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Recent seismicity and realistic waveforms modeling to reduce the ambiguities about the 1303 seismic activity in Egypt

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Abstract

The Hellenic arc is located about 500 km away from the Egyptian coasts, even then earthquakes generated in this area severely affect Egypt. The observed shaking durations in Lower Egypt, due to strong events located in the Hellenic arc, are in general around 3 min. The seismic activity of 8th of August 1303 seems to be an exception to this pattern in terms of damage and duration of shacking. It was strongly felt in Lower Egypt for about 15 min and caused a widespread damage in Crete, Egypt, Rhodes, Jordan, Syria, Palestine, Turkey and Cyprus. The location of the seismic source(s) of damage is ambiguous. Recent seismic activity, tsunami and ground motion modeling are used to infer the parameters of the possible source(s) from the available historical records. Using the available macroseismic and tsunami information as the constraint, we support the idea that at least two events occurred on the 8th of August of 1303. One earthquake was a shallow event with small to moderate size, located in Egypt, probably to the south of Cairo, beneath the Nile valley. This event can be the source behind the extensive damage in the Nile Delta, Cairo, Upper Egypt and the strong fluctuation of the water in the Nile valley. The other earthquake had a relatively larger size and occurred in the Hellenic arc at a shallow depth. This source can explain the observed tsunami in the Eastern Mediterranean, the minor to moderate macroseismic effects in a wide area, including sites in, Jordan, Palestine, Syria and Turkey, and the extensive damage in Crete and Alexandria of Egypt. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Historical seismicity; Tsunami; Synthetic seismograms and seismic hazard; Egypt; Eastern mediterranean

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1. Introduction

Historical seismic activity is characterized by a relatively large uncertainty in location and magnitude. This uncertainty might lead to severe errors in the interpretation of the associated damage. A good example is presented by the 8th of August 1303 seismic activity. On this day a large area of the Mediterranean region (Fig. 1) was shaken by seismic waves that caused severe damage in Crete and Egypt, moderate to minor damage in Palestine, Syria, Cyprus and Turkey. The distribution of damage, the duration of shaking and other associated phenomena caused by this earthquake are very different from that reported for most of the largest earthquakes felt in the area (Table 1).

The activity of the 1303 was felt in a wide area and it is listed in most descriptive and parametric

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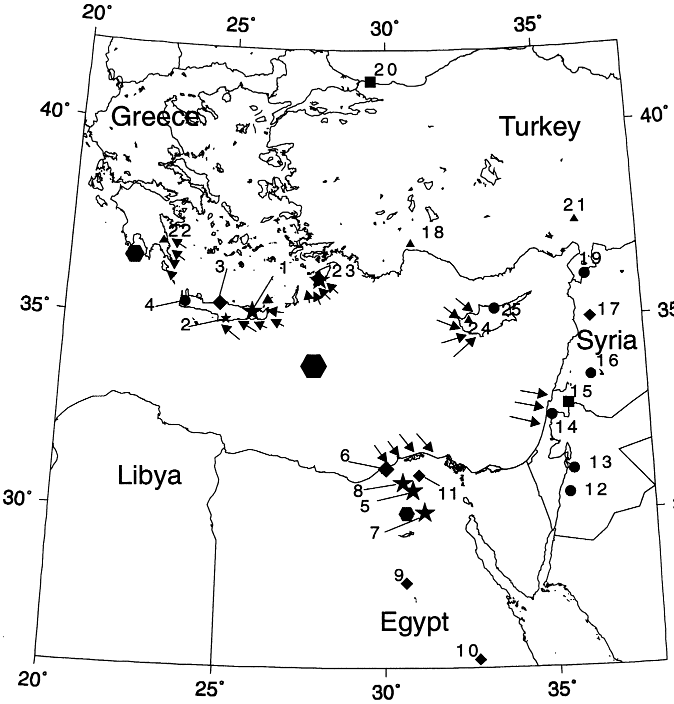

Fig. 1. Proposed locations of the event(s) of August 8, 1303 and of the damaged cities. Stars = extensive damage or total collapse, diamond = heavy damage, circle = low damage, triangle = generic damage, and square = felt. Hexagons indicate the epicenters proposed by Sieberg, 1932 (small), Maamoun et al. (1984) (medium) and Ambraseys et al. (1994) (large). Arrows indicate the areas affected by tsunami. The numbers identify the sites listed in Table 3.

catalogues of earthquakes in the Mediterranean basin. Twenty seven authors have studied the seismic activity of the 8th of August 1303 and proposed considerably different parameters (location and magnitude) for the possible seismic sources (see Guidoboni and Comastri, 1997).

The origin times reported in the different catalogues cover about 2 years (Ambraseys et al., 1994, p. 170). This huge difference in the reported time is mainly due to errors in converting the Islamic time to the Georgian one (Maamoun et al., 1984). Due to such errors the damage associated with one event might be related to two events or vice versa (Ambraseys et al., 1994). Similarly, the obtained locations and magnitudes are very different.

In general, the seismic activity of 1303 were described by different authors as:

(1) a big shock in the Hellenic arc (Ambraseys, 1994; Guidoboni and Comastri, 1997);

(2) a big shock south of the Peleponnese, Greece (Maamoun, 1984);

(3) a sequence of shocks that hit Egypt, Syria and Crete (see, e.g. Sieberg, 1932; Ben-Menahem, 1979; Antonopoulos, 1980).

In spite of such a relevant effort the following questions still remain open: (1) Why is the effect of the seismic activity of 8th of August 1303 different from that of the other historical events occurred in the Hellenic arc and/or Egypt? (2) Is the widespread damage and tsunami reported on that day due to one or more earthquake(s)? (3) Where is/are the earthquake(s) located? (4) What can be the source mechanism of such event(s)?

Our aim in this study is to use the recent seismic activity and synthetic waveforms, to discuss possible scenarios consistent with the source(s) proposed in the literature and eventually to supply plausible answers to the above questions.

Table 1
Larger earthquakes in the Hellenic arc and that were felt strongly in Egypt both in historical and recent times; lat. = Latitude (N), lon. = longitude (E), *D* = reported duration of shaking (minutes)

Year	Lat. (°)	Lon. (°)	*D*	Comment
365 a.c.	36.0	23.0		Tsunami flooded 50,000 houses killing 5000 people at Alexandria
796	36.0	26.0		The upper part of the lighthouse was collapsed
881	36.0	27.0		Felt but no damage reported
963	35.0	26.0		Felt but no damage reported
1303	34.0	28.0	15	Complete and heavy damage was reported in lower Egypt and along the Nile Valley
1353	35.0	28.0		Felt but no damage reported
1438	35.0	28.0		Felt but no damage reported
1500	36.0	23.0	0.5	Minor damage was reported
1508	35.0	27.0		Felt but no damage reported
1509	35.0	27.0		Felt but no damage reported
1609	35.0	28.0		Felt but no damage reported
1613	35.0	27.0		Felt but no damage reported
1633	37.0	21.0		Felt but no damage reported
1664	35.5	25.0		Felt but no damage reported
1741	35.0	28.0	4–6	The minarets of four to five mosques and few houses were thrown down
1756	36.0	23.0	3	Felt but there were no damage reported
1790	35.0	25.0		Felt but there were no damage reported
1805	36.0	24.0	4	Felt but there were no damage reported
1810	36.0	23.0	4	One minaret fell other partially collapsed and few houses suffered damage
1846	36.0	25.0	3	Felt but there were no damage reported
1851	36.0	28.0		Widely felt but no damage reported
1856	35.5	26.0	2	Widely felt but no damage reported
1863	36.5	28.0	0.5	Widely felt but no damage reported
1886	37.0	21.3		Widely felt but no damage reported
1887	36.0	26.0	1	Three minarets collapsed, killing one person
1896	34.3	33.0	1	Widely felt but no damage reported
1903	36.0	23.0	2	Widely felt but no damage reported
1910	35.7	24.0	3	Widely felt but no damage reported
1922	36.0	28.0		Widely felt but no damage reported
1923	35.0	25.0		Widely felt but no damage reported
1926	36.0	24.0		Widely felt but no damage reported
1926	36.5	27.5	3	Casualties and moderate damage were reported in the Nile Delta and Nile Valley
1926	36.5	23.3		Widely felt but no damage reported
1927	36.7	22.7		Widely felt but no damage reported
1930	35.7	24.8		Widely felt but no damage reported
1948	34.4	24.5		Widely felt but no damage reported
1957	36.5	28.8		Widely felt but no damage reported
1965	38.1	28.8		Widely felt but no damage reported

2. General review

2.1. Damage

The information given in this section represents a summary of the work by Ambraseys et al. (1994) and Guidoboni and Comastri (1997) to which the interested reader can refer to for more details.

The information that is supplied by Guidoboni and Comastri (1997) indicates that the worst effects of the 1303 seismic activity were observed in Crete. In Candia, the principal city, collapses involved the city walls, houses, churches, the town hall, the local castle and the tower of the harbour; the arsenal was damaged severely and a large number of people were killed.

According to Arabic sources the earthquake effects were also severe in Egypt (Ambraseys et al., 1994;

Guidoboni and Comastri, 1997). In Alexandria, many houses were ruined and much of the city wall was destroyed: 46 buttresses and 17 towers collapsed killing a large number of people. The lighthouse at Alexandria was shattered and its top collapsed.

Elsewhere, in the Nile Delta there was widespread damage. Two villages in the Sharqiyya district were destroyed and Sakha, Abyar and Damanhur al-Wahsh were among the towns that were ruined completely.

In Cairo, almost all the houses suffered some damage. The earthquake caused panic and women ran into the streets without their veils. Streets littered with fallen parapets and free-standing walls slowed down the evacuation of the city, whose inhabitants encamped that night outside Cairo between Bulaaq and Rauda, leaving their houses to be rifled by looters. It appears that there were relatively a few casualties, probably because when the earthquake struck, the streets were relatively empty. Most people returned to Cairo the following day, which was a Friday, and prayed in the mosques, where it was apparently safe to return. Many large public buildings in Cairo were, however, damaged and some collapsed. Minarets in the Mosques of the Cairo and Fustat were particularly affected. The mosque of al-Azhar, al-Hakim and Amr ben Al-as at Fustat partly collapsed and had to be pulled down and rebuilt. The minarets of the mosques of al-Hakim, of al-Fakkahin and al-Salih ben Ruzaik outside the Bab Zuailia, and the Madrasa al-Mansouriyya, were either destroyed or damaged to the extent that they had to be pulled down and rebuilt. It is reported that after the earthquake, Cairo looked as though a conquering army had wrecked it; the Mamluk amirs spent large sums of money over the next two years on the repair and restoration of public building. In lower Egypt, (northern Egypt, including Nile Delta and Cairo), the ground motion were slow (long period) and lasted several minutes, making people walk with difficulties while those on the horseback were thrown down. According to Arab writers, the aftershocks continued for 20 days (Ambraseys et al., 1994).

Sporadic damage is reported in Upper Egypt. Guidoboni and Comastri (1997) report the following text of an anonymous writer who was at Minya during the earthquake “At that time I was on the coast of Minya. At dawn we felt thunder beneath us: it was the earth shaking. I looked towards the mountains in the east and saw rocks falling to right and left. I looked towards the Nile, and I saw the water part, revealing the riverbed, before coming together again. In the city of Minya, the Mosque collapsed as did houses and other buildings”.

Qus, further south, has also suffered damage. There is a story about a man milking a cow at Qus, both the man and his cow were lifted by the earthquake waves (may be exaggerated).

Elsewhere, in Palestine, the most severely damaged city was Safad. One side of the Citadel and two towers collapsed; and there was also damage at Karak and Shaubak. In Syria, part of the city walls of Hamah collapsed and there are reports of unspecific damage at Antioch as well as slight damage to the Great Mosque in Damascus. There are unspecific reports of damage at Antalya on the south coast of the present day Turkey, as well as Seis. In Greece, many places in the Peleponnese were damaged, especially Korone and Methone. The island of Rhodes suffered a great deal of damage. Reports about Cyprus are contradictory. In Italy, the shock was felt in Venice but no damage was reported.

2.2. Tsunami effects

From Ambraseys et al. (1994) and Guidoboni and Comastri (1997) we can conclude that on the 8th of August 1303 a strong tsunami affected the following sites.

Crete — the sea swept into the city with such a force that it destroyed buildings and killed inhabitants; then receded rapidly from the port, leaving the beach visible.

Acre — the sea of Acre receded about two-parasange (12.8 km) revealing object that had been thrown into the sea during the Arabic siege of the city, on the seabed. Some people tried to pick them up, but were swept away and down by a huge wave. The sea flooded in almost as far as Tall al-Fudul in Acre.

Alexandria — the sea first receded and then flooded the shore, reaching as far as the city walls; laundrymen’s shops were submerged and destroyed, as were many foodstuffs near the seashore. At the port, ship’s moorings broke and many boats were thrown onto the rocks.

Rhodes — damaging tsunami were reported; no more details are available.

Cyprus — no details available.
Koroni — no details available.

2.3. Phenomena reported only on 1303

The reports about the seismic activity in 1303 describe phenomena that are not common to other strong events in the Eastern Mediterranean. Among others, we consider particularly relevant that follows.

2.3.1. The existence of short-period effects in Egypt

The analysis of the historical information given by Ambraseys et al. (1994) and Guidoboni and Comastri (1997) shows that only for Egypt, both short- and long-period effects are reported. Accordingly with the description contained in the modified Mercalli scale published by Richter (1958), the following long-period effects can be listed: (1) the shattering of the lighthouse and the collapse of its top; (2) the slow ground motion that made people walk with difficulties, while those on the horseback were thrown down; and (3) people felt the earthquake for several minutes.

Among the short-period effects can be listed: (a) the complete and/or heavy damage reported in Cairo, Abyar and Damanhur al-Wahsh, including the public buildings that were usually of good quality; and (b) the way the earthquake was felt by people, the movement of the water in the Nile, the rock-falling and landslides near by Minya.

2.3.2. The distribution of life losses

The distribution of the life losses cannot be easily reconciled with the damage and with the given origin time (3.30 GMT see Guidoboni and Comastri, 1997). Life losses were negligible in the areas of total collapse or of severe damage and densely populated like Cairo, but they were considerable in areas of relatively low damage like Alexandria. Ambraseys et al. (1994) argue that probably when the earthquake struck Cairo the streets would have been relatively empty, nevertheless, panic among the people was also reported by them. The given origin time is 5:30 (local time). At that time most of the people were sleeping at home, i.e. life losses are expected to be large in the areas of total collapse.

2.3.3. The motion of water in the Nile Valley

On the 8th of August 1303 the Nile was flooded with great sound, throwing its boats a bow-shot on land smashing their anchors; then, water retreated leaving the boats on the land; and those were sailing in the middle of the river were thrown on its banks, the bed of the Nile was briefly visible as the water parted (Antonopoulos, 1980).

3. Theoretical clarification

The reported tsunamis strongly support that the seismic activity occurred at sea, i.e. in the Hellenic arc (Ambraseys, 1994; Guidoboni and Comastri, 1997) or south of the Peleponnese, Greece (Maamoun, 1984). To identify a plausible location, tsunami motion is calculated theoretically at the sites that according to the available information have experienced strong tsunamis. The input that is necessary is: (1) the lithosphere and bathymetery models from the source area to the site of interest; and (2) the fault parameters — magnitude, depth and focal mechanism — for the assumed seismic source.

The models for both the crustal structure and the bathymetery are obtained from the GIS database of Cornell University, USA (see, e.g. Barazangi et al., 1996), while for the deeper part, the model given by Du et al. (1998) is used. The crust in the eastern Mediterranean is, on average, 25 km thick and it is modeled with two layers, the uppermost sedimentary layer overlaying a basaltic one. The thickness of the two crustal layers varies from 5 to 15 km, while the thickness of the water reaches a maximum of about 3 km (Fig. 2).

Out of the twenty-seven authors, nine report magnitude with values that vary from 6.5 to 8.0. Therefore, different calculations have been carried out assuming different source sizes, depths and mechanisms consistent with the present tectonics of the proposed epicentral area. Generally, earthquakes occur in the Hellenic arc at shallow–intermediate depth and have focal mechanisms varying from normal, reverse to strike slip (see Fig. 3), as it is typical for a subduction zone. We assume that all events in the suggested areas had or will have one of these mechanisms.

3.1. Synthetic tsunami motion

In general, subduction earthquakes (i.e. like that of the Hellenic) generate tsunami by several

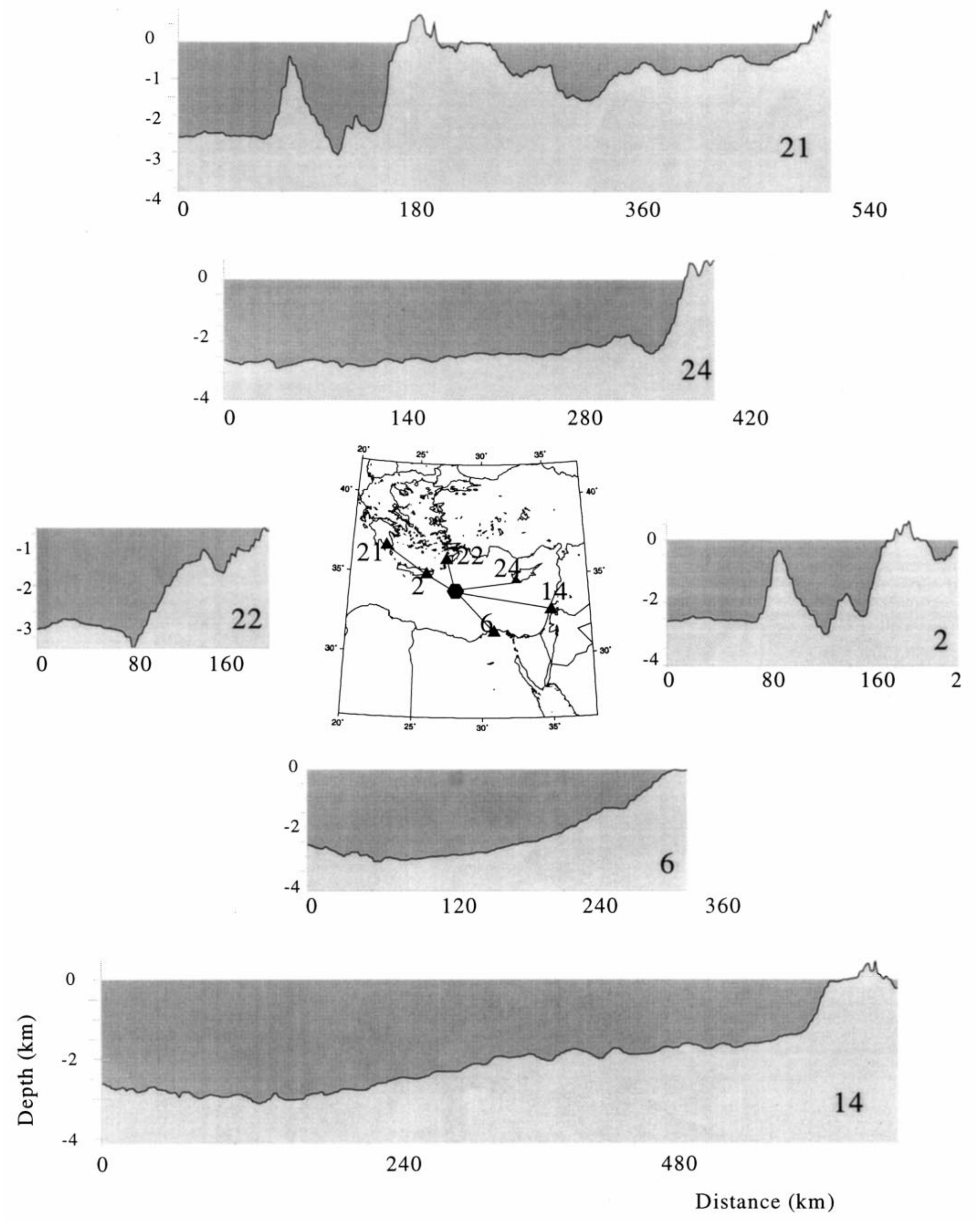

Fig. 2. Bathymetery along the cross-sections from the source to the sites where tsunami have been computed (atlas of geology, Cornell University, USA, e.g. Barazangi et al., 1996). The large numbers identify the sites listed in Table 3.

processes: (1) deforming the seafloor and elevating or depressing the overlying water column; (2) shaking and exciting the water column by long-period seismic wave; and (3) triggering submarine or coastline landslides that displace large volumes of water.

Tsunami produced from coseismic uplift and subsidence of the seafloor (no. 1) during large subduction

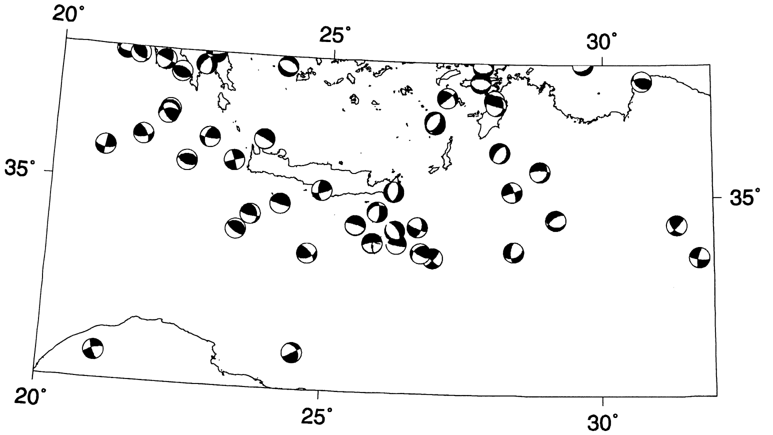

Fig. 3. Focal mechanism solutions in the Hellenic arc for the events of magnitude 5.5, that occurred in the time period 1975–1998 (CMT catalogue).

earthquakes are commonly regional or transoceanic in extent. Run-up is greatest along the coast adjacent to the rupture and attenuates slowly with distance from the source. Examples on this type of tsunami can be found in McCaplin (1996). Tsunamis produced by regional seafloor deformation during subduction earthquakes typically include trains of waves with periods of several tens of minutes (no. 2). Successive wave crests arrive along the coast for several hours and create repeated landward surges, followed by seaward return flows of the marine water. The rise and fall of sea level associated with the arrival of each wave at the coast is typically rapid; water level can change several meters or more in a few minutes (McCaplin, 1996). In general, process no. 1 and 2 are two coherent processes and related directly to the occurrence of an earthquake.

The synthetic tsunami motions are calculated for normal, reverse and strike–slip faulting mechanisms (the representative mechanisms in the studied area) and for the sites at which strong tsunami were reported (see Fig. 1 and Table 2). The method used is the one developed by Panza et al. (2000), and it is based on the efficient algorithms for the production of synthetic seismograms due to the excitation, by seismic sources, of the tsunami mode propagating in laterally varying oceanic structures. With Panza et al. (2000) approach, the tsunami excitation processes (1 and 2) are efficiently described. For each of the selected locations we report the mechanism that allows a quantitative match with the historical reports describing the tsunami and which also fit with the tectonics of the epicentral area.

For example, by using Ambraseys et al. (1994) location and normal faulting mechanism it is possible to generate tsunami in the sites mentioned in Section 2 (Fig. 4b), the strongest effects being in Rhodes, Acre and Cyprus (localities where damaging tsunamis were reported). Within the tested sources, the best qualitative agreement between the reported and the calculated tsunami is given by an event of magnitude 7.3 with normal faulting mechanism and focal depth of 15 km (Fig. 4c). The synthetic scenario is in agreement with the tsunami description reported by Guidoboni and Comastri (1997): progression into land and then rapid regression of the sea in Crete; regression of the sea and then progression into land in Acre and Alexandria.

The first arrivals of the calculated radial tsunami are strongly regressive at Alexandria and Acre. The sea floor at Acre is very shallow (Fig. 2), and therefore, a strong negative pulse may expose a large area of the seabed, which was estimated to be around 13 km (Guidoboni and Comastri, 1997). The initial regression indicated by our computation for Crete (about 1.5 m) may not have been observed, due to the rather steep topography (see Fig. 2) near to the shoreline, while the amplitude (about 3 m) and period (2 min) of the subsequent progressing wave may explain the reported damage and rapid regression.

Table 2

Calculated horizontal tsunami motion peak values at Alexandria, corresponding to Ambraseys location (lat. = 34°N and long. = 28°E), assuming different magnitudes, focal mechanisms and depths; R, N, S denote reverse (strike = 227°, dip = 37° and slip = 24°), normal (67, 48 and −34°) and strike slip fault mechanism (135, 76 and 13°); Tsunami peaks (in meter) are calculated for three different focal depths; the three focal mechanisms considered correspond to the mechanisms of the events of July 22, 1985 (mb = 5.4), September 27, 1985 (mb = 5.5) and May 22, 1986 (mb = 5.1) located at latitude 34.16°N longitude 28.40°E, 34.05°N–26.97°E and 34.12°N–26.72°E, respectively; sites are shown in Fig. 2; bold numbers in the table indicate the values that can be supported by the reported description (Ambraseys et al., 1994; Guidoboni and Comastri, 1997)

Magnitude				Mechanism			Tsunami (m) at site (6)			Tsunami (m) at site (14)			Tsunami (m) at site (24)			Tsunami (m) at site (22)			Tsunami (m) at site (2)			Tsunami (m) at site (21)		
8.0	7.5	7.3	7.0	R	N	S	10	15	20	10	15	20	10	15	20	10	15	20	10	15	20	10	15	20
X				X			21.73	20.45	7.69	21.28	24.76	11.79	25.35	27.41	12.01	41.82	43.95	18.00	28.30	26.15	9.79	14.16	13.62	5.15
X					X		32.45	20.84	12.38	26.71	13.68	7.59	31.95	34.17	14.03	53.51	54.55	22.16	42.71	33.69	18.67	19.68	17.83	10.48
X						X	10.23	12.09	5.44	7.45	6.37	5.43	13.56	11.40	8.54	24.02	17.84	12.47	12.18	13.30	5.25	5.73	5.91	3.01
	X			**X**			**3.87**	**3.64**	**1.38**	**3.79**	**4.41**	**2.10**	**4.52**	**4.89**	**2.14**	**7.50**	**7.87**	**3.22**	**5.05**	**4.66**	**1.74**	**2.52**	**2.42**	**0.92**
	X				**X**		**5.79**	**5.69**	**2.21**	**4.25**	**4.76**	**2.08**	**5.71**	**6.10**	**2.50**	**9.57**	**9.75**	**3.96**	**7.70**	**6.06**	**3.34**	**3.53**	**3.19**	**1.87**
	X					**X**	**1.84**	**2.16**	**0.98**	**1.33**	**1.14**	**0.97**	**2.43**	**2.04**	**1.52**	**4.34**	**3.20**	**2.23**	**2.26**	**2.38**	**0.94**	**1.03**	**1.05**	**0.53**
		X		**X**			**1.94**	**1.82**	**0.69**	**1.90**	**2.21**	**1.05**	**2.27**	**2.45**	**1.07**	**3.76**	**3.95**	**1.62**	**2.53**	**2.34**	**0.88**	**1.26**	**1.21**	**0.46**
		X			**X**		**2.91**	**2.85**	**1.10**	**2.13**	**2.39**	**1.04**	**2.86**	**3.06**	**1.25**	**4.80**	**4.89**	**1.99**	**3.87**	**3.04**	**1.68**	**1.77**	**1.60**	**0.94**
		X				**X**	**0.92**	**1.08**	**0.49**	**0.67**	**0.57**	**0.48**	**0.48**	**1.52**	**1.02**	**2.17**	**1.61**	**1.12**	**1.13**	**1.19**	**0.47**	**0.52**	**0.53**	**0.27**
			X	X			0.69	0.64	0.24	0.68	0.78	0.37	0.81	0.87	0.38	1.33	1.40	0.57	0.89	0.83	0.31	0.44	0.43	0.16
			X		X		1.03	1.01	0.39	0.75	0.85	0.37	1.01	1.08	0.44	1.70	1.73	0.71	1.37	1.08	0.59	0.62	0.56	0.33
			X			X	0.33	0.38	0.17	0.23	0.20	0.17	0.43	0.36	0.27	0.77	0.57	0.39	0.40	0.42	0.16	0.18	0.17	0.07

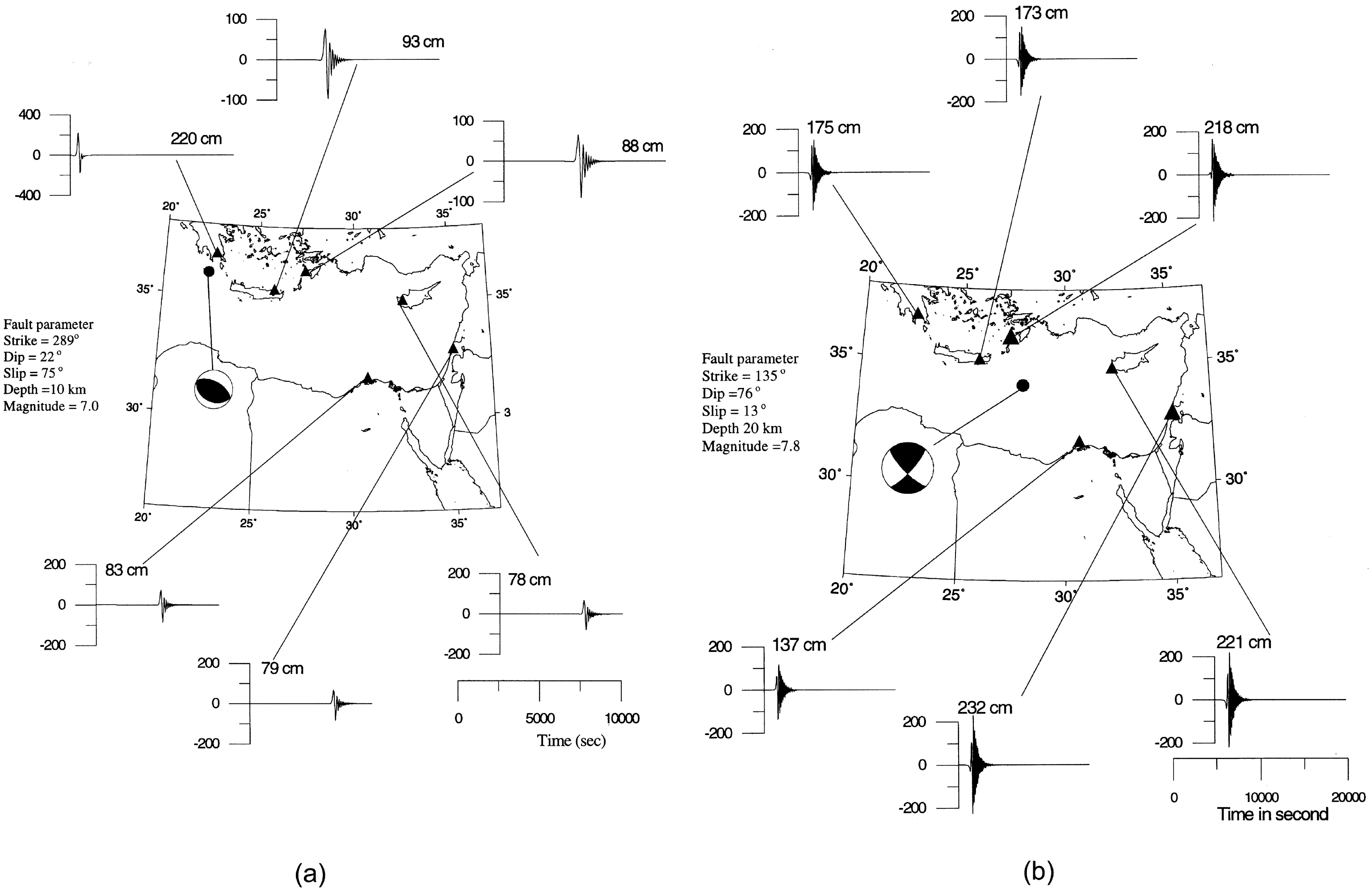

Fig. 4. Tsunami computed using: (a) Maamoun et al. (1984) location; (b and c) Ambraseys et al. (1994) location for different focal mechanism; (d) Ambraseys et al. (1994) location for a multiple event.

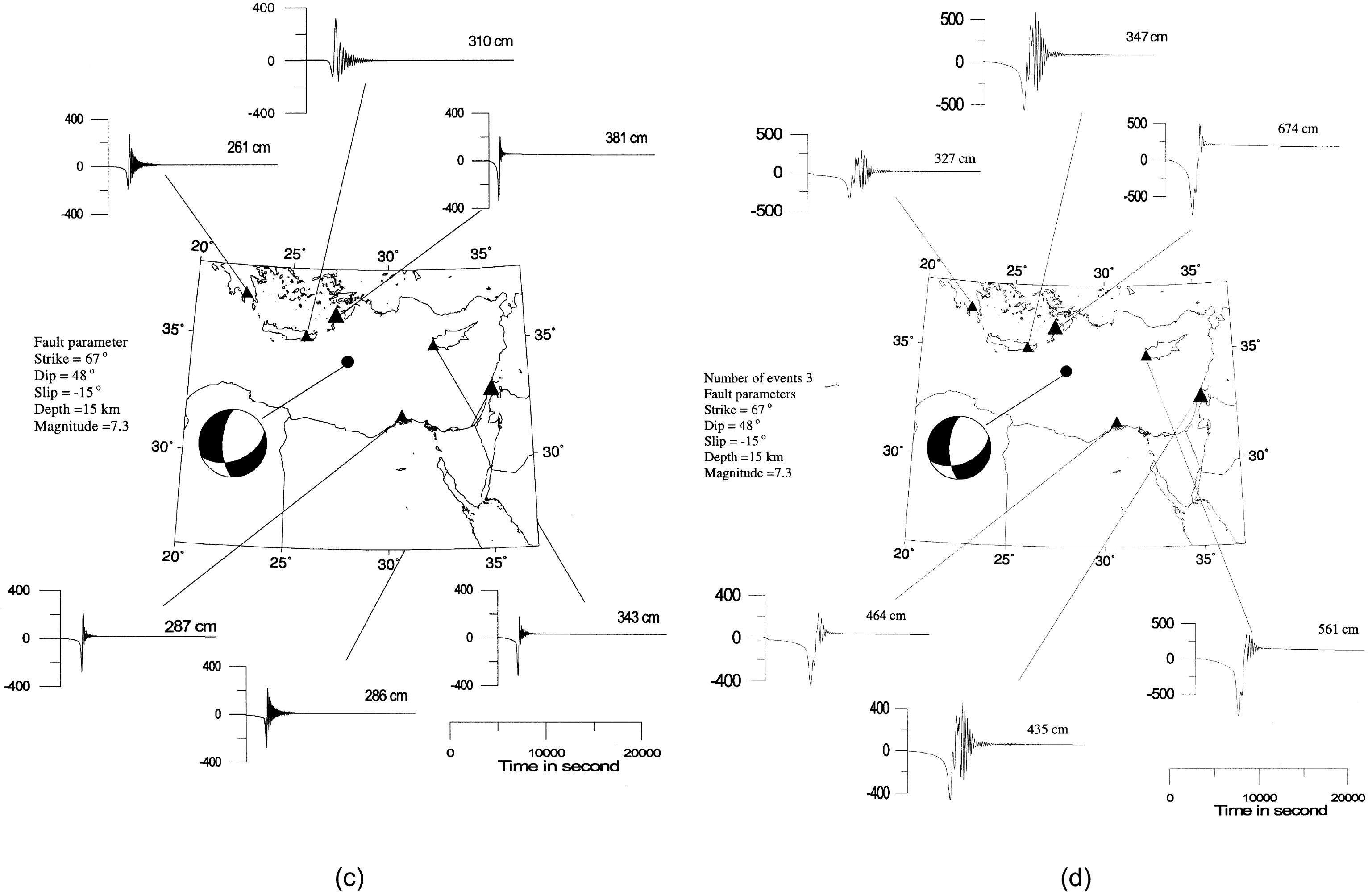

Fig. 4. (*continued*)

The state of alert is certainly different at the time of the second regression that, accordingly with the synthetic signal shown in Fig. 4b, may have had peak amplitude at least 50% larger than the first one.

For the chosen mechanism, tsunami can be calculated assuming that the activity of 8th of August 1303 occurred as a multiple (complex) event, i.e. a sequence of shocks separated by a few minutes. We tested several possibilities and report here just one example corresponding to the sum of three events, each with magnitude 7.3, and separated by 3 min. The peak values, duration and phases of the tsunami obtained for a single and multiple event are different (see Fig. 4d). Considering a multiple event gives a tsunami well consistent with an initial regression lasting for about 20 min in agreement with the reported phenomena in Acre and with a large regression in the places where the seabed was temporarily visible, i.e. a multiple event in the Hellenic Arc can generate strong tsunamis over a large area of the Eastern Mediterranean.

On the other hand, the tsunami calculated using a seismic source located according to Maamoun et al. (1984), for the three considered mechanisms, produces a scenario in strong disagreement with the reported tsunami effects (Fig. 4a). In fact, the calculation based on this location gives a noticeable value only at Koroni, Greece, 75 km from the proposed epicenter, where strong but not damaging tsunami was reported. Therefore, Maamoun et al. (1984) location is excluded from our further investigations.

3.2. Synthetic ground motion

To investigate if an event in the Hellenic Arc can also explain the reported damage in Egypt or not, ground motion parameters (displacement, velocity and peak ground acceleration) are calculated using Costa et al. (1993) and Panza et al. (1999) approach. This method is based on the modal summation technique developed by Panza (1985), Panza and Suhadolc (1987) and Florsch et al. (1991). The source parameters and structure model are the same used in the tsunami modeling (Fig. 4c).

The calculated shaking in Egypt from an $M = 7.3$ earthquake in the Hellenic arc turns out to last around 4 min with periods as large as 30 s (in case of displacement), in agreement with the values reported in Table 1. The great exception is represented by the event of 1303, which was felt for over 15 min (Table 1). Our calculation show that we can get a duration significantly longer than 5 min when we consider a multiple event like the one adopted in the tsunami calculations shown in Fig. 4d.

In the synthetic ground motion, most of the energy is contained in the range (<1 Hz) even if in Alexandria, Cairo and Abayer a secondary peak at frequencies higher than 2 Hz are observed (Fig. 5a). The records at Kottamya station (80 km to the south east of Cairo) of the recently occurred earthquake in the Hellenic Arc ($mb = 6.4$ event of July 20, 1996) are characterized by similar spectral properties (compare the spectra in Figs. 5b and 6a for Cairo, site 7 in Fig. 1).

The calculated frequencies (<2 Hz) of the peak ground parameters in Egypt (acceleration in the range 0.21–1.92 cm/s^2 (Table 3)) explain the reported damage in Egypt. Consequently, it might be attributed to a moderate local earthquake (see, e.g. Sieberg, 1932; Ben-Menahem, 1979; Antonopoulos, 1980).

Therefore, synthetic seismograms have been computed considering the source location and magnitude proposed by Sieberg (1932). The source depth ($h = 10$ km) and normal faulting mechanism are chosen similar to the source properties of the October 12, 1992 event that occurred nearby. As it is shown in Fig. (5b), in the considered Egyptian sites the main part of the energy is contained in the range 1–10 Hz. The records of the October 12, 1992 earthquake at Kottamya station (KEG), at a distance of 80 km from the epicenter, are characterized by similar spectral properties (compare the spectra in Figs. 5a and 6b for Cairo, site 7 in Fig. 1).

4. Discussion

Time and space definition of the historical seismicity is affected by large ambiguities. The damage and tsunami associated with the 1303 activity have been related by some authors to a big event in the Hellenic arc, while others, propose at least two events, one in the Hellenic arc and the other in Egypt. Combining the available historical information with theoretical calculations of tsunami and ground motion one may attempt to reduce this ambiguity.

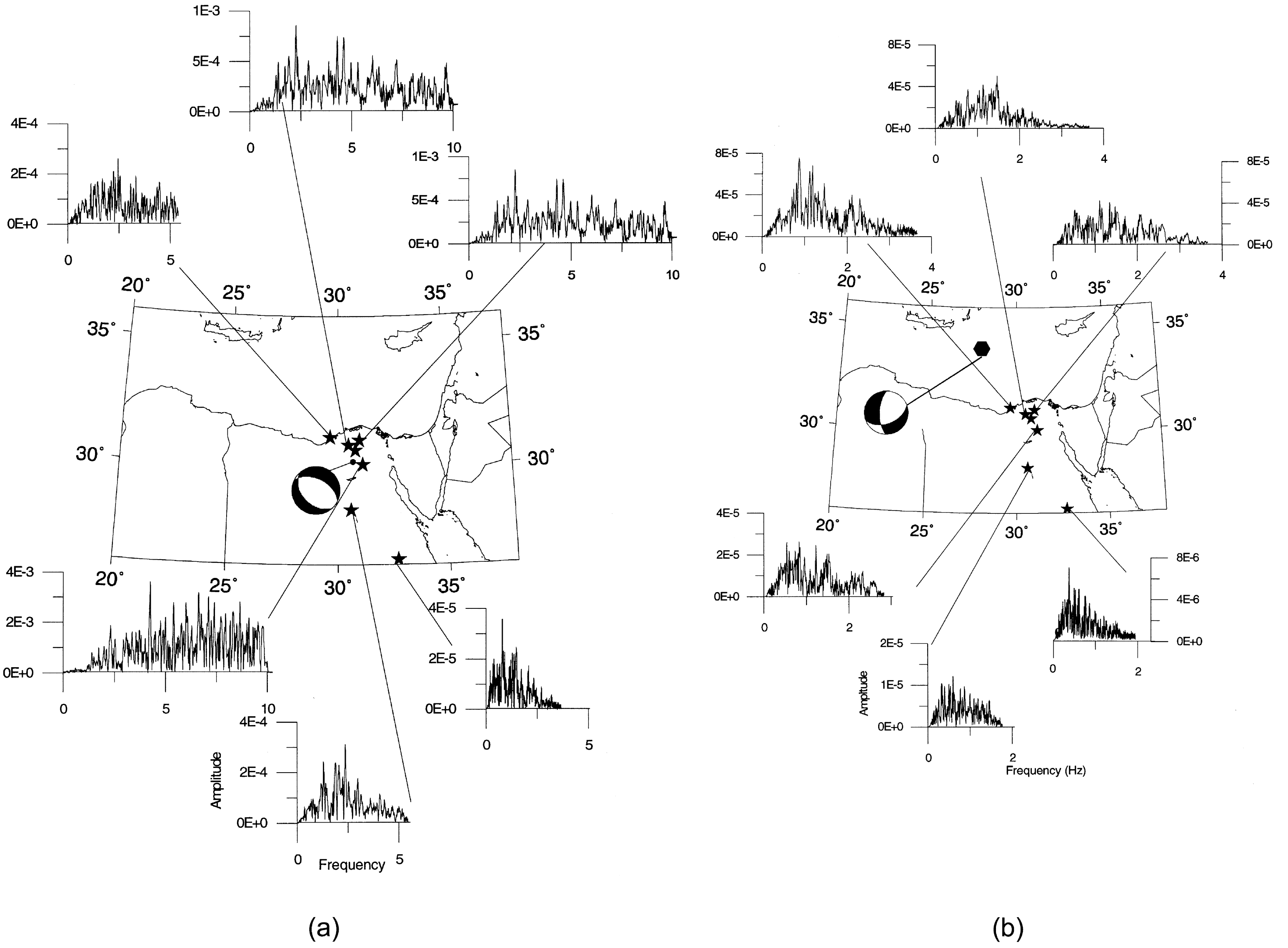

Fig. 5. Frequency content of the calculated ground accelerations in the damaged areas in Egypt by considering: (a) Ambraseys's location, (b) Seiberg's location. Locations of sites are given in Fig. 1 and Table 3.

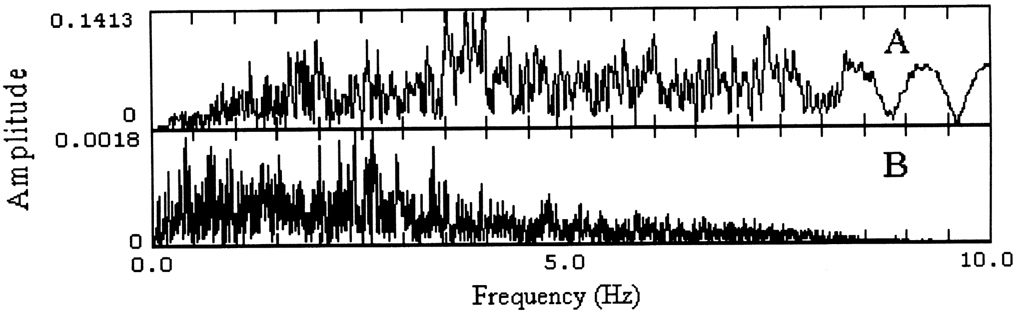

Fig. 6. Fourier amplitude spectra of the accelerations time series recorded at Kottamya (KEG), very broad band (20 sample/s) station in Egypt (80 km south Cairo) derived from the vertical velocity time series record, for: (a) Hellenic Arc earthquake of July 20, 1996; and (b) October 12, 1992 earthquake.

Table 3

Calculated peak values of ground motion for the sites damaged or affected by the 1303 earthquakes; Dist = distance (km), Long. = longitude, Lat. = latitude, Eff. = effect, D = ground displacement (cm), V = ground velocity (cm/s), A = ground acceleration (cm/s^2), I = reported intensity from the analysis of the historical reports (Ambraseys et al., 1994; Guidoboni and Comastri, 1997), L = low damage, d = generic damage, F = felt, E = extensive or total collapses, T = Tsunami, H = heavy damage, and La = landslide; number identifies the damaged sites shown in Fig. 1

Number	Location	Dist	Lat. (°)	Long. (°)	Eff	*D*	*V*	*A*	I
1	Crete	255	35.40	25.79	E,T	1.34	1.41	4.89	VIII
2	Crete	300	35.40	25.20	E	1.25	1.10	3.08	VIII
3	Crete	332	35.40	24.80	L	1.12	0.92	2.30	VIII
4	Crete	365	35.20	24.30	L	1.20	0.75	2.32	VIII
5	Egypt, Abayr	460	30.60	30.80	E	1.08	0.56	1.17	VIII
6	Alexandria	355	31.12	29.65	H,T	2.16	0.91	1.92	VIII
7	Cairo	531	30.03	31.15	H	1.00	0.47	0.91	VII
8	Damanhur	426	30.80	30.50	H	1.19	0.76	1.52	VIII
9	Minya	689	28.20	30.60	H, La	0.98	0.47	0.61	VII
10	Qus	975	26.21	32.70	H	0.58	0.24	0.21	VII
11	Sakha	436	31.00	31.00	H	0.86	0.63	1.39	VII
12	Jordan, Karak	786	31.10	35.64	L	0.45	0.29	0.72	VI
13	Shaubak	575	30.50	35.50	L	0.39	0.34	0.58	VI
14	Palestine, Acre	717	32.80	35.58	T	0.83	0.38	0.47	VI
15	Safad	708	32.90	35.50	H	0.86	0.40	0.43	VI
16	Syria, Damascus	771	33.50	36.30	L	0.87	0.45	0.56	VI
17	Hamah	777	35.00	36.38	H	0.88	0.45	0.48	VI
18	Turky, Antalya	419	37.00	30.80	d?	0.81	0.46	0.87	–
19	Antioch	792	36.10	36.30	L	0.78	0.40	0.47	–
20	Istanbul	809	41.20	29.50	F	0.72	0.37	0.37	–
21	Sis	829	37.50	36.10	d	0.58	0.32	0.32	–
22	Greece, Koron	566	36.93	22.90	d,T	0.52	0.46	0.80	–
23	Rodes	227	3600	27.49	H,T	3.60	2.43	7.80	IX–XI
24	Cyprus, land	437	35.00	32.60	d,T	1.89	0.80	1.13	VI
25	Leukosia	516	35.30	33.40	L?	1.28	0.62	1.08	–

4.1. One event?

The reported strong regression of the sea that lasted for a long time in places like Acre, Alexandria and Rhodes suggests the occurrence of a shallow complex event in the Hellenic arc (Fig. 4d). A shallow focal depth for the 1303 event(s) is supported by the long-period effects that can be explained by the propagation of relevant surface waves that, in the few seconds range, are much more efficiently generated by crustal sources than by intermediate-depth earthquakes (Panza et al., 1973; Kulhanek, 1990). In favor of a shallow depth, we can also quote that the earthquakes of June 26, 1926 ($M = 7.4$), with a focal depth of about 115 km, did not generate any tsunami, as one could expect also from theoretical calculations (Ward, 1980; Panza et al., 2000).

An alternative explanation for the tsunamis of 1303 could be a huge submarine landslide triggered by the seismic activity. However, tsunamis generated by submarine landslides can locally reach the exceptional run-up heights of many tens to hundreds of meters, as occurred in Lituya Bay, Alaska, in 1958 and Valdez, Alaska, in 1964. These extreme run-up heights from landslides-generated tsunami are typically limited to a small part of the coastline, often a single bay, and attenuate away rapidly from the origin (McCalpin, 1996). In 1303 tsunamis were widely reported in the eastern Mediterranean and this may support an origin from the deformation of the seafloor or equivalently from the seismic excitation of the tsunami mode.

Moreover, tsunamis triggered by submarine landslides generally, cause sea regression that last for a very long time, followed by a progression into land. This does not agree with the description of the tsunami in Crete and Alexandria where the initial (short period) sea regression has been followed by a strong progression).

Based on our theoretical calculations and on recent tsunami observation (McCaplin, 1996) the 1303 reported tsunami in the Eastern Mediterranean is more likely to be due to a relatively large ($M \sim 7.5$), shallow ($h < 20$ km) earthquake in the Hellenic arc. This event could explain the severe damage in Crete, Rhodes (nearby site) and the low damage reported for the other areas, while more questionable remains the explanation of the severe damage in Egypt (located at a large epicentral distance).

4.2. Difficulties faced by the one event scenario

An event in the Hellenic arc does not explain:

—the strong oscillations of the water in the Nile Valley;

—the coexistence of long- and short-period effects in Egypt;

—the huge difference between the effects in Lower Egypt related to the 1303 event and to other events in the Hellenic arc;

—the contradiction between the damage and life losses reports.

Ambraseys et al. (1994) indicate that the event of 1303 in the Hellenic arc could not explain the partition of the water that leaves the Nile bed briefly visible and they relate the strong oscillation of the water to strong wind that might have occurred on that day. Actually, in Egypt, it is not common to have strong wind in August. Strong wind usually occurs at the end of April and beginning of May each year (Reda, personal communication).

Strong events in the Hellenic arc are expected to generate long-period motion in Egypt (as confirmed by our calculation), which may explain the partial collapse of the lighthouse, Minarets and difficulties faced by people while walking. At the same time, strong events in the Hellenic arc can hardly cause a complete damage at distances of about 500–600 km (Fig. 1 and Table 1), cause rock-falling and landslides nearby Minya. Therefore, the use of the Hellenic arc source to explain the heavy and/or complete damage in Sakha, Abyar and Damanhur contradicts the fact that the proportion of the long-period to short-period energy tends to increase with increasing distance from the epicenter.

We cannot invoke the building vulnerability and/or local site amplification to explain the difference between the effects associated with the seismic activity of 1303 and with the other seismic events in the Hellenic arc, because they are supposed to be common factors for all earthquakes. However, the surprising large destruction in the Cairo area caused by relatively small earthquakes, e.g. in 1992, is probably related to the local amplification of the ground motion due to the soft surface layering (e.g. sedimentary basins) and/or topographical effects. We also admit that the vulnerability of buildings in the Nile Valley is notoriously high and buildings collapse every year, even without earthquakes. The self-collapse of buildings in the Nile Delta happens only during the dry season, as a result of liquefaction, but August is not a dry season.

The distribution of the life losses cannot be easily reconciled with the damage and with the given origin time. Life losses are negligible in the areas of total collapse or of severe damage and densely populated like Cairo, but they are considerable in areas of relatively low damage like Alexandria. Ambraseys et al. (1994) argue that probably when the earthquake struck Cairo the streets would have been relatively empty, nevertheless, panic was also reported by them. The given origin time is 5:30 (local time). At that time most of the people were sleeping at home, i.e. life losses are expected to be large in the areas of total collapse.

4.3. Two events?

To explain the short period effects in Egypt it turns out quite natural to accept the occurrence of a local earthquake too (see, e.g. Antonopoulos, 1980).

On the basis of our calculations and on the available information, these difficulties can be eliminated if two sources with different origin time and location are postulated. The first distant event destroys tall and poor quality building (frequencies not exceeding 1 Hz), kills a number of people in Alexandria and is strongly felt, i.e. alarms people in the Nile Delta. The second (local) event (to the southeast of Cairo more likely beneath the Nile valley) causes severe damage in the Nile Delta (frequencies in the range from 2 to 10 Hz), but not life losses and may create strong water oscillations, that threw all boats on the Nile banks and parted the water leaving the bed briefly visible.

The events of 1847, 1926, 1992, 1995 and 1996 can be used to define the differences between the effects of moderate local, and large distant earthquakes.

The events of 1847 and 1992 are moderate local earthquakes, i.e. similar to that proposed by Sieberg (1932). The reported damage for these two earthquakes are very similar to that reported on 1303. For example, the earthquake of October 12, 1992 was felt in large parts of Egypt (from Aswan to Alexandria) and practically in all parts of Israel. It was followed by a series of aftershocks that were widely felt for over 30 days. Some inhabitants refused to go back home and spent the first few nights outdoors. The maximum damage was reported from the Nile Delta and Nile Valley. At least 541 people were killed, 6500 people were injured and 8300 buildings were damaged or destroyed in the Cairo area alone (El-Sayed, 1996). More than 1000 Egyptian schools and many historical Egyptian constructions, e.g. mosques and temples, were damaged. Preliminary estimates indicate losses of about 300 million US$.

The events of 1926, 1995 and 1996 are larger distant earthquakes (magnitude 7.4, 7.3 and 7.0, respectively), i.e. similar to that proposed by Ambraseys et al. (1994). In the case of 1926, 1995 and 1996 events there was isolated damage in the Nile Delta, which can be mainly due to the poor quality of building and to local soil conditions. For example, the event of November 22, 1995, (at a distance of 300 km from Cairo) with magnitude 7.2 and depth of 14 km, has been strongly felt in Palestine, Israel, Jordan, Saudi Arabia and in Egypt, causing a minor damage at three houses in the Nile Delta. This event was followed by hundreds of aftershock with magnitude as large as 6.9 that were not felt in Egypt. Therefore, the aftershocks sequence that have been felt on 1303 only in Egypt for 20 days supports that the mainshock was in the vicinity of Egypt.

Another example of large distant earthquake is, the event of 21 July 365 in the Hellenic arc (Ambraseys et al., 1994). This event was associated with a very strong tsunami: in Alexandria over 50,000 houses were flooded and more than 5000 people were killed (see Ambraseys et al., 1994). According to our calculation (Table 2) this strong tsunami could be explained by an event of magnitude larger than 7.5. There was no severe damage reported on land in Egypt or elsewhere due to this earthquake and this is in agreement with our computations that predict mostly long-period motion in Egypt from an event in the Hellenic arc.

In the recent past, a similar situation is reported by the sequence of earthquakes with magnitude up to 5.5 that begun to struck the Gulf of Aqaba and northern Red Sea, on July 30, 1993. After 40 min from the first shock of the sequence, an earthquake with $mb = 6.1$, struck Sudan (about 1500 km from the first shock). These earthquakes have caused isolated damages in Egypt and Sudan, and have been widely felt in Saudi Arabia and Jordan. If we mimic the location procedure followed with historical events, for which a difference in the origin time of less than one hour can hardly be detected, i.e. if we use only the global damage distribution, we could conclude that a single large earthquake occurred in the Northern Red Sea. Similar situation occurred on February 23, 1995 and October 9, 1996.

5. Conclusions

The damage distribution, tsunami and duration of shaking, reported on the 8th of August, 1303 in the Eastern Mediterranean is very different from that caused by other events located in the Hellenic arc. It seems difficult to explain all the reported phenomena considering only one source, while it is much easier to explain most of the observations when two events with different location and origin time are considered. One event, likely multiple events with magnitude between 7.0 and 7.5, depth 10–15 km and normal faulting mechanism, can explain the observed tsunami (at 6 sites) and the extensive damage in Crete, Rhodes, Alexandria as well as the low damage in Palestine, Jordan, Syria, Turkey and Cyprus. The other earthquake is a moderate event that occurred very likely to the south of Cairo, beneath the Nile valley. The strong water oscillation, short period effect, and extensive damage in Cairo and along the Nile valley can be explained by this event, whose focal depth (between 15 and 20 km) and mechanism could have been similar to the earthquake of 1992.

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