IMPACT OF THE SUMATRAN TSUNAMI ON THE GEOMORPHOLOGY AND SEDIMENTS OF REEF ISLANDS: SOUTH MAALHOSMADULU ATOLL, MALDIVES

BY

PAUL S. KENCH,[1] SCOTT L. NICHOL,[1] ROGER F. McLEAN,[2]
SCOTT G. SMITHERS,[3] and ROBERT W. BRANDER[4]

ABSTRACT

Mid-ocean atoll islands are perceived as fragile landforms being physically susceptible to climate change, sea level rise and extreme events such as hurricanes and tsunami. The Sumatran tsunami of 26 December 2004 generated waves that reached reef islands in the Maldives 2,500 km away, that were up to 2.5 m high. Here we present observations of the affects of the tsunami, based on pre- and post-tsunami topographic and planform surveys of 13 uninhabited islands in South Maalhosmadulu atoll, central Maldives. In contrast to the devastation along the continental coasts subjected to the tsunami, and also to the infrastructure on inhabited resort, village, capital and utility islands in the Maldives, our surveys show there was no extreme island erosion or significant change in vegetated island area (generally <5%). Instead, the tsunami accentuated predictable seasonal (monsoonal) oscillations in shoreline change promoting localised retreat of exposed island scarps, commonly by up to 6 m; deposition of cuspate spits to leeward; and, vertical island building through overwash deposition, up to 0.3 m thick, of sand and coral clasts covering a maximum 17% of island area. The main erosional and depositional signatures associated with the tsunami were scarping and gullying, and sand sheets and spits respectively. It is believed that these signatures will be ephemeral and not permanent features of the Maldivian islandscape.

INTRODUCTION

The Maldives form a 750 km long archipelago comprising a double chain of 22 atolls that extend from 6°57'N to 0°34'S in the central Indian Ocean (Fig. 1a, b). The archipelago forms the central section of a larger geological structure that stretches from the Lhakshadweep (to the north) to Chagos Islands (in the south). The Maldivian atolls are host to more than 1,200 reef islands that are mid- to late-Holocene in age (Woodroffe 1993; Kench et al., 2005). The islands are small, and rarely reach more than 2-3 m above

[1]School of Geography and Environmental Science, The University of Auckland, Private Bag 92019, Auckland, New Zealand. email: p.kench@auckland.ac.nz
[2]School of Physical, Environmental and Mathematical Sciences, University of New South Wales, Canberra, ACT 2600, Australia
[3]School of Tropical Environment Studies and Geography, James Cook University, Queensland 4811, Australia
[4]School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW 2052, Australia

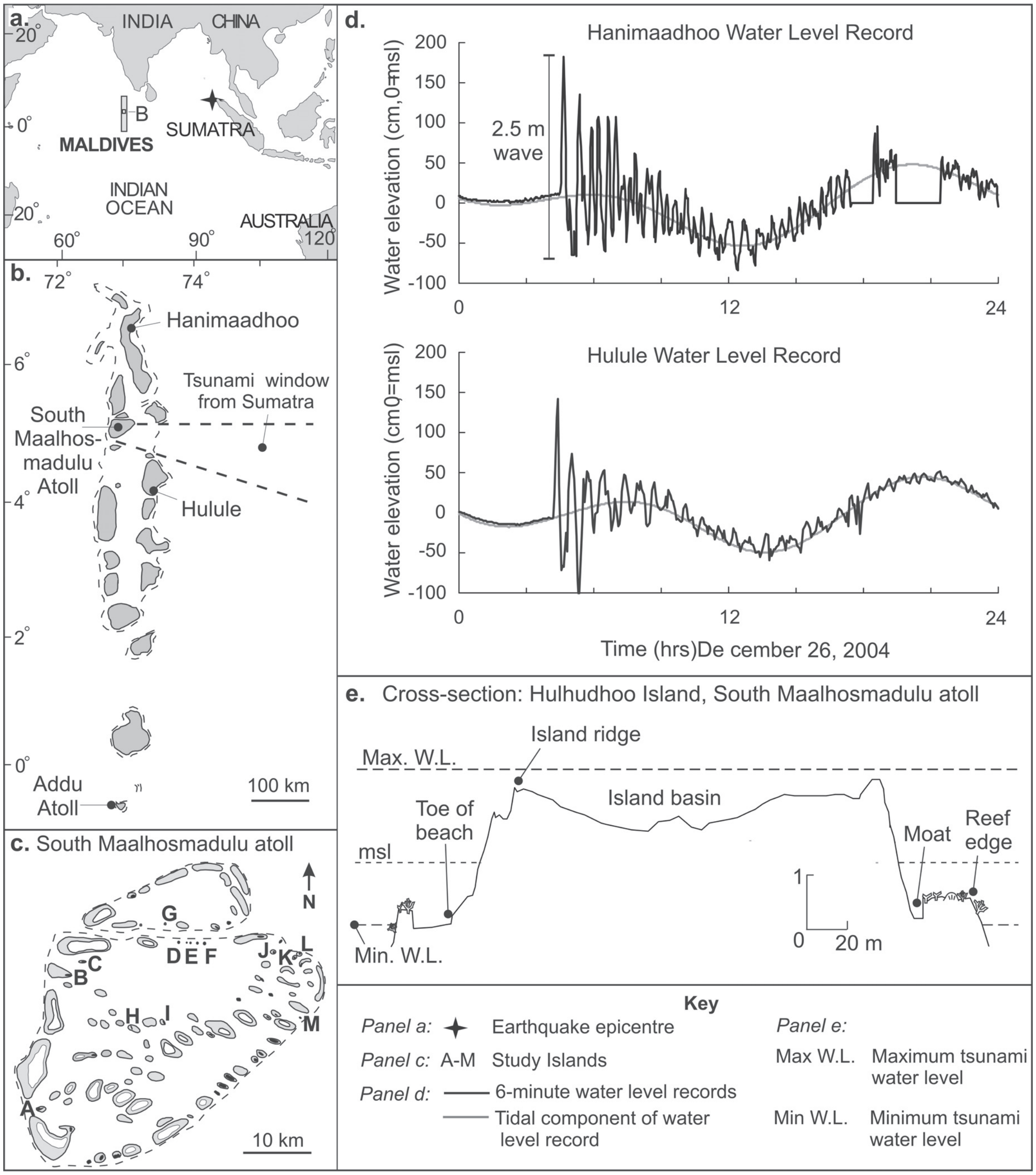

Figure 1. Location of Maldives and South Maalhosmadulu atoll in relation to the epicenter of the Sumatran tsunamigenic earthquake (A-C); Water level records from the northern and central Maldives (D); Surveyed west-east cross-section of Hulhudhoo Island showing maximum and minimum water levels occurring with passage of the first tsunami wave as recorded at the Hanimaadhoo tide gauge (E). Water level records provided by the University of Hawaii Sea Level Center.

sea level. They are made up of unconsolidated calcareous sand and gravel sediments derived from skeletal remains of organisms living on the adjacent reef including coral, coralline algae, foraminifera and molluscs. The Maldivian islands are located in a predominantly storm-free environment with a process regime marked by strong seasonal reversals in monsoonal conditions from the west (April to November) and northeast (December to March) that govern short-term changes in island shorelines (Kench et al., 2003). Notably, it was during the northeast monsoon that the Boxing Day 2004 tsunami struck the Maldives with tsunami waves also emanating from the east.

In recent years, it has been argued that the combination of their small size, unconsolidated sediments and low elevation means that the Maldives are particularly sensitive to climate change and rising sea level. Indeed, it has been suggested that the future habitability of these islands is in doubt. Not only are the long-term impacts seen as threatening, but also the impact of contemporary extreme natural events such as tropical cyclones and tsunami. Although the Maldivian islands are not located in a tropical cyclone generating area, they are subject to flooding and swell waves from far distant areas (Harangozo, 1992; Kahn et al., 2002) and tsunami, though the impact of tsunami on the Maldives has not been reported previously. For instance, there is no mention of tsunami in Maniku's (1990) comprehensive summary of changes in the topography of the Maldives. In fact, the role of tsunami in the geological development of atoll islands has only been inferred (Vitousek, 1963) and attempts to distinguish between tsunami and storm deposits in reefal areas in general has not been successful (Bourrouilh-Le and Talandier, 1985; Nott, 1997).

This article presents detailed observations on the geomorphic and sediment changes on reef islands in South Maalhosmadulu atoll, Maldives, resulting from the Sumatran tsunami in December 2004. The observations reported here were made six weeks after the tsunami and were compared with our previous surveys of the islands carried out in 2002 and 2003. These earlier surveys examined the Holocene evolution of islands (Kench et al., 2005), the morphological adjustment of islands to seasonal monsoon shifts in wind and wave patterns (Kench and Brander, 2006), and documented the process regime that controls reef island change (Kench et al., 2006).

THE TSUNAMI WAVES IN THE MALDIVES

The tsunami of December 26th 2004 was generated by a magnitude Mw 9.3 earthquake off the northwest coast of Sumatra (Stein and Okal, 2005). The Maldives were in the direct path of the tsunami in its westward propagation across the Indian Ocean. The first tsunami waves reached the Maldives, situated 2,500 km west of Sumatra, 3.5 hours after the earthquake.

Water levels (Fig. 1d) recorded in the northern region of the archipelago (Hanimaadhoo) indicate that the islands were impacted by an initial 2.5 m high wave with water levels reaching 1.8 m above mean sea level (msl). During the following six hours, an additional 5-6 waves, diminishing in height from 1.8 – 1.2 m, impacted the islands at periods of 15-40 minutes. Water levels recorded in the central archipelago (Hulhule) showed a slightly reduced initial wave height of 2.1 m with water levels of 1.6 m above msl (Fig. 1d). Subsequent waves were also much lower than in the north. The highest waves during the tsunami were coincident with a neap high tide and combined with an ambient southerly swell of about 0.75 m resulted in water levels sufficient to inundate islands across the archipelago (Fig. 1e).

Reconstructions of the tsunami wave height across the Indian Ocean show that interaction of the waves with the Maldives archipelago and broad carbonate bank, extracted significant energy from the initial wave, reducing the height by approximately 0.5 m in its propagation westward across the Indian Ocean.

While the tsunami waves were not as large as those that traveled to the continental margins of southeast and south Asia, they nevertheless had catastrophic consequences, particularly on the inhabited islands. Over 80 lives were lost and a further 100,000 people (1/3 of the population) were affected by the tsunami. Fifty-three of 198 inhabited islands suffered severe damage to infrastructure, while several of the worst affected islands were abandoned (UNEP, 2005).

STUDY ATOLL AND ISLANDS

The focus of this study is South Maalhosmadulu atoll (Fig. 1b, c), located in the central zone and western side of the archipelago. Tsunami waves were able to propagate toward the atoll through a 60 km wide window, between two eastern atolls where depths greater than 2000 m are reached (Fig 1 b). The atoll is approximately 40 km long and wide, and has a discontinuous rim characterised by numerous deep passages up to 40 m deep and 4500 m wide. The effective aperture of the atoll rim (proportion of gaps in the reef) is 37% which allowed propagation of tsunami waves through the atoll lagoon. Eye-witness accounts and photographs taken on Kendhoo Island, situated in the north-central part of South Maalhsomadulu, suggest that waves were manifest as quickly rising surges of small, progressive bores lacking the size and power of the tsunami waves that impacted continental shorelines.

South Maalhosmadulu contains 53 islands found on peripheral and lagoon reefs, with most islands concentrated on the east to southeastern side of the atoll (Fig. 1c). Some of the islands were described by Gardiner (1903: 380-386). Kench et al., (2005) have shown the islands are low-lying accumulations of calcareous materials of mid-Holocene age. Here we present results from repeat surveys on thirteen islands located across the atoll. The islands and their reef platforms have differing dimensions and shapes that are mirrored in the islands they contain and which occupy varying proportions of the reef flat (Table 1).

METHOD

In January 2002, a network of benchmarks was established on 13 uninhabited islands on South Maalhosmadulu atoll (Fig. 2). The number of benchmarks on each island was a function of island size and shape, but was generally between four and six, the locations representing the dominant shoreline exposures. Initial cross-shore beach and reef profiles were surveyed by automatic level. Planimetric details of the vegetation edge and toe of beach lines were mapped using global positioning system (GPS) surveys with Trimble ProXL and Trimble Geoexplorer 3 instruments with a mean horizontal positioning error of +/- 1.8 m. A full description of the methodology and subsequent data analysis associated with the GPS surveys is given by Kench and Brander (2006).

Table 1. Physical characteristics of study islands and reefs in South Maalhosmadulu atoll.

Island	[a]Reef Area (m^2)	[b]Island footprint (m^2)	[c]Veg. area (m^2)	Beach area (m^2)	Isld. length (m)	Isld. width (m)	% reef occupied by Island
Gaaviligilli	990,000	23,130	17,701	5,429	336	129	2.4
Fares	3,579,945	125,297	101,585	23,713	691	212	3.5
Dhakandhoo	219,136	62,121	45,041	17,080	499	158	28.4
Keyodhoo	88,796	28,985	21,702	7,283	218	180	32.6
Hulhudhoo	85,512	39,236	30,579	8,657	249	209	45.9
Udoodhoo	222,275	124,340	112,957	11,383	409	403	55.9
Boifushi	132,000	10,447	0	10,447	266	55	7.9
Nabiligaa	189,000	21,822	2,069	19,753	596	61	11.6
Mendhoo	270,000	145,907	130,346	15,561	626	320	54.0
Madhirivadhoo	170,920	57,060	40,083	16,977	339	261	33.4
Milaidhoo	350,322	51,390	36,070	15,320	341	216	14.7
Thiladhoo	217,189	46,547	33,375	13,172	281	220	21.4
Aidhoo	149,620	32,316	23,650	8,666	414	110	21.6

[a]Reef area calculated from aerial photographs. [b]Island footprint refers to both the vegetated stable island and the dynamic outer beach. [c]Vegetated area. Island area values calculated based on January 2002 gps surveys.

The cross-section and planimetric morphological surveys were repeated for a sub-set of eight islands in June 2002 and February 2003 to document seasonal island dynamics in response to changing monsoonal conditions. The findings are described by Kench et al. (2003) and Kench and Brander (2006) and represent a baseline against which tsunami impacts can be quantified and assessed.

Both plan and profile surveys were repeated six weeks after the tsunami in February 2005. All of the original 13 islands were measured to assess potential changes in island area, shape, position and sediment volume in response to the tsunami waves. Additional mapping and surveying of tsunami inundation zones was conducted using both automatic level and GPS. Erosional and depositional imprints of the tsunami were also surveyed with subsurface stratigraphy being observed through trenching and shallow coring.

PLAN AND PROFILE SURVEY RESULTS

Results of plan and profile surveys on each island are summarized in Figures 3-14 and described below, from east to west across the atoll. Changes in vegetated island area and area of island beach footprint are summarized in Table 2 for all islands. Photographs are presented at the end of the text.

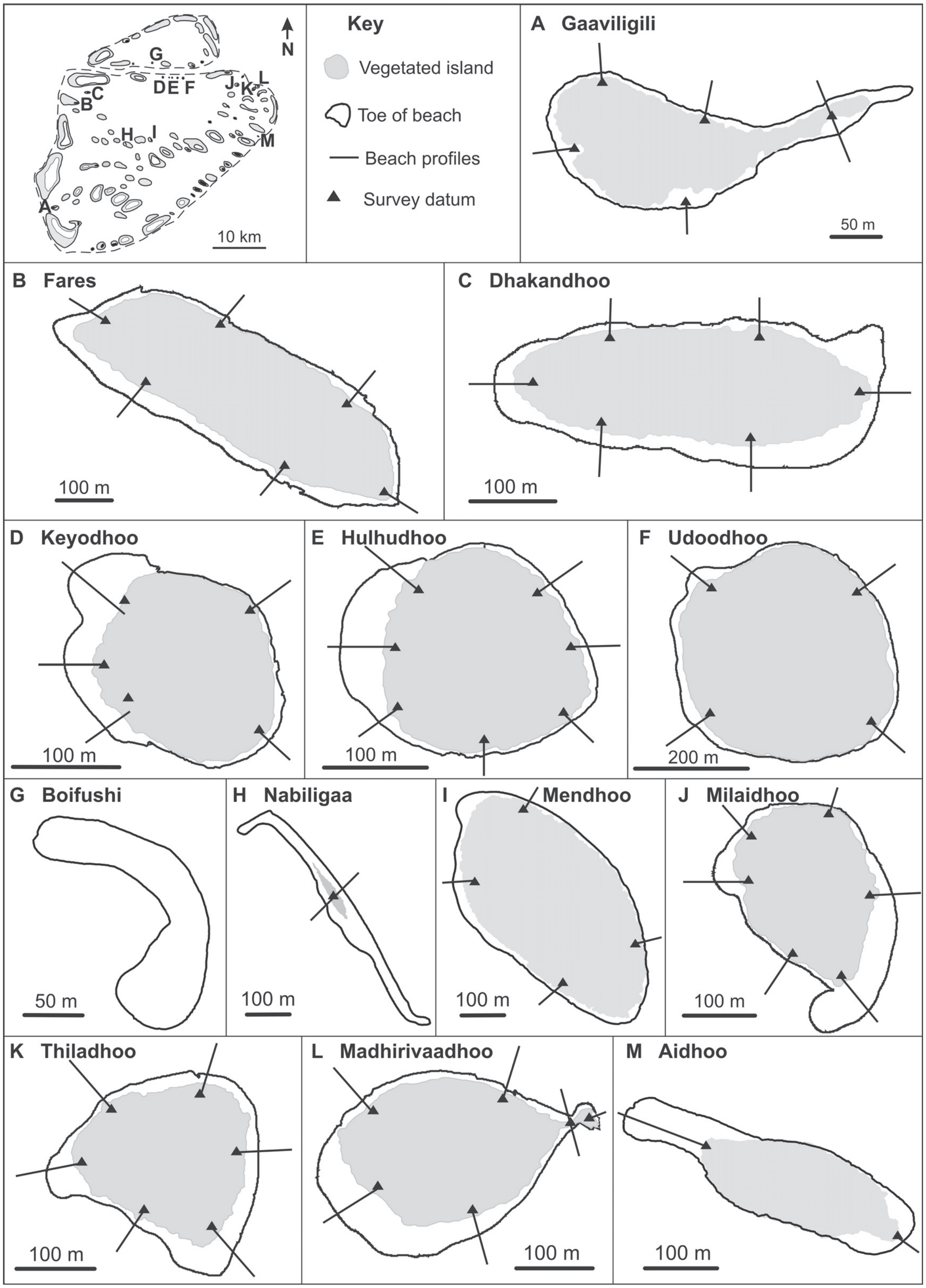

Figure 2. Surveyed islands on South Maalhosmadulu atoll showing vegetated island area and toe of beach line in January 2002 based on GPS surveys, and location of island-beach-reef profiles and benchmarks.

Table 2. Summary and comparison of pre- and post-tsunami surveys of island characteristics in South Maalhosmadulu atoll.

Island	Pre-tsunami surveys				Pre-tsunami dynamics of island beach					Post-tsunami Surveys		Pre- vs post-tsunami changes in reef islands			Tsunami impacts		
	[a]Veg. isld. Area	[b]Beach area			[c]Seas. change	[d]Seas. change	Net change Jan 02 Š Feb 03	[e]Annual change	[f]Mean beach area NE	[a]Veg. isld. Area	Beach area	[g]Beach area	[h]Veg area	[i]Beach expan-sion	Max. Over-wash depth	Area over-wash	Scarped shoreline
	Jan 02 (m^2)	Jan 02 (m^2)	Jun 02 (m^2)	Feb 03 (m^2)	(m^2)	(%)	(m^2)	(%)	(m^2)	(m^2)	(m^2)	(%)	(%)	(m^2)	(m)	(%)	(%)
Aidhoo	23,650	8,666	-	-	-		-	-	8,666	21,521	11,916	37.5	-9.0	5,079	0.10	17.4	21
Madhirivad.	40,083	16,977	18,141	15,620	2,521	± 15	-1,357	-8.0	16,298	36,848	15,572	-4.5	-8.07	2,490	0.20	16.0	54
Thiladhoo	33,375	13,172	14,114	14,885	942	± 7	1,713	13.0	14,029	31,252	15,128	7.8	-6.36	3,163	0.30	17.4	28
Milaidhoo	36,070	15,320	18,619	14,821	3,798	± 25	-499	3.3	15,070	34,087	19,169	27.2	-5.5	3,671	0.30	14.1	40
Udoodhoo	112,957	11,383	18,730	11,163	7,567	± 66	-220	-1.9	11,273	112,867	11,209	-0.6	-0.08	1,550	0.04	9.1	17
Keyodhoo	21,702	7,283	8,408	8,049	1,125	± 15	766	10.5	7,666	21,846	6,195	-19.2	0.67	1,572	0.10	4.7	30
Hulhudhoo	30,579	8,657	10,734	9,975	2,077	± 24	1,318	15.2	9,316	29,521	8,222	4.3	-3.46	1,154	0.13	12.8	31
Boifushi	0	10,447	10,553	10,446	107	± 1	-1.0	-0.01	10,447	0	9,331	-10.7	0	2,482	0.0	100	0
Nabiligaa	2,069	19,753	-	-	-	-	-	-	19,753	536	23,024	17.2	-80.47	9,729	0.10	48.0	23
Mendhoo	130,346	15,561	-	-	-	-	-	-	15,561	129,866	17,754	14.1	-0.37	3,396	0.10	<1.0	0
Dhakandhoo	45,041	17,080	12,875	19,421	6,546	± 38	2,341	13.7	18,251	42,782	20,535	12.5	-5.2	2,915	0.20	7.7	27
Fares	101,585	23,713	19,128	23,114	4,585	± 19	-599	-2.5	23,413	99,746	26,136	11.6	-1.8	1,914	0.10	0.7	24
Gaaviligilli	17,701	5,429	-	-	-	-	-	-	5,429	17,500	6,321	12.7	-1.14	1,609	0.10	10.3	26

[a]Vegetated island area. No significant change was observed between January 2002 and February 2003. [b]Area of beach that extends from the vegetated island ridge and intersects the reef platform. [c]Maximum seasonal changes in beach area. [d]Maximum seasonal fluctuation as percentage of Jan 2002 beach area. [e]Net annual change in beach area. [f]Net annual change as percentage of January 2002 beach area. [g]Change in beach area as percentage of the mean beach area in the NE monsoon from baseline monitoring. [h]Change in vegetated island areas as percentage of the 2002/3 vegetated island area. [i]Area that toe of beach extends beyond both the Jan 2002 and Feb 2003 footprint. All calculations based on GIS analysis of GPS surveys.

Eastern Islands

Aidhoo (Figure 3). Aidhoo, the easternmost of the surveyed islands comprises a sequence of gravel ridges on its eastern margin, whereas the western end of the vegetated island is composed of sand. A sand spit extends lagoonward, towards the northwest for over 150 m across the reef platform. Comparison of pre- and post- tsunami GPS surveys indicates that the vegetated island area was reduced by 9% with most of this reduction occurring along the southern and northern shorelines where erosional scarping was notable (Fig. 3).

Little change was detected in the toe of beach GPS surveys, and in the profiles across the eastern gravel ridge sequence (Fig. 3 b). Note however, that the beach toe retreated a short distance along both the northern and southern flanks of the island. In contrast, the trailing sand spit extended lagoonward both to the north and west toward the edge of the reef platform and beyond the footprint of the beach of earlier surveys. This expansion represents an increase in beach area of about 37% which extends across approximately 5,000 m^2 of reef surface.

Figure 3 also shows that the island surface experienced wave inundation from the tsunami. Overwash sediments consisting of discontinuous veneers of sand together with deposits of coarser coral gravel covered approximately 17% of the vegetated island surface extending from the eastern end of the island along most of the northern shoreline.

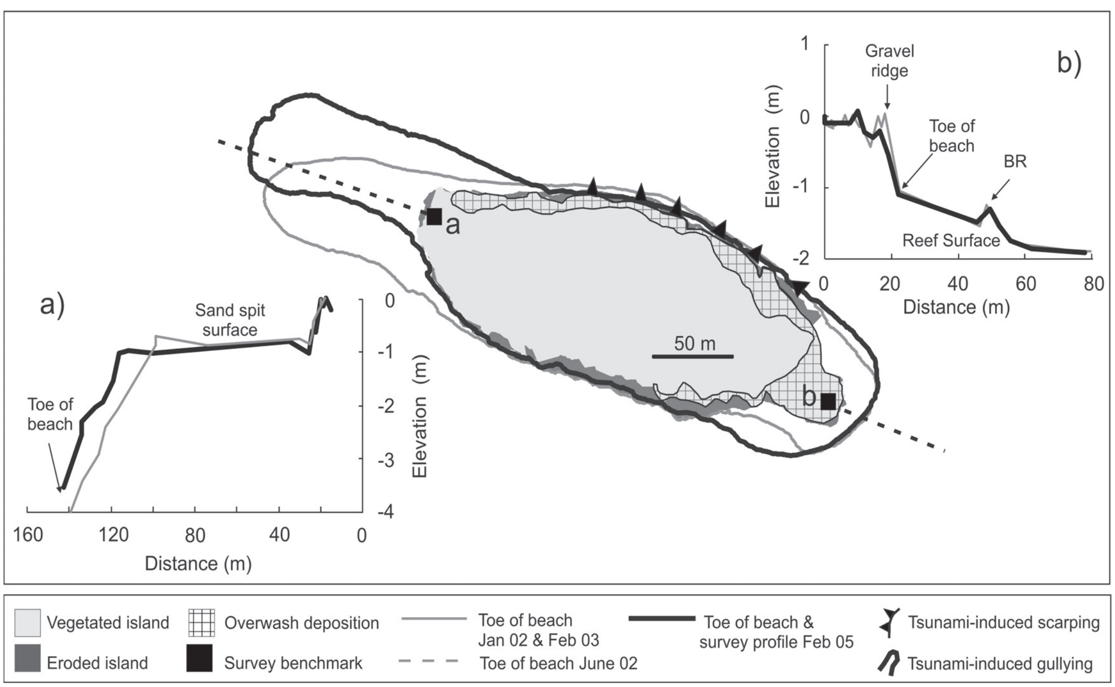

Figure 3. Pre- and post-tsunami plan and profile changes on Aidhoo Island. Location of island shown in Figure 2.

Madhirivadhoo (Figure 4). Mahirivadhoo, the northernmost of the study islands, consists of a small gravel island situated close to the reef edge in the east, and a much larger sand island that occupies the central to southwestern sector of the reef platform. Prior to the tsunami, the two parts of the island were connected by a narrow sand tombolo but during the tsunami the tombolo was breached and a 10 m wide channel separated the two islands when surveyed in February 2005 (Fig. 4, Plate 1). Pre- and post-tsunami GPS surveys record significant erosion along the northern to southeastern shoreline (Fig. 4) which accounted for about an 8% loss in vegetated island area. These sectors, totaling 54% of the shoreline, also exhibited distinct scarping, including root scour that undermined vegetation at the island margin (e.g. Plate 2).

Surveyed cross-sections clearly show both erosional and depositional signatures with shore retreat by up to 6 m (Fig. 4b) and extensive overwash sedimentation covering 16 % of the island (mean depth 0.2 m) primarily on the north to southeastern sections of the island (Fig. 4). Paradoxically, in these same areas the position of the toe of beach had

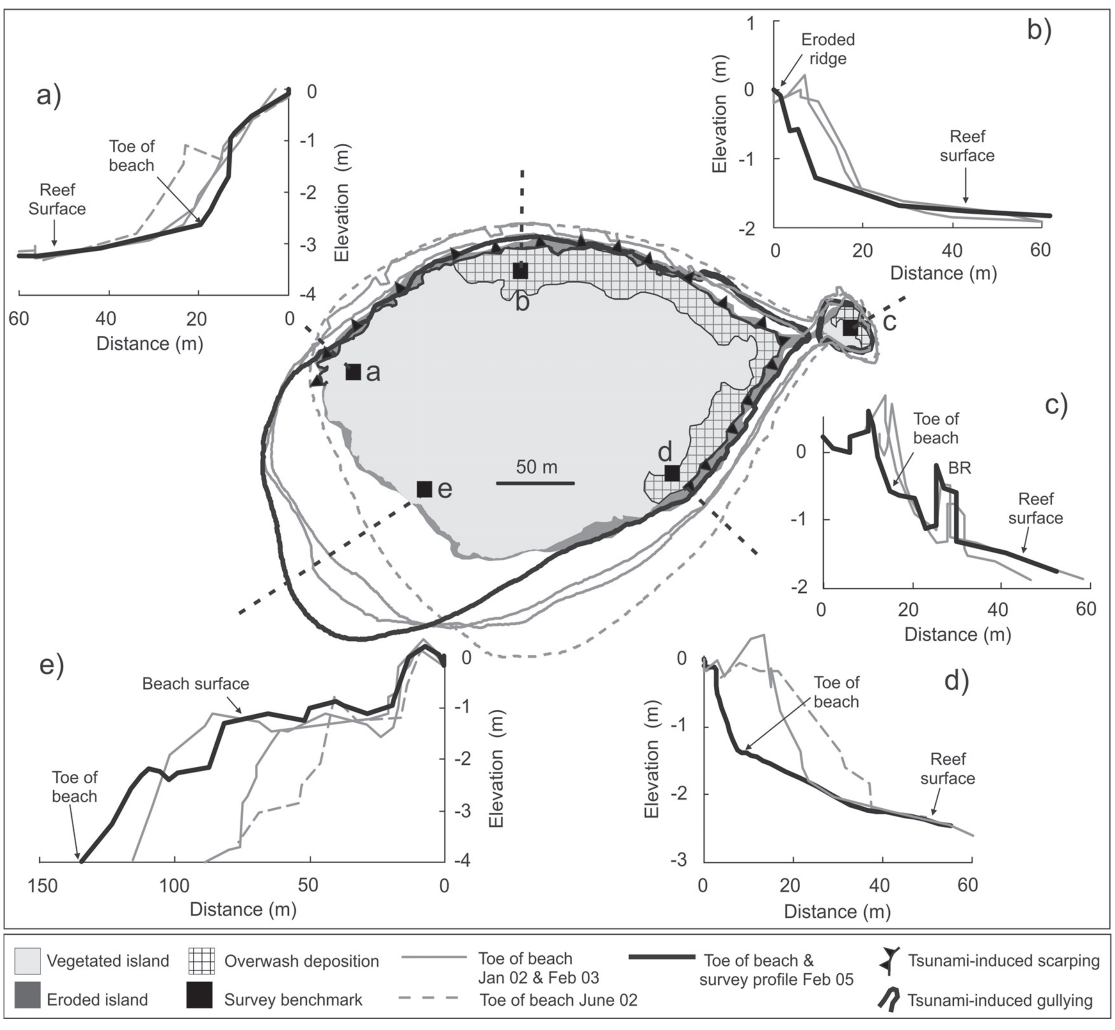

Figure 4. Pre- and post-tsunami plan and profile changes on Madhirivadhoo Island. Location of island shown in Figure 2.

contracted landward of the envelope of positions observed in pre-tsunami surveys, and the total beach area had been reduced by 4.5%. In the southwest of the islandthe response was quite different, the beach toe extending well beyond the positions previously surveyed, by more than 20 m and occupying an additional 2,490 m^2 of reef flat surface (Fig 4 e). Indeed, in the extreme southwest the sand lobe extended to the reef edge and sand was observed cascading off the reef flat down the fore-reef. This was one of the few examples where there was clear evidence of off-reef sediment transport.

Thiladhoo (Figure 5). Thiladhoo is a crudely triangular shaped island with its apex towards the northeast. In this area, and along the western and eastern shorelines, erosion of up to 9 m was measured (Fig. 5 b) with scarping common. In total, erosion accounted for nearly 7 % loss in vegetated island area. In spite of this, tsunami overwash deposition covered a greater area and occupied 17% of the island surface (Fig. 5). Overwash deposition reached its maximum thickness of 0.3 m at the island edge and tapered landward. The toe of beach had contracted landward on the tsunami-exposed eastern flank of the island, with depositional lobes extending towards the south and southwest. These nodes of accumulation were extensive, reaching up to 30 m across the reef surface, and covering an additional 3,160 m^2 of reef surface burying live corals in the process.

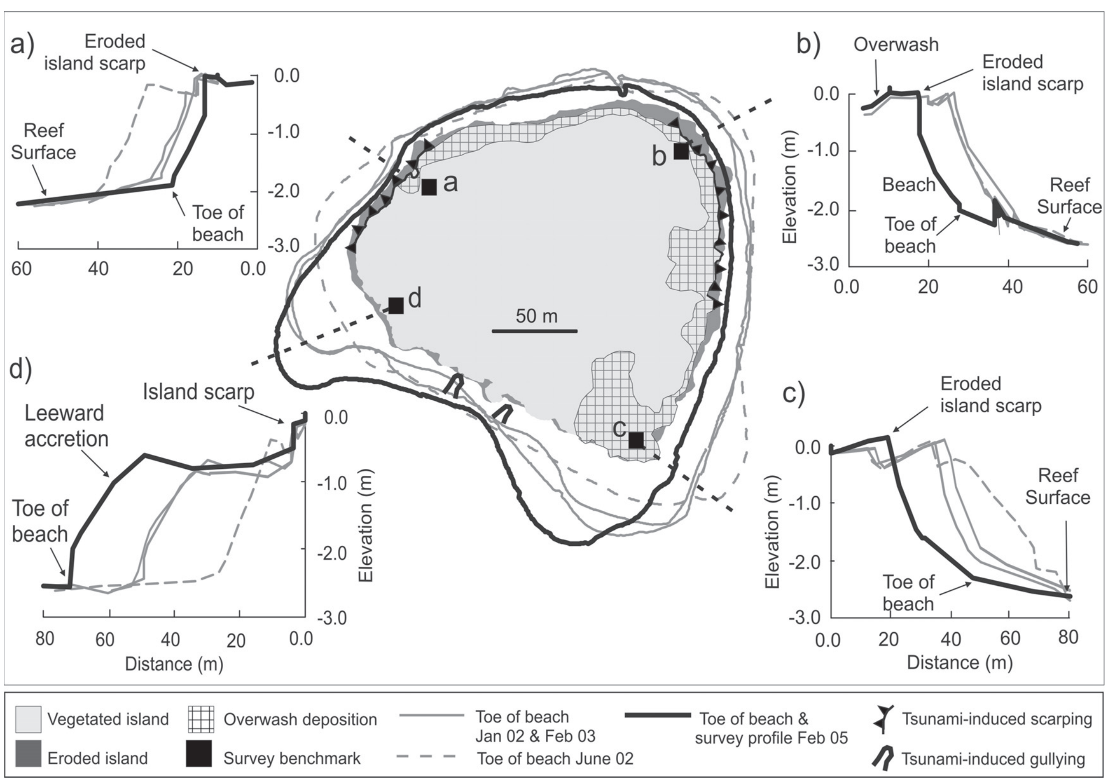

Figure 5. Pre- and post-tsunami plan and profile changes on Thiladhoo Island. Location of island shown in Figure 2.

Milaidhoo (Figure 6). Comparison of GPS surveys indicates that tsunami-induced erosion reduced the vegetated area of Milaidhoo by an estimated 5.5%. Most erosion occurred along the northern shoreline with surveyed cross-sections indicating erosion of up to 4 m (Fig. 6 b). Overwash sedimentation on the vegetated island surface was not common in this area, but was concentrated in the southern half of the island on both eastern and western surfaces. The southeastern overwash sheet was up to 0.3 m thick and it appeared that these sediments originated from the broad sandy beach and berm along the eastern side of the island which had been deposited towards the end of the westerly monsoon season. Further details of the morphostratigraphy and sediments of the tsunami deposits on Milaidhoo are presented later in the section on depositional signatures.

Similar to other eastern islands, the base of the beach was located landward of its pre-tsunami position on the northwestern, northern and southeastern sides of the island (Fig 5 a, b, e) but had expanded as a broad, recurved spit across the reef surface on the southern side of the island occupying a further 3,500 m^2 of reef flat.

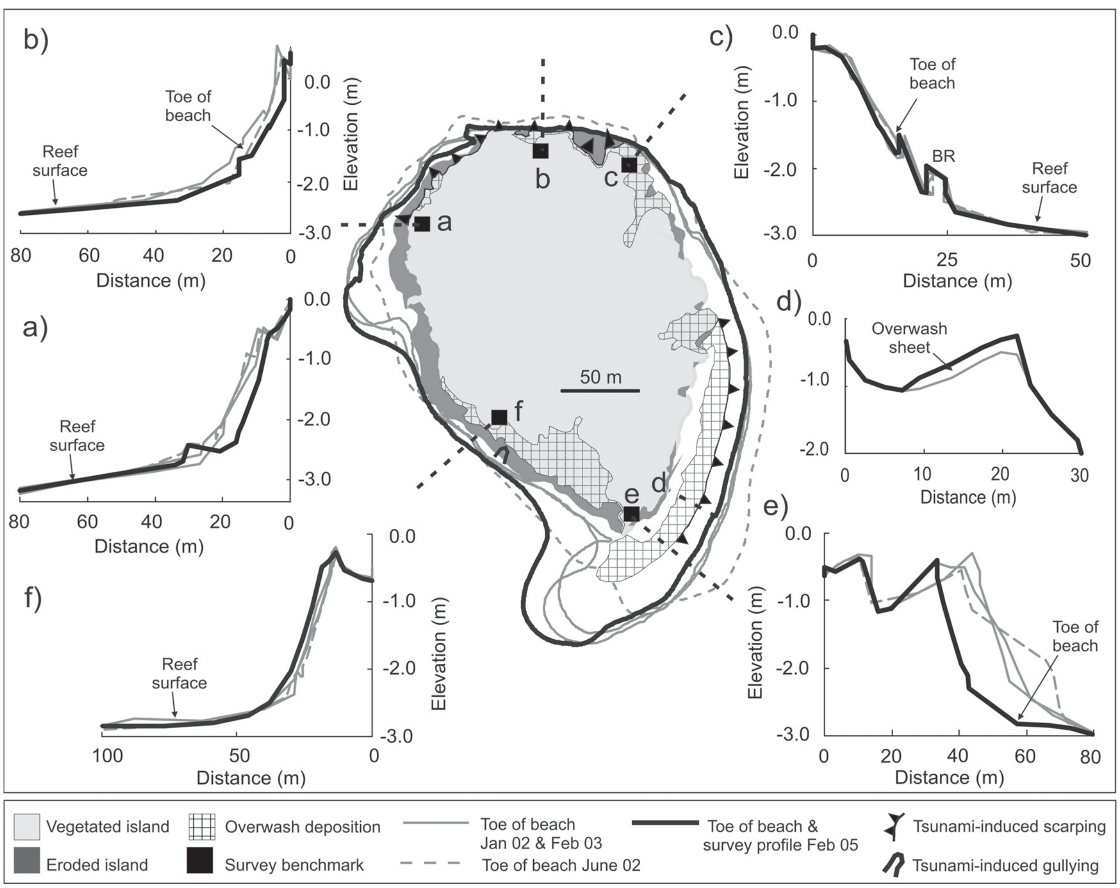

Figure 6. Pre- and post-tsunami plan and profile changes on Milaidhoo Island. Location of island shown in Figure 2.

Central Islands

Udoodhoo (Figure 7). Located in the central north of the atoll, the circular island of Udoodhoo is the second largest island in the study (Table 1) covering over 100,000 m^2 and occupying about 56% of its reef platform. Pre- and post-tsunami survey data indicate Udoodhoo experienced no significant loss in vegetated island area (0.01%). Similarly, the detailed profile surveys show only localized scarping of the island margin notably on the northeast shoreline (Fig. 7 b, c). However, part of the island was overtopped by the tsunami as indicated by a thin sheet (0.04 m) of overwash deposition on the east to southeastern margins which covered about 9% of the total island area (10,239 m^2). On Udoodhoo the toe of beach had marginally contracted landward of the pre-tsunami survey positions along the eastern shoreline and had extended reefward along the western margin of the island.

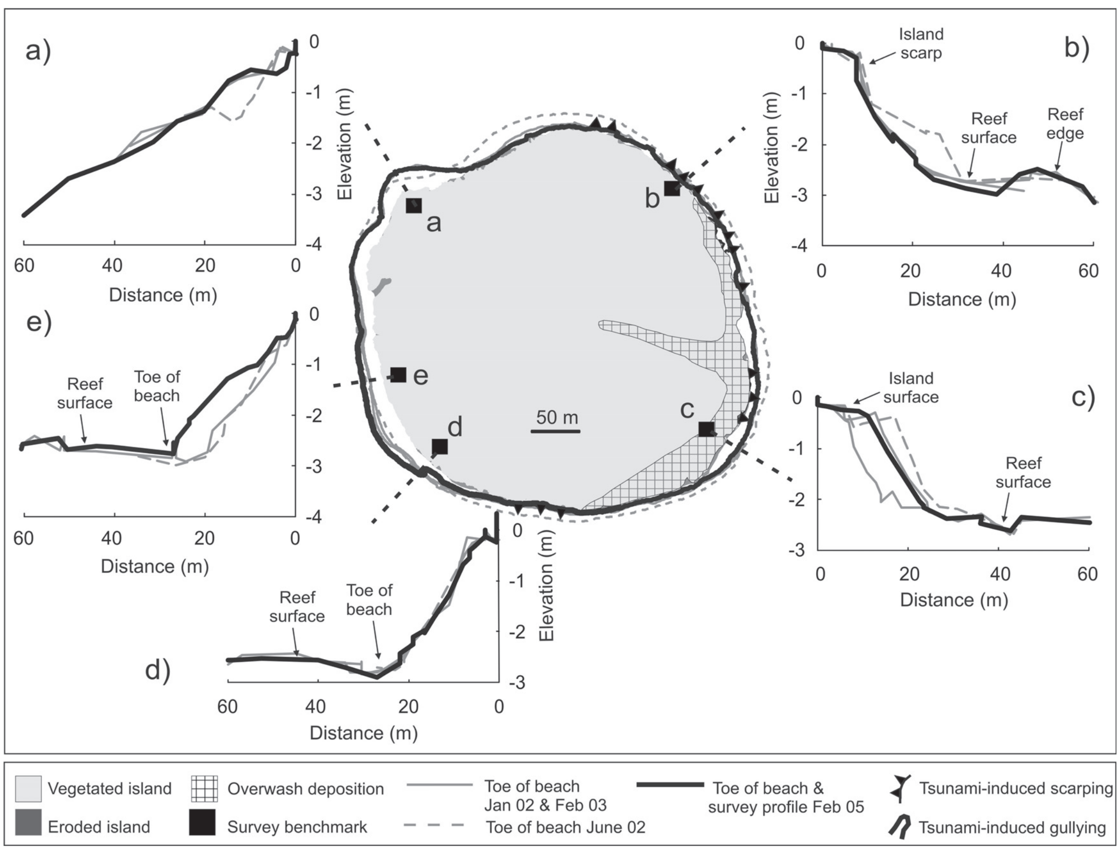

Figure 7. Pre- and post-tsunami plan and profile changes on Udoodhoo Island. Location of island shown in Figure 2.

Hulhudhoo (Figure 8). Hulhudhoo, a smaller but similar circular island to Udoodhoo, experienced erosion on its northern, eastern and southern shoreline though again the total loss of vegetated area was small (approximately 3.5 %). Scarping was evident along the eroded sections with maximum shoreline displacement of approximately 6 m on the southeast section of coast (Fig. 8 d). A large splay of overwash deposition occurred on the northeast section of the island with sediments to a maximum thickness of 0.13 m extending up to 50 m landward of the seaward island ridge. This deposit covered about 13% of the island surface. Elsewhere, there was no evidence of overwash deposition.

Of the six beach profiles around the island, five showed that the toe of beach was displaced landward of its pre-tsunami position by variable amounts, except on the western lee-side of the island where it extended beyond the prior envelope of change and occupied a further 1,154 m^2 of reef flat beyond the inner moat surface (Fig. 8f).

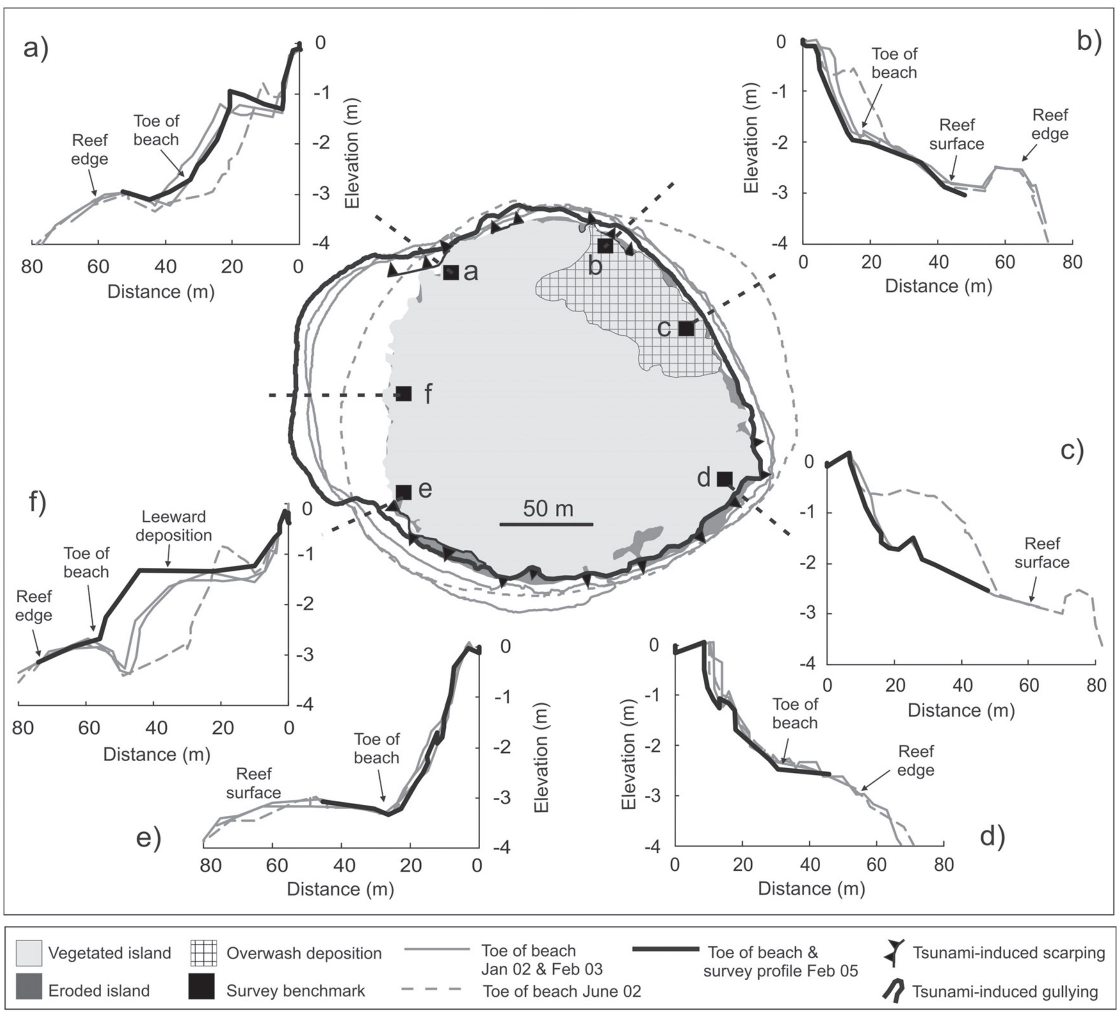

Figure 8. Pre- and post-tsunami plan and profile changes on Hulhudhoo Island. Location of island shown in Figure 2.

Keyodhoo (Figure 9). Keyodhoo is one of the smallest vegetated islands studied and geomorphic changes were similar to those on Hulhudhoo. In particular, marginal erosion occurred on the northern, eastern and southern shorelines with maximum retreat of approximately 6 m in the southeast. Such extensive erosion was, however, quite localized and the total loss of vegetated island area was estimated to be less than 1%. Tsunami-induced overwash deposition on to the vegetated island surface was limited to two locations in the east and covered less than 5% of the island area. However, like Milaidhoo substantial overwash occurred on the broad spit platform located on the protected northwestern side of the island. Toe of beach surveys are consistent with these trends. Landward contraction is indicated on the tsunami exposed eastern and lateral flanks of the island, while to the northwest the beach base had extended further across the reef surface (Fig. 9a), commonly by more than 10 m.

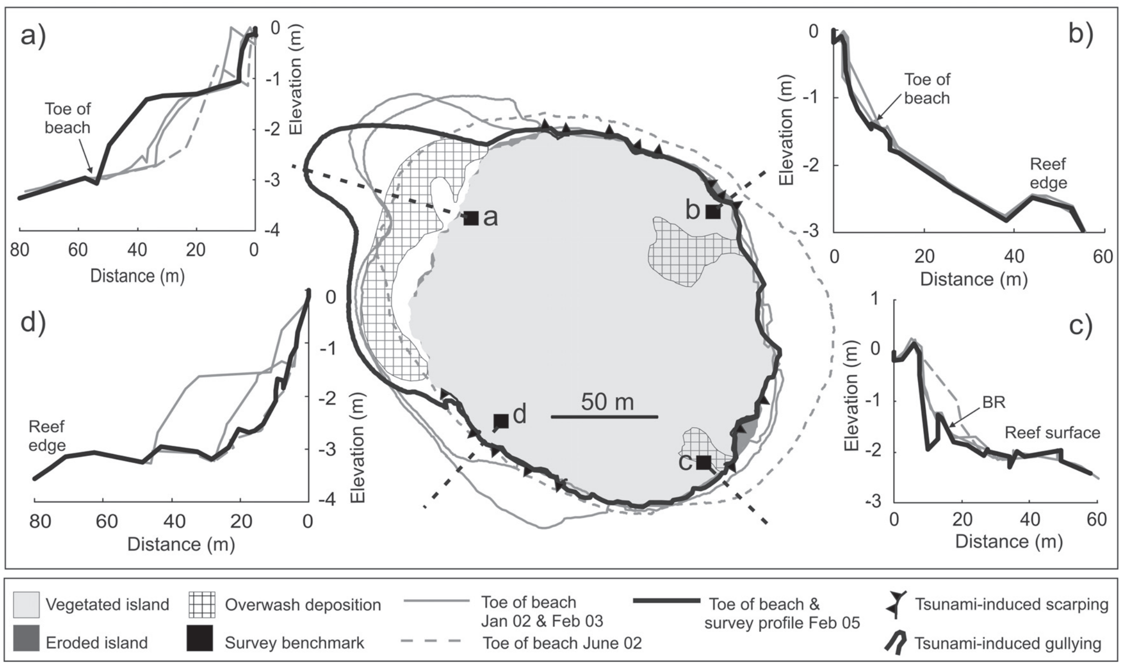

Figure 9. Pre- and post-tsunami plan and profile changes on Keyodhoo Island. Location of island shown in Figure 2

Mendhoo (Figure 10) *and Nabiligaa* (Figure 11). These two islands are located in the centre of the main lagoon of South Maalhosmadulu. Both islands are oriented NW-SE, that is orthogonal to the direction of tsunami propagation. Nabiligaa is elongate, with a long axis of about 500 m and a width of 50 m. It is a sparsely vegetated sand cay, vegetation covering only about 2,000 m^2 in 2002. The island occupies about 12 % of the reef platform. Mendhoo is larger, oval in shape with a long axis of about 700 m and maximum width of 400 m and occupying about 54.5 % of the reef platform. Pre- and post- tsunami GPS surveys were carried out on both islands, but there are no post-tsunami profile surveys. On Mendhoo the GPS surveys show negligible changes in shoreline position. In contrast, evidence indicates that tsunami waves swept across the entire surface of Nabiligaa and promoted loss of 80% of the island vegetation (approximately 1,600 m^2). The cay footprint (denoted by the toe of beach) increased in area by 17% occupying a further 9,729 m^2 of reef surface compared with pre-tsunami surveys. These changes in island footprint suggest the tsunami wave spread the reservoir of cay sediment across a broader area of reef than identified in earlier surveys. Scarping was measured along one quarter of the western shoreline whereas overwash deposition buried vegetation along the eastern margin of the island, reaching a maximum depth of 0.15 m.

Boifushi (Figure 12). Boifushi was the only unvegetated sand cay included in the study. Observations of the cresent-shaped cay indicate the tsunami waves swept over the surface depositing sediments to the west (Fig. 12). While the total area occupied by the cay footprint was reduced by about 10% the discrete mass had migrated up to 20 m southwestward covering 2,500 m^2 of reef surface that had previously not been covered with cay sediments. However, all of our surveys show that the sand cay is mobile both between seasons and between years and the magnitude of the tsunami-induced movement was not exceptional.

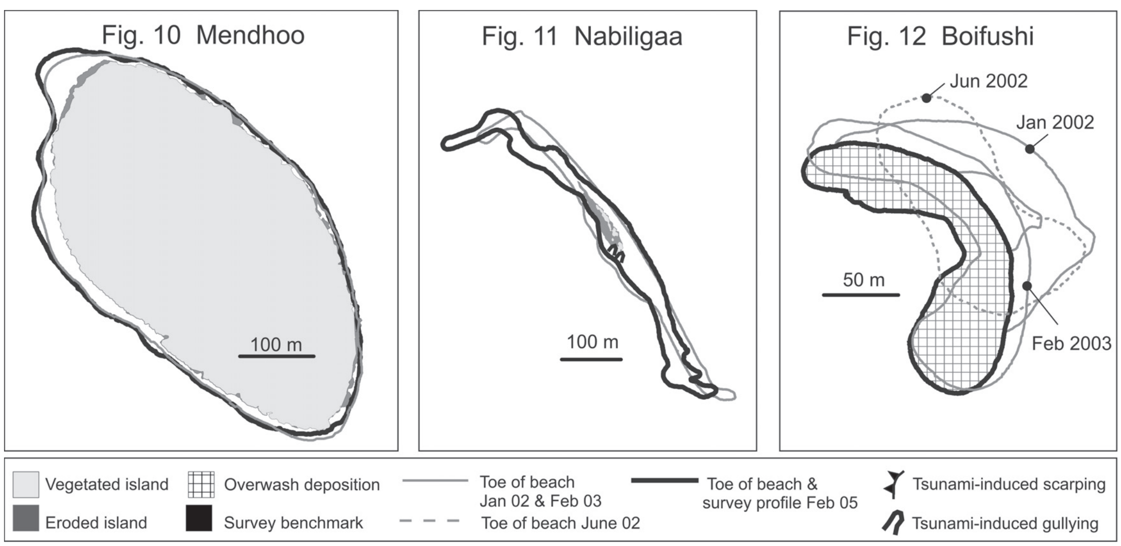

Figure 10-12. Pre- and post-tsunami plan and profile changes on Mendhoo, Nabiligaa and Boifushi Islands. Location of islands shown in Figure 2.

Western Islands

Dhakandhoo (Figure 13). Dhakandhoo is an unusual elongate island in that its long axis is oriented E-W. Erosion was concentrated along the eastern and northwestern shorelines. Prior to the tsunami the eastern end of the island had accreted as a sequence of chevron-shaped ridges and recently colonized by *Scaevola* and *Pemphis* bushes. The tsunami caused significant retreat of this newly accreted area (20 m, Fig 13 d) which provided the greatest contribution to the total loss of vegetated island area of approximately 5%. On Dhakandhoo, overwash sedimentation was observed at two locations. First, a sand deposit on the northeastern sector of the island, which extended up to 50 m in from the shore, reached a maximum thickness of 0.2 m and accounted for the majority of the 8% of the island surface covered by overwash. The second minor sand deposit occurred on the vegetated berm along the central southern shore.

The toe of beach was situated well landward of the positions surveyed in pre-tsunami surveys on the eastern extremity of the island (Fig 13 d). However, elsewhere the toe of beach was generally seaward of the earlier positions, especially along the southern shore (Fig. 13 e, f). Of note, the total beach area increased by 12.5 % and extended across a further 2,900 m^2 of reef flat surface.

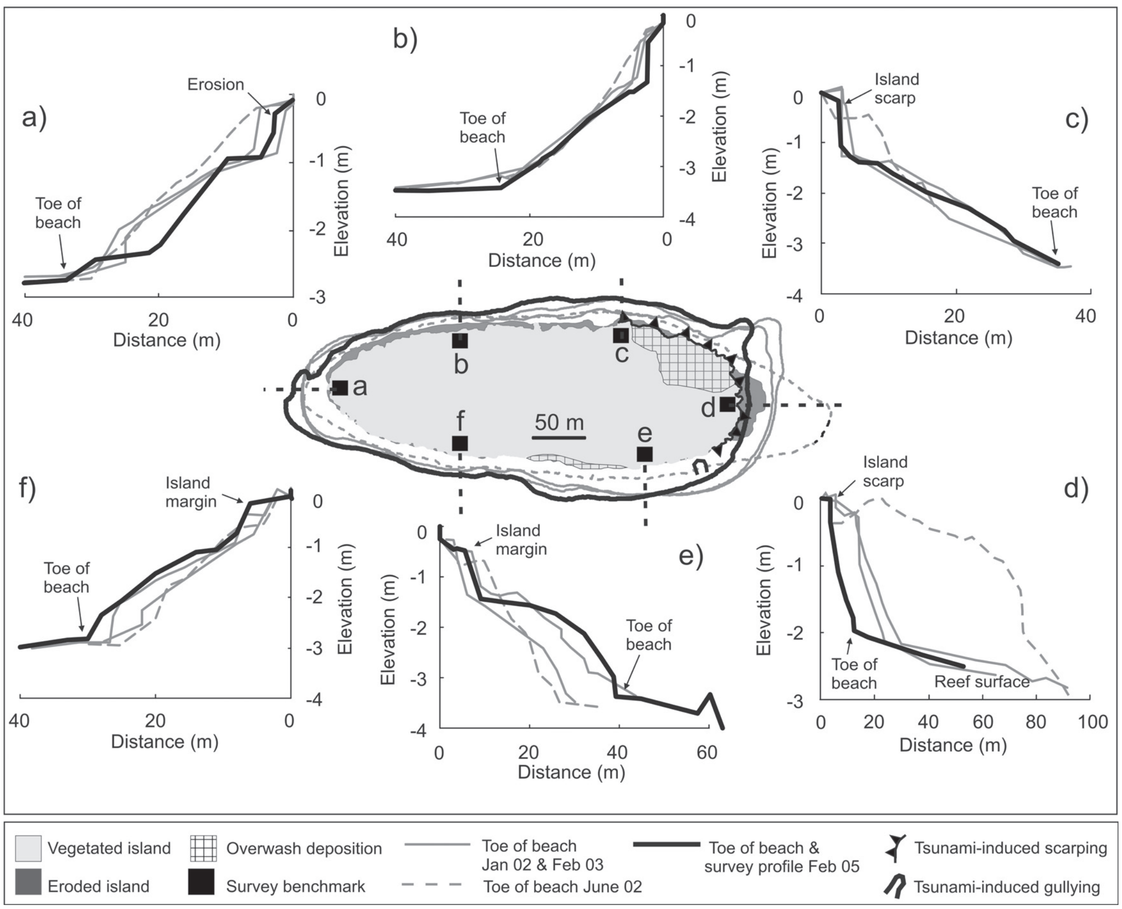

Figure 13. Pre- and post-tsunami plan and profile changes on Dhakandhoo Island. Location of island shown in Figure 2.

Fares (Figure 14). The geomorphic impacts of the tsunami on the elongate island Fares were similar to those on Dhakandhoo. Shoreline erosion and scarping was most evident along the northern and eastern shoreline although the total loss of vegetated area was only 1.8%. Like Dhakandhoo the eastern end of the island experienced significant retreat (15 m, Fig. 14 d). Overwash sedimentation was limited to a small zone on the eastern end of the island and an isolated sand splay on the southern shoreline and affected only 0.7 % of the island surface.

The Fares toe of beach was also located landward of the positions identified in pre-tsunami surveys on the eastern end of the island and showed little change or was further seaward around the remainder of the shoreline (Fig. 14 d, a). Indeed, the beach area increased by 11.6% and occupied a further 1,914 m^2 of reef surface.

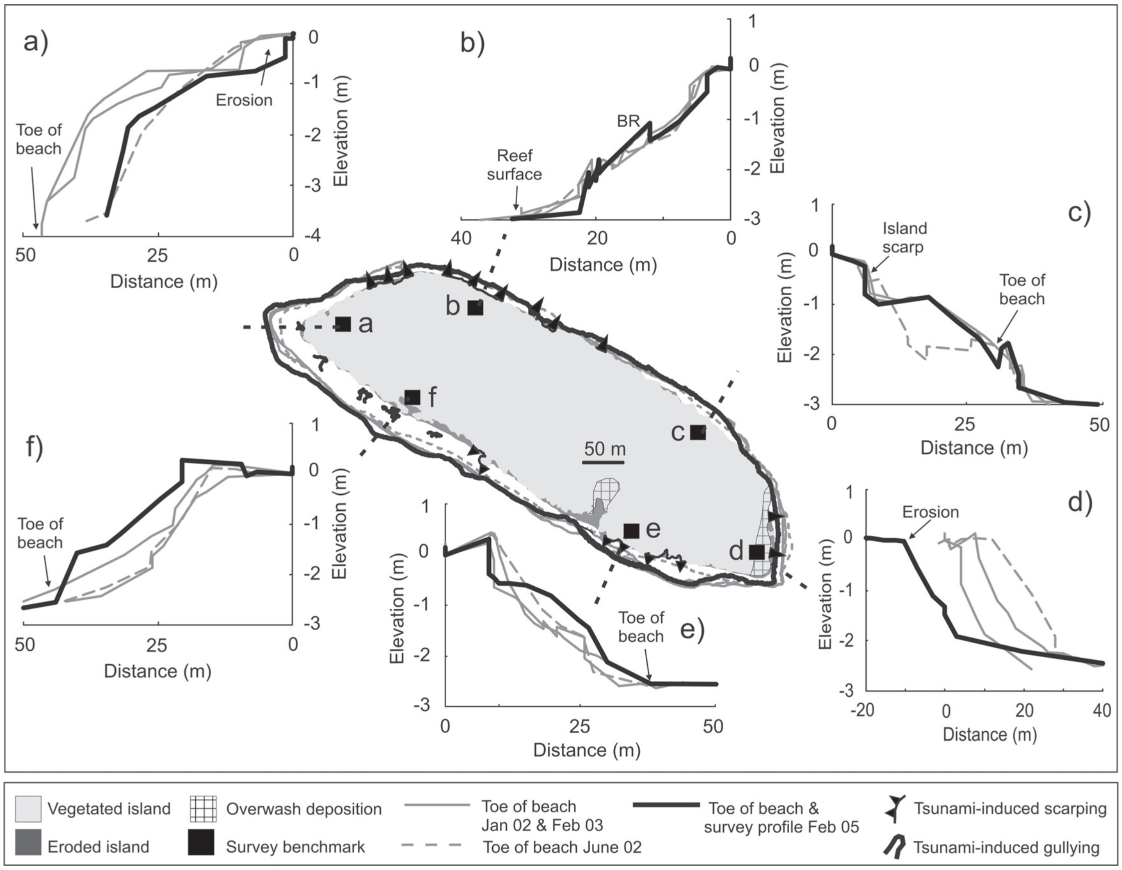

Figure 14. Pre- and post-tsunami plan and profile changes on Fares Island. Location of island shown in Figure 2.

Gaaviligili (Figure 15). Located on the southwestern periphery of the atoll Gaaviligili is composed of gravel at its western margin with a vegetated sand spit that trails across the reef platform toward the ENE and centre of the lagoon. GPS surveys indicate the vegetated island area reduced by 1.14% as a consequence of the tsunami. While marginal trimming of the exposed westward shoreline is evident (Fig. 15 c, d) the gravel ridges experienced minor modifications. In contrast, the eastern one-third of the island, including the sand spit was covered with fresh overwash deposits that in places spilled completely over the island from the northern to southern shore.

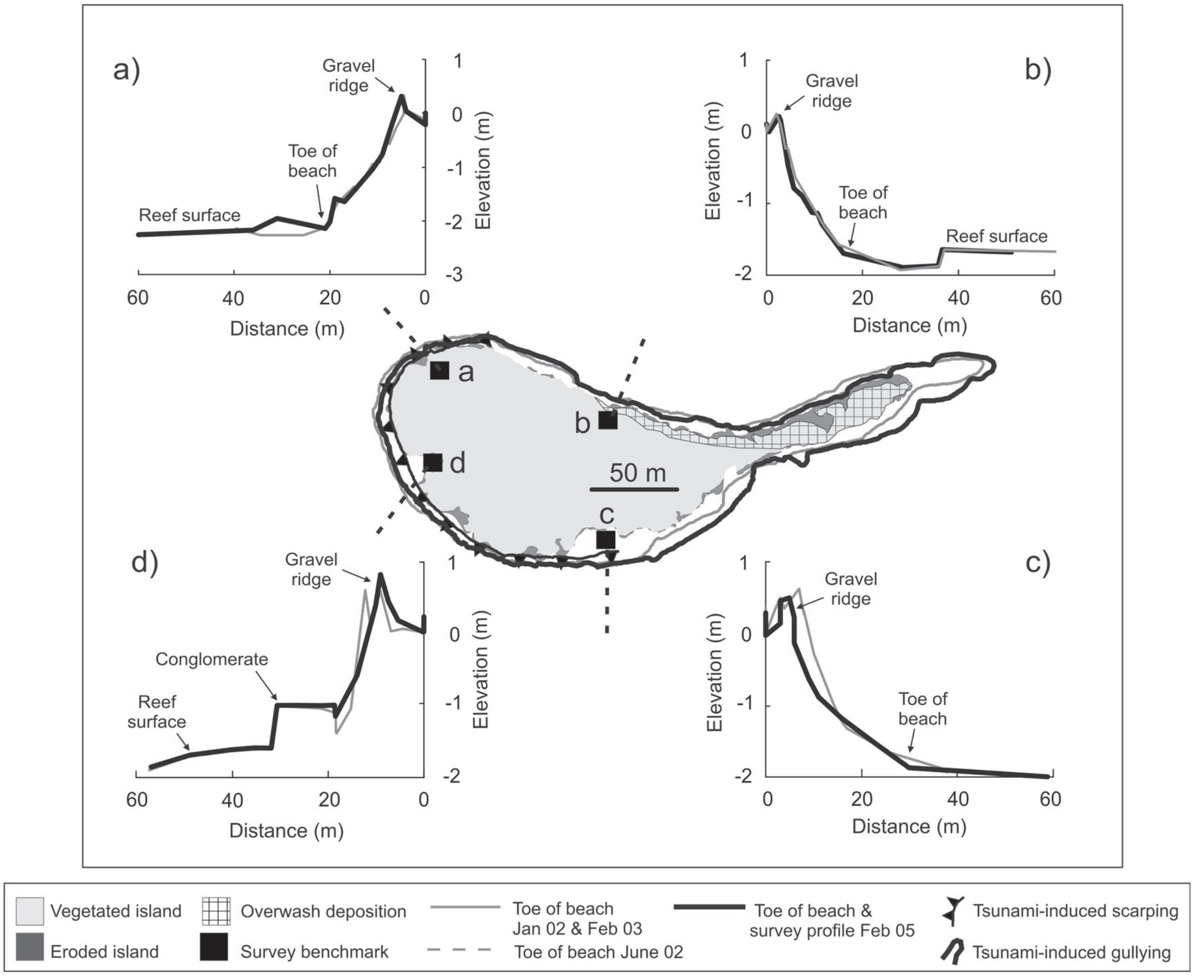

Figure 15. Pre- and post-tsunami plan and profile changes on Gaaviligili Island. Location of island shown in Figure 2.

EROSIONAL AND DEPOSITIONAL SIGNATURES

The changes in island area and beach dimensions described above resulted from tsunami-driven erosional and depositional processes. These processes produced distinctive morphological and sedimentary signatures, which if preserved, can be used as indicators of the incidence of tsunami. During the field survey, observations and measurements were made of both erosional and depositional signatures which are briefly described below.

Erosional Signatures

There were two main forms of tsunami-induced erosion on the study islands: erosional scarps and gullying.

Erosional scarps. The most common evidence of erosion included fresh scarps cut into the vegetated island ridge, exposing root systems and in some cases leading to collapse of trees (Plate 2). On several islands the scarps were impressive features being vertical and up to 2+m high, though more often they were not as high, with a ramp of beach sand and occasionally rubble extending seawards of the scarp marked by a distinct break of slope around the high water mark. While it was obvious that the tsunami had created or freshened up a large number of scarp faces, our data shows that on many islands the scarp at the top of the beach existed before the tsunami, being the product of wave scour during normal monsoonal conditions. The location of pre-existing island scarps varies across the atoll, a pattern that was largely unaltered by the tsunami. Thus, on eastern islands pre-tsunami scarps are generally on the northern and eastern shores while on the elongate islands of the western atoll they occur along western, northwestern and southwestern shorelines. For all islands our post-tsunami surveys record no significant change to the position of these scarps since 2002. However, careful examination of pre- and post-tsunami surveys indicates tsunami-induced scarping did affect up to 54 % of the shorelines on eastern islands, but had relatively little impact on central islands, though fresh scarping also occurred on the exposed eastern tips of the western islands.

Gullying. The second erosional signature of tsunami impact is localised gully scour across the upper beach. In some cases, gullying extends back into the island ridge such as on Fares at the western side of the atoll. Gully dimensions range from 2 - 12 m in cross-shore direction and 2 - 20 m alongshore, with maximum depth of 1.5 m. In all cases the gully headwall is incised into the upper beach, or island ridge with flow indicators (sand splays, exposed roots) recording seaward discharge of water (Plate 3). We interpret these features as evidence for seawater that was ponded in the island basin exiting through low points on the island ridge, and as such represents the only evidence for return flow of tsunami waters. A second process that could have produced gullying is drainage and seepage through the beach foreshore and berm on the receding (drawdown) phase of the tsunami waves. Generally, gullies formed or were preserved most often on the southern and western shores of islands and were best developed where sandy beaches and berms developed seaward of the island vegetation line.

It is possible that more extensive beach gullying may have occurred during the tsunami, but had been infilled by the time of our survey. We consider the long-term preservation potential of these erosional features is poor.

Depositional Signatures

Tsunami deposits on the study islands include localised sand sheets, sand lobes and isolated coral clasts on the island surface, strandlines of coral clasts and rubbish (organic debris & plastic bottles) on the upper beach, and strandlines of rafted debris (coconuts, palm fronds) on island interior basins.

Sand sheets. Localised sand sheets are principally deposited on the northeast to eastern shorelines of islands. They comprise medium to very coarse coral-algal sands that extend from the island scarp across the landward sloping surface of the island ridge, terminating sharply on the flatter island basin surface (Plate 4) or, more commonly, against dense vegetation. Sand sheet thickness ranges from 0.3 m at the island edge (Plate 5) to <0.01 m up to 60 m landward. The primary sediment source for sand and coral deposits was the beachface with minor contributions from reef flat sediments and reworking of island soil. Where the supply of sand from the beach was sufficient, sand sheets have buried the island scarp forming a continuous deposit from the beach to island surface (Plate 6). Where the sand supply was limited, sand sheets are separated from the island scarp by a bypass zone of non-deposition, typically no wider than 10 m (Plate 7).

Sand sheets on Milaidhoo. Of the 13 study islands, Milaidhoo recorded the most extensive tsunami sand sheet deposit, providing an opportunity to document details of the flow behavior as recorded by sedimentary texture and structure. On the eastern shore of Milaidhoo the tsunami laid down a sand sheet that extends 180 m alongshore, 20 m across-shore and is up to 0.3 m thick.

The sand sheet is a continuous deposit that drapes the former beach face and partially buries vegetation on the backshore (Fig. 16a, Plate 6). Trench excavation of the sand sheet exposed continuous, landward-dipping tabular bedding defined by variations in grain size and composition (Fig. 16a, b, d). Bed thickness ranges from 1 cm to 10 cm, and mean grain size from 0.4 to 0.9 mm. The coarse sand fraction (>0.7 mm) is dominated by whole *Halimeda* flakes and coral fragments. On the surface of the sand sheet, this coarse fraction is deposited as single-grain drapes that in plan view clearly show the run-up limit of wave swash across the sand sheet (Fig. 16c). We interpret these surface drapes as the product of wind-wave action superimposed upon the tsunami-elevated sea surface. The preservation of these drapes is additional evidence that the tsunami did not develop a strong backflow; rather, tsunami waters percolated into the backshore sands and/or drained downslope and alongshore toward the southeast tip of Milaidhoo (Fig. 6). In sum, the well developed tabular bedding and absence of cross-bedding in the trench section suggests that tsunami flow was unidirectional, producing an upper-stage plane bed characterised by pulses of deposition (one pulse per tsunami crest?), with additional flow generated by swash action of wind-waves as tsunami flow waned.

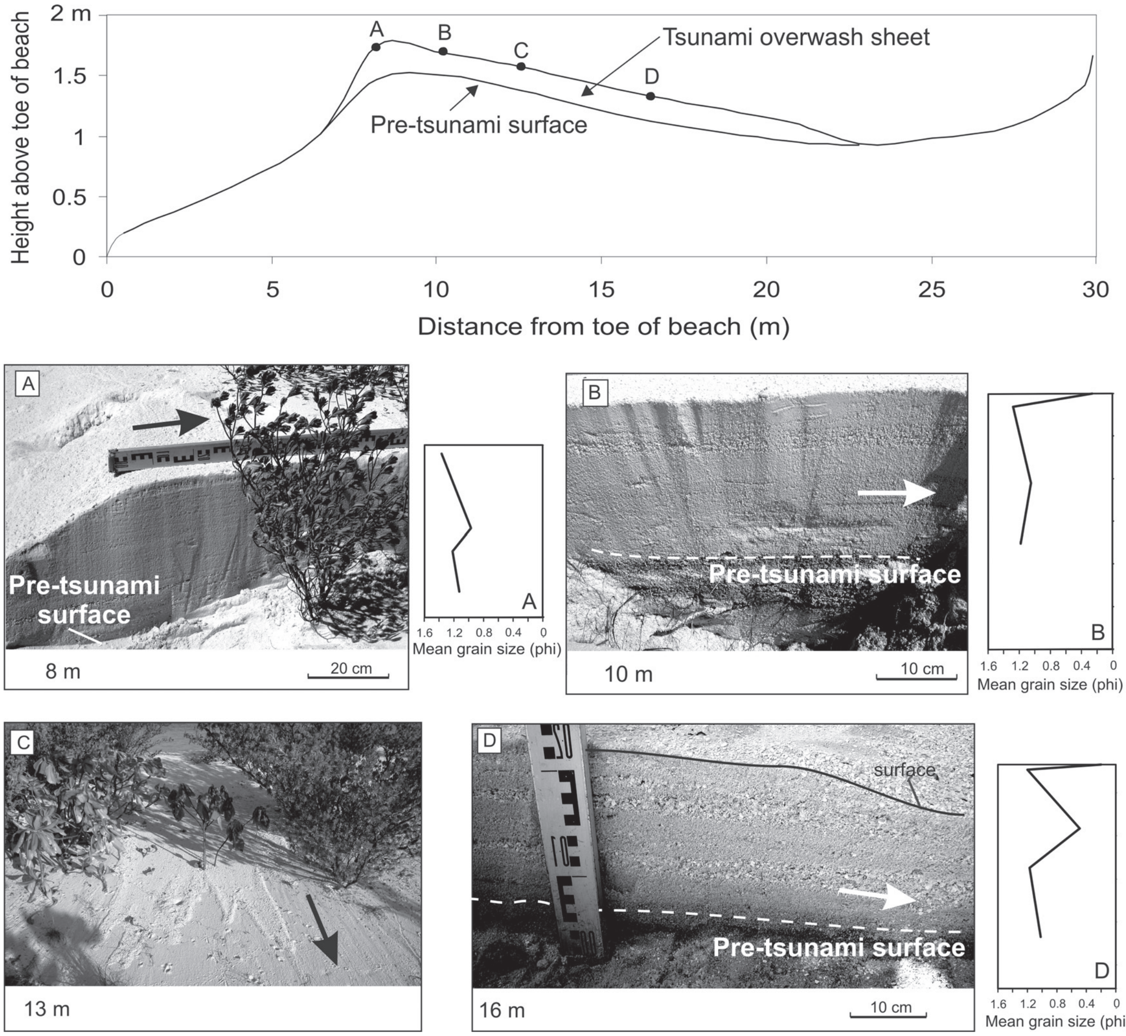

Figure 16. Cross-section profile and trench photos (A, B, D) showing continuous tabular bedding and mean grain size variability of tsunami overwash sheet on Milaidhoo eastern shore. Also showing surface drape of *Halimeda* flakes (C) deposited during waning flow. Arrows indicate direction of tsunami flow.

Sand lobes. Less extensive and more elongate than sand sheets, sand lobes are also commonly convex in cross-section and taper in a landward direction. Isolated sand lobes occurred on several islands. Typically they formed deposits on the island ridge in areas where dense vegetation interrupted tsunami flow, leading to discontinuous sand deposition in the lee of obstacles to a maximum thickness of 10 cm. They also were present at low points around an island's vegetated margin, extending up to 20-30 m inland. Like sand sheets the primary source of sand was the adjacent beach, though in several cases the seaward side edge of the lobe was marked by an erosional scarp.

Coral clasts and vegetative debris. Discontinuous strandlines of coral clasts occurred on island surfaces along the more exposed shores, in places reaching up to 5 m from the vegetation edge or scarp (Plate 8). Isolated coral clasts were deposited across the island ridge along the trailing shores of islands with respect to the tsunami path. Strandlines of buoyant debris on the upper beach were only preserved on the lee side of islands where tsunami inundation did not cross the island ridge. Together, these forms of depositional evidence only record tsunami run-up, with no evidence for return flow or backwash. This is further evidenced by uprooted and flow-flattened vegetation and stranded rafts of organic debris in the island interior. On some islands, tsunami waters ponded on the island basin leading to forest dieback. On Madhirivaadhoo, for example, water remained ponded in the island interior six weeks after the tsunami.

Beach rock fracture and transport. Beachrock outcrops are exposed on the shorelines of many of the study islands, and at several it was clear that beachrock slabs had been detached and moved further shoreward by the tsunami (Plate 9). The largest slab observed to have been moved was roughly rectangular in shape, and measured around 2 x 1.4 x 0.15 m, and had been transported approximately 3 m up the beach on the northwest coast of Milaidhoo. Detachment and entrainment of beachrock slabs of smaller size was also observed on the southeastern shore of Hulhudhoo, where they were deposited in an imbricated fashion against a pronounced beachrock ledge at about mid-tide level (Plate 10). It would be difficult to distinguish tsunami-transported slabs from those deposited during higher energy storm conditions. The presence of slabs at the foot of the fresh scarp higher on the beach at this site suggests that they were emplaced after the scarp had developed, by one of the later waves in the tsunami event. We found no instances where beachrock slabs had been moved from the foreshore onto the island surface.

DISCUSSION AND CONCLUSIONS

The gross changes in reef island morphology associated with the Sumatran tsunami described here, are primarily the effect of the transfer of beach sediments from the eastern to north eastern end of most islands to the western or southwestern side, with reef islands on the eastern side of the atoll generally experiencing greater erosion than those further to the west. The reductions in island area, which decline from 5.5-9% on the eastern islands of South Maalhosmadulu to 1-5% on the western islands bear out this east-west trend, although the large reduction in vegetated island area recorded at the small elongate island of Nabiligaa (80.5%), in the centre of the atoll, suggests that island size, shape and exposure may also have been important.

The spatial distribution and significance of this sediment transfer is shown on most islands by comparing the position of the toe of the beach at the end of the two previous NE monsoons, with the toe of beach position following the tsunami. On most of the islands surveyed the toe of beach following the tsunami was further west over at least part of the eastern shore than it would normally be at the end of the northeastern monsoon, although we note that for Aidoo and Mendhoo on the eastern atoll rim these effects are not well developed, and at Gaavilgili on the western atoll rim the direction of transfer seems to be dominantly from west to east. These results suggest complex behaviour of the tsunami waves around the atoll rim and within the lagoon. They also confirm laboratory experiments (Briggs et al., 1995) as well as field observations (Yeh et al., 1994; Minoura et al., 1997) on tsunami run-up around circular islands.

Our data also show that the Sumatran tsunami amplified seasonal movements of the beach from east to west stripping sand from exposed shorelines and transferring it to leeward depocentres. Depletion of sediment in the eastern quadrants exposed these shorelines to prolonged northeast monsoon energy resulting in post-event scarping and extending leeward depocentres beyond the envelope of change in 2002 and 2003. This suggests that had our field surveys been carried out earlier than six weeks after the tsunami, the results would have been subtly different to those that we encountered.

There are three final points that emerge from this study. First, the timing of the tsunami, early in the northeast monsoon, when the beach sand reservoir is positioned on the eastern sides of islands, acted as a buffer to erosion and minimized the direct impact of the tsunami. Second, deposition of sand sheets and sand lobes (<0.3 m thick) on island surfaces is a permanent addition to the islands, increasing elevation and stability. However, the integrity of these tsunami-derived overwash deposits is unlikely to be preserved on the islands we studied due to bioturbation and soil formation. Thus, in contrast to the tsunami imprints described by Dawson and Shi (2000) and Scheffers and Kelletat (2003), recognition of these deposits as tsunami signatures in the geological record is unlikely. Finally, our data show that the uninhabited islands of the Maldives experienced only minor physical impacts from the Sumatran tsunami. This suggests that unmodified atoll islands are robust rather than fragile landforms, which contrasts markedly with the devastating impacts on the modified reefs and inhabited islands elsewhere in the Maldives.

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Plate 1. Tsunami breach point through former tombolo, northeast tip of Madhirivadhoo. Arrow indicates general tsunami flow direction.

Plate 2. Tsunami-induced scarping and root scour of island margin, northern shoreline of Thilaidhoo.

Plate 3. Water escape channel promoting gullying of upper beach and shoreline, Fares Island. Arrow indicates general flow direction.

Plate 4. Localised sand sheet with abrupt inner limit against low rise on island surface, eastern Dhakandhoo.

Plate 5. Post-tsunami scarping of island margin showing depth of overwash deposition (white band of sediment 0.2 m thick), northern shoreline Thiladhoo.

Plate 6. Localised sand sheet and partially buried vegetation on backshore, eastern Milaidhoo.

Plate 7. Thin sand sheet and sediment bypass zone above pre-existing island scarp, northern Milaidhoo.

Plate 8. Strandline of coral clasts along inner edge of bypass zone, 5 m landward of pre-existing island scarp, northeast Aidhoo.

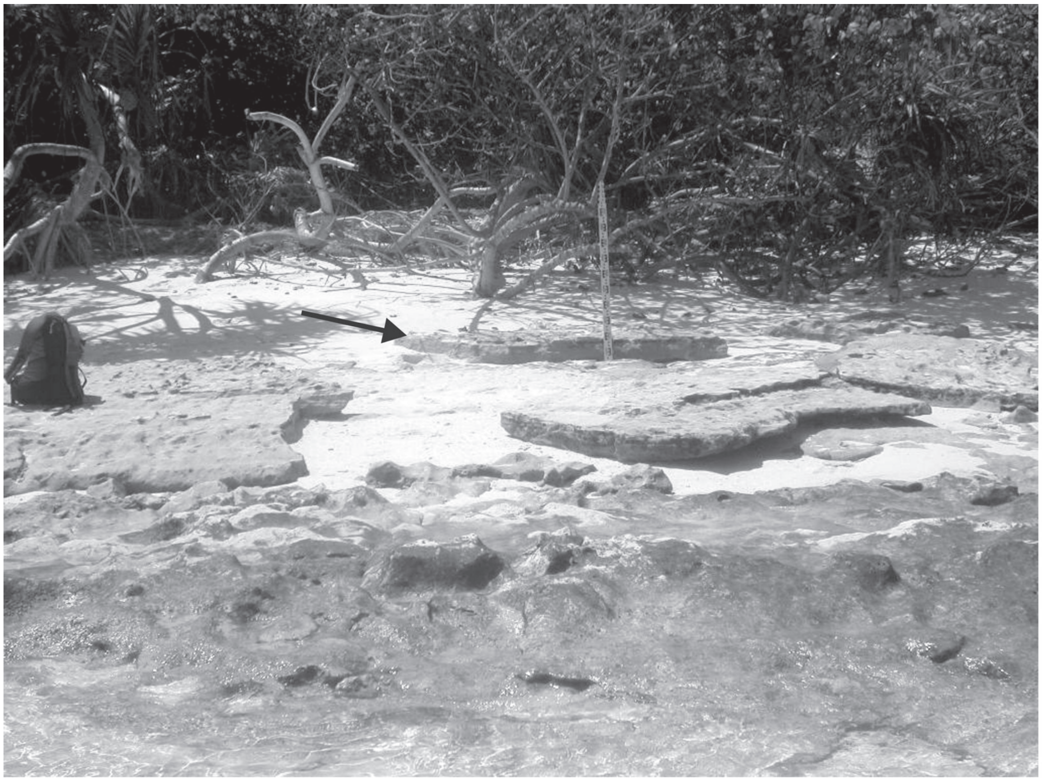

Plate 9. Freshly exposed beachrock surface where slab marked by arrow has been detached and moved, northern shoreline of Milaidhoo. Beachrock slab is approxinately 1.7 x 1.2 x 0.2 m.

Plate 10. Fractured and imbricated beachrock slabs deposited near the SE point of Hulhudhoo. Slabs to 1.2 x 1.0 x 0.2 m common. Fresh face indicative of fracture and transport during tsunami shown by arrow.