# Late Holocene Palaeotsunami Events Archived along the Gujarat Coast, Western India


**Drasti Gandhi[1,2*], Siddharth Primowala[1], N.Y.Bhatt[2] and Nilesh Bhatt[3]**

[1]Earthquake and Environmental Geology, Institute of Seismological Research, Gandhinagar, India-382009

[2]Geology Department, M. G. Science Institute, Ahmedabad, India-380009

[3]The Geology Department, M. S. University of Baroda, Vadodara, India-390002

*E-Mail: gdrashti15@gmail.com



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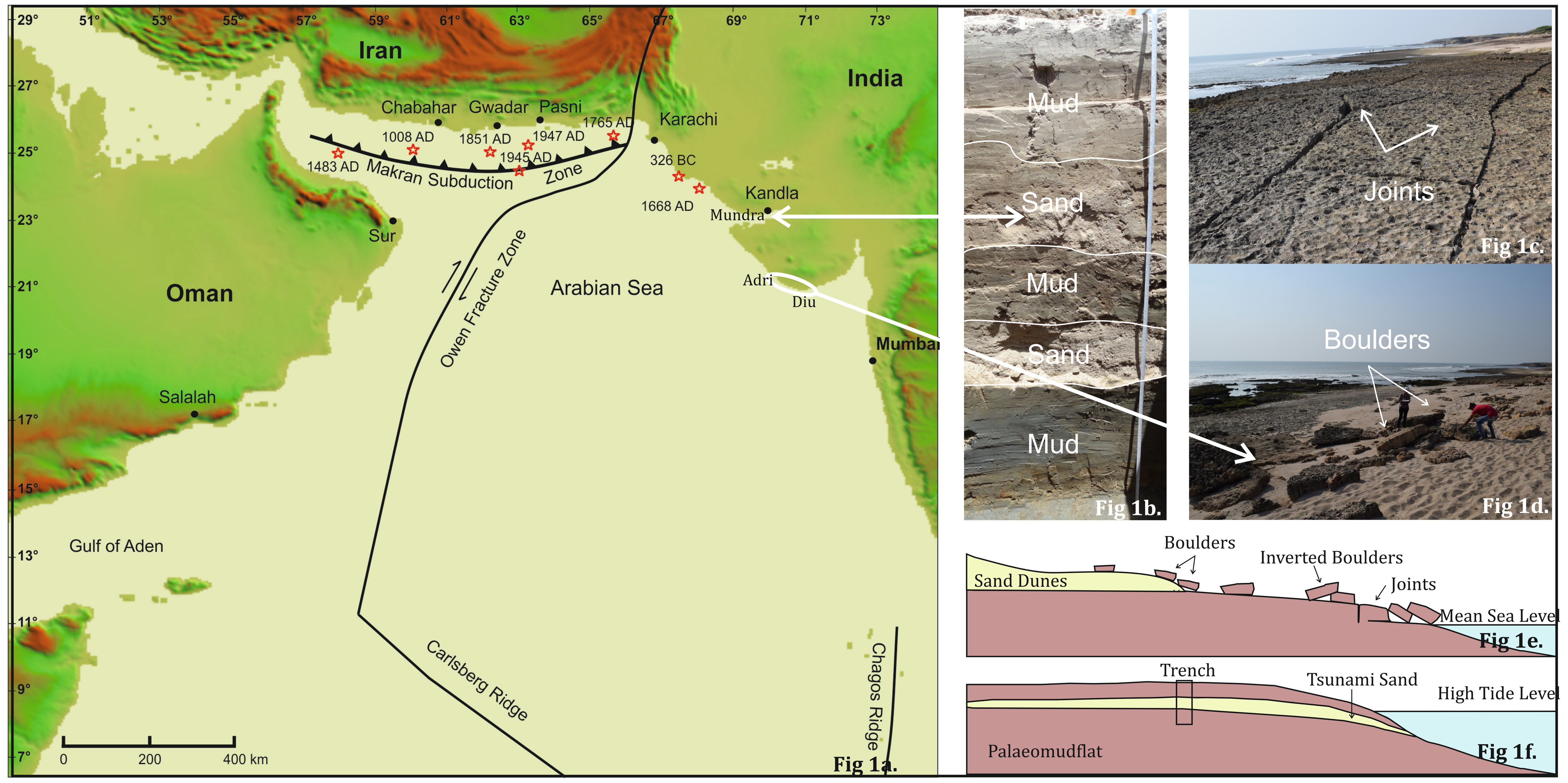
**Abstract:** Gujarat state is situated in the western most part of India and has the longest coastline of 1600 km facing the Arabian Sea. Historically the coastline has been affected by tsunami waves with the latest one being the 1945 Makran tsunami which had run up height of 11 m along the Gulf of Kachchh coastline. From all over the world, several scientists recognized boulders/megaclasts, presence of mud intraclasts in sand layers and abrupt sand layers between clayey layers as the geological signatures of palaeotsunami deposits. As Gujarat coastline comprise of both rocky coastline of Saurashtra and sandy Coastline of Kachchh, providing a fascinating scenario to study palaeotsunami deposits of varied textural sizes. We studied the rocky coastline of south-western Saurashtra (i.e. From Navibander to Mangrol) and observed the presence of boulder deposits, scattered above the high tide line upto tens of meters inland. Using various physical parameters anRefd numerical models it was estimated that a tsunami wave of 3.5 m wave height had detached and mobilized these boulders to their inland final position. Using optical dating technique, the age of deposition of the dune on which those boulders were lying was estimated to be 3.4 ± 0.23 ka. This suggests the tsunami event took place sometime during the last 3.4 ka. Similarly at the Mundra coastline of Kachchh, a shallow trench of about 1.5 m was dug at an elevation of 2m from high tide line. This sequence shows a typical tidal flat sedimentation comprising silty – clayey layers (unit-1 to unit 6). However unit 6 and unit 4 were sandy in nature and supported their deposition in form of a high energy marine flooding event. Geochemical analysis of this sequence showed decrease in concentration of major and trace elements at unit 3 and unit 5. Based on sedimentology and geochemical signatures we suggest that the Unit-3 was deposited on account of a storm surge as it showed seaward dipping mega ripples ~ a characteristic feature of strong ebb tide. Whereas Unit-5 is a palaeotsunami deposit characterized by rip-up mudclasts, broken shell fragments and sand layer sandwiched between mud layers which are characteristics features of palaeotsunami deposits. The bivalve shells dated from bottom of unit 5 gave a 14C AMS age of AD 997 – 1107. It is interesting to note that a tsunami has been recorded historically around 1008 AD in Strait of Hormoz, Iran. This sand layer (Unit-5) most likely is geological signature of the 1008 Strait of Hormoz Tsunami.


## STUDY AREA




- The Gujarat Coastline faces the Arabian Sea which hosts multiple tsunamigenic sources like Makran Subduction Zone (MSZ), Owen Fracture Zone and Carlsberg ridge. An earthquake with magnitude greater than 6.5 can generate tsunami which may affects the Gujarat coastl (Fig 1a). However the knowledge of past tsunami events along Gujarat coast is '*Terra Incognita*'.
- The Gujarat coastline comprises of both sandy (Kachchh) as well as the rocky (Saurashtra) coastline.
- Here we investigated 2 segments, each in Kachchh coast (Fig 1b) and Saurashtra coast (Fig 1c-d).
- The Saurashtra coast from Diu to Adri shows presence of a jointed shore platform made of Miliolite Limestone, which acts as source of boulders during a tsunami event (Fig 1c).
- The segment between Diu to Adri shows scattered, imbricated as well as inverted boulders spread (Fig 1d) along the coastline above the high tide line (Fig 1c - e).
- Based on geomorphology we designated Kachchh region, which comprise of the palaeomudflat, as a segment with higher preservation potential.
- Based on trenching in palaeomudflat along Mundra region we encountered a sand layer sandwiched between the mud layers (Fig 1f).

## METHODOLOGY

For Boulder Deposits, Saurashtra coastline

- Measurements of the boulder dimension namely the long (a), intermediate (b) and shorter (c) axis were recorded in addition to their distance from the high tide line using Bosch GLM 250VF Professional distometer.
- Samples were collected for estimating the bulk density in laboratory following equation

$\rho_{bi} = \rho_{sw} * W_a/(W_a - W_f)$

Where, $\rho_{bi}$ is the bulk density of boulder; $\rho_{sw}$ is the density of sea water = 1.02 g/cm3; $W_a$ and $W_f$ are the weights of the sample in air and in sea water respectively

- We used equations suggested by Pignatelli et al. (2009) for joint bounded boulder transport for storm and tsunami waves to estimate the minimum wave height required to dislodge and transport these boulders

$H_t \geq [0.5c\,(\rho_s - \rho_w/\rho_w)]\,/CL$

$H_s \geq [2c(\rho_s - \rho_w/\rho_w)]\,/CL$

Where, $H_t$ is the tsunami wave height and $H_s$ is the storm wave height at breaking point; a, b and c are the boulder long, intermediate and short axis length; $\rho_w$ is the sea water density=1.02; $\rho_s$ is the boulder's density=2.75; CL is the coefficient of lift=0.178.

- Simultaneously samples were collected from the sand dune on which these boulders were scattered for estimating the age of the event using OSL chronology technique.

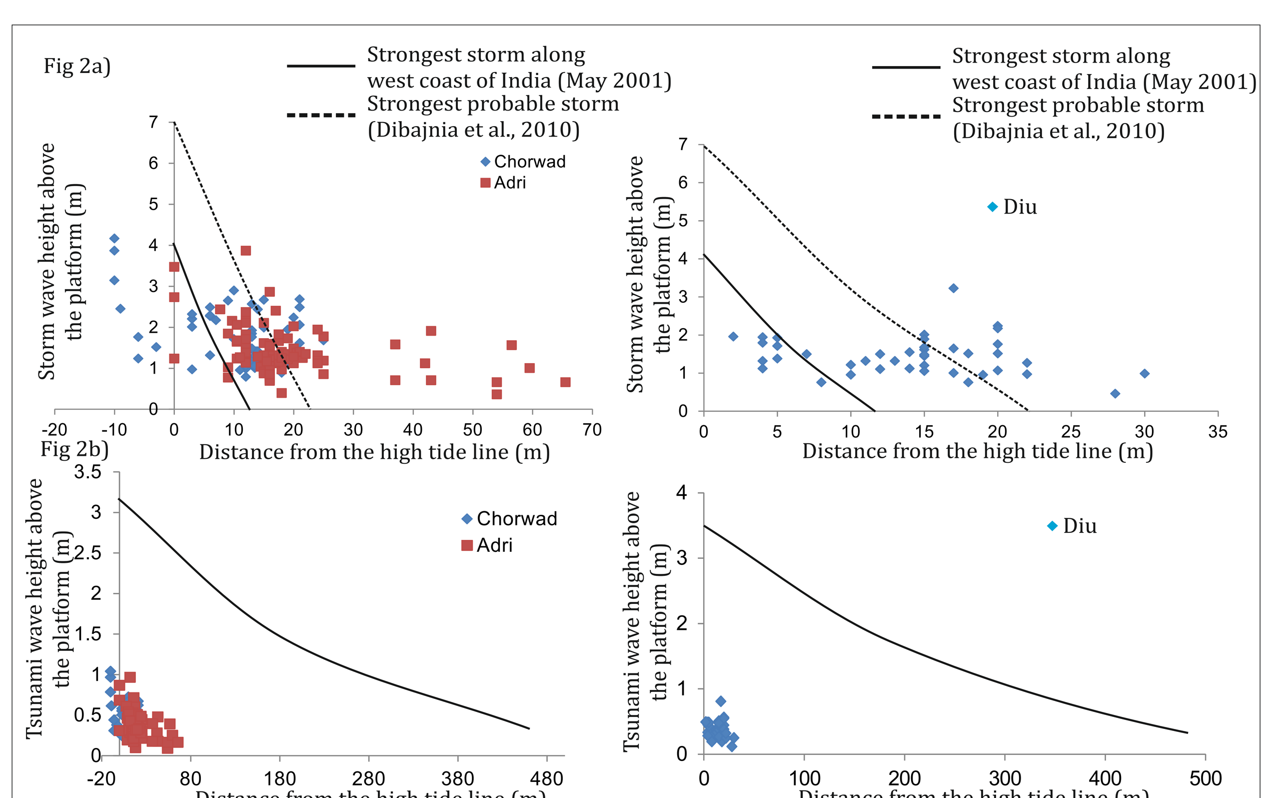
For Sand Deposits, Kachchh coastline

- Geomorphological maps of various segments of Kachchh and Saurashtra coast were prepared using Survey of India topographic sheets on 1:50,000 scale and high resolution satellite images.
- We then designated various landforms along the coastline as per their response to the tsunami waves: For example (i)river mouths, creeks, tidal channels etc. act as 'conveyor' which allow the tsunami waves inland and cause wide destruction up to considerable distance (ii) sandy beaches and mangrove swamps absorbs the energy and velocity of tsunami waves. The extent to which such absorber landform would reduce the energy of a tsunami wave depends on height and width of the landform (iii) palaeomudflats, swales, back swamps etc. act as 'accommodators' which accommodate most of tsunami wave energy and material carried by it. Accommodator has a high preservational potential for tsunami deposits (iv)landforms like beach ridges, cliffs and coastal dunes act as a 'barrier' to the tsunami wave by obstructing it inland. The capacity of such barrier will depend upon height of tsunami surge and elevation and width of the barrier.
- The remote sensing study was followed by field investigation near Mundra region of Kachchh in which we dug a trench of about 1.5 m depth in a palaeomudflats environment which is 3m high from the present sea level.
- The sedimentary section was studied in detail for its sedimentological attributes and sampled at 2 cm interval. The samples packed in polythene bags and brought to laboratory where they were subjected to geochemical analysis (major and trace elements).
- Several molluscs bivalve shells were collected from the base of the sand unit for AMS $^{14}C$ dating.

## Results

For Saurashtra coast

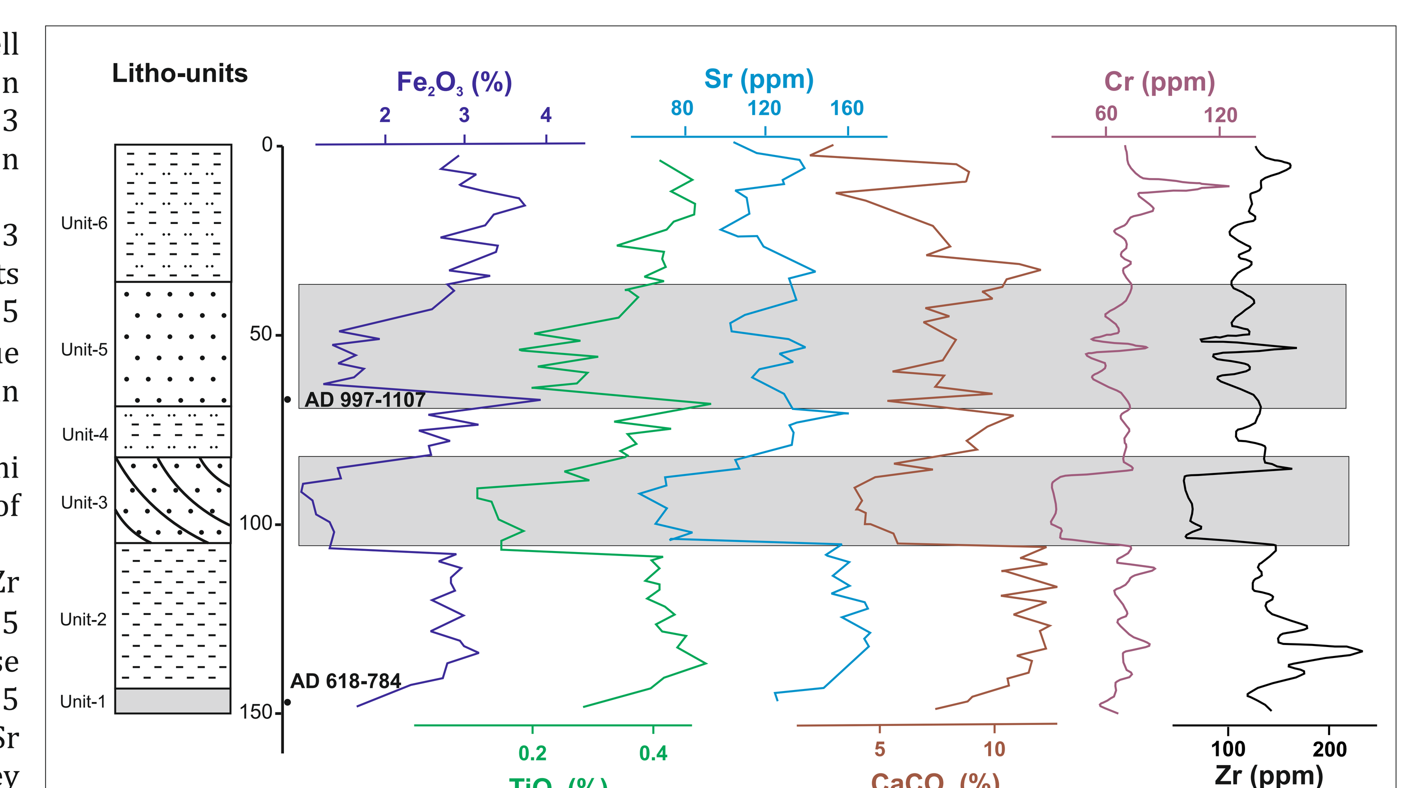
- We investigated a total of 210 boulders and recorded their physical dimensions and shapes along with their distance from high tide line.
- The boulders were present in scattered, imbricated and embedded manner along the entire southwestern Saurashtra coastline.
- On the basis of imbrication directions of these boulders, it is suggested that the source of tsunami wave lies in southwestern direction, most likely the OFZ (Prizomwala et al. 2015).
- Numerical stimulations using Pignatelli et al. (2009) suggested that 'to dislodge all the boulders from their offshore position and to place them to their present landward position' would require a storm with a minimum wave height of 17.1 m.
- Whereas the same boulders can all be placed to their present position by a tsunami wave of 3.5 m.
- We compared the wave heights calculated from our data with strongest storm to hit the west coast of India as well as with strongest probable modelled storm in the Arabian Sea.




- Fig 2 a) is the plot of the wave height at the final position of boulders with the distance and comparison of it with highest storm that the coast of Saurashtra has experienced along with strongest probable storm in Arabian Sea and b) a tsunami wave computed from these boulders.
- An OSL age of 3.4 ± 0.3 ka was estimated from dune on which these boulders were scattered which implies that this event took place sometime during last 3.4 ka period i.e. Late Holocene Period.

For Kachchh coast

- The presence of mudballs, assorted nature of sand, broken shell fragments and an abrasional contact with bottom mud horizon suggests the origin of unit-5 as tsunamigenic, compared to unit-3 which has landward dipping foreset ripples, mostly deposited on account of ebb storm surge wave.
- Geochemistry of this sequence showed that the sand layers (Unit-3 and Unit-5) shows depletion in major oxides and trace elements concentrations. The concentration of $CaCO_3$ shows increase in Unit-5 and a simultaneous decrease in Unit-3. This is resulted most likely due to presence of broken shell fragments in Unit-5 and lack of the same in Unit-3.
- We presume deposition of Unit-5 to be on account of palaeotsunami wave, which might have eroded shell/bioclastic rich sea bed of Gulf of Kachchh and deposited it on landward side.
- Similar to $CaCO_3$ concentrations the Unit-3 shows lesser amount of Zr and Cr compared to Unit-5. The higher amount of Zr and Cr in Unit-5 testifies its origin from offshore sands which are normally rich in these elements compared to fluvial sands of Kachchh. Similarly, the Unit-5 shows enrichment in Sr concentrations compared to Unit-3. The Sr concentrations in Unit-5 is comparable to Sr concentrations in clayey silt units, which points at their alike provenance.




- The Mollusc shells dated from bottom of the unit-5 unit gave an AMS $^{14}C$ age of AD 997 – 1107. Whereas the bottommost unit-1 yielded an age of AD 618 - 784, which would serve as older age bracket to our sequence.

## Conclusion

- The coastal archives of Gujarat provides a fascinating scenario to study and decouple the geological signatures of palaeotsunami and palaeostorm deposits.
- Our present study suggest a tsunami wave of 3.5 m wave height at the coastline of Saurashtra dislodged boulders from there offshore position and deposited them inlands. The event took place sometime during the last 3.4 ka. Based on boulder imbrications, the Owen Fracture Zone is believed to be source of this event.
- Another tsunami event took place around 997-1107 AD. This is archived in form of a sand layer (Unit-5) sandwiched between mud layers of Mundra coast, Kachchh.
- We also for the first time report evidences of a palaeostorm deposit in form of Unit-3 which was deposited on account of high flux of sediment during ebb-tide

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