Nat Hazards (2007) 42:47–66
DOI 10.1007/s11069-006-9045-6

ORIGINAL PAPER

Archaeoseismological investigation of the ancient Ayla site in the city of Aqaba, Jordan

Eid A. Al-Tarazi · Andrey M. Korjenkov

Received: 3 January 2006 / Accepted: 30 July 2006 / Published online: 21 April 2007

Abstract Many tens of severe earthquake damage patterns were revealed at the ancient city of Ayla. The seismic deformation patterns are of various types, including systematic tilting of walls, systematic shifting and rotation of wall fragments and individual stones, arch deformations and joints crossing two or more stones. Features of later repair, supporting walls and secondary use of building stones suggest that the damage patterns can be explained by two historical devastating earthquakes: (I) revealed in the constructions built during the late Rashidun period (644–656 A.D.); (II) revealed in the structures restored and/or built during the Fatimid period (1050–1116 A.D.). The maximum observed intensity of both earthquakes at the studied site was not less than IX (EMS98 scale). The sources of the seismic events were probably the Dead Sea Transform and Wadi Araba Faults that cross the site obliquely. The last 1995 Nuweiba earthquake with maximum observed intensity VIII has also left its clear traces in the excavated ancient Ayla buildings. The severity of the destruction was significantly increased because of site effects.

Keywords Archaeoseismology · Ayla (Aqaba) · Jordan · Historical earthquakes · Ancient cities

1 Introduction

Ayla is the old name of the Red Sea port of Jordan, called today Aqaba (Whitcomb 1994), an early Islamic town that was originally established during the caliphate of ''Utman ibn Affan'', between 644 and 656 A.D. (Ghawanmah 1992; Whitcomb 1994). The Crusaders

E. A. Al-Tarazi (✉)
Department of Earth and Environmental Sciences, Hashemite University, Zarqa 13115, Jordan
e-mail: eid@hu.edu.jo

A. M. Korjenkov
Institute of Seismology, National Academy of Sciences, Asanbay 52/1, Bishkek 720060, Kyrgyzstan
e-mail: akorjen@elcat.kg

conquered the town in 1116 A.D. without a fight, which indicates that the city might have been abandoned, probably after a severe earthquake in 1068 A.D. (Ghawanmah 1992; Whitcomb 1997).

Whitcomb (1993) divided the establishments and reconstructions of Ayla, during the Islamic period, into five phases namely A to E, which began on 650–750 A.D. (Late Rashidun and Umayyad), 750–850 A.D. (Early Abbasid), 850–950 A.D. (Middle Abbasid), 950–1050 A.D. (Late Abbasid) and 1050–1116 A.D. (Fatimid), respectively.

Previous studies at the Ayla site mainly consisted of archaeological excavations done by the Oriental Institute of the University of Chicago during the period 1986–1993. Whitcomb (1994) reported traces of displacements affecting the wall of ancient Ayla (Fig. 1). They

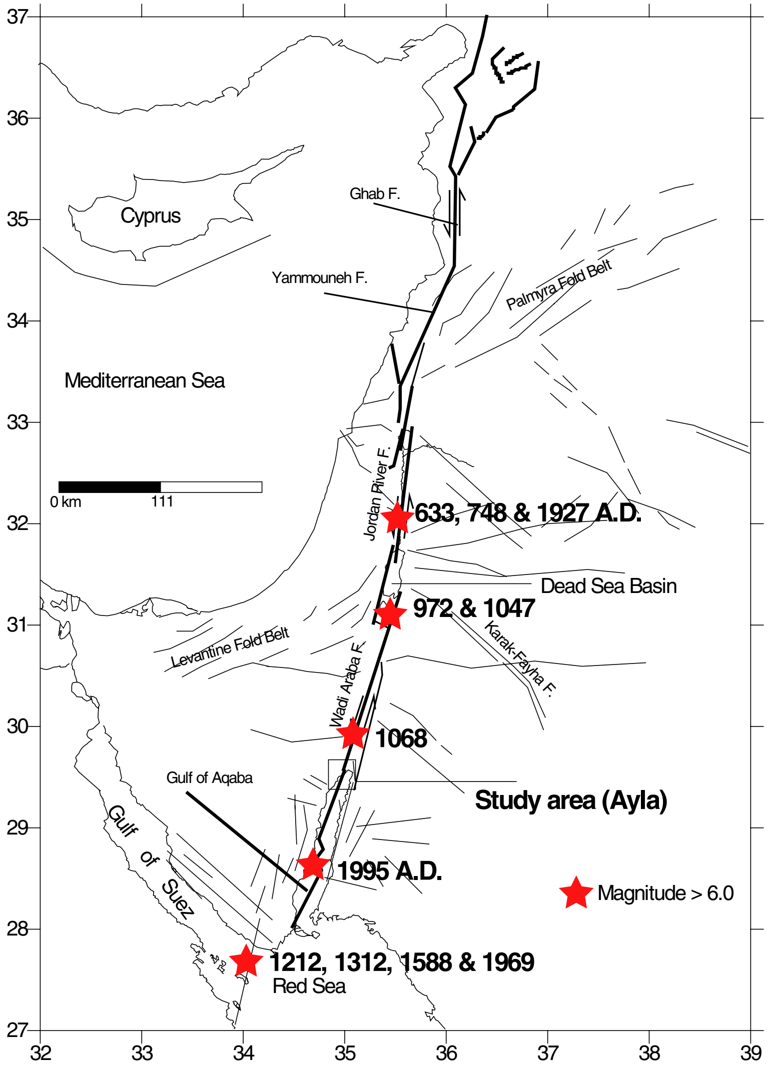

Fig. 1 The regional tectonics of the studied site of Ayla, showing the locations of the major earthquakes that affected Aqaba during the period 633–1995 A.D.

were described as an outward slump of a portion of the SW wall of the city, accompanied by the shifting of its foundation, and Whitcomb placed on the site-map a NE–SW proposed fault that displaces the whole town left-laterally. Furthermore, Galli and Galadini (2001) proposed other traces of deformation affecting the NW town wall, specifically northward of the Egyptian Gate where the wall appears rotated counterclockwise in its northern portion (Fig. 2).

Rucker and Niemi (2005) tested Whitcomb's hypothesis. Based on two trenches excavated at the eastern and the southern city walls, they conclude that no fault offset exists in the NE or SE city wall of Ayla or through the corner tower in the Wadi. They also suggest that liquefaction and subsidence may have caused such damage at the site. According to Mansor et al. (2004), Ayla lies in an area of high liquefaction susceptibility, due to the presence of saturated sands at shallow depth. Al-Homoud and Tal (1998) conducted geotechnical investigations using three boreholes to a depth of 12 m near the Ayla site (Fig. 2). Archaeological deposits overlie sands and fluvial gravels. They noted tilting and sinking of exterior walls that they interpreted as slumping due to horizontal

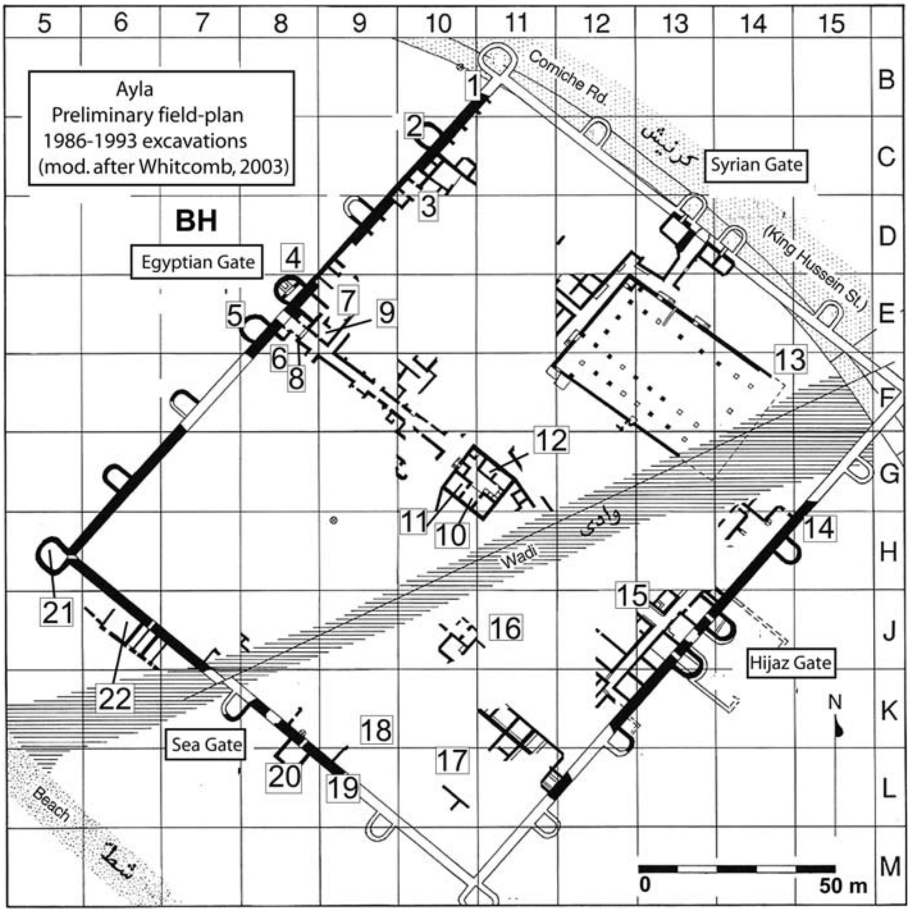

Fig. 2 Plan of the ancient city of Ayla with the locations of the measured stations (numbers inside boxes) described in the text. Hatched diagonal structure is a Wadi bed BH is a borehole near the Egyptian gate (modified after Whitcomb 1993)

ground acceleration during an earthquake. The NW corner is underlain by 5 m of sand below the water table, based on a borehole outside the Egyptian gate towers (Fig. 2). Incidentally, areas in the city of Aqaba that experienced subsidence during the Nuweiba earthquake of 1995 lie along the beach zone near the ancient Ayla (Wust 1997; Malkawi et al. 1999). Al-Tarazi (2000) observed intensity VIII at MMI scale at the beach zone due to the same earthquake from which acceleration measurements were also made. The first station at the beach recorded 160 cm/s^2 while the other one (3 km far toward northeast of Aqaba city) 60 cm/s^2 (see Fig. 3).

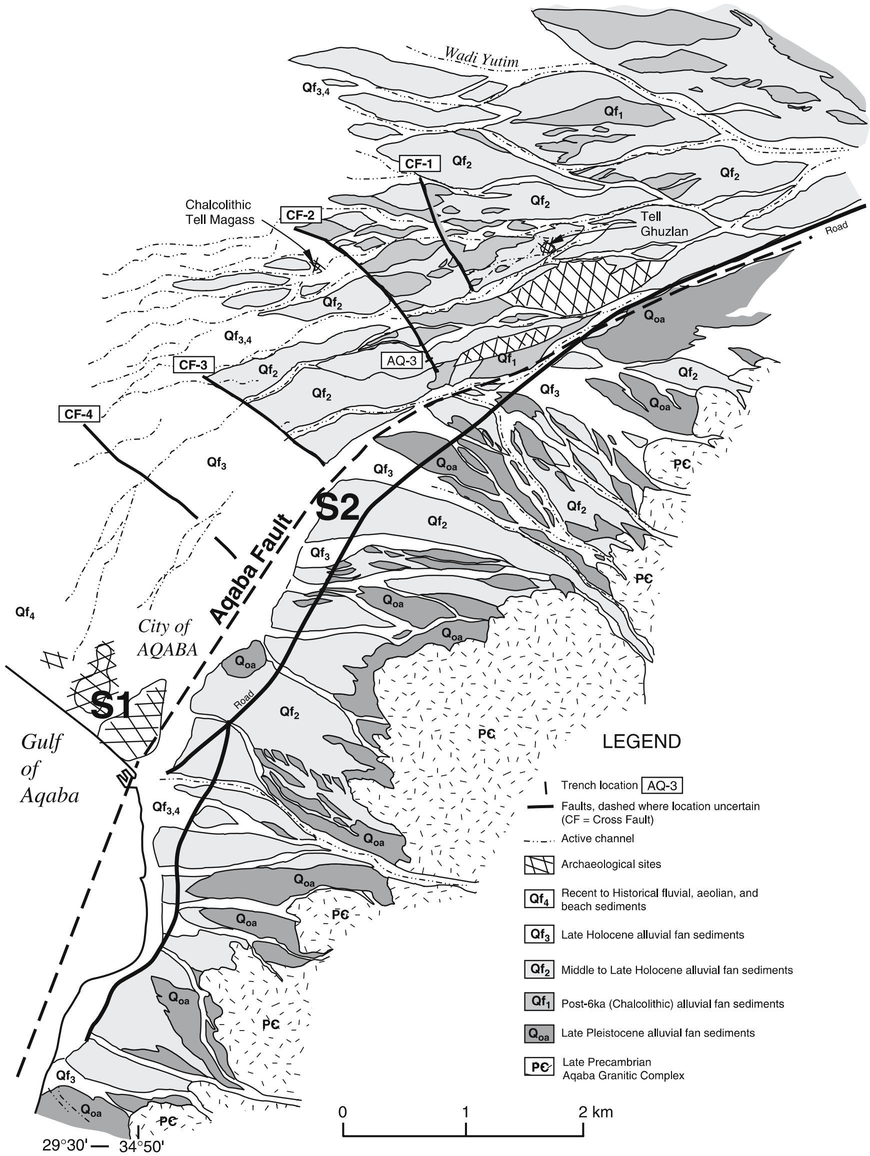

Fig. 3 The main tectonic and geological features of the city of Aqaba (modified after Slater and Niemi 2003). S1 and S2 are strong motion stations near Ayla town

During our study at Ayla in 2004, we did not discover offset and rotations affecting the NW town wall as described by Galli and Galadini (2001), while we agree with Rucker and Niemi (2005) that discard the faulting hypothesis (Galli and Galadini 2001) and interpret the site history in terms of liquefaction and differential subsidence. Furthermore, the lack of evidence for the Wadi fault hypothesis of Whitcomb claims for a reexamination of the earthquake damage observed at the site. This is one of the main goals of our study.

In the thousand-year period between 600 A.D. and 1600 A.D. at least two historical earthquakes affected the Ayla site. The first was in 748 A.D. and the second in 1068 A.D. The published catalogues of the seismicity of the Jordan-Dead Sea transform (DST) (Abou Karaki et al. 1993; Galli and Galadini 2001; Ken-Tor et al. 2001) locate the first event about 300 km north of Ayla, with surface wave magnitude ($M_s = 7.4$), while the second event is located about 80 km north of the site (Fig. 1 and Table 1). This paper aims to verify this historical fact based on field observations and measurements performed at the Ayla ancient site using an archaeoseismological approach (Stiros 1996; Korjenkov and Mazor 1999a–c; 2003). Furthermore, it investigates whether other historical earthquakes that occurred along and near the DST possibly affected Ayla during the past 14 centuries (Table 1).

2 Geological and tectonic setting

The modern city of Aqaba in South Jordan is located along the seismically active DST at the northern shore of the Gulf of Aqaba (Fig. 1). Most of the major destructive earthquakes that occurred in the area associated with the DST (Slater and Niemi 2003; Al-Tarazi 2004). The city is located along a branch of the DST at the northern end of the Gulf. Between the Gulf of Aqaba and the Dead Sea, to the north, the DST is defined by a linear valley bordered by a zone of normal faulting and uplifted mountains (Ben-Avraham et al. 1990). The active strike-slip faulting occurs within this valley and trends obliquely across it (Slater and Niemi 2003). This structural pattern is also observed within the Gulf of Aqaba

Table 1 The date, location and magnitude of major earthquakes that presumably affected Ayla during the period between 600 A.D. and 1995, M_s surface wave magnitude

Date Yr. Mo. D.	Location		M_s
	Latit. N°	Long. E°	
0633 00 00	32.000	35.500	6.6
0748 18 01	32.200	35.500	7.4
0972 00 00	31.000	35.500	6.5
1047 00 00	31.000	35.500	6.5
1068 03 18	30.000	35.000	6.7
1212 05 02	27.700	34.000	6.0
1312 01 05	27.700	34.000	6.7
1588 01 14	27.700	34.000	6.0
1927 07 11	32.000	35.500	6.0
1969 03 31	27.610	33.910	6.1
1995 11 22	28.760	34.680	7.1

Parameters from Russell (1985), Abou Karaki (1987), Amiran et al. (1994), Ambraseys et al. (1994), and Al-Tarazi (2000) where deep basins are oriented at a clockwise angle to the DST axis and are interpreted as pull-apart basins (Ben-Avraham 1985; Ben-Avraham and Tibor 1993).

The faults are the dominant structural features in the Gulf. Garfunkel (1970) and Quennell (1959) mapped two main normal faults that are parallel to the northeast-striking shoreline of the Gulf of Aqaba and extend northerly under of the city of Aqaba (Fig. 3). Slater and Niemi (2003) delineate a third main fault, called Aqaba fault, that emerges from the gulf and steps 4.5 km west forming a releasing geometry with the Eilat fault (Fig. 3). The fault morphology is obscured by urban development within the city of Aqaba (Slater and Niemi 2003). Other four NW-trending cross faults are inferred based on distinct fault scarps. From a structural point of view, the normal to oblique slip further cross faults indicates active NE-directed extension that produces subsidence at the head of the Gulf of Aqaba (Slater and Niemi 2003). The city of Aqaba is mainly located on alluvial fan sediments derived from the pre-Cambrian basement mountain ranges to the east (Fig. 3).

3 Seismicity

The recent seismicity of the Gulf of Aqaba is characterized by several seismic sequences like those of 1969, 1983, 1990, 1993, and 1995. The earthquake of November 11, 1995 with M_w 7.1 (Hofstetter 2003) was the largest that affected the city since 1068 A.D. with maximum observed intensity VIII MMI-scale on Aqaba city (Al-Tarazi 2000). During this event, site effects were determined in both Aqaba and Eilat (Saffarini and Kabalawi 1999).

The archaeological record confirms that major destruction in Aqaba occurred to the Late Roman-Byzantine structures, due to the 363 A.D. earthquake (Parker 1999), and to the Islamic city of Ayla, due to the 748 and 1068 A.D. earthquakes (Whitcomb 1997). The field investigations and measurements done in this study are devoted to check this archaeological evidence at the Ayla site.

4 Damages in the Fatimid buildings

Whitcomb (1993, 1994, 1997) supposed that the city was abandoned because it was destroyed by the 1068 A.D. earthquake which occurred during Fatimid time. Whitcomb described the 1068 earthquake effect as following ‘‘the layers show debris of wall collapsed and extensive accumulations of ash and refuse, all of which may be evidence of the 1068 earthquake and the subsequent efforts at reconstruction and rehabilitation’’. The significant degree of deformation that Whitcomb observed in the remaining parts of the Fatimid buildings makes room to the hypothesis that practically all houses were damaged, therefore suggesting an intensity IX (EMS-98) vulnerability class D with damage grade 4 or more (Grünthal, 1998). The Arabian manuscripts also support this conclusion. Ghawanmah (1992) documented that only 12 Ayla citizens survived this earthquake because they were at sea, fishing.

We conducted a detailed archaeoseismological study of the Ayla ruins in 2004. Almost every ancient building (Fig. 2) show one or more of the following damage features.

4.1 Systematic tilting of walls

A preferentially oriented tilt of the walls is becoming a common technique for the recognition of a seismic nature of damage in Archaeoseismology. For example, Hancock and

Altunel (1997), and Altunel (1998) described this phenomenon in ancient ruins in Turkey; Vinokurov and Nikonov (1998) mentioned this in their paper on the Crimean Peninsula; Korjenkov and Mazor (1999a–c, 2003) used them in their work in the Negev desert.

At Ayla, a wall in the southern room of the Sea Gate building complex K (Station 20 in Fig. 2) is tilted toward SSW at an angle of up to 66° (in its central part) with a declination azimuth of 213° (Fig. 4a). Another example of the same damage pattern is in station 21 (in the western corner of the city wall), where a fragment of the wall is tilted at an angle of 72° with a declination angle of 210° (Fig. 4b).

The data of surveyed cases of tilting are summarized in Table 2 and in Fig. 4c. A 24 cases of tilting were observed at walls trending between 105° and 145°, 19 out of these are tilted toward SW and only 5 are tilted towards NE (Fig. 4c). In contrast, only 11 cases of tilting were observed in the perpendicular walls, with a 10°–45° trend, and no systematic tilting was observed.

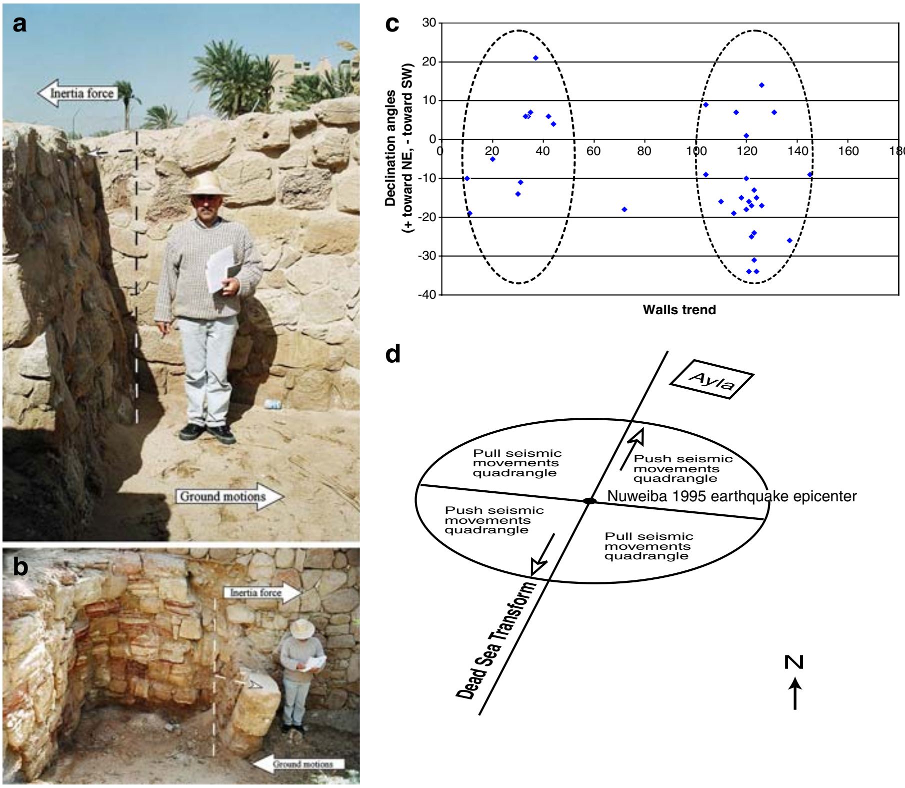

Fig. 4 Tilted walls in Ayla towards the SSW: (**a**) In a room of the Sea Gate building complex (Station 20); (**b**) In seashore area (Station 21). Note the tilting of both the lower fragment of a column and a later built supporting wall. (**c**) Summary of measurements: direction of tilting patterns observed in Ayla as a function of the direction of the walls. ESE trending walls have systematic tilt toward SSW. (**d**) Qualitative model showing the types of propagation of the seismic motions during the Nuweiba 1995 earthquake. Ayla was in the compression quadrangle and most of the walls oriented SE were tilted towards SW due to inertia

Table 2 Tilting of walls and other building elements at Ayla at all observed stations

Nos. of observations	Observation stations (see for location Fig. 2 – the plan of ancient Ayla)	Wall trends (degrees)	Declination azimuth (direction where the wall was tilted) (degrees)	Declination angle (degrees)
1	1	120	210	10
2	2	115	205	19
3	2	11	281	19
4	2	123	203	13
5	3	121	211	34
6	4	110	200	16
7	4	122	212	25
8	4	118	208	15
9	4	126	216	13
10	4	44	314	4
11	6	34	124	6
12	6	33	123	6
13	7	131	41	7
14	7	137	227	26
15	8	20	290	5
16	8	35	125	7
17	8	42	132	6
18	9	116	26	7
19	10	37	307	21
20	13	120	30	1
21	13	31	301	11
22	14	122	212	17
23	15	30	300	14
24	16	126	36	14
25	16	121	211	16
26	17	72	162	18
27	18	124	214	34
28	19	123	213	31
29	20	123	213	24
30	21	120	210	18
31	21	145	235	9
32	22	124	214	15
33	22	104	14	9
34	22	104	194	9
35	22	10	100	10

4.2 Lateral shifting of building elements

In Ayla, a 75 cm wide wall attached and perpendicular to a major city wall (station no. 1 — close to the northern corner of the city wall) has an original trend of 120°. Its upper part is shifted towards SSW (210°) of about 16 cm (Fig. 5a). The lower and undisturbed portion of

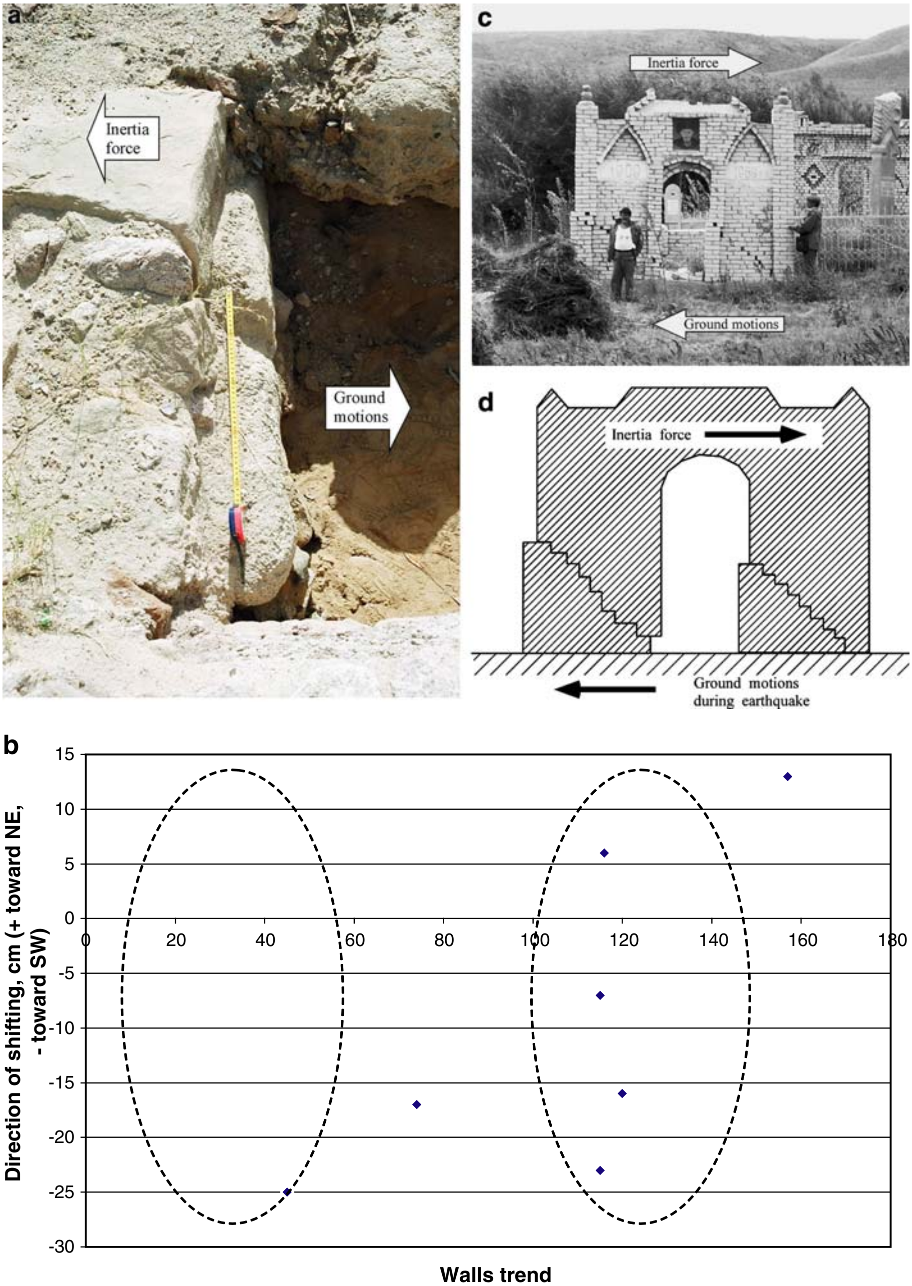

Fig. 5 Shifting of wall fragments in Ayla: (**a**) Shift toward the SSW of the upper part of a wall attached and perpendicular to the city wall (station no. 1). (**b**) Summary of measurements: direction of shifting patterns observed in Ayla as a function of the direction of the walls. ESE trending walls have systematic shift toward SSW. (**c**) photograph and (**d**) scheme. Shift toward the epicenter of the upper part of the grave monument during Suusamyr (1992, M_s = 7.3) earthquake in Kyrgyzstan

the wall is 44 cm above the bottom of the excavation trench. The height of the preserved shifted fragment is 18 cm. The wall is composed of cemented sandstone and granite blocks.

The upper part of the highly deformed wall attached and perpendicular to the city wall (Station 3 in city Quarter E) was shifted 7 cm toward SSW. The wall trend is 115°, while the direction of shifting is 205°. Total height of the wall is 81 cm above the bottom of the excavation trench. At a later stage, a supporting wall of 84 cm width was built from the southern side in order to impede the collapse from the original wall.

Other seven cases of clear shifting were observed (Fig. 5b). Most of them are in walls trending 105°–120°. Three wall fragments were pushed toward the SSW and in one case the wall part was moved towards the opposite direction.

4.3 Rotation of wall fragments around a vertical axis

In Ayla, there is a rotation pattern in the northwestern wall of the 4th city tower (station no. 2). The height of the remaining wall is 139 cm above the bottom of the excavation trench. The trend of the undisturbed wall is 124°, while the strike of the rotated wall fragment is 115°, this suggesting a counterclockwise rotation on 9° with maximum degree of rotation for the lower row of the wall (Fig. 6a). The maximum horizontal offset between two wall fragments is 8 cm.

Another example is at station no. 12 (Ayla's city quarter A), where the upper part of the wall was rotated 15° clockwise by (Fig. 6b). The strike of the undisturbed wall is 117° and the strike of the rotated wall is 132°. The height of the undisturbed wall fragment is 40 cm, while the rotated part is 60 cm high. Width of the wall is 40–50 cm; its length is 2 m.

Walls striking 20°–45° revealed six cases of rotation and out of them five are counterclockwise and only one is clockwise (Fig. 6c). The perpendicular walls, trending 115°–130° revealed five cases of rotation, out of which two cases are counterclockwise and three cases are clockwise. Thus, a systematic picture of rotations is obtained: counterclockwise in NNE trending walls and clockwise in ESE walls (Fig. 6c).

4.4 Fractures across walls

Long through fissures cutting a whole wall are common phenomena among earthquake damage patterns (Stiros 1996; Korjenkov and Lemzin 2000). Several such patterns were also observed in Ayla. For example, a secondary wall attached and perpendicular to the main city wall (Station 3 in city Quarter E) was cut by a joint. The 55 cm long joint (left one in Fig. 7) crosses two stones of a 121° trending wall.

Another joint (Fig. 6a, shown by arrows) cutting through two adjacent stones which are located in the northwestern wall of the 4th city tower (station No. 2). The height of the wall is 139 cm above the bottom of the excavation trench. The trend of the wall fragment is 124°.

The described damage pattern occurred during last strong 1995 earthquake (I = VIII, Al-Tarazi 2000), was strong enough to cause significant damage in weak remnants of ancient buildings, especially those already excavated. Local site effects like liquefaction and subsidence could have increased the damage level.

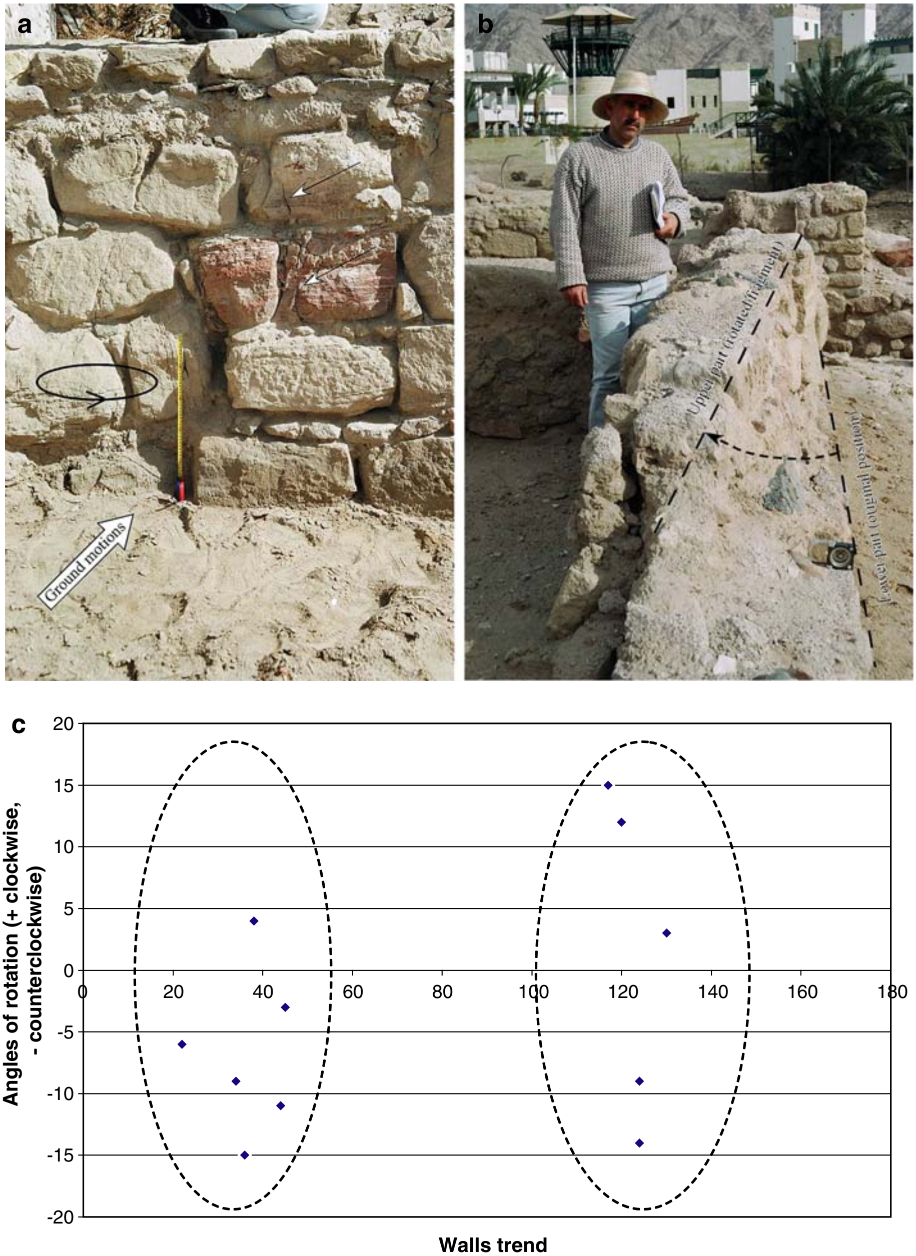

Fig. 6 Rotations of the wall fragments in Ayla. (**a**) A counterclockwise rotation in the northwestern wall of the 4th city tower. The arrows point to a through-going joint (station no. 2). (**b**) Ayla city complex A: Upper part of the wall was rotated clockwise by 15° (station no. 10). (**c**) Angle of rotation as a function of the wall trend: mostly counterclockwise rotations were observed in NNE walls and more clockwise rotations in ESE walls

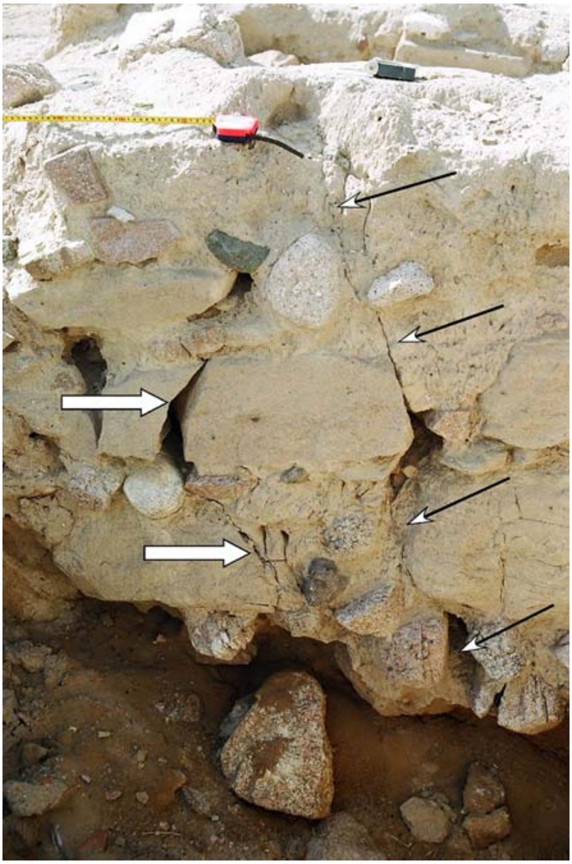

Fig. 7 A long fissure (shown by black arrows) cutting wall attached/perpendicular to the city wall. White arrows point to a through-going joint (Station no. 3)

5 Archaeoseismological inferences

Damage patterns of rotations, displacements are commonly associated with earthquakes (Korjenkov and Mazor 1999a, 2003). At Ayla these patterns occur together with tilted structures, supporting the hypothesis that the latter are of seismic origin as well.

A clear preference of southwest tilting is observed at the ruins of Ayla. Accordingly, the seismic shock likely arrived from the SW (Fig. 4d). As it is known the DST is a sinistral strike-slip fault and Ayla is located on the eastern block that moves northwards during strong earthquakes. Therefore, the building constructions are tilted to opposite direction because of inertia (Fig. 4d). This interpretation is not new and it has been explained based on an analogical approach by Nur and Ron (1996). They studied ruins of several synagogues in Galilee, which were destroyed during 363 earthquake, showing that in most of investigated sites west of DST the synagogues' columns fell toward NW, whereas in the sites east of the fault the columns fell toward SW. Nur and Ron (1996) assumed that these more-or less free-standing columns fell in a direction of horizontal strong ground motions. Accordingly, these directions can be used for determination of the fault sides' movements.

Also the displacement of the building elements is a known phenomenon of earthquake deformation in ancient buildings (Stiros 1996; Altunel 1998; Buck 1999) and was used for the determination of the directions of seismic motions even wall tilt or collapse (Korjenkov and Mazor 1999b, c, 2003).

Based on the above description of shifted building elements, the seismic shocks arrived from the SSW and the movements were transmitted from the ground to the building foundations, causing the upper wall fragments to move in an opposite direction due to inertia. Recent examples of this behavior have been observed in Kyrgyzstan after the Suusamyr (1992, $M_s = 7.3$) earthquake (Fig. 5c, d).

Also rotation of individual stones, fragments of the walls, or whole walls around a vertical axis during strong earthquakes is a common phenomenon in modern and ancient buildings (Nikonov 1996; Altunel, 1998; Korjenkov and Mazor 1999a–c, 2003). Pulling out of foundation stones accompanied by their rotation (in spite of their solid cement) testifies to the dynamic beating out of the stones in the process of sharp horizontal oscillations. This process concerns to the whole wall (and not only of its upper part) relative to the foundation. Seismic ground motion is the only mechanism that can cause rotation of building elements, a conclusion well supported by the large number of observed rotation cases and the obvious directional systematic. The theoretical background of this phenomenon in the buildings was described in detail by Korjenkov and Mazor (1999a, b).

The analysis of the clockwise and anticlockwise rotations supports a likely NNE-SSW direction of the seismic motion. Joints crossing a few adjacent stones could be induced by coseismic deformation (Stiros 1996). Indeed, the occurrence of such joints has been reported in many macroseismic studies. For example, Korjenkov and Lemzin (2000) described such joints formed in modern buildings during the Kochkor-Ata (southern Kyrgyzstan) 1992 earthquake of a magnitude $M_L = 6.2$. Such through-going joints are likely formed as a result of high intensity earthquake, while high energy is necessary to overcome the stress shadow of free surfaces at the stone margins (i.e., the free space between adjacent stones). For details, see papers by Korjenkov and Mazor (1999b, c).

6 Evidence of earlier earthquakes

During the Fatimid occupation we found in Ayla the evidence of rebuilding, repair and reinforcement suggesting the occurrence of an earlier seismic event(s), likely during the Umayyad period. An example is represented by the poor quality repairs of the Ayla city wall NE from the city tower 8 (Station 1 near northern corner of the city wall) Fig. 8.

Fig. 8 Traces of poor quality repair in Ayla city wall to the NE from the city tower no. 4 (station no. 3)

In Ayla, two building phases are inferred by the occurrence of a new wall built on top of the old foundation, but following a somewhat different direction. Such a phenomenon was also observed in the ruins of ancient cities in the Negev Highlands like Avdat/ Oboda (Korjenkov and Mazor 1999b), Shivta/Sbayta (Korjenkov and Mazor 1999c) and Mamshit/ Mampsis (Korjenkov and Mazor 2003), which were damaged by strong historical earthquakes. Similar cases were described by Stiros and Papageorgiou (2001) at Kisamos of Western Crete during third stage of the town rebuilding after the strong earthquake, where ''The plan of the town and of houses changed: walls had a different orientation...'' (p. 388).

Another example is observed in city quarter D (station 9) where there is a clear mismatch between the lower row of stones and the upper wall fragment (Fig. 9). The height of the lower row is 40 cm above the bottom of the excavated trench, where the height of the upper wall fragment is 160 cm. The azimuth of the lower row is 34°, while that of the upper wall fragment is 25° showing a difference of 9°.

Various segments of walls were likely tilted by an earlier earthquake (during the Umayyad period) and repaired later on during the Early Abbasid period. Similar supporting walls are also observed at other sites in the adjacent Negev desert, like Avdat (Korjenkov and Mazor 1999b), Shivta (Korjenkov and Mazor 1999c), Mamshit (Korjenkov and Mazor 2003), Rehovot-ba-Negev (Mazor and Korjenkov 2001) and Sa'adon. Together with other direct evidence of the seismic deformations, they can be indirectly used as additional

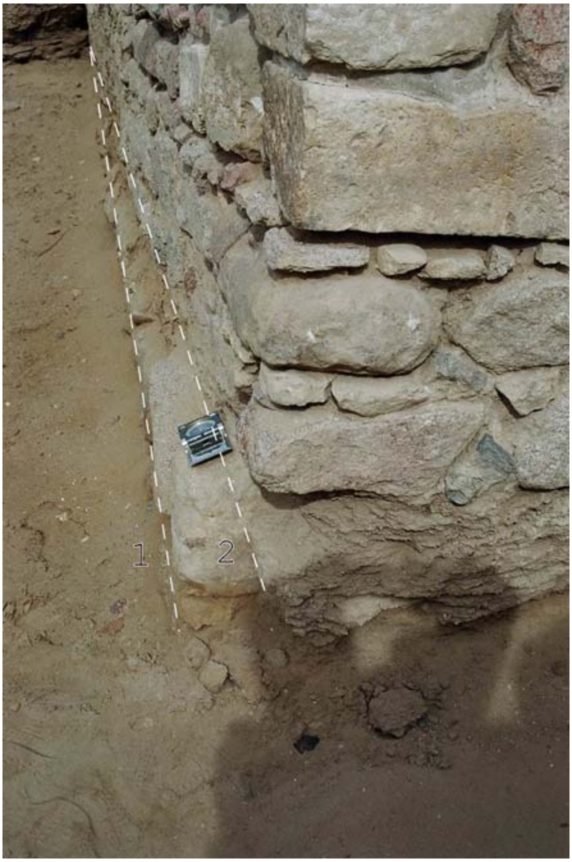

Fig. 9 Mismatch of lower row of stones and upper wall fragments in city quarter D (station no. 6). There is a difference of 9° between the trends of two walls

evidence of earthquake damage. Thus, a wall perpendicular to the city wall (Station 7 in city Quarter D) has a supporting wall on its NE side. The letter wall was built later in order to strengthen the original one that was tilted toward the NE (Fig. 10). The height of the original wall is 300 cm above the bottom of the excavation trench has a declination azimuth of 41° and a tilt angle of 83°.

Another example of a supporting wall is observed in Fig. 4b (station 21 in the western corner of the city wall), where a short secondary wall was built in order to support (apparently) a deformed column. Deformation of the column possibly occurred during the 748 Umayyad earthquake. Subsequently, both column and supporting wall were tilted toward SSW during the second-Fatimid earthquake of 1068.

Tens of supporting walls were observed in the ruins of Ayla, suggesting the hypothesis that during the first Umayyad period earthquake the city was seriously damaged. Building elements were tilted, shifted, distorted, and special supporting walls were subsequently built in order to reinforce damaged constructions.

Another indirect evidence of an earlier destructive event is represented by the rather common secondary use of building materials in the Early Abbasid period buildings. The possibility that stones of secondary use are an evidence of building reconstruction, is mentioned in works by Altunel (1998), Ellenblum et al. (1998), Stiros (1998), Hancock et al. (2000), and Korjenkov and Mazor (2003) among others. In Ayla, there are also such examples like a column drum which is now inside of the street wall in city quarter D (Station 9, Fig. 11a).

Another example is represented in Fig. 11b (Station 13 at city quarter F) showing two column drums belonging to a column likely damaged during the Umayyad earthquake. Another column drum (left in Fig. 11b) was later used in order to support the damaged column, while during the Fatimid earthquake, the column was finally destroyed and both drums were shifted out from their previous position.

Fig. 10 A wall perpendicular to the city wall (city Quarter D; station no. 7) has a supporting wall from its NE side. The last wall was built later in order to strengthen the original one that was tilted toward NE

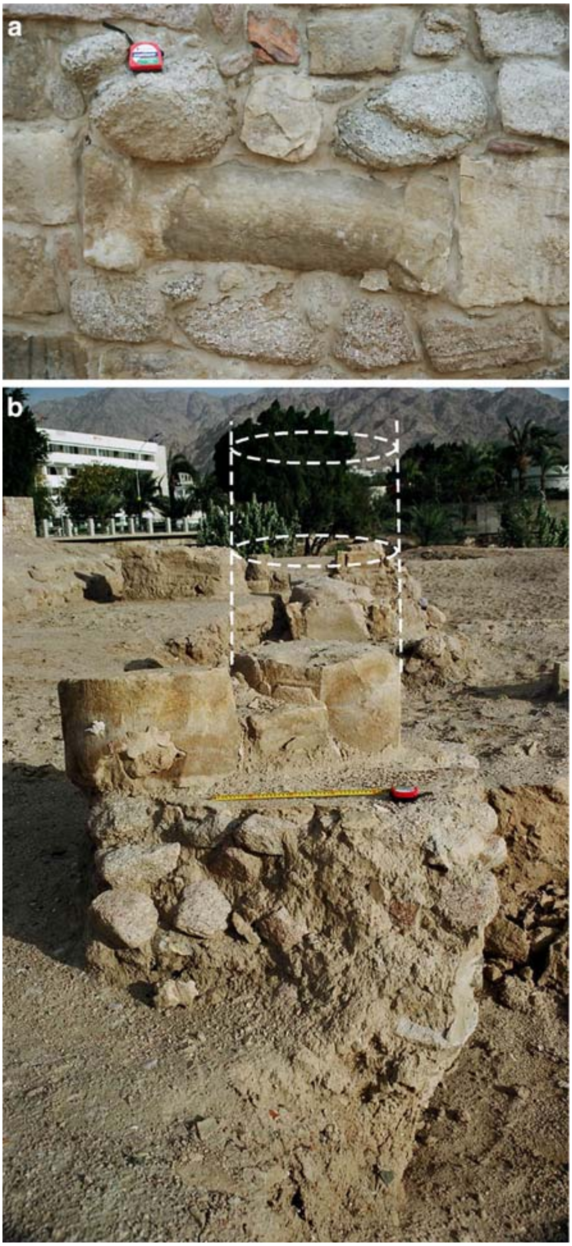

Fig. 11 Secondary use of building stones in Ayla. (**a**) A column drum built into the street wall in city quarter D (station no. 7). (**b**) Two column drums at city quarter F (station no. 13): the right one belonged to the lower part of the column. It was probably damaged during the Umayyad earthquake. The left column drum was used later in order to support and reinforce the damaged column

7 Macroseismic intensities

The percentage of collapsed buildings of the Rashidun town is hard to estimate as most of the buildings have been cleared away and rebuilt. Nevertheless, an estimate can be done because most of the second floors or upper parts of high structures were rebuilt at the Umayyad and Early Abbasid stage leading to the estimate that at least 15% of the buildings were destroyed by the earthquake occurred at the end of the Umayyad period. According to the EMS-98 an earthquake intensity of IX or more is inferred.

In contrast, the percentage of collapsed buildings of the Fatimid town can be well estimated as the ruins were left untouched. The survey disclosed that at least 15% of the well-built stone buildings of Fatimid Ayla collapsed and in practice no second floor structures survived with no severe damage. Again an EMS-98 intensity of IX or more is assumed.

As above mentioned the recent Nuweiba earthquake had seismic intensity of VIII at the investigated site. Estimated degrees of the seismic intensity were probably significantly increased due to site effects like liquefaction and subsidence.

8 Concluding remarks

The analysis of the observed damage and the directional preferences lead to the following conclusions.

(1) At the end of the Umayyad period the settlement of Ayla was struck by an earthquake (Whitcomb 1994). This was a strong earthquake with a relatively close epicenter (few tens of kilometers) and an EMS-98 scale intensity of IX or more (Grünthal 1998). This is a minimum value because the ruins of the most badly struck buildings had most probably been completely removed, leaving no trace.
(2) At the end of the Fatimid period a second earthquake hit the place, the epicenter was at some distance from the site, and the intensity was also IX or more.
(3) Third Nuweiba earthquake with intensity I = VIII has also left its traces in ancient ruins and its epicenter was located at 100 km's from ancient Ayla (Al-Tarazi 2000).

Although based on limited observations the direction of tilt and resystematic block towards NE during Umayyad (748 A.D) and Fatimid (1086 A.D.) earthquakes are likely evidence of seismic motions radiated from the earthquake sources located NE of Ayla (Fig. 12a).

During the 1995 Nuweiba earthquake seismic motions came from the SW (Fig. 12b). This statement is based on numerous observed systematic damage patterns (tilts, shifts, rotations). Known earthquakes within the study area are shown in Table 1. The three earthquakes were mainly distinguished on the basis of the directional systematic that is statistically sound. This demonstrates the need to make large numbers of measurements of identified seismic damage patterns.

At the beginning of this paper, the complexity of the earthquake process was mentioned. The question was raised which seismic components are devastating? Are the P-waves, S-waves, and surface-waves all destructive? Is damage caused during the foreshocks, the main shock and/or the aftershocks? Do mainly lateral or vertical movements cause the damage? Is the diversity of seismic compounds causing the terrain to be shaken in many directions? All these questions may be addressed based on the recorded information preserved in stone-built ruins.

The large body of damage evidence surveyed at Ayla provides a fairly simple picture: mainly lateral movements that arrived from the fault rupture zone caused devastation. These observations were made for three earthquakes: the first at the end of the Umayyad period (748 A.D.), the second at the end of the Fatimid period (1068 A.D.), and the last in modern times (1995).

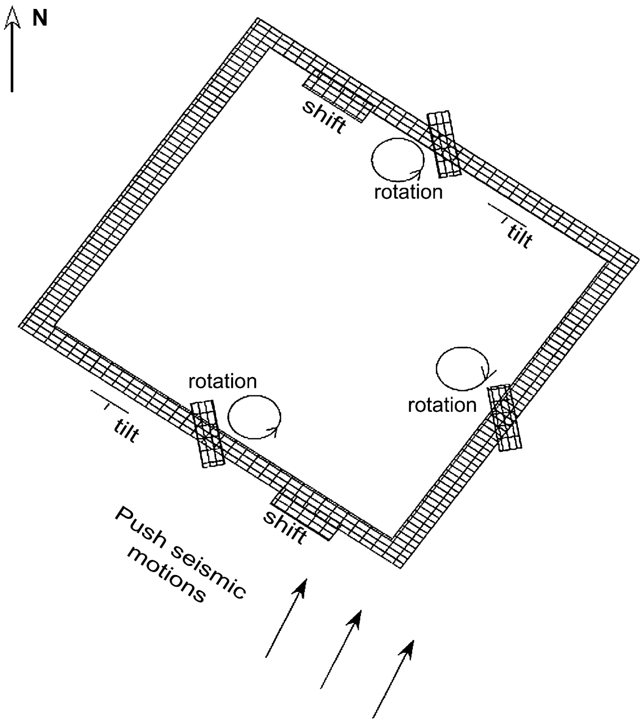

Fig. 12 Suggested destruction of preferential ground oscillation during the 1995 Nuweiba earthquake. Ayla city is schematically presented as a single room

The answers regarding the devastation mechanism may differ from one case study to the other, e.g. reflecting different hypocenter and site location relations, but putting the results from many archeoseismic case studies together, a general picture may eventually emerge, improving our knowledge of the earthquakes parameters.

The systematic directional deformation patterns suggest that the hypocenters were not beneath Ayla, but to the NE and SW of it and the inferred intensity of IX or more for ancient earthquakes and VIII for Nuweiba earthquake suggests that the epicenters were few tens of kilometers away.

Acknowledgements The authors would like to thank Dr. Khairieh Amr from Department of Antiquities, Jordan for revising and commenting on the initial draft of this paper. We are grateful for his encouragement to complete this work by supplying us with the original references by Donald Whitcomb of the Oriental Institute at the University of Chicago.

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