Chapter 25
Seismological and Remote Sensing Studies in the Dead Sea Zone, Jordan 1987–2021

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Abstract The Dead Sea area is draining massive tourism and infrastructure investments. However, the area is prone to both induced anthropogenic and natural geological hazards, with indicators requiring innovative monitoring. Hazards are resulting from the zone's plate boundary tectonic setting and seismicity added to the generalized subsidence and sinkholes proliferation related to decades of accelerating water level lowering of this terminal lake.

The Jordan Dead Sea Transform Fault System (JDST) is an N-S trending and ~ 1000-km-long plate boundary that accommodates ~5 mm/year. left-lateral slip. We focus on the main research results concerning the whole spectrum of destructive seismicity components, i.e. Instrumental, historical, archaeo and paleoseismicity. Field investigations in earthquake geology and paleoseismology point out the identification of seismic gaps with long-term temporal quiescence reaching 851 years on the Jordan valley fault segment compared to 988 years for the Missyaf fault segment of the JDST further north in Syria (as per the year 2021). Destructive historical and instrumental seismicity were subjected to careful robust revision processes. The repetition of seismic events and related earthquake faulting parameters suggest a high level of seismic hazard and risk along the JDST.

From 1992 onwards, research based on space remote sensing techniques, Geographical information systems, and field data collection has been undertaken to develop a predictive model for salt karst hazards along the Dead Sea coast.

Radar and optical image processing produced images capable of being interpreted in a geographic information system (GIS).

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The field observations were systematically georeferenced using a GPS and then imported into the GIS to be analysed with the processed satellite images. Each independent data source was used to establish an explanatory model for the prediction of areas at risk of collapse.

This approach has been improved over time due to the arrival of an ever greater number of optical and radar images. Image resolution has also increased, allowing inventories of sinkholes, especially in the most dangerous locations.

This Chapter contributes in filing the gap in the seismological, and remote sensing studies necessary to the sustainable preservation of this world class cultural heritage zone, the safe economic upgrading of the area and the safety of its inhabitants and visitors.

Keywords Dead Sea fault · Paleoseismicity · Radar interferometry · Seismicity · Sinkholes · Subsidence

25.1 Introduction

The Jordan Dead Sea Transform Fault System (JDST) is a north-south trending left lateral strike slip known as the Levant fault zone(Abou Karaki, 1987). It is a documented plate boundary of the transform type (Abou Karaki, 1987; Garfunkel et al., 1981; Meghraoui, 2015; Wilson, 1965). The JDST forms the limit between the Arabian and African (Sinai) plates accommodating the northward motion of Arabia to the east in relative to Africa to the west (Fig. 25.1a). Both plates show a northward movement toward Eurasia with different rates, the Arabian plate rate being about 18–25 mm/year. and the African plate having a slower movement rate of about 10 mm/year. (Reilinger et al., 2006). The JDST extends for about 1000 km passing through the Dead Sea. The Transform connects the Red Sea developing mid-oceanic ridge south of the entrance of the Gulf of Aqaba in the south to the triple junction area to the north in Turkey where it joins the East Anatolian Fault (EAF) and the Cyprus Arc (CA). In its north central part in Lebanon the JDST bends rightward and become oriented N30°E, and across Syria the northern segment trends N–S and bends towards NNE showing splays into several small fault segments (Fig. 25.1a) in southern Turkey (Westaway, 2004). A rate of left lateral displacement of 4 to 7 mm/year. has been estimated by several geological and geodetic studies along the JDST (Alchalbi et al., 2010; Ferry et al., 2007; Gomez et al., 2007; Le Béon et al., 2008; Meghraoui et al., 2003; Pe'eri et al., 2002; Wdowinski et al., 2004).

Geological and geomorphological studies show that the JDST is not acting as a tectonic structure with uniformly distributed deformation. We observe a difference in total motion between the south and the north segments of the transform: and also in the historical seismicity (Abou Karaki, 1987): a total cumulative sinistral slip of about 107 km has been documented along the southern part of the fault (Wadi Araba) and was accumulated 15–20 Ma since, when the JDST was initiated in the Middle Miocene (Freund et al., 1968; Quennell, 1958). In the northern part of the

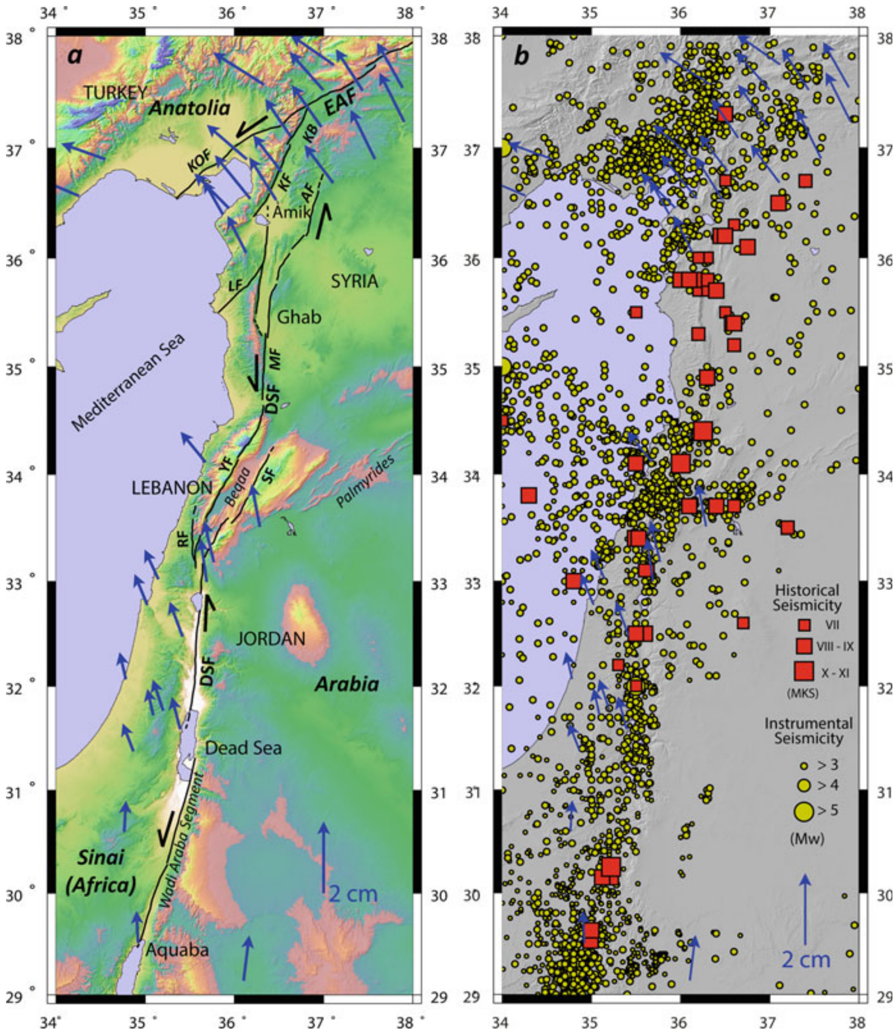

Fig. 25.1 (**a**) The Dead Sea fault segments, Fault mapping and slip rates from (Gomez et al., 2007; Khair et al., 2000; Meghraoui, 2015; Westaway, 2004) Abbreviations for some key tectonic features: *AGF* Al-Ghab fault, *AF* Afrin fault, *CA* Cyprus Arc, *KB* Karasu basin, *KF* Karasu fault, *KOF* Karatas-Osmaniye fault, *LF* Lattakia fault, *DSF* Dead Sea fault, *EAF* East Anatolian fault, *MF* Missyaf fault, *SF* Serghaya fault, *RF* Roum fault, *YF* Yammuneh fault. (**b**) Instrumental seismicity of the Dead Sea fault between 1964 and 2011, M > 3. Data are from: IRIS; Incorporated Research Institutions for Seismology (http://www.iris.edu/hq/), ISC; The International Seismological Center (http://www.isc.ac.uk/) and NEIC; The National Earthquake Information Center. The seismicity depending on international organizations lists for this area's earthquakes of magnitudes <4 is misleading. The clusters of yellow "epicenters" around (30°N, 36.4°E and 31.2°N,36.4°E) are most probably explosions these areas correspond to the "Phosphate Mines Co." locations of Al-Shidiah and Al-Hisa exploitation areas south of Jordan respectively where up to 10 Tons of explosives are detonated frequently on routine basis in the framework of the industrial exploitation of the mines. See Fig. 25.5b

system (Lebanon, AL-Ghab and Karasu basin; Fig. 25.1a) the total documented amount of slip is 70–80 km (Chaimov et al., 1990; Freund et al., 1970; Westaway, 1994; Westaway, 2004) which suggests that the difference in total motion between north and south along the JDST is at least ~25 km. This value was justified by the existence of the Palmyride fold belt and the Serghaya and Beqa'a faults (Ambraseys & Barazangi, 1989; Khair et al., 1997; Westaway, 1994).

25.2 General Seismotectonic Setting

The JDST consists in the north and the south zones (Fig. 25.1a) connected to each other by an active transpressive zone: the restraining Lebanese bend (Griffiths et al., 2000, Gomez et al., 2007). The principal issue is the ~25 km difference of accumulated slip rate between the northern and southern parts of the fault (Chaimov et al., 1990; Freund et al., 1970; Westaway, 1994). The JDST was divided into five major segments (Wadi Araba, Jordan Valley, Albeqa'a basin, Ghab Basin and Karasu Valley) (Khair et al., 2000); the segmentation was proposed due to the difference in geometry, geomorphology, geology and seismicity of each part (Fig. 25.1b). All these segments have N-S trending in general with small deviation to the NNE for the central and the northern segment of the fault.

The tectonic markers of Quaternary deformation are observable at all scales and on all sections along the JDST. Using the geological and geomorphological maps, the linear shape of the fault affecting late Pleistocene and Holocene deposits can be identified on Landsat, SPOT, and QuickBird satellite photographs as well as on aerial photographs. In the southern part the JDST zone crosses the western edge of the Gulf of Aqaba and extends further north for about 40 km crossing fluvial and alluvial terraces of Avrona Playa and the Wadi Araba Valley. Several fault branches outcrop showing normal geometry in this area, but they may result from the slip partitioning on branches of the main JDST (Niemi et al., 2001).

To the north, except for the accumulation of sand dunes that conceals the fault zone around latitude 30°N, the fault can be seen to affect successive stream channels and terraces. In the northern half of the Wadi Araba, the DSF fault exposes outstanding tectonic geomorphology with linear fault scarps showing offset alluvial fans and channels visible until the south eastern edge of the Dead Sea (Barjous & Mikbel, 1990). The southern end of the DSF meets the Gulf of Aqaba that shows NNE–SSW trending relay fault system with large pull-apart basins in the sea bottom that may act as a geometrical barrier that limits the Wadi Araba fault zone to the south. Indeed, the DSF including the Wadi Araba section is about 200-km long if we include its extension in the eastern edge of the Dead Sea area (Fig. 25.1a), it may constitute a single fault segment or two distinct segments if a major geometrical complexity (relay zone) is hidden below the mid-distance sand dunes.

25.2.1 Dead Sea Area Fault Segments

25.2.1.1 Wadi Araba

Wadi Araba is the southern part of DSF that starts from the Red Sea (Aqaba Gulf) at 29.5° N and extend for about 160 km till the basin of the Dead Sea at 31° N (Fig. 25.1a) (Klinger et al., 1997, 2000a). Along this segment, the fault have a sharp morphological discontinuity that can easily be traced across the Quaternary deposits and alluvium sediments, excluding where the fault is covered with sand dunes or cuts across very recent alluvial terraces. The principal fault is rather straight, striking N20° E, and showing limited structural discontinuities, with a simple geometry is reliable with basically pure strike slip motion (Meghraoui, 2015).

An estimation of the slip rate along Wadi Araba segment based on time varying geodetic study (GPS) of 4.9 ± 1.4 mm/year. was given by (Le Béon et al., 2008), this value rely on 6 years of time span and a locking depth of 12 km.

Regarding the historical seismicity catalogs, few seismic events are reported during the last 2000 years along the Wadi Araba. The largest reported events occurred in AD 1068, 1212, 1293 and 1458 (Abou Karaki, 1987; Abou Karaki et al., 1993; Ambraseys et al., 1994; Klinger et al., 2000b) These events seem to be smaller than the 1995 earthquake which struck the Gulf of Aqaba with a Mw ~ 7.3 (Abou Karaki, 1987, 2001a, b).

25.2.1.2 Jordan Valley

The N-S trending Jordan Valley extends for about 180 km between the Dead Sea pull-apart basin at 30.7° N and the Hula Basin in the north before connecting with the Lebanese restraining bend at 33.1° N. The northern end of this segment attests in the division of the fault into many fault branches trending toward the NNE, the Serghaya, Rashaya, Hasbaya, and Yammuneh faults (Fig. 25.1a). This segment is connecting the two pull-apart basins of the Dead Sea and the Tiberiade Lake. It was the object of paleoseismologic and geomorphologic studies which estimated its slip rate to be ranging from 2.5 to 10 mm/year (Galli, 1999; Marco et al., 1997).

The largest estimated magnitude for the paleoearthquakes in the Jordan Valley segment is Mw 7.3 (Ferry et al., 2007). Studies of macroseismic damage from historic events and archaeological evidence conclude that several large destructive earthquakes (Ms > 6) occurred in the northern Jordan Valley segment during the past 2000 year (Abou Karaki, 1987; Ambraseys et al., 1994; Guidoboni et al., 1994; Guidoboni & Comastri, 2005; Marco et al., 2003).

25.2.2 Paleoseismicity

The Levant area is one of the oldest inhabited regions of the world and by consequence it has among the richest written history, including on earthquakes. The Earthquakes as any other well-known natural events were recorded and described carefully. The old documents describe the earthquake effects on nature and man-made structures, such as faulting rupture, co-seismic deformation, landslide, springs appearing and disappearing, lives casualties, houses destruction, . . . etc. This allows us to have, nowadays, a very rich earthquake catalog for more than 3000 years in the region (Abou Karaki, 1987; Ambraseys, 2009; Guidoboni & Comastri, 2005; Sbeinati et al., 2005).

The Dead Sea area has the characteristics of a large pull-apart basin (100-km long, 17-km wide) limited by two north striking segments, the southern Wadi Araba fault zone and the northern Jordan valley fault segment. The latter segment follows the Jordan River, extends from the Dead Sea (right bank of the Jordan River) to the Tiberiade Lake and is made of a succession of 10–20-km-long subsegments (mostly on the left bank of the Jordan River) for a total length of 110 km. In the valley, small pull-apart basins and restraining bends limit the subsegments and show left-lateral slip of stream channels (Fig. 25.2a, b) (Ferry et al., 2007; Ferry et al., 2011).

25.2.3 Archaeoseismicity

The richness of exposed JDST and archaeological sites along the Jordan Valley constitutes an exceptional advantage for dating prehistorical earthquakes. There are about 120,000 recognized archaeological sites in Jordan, forming part of the cultural heritage of this open museum country. The number is expected to reach half a million sites after the introduction of new survey techniques. Most major Jordanian archaeological sites and other ancient sites in the neighbourhood of the JDST show evidences of earthquake related damage, often historically documented as well, some of these sites located in the immediate neighbourhood of the DSF have already been subjected to archaeoseismicity investigations (Galli, 1997, 1999; Galli & Galadini, 2001; Klinger et al., 2000a, b; Niemi et al., 2001; Niemi & Smith, 1999). More specifically. The areas of Aqaba (South of Wadi Araba), Petra (Middle of Wadi Araba), Dahl (northern Wadi Araba), Jerash, Amman (East of the Jordan valley), Umm Quais and Tabkat-Fahl (Northern Jordan Valley) represent a set of places singled out as a result of previous historical seismicity studies. All were affected by relatively large historical earthquakes of equivalent Mw 7.0 $\pm$ 0.5. during the last 2000 years. Field investigations revealed left-lateral faulting of the following archaeological sites: a total of 2.1-m offset walls of a Crusader castle during the 20 May 1202 and 30 October 1759 earthquakes (Ellenblum et al., 1998); the offset of walls in the Tiberiade area during the 18 January 749 earthquake (Marco et al., 2003); at Tell Saidiyeh and Ghor Katar in the Jordan Valley paleo-earthquakes have been identified in 759 B.C., 1150 B.C., 2300 B.C., and 2900 B.C. (Fig. 25.2a, b) in (Ferry et al., 2011), the 2.2-m offset wall of Qasr Tilah that can be related to an

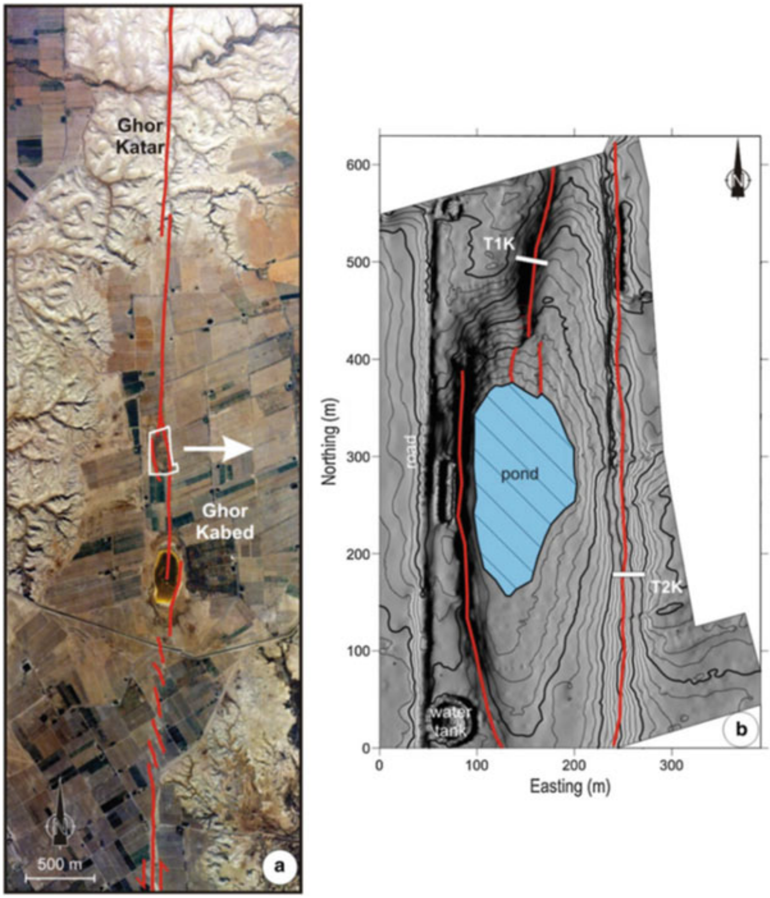

Fig. 25.2 (a) The Jordan valley fault (red lines) seen on an aerial photograph that exposes small pull-apart basins with left-lateral en echelon fault structures and stream channel offsets (at Ghor Katar), (**b**) Paleoseismic site with at Ghor Kabed pull-apart basin with high-resolution topography and fault branches affecting the Lisan lacustrine deposits (see also trench sites TK1 and TK2 in (Ferry et al., 2011))

earthquake event in 608–826 AD (Klinger et al., 2000a, b); the cumulative offset of the Roman–Byzantine–Islamic Qasr Tilah site of the northern Araba valley during the 634 or 659/660, 873, 1068, the minimum 1 m vertical slip of a qanat during the 1068 earthquake on the southern DSF near Eilat (Zilberman et al., 2005). These archaeoseismological studies of the JDST are complemented with tectonic geomorphology and paleoseismic investigations that constrain paleoearthquake faulting episodes and slip rates. In trenches, radiocarbon dating brackets the 1759 earthquake on the northern Jordan valley fault segment and the Serghaya fault branch through 3D trenching with 0.5 and 2.5-m left-lateral slip, respectively (Gomez et al., 2003; Marco & Agnon, 2005). Faulting of the 749 earthquake of the Jordan valley segment is resolved at Beyt Zayda (north of Tiberiade Lake) and Tell Saidiyeh (south Jordan valley) paleoseismic sites (Ferry et al., 2011; Marco & Agnon, 2005). The longest paleoseismic records on the JDST are determined in the Jordan valley with a sequence of 12 coseismic surface ruptures over the last 14 ka (Ferry et al., 2011). Although the correlation with individual fault segments is problematic, another source of earthquake records in the Dead Sea lake sediments and speleothems indicates a succession of seismites (El-Isa & Mustafa, 1986), synchronous to historical earthquakes in 1927, 1293, 1202/1212, 749, 551, 419, 33 AD and 31 BC and mid-second century BC (Kagan et al., 2011; Marco et al., 1997). From recent paleoseismic trenching (Klinger et al., 2015; Meghraoui, 2015) identified faulting events along the southern DSF in the Wadi Araba, which can be correlated with past earthquakes in 1458, 1212, 1068, and 363 AD, in addition of one faulting event bracketed between 806 AD and 1044 AD.

In conclusion, field investigations and studies in earthquake geology and paleoseismology conducted in the frame of the APAME Project (2003–2007) and other or subsequent studies point out the identification of seismic gaps with long-term temporal quiescence reaching 988 and 851 years (as per the year 2021) on the Missyaf fault segment in Syria and the Jordan valley segments of the JDST. The repetition of seismic events and related earthquake faulting parameters suggest a high level of seismic hazard and risk along the JDST including the Jordan Valley.

25.2.4 Historical Seismicity

The great importance of genuine historical seismicity catalogs, has been well recognized (Ambraseys, 1971). In our region, for historical and cultural reasons as the center of the ancient world civilizations and birthplace of writing, a wealth of Historical Seismicity material exists. This has been emphasized in many modern works (Abou Karaki, 1987, 1992, 1995a, 1996a, b, 1999; Al-Ghunaim, 2002; Amiran et al., 1994; Ben Menahem, 1991; Ghawanmeh, 1990; Guidoboni et al., 1994; Guidoboni & Comastri, 2005; Poirrier & Taher, 1980; Sbeinati et al., 2005). It is also necessary to recognize the importance and contributions of pioneering works of a great number of historians and scientists who compiled historical earthquake lists and catalogs, Impressive lists and references of these works is found in (Vered & Striem, 1977; Willis, 1928, 1933).

Nevertheless, rigorous analysis of the historical seismicity information in our area clearly demonstrated that most lists were contaminated by a variety of chronological and interpretation errors, some of them heavily, thus, to be fully useful historical seismicity lists need to be reassessed on detailed, objective and robust basis (Abou Karaki, 1987, 1995a), this was done as briefly introduced hereafter.

25.2.4.1 The General Mechanisms at the Origin of the Historical Seismicity Errors

Abou Karaki (1987, 1992, 1995a) defined the following, general, and in some cases, systematic causes and mechanisms of errors which led to a wide scale contamination of the historical seismicity catalogs depending mainly on Arabic manuscripts and documents in the Middle East and parts the wider Mediterranean and far East areas.

Timing and Chronological Calendar Systems Related Errors

The first step and most important factor for the correct identification of a historical earthquake is to accurately determine its time of occurrence. Any duplication of the timing may result in a direct duplication of the earthquake in future compilations and catalogs. The typical negative implications of this, are of some wide range consequences for seismic hazard evaluations and understanding of earthquake generating processes in the area. We agree that the greatest part of historical seismicity information related to this area, is provided by Arabic documents, manuscripts and chronicles, as was noticed by Ambraseys et al. (1994) p.7 "Arabic chronicles are the primary source for the history of the Middle east, and certainly for its earthquake history, from the ninth century at least until the end of the seventeenth centaury". However, the time window that looks like a restriction, is without any practical consequences because the core part of the area's available historical seismicity information is concentrated within the upper mentioned time interval specified in (Ambraseys et al., 1994) It is also well known that this area is characterized by the multiple aspects of its cultural heritage diversity. The area adopted a number of chronological calendar systems. Different calendars may have been simultaneously in use in a same place (Village, city, region, or stat). Hence a same and one earthquake may be reported from the same region associated with two or more dates in different calendar systems representing the same absolute point in time. Moreover, When a calendar is changed or modified at a certain point in time, usually following an important historical event, or simply, decision, in a given part of the area, chronicles did not uniformly follow the new style right away in all localities of the region. By far, the most important problem resulting in event duplications is the confusion between calendar systems in later compilations, and ambiguities related to this issue, a somewhat more complex case, is the more or less inaccurate careless date transformations between calendar systems. We identified six main mechanisms led to an equal number of error types in the historical seismicity of the area. These were defined by Abou Karaki (1987, 1992, 1995a) and further developed in this work, as follows:

Type I Errors

Instead of one genuine original earthquake, the date of which is eventually given in two different calendar systems, the earthquake is wrongly associated with two different dates given in one of the two calendar systems, e.g. the earthquake of the year 598 AH (After Hijra Muslim lunar Calendar) which is the same of 1202 AD, figuring in a catalog as two independent earthquakes associated respectively with the years 598 AD and 1202 AD, or, although less frequently, to 598 AH and 1202 AH)). Tens of such "earthquakes "that we call "false earthquake twins, or simply, *twins*" figures in Willis's list in his work of 1928, these errors were copied and passed on within the global seismicity lists of Seiberg in 1932 (Willis, 1933), such errors were corrected partially (rather inaccurately, and too late) in 1928 (Willis, 1933) then (Ambraseys, 1962).

Type II Errors

This type of errors refers to *twins* resulting from an inaccurate date transformation between calendar systems. This provides an explanation to the case of many major earthquakes with reasonably similar locations, effects, and descriptions occurring within ±2 years from each other in a given section of the fault, a clear example on this is found in the work of Taher (1979) (Taher, 1979). The earthquake of the month of Ramadan 130 AH is wrongly associated to the year 747 AD the correct year corresponding to the month of Ramadan in the year 130 or 131 AH should be 748 or 749 AD In some existing or future "complete" catalogs the years 746, 747, 748 and 749 AD would be listed as major earthquakes happening in almost the same geographic area. So the existence of two major earthquakes occurring in the same area and associated with the years 747 AD and 748 AD if given in a historical seismicity list would be the result of a type II error.

Type III Errors

This type of errors refers to a confusion between BC and AD dates. A full example illustrating this type of errors is shown in Table 25.1.

Type IV Errors

This is another source of timing errors potentially leading to multiple duplications in the historical seismicity catalogs. It refers to the difficulty to determine the exact year in the original manuscripts and historical seismicity primary sources, due to the frequent use of abbreviated numbers to represent the date in the original text. In many Arabic original manuscripts the full number representing the year of occurrence of a given event is in fact given partially. So a statement like "there was an earthquake in the year 37" might mean 37 AH or 137, 277,. . ., or 1437 AH and so on. Victims of such errors are typically those who depend upon translated short pieces of an original text. To overcome this problem, it was often necessary for us to perform the time consuming task of carefully reexamining a number of pages before

Table 25.1 An example illustrating the historical seismicity error type III, 2 independent earthquakes are listed instead of one

Date	Description	Io	ML	Type III EError in
525 BC	Of coast Sur, Sidon greatly damaged.	XI	7.5	Ben Menahem (1979)
525 AD	Of coast Sidon	IX-X	6.7	Ben Menahem (1979)

Notice the difference in the magnitude evaluations of Ben-Menahem (Ben Menahem, 1979), corresponding to this one and same earthquake and/or after a given purely pertinent description of the effects of an earthquake to find or clearly deduce its correct year of occurrence.

Manuscripts Reproduction Related Errors (Type V)

The only way to reproduce manuscripts was to recopy them manually, often by others than the original author. Different versions exist derived from an original work. The famous work of the Muslim tenth century paleographer Jalal-Eddine Al-Suyouti exists in twenty copies of variable qualities (Al-Sadani, 1971) p. XVII). One of them, namely that of the British Museum library, Ms. No. 5872, is known to be incomplete and to have some lack of accuracy problems (Al-Sadani, 1971) p. XIV). To illustrate this kind of difficulties by an example, the earthquake of 11 March 1068 AD is said to have destroyed the totality of Ramla except 2 *"houses"* (in Arabic *DARRAN*) in one manuscript or except 2 *"lanes"* (*DARBAN*) in another copy. The process of copying tend to produce, propagate and amplify errors. However this is not the only aspect of the problem, the ancient Arabic writing style is much more difficult to read and interpret. Recognizing the correct signification of a written word which could have a number of very different meanings is a matter of habit, training and context. Old style writing means more difficulties at least as far as the habit factor of the reader is concerned.

Erroneous Seismological Quantifications Based Upon Inaccurately Translated or Understood Texts (Type VI):-

This is best represented by the following case; Taher (1979) (Poirrier & Taher, 1980) presented "A full corpus of texts from Arabic sources and a summary French translation". This work is considered to be "By far the most valuable compilation of material on the seismicity of the region" Ambraseys et al. (Ambraseys et al., 1994, p.7). Although we agree with the general ideas implicated by the upper mentioned statement, it is necessary to say that some parts of Taher's translations were potentially very misleading from the seismological point of view. In his revision of the area's seismicity, Abou Karaki (1987) gave the following example concerning the earthquake of the year 425 AH = 1033 AD, Taher's French translation of part of the Arabic text concerning that earthquake began as follows *"Cette annèe un très violent tremblement de terre ravagea la Syrie et l'Egypt = This year a very violent earthquake ravaged Syria and Egypt"*(Taher, 1979) p. 35). A more accurate and faithful translation of the Arabic text would in fact be *"This year there was an increase (or multiplication) of earthquakes in Syria and Egypt"*(Abou Karaki, 1987), p.131). It is clear that the first seismologically erroneous translation would give a much higher magnitude for "the earthquake", if a magnitude calculation operation based on that translation and the "radius of perceptibility" concept is "committed". The work of Taher (1979) was the basis of the parametric-macroseismicity information catalog of Poirrier and Taher (1980). Despite the inaccuracies "It nevertheless remains the most authorative and reliable list of events in the region up to 1800, thanks to its reliance on primary sources" that was the opinion expressed by Ambraseys et al. (1994). However we think that primary sources when they exist are not quite enough, it should be mentioned here that "Taher's work is the starting point for (Ambraseys et al., 1994) retrieval and reassessment of historical information" (Ambraseys et al., 1994, p. 11). Our revision of Poirrier and Taher's work of 1980, and the application of Abou Karaki's algorithm for the detection of errors in the historical seismicity catalogs of the Arab region, (Abou Karaki, 1987, 1992, 1995a) allowed us to discover that 59 dates out of 240 ones associated with the historical earthquake's list of Poirrier and Taher (1980) are in fact erroneous. Some quantifications and interpretations are not less erroneous and misleading, and have already injected new ambiguities in the historical seismicity domain of this area. One example is provided by examining the following statement concerning, once more, the earthquake of March, 18th 1068 AD in Poirrier and Taher's remark "d" (Poirrier & Taher, 1980) p. 2199 (which should be "c" by the way) they wrote "*Al Djawzi reports that at Khaibar, the ground opened up and treasures were revealed. As Sayouti reports that at Tayma, the ground opened up. These features of ground deformation, usually restricted to the epicentral zone, plus the widespread destruction in Arabia suggest that this was an intraplate earthquake with its epicenter in Arabia despite the fact that there were sea waves on the Egyption and Israeli coasts. Perhaps we are dealing here with two close seisms*". Independently "?" of this statement Ambraseys and Melville (1989), and later Ambraseys et al. (1994), also enhanced this ambiguity by presenting a somewhat "artificially" strong case for the major 1068 AD earthquake along with two other less "well" documented ones (873 AD, 1588 AD) to be considered as intraplate earthquakes taking place inside northwestern Arabia, more than 150 to 250 km east of the nearest plate boundary zone in the area. This aspect along with other various sources of errors will be briefly discussed under our description and revision of the following case.

25.2.4.2 The "Ramla" Earthquake of 11 Jumada I, 460 AH, March 18, 1068 AD

We briefly show results of our revision processes and analysis as applied on the case of the Tuesday, 11 Jumada Al-Awla 460 AH 18 March 1068 AD well documented earthquake. This historical earthquake is reported in primary sources of Arabic documents and manuscripts, to have destroyed Ramla in Palestine (causing 15,000 to 25,000 causalities, mostly at Ramla as a result of a tsunami following the earthquake), and to have destroyed Ayla (modern Elat and Aqaba with the death of all but 12 of its inhabitants, Banyas to the North in southwestern Syria, suffered 100 casualties), and to have affected parts of Egypt, northwestern Arabia and Iraq. However the earthquake is referred to in most Arab manuscripts and primary sources as the earthquake of Ramla.

Our Analysis of some modern works revisiting the March, 18 1068 AD earthquake show important problems in interpreting the earthquake effects with some degree of information manipulation freely practiced on the historical data in other contributions as well. Some of the historical seismicity information has clearly been misinterpreted. We detected in a number of otherwise, usually "Authorative" historical seismicity works (Ambraseys et al., 1994; Ambraseys & Melville, 1989), a clear tendency and efforts to maximize the destructive effects of this earthquake in Arabia and to minimize these effects in Ramla and elsewhere. This led to shifting of the earthquake's epicenter hundreds of kilometers from the southern part of the JDST to northwestern Arabia near Tabuk about 250 km far away from the nearest recognized "axis" of the plate boundary. However, the simple plate tectonics and seismogenic sources basic principles are also certainly not in favor of the new location. The Ambraseys approach in dealing with historical texts was further criticized by a specialist "The Translations of Ambraseys were not complete, he altered the description of events in a way incompatible with the way ancient historical text should be treated" Al-Ghunaim (2002) p. 27. This led to very serious location and timing problems for this major earthquake that we examine hereafter.

Location Problems of the Earthquake of Ramla 18 March 1068 AD

Table 25.2 gives a synoptic summary allowing at this stage to compare between what we consider as the more realistic accounts concerning the Ramla earthquake affects and locations (Ambraseys, 1962) and the somewhat artificial radical evolution of ideas concerning this earthquake's description and location as revisited in (Ambraseys & Melville, 1989; Ambraseys et al., 1994).

Table 25.2 Showing the extent in the location evolution of the 1068 AD earthquake

Description after Ambraseys (1962) (Ambraseys & Melville, 1989)	Description after Ambraseys et al. (1994)
An earthquake in Palestine. Ramla was destroyed; it extended to the Hejaz. It reached also Wadi-el-Szafrh (Safra), Khaibar, Bedr (Badr), Yanbah(Yanb'u), Wadi Kora,Teima and Tabuk, and it extended as far as Kufa, **only two houses remained and 25,000 persons perished**	**A major Earthquake in the Hejaz and northern Arabia**...killed in all about 20,000 people. Aila was completely destroyed with all but 12 of its inhabitants. In Tabuk, three springs of water appeared and in Taima the ground was "split open." Near here a spring of water gushed out. The earthquake was felt at Khaibar, Medina (where the shock brought down two decorative crestings of the mosque of the prophet), Wadi al-Safra, Wadi al-Qura, Badr, and Yanbu'...**the earthquake was strong enough in Palestine to damage al-Ramla and ruin many houses with loss of life.** Damage was reported from Baniyas, where about 100 people were killed
In conclusion, it is clear from the comparison of the 2 texts (the **bold** parts in particular) that there was a shift of ideas implicating a serious shift of emphasis which led to a transfer of this earthquake's probable location from the DSF to a none probable one somewhere in Hejaz and northern Arabia. It should be mentioned that first hints implicating a new location of this earthquake to be in Arabia were suggested by (Ambraseys & Melville, 1989)	

This evolution is unjustified when closely examined after the original Arabic primary sources

A possible hint and clue towards an explanation of the inherent cause of this transfer of location to Arabia may be in the following “It is a shame, in a sense, that there are not more earthquakes to record in Saudi Arabia itself, and that the focus of our attention has thus strayed inevitably to the surrounding regions.” Ambraseys et al. (1994) page xix. Who also admitted the lake of robustness of the earthquake’s location in Arabia later elsewhere “A major event in 1068 in the Hejaz in north-western Arabia is unusual not only because of its location but also because of the evidence admittedly slight, suggesting a surface rupture. The location of which must be sought in the region of Tabuk”. Ambraseys and Jackson (1998) p. 399 point 9. It should be stressed that the reported “surface rupture” is not at all credible, the primary source this was based upon put it this way “Al Djawzi reports that at Khaibar, the ground opened up and **treasures were revealed**” (Poirrier & Taher, 1980*)* p. 2199. An extensive compilation of the Arabic sources of the earthquake of Tuesday 11 Jumada I 460 AH = 18 March 1068 AD is found in Al-Ghunaim (2002) pp.117–120.

Timing Problems and False Twins Related to 1068 AD Ramla Earthquake

After the application of Abou Karaki’s algorithm for the detection of errors in the historical seismicity catalogs (Abou Karaki, 1987, 1992, 1995a), the following dates in various catalogs of the region must be regarded as very probably twins of false historical seismicity earthquakes 160 AH, 11 Jumada I 462 AH, 20 April 1067 AD, 20 April 1068 AD, 1069 AD, 2 Feb. 1070 AD, 25 Feb. 1070 AD, 26 Feb. 1070 AD.

These are all related to the Ramla 18 March 1068 AD earthquake, resulting from various possible errors populating a number of lists, references and catalogs, one or more of these or similar errors are still found and possibly propagating in the following works (Abou Karaki, 1987; Ambraseys, 1962, 2009; Ambraseys et al., 1994; Ambraseys & Melville, 1989; Amiran et al., 1994; Ben Menahem, 1979, 1991; Khair et al., 2000; Poirrier & Taher, 1980; Seiberg, 1932; Taher, 1979; Vered & Striem, 1977; Willis, 1928, 1933) a non-exhaustive list.

In conclusion, historical seismicity data was reassessed and subjected to an algorithm for the detection of errors in the historical seismicity catalogs (Abou Karaki, 1987, 1992, 1995a). Tens of false earthquakes were purged from the lists. The critical revision of the historical seismicity catalogs resulted in the following revised slim list Table 25.3.

25.2.5 Instrumental Seismicity of the DSF, 1900–2021, M ≥ 6

The first relatively nearby seismological station to the DSF was established very early in 1892 in Helwan Egypt, the second closer one started in Ksara in Lebanon in 1910, both along with 80 world stations recorded the Palestine (Jericho) earthquake of 11 July 1927 M 6 ¼ which caused more than 300 killed and widespread

Table 25.3 Historical seismicity list of the DSF for equivalent ~ M 6 or more based on a revised version of Abou Karaki (1987) and references therein

Date	φ°N	λ°E	Affected localities, intensity class, remarks	Io	Mag.	Fault segment (s) locations, remarks
31 BC	32	35.5	Qumran (2), Jerusalem(2), Jordan Valley	2	6.5	JVA (PS)
33 AD	32	35.5	Jerusalem	2	6.0	JVA
48	30	35.2	Jabal Rum, Petra, Tal El-Khalaifeh	2	6.5	WAR/GAQ
112	31.5	35.5	See Russel (1985).		6.5	WAR/JVA
19 05363	31	35.5	See Russel (1980), Guidoboni et al. (1994)	2	6.5	WAR/JVA
419	33	35.5	Safad (2), Aphek (2), Jerusalem (1)	2	6.0	JVA/BEQ
634/635	32.5	35.5	Palestine (30 days of Activity).		6.0	JVA
748/749 AD = Ramadan 130 AH. (or 131)	32	35.5	Jerusalem (2), Tiberias (2), Lod (2), Jerash (2), Jericho (2), Arad (2), Damascus (1), Syria (1), Egypt (1), Arabia (1), Mesopotamia (1)		7.0	JVA (PS) A minimum of 3 Shocks.
853/854	33	35.5	Tiberias	2	6.0	JVA
1033	32.5	35.5	Ramla, Tiberias, Jericho,Nablus Jerusalem, Akka, Gaza, Askalan	2 2	6.5	JVA
1047/48 439 AH	31	35.5	Ramla	2	6.0	Jordan Valley or Wadi Araba (JVA/WAR)
Tuesday 18 031068 AD 11 Jumada I 460 AH	31.5 30.0	35.5 35.0	Ramla (2), Banias (2), Jerusalem Aqaba (2), Tabuk (1), Tayma (1) Khaibar(1), Wadi Es Safra (1), Egypt (1)	2	7.0 6.5	WAR WAR or Gulf of Aqaba (GAQ)
24 121,105			Jerusalem	2	6.0	JVA
1156/59	31	35	Petra (2), Bethlehem (1), Egypt (1)	2	6.5	WAR
1160	32	35.5	St Jean Monastery	2	6.0	JVA
2 051212	30	35	Aqaba-Elat (2), Shobak (2), Karak (2), Cairo (2), Egypt (2)	2	6.5	WAR/GAQ
March/April 1260	32.5	35.5	Beisan (2), Galilee (2), Damascus (1)		6.5	JVA (Ambiguity) Abou Karaki (1987)
1261/1262	30	35	Karak, Shobak, Cairo		6.0	WAR
1269	32	35	Qualquilia (2), Imoisse (2), Sernour (2), Ballouta (2), Hajar al-Asher (2)	2	6.5	JVA, 8000 victims
January/ February 1293	31	35.5	Karak (2), Ramla (2), Gaza (1), Lod (1)	2	6.0	WAR
1458/1459	31	35.5	Karak (2) 100 victims in Karak	2	6.0	WAR

(continued)

Table 25.3 (continued)

Date	φ°N	λ°E	Affected localities, intensity class, remarks	Io	Mag.	Fault segment (s) locations, remarks
Jan 1546	32	35.5	Jerusalem (2), Hebron (2), Karak (2), Salt (2), Nablus (2), Jaffa (2), Gaza (2), Damascus (2)	2	6.5	JVA
5 01 1588	30	35	Aqaba (2), Cairo (2), Egypt, Sinai	2	6.5	WAR/GAQ
23 05 1834	32	35.5	East of the Dead Sea, Karak, Jerusalem, Gaza (2), Nablus (2), Askalane (2), Akka, Tiberias, Palestine, Syria	2	6.0	JVA
1 01 1837	33	35.5	Safad (2),Tiberias (2),Reineh (2), Ein Zeitoun (2),El-Jish (2), Sejera (2), Tyr (2),Sidon (2),Beirut (2), Damascus (2), Nazareth (1),Jerusalem (1),Hebron (1), Jericho (1), Tripoli (1).	2	6.5	JVA or north 5000 victims Asphalt Blocks in the Dead Sea.

Abou Karaki (1995a) 2 additional events (112 AD and 363 AD) were added from Russel (1980, 1985) and Guidoboni et al. (1994). Intensity classes 1 = Non-destructive [III, VI]. 2 = Destructive [VII-IX]. 3 = Very Destructive [X-XII]. Location errors of about ±1° are possible for the historical earthquakes, magnitude estimates for these earthquakes are generally minimum equivalent Ms. (Abou Karaki, 1987) The earthquakes listed in this catalog were individually discussed in Abou Karaki (1987) pp. 81–178. And 352–359. (PS) = C14 dated with additional Paleoseismicity evidences

destruction both sides of the DSF, the routine modern monitoring of the seismicity by a local network of seismological stations (Jordan Seismological Observatory, JSO) only started to operate East of the DSF in 1983. Just after the Institute of Petroleum Research and Geophysics (IPRG) based in Holon and operating west of the DSF. There were important location accuracy problems at the beginning of the JSO operations in particular (Abou Karaki, 1987). A number of swarms in 1983 near Haql at the gulf of Aqaba starting January 21, and in the Carmel Wadi El-Fara'a area in 1984 were analyzed and relocated (Abou Karaki et al., 1993; Abou Karaki, 1987, 1994, 1995a, b). Several earthquakes of these swarms were around ML = 5 the maximum magnitude did not exceed 5.2. Only 3 destructive or potentially destructive earthquakes occurred on the DSF during the instrumental period, their parameters are shown in Table 25.4.

To illustrate the revision processes aspect, we examine the results of our analysis as applied on the case of the earthquake of Palestine of 1927. The most destructive DSF earthquake during the instrumental seismicity era.

25.2.5.1 The Location of the Earthquake of Palestine 1927

The earthquake of Palestine (known also as the earthquake of Jericho), took place near the Damia area in the Jordan valley on the early afternoon of Monday 11-07-

Table 25.4 The M ≥ 6 class of instrumental earthquakes on the DSF

Date	φ°N	λ°E	Affected localities, intensity class, remarks	Io	Mag.	Fault segment (s) locations, remarks
11 07 1927	32	35.5	Nablus(2),Salt(2),Ramla(2),Jericho(2), Reineh(2). From Abou Karaki (1999)	2	6.2	JVA, Abou Karaki (1999)
03 08 1993	28.75	34.6	Aqaba- Elat 1, Haql 1, Cairo 1,	1	6.0	GAQ
22 11 1995	28.75	34.8	Nuweiba 2, Dahab(2), Haql (2), Aqaba-Elat (2), Tabuk (2) from (Abou Karaki, 2001a; Klinger et al., 1999).	2	7.3 *Mw*	GAQ (Abou Karaki 2001a)

The locations of the 1927 and 1995 earthquakes were fully discussed respectively in (Abou Karaki, 1999, 2001a). A brief reminder of the most destructive instrumental earthquake and related problems is reminded herein

1927, This Magnitude 6 ¼ earthquake, is still the most destructive earthquake since the earthquake of Safad back in 1837 AD on both sides of the river Jordan and the JDST. It caused more than 300 killed and widespread destruction. Figure 25.3 (Abou Karaki, 1987; 1999; Vered & Striem, 1977; Willis, 1928) and references therein. A reasonably accurate determination of this earthquake's epicenter is an important factor for a useful assessment of the seismic hazard in this part of the JDST. However, there were a number of new attempts to relocate this earthquake by applying rather modern location techniques using old data of questionable quality, recorded by that time seismological stations that were always suffering from known serious synchronization problems thus affecting the internal consistency of the different arrival times. A new calculated epicenter location resulted from those attempts (Avni et al., 2002; Shapira et al., 1993) clearly and anomalously shifting the location of the 1927 earthquake out of the main macroseismic area of damage. The quality of the new location (31.6°.0 N, 35°.4E) was analyzed, critically examined and finally assessed as being far less convincing than the old original ISS location (32°.0 N, 35°.5E) (Abou Karaki, 1995a)The main basis for the rejection of the new location could be seen on Fig. 25.3 and Table 25.4.

The (SAN) location Fig. 25.3 is a direct consequence of the lack of internal coherency in the data used as an input for the location computations. This is evidenced by examining the following elements:

The Earthquake was located assuming a normal depth and using the IASPEI travel time tables applied on data provided by 30 seismological stations. The calculated – observed residual values as derived from the data of Table 25.1 in (Shapira et al., 1993) were generally and unacceptably high. The nearest stations were (KSA) Ksara in Lebanon, situated at some 200 km north of the epicenter, has a calculated-observed residual of 4.6 s, and (HLW) in Helwan-Egypt at some 450 km south west of the epicenter has a residual of −2.5 s. 78% of the arrival times used in the computations yielded residual values (C-O) > |1.5 s| among these 22% were associated with (C-O) values > |4.0 s|. These elements show that the "new" epicenter

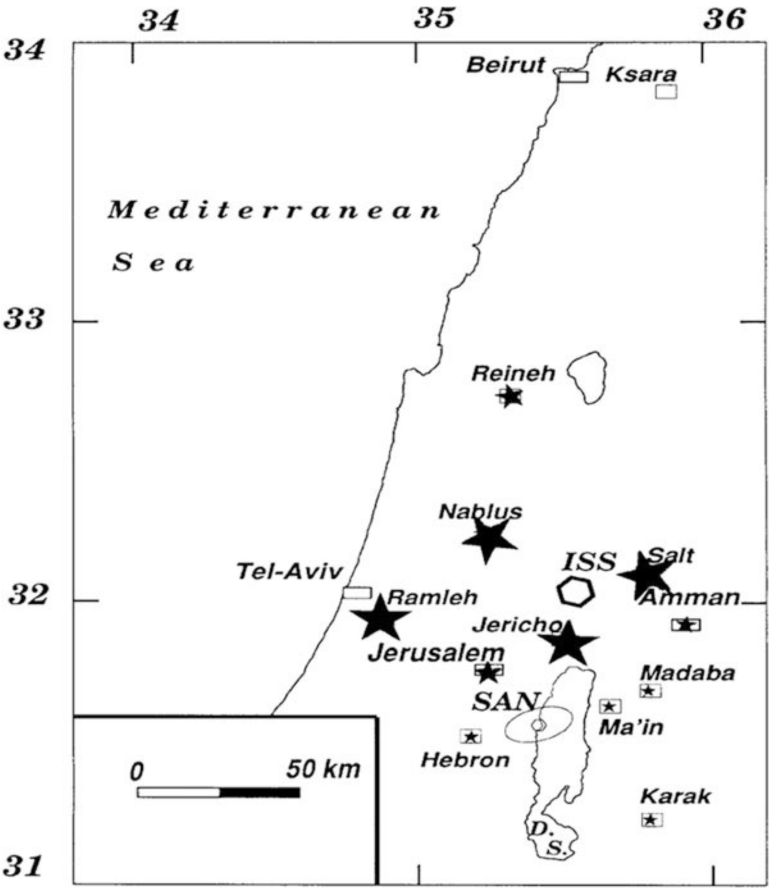

Fig. 25.3 Macroseismic effects of the earthquake of Palestine 1927 based on the best available primary sources (Abou Karaki, 1999). Damage proportional to the size of star, main destructive effects in Nablus, Salt, Ramla, and Jericho, minor damage in Hebron, Ma'in, Madaba. Original (ISS) epicenter location is shown. A new location, some 50 km to the south of the ISS location is also shown along with its "uncertainty ellipse" after (Avni et al., 2002; Shapira et al., 1993) (SAN). This location, clearly, does not fit the macroseismic data, it is based upon new computations using body waves arrival times as recorded by that time seismological stations which used to suffer from serious synchronization problems. The consequences of this are clearly shown in Table 25.4

is at best mathematically equivalent to the old one and the computational arguments of such nature and in such circumstances can't be used to justify or validate a new location of the epicenter. Furthermore the particular C-O values of KSA and HLW resulting from the new epicenter calculation mean that the epicenter should better be closer to KSA and more far away from HLW this is just the case of the ISS original epicenter (Table 25.5).

Yet it is noticed that the new location is already being uncritically followed and adopted by a number of more recent seismicity studies (Amiran et al., 1994; Jaber, 1994; Ken-Tor et al., 2001).

Table 25.5 Shows a representative part of the data used to calculate The (SAN) epicenter, those with epicenter-station distance <20°

Station	Phase	Arrival time	Calc-Obs (s)	Distance(deg)	Azimuth
KSA	P	13:04:43	4.6	1.8	1
HLW	P	13:05:10	−2.5	4.3	241
	S	13:06:07	2.9		
BAK	P	13:07:34	5.1	14.2	49
MKY	P	13:07:55	−3.0	16.4	5
	S	13:10:58	−4.2		
BEO	P	13:08:10	−1.6	17.5	321
	S	13:11:32	3.6		
BMP	P	13:12:13	4.2	19.2	303
NPL	P	13:08:37	4.1	19.3	303
LVV	P	13:12:23	0.7	19.8	337

Partially reproduced from Table 1 in (Shapira et al., 1993)

25.3 Conclusions About the JDST Seismicity – Identification of Seismic Gaps

It is important to notice some aspects of the seismicity of the Wadi Araba-Gulf of Aqaba segment(s) of the JDST. These segments, located south of the Dead Sea, are particularly interesting. From the historical seismicity data (Abou Karaki, 1987) the Gulf of Aqaba part of the transform passed from a clear state of seismic quiescence for the last few centuries, (since 1588 AD at least) (Abou Karaki, 1987), and from the status of the least seismically active segment of the transform during these centuries to the most active zone of the JDST since January, 1983 (Abou Karaki, 2001a), when it entered into a period of increased activity marked by a number of swarms, starting on January, 21, 1983 (Abou Karaki et al., 1993; Abou Karaki, 1987; Alamri et al., 1991; El-Isa et al., 1984; Russell, 1985) and culminating with the 7.3 Mw earthquake of November, 22 1995 (Abou Karaki, 2001a, b; Klinger et al., 1999). Paleoseimicity investigations Kanari et al. 2020 (Kanari et al., 2020) generally confirmed our conclusions from the historical seismicity results and catalogs (Abou Karaki, 1987, 2001a) and as shown in Table 25.3.

The Wadi Araba part (WAR) remained quiescent till now (Jan. 2022), this makes of the Wadi Araba-Gulf of Aqaba adjacent segments, the least and respectively most seismically active segments of (JDST), during the instrumental seismicity era.

In Conclusion, historical and instrumental seismicity of the JDSF along with relative seismic gap areas are shown on Fig. 25.4.

Finally Fig. 25.5a presents the JDSF instrumental seismicity 1900–2020 for $M \geq 4$ to avoid the noisy epicentres resulting from artificial events resulting from industrial mining explosions an example of which is given in Fig. 25.5b.

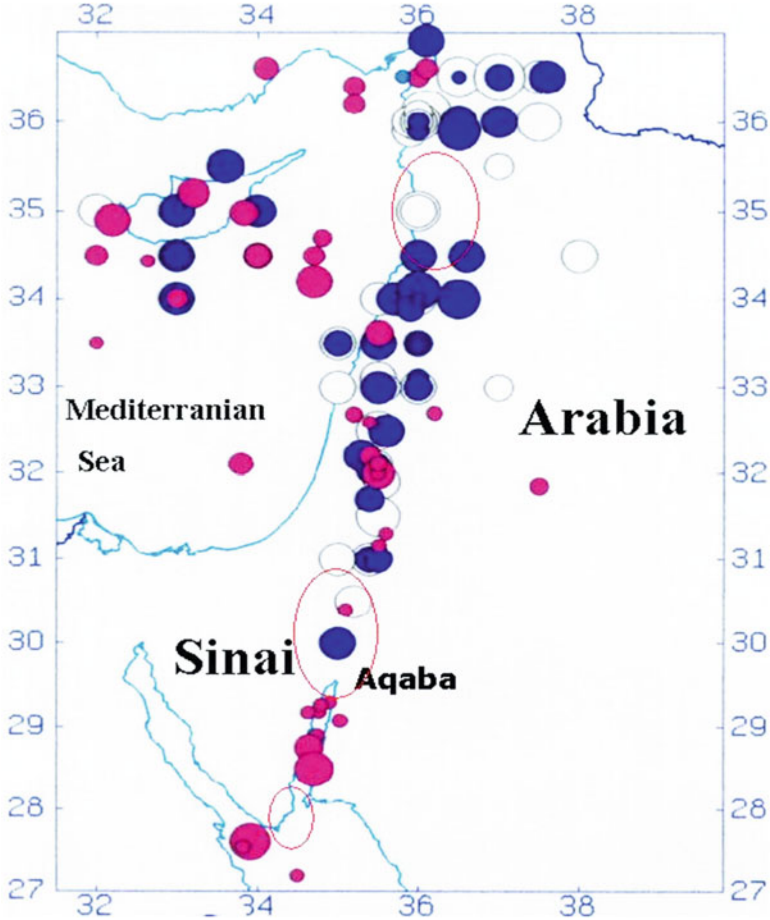

Fig. 25.4 Seismicity of the JDST from 31 BC up to 2020 AD. Open circles represent the historical earthquakes for the period from 31 BC–1200 AD. Bleu circles from 1200–1900 AD. With equivalent Ms. Magnitudes [6, 7.5] based on the revised catalog of Abou Karaki 1987 revised 2021. Instrumental seismicity epicentres from 1900 and on are represented in red solid circles for magnitudes from [5, 7.3] (Abou Karaki, 1994, 1995a, 2001a) and USGS, EMSC databases. Resulting locations of 3 relative seismic gap areas are represented in elliptical forms on this figure namely centred around the latitudes (28°N, 30°N and 35°N ± 0.5°)

25.4 Dead Sea Remote Sensing Studies

25.4.1 Problems Related to Subsidence in the Dead Sea Coastal Areas

Since the 1960s, the Dead Sea coastal areas are expanding because the Sea is undergoing what is an essentially induced, and extremely rapid decrease of its water level (Abou Karaki et al., 2007). The drop in the Dead Sea level caused the

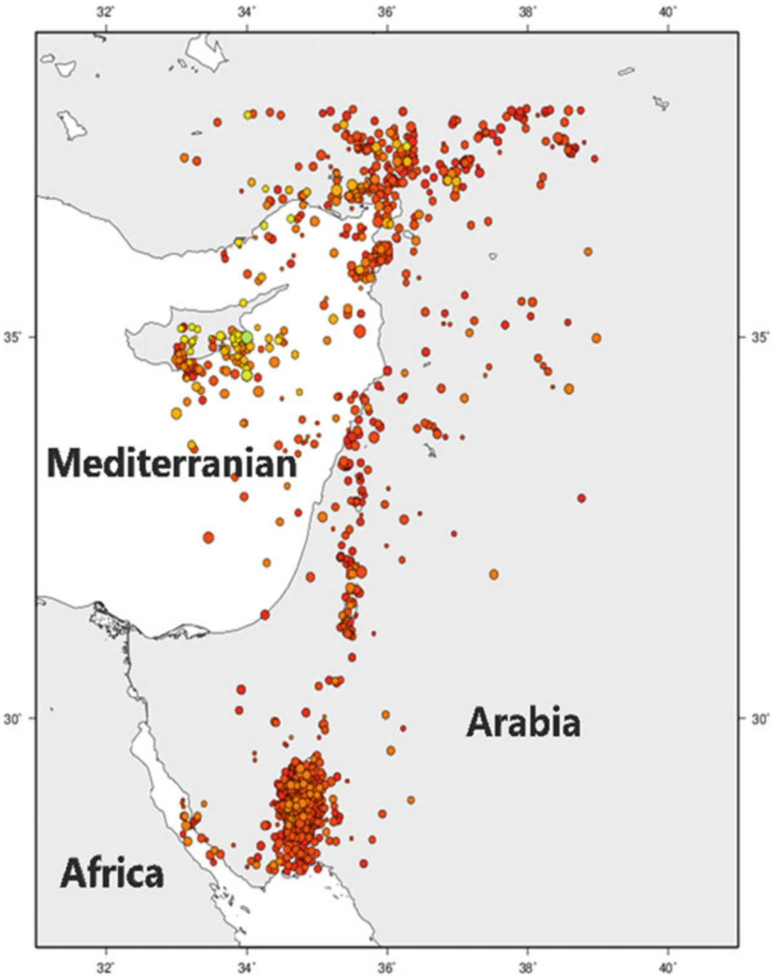

Fig. 25.5 (**a**) It is interesting to compare the locations of the relative seismic gaps represented in Fig. 25.4 with the instrumental seismicity map Fig. 25.5. For the magnitudes ≥4 It is still possible to identify the 2 main gaps which are comparable on the two figures (≈ 30°N and 35°N. ± 0.5°). Epicentres are from the same sources of data as Fig. 25.1a In conclusion it is clear that limiting the represented magnitudes on the seismicity map of the JDST from ≥3 in Fig. 25.1a to ≥4 in Fig. 25.5 is more robust and useful for the tectonic significance of the epicentres distribution if the unchecked international seismicity monitoring organizations data is used. (**b**) Industrial detonations amounting to 10,000 kg of explosives are routinely used in mining operations of the Phosphate Mines Co. at the Phosphate extraction sites in Southern Jordan (El-Hisa and Al-Shidia Mines). This explains the "epicentral" non-tectonic clusters with low magnitudes around the coordinates (30°N, 36.4°E and 31.2°N, 36.4°E) in Fig. 25.1a

Fig. 25.5 (continued)

loss of more than a third of its water surface (Salameh & El-Naser, 1999, 2000). This is already inducing serious hazards in the area related to subsidence and hydrogeological problems (Abou Karaki et al., 2016, 2017; Salameh et al., 2019). The fundamental cause of these hazards is known to be the sharp imbalance in the water budget of the Dead Sea. This is provoking a steady shrinkage of the sea surface and the emergence of new unstable lands in the coastal areas of the sea coupled with the development and proliferation of rapid collapse features (Sinkholes) on both sides of the Dead Sea zone. If the Dead Sea level continues to decrease, these hazards are only expected to increase in intensity and extension.

Between 1992 and 2021, we have intensely studied the Jordanian part of the Dead Sea with remote sensing techniques (Abou Karaki et al., 2016, 2017, 2019; Al-Halbouni et al., 2017; Closson & Abou Karaki, 2009, 2014; Closson et al., 2003, 2005, 2010; Fiaschi et al., 2017; Watson et al., 2018) The nature of this work and the methods of image processing have evolved along with the discipline. We have tested many optical and radar sensors. One of our studies (Abou Karaki et al., 2016) was classified by (p.9, tables 4 and 5 in (Pricope et al., 2019)) as the study which used a maximum of satellite sources among 83 analyzed studies worldwide. Table 25.6 takes up the list of satellites used during the investigation period.

Table 25.6 provides an overview of the technologies' evolution over the past 60 years. In the 1990s, there were only a few optical satellites equipped with imaging systems capable of providing images with a resolution between 10 and 30 m (Spot, Landsat).

It was therefore impossible to visualize sinkholes with this data, except for the larger ones. Radar images provided an alternative but there was still no software capable of processing radar images in the manner of a freeware like SNAP.

Table 25.6 List of satellites used, investigation period, and image processing applied

Radar satellites	Periods of investigation	Image processing
ERS-1	1992–1999	Interferometry: InSAR (DSM); DInSAR; PS; SBAS
ERS-2	1997–2011	
Envisat	2003–2012	
ALOS-1	2008–2010	Interferometry: DInSAR
Cosmo-SkyMed	2011–2013	
Sentinel-1	2014–2021	Interferometry: DInSAR; PS; Sbas
Space Shuttle	1994	Visual interpretation of greyscale Intensity
Optical satellites	Periods of investigation	Image processing
Corona	1963–1971	Geocoding; visual interpretation of greyscale Intensity
Landsat 1 to 8	1972–2021	Geocoding improvement; textural filtering; band ratio and combination diachronic color composition; LULC classifications
Sentinel-2	2015–2021	
Spot	1992–1994, 2003	
Ikonos	2000, 2003, 2006	Geocoding improvement; textural filtering; band ratio and combination diachronic color composition; LULC classifications; detection of sinkholes,vegetation, and sel pillars in evaporation ponds
Aster	2000–2005	
Worldview	2010–2012	
Geoeye	2009	
Rapideye	2010	
Planet Lab	2018	
Bing; Google Map	2000–2021	Geocoding; visual interpretation

Soil moisture detection algorithms were used on optical images to detect wetlands (Closson & Abou Karaki, 2014) within land discovered because of the Dead Sea water level lowering (> 1 m/year). These moisture anomalies have been interpreted as the places where groundwater moves from the recharge zones to the ultimate base level (i.e. the Dead Sea), but also rivers eroding their beds in order to stay in balance with the base level (Abou Karaki et al., 2016).

We have observed that between the time of their emergence, in the 1980s, and the 2010s, these underground water flows gave rise to real karst networks capable of destroying agricultural land, destabilizing the installations and industrial dikes of the Arab Potash Company APC, as well as national roads bridges and hotels.

Figures 25.6 and 25.8 illustrate this point. Its principle can be generalized to the entire shores of the Dead Sea (Abou Karaki et al., 2019). These geomorphological maps were drawn from multiple observations made with optical Fig. 25.7 and radar images collected in 1992 to 2015 (Closson & Abou Karaki, 2009; Closson et al., 2003, 2005, 2010; Watson et al., 2018).

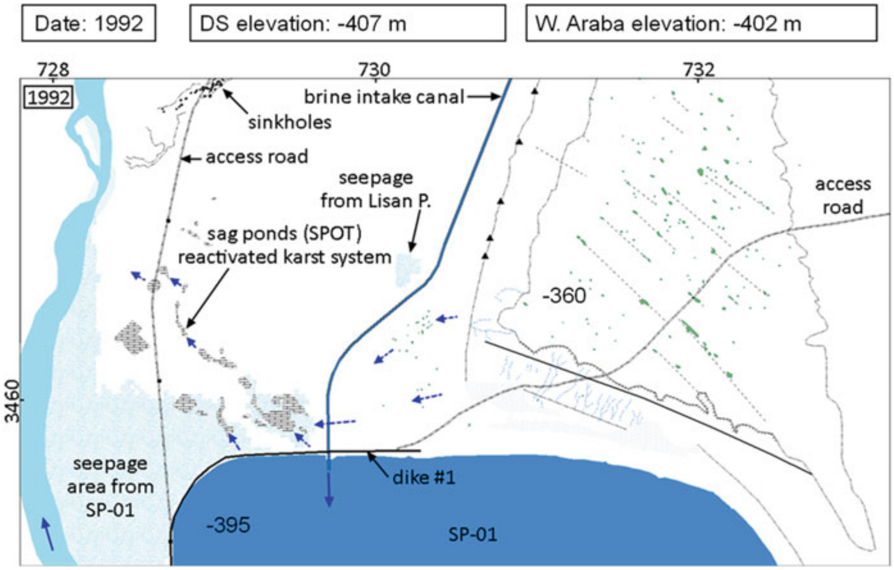

Fig. 25.6 Development of a karst system in the early 1990s with the Landsat and Spot satellites

Fig. 25.7 Satellite image (source: https://www.bing.com/maps) most likely acquired in 2015. This image is contemporary of Fig. 25.8

The region corresponds to Cape Molyneux (see the elevation of −360 m). The coordinates are expressed in UTM kilometers. Eastern side, a plateau bounded by a cliff dominates a gentle plain inclined to the North, towards the Dead Sea. This plain is crossed by the Wadi Araba (river to the west). In 1992, the Wadi Araba had an altitude of −402 m. It was therefore 42 m lower than the karst plateau of Cape Molyneux.

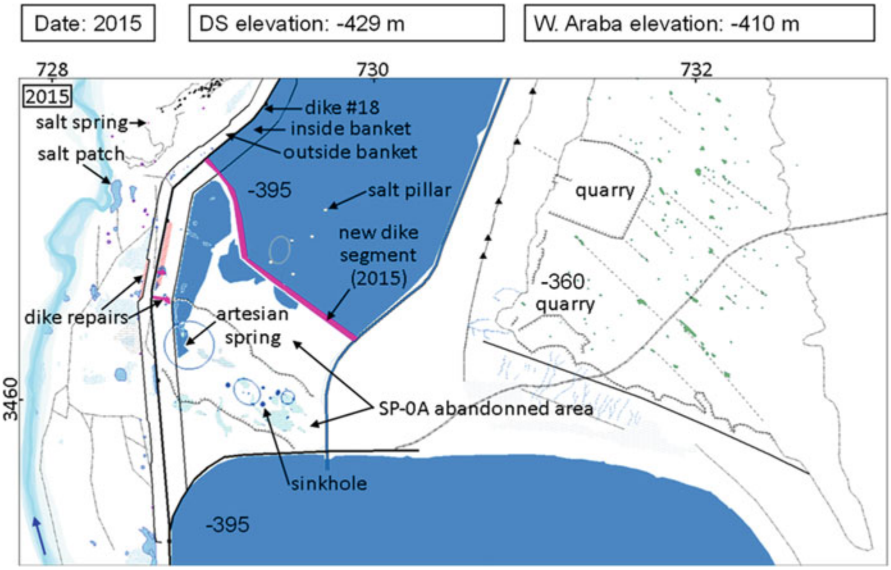

Fig. 25.8 Geomorphological map of the region west of Cape Molyneux in 2015. A levee (purple) was created to isolate a segment of the dam threatened with collapse. Many sinkholes attest to an intense flow of water below the basin

In winter, rainwater enters through the plateau because of hundreds of sinkholes developed along lineaments of tectonic origin (green spots and dashed lines). These lineaments and sinkholes are accessible via an access road that leads to the APC dikes' system.

The southern part of the cliff is of tectonic origin. A fault segment ESE-WNW (continuous black line) is represented. It is a small segment of a major transversal fault zone that connects the East and West fault systems of the Dead Sea Basin. This fault zone is kilometer-deep and drains some of the fresh water coming from the eastern part to the Wadi Araba. This fact is attested by the presence of fresh water sources in the Cape Molyneux area (oral communication of APC dike safety engineers, 2015).

South of Cape Molyneux is an evaporation basin (SP-01; −395 m). Given the difference of 7 m in water level between this basin and Wadi Araba (−402 m), the water stored in the reservoir naturally tends to escape to reach the local base level. Earthen dike #1 holds the water in the reservoir. Due to the significant fracturing of the subsoil, a portion of the brine manages to escape and reach the Wadi Araba.

This percolation of water greatly increases soil moisture. Very clear infrared signatures appear on the optical images where these percolations occur. We detected a karst system that was reactivated by water from the SP-01 basin and also fed by the transversal fault zone (underground flows giving rise to a development of shrub vegetation). The blue arrows indicate the flow direction subparalel to the transverse fault.

Optical and radar images have allowed us to study in great detail the impact of the gradual development of the karst system on the stability of the APC dikes built in the late 1990s (Fiaschi et al., 2017). So, a few years after the retreat of the Dead Sea, at the time when the karst system was being reactivated.

Data on land use land cover changes and soil nature have all been mapped: creation of new salt evaporation ponds; seepage areas contemporary to the feeding operations; partial draining and gradual drying of the ponds to increase the safety coefficient; various repairs; refilling sinkholes; widening of dikes; collapse of dikes; appearance and disappearance of springs; appearance and disappearance of vegetation in connection with an underground freshwater supply; faults and fractures; subsidence; landslides; soil collapse; structural lineaments; erosion resistance ...

With the increase in sensor resolution (Fig. 25.7), it has been possible to visualize sinkholes both inside and outside the evaporation basins. Combining optical observations and radar, at the end of 2012, it was possible to send warning signals to the APC. The observed elements have enabled security engineers to deploy considerable geophysical means. Prediction of collapses based on diachronic analysis of high- and very high-resolution radar and optical satellite images was one of the major culminations of two decades of research.

Figure 25.2 illustrates this point. Its interpretation is in (Fig. 25.8). It shows the amputated part of an evaporation basin. A levee (SE-NW and SSE-NNW) was created in early 2015 to completely isolate the most unstable part of the dike. 2.5 km were drained for repair. Detailed analysis of the bottom shows that it is perforated in multiple locations by sinkholes (Fig. 25.8). These are organized according to an underground karst network whose main axes were already visible in 1992 (Fig. 25.6), several years before the creation of the basin.

Cape Molyneux was surrounded by the waters of the Dead Sea until late 1970s. During the 1980s, major development work took place in the southern part of the terminal lake. The wadi Araba delta was transferred from the southern Dead Sea basin to the northern one via a 20 km long channel leading to Cape Molyneux. Naturally, this river has become the local base level for all surrounding water tables (including brine stored in evaporation basins). Wadi Araba, like all other rivers flowing into the terminal lake, is forced to rejuvenate its longitudinal profile to adapt to Dead Sea level. As a result, all water stored in basins and adjacent freshwaters are gradually being mobilized.

Large layers of water stored in the marls of the Lisan Peninsula were thus displaced by the force of gravity. Underground water flows appeared very early after the Dead Sea was withdrawn. These waters have taken all areas of tectonic weaknesses created either by the rise of the salt diapir or by the tectonic activity of the Dead Sea basin.

As early as the 1990s, radar images were able to detect millimeter movements of the ground in a relative way. This information has been very useful to us in improving knowledge in the field of neoctonics. The absence of geological maps, the study of tectonics on the border (military zone),etc. was more than compensated by the contribution of radar interferometry data. The detection of active faults in connection with the Lisan diapir allowed us to place sinkholes on a map of active

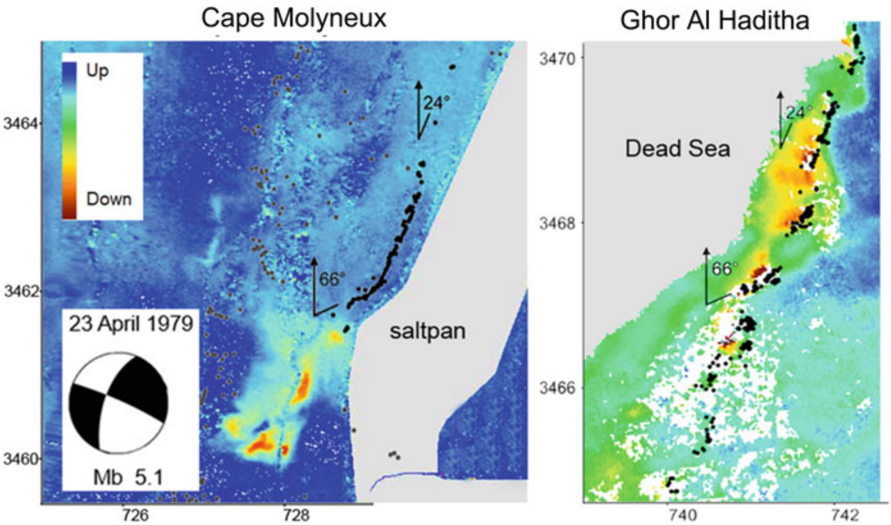

Fig. 25.9 Comparison between the distribution of sinkholes (black dots) of Cape Molyneux and Ghor Al Haditha. Two structural directions appear: N24E and N66E. N24E is in agreement with the EQ event of 23-04-1979 (Lisan). Focal mechanism after (Arieh et al., 1982). In Cape Molyneux region, the karst system is very active in the southern part of the lineament. The colors are those of an ALOS-2 differential interferogram. The bright colors correspond to the most intense subsidence during the observation period. Acquisition dates 01 April 2008–17 May 2008; T 46 days; perpendicular baseline 17 m; altitude of ambiguity 2705 m

faults and draw conclusions/models as to the genesis of sinkholes affecting the earthen dikes of the APC.

The main finding that can be attributed to the combination of image processing techniques with field observations is presented in Fig. 25.9.

Figure 25.9 is relevant in that it clearly shows the co-occurrence between elements of structural geology and ground collapses. The sinkholes that make up the two lineaments account for the majority of known collapses on the Jordanian side. Moreover, these two lineaments appeared at the same time, during the 1980s, a few years after the earthquake of 23-04-1979.

In this case, radar interferometry brings the dynamic dimension of the system. Optical sensors allow the counting and delimitation of sinkholes. Field observations provide information on the nature of the layers affected by collapses, as well as networks of cracks undetectable from space or even aerial photos. Differential radar interferometry shows the actual spatial extent of the phenomenon and its dynamics over time. Advanced techniques such as PS and SBAS have allowed us to establish a 25-year time series of data (Fiaschi et al., 2017).

Subsidence and sinkholes related problems and major expected resulting hazards in the sensitive Dead Sea area added to the recognized seismic hazards there (Abou Karaki, 1987; Bonnin et al., 1988) require mitigation, cooperation, funding and extensive multidisciplinary work (Abou Karaki & Closson, 2012).

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