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Geologic Impacts of the 2004 Indian Ocean Tsunami on Indonesia, Sri Lanka, and the Maldives

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with 10 figures

Summary. The December 26,2004 Indian Ocean tsunami was generated by a large submarine earthquake (magnitude ~9.1) with an epicenter located under the seafloor in the eastern Indian Ocean near northern Sumatra, Indonesia. The resulting tsunami was measured globally and had significant geologic impacts throughout the Indian Ocean basin. Observations of tsunami impacts, such as morphologic change, sedimentary deposits, and water-level measurements, are used to reconstruct tsunamogenic processes. Data from Sumatra, Sri Lanka, and the Maldives provide a synoptic view of tsunami characteristics from a wide range of coastal environments both near- and far-field from the tsunami origin. Impacts to the coast as a result of the tsunami varied depending upon the height of the wave at impact, orientation of the coast with regard to direction of wave approach, and local topography, bathymetry, geology, and vegetation cover. Tsunami deposits were observed in all the countries visited and can be generally characterized as relatively thin sheets (<80 cm), mostly of sand.

Zusammenfassung. *Geologische Wirkung des Tsunamis 2004 im Indischen Ozean auf Indonesien, Sri Lanka und die Malediven.* Der Tsunami im Indischen Ozean am 26. Dezember 2004 wurde durch ein starkes submarines Beben (ca. 9,1) mit Epizentrum unter dem Meereesboden im östlichen Indischen Ozean nahe Sumatra (Indonesian) ausgelöst. Der daraus resultierende Tsunami konnte weltweit gemessen werden und hatte signifikante Einflusse entlang aller Kusten des Indischen Ozeans. Zur Rekonstruktion dieser Prozesse wurden Einflüsse des Tsunami wie morphologische Veränderungen, Sedimentablagerungen oder Änderungen der Wasserstände untersucht. Daten von Sumatra, Sri Lanka und den Malediven liefern ein Gesamtbild der Tsunami-Charakteristika aus sehr unterschiedlichen Kustengebieten und sowohl in der Nähe wie auch weit entfernt vom Epizentrum. Die Wirkungen an den Kusten sind sehr unterschiedlich in Abhängigkeit von der Höhe der Tsunamiwelle, die Ausrichtung der Küste zum Wellenangriff, der lokalen Topography, Bathymetrie, Geologic oder Vegetationsbedeckung. In alien besuchten Ländern konnten Tsunami-Ablagerungen gefunden werden, meist als dunne Sandlagen von weniger als 80 cm Mächtigkeit.

1 *Introduction*

The December 26,2004 Indian Ocean tsunami was generated by a great submarine earthquake (magnitude ~9.1) with an epicenter located under the seafloor in the eastern Indian Ocean near northern Sumatra, Indonesia. The resulting tsunami was measured globally and had significant geologic impacts throughout the Indian Ocean basin. Field studies in the aftermath of this significant geologic event were conducted to observe and measure geologic impacts from a number of geographic locations. Tsunamis can have a devastating impact on coastal communities and environments and with population growth rapidly increasing along the world's coasts it is imperative to better understand the impacts of natural hazards, especially tsunamis. With the exception of Japan where there is a 500+ year written record of tsunamis, the historical record of tsunamis is

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generally poorly known. This has prompted increased interest within the scientific community to document modern tsunami impacts as a tool to better understand ancient tsunami deposits in the geologic record. This study focused on geologic impacts of the recent Indian Ocean tsunami to better understand: a) tsunami erosion and deposition patterns, b) geologic and morphologic controls on tsunami impacts, and c) continue to develop criteria to distinguish storm from tsunami deposits.

Field observations of modern tsunamis (for example, GELFENBAUM & JAFFE 2003, MOORE et al. 2006) and conceptual models (JAFFE & GELFENBAUM, in press) typically show three shore-parallel erosional/depositional zones: 1) a zone of erosion extending from the shore inland 10's to a few hundred meters, 2) a broad zone, ~100's to 1,000 m, of tsunami deposition landward of the erosion zone, and 3) a narrow wave runup zone with neither deposition nor erosion near the limit of inundation. The three zones are thought to represent respectively: 1) a zone of erosion formed by the tsunami accelerating as it moves onshore, 2) a broad zone of deposition that is created by quasi-uniform flow where the tsunami is neither strongly accelerating nor decelerating and sediment settles out of suspension when flow speed decreases everywhere as the tsunami reaches its limit of inundation, and 3) a narrow zone where neither erosion or deposition occurs as the tsunami flow speed drops to where it is unable to transport sediment. The size of each of these zones depends on tsunami characteristics, sediment source, substrate that the tsunami travels over, and topography. There are sites where not all of the zones are present, but commonly all three zones are present.

The Indian Ocean tsunami affected an expansive geographical area and variety of coastal environments. Post-event field studies provide a unique opportunity to examine causative factors that control tsunami impacts such as erosion and deposition patterns. Since 1992 there have been over a dozen studies of post-tsunami impacts throughout the world (SYNOLAKIS et al. 2005). However, previous post-tsunami studies were typically restricted to a few coastal environments and limited geographical area. The Indian Ocean tsunami was a basin-wide event that affected a broad spectrum of coastal environments, geologic settings, and physiographic provinces. In this study we describe field observations from three vastly different islands (Fig.1) the rugged islands of Indonesia, primarily Sumatra (B.E.J., G.G., R.A.M.), the pre-Cambrian island of Sri Lanka and it's broad coastal plains (B.M.R., B.E.J., R.A.M.), and the atoll islands of the Maldives (B.M.R.). For each study area we briefly describe the geologic setting, tsunami characteristics, and geologic impacts.

2 *Post December 2004 Tsunami Country Studies*

2.1 *Sumatra, Indonesia*

The elongated northwest-southeast trending island of Sumatra is the largest island in Indonesia and the fifth largest island in the world (BARBER et al. 2005). Sumatra and adjacent islands are tectonically active and geologically complex with numerous faults and young volcanoes. A young mountain range runs the length of the island resulting in west-facing coasts that are characterized by steep headlands and intervening beach-ridge coastal plains (BIRD 1985), discontinuous fringing coral reefs, and deeply incised river valleys (Fig. 2). West of Sumatra is a linear ridge with emergent islands that extend to the southeast from Simeulue. The islands are separated from Sumatra by marine basins, 1-2 km deep, and are bordered to the southwest by the deep SundaTrench (5 km +). Sumatra occurs at the site of oblique subduction between major tectonic plates at the southeast margin of the Eurasia (LAY et al. 2005).

The south and northwest coasts of Sumatra and offshore islands were particularly hard hit by the December 2004 tsunami. Tsunami waves exceeding 30 m in some areas reached west-facing Sumatra coastlines within 15–30 minutes of the earthquake (TSUJI et al. 2005). Maximum tsunami flow depths were greater than 13 m along a 135 km stretch of coast in northwest Sumatra (JAFFE et al., in press) resulting in widespread destruction and modification to the coastal zone (Fig. 3). Tsunami flow depths were as much as 10 m at 1500 m inland from the shore. On the offshore island of Simeulue and nearby islands, tsunami elevations were smaller, but still large (5-14 m). Tsunami elevation decreased significantly to the south.

Tsunami deposits, composed primarily of sand, were widespread in northern Sumatra where tsunami inundation distances were great and there was an abundant supply of sediment. Deposits extended from the zone of no deposition or erosion near the shoreline to within about 20 m of the limit of inundation at most sites. The width of the erosional zone typically increased with tsunami height up to a maximum width of about 80 m, although in many cases the actual width was difficult to determine because of shoreline erosion. The maximum shore-normal extent of tsunami sand deposits measured was about 1660 m (JAFFE et al., in press) and mud-layers were deposited as much as 5 km inland (MOORE et al. 2006). Deposit coverage generally varied with the limit of inundation, which is a function of the size of the tsunami wave and slope of the land. Smaller tsunami size and steeper slopes resulted in a narrower shore-normal coverage of the deposit.

Tsunami deposit thickness typically varied along transects and from site to site resulting in a discontinuous depositional sheet. In general, the deposits thicken away from the coast to a point where it becomes "relatively" constant over most of its extent, and then thins abruptly near the landward limit. Changes in thickness of the sand sheet are commonly related to changes in surface topography where depressions are infilled and highs have a thin or no deposit. In areas with beach ridges, deposit thickness variation was large with greater thickness in the swales. The maximum sand deposit thickness observed was ~80 cm, although typical thicknesses were 5 to 20 cm (JAFFE et al., in press, MOORE et al. 2006). The thickest deposits did not necessarily correlate with the deepest tsunami flow depths. Deposits were usually composed of multiple layers; the total thickness may reflect deposition during multiple waves and/or during uprush and return flow. Both normal and inverse grading was observed, as well as what appeared to be massive sand units (Fig. 4). Although the tsunami was capable of transporting boulder sized objects, as evidenced by the widespread transport of large man-made objects, there was little in the way of coarse-clastic deposits because of a general lack of natural coarse material in the sites visited. In some areas isolated coral boulders were observed landward of the beach and appeared to be deposited by the tsunami.

Tsunami flow patterns, as determined by measurements of flow indicators such as downed trees, were complex and controlled by local topography and offshore bathymetry. The coastline of Sumatra is highly irregular with numerous embayments separated by headlands. Flow was typically channelled between topographic highs both during uprush and return flow episodes. Low-lying areas were inundated for great distances.

Evidence for co-seismic uplift or subsidence was observed at a number of sites. The maximum estimated subsidence, 2 m, was in northwestern Sumatra. Beaches in subsided regions showed evidence of continued erosion 4 to 5 months after the event because the nearshore profile and beach were still adjusting to the higher sea level caused by the subsidence. Uplifted fringing coral reefs and adjacent shoreline deposits were observed north of Simeulue Island where the maximum estimated uplift was 2.4 m, (JAFFE et al., in press).

2.2 Sri *Lanka*

The island country of Sri Lanka lies to the southeast of India and has a total coastline of about 1,700 km (SWAN 1985). Sri Lanka occupies a tectonically stable intraplate setting on the Indo-Australian plate. The island consists primarily of a Precambrian bedrock core forming the rugged central highlands that are surrounded by a wide coastal plain composed of alluvial and coastal deposits (Fig. 5). In the north and northwest, Miocene limestone and Quaternary deposits occur adjacent to the shallow continental shelf that extends to India. Elsewhere the shelf is generally narrow and is coincident with higher wave energy at the coast. The east, south, and west coasts are dominated by either long barriers and spits or bays and headlands. Lagoons and estuaries occupy embayments between headlands. Expanses of sandy beach are greatest on the east and southeast coast and diminish towards the west where cliff headlands are more common. Sand dunes are locally well developed with the best examples on the southeastern beaches where sand supply is abundant and the climate is relatively dry. Beach sands are composed predominantly of quartz sand with variable amounts of carbonate material consisting of shell and fragments of coral reef (SWAN 1985). Coral reefs are widespread but discontinuous and patchy in distribution. In addition to coral reefs there are widespread rock reefs, mostly sandstone and/or limestone, often with scattered coral colonies on their upper surface.

Sri Lanka is approximately 1500 km from the December 2004 earthquake epicenter. The tsunami waves arrived between 2–3 hours after the earthquake and consisted of waves striking the east, south, and west coasts. The tsunami arrived first and was highest on the east coast and proceeded to refract around the island to the south and west coasts. Along the southwest coast a later wave, that is believed to have been reflected off the Maldives and/or India, was reported to have been several meters high and caused severe damage (LIU et al. 2005). Depending upon location, between one and three recognizable waves occurred. Tsunami wave heights were typically in the 4-6 m range and reached 12 m of runup at Yala. Wave heights were typically greatest along the east and south coasts with inundation of several hundred meters common. Wave height varied locally and appears to be highly dependent upon local topography and bathymetry.

Headlands acted to block tsunami inundation thereby preventing interior inundation, whereas the embayments focused the waves and increased the limits of inundation and runup. There were many instances of human modifications, such as removal of sand dunes and/or vegetation, that appeared to increase tsunami inundation. At a number of coastal sites tsunami inflow and return flow created extensive and deep scour channels that preferentially formed in topographic lows or places where structures concentrated flow. In many cases this led to scour around buildings, and, in some cases the complete removal of structures. There is some indication that human alterations to coral reefs, primarily through illegal mining activities, resulted in greater tsunami impact to the adjacent shore along the southwest coast (FERNANDO et al. 2005). However, in general coral reefs in Sri Lanka suffered light damage when compared to the severe bleaching event of 1998 where reefs to the south and west suffered nearly 90% coral mortality (RAJASURIYA et al. 2005). Sediment, primarily sand, was typically eroded from the shoreface and beaches and deposited inland in sheets and pockets ranging from 5–37 cm thick and up to nearly 400 m inland (GOFF et al., in press). Local microtopography exerted a strong control on the deposit shape and thickness. Tsunami deposit compositions mimic the adjacent beaches and nearshore sediments from which they were primarily derived (Fig. 6). Beach recovery was rapid in some areas as many beaches exhibited little tsunami damage by August of 2005 (Fig. 7). Beach erosion was a serious problem for many communities even before the tsunami as evidenced by numerous shoreline protection structures. At some locations, shoreline stabilization structures such as riprap revetments and gabions were damaged or rendered ineffective by the tsunami.

2.3 **Maldives**

The Maldive Islands comprise over 1200 islands on 22 atolls that encompass an area of ~107,500 km^2 of which less than 0.3 percent is land area (PURDY & BERTRAM 1993). The islands occupy the central 700 km-long portion of the 3000 km-long Lacadive-Chagos submarine ridge where they form a double chain of north-south oriented parallel atolls separated by an inner sea (Fig. 8). The atolls rest on a submarine plateau that is 275–700 m deep, 700 km long and up to 130 km wide. There are several east-west trending deep channels (~1000m) separating atoll groups. The islands themselves are low-lying Holocene features that began forming between 3,000 and 5,500 years ago (WOODROFFE 1992, KENCH et al. 2005). The islands represent the most recent deposition along a submarine plateau that is underlain by approximately 2100 meters of mostly shallow-water carbonates resting on slowly-subsiding Eocene volcanic foundation (Purdy 1981). The islands are composed primarily of reef-derived carbonate sediment that has been deposited by waves and currents. Morphology of the reef islands has been discussed by Stoddart (1966), Woodruff (1992), Kench, et al. (2005). In simple terms the islands tend to be either: a) seaward-edge islands on the peripheral atoll rim formed of sand and gravel with steep, coarse beaches along their seaward margins and sand beaches along their lagoon (protected) shores; b) lagoon-edge islands composed mostly of sand with minor amounts of gravel; and c) sand-cay type islands which form both on peripheral rims and within lagoonal reef-top settings. Land elevation is generally less than 2 m above mean sea level. Because of their unconsolidated nature, the islands should be considered ephemeral features over geologic timescales and their low elevation makes them particularly vulnerable to changes in sea level.

The tsunami waves, up to ~4 m high, arrived about **3** hours after the earthquake and inundated many islands with the most extensive damage occurring along islands of the eastern margin. Sea-level records reported by the University of Hawaii Sea Level Center (http://ilikai.soest.hawaii.edu) show a southward decrease in the amplitude of the tsunami from ~1.8 m above msl at Hanimaadhoo in the north, ~1.5m for Hulhule, Male in the central region, and ~0.8 m for Gan in the south. Tsunami inundation heights ranged from 0.65 m in South Male to **3.22** m in L.Fonadhoo as reported for 59 locations by "The Research Group on The December 26,2004 Earthquake Tsunami

Disaster of Indian Ocean" (http://www.drs.dpri.kyoto-u.ac.jp/sumatra/maldives/maldives.htm). A maximum run-up height of 4.43 m above msl was also measured at L. Fonadhoo. Uncorrected tsunami water levels measured in the present survey from 15 islands show a range from barely measurable to 3.25 m – most measurements were in the 2.0 – 2.6 m range. The tsunami height typically decreased from east to west as the tsunami traveled across islands. Eyewitness accounts from a number of islands reported the tsunami approaching from the west, which is believed to be a result of the tsunami refracting around the ends of the individual islands. The tsunami varied from complete island overwash to inundation around island margins. Wave effects were most pronounced on eastern shores but flooding was widespread among the islands

In general, changes to coastal morphology was greatest among islands located close to the eastern reef rim facing the main direction of tsunami approach. Beach erosion was widespread and characterized by the formation of erosional scarps typically 0.3 to 0.5 m high. On eastern beaches that consisted mostly of gravel-sized reef debris, material was deposited as sheets, 10-20 m wide and 10-20 cm thick, landward of the berm. In areas where an island was overwashed, prominent scarps developed along western sandy shorelines (Fig. 9) and were accompanied by sediment deposition westward into adjacent reef flat/lagoon areas (Fig. 10). Changes to island interiors was generally limited to local scour around obstacles, such as buildings, and development of thin patchy sediment deposits. Overall, shoreline change as a result of the tsunami was relatively minor with serious erosion generally confined to within 5 m of the shoreline. These observations are consistent with pre- and post-tsunami topographic profiles and observations as presented by Kench et al. 2006.

Important parameters that appear to be controlling factors in the local variability of impacts include: a) width of the reef flat (wider reef flats dissipate more wave energy and therefore offer more protection to the coast); b) height of the beach berm (higher berms provide a physical barrier to overtopping; berms in the Maldives usually range between 1-2m); and c) orientation to tsunami approach (islands oriented parallel to wave approach suffered more damage). Offshore bathymetry appears to have influenced tsunami characteristics as it approached land but there is such little information from the Maldives it is difficult to quantify the effects.

Other observations related to the tsunami impacts in the Maldives include:

Immediately prior to the tsunami impact there were many reports of freshwater flowing out of wells and from the ground. In many cases, house floors were buckled upward by the pressure. This suggests high permeability of the subsurface and a direct connection between groundwater and the surrounding seawater.

The tsunami worsened existing chronic shoreline erosion caused by sand mining operations and poorly designed coastal engineering structures. For example, the north end of K. Guraidhoo appears to have been undergoing long-term erosion as a result of reef flat dredging operations from a nearby resort. The tsunami accelerated the erosion resulting in the undermining of several coastal structures. Dredging of sand and gravel from reef areas is a widespread practice in the Maldives.

Scour around foundations and walls from the tsunami was prominent along eastern areas resulting in the collapse of many structures. Inadequate foundations, either too shallow or improper reinforcement, appeared to be a major cause.

It was observed at numerous locations that natural shorelines and land surfaces, either on uninhabited islands or "natural"areas of inhabited islands, exhibited much less damage than developed areas.

3 *Discussion*

3.1 *Geologic Setting*

The geologic setting influenced tsunami impact in two important ways: vertical tectonic movement associated with the tsunami generating earthquake and lithologic materials at the coast.

In Sumatra and nearby islands co-seismic subsidence or uplift had a dramatic change on coastal environments. For example, uplift up to 2.4 m occurred in islands to the west of Sumatra and resulted in fringing coral reefs and associated coastal deposits moved upwards out of their zone of formation and equilibrium. The emerged coral reefs act as a natural barrier protecting the uplifted beaches and coastal lands behind them. Where subsidence was prevalent, such as the nearly 2 m that occurred in northwest Sumatra, there is continued erosion as coastal environments seek to re-establish equilibrium to the new (higher) sea-level position. Erosion at the shoreline was a common process during the passage of the tsunami and along subsided coasts that erosion appears to be more severe lasting for months after the initial tsunami.

Erodability of the coast exerted some control over the tsunami impacts. Hard rock or consolidated coastal deposits that are non-erodable controlled the flow of tsunami waters. Surficial deposits, such as soil and vegetation, were removed but the unyielding underlying material forced the tsunami to follow pathways of least resistance and there was little morphological change. In contrast, coasts of unconsolidated sediment that were easily eroded often underwent significant change. In addition to the removal of surficial materials, the underlying sediment was often scoured and transported away. Eroded beaches, scour channels in sand, and scour around structures was common. In areas of moderate tsunami heights (< ~4-7 m) where coastal dunes were higher than tsunami elevations, the dunes often provided a modest level of protection. There are many examples on the southeast coast of Sri Lanka where natural dune fields protected adjacent coastal areas, whereas areas where the dunes were modified or removed suffered severe coastal damage because the tsunami was able to breach the coastal barrier.

3.2 *Tsunami Characteristics*

There are a number of tsunami characteristics that are important in regard to potential impacts. The most obvious characteristic is tsunami height. The three areas studied can be qualitatively described as impacted by extreme, large, and moderate tsunami. Impacts varied in relation to tsunami height that varied in relation to distance from source and wave modification as it propagated through the ocean basins and coastal waters. The tsunami clearly had a directionality focus. For example, eastern Sri Lanka which lay in the direct path of the tsunami, experienced higher wave heights and greater impacts than southeastern Sumatra which was oriented away from the direct path of the tsunami but closer to the source.

Extensive areas of coastal Sumatra were overpowered by the extreme wave that was at least 15 m high over 100+ km of coast. Near complete destruction of coastal dwellings and vegetation was a result of the extreme wave. Beyond the near-field locations, the tsunami appeared to be strongly affected at the coast by shoaling, refraction, reflection, and diffraction – bathymetry exerted a strong control on tsunami characteristics. For example, in Maldive islands that were not completely overwashed there were numerous reports of the tsunami approaching from the west as a result of tsunami refraction around the islands. Several east-west trending deep channels between atolls served as pathways for tsunami diffraction. Although detailed bathymetric data is generally lacking in the Maldives it is clear from the variations in tsunami characteristics and impacts that bathymetric control strongly affected the tsunami. In Sri Lanka it appears the west coast was not only affected by refracted waves but also by wave reflection from either India or the Maldives (LIU et al. 2005). Increase of tsunami heights in embayments was also common due to the funnelling and runup of the wave. A small offshore island near Langi on northwest Simeulue Island suffered greater impact by wave reflection and a large return flow as the tsunami reflected off adjacent Simeulue.

3.3 *Geologic Impacts*

Geologic impacts varied with the size of the tsunami but there were some impacts that occurred throughout affected coasts. On depositional coasts with beaches, erosion at the shoreline was common and usually accompanied tsunami deposition of sheet-like deposits inland. In general, tsunami deposits occurred where there was an abundant source of sediment, usually beaches, and a suitable surface for deposition landward of the erosion zone. Sand deposits were the most common type of deposit observed although mud and gravel deposits were also noted. Scour around obstructions such as buildings, walls, trees etc. was widespread. Large depositional gravel ridges/ramparts have not been observed, however, some movement of coral rubble on the reef flat was observed in the Maldives.

Long-term morphological change as a result of the tsunami appears to be relatively limited. Sediment deposition from the tsunami was widespread but generally thin and no large morphological features were produced. Many beaches in Sri Lanka that were eroded during the passage of the tsunami had recovered by August 2005. However, coasts that experienced significant vertical tectonic movement, either uplift or subsidence, will probably take a long time (decades to centuries) to re-adjust to their new sea-level position.

Coral reefs throughout the Indian Ocean were affected by the tsunami, but, in general the impacts were less that expected (GCRMN 2005). Because of their steep offshore profile and broad flat surface, coral reefs in may areas caused shoaling of the tsunami and some dissipation of wave energy. In the Maldives there appeared to be more damage from a 1997-98 El Niiio bleaching event than from the tsunami as evidenced by numerous dead and recovering *in situ* coral colonies. Presumably, tsunami damage would have included accumulations of fresh coral debris. In Sri Lanka it has been hypothesized (FERNANDO et al., 2005) that coral mining resulted in greater coastal impacts from the tsunami because of reduction in the natural reef protective buffer.

4 *Conclusions*

The December 26,2004 Indian Ocean tsunami was measured globally and had significant impacts throughout the Indian Ocean basin. The tsunami caused a tragic loss of life and widespread destruction of coastal properties. The impact of the tsunami was largely controlled by the size of the wave as it reached coastal areas and subsequent modification by local bathymetry and topography. In general, depositional shorelines underwent erosion with the eroded material deposited as sheets further inland. Tsunami deposition was widespread but locally variable. The characterization of tsunami deposits can provide valuable criteria for distinguishing paleo-tsunami deposits in areas where little historic information exists. Considering the widespread impact of the tsunami, the long-term geologic change associated with the tsunami will probably be relatively minor. Shoreline erosion was common but observed to be only a short-term perturbation along many coasts. Coasts near the earthquake epicenter that underwent vertical tectonic movement will most likely take a much longer time to re-adjust the new sea-level position.

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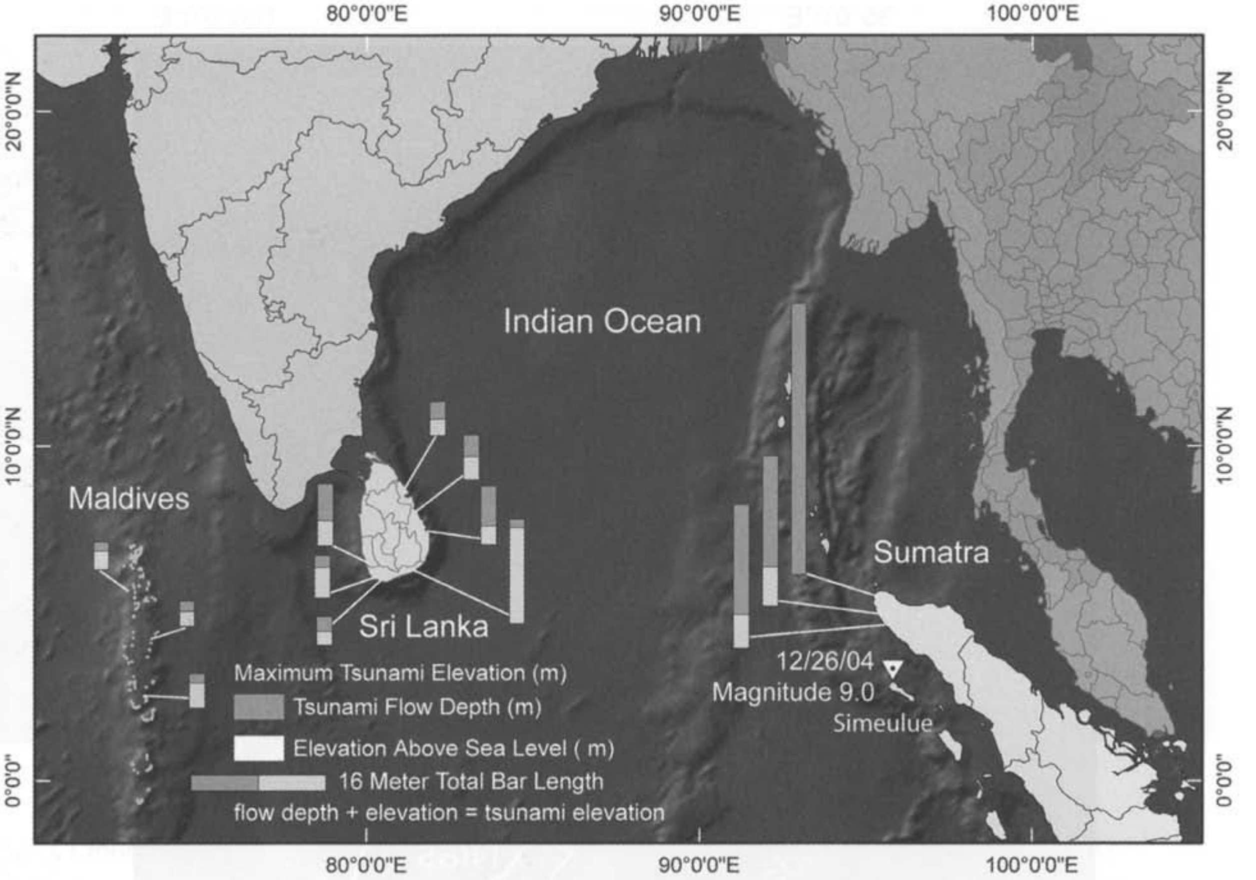

Fig. 1. Location of the islands studied and representative tsunami elevations (the combination of flow depths and elevation above sea-level). Tsunami heights compiled from International Tsunami Survey Team data. Base map from ESRI WorldSat shaded relief mosaic.

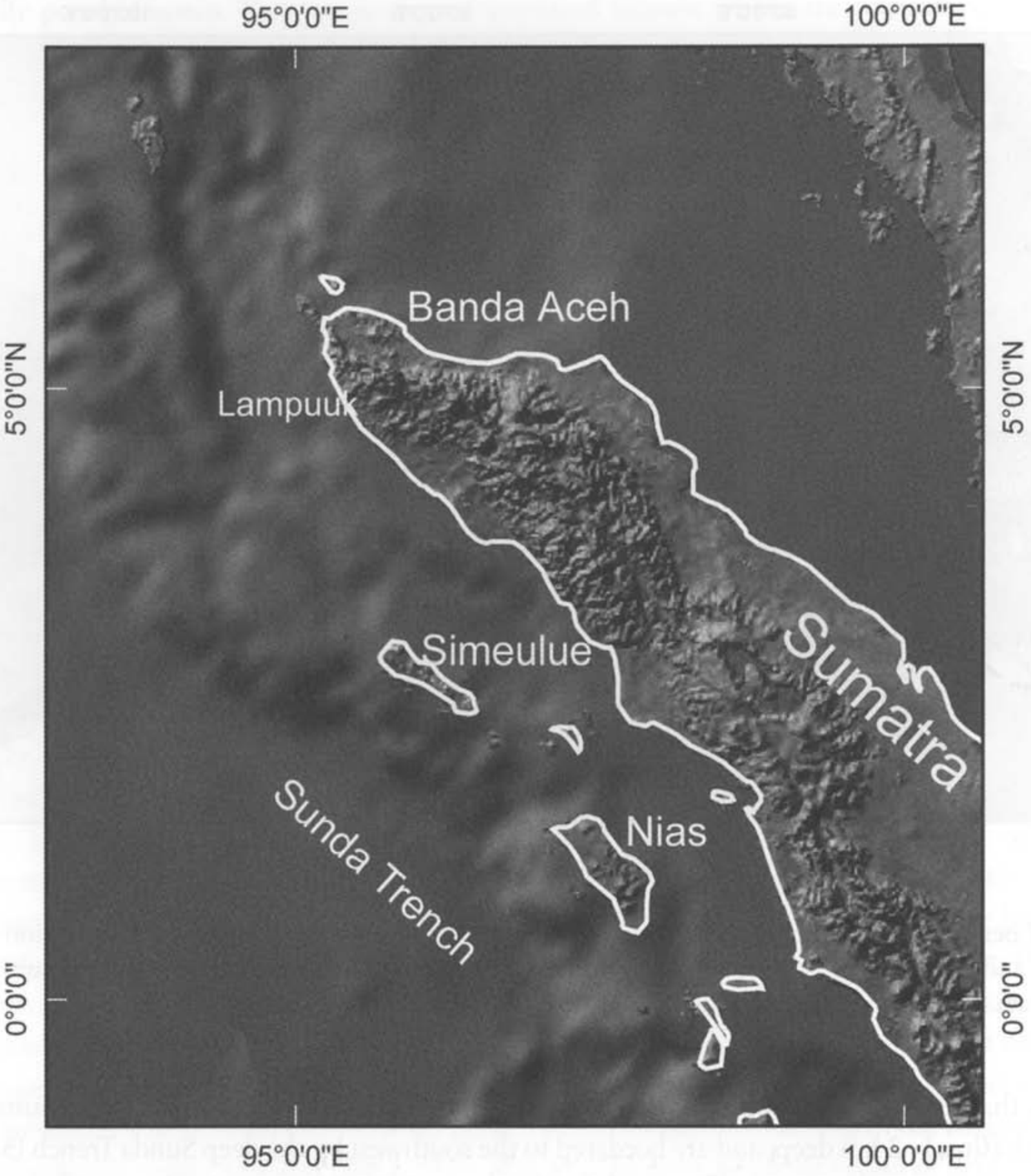

Fig. 2. Location map of northwest Sumatra. Base map from ESRI WorldSat shaded relief mosaic.

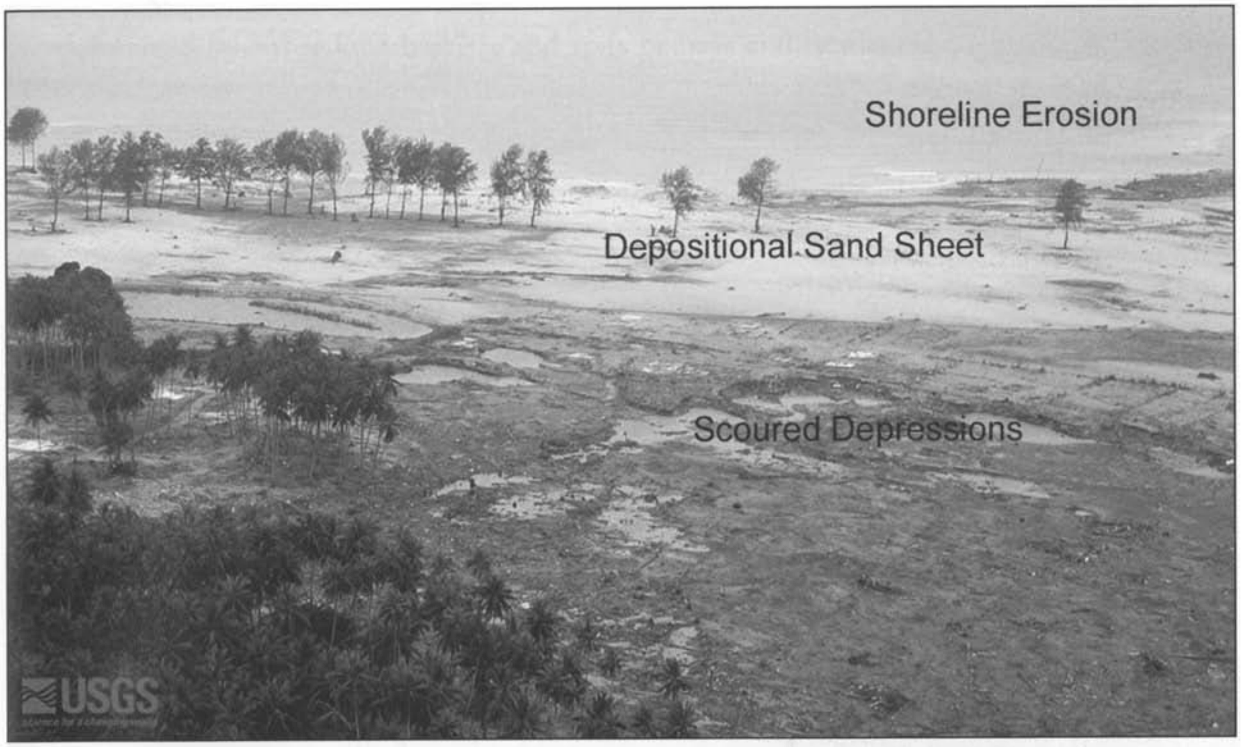

Fig. 3. Oblique aerial photograph from the northwest coast of Sumatra near Lampuuk in April 2005. There is an extensive depositional sand sheet landward of the shoreline erosional zone. Further landward there is some additional scouring caused by tsunami driven water flowing in a valley between two highs.

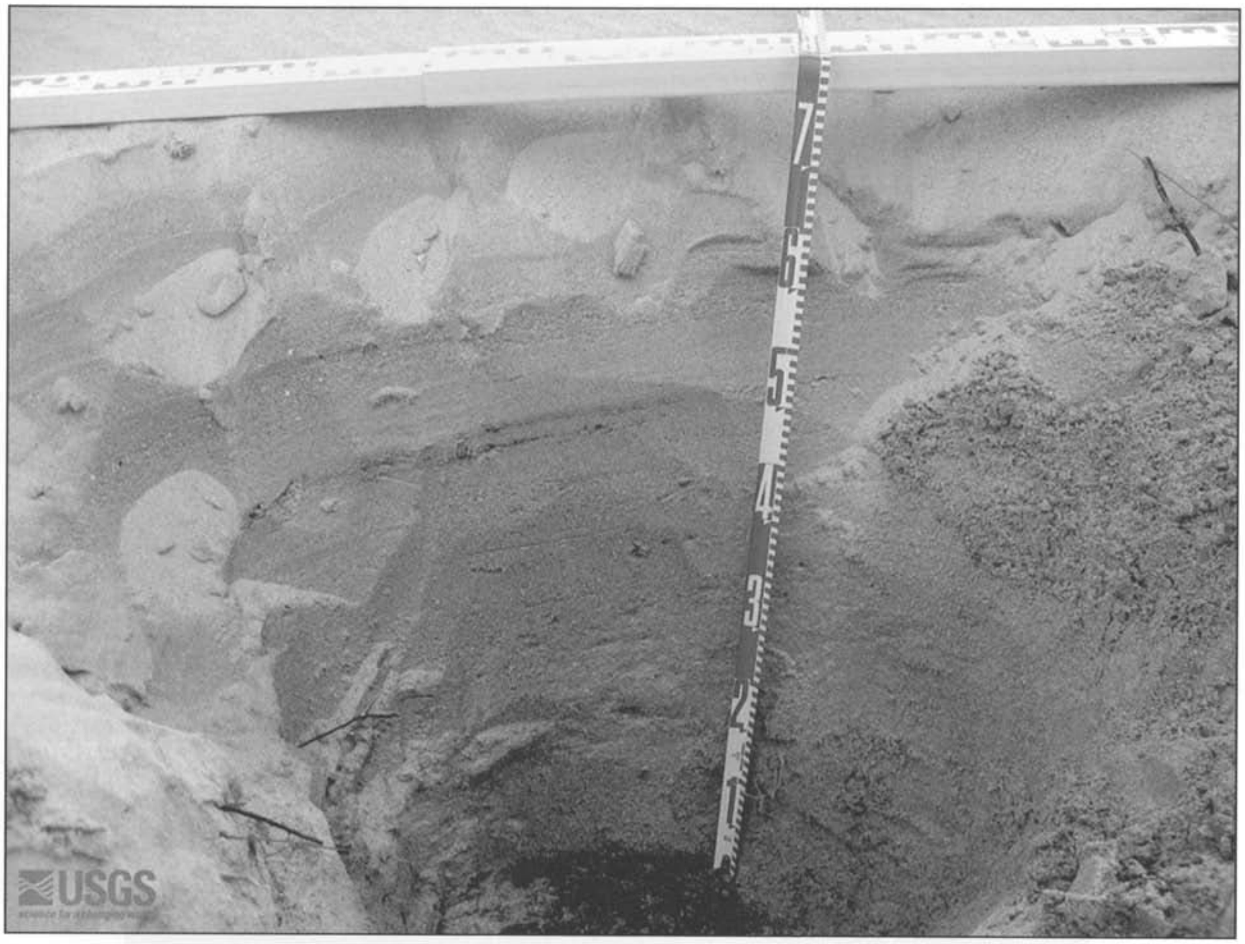

Fig. 4. Photograph from Lampuuk northwest Sumatra showing approximately 75 cm of tsunami sand deposits overlying a dark soil horizon (bottom of trench). Multiple layers are present as well as some thick (10 + cm) units that appear massive.

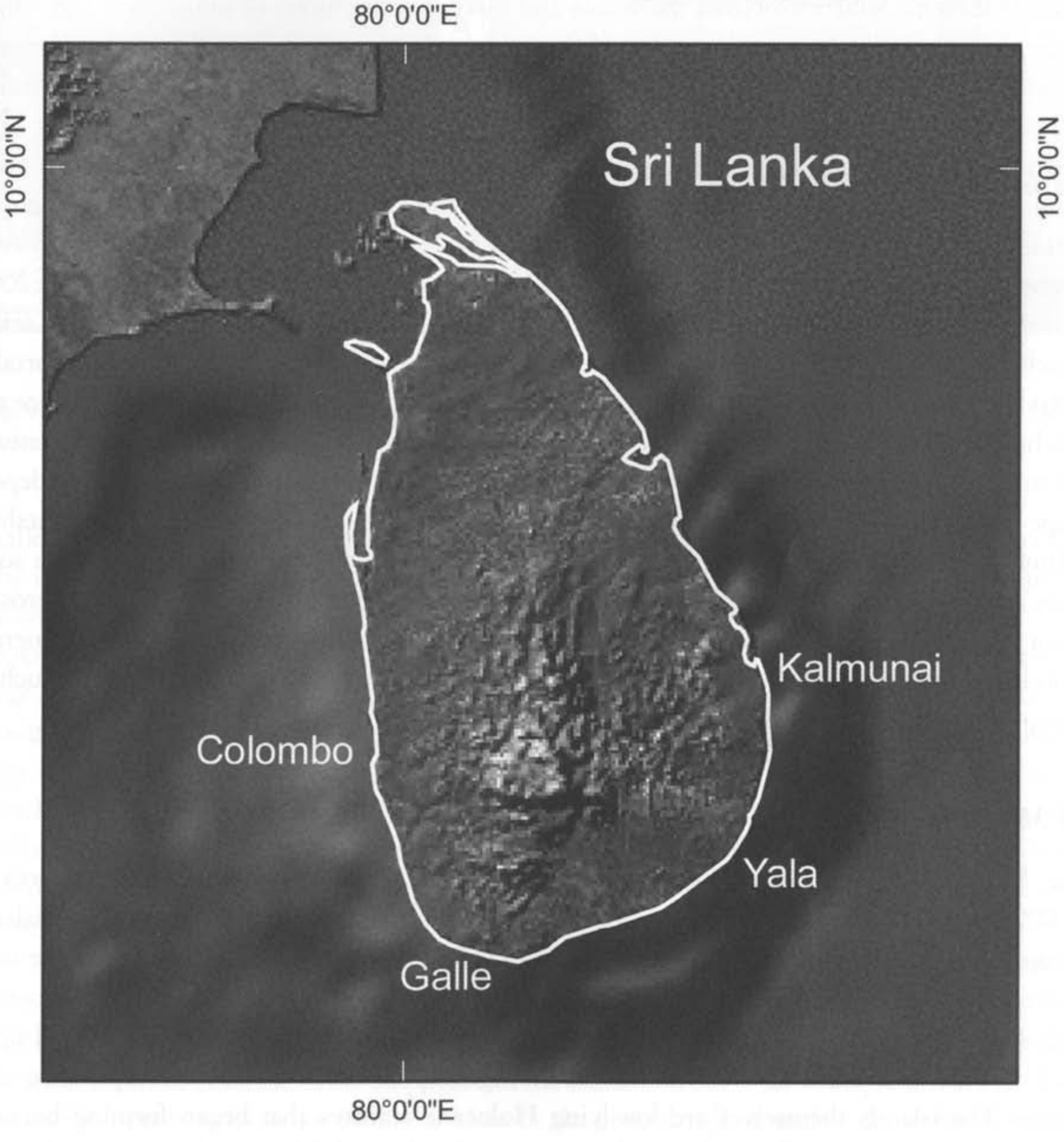

Fig. 5. Location map of Sri Lanka. Base map from ESRI WorldSat shaded relief mosaic.

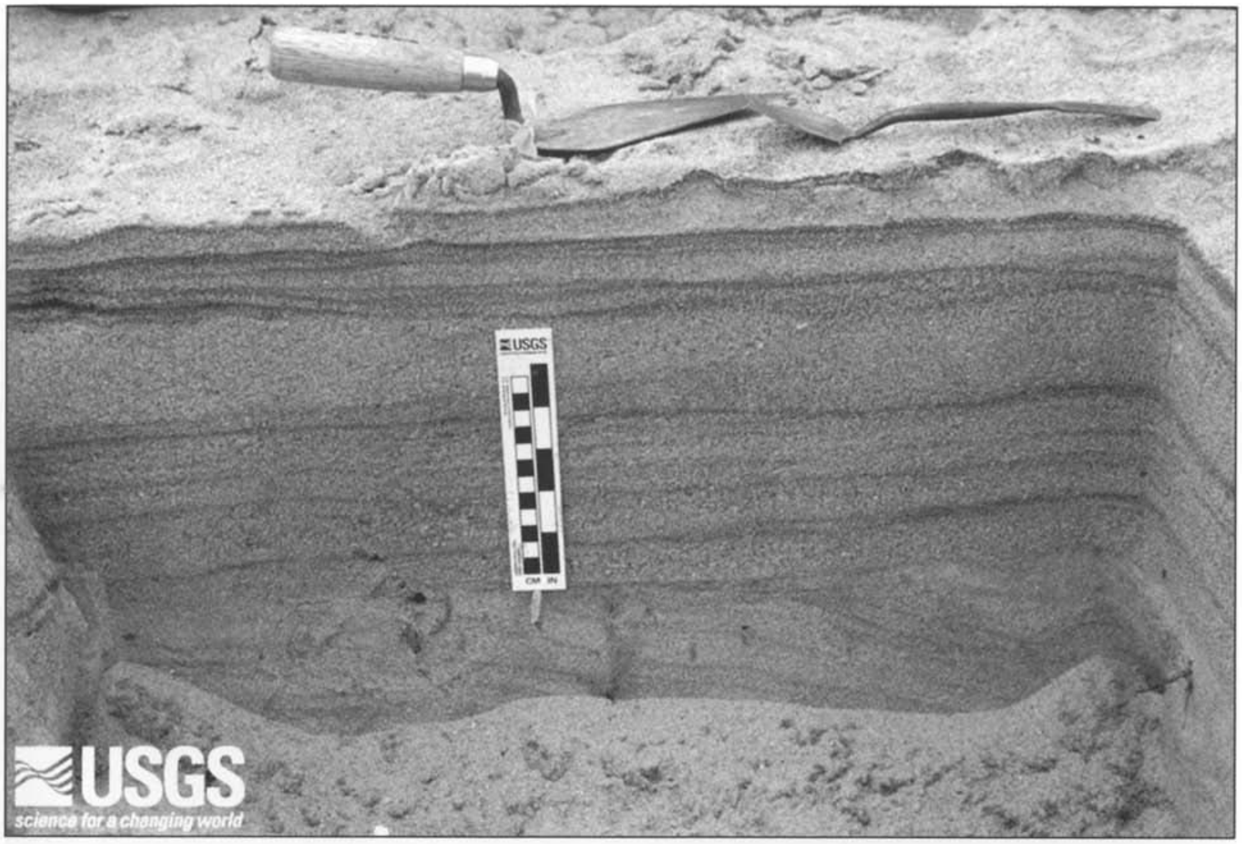

Fig. 6. Trench at Yala on the southern coast of Sri Lanka showing an ~22 cm thick tsunami sand deposit with multiple laminations. Flow depth at this site was about 4.5 m.

Fig. 7. The east coast of Sri Lanka near Kalmunai in August of 2005 showing recovered beach (foreground), pre-tsunami revetment (center right) as evidence of a prior erosion problem, and post-tsunami debris emplaced along coast (center left). The mosque survived relatively intact but most coastal homes in the area were severely damaged.

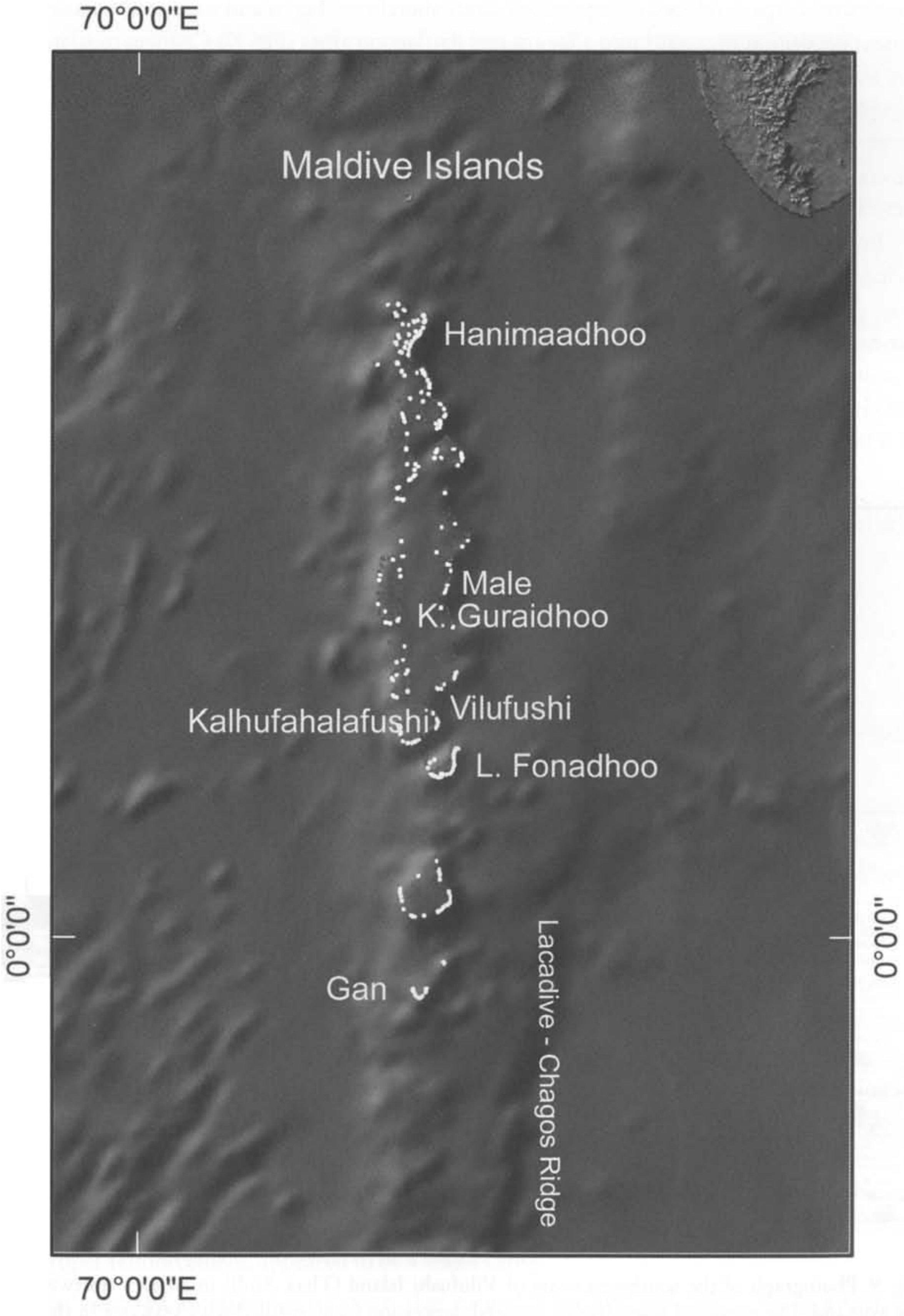

Fig. 8. Location map of the Maldive Islands. Base map from ESRI WorldSat shaded relief mosaic.

Fig. 9. Photograph of the southwest coast of Vilufushi Island (Thaa Atoll) in an area overwashed by the tsunami. The erosional scarp (right), scoured depression (center; filled with seawater in the photograph), and lagoonal deposit (left) were formed as the tsunami flowed over the island. Sediment in the lagoon includes both natural and manmade debris.

Fig. 10. Oblique aerial photograph of the southern end of Kalhufahalafushi Island (Thaa Atoll) showing a large sediment body deposited towards the west into the lagoon. View to the east.