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Field Survey of the 1945 Makran and 2004 Indian Ocean Tsunamis in Baluchistan, Iran

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Abstract—We report the result of a 2010 survey of the effects on the Iranian coastline of the tsunami which followed the earthquake of 27 November 1945 ($M_0 = 2.8 \times 10^{28}$ dyn cm; $M_w = 8.2$), the only large event recorded along the Makran subduction zone since the onset of instrumental seismology. Based on the interview of elderly survivors of the event, we obtained a database of nine values of run-up or splash amplitudes on a segment of shore extending 280 km from Souraf in the West to Pasabandar near the Pakistani border, and ranging in vertical amplitude from 2.3 to 13.7 m. Witness reports are consistent with a significant delay (estimated at $\sim$2.5 h) of the tsunami waves, suggesting that they were generated by an ancillary phenomenon, such as a landslide triggered by the earthquake. None of our witnesses bore ancestral memory of comparable events in the past, suggesting that reported predecessors to the 1945 earthquake may have been smaller in size. The survey also allowed the compilation of previously unreported data concerning the effects of the 2004 Sumatra–Andaman tsunami.

1. Introduction and Background

This paper presents the results of a field survey of the 1945 Makran tsunami conducted in October 2010 in the provinces of Sistan-e-Baluchistan and Hormozgan, Southeastern Iran. This survey was organized under the auspices of UNESCAP and the Intergovernmental Commission of UNESCO in the aftermath of a workshop held in Tehran in May 2010, with the principal goal of establishing of a homogeneous scientific database of field measurements of the 1945 tsunami, based on the interview of elderly survivors.

1.1. The 1945 Makran Earthquake

The Makran earthquake of 27 November 1945 (local date 28 November) stands alone as the only interplate thrust subduction event having inflicted a devastating tsunami in the Indian Ocean West of the Indian subcontinent since the dawn of instrumental seismology. It was assigned a "Pasadena" magnitude of 8.3 by GUTENBERG and RICHTER (1954), and studied in detail by BYRNE *et al.* (1992).

As shown on Fig. 1, the convergence between the stable blocks of the Arabian and Eurasian plates takes place at a local rate of $\sim$2.7 cm/year in the azimuth N10°E (SELLA *et al.* 2002), with a sizable fraction taken up by deformation in the mountains of Southeastern Iran (e.g., VERNANT *et al.* 2004). In this context, the 1945 earthquake is one of the rare events expressing active subduction at the plate interface.

We relocated the 1945 earthquake using arrival times listed in the International Seismological Summary (ISS) and the technique of WYSESSION *et al.* (1991), which estimates a confidence ellipse based on a Monte Carlo procedure consisting of injecting Gaussian noise (with standard deviation $\sigma_G = 4$ s) into the data. The resulting epicenter (24.88°N; 63.53°E) is shown in Fig. 1, and compared with other available locations. The origin time 21:56:51.9 GMT corresponds to a local time of 01:27 in Iran and 03:27 Indian Standard Time, both on the 28 November. Our solution is essentially identical to the epicenters obtained by both the ISS and ENGDAHL and VILLASEÑOR (2002) as part of their Centennial catalog, and also in excellent agreement with QUITTMEYER and JACOB's (1979). Only GUTENBERG

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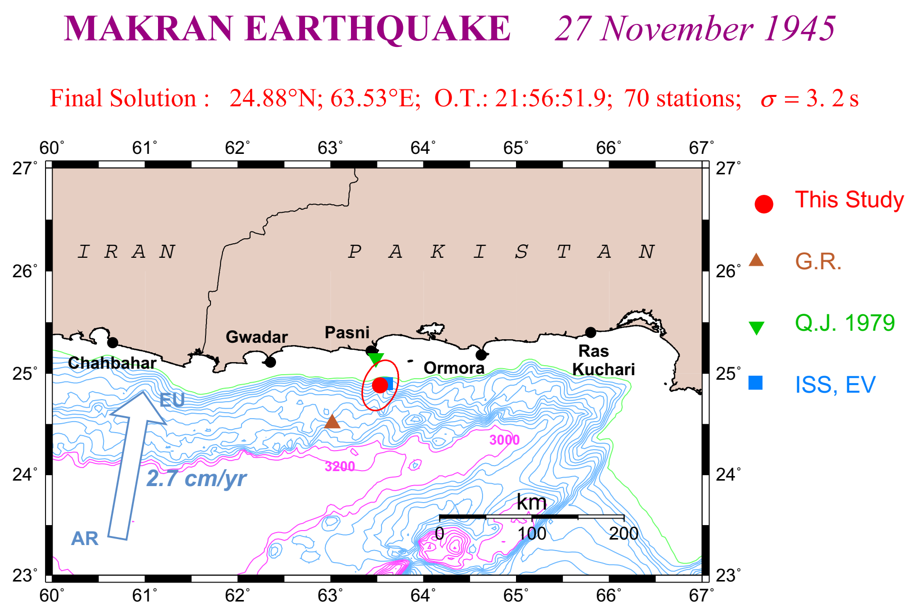

Figure 1
Epicentral estimates for the 1945 Makran earthquake. The *red dot* shows the epicenter relocated in this study, with associated Monte Carlo ellipse, the *blue square* the ISS location, which on this scale, is undistinguishable from Engdahl and Villaseñor's (2002) (EV), the *green inverted triangle* Quittmeyer and Jacob's (1979) source. Only Gutenberg and Richter's (1954) location (*brown triangle*) is significantly displaced. The *large arrow* at *left* shows the convergence vector of the Arabian and Eurasian plates (Sella *et al.* 2002). Isobaths are at 200-m interval with depths greater than 3000 m (labeled) in *magenta*

and Richter's (1954) original solution, 68 km from our preferred epicenter, lies outside our confidence ellipse. Note that depth could not be resolved from the available dataset of arrival times.

The focal mechanism of the earthquake was studied by Byrne *et al.* (1992), who advocated a low-angle thrust mechanism ($\phi = 246°$; $\delta = 7°$; $\lambda = 89°$), with a seismic moment of 1.8×10^{28} dyn cm. Note that the azimuth of their slip vector is 34° away from that of the relative plate motion, and also $\sim$25° from that of the normal to the plate boundary as expressed by the coastline. As part of the present study, we inverted a moment tensor from spectral amplitudes of mantle surface waves at five stations, using the preliminary determination of focal mechanism (PDFM) method (Reymond and Okal 2000), which is particularly well suited to historical events (Okal and Reymond 2003). The resulting mechanism, shown in Fig. 2, confirms a shallow-angle thrusting geometry ($\phi = 261°$; $\delta = 9°$; $\lambda = 89°$), rotated 15° from Byrne *et al.*'s (1992) in the formalism of Kagan (1991), and in better agreement with local plate tectonics geometry. Our seismic moment, $M_0 = 2.8 \times 10^{28}$ dyn cm ($M_w = 8.2$), is significantly larger than proposed by Byrne *et al.* (1992), but identical to the value obtained by Heidarzadeh and Satake (2015) from the inversion of maregraph and geodetic data.

In more recent times, the catalog of GlobalCMT solutions in the region is extremely scarce, featuring only two small thrust fault events in the vicinity of the 1945 epicenter, on 07 December 1991 and 30 January 1992, rotated 8° and 5°, respectively, from our PDFM mechanism. Quittmeyer and Jacob (1979) and Byrne *et al.* (1992) also compiled WWSSN-era seismicity along the Eastern Makran, featuring a wide variety of mechanisms, including several thrust events of a geometry comparable to that of the 1945 earthquake. Farther West, we note one significant GlobalCMT thrust faulting solution on the Iranian coast, albeit with much steeper dip ($\phi = 305°$;

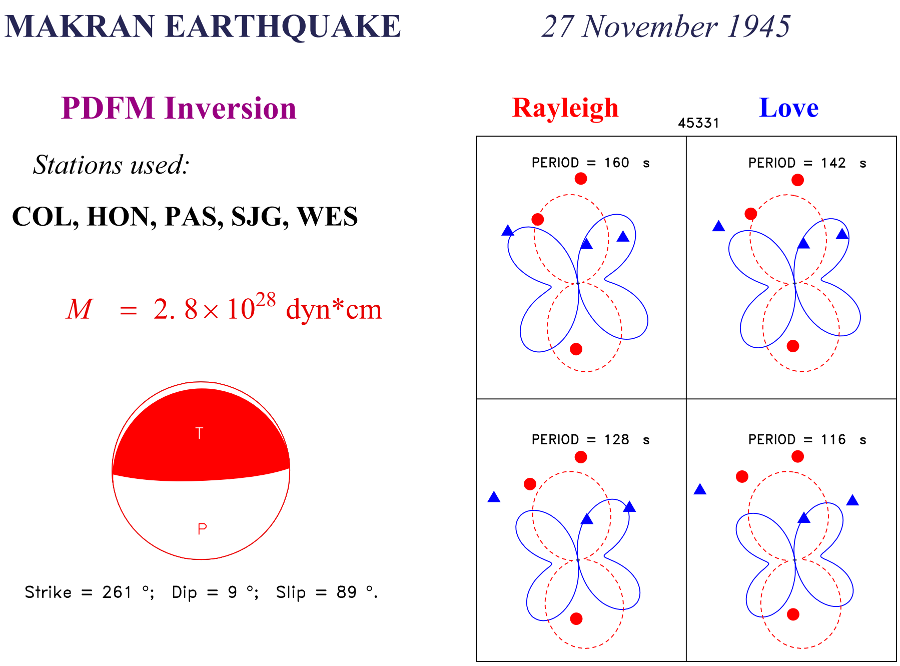

Figure 2
Results of PDFM inversion of mantle waves for the 1945 Makran event: *Left:* inverted focal mechanism and scalar moment. *Right:* inverted spectral amplitudes at representative periods. The theoretical azimuthal radiation patterns are shown as the *blue solid* (Love) and *red dashed* (Rayleigh) *lines*, the observed ones as individual symbols (*red circles*: Rayleigh; *blue triangles*: Love). See Reymond and Okal (2000) for methodological details

$\delta = 54°$; $\lambda = 80°$) at 25.9°N, 59.0°E (07 December 1989), and a small one (22 July 2009) inside the Gulf of Oman at 26.8°N, 55.8°E.

1.2. The 1945 Tsunami

The 1945 Makran earthquake generated a tsunami which can be described as devastating along the coast of the Eastern Makran (present-day Pakistan), despite the scarcity of documentation from what was then a very remote area, in the immediate aftermath of the second World War. Run-up was reported to have reached 12–15 m at Pasni (Pendse 1946), with "serious loss of life and property" at both Pasni and Ormara. Waves were reported at Karachi (1.5 m) and Bombay (2 m with fatalities). The total number of casualties due to the tsunami is difficult to assess given the lack of precise reports and the impossibility to separate victims of the earthquake and of the waves. It could be as high as several thousand, but is given conservatively as 300 by Ambraseys and Melville (1982).

A most remarkable aspect of the 1945 tsunami is that its main waves were significantly delayed (on the average 2.5 h) with respect to the earthquake. This is described in some detail along the Eastern Makran coast, at Karachi and Bombay in Pendse's (1946) report, and at Mahé, Seychelles in a short note by Beer and Stagg (1946); as detailed below, it is also clear from the testimony of several of our witnesses from the Iranian coast. To explain this delay in the maximum wave, several models were proposed, notably the development of an edge wave along the continental shelf of the Indian subcontinent (Neetu *et al.* 2011). More generally, Heidarzadeh and Satake (2015) were able to model the tidal gauge records at Karachi and Bombay (including their arrival times) using heterogeneous coseismic slip on a fault plane consistent with Byrne *et al.*'s (1992) focal geometry, but their model can be reconciled neither with the extreme amplitudes reported at Pasni, nor with the delays observed in Iran and the Seychelles. Beer and Stagg (1946) noted that interpreting the earthquake as the source of the tsunami would result in an average ocean depth between its source and the Seychelles of only 1.3 km (assuming an undispersed celerity $c = \sqrt{gh}$), and went on to suggest that the first wave recorded at Mahé, arriving approximately $\sim$170 min late, had to be the eighth one in the wavetrain, without providing a rationale for this singular sequencing of tsunami energy among subsequent waves. A much more probable model would invoke generation by a landslide, itself triggered by the earthquake with a delay of $\sim$2.8 h, in a scenario generally similar to the case of the 1998 Papua New Guinea or 1990 Rudbar events (Synolakis *et al.* 2002; Salaree and Okal 2015). A critical observation in this respect is the fact that the Karachi–Muscat section of the Bombay–London telegraphic cable was severed on that day, although the precise timing is not available (Times of India 1945a; Ambraseys and Melville 1982). A long history of such cable breaks and of their subsequent repairs after the earthquakes in Grand Banks (1929), Luzon (1934), Suva (1953), El Asnam (*ex*-Orléansville, 1954; 1980), Boumerdes (2003), and even possibly Rukwa (1910), has shown that cables were always ruptured during a major underwater mass movement, rather than by the earthquake shaking, and thus cable breaks have become a proxy for the generation of a tsunami by underwater landslides (Repetti 1934; Heezen and Ewing 1952, 1955; Houtz 1962; El-Robrini *et al.* 1985; Bouhadad *et al.* 2004). In addition, the Times of India (1945b) reports the presence of subaerial landslides on the coast, suggesting their probable triggering underwater as well. Note finally that Heidarzadeh and Satake (2014) have suggested an underwater landslide in essentially the same area as the source of the tsunami generated by the 2013 Pakistani earthquake whose fault zone was located more than 200 km inland.

1.3. *Other Historical Events*

There exist a number of historical reports of severe earthquakes in the immediate vicinity of the 1945 event. An earthquake is mentioned at Ras Kuchari, Pakistan ($\sim$65.7°E) around 1765, which allegedly caused an entire hill to slump into the sea, as compiled by Ambraseys and Melville (1982). Another shock is described at Gwadar (present-day Pakistan) in 1851 with a possible aftershock in 1864 (Oldham 1893; Wilson 1930; Quittmeyer and Jacob 1979), but these earthquakes are not compiled as a separate entry in Ambraseys and Melville's (1982) catalog. These authors simply mention the 1864 event in a footnote to their description of the 1945 earthquake; remarkably, they cite a report by Walton (1865) of a break in the telegraphic cable between Karachi and Telegraph Island near the Strait of Hormoz, which had been laid a few months earlier, again suggesting the triggering of an underwater mass movement; this would suggest that the 1864 event may have been the greater of the two. However, the cable rupture is not mentioned in the original reference (Walton 1865); it may have been included in a document originally appended to Walton's correspondence, but presently unavailable. In addition, a large earthquake was reported widely felt in Western Makran in 1483 and "about the same time" in Oman (Ambraseys and Melville 1982; Byrne *et al.* 1992), which would suggest a source in the Western part of the Gulf of Oman.

Finally, it is worth recalling that, under the command of Nearchus of Crete in 325–324 B.C., the fleet of Alexander the Great was impacted by a phenomenon often interpreted as a tsunami similar to the 1945 event. However, a careful compilation of the chronicle by Arrian (1983, pp. 367–415) indicates that at that point, Nearchus had sailed an estimated 12,500 stadia from the Indus River delta. This can be converted to a distance of 1950 km, using Eratosthenes' estimate of 40,800 stadia for the Earth' radius. The distance between the Indus delta and present-day Chabahar would be only 830 km hugging the coast, while the Strait of Hormoz is around 1450 km from the Indus. Cabotage along the coast could increase distances by 35 %, but probably not by a factor of 3. Furthermore, Arrian (1983; p. 417) indicates that only 600 stadia ($\sim$100 km) after the wave impact, Nearchus left the coast of "Carmania" for that of "Persia", which if Carmania is taken to be equivalent to present-day Kerman province in Iran, would correspond grossly to the boundary between the present-day Sea of Oman and Persian Gulf. It is, therefore, probable that the wave impact took place in the vicinity of the Strait

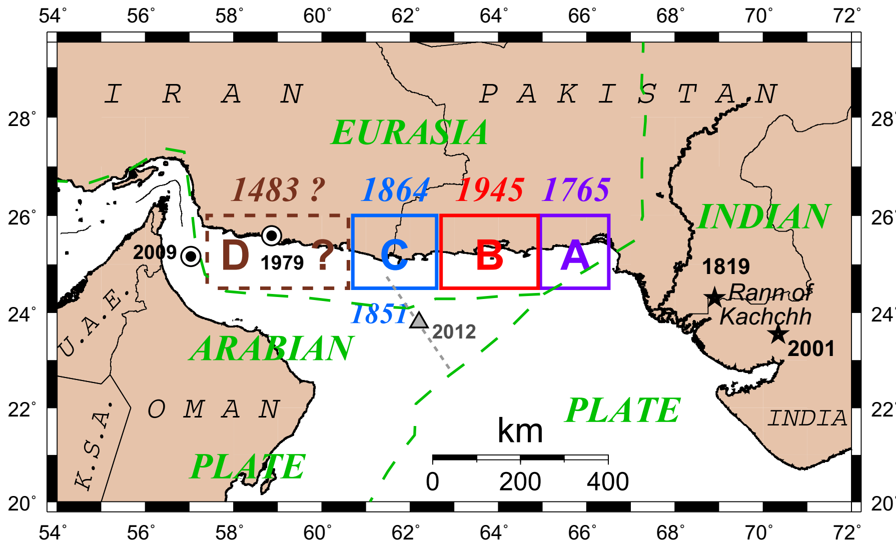

Figure 3

Schematic map of the possible layout of historical earthquakes along the Makran subduction zone. Inspired by Ando (1975) and adapted from Byrne *et al.* (1992) and Okal and Synolakis (2008). *Green dashed lines* are plate boundaries (Bird 2003). The historical events in 1765, 1945 and 1864 may correspond to the rupturing of individual fragments (*A*, *B*, *C*) along the Arabian–Eurasian boundary. The hypothetical 1483 event may involve a fourth (*D*) block, shown as the *dashed box* to the West. The intriguing GlobalCMT solutions of 1979 and 2009 are shown as bull's eye symbols. The Sonne fault is sketched as the *gray dotted line*, with the 2012 strike-slip event shown as a *gray triangle*

of Hormoz, and thus would have been more likely similar to the putative earthquake in 1483, than to the recent one farther East in 1945.

Figure 3, adapted from Fig. 6 of Byrne *et al.* (1992), summarizes the distribution of these large earthquakes along the Makran coast. It is tempting to interpret them in the context of Ando's (1975) now classical study of historical earthquakes along the Nankai trough, where he documented a fragmentation of the subduction zone into several segments (A, B, C,…), with subsequent earthquakes rupturing one or several segments in an apparently random way. This model was later confirmed by tsunami modeling and paleotsunami studies in the Kuriles, Cascadia, Peru and Southern Chile (Nanayama *et al.* 2003; Cisternas *et al.* 2005; Kelsey *et al.* 2005; Okal *et al.* 2006a). Under this model, Okal and Synolakis (2008) have envisioned as worst-case scenarios for tsunami hazard in the Makran, a simultaneous rupture of blocks A, B, C on Fig. 3 (their scenario 5), corresponding to an earthquake of moment $M_0 = 2.7 \times 10^{29}$ dyn cm ($M_w = 8.9$).

An unresolved problem in regional tectonics is whether convergence in Westernmost Makran is (1) entirely accommodated by onland orogeny; or (2) possibly by creep at the plate contact; or (3) partially taken up during infrequent large subduction earthquakes. In terms of tsunami potential, only (3) carries significant hazard. Under models (1) and (2), the difference in the modes of convergence between Western and Eastern Makran (in simple terms at the Iranian and Pakistani coasts) could be attributed to a fragmentation of the Arabian plate into two blocks separated by the left-lateral strike-slip Sonne fault (Kukowski *et al.* 2000), where one compatible strike-slip GlobalCMT solution has recently been documented (01 June 2012; triangle on Fig. 3). These models would also be supported by the low level of background seismicity in Western Makran, and by an inconclusive search for ancient earthquakes using paleoseismicity (Rajendran *et al.* 2013). Musson (2009) also used historical documents to argue against a common source to the earthquake reports in Hormoz and Oman at the end of the XVth century.

On the other hand, several regional characteristics could favor seismic subduction through rare, but great earthquakes, under model (3), including significant GPS residual motion between Oman and coastal Iran, the presence of a deep oceanic basin and active sediment deformation in the Gulf of Oman, and of terraces on the Iranian coast (Masson *et al.* 2007; Mokhtari *et al.* 2008). Such patterns, as well as the absence of background seismicity during a short OBS deployment (Niazi *et al.* 1980), are indeed reminiscent of their counterparts off Cascadia (White and Klitgord 1976), an area then regarded as featuring aseismic subduction (2), but now known to entertain occasional megathrust earthquakes (3) (Satake *et al.* 1996; Kelsey *et al.* 2005). This legitimizes, at least in principle, the concept of rare megathrust events in the Western Makran (although not necessarily in 1483), leading to a tentative "D" block at the Western end of the region (Fig. 3), and hence to the possibility of an extreme worst-case scenario for tsunami risk in the Makran, involving all four blocks (Model 6 in Okal and Synolakis 2008; $M_0 = 4.7 \times 10^{29}$ dyn cm; $M_w = 9.0$).

It is in this general context for tsunami hazard in the Makran region that we conducted a field survey of the 1945 tsunami in Iran in October 2010. A similar program across the border in Pakistan has resulted in the identification and interview of scores of witnesses, and the quantification of the relevant dataset is presently under way (Kakar *et al.* 2015; Anonymous 2015).

2. *Survey Methodology*

The methodology of the present project follows the now classical techniques initially developed by Okal *et al.* (2002) for the survey of the 1946 Aleutian tsunami in the Pacific, and since then extended to several other events, e.g., Amorgos (Greece), 1956 (Okal *et al.* 2009a). They consist of identifying elderly witnesses of the tsunami, conducting their interview (if possible recorded), and traveling with the witness to the location inundated during the tsunami, to document and survey the extent of penetration of the wave. We recall that *Inundation* is defined as the horizontal extent of penetration of the tsunami on initially dry land; *Flow level*, the sum $(z + h)$ of the depth h of the water column flowing past a reference point at an altitude z ($z = 0$ at the original coast line); and *Run-up*, the altitude z, with respect to unperturbed sea level at the time of the tsunami, of the point of maximum penetration where inundation is measured (or flow level at the limit $h = 0$).

A particularly challenging aspect of the present survey was the very advanced age of any reliable witnesses, who would have had to be at least 10 years old in 1945, and thus 75 at the time of the interview in 2010. In this context, and while we tried very hard to recover information about our witnesses, the question of their exact age often remained unresolved. Several witnesses claiming to be in their early sixties had unquestionably vivid memories of the tsunami which should then have predated their birth. By contrast, younger family members had a general tendency to extrapolate the age of their elderly relatives, one adolescent even describing his grandfather as being 100 years old while offering him a sporty ride on his moped; in our opinion, this witness was probably in his seventies, as suggested by his status as a bachelor at the time of the 1945 tsunami. It is with such reservations that we offer estimates of the age of our witnesses. Figure 4 shows a sample of interviews of our witnesses.

Similarly, absolute times given by witnesses for the observation of natural phenomena are generally approximate. Whenever possible, we attempted to ascertain them using reference activities (e.g., morning prayer). We regard as generally more reliable relative timing differences between various aspects of the phenomenon, most notably between the feeling of earthquake tremors and the arrival of the waves.

3. *Tsunami Survey, 10–15 October 2010*

The team assembled in Tehran on 09 October 2010, and flew to the field on 10 October 2010. Authors EAO and MAH covered the Eastern part of the province, operating out of the INIO office at Chabahar, where they were met by JG. Over the next 5 days, this Eastern team visited the coastal areas between Bir Daf (Longitude 59.8°E) and Pasabandar (Longitude 61.4°E). Because of security constraints,

Figure 4
Examples of interviews of witnesses of the 1945 tsunami. **a** Chabahar, 11 October. *Left* to *right*: JG, EAO, MAH, INIO driver, Witness. **b** On the beach at Lipar, 12 October. *Left* to *right*: MAH, Witness Mr. Dadshahpour, EAO. **c** Beris, 13 October. *Clockwise* from *left*: JG, EAO, Witness Mr. Khaled Baluch, INIO driver (with back to camera). **d** Pasabandar, 13 October. *Left* to *right*: MAH, INIO driver, Witness Mr. Adam Baluch and grandsons, EAO

it was not possible to pursue the survey East of Pasabandar to the village of Gavater at the Pakistani border, but it is doubtful that any elderly witnesses could have been found in Gavater given that the area has seen development only recently, in the form of an extensive shrimp farm. In the meantime, traveling from Bandar Abbas, Author HMF covered the Western part of the Makran coast, from the Strait of Hormoz, including both Qeshm and Hormoz Islands, to Abkouhi, with an additional emphasis on damage inflicted by recent meteorological events such as Cyclone Gonu, the strongest tropical cyclone on record in the Arabian Sea (Fritz *et al.* 2010). This aspect of the survey, being unrelated to the 1945 tsunami, is not reported in the present work.

In addition to identifying and interviewing elderly witnesses of the 1945 tsunami, we also gathered information on the effects of the 2004 Sumatra–Andaman tsunami, which apparently had not been surveyed along the Iranian coast. All data are compiled in Tables 1 and 2.

Flow level and run-up values were measured using conventional techniques (leveling rod and hand-held eye level; Eastern team) and laser ranging (Western team). The precision of these measurements is estimated at ~ 5 cm. Inundation was derived from GPS measurements with a precision of 1 m.

- *Tiss*, Sunday, 10 October 2010

On Sunday afternoon, 10 October, we visited the jetty in the port area of Tiss, a suburb of Chabahar. We met a fisherman in his sixties, who related the story of his late father who had observed the water running up in the drainage channel of the village of Tiss, across the bay, up to the vicinity of the village mosque. This transect was surveyed on Monday, 11 October, with a run-up of 2.00 m and an inundation of 1289 m (Site Number 01).

An additional testimony, not directly relevant to the Iranian survey, was obtained from a 62-year-old man who had heard from a sailor who had been in Jiwani (in present-day Pakistan) during the 1945 tsunami, and witnessed the emergence of a new

Table 1

Dataset for 1945 Makran tsunami

Number	Latitude (°N)	Longitude (°E)	Vertical amplitude (z; m)		Nature[a]	Inundation (m)	Date and time surveyed		Notes
			Raw	Corrected				(UTC)	
01	25.35663	60.60562	2.00	2.26	R	1289	11-Oct-2010	5:50	Tiss
02	25.35383	60.40205	3.05	3.24	R	52	12-Oct-2010	7:25	Konarak
03	25.29643	60.62480	3.65	2.76	R	367	13-Oct-2010	12:08	Chabahar
04	25.26528	60.75295	7.15	7.14	S		13-Oct-2010	7:59	Ramin
05	25.25090	60.83202	2.80	2.64	R	540	13-Oct-2010	6:26	Lipar
06	25.15668	61.17877	5.60	5.02	R	212	14-Oct-2010	11:54	Beris
07	25.08618	61.40825	10.00	9.71	R	660	14-Oct-2010	10:10	Pasabandar
08	25.06988	61.41115	13.90	13.66	S	61	14-Oct-2010	9:43	Pasabandar
09	25.57596	58.69028	7.00	6.99	R	406	13-Oct-2010	7:58	Souraf

[a] Codes to nature of vertical measurements: R: run-up, S: splash, z = terrain elevation

Table 2

Dataset for 2004 Sumatra tsunami

Number	Latitude (°N)	Longitude (°E)	Vertical amplitude (m)		Nature[a]	Inundation (m)	Date and time surveyed		Notes
			Raw	Corrected				(UTC)	
21	25.35523	60.60022	3.35	2.73	F		10-Oct-2010	11:05	Tiss Harbor
22	25.35383	60.40205	2.20	3.38	R	26	12-Oct-2010	6:52	Konarak
23	25.36018	60.31382	1.10	2.22	R		12-Oct-2010	8:23	Pozm
24	25.35823	60.31350	1.95	3.04	R		12-Oct-2010	8:30	Pozm
25	25.06838	61.41687	1.00	1.75	F		14-Oct-2010	9:55	Pasabandar
26	25.35720	59.89457	1.10	1.69	R		15-Oct-2010	8:47	Tang
27	25.40330	59.81385	3.80	4.43	R	35	15-Oct-2010	10:02	Bir Daf
28	25.56027	58.81188	2.30	3.63	R	38	12-Oct-2010	6:48	Gugsar
29	25.56922	58.70397	1.80	2.59	R	62	13-Oct-2010	5:31	Geshmi
30	25.56746	58.20059	1.60	2.18	R	21	15-Oct-2010	6:00	Surgalm
31	25.74628	57.73546	3.10	3.56	R	55	16-Oct-2010	7:27	Lafi

[a] Codes to nature of vertical measurements: R: run-up, F: flow level ($z + h$) with z = terrain elevation, h = flow depth above terrain

island, to a reported height of 15 m above sea level; this island is said to be gradually coming down now.

Regarding the 2004 Indonesian tsunami, we obtained the testimony of Mr. Abdalghani Siahuee, who described an anomalous sound around 11 a.m. (07:30 GMT), followed an hour later by flooding of the jetty up to a height of 3.35 m (uncorrected for tides; Site Number 21), resulting in several boats breaking their moorings.

• *Konarak*, Tuesday 12 October 2010

On Tuesday, 12 October 2010, we traveled to the western shores of the Bay of Chabahar, home of the major fishing community of Konarak, and later to the port of Pozm.

A first witness gave us a precise report of the inundation of the 1945 tsunami reaching to the middle of the block past the mosque, and related that the water penetrated into a house adjacent to the mosque, disrupting a week-long wedding ceremony. The witness remembers being about 12–13 years old at the time, but claims to be only 67 in 2010.

A second witness confirmed inundation of the mosque, but was clearly confused in terms of dates, claiming to have been in his twenties at the time, but only 60 years old in 2010.

A third, and in our opinion more reliable, witness confirmed that the water penetrated the mosque, disrupted morning prayers (estimated around 4 a.m. local time), broke windows and left a few people injured with broken limbs, although no deaths were known to him in Konarak. One month later, he traveled to Pasni and Ormara (in Pakistan), where the city had been totally destroyed. This witness claimed to have been 20–25 years old at the time and to be in his eighties now.

The combination of these testimonies is translated into a surveyed run-up of 3.05 m and an inundation of 52 m (Site Number 02).

Regarding the 2004 tsunami, witnesses reported flooding to the front of the coastal road, for a run-up of 2.20 m and an inundation of 26 m (Site Number 22).

- *Pozm*, Tuesday 12 October 2010

We could not find witnesses of the 1945 tsunami in Pozm, where the 2004 tsunami was remembered by a number of witnesses on the port jetty. The latter, measured at 1.80 m above sea level, was not flooded to its top. In the village, a witness indicated that his boat, which he was cleaning, was beached during the ebbing phase, and later floated back. At the estuary of the river, the sea ran up to 1.10 m on the local beach (Site Number 23), and 1.95 m on a bluff near the town schoolyard (Site Number 24).

- *Chabahar*, Monday 11 October, and Wednesday, 13 October 2010

We were able to interview several reliable witnesses in the city of Chabahar itself on Monday, 11 October (Fig. 4a). Among them, we had a long interview in his house with Mr. Rahmat Khodadian, who claimed to be 75 years old, clearly a very educated person, who indicated an arrival of the waves around 03:30 a.m., and an inundation reaching to the present location of the Bank Melli, near the downtown beach. This location (Site Number 03) was surveyed on 13 October for a run-up of 3.65 m and an inundation of 367 m. The witness mentioned as his only known ancestral memory (i.e., transmitted by previous generations of family members) of major inundation following an earthquake a case “about 200 years ago in India”, which is most probably the 1819 earthquake in Gujarat, during which the Rann of Kuchchh was flooded, but without generation of a genuine tsunami by this continental earthquake. This observation reinforces the absence of ancestral memory from true tsunamigenic events other than the 1945 one along the Makran coast. Mr. Khodadian also mentioned that the telegraph cable (presumably from Europe) was not severed in Chabahar, by contrast with the situation farther East, as reported in the Indian press, suggesting that the Indian cable was cut by a local submarine landslide.

We also interviewed a female witness, aged about 13 at the time of the tsunami, who recalled the destruction, by the waves, of straw houses in the low lands neighboring the beach, resulting in several fatalities, a description which would generally agree with the run-up surveyed at Site Number 03.

During the 2004 Indonesian tsunami, the main cargo harbor of Chabahar saw some 500-ton ships break their moorings and wander inside the harbor, reportedly around 5 p.m. local time, i.e., 13:30 GMT or 5–6 h after the arrival of the first waves. These episodes are reminiscent of similar effects in Toamasina, Madagascar; Le Port, Réunion; Dar-es-Salaam, Tanzania, and Salalah, Oman (Okal *et al.* 2006b, c, d, 2009b). They are attributable to the arrival of higher-frequency components of the tsunami, dispersed outside the shallow-water approximation, and capable of setting ports in resonance.

- *Ramin*, Tuesday 12 October 2010

Ramin is a village located 12 km East of Chabahar on the coastal highway. It is built at an altitude of about 15–20 m, behind dunes topping at an estimated 40 m. It features an improved harbor, next to a small beach which drains a river bed (dry at the time of our visit). To the East, the coast transforms into a series of cliffs, on which lie a large number of imbricated boulders (Fig. 5). These boulders were described by Shah-hosseini *et al.* (2011) who have suggested that maximum-scenario storm waves are insufficient to have deposited them on the cliff, and that they must, therefore, have been deposited by a tsunami. We identified a witness who reported to us that the boulders were reached by the 1945 tsunami, but that they had been present before, which would support Shah-hosseini *et al.*’s (2011) much greater radiocarbon ages (1100–1600 years) for bivalves collected from the boulders. We quantify our witness’ report as a splash on the cliff at a height of 7.15 m (Site Number 04).

Figure 5
Imbricated boulders on the cliff near Ramin, 12 October. These boulders were described by SHAH-HOSSEINI *et al.* (2011); they were reached by the 1945 tsunami, but their deposition predates this event

• *Lipar*, Wednesday 13 October 2010

Lipar is a small community located at the mouth of a major river (also named Lipar) which drains a vast hinterland plain, capable of retaining some water in the form of intermittent lakes and marshes after heavy precipitations, following the building of a levee damming the Lipar. The coastal road crosses the valley on an artificial causeway. Lipar is presently inhabited by about a dozen people, but in 1945, a community existed at the foot of the cliffs, some 3 km inland. We identified as a witness Mr. Ghalamhossein Dadshahpour, who used to live in Lipar but now living in Ramin, who remembered being in his early teens at the time of the tsunami (and claimed to be 73 years old in 2010). We drove him in our field vehicle to the beach in Lipar, where he guided our survey (Fig. 4b). He described three big waves coming in "the early morning", and which carried boulders from the sea to the berm at the estuary (lately covered with sediments). Based on his recollections, we measured (Site Number 05) a run-up of 2.80 m for an inundation of 540 m, to the present huts (which did not exist in 1945); the tsunami penetrated some 3–4 km inside the river bed (now beyond the damming levee).

• *Beris*, Thursday 14 October 2010

On Thursday 14 October, we traveled to the easternmost part of the shoreline, and visited the communities of Beris and Pasabandar.

Beris is a fishing port established in a natural bay sheltered by a prominent headland. The main village is, at least at present, established behind the headland, at an altitude of about 50 m, but in 1945, some people lived in huts on the low lands in the vicinity of the beach. Our witness, Mr. Khaled Baluch, remembers being about 10 years old at the time of the tsunami, but claimed to be 80–90 years old in 2010; a more probable figure being about 75 (Fig. 4c). He recalled that the earthquake was indeed felt, but weakly, around 1 a.m. (a remarkable estimate, the correct time being 1:30 a.m. GMT + 3:30), and that three waves came 3–4 h later. Ships in the harbor were smashed against each other, breaking anchorages. Mr. Baluch had no knowledge of any ancestral memory of similar events going back at least three generations. His descriptions were corroborated by a second witness, Mr. Khalil Taherat, said to be 82 years old in 2010, who confirmed three waves reaching to the front of the beachside mosque. This point (Site Number 06) was surveyed for a run-up of 5.60 m and an inundation of 212 m.

In 2004, currents in the port resulted in the break-up of a vessel which had remained docked; the other boats were at sea at the time.

• *Pasabandar*, Thursday 14 October 2010

This is the last important fishing village before the border with Pakistan. The village is built on an uplifted promontory reaching an estimated altitude of 25–30 m above sea level. We obtained a testimony from Mr. Adam Baluch (Fig. 4d), obviously an educated man, fluent in Arabic, and who recalled being about 12 years old at the time of the tsunami (which essentially agrees with his claimed age of 76 years in 2010). He described three waves coming at dawn (around 4 a.m.), splashing about midway up the promontory (Site Number 08), at an altitude surveyed at 13.9, and 61 m from the sea. He further described the water as reaching to the base of the hills along the road to Gavater. This point (Site Number 07) was estimated at an altitude of 10.0 m, for an inundation of 660 m, measured to the nearest point of coastline. Mr. Baluch further commented that the waves reached up to 10 km inland along the river bed.

Regarding the 2004 tsunami, the wharf at Pasabandar was not inundated, corresponding to a flow depth of 1.0 m, based on a description by a number of witnesses (Site Number 25).

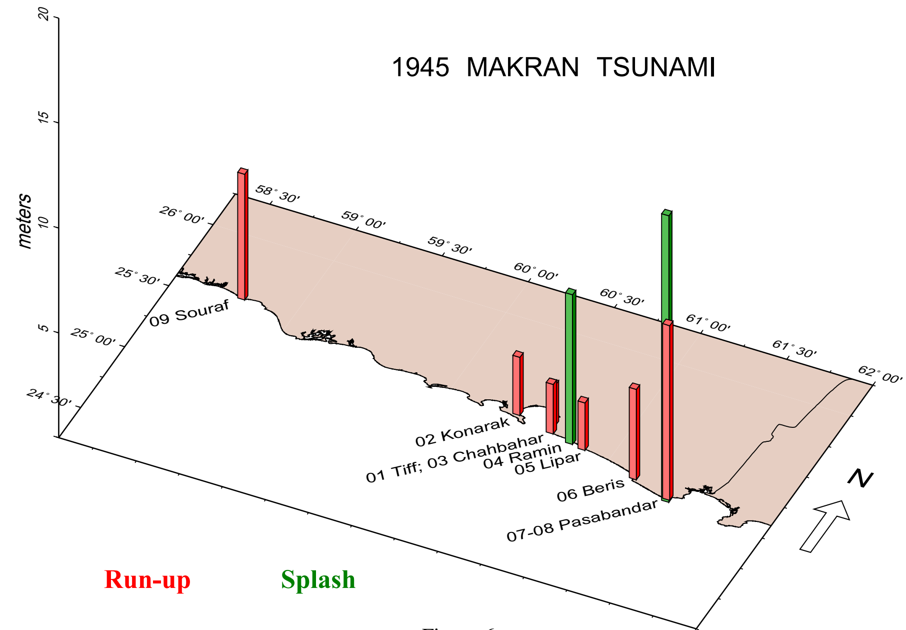

Figure 6
Map of survey results for the 1945 Makran tsunami. *Vertical bars* are scaled with the amplitudes of run-up (in *red*) or splash (in *green*). Site numbers refer to Table 1

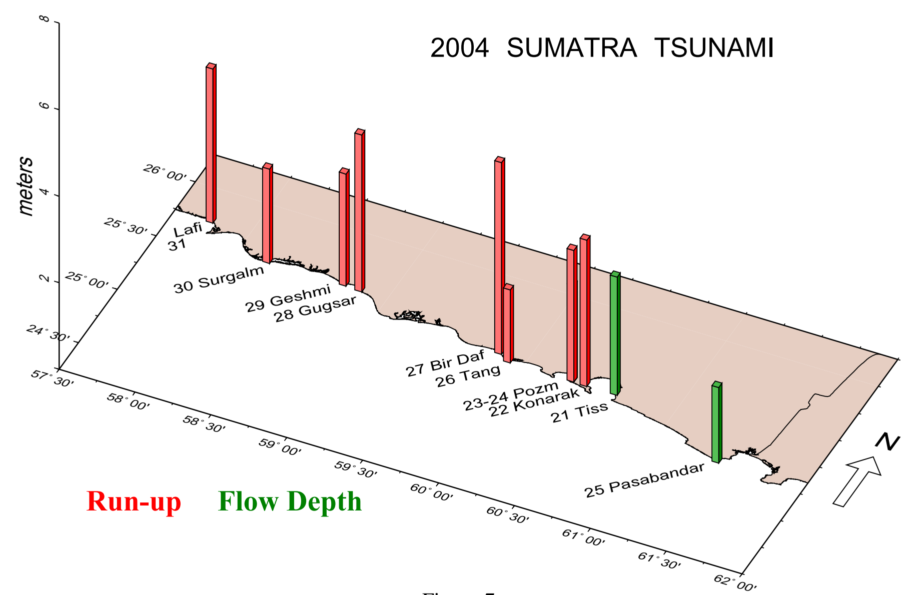

Figure 7
Map of survey results for the 2004 Sumatra tsunami. *Vertical bars* are scaled with the amplitudes of run-up (in *red*) or flow level (in *green*). Site numbers refer to Table 2

- *Tang*, Friday 15 October 2010

Finally, on Friday 15 October, we explored the Western part of the province in the communities of Tang and Bir Daf. In neither of them, could we find witnesses of the 1945 tsunami. In Tang, the only elderly man in town, Mr. Shahul Neshat, claiming to be 75 years old, could not remember any such event. By contrast, in 2004 several witnesses described 3 waves arriving in late morning which deposited a boat at the maximum storm surge water mark, and sank another one during an ebbing phase. Based on these witnesses' testimony, we surveyed a 2004 run-up of 1.1 m for an inundation of 229 m at this location (Site Number 26), protected by a barrier island.

- *Bir Daf*, Friday 15 October 2010

To the West, the community of Bir Daf is built 1.5 km inland. The beach slopes quickly to a berm of dunes. A witness of the 2004 tsunami described to us the arrival of two waves, around 8 a.m. (which is probably erroneous), and a run-up half-way up the berm, to a height of 3.8 m, for an inundation of 35 m (Site Number 27).

- *Souraf*, Wednesday 13 October 2010

This location was visited on 13 October 2010 by the Western team led by Author HMF; they were able to obtain one witness report of the 1945 tsunami at Souraf (Site Number 09), from a resident aged over 90 years, Mrs. Khairi, who described how she "saw the water coming around 6 a.m.", resulting in the destruction of the coastline settlement, which was eventually rebuilt farther inland. This translates into a run-up of 7.0 m, for an inundation of 406 m.

Furthermore, four reports were obtained by the Western team regarding the 2004 Indonesian tsunami along a 115-km stretch of coastline. (Site Numbers 28–31), with run-up ranging from 1.60 to 3.10 m.

3.1. Data Processing

All the data points listed above were surveyed using GPS devices and the exact time at which the survey took place was recorded to allow correction of the raw values listed above for tide level at the time of tsunami arrival. This correction used the OSU tidal prediction software (Egbert and Erofeeva 2002). The measured data of the western and eastern survey teams were corrected using tide predictions for Jask and Chabahar, respectively.

The entire dataset for 1945, including raw and corrected data, is listed in Table 1, that for 2004 as Table 2. The datasets are presented graphically on Figs. 6 and 7.

4. Conclusions

- We were able to build a set of 9 data points for the 1945 Makran tsunami. While most run-up values are in the 3–7 m range, they ramp up to significantly higher values near the Pakistani border, in general agreement with historical reports from present-day Pakistan, and with the testimony of some of our witnesses who were on travel there in 1945, and who confirm a much higher level of inundation and destruction.
- The witnesses generally described a series of three waves, arriving between 4:00 and 5:00 a.m., local time, in the Eastern part of the survey, and possibly 6 a.m. at Souraf. In this respect, the phenomenon is clearly delayed with respect to direct propagation from the source area, which should not take more than 30 min (Heidarzadeh and Satake 2015), resulting in an expected arrival time of ~02:00 local time (GMT + 3:30; 30 min later at Souraf). This delay of approximately 2.5 h is comparable to, if slightly smaller than, that inferred from Beer and Stagg's (1946) observation at Mahé, and therefore does not lend itself to interpretation as a dispersive effect, which should be a function of distance, or as propagation as an edge wave on the continental shelf, the latter being poorly developed along the Makran coastline, as compared to the coastal area of the Indian subcontinent. Rather, a 2.5-h delay in the arrival of the tsunami advocates its generation by an ancillary phenomenon, such as an underwater landslide, which is also the preferred model to explain the rupture of the Bombay–London telegraphic cable. A crucial datum in this respect would be the exact timing of that rupture.
- The witnesses we interviewed did not possess any ancestral memory of comparable events prior to the occurrence of the 1945 tsunami. By contrast, one of our witnesses expressed ancestral memory for the distant earthquake of 1819 in the Rann of Kuchchh. This would suggest that the Makran earthquakes of 1851 and 1864, originally reported by Oldham (1893) to have occurred to the West of the 1945 shock, were of comparatively lower magnitude.
- The 2004 Sumatra tsunami had significant run-up, in the 3–4 m range, along the whole surveyed segment of coastline. This is comparable to observations in Oman (Okal *et al.* 2006c), while

significantly less than at the southern boundary of the Arabian Sea along the Horn of Africa in Somalia (Fritz and Borrero 2006) and Socotra Island, Yemen (Fritz and Okal 2008). The 2004 tsunami involved delayed response effects in the port of Chabahar, due to the dispersed arrival of the higher-frequency components of the tsunami.

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