Distance-related thresholds and influence of the 2004 tsunami on damage and recovery patterns of coral reefs in the Nicobar Islands

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The earthquake and tsunami of 2004 resulted in the devastation of marine and coastal ecosystems across the Indian Ocean. However, without adequate baseline information it has been difficult to properly gauge its full impact. The reefs of the Nicobar Islands in the Bay of Bengal lie on a path that ranges from 190 to 500 km from Banda Aceh, the epicentre of the 2004 tsunami. In 2008, we recorded benthic damage as a result of the tsunami to reefs off 14 Nicobar Islands across a gradient of distance from the epicentre. A clear pattern was observed in the demographic structure of the most abundant coral genera, *Acropora* and *Porites* across the distance gradient. Significantly, for the largest coral individuals of both genera (> 50 cm diameter), there were distinct threshold effects – their abundance declining dramatically in reefs closer than 350 km from the epicentre. Corals between 20 and 50 cm diameter also increased with distance from the epicentre, but in a more linear fashion. Smaller size classes either showed no apparent trend (*Acropora*) or decreased linearly (*Porites*) with distance. These genera represent very different life-history strategies: *Acropora* is fast-growing and highly susceptible to a range of disturbances, while *Porites* typically grows slowly but is resistant to disturbance. The fact that both genera showed similar thresholds indicates that, close to the epicentre, the impact of the earthquake and tsunami was large enough to override any species-specific resistance. Also, algal cover was also much higher than at locations further north, linked to higher coral mortality at these locations. However, the fact that smaller size class coral individuals were relatively abundant and even increased close to the epicentre indicates possible paths of reef recovery after the catastrophe.

Keywords: Catastrophic damage, coastal ecosystems, coral reefs, distance gradient, tsunami.

THE Sumatran–Andaman earthquake of 26 December 2004 was the second largest earthquake recorded, with a magnitude of 9.3 on the Richter scale, generating a tsunami that was recorded worldwide[1]. Many coastal locations reported tsunami waves between 7 and 12 m in height[2]. The tsunami caused extensive long-lasting damage to coastal forests, mangroves and coral reefs and resulted in a huge loss of human life and coastal infrastructure in parts of the Andaman Sea, the Indian Ocean and the Bay of Bengal[3].

A suite of co-acting factors appeared to determine its impact on coastal systems, the chief among them being distance from the epicentre in Banda Aceh, nearshore benthic topography, cover of mangroves and coral reefs, and the shallowness of nearshore reefs[4]. In some coastal areas the damage was relatively low, while in others the damage was severe. For instance, along the Indian coastline, parts of Palk Bay and Gulf of Mannar coast in Tamil Nadu were less affected[5]. On the other hand, parts of Thailand, Indonesia, Andaman and Nicobar Islands, and the east coast of Sri Lanka were severely affected[6–9]. However, in the northwestern coast of Aceh, where the tsunami was most severe[2], the overall damage to corals was limited[10]. While at a coarse scale the distance from the epicentre appears to be a good predictor of coral-reef damage, a more detailed examination suggests that the impact of the tsunami was highly context-specific, implying that the reefs respond in complex ways to disturbances like tsunamis.

The Nicobar Islands are located in the Bay of Bengal along a roughly latitudinal gradient, radiating away from Banda Aceh. The islands span a distance between 190 and 500 km from the epicentre. The extent of destruction varied between islands and it was more severe in the Nicobar than the Andaman Islands[7,11,12]. The Nicobar reefs are characteristic of Southeast Asia and are among the most diverse of all the reef areas of the Indian subcontinent[13]. Reports indicate that scleractinian corals dominated the benthic substrate at most sites before the tsunami, with estimates of 70–90% coral cover. However, they are poorly documented and there are only a few studies prior to the tsunami, most of them limited to diversity and taxonomic surveys[14–18]. Studying the marine environment of Nicobar is hindered by the remoteness of the islands and the fact that it is an indigenous community reserve with restricted access. The absence of baseline information precludes a comparative study of pre- and post-tsunami reef conditions.

In this study, benthic surveys of the archipelago were conducted in early 2008 to determine if, three years after the event, we could find patterns of impact and recovery along a gradient of distance from the epicentre. The reefs lie on a path of the epicentre of the 2004 tsunami. This provided a 'natural experiment' to examine reef response to damage across distance. Trends in reef benthic composition and the size structure of the two most common and ubiquitous genera in these reefs – *Acropora* and *Porites* were examined.

The Nicobar Islands, covering an area of 2000 sq. km, are in the southeast Bay of Bengal in the Indian Ocean.

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The archipelago comprises 21 islands, of which 12 are inhabited (Figure 1).

To the south lies the Great Nicobar group consisting of two islands > 100 sq. km, nine islets > 5 sq. km in area, and a few small islets. Among them, Great Nicobar, Little Nicobar, Kondul and Pilo Milo are inhabited, and Meroe, Treis, Trax, Menchal, Megapode, Cabra and Pigeon are uninhabited. About 58 km north of the Great Nicobar group is the Nancowry group (Figure 1) comprising three islands > 100 sq. km, two of 36 and 67 sq. km, three < 17 sq. km, two small islets and a few rocks. Except for the islets, all other islands of the Nancowry group are inhabited. The northernmost subgroup is comprised of Batti Malv and Car Nicobar, which are 88 km north of the Nancowry group. Two indigenous groups of people inhabit the Nicobar Islands, along with few settlers from the Indian mainland. The Shompen, who now number 150, are a semi-nomadic hunter-gather tribe who inhabit the forests of the central uplands. The Nicobarese have several settlements along the coast and constitute the largest tribal group of 27,000 people.

The islands receive 3200 mm rainfall annually from the southwest and northeast monsoons[19]. The western aspect of these islands is strongly influenced by waves and currents during the southwest monsoon of May–September. The eastern aspect is influenced by waves and currents during the northeast monsoon of September–January.

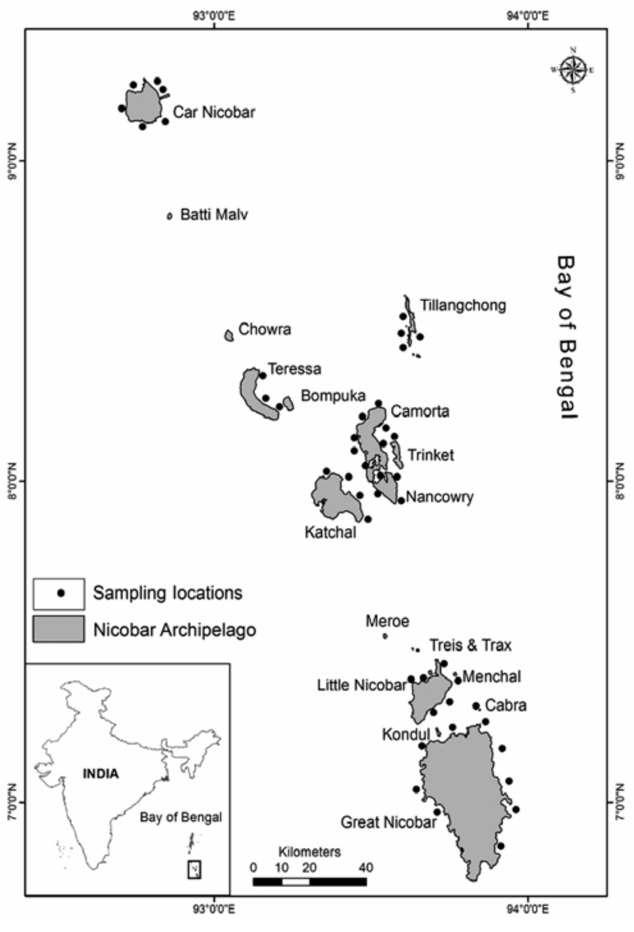

Figure 1. Map of Nicobar Islands indicating location of the study area.

Sampling was carried out in 14 islands at varying distances from the epicentre of the tsunami between January and July 2008 – islands closest to the epicentre of the tsunami (viz. Great Nicobar, Kondul, Cabra, Pigeon, Little Nicobar, Pilo Milo and Menchal), mid-distance islands (viz. Katchal, Camorta, Nancowry and Trinket), and islands farthest from the epicentre (Teressa, Tillangchong and Car Nicobar; Figure 1). Some of the smallest islands were grouped with nearby larger islands for the analysis. The islands were classified into close, mid and farther based on their distribution and natural grouping with respect to their proximity to each other.

Reefs were sampled on the eastern and western aspects of each island, wherever possible. In each island, several reef sites were systematically sampled, with a distance of 2–3 km between sites (Figure 1). At each site, six 1 sq. m quadrats were placed at 10 m intervals along a 50 m tape laid along a depth contour of the reef, parallel to the coast[20]. The number of quadrats sampled at each location averaged 30.

Within each quadrat, the cover of benthic communities and coral size classes were determined. Areal cover was assigned to the following categories: live coral, dead coral, rubble, sand, algal turf (dead coral with turf algae), fleshy macro algae, crustose coralline algae, filamentous and calcareous algae, and sessile invertebrates and soft corals. The width of the two most common and ubiquitous genera – *Acropora* and *Porites* was noted and grouped into four size classes: 1–5 cm, 5–20 cm, 20–50 cm and > 50 cm. Coral colonies with > 50% cover outside the quadrat were excluded. A regression approach was used and trends in different size classes in relation to the epicentre of the tsunami were shown with the help of scatter plots[21]. Additionally, all scleractinian corals within the sampled quadrats were photographed and identified to the genus level[22,23].

The locations were logged in a Global Positioning System (Garmin 12 XL GPS) with accuracy of ±10 m. The distance from the epicentre of the tsunami to each sampling location was estimated using Google earth software (version 6.1.0.5001).

The percentage cover of important benthic categories, i.e. live coral, tsunami-related dead coral (TDA), dead coral with algae (DCA) and rubble was averaged across quadrats for each reef and compared between islands. A generalized linear model was used with a quasi-binomial error and logit link function to statistically test for differences in benthic variables (live coral, TDA, DCA and rubble) in relation to the epicentre of the tsunami for different islands[24]. The basic assumptions of generalized linear models were followed, i.e. all data points are independent and follow a binomial or Poisson distribution (Table 1).

Table 1. Generalized linear model table comparing trends in benthic categories with distance of the islands

Model	Intercept	Slope	Dispersion parameter	*P*-value
Live coral~distance	0.326	0.001	0.309	0.001*
Dead coral~distance	0.530	0.002	0.222	0.010*
Algal turf~distance	0.371	0.001	0.253	0.002*
Rubble~distance	0.527	0.001	0.305	0.382

*Indicates the model is significant.

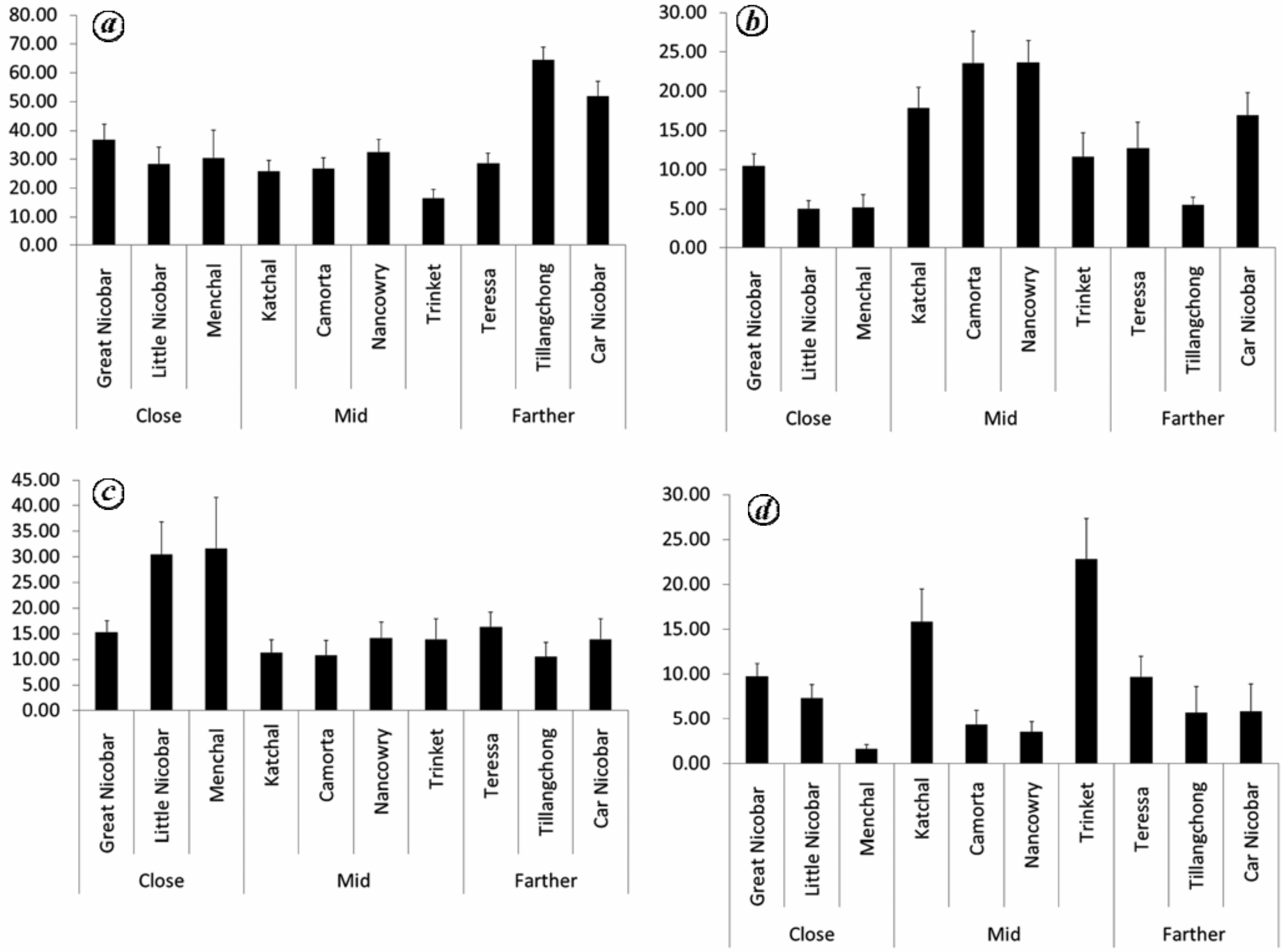

Figure 2. Percentage cover of live coral (***a***), tsunami-related dead coral (***b***), dead coral with algae (***c***) and rubble (***d***) in the Nicobar Islands reefs. Bars represent average percentage cover on the close, mid and farther islands from the epicentre of the tsunami. Error bars are standard errors.

The generic diversity of corals was averaged across quadrats for each reef and compared between islands. The Shannon–Weiner diversity index[25] was used to calculate the generic diversity for close, mid and farther islands. All analyses were conducted using the statistical program *R* 2.7.0 (ref. 26).

Three years after the tsunami, live coral cover occupied between 15% and 65% of the substrate, dead coral varied between 5% and 22%, algal cover between 10% and 30%, and coral rubble between 3% and 20% (Figure 2). The percentage cover of live coral increased with distance from the epicentre of the tsunami, whereas the percentage cover of DCA showed a reverse trend from closer to farther islands. The generalized linear model showed statistically significant difference in live coral cover, dead coral cover and algal turf between close, mid and farther islands (Table 1), indicating a distance-driven impact on the reef.

Small-sized coral individuals (> 5–10 cm) were high across distance classes for *Acropora*, whereas for *Porites* these numbers were comparatively lower. The abundance of medium-sized coral individuals (5–20 cm) of *Acropora*

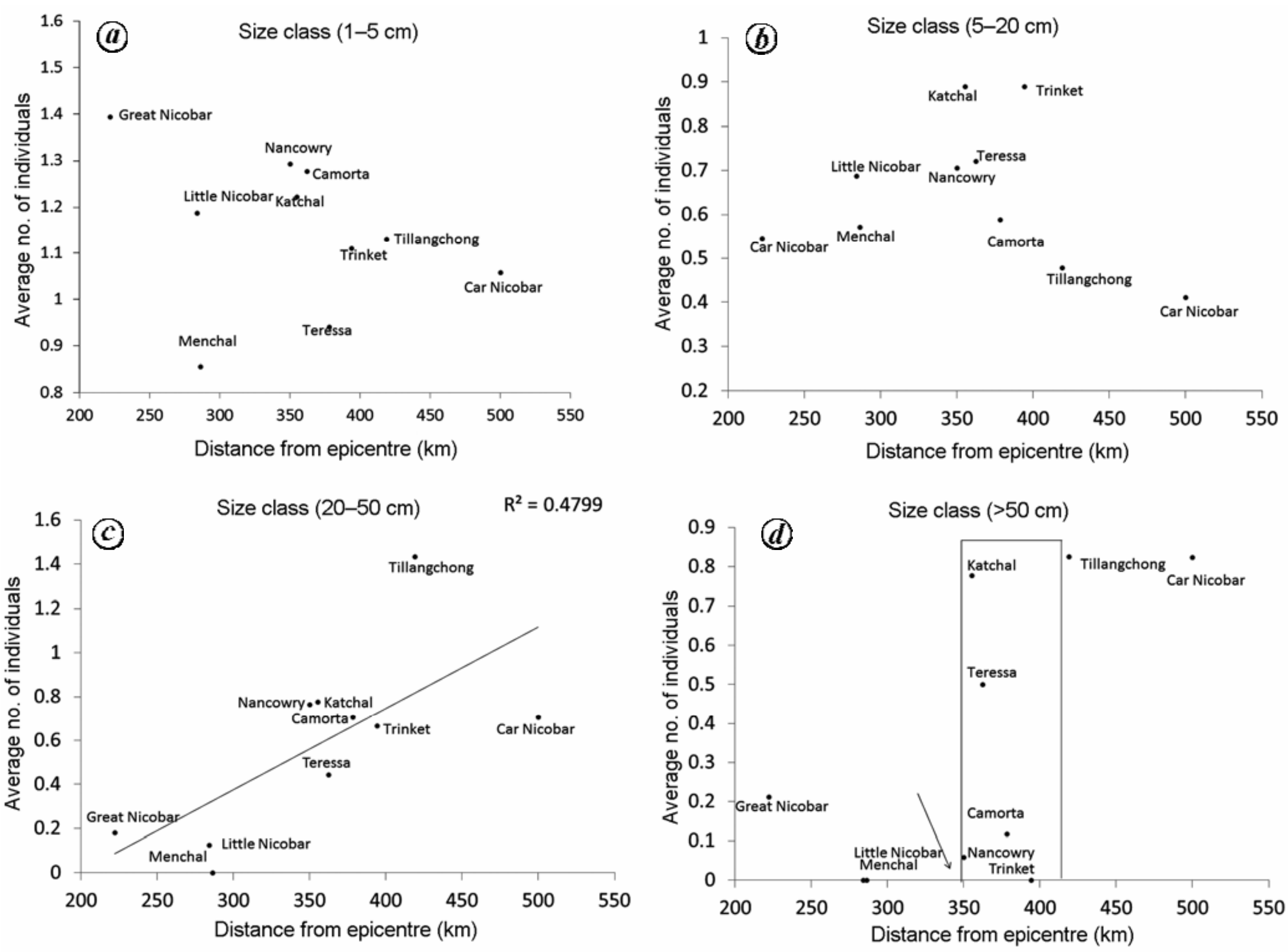

Figure 3. ***a*–*d***, Regression plots for size-class (sq. cm) structure of *Acropora* coral individuals from the epicentre of the tsunami. Bar in large sized individuals (> 50 cm; ***d***) represents a threshold indicating minimal damage to the coral reefs at distances beyond 350 km from the epicentre.

was higher than *Porites* in close, mid and farther islands, but no distinct trends were observed in this size class for both the genera across the island groups. Coral individuals in the size class 20–50 cm showed a significant linear increase with distance from the epicentre for both *Acropora* ($R^2 = 0.4799$ and $P = 0.0237$) and *Porites* ($R^2 = 0.3852$ and $P = 0.0366$).

An examination of the largest coral individuals (> 50 cm diameter) of both *Acropora* and *Porites* showed a distinct trend across the distance gradient, with an increase in the number of this size class for both the genera from the closer to father islands. A closer examination revealed an evident threshold at reefs further than 350 km from the epicentre; beyond this distance, the number of individuals in this size class for both the genera was high, indicating lower or minimal damage to coral reefs at distances beyond approximately 350 km from the epicentre.

A total of 49 genera of corals were recorded in a spatial scale of 1 sq. m quadrats. The Shannon–Weiner index of diversity H' was 3.09 for closer islands, 3.17 for mid islands and 3.01 for farther islands (Figure 3).

Data on coral size-class distribution in this study indicate that at locations closer to the epicentre, the smaller size classes were dominant compared to large size classes, which were either the low or absent. This suggests that the tsunami had a direct physical impact on the corals of these reefs and that this impact attenuated with distance (Figures 3 *a* and 4 *a*). It is encouraging to observe that post-tsunami recruitment and regrowth is proceeding apace and that these reefs are recovering relatively well.

The higher number of individuals in the medium size class of *Acropora* compared to *Porites* could be because these individuals recruited shorter period after the tsunami, whereas the medium size *Porites* indicate individuals that survived the tsunami due to their sturdy nature. It is unlikely that individuals of *Porites* in this size class could have recruited within a short period after the tsunami, since *Porites* typically grow at the rate of a few centimetres a year, unlike *Acropora* that grow much more rapidly.

Overall, high percentages of live coral cover and the large number of corals in the small and medium size

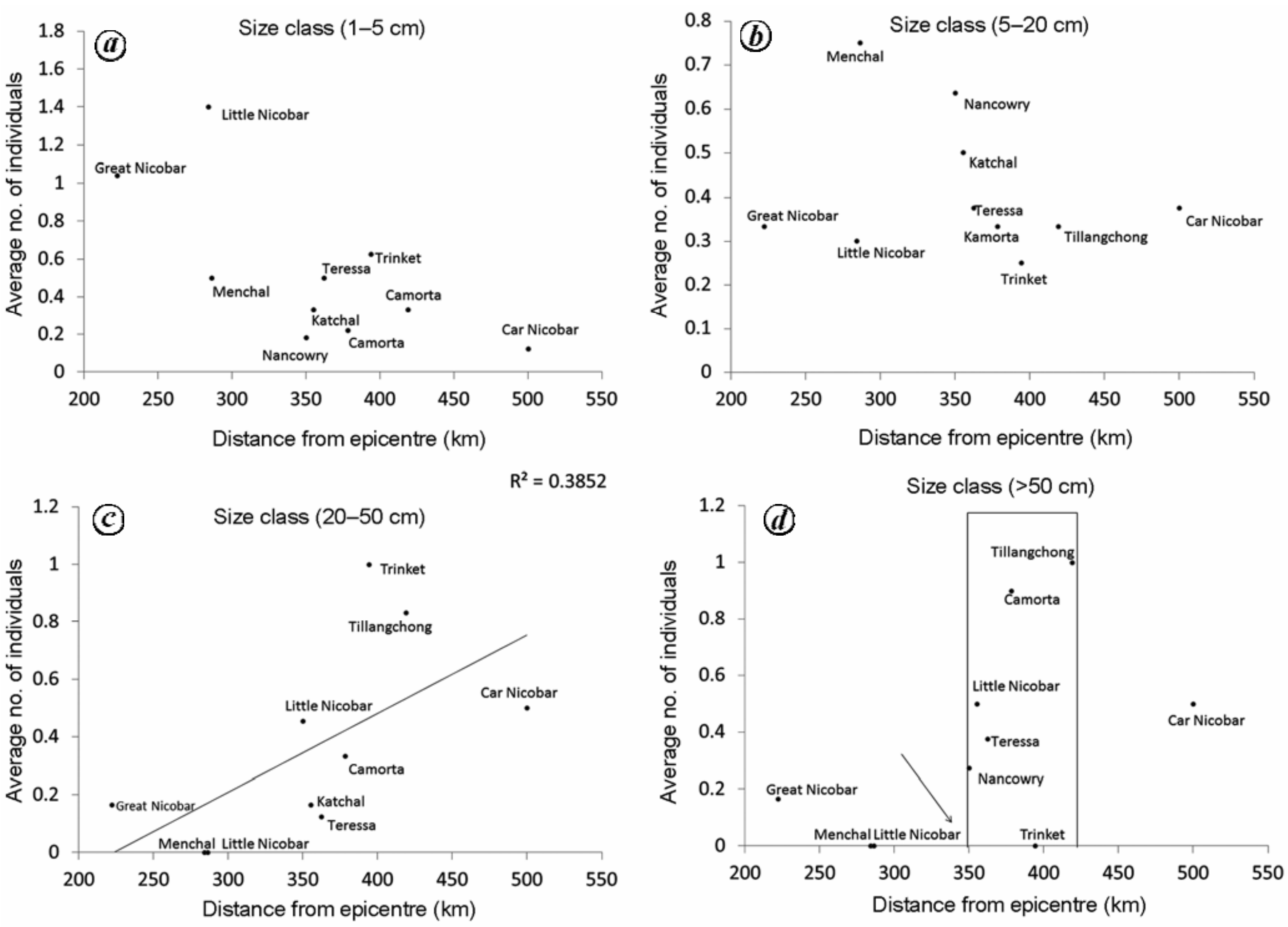

Figure 4. ***a–d***, Regression plots for size-class (sq. cm) structure of *Porites* coral individuals from the epicentre of the tsunami. Bar in large-sized individuals (> 50 cm; ***d***) represents a threshold indicating minimal damage to the coral reefs at distances beyond approximately 350 km from the epicentre.

classes suggest that rapid re-colonization has occurred in these reefs driven by strong recruitment events. If undisturbed, these individuals would potentially grow to dominate the reefs post-tsunami. The presence of a large number of coral genera clearly shows that the Nicobar Islands still retain a high coral diversity.

The distance from the tsunami epicentre played an important role in determining the patterns of benthic cover, coral size structure and apparent recovery in the Nicobar reefs. Although live coral cover varied considerably across the distance gradient, locations further from the tsunami had distinctly higher levels of coral cover, occupying as much as 60% of the substrate. At the southernmost locations, coral cover was considerably lower, and the reefs had extensive algal turfs growing on the skeletons of dead coral, rubble and bare substrate. The coral biota at these locations was also dominated by smaller size classes. Most significantly, there were clearly observable thresholds in the abundance of the largest individuals at locations closer than 350 km from the epicentre. These large individuals were potentially most susceptible to the earthquake and tsunami, and these southern reefs were scattered with dead, upturned skeletons of large coral boulders and tables that were clearly the result of the tsunami. Mid-sized individuals (20–30 cm) also showed a clear pattern of increasing away from the epicentre, but it was a more linear increase, without a distinct threshold. This suggests that the direct force of the tsunami may have influenced larger coral individuals differently and beyond 350 km, these large individuals were resistant enough to withstand the onslaught of the tsunami wave.

Acropora and *Porites* exhibited different life-history strategies in response to disturbance and recovery. While *Acropora* is typically fast-growing, it is highly susceptible to a range of different disturbances, including storm and wave damage, coral bleaching events, crown of thorns outbreaks, etc.[27,28].

In contrast, *Porites* tend to be slow-growing, but have sturdy skeletons that resist disturbances well[29]. The fact that the Nicobar reefs showed significant tsunami impacts for both genera is testimony to the fact that the force of the disturbance close to the epicentre was sufficient to override any potential species-specific differences in susceptibility.

From the evidence available it appears that in some damaged habitats extensive coral recovery has occurred as rapidly as within five years, but in many others, the recovery time is estimated to be 40–70 years, or longer[30]. Based on the present data, it is clear that the recovery potential of the Nicobar reefs is good, with observed high number of smaller individuals, a 30–40% average coral cover. The future of reefs will depend on them not being subjected to widespread mortality from any other natural calamity or anthropogenic impacts. Given favourable conditions (recruitment availability, adequate settlement substrate, high post-recruitment survival and low anthropogenic pressures), the prospect for coral recovery in even the worst-impacted reefs in the Nicobar Islands appears bright.

The absence of any pre-tsunami baseline data is the biggest constraint in this study. The lack of any quantitative studies of pre-tsunami coral communities and the degree of damage sustained has prevented a detailed examination of the successive phases of reef recovery. While this study has attempted to record changes in coral and benthic categories post-disturbance, without information on the pre-disturbance condition, it is not possible to know if the reefs are returning to the earlier condition (recovered), or if reef communities are setting a new path of species assemblage[31,32].

The geographical proximity of the Nicobar Islands to the East Indies triangle, that is believed to be a centre of radiation/origin[33,34], can potentially aid in the dispersal of elements of the marine fauna from these high-diversity regions. Though the Nicobar reefs showed high resilience to the tsunami, the potential of reef damage from bleaching and chronic anthropogenic factors has not been considered in this study[35]. Nevertheless, this study forms a baseline for future studies and provides an overview of reef condition three years after the tsunami of 2004. Research on the distribution and intensity of human activities and the overlap of their impacts on the reef ecosystem is essential. From the point of view of management, there is a need for continuous monitoring of the reefs to understand the successive phases of reef recovery.

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Authigenic carbonates in the sediments of Goa offshore basin, western continental margin of India

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Euhedral crystals (~ 1 mm) of authigenic carbonates are identified in 5 m long sediment cores collected from the western continental margin of India in water depths between 2665 and 3070 m. Low-Mg calcite and aragonite are the dominant authigenic minerals while high-Mg calcite, dolomite and siderite occur in minor amounts. Morphological evidences such as euhedral carbonate crystals and slender radiating aragonite crystals suggest that they are formed authigenically in the sediment column. The δ^{13}C values of the authigenic carbonates range between 0.63‰ and –8.12‰, and is attributed to the contribution of isotopically light carbon derived from the oxidation of sedimentary organic matter in the surficial sub-oxic Fe reduction and the bacterial sulphate reduction zone during early diagenesis. Mineralogy, morphology and stable carbon isotope signatures of authigenic carbonates and the occurrence of pyrite framboids and octahedral crystals and the evaluation of pore-fluid chemistry are not indicative of enhanced methane flux. They argue against a precipitation of carbonates due to anaerobic oxidation of methane and refute the possible connection of methane gas from the shallow gas-charged sediments to the observed carbonates.

Keywords: Authigenic carbonates, euhedral crystals, methane flux, sediment core.

AUTHIGENIC carbonates are indirect indicators of high methane flux regions which are common in areas overlying gas hydrate deposits in various geological settings[1–4]. A variety of authigenic carbonates have been observed at numerous locations adjacent to gas seepages and pore fluid venting[2,5] as individual slabs, thinly lithified pavements, vertical pillars, mushroom-like structures, microbial mats, dispersed crystal aggregates, carbonate build-ups and as micro-concretions[1]. Precipitation and consequent preservation of authigenic carbonates is mainly due to increase in pore water bicarbonate [HCO_3^-] ion concentration due to anaerobic oxidation of methane (AOM) from the gas hydrate system and concomitant sulphate reduction process in the sediment sequence[1,6–9]. Authigenic carbonates can also be formed due to degradation of organic matter during early diagenesis[3,5,10]. These processes increase pore water alkalinity by the production of bicarbonate [HCO_3^-] thus favouring precipitation of authigenic carbonate minerals in the shallow subsurface[1,7]. Determining which of the above two processes is responsible for the authigenic carbonate precipitation is essential, as it provides definite evidence for high methane fluxes either due to localized diagenetic processes or due to the presence of gas hydrates beneath[11–13]. Goa offshore basin is characterized by shallow gas charged sediments and several gas escape features[14]. Geophysical studies in the Goa offshore basin, west coast of India revealed the presence mud diapirs[15,16] and bottom simulating reflectors (BSRs) and vent-like features representing gas escape features from the seafloor[17,18]. In the northern Indian Ocean occurrences of methane-derived authigenic carbonates are reported from the Krishna–Godavari basin, eastern continental margins of India[19,20] and Makran accretionary prism off Pakistan[3,4,21] in the Arabian Sea. Recent drilling work carried out on-board JOIDES Resolution Leg-3A (ref. 22) confirmed the presence of massive authigenic carbonate nodules/concretions[23] along with more than 100 m thick accumulation of gas hydrates in the Krishna–Godavari offshore basin, and fully developed gas hydrate system in the Mahanadi offshore area, Bay of Bengal[22,24,25].

Since occurrence of authigenic carbonates can help decipher the source of gas seepages in an area[11,13,19,20,23,26], we undertook a study of authigenic carbonates from the sediments of Goa offshore basin characterized by shallow gas charged sediments[14,27]. In the present study, we report the occurrence of dispersed authigenic carbonates in

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