INTERNATIONAL TSUNAMI SURVEY TEAM REPORT ON FIELD SURVEY IN OMAN OF THE 2004 SUMATRA TSUNAMI

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Report on ITST Field Survey, Oman, August 2005

An International Tsunami Survey Team (ITST) visited Oman from 08 to 16 August 2005, in order to survey the effect of the great Sumatra tsunami of 26 December 2004 on the Southern coast of the country.

Members of the team included:

- **Emile A. Okal,** Professor, Northwestern University, Evanston, USA, *Team Leader*;
- **Hermann M. Fritz,** Assistant Professor, Georgia Institute of Technology, Savannah, USA;
- **Peter E. Raad,** Professor, Southern Methodist University, Dallas, USA;
- **Costas E. Synolakis,** Professor, University of Southern California, Los Angeles, USA; and Technical University of Crete, Chania, Greece;
- **Yousuf Al-Shijbi,** Staff Scientist, Earthquake Monitoring Center, Sultan Qaboos University, Al Khod;
- **Majid Al-Saifi,** Staff Scientist, Earthquake Monitoring Center, Sultan Qaboos University, Al Khod.

The team assembled on 09 August at the Earthquake Monitoring Center of Sultan Qaboos University in Al Khod, 45 km West of the capital city of Muscat, hosted by Professor Ali Al-Lazki. Given the large distances to be covered along the coast, it was decided to split the team into two groups working independently.

- The first ("Southern") group (E. Okal, C.E. Synolakis and Y. Al-Shijbi) flew to Salalah on 10 August, and explored by rental 4WD vehicle the coastal area from Dhalkut in the West, to Al Shouyamiya in the East, covering 300 km of coastline.
- The second ("Northern") group (H. Fritz, P. Raad and M. Al-Saifi) left Muscat by rental 4WD vehicle and covered the segment of coast from Al Najdah in the North (including Masirah Island) to Serbarat in the South, over a distance of roughly 420 km.

The two groups returned to Muscat in the late evening of 15 August and early morning of 16 August, having thus covered a total of 750 km along the coast of the Indian Ocean. Debriefing took place at the Earthquake Monitoring Center on 16 August.

Methodology

The team used traditional ITST procedures in order to map the penetration of tsunamis in the far field: identification and interviews of eyewitnesses (Figure 1), and recording of their testimonies, followed by topographic measurements based on their descriptions. On a few rare occasions, team members were able to observe and survey tsunami deposits, principally algae, but also a 10−meter fishing boat moved in land by the tsunami (Figure 2; Site 4). In this context, we define:

* *Inundation* as the measure of the maximum extent of horizontal penetration of the wave;

* *Flow depth* as the measure of the altitude, relative to unperturbed sea level, of the crest of the wave at a location close to the beach;

* *Run-up* as the measure of the altitude, relative to unperturbed sea level, of the point of maximum inland penetration of the wave, where inundation (see above) is in principle measured.

Flow depth and run-up measurements were made by optical means, using eye- and laser-levels and surveying rods (Figure 3); inundation measurements were taken by differential GPS and laser leveling. The exact dates and times of the individual surveys were recorded, in order to later effect tidal corrections, which allow to relate flow depth and run-up measurements to the exact sea level at the time of arrival of the tsunami wave.

Results

Table 1 details the database (or product) gathered during the survey. Forty-one measurements were retained, principally run-up values obtained from eyewitness reports. The map on Figure 4 summarizes the database. In order to streamline the presentation, it features for each locality the maximum vertical penetration (flow depth or run-up; in meters) among sites in its immediate vicinity. Red symbols denote points surveyed by the Northern group, and green ones by the Southern group.

The principal conclusions of the survey are as follows:

1. Maximum heights compiled in Table 1 and plotted on Figure 4 are typically on the order of 1 to 3 m (the maximum value of 5.4 m at Site 34b reflects the effect of the wave splashing on a cliff in the immediate vicinity of the shoreline). Thus, they are comparable to those reported further South on Réunion and Rodrigues Islands, but remain significantly smaller than surveyed along the coast of Somalia (7 to 8 m; *Fritz and Borrero* [pers. comm., 2005]), where systematic structural damage had been inflicted to ports and buildings. Similar destruction was not reported in Oman. Also, and to our knowledge, no casualties were lamented in Oman, as opposed to about 700 tsunami deaths documented in Somalia.

2. Surveyed values are generally homogeneous, but do feature some lateral variability along the coast. In practice, one can outline the following trends: the larger run-up 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 Ras al Madrakah, features run-up values consistently under 2 m; further North, from Al Shuaayr to Masirah Island, run-up values are slightly larger, reaching 2.6 meters at Ras al Duqm (Site 32), but feature more scatter.

We note that the tsunami was described to the team as not having been observed at the Southern Cape of Masirah Island; this locality is labeled "NIL" in Table 1. Our experience in other tsunami surveys (*e.g.*, Madagascar) indicates that run-up as small as 0.70 m was recognized, and thus we propose that the amplitude of the tsunami at Site 25 must not have exceeded 0.50 m.

3. The physical properties of the waves described to us by eyewitnesses, and their arrival times, feature fluctuations typical of ITST surveys. A consensus can be drawn among most witnesses, indicating 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 meters. 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 was followed by a series of positive waves (typically three or more), with the first or second wave generally described as the largest.

Temporal estimates (time of arrival and period of the waves) are traditionally among the least precise informations obtained from witnesses; however most descriptions indicate a phenomenon starting around noon to 1 p.m., local time (GMT +4), and lasting several hours, up to the whole day (with dusk falling around 17:30 at that time of the year).

Epicentral distances vary between 4400 km at Masirah Island and 4800 km at Dhalkut, but the tsunami must travel around the Indian Subcontinent and thus outside the great circle, with travel times predicted at 7 hours in the North and 7.5 hours in the South of the surveyed area, for arrival times of 12:00 (GMT+4) in the North and 12:30 in the South, in good agreement with the eyewitness reports.

The periods of the waves are generally estimated in the range of 15 to 30 minutes.

4. In the fortunate absence of casualties along the coast of Oman, the most spectacular effects from the tsunami were the development of turbulent eddies in the port of Salalah, described in detail below. Damage to small boats was minimal, especially as compared to the case of the ports on Réunion Island.

5. *The eddies in the port of Salalah*

The port of Salalah is one of the major container terminal facilities in the Middle East, presently offering four berths accommodating the largest container ships (Figure 5*b*). 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−meter freighter *Maersk Mandraki* (Figure 5*a*) broke her moorings at Berth Number 4, and started wandering for a period of several hours, both inside the harbor, where she was caught in a system of eddies from which all efforts to free her using tug boats were in vain, and outside the port itself where she reached the far side of the breakwater, before eventually returning towards the port and beaching on a sand bar to the East of the main wharf (Figure 5*c*).

Similarly, her sister ship the 292−m long *Maersk Virginia* was rocked by the tsunami as she was attempting to enter the harbor, to the extent that the Captain waited about seven hours to proceed; yet the vessel was pulled towards the breakwater, which she contacted resulting in minor damage to a fuel tank. Miraculously, the wandering "ghost" vessel *Mandraki* did not collide with other ships or with harbor structures, and the damage to the *Virginia* was minor and contained to the ship herself, without impact on other ships or infrastructure.

We note that this incident is strikingly similar (albeit on a much larger scale) to that of the freighter *Soavina III* in the harbor of Toamasina, Madagascar. It is noteworthy, and obviously of great concern, that in both cases, the turbulent activity inside the harbor (and, in the case of Salalah outside the breakwater) lasted well into the night, *i.e.*, many hours after the end of the low-frequency wave activity associated with the most visible (vertical) effects of the tsunami. There are, however, significant differences between the two situations, as the *Mandraki* broke her moorings at 1:42 p.m. local time (09:42 GMT), *i.e.*, during the period of maximum activity of low-frequency waves, whereas in Toamasina, *Soavina III* did not break hers until four to five hours after the time of maximum vertical oscillation of the sea level. This discrepancy is certainly due to a difference of response between the two harbors, and probably reflects the more complex geometry and much smaller size of the harbor in Toamasina, Madagascar, as compared to the port of Salalah.

→ These and other topics were discussed in detail during a lecture on *"Coastal impacts of tsunamis"*, which Professor Synolakis gave at the headquarters of the Port of Salalah, on Saturday, 13 August. During the extended question-and-answer session, Professors Synolakis and Okal fielded many questions on geological and engineering aspects of tsunami hazards, from an audience of approximately twenty executives and officials from the Port of Salalah and various law enforcement and emergency services of the city and its region. A more informal presentation was given later in the day to the Commander of Civil

Defense in Salalah, in the presence of the Director of the local branch of the National Meteorological Service.

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 (see Figure 4), to the extent that residents had called the mainland requesting evacuation from the island. If confirmed, this would suggest run-up amplitudes in excess of those measured on the mainland, and in particular on the relevant sections of the coastline, where run-up does not exceed 1.5 m from Hasik to Serbarat (Figure 4). 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 wavelengths on a continental shelf.

TABLE 1: Dataset surveyed by the ITST in Oman, August 2005

Number	Site	Latitude (deg. N)	Longitude (deg. E)	Vertical Survey (m)	Vertical Survey Nature	Inundation (m)	Date and Time Surveyed (GMT)		Notes
					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	Run-up along road at Al Hafa Beach
7	Taqah	17.033617	54.403883	2.44	R	73	11-Aug-2005	12:30	Run-up to garbage box on beach
8	Mirbat	16.986133	54.687217	1.73	R	22	11-Aug-2005	13:50	Run-up 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	Run-up to pole on beach at head of bay
11	Hadbeen	17.205833	55.233183	1.55	R	12	12-Aug-2005	08:20	Run-up 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	Run-up 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	Run-up 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	Run-up to large rock at head of port
17	Rakhyut	16.745883	53.425517	1.81	R	27	13-Aug-2005	13:30	Run-up to beach at East end of town
18	Rakhyut	16.744900	53.417333	2.62	R	59	13-Aug-2005	13:45	Run-up 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	Run-up to road at Al Hafa Beach
21	Al Shouyamiya	17.881600	55.607417	1.48	R	6	15-Aug-2005	09:00	Run-up on beach in front of village

TABLE 1: Dataset surveyed by the ITST in Oman, August 2005 (ctd.)

Number	Site	Latitude	Longitude	Vertical Survey		Inundation	Date and Time Surveyed		Notes
		(deg. N)	(deg. E)	(m)	Nature	(m)		(GMT)	
					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	NIL					Eyewitness -- No run-up (?)
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	Eyewitnes
28a	Ras al Jazirah	20.57542	58.93170	1.80	R	59	11-Aug-2005	12:48	Eyewitnes; First wave
28b	Ras al Jazirah	20.57542	58.93170	1.50	R	24	11-Aug-2005	12:48	Eyewitnes; Second wave
29	An Najdah	20.84741	58.73710	0.40	R	4	12-Aug-2005	09:27	Eyewitnes; Boat
30	Mahwat Island	20.57478	58.17527	0.70	R	13	12-Aug-2005	12:19	Eyewitnes; 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	445	14-Aug-2005	13:25	Eyewitness; debris; algae
41	Serbarat	17.93347	56.27334	1.10	R	25	15-Aug-2005	08:08	Eyewitness

Codes to nature of vertical mesurements: **F**: Flow depth; **R**: Run-up; **S**: Splash.

Figure 1.: Professor Raad (right) interviewing witnesses of the tsunami at Haqal (East coast of Masirah Island; Site 24).

Figure 2.: Surveying techniques demonstrated at Ras al Duqm (Site 31). Professor Fritz uses laser ranger at coast line *(left)*, while 43 m away, Professor Raad and tsunami witness Mr. Soubayh bin Rajid bin Sa'id Al-Joubaybi identify site of maximum penetration with surveying rod *(right)*, defining run-up of 2.6 meters.

Figure 3.: Tsunami survey at Site 4, between Salalah and Raysut. This 10−m boat was deposited by the tsunami on the beach berm, 35 m from the shore (visible at right). The corresponding flow depth at the location of the boat is 3.10 m. Run-up was estimated at 3.25 m, based on shell deposits found at the point of maximum penetration (Site 5), 36 m farther inland (to the left of the picture).

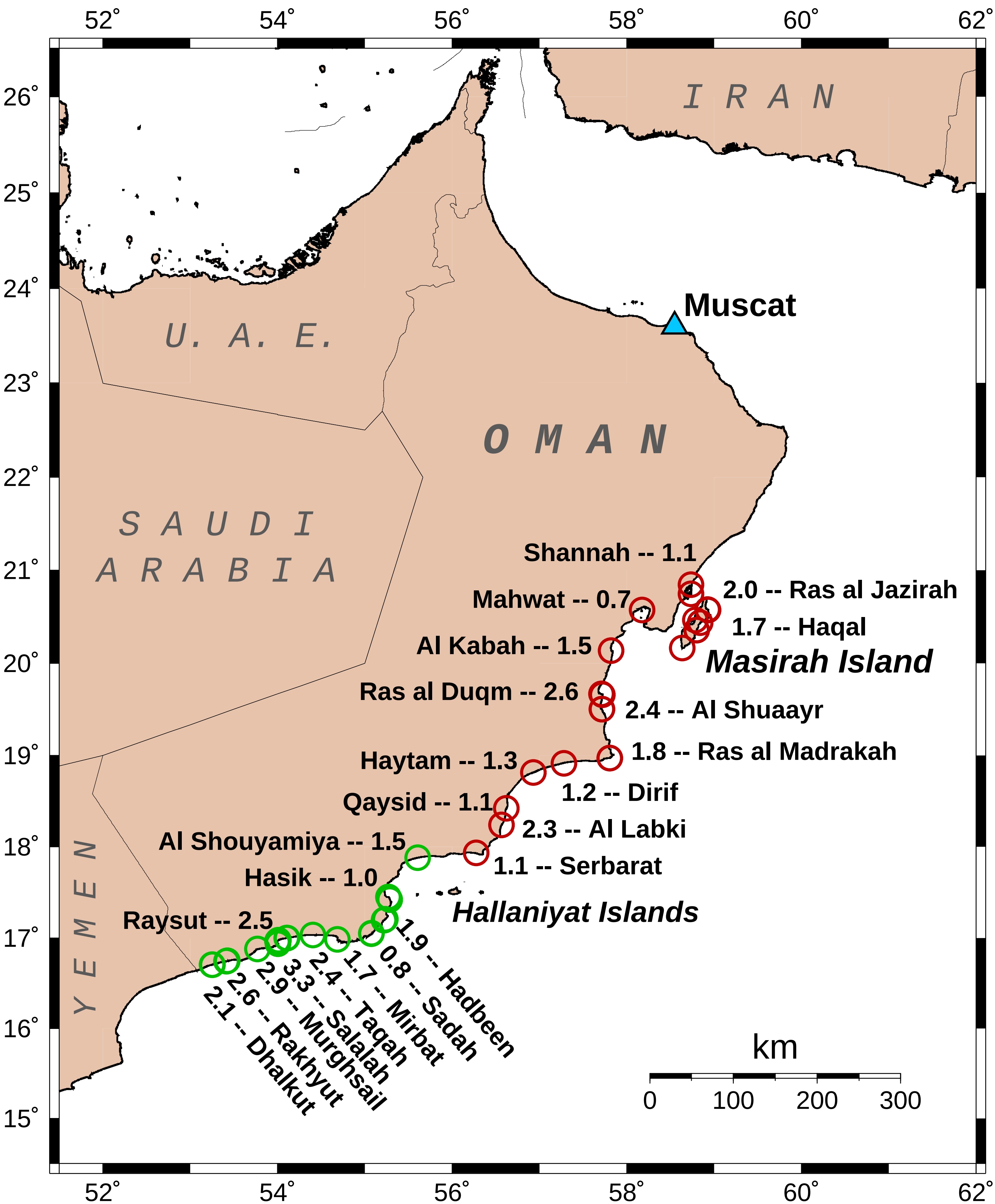

Figure 4.: Map of Oman showing maximum run-up values (in meters) surveyed at the various sites visited by the Northern group (in red) and the Southern group (in green).

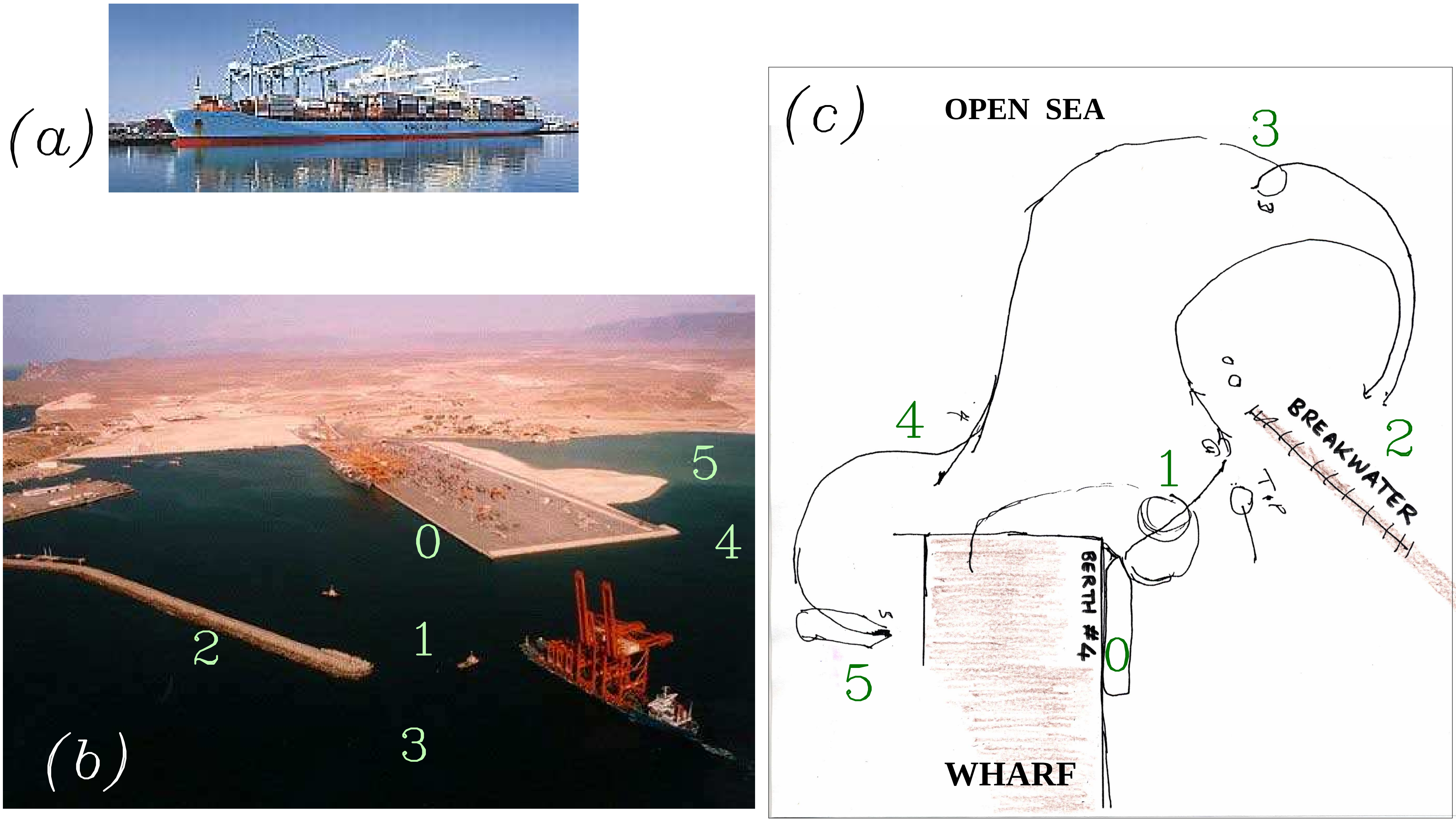

Figure 5.: *(a)* Photograph of a Class−M Maersk container ship analogous to the *Mandraki*. *(b):* Aerial photograph of the port of Salalah looking inland (North); on this file photograph (www.salalahport.com), overprinted numbers are keyed to the description of the path of *Mandraki* after she broke her moorings. *(c):* Drawing, looking South (out to sea) handwritten by port worker during testimony to ITST (14 August 2005). Overprinted numerals show **(0)** initial position of *Mandraki* while moored at Berth 4; **(1)** position of ship caught in strong eddy following rupture of moorings; **(2)** position of ship outside harbor while approaching far side of breakwater; **(3)** subsequent loop covered by *Mandraki* outside harbor; **(4)** return to harbor; and **(5)** eventual grounding on sand bar East of harbor.