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Tsunami as agents of geomorphic change in mid-ocean reef islands

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Abstract

Low-lying atoll islands appear highly vulnerable to the effects of climate change and extreme natural events. Potentially disastrous effects of future sea-level rise have been inferred in many studies, and the actual impacts of tropical storms on island destruction and formation have been well documented. In contrast, the role of tsunami in the geomorphic development of atoll islands has not been investigated. The Sumatran earthquake of 26 December 2004 generated a tsunami that reached the Maldives 2500 km away, with waves up to 2.5 m high. Observations on the geomorphic changes resulting from the tsunami are detailed here, based on pre-and post-tsunami profile measurements of island, beach and reef topography, and GPS surveys of the planform shape of islands and beaches of 11 uninhabited islands in South Maalhosmadulu atoll, Maldives. Erosional and depositional impacts were observed on all islands and these have been quantified. In general the changes were of a minor nature with a maximum reduction in island area of 9% and average of 3.75%. Rather, the tsunami accentuated predictable seasonal oscillations in shoreline change, including localised erosion reflected in fresh scarps and seepage gullies. Depositional features in the form of sand sheets and sand lobes emplaced on the vegetated island surfaces provide clear evidence that the tsunami waves washed over parts of all the islands. Both erosional scarps and overwash deposits were concentrated at the tsunami-exposed eastern sides of the islands. Impacts on leeward shores were primarily accretionary, in the form of spit and cuspate foreland extension. Whereas the nature and magnitude of intra-and inter-island impacts was variable, an east to west decline in aggregate effects was noted. Detailed consideration of the morphodynamic interaction between the tsunami waves and island morphology, show that this cross-atoll gradient resulted not just from the reduction in tsunami energy as it passed through the atoll, but also from variations in elevation of the encircling island ridge, and the quantity and distribution of sediment in the antecedent beach. A conceptual model identifying the sequence of changes to individual islands supports the observational data and the pattern of geomorphic changes resulting from the tsunami. This model leads to consideration of the longer-term impacts of the tsunami on the future stability of islands. Four scenarios are presented, each of which has a different island-beach sediment budget, and different relaxation time to achieve dynamic equilibrium.

Keywords: Coral reefs; Atoll islands; Indian Ocean; Tsunami

1. Introduction

Mid-ocean reef islands are low-lying accumulations of biogenic sand and gravel deposited on coral reef platforms through the focussing of wave and current processes

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(Stoddart and Steers, 1977; Kench et al., 2006a). They are morphologically sensitive to changes in boundary conditions (sea level, waves and currents) at a range of timescales. For example, reef islands are considered prone to widespread destruction in response to future sea-level rise (Dickinson, 1999; Kahn et al., 2002), and have been shown to morphologically adjust to climate variations at interdecadal (Taylor, 1924; Umbgrove, 1947; Verstappen, 1954; Stoddart et al., 1978; Flood, 1986) and seasonal timescales (Hopley, 1981; Kench and Brander, 2006). Extreme natural events can also alter reef island geomorphology and the character and distribution of sediments. Tropical storms and hurricanes have caused a range of effects from catastrophic erosion and devegetation on sand islands (Stoddart, 1963, 1971; Bayliss-Smith, 1988; Harmelin-Vivien, 1994) to the movement of vast quantities of reef rubble that can promote accretion of coral gravel islands (Maragos et al., 1973; Bayliss-Smith, 1988; Scoffin, 1993).

In contrast to studies of the effect of climate variations, hurricanes and storms, the role of tsunami in the geological development of reef islands has not been previously investigated. Bourrouilh-Le and Talandier (1985) assessed possible impacts of tsunami in the Tuamotu archipelago inferring boulders on the reef flat as depositional evidence, and ocean to lagoon passages between islands as erosional evidence of tsunami, though they did not dismiss the possibility that these impacts were due to tropical cyclones.

Atoll islands, of mid-Holocene age, occur throughout the Indian and Pacific Oceans and are surrounded by active seismic zones that yield both near-and far-field tsunamis. Scheffers and Kelletat (2003) suggest that as many as 2000 tsunamis (including at least 100 mega tsunami) have been generated in the Indian and Pacific Oceans over the past four thousand years. This time-frame corresponds to the window over which mid-ocean reef islands formed or have persisted on coral reef platforms (McLean and Hosking, 1991; Woodroffe et al.,

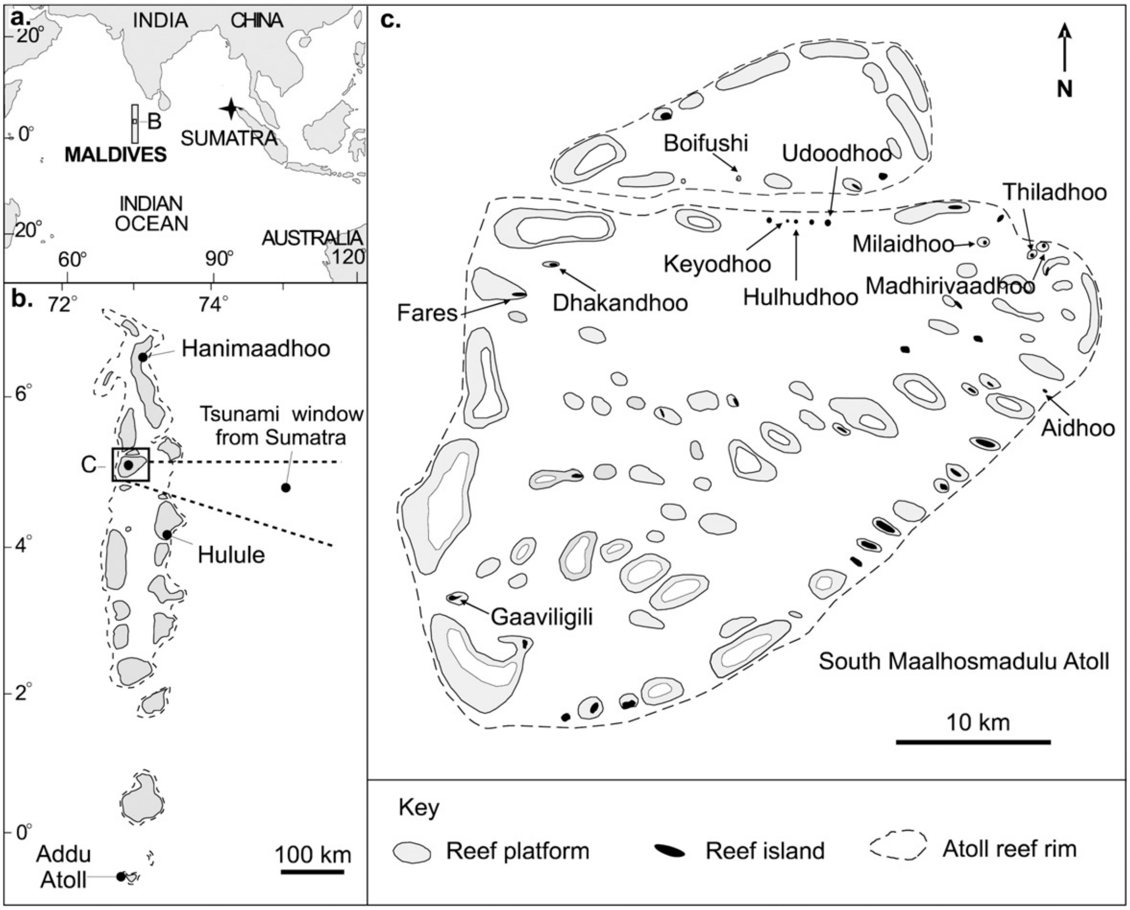

Fig. 1. Location of Maldives and South Maalhosmadulu atoll in relation to the epicenter of the Sumatran tsunamigenic earthquake (a, b). Location of study islands also indicated (c). After Kench et al. (2006b).

1999; Kench et al., 2005). Consequently, it is likely that reef islands have been affected by multiple tsunamis during their geological histories. However, few direct and quantitative observations of the geomorphic effects of tsunami on atoll islands have been made, although such a study has global significance for understanding

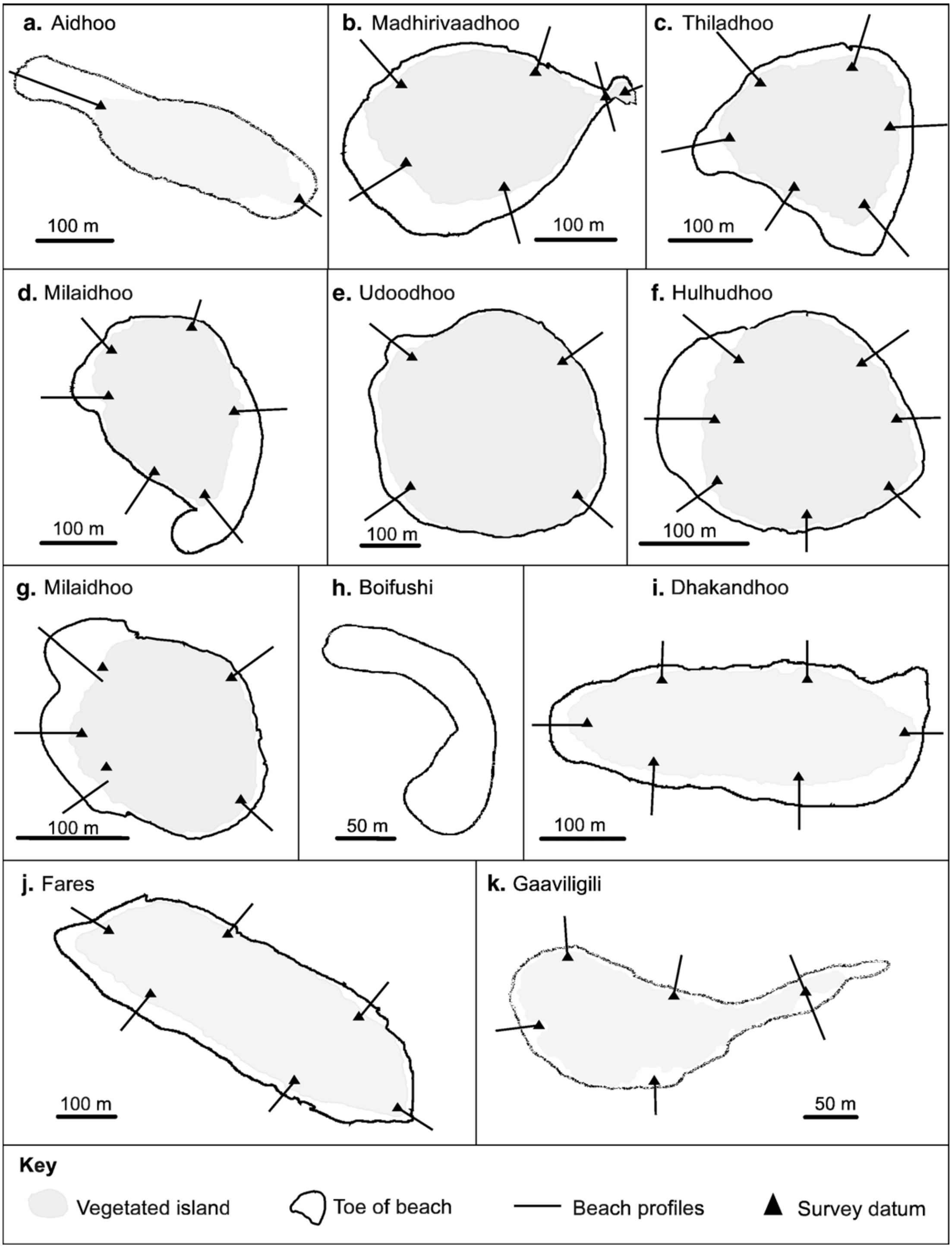

Fig. 2. Surveyed islands on South Maalhosmadulu atoll showing vegetated island area and toe of beach line in January 2002 based on GPS surveys, and location of island-beach-reef profiles and benchmarks.

the stability of reef islands. Kench et al. (2006b) presented summary data on the impacts of the Sumatran tsunami on reef islands in the Maldives. This study presents detailed analysis of the geomorphic and sedimentological impact of the Sumatran tsunami on 11 Maldivian reef islands. Results are examined with respect to the interaction of tsunami waves with islands and their location in the atoll; medium-term effects on sediment budgets; island stability and the relative role of tsunami on island geomorphic development.

2. Field setting

The Maldives archipelago is 750 km long and comprises a double chain of 21 atolls and four reef platforms extending from 6°57′N to 0°34′S in the central Indian Ocean (Fig. 1a, b). The archipelago is situated on a broad carbonate bank that rises from the deep ocean to an approximate depth of 2000 m. The atolls are host to more than 1200 reef islands that are middle to late Holocene in age (Woodroffe, 1993; Kench et al., 2005). The focus of this study is South Maalhosmadulu atoll (Fig. 1c) located in the central zone and western side of the archipelago. The atoll is approximately 40 km wide and long and has a discontinuous rim characterized by numerous deep (up to 40 m) and wide (up to 4500 m) passages. The atoll contains 53 islands located on peripheral and lagoon reefs, with the highest concentration of islands on the east to southeastern sides of the atoll.

This study presents detailed measurements undertaken on ten vegetated islands and one unvegetated sand cay located east to west across the atoll (Figs. 1c and 2). The islands and their reef platforms have differing dimensions and shapes and occupy varying proportions of the reef flat (Table 1). Most islands are composed of sand-size sediments although Gaaviligili on the west and the eastern islands of Aidhoo and Madhirivaadhoo have significant coral gravel and rubble deposits on their oceanward margins. Surveyed cross-sections show a number of characteristic features of island morphology (Fig. 3a). All islands have high peripheral ridges with maximum and mean elevations of 2.5 m and 1.4 m above MSL, respectively. These ridges enclose low central depressions which range in elevation from 0.2 to 0.6 m above MSL. The contemporary beach extends seaward of the vegetated island margin and its outer boundary terminates on the reef flat, normally with a distinct break in slope at the toe of the beach. Beach width and the position of the toe of beach vary considerably around islands and exhibit cyclical variations in response to seasonal changes in monsoon conditions (Kench and Brander, 2006).

The oceanographic regime is characterized by microtides with a maximum spring tide range of 1.2 m. Mean high water spring (MHWS) tide level is approximately 0.6 m above MSL. The atoll experiences seasonal variations in incident wave energy that can be divided into two components (Kench et al., 2006a). Oceanic swell propagates from the south to southwest and ranges from 1.5 m to 0.75 m in June and February respectively (Kench and Brander, 2006). Monsoon-driven locally generated sea also impacts the atoll from the west (April–November) and northeast (December–February).

3. Behaviour of tsunami waves in the Maldivian archipelago

The tsunami of December 26, 2004 was generated by a magnitude Mw 9.3 earthquake off the northwest coast

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]Vegetated area (m^2)	Beach area (m^2)	Island length (m)	Island width (m)	% reef occupied by island
Aidhoo	149,620	32,316	23,650	8,666	414	110	21.6
Thiladhoo	217,189	46,547	33,375	13,172	281	220	21.4
Madhirivaadhoo	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
Udoodhoo	222,275	124,340	112,957	11,383	409	403	55.9
Hulhudhoo	85,512	39,236	30,579	8,657	249	209	45.9
Keyodhoo	88,796	28,985	21,702	7,283	218	180	32.6
Boifushi	132,000	10,447	0	10,447	266	55	7.9
Dhakandhoo	219,136	62,121	45,041	17,080	499	158	28.4
Fares	3,579,945	125,297	101,585	23,713	691	212	3.5
Gaaviligilli	990,000	23,130	17,701	5,429	336	129	2.4

[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.

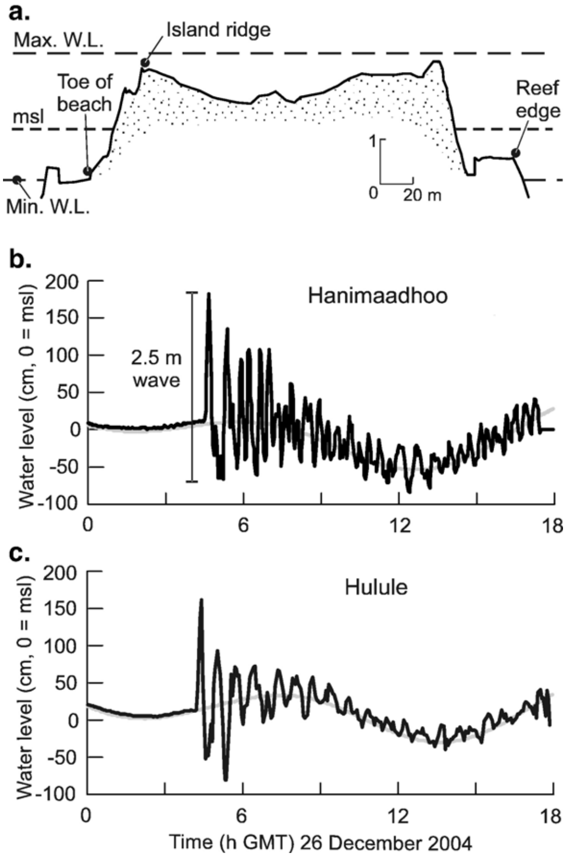

Fig. 3. Surveyed west-east cross-section of Hulhudhoo Island (a) showing maximum and minimum water levels occurring with passage of the first tsunami wave as recorded at the Hanimaadhoo tide gauge. Water level records from the northern (b) and central Maldives (c). Water level records provided by the University of Hawaii Sea Level Center. After Kench et al. (2006b).

of Sumatra (Stein and Okal, 2005). The Maldives archipelago was situated in the direct path of tsunami waves in their westward propagation across the Indian Ocean. Modelling of the tsunami propagation has shown that interaction of waves with the archipelago and broad carbonate bank, resulted in significant wave modification and energy reduction ultimately extracting substantial energy (wave height reduction of 0.5 m) from tsunami waves as they proceeded westward (Titov et al., 2005).

The first tsunami waves reached the Maldives, situated 2500 km west of Sumatra, 3.5 h after the earthquake. Water levels recorded in the northern archipelago (Hanimaadhoo, Fig. 3b) indicate that the islands were impacted by an initial 2.5 m high wave with water levels reaching 1.8 m above MSL (1.2 m above MHWS). During the following six hours an additional 5–6 waves, diminishing in height from 1.8–1.2 m, struck the islands at intervals of 15–140 min. In the central archipelago water level records showed a slightly reduced initial wave height of 2.1 m with water levels 1.6 m above MSL. Subsequent waves were also slightly lower than those in the north (Fig. 3c).

Tsunami waves were able to propagate toward South Maalhosmadulu atoll through a 60 km wide gap, between two atolls on the eastern side of the archipelago, in water depths of 2000 m. The large gaps in the atoll rim (up to 4500 m wide) would also have allowed tsunami waves to penetrate the atoll lagoon. However, due to the rapid transition from deep (2000 m) to shallow water in the vicinity of the atoll rim shoaling of tsunami waves was limited. Eye-witness accounts and video evidence from inhabited islands in the atoll suggested that waves were manifest as rising tidal surges, rather than broken turbulent bores of water, and lacked the size and power of the tsunami waves that impacted continental shorelines.

Nevertheless, the highest waves during the tsunami coincided with a neap high tide and combined with an ambient southerly swell of about 0.40 m resulted in water levels sufficient to inundate sections of the islands on South Maalhosmadulu atoll. Fritz et al. (2006) measured flow depths ranging from 0.17 to 1.60 m above the land surface on the atoll's capital island, Eydhafushi.

4. Methods

Geomorphic change on islands was established through repetitive surveys of each island and comparison of pre-and post-tsunami surveys. A network of survey benchmarks was established on the study islands in January 2002, almost two years prior to the tsunami. Topographic surveys were undertaken from each benchmark across the island ridge, beach and reef surface using an automatic level. Planimetric changes in island area and shape were measured using global positioning system (GPS) surveys with Trimble ProXL and Trimble Geoexplorer 3 instruments with a mean horizontal positioning error of ±1.8 m. Separate perimeter transects of the island edge of vegetation and toe of beach were obtained by walking the instruments while logging in 'line' mode at a frequency of 1 Hz. The toe of beach is a well defined break in slope from the unconsolidated beach sediment to sub-horizontal reef flat surface. Capture of all GPS tracks has been undertaken by only two researchers in order to minimize differences in interpretation of the edge of vegetation. The auto-level and GPS surveys were repeated in June 2002 and February 2003 to document seasonal island dynamics in response to changing monsoonal conditions. The results are described by Kench and Brander (2006) and represent a baseline against which tsunami impacts can be quantified and assessed. Of note, this study does not examine results from two islands in the central lagoon (Nabiligaa and Mendhoo) which were reported by Kench et al. (2006b). This is due to a lack of pre-tsunami monitoring that prevented detection of the seasonal dynamics of island shorelines on those islands.

Both plan and profile surveys were repeated six weeks after the tsunami in February 2005. All islands were measured and compared against the previous surveys to identify changes in island area, shape, position and sediment volume in response to tsunami waves. All changes were calculated against the first survey (January 2002) which provided baseline values of island and beach footprint area. Details of the GIS method to compare sequential GPS surveys and identify changes in planimetric area of islands are detailed in Kench and Brander (2006).

Additional mapping and surveying of tsunami inundation zones was conducted using both automatic level and GPS. Erosional and depositional effects of the tsunami were also surveyed, and shallow cores and trenches excavated to examine the subsurface stratigraphy. Stratigraphic units were sampled and sediments analysed to determine standard grain-size characteristics, using settling tube analysis. Consequently, all grain sizes reported refer to hydraulic equivalent sizes (Kench and McLean, 1997).

In the absence of a conventional terminology, Table 2 defines terms used to describe tsunami-driven processes and their depositional and erosional products on the study islands.

Table 2
Definitions of tsunami terms used in this study

Tsunami term	Definition
Overwash deposit	A sedimentary unit associated with tsunami-wave deposition preserved either landward and/or above the limit of sediment transport normally achieved by wind or wind-generated waves, including storm surge.
Sand sheet	A continuous to semi-continuous deposit that is sand-dominated and has an alongshore dimension (length) greater than its cross-shore dimension (width). Discontinuity of a sand sheet is local and typically associated with objects that interfere with tsunami flow (e.g. trees, artificial structures)
Sand lobe/ tongue	A continuous to semi-continuous deposit that is sand-dominated and has an alongshore dimension (width) less than its cross-shore dimension (length). A sand lobe/ tongue typically forms where a local variation in surface form and/or ground cover allows focused tsunami flow (e.g. drainage depression or open forest area).
Inundation limit	Maximum landward distance of tsunami flow measured from the shoreline. The limit of flow may not always be associated with a sedimentary deposit, in which case can only be defined using damage to vegetation or artificial structures.
Run-up limit	Maximum elevation above mean sea level of tsunami flow. The run-up limit may not always be associated with a sedimentary deposit, in which case can only be recognised from damage to vegetation or artificial structures.
Bypass zone	A zone of non-sediment deposition along the path of tsunami flow located between the sediment source (e.g. beach face) and tsunami deposit (e.g. sand sheet). It is typically associated with a minor topographic high (e.g. berm or low ridge) that is resistant to scour and causes local flow acceleration, hence non deposition.
Seepage gully	A local incision into pre-existing topography caused by seaward flow of temporarily ponded tsunami waters on island surface. Seepage initially occurs through a peripheral island ridge and emerges on the upper beach face to cause headward gully erosion.
Flow depth	Elevation of tsunami water level above island and/or beach surface.

5. Results

5.1. Island planform and profile adjustments

Results are briefly described for each island from east to west across the atoll. Details of plan and profile surveys are summarised in Figs. 4–6 while changes in vegetated island area and area of the beach footprint are included in Table 3.

5.1.1. Eastern islands (Fig. 4)

Aidhoo, the easternmost of the study islands comprises gravel ridges on its eastern (oceanward) margin and a long sand spit that extends over 150 m westward across the lagoon reef flat. GPS surveys indicate the vegetated island area reduced by 9% with erosion along the northern and southern shorelines where scarping was evident (Fig. 4a). In spite of this evidence of erosion, both profile and GPS surveys show there was little change in the position of the toe of beach at the eastern end of the island. Here the shore comprises a sequence of gravel ridges which appeared unaffected by the tsunami flow. In contrast, the trailing sand spit extended in a westerly and northerly direction toward the edge of the reef platform. Indeed, it extended beyond the area occupied by the spit identified in the baseline survey. Spit expansion represents an increase in beach area of 37% accounting for 5000 m^2 of reef flat area. Tsunami inundation of Aidhoo was also apparent from the presence of overwash sediments deposited on the island surface. Discontinuous sand sheets (less than 1 cm thick) and clasts of coarser coral gravel covered

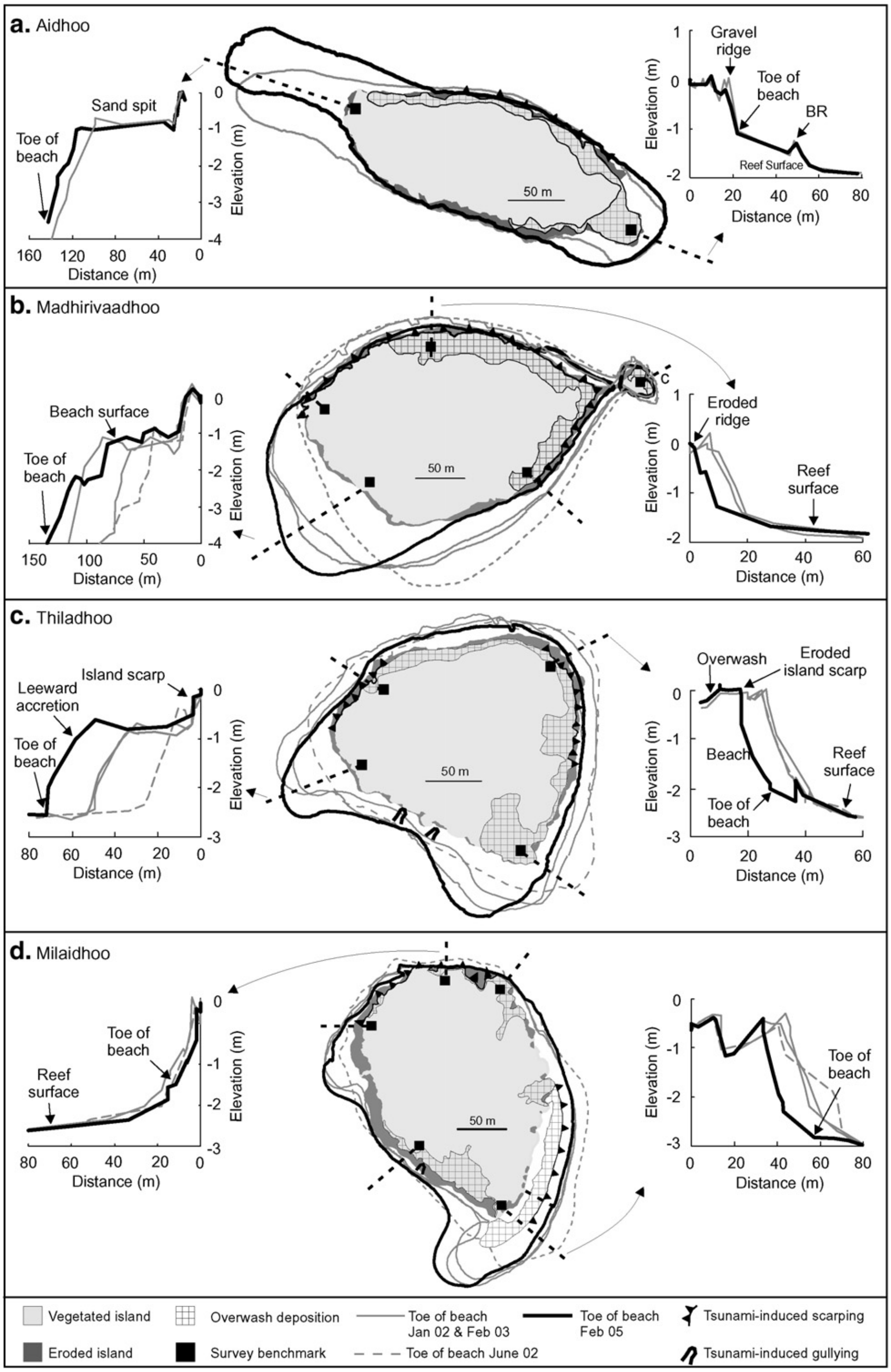

Fig. 4. Pre-and post-tsunami plan and profile changes on eastern islands in South Maalhosmadulu atoll. Location of islands shown in Fig. 1c.

approximately 17% of the vegetated island and extended from its eastern end along the northern shoreline.

Madhirivaadhoo consists of a small gravel island located close to the reef edge in the east, and a much larger sand island to the west (Fig. 4b). Prior to the tsunami, these two parts were connected by a narrow sand tombolo, that was breached during the tsunami and at the time of survey a 10 m wide channel separated the two islands. GPS

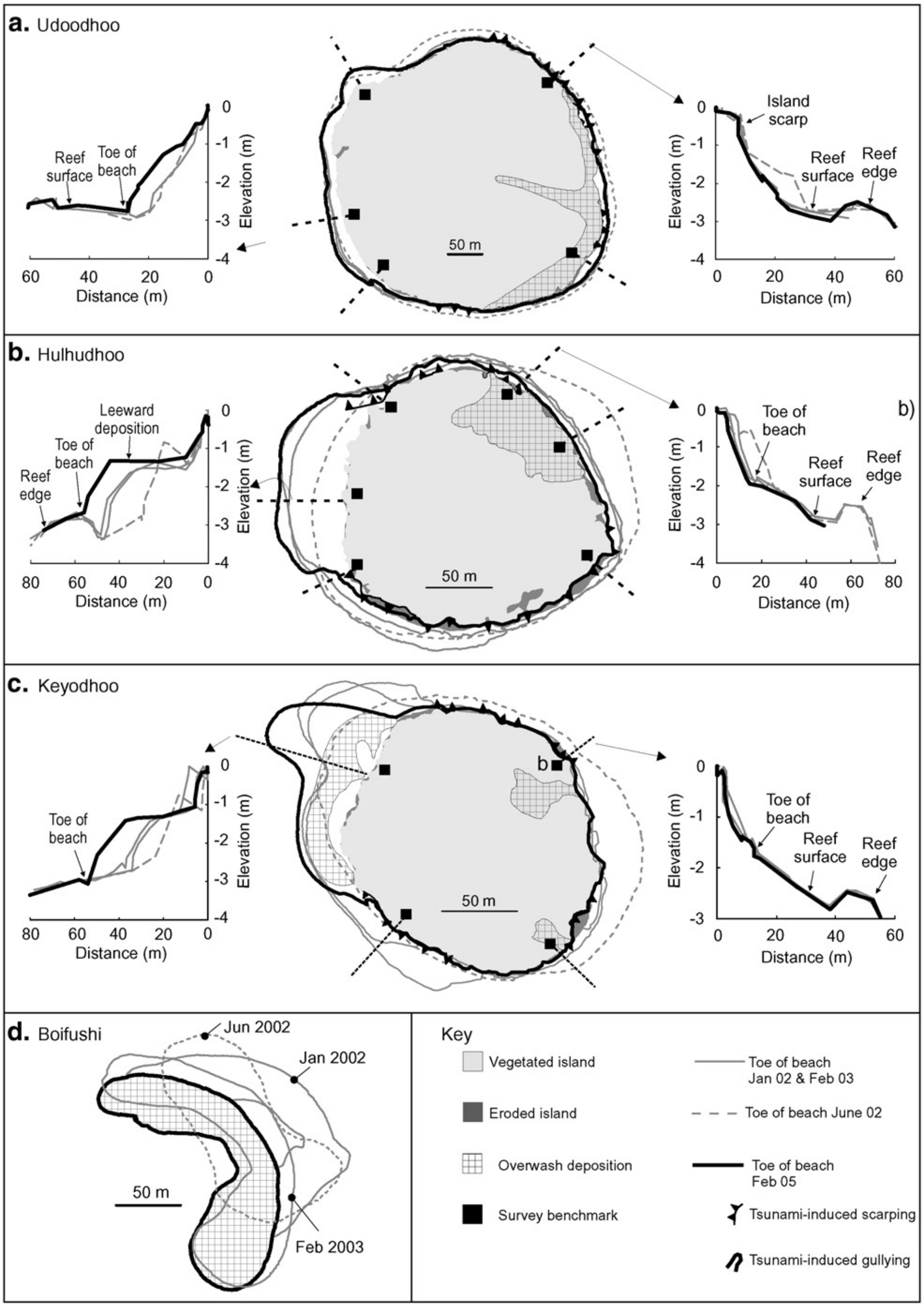

Fig. 5. Pre-and post-tsunami plan and profile changes on central islands in South Maalhosmadulu atoll. Location of islands shown in Fig. 1c.

surveys identified significant erosion along the northern shoreline accounting for an 8% loss in vegetated island area. Surveyed profiles identified maximum shoreline retreat of 6 m (Fig. 4b) and distinct scarping along both the northern and southern shorelines. Tsunami overwash deposition extended over 16% of the island surface along the north to southeastern shorelines (mean depth of 0.2 m). The beach footprint had contracted landward of its pre-tsunami position along the northern and southeastern shorelines but had expanded well beyond that position (by 20 m) in the southwest, and occupied an additional 2500 m^2 of the reef flat (Fig. 4b, Table 3).

Thiladhoo, exhibited similar geomorphic changes to other eastern islands (Fig. 4c). Erosion prevailed along the

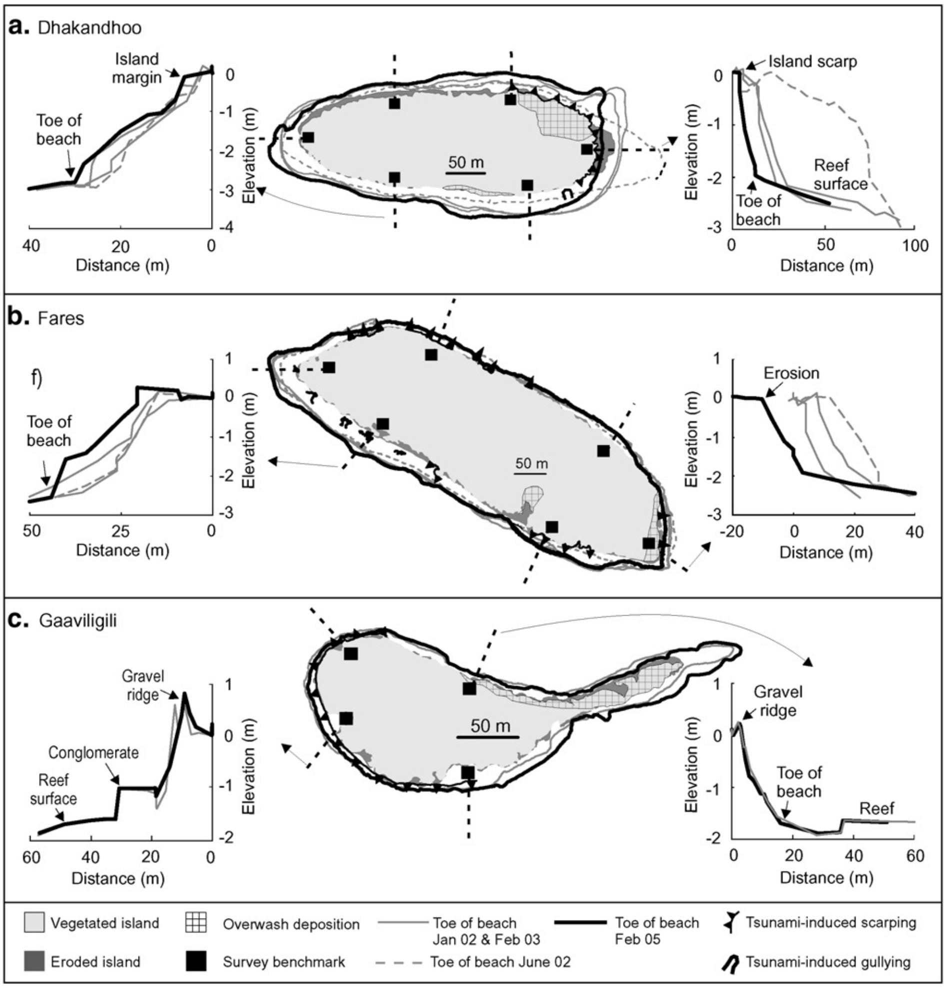

Fig. 6. Pre-and post-tsunami plan and profile changes on western islands in South Maalhosmadulu atoll. Location of islands shown in Fig. 1c.

western to northeastern shoreline with maximum horizontal displacement of the vegetated shoreline of 9 m (Fig. 4c). Erosion accounted for 7% loss in vegetated island area. Overwash sedimentation covered 17% of the island surface around the northwestern to southeast margin of the island, reached a maximum depth of 0.3 m at the island edge and tapered towards the interior. The toe of beach had contracted landward on the tsunami-exposed eastern flank of the island, with depositional lobes extending south and southwest (Fig. 4c). These nodes of accumulation extended across the reef flat, beyond the pre-tsunami survey positions, by up to 30 m, covering an additional 3160 m^2 of reef surface and burying live coral.

Survey results indicate that tsunami-induced erosion reduced the vegetated area of *Milaidhoo* by approximately 5.5%. Erosion of up to 4.0 m was concentrated along the northern shoreline (Fig. 4d). Overwash deposition was limited to discrete zones on the northeast, southeast and southwest sectors of the island. Overwash sedimentation along the southeastern shoreline was up to 0.3 m thick and occurred as a lateral prograded berm. The toe of beach was also located landward of its pre-tsunami survey position on the northwestern, northern and southeastern sides of the island (Fig. 4d) but extended across the southern reef as a broad recurved spit that occupied a further 3500 m^2 of reef surface covering live corals in the process.

5.1.2. Central islands (Fig. 5)

Udoodhoo, Hulhudhoo and Keyodhoo are all circular islands located in the centre of the atoll. The islands vary in size and proportion of reef flat they occupy (Table 1) although the physical changes from the tsunami were similar (Fig. 5a–c). Reductions in vegetated island area were small, ranging from less than 1% on Udoodhoo

Table 3
Summary and comparison of pre-and post-tsunami surveys of characteristics of islands 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]Vegetated island area	[b]Beach area			[c]Seas. change	[d]Seas. change	Net change Jan 02–Feb 03	[e]Annual change	[f]Mean beach area NE	[a]Vegetated island area	Beach area	[g]Beach area	[h]Vegetated area	[i]Beach expansion	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	8666	–	–	–		–	–	8666	21,521	11,916	37.5	−9.0	5079	0.10	17.4	21
Madhirivad	40,083	16,977	18,141	15,620	2521	±15	−1357	−8.0	16,298	36,848	15,572	−4.5	−8.07	2490	0.20	16.0	54
Thiladhoo	33,375	13,172	14,114	14,885	942	±7	1713	13.0	14,029	31,252	15,128	7.8	−6.36	3163	0.30	17.4	28
Milaidhoo	36,070	15,320	18,619	14,821	3798	±25	−499	3.3	15,070	34,087	19,169	27.2	−5.5	3671	0.30	14.1	40
Udoodhoo	112,957	11,383	18,730	11,163	7567	±66	−220	−1.9	11,273	112,867	11,209	−0.6	−0.08	1550	0.04	9.1	17
Keyodhoo	21,702	7283	8408	8049	1125	±15	766	10.5	7666	21,846	6195	−19.2	0.67	1572	0.10	4.7	30
Hulhudhoo	30,579	8657	10,734	9975	2077	±24	1318	15.2	9316	29,521	8222	4.3	−3.46	1154	0.13	12.8	31
Boifushi	0	10,447	10,553	10,446	107	±1	−1.0	−0.01	10,447	0	9331	−10.7	0	2482	0.0	100	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	4585	±19	−599	−2.5	23,413	99,746	26,136	11.6	−1.8	1914	0.10	0.7	24
Gaaviligilli	17,701	5,429	–	–	–	–	–	–	5429	17,500	6321	12.7	−1.14	1609	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. After Kench et al. (2006b).

and Keyodhoo to 3.5% on Hulhudhoo. All three islands showed evidence of scarping along the northeast to southeast shorelines with maximum erosion of up to 6 m recorded on Hulhudhoo and Keyodhoo (Fig. 5b, c). Overwash deposition was also most evident on the eastern sectors of island surfaces. A large splay of overwash deposition occurred on northeast Hulhudhoo (Fig. 5b) with sediments to a maximum thickness of 0.13 m extending up to 50 m into the island interior, and covering 13% of the island surface. Overwash sedimentation spread across 9% and 5% of the island surfaces of Udoodhoo and Keyodhoo respectively. Changes in the toe of beach were also consistent between islands, having contracted landward of the pre-tsunami survey positions on the eastern and lateral flanks of islands and expanded further across the reef surface on the northwest (Hulhudhoo and Keyodhoo) and western (Udoodhoo) side of the islands (Fig. 5a–c).

Boifushi was the only unvegetated sand cay monitored as part of this study (Fig. 5d). While, the total area of this crescent-shaped cay was reduced by 10%, the whole islet migrated up to 20 m in a southwestward direction and covered an additional 2500 m^2 of reef surface. However, pre-tsunami surveys show the cay is mobile both between seasons and between years and the magnitude of tsunami-induced movement was not exceptional (Fig. 5d, Table 3).

5.1.3. Western islands (Fig. 6)

Dhakandhoo and *Fares* are both elongate islands located on the western side of the atoll. Erosion was prevalent at the eastern and northern shorelines of both islands and accretion along the western and southern shores. Similar patterns were also evident in the toe of beach surveys (Fig. 6a, b). Pre-tsunami surveys showed that the eastern ends of Dhakandhoo and Fares consisted of a sequence of fresh cuspate ridges colonized by young Scaevola and Pemphis bushes. The tsunami caused significant retreat of this recently accreted area by up to 20 m and 15 m on Dhakandhoo and Fares respectively, cutting back into the island core resulting in a reduction in vegetated island area of 5% on Dhakandhoo and 1.8% on Fares. On the other hand, the area of the island surface affected by overwash sedimentation was limited to small splays (divergent deposits) on the eastern and southern sides of the islands that covered a total area of 8% and 0.7% on Dhakandhoo and Fares respectively. The largest overwash deposit on Dhakandhoo occurred in the northeast of the island and extended 50 m inland with a maximum thickness of 0.2 m.

Gaaviligili, an island on the southwestern periphery of the atoll, is composed of gravel and cobble size clasts at its western margin with a vegetated sand spit that extends across the reef platform toward the east (Fig. 6c). GPS surveys indicate the vegetated island area reduced by 1.1% as a consequence of the tsunami. While marginal scarping of the exposed westerly shoreline is evident (Fig. 6c) only minor modification of the gravel ridges occurred. Overwash sedimentation was observed across the eastern side of the island extending right across the island at its narrowest part (Fig. 6c).

5.2. Erosional and depositional signatures

The changes in island area, beach dimensions and distribution of sediments described above resulted from tsunami-driven erosional and depositional processes which produced several morphological and sedimentary signatures.

5.2.1. Erosional signatures

Two principal forms of tsunami-induced erosion were observed: erosional scarps and seepage gullies (Table 2).

Erosional scarps — were the most common evidence of erosion and included fresh scarps cut into either recently accreted beach berms and cuspate forelands, or into the vegetated island ridge, exposing root systems and in some cases undermining trees leading to their collapse (Fig. 7a, b). In the first instance the erosional effect is likely to be ephemeral, whereas in the second the impact may be more permanent and have implications for island stability. Vertical scarps, cut into the island core, reached up to 2.2 m high on Thiladhoo, though more commonly they ranged in height from 1.0–1.5 m. Frequently, a ramp of beach sand and occasionally rubble extended seawards of the scarp-base marking a distinct break of slope around high water mark (Fig. 7b). While the tsunami created or reactivated a number of scarp faces, baseline surveys show that similar scarps existed on many islands prior to the tsunami, the position of which varies across the atoll. 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. Post-tsunami surveys record no significant change to the position of these scarps, and comparison with earlier surveys suggest they have persisted at least since January 2002. However, careful examination of the pre-and post-tsunami survey data indicates tsunami-induced scarping did affect up to 54% of the shorelines on eastern islands (mean of 34%, Fig. 4, Table 3). New scarping was rare on central islands of the atoll (Fig. 5), though fresh faces were cut into the recently accreted forelands on the exposed eastern tips of the western islands (Fig. 6).

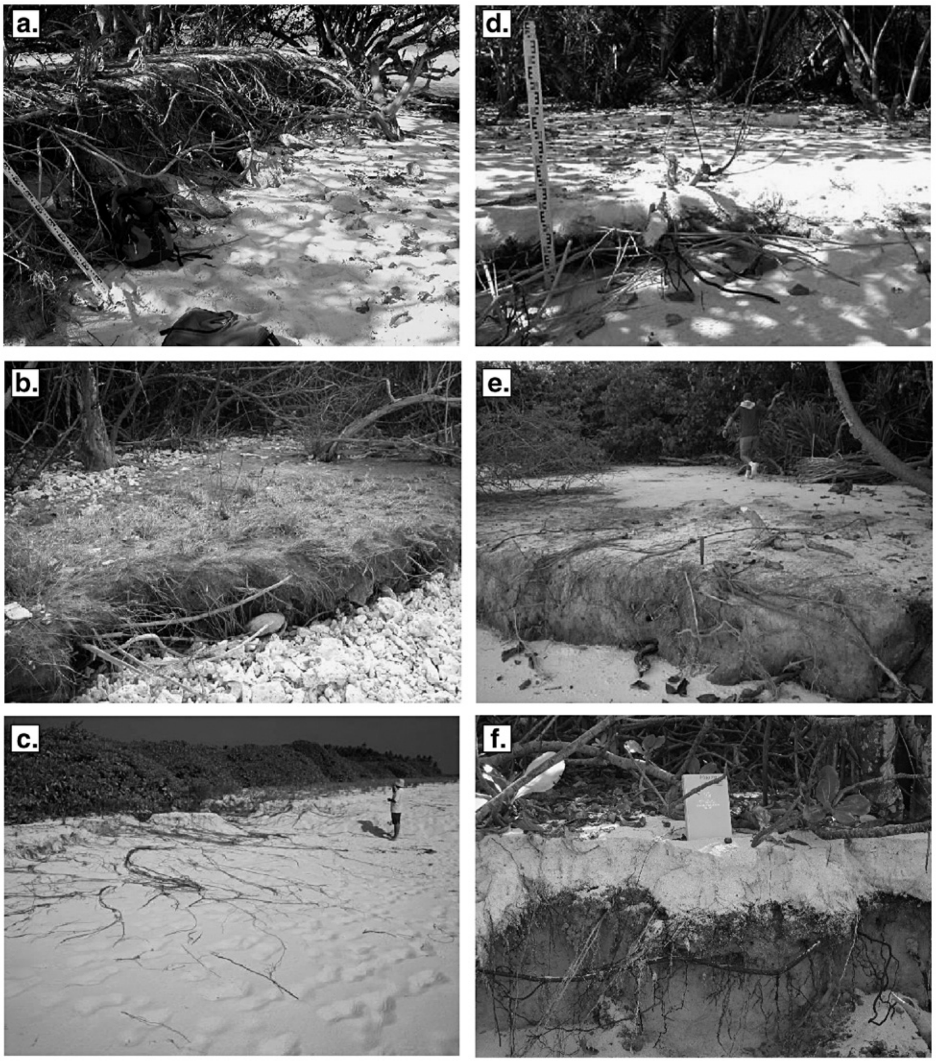

Fig. 7. Photographs depicting a range of erosional and depositional evidence on islands in South Maalhosmadulu atoll. a) erosional scour and root stripping on Thiladhoo; b) erosion of island margin, deposition of gravel against erosion scarp and overwash gravels; c) gully erosion across beach at Fares; d) overwash sedimentation smothering island scarp on Hulhudhoo; e) scarped island margin and overwash sedimentation separated by sediment bypass zone on island margin; f) perched overwash sediment deposit resulting from post-tsunami scarping of island margin.

Localized seepage gullies occurred across the upper beach on a number of islands and in some cases, gullies extended back into the island ridge (e.g. Fares, Fig. 7c). Gully dimensions ranged from 2–12 m in a cross-shore direction and 2–20 m alongshore, with maximum depth of 1.5 m. In all cases the gully headwall incised into the upper beach, or island ridge with flow indicators (sand splays, exposed roots) recording seaward discharge of temporarily pond water.

5.2.2. 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 rubble and rubbish (organic debris and plastic bottles) on the upper beach, and of rafted debris (coconuts, palm fronds) on island interior basins.

Sand sheets (Table 2) composed of medium to very coarse coral-algal sands are principally deposited on the northeast to eastern surfaces of islands (Fig. 4–6). They extend from the island scarp across the landward sloping surface of the island ridge, terminating sharply on the flatter island basin surface or, more commonly, against dense vegetation. Sand sheets cover up to 17% of the area of island surfaces (Table 3) with a clear reduction in their extent east to west across the atoll. They range from 0.3 m thick at the island edge to <0.01 m at their distal end which may be up to 60 m landward, and are primarily composed of beach-derived sand and coral with only minor contributions from reef sediments and from reworking of island soil and substrate.

Sand sheets were associated with the active beach in three main ways. First, the sand sheet and upper beach were contiguous, with the active beach burying the pre-tsunami island scarp (Fig. 7d). Second, the island sand sheet and active beach were separated by a bypass zone of non-deposition, typically no wider than 10 m (Fig. 7e). And third, the island sand sheet and active beach were separated by a vertical scarp, which through continued erosion of the island ridge and beach lowering following the tsunami, effectively abandoned the sand sheet (Fig. 7f).

Of all the study islands, Milaidhoo (Fig. 4d) recorded the most extensive tsunami sand sheet deposits and provided 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. 8). Trench excavation of the sand sheet exposed continuous, landward-dipping tabular bedding defined by variations in grain size and composition (Fig. 8a, 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. 8c).

Less extensive and more elongate than sand sheets, *sand lobes* (Table 2) are 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 towards the island's interior. Like sand sheets, the primary source of sand lobe sediment was from the adjacent beach, though in several cases an erosional scarp separated the two features.

Although quantitatively small, 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. Isolated tsunami-emplaced coral clasts were also present across the island ridge and in *Pandanus* and *Scaevola* bushes along the trailing shores of islands with respect to the tsunami path.

Evidence of *beach rock fracture* and transport was also observed. Beachrock outcrops are exposed on the shores of many of the study islands, and at several locations beachrock slabs had been detached and moved shoreward or alongshore by the tsunami. The largest slab was rectangular in shape, and measured around 2 × 1.4 × 0.15 m, and had been transported approximately 3 m up the beach on the northwestern coast of Milaidhoo. Evidence of detachment and entrainment of smaller beachrock slabs was also observed on the eastern shore of Thiladhoo and on the southeastern shore of Hulhudhoo, where imbricated slabs were deposited against a pronounced beachrock ledge at about mid-tide level. No instances were found where beachrock slabs had been moved from the foreshore onto the island surface.

6. Discussion

Comparison of pre and post-tsunami surveys indicate that the immediate effects of the Sumatran tsunami on morphology of reef islands in South Maalhosmadulu atoll were detectable but minor. Changes in the more stable vegetated core of islands were small with a mean reduction in area of 4% (ranging from <1% to 9%). At the broadest scale, the changes on all islands were quite consistent with beach and island erosion on the tsunami-exposed eastern shores of islands, and accretion of beaches, spits and forelands on the leeward, western sides of islands. Between these two, on the lateral flanks, changes in morphology and sediments were less consistent. Nevertheless, erosional and depositional evidence of the tsunami was observed and documented on each of the islands surveyed, though it is likely that some effects were modified during the northeasterly monsoon in the 6-week period after the tsunami.

Several issues arise from our surveys, which relate to both the immediate geomorphic impacts of the tsunami, and its longer term consequences for atoll island stability. Here we discuss the spatial changes in island geomorphology and sediments and evaluate the importance of three factors that may explain those changes: relative position and exposure of islands to the eastern reef rim and the source of tsunami waves; subtle differences in the morphological characteristics of individual islands and reefs; and, natural dynamics of island shorelines, especially their response to the seasonal reversal in monsoonal conditions. How the tsunami waves interacted with the reef islands is also examined in detail, and a conceptual model developed that identifies a sequence of

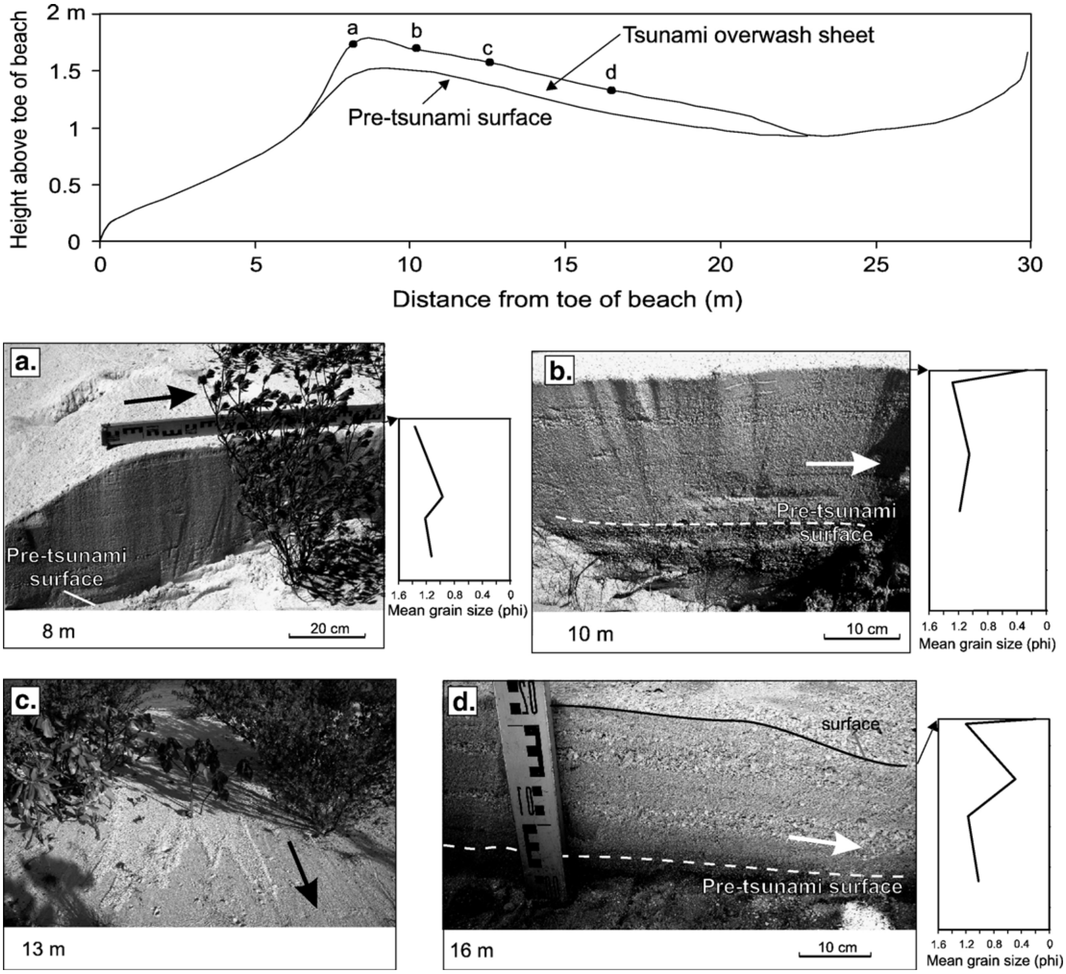

Fig. 8. Cross-section profile and trench photos (a, b, d) showing continuous tabular bedding and mean grain size variability of tsunami overwash sheet on Milaidhoo eastern shore. Also showing surface drape of *Halimeda* flakes (c) deposited during waning flow. Arrows indicate direction of tsunami flow.

critical interactions between tsunami waves and island morphology. This model accounts for the observed spatial differences in geomorphic impacts and is used to highlight potential disturbances to the sediment budget that may promote island instability over the medium-term (decades).

6.1. Spatial differences in tsunami impact

The degree of island erosion, island scarping and the percentage area covered by overwash deposits all decreased along an east to west gradient across the atoll (Fig. 9). This gradient in geomorphic impacts may be due to several factors including: a reduction in cross-atoll tsunami wave energy; spatial variations in island elevation and geomorphology; differences in sediment availability; and, the timing of the tsunami with respect to the background seasonal patterns of island beach dynamics, and antecedent conditions.

6.2. Interaction of tsunami waves with study islands

Critical to understanding the cross-atoll variations in island impact and the observed washover deposition, is the behaviour of tsunami waves and how and where they may have overtopped island surfaces. As shown in Fig. 3 the tsunami comprised multiple waves of diminishing height, that occurred over at least a 12 h period, and which would have interacted differently with islands across the atoll.

One obvious explanation for the reduced east to west impact observed across the atoll is that tsunami wave energy also declined along this gradient through interaction with the atoll's bathymetry and reef structures, or that

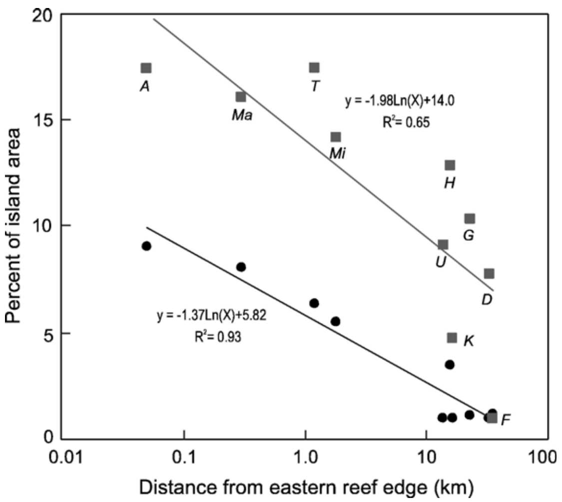

Fig. 9. Cross-atoll variations in tsunami-induced island erosion (circles) and area of washover sedimentation on island surfaces (squares). Letters denote island name. Source data in Table 2.

the western and central islands were sheltered by reefs and islands to the east. Although data exist that show significant reduction in deep ocean tsunami wave height either side of the archipelago (Titov et al., 2005) it is questionable whether differences in tsunami wave energy would have been sufficient to account for the observed spatial differences in geomorphic impacts. First, evidence for island flooding was observed on all islands. Second, it is likely that the tsunami waves maintained sufficient energy in traversing the atoll to continue impacting islands, noting that the energy spectra of the tsunami waves was four orders of magnitude greater than the background pre-tsunami energy spectra at Hanimaadhoo (Leonard, 2006). Moreover, it is clear that the tsunami wave velocities were well in excess of the threshold entrainment condition for carbonate sands (0.2–0.3 m s^{-1}) found on all beaches across the atoll (Kench and McLean, 1996).

The number of tsunami waves that inundated island surfaces is also of interest in explaining observed geomorphic changes across the atoll. The initial tsunami waves coincided with neap high tide, which raised water levels to 1.83 and 1.42 m above msl respectively on tide gauges at the northern (Hanimaadhoo) and central (Hulule) locations in the archipelago (Fig. 3b, c, Table 4). Combined with ambient northeast wave conditions of around 0.4 m (Kench et al., 2006a) tsunami water levels clearly had the capacity to overtop parts of the peripheral margins of islands and reach into island interiors (Table 4). The presence of sand sheets and sand lobes confirm that portions of all islands were inundated to a greater or lesser extent, with a flow depth up to 0.5 m measured on the western island of Fares. Wave overtopping of island surfaces provides the mechanism for overwash deposition to occur, and Table 4 identifies the elevation of the first few waves above mean sea level compared with the ridge elevations of three of the study islands across the atoll. These data indicate that the highest waves could pass over parts of the peripheral ridges, but that subtle differences in elevation resulted in both intra-and inter-island differences in the magnitude of inundation on the three islands. Our survey data of individual islands confirms that the tsunami did not result in wholesale inundation of island surfaces, but rather localized overwash of island margins. Whereas the first tsunami

Table 4
Comparison of raised water levels associated with tsunami waves and island ridge elevations, South Maalhosmadulu atoll, Maldives

Thiladhoo inundation levels						Hulhudhoo inundation levels				Dhakandhoo inundation levels			
Water level	Ridge elevation v *h* at Hanimaadhoo		Water level	Ridge elevation v *h* at Hulule		Ridge elevation v *h* at Hanimaadhoo		Ridge elevation v *h* at Hulule		Ridge elevation v *h* at Hanimaadhoo		Ridge elevation v *h* at Hulule	
(m)	Min *E*	Max *E*	(m)	Min *E*	Max *E*	Min *E*	Max *E*	Min *E*	Max *E*	Min *E*	Max *E*	Min *E*	Max *E*
Hanimaadhoo	1.08 m	1.59 m	Hulule	1.08 m	1.59 m	1.32 m	2.51 m	1.32 m	2.51 m	1.44 m	2.2 m	1.44 m	2.2 m
2.23	**1.15**	**0.44**	1.82	**0.74**	**0.23**	**0.91**	−0.28	**0.50**	−0.69	**0.79**	**0.03**	**0.38**	−0.38
1.75	**0.67**	**0.16**	1.14	**0.04**	−0.45	**0.43**	−0.76	−0.18	−1.37	**0.31**	−0.45	−0.30	−1.06
1.35	**0.27**	−0.24	0.92	−0.16	−0.67	**0.03**	−1.16	−0.40	−1.59	−0.09	−0.85	−0.52	−1.28
1.47	**0.39**	−0.12	0.94	−0.14	−0.65	**0.15**	−1.04	−0.38	−1.57	**0.03**	−0.73	−0.50	−1.26
1.46	**0.38**	−0.13	0.58	−0.60	−1.01	**0.14**	−1.05	−0.74	−1.93	**0.02**	−0.74	−0.86	−1.62
1.47	**0.39**	−0.12	0.87	−0.21	−0.72	**0.15**	−1.04	−0.45	−1.64	**0.03**	−0.73	−0.57	−1.33
0.74	−0.34	−0.85	0.80	−0.28	−0.79	−0.58	−1.77	−0.52	−1.71	−0.70	−1.46	−0.64	−1.40

NB: water levels (*h*) represent maximum wave heights as measured on the Hanimaadhoo and Hulule water level recorders plus the maximum background wave height recorded on reef flats as recorded by Kench et al. (2006a). Positive (bold) values represent potential overwash water depth at island ridge. Min *E* and Max *E* refer to minimum and maximum ridge elevations around islands.

waves had the potential to promote the greatest degree of island flooding and mobilization of beach and reef sediments, it is unlikely that the later waves could have had a similar impact and produced the overwash sheets on island surfaces.

The sedimentology of the overwash sand sheets covering the island surfaces also suggests that they were deposited during the highest inundation events. The sediments comprising these sand sheets are generally thin (<0.05 m), 0.34–0.87 mm in size, which contain a single sedimentation unit and exhibit no bedding. Generally, the deposits taper landward as would be expected with decelerating flow. However, detailed description of tsunami overwash deposits also identifies a coarsening trend within the first 10 m of the peripheral island ridges. These thicker units comprised a higher proportion of *Halimeda* flakes deposited on the sediment surface as terminal drapes. We interpret these surface drapes as the product of wind-wave action superimposed upon the tsunami-elevated sea surface that would have overtopped the peripheral ridges, with sediment settling a short distance in from the island ridge. 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.

In contrast to the sand sheets and sand lobes deposited on vegetated island surfaces multiple wave deposition is clearly evident on the southeastern shoreline of Milaidhoo (Fig. 8). This lateral berm of the island is lower in elevation than the vegetated island ridges and in trench section displays well developed tabular bedding, with no cross-bedding (Fig. 8d). This suggests tsunami flow was unidirectional, producing an upper-stage plane bed characterised by pulses of deposition with successive waves and additional flow generated by swash action of wind-waves as tsunami flow waned (Fig. 8).

The low elevation of islands also promoted distinct differences in the interaction of waves with the islands. First, due to their low relief waves flowed across island surfaces and continued propagating westward, though not across the entire island surface. Two other features of tsunami flow are evident. First, there was little or no backwash, and second, the basin shape of islands (Fig. 3a) resulted in water ponding in the interior depressions, which was still evident six weeks after the tsunami on the island of Madhirivaadhoo. The release of ponded water, interacting with antecedent groundwater, provides the principal mechanism for gully erosion in island berms and beaches. Two processes in the formation of seepage gullies are envisaged. First, by ponded water in the island basin exiting through low points in the island ridge, such discharge representing the only example of return flow of tsunami waters. Second, through drainage and seepage through the beach foreshore and berm on the receding (drawdown) phase of tsunami waves. Generally, gullies formed or were preserved most often on the southern and western shores of islands and were best developed where sandy berms occurred seaward of the island vegetation line.

6.3. Role of spatial variations in island elevation

Table 4 indicates that spatial differences in island elevation are also present across the atoll with lower elevation peripheral ridges in the east on Thiladhoo ($\bar{x}$ = 1.29 m) increasing at Hulhudhoo ($\bar{x}$ = 1.77 m) and reaching a maximum on the western island of Dhakandhoo ($\bar{x}$ = 1.9 m). This east to west increase in ridge elevation is associated with cross-atoll variations in mean wave climate. Based on wave measurements on reef flats, Kench et al. (2006a) show that western islands have a higher wave energy input on an annual basis, and this is likely to control the elevation of wave runup and the height of island building. Of importance in this study is that the eastern islands as reflected in the Thiladhoo data, have a higher proportion of peripheral ridges below 1.5 m above MSL thus allowing the tsunami waves to overtop a greater proportion of the island rim than elsewhere. The distribution of washover sand sheets supports this interpretation with the entire northern and eastern sections of the island blanketed with washover sediments that extend over 17% of the island surface.

In contrast, on Hulhudhoo and Dhakandhoo the peripheral ridges are significantly higher, by more than 0.5 m on average, and reach more than 2.0 m above MSL in places. These shorelines present a higher physical barrier to wave overtopping. On these islands washover sedimentation was localized and particularly associated with lower elevation sections of the peripheral rim. On Hulhudhoo washover sand sheets primarily occurred on the northeast to eastern shoreline where the ridge elevation is only 1.32–1.40 m above MSL. Similarly, the major washover deposit on Dhakandhoo is located on the eastern margin of the island where the ridge elevation is lowest at 1.44 m above MSL. Little or no evidence of washover deposition was present at locations with ridge elevations of +1.7 m MSL and above.

6.4. Sediment availability and seasonal dynamics of islands

Spatial differences in geomorphic impacts across the atoll may also be related to the distribution and the availability of sediment around island shorelines. The Sumatran tsunami occurred in the early stages of the northeast monsoon, when the mobile beaches tend to be concentrated at the eastern ends of islands, though there are differences dependent on island shape. For instance, Kench and Brander (2006) found that on elongate western islands seasonal changes in beach position are constrained to the eastern end of islands, while the beaches on the circular islands (those in the central lagoon) oscillate in position from the western shoreline (at the end of the northeast monsoon) to the eastern shoreline (at the end of the westerly monsoon, e.g. Fig. 4b). A third pattern of seasonal response was observed on the eastern islands where beach change is focussed at nodal positions on the southwestern and southeastern sectors of islands. Consequently, on the eastern islands large deposits of beach material are not usually found on the tsunami-exposed northeastern shorelines, whereas they do accumulate on the eastern and northeastern shorelines of central and western islands. The fact that the greatest amount of overwash sedimentation occurred on eastern islands (where beaches are generally narrowest) suggests that sediment availability was not a limitation on the westward decline in overwash deposition across the atoll (where beach material is more plentiful).

On the other hand, differences in beach position and the immediate availability of sand have played a major role in determining the magnitude and location of island erosion across the atoll. On eastern islands the mobile beach is rarely present on eastern shores, which means that the tsunami-exposed shorelines lacked a substantial sediment reservoir to buffer the impacts of tsunami waves. As a result the limited sediment was readily stripped from these shorelines, and the vegetated island ridge was exposed to higher energy levels that produced shoreline erosion.

In contrast, the size and position of the mobile beach protected central and western islands from more extensive erosion during the tsunami. In late December the mobile beach is at its most easterly position on these islands. Consequently, they had substantial beaches along the tsunami-exposed shorelines and the lower levels of erosion and scarp cutting may be directly related to the buffering effect of those beaches. At the same time the beaches provided the immediate source of sediment for overwash deposition onto adjacent island surfaces. One implication of this analysis is that islands in the central and western sides of the atoll would have experienced more substantial erosion if the tsunami had struck later in the northeast monsoon, when the eastern beaches are narrower and more erosion prone.

6.5. Conceptual model of tsunami-island interactions

Based on consideration of the tsunami wave elevations, geomorphic changes in islands and analysis of overwash deposits, a conceptual model of island-wave interactions is proposed (Fig. 10). This model accounts for observed geomorphic impacts especially on the central circular islands of the atoll, whose pre-tsunami beach condition early in the northeasterly monsoon (December) is typically as illustrated in Fig. 10a.

6.5.1. Island inundation and overwash deposition

The first tsunami waves had sufficient energy and elevation to overtop the lower sections of island shorelines promoting widespread island flooding. These waves, and their associated troughs, entrained and transported beach sediments to the island surface as overwash deposits (Fig. 10b). As the waves flooded across the island rim, flow decelerated resulting in deposition of sand sheets and sand lobes. Overwash deposition also smothered lower elevation island scarps (Fig. 7d).

Without significant relief the tsunami waves had little backwash. Rather water temporarily trapped in the interior basin exited through low elevation sections of the peripheral ridge or through beach effluent channels. Both mechanisms contributed to the formation of seepage gullies developed in accretionary berms and island margins.

6.5.2. Shoreline erosion and sediment transfer

The later tsunami waves were not of sufficient elevation to cause widespread inundation or significantly increase either the size or occurrence of washover deposits. As over-island flow was no longer dominant the later tsunami waves were deflected alongshore and around island shorelines. This lateral flow would have mobilized and transported sediments (promoting scour) along island shorelines causing accretion in leeward depocentres (Fig. 10 c). These flows, and the subsequent smaller waves (Fig. 3b, c) resulted in substantial reworking of island shorelines. Pre-tsunami baseline monitoring indicates that the amount of sediment transfer in the 12-hour period that tsunami waves interacted with island shorelines was quantitatively comparable to the total geomorphic work that usually takes place over the four months of the northeast monsoon.

6.5.3. Post-tsunami monsoon modifications

Following the tsunami the islands were subject to the ongoing effects of the northeast monsoon. This season is

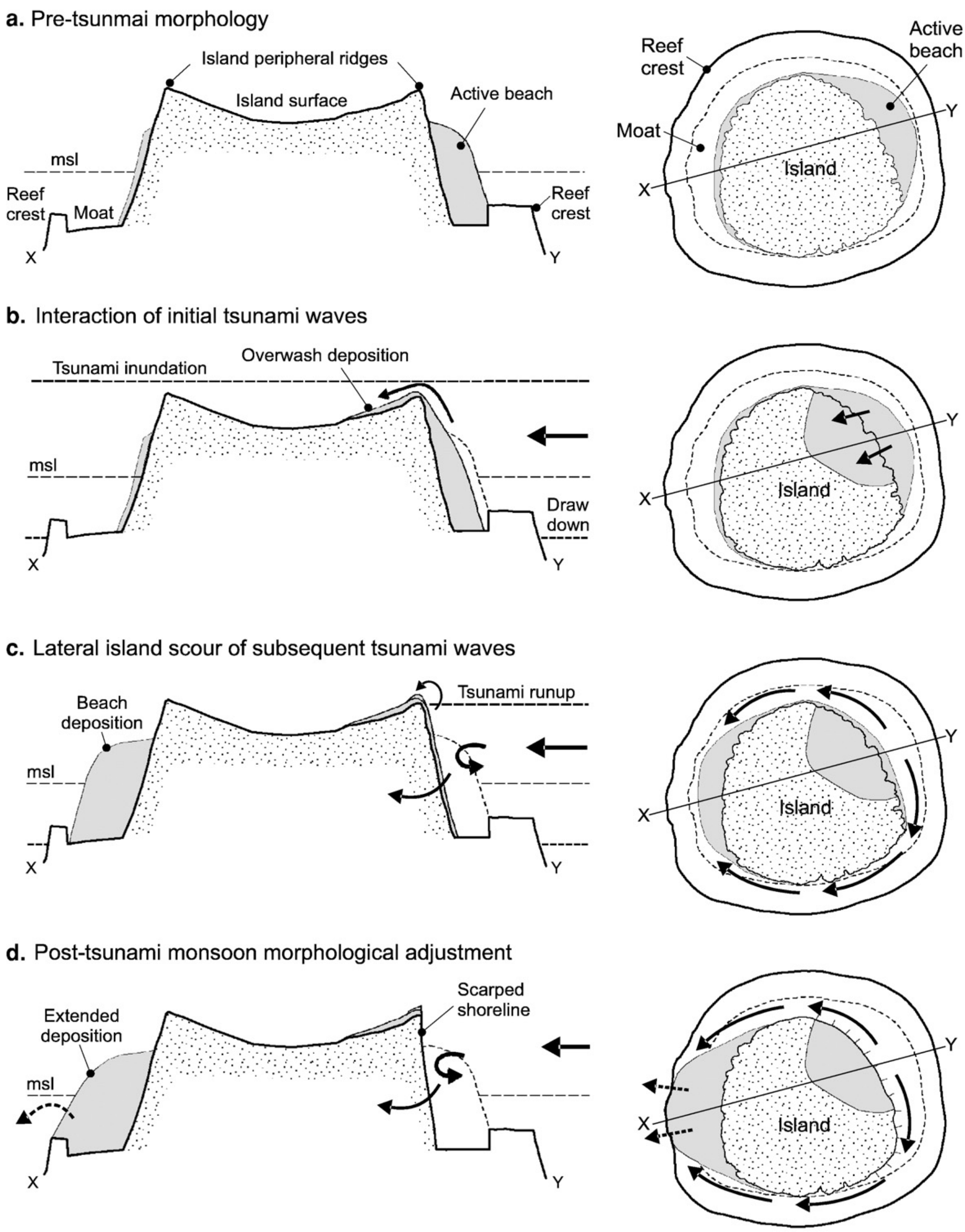

Fig. 10. Conceptual diagram of process mechanisms promoting island change (shown in cross-section and planform) during and after the Sumatran tsunami. a) Pre-tsunami morphology. b) and c) Illustrate the interaction of tsunami waves and post-tsunami monsoon energy with reef islands and resultant sediment transfers. d) Modification of shoreline after the tsunami in response to prevailing northeast monsoon conditions.

characterized by incident waves from the northeast that result in a southwestward transfer of sediments, that is, from the eastern to the western depocentres (Kench and Brander, 2006). Another consequence of this transfer is that the eastern shorelines become sediment depleted and exposed to further erosion, in places trimming back the vegetated island margin leaving scarps which occasionally revealed perched overwash layers emplaced during the tsunami (Fig. 7f). Furthermore, continued transfer of sediment to leeward depocentres promoted extension of beaches beyond the moat, and across the living reef towards the reef edge (Fig. 10d).

6.6. Implication of tsunami impacts for island stability

While the immediate impacts of the tsunami were relatively minor, the observed changes could promote medium-term (interannual to decadal) instability of islands due to alterations in island sediment budgets. A critical question for island stability is: have the island sediment budgets been shifted out of their seasonal equilibrium pattern as a result of the tsunami? On the study reefs there are three spatially distinct sediment reservoirs: the reef surface; mobile beach; and vegetated island core. Each of these stores has a different role with regard to the sediment budget. i) *The reef surface* is the primary production zone and sediment generated on the reef can be transferred to the mobile beach, off the reef platform, or be reincorporated into the reef framework. ii) The *beach* is a mobile and temporary store of sediment. Sediment can be exchanged with either the adjacent reef or the vegetated island core. Pre-tsunami surveys of the islands indicated that despite large seasonal fluctuations in shoreline position around islands there was little net change in beach sediment volume (Kench and Brander, 2006). This suggests that the beaches either conserve the sediment reservoir, or that net sediment inputs and losses are near-balanced over annual timescales. iii) The *vegetated island core* is a medium to long-term store of sediment. Kench et al. (2005) consider the islands to have been relatively stable over the past 4500 years and baseline investigations identified negligible change in vegetated island area between 1998 and 2004.

The volume and position of sediment within each of the reservoirs was modified during the tsunami. The *mobile beach sand reservoir* was generally displaced beyond the normal envelop of change as a result of the efficiency of tsunami wave energy to perform the majority of work of the northeast monsoon in a few hours. This impact was exacerbated during the post-tsunami monsoon conditions which continued to mobilize shoreline sediments promoting sustained erosion and deposition around the islands. The net result of these combined processes has been for accretionary deposits to occupy a greater area of the reef surface than previously (Table 3), and in the process smothering potential sediment producers. Sediment has also been lost from the mobile beach through overwash deposition to the island surface and by leakage over the leeward reef rim. Quantitatively overwash losses have not been great, ranging from 20 m^3 on Fares to more than 880 m^3 on Madhirivaadhoo (Table 5). The magnitude of sediment loss off reef platforms is unknown. However, sediment losses from the mobile beach may be partly, or fully, compensated by inputs of sediment transferred from the reef surface or eroded from the vegetated island core (discussed below). Extensive pre-tsunami surveys of the reefs identified quite limited reservoirs of unconsolidated sediments, which were dominated by solid substrates and living and dead corals. Consequently, sediment inputs from reef to beach are considered small.

The *vegetated island sand reservoir* was also altered by the tsunami. Overwash sedimentation represents a net addition to the vegetated island core and contributes to vertical island building. It also represents a transfer from the temporary beach store to a longer-term sediment sink. As noted above, such additions were highly variable in extent and amount (Table 5). On the other hand, erosion of the vegetated shoreline represents a loss from the island reservoir. Erosional losses range from 204 m^3 on Udoodhoo to 5789 m^3 on Madhirivaadhoo (Table 5). In volumetric terms erosion was generally greater on the eastern and western islands, than the central islands (Table 5).

These results clearly indicate that the tsunami promoted an event-driven redistribution of sediment between the three sediment stores. In most cases this resulted in a sediment deficit to the vegetated island core ranging up to −5455 m^3 (Table 5). It is assumed that the

Table 5
Impact of the Sumatran tsunami on the sediment reservoir of vegetated islands, South Maalhosmadulu atoll, Maldives

Island	Volume of overwash sedimentation (m^3) [a]	Volume of island shoreline erosion (m^3) [b]	Island sediment balance (m^3)
Aidhoo	206	3809	−3603
Madhirivaadhoo	882	5789	−4907
Thiladhoo	599	3798	−3199
Milaidhoo	719	3551	−2832
Udoodhoo	511	204	+307
Hulhudhoo	227	2401	−2174
Keyodhoo	51	329	−278
Dhakandhoo	166	5621	−5455
Fares	20	4389	−4369
Gaaviligilli	181	402	−221

[a] Overwash volume calculated based on the area of overwash and mean sediment depth of deposits.
[b] Volume of island erosion calculated based on the proportion of island area eroded (Table 2) multiplied by the mean elevation of island peripheral ridges.

losses were initially added to the mobile beach, though some off-reef losses could have occurred.

6.7. Geomorphic responses to changes in sediment reservoirs

Changes in sediment volumes between the beach and island core are likely to trigger ongoing adjustments which will manifest as alterations in island area and perhaps in the actual position of islands on reef platforms. The magnitude of ongoing adjustment is graphically illustrated in Fig. 11 and is dependent on the degree to which the beach sediment reservoirs have been altered, and the redistribution of sediment between the island and beach sediment stores. Four scenarios can be envisaged.

First, if there has been little net change in mobile beach sand volume, the beach would resume its normal oscillation during the subsequent westerly monsoon. Sediment would be transported to the eastern and northern shorelines, and the resulting deposition will mask the tsunami-enhanced erosion scarps, and buffer the shoreline from further erosion. In this scenario no further shoreline erosion would be anticipated though erosional losses resulting from the tsunami would persist (Fig. 11a).

Second, if the beach reservoirs increased during the tsunami (from erosion of island sources) beaches would also be expected to resume their oscillating adjustments to monsoonal changes. However, the increased sediment volume may be now in excess of the capacity of the normal monsoon energy to redistribute the entire beach. In such circumstances residual sediment would be retained at the shoreline, and be colonized by grasses and shrubs, thus allowing extension of the vegetated island core. In the study islands this scenario would be expressed as accretion, primarily along the sides of islands not exposed to tsunami impacts. Such a response is also likely to be rapid and result in migration of the centroid of islands on the reef platform.

Third, if the beach volume has been reduced (rather than maintained or increased as in the first two cases) the transfer of sediment will be completed earlier in the

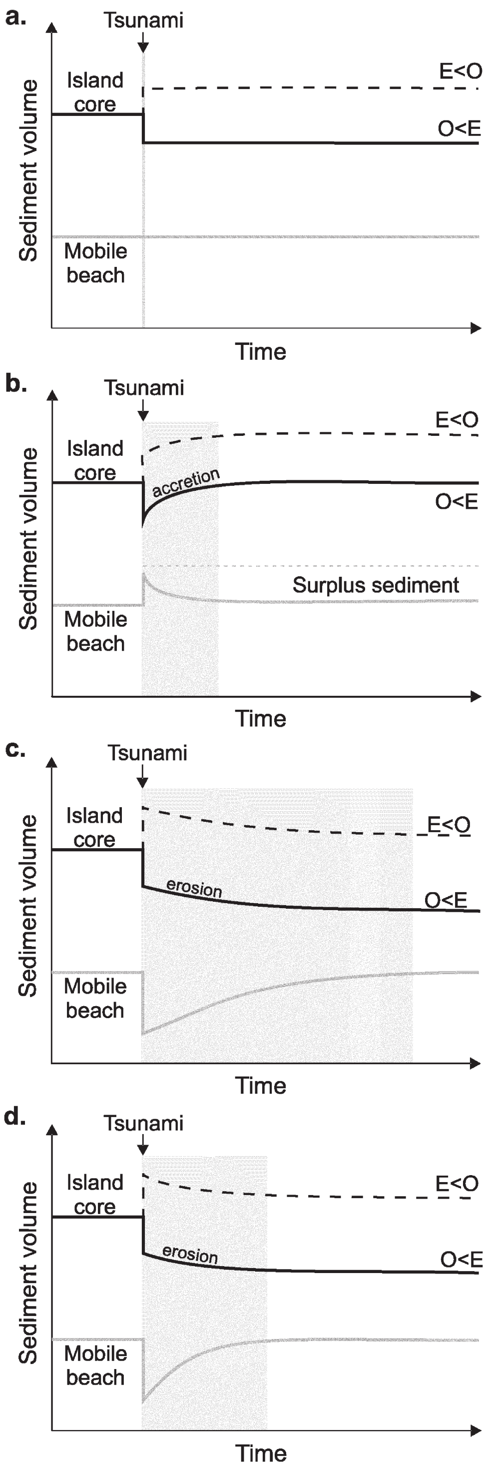

Fig. 11. Projected relationships between the mobile beach and vegetated island sediment reservoirs and the morphological response of islands. Black lines represent island sand volume. Grey lines represent the volume of the mobile beach. Shaded areas represent time periods of island instability. Differences in time (width of shaded area) reflect the magnitude of disturbance in mobile beach sediment volume following the tsunami and the redistribution of sediment between stores. Four scenarios are presented: a) no change in mobile beach sand volume; b) increased beach sand volume; c) reduction in beach sand volume and its recovery constrained to sediment eroded from island shoreline; d) reduction in beach volume and its recovery through addition of sand from both the island core and reef surface. E=shoreline erosion, O=overwash sedimentation. $E<O$=net addition to island surface. $O<E$=net erosion of island sediment. Note: island adjustments are projected in each scenario for conditions of initial island accretion (dashed line) and erosion (solid black line).

monsoon period, exposing the western shorelines to more prolonged wave attack than under pre-tsunami conditions. Scarping and erosion of the western shorelines would result with the eroded products being added to the mobile beach, increasing the beach sediment reservoir. Such a process may continue in alternating monsoon periods until the mobile sand volume is replenished. The morphological result on the vegetated island is a diminishing rate of erosion and no change in island position (Fig. 11c).

Fourth, critical for island stability is the time period for the mobile beach to replenish and resume its function as a protective buffer to shoreline erosion. It is this temporal window in which both shoreline accretion and erosion can occur. The duration of island instability will be controlled by two factors: the initial magnitude of change in the beach sediment reservoir; and, the time taken for the beach to achieve its optimal sand volume as a buffer against shoreline erosion. In cases where the beach sediment volume increases it is expected that there is rapid return to optimal beach change conditions with residual sediment contributing to island accretion. In cases where the beach sediment reservoir has been depleted, the time period of island instability will be dependent on whether replenished sediment is sourced only from the vegetated island core, promoting further erosion and a longer time period for recovery (Fig. 11c) or both from the island core and surrounding reef flat, causing less erosion and shorter recovery (Fig. 11d).

These four scenarios make it clear that the tsunami can have much longer lasting and potentially more significant geomorphic consequences than the immediate effects would imply. Both the size and location of islands may change as a result of tsunami-induced perturbations to the sediment budget. Consequently, the medium-term geomorphic stability of the islands is considered to be closely linked to changes in both the island and beach sediment reservoirs. If such changes are minor islands will not experience further erosion and area loss. However, if the sediment budgets have been significantly altered a greater degree of erosion may be expected, increasing island instability.

6.8. Preservation of tsunami imprint

Given the dynamics of island shorelines and the limited magnitude of tsunami impacts, it is unlikely that the observed changes in island geomorphology and sediments will be preserved as tsunami signatures. The extension of the beaches beyond their usual footprint is likely to be temporary, and they will resume their usual oscillating pattern driven by seasonal changes in monsoons. Island scarps are likely to be masked by resumption of monsoonal shifts in the mobile beach, and be unrecognizable from pre-tsunami scarping. Furthermore, while overwash sedimentation represents a net addition to island building, the sand sheets and lobes are not likely to be preserved as recognizable tsunamite layers because: the sand sheets are very thin (average of 0.01 m); pedogenic processes and bioturbation are likely to vertically mix the sediments; and, the sand sheets will be difficult to recognize owing to their composition of homogenous medium-sands with no distinct bedding. The greatest chance for preservation of overwash deposits is at the peripheral ridges where the deposits can be up to 0.2 m thick. Detailed description of the Milaidhoo washover sheets seaward of the island's peripheral ridge (Fig. 8) do show that thicker deposits (0.3 m) can occur, and they provide an indication of the nature of bedding in multiple tsunami wave flows. However, in general, deposits on peripheral ridges are discontinuous and are found only on the lower-lying margins. Both these and any thicker deposits on peripheral ridges are susceptible to scarping and reworking.

7. Conclusions

Pre-and post-tsunami surveys of 11 islands in South Maalhosmadulu atoll, Maldives provide a unique opportunity to quantify the effects of the December 26, 2004 Sumatran tsunami on mid-ocean reef islands. Results provide insights into the role of tsunami in geomorphic development and change of reef islands at a range of timescales.

The immediate impacts of the tsunami were relatively minor with reductions in island area ranging from <1% to 9%. Depositional and erosional evidence was observed on all islands. Overwash deposits, in the form of sand sheets and sand lobes, as well as strandlines and individual clasts of coral rubble, were the most common accretionary forms. These deposits represent a net addition to island surfaces, although their preservation potential as tsunami signatures is not high. Two types of erosion were apparent: scarps cut into the vegetated margins of islands and mobile beaches; and, seepage gullies on recently accumulated lateral shores.

An east to west gradient in island impacts (magnitude of erosion and extent of sediment overwash) away from the tsunami source was observed. Although it is inviting to explain this gradient in terms of energy reduction as the tsunami waves passed through the atoll, two other factors contributed. First, cross-atoll variations in the elevation of peripheral island ridges; and, second, spatial differences in the distribution and quantity of beach sediment around island shorelines, the latter resulting from normal seasonal monsoon changes.

A conceptual model of the interaction of tsunami waves with island morphology, and the effect of post-tsunami monsoon processes has been developed to account for observed geomorphic changes. This model illustrates the importance of the antecedent seasonal conditions and the sequence of impact events through the initial and later stages of the tsunami. It also suggests that the geomorphic impacts would have been quite different had the tsunami occurred during the westerly monsoon or at a different time of the year.

Despite the short-term effects of the tsunami being minor, alterations in the island and beach sediment reservoirs resulting from the tsunami may promote future island instability, through changes in seasonal erosion and accretion patterns. These could ultimately manifest in island migration on reef surfaces. Four alternative scenarios are presented and these suggest that the time period of instability is dependent on both the magnitude by which the island beach sediment volumes have been altered by the tsunami, and on the self-regulating nature of the seasonal sand budget.

Our results clearly indicate that reef islands in the Maldives were geomorphically resilient to the impact of the Sumatran tsunami. Over geological timescales multiple tsunami are likely to have promoted phases of island instability contributing to the short-to medium-term process that govern island shape and location on reef platforms. Furthermore, multiple tsunami throughout the Holocene are likely to have added sediment to reef island surfaces and contributed to vertical island building. However, the thin veneer of overwash sediments, homogeneous nature of sediments, pedogenic processes and reworking of island margins suggest such deposits are not likely to be identifiable in the sedimentary record.

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