# Oman Field Survey after the December 2004 Indian Ocean Tsunami

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In August 2005, a team surveyed the effects of the December 2004 Indian Ocean tsunami on the southern coast of Oman. Runup and inundation were obtained at 41 sites, extending over a total of 750 km of shoreline. Measured runup ranged from 3.25 m in the vicinity of Salalah to a negligible value at one location on Masirah Island. In general, the largest values were found in the western part of the surveyed area. Significant incidents were documented in the port of Salalah, where a 285-m-long vessel broke its moorings and drifted inside and outside the port, and another ship struck the breakwater while attempting to enter the harbor. The general hazard to Oman from tsunamis may be greatest from the neighboring Makran subduction zone in western Pakistan. [DOI: 10.1193/1.2202647]

## INTRODUCTION AND BACKGROUND

This paper reports the findings of an International Tsunami Survey Team (ITST) that visited Oman in August 2005, in order to survey the effect of the 26 December 2004 Indian Ocean tsunami on the southern shore of the country. We recall that this disaster carried a human toll approaching 250,000 and was the first event since the 1964 Alaska earthquake to export death and destruction across an oceanic basin (Synolakis et al. 2005). From the seismological standpoint, the 2004 Great Sumatra earthquake featured the largest seismic moment in the last 40 years ($M_0 = 1.0 \times 10^{30}$ dyne-cm), surpassed only by the 1960 Chile earthquake, and possibly by the 1964 Alaska earthquake (Stein and Okal 2005, Nettles et al. 2005).

The catastrophic devastation wrought by the tsunami occurred primarily in the eastern part of the Indian Ocean (Indonesia, Thailand, Sri Lanka, and India). However, substantial damage was also documented in Somalia, where some 300 deaths were reported (Fritz and Borrero 2006, this issue). In this respect, it became important to document any variability between the effects of the tsunami on various distant shores in Africa and Arabia, in order to build a complete, homogeneous database of runup and inundation

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parameters. The latter can then serve as a benchmark for simulation models aimed at understanding the distal or local parameters controlling the development and amplification of waves at the beach.

In this context, surveys were carried out in March 2005 in Somalia (Fritz and Borrero 2006, this issue) and on the Mascarene Islands of Rodrigues, Mauritius, and Réunion, and during the summer of 2005 in Madagascar and in Oman. The present paper reports on the survey in Oman, and companion papers cover the Mascarenes and Madagascar (Okal et al. 2006a, this issue; Okal et al. 2006b, this issue).

## LOGISTICS AND METHODOLOGY

After the team assembled on 9 August 2005 at the Earthquake Monitoring Center of Sultan Qaboos University in Al Khod, in the suburbs of the capital city Muscat, it was decided to split the team into two groups working independently, in order to cover the maximum distance along the shoreline. The northern group, consisting of Fritz, Raad, and Al-Saifi, traveled by a 4WD vehicle from Muscat and worked between Shannah and Serbarat, including a side trip on Masirah Island. The southern group, consisting of Okal, Synolakis, and Al-Shijbi, flew to Salalah and used a 4WD vehicle to explore the section of coast from Dhalkut to Al-Shouyamiya. A total of 750 km of shoreline was thus covered (Figure 1).

We refer to Synolakis and Okal (2005) for a description of the standard surveying methods used by members of ITSTs over the last 13 years. In the present survey, we relied primarily on the identification and interviews of eyewitnesses and on recording their testimony, followed by in situ visits with them to the affected sites, and topographic measurements of the relevant penetration of the tsunami waves. On a few occasions, the eyewitnesses led us to permanent marks of the tsunami action, such as fishing boats deposited on berms (Site 4), and deposits of algae (Site 40) or marine shells (Site 5). In this context, we recall the following definitions:

- Inundation is the measure of the maximum extent of horizontal penetration of the wave.
- Flow depth is the measure of the altitude, relative to unperturbed sea level, of the crest of the wave at a location close to the beach.
- Runup is the measure of the altitude, relative to unperturbed sea level, of the point of maximum inland penetration of the wave, where inundation (as defined above) is, in principle, measured.

Topographic measurements were made via surveying rods and a combination of laser and eye levels (Figure 2); inundation measurements were made by laser ranging or differential GPS. An exact roster was kept of the dates and times of the individual surveys, to allow future tidal corrections, in order to relate flow depth and runup measurements to the local level of unperturbed sea surface at the time of the arrival of the tsunami.

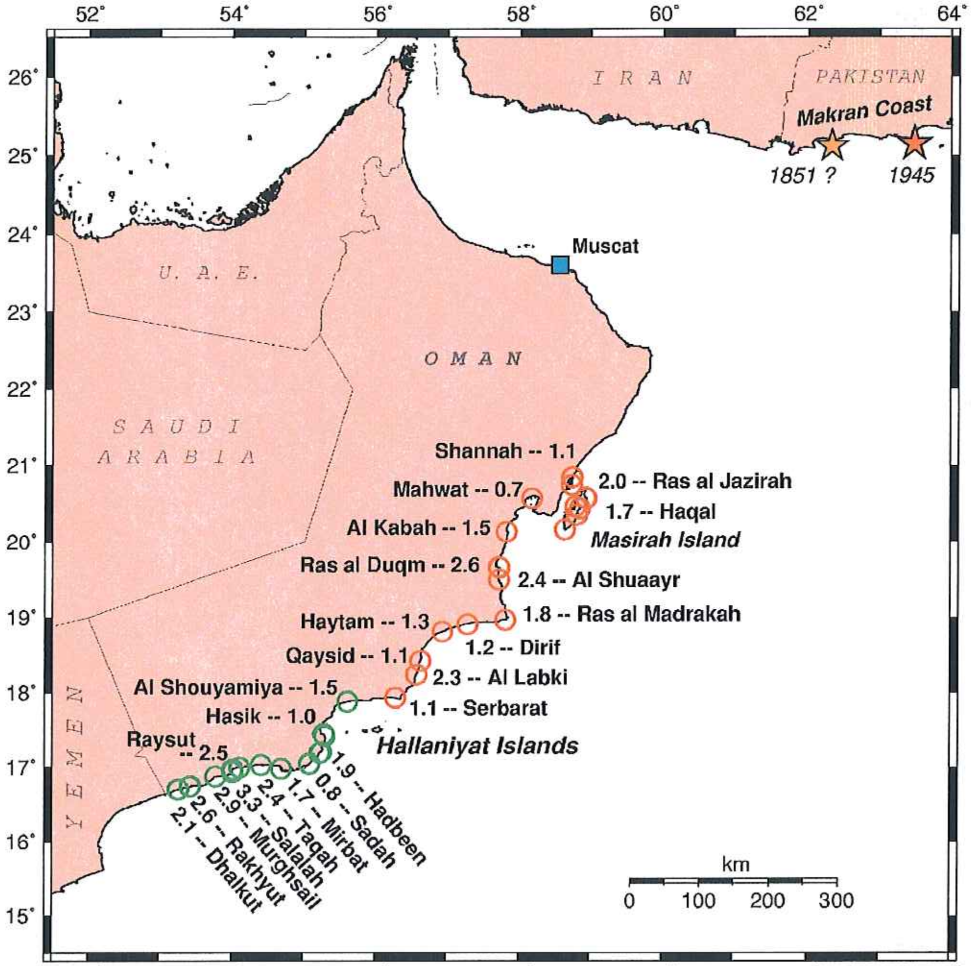


**Figure 1.** Maximum runup values (in meters) surveyed at the various sites visited. The stars along the coast of Pakistan identify the epicenter of the large 1945 earthquake and, tentatively, of the 1851 earthquake to the west. This region poses the greatest tsunami threat to Oman.

## RESULTS

Table 1 presents the full data set gathered during the survey. Forty-one measurements were retained, mostly runup values obtained from eyewitness reports. The data set is summarized in Figure 1, which for each locality shows the maximum vertical penetration (flow depth or runup, in meters) among sites in its immediate vicinity. Circles denote points surveyed by the northern or southern group.

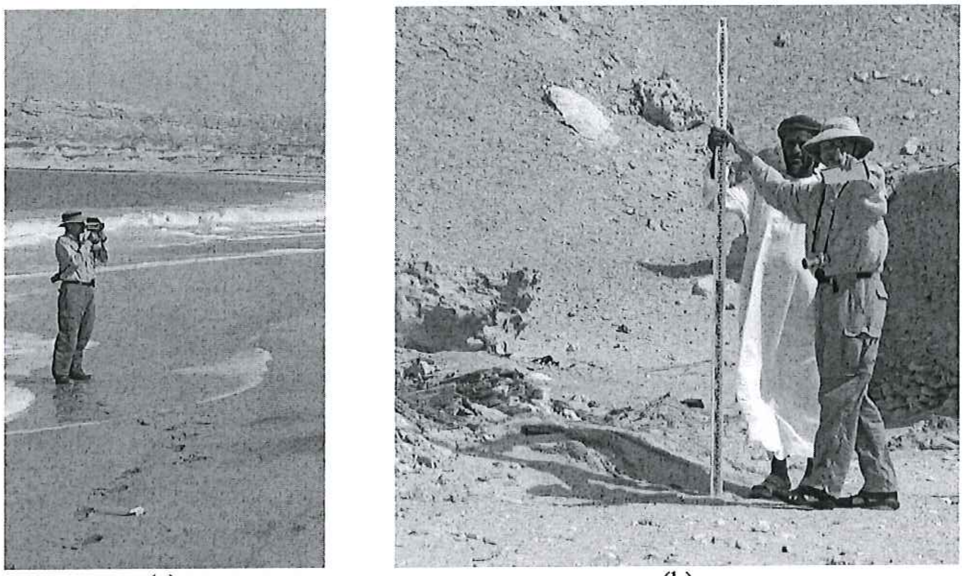

(a) (b)

**Figure 2.** Surveying techniques demonstrated at Ras al Duqm (Site 31). (a) H. Fritz uses a laser ranger at the coastline. (b) 43 m away, P. Raad and tsunami eyewitness Mr. Soubayh bin Rajid bin Sa'id Al-Joubaybi identify the site of maximum penetration with a surveying rod, defining a runup of 2.6 m.

## PRINCIPAL CHARACTERISTICS

The maximum heights compiled in Table 1 and plotted in Figure 1 are typically on the order of 1–3 m, with a single value of 5.4 m at Al Shuaayr (Site 34b). However, that point involves splashing of the waves on a steep cliff, and such data points are not representative of the general penetration of the wave, as documented in previous surveys, notably after the 2001 Peru tsunami (Okal et al. 2002a). The low value of 0.13 m at Hadbeen (Site 14b) refers to a depression behind a sand berm with significantly larger flow depth at the top of the berm (1.85 m, Site 14a). In general terms, our runup values remain significantly smaller than those surveyed along the coast of Somalia, only 750 km to the southwest (5–9 m), where considerable structural damage was inflicted on coastal communities (Fritz and Borrero 2006, this issue). Furthermore, Oman suffered no casualties during the tsunami, whereas about 300 people were killed in Somalia. Rather, the runup values in Oman are comparable to those surveyed farther south on the islands of Réunion and Rodrigues, and along the eastern coast of Madagascar (Okal et al. 2006a, this issue; Okal et al. 2006b, this issue).

The surveyed values are generally homogeneous, but they do feature some lateral variability along the coast. In practice, one can outline the following trends: the larger runup values (above 2 m and up to 3.3 m) are regrouped at the western end of the surveyed area, i.e., from Dhalkut to Taqah. The next section of the coastline, from Mirbat to

**Table 1.** Data set gathered by the ITST in Oman, August 2005

| Number | Site | Latitude (° N) | Longitude (° E) | Vertical survey | | Inundation | Date and time surveyed | | Notes |
|---|---|---|---|---|---|---|---|---|---|
| | | | | (m) | Nature[a] | (m) | Date | UTC | |
| Southern Group | | | | | | | | | |
| 1 | Raysut | 16.937500 | 54.006550 | 2.50 | F | | 11 Aug 2005 | 07:45 | Flow depth at head of old port |
| 2 | Raysut | 16.963667 | 53.999783 | 1.71 | R | 88 | 11 Aug 2005 | 09:38 | Front of (new) restaurant; fishing port |
| 3 | Raysut | 16.965483 | 54.000433 | 1.24 | R | 154 | 11 Aug 2005 | 09:57 | Parking lot of fishing port |
| 4 | Salalah | 16.975850 | 54.010100 | 3.10 | F | 35 | 11 Aug 2005 | 09:00 | Boat moved at beach west of Hilton Hotel |
| 5 | Salalah | 16.976017 | 54.010050 | 3.25 | R | 71 | 11 Aug 2005 | 09:20 | Watermarks beyond boat |
| 6 | Salalah | 17.000100 | 54.109033 | 2.67 | R | 13 | 11 Aug 2005 | 11:08 | Runup along road at Al Hafa Beach |
| 7 | Taqah | 17.033617 | 54.403883 | 2.44 | R | 73 | 11 Aug 2005 | 12:30 | Runup to garbage box on beach |
| 8 | Mirbat | 16.986133 | 54.687217 | 1.73 | R | 22 | 11 Aug 2005 | 13:50 | Runup along beach at end of port |
| 9 | Sadah | 17.048250 | 55.074817 | 0.82 | R | 36 | 12 Aug 2005 | 07:20 | Sandy cove at east entrance to port |
| 10a | Sadah | 17.049483 | 55.072883 | 1.30 | F | 13 | 12 Aug 2005 | 07:35 | Flow depth at beach berm; head of bay |
| 10b | Sadah | 17.049483 | 55.072883 | 0.21 | R | 58 | 12 Aug 2005 | 07:35 | Runup to pole on beach at head of bay |
| 11 | Hadbeen | 17.205833 | 55.233183 | 1.55 | R | 12 | 12 Aug 2005 | 08:20 | Runup at beach at head of port, NE of village |
| 12 | Hasik | 17.422067 | 55.287217 | 0.83 | R | 4 | 12 Aug 2005 | 09:22 | Fishing port south of town |
| 13 | Hasik | 17.449450 | 55.270917 | 1.04 | R | 4 | 12 Aug 2005 | 10:06 | Runup at beach in front of town |
| 14a | Hadbeen | 17.196300 | 55.218500 | 1.85 | F | 22 | 12 Aug 2005 | 11:20 | Flow depth at berm; large beach SW of village |
| 14b | Hadbeen | 17.196300 | 55.218500 | 0.13 | R | 82 | 12 Aug 2005 | 11:20 | Runup in flat land behind berm |
| 15 | Dhalkut | 16.703933 | 53.254117 | 1.64 | F | | 13 Aug 2005 | 11:11 | Secondary breakwater at police station |
| 16 | Dhalkut | 16.704133 | 53.251717 | 2.13 | R | 184 | 13 Aug 2005 | 11:53 | Runup to large rock at head of port |
| 17 | Rakhyut | 16.745883 | 53.425517 | 1.81 | R | 27 | 13 Aug 2005 | 13:30 | Runup to beach at east end of town |
| 18 | Rakhyut | 16.744900 | 53.417333 | 2.62 | R | 59 | 13 Aug 2005 | 13:45 | Runup to beach at west end of town |
| 19 | Murghsail | 16.878150 | 53.771967 | 2.88 | R | 9 | 14 Aug 2005 | 06:53 | Rocky berm in front of restaurant |
| 20 | Salalah | 16.999350 | 54.104983 | 2.34 | R | 27 | 14 Aug 2005 | 08:45 | Runup to road at Al Hafa Beach |
| 21 | Al Shouyamiya | 17.881600 | 55.607417 | 1.48 | R | 6 | 15 Aug 2005 | 09:00 | Runup on beach in front of village |

**Table 1.** (cont.)

| Number | Site | Latitude (° N) | Longitude (° E) | Vertical survey | | Inundation | Date and time surveyed | | Notes |
|---|---|---|---|---|---|---|---|---|---|
| | | | | (m) | Nature[a] | (m) | Date | UTC | |
| Northern Group | | | | | | | | | |
| 22 | Shannah | 20.74635 | 58.73264 | 1.05 | F | | 10 Aug 2005 | 11:09 | Vertical wall of vehicle ramp at ferry dock |
| 23 | Ras al Jazirah | 20.43837 | 58.84107 | 1.80 | R | 29 | 11 Aug 2005 | 06:31 | |
| 24 | Haqal | 20.35828 | 58.79884 | 1.70 | R | 42 | 11 Aug 2005 | 07:14 | |
| 25 | South Cape, Masirah | 20.16627 | 58.63723 | D-D | | | | | Downdraw only; no positive wave |
| 26 | Ru | 20.46554 | 58.78273 | 1.30 | R | 143 | 11 Aug 2005 | 10:47 | Eyewitness and debris |
| 27 | Ras al Jazirah | 20.58067 | 58.92474 | 2.00 | R | 79 | 11 Aug 2005 | 11:57 | Eyewitness |
| 28a | Ras al Jazirah | 20.57542 | 58.93170 | 1.80 | R | 59 | 11 Aug 2005 | 12:48 | Eyewitness; 1st wave |
| 28b | Ras al Jazirah | 20.57542 | 58.93170 | 1.50 | R | 24 | 11 Aug 2005 | 12:48 | Eyewitness; 2nd wave |
| 29 | An Najdah | 20.84741 | 58.73710 | 0.40 | R | 4 | 12 Aug 2005 | 09:27 | Eyewitness; boat |
| 30 | Mahwat Island | 20.57478 | 58.17527 | 0.70 | R | 13 | 12 Aug 2005 | 12:19 | Eyewitness; north shore of island |
| 31 | Al Kabah | 20.13718 | 57.81995 | 1.50 | R | 72 | 13 Aug 2005 | 06:58 | Eyewitness |
| 32 | Ras al Duqm | 19.65993 | 57.72089 | 2.60 | R | 43 | 13 Aug 2005 | 11:06 | Eyewitness |
| 33 | Ras al Duqm | 19.66614 | 57.70798 | 2.30 | R | 48 | 13 Aug 2005 | 11:26 | Eyewitness |
| 34a | Al Shuaayr | 19.50029 | 57.71287 | 2.40 | R | 42 | 13 Aug 2005 | 12:03 | Eyewitness |
| 34b | Al Shuaayr | 19.50029 | 57.71287 | 5.40 | S | 29 | 13 Aug 2005 | 12:03 | Splash on cliff; eyewitness |
| 35 | Ras al Madrakah | 18.97030 | 57.80395 | 1.80 | R | 32 | 14 Aug 2005 | 07:20 | Eyewitness |
| 36 | Ras al Madrakah | 18.97013 | 57.80364 | 1.70 | R | 42 | 14 Aug 2005 | 07:26 | Boats moved by tsunami |
| 37 | Dirif | 18.91070 | 57.28212 | 1.20 | R | 15 | 14 Aug 2005 | 09:25 | Eyewitness |
| 38 | Haytam | 18.81316 | 56.92918 | 1.30 | R | 25 | 14 Aug 2005 | 10:40 | Eyewitness |
| 39 | Qaysad | 18.42390 | 56.62197 | 1.10 | R | 162 | 14 Aug 2005 | 14:28 | Eyewitness |
| 40 | Al Labki | 18.23859 | 56.56582 | 2.30 | R | 447 | 14 Aug 2005 | 13:25 | Eyewitness; debris; algae |
| 41 | Serbarat | 17.93347 | 56.27334 | 1.10 | R | 25 | 15 Aug 2005 | 08:08 | Eyewitness |

[a] **F**=flow depth; **R**=runup; **S**=splash.

Ras al Madrakah, features runup values consistently under 2 m; further north, from Al Shuaayr to Masirah Island, runup values are slightly larger, reaching 2.6 m at Ras al Duqm (Site 32), but these values feature more scatter.

At the Southern Cape of Masirah Island (Site 25), the tsunami was observed as a significant downdraw, but the water returned to its original level with no positive wave inundating the shore; this observation is entered as "D-D" (for "downdraw") in Table 1. Our experience in other tsunami surveys such as in Madagascar (Okal et al. 2006b, this issue) indicates that a runup as small as 0.70 m was recognized, and thus we propose that the amplitude of the positive wave at Site 25 must not have exceeded 0.50 m. However, we stress that this observation is different from the case of the localities in Madagascar (Vatomandry and Manahoro), where the tsunami had been observed as neither a positive nor a negative wave (Okal et al. 2006b, this issue).

Descriptions by eyewitnesses of the physical properties of the waves and of their arrival times were generally typical of descriptions gathered during previous international tsunami surveys (Synolakis and Okal 2005). Most witnesses recalled that they were alerted to the tsunami by an initial recess of the sea, over distances difficult to quantify but generally interpreted as reaching 100 m; in some instances along particularly flat beaches in the north, the distances were 0.5 – 1 km. From a number of testimonies, notably in the Hadbeen-Hasik area, it is suggested that this depression may have been preceded by a small positive wave, too weak to have been universally observed. This time history of the wave is indeed predicted in western azimuths by the geometry of the earthquake source, was observed in Sri Lanka (e.g., Chapman 2005), and agrees with the results of preliminary global simulations (e.g., Titov 2005). It is also supported by the lone available maregram, recorded in the port of Salalah (Figure 3), showing a positive first wave at 08:12 UTC with an amplitude not exceeding 20 cm, followed 30–45 minutes later by a much stronger depression with a negative amplitude of $\sim 1$ m. There followed a series of positive waves (typically three or more), with the first or second of them generally described as the largest. In particular, and based on an eyewitness testimony, we obtained separate runup measurements for the first and second waves (1.8 m and 1.5 m, respectively) at Site 27 (Ras al Jazirah, Masirah Island).

Our experience has been that temporal estimates (the time of arrival and the period of the waves) are traditionally prone to large uncertainties in eyewitness reports. In the present survey, many descriptions indicate a phenomenon starting around noon to 1 P.M. local time (UTC+4) and lasting several hours, up to the whole day (which we interpret as dusk, with the sun setting at about 18:00 local time at that time of the year). This is again supported by travel times computed from ray tracing models (Titov 2005). Epicentral distances vary from 4,400 km at Masirah Island to 4,800 km at Dhalkut, but the tsunami must travel around the Indian subcontinent and across the Maldives Archipelago, thus outside the great circle and over shallow bathymetry. This results in a delay of more than one hour, with travel times of 7–7.5 hours for most of the surveyed area. Combined with a seismic origin time of 00:58:50 UTC, this predicts first arrivals between 12:00 and 12:30 (UTC+4), as indeed were observed for the first positive wave of small amplitude on the Salalah maregram (Figure 3). However, many eyewitness reports, especially from the northern group's survey, assign times of 4:00–5:00 P.M. (local time).

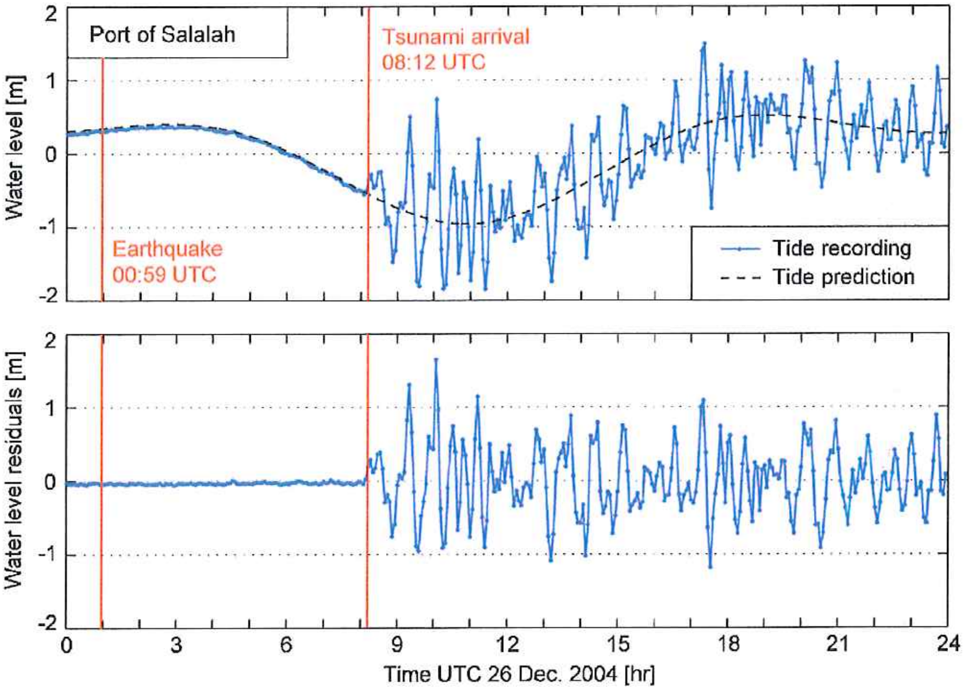


**Figure 3.** Maregram of the Sumatran tsunami recorded in the port of Salalah (source: University of Hawaii Sea Level Center). The top frame shows the raw data, and the bottom frame shows the tsunami signal, after the predicted tide is subtracted. Local times are 4 hours ahead of the UTC. Note the initial low-amplitude inundation, followed by a much larger downdraw, and then followed by two large positive waves. Many eyewitnesses may not have noticed the first small, positive wave.

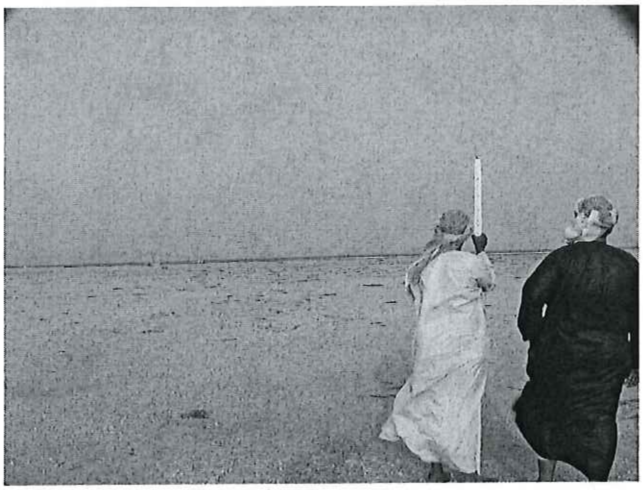
These discrepancies can be explained partly by the generally poor precision of timing estimates from eyewitnesses who are speaking from memory, and partly by probable reference to the maximum amplitude of the phenomenon, expected to occur one to two hours after the initial arrival. However, the discrepancies could also involve a group time delay for the waves, resulting from complex interaction with shallow bathymetry that was not included in preliminary models. On the other hand, one witness described a downdraw as early as 10:30 A.M. (06:30 UTC), which is highly suspicious, given that it would be noncausal in Titov's (2005) model.

Similarly, the description of the periods of the waves is highly variable, with estimates ranging from a few minutes to 30 minutes.

## SPECIFIC SITES

In the following sections, we highlight the sites where the most significant observations were made, arranged geographically from north to south.

(a)



(b)

**Figure 4.** Site 40, Al Labki. (a) On this exceptionally flat beach, the tsunami deposited algae and seaweed far inland. (b) The survey revealed an inundation of 447 m, with a runup of 2.3 m.

### Site 40, Al Labki

On this remarkably flat beach, inundation was measured at a record 447 m, for a runup of 2.3 m. The beach was strewn with marine debris and algae (Figure 4), identified by a witness as having been left by the tsunami.

### Site 4, The Beach West of Salalah

This site is located on the beach between Salalah and Rasyut, a few kilometers west of the Hilton Salalah Hotel and Resort, barely discernible in the background of Figure 5. Eyewitnesses led us to a 10-m-long fishing boat that the tsunami had deposited on the sand berm. Flow depth was estimated from the flotation line of the boat at a minimum of 3.1 m; runup was 3.25 m, 36 m farther inland, on the basis of marine shell deposits. Except for the splash at Site 34b, this constitutes the largest runup value in the survey.

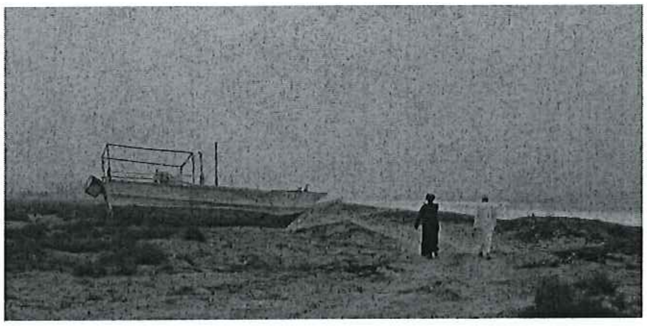


**Figure 5.** Site 4, the beach between Salalah and Raysut. This 10-m fishing boat was moved by the tsunami to the top of the berm, 35 m from the shore. On the basis of the flotation line of the boat, flow depth at that location was computed at 3.1 m; watermarks are preserved another 36 m inland. In the distance to the left of the boat is the Hilton Hotel and resort, and to the right of the prow is a smaller fishing boat, reportedly also deposited by the tsunami.

## The Eddies in the Port of Salalah

The Port of Salalah is one of the major container terminal facilities in the Middle East. In Figure 6 are two file photos of the port that show the main wharf, which offers four berths capable of accommodating the largest container ships. According to reports obtained from the harbor master, Captain Ahmed Abdullah, the manager of marine services, Captain Geerd Gunther, and several other port employees, the 285-m freighter *Maersk Mandraki*, which was docked at Berth 4 (Figure 7a), broke its moorings at 1:42 P.M. (09:42 UTC) and started drifting for a period of several hours. It drifted both inside the harbor, where it was caught in a system of eddies from which all efforts to free it via tugboats were in vain, and outside the port itself, where the ship reached the far side of the breakwater before eventually returning toward the harbor and beaching on a sand bar to the east of the main wharf (Figure 7b).

Similarly, the 292-m-long *Maersk Virginia*, comparable in length and tonnage to the *Mandraki*, was rocked by the tsunami as it was attempting to enter the harbor, to the extent that the captain had to wait about seven hours outside the harbor to proceed. During that time, the ship was pulled toward the breakwater and contacted it, resulting in minor damage to a fuel tank. Miraculously, the wandering "ghost" ship *Mandraki* did not collide with other ships or with harbor structures, and the damage to the *Virginia* was minor and was confined to the ship itself, without impact on other ships or infrastructure.

We note that two similar incidents took place on the same day—one in the port of Toamasina, Madagascar, involving a much smaller, 50-m-long freighter (Okal et al. 2006b, this issue), and one in the harbor of Le Port on the island of Réunion (Okal et al. 2006a, this issue), involving a 196-m container ship. It is noteworthy, and obviously of great concern, that in all three cases the turbulent activity inside the harbor (and, in the

**Figure 6.** Aerial file photos of the Port of Salalah (source: www.salalahport.com). (a) Looking west-southwest; also shown is survey Site 1 in the old port. (b) Looking west-northwest. In both these photos, overprinted numbers are keyed to the description of the path of the *Mandraki* (Figure 7b) after the ship broke its moorings at Berth 4 (position 0 in both photos).

case of Salalah, outside the breakwater) lasted several hours after the end of the low-frequency wave activity associated with the visible (vertical) effects of the tsunami, as reported to us at most other sites. This is evidenced in Salalah by the incident of the *Virginia*, which could not dock into the harbor before 11:00 P.M. local time, i.e., more than 9 hours after the *Mandraki* broke its moorings, and is further supported by the maregram in Figure 3, showing strong oscillations in sea level at about 9:30 P.M. local time. We recall that, during the incident in Toamasina, the ship broke its moorings four to five hours after the time of maximum vertical oscillation of the sea level (Okal et al. 2006b, this issue). In Réunion, the ship went astray twice, once 1.5 hours after the end of the period of maximum wave activity, and again 2.5 hours later, after tugboats had managed to control the ship and moor it back to the wharf. Differences exist among the three in-

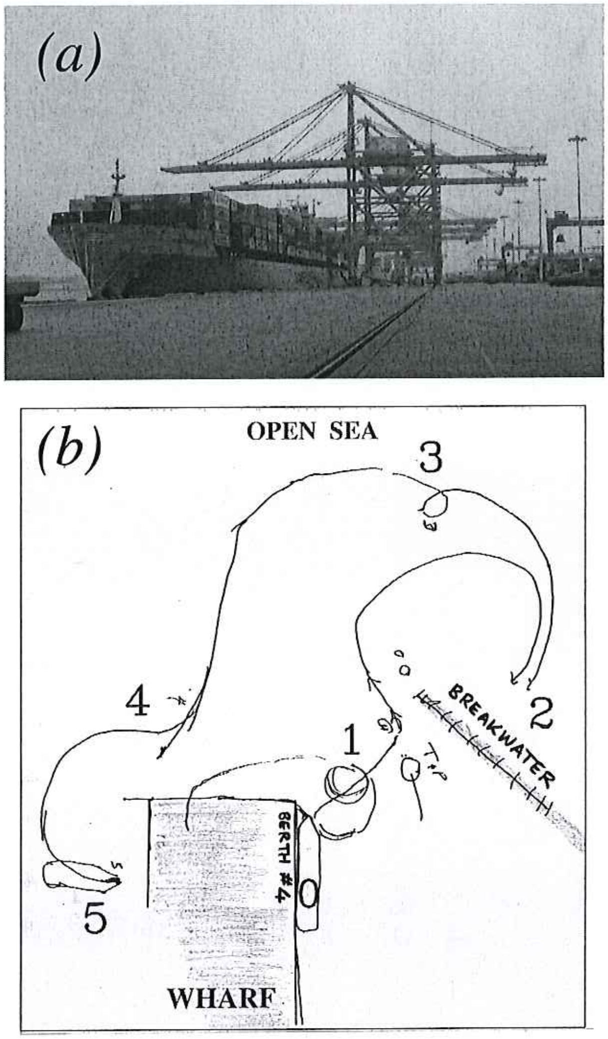


**Figure 7.** (a) The *Maersk Carolina* moored at Berth 4 on 14 August 2005. This is a sister ship of the Virginia and is also essentially comparable to the *Mandraki*. (b) A hand-drawn sketch by the eyewitness, looking east-northeast (out to sea) and detailing the drift of the *Mandraki*. The numeral 0 shows the initial position of the *Mandraki* moored at Berth 4, 1 shows the ship caught in a strong eddy after the rupture of its moorings, 2 shows the ship outside the harbor approaching the far side of breakwater, 3 shows the subsequent loop outside the harbor, 4 shows the return to the harbor, and 5 shows the eventual grounding on a sand bar east of the harbor.

cidents, most importantly the timing of the initial rupture of the moorings relative to the arrival time of the tsunami. However, a common origin of these incidents can be sought in the resonant oscillation of the harbors excited by an appropriate component of the tsunami wave, whose frequency would depend on the shape and size of the harbor, and naturally lead to a variable delay, due to the strong dispersion of short tsunami waves across the oceanic basin, outside the frequency domain of the shallow-water approximation.

Of the three incidents, the one in Salalah was probably the most spectacular, as it involved two marine behemoths rendered essentially uncontrollable for several hours in the midst of critical port infrastructure—involving, in particular, giant hydrocarbon storage facilities. A lesson to be heeded from such incidents is that the hazard posed by the arrival of a distal tsunami in the harbor of a coast that is otherwise largely spared by the wave may last much longer and even start much later than the more conventional inundation of a beach. It will certainly warrant the reassessment of civil defense policies in port facilities, in particular concerning the very sensitive issue of the "all clear" message, which may have to be significantly delayed in a harbor environment.

## THE CASE OF THE HALLANIYAT ISLANDS

During the visit of the ITST to the Civil Defense Headquarters in Salalah, it was reported to us that the tsunami had been widely observed on the Hallaniyat Islands (Figure 1), to the extent that residents had called the mainland requesting evacuation from the island. If confirmed, this would suggest runup amplitudes in excess of those measured on the mainland, and in particular on the relevant sections of the coastline, where runup does not exceed 1.5 m from Hasik to Serbarat (Figure 1). This motivated us to attempt to visit the island, but difficulties with logistics made it impossible to organize such a trip during the time available to the ITST. We strongly recommend that the survey be pursued on the Hallaniyat Islands, as this should shed light on the still poorly understood problem of the relationship between inundation parameters on mainland shorelines and on islands lying offshore—in this case, at a distance of approximately 50 km, comparable to typical tsunami wave lengths on a continental shelf.

## CONCLUSION AND PERSPECTIVE

The interviewing of well over 100 eyewitnesses of the 26 December 2004 tsunami has resulted in the compilation of a homogeneous database of 41 inundation sites. With the exception of a large value interpreted as a splash on a cliff, the runup reaches at most 3.25 m (at Site 4). Such values, which will need to be corrected for tides, explain the relatively minor damage wrought by the tsunami in Oman, which amounted to a few damaged fishing boats and a handful of vehicles displaced on beaches, with no reported casualties. By contrast, there were more than 300 fatalities and numerous destroyed villages in Somalia, a mere 750 km to the southwest (Fritz and Borrero 2006, this issue). This strong difference in the effects of the tsunami illustrates the narrow lobe of constructive interference in the far field, oriented in the azimuth perpendicular to the direction of faulting (Ben-Menahem and Rosenman 1972, Okal and Talandier 1991), as well as the probable diffraction of the wave around the Indian subcontinent.

Despite the generally benign character of the tsunami in Oman, the incidents in the port of Salalah constitute an ominous warning to port authorities worldwide regarding the very special characteristics of the threat that tsunamis pose to harbor facilities. The container ships *Mandraki* and *Virginia* drifted uncontrolled inside the harbor and in its immediate vicinity for several hours, the former after breaking its moorings, and the latter drifting despite the efforts of its crew. While in the end no major damage was reported, disaster was averted only through a stroke of luck, because critical infrastructure could have been struck by the ships. The most important aspect of these incidents is their duration, because they lasted significantly longer than the phenomenon described by eyewitnesses on beaches. These singular characteristics should govern the reassessment of the tsunami warning and mitigation procedures for port installations.

Finally, we wish to comment briefly on the matter of future tsunami risk for Oman. The 1,200-km fault length of the 26 December 2004 earthquake is generally interpreted as expressing the full release of the tectonic strain accumulated over a full tectonic cycle (Stein and Okal 2005), and a similar earthquake of comparable catastrophic tsunami potential may not occur at the same location for several centuries. Among other tsunamigenic sources in the Indian Ocean, it is widely expected that a mega-earthquake could occur soon along the southern part of the Sumatran subduction zone, probably as a result of the transfer of Coulomb stresses from the faulting areas of the 26 December earthquake and of its smaller (albeit still gigantic) companion on 28 March 2005 (Nalbant et al. 2005). Due to the geographic curvature of the Andaman-Sumatra subduction zone, this event would radiate maximum tsunami amplitudes toward the southwestern Indian Ocean (Ben-Menahem and Rosenman 1972), thus most probably sparing the Arabian peninsula.

On the other hand, the greatest tsunami danger to the country of Oman probably lies in the Makran subduction zone off the coast of western Pakistan, less than 500 km away from Muscat (Figure 1). This was the site of a very large earthquake on 27 November 1945, whose moment was estimated at $2 \times 10^{28}$ dyne-cm by Byrne et al. (1992). It caused a tsunami that wrought considerable damage upon the few settlements then present on the Makran coast, and as far away as Karachi and Mumbai (Pendse 1948), with Ambraseys and Melville (1982) reporting tsunami damage in Muscat. The question of the recurrence times of such earthquakes remains open, in view of the large deformation of the overriding plate at the Makran boundary, but we note that the Arabian plate converges locally at 4 cm/yr toward the rigid Eurasian block (DeMets et al. 1990), which would give a gross estimate of 150 years for the recurrence of the 6 m of slip inferred by Byrne et al. (1992) for the source of the 1945 event. In this context, little is known about the actual size of an 1851 shock that took place to the west of the 1945 fault zone (Oldham 1882), but even a moderately large ($M \approx 7$) earthquake at that location could pose a threat to the northeastern shores of Oman. In this general framework, and notwithstanding the difficulties inherent in the tremendous development of the country during the last 35 years and in the extreme youth of its population, it would be desirable to confirm and hopefully quantify the effect of the 1945 tsunami in and around Muscat, possibly through the interviewing of elderly eyewitnesses, along the lines of our previous work on historical tsunamis in the Pacific (Okal et al. 2002b) and the Aegean Sea (Okal et al. 2004).

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## REFERENCES

Ambraseys, N. N., and Melville, C. P., 1982. *A History of Persian Earthquakes*, Cambridge University Press, 236 pp.

Ben-Menahem, A., and Rosenman, M., 1972. Amplitude patterns of tsunami waves from submarine earthquakes, *J. Geophys. Res.* **77**, 3097–3128.

Byrne, D. E., Sykes, L. R., and Davis, D. M., 1992. Great thrust earthquakes and aseismic slip along the plate boundary of the Makran subduction zone, *J. Geophys. Res.* **97**, 449–478.

Chapman, C. H., 2005. The Asian tsunami in Sri Lanka: A personal experience, *EOS Trans. Am. Geophys. Union* **86**, 13–14.

DeMets, D. C., Gordon, R. G., Argus, D. F., and Stein, S., 1990. Current plate motions, *Geophys. J. Int.* **101**, 425–478.

Fritz, H. M., and Borrero, J. C., 2006. Somalia field survey after the 2004 Indian Ocean tsunami, *Great Sumatra Earthquakes and Indian Ocean Tsunamis of December 26, 2004 and March 28, 2005, Earthquake Spectra* **22** (S3), June (this issue).

Nalbant, S. S., Steacy, S., Sieh, K., Natawidjaja, D., and McCloskey, J., 2005. Updated earthquake hazard in Sumatra, *Nature* **435**, 756–757.

Nettles, M., Ekström, G., Dziewonski, A., and Maternovskaya, N., 2005. Source characteristics of the great Sumatra earthquake and its aftershocks, *EOS Trans. Am. Geophys. Union* **86** (18), JA11, abstract.

Okal, E. A., and Talandier, J., 1991. Single-station estimates of the seismic moment of the 1960 Chilean and 1964 Alaskan earthquakes, using the mantle magnitude $M_m$, *Pure Appl. Geophys.* **136**, 103–126.

Okal, E. A., Dengler, L., Araya, S., Borrero, J. C., Gomer, B., Koshimura, S., Laos, G., Olcese, D., Ortiz, M., Swensson, M., Titov, V. V., and Vegas, F., 2002a. A field survey of the Camana, Peru tsunami of June 23, 2001, *Seismol. Res. Lett.* **73**, 904–917.

Okal, E. A., Synolakis, C. E., Fryer, G. J., Heinrich, P., Borrero, J. C., Ruscher, C., Arcas, D., Guille, G., and Rousseau, D., 2002b. A field survey of the 1946 Aleutian tsunami in the far field, *Seismol. Res. Lett.* **73**, 490–503.

Okal, E. A., Synolakis, C. E., and Yalçıner, A. C., 2004. The Amorgos, Greece earthquake and tsunami of 9 July 1956: Focal mechanism and field survey, *EOS Trans. Am. Geophys. Union* **85** (47), F1042, abstract.

Okal, E. A., Sladen, A., and Okal, E.A.-S., 2006a. Rodrigues, Mauritius, and Réunion Islands field survey after the December 2004 Indian Ocean tsunami, *Great Sumatra Earthquakes and Indian Ocean Tsunamis of December 26, 2004 and March 28, 2005, Earthquake Spectra* **22** (S3), June (this issue).

Okal, E. A., Fritz, H. M., Raveloson, R., Joelson, G., Pančošková, P., and Rambolamanana, G., 2006b. Madagascar field survey after the December 2004 Indian Ocean tsunami, *Great Sumatra Earthquakes and Indian Ocean Tsunamis of December 26, 2004 and March 28, 2005, Earthquake Spectra* **22** (S3), June (this issue).

Oldham, J., 1882. A catalogue of Indian earthquakes, *Mem. Geol. Surv. India* **19**, 163–215.

Pendse, C. G., 1948. The Mekran earthquake of 28th November 1945, *Science Notes* **10**, 141–145. Indian Meteor. Department.

Stein, S., and Okal, E. A., 2005. Size and speed of the Sumatra earthquake, *Nature* **434**, 581–582.

Synolakis, C. E., and Okal, E. A., 2005. 1992–2002: Perspective on a decade of post-tsunami surveys in *Tsunamis: Case Studies and Recent Developments*, edited by K. Satake, vol. 23, Advances in Natural and Technological Sciences Series, pp. 1–30, Springer, New York.

Synolakis, C. E., Okal, E. A., and Bernard, E. N., 2005. The mega-tsunami of December 26, 2004, *The Bridge* **35** (2), 26–35.

Titov, V. V., 2005. Modeling of the Indian Ocean tsunami: Lessons for warning and hazard mitigation, in *Proceedings, Ann. Meeting Europ. Un. Geosci.*, Vienna, Austria, p. 230, abstract.

Wessel, P., and Smith, W.H.F., 1991. Free software helps map and display data, *EOS Trans. Am. Geophys. Union* **72**, 441 and 445–446.

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