Constraining large earthquakes along the Andaman trench using deepwater turbidites: prospects and challenges

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The 2004 Sumatra–Andaman earthquake was unprecedented in terms of its magnitude (M_w 9.2), rupture length along the plate boundary (1300 km) and size of the resultant tsunami. Since 2004, efforts are being made to improve the understanding of the seismic hazard in the Sumatra–Andaman subduction zone in terms of recurrence patterns of major earthquakes and tsunamis. It is reasonable to assume that previous earthquake events in the Myanmar–Andaman segment must be preserved in the geological record in the form of seismo-turbidite sequences. Here we present the prospects of conducting deep ocean palaeoseismicity investigations in order to refine the quantification of the recurrence pattern of large subduction-zone earthquakes along the Andaman–Myanmar arc. Our participation in the Sagar Kanya cruise SK-273 (in June 2010) was to test the efficacy of such a survey. The primary mission of the cruise, along a short length (300 km) of the Sumatra–Andaman subduction front was to collect bathymetric data of the ocean floor trenchward of the Andaman Islands. The agenda of our piggyback survey was to fix potential coring sites that might preserve seismo-turbidite deposits. In this article we present the possibilities and challenges of such an exercise and our first-hand experience of such a preliminary survey. This account will help future researchers with similar scientific objectives who would want to survey the deep ocean archives of this region for evidence of extreme events like major earthquakes.

Keywords: 2004 Andaman–Sumatra earthquake, Bay of Bengal, deepwater turbidite, subduction zone.

TURBIDITE palaeoseismology is essentially a study of submarine landslides caused due to the ground shaking associated with large earthquakes. The damaging potential of submarine landslides was realized when an earthquake-induced turbidity current broke submarine cables off the coast of Newfoundland[1]. Then, in the 1960s, coring in deep-sea channel systems off the coast of the Pacific Northwest (Cascadia subduction front) resulted in the discovery of multiple ‘rhythmic’ sediment sequences. These deposits, identified as seismic-turbidites by Adams[2], were attributed to large earthquakes in the geologic past and have since been used to establish the temporal pattern of seismicity along the Cascadia margin. Similar work has been carried out along other subduction zones globally, and more recently, seismo-turbidites have been identified in cores collected off Sumatra[3–5].

The basic questions of earthquake recurrence are centred on the seismic gap theory (that characteristic earthquakes assume stress build-up proportional to the time since the last earthquake), and the clustering of earthquakes (due to stress triggering and fault interaction). It is in the context of understanding such questions along subduction zones that turbidite palaeoseismology assumes importance. Global Positioning System (GPS), a widely used tool in recent times, represents about two decades of precise strain measurements related to the seismic cycle. Seismo-turbidite sequences in marine sediment cores represent an undisturbed proxy for earthquake recurrence, over a longer time-span. This makes them more robust than onshore geological records that are subject to several extraneous processes affecting the preservation potential of such deposits[6,7]. Turbidite seismology can be used to supplement and bridge gaps in the current land-based record of palaeoearthquake recurrence timescales.

After the 2004 Sumatra–Andaman earthquake, though coastal palaeoseismology and/or tsunami geology studies have been carried out in India[8–12], Indonesia[13], Thailand[14] and Sri Lanka[15], offshore studies have been attempted only off Sumatra[3–5]. We are interested in the northern Bay of Bengal, where the rupture of the 2004 earthquake terminated. Several large earthquakes have occurred in

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this region in 1679, 1762, 1881 and 1941, all of which broke smaller patches of the Sumatra–Andaman–Myanmar plate boundary, but the 2004 earthquake overprinted all these smaller ruptures in a mega-thrust event rupture (Figure 1). The segment between North Andaman and Myanmar, however, has not generated plate-boundary breaking earthquakes in recorded history. It is also suggested that the subducting India plate under the Irrawady region (between 15°N and 18°N) is aseismic due to a subhorizontal tear in the slab[16]. Thus this problem deserves a thorough investigation in terms of proving actuality of two contrasting scenarios. In this article, we discuss the prospects of undertaking such a study in this region based on our first-hand experience of a preliminary survey with details of our expedition and the results.

Background

The generation of submarine slides and turbid flows at subduction margins in the ocean can be attributed to several possible mechanisms. Adams[2] suggested storm wave loading, great earthquakes, tsunamis and sediment loading. Goldfinger *et al.*[6,7] added crustal earthquakes, slab earthquakes, aseismic accretionary wedge slip, hyperpycnal flow and gas hydrate destabilization to the list. Seismo-turbidites, as the name suggests, are turbidity current deposits formed due to energy release and subsequent ground shaking associated with large earthquakes. In order for a turbidite sequence to be classified as a seismo-turbidite, it is necessary to systematically eliminate the other possible causes for its generation.

Using turbidite sequences in palaeoseismology requires an understanding of the depositional environment and mechanisms, and the physiography of the seafloor. Ideally, turbidity current deposits are expected to show a 'Bouma' sequence of deposition (Figure 2 *a*), a typical fining upward sequence of sediments representative of the upper and lower flow regimes seen in unidirectional turbulent fluidized systems[17–19]. However, such complete sequences are not common in turbidite environments as they vary upon the depositional regimes, most often resulting in partial Bouma sequences. The base of each of these sequences is a layer of pelagic ooze, scoured due to the velocity of the turbid flow. It is easier to date the time of deposition of the sequence using calcareous microfossil tests from this layer, provided the core is collected from above the calcite compensation depth (CCD). A Bouma sequence shows the depositional characteristics of an upward reducing flow velocity, where the massive bed at the base is overlaid by fine laminae of the upper flow regime (Figure 2 *a*). The basal bed, though massive, may show some grading, both normal and reverse. The lower flow regime, due to reduction in the velocity of the current in the presence of higher particle density, leads to the formation of sediment ripples, which gradually turn into fine laminae that in time merge with pelagic sedimentation typical of deep oceans[17,18].

A marine sediment core collected off a subduction margin should preserve, several such 'Bouma' sequences that can give us estimates of the intervening time between two earthquake events. Several sediment cores taken from suitable sites all along a subduction zone should constrain both the spatial and temporal pattern of large earthquakes in the past by correlating the turbidite sediment sequences (Figure 2 *b*). A full turbidite sequence consists of a coarse-grained base and muddy tail. An important criterion that distinguishes seismogenic turbidites from those formed by other mechanisms (storm-water loading, sediment loading and hyperpycnal flow) is the occurrence of multiple pulses (coarse-grained part of the turbidite) that can be related to seismic shaking[20]. The synchronous deposition of such deposits in distant channels

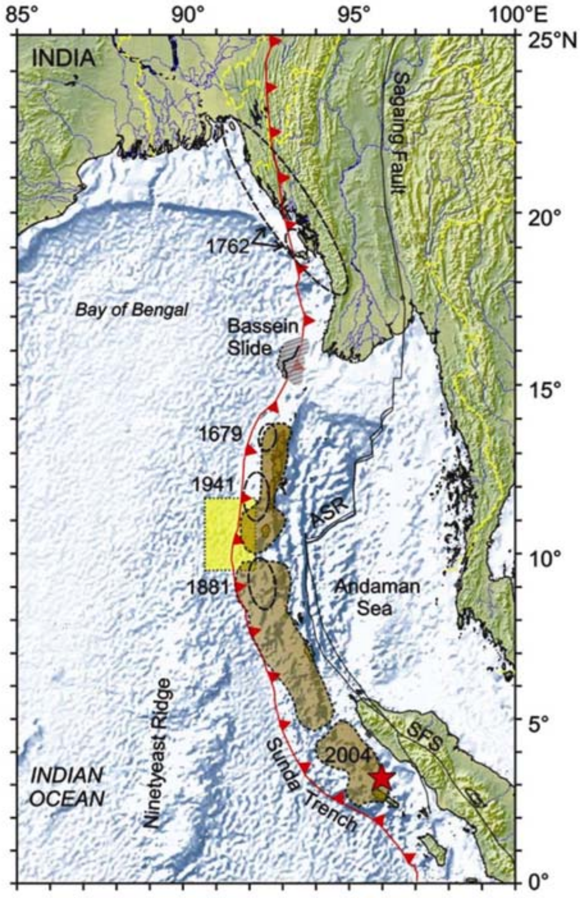

Figure 1. A regional map showing the Sunda trench, the Sumatran Fault System (SFS) and the Sagaing fault, which between them absorb the convergence of the India–Australia plate and the Eurasia plate[29]. The Ninetyeast Ridge disappears beneath the Bay of Bengal sediments at about 10°N. Yellow shaded rectangle indicates the SK-273 survey zone. Ellipses represent the ruptures of the 1679, 1762, 1881 and 1941 earthquakes[9,23,30,31]. Red star shows the epicentre of the 2004 earthquake and the brown shaded region shows the rupture zone. The proximal toe of the Bassein slide is marked by a solid black line and the distal toe by a dotted line. The approximate area that the slide affected is shown in grey[24]. Sunda Trench, SFS, Andaman Spreading Ridge (ASR) and Sagaing fault modified after Socquet *et al.*[29].

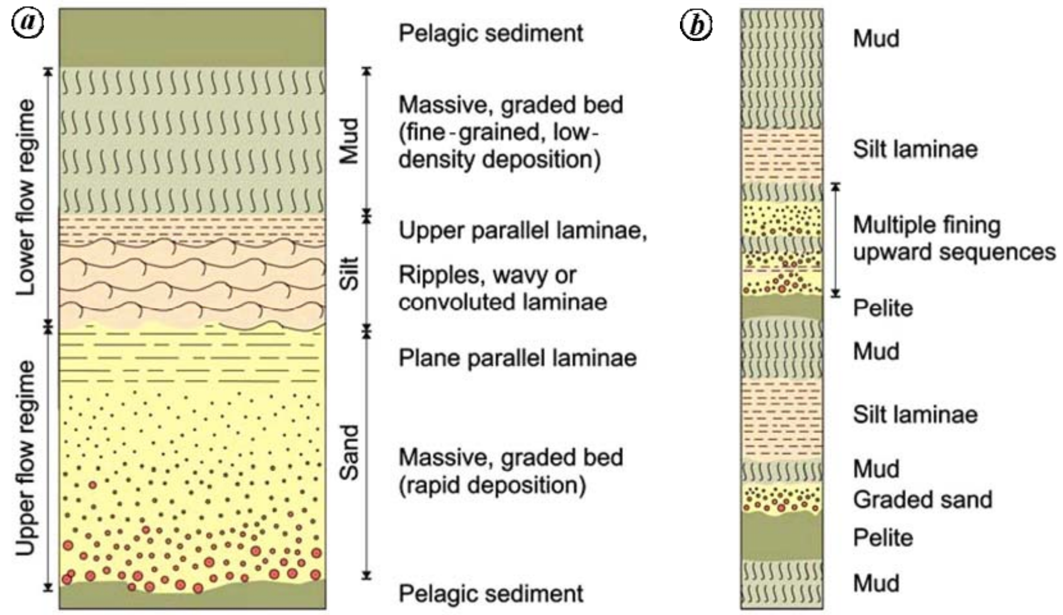

Figure 2. ***a***, A Bouma sequence[17] (modified after Shanmugam[19]). ***b***, A turbidite sequence from a core off the northern San Andreas Fault (modified after McCalpin[32]).

separated by long distances helps constrain the possible links to major earthquakes[6]. Techniques including radiocarbon age dating, geochemical, sedimentological and micropalaeontological analyses can contribute to the identification of the origin mechanism. Relative age dating is possible using events like large volcanic eruptions that may have deposited ash or volcanic glass fragments that are preserved within the turbidite column[2]. Besides providing the approximate age of an event, seismoturbidites should also help us estimate the spatial extent of rupture propagation as well as the frequency of occurrence of earthquakes, which can be used for the seismic hazard analysis in a region.

Regional setting

In the wake of the 2004 earthquake, palaeoseismological studies picked up, all along the Sumatra–Andaman subduction front, which had no record of a mega-earthquake in its documented history. In the eight years since, studies carried out in the Andaman and Nicobar Islands have explored near-source records of land-level changes due to the crustal deformation associated with seismic cycles[12]. Uplifted corals, boulder beds and raised beaches, found as multiple terraces above the mean sea level are typical of regions that were uplifted repeatedly in the seismic cycle. On the other hand, dead tree lines and mud-over-peat layers found below the present-day surface and post-earthquake waterlogged regions are evidence of land subsidence[9,21]. Evidence found along these islands can be correlated with archaeological and sedimentological evidence from regions far from the earthquake source, like the east coast of India[8,11], Thailand[14], Sri Lanka[15,21] and Sumatra[13] to better constrain the recurrence interval of large earthquakes in this region. Land-based geological records may not represent the complete sequence of events. In order to obtain a more complete and high-resolution picture of the Holocene seismicity along the Andaman and Nicobar subduction front, we considered using offshore proxies like seismo-turbidites.

Along a subduction margin, traditionally, the run-offs from rivers/glaciers with large sediment loads (deposited on the continental shelf and slope) form the material of the turbidity current. Given their area and topography, the Andaman and Nicobar Islands do not host any major rivers with large sediment loads flowing into the Bay of Bengal. While the accretionary wedge contains sediments scrapped off the subducting Indo-Australian plate, large volumes of sediment are brought into the Bay of Bengal from perennial rivers draining the South Asian land mass (Figure 1). This sediment forms the Bay of Bengal Fan and persists into the Indian Ocean, south of the equator. The fan sediments are responsible for the presence of a filled trench till about 10°N lat., where their propagation further south into the trench is impeded by the presence of the Ninetyeast Ridge and its impingement on the Sunda trench[22]. The Myanmar and North Andaman segments receive a high sediment load and a major shaking or slope instability incident due to the continued loading could result in slope failure and the generation of a turbid flow, which would carry the sediment with its organic matter and fauna down channels and canyons, across the trench axis to the abyssal plain on the subducting plate.

The 2004 earthquake rupture terminated close to 15°N, marking the Andaman–Myanmar segments a potentially hazardous zone. Turbidite sequences due to localized slumps would not reflect or correlate in cores collected along the entire length of a segment or a subduction front. A case in point would be the 1762 earthquake, which generated a tsunami, that was perhaps caused or amplified due to the slumping of sediments at the continental slope. Though complicated by the presence of the Bengal Fan sediments, it would be prudent to look for turbidite sequences to correctly estimate the size of the earthquake rupture (see also Cummins[23]). Another example is the large sediment deposit known as the 'Bassein' slide (Bassein is tributary of the Irrawaddy River), reported by Moore *et al.*[24]. Though mapped successfully, the age of this slide remains unknown. Its origin is a matter of debate, since it could be a combination of earthquake activity and a consequent sediment slump or a slide due to the continuous sediment loading from the Bassein River. Over time the toe of this slide has probably merged into the Bengal Fan sediments.

Dating the seismo-turbidites (like using the Mazama Ash beds in Cascadia; see Adams[2]) is another important consideration. Other than from radiocarbon dating, in the case of the Bay of Bengal, we could count back using the 2004 earthquake deposits, if identifiable, though we have volcanoes in the region capable of generating such a signature, the most recent of which is the 1883 Krakatoa eruption. For the purpose of developing a better constrain on the time of deposition of previous seismo-turbidites along the entire Sumatra–Myanmar arc, understanding the regional atmospheric spread patterns of volcanic ash associated with older eruptions in the region, their residence time and settling patterns are of considerable importance. Such topics are not discussed in this article.

Results from the cruise

We discuss our experiences with core citing and then briefly summarize the deep-sea coring carried out on-board the Ocean Research Vessel (ORV) *Sagar Kanya*. The swath-bathymetric survey carried out as part of the scientific agenda of cruise SK-273 was located conveniently along the Andaman trench allowing us a first-hand view of the bathymetry of the study region. As the ship made several N-S traverses, on-board data processing showed us that there were many sites, especially to the north of the study area (Figure 3) which had well-developed channels that crossed over the trench axis, that were potential sites for the preservation of turbidite sequences (Figure 4). We also had an encounter with a false positive, i.e. one of the splay faults on the accretionary wedge that had what appeared to be a channel from unprocessed swath bathymetry data. Five attempts were made to retrieve cores from sites selected through analysis of the processed bathymetric data (Table 1). A basic gravity corer was used for all the attempts and the final coring locations were selected by observing the reflectance seen on the single-beam sub-bottom profiler. Ideally, a moderate reflectance is preferred over sharp or hazy reflectance patterns, to enable easy penetration of the core barrel (especially while using a gravity corer) into the surface sediment and its subsequent retrieval. Using a single beam sub-bottom profiler, the selected core sites may not be ideal, i.e. they may have some inherent errors in their location and surface sediment types.

The last core retrieval attempt (SK-273/GC-05) was partially successful (see Figure 4, for location). Recovered in rough weather, its length was less than 0.5 m and the top 10 cm of the core was found broken and displaced from the rest, within the core liner. It was oriented in the best way possible before being packed and stored. All surface samples obtained from the five coring locations as well as sub-samples from core GC-03 (11 cm recovery) were processed on-board for performing spot-checks on their foraminifer content. On-board, a sediment volume of 5 cm^3 was taken from each sample, washed gently in freshwater on a 63 μm sieve, and examined wet in a petri dish under a binocular microscope at 10–40 times

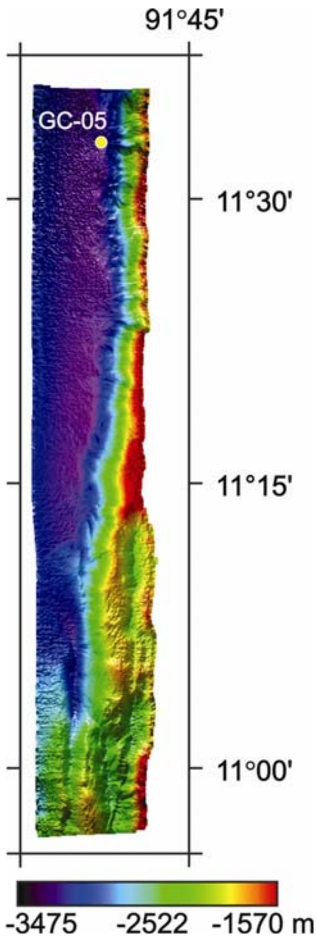

Figure 3. Processed data for the northern part of the study region with several channel systems visible that were considered as potential core sites. Core site SK 273/GC-05 is marked by a yellow circle.

Table 1. Details of coring attempted in the study area

Core type and number	Latitude (N)	Longitude (E)	Water depth (m)	Date and ship time
Successful attempt				
SK-273/GC-05	11°33.315′	091°40.855′	3230.11 m	17/06/2010 and 1945 h
Comments	40–50 cm of the topmost sediment collected. Core liner was cut, but core was not sub-sampled on-board. No sub-bottom profile image available for corroboration of surface sediment type.			
Unsuccessful attempts				
SK-273/GC-01	09°56.075′	091°49.997′	2177.20 m	14/06/2010 and 1015 h
Comments	Coring failed. Sample was impenetrable and clogged the core catcher. Surface sample stuck to outside of the corer was collected. Core catcher sample collected. No sub-bottom profile image available for corroboration of surface sediment type.			
SK-273/GC-02	09°55.379′	091°49.997′	1816.56 m	14/06/2010 and 1312 h
Comments	Coring failed. Sample was impenetrable and clogged the core catcher. Core catcher sample collected. No sub-bottom profile image available for corroboration of surface sediment type.			
SK-273/GC-03	09°55.778′	091°48.069′	2714.74 m	14/06/2010 and 1632 h
Comments	11 cm of topmost sediment collected and sub-sampled. Sample from core catcher also collected. No sub-bottom profile image available for corroboration of surface sediment type.			
SK-273/GC-04	11°32.956′	091°39.342′	3301.16 m	17/06/2010 and 1545 h
Comments	Coring failed. Topmost sediment might be sandy. Corer did not penetrate. Some sand was found in the core catcher. No sub-bottom profile image available for corroboration of surface sediment type.			

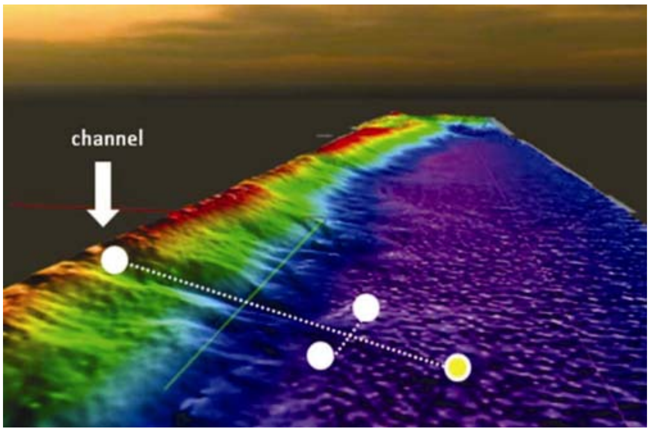

Figure 4. Screen-capture image of the core site SK-273/GC-05 (facing SSE). The yellow solid circle marks the actual core location at the distal end of the channel, sufficiently far away from the base so as to avoid erosion due to subsequent slumps. The longer dotted line marks the channel axis and the shorter dotted line marks the elevated sediment fan found at the base of the channel, on either side of the channel thalweg. The central part of the fan has probably been eroded by continued sediment slumps. Ideally cores should have been taken at the distal edges of the fan, marked by white solid circles on both side of the shorter dotted line. The elevated white solid circle marks the channel head.

magnification. In case of all the samples examined, the sediment was siliciclastic in nature, with notable mica content. Planktonic foraminifera were observed in all samples, while benthic foraminifera were rare to absent. The most abundant species recovered were *Globigerinoides* sp., *G. inflata*, *G. ruber*, *G. sacculifer*, *G. mennaridae*, *Globorotalia hirsute* and *Orbulina universa*. Characterization of the core samples based on their foraminiferal content is a key on-board task, to help isolate and identify turbidite layers in the core. For example, the near absence of benthic foraminifera and a dominance of planktonic foraminifera in this case are indicative of transportation, prior to deposition.

Post-cruise analysis

Core GC-05 was split into two halves at the National Centre for Antarctic and Ocean Research (NCAOR), Goa using a core splitter. The broken top of the core did not have a 'clean-break' nor did we manage to replace the broken sample correctly, both before and after using the core splitter. Ideally a core collected from an abyssal plain should have nothing other than fine pelagic material, especially since the site is far removed from continental land mass. The topmost sediment layers in this core were enriched in mica flakes, and contained a piece of wood – found embedded in the sediment about 10 cm from the top of the core. The date obtained (> 40,000 years BP) is beyond the acceptable age range allowed for calibration of the samples using radiocarbon dating. We believe that this sample was most likely transported and deposited, as suggested by its depth in the core. It was hard and black with sand particles stuck to it. The half-core (Figure 5 *a*) brought to the Indian Institute of Science (IISc) was subsequently scanned using a local CT scanner to determine the structures present in the core (Figure 5 *b*) and at the National Institute of Oceanography (NIO), Goa using the GeotekMulti-Sensor Core Logger (MSCL) to determine its magnetic susceptibility and gamma density values (Figure 5 *c* and *d*). The original CT scan of core GC-05 in Figure 5 *a* is redrawn as a schematic

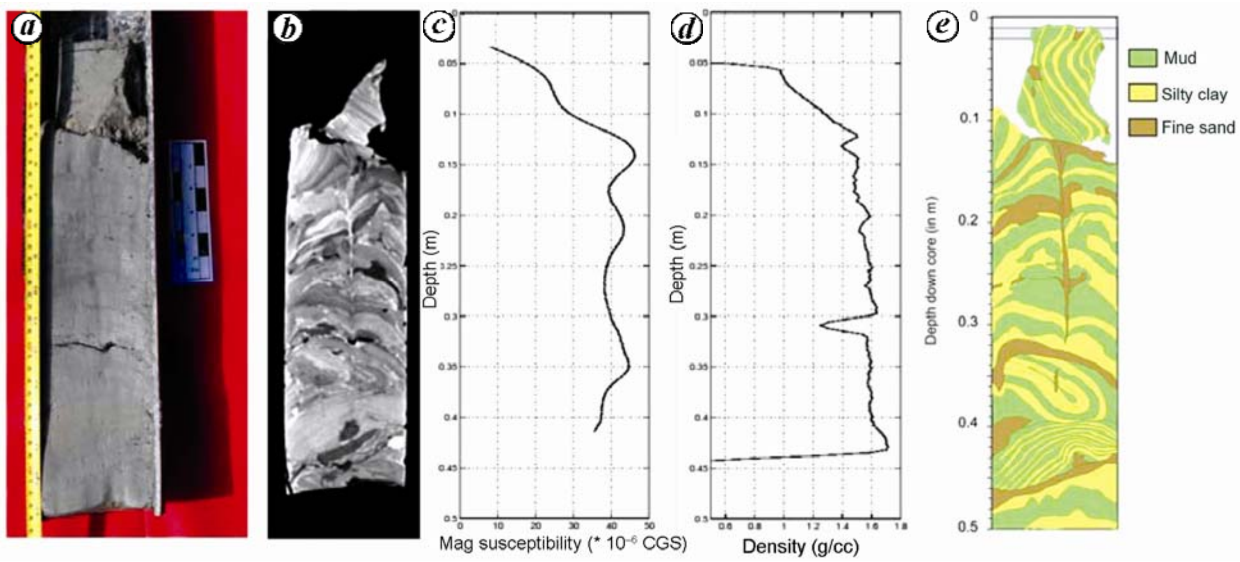

Figure 5. (***a***) Photograph, (***b***) CT scan, (***c***) magnetic susceptibility and (***d***) gamma density log of the half-core SK-273/GC-05; (***e***) Core schematic, redrawn using the CT image in correlation with visual logging of the core.

in Figure 5 *e*. The core was further cut lengthwise into two halves (quarter-cores), of which one half has been sub-sampled at 1 cm interval for the first 12 cm and 2.2 cm for the next 30 cm. The other quarter-core has been stored as an archive.

Though by-and-large a function of the monsoon and the consequent river run-off, the sediment fluxes in the northern Bay of Bengal are estimated as 50 g^{-2} $year^{-1}$ using deep sediment traps, which corroborates with an average sedimentation rate of 2–40 mm per thousand years in the region[25]. If composed of only pelagic sediments, the core should represent more than 5000 years in sedimentation history for the northern Bay of Bengal. GC-05 was collected from the distal part of the channel, on the abyssal plain. If the core is composed of both pelagic and turbidite sequences, then the age span it represents may be considerably less. For distal turbidites, rather than expecting a complete Bouma sequence, we expect to see only the (upper) lower flow regime deposition, i.e. parallel laminations of the material brought by the turbid flow (shown in Figure 5). This sediment core is most likely part of the 2004 earthquake-related turbidite deposit (we suspect, the latter part of the fining upward sequence as in a turbidite tail), though in the absence of multiple cores it is not easy to corroborate this. The split core appeared to have a uniform greenish-grey colour, though after cleaning the cut surface, we could see the presence of some layers and what appeared to be a (fine sand) dyke based on the sediment texture (Figure 5 *e*). The top sediment layers appear disturbed, which may be an artefact of using a basic gravity corer. The top 5 cm of sediment was mostly (sandy) silt, highly enriched in mica. If this sediment sequence in the core is a part of a turbidity current deposit, the sand dyke probably formed due to over-pressurization during the deposition. It is also possible that the turbidite after deposition was subjected to liquefaction due to a strong aftershock.

Three samples from the core that appeared to be rich in fine-grained sand (SK-2, SK-6 and SK-8) were analysed using X-ray fluorescence (XRF) for their elemental and oxide content. From the elemental and mineralogical analyses of the samples, we noted that the loss on ignition (LOI) values increased down-core. All the three sub-samples contain high proportions of quartz. Alumina and iron oxides were also relatively higher compared to other oxides. A low Ca/Fe ratio and high Sr peaks were noted in the samples analysed. Seismic turbidites have higher Fe and lower Ca values compared to pelagic deposits, whereas a varying Ca/Fe profile in pelagic layers will reflect a heterogeneous sediment fabric. Ca peaks are used to separate shell-rich beds from quartz-enriched layers, while higher Sr-peaks are typical of high-Sr aragonite from shallow-water sources[26]. Analysis of the further samples is required to allow us to better understand the centimetre-scale variation in the core sediment properties.

Future work

This is the first attempt of its kind in Indian waters and it has the potential to be developed into an excellent tool for understanding the seismicity and geodynamics of the Andaman and Nicobar region. Although we did not succeed in retrieving sufficiently productive cores of turbidite sequences, the preliminary results, including the retrieval of turbidite tail deposit associated with the 2004 earthquake suggest possibilities for future work. The reports on turbidite studies off Sumatra suggest that in addition to the 2004 deposit, there are eight more deposits which have been dated at 400, 600, 800, 1000, 1500, 2300, 6000 and 7100 years ago (http://active tectonics.coas.oregon-state.edu/Sumatra_turbs.htm). Our onshore geological work of the Andaman–Nicobar Islands suggests this region generated as many as five tsunamis in the last 2000 years[12]. Our study suggests that the earliest tsunamis occurred between the second and sixth centuries AD, and a subsequent tsunami occurred around AD 770–1040. This event may be the true predecessor of the 2004 event in terms of its magnitude and rupture extent. Sedimentary sections in the Andaman Islands also provided clues for a tsunami that occurred between AD 1250 and 1450. Thus, age data from Andaman–Nicobar Islands suggest that the palaeo-earthquakes and tsunamis occurred with an approximate interval of 500 years – a result that is not at variance with the studies off and on Sumatra. But not all the previous earthquakes can be full-rupture events like the 2004 earthquake. Thus a major question that remains to be resolved in these studies is the distinction between the full and partial ruptures of the subduction interface. As the Andaman segment occurs at the northern extremity of a full-rupture earthquake in the region, the turbidite cores from the subduction zone axis off the Andaman Islands will be able to provide key evidence for previous full-rupture earthquakes.

Our work also serves an equally important purpose of underscoring the deep-sea geodynamic research in the northern Bay of Bengal, especially as the region has not experienced any large earthquakes in the historical past, other than the 1762 earthquake whose magnitude and tsunamigenic nature has been reassessed to focus on the damage it caused along the northeastern coast of the Bay of Bengal[23]. On the basis of subsequent reinterpretation of historical data on the 1762 earthquake, Gupta and Gahalaut[27] suggested that it was a non-tsunamigenic event, although earlier reports on this earthquake always termed this event as tsunamigenic[28]. The submarine landslide (called Bassein slide) identified around 15°N, off the region between the southern Myanmar coast and North Andaman[24] (see Figure 1 for location) should provide the starting point for such a work. This slide covers an area of ~ 4000 km^2 and has a total volume of > 900 km^3. What generated the slide? Was it due to seismic shaking resulting from a large earthquake or due to mere slope instability of non-tectonic origin? If it was indeed due to a large earthquake sourced nearby, then is to be believed that the region is now undergoing an interseismic process? Also, if the 1941 earthquake of South Andaman and the 1762 Arakan region earthquake mark the boundaries of two historical rupture zones, then the region between them could be termed as a seismic gap, a possible location for a large earthquake. It is important to understand if the region between the North Andaman and the Irrawaddy delta (off Myanmar) could be a potential source zone for a major earthquake-cum-tsunami that poses threat not only to the east coast of India, but also the coasts of Bangladesh and Myanmar. This is an area where all these countries stand to benefit from cooperative deep-sea scientific research.

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