Geological effects of tsunami on mid-ocean atoll islands: The Maldives before and after the Sumatran tsunami

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ABSTRACT

Low-lying coral islands are fragile landforms susceptible to long-term sea-level rise and extreme events, such as hurricanes and tsunamis. The Sumatran earthquake of 26 December 2004 generated waves that reached the Maldives 2500 km away. Observations of the effects of the tsunami are presented here, based on pre- and post-tsunami topographic and planform surveys of 13 uninhabited Maldivian islands. The surveys showed there was no substantial island erosion and no significant reduction in island area. Rather, the tsunami accentuated predictable seasonal oscillations in shoreline change, including localized retreat of exposed island scarps by up to 6 m, deposition of cuspate spits to leeward, and vertical island building through overwash deposition of sand sheets up to 0.3 m thick, covering up to 17% of island area. These results have implications for island stability indicating that low-lying reef islands are physically robust and the geological signature of tsunamis on atoll island development is minor.

Keywords: tsunami, Indian Ocean, atoll islands, carbonate sediments.

INTRODUCTION

Mid-ocean coral islands are low-lying accumulations of locally derived calcareous sand and gravel deposited on reef platforms that provide the only habitable land in atoll nations such as the Marshall Islands, Kiribati, Tuvalu, and the Maldives. Atoll islands are morphologically sensitive, susceptible to widespread destruction given future sea-level rise (Dickinson, 1999; Khan et al., 2002) and significant alteration during extreme natural events. The physical effects of tropical storms on reef island destruction and formation are well documented (Maragos et al., 1973; Scoffin, 1993). In contrast, the role of tsunamis in the geological development of reef islands has only been inferred, and attempts to distinguish between tsunami and hurricane deposits in reefal areas has not been successful (Bourrouilh-Le and Talandier, 1985; Nott, 1997). Atoll islands occur throughout the Indian and Pacific Oceans and have been exposed to multiple tsunamis during their geological histories (Scheffers and Kelletat, 2003). However, no direct and quantitative observations of the geomorphic effects of tsunamis on atoll islands have been made, although results would be important in identifying tsunami signatures and determining island stability.

The tsunami of 26 December 2004 was generated by a magnitude Mw 9.3 (Stein and Okal, 2005) earthquake off the northwest coast of Sumatra (Fig. 1A). Tsunami waves reached the Maldives, 2500 km west of the epicenter, 3.5 h after the earthquake. Highest recorded water levels associated with the first wave reached 1.80 m above mean sea level (msl) (Fig. 2A). In the following 6 h, multiple surges occurred at periods of 15–40 min, with water levels fluctuating from 1.1 m below to 1.4 m above msl and the highest waves reaching levels sufficient to inundate the islands (Fig. 2), causing the loss of at least 80 lives, flooding of the capital, Male, and damage to many of the inhabited and resort islands. Several of the worst-affected islands were abandoned.

FIELD SETTING AND METHOD

The Maldivian atolls contain ~1200 low-lying islands (mean elevation <2 m above msl) of middle to late Holocene age (Kench et al., 2005). The archipelago is situated in a predominantly storm-free environment, with a process regime marked by strong seasonal reversals in monsoon winds and seas from the west (March to October) and northeast (November to February) that govern short-term changes in island shorelines (Kench et al., 2003). Significantly, the tsunami coincided with the northeast monsoon.

In January 2002, a network of survey benchmarks was established on 13 uninhabited islands on South Maalhosmadulu atoll (Fig. 1C; Fig. DR1[1]). Cross-beach profiles were surveyed by automatic level. Island planforms were mapped using global positioning systems (Trimble ProXL and Geoexplorer 3) with a mean horizontal positioning error of ±1.8 m. Islands were surveyed on three occasions in 2002 and 2003, and six weeks after the tsunami in February 2005. The pre-tsunami surveys documented monsoon-driven island dynamics. They indicated that vegetated islands were stable but the surrounding beaches were highly changeable and responsive to monsoonal shifts in wind and wave regimes (Kench et al., 2003, 2005). Typically, windward beaches erode and leeward beaches accrete on each phase of the monsoon cycle (Fig. 3; Fig. DR2, Table DR2 [see footnote 1]), and the island footprint is marked by sub-

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[1]GSA Data Repository item 2006033, methods; Figure DR1, location and planform characteristics of study islands; Figure DR2, summary of the physical impacts of tsunami on 12 islands; Table DR1, physical characteristics of study islands and reefs; and Table DR2, island area characteristics for pre- and post-tsunami surveys, are available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

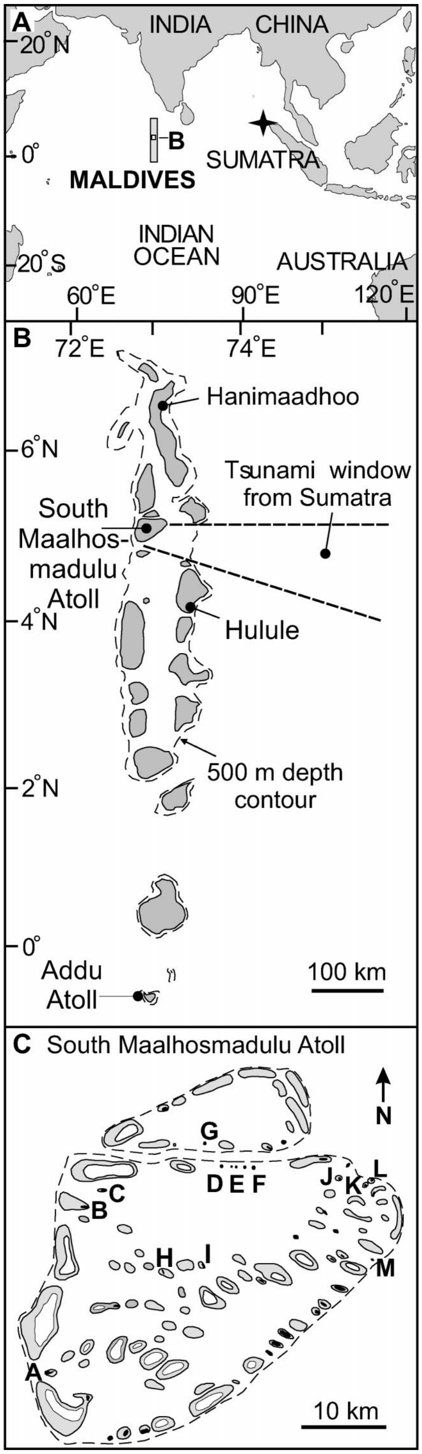

Figure 1. A–C: Location of study islands in South Maalhosmadulu Atoll, Maldives, Indian Ocean. Note location of earthquake epicenter. Letters A–M in part C denote location of study islands presented in Figures DR1 and DR2 and listed in Tables 1, DR1, and DR2 (see footnote 1).

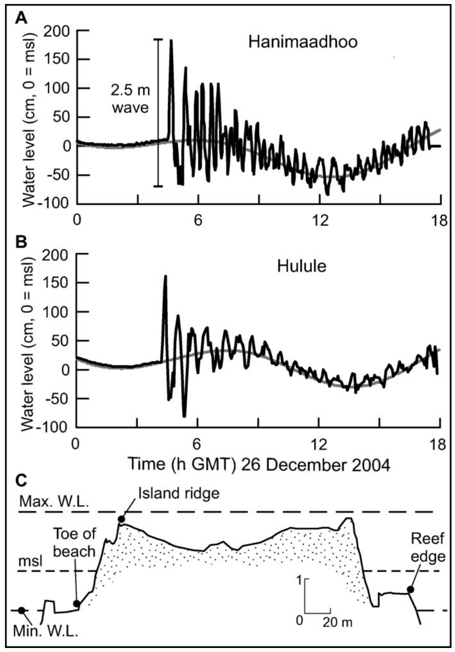

Figure 2. Expression of tsunami waves in the Maldives. A, B: Water level records from northern (A) and central (B) archipelago. C: Surveyed west-east cross section of Hulhudhoo island (E in Fig. 1C) showing maximum and minimum water levels occurring with passage of the first tsunami wave as recorded at Hanimaadhoo tide recorder and potential for island overtopping and inundation. Water level records were provided by the University of Hawaii Sea Level Center. W.L.—water level; msl—mean sea level.

annual variations in the position of the toe of the beach.

IMPACTS OF THE SUMATRAN TSUNAMI

Although South Maalhosmadulu is located on the archipelago's western side, a 60-km-wide gap between two eastern atolls, with depths >2000 m, allowed tsunami waves to propagate toward the atoll and penetrate the lagoon through numerous passages (up to 42 m deep and 4500 m wide) in the atoll rim (Fig. 1B, 1C).

The Sumatran tsunami had distinct geomorphic and sedimentologic impacts that can be distinguished from monsoon-driven changes. Generally, the magnitude of impact declined along an east-west gradient away from the tsunami source (Table 1; Fig. DR2 [see footnote 1]). Erosion of vegetated islands resulted in small reductions in island area from 5.5%–9% on the eastern islands to 1.1%–5% on the western islands. One exception was the small, elongated island of Nabiligaa in the center of the atoll, which lost 80.47% of its vegetative cover (Table 1; Fig DR2H). Island footprints (defined by the toe of the beach) were modified in a consistent way. On tsunami-exposed shores and lateral flanks, beach width was reduced, but it was expanded on lee shores, adding to the depositional nodes formed during the northeast monsoon (Fig. 3A–E). As a result, lee beaches occupied an extra 1154–9729 m^2 of reef flat area and extended beyond the normal monsoonal beach envelope, by up to 22 m (Fig. 3A, 3E).

Changes in island area and beach dimensions resulted from tsunami-driven erosional and depositional processes. Two forms of erosion have been recognized. First, fresh scarping of the encircling vegetated island ridge was documented, which typically exposed tree roots and destabilized trees (Fig. 3F). Significantly, pre-tsunami surveys indicate scarps are a persistent feature on most island shorelines (Fig. 3G). However, careful examination of pre- and post-tsunami surveys indicates that tsunami-induced scarping affected up to 54% of the shorelines on eastern islands, but had relatively little impact on central islands (Fig. 3A; Fig. DR2). Scarp retreat of up to 6 m was most extensive along the north and eastern shorelines of eastern islands, and also occurred on the exposed eastern tips of western islands. Second, localized gully scour was observed across the upper beach. Gully dimensions ranged from 2 to 12 m cross shore, 2 to 20 m alongshore, with depths up to 1.5 m. In rare instances, gullies had cut back into vegetated island ridges. Gullies were located on the least-exposed shores, where ponded water exited through low points in the island ridge.

Primary depositional signatures on vegetated island surfaces included continuous sand sheets (Fig. 3H, 3I), discontinuous sand veneers, and isolated coral clasts. The main source for these deposits was the adjacent beach, with minor contributions from the outer reef and reworking of soil, all of which could be distinguished by sediment size, abrasion, color, and composition. Continuous washover sand sheets were located principally on the northern to eastern sectors of islands and were more extensive on the eastern islands, where they covered up to 17% of the island surface and extended up to 60 m inland (Table 1). Typically, these sheets were composed of coral-algal sands that tapered from a maximum thickness of 0.30 m at the island edge to <0.01 m inland, in a similar manner to the sand wedges described by Dawson and Shi (2000) and Minoura et al. (1997). Internal stratification reflecting differences in sediment size and composition was evident only in the thickest deposits. Terminal drapes contained unmodified coarse *Halimeda* flakes, small molluscs, and discoidal foraminifera (*Marginopora* sp.). Discontinuous sand veneers to a thickness of 0.10 m and lacking stratification were deposited on island ridge areas where dense vegetation interrupted tsunami flow. Isolated coral clasts (*a* axis up to 0.25 m) were deposited amongst strand vegetation as well as on the island ridges, especially along trailing shores with respect to the tsunami path. Occasionally, on exposed beaches, slabs of intertidal beach rock were shifted a few meters alongshore.

IMPLICATIONS FOR REEF ISLAND STABILITY

These results show that the Sumatran tsunami had measurable geomorphic impacts on both exposed and sheltered sides of the is-

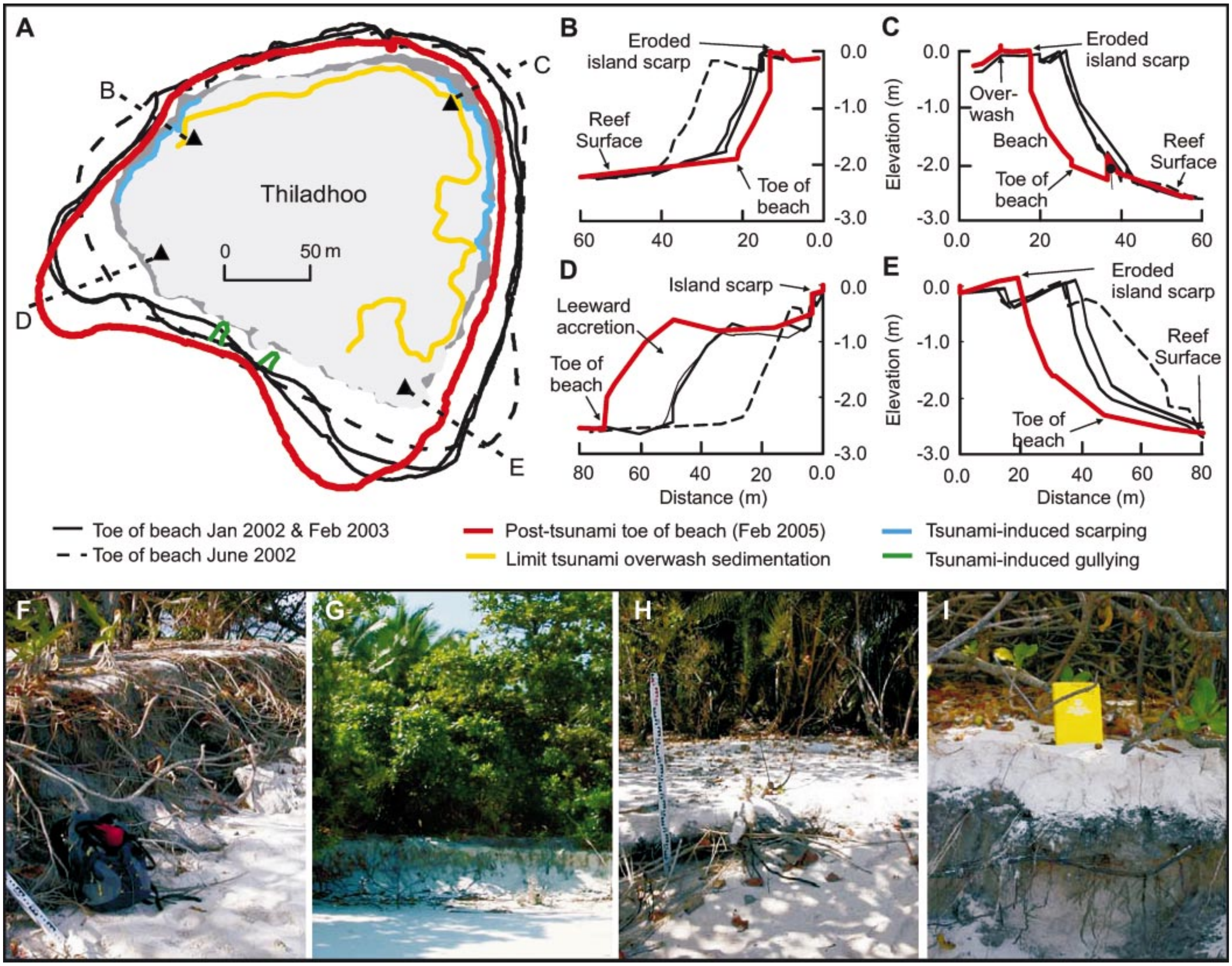

Figure 3. Summary of physical impacts on Thiladhoo island (location in atoll: K in Fig. 1). A: Thiladhoo island showing pre- and post-tsunami vegetated shoreline and toe of beach positions. Note erosion of vegetated shoreline along northwest and northeast shorelines; landward movement of toe of beach position on exposed northeast shoreline; extension of depositional zones on western and southern lobes beyond the surveys previously undertaken at same stage of northeast monsoon (January 2002, February 2003); and shift in beach position resulting from the southwest monsoon conditions (dashed line). B–E: Island to reef topographic surveys showing landward movement of vegetated scarp (B, C, E) and significant deposition on western lobe (D). F: Tsunami-induced scarping. G: Example of pre-tsunami island scarping evident on most islands. H: Overwash sand sheet extending 15 m landward and covering old erosional scarp. I: Overwash sand sheet (0.2-m-thick, light-colored sand) exposed at island edge overlying older island soil (dark), which has undergone post-event scarping.

lands, confirming laboratory experiments (Briggs et al., 1995) and field observations (Yeh et al., 1994; Minoura et al., 1997) on larger circular islands located on shallow coastal shelves. Of relevance to island stability and change is the magnitude of impacts and their permanence. Though the larger vegetated islands were reduced in area (mean 4.1%), these impacts do not appear to have destabilized the islands. Island persistence is further demonstrated by the unvegetated sand cay Boifushi, which changed little in area; its westward movement by 18 m is consistent with its pre-tsunami rate of migration (Fig. DR2G, [see footnote 1]).

Deposition of a layer of sand ($<$0.3 m thick) on island surfaces is a permanent addition to the islands, increasing elevation and stability. However, the integrity of tsunami-derived overwash deposits is unlikely to persist, because of bioturbation and soil formation, and thus preservation of these deposits as tsunami signatures in the geological record is also unlikely.

The Sumatran tsunami amplified seasonal movements of the beach from east to west, stripping sand from exposed shorelines and transferring it to leeward depocenters. Depletion of sediment exposed these shorelines to prolonged northeast monsoon energy, resulting in postevent scarping (Fig. 3I) and extending leeward depocenters beyond the envelope of change in 2002 and 2003. The timing of the tsunami, early in the northeast monsoon, when the beach sand reservoir is positioned on the eastern sides of islands, may have acted as an erosional buffer and minimized the direct impact of the tsunami.

Island stability over the short to medium term depends on the response of the beach system to future monsoon cycles. If beaches resume fluctuating within the pre-tsunami envelope, further island erosion will be limited. However, westward extension of the beaches during and since the tsunami may have placed the beach system in disequilibrium. Thus, if the return transfer of sediment to the eastern sides of islands in the westerly monsoon does not achieve its pre-tsunami survey configuration, a small migration of the islands to the west and southwest could result.

TABLE 1. IMPACTS OF THE SUMATRAN TSUNAMI ON ISLANDS OF SOUTH MAALHOSMADULU ATOLL

Island*	Baseline dynamics of island beach area		Pre- vs. post-tsunami changes in reef island characteristics			Summary of depositional and erosional signatures of tsunami		
	Seasonal change (%)[†]	Annual change (%)[§]	Beach area change (%)[#]	Veg. area change (%)**	Extra beach extension over reef (m^2)[††]	Max. thickness overwash (m)	Area of overwash (m^2)(%)	Length of shoreline scarped (m)(%)
Gaaviligilli (A)[§§]	N.A.	N.A.	12.7	−1.14	1609	0.10	1811 (10.3)	288 (26)
Fares (B)	±19	−2.5	11.6	−1.8	1914	0.10	680 (0.7)	457 (24)
Dhakandhoo (C)	±38	13.7	12.5	−5.2	2915	0.20	3314 (7.7)	287 (27)
Keyodhoo (D)	±15	10.5	−19.2	0.67	1572	0.10	1020 (4.7)	180 (30)
Hulhudhoo (E)	±24	15.2	4.3	−3.46	1154	0.13	3786 (12.8)	268 (31)
Udoodhoo (F)	±66	−1.9	−0.6	−0.08	1550	0.04	10,239 (9.1)	270 (17)
Boifushi (G)	±1	−0.01	−10.7	0	2482	N.D.	1000 (100)	0
Nabiligaa (H)[§§]	N.A.	N.A.	17.2	−80.47	9729	0.10	992 (48.0)	113 (23)
Mendhoo (I)[§§]	N.A.	N.A.	14.1	−0.37	3396	0.10	<1000 (<1)	0
Milaidhoo (J)	±25	3.3	27.2	−5.5	3671	0.30	4793 (14.1)	360 (40)
Thiladhoo (K)	+7	13.0	7.8	−6.36	3163	0.30	5453 (17.4)	212 (28)
Madhirivadhoo (L)	±15	−8.0	−4.5	−8.07	2490	0.20	5881 (16.0)	495 (54)
Aidhoo (M)[§§]	N.A.	N.A.	37.5	−9.0	5079	0.10	3747 (17.4)	164 (21)

Note: Data to calculate baseline dynamics and compare differences between pre- and post-tsunami surveys are presented in Table DR2 (see footnote 1). N.D.—maximum thickness not distinguishable. N.A.—not applicable.
*Letter in brackets identifies island position on Figure 1C.
[†]Maximum seasonal fluctuation as percentage of January 2002 beach area.
[§]Net annual change as percentage of January 2002 beach area.
[#]Percent difference in beach area between mean NE monsoon beach area and post-tsunami survey.
**Percent difference to pre-tsunami vegetated area.
[††]Area that toe of beach extends beyond both the January 2002 and February 2003 footprint, as calculated from GIS (geographic information systems) analysis of global positioning system surveys.
[§§]Islands not included in all pre-tsunami surveys.

These responses are partly dependent on whether the sand reservoir was conserved during the tsunami. Migration of sand lobes close to the reef edge suggests some sediment loss off the reef platform, and overwash deposition on islands represents further loss to the beach system. In such cases the beach sand reservoir is depleted and total beach volume reduced. Whether increased reefal sediment production will compensate for this reduction in the future can be assessed only with continued monitoring.

CONCLUSIONS

Contrary to popular perceptions of the fragility and vulnerability of atoll islands, our data show that the uninhabited islands of the Maldives are robust landforms that experienced relatively minor physical impacts from the Sumatran tsunami. This conclusion is in accord with Vitousek's (1963) observations of the effects of the 1960 Chilean tsunami on the Tuamotu atolls, French Polynesia. In the Maldives, where islands have been subject to multiple tsunamis during the middle to late Holocene, the net long-term geological effect appears to be minor. On the other hand, our short-term monitoring shows that island shorelines are highly dynamic in response to monsoonal shifts. In fact, gross volumes of sediment reworked on a seasonal basis were considerably greater than net changes associated with the Sumatran tsunami. Morphological and sedimentary evidence suggests that although tsunamis do generate both erosional and depositional signatures, they do not promote gross instability of islands. We conclude that far-field tsunamis are unlikely to be important mechanisms of atoll island destruction or formation and that any permanent addition of tsunami sediment to island surfaces is unlikely to be distinguishable in the stratigraphic record.

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