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Socotra Island, Yemen: field survey of the 2004 Indian Ocean tsunami

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Abstract The tsunami of 26th December 2004 severely affected Yemen's Socotra Island with a death at a distance of 4,600 km from the epicenter of the Magnitude 9.0 earthquake. Yemen allowed a detailed assessment of the far-field impact of a tsunami in the main propagation direction. The UNESCO mission surveyed 12 impacted towns on the north and south shores covering from the east to the west tip of Socotra. The international team members were on the ground in Yemen from 11 to 19 October 2006. The team measured tsunami run-up heights and inundation distances based on the location of watermarks on buildings and eyewitness accounts. Maximum run-up heights were typically on the order of 2–6 m. Each measurement was located by means of global positioning systems (GPS) and photographed. Numerous eyewitness interviews were recorded on video. The tsunami impact on Socotra is compared with other locations along the shores of the Indian Ocean.

Keywords Tsunami · Runup · 26 December 2004 earthquake · Indian Ocean · Yemen · Socotra Island · Horn of Africa · Field survey

1 Introduction

On Sunday, 26 December 2004 at 00:58:53 UTC, a great earthquake with a moment magnitude of 9.0—or possibly greater (Stein and Okal 2005)—nucleated 250 km southwest of the North tip of Sumatra, Indonesia. A large tsunami was generated and severely damaged coastal communities in countries along the Indian Ocean, including Indonesia, Thailand, Sri Lanka, India, Maldives, and Somalia (Synolakis and Kong 2006; Synolakis and Okal 2005). The tsunami death toll was estimated at 300,000. Beyond the loss of human lives, the tsunami also destroyed livelihoods, traumatized whole populations, and

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severely damaged habitats. In the near field of the epicenter, Sumatra was hardest hit by the tsunami (Borrero 2005a, b; Borrero et al. 2006; Fritz et al. 2006a). In the mid-field the tsunami severely affected Sri Lanka across the Bay of Bengal at a distance of 1,600 km from the epicenter or at a third of the distance between Sumatra and Somalia along the westward path of the tsunami (Liu et al. 2005). The Maldives at half-way point between Sumatra and Somalia were hit an hour after Sri Lanka at a distance of 2,500 km from the epicenter shown in Fig. 1a (Fritz et al. 2006b). The global propagation of the tsunami was computed with the MOST-model (Titov et al. 2005). The computed maximum tsunami wave heights are shown Fig. 1b.

In East Africa the tsunami impact focused on Somalia, some 5,000 km to the west of the earthquake epicenter (Fritz and Borrero 2006). The Puntland coast in northern Somalia was impacted by tsunami runup heights of up to 9 m and inundation distances of up to 700 m (Fig. 2b). Hardest hit was a 650 km stretch of the Somali coastline between Garacad (Mudung region) and Xaafuun (Bari region), which forms part of the Puntland Province near the Horn-of-Africa. The tsunami resulted in the death of some 300 people and extensive destruction of shelters, houses and water sources, as well as fishing boats and equipment. Most of the victims were reported along the low-lying Xaafuun peninsula. The runup heights started to decline to 6 m in Bargaal at mid-point in terms of latitude between Socotra Island and Xaafuun. However, only 700 km to the north of Somalia the run-up heights rapidly decayed to 1–3 m in Oman as shown in Fig. 2a (Okal et al. 2006b).

Hence, it remained of utter importance to fill the gap in tsunami run-up surveys to determine the exact location of the rapid decay between Somalia and Oman. Further, the exposed location makes Socotra Island an excellent location for the positioning of a tide gauge as secondary warning system for East Africa given the shorter travel time. Synolakis and Okal (2006) simulated a number of potential mega-earthquakes on the shores of the Indian Ocean including of relevance for Socotra: (A) a repeat of the 1833 Southern Sumatra earthquake, (B) simultaneously rupturing the faults of the 1851, 1945, and 1765 events in the Makran (off Pakistan and Iran). The South Sumatra scenario (A) potentially generates a tsunami with stronger impact than in 2004 on the SW Indian Ocean Islands of the Mascarenes and on Madagascar. A South Sumatra event also poses the main potential hazard along Socotra's scarcely populated south coast. The Makran tsunami (B) strongly affects Western India, the Maldives, and the Seychelles, as well as the Kerguelen Islands. A Makran tsunami poses the main hazard for Socotra's densely populated north coast (Fig. 3).

2 Post tsunami field survey

The immediate response by various UN agencies and other organizations focused on saving livelihoods (UNEP 2005). Damage to the fisheries sector was reported for eastern Yemen's Al-Mahrah province bordering Oman and Socotra Island. According to the Ministry of Transport, the main Yemeni ports did not suffer damage, even though water levels rose on average by 0.6 m during the tsunami. The highest water level rise of 2 m inside a port was reported at Nishtun port located 240 km west of Salalah, Oman (Fig. 4). No industrial facility was reported to have been affected by the tsunami. However, limited scientific information was available on the tsunami impact on Socotra Island. Given the exposed location of Socotra Island 250 km east of the Horn of Africa in the Arabian Sea, similar run-up heights as in northern Somali towns, such as Bargaal and Xaafuun, were expected. Therefore, a UNESCO expedition was organized through the Intergovernmental Oceanographic Commission (IOC) in Paris to fill the gap in tsunami inundation and run-up

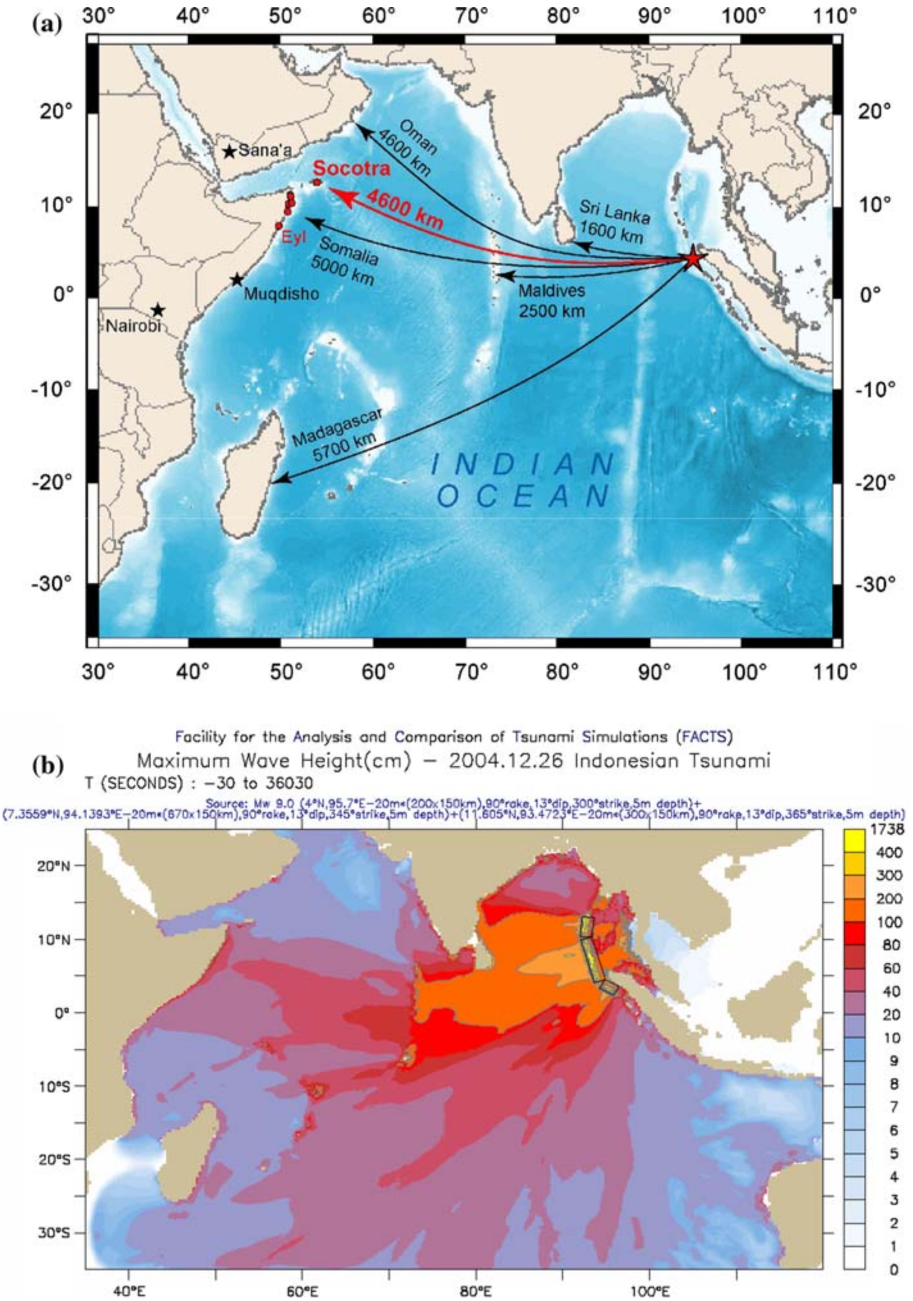

Fig. 1 (**a**) Map of the Indian Ocean locating Socotra off the Horn of Africa. Distances from the epicenter of the 2004 Sumatra–Andaman earthquake (red star) are shown for companion surveys: Sri Lanka (Liu et al. 2005), Maldives (Fritz et al. 2006a, b), Oman (Okal et al. 2006a, b, c) and Madagascar (Okal et al. 2006a, b, c). (**b**) MOST-tsunami model simulation: maximum computed wave heights in cm (Titov et al. 2005)

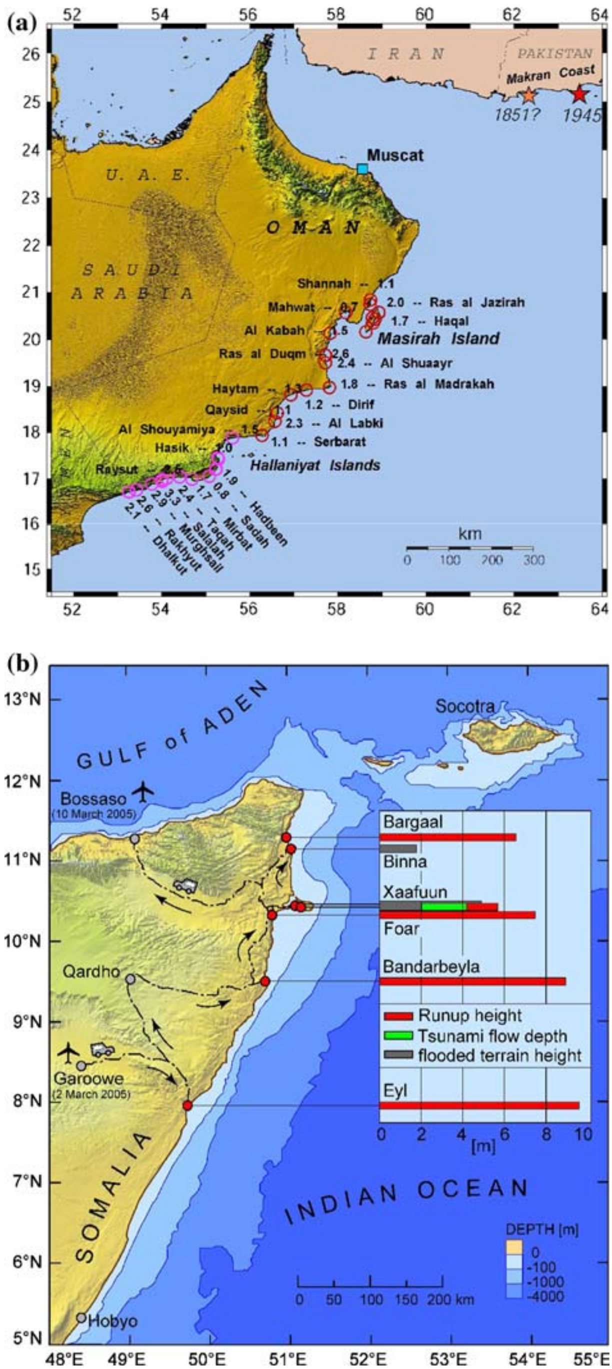

Fig. 2 (**a**) Map of Oman showing maximum run-up values (in m) surveyed at the various sites (Okal et al. 2006a, b, c). (**b**) Map of Somalia's Puntland coast, the GPS-track of the expedition with surveyed locations and the maximum measured tsunami flow depths and run-up heights (Fritz and Borrero 2006)

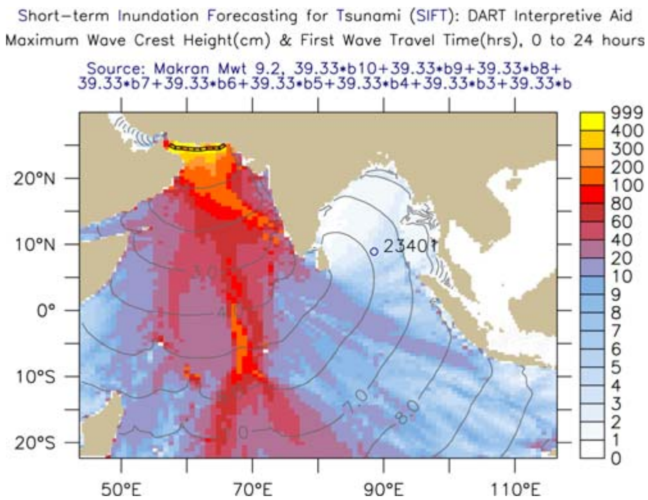

Fig. 3 Makran rupture simulated with the MOST-tsunami model: maximum computed wave heights in cm (pers. comm. Titov 2007)

data between Somalia and Oman. The west tip of Socotra is located more than 500 km SE of Al-Mukalla across the Gulf of Aden (Fig. 4). The archipelago consists of the main island of Socotra (3625 km^2), three smaller islands known collectively as "the Brothers"—Abd Al-Kuri, Samha, Darsa—and other uninhabitable rock outcrops. Abd Al-Kuri and Samha have a cumulated population of a few hundred people, while Darsa is uninhabited. Almost all inhabitants of the Socotra archipelago live on the main island. The principal and only city is Hadiboh with an estimated population of 43,000 in 2004 on the central north shore of Socotra. The total population of Socotra is estimated at 80,000 with seasonal variations.

On 13 October the International Tsunami Survey Team was dispatched from Sana'a to Hadiboh via Al-Mukalla. On Socotra Island the international team members were joined by a local guide and traveled with a four-wheel drive vehicle. Remote settlements at the east and the west capes of the island were visited by small fishing boats from the nearest accessible villages on 40 km long roundtrips (Qalansiyah to Shoaab and Ras Arsal to Shazhor). The survey locations and an overview of measured run-up heights are shown in Fig. 5. The measured data was corrected for the tide level upon tsunami arrival, based on tide predictions for Shiq on Socotra Island (4 km NE of Hadiboh). The difficult and steep terrain on Socotra limited the access to the shoreline to selected locations in particular along the capes and the south coast. The authors surveyed the tsunami impact and wave run-up in 12 coastal settlements; four on the south coast: Shazhor, Mahfarhan, Abadhar, and Bedhoola; eight on the north coast: Arher Qariyah, Hamhariten, Qalansiyah, Shoaab, Ghebbat, Daiham, and Ras Arsal.

A variety of standard tsunami field survey techniques (e.g., Tsuji et al. 1995; Okal et al. 2002; Synolakis and Okal 2005) were used. Numerous eyewitness interviews, which were recorded on video, were used to estimate the number of waves, their height and period, as well as the tsunami arrival time. The team measured the tsunami run-up heights and local flow depths based on watermarks and eyewitness accounts. The maximum run-up and inundation were determined relative to the sea level at tsunami impact with a laser range finder with integrated digital inclinometer and compass. Each watermark was located using

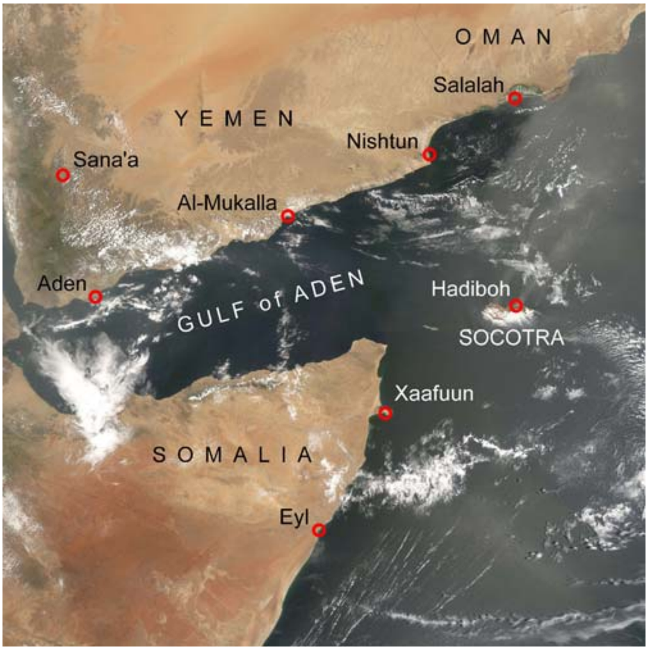

Fig. 4 Satellite image of the Gulf of Aden with Socotra located 250 km east of the Horn of Africa and 350 km south of the Arabian Peninsula (Terra-MODIS satellite image acquired 9 September 2006, NASA)

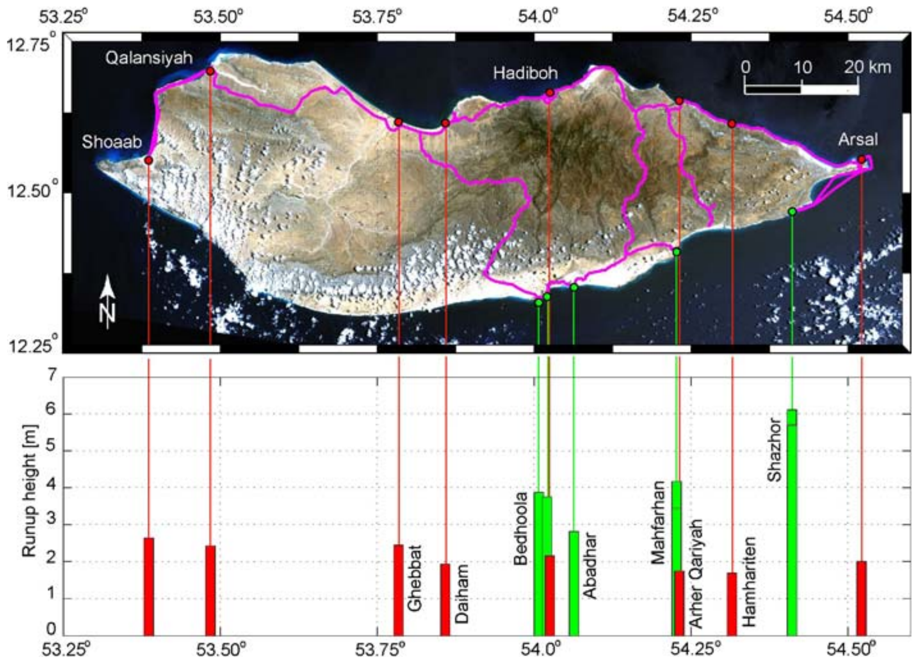

Fig. 5 Map of Socotra Island, the GPS-track of the expedition with surveyed locations and the maximum measured tsunami run-up heights on a Landsat satellite image (NASA)

a handheld global positioning system (GPS) receiver and photographed. Further inundation distances and areas of inundation were documented. In selected areas, such as Mahfarhan and Shazhor a detailed grid of multiple transects and shoreline surveys documented local topography.

The north coast showed a surprisingly uniform tsunami runup centering around 2 m and inundation distances shorter than 70 m. Nevertheless the only fatality was reported in Qalansiyah on the northwestern coast. In the second largest town of Qalansiyah a 7-year-old was washed away and perished while trying to catch a fish from the exposed seafloor during a drawdown. This fatality illustrates the importance of raising the tsunami awareness through education. The barely inhabited south coast was seriously impacted with runup heights roughly doubling those on the north coast. The settlement of Shazhor on the steep southeastern coast exhibited the highest runup of 6.1 m and reported 2 destroyed rock houses. In Mahfarhan some 20 km further to the west a tsunami runup of 4.1 m and the largest inundation limit of 224 m were recorded along a low-lying coastal plain with boats rafted up to 200 m inland.

Table 1 gives the full database gathered during the survey excluding additional transect points. Sixteen measurements were made; principally run-up values obtained from debris, watermarks, and eyewitness reports. The map shown in Fig. 5 summarizes the database. In Darham on the north coast no observations were reported by inhabitants. Similarly at the jetty in Hawlaf, located 7 km NE of Hadiboh, none of the mariners present during the survey was at the jetty during the tsunami. Accounts from the island Abd Al-Kuri—at half-way point between Socotra and Somalia—were reported by mariners but could not be determined during this survey as Abd Al-Kuri was off limits.

Thus, the tsunami runup was comparable to those reported to the north in Oman (Okal et al. 2006b) and to the south on Madagascar (Okal et al. 2006a), as well as Réunion and Rodrigues Islands (Okal et al. 2006c), where also only limited structural damage and only a few casualties were reported. The only exception was Shazhor were the 6.1 m tsunami runup height placed it geographically correct between Oman and Somalia. The Puntland coast in northern Somalia was by far the area hardest hit to the west of the Indian Subcontinent by the 26 December 2004 tsunami (Fritz and Borrero 2006).

3 Field observations

3.1 Shazhor

The fishing settlement of Shazhor is located 20 km southwest of Rhiy Di-Irisal, the east cape of Socotra. Shazhor is situated on a landslide deposit cone at the foot of steep cliffs with the beach facing to the east. Socotra's south coast is impacted by extreme hurricane force winds and storm waves during the southwestern monsoon in the summer months. Therefore, most settlements are located either inland or along bays that are facing to the east, such as Shazhor, Mahfarhan, and Bedhoola. The southwestern monsoon forces inhabitants to vacate the settlements along the south coast and move inland or to the north shore for a couple of months. The eyewitnesses in Shazhor reported 2 destroyed rock houses and 10 lost fishing boats including outboard engines and fishing nets. The highest runup of 6.1 m was determined by eyewitnesses and sand deposits in the vegetation along a 5% sloping transect.

Table 1 Dataset recorded on Socotra Island by the UNESCO-survey-team in October, 2006

Number	Site	Latitude	Longitude	Vertical Survey		Inundation	Date and Time Surveyed		Notes
		°N	°E	[m]	Nature	[m]		(UTC)	
1	Arher Qariyah	12.64378	54.23122	1.74	R	12.0	13-Oct-2006	12:47	Eyewitness
2	Hamhariten	12.60813	54.31507	1.69	R	30.1	13-Oct-2006	13:23	Eyewitness
3a	Bedhoola	12.32906	54.00783	3.87	R	8.2	14-Oct-2006	5:51	Eyewitness
3b1	Bedhoola	12.32917	54.00726	3.37	R	10.4	14-Oct-2006	5:53	Eyewitness
3b2	Bedhoola	12.32952	54.00735	1.97	I	50.5	14-Oct-2006	5:53	Eyewitness
3c	Bedhoola	12.33822	54.02038	3.75	R	37.0	14-Oct-2006	6:13	Boat
4	Abadhar	12.35276	54.06333	2.81	R	18.8	14-Oct-2006	6:53	Eyewitness
5a1	Mahfarhan	12.40991	54.22666	3.97	B	203.7	14-Oct-2006	8:41	Boat
5a2	Mahfarhan	12.40983	54.22685	4.17	R	224.0	14-Oct-2006	8:35	Debris and eyewitness
5b1	Mahfarhan	12.40872	54.22781	3.14	B	105.6	14-Oct-2006	8:55	Boat
5b2	Mahfarhan	12.40834	54.22682	3.44	R	223.8	14-Oct-2006	8:55	Debris and eyewitness
6	Qalansiyah	12.68991	53.48402	2.42	R	15.9	15-Oct-2006	8:15	Eyewitness
7	Shoaab	12.55080	53.38595	2.64	R	18.0	15-Oct-2006	9:47	Eyewitness
8a1	Ghebbat	12.61063	53.78388	2.44	R	27.6	15-Oct-2006	12:21	Eyewitness
8a2	Ghebbat	12.61031	53.78379	0.84	I	64.5	15-Oct-2006	12:21	Eyewitness
9	Daiham	12.60909	53.85832	1.93	R	14.3	15-Oct-2006	12:43	Eyewitness
10	Ras Arsal	12.55230	12.55257	2.00	R	26.5	16-Oct-2006	7:20	Eyewitness
11a	Shazhor	12.46983	54.41071	6.11	R	132.4	16-Oct-2006	8:42	Debris and eyewitness
11b	Shazhor	12.47117	54.41113	5.70	R	27.2	16-Oct-2006	8:52	2 houses destroyed
12	Dahrham	12.60539	54.33304				16-Oct-2006	11:55	No observation
13	Matyaf	12.44905	54.27829				17-Oct-2006	9:29	Not surveyed
14	Hadiboh	12.65653	54.02516	2.15	R	11.8	17-Oct-2006	12:58	Eyewitness

Codes to nature of vertical measurements—R: Run-up, B: Rafted boat, I: Inundation limit not at transect high-point

3.2 Mahfarhan

The fishing town Mahfarhan is located 40 km southwest of Rhiy Di-Irisal (the east cape of Socotra) and 20 km west of Shazhor along a wadi delta plain with cliffs 2 km inland to the north. The location along an eastward facing beach shelters Mahfarhan from the extreme hurricane force winds and storm waves during the southwestern monsoon in the summer months. This typical eastward setting of towns along the southeast coast protects against the southwest monsoon but makes them particularly vulnerable to far field tsunamis originating from the Sumatra subduction zone. In Mahfarhan a tsunami runup of 4.1 m and the largest inundation limit of 224 m were recorded based on a debris line along the low-lying coastal plain with boats rafted up to 200 m inland (Fig. 6). The comparison of the two surveyed cross-shore transects at Mahfarhan against the maximum runup transect at Shazhor emphasizes the location specific runup topographies (Fig. 7a).

The shallow coastal delta and the large inundation distances give the eyewitness interviews in Mahfarhan a high credibility in terms of wave characteristics and wave sequence. The eyewitnesses reported: an initial rise late morning between 11:00 and 12:00 (UTC + 3); a subsequent drawback exposing fish on the seafloor; a total of 3 waves approaching from the east with the second wave being the highest; the waves were described as a gradual rise like an extraordinary high and fast tide; nobody was killed in Mahfarhan; 50 houses and 50 boats with engines were destroyed; survivors ran inland. Travel times are expected to be from 7.0 to 7.5 h based on the epicentral distance of 4,600 km and taking into account the variable depth of the Indian Ocean Basin (Titov et al. 2005). With a seismic origin time of 00:58:53 GMT, this predicts first arrivals between 11:00 and 11:30, in good agreement with the eyewitness reports. The tide level prediction

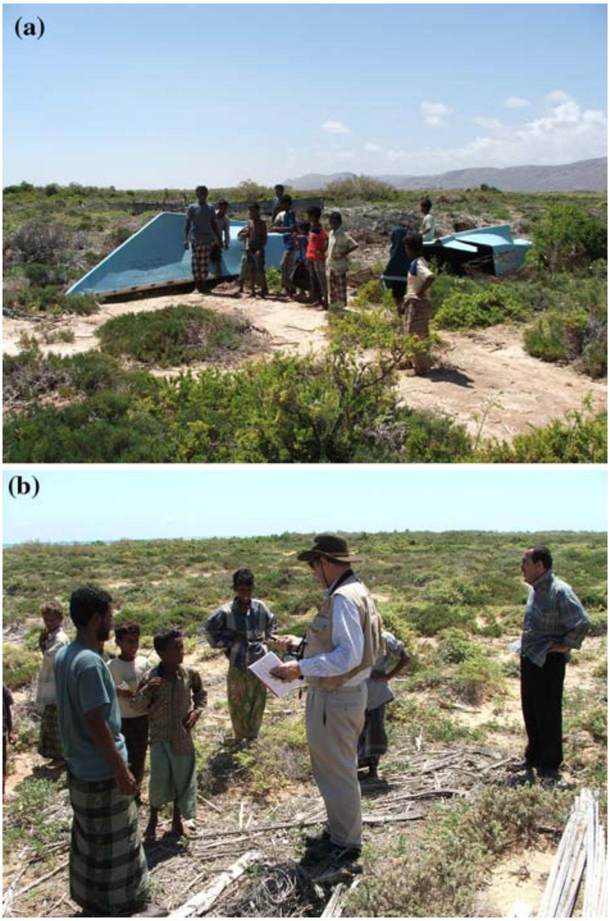

Fig. 6 *Mahfarhan*: (**a**) Fisherman and locals with a destroyed boat rafted 200 m inland (*note*: a second rafted boat and debris in the background); (**b**) GPS-surveying of the debris line marking the inundation limit in the low vegetation along the wadi delta plain

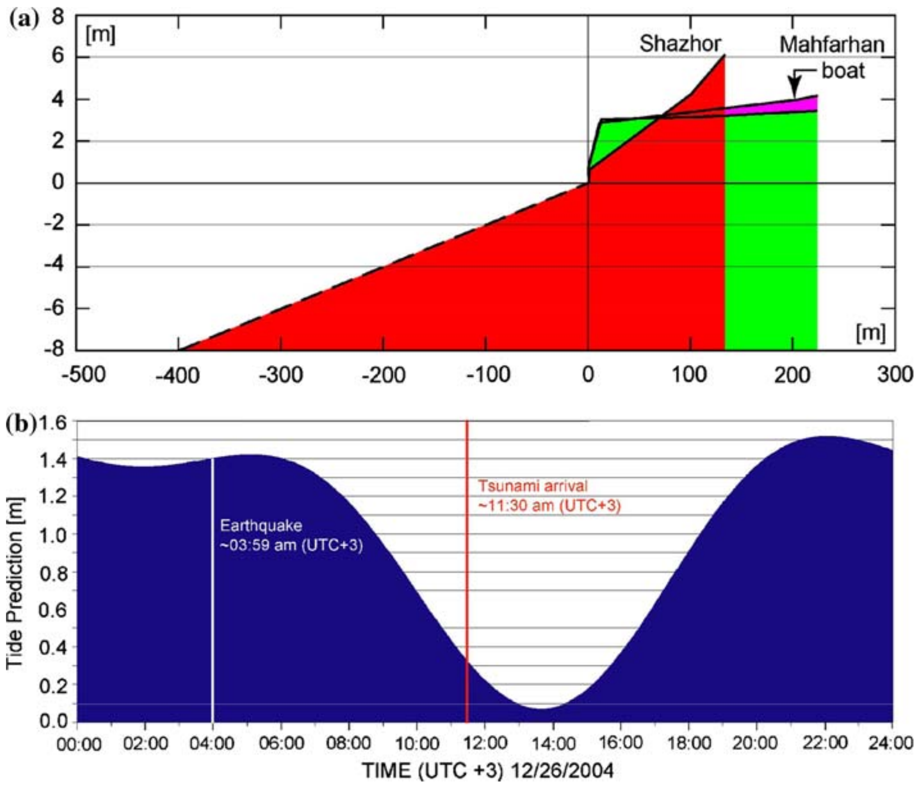

Fig. 7 (**a**) Selected cross-shore transects surveyed at Shazhor (maximum runup $R = 6.1$ m, inundation $I = 132$ m) and Mahfarhan ($R = 4.2$ m, $I = 224$ m), bathymetry estimated from Royal Navy nautical charts (UK); (**b**) Astronomic tide level prediction for 26 December 2004 at Shiq along Socotra's north shore (4 km northeast of Hadiboh) with time of earthquake off Sumatra and estimated tsunami arrival at Socotra in local time (UTC + 3)

for Shiq 4 km northeast of Hadiboh is shown in Fig. 7b. The tide levels in Yemen exhibit strong variations throughout the year switching from diurnal to semi-diurnal. Fortunately the main tsunami waves arrived close to low tide during a receding tide. A tsunami arrival during high tide could have increased the run-up heights by up to 2 m depending on location and season.

4 Conclusions

The deployment of the survey team to Socotra, almost 2 years after the 26 December 2004 catastrophic event led to the recovery of important data on the characteristics of the tsunami effects and inundation on Socotra in the tsunami far field. The south coast was severely impacted by the tsunami with a maximum runup height of 6.1 m and a maximum inundation distance of 224 m, whereas the impact along the north shore was centered around 2 m runup heights. The human loss was limited to one fatality in part because the south coast of Socotra is one of the least populated coastlines along the shores of the Indian Ocean and the densely populated north coast was widely spared. The tsunami runup was comparable to those reported to the north in Oman (Okal et al. 2006b) and to the south on Madagascar (Okal et al. 2006a), as well as Réunion, Mauritius and Rodrigues Islands (Okal et al. 2006c), where only some limited structural damage and a few casualties were reported. The only exception was Shazhor were the 6.1 m tsunami runup height placed it geographically correct between Oman and Somalia. The Puntland coast in northern Somalia was by far the area hardest hit to the west of the Indian Subcontinent by the December 26, 2004 tsunami (Fritz and Borrero 2006).

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