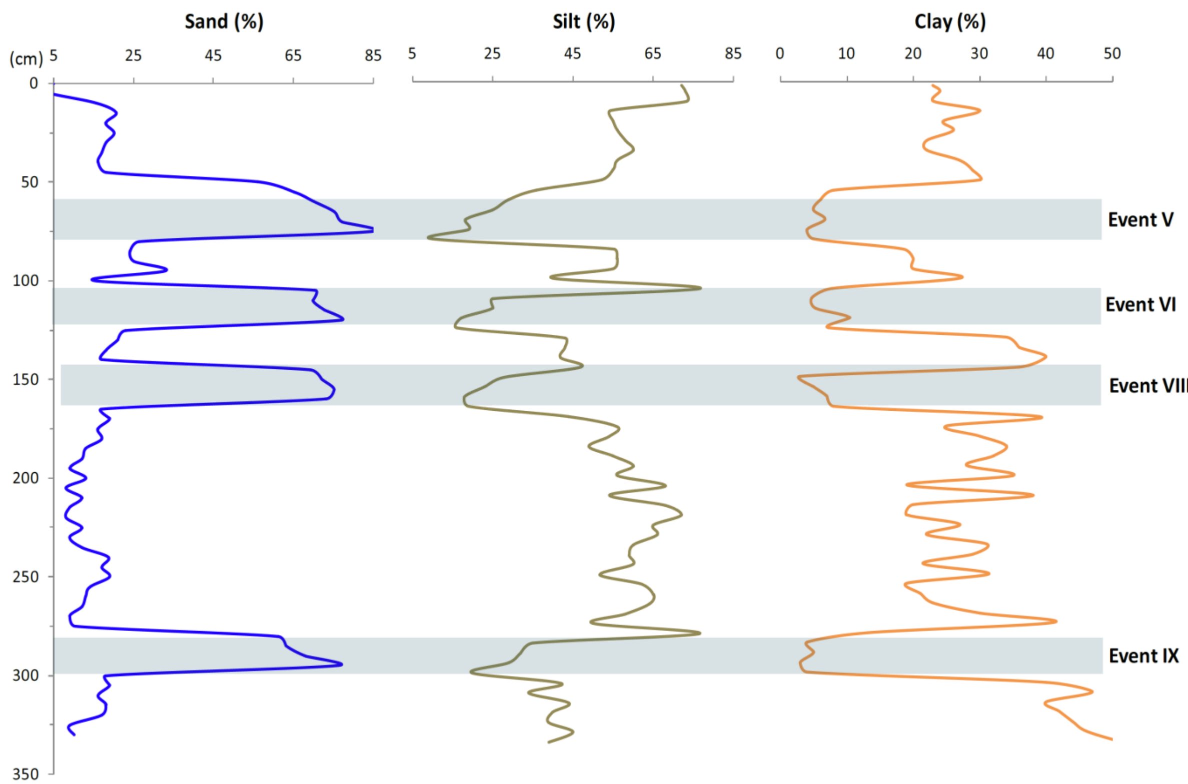

Figure S10. Percentage of grain size distribution of the sediment samples estimated from Chouldari-2 cores. Graph shows an increasing trend of sand within the out-of-sequence deposits.

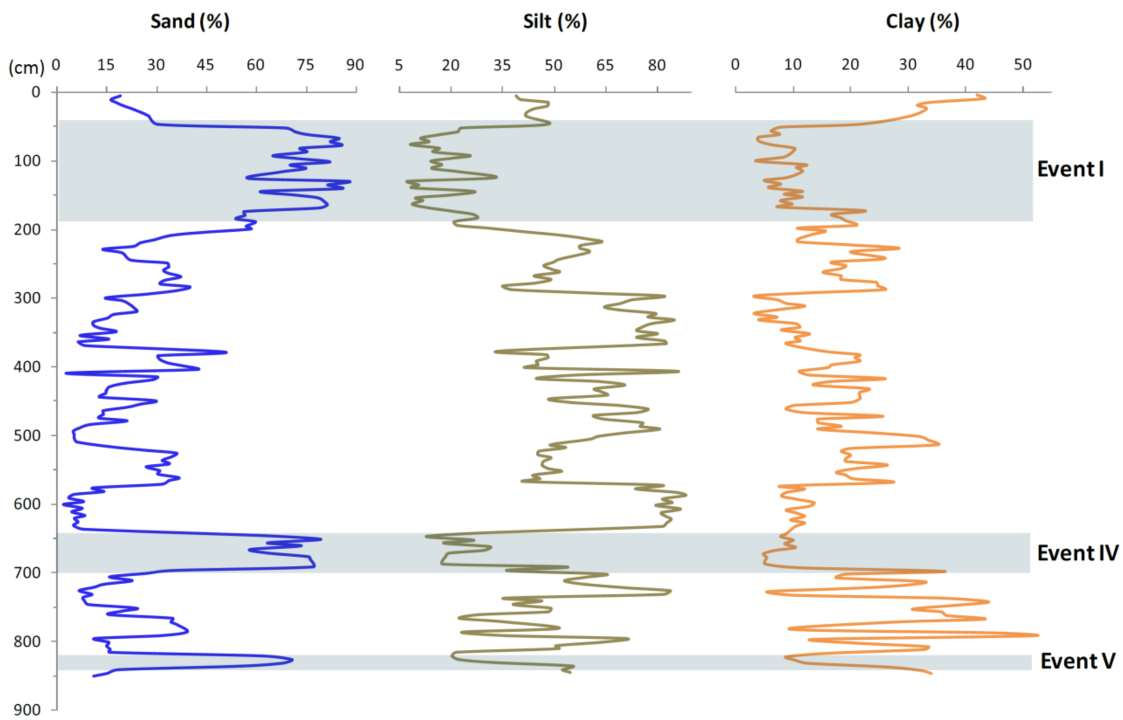

Figure S11. Percentage of grain size distribution of the sediment samples estimated from Wandoor cores, indicating increasing trend of sand within the out-of-sequence deposits.

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).

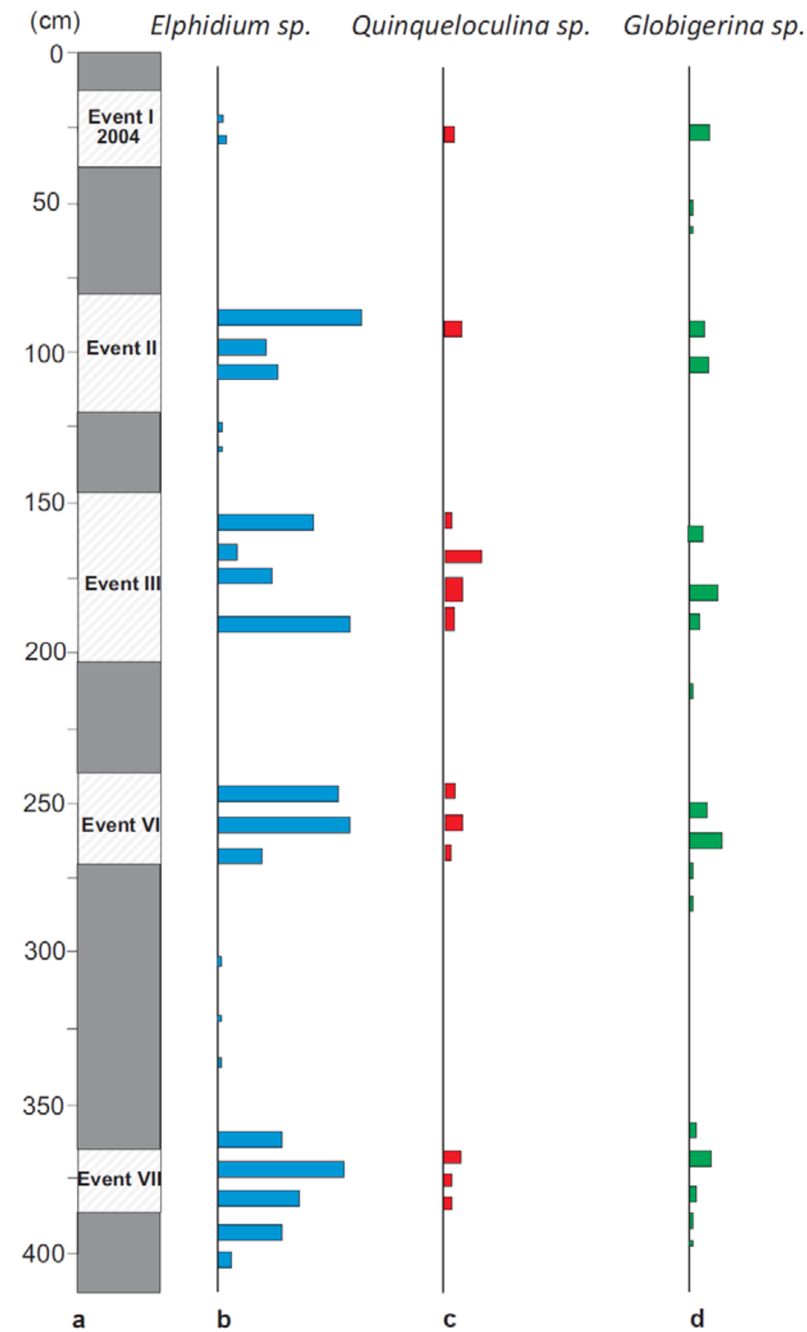

Figure S12 a. Core from Chouldari-1; b-d. Showing the abundance of foraminifera species

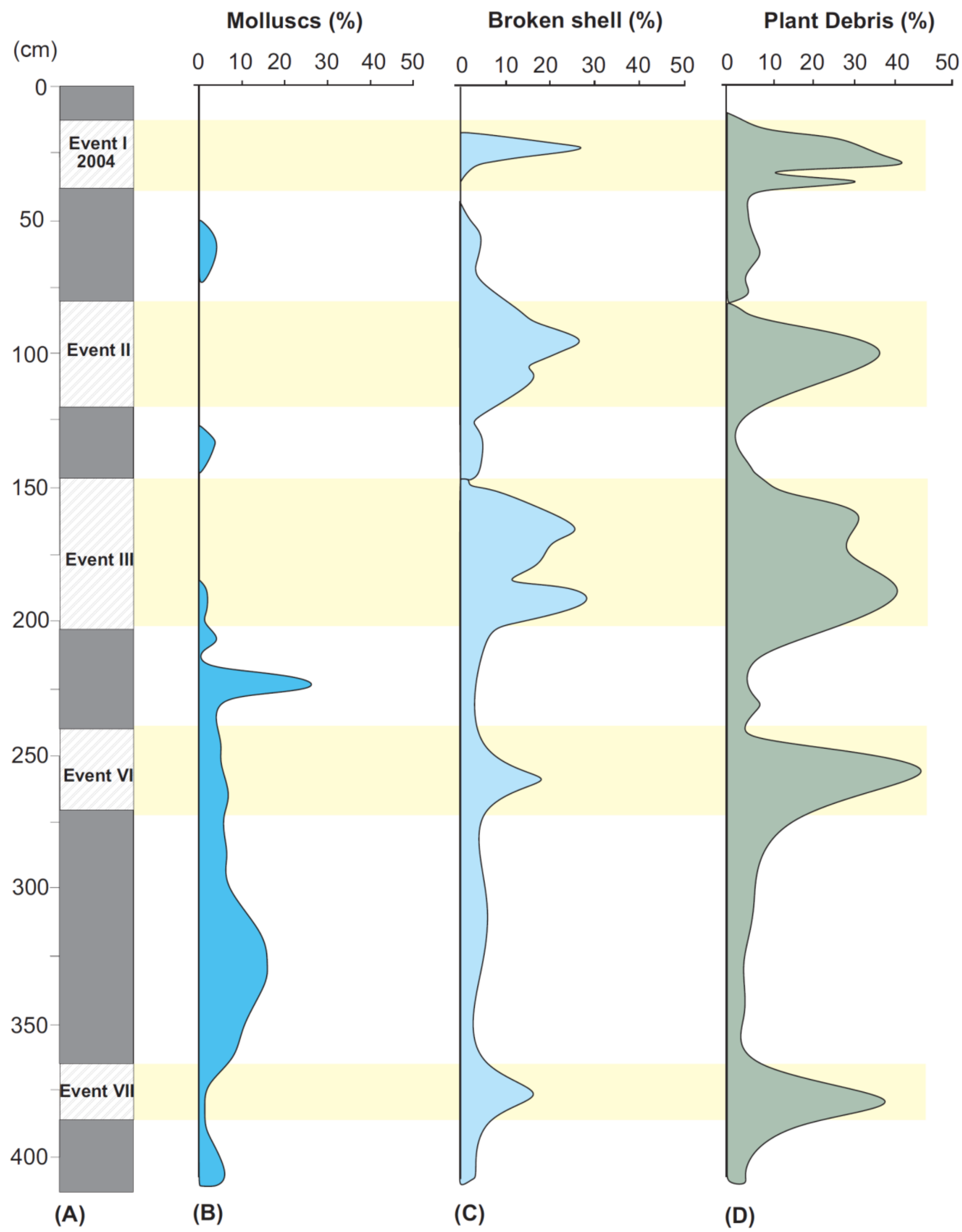

Figure S13 a. Core log from Chouldari-1; b-d. Graph shows the representative percentage of molluscs, broken shells and plant debris in the out-of-sequence deposits from the macro-sieve (>2 mm) fraction.

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.

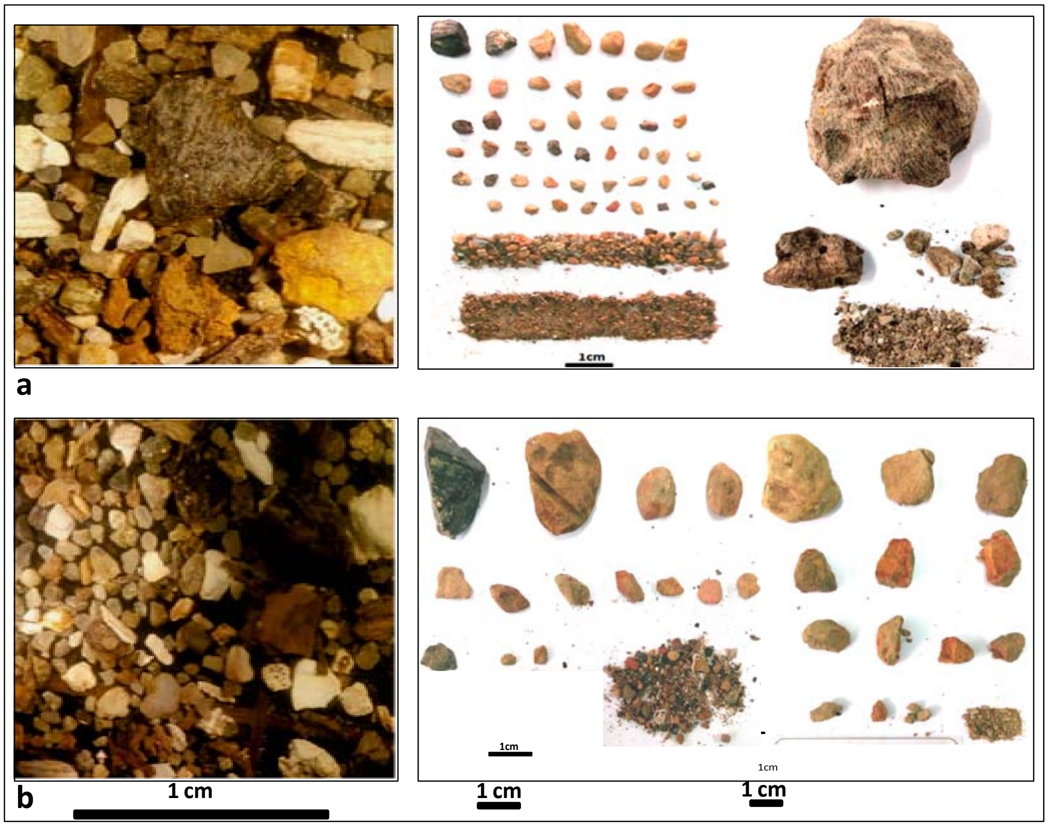

Figure S14 a. Examples of vegetational and carbonate material found in 2004 tsunami sediment observed at Chouldari-1. b. Microscopic view of the coarse-grained fraction from out-of-sequence sediment (Event III) recovered from Chouldari-1. Coarser clasts in out-of-sequence sediments often show the marks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

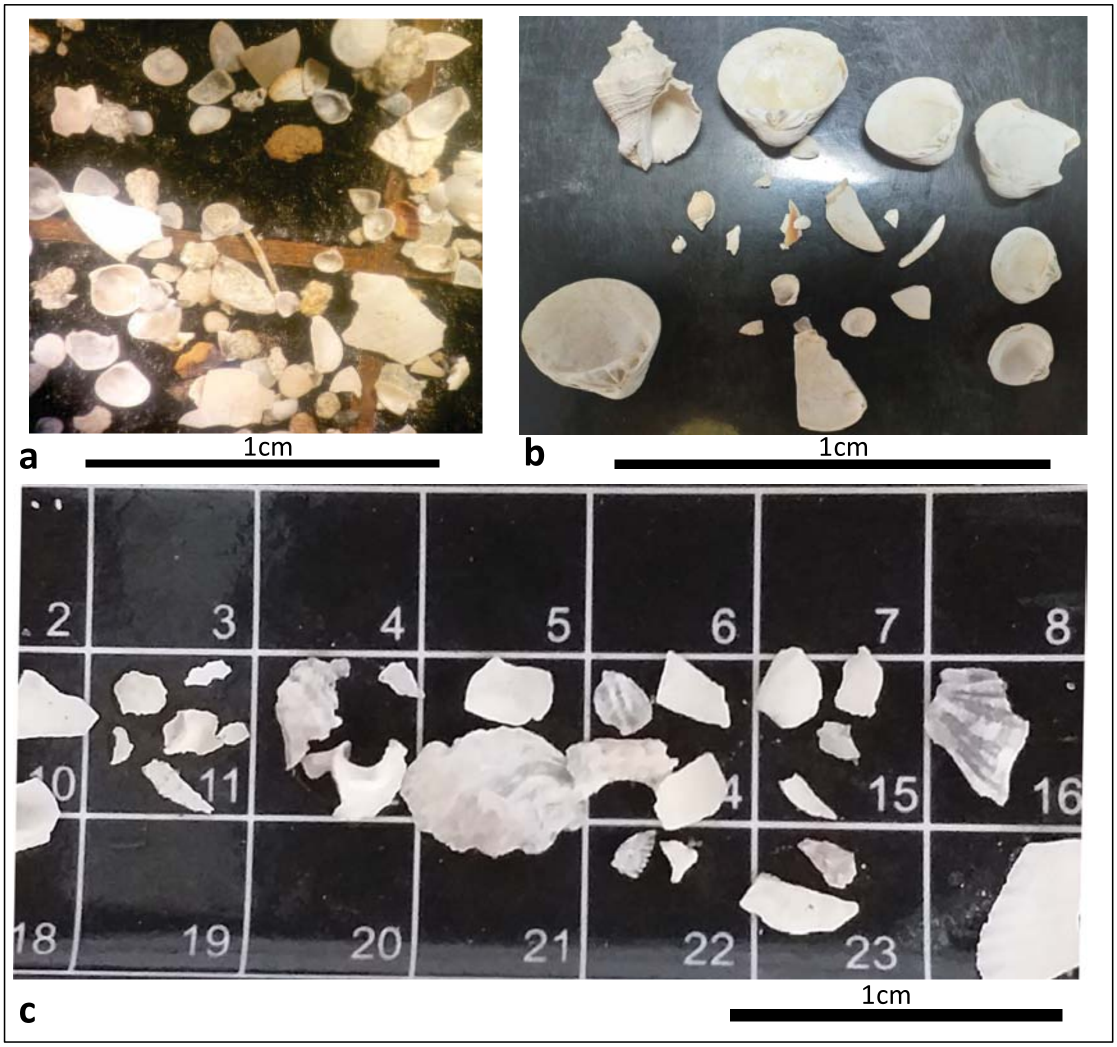

Figure S15. a and b. Microscopic views of the broken and complete shells recovered from 2004 tsunami sediment from Wandoor. c. Microscopic views of the broken shells recovered from out-of-sequence sediment (Event IV) recovered from Chouldari-2.

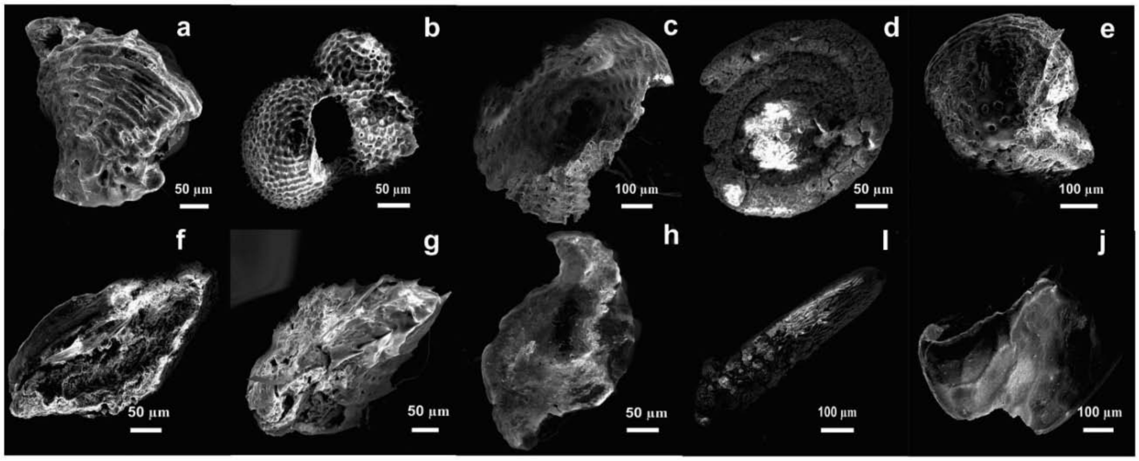

Figure S16. Broken and reworked shells recovered from Wandoor core. a) Broken shell of *Elphidumadvenum*; b) *Globigerina bulloides*; c) *Elphidium carticulatum*; d) *Spriulina sp.* e) *Elphidium advenum*; f) Chemically altered *Spiroloculina sp*. g) *Rusella spinulosa*; h) Broken shell of *Spriloculina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

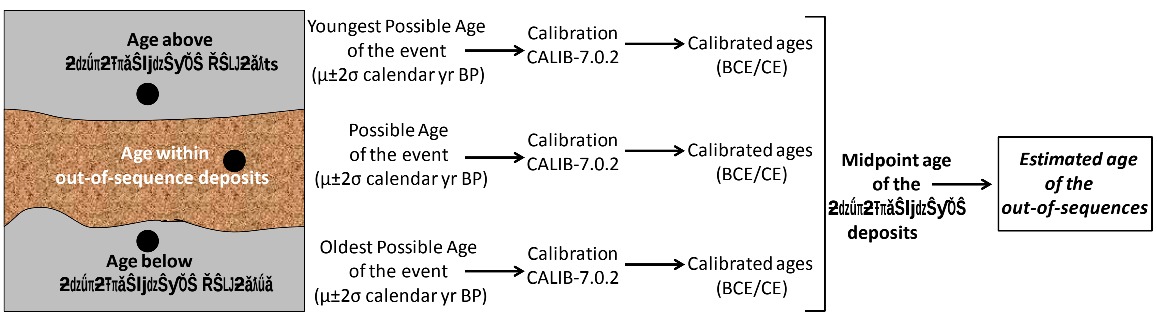

Figure S17. A schematic figure showing how the ages of event layers were estimated by using AMS radiocarbon dating of the bulk tidal sediment from above and below the ÏÕôζÏÆζÓÅÑÕÅÎÃÅ sediments. In some cases, contemporary ages were estimated based on the dates from within the event layers. The ages of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

References

Folk, R.L., Ward, W.C., 1957, Brazos River bar: a study in the significance of grain size parameters, Journal of Sedimentary Petrology, v. 27, p. 3–26

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., Cheng, H., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Haflidason, H., Hajdas, I., Hughen K.A., Kaiser K.F., Kromer, B., Manning S.W., Niu, M. Reimer, R.W., Richards D.A., Scott, E.M., Southon, J.R., Richard, A.S., Turney C.S.M., Plicht, J.v.d., 2013, IntCal13 and Marine13 Radiocarbon Age Calibration Curves 0–50,000 Years cal BP, Radiocarbon, v. 55, p. 1869–1887.

Stuiver, M., Reimer, P.J., 1993, Extended (super 14) C data base and revised CALIB 3.0 (super 14) C age calibration program, Radiocarbon, v. 35, p. 215–230.

Location	Lab no.	Depth of the sediment (cm)	Sample type	^{14}C ages (μ±2σ 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.