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Coseismic uplift, slow plant mortality and ecological impact in North Andaman following the December 2004 (M_w > 9.2) earthquake

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We present here the phenomenon of gradual decay leading to plant mortality in vast stretches (measuring several square kilometres) of vibrant mangrove forests in the coastal wetlands of North and Middle Andaman. We interpret the phenomenon as an effect of static ground uplift following the 26 December 2004 Sumatra–Andaman earthquake. The decimetre to metre scale uplift has cut-off tidal water flow into those parts of the wetlands that were elevated from intertidal to supratidal levels. The consequent thermal shock, desiccation and gradual depletion of soil salinity affected the plants in the elevated parts. However, desiccation due to lack of tidal-water inflow caused the plant mortality which took the proportions of an ecological disaster about three to four years after the earthquake. The voluminous forest debris produced by the withered plants is likely to be preserved in the coastal sedimentary sequences as peat beds and serve as palaeoseismic indicators.

Keywords: Coseismic uplift, earthquake, ecological impact, mangrove swamp, plant mortality.

WHILE discussing ground uplift in North and Middle Andaman Islands following the great Sumatra–Andaman earthquake of December 2004, we had predicted that the intertidal flora of the coastal mangrove forests that were coseismically uplifted from intertidal to supratidal levels would perish within a few years[1]. We further predicted colonization of the perished intertidal forests by sweet-water plants. To test the validity of the predictions that point to a distinct type of ecological disaster, we carried out repeat surveys of the coastal wetlands of North Andaman more than four years after the earthquake. Here we give a brief introduction to the tectonic setting of the Andaman and Nicobar Islands, and an account of what we observed in the context of our prediction. The survey revealed widespread plant mortality affecting the pristine mangrove forests of the coastal wetlands.

The 800-km-long Andaman–Nicobar chain of islands delineates the arcuate axial zone of the forearc ridge of the Indonesian subduction complex[2]. The chain of islands is broadly parallel to the subduction zone trench, known as the Sunda–Java trench[2], that represents a trace of the interface along which the Indian–Australian plate is subducting beneath the Eurasian–South East Asian plate (Figure 1). A general northeasterly convergence of the plates has been inferred[2]. Sediments deposited on the down-going oceanic plate have been scraped, and piled up by thrust faults to build up the accretionary prism and

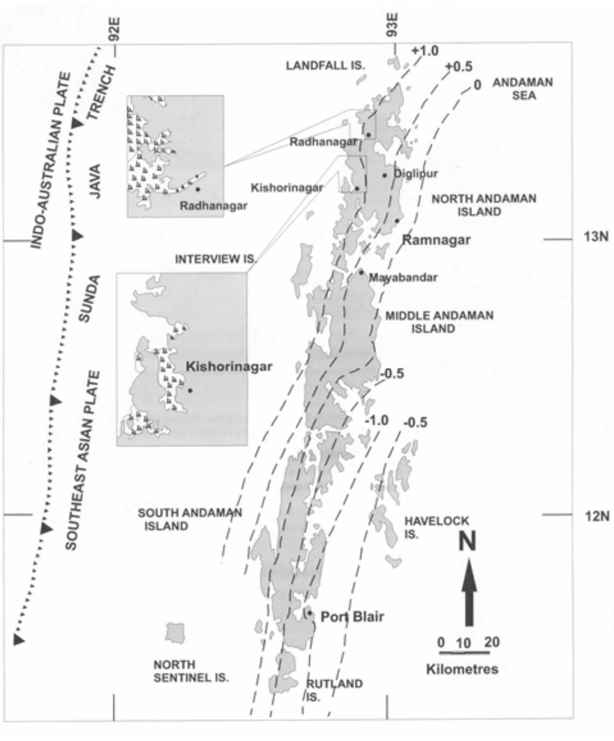

Figure 1. Map showing the location of the Sunda–Java trench[2] and distribution of coseismic vertical ground movement in the Andaman region, caused by the 26 December 2004 megathrust earthquake[1,12,13]. The dashed lines represent the contours of vertical ground movement. Values assigned to the contour lines give the estimated vertical offset in metres. The '+' and '–' signs indicate ground uplift and subsidence respectively. The '0' value contour represents the neutral line[1]. (Insets) Pre-earthquake extent of the Kishorinagar and Radhanagar wetlands. The grass symbol marks the tidal swamps (wetlands) that support dense mangrove forests. The grey shade shows the land areas. IS., Island.

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the forearc ridge. The sub-aerial parts of the ridge represent the Andaman–Nicobar group of islands[2–4]. The Narcondam and Barren Island volcanoes, about 130 km to the east of the Andaman Islands, represent the inner volcanic arc and indicate about 250 km arc–trench separation. Instrumentally recorded data[5–7] indicate that non-uniform slip up to a maximum of about 20 m distributed on a 1600 km-long eastward dipping thrust-fault rupture at the subduction zone interface generated the earthquake[5–7] of moment magnitude (M_w) > 9.2.

The earthquake was associated with regional ground uplift and subsidence, which may be explained as the vertical component of the coseismic static ground deformation that commonly affects the hanging-wall blocks of seismic faults[1,8–11]. Field mapping of the static land-level changes[1,12,13] that caused uplift/subsidence in the islands of North, Middle and South Andaman has brought out a pattern of distribution of the vertical movement (Figure 1). A neutral line, along which no vertical ground movement is discernible, separates the domain of coseismic uplift to the west, from the domain of subsidence to the east of the line. The neutral line and the contour lines of vertical ground movement (Figure 1) are broadly parallel to the trench axis. North Andaman falls within the domain of coseismic uplift that increases from 0.3 m in the east coast near Ramnagar beach to about 1.5 m near Kishorinagar–Radhanagar area in the western coast[1].

Coastal drainages and strandlines are sensitive to land-level changes by tectonic deformations[14]. In the case of slow deformation as during the inter-seismic intervals, the coastlines and the drainage systems adjust slowly to the changes. The adjustments, however, may be abrupt in response to the fast, almost instantaneous (in geological perspective) coseismic land-level changes associated with morphogenic earthquakes (i.e. the earthquakes that produce recognizable surface deformation[15]). Coseismic subsidence induces landward shift of the coastline resulting in drowning of the coasts and consequent distress, whereas uplift induces seaward migration of the coastline, exposing stretches of the seafloor. Moreover, the land-level changes lead to a change in the configuration of the intertidal zones (tidal swamps/mudflats/wetlands/estuaries), which may also shrink (Figure 2) or expand due to ground uplift and subsidence respectively[14].

The western coastline of North Andaman is indented by several tidal marshes/swamps, bays, estuaries and mudflats. Vast stretches of intertidal wetlands covered by luxuriant mangrove forests (i.e. mangrove swamps) and traversed by a network of tidal creeks occur along the western coast (Figure 1). The estimated 0.3–1.5 m uplift and its easterly tilt in the North Andaman Island have caused many changes in the coastal geomorphic pattern. The strandline has moved seaward exposing vast stretches of seabed and the fringing coral reefs[1]. Upper reaches of the tidal creeks, and streams that flow from the hilly interior of the island to the sea have dried up[1], leaving dry streambeds with stagnant pools of water. The boundary of the tidal zones has migrated towards the central drainage channels, converting the upper intertidal swamps to sub-aerial coastal uplands (Figure 2). At the

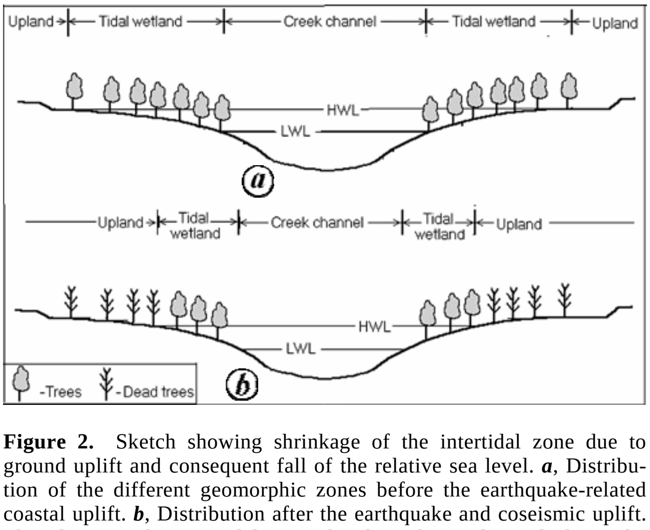

Figure 2. Sketch showing shrinkage of the intertidal zone due to ground uplift and consequent fall of the relative sea level. ***a***, Distribution of the different geomorphic zones before the earthquake-related coastal uplift. ***b***, Distribution after the earthquake and coseismic uplift. The plants in the intertidal zone that have been elevated above the high-tide level slowly wither away and perish due to desiccation. The upper boundary of the tidal zones on both sides of the central drainage channel migrates towards the channel, converting the upper fringes of the intertidal swamps to sub-aerial coastal uplands. Sweet-water plants will gradually colonize the tidal swamps that are converted to coastal uplands. HWL, High water level; LWL, low water level.

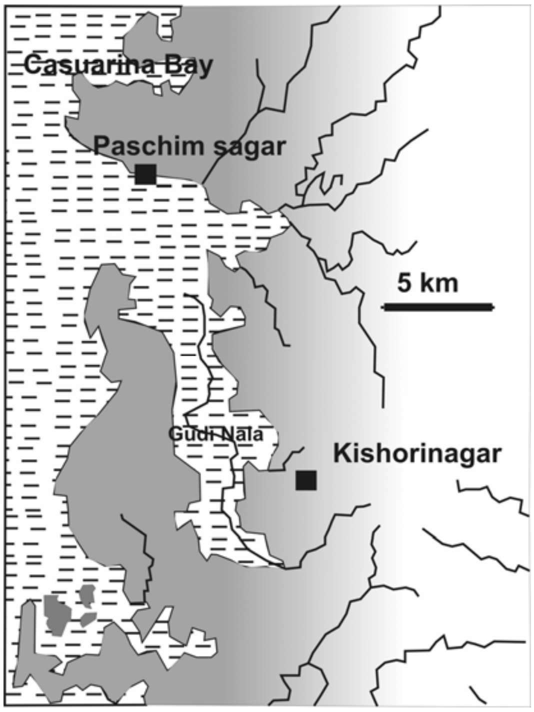

Figure 3. Drainage system in and around the tidal wetlands of the Kishorinagar area. The Gudi nala shown in the map is the central drainage of the Kishorinagar wetland. The wetlands join the open sea at the Casuarina Bay. The dashed line ornamentation marks the tidal zones and the open sea.

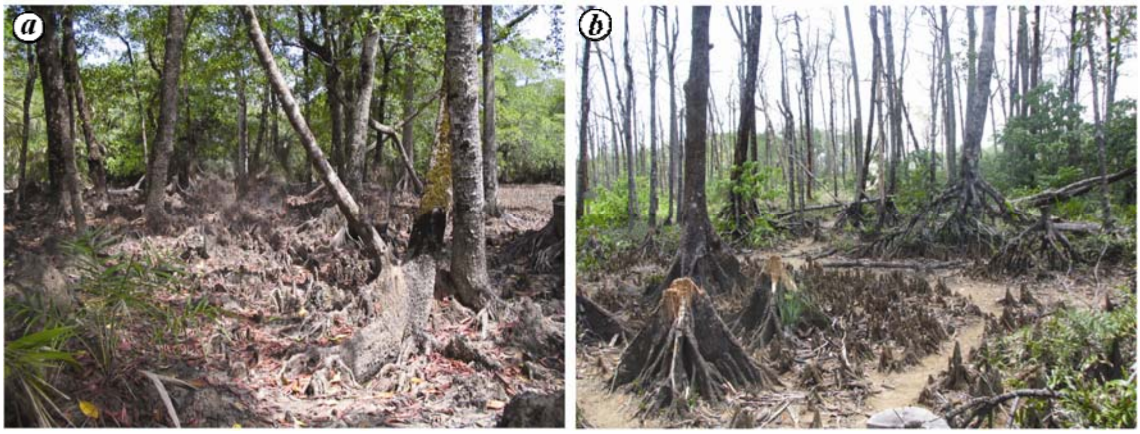

Figure 4. Impact of coseismic coastal uplift on the plants of the Kishorinagar tidal marsh. ***a***, Dense mangrove forest of the uplifted part of the wetland (tidal marsh) in May 2005. The mud and slush of this part of the wetland (seen in the photograph) have dried up to form a semisolid surface on which we could walk. Tidal water no longer submerges the area because of the coseismic uplift to supratidal level on or immediately after the 26 December 2004 earthquake. Even 20 weeks after the uplift, the lush green plants of this uplifted section do not show any sign of their impending mortality within 2–3 years. The plants are surviving on the moisture, salinity and vital nutrients still retained in the soil. The sub-aerial mangrove roots are seen in the foreground. ***b***, The same section of the forest after four years (in May 2009) shows extensive plant mortality. The dry and barren but erect stems and branches of the trees are remnants of the earlier vibrant mangrove forest of the area seen in (***a***). Gradual loss of soil moisture due to abrupt tectonic uplift caused this mortality (see text). The green, live bushes and shrubs are sweet-water plants that have grown after the uplift and will gradually colonize the area converting the pre-earthquake tidal forest to an upland sweet-water forest. The foot-track seen in the photograph is about a metre wide.

time of our field visit in May 2005, the tidal swamp near Kishorinagar (Figure 3) had become dry with only ankle-deep mud at places. We could walk around within the mangrove forest of the swamp (Figure 4 *a*), which, according to the local residents, used to be difficult before the earthquake because of knee-deep mud and slush in the area. Locally desiccation cracks have developed[1], and water from the creeks no longer submerges the area even during high tide. We attribute these changes to coseismic uplift of the area above the high-tide level[1]. We infer similar changes in terrain condition at the pre-earthquake tidal swamps near Radhanagar (Figure 1) and all other wetlands along the western coast of North and Middle Andaman Islands and the smaller islands to the west, that were uplifted above the high-tide level.

The intertidal flora needs periodic submergence of the roots and lower stems by the tidal surges for its survival. The tectonic uplift associated with the earthquake has elevated and perched large segments along the outer fringe of the pre-earthquake intertidal zones above the high-tide line. Tidal water can no longer enter into these perched tidal flats in which the mangroves and other biota of the intertidal ecosystem are likely to perish due to desiccation and thermal shock (Figure 2). The intertidal organisms, particularly the sessile species, generally perish within a couple of weeks[16] of the uplift to supratidal levels. However, in May 2005, the lush green mangrove forests of the perched intertidal zones of North Andaman (Figure 4) did not betray any sign of the impending doom that the theoretical considerations predict. We observed lush green, dense mangrove forests on both the banks along the entire 11 km tidal segment of the channel[1]. We interpreted that the mangroves and other flora of the intertidal ecosystem were surviving (in May 2005) on the moisture, salinity and vital nutrients still retained in the soil even 20 weeks after the earthquake and the coseismic ground uplift. But the salinity and moisture content in these perched zones and the nutrients that the tidal surges bring would gradually diminish leading to total mortality of the flora and the organisms that the intertidal (mangrove) ecosystem supported.

Four years later in May 2009, a boat journey along the central tidal channel of the Kishorinagar wetland revealed extensive plant mortality that has devastated the mangrove forests (Figure 5 *a*) in estimated 50–500 m wide zones on both sides of the tidal segment of the channel. On both the banks of the channel we observed 10–500 m or more wide zones of live green mangrove colony. Beyond these zones on both the banks occur the dead but still erect stumps of mangroves of the zone of plant mortality (Figure 5 *a*). The live mangroves delineate the present (post-earthquake) limit of the intertidal zone. Our rough estimates indicate that the mangrove forest of about 4–5 sq. km area has perished in the Kishorinagar tidal swamp and the estimate is about 40 sq. km for North Andaman. The pathetic sight of dry, barren, tree stumps and branches standing like skeletons of the once vibrant mangrove forests of the area (Figure 5 *b*) supports the interpretation that predicted total mortality of the intertidal forests in the perched intertidal zones within a few years. At one place we ventured within the dead mangrove forest for a closer look. In addition to the dry stems and roots of mangroves, we found (Figure 4 *b*) some green shrubs and bushes of sweet-water plants that will gradually colonize the once vibrant mangrove forests of the perched intertidal zones.

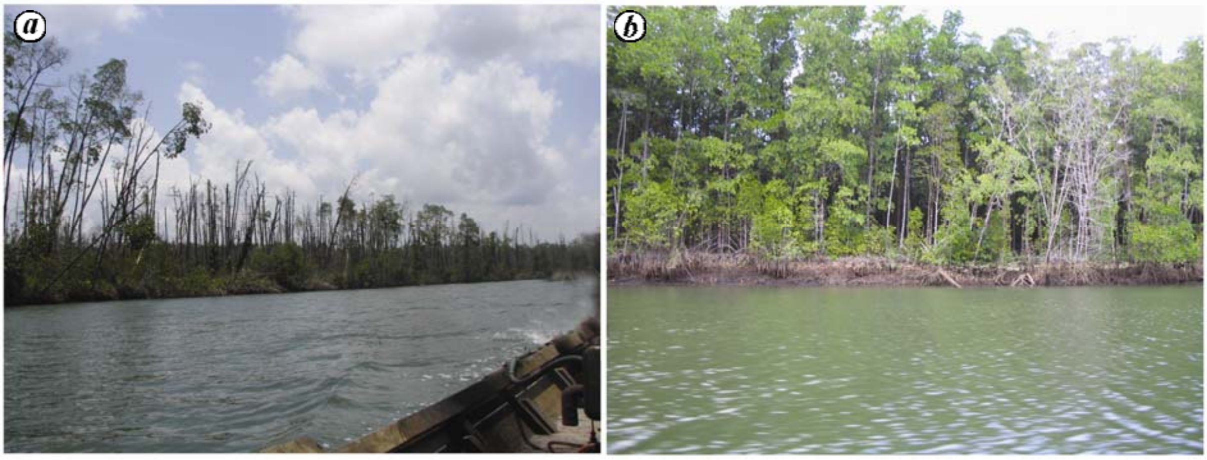

Figure 5. ***a***, Dry stems and branches of dead but erect mangrove trees four years after the earthquake (in May 2009) on the banks of the central drainage of the Kishorinagar wetland indicate extensive plant mortality destroying a large part of the pristine mangrove forests. The state of preservation of the dead trees indicates that they perished about a year ago or earlier. The live mangrove trees within approximately 10 m from the creek on the banks fall within and define the present (post-uplift) intertidal zone. The zone extends up to the present high-tide line. Beyond the high-tide line lies the plant mortality zone that extends (Figure 2) from the post-uplift to the pre-uplift high-tide lines (up to about 500 m in the photograph). ***b***, Vibrant, lush green, dense mangrove forest of the Kishorinagar wetland seen in the photograph (of May 2005) contrasts sharply with the devastated state of the forest in May 2009, and gives an idea about the extent of the mortality.

Only centimetre-scale post-seismic displacements in two years following the coseismic phase of the earthquake have been inferred in South Andaman[17]. This small and negligible post-seismic, finite, vertical movement indicates that the decimetre to metre-scale static ground uplift of North Andaman recorded[1] about 20 weeks after the earthquake was due to coseismic vertical ground movement. The desiccation of mud and slush to a semi-solid state in the uplifted segments of the Kishorinagar wetland (Figure 4 *a*), and the desiccation cracks recorded by us[1] in May 2005 indicate that the uplift, which initiated the desiccation process, occurred several weeks before May 2005 and is probably coseismic. We therefore attribute the plant mortality to coseismic ground deformation of the earthquake.

The Andaman and Nicobar region experiences a long dry spell from December to May, which is broken by the advent of the southwesterly monsoon. Subsurface percolation of the heavy monsoon precipitation dissolved and depleted the stored salinity in the soil of the perched intertidal zones. However, mangroves are capable of withstanding an extreme range of soil salinity. The floral withering therefore appears to be due to depletion of soil moisture and consequent desiccation caused by tectonic uplift of the area above the tidal reach. The withering started as the soil moisture levels depleted below the critical limit. From the dry and withered state of the mangroves (Figures 4 *b* and 5 *a*) in May 2009, we interpret that the decay started after the first rainy season and total mortality had set in after the third monsoon rains in May–September 2007. The decimetre to metre-scale vertical uplift of the vast expanse of intertidal forests in western Andaman coastal tracts severely impacted the ecological balance of this remote area and gradually assumed the proportions of an ecological disaster within three years of the uplift.

Unlike most other primary and secondary seismic hazards like collapse of man-made structures, landslides, floods, etc. that strike within minutes and hours, the hazard of plant mortality operates slowly and its impact becomes apparent about 2–3 years after the earthquake. Moreover, this type of seismic hazard is associated with only morphogenic earthquakes affecting coastal areas. Therefore, widespread plant mortality in tidal wetlands may be a reliable indicator of abrupt coastal uplift associated with such earthquakes. The uplift can be estimated by measuring the level difference between the lower and upper boundaries of the withered intertidal forests. The observed mortality in the intertidal mangrove forests therefore confirms the coastal coseismic uplift inferred[1,13] by ground surveys in Andaman Islands within weeks after the earthquake. Such an abrupt tectonic uplift destroys a part of the protective mangrove forests that can check the wrath of tsunami surges to some extent[18]. The present study shows that morphogenic earthquakes in coastal areas are potential threats for intertidal organisms and plants, and may slowly lead to ecological disasters within a few years.

The extensive plant mortality within a short span of time will generate a large volume of forest debris that is likely to be transported and preserved in the coastal sedimentary records as peat beds. The peat horizons of soil–mud–sand–peat sequences, common in the sedimentary records at subduction zone coasts[11], may owe their origin to such abrupt plant mortality, and therefore may be indicators of palaeoseismic events and provide material suitable for dating such events. We have reported one such peat bed within the sand horizons of the western coastal sedimentary sequence of North Andaman[1].

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Sexual reproduction in *Odontella regia* (Schultze) Simonsen 1974 (Bacillariophyta)

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We report here on the sequence of spermatogenesis and sperm cell count of *Odontella regia* (Schultze) Simonsen from Indian waters. The sequence of events in the spermatogenesis producing 16 spermatogonia following four differentiating (depauperating) mitosis to produce 64 sperms per cell and dehiscence is reported. Fertilization, auxosporulation and size restoration in *O. regia* are also shown.

Keywords: Depauperating mitosis, diatom, *Odontella regia*, sexual reproduction, spermatogenesis.

THE most characteristic feature of a diatom is the bipartite (made up of two halves), silicious cell wall, called the frustule. One half is larger (epitheca) and overlaps the other half, which is slightly smaller (hypotheca), analogous to a box. Diatoms reproduce vegetatively by binary fission, and two new individuals are formed within the parent cell using the parent theca as the epitheca and producing a new hypotheca. Therefore, one daughter cell retains the original size, whereas the other is slightly smaller. This brings about a steady reduction in size with every mitotic or vegetative division, and was described by the MacDonald–Pfitzer rule[1,2]. A gradual decrease in the cell diameter in centric diatoms and cell length in pennate diatoms is usually observed. Generally a diatom cell undergoes gametogenesis when it reaches about 30–40% of it original size. This size is believed to be the cue for the 'biological clock'[3], to which the diatoms respond with sexual reproduction to restore cell size. Restoration of cell size by sexual reproduction is therefore a unique feature of the diatom community[4], making sexuality obligatory rather than a factor in dormancy or dispersal[5].

It is well known that diatoms are sexual organisms. However, sexual stages are known from only a tiny minority of diatom species[6]. This lack of observation has been attributed to the long time intervals between each sexual phase in a population[5,7]. Furthermore, only a small proportion of a vegetative population is involved[8–10], thereby increasing the chances of missing out witnessing sexual reproduction.

Although 'auxosporulation' was mentioned in 1847 (ref. 11) and 'microspores' were reported as early as 1927 (ref. 12), the fact that centric diatoms underwent oogamy was only established in 1950 (ref. 13). Most of the earlier

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