PALEOSEISMOLOGY AND ARCHAEOSEISMOLOGY ALONG THE SOUTHERN DEAD SEA TRANSFORM IN WADI ‘ARABAH NEAR THE MUNICIPALITY OF AQABA, JORDAN

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DOCTOR OF PHILOSOPHY

by
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PALEOSEISMOLOGY AND ARCHAEOSEISMOLOGY ALONG THE SOUTHERN DEAD SEA TRANSFORM IN WADI ‘ARABAH NEAR THE MUNICIPALITY OF AQABA, JORDAN

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ABSTRACT

The southern Wadi ‘Arabah Valley in Jordan provides an ideal location to investigate both the paleoseismology and archaeoseismology of the region because it is situated directly along the active Dead Sea transform, and because the area has a long history of human occupation. The region is rich in archaeological ruins as a result, many of which have been damaged by earthquakes in the historic past.

An archaeoseismic excavation conducted at Early Islamic Ayla (7th-12th C.) in the city of Aqaba, Jordan revealed that a 3.5 m-long section of original city wall that leans out toward the Gulf of Aqaba was likely damaged because of liquefaction caused by ground shaking from a historic earthquake, and was buttressed shortly thereafter. Stratified pottery and radiocarbon dated charcoal collected from within and beneath the revetment wall suggest a revetment construction in the early 11th century. Based on known historical earthquakes of the region, damage to the Ayla city wall likely occurred as a result of the A.D. 1033 earthquake.

Paleoseismic data collected at the Sisters’ School site in Aqaba, and from the Taba Sabkha trench located 35 km north of the city, suggest that southern Wadi ‘Arabah was more seismically active during the Holocene than previously understood. In Taba, paleoseismic trenching data suggests that between two to four earthquakes ruptured the sabkha from the 8th to the 16th centuries, although a three-event model is preferred. When correlated with major earthquake catalogs, these ruptures likely represent the A.D. 746/749 or 757 earthquakes, the March 1068 event, and either the 1546 or 1588 earthquake.

At the Sisters' School site, at least five early to mid-Holocene earthquakes are visible in the southwest trench wall, as is evidence of paleoliquefaction in the form of clastic sand and silt dikes. Optically stimulated luminescence and radiocarbon dates suggest that the Sisters' School site dates to as early as the Pre-Pottery Neolithic and as late as the Bronze Age. Ashy deposits and a fire pit exposed in cross-section, dated to 6200-3000 B.C. and 4986-4840 B.C. respectively, also suggest early human occupation at the head of the Gulf of Aqaba in antiquity.

The faculty listed below, appointed by the Dean of the School of Graduate Studies, have examined a dissertation titled “Paleoseismology and Archaeoseismology Along the Southern Dead Sea Transform in Wadi ‘Arabah Near the Municipality of Aqaba, Jordan,” presented by Alivia Janeil Allison, candidate for the Doctor of Philosophy degree, and certify that in their opinion it is worthy of acceptance.

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ACKNOWLEDGEMENTS

I owe the completion of this dissertation to the help of many wonderful people, but this journey ultimately began when my structural geology professor and mentor, Dr. Tina Niemi, took me to Jordan for the first time in 2002 to work with her on a geoarchaeological excavation at the site of Qasr Tilah. I was an undergraduate student during that pivotal first trip, but I was hooked immediately. She taught me the art of grant writing which allowed me to travel back to Jordan again and again, allowing me to complete both a Master's degree and now my Ph.D. in this geoarchaeologist's paradise. The country of Jordan has become my home-away-from-home, and a place that will forever hold very special memories for me. Tina is a brilliant geologist and professor, and she has inspired me to follow in her footsteps. My life is exceedingly richer because of her, and try as I might, I will never be able to thank her enough for all she has done for me.

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This dissertation was largely written as I worked as an Earth Science Instructor in the Physical Sciences Department at Emporia State University in Emporia, Kansas. I want to sincerely thank the Chair of the Department, Dr. Richard Sleezer, for believing in me and for hiring me (twice) while still an A.B.D. doctoral candidate. His support and encouragement were incredibly uplifting when I needed it most. He is a wonderful professor and scientist from whom I am always learning something new. Along with Dr. Sleezer, Dr. Michael Morales, Dr. Marcia Schulmeister, and Mrs. Ginger Tabares have also been great sources of encouragement. I am extremely fortunate that even prior to the completion of this dissertation, I found a university and a science department that already feels like home.

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Although you don’t know it yet, you helped me write this.

May this show you that anything is possible if you just believe you can do it.

Thank you for being the ray of light we were all waiting for…

This is for you.

CHAPTER 1

INTRODUCTION

Overview

One of the most destructive of natural hazards, earthquakes are the cause of injuries and fatalities around the world each year due to their unpredictable nature and the large area potentially affected by any one seismic event. Earthquakes are particularly treacherous in developing countries where building construction standards are often severely lacking or absent, and public alerts such as tsunami warnings are typically slower to circulate to the general population, for instance. Seismic activity in these locations, in particular, can cause incredible devastation and be potentially catastrophic to those living in and around active fault lines. As described by Ambraseys (2009), earthquakes are destructive to people and our belongings because we have made them so by insisting on investing our wealth and livelihoods into properties situated in seismically hazardous areas, often with blatant disregard for the geologic hazards of which we are now quite aware. While studies of both modern and ancient earthquakes reflect how differently people have viewed natural hazards through time, both then and now these disasters are known to cause economic, political, and societal crises in their aftermath (Ambraseys, 2009). In the historic past, the sudden devastation of a village or town from an earthquake often resulted in the abandonment of that establishment and often triggered large population migrations. Invasions and wars also commonly occurred after large seismic disasters as people fought over resources and land, and those not affected by the devastation of the earthquake could more easily take advantage of those who were (Ambraseys, 2009). Today, the primary cause of death and damage resulting from an earthquake can be attributed to the collapse of buildings and other structures that are built in seismically active and thus vulnerable areas, although seismic ground shaking can also trigger other types of damage as well (Hyndman and Hyndman, 2013). Broken pipelines can start widespread fires, for instance, and in the days after a large seismic event, epidemics may result due to contaminated water if broken or damaged sewage lines leak into water mains (Hyndman and Hyndman, 2013).

Zeilinga de Boer and Sanders (2005) present an interesting “vibrating string” model to explain the lasting effects of catastrophic events. They suggest that the effects of a large earthquake, for example, can be imagined as a long, tight string that you pluck, such as a guitar string, where the string represents time and the initial release of the string represents the incredible amount of seismic energy released during an earthquake. At this point, the vibrations of the string will have a large amplitude, but short wavelengths. Farther along the string and with the passage of time, however, the amplitude of each wave will decrease and the wavelength or the aftereffects of an earthquake can increase. This example is meant to explain the relationship of the intensity of an environmental disaster to the length of influence, where the aftereffects will become less intense as time passes, but will last much longer than the initial event (Zeilinga de Boer and Sanders, 2005). Damage from modern earthquakes can be greatly minimized, however, if we understand these seismic hazards and how and where they can occur, which is essentially reliant on understanding how specific fault lines have ruptured and behaved in the historic past.

The purpose of this research is to use archaeological excavation and geological mapping techniques to document evidence for the history of earthquakes occurring during late antiquity and forward in the region south of the Dead Sea in Wadi ʻArabah with a special focus on the area in and around the city of Aqaba, Jordan (Figure 1.1). By studying ancient earthquake damage records, the primary goals of this research are to improve the earthquake catalogs for southern Jordan and to help us better understand the relationship between natural disasters and cultural history, to increase scientific knowledge of earthquake rupture models for transform faults, and to help improve the characterization of future earthquake potential in the region.

In order to conduct archaeological excavations in the Middle East, it is imperative to understand the history of the region, including the migration and settlement of populations through time. Archaeology utilizes material remains unearthed by excavation to supplement written historical records. Furthermore, conducting geoarchaeological research in the Middle East, compared to similar work in North America for example, is unique because areas such as Jordan have been occupied since the Paleolithic (e.g. Smith and Niemi, 1994; Smith et al., 1997). In antiquity, Aqaba was an important route of trade and cultural connections, and as a result is extremely rich in archaeological materials. This adds a significant historical component to this geological research, and increases the complexity of the archaeology as well.

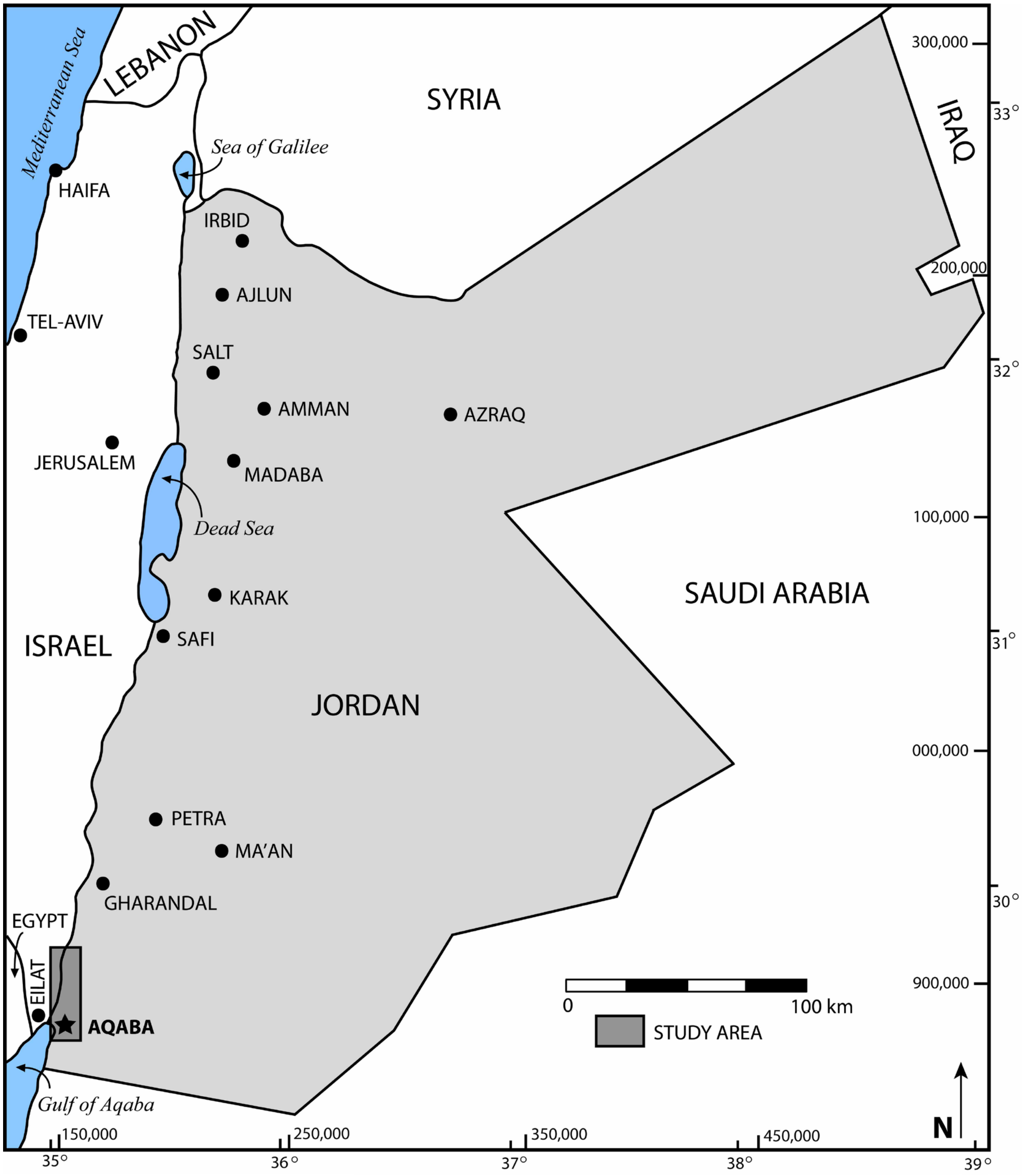

Figure 1.1 Location map of the study area in Jordan (after Rashdan, 1988).

The earthquake record in Jordan south of the Dead Sea from the 7th to the 15th centuries -- the periods known as the Umayyad, Abbasid, Fatimid, Crusader, Ayyubid, and Mamluk -- is sparse. Only two large earthquakes are known to have occurred in the Wadi ‘Arabah during this time period: the A.D. 1068 and 1212 earthquakes (Guidoboni, 1994; Guidoboni and Comastri, 2005; Ambraseys, 2009). However, recent excavations at the archaeological sites of Qasr Tilah in northern Wadi ‘Arabah (Haynes et al., 2006; Niemi, 2007a) and at the ruins of Byzantine Aila in Aqaba (Thomas et al., 2007) both document evidence for several post-7th century earthquakes. These data suggest that the historical earthquake catalogs for southern Jordan are incomplete and may be biased toward areas that were more heavily populated during antiquity (Niemi, 2007b). In fact, it is possible that many earthquake events that have been attributed to northern fault motion of the Dead Sea transform (DST) may have actually been caused by ground rupture originating on the southern portion of the DST in the Wadi ‘Arabah. During the Islamic periods there were fewer people living in and around Wadi ‘Arabah to experience and pass on knowledge of such seismic events, and thus many earthquakes originating in the south have likely gone unrecorded or were incorrectly reported as having a different source location or epicenter.

With the level of technology we currently possess, earthquakes cannot be prevented, but by studying faults in seismically active regions using paleoseismological and archaeoseismological techniques, along with historical accounts of these seismic events, we can work to better understand how each fault has behaved through time, and how and to what extent they may rupture in the future. The field of paleoseismology, the study of the location, timing, and size of prehistoric earthquakes through geologic evidence (McCalpin and Nelson, 2009), is now well established around the world. Before the 1980s, however, the assessment of earthquake hazards was built almost completely from the historical record – records of typically large ($M > 6.5$) seismic events recorded in journals, personal diaries, political documents, literature, and so forth. Urged by seismologists to adopt this newer technique, by the 21st century most countries with seismically active faults now consider paleoseismic data in their seismic hazard analyses (McCalpin, 2009). Likewise, the seismological subfield of archaeoseismology uses detailed excavation of archaeological sites located in seismically active areas to collect data about the seismic past. Rectifying the local earthquake record in Jordan is of great importance because clearly understanding the movement along the Dead Sea transform fault will allow geologists to more precisely create earthquake motion models of the region that will undoubtedly save lives once earthquake codes and regulations are updated in the region.

Research Questions

This dissertation research highlights three earthquake studies that were conducted along the Dead Sea transform fault in southern Jordan as a part of the Wadi ‘Arabah Earthquake Project (WAEP) (Figure 1.2). The first of these research projects is an archaeoseismic study of the archaeological ruins of Early Islamic Ayla (7th – 12th C.), located in the modern city of Aqaba, Jordan, that are hypothesized to have been damaged by the ground shaking of an earthquake in the historic past. The remaining two projects are paleoseismological studies, with one paleoseismic trench located within the city of Aqaba,

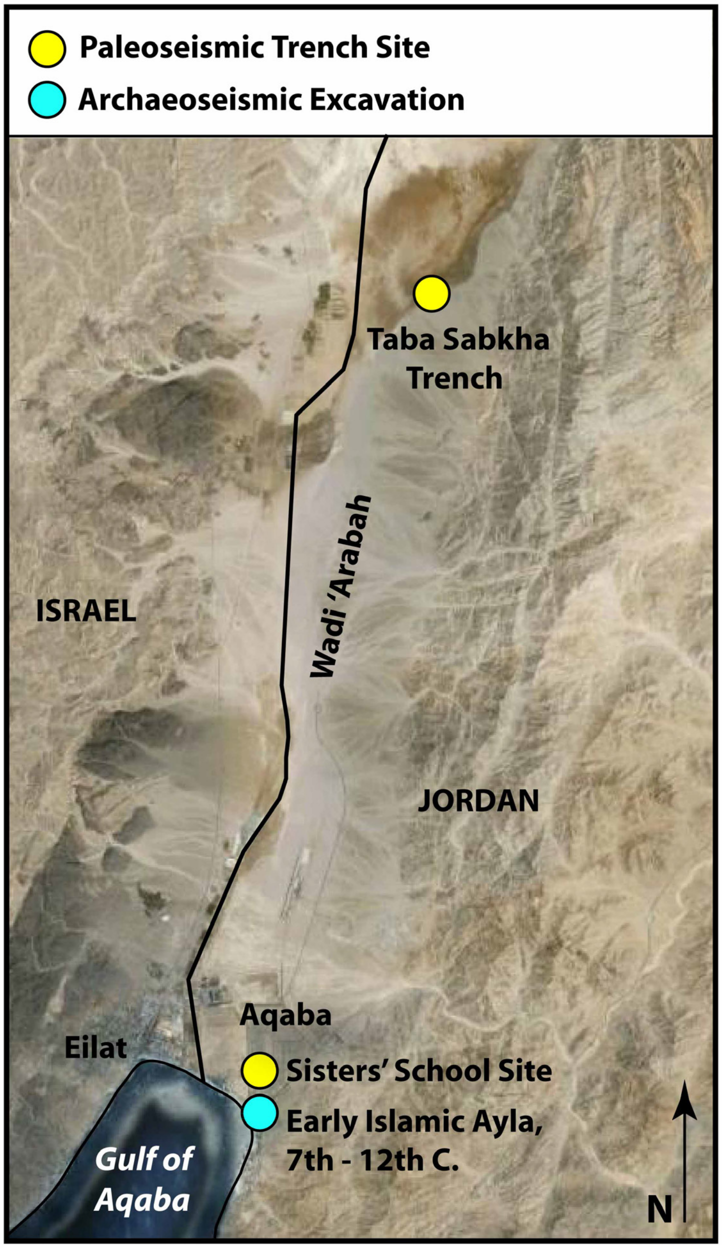

Figure 1.2 Location map of research sites in southern Wadi ‘Arabah, Jordan (Google Earth, 2013a).

Jordan at a site referred to as the Sisters' School site, and another paleoseismic trench site located approximately 35 km north of the Gulf Aqaba in the Taba Sabkha.

For the purposes of this research, both paleoseismic and archaeoseismic data collected was used to constrain the timing of the last few seismic events occurring in the southern Wadi ʻArabah, and to date the timing of these ancient earthquakes using detailed stratigraphic mapping and radiocarbon dating of the subsurface stratigraphy. The paleoseismic record is evidence of predominately large (M > 6.5) or great (M > 7.8) earthquakes because rarely is the geologic evidence of small to moderate-sized seismic events created or preserved near the Earth's surface (McCalpin, 2009). The paleoseismic data collected for the purposes of this dissertation, therefore, represents seismic events that were potentially large enough in magnitude to have affected the Aqaba region in antiquity even from some distance away. The determination of earthquake recurrence intervals is also a major factor of earthquake-hazard assessment. By studying the paleoseismology of the region, the goal is to gain a better working knowledge of the seismic potential of the Dead Sea transform. The overall purpose of this research, therefore, is to determine the number and frequency of seismic events that have ruptured along the segment of the Dead Sea transform fault in the southern Wadi ʻArabah, and to correlate this seismic activity to historical earthquakes that have occurred in southern Jordan over the last few millennia.

Dissertation Format

This dissertation is divided into six chapters. The first chapter outlines the purpose of this study, briefly discusses the basic principles of paleoseismology and archaeoseismology, and discusses the research questions addressed within this dissertation. The second chapter details the geography and climate of the greater Aqaba, Jordan region where this study was conducted, summarizes the tectonics and seismicity of the Aqaba coastal zone, and provides a summary of the earthquake catalogs for the southern Dead Sea transform.

The next three chapters, chapters three, four, and five, each highlight a specific study area researched as a part of this interdisciplinary dissertation. The archaeoseismic excavation conducted at the site of Early Islamic Ayla is detailed within the third chapter. Chapter three also contains a discussion of the motivation for research and the field of archaeoseismology, a summary of the previous archaeological excavations conducted at Islamic Ayla, and summaries of the cultural history and ceramics associated with the site. A discussion of the liquefaction susceptibility of Ayla and the region is also highlighted in this chapter. Chapter four presents and discusses the paleoseismological research conducted along the Dead Sea transform in the Taba Sabkha, and details the previous geophysical surveys and paleoseismic studies conducted in southern Wadi ‘Arabah. Chapter five discusses a paleoseismology study conducted within the city of Aqaba, Jordan at the Sisters’ School site, and also presents evidence of paleoliquefaction. Finally, the sixth chapter discusses and compares the paleoseismological and archaeoseismological results of research conducted at these three study sites in Jordan, and considers future work to be carried out at these sites and elsewhere in the region.

CHAPTER 2

SETTING: SOUTHERN WADI ‘ARABAH

Geography and Climate

Situated along the international boundary between the countries of Jordan and Israel in the Middle East, the southern Wadi ‘Arabah Valley is an arid region, and desert conditions dominate because of its position in the rainshadow of the mountains located to both the east and west (Saqqa and Atallah, 2004). The region is sparsely vegetated and the modern climate is characterized by short, cool winters and long, hot summers. The mean air temperature is 15˚C in January and 33˚C in August. Maximum temperatures in the summer months can reach up to 50˚ C daily, and winter temperatures can be as low as 0˚C. The daily temperature disparity for the region is often greater than 30˚C which is significant enough to restrict plant growth throughout the southern Wadi ‘Arabah Valley (Saqqa and Atallah, 2004). Based on long-term meteorological data obtained from the Ghor As-Safi Meteorological Station (GSMS) and the Aqaba Airport Meteorological Station (AAMS) which was collected from 1955-2002, the annual precipitation decreases from approximately 80 mm (GSMS) to 40 mm a year (AAMS) from north to south down the Wadi ‘Arabah (Saqqa and Atallah, 2004). The mountains located to the east of the valley receive around 200 mm of precipitation per year, while the mountains that border the western (Israeli) side of this wadi receive only 50 mm of precipitation on average (AAMS).

Tectonics

Tectonic Setting and Geologic History

The Dead Sea transform (DST) is a 1,100 km-long sinistral transform plate boundary that separates the Arabian Plate on the east from the Sinai subplate, an appendage of the African tectonic plate, to the west. A series of pull-apart basins are arranged in an *en-echelon* pattern along strike (e.g. Quennell, 1956, 1959; Freund et al., 1970; Garfunkel et al., 1981). The linear structure of the Wadi 'Arabah Valley, however, was once thought to be a rift zone caused by tectonic activity along normal faults that bound the valley margins (Anderson, 1852; Lartet, 1869; Hull, 1886; Blanckenhorn, 1912, 1914). The DST trends approximately N15˚E and connects the Red Sea spreading center in the south with the collisional belt of the Taurus-Zagros Mountains at the north end of the fault system in southern Turkey. The Red Sea, the boundary between the African and Arabian plates, bifurcates into two branches at its northern end known as the Gulf of Suez and the Gulf of Aqaba (Eilat). While the Gulf of Suez follows the main trend of the Red Sea, the Gulf of Aqaba forms the southern part of the NNE striking Dead Sea transform plate boundary. The southern portion of the Gulf of Aqaba is also one of the few places in the world where a mid-ocean ridge intersects a continent and transitions into a transform feature (e.g. Ben-Avraham et al., 1979; Ben-Avraham, 1985). The DST boundary formed when the African-Arabian continent broke up during the Mid-Cenozoic, and the Red Sea (Gulf of Aqaba/Eilat) and the Gulf of Suez are subsequent rifts along adjacent cracks (Garfunkel et al., 1981).

On a regional scale, the Dead Sea transform crosses a continental area that was originally consolidated during the Late Proterozoic Pan-African Orogeny. Garfunkel and

Ben-Avraham (1996) explain that during most of the Phanerozoic this area acted predominately as a stable platform and was covered by several kilometers of mostly marine sediments. This platformal history was interrupted by a few phases of tectonic and igneous activity, but more important are the various rifting events that took place during the Permian, Triassic and Early Jurassic periods. This rifting is directly related to the initial formation of the Eastern-Mediterranean branch of the Neo-Tethys Sea, and acted to shape its passive margins (Garfunkel and Ben-Avraham, 1996). Closing of the Neo-Tethys began in the late Cretaceous as marine sediments were still being deposited over the area, and this movement was accompanied by mild compressional deformation (the Syrian arch phase) which continued into the Miocene (Garfunkel and Ben-Avraham, 1996).

Three main geologic evolutionary stages can be summarized for this region (Garfunkel and Ben-Avraham, 1996). The first of these stages is the Precambrian Pan-African orogenic stage in which igneous and metamorphic activity formed the Arabo-Nubian crystalline basement. Deposited secondly was the extensive sedimentary sequence laid down during the Early Cambrian to Eocene stable platform stage. The final evolutionary stage represented by the Dead Sea transform is the Mid-Cenozoic to Recent stage that was accompanied by alkali olivine basalts, basinites, and nephlinites igneous activity (Garfunkel and Ben-Avraham, 1996). Around 30-25 mya, the continental break-up phase began, which ultimately led to the detachment of Arabia from Africa. This tectonic divergence created the currently linear Red Sea where sea-floor spreading continues to take place today (e.g. Coleman, 1984; Garfunkel and Ben-Avraham, 1996).

Local Geologic Setting: Southern Wadi ‘Arabah

The local setting of this study is geologically driven by Quaternary deposits as well as eroded granitic bedrock materials. The city of Aqaba is built upon alluvial fan sediments washed down from Wadi ‘Arabah and Wadi Yutim and deposited from the granitic mountains located to the east of the city. These two valleys act as a large drainage system that empties into the northern portion of the Aqaba coastal zone, and as a result have created large alluvial fans (Figure 2.1). Niemi and Smith (1999) surveyed the southern portion of the Wadi ‘Arabah and found that the modern city of Aqaba is constructed on top of these unsorted sand and gravels deposits, or wadi deposits, that date from the Pleistocene to the Holocene.

Quennell (1951) conducted the first detailed study on the basement rocks of southwest Jordan following the pioneering work of Blanckenhorn (1912, 1914), Fuchs (1915), Blake (1936), and Picard (1941). Quennell (1951) defined the "Aqaba Granite Complex" basement rocks and compiled three 1:250,000 maps for Jordan east of the Dead Sea rift, including the Aqaba area. Bender (1968) compiled the same scale maps for all of Jordan, and three 1:100,000 maps were produced by the German Geological Mission for southwest Jordan (Bender, 1974) that incorporated a six-fold division of the crystalline basement in the Aqaba region. Precambrian igneous rocks of the Aqaba Granite Complex are exposed east of Aqaba and for approximately another 50 km north of the city (e.g. Quennell, 1959; Bender, 1975; Rashdan, 1988). These rocks are composed of granite, monzogranite, granodiorite, and quartz diorite. Some of the most noticeable features of the mountains east of Aqaba are the multiple igneous dikes that cross-cut the granitic complex.

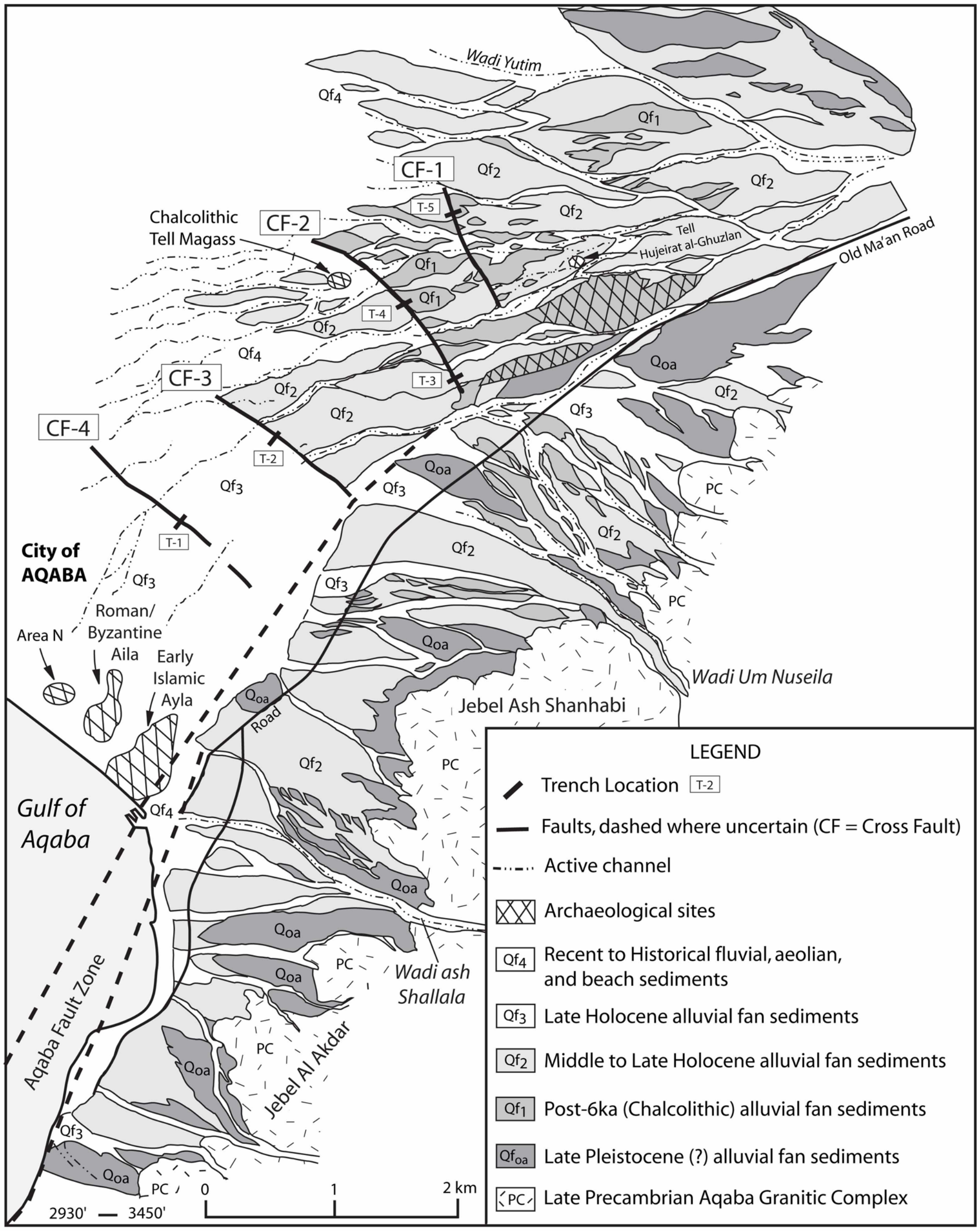

Figure 2.1 Geologic map of the Aqaba region based on interpretation of 1:25,000 scale air photos from 1953. Cross fan faults (CF 1-4) are mapped as continuous lines even though features are eroded by wadi washes. These cross faults formed as normal to oblique-slip faults associated with a left step-over in the Dead Sea transform. The cross faults accommodate active tectonic subsidence at the head of the Gulf of Aqaba. Archaeological ruins and artifacts provide additional age constraints of surface deformation (modified after Niemi, 2013).

Although metamorphic rocks are not common in the area, there are pockets of slate, biotite schist, and gneiss found along the western shore of the Gulf of Aqaba and in the area of Wadi Abu Barqa, located north of Aqaba (e.g. Bentor et al., 1965; Bender, 1975; Ibrahim, 1993).

Cambrian arkosic sandstones and conglomerates unconformably overlay the Aqaba Granite Complex from which they are derived and grade into a massive Cambrian to Silurian-aged quartzose Nubian Sandstone (Rashdan, 1988). This sandstone unit is present some 50 km northeast of Aqaba along the eastern mountain range and is particularly important because it provides the sand from which a dune field formed between the sabkhas of Taba and Qaa' es-Sa'idiyeen (Niemi and Smith, 1999). Precambrian to late Cretaceous rocks outcrop along the Dead Sea rift and more recent Neogene to Quaternary sediments overlay these basement rocks and fill in deep basins that developed along the DST (Garfunkel et al., 1981). The mountains located to the west of the Wadi 'Arabah are composed primarily of Cretaceous sandstones, limestones, and dolomites which are often fossiliferous, and interbedded with chert, shale, and phosphate (Niemi and Smith, 1999). Bender (1974) provides a geological summary of the region, and the metamorphic history and the geochronology are reported by Lenz et al. (1972), Farhat (1979), Jarrar et al. (1983), and Jarrar (1985).

There are several drainage basins in the Aqaba region, as mentioned, but the largest drainage basin in the southern Wadi 'Arabah Valley is Wadi Yutim which reaches the furthest into the eastern plateau and covers over 4,545 km^2 (Foote et al., 2011). Furthermore, there are several branches of the Wadi Yutim drainage basin that flow to the south toward the Gulf of Aqaba. The Wadi ‘Arabah Valley itself is an area of low relief that slopes from an elevation of 300 m south of the Dead Sea down to sea level at the head of the Gulf of Aqaba, and the valley floor is covered in Holocene to Pleistocene-aged alluvial fan and mudflat sediments (Niemi and Smith, 1999). Niemi and Smith (1999) mapped the alluvial fans of Aqaba and of the Wadi ‘Arabah. Three cycles of fan alluviation, entrenchment, and soil development can be distinguished, and the two Holocene-aged fan progradations correlate well with the archaeological record at 6 ka and 2-3 ka (Niemi and Smith, 1999).

Fault Geometry

Strike-slip faults are the dominant structural component along the Dead Sea transform, although normal faulting is present as well. Hamiel et al. (2009) suggest that normal faulting along the southern Wadi ‘Arabah portion of the DST accounts for approximately 10% of the total paleoseismic motion over the last 60,000 years. The majority of the length of the Dead Sea transform is also marked by prominent, fault-controlled morphotectonic depressions or basins that vary in depth and are often filled with Neogene- to Quaternary-aged sediments many kilometers thick (Garfunkel et al., 1981). As Ambraseys (2006) discusses, in common with all major continental transform faults, the DST system is segmented and earthquake rupture is limited in length by structural discontinuities or bends along each fault line. There are several major depressions developing at jogs between successive segments of the DST fault that are present in the country of Jordan. From south to north these basins include: the Gulf of Aqaba basin, the Wadi ‘Arabah (Timna) basin which extends from the Gulf of Aqaba to the Dead Sea, the

Dead Sea basin near the center, and the Jordan Valley in the north (e.g. Garfunkel, 1981; Ben-Avraham, 1985; ten Brink et al., 1999). Each basin is flanked by marginal blocks surrounded by normal faulting.

Several sub-parallel faults have recently been mapped in the Gulf of Aqaba (Eilat) including the Aqaba fault, West-Aqaba fault, East Ayla fault, Ayla fault, Wadi ʻArabah (Evrona) fault, and the Eilat fault (Hartman, 2012). In the city of Aqaba, Jordan however, the specific location where the Aqaba fault emerges from the Gulf of Aqaba remains somewhat uncertain because it has never been exposed in paleoseismic trenches near the shoreline and is currently masked by urbanization (Niemi and Smith, 1999). Geological studies of the Aqaba area conducted by Mansoor (2002) and Slater and Niemi (2003) showed that the Aqaba fault emerges from the Gulf of Aqaba and steps 4.5 km west to the Wadi ʻArabah fault along northwest-striking, normal-to-oblique slip faults. The Aqaba fault zone borders the Gulf's east side and dies out under the city of Aqaba where it is covered by rapidly growing urban development. Whitcomb (1993a) hypothesized that the drainage (wadi) that cuts across the archeological site of Early Islamic Ayla (7th- 12th C.) in Aqaba was created as a result of erosion from precipitation and flood waters draining out into the Gulf along the structurally weak DST fault trace. Previous excavations at the site of Islamic Ayla, however, provided evidence that this wadi is not the eroded DST fault trace (Rucker and Niemi, 2005), but that the fault line most likely is located to the east (Niemi, 2013; Rucker and Niemi, 2013).

Seismicity of the Dead Sea Transform

Although still seismically active (Figure 2.2), the fault segments of the Dead Sea transform situated between the city of Aqaba and the Dead Sea have been largely quiescent for the last few decades, especially along the southern segment of the DST where the Wadi ‘Arabah (Evrona) fault is the main strike-slip fault. Shapira (1997) attributes the episodic low-magnitude seismic activity of the region to motion on near-by branching fault segments. Large historical earthquakes are known to occur along the Dead Sea transform (e.g. Ambraseys et al., 1994; Guidoboni, 1994; Guidoboni and Comastri, 2005; Ambraseys, 2009), although according to Ambraseys (2006), the rate of seismic activity observed over the last one hundred years has been far lower than is necessary to account for the total Arabia-Africa motion along the DST.

Klinger et al. (1999) suggest that at least since the start of the instrumental period around the turn of the 20th century that the primary characteristic of the seismicity in the Gulf of Aqaba region is the occurrence of earthquake swarms. In the last thirty years, three sequences of earthquakes have been observed and recorded, all of which start and end gradually without a single dominating event (Klinger et al., 1999). To those living in the southern Jordanian city of Aqaba and in the near-by city of Eilat, Israel, the local seismic activity within the Gulf region became apparent after the 1983 seismic swarm when more than five hundred earthquakes were recorded, the largest of which was M_L= 4.85 (El-Isa et al., 1984). Two other seismic swarms centered in the Gulf of Aqaba affected the area again in 1990 and 1993. The maximum magnitude of the 1990 swarm, which involved approximately 150 earthquakes, was M_L= 4.2, and the maximum magnitude of the swarm in

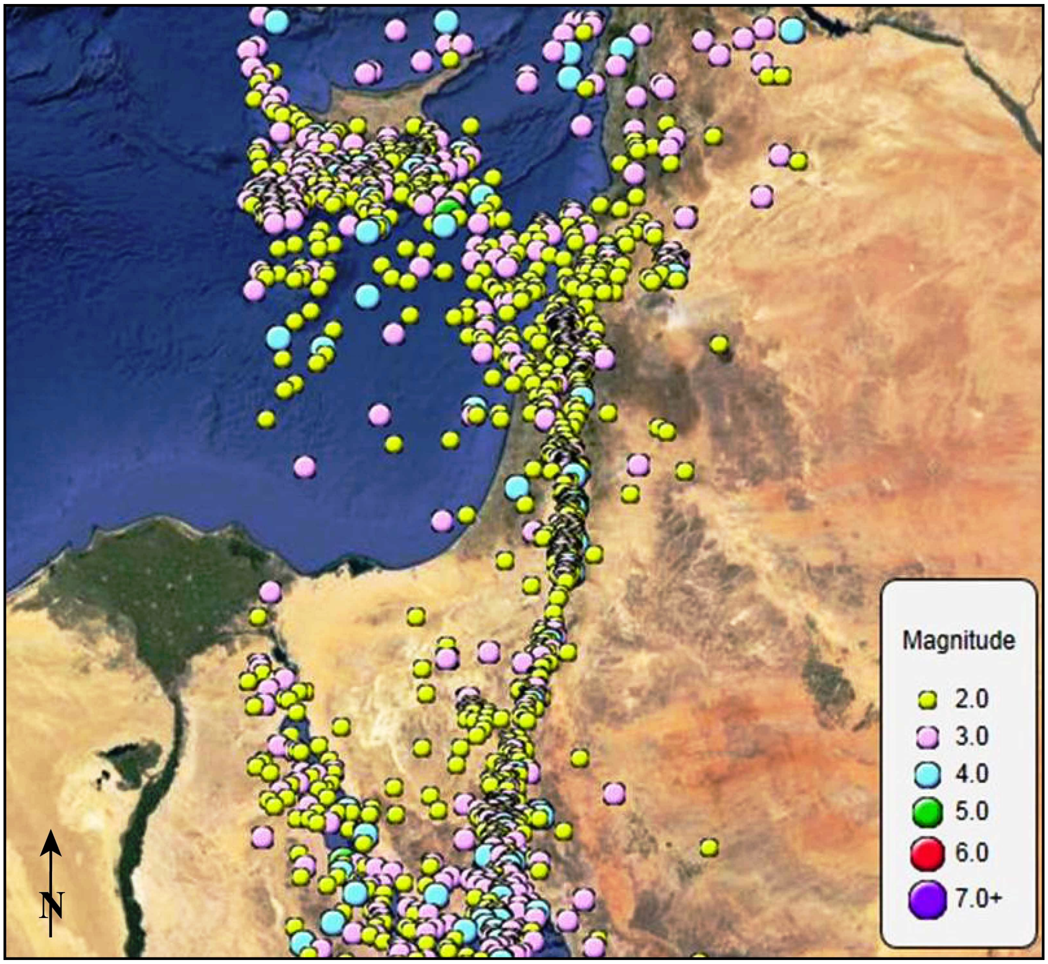

Figure 2.2 Seismicity map of the Mediterranean and Middle East regions from 1/1/2000 to 12/31/2013 (from the Geophysical Institute of Israel, Seismology Division, 2013).

1993 was M_L= 5.34 when several hundred earthquakes were again recorded in the region (e.g. Amrat, 1996; Husein Malkawi and Fahmi, 1996; Osman and Ghobarah, 1996). The location of the main seismic activity for all three of these earthquake swarms moved from north to south along the tectonically controlled basins in the Gulf of Aqaba (Klinger et al., 1999). The majority of the 1983 and 1990 earthquakes occurred in the tectonic basin known as the Eilat Deep, the northernmost of the Gulf of Aqaba basins, and the majority of the 1993 events were located in the Aragonese Deep basin near the center of the Gulf of Aqaba (Klinger et al., 1999). With each of these three particular swarms, the full process of increasing and decreasing seismic activity took place within a few months (Klinger et al., 1999). The 1983 seismic swarm lasted from January until April, for instance (El-Isa et al., 1984).

Further north, in a study by Hofstetter et al. (2007), some seventy-eight earthquake events with a magnitude of 2.0 or greater occurring between 1986 and 1997 were plotted with a reliable location between the Sea of Galilee and the Gulf of Aqaba. Using data collected from a total of 118 seismological stations positioned in the region, Hofstetter et al. (2007) found that the majority of these sesimic events are concentrated within the Wadi ‘Arabah Valley itself, with a large part of the seismicity concentrated within the Dead Sea basin. They attribute the asymmetry of this basin (ten Brink et al., 1999) to the concentration of seismicity toward the eastern side of this deep depression. However, despite a clear morphogenic signature in the Quaternary-aged sediments within the Wadi ‘Arabah Valley, Hofstetter et al. (2007) found that this area displays only relatively minor background seismicity. Based on this study, it is also clear that the tectonics become even more complex north of the Dead Sea.

Despite the number of seismic events plotted by Hofstetter et al. (2007), the earthquake swarms mentioned previously, and the type of tectonic boundary involved -- a major transform plate boundary -- the seismic activity of the Dead Sea transform fault is still surprisngly low. The most sizeable earthquake to occur in the region of the southern Wadi ‘Arabah in the last century, with a moment magnitude $M_W = 7.3$ and a local magnitude $M_L = 6.2$, occurred near Nuwebei, Egypt in the Gulf of Aqaba approximately 70 km south of the head of the Gulf in the early morning hours of November 22, 1995 (e.g. Dziewonski et al., 1997; Baer et al., 1999; Husein Malkawi et al., 1999; Klinger et al., 1999; Al-Tarazi, 2000). The Nuweiba earthquake ruptured along a N-NE trending sinistral strike-slip fault within the Gulf. The hypocenter was located approximately 4 km offshore in the Aragonese Deep basin at a depth of 12 km, partway between the Egyptian towns of Dahab and Nuweiba on the Sinai Pennisula. This event actually nucleated near where the 1993 earthquake swarm originated in the Aragonese Deep (e.g. Osman and Ghobarah, 1996; Husein Malkawi et al., 1999; Klinger et al., 1999). This earthquake, which killed several people as a hotel collapsed in Nuweiba and substantially damaged the near-by coastal cities of Aqaba, Jordan and Eilat, Israel among others, experienced a maximum observed intensity of VIII on the Modified Mercalli intensity (MMI) scale (e.g. Osman and Ghobarah, 1996; Al-Tarazi, 2000). Ground shaking from this earthquake, which continued for two minutes in most locations, was felt over an area approximately 200 km-long and 150 km-wide, from Syria and Lebanon in the north to the northern frontier of the Sudan in the south (Husein Malkawi et al., 1999). This event was then followed by a swarm of more than 2000 earthquakes ranging in magnitude from $M_L = 2 - 6.2$, although unlike the aforementioned earthquake swarms of 1983, 1990, and 1993, this subsequent seismic activity or series of aftershocks occurred over the course of the next two years and thus did not dissipate quickly (e.g. JSO Bulletin, 1998; Al-Tarazi, 2000).

Most recently, a $M_L = 5.2$ earthquake occurred within the northeastern Dead Sea basin in February 2004, the largest seismic event to affect this region since the 1927 Jericho earthquake which was a $M_L = \sim 6.2$ event (e.g. Shapira et al., 1992; Shamir, 2006). Some forty-six aftershocks with $M_L \geq 2$ occurred within the following year. Shamir (2006) determined that this was not a typical mainshock-aftershock sequence, but a series of apparently triggered events on a fault array that has yet to be resolved. A seismicity study by Shamir (2008) showed that these aftershocks consisted of a main near-field cluster in the northern Dead Sea and two minor sequences which were located approximately 30 km to the south around the central Dead Sea area, and 30 km to the north within the Fazael Valley. Ultimately, recent seismic events such as the 1995 Nuweiba earthquake and the 2004 earthquake in the Dead Sea basin acted as both a reminder and confirmation that the Dead Sea transform is very much an active transform boundary with enough seismic potential to cause great structural damage and loss of life.

Summary of Earthquake Catalogs for the Southern Dead Sea Transform

In order to study earthquakes that occurred prior to the use of seismic monitoring instrumentation in the southern Wadi ‘Arabah, the historical record can be utilized to help build a list of seismic dates and intensities based on reported earthquake damage or evidence of earthquake damage acquired through the archaeological record. For several thousand years, since about the first Egyptian Dynasty in 3100 B.C., the dates and occurrences of large ($M > 7$) earthquakes have been recorded in various texts throughout the Mediterranean and Middle Eastern regions (Ambraseys et al., 1994), providing a highly detailed record of major earthquakes for the past few thousand years. Modern earthquake catalogs are compilations of historical records of earthquakes which have occurred within a region throughout the last several millennia, typically arranged in chronological order by year of occurrence. These catalogs focus on detailing seismic events that occurred prior to the use of seismic monitoring and recording instrumentation at the start of the 20th C, and are thus very important resources in the study of the paleoseismology and archaeoseismology of a region.

The evaluation of earthquake catalogs requires a critical assessment of the historical records that cite each event. The historical sources cited within these earthquake catalogs include primary, secondary, and even tertiary sources, although primary sources are the rarest type of historical source and the most desirable in terms of credibility. Other types of sources often included within earthquake catalogs are epigraphical sources such as stone inscriptions, coins, and other archaeologically relevant artifacts found in context with specific earthquake event horizons. Previously constructed earthquake catalogs from within the same region and historical studies and scientific literature are also used to obtain more accurate dating or location/epicenter data for specific seismic events.

While an invaluable resource to help scientists understand and better interpret the present seismicity of a region and to begin to anticipate future seismic events, earthquake catalogs can potentially be somewhat biased for a variety of reasons. First, historical sources were generally more apt to record the larger seismic events than the typically more numerous small to medium-sized earthquakes. Also, the more damaging and widespread the effects of an earthquake, the more likely that earthquake was to be recorded by a variety of sources in various locales, and the earthquakes included within the various catalogs, therefore, tend to be biased toward large, damaging events.

Geographical and population factors also play a part in the documentation of historic seismic events. Sparse habitation throughout history and an uneven population distribution within a region, such as is seen in both modern and pre-modern Jordan due to a relatively harsh, arid climate with limited water resources, both may have biased historical accounts of earthquake extent, damage, and even accuracy of the dates of occurrence. If the only place where a specific earthquake was felt and recorded, for example, was far away from the epicenter, a much larger earthquake may be recorded as a smaller event based on the perceived effects at that distant location. Furthermore, because the majority of historical sources used to document pre-instrumental earthquakes are secondary and tertiary sources, the possibility of distortion or error during translation and transcription of an event is even greater than with primary sources which are recorded at or very near the time of the actual earthquake. In general, the more time between the actual occurrence and recording of any event, seismic or otherwise, the more likely the details of that event are to be skewed, exaggerated, forgotten, misrepresented, and so forth. Multiple earthquakes within a region that occurred closely in time may also be combined into one single event when recorded, or the opposite may occur where one large, widely felt event is documented as two separate earthquakes in the historical record.

There are several earthquake catalogs that focus on the historical earthquakes of the Mediterranean and Middle Eastern regions that include earthquakes specifically attributed to the southern Dead Sea transform. For the purposes of this archaeoseismic and paleoseismic research along the DST, the major recent historical catalogs were evaluated and the seismic event dates compared. Table 2.1 summarizes the regional historical earthquakes from Guidoboni (1994), Guidoboni and Comastri (2005), and Ambraseys (2009) that likely affected the Dead Sea, Wadi ‘Arabah, and Gulf of Aqaba regions. Due to the inherent variations among the earthquake catalogs concerning key seismic dates and damage reports, the supporting data for each seismic event was evaluated and the best-supported dates are listed in the historical earthquake table by catalog. Table 2.1 also lists, where available, the maximum intensity of each earthquake and the city where these effects are known to have been the greatest. The paleoearthquakes discussed here are evaluated by the intensity of the damage at specific locations based on historical damage accounts, or evidence of damage encountered through archaeological excavation. The Modified Mercalli Intensity (MMI) scale is a qualitative measure of earthquake-induced damage based on the severity of ground shaking with intensity values ranging from I to XII, with I representing the level at which ground shaking may be felt slightly and XII representing total destruction (e.g. Wood and Neumann, 1931; Obermeier, 2009). Earthquake catalogs generally focus on a specific set of years or centuries, primarily due to the sheer volume of paleoseismicity and historical accounts to report and discuss. Guidoboni (1994), for example, cites all known earthquakes

TABLE 2.1

SUMMARY OF HISTORICAL EARTHQUAKES
IN SOUTHERN WADI ‘ARABAH

Date of Earthquake (A.D.)	Earthquake Catalogs	Possible Fault Segment(s)	Damage Accounts; Max. MM Intensity (Value and City, if available)
January 4, 1588	Ambraseys, 2009	Gulf of Aqaba	Tabuk castle and St. Catherine’s mosque collapsed; felt in Cairo
January 14, 1546	Ambraseys, 2009	Dead Sea	Nablus, Ramla and Jerusalem damaged; MMI = IX-X, Nablus
November 8/16, 1458	Guidoboni and Comastri, 2005; Ambraseys, 2009	Dead Sea	100 died in Karak; minarets collapsed at Ramla and Hebron; MMI = IX, Karak
January 1293	Guidoboni and Comastri, 2005; Ambraseys, 2009	Dead Sea	Houses and citadel in Karak destroyed; Ramla, Gaza, Ludd (Lod), Qaqun also affected; MMI = IX, Karak
May 1, 1212	Guidoboni and Comastri, 2005; Ambraseys, 2009	Gulf of Aqaba	Strongest damage at head of Gulf of Aqaba; people crushed by collapsed structures in Karak and Shaubak; MMI = IX-X, Aqaba
May 29, 1068	Guidoboni and Comastri, 2005; Ambraseys, 2009	Wadi ‘Arabah	≥15,000 casualties in Ramla and a tsunami wave is reported; damage was local and may be exaggerated; MMI = X, Ramla

(Table 2.1 continued)

TABLE 2.1 -- Continued.

SUMMARY OF HISTORICAL EARTHQUAKES
IN SOUTHERN WADI ‘ARABAH

Date of Earthquake (A.D.)	Earthquake Catalogs	Possible Fault Segment(s)	Damage Accounts; Max. MM Intensity (Value and City, if available)
March 18, 1068	Guidoboni and Comastri, 2005; Ambraseys, 2009	Gulf of Aqaba	Major damage from Palestine to the Hejaz; EQ destroyed Islamic Ayla; new springs appeared in Tabuk and fissures in Taima; MMI = X, Aqaba
December 5, 1033	Guidoboni and Comastri, 2005; Ambraseys, 2009	Jordan Valley	Ramla, Nablus, Jerusalem, Jericho had worst damage; Tsunami wave on Mediterranean coast; MMI = IX-X, Ramla
March 9, 756/757	A.D. 757 – Guidoboni, 1994; A.D. 756 – Ambraseys, 2009	Jordan Valley (?)	EQ collapsed villages near Habura; damaged sites in Palestine and Syria; MMI = IX, Mesopotamia
January 18, 746/749	A.D. 749 - Guidoboni, 1994; A.D. 746 - Ambraseys, 2009	Jordan Valley	Jerusalem and Tiberias heavily damaged; landslide near Mt. Tabor; MMI = IX- X, Jerusalem
June 659	Guidoboni, 1994; Ambraseys, 2009	Dead Sea	Strong EQ in Jericho and all its churches largely destroyed; MMI = ≥ VIII and ≤ X, Palestine, Syria

(Table 2.1 continued)

TABLE 2.1 -- Continued.

SUMMARY OF HISTORICAL EARTHQUAKES IN SOUTHERN WADI ‘ARABAH

Date of Earthquake (A.D.)	Earthquake Catalogs	Possible Fault Segment(s)	Damage Accounts; Max. MM Intensity (Value and City, if available)
September 634	Guidoboni, 1994; Ambraseys, 2009	Dead Sea	Associated with appearance of a comet in A.D. 634; aftershocks went on for thirty days; MMI = ≥ VIII and ≤ X, Jerusalem
<597-598	Ambraseys, 2009	Wadi ‘Arabah (?) or Dead Sea (?)	Unknown range; only source, a stone inscription found in Rabbat Moab (Areopolis), cites EQ restoration
418/419	A.D. 419 - Guidoboni, 1994; A.D. 418 - Ambraseys, 2009	Dead Sea/ Wadi ‘Arabah	Damage not named by town, but many non-Christians were baptized out of terror; MMI = ≥ IX and ≤ XI, Palestine
May 18-19, 363	Guidoboni, 1994; Ambraseys, 2009	Jordan Valley Dead Sea/ Wadi ‘Arabah	Destructive EQ affecting most of Palestine and Jordan; MMI = X, Jerusalem
A.D. 110-114 (?)	Ambraseys, 2009	Wadi ‘Arabah/ Dead Sea	Early 2nd C. destruction at Petra, Masada, and Avdat (sites along Petra-Gaza Road)

Summary of historic earthquakes based on recent earthquake catalogs for the Gulf of Aqaba, Wadi ‘Arabah, and Dead Sea regions from the 2nd - 16th C.

in the region from 760 B.C. through the end of the 10th century, Guidoboni and Comastri (2005) list earthquakes from the 11th -15th centuries (A.D. 1000-1499), while Ambraseys (2009) is more encompassing and lists all known earthquakes occurring in the Mediterranean and Middle Eastern regions from 2100 B.C. up until A.D. 1900, reporting some 2000 earthquakes in all.

Historical Earthquakes in Southern Wadi ‘Arabah

The first earthquake event that may have potentially affected the southern Wadi ‘Arabah region within the last two millennia dates to A.D. 110-114. Of the catalogs used to compile this historical earthquakes review, Ambraseys (2009) is the only one that mentions this event. Archaeological evidence at the sites of Petra, Masada, Avdat (Figures 2.3 and 2.4), and at other locations along the Petra-Gaza road suggests a 2nd century destruction (Russell, 1985), although Ambraseys (2009) acknowledges that there is no corroborating documentary or archaeological evidence that the destruction identified from these archaeological excavations was a result of seismic damage. Some archaeologists suggest that the damage at Petra, in particular, could be seismic in nature, but others cannot rule out that the damage may have been caused by the sacking of the city by Safaitic and Thamudic hordes sometimes in the mid-first century A.D. (Ambraseys, 2009). A coin found buried in destruction rubble in Masada provides the earliest date of A.D. 110-111 for the proposed earthquake. Russell (1981) cites a *terminus ante quem* of A.D. 114 which was determined from a monumental inscription to Trajan found at Petra, but it is not known whether this

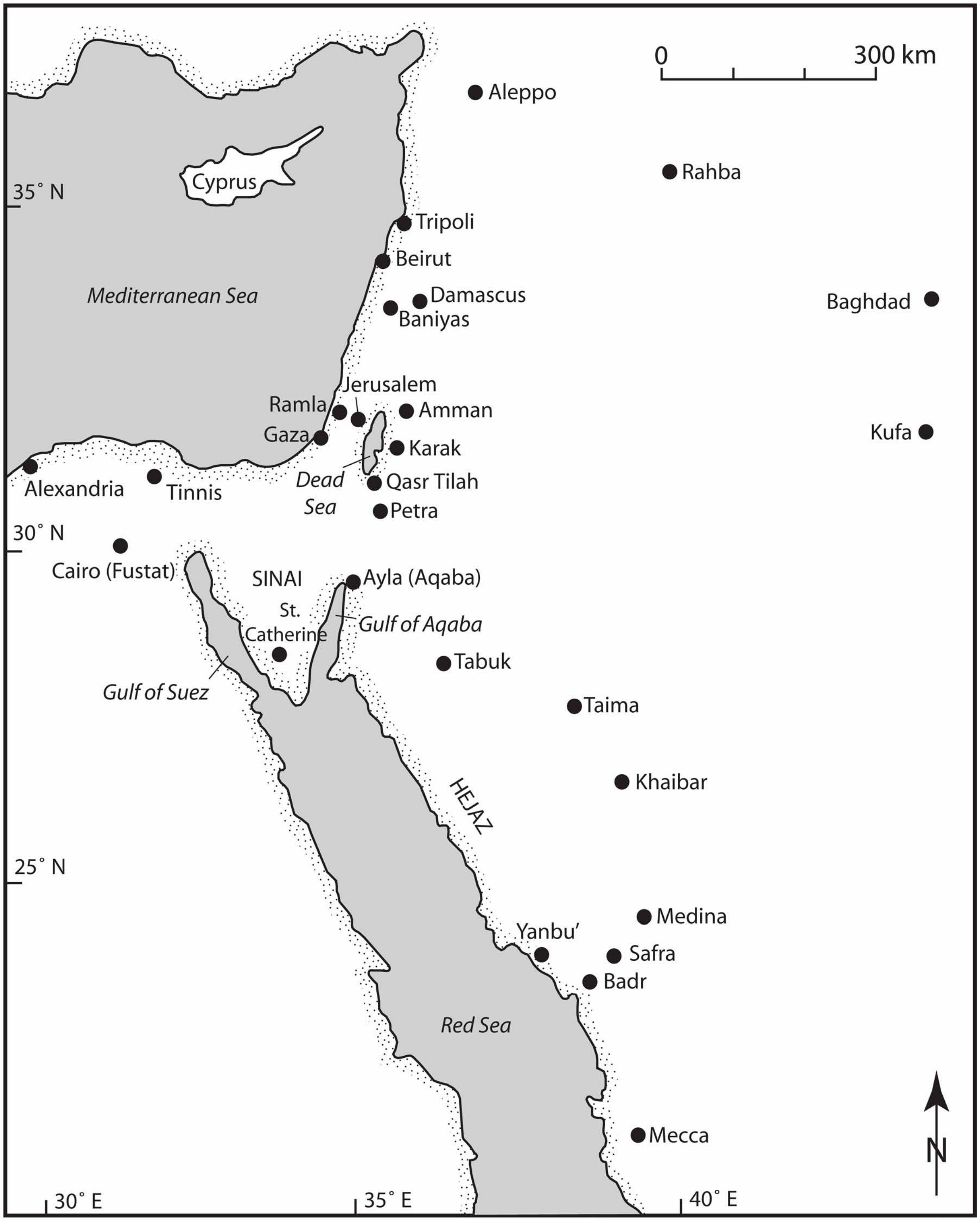

Figure 2.3 Regional historical seismicity map of area and cities of eastern Mediterranean and Middle East regions affected by earthquakes from the 2^{nd} century to the present (modified after Ambraseys et al., 1994).

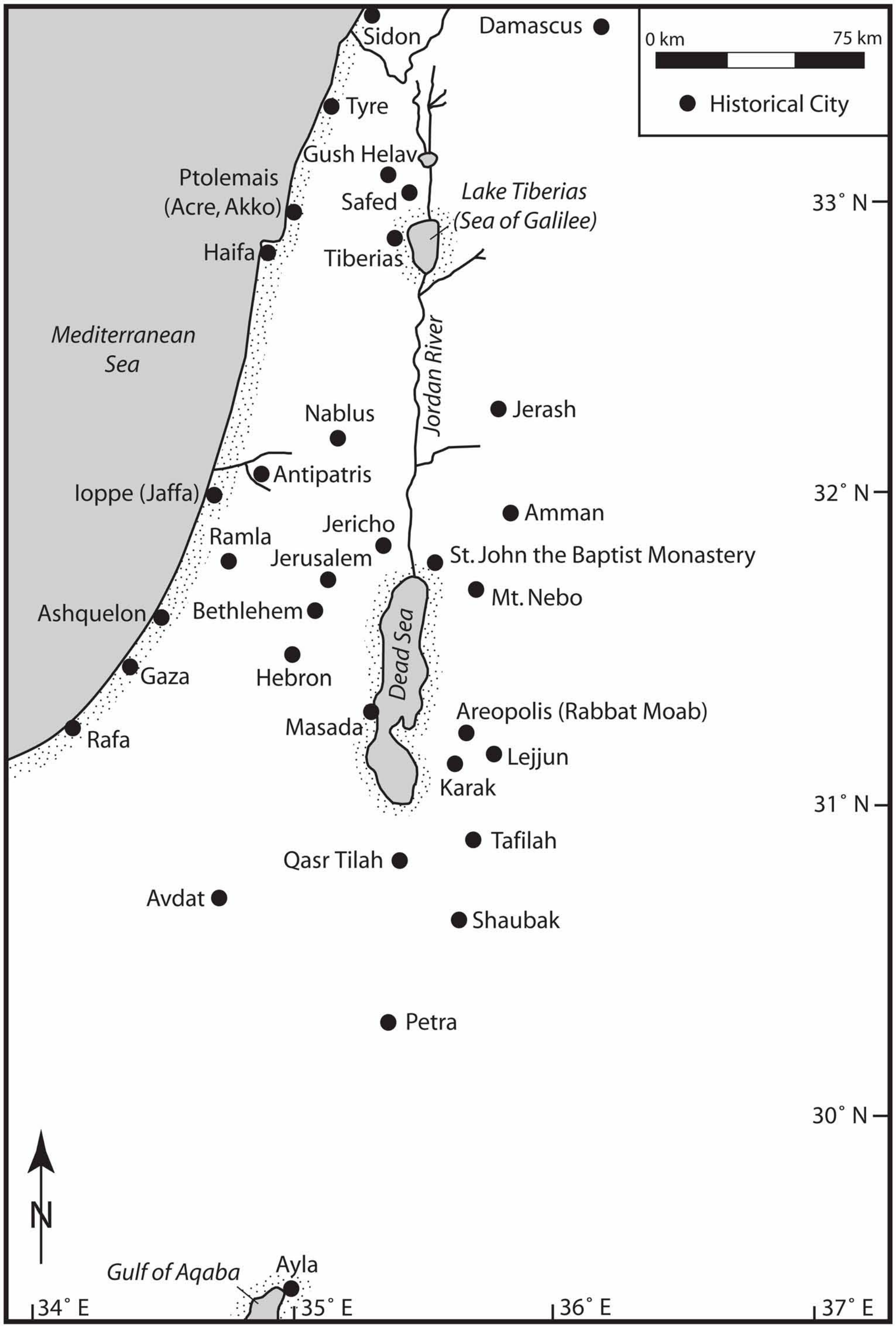

Figure 2.4 Historical geographical map showing cities with reported historical damage from earthquakes from 2nd to 18th century Palestine (present-day Israel and Jordan) (modified after Russell, 1985).

monument was constructed during or after the city's reconstruction so this date is tentative as well (Ambraseys, 2009).

Ambraseys (2009) and Guidoboni (1994) report that the large A.D. 363 event actually included two distinct earthquakes in Palestine occurring six hours apart on the evening of May 18-19. These earthquakes destroyed twenty-two towns in Palestine and Syria, damaged many more in the region including Areopolis (Rabbat Moab) and Ghor Safi in Jordan, and caused a great loss of life. Petra was severely damaged as was Jerusalem. Resultant fires and heavy rains also added to the destruction, and the Dead Sea was reported to have flooded its shores (Ambraseys, 2009). Some Syriac sources record that there was indeed a disastrous seismic event that destroyed much of the land. Unfortunately these two seismic events often get amalgamated into a single earthquake in the historical record both by contemporary and later sources, but there are numerous reports that also detail each earthquake individually. According to Ambraseys (2009), the event on the night of the 18th of May seems to have occurred in the north (Jordan Valley?), and the earthquake that happened later that same night (after midnight) on the 19th occurred in the south (Wadi 'Arabah?), based on regional damage reports. Among those killed by this earthquake, and acting to solidify this event date, three funerary inscriptions were found written in Greek in Ghor Safi, a small town located approximately 170 km north of Aqaba, Jordan and 32 km to the southeast of the Dead Sea (Ambraseys, 2009). This earthquake is estimated to have had a maximum intensity of X based on the Modified Mercalli Intensity (MMI) scale (Guidoboni, 1994).

The A.D. 418/419 earthquake was the next seismic event to affect the southern Wadi ‘Arabah region. Ambraseys (2009) reports that many towns and villages near Palestine were destroyed, but the damage reports do not themselves contain exact names. It is known from Augustine’s *Sermons*, however, that this earthquake caused thousands of non-Christians to be baptized out of terror of another similar event happening (Guidoboni, 1994; Ambraseys, 2009). Ambraseys (2009) suggests a date of 418 based on earthquake reports that it happened after a solar eclipse, one of which is known to have occurred on July 19, 418, at or about the time coinciding with a fire in the sky, likely an allusion to the comet of September 418. Guidoboni (1994), however, prefers a date of 419 based on evidence from Marcellinus and the *Consularia Constaniinopolitana*. Manuscripts date a report from Hydatius, a mid-5th century Spanish bishop, to A.D. 418. However, as A. Tranoy (the editor of the text) has argued, the scribe seems to have confused a mention of bishop John of Jerusalem (who was already deceased by this time) with bishop Eulalius of Rome, who is referred to in paragraph 66 of the *Chronicle.* Guidoboni (1994) explains that Tranoy, therefore, dates the earthquake to 419 on the basis of evidence from Marcellinus and the *Consularia Constaniinopolitana*, but does not clarify further. This earthquake is estimated to have had a maximum intensity of ≥ IX and ≤ XI based on the Modified Mercalli Intensity scale (Guidoboni, 1994).

The only source for the occurrence of an A.D. <597 earthquake is a stone inscription obtained during the Jordanian Department of Antiquities’ excavation of the area in 1962-1963 from a modern resident of the village of Rabbat Moab, the site of the ancient city of Areopolis, which is located 12 km north of Karak, Jordan and approximately 205 km north of Aqaba. The date on the inscription is 492 in the Arabic calendar, which translates to A.D.

597-598, although the inscription does makes it clear that the year on the stone fragment is not the year of the earthquake, but instead the year of restoration of the city. For this reason, the date Ambraseys (2009) associates with this event is sometime before A.D. 597. Ambraseys (2009) is the only catalog used for this review that evaluates this earthquake.

The two main sources for the A.D. 634 earthquake that struck the region come from Theophanes, a Byzantine chronicler, and Michael the Syrian, a Syrian historian (Guidoboni, 1994; Ambraseys, 2009). There is some debate as to whether this earthquake occurred in September 634 or whether it occurred somewhere between September 632 to August 633 as reported by Theophanes. Michael the Syrian provides two records for this earthquake according to both Guidoboni (1994) and Ambraseys (2009), one of which includes a report of a comet being seen in the night sky at the same time of the earthquake, while his other report just mentions the earthquake. Theophanes also makes mention of seeing something in the sky at the same time of the earthquake, which he referred to as a meteor, and which he also interpreted as being a sign foretelling Arab domination (Guidoboni, 1994). Both Guidoboni (1994) and Ambraseys (2009) point out that the most useful piece of evidence for dating this earthquake is the comet/meteor referred to by both Theophanes and Michael the Syrian. They suggest that it is probably the same one that was observed by Chinese and Japanese astronomers in September A.D. 634 (e.g. Ho Peng Yoke, 1962; Yeomans, 1991), and thus if these are indeed the same celestial events, then the earthquake in question should likely be dated to September A.D. 634 as well (Guidoboni, 1994; Ambraseys, 2009). This earthquake is estimated to have had a maximum intensity of ≥ VIII and ≤ X based on the Modified Mercalli Intensity (MMI) scale (Guidoboni, 1994).

Just twenty-five years later, the earthquake that occurred in A.D. 659 was a violent event that destroyed the majority of Jericho, including the monastery and the Church of St. John the Baptist near the Jordan River (Guidoboni, 1994; Ambraseys, 2009). This earthquake was strongly felt in present-day Jordan, and many villages in Palestine and presumably in Syria were destroyed. There is no evidence that Jerusalem was damaged from this event, although the monastery of Aba Euthymius located just 15 km east of Jerusalem collapsed, and sanctuaries in the Jordan Valley may have also been affected (Ambraseys, 2009). This earthquake is estimated to have had a maximum intensity of ≥ VIII and ≤ X based on the Modified Mercalli Intensity scale (Guidoboni, 1994).

The earthquakes of the mid-eighth century that affected the Jordan region are somewhat problematic to date and are surrounded by confusion. This is largely because there were several earthquakes that occurred within just a few years of each other, and because the people recording these events used different dating systems. Guidoboni (1994) and Ambraseys (2009) both report a major, damaging earthquake occurring on January 18 sometime between 746 and 749 in the Jordan Valley. Sources for this earthquake typically agree that this seismic event occurred on the 18th of January, but the year of this event varies within the historical record. Ambraseys (2009) attributes the confusion of the year of this earthquake to a systematic error made by Theophanes, the most contemporary author who mentions this event as affecting Palestine and Syria, in his conversion from the Annus Mundi, which follows the Alexandrian calendar system, to other calendar dating systems. The effects of this earthquake extended over a very large area, from Egypt across to Turkey, and from the eastern coast of the Mediterranean Sea to the Euphrates River in modern Iraq

(Guidoboni, 1994; Ambraseys, 2009). Serious damage was inflicted at Jerusalem and Tiberias with a great loss of life occurring throughout the region, and the intense ground shaking resulted in a landslide at a village near Mt. Tabor (Guidoboni, 1994). This earthquake is estimated to have had a maximum intensity of IX-X based on the Modified Mercalli Intensity scale (Guidoboni, 1994).

Little is actually known about the March 9, 756/757 earthquake that struck the region, the last to do so in the mid-eighth century A.D. that could have potentially affected sites in and around the Wadi ‘Arabah region. This earthquake is described as having strongly affected the lands of Mesopotamia, as damaging sites in Palestine and Syria, and as being the second earthquake in just a few years to affect Jerusalem where it apparently destroyed the repairs made to the Aksa Mosque, which was damaged in the earlier 746/749 earthquake (Ambraseys, 2009). Theophanes is again the primary source for this event, and reports it as being a strong earthquake in the year of the world 6248 (A.D. 756-757). This earthquake is estimated to have had a maximum intensity of IX based on the Modified Mercalli Intensity scale (Guidoboni, 1994).

A damaging earthquake with widespread effects shook the region of Palestine again on December 5, 1033, with much of the damage occurring in Ramla, Nablus, Baniyas, and Jericho (Guidoboni and Comastri, 2005; Ambraseys, 2009). It is estimated that one-third to one-half of the houses in Ramla collapsed, and great panic ensued. Many people died as a result of this earthquake, including at least 300 in the city of Nablus where it is also reported that half of the homes collapsed, and the neighboring countryside was almost totally destroyed. This event was felt from Egypt to the Negev desert, along the Mediterranean coast, and from the mountains of Galilee to Syria (Guidoboni and Comastri, 2005; Ambraseys, 2009). There was again serious destruction in Jerusalem including damaged city walls, and a large part of the Aksa Mosque, part of the Dome of the Rock, and numerous convents were badly damaged (Guidoboni and Comastri, 2005; Ambraseys, 2009). There was a tsunami wave (seismic sea wave) reported in the town of Acre on the Mediterranean coast, which drowned those who had rushed to forage the seabed when the water pulled out, but the wave reportedly did not cause destruction or loss of life further inland when the water returned an hour later. Most sources just report flooding of the coastline (Ambraseys, 2009). This earthquake is estimated to have had a maximum intensity of IX-X based on the Modified Mercalli Intensity scale (Guidoboni and Comastri, 2005).

The first of two earthquakes in the year A.D. 1068 occurred in the early morning of March 18 in the Gulf of Aqaba and the Hejaz (Guidoboni and Comastri, 2005; Ambraseys, 2009). This earthquake is known to have destroyed the town of Early Islamic Ayla located at the head of the Gulf of Aqaba, and it is reported that this seismic event killed all of the town's inhabitants except for twelve fishermen who were out fishing on the Gulf at the time of the earthquake (Makdisi, 1956; Guidoboni and Comastri, 2005; Ambraseys, 2009). Ground fissures were reported in Taima, and new springs appeared in Tabuk as a result of this event. In the Arabian Peninsula, there was damage at Medina where two merlons fell from the Mosque of the Prophet. This earthquake was also felt in Egypt, where Tinnis was damaged, as was Cairo, although the damage in Cairo was restricted to the 'Amr mosque in Fustat (Old Cairo) (Ambraseys, 2009). Ground shaking was also felt as far north as Damascus and Rahba, and as far east as Kufa on the Euphrates River in Iraq where the water reportedly sloshed over its banks, as well as being felt in Baghdad (Ambraseys, 2009). Overall, ground shaking during this earthquake was felt within a radius of 600 km, clearly a large-magnitude event, and the epicenter was likely in the Gulf of Aqaba (Ambraseys, 2009). This earthquake is estimated to have had a maximum intensity of X based on the Modified Mercalli Intensity scale (Guidoboni and Comastri, 2005).

Only a little more than two months later on May 29, 1068, a locally damaging earthquake centered near Ramla, Palestine shook the southern Wadi ʻArabah region again (Guidoboni and Comastri, 2005; Ambraseys, 2009). All the houses in Ramla collapsed except for two buildings and part of the town walls, and sources report that at least 15,000 people perished in Ramla with 200 of those being students at a boy's school. A tsunami or seismic sea wave was also reported along the Mediterranean coast in Ramla on this day in 1068 (Guidoboni and Comastri, 2005; Ambraseys, 2009). The reports of damage vary considerably for this event, and may very well be exaggerated based on the large discrepancies in the available historical sources. Many sources also amalgamate the damage effects of the March 18 event with this earthquake in May since the damage of each event is not altogether separable; some locales experienced only one of the earthquakes while other locations experienced both events (Guidoboni and Comastri, 2005; Ambraseys, 2009). Both earthquakes are also often reported together in the earthquake catalogs since they occurred so closely in time, as is the case with the catalogs reviewed here, and because of the complexity of the historical sources (Ambraseys, 2009).

Ibn al-Banna, a contemporary writer who lived in Baghdad in 1068 is one of the sources who combined these two seismic events into one as he wrote an impressive amount of detail about the earthquake he felt, along with accounts of the damage as they filtered in the city (e.g. Makdisi, 1956; Guidoboni and Comastri, 2005). In the following passage, Ibn al-Banna first brings together a description of earthquake effects in both Arabia and Palestine, dating them all to March 18, 1068, but in a later passage in his diary the seismic effects in Palestine are dated to May 29, 1068 on the basis of news passed on to him by traveling merchants in August 1068. Ibn al-Banna wrote:

> "News has arrived that there was a terrible earthquake in the city of the Prophet (Medina)…which brought down two merlons from the minaret of the Mosque of the Prophet – peace be on him! The people were greatly disturbed by the earthquake…and they turned to God in penitence for their evil deeds, broke instruments of pleasure, and poured away intoxicants. The governor of the city, known as 'the perfumer of adulterous women' was banished. Death itself is what they encountered. …As for Ayla, its inhabitants all perished except for 12 persons who had gone fishing at sea, thus escaping death. …the earthquake then ploughed through al-Ramla, 15,000 persons perished …and nothing was left of it, but two houses…" (e.g. Makdisi, 1956; Guidoboni and Comastri, 2005).

While the historical details do vary, both Ambraseys (2009) and Guidoboni and Comastri (2005) are convinced that two separate earthquakes occurred in the region of this year, on March 18 and May 29. The May seismic event is estimated to have had a maximum intensity of X based on the Modified Mercalli Intensity scale (Guidoboni and

Comastri, 2005), although according to Ambraseys (2009) the magnitude was likely smaller than the March 18 event based on the radius of damage reported.

On May 1, 1212 another sizeable and destructive earthquake occurred in the Gulf of Aqaba and in southern Palestine with the worst damage at the head of the Gulf of Aqaba (Guidoboni and Comastri, 2005; Ambraseys, 2009). Widespread collapses were reported in the southern Wadi ʻArabah region. Very serious damage and deaths occurred in Cairo, Egypt, and also at Karak and Shaubak in Jordan (Guidoboni and Comastri, 2005; Ambraseys, 2009). In the Sinai peninsula, the monastery of St. Catherine was severely damaged, and its fortifications were largely destroyed. Aftershocks are said to have continued for a year (Ambraseys, 2009). Because no seismic details are recorded for Syria, and based on the significant damage incurred in the south, the epicenter for the 1212 event was likely in the Gulf of Aqaba or perhaps in the Wadi ʻArabah south of the Dead Sea (Ambraseys, 2009). This earthquake is estimated to have had a maximum intensity of IX-X based on the Modified Mercalli Intensity scale (Guidoboni and Comastri, 2005).

Later that century, in January 1293, an earthquake centered near Karak damaged three towers of the citadel there as well as many houses (Guidoboni and Comastri, 2005; Ambraseys, 2009). According to one source, buildings also collapsed in Tafilah which is located south of Karak in Jordan (Guidoboni and Comastri, 2005). Amir Ala al-Din of Damascus was sent with a team of artisans to evaluate and rebuild what had been destroyed at Karak (Guidoboni and Comastri, 2005; Ambraseys, 2009). The 1293 earthquake affected the Palestinian coast from Gaza in the south where a minaret collapsed to Ramla further north where a destructive flood accompanied the earthquake (Ambraseys, 2009). The city of

Ludd (present-day Lod) and the castle of Qaqun in the north were also affected by this event. This earthquake is estimated to have had a maximum intensity of IX based on the Modified Mercalli Intensity scale (Guidoboni and Comastri, 2005).

Another earthquake affected the Dead Sea and southern Wadi ‘Arabah regions in November 1458. This event, which occurred on either the 8th or the 16th of November depending on the source considered, destroyed parts of the citadel in Karak, and at least 100 deaths were reported in Karak alone (Guidoboni and Comastri, 2005; Ambraseys, 2009). Minarets collapsed at Ramla and Hebron, and part of a minaret collapsed in Jerusalem, as well as the great dome next to the Church of the Holy Sepulchre. The shock was also felt to a slight extent in Cairo (Guidoboni and Comastri, 2005; Ambraseys, 2009). This earthquake is estimated to have had a maximum intensity of IX based on the Modified Mercalli Intensity scale (Guidoboni and Comastri, 2005).

On January 14, 1546, an earthquake with widespread effects occurred in Palestine that is considered to be one of the most important earthquakes in the Middle East because of its placement in the Holy Land, according to Ambraseys (2009). Much confusion and seemingly exaggerated reports surround the historical sources evaluated for this seismic event. The areas that were strongly affected were limited to in and around Nablus, Ramla, and to some point just north of Jerusalem, although Nablus suffered the worst structural damage overall (Ambraseys, 2009). Reports concerning Jerusalem were some of those that were exaggerated. Ambraseys (2009) explains that the damage in Jerusalem was widespread and occurred mainly to tall structures, but the damage was repairable. Structures were also damaged in Bethlehem, Hebron, Gaza, and the earthquake was also felt as far north as

Damascus (Ambraseys, 2009). A tsunami was reported to have flooded the coast between Gaza and Jaffa, causing an additional loss of life. Ambraseys (2009) suggests that the seismic sea wave was due to an underwater landslide triggered by the earthquake rather than a wave created directly by the severe ground shaking in this location. Ben-Menahem (1979) estimates that the maximum MMI of this event was between IX-X, although Ambraseys (2009) warns that the available evidence for this earthquake suggests that this was not a major seismic event as far as magnitude is concerned, even though ground shaking could have been very strong near the epicenter.

The last historic earthquake that affected the study region at the center of this research occurred on January 4, 1588. Reports of this event come from relatively few sources which indicate that along the Syrian pilgrim route the castle in Tabuk collapsed, as did the mosque within the monastery of St. Catherine in Sinai (Ambraseys, 2009). The earthquake was destructive in the Aqaba/Eilat area and caused rock falls on the Egyptian pilgrim route to Mecca. A strong earthquake shock of long duration was also felt in Cairo where many minarets shook, with some of them toppling over, as did basins and water tanks (Ambraseys, 2009).

While other earthquake occurred around the region throughout the 2nd-16th centuries, the seismic events discussed in this earthquake catalog summary (A.D. 110-114, 363, 418/419, <597, 634, 659, 746/749, 756/757, 1033, March 1068, May 1068, 1212, 1293, 1458, 1546, and 1588) are the events that occurred along the Dead Sea transform that are the most likely to have affected the southern Wadi ‘Arabah and Gulf of Aqaba regions where this research is centered.

Previous Archaeological Excavations in the Greater Aqaba Region

The Middle East, because of its long record of human occupation, is one of the most archaeological rich regions of the world. Strategically located, Aqaba is the only port city of the present-day country of Jordan and provides invaluable access to the Red Sea. Aqaba lies at the junction of both land and sea routes from Asia, Africa, and Europe, and in antiquity it was a very important route of trade and cultural connections (e.g. Khouri and Whitcomb, 1988). In terms of conducting archaeological research, the Aqaba region is easily accessed, although until rather recently it was archaeologically unexplored. Although there are accounts of western travelers passing through the Aqaba coastal zone in the early nineteenth and twentieth centuries and noting the strewn ancient ruins, it was not until the 1930s that archaeological research was conducted and published on the region.

The Wadi 'Arabah Valley, the linear valley that drains down into the coastal zone of Aqaba following the trend of the Dead Sea transform, was investigated by Smith and Niemi in the 1990s as a part of the Southeast ‘Arabah Archaeological Survey (SAAS), a unit of the Roman Aqaba Project (RAP) (Smith and Niemi, 1994; Smith et al., 1997; Niemi and Smith, 1999). In 1994, this survey produced the earliest evidence of human occupation found in the region thus far. Chipped stone artifacts recovered from several sites in southern Wadi 'Arabah were dated to the Middle Paleolithic period (Smith and Niemi, 1994; Smith et al., 1997; Niemi and Smith, 1999), and could perhaps date as far back as 200,000 B.C., according to Parker (1997). This survey found that the majority of archaeological sites and artifacts in the region can be dated to either the Chalcolithic/Early Bronze periods, or to the Nabataean/Roman-Byzantine periods. Parker (1997) points out that the history between the

Chalcolithic and Iron Age periods in or near Aqaba is problematic because of sparse archaeological evidence. There is evidence, however, of Egyptian exploitation of the Timna copper mines located in present-day Israel during this Late Bronze Age to Iron Age transition (Rothenburg, 1988, 1993).

In 1985, Lutfi Khalil first excavated the late Chalcolithic site of Tell al-Magass, a small tell located 4 km north of Aqaba, and later excavated the residential site of Tell Hujayrat al-Ghuzlan associated with Tell al-Magass, located 1.5 km to the east of the tell (Figure 2.5) (Khalil, 1987, 1988, 1992, 2009). In 1998, Ricardo Eichmann, from the German Institute of Archaeology, collaborated with Khalil and continued the investigation of the al-Magass area and Tell Hujayrat al-Ghuzlan (Khalil and Eichmann, 1999, 2001; Khalil et al., 2003). Tell al-Magass was determined to contain the earliest evidence of sedentary occupation found thus far in the Aqaba region. The site was also interpreted to be an industrial site for copper smelting during the Chalcolithic period (Khalil, 1987, 1992, 1995, 2009; Khalil and Riederer, 1998; Hauptmann et al., 2009). Tell Hujayrat al-Ghuzlan, also dated to the Chalcolithic, was interpreted as the residential site for these inhabitants (e.g. Khouri and Whitcomb, 1988). In 1998, these sites were again studied by Helmut Brückner and colleagues in an attempt to better understand the Chalcolithic sites of the Aqaba region (Brückner et al., 2002). Tell Hujayrat al-Ghuzlan, situated on the alluvial fan of Wadi Yutim 2 km west of its convergence with Wadi 'Arabah, is subject to large amounts of runoff as is evidenced in the substantial erosion and weathering of the ruins. This site is interpreted as a possible water management site for Tell al-Magass (Brückner et al., 2002). Because the site consists of mainly sand and gravel washed down from the wadi, it is also not at all favorable

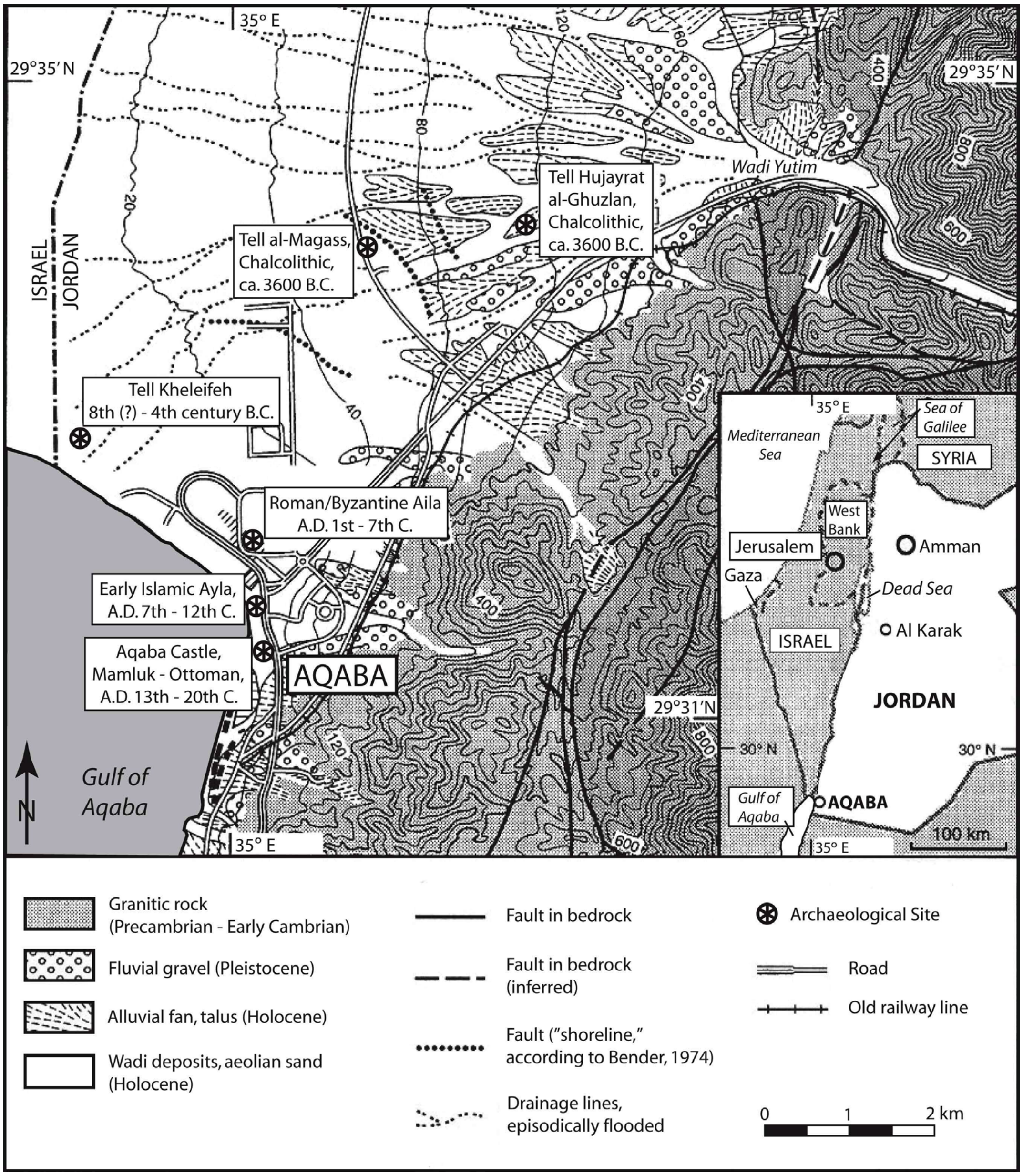

Figure 2.5 Map of archaeological sites in greater Aqaba, Jordan region (modified after Brückner et al., 2002).

for agriculture. Therefore, channeling the flow of water, management of water drainage, and soil development was likely the top priority of ancient settlers at Tell Hujayrat al-Ghuzlan (Brückner et al., 2002; Heemeier et al., 2009).

Some of the earliest recorded archaeological work in Aqaba was conducted at Tell Kheleifeh, an archaeological site located 500 m north of the modern shoreline of Aqaba along the present-day Jordanian-Israeli border. Fitz Frank first studied the tell in 1933 and associated the site with King Solomon's Ezion-Geber of biblical tradition (Frank, 1934). The site was later surveyed in 1937 and excavated from 1938-1940 by Nelson Glueck who agreed with Frank and initially dated the earliest phase of occupation of Tell Kheleifeh to the tenth century B.C. (Glueck, 1935, 1937, 1938, 1965). The archaeological site was again reexamined by Gary Pratico in the mid-1980s, and excavations here revealed a series of successive settlements between the eighth and fourth centuries B.C. (Pratico, 1985, 1993). Pratico determined that the site was not founded prior to the eighth century B.C. as Frank and Glueck had originally postulated, but that it was likely established by the Edomites, a group of peoples who typically inhabited the Negev Desert and the Arava Valley (Wadi 'Arabah Valley) in southern Israel between the eighth and sixth centuries B.C. (Pratico, 1985, 1993). The complete lack of Nabataean pottery at the site, which is very common elsewhere in Aqaba, strongly indicates that Kheleifeh was abandoned before the first century B.C. Like Tell al-Magass, archaeological excavation has revealed evidence of copper processing or smelting at Tell Kheleifeh as well (Parker, 1997).

Archaeological survey and excavation projects have also been conducted in Aqaba and in the surrounding region. Near the Gulf of Aqaba, Meloy (1991) first surveyed the land located within the region once referred to as the ‘Circular Area,’ circular-shaped because of the road that wrapped around it, and which will be home to a large vacation resort and luxury apartments called Saraya once construction is complete. Meloy (1991) identified several mounds, traces of mudbrick walls, and scatters of surface artifacts that he suggested were the remains of Classical Aqaba (referred to in ancient texts as Aila) dating to the first six centuries A.D. S. Thomas Parker later conducted an extensive research campaign known as the Roman Aqaba Project (RAP) from 1994-2002 in which he excavated many sites dated to the Nabataean/Roman-Byzantine periods in and around the Circular Area of Aqaba and succeeded in definitively locating the ancient city of Aila. During the course of Parker’s excavations, he was able to recover a complete stratigraphic sequence extending from the first century B.C. during the Nabataean/Early Roman period, through the Late Roman, Early Byzantine, Late Byzantine, and into the Early Islamic period, to possibly as late at the tenth century (Parker, 1994, 1996, 1997, 1998, 2000, 2002, 2003).

In 2003, Ross Thomas and Tina Niemi conducted a detailed archaeological excavation and geologic mapping survey as a part of the Wadi ‘Arabah Earthquake Project along an active fault that cuts through the Late Roman/Byzantine to Early Islamic ruins of Aila in a section of the site known as Area J-East (Thomas et al., 2007). Located 500 m north of the modern shoreline, Area J-East is a multiphase site incorporating Byzantine to Early Islamic domestic occupation and a late third- to fourth-century monumental mudbrick structure hypothesized to be an early church (e.g. Parker, 1998). Research based on faulting at the site revealed evidence for “an unprecedented record” of seven earthquakes that have ruptured the city of Aqaba since the second century A.D. (Thomas et al., 2007). These earthquake data collected by Thomas et al. (2007) also help to illustrate that the available earthquake catalogs are incomplete with respect to smaller, less damaging earthquakes since there are more seismic events identified as having ruptured Aila than previously understood.

The archaeological site of Early Islamic Ayla (7th -12th C.), located 250 m further south down the coast of the Gulf of Aqaba, has been excavated by Donald Whitcomb (1986, 1987, 1988a, 1988b, 1989a, 1989b, 1992, 1993a, 1993b, 1994a, 1994b, 1995a, 1995b), S.T. Parker (2002), Tina Niemi and John Rucker (2005), and by Kristoffer Damgaard (2008, 2010, 2011; Damgaard and Jennings, 2010). This archaeological site is the focus of the archaeoseismic portion of this research and will be discussed in detail in the following chapter concerning Islamic Ayla.

In addition to his work at Tell Kheleifeh, Nelson Glueck (1935) was also the first to identify a castle situated "about a kilometer west-northwest of ‘Aqabah." This castle is thought to have been built by the Crusaders to act as a small fort for their garrison upon their arrival to the area in A.D. 1116 (e.g. Khouri and Whitcomb, 1988; Whitcomb, 1994a). The fortress, now commonly known as the Aqaba Castle, was constructed in the twelfth century some 1.5 km to the southeast of Early Islamic Ayla. The Aqaba Castle was excavated between 2000 and 2008 under the direction of Johnny De Meulemeester, Denys Pringle (2000-2003), and Reem as-Shqour (2005-present). Primarily Mamluk in age in its extant form, multiple excavations of the castle uncovered a total of ten phases of use, four of which are located beneath the current ground surface and six phases above ground. These various building phases represent a complicated history of use and reuse of the structure. The castle continued to be occupied periodically up until the 20th century when it was used as a military fort during World War I (De Meulemeester and al-Shqour, 2008). Today, the Aqaba Castle quite fittingly serves as the Department of Antiquities headquarters in the city of Aqaba, Jordan.

CHAPTER 3

EARLY ISLAMIC AYLA EXCAVATION

Motivation for Research and Field of Archaeoseismology

Archaeological sites situated along or near seismically active fault zones provide a unique opportunity to study the paleoseismicity of a region because these sites often preserve evidence of the seismic past in the form of damaged or ruptured structures or buried artifacts. Repairs and reconstruction of damaged structures made in antiquity can help to constrain the recurrence intervals of specific faults, and the type of failure or collapse can provide information concerning the intensity of past earthquakes. Archaeological sites also usually contain a variety of datable materials such as pottery and charcoal fragments, which can provide an important means for age control and paleoseismic event correlation for multiple events.

Archaeoseismology is a subfield of seismology that focuses on the study of past earthquakes through the traces left behind in the cultural record (Sintubin and Stewart, 2008), and was essentially born in the Mediterranean region and Middle East as a result of the active tectonics and plentiful cultural ruins and deposits present in these areas (Jones and Stiros, 2000). Archaeoseismology is an interdisciplinary science because it incorporates the fields of seismology and archaeology, along with geology, geotechnics, geomorphology, and even civil engineering at times, in order to gather data about both the pre-instrumentation and prehistoric seismic past (Jones and Stiros, 2000). The term prehistoric, as it is used here, is meant to delineate between historically recorded earthquakes and those without a historical record of occurrence. The use of archaeological data to investigate poorly known historical earthquakes or even unknown events actually began in the late 19th to early 20th centuries, but has only really developed into the subfield we know today in the last few decades (Hinzen, 2010). Since first used, however, the field of archaeoseismology has continued to grow as has the acceptance of this type of interdisciplinary science (Galadini et al., 2006). Sintubin et al. (2010) cite a major problem plaguing those who study ancient earthquakes (defined as pre-instrumental earthquakes that can only be identified through indirect evidence in the archaeological or geological record), which is that the instrumental record is too short to be very useful, and the historical record is often incomplete. Archaeoseismology, which can potentially delve much deeper into the historic and pre-historic past, is a subdiscipline that developed out of the need to overcome both of these issues (Noller, 2001).

With its richness of history and abundance of archaeological ruins, the Middle East is a prime location in which to utilize archaeoseismology to study the seismicity of the region. Compared to studies conducted in North America, for example, archaeoseismic studies undertaken in the Middle East and Mediterranean regions have the advantage of being able to incorporate a much longer historical record into those archaeoseismic efforts. With a record of historical earthquakes extending back over 2000 years, the seismic record of Jordan is impressively one of the longest records in the world (Thomas et al., 2007). In an attempt to better understand the behavior of the Dead Sea transform fault, the chronology of historical earthquakes along with any historical accounts have been organized into earthquake catalogs for easy reference. Earthquake catalogs will be discussed in more detail in a later section. The Dead Sea seismic zone also benefits from a longer and more comprehensive record of archaeoseismic practice, which acts to add validity to the more recent and perhaps more refined studies being conducted in recent years.

Much of what we know about the seismic history of the Middle East and Mediterranean region before the Christian era has come from a collection of archaeoseismic investigations and excavations (McCalpin and Nelson, 2009). The archaeoseismic studies conducted there are more common than in North America primarily because the availability of cultural remains is exponentially more abundant. Many ancient sites are located within 100 km of the Dead Sea transform fault, for example, and therefore have a greater chance of being damaged by earthquakes in the region (e.g. Marco et al., 1997; Ellenblum et al., 1998; Meghraoui et al., 2003; Haynes et al., 2006). Ancient structures in the Middle East are also often constructed from more resistant materials such as worked and unworked stone as opposed to wood, which arid regions like Jordan generally lack in any significant quantity. The arid climate and the generally slow sedimentation rates along the Dead Sea rift also play a role in the preservation of cultural remains, and have allowed for materials like mudbrick to be used for construction purposes in antiquity, much of which is still preserved until today (Thomas et al., 2007).

The best and most clearly defined examples of faulting happen when an earthquake fault ruptures a standing wall, aqueduct, or other cultural lines that act as piercing points where the amount and direction of offset is measureable. The Dead Sea transform not only exemplifies near-textbook left-lateral, strike-slip motion when the fault rupture makes it to the surface, but faulting of this sort allows archaeoseismologists the opportunity to measure the actual offset or distance the fault slipped during a specific event, or the cumulative offset from multiple events (e.g. Noller, 2001; McCalpin, 2009). In this way, strike-slip faults that occur within cultural deposits with substantial architecture are not only easier to study, but also provide a greater abundance of faulting information. Archaeoseismology has the potential to bridge the gap between instrumental and historical seismology on one hand, and paleoseismology and earthquake geology on the other (Galadini et al., 2006), but can only be conducted in locations where seismic activity and past human activity have intersected in a meaningful way.

Numerous archaeological sites situated along both sides of the Dead Sea transform have been the focus of archaeoseismological studies in the past. With one of the most tightly constrained historical records, the site of Vadum Jacob, also known as the Ateret Fortress, is an example of using a seismically damaged archaeological site to assess the history of faulting in an active tectonic zone (e.g. Marco et al., 1997; Ellenblum et al., 1998). Ateret, built in A.D. 1179, is a castle overlooking the Jordan River in modern-day Israel that once served as an outpost during the Crusader period. The foundation stones of the castle were actually laid down in A.D. 1178, but it was conquered and destroyed only eleven months later on August 30, 1179 by Saladin and his troops (e.g. Marco et al., 1997; Ellenblum et al., 1998). Numerous independent historical sources pinpoint this specific date of destruction, and thus the associated destruction layer exposed in cross-section in a trench located just outside of the castle wall (e.g. Abu-Shama; Lyons and Jackson, 1982; Raphael, 2010).

The Ateret Fortress is built on the active Jordan Gorge Fault, a straight segment of the Dead Sea transform located between the Sea of Galilee and the Hula Valley in the north. Archaeoseismic research conducted at Vadum Jacob by Marco et al. (1997) and Ellenblum et al. (1998) has revealed numerous offset archaeological structures. Most noticeably displaced are the four-meter-thick stone walls that surround the castle, and aqueducts situated across the DST fault are also offset. Stratigraphically, the destruction layer dated to A.D. 1179 was also offset, so the castle was clearly faulted after it was destroyed. Historical records indicate that only four sizable earthquakes occurred in the region after the late 12th C. construction date of the castle. These are the earthquakes of A.D. 1202, 1546, 1759, and 1837 (e.g. Amiran et al., 1994; Ambraseys, 2009), and thus these are the only known seismic events that could have potentially affected the region of Israel in which the castle is built. Of these earthquakes, Ellenblum et al. (1998) explain that the Ateret Fortress was likely located too far north for the A.D. 1546 earthquake to have faulted the site based on the known damage radius, although this earthquake would have been felt there (Ambraseys, 2009). Instead, excavations have shown that the fortress was most significantly deformed by the historic M>7 earthquake that occurred at dawn on May 20, 1202.

In all, both the north and south four-meter-thick stone fortress walls were offset by a total of 2.1 m due to earthquake faulting. Of this total measured displacement, 1.6 m of offset is attributed to the left-lateral motion of the Dead Sea transform during the 1202 event, and the remaining 0.5 m of measureable offset is attributed to either the 1759 and/or 1837 seismic events (Marco et al., 1997; Ellenblum et al., 1998). Post-Crusader structures built at the Vadum Jacob site were clearly not affected by the 1202 earthquake because, in addition to their construction post-dating the occurrence of this historical earthquake, they are also only offset by 0.5 m, which serves to constrain the amount of displacement resulting from each of these seismic events. In particular, a Muslim mosque at the site, originally built in the 12th C., was destroyed and rebuilt again either once or twice during the Turkish Ottoman period (1516-1918) based on archaeological excavation and study of associated pottery finds (Ellenblum et al., 1998). The latest or youngest rebuilding phase of the mosque during the Turkish Ottoman period shows 0.5 m of offset in its northern wall, but lacks the cumulative 2.1 m offset observed in the Crusader castle wall.

The thick, fortified walls that surround the Ateret Fortress are also of particular sturdy construction for the time period. Built with the intention of preventing attacks directly to the castle itself, the walls are also substantial enough to prevent potential intruders from being able to easily dismantle and break through the stone walls before being detected. Ellenblum et al. (1998) describe the walls as being composed of a parallel pair of meticulously laid ashlar supports that enclose a 3-meter-thick fill of cemented basaltic cobbles built by "highly skilled Crusader masons." Particularly important to note is that these walls were erected with great precision along smooth, straight lines, and thus serve as quite reliable strain gauges for any deformation occurring after A.D. 1179 (Ellenblum et al., 1998). Essentially, the detailed historical records available for the site allow Vadum Jacob to be dated with unusual precision. The abundance of well-dated structures and only a small number of candidate earthquakes that could have damaged the castle walls also makes Vadum Jacob an excellent site for geoarchaeological and archaeoseismic research along the Dead Sea transform.

On the opposite side of the rift valley, the site of Qasr Tilah located in Jordan approximately 30 km south of the Dead Sea in the Wadi ‘Arabah is another well-documented example of an archaeological site that has been clearly faulted and offset by the Dead Sea transform, and is the subject of archaeoseismic study. The site of Qasr Tilah consists of a Roman-period fort (caravanserai), a Byzantine - Early Umayyad water reservoir (birkeh), an aqueduct irrigation system, and agricultural fields. Detailed archaeological excavation of the site, which was first conducted by Niemi (2000, 2002) as a part of the Wadi ‘Arabah Earthquake Project, has revealed that structures situated across the DST fault were offset laterally by earthquakes in the past, including the north wall of the 30 m x 30 m stone birkeh and a portion of the aqueduct system. The aqueduct system was built so that two aqueducts first funneled water into the birkeh from the adjacent Wadi Tilah where particulates could settle out of suspension in a small settling pool, then a short NW-trending aqueduct connects the settling pool to a W-trending aqueduct that carried water away from the reservoir and, presumably, into a nearby agricultural field during periods of overflow (Haynes et al., 2006).

The northwest corner of the birkeh has a large crack caused by left-lateral offset of the DST by 1.5-2 m which is indicative of earthquake rupture (e.g. Niemi, 2000; Niemi and Atallah, 2000; Klinger et al., 2000a; Galli and Galadini, 2001). Charcoal collected from within the mortar of the original birkeh construction was radiocarbon dated to A.D. 641-687 (Niemi, 2000), a date that agrees with radiocarbon published by Klinger et al. (2000b). Investigation of the structure revealed that a repair made to the northwest corner of the birkeh wall suggests that an earthquake damaged the birkeh not long after it was constructed

(Niemi and Atallah, 2000). Due to subsidence of the damaged corner of the birkeh, another course of stones was laid on top of the wall and covered in a layer of plaster in an effort to repair the structure. A radiocarbon date from the repair made to the corner of the birkeh agrees very closely with a radiocarbon date collected from the lower portion of the original birkeh wall, which supports the hypothesis that the birkeh was initially damaged shortly after construction, or perhaps that the birkeh was rebuilt over an earlier structure after being damaged (Haynes et al., 2006). Archaeological excavation by Haynes et al. (2006) also revealed the NW-trending portion of the aqueduct system, which was determined to have been constructed below ground using mortar and stones laid in a trench, to be laterally offset 1.6 +/- 0.4 m.

The site of Qasr Tilah is faulted by the Wadi ‘Arabah Fault, which is a segment of the southern Dead Sea transform fault. Radiocarbon dating of charcoal samples from significant subsurface horizons provided one means of age control, and ceramic analysis of pottery sherds and artifacts collected during excavation of the site also provided age control by relative typological dating (Haynes et al., 2006). Using offset stratigraphic horizons, upward terminations of faults, fissure fills, and outward splaying faults (flower structures) visible in the trench walls, Haynes et al. (2006) identified evidence of four ground-rupturing earthquakes at the site ranging from the sixth to the nineteenth centuries. The archaeoseismic data was combined and examined with historical records to determine possible calendar dates for each event. The data suggests that these four ruptures likely represent the historical earthquakes of A.D. 634 or 659/660, 873, 1068, and 1458 or 1546 (Haynes et al., 2006). In all, the site of Qasr Tilah provides an excellent example of how studying seismic damage and deformation of an archaeological site can provide insight into the seismic past. The ability to date the structural repairs made to the damaged birkeh act to further constrain these earthquakes based on radiocarbon dating, and stratigraphic analysis of a trench excavated across the fault trace acts to corroborate this data as well.

North of both Qasr Tilah and the Ateret Fortress, the site of Al Harif in Syria is another archaeoseismically relevant site that has been directly faulted and offset by the Dead Sea transform. The Al Harif site is located in northwestern Syria and consists of a Roman-period aqueduct that has been repeatedly left-laterally displaced by the approximately 90 km-long Missyaf fault, a northern segment of the DST (Meghraoui et al., 2003; Sbeinati et al., 2010). The site was first studied by Meghraoui et al. (2003) who used microtopographic surveys and trenching techniques to determine that the Roman aqueduct was faulted three times in the last 2000 years and displaced a total of 13.6 +/- 0.2 m (Meghraoui et al., 2003). Meghraoui et al. (2003) documented the occurrence of earthquakes between A.D. 100 and 750, between A.D. 700 and 1030, and between A.D. 990 and 1210 based on the radiocarbon dating of faulted alluvial deposits.

The aqueduct, originally dated to between A.D. 30 and A.D. 70 by bracketing the age of the sedimentary units below its foundation and from early travertine accumulation on its wall, was used to bring fresh water from the wet, western high mountains to wheat and olive oil fields (mills), and local cities and villages located in the eastern plains (Meghraoui et al., 2003). A bridge even allows the aqueduct to cross the Al Harif River without disrupting the flow of water. A later study conducted by Sbeinati et al. (2010) consisting of four archaeological excavations, three paleoseismic trenches, and coring of accumulated tufa deposits (previously identified as travertine by Meghraoui et al., 2003) on the aqueduct at the Al Harif site, further refined the construction date of the Roman aqueduct to between A.D. 63 and A.D. 70.

Like the abundant historical records in Jordan, the historical record of seismicity of Syria and surrounding regions is also very rich because of the numerous archaeological and historical sources that date back at least to 1365 B.C. (e.g. Ben-Menahem, 1979; Ambraseys and Jackson, 1998; Guidoboni, 1994). Combining historical sources with data collected from trenching, excavation, and sediment coring, Sbeinati et al. (2010) identified as many as four earthquakes that have affected the site in the last 3400 years. The fourth seismic event back (Event W) occurred sometime between 2300-510 B.C., and a cluster of three other seismic events occurred in A.D. 160-510 (Event X), A.D. 625-690 (Event Y), and A.D. 1010-1210 (Event Z) (Sbeinati et al., 2010). The most recent seismic event, Event Z, is likely correlated with the large historical earthquake that occurred on June 29, 1170 (Meghraoui et al., 2003; Sbeinati et al., 2010). Events X, Y, and Z each ruptured and progressively offset the Roman aqueduct, while Event W occurred prior to the construction of the aqueduct. Further, two reconstruction phases at the Al Harif site were identified through the analysis of building stone type, related cement dating, and tufa deposits on the aqueduct. These reconstruction episodes most likely occurred in A.D. 340 +/- 20 and A.D. 720 +/- 20 (Sbeinati et al., 2010).

The large earthquakes of Events X and Z have been estimated as M_w = 7.3-7.5 based on detailed historical reports of ground shaking and damage (Meghraoui et al., 2003), and incurred successive faulting events, fault segment length, and related amount of coseismic slip (Sbeinati et al., 2010). The study by Sbeinati et al. (2010) also helped to constrain the slip rate of the Dead Sea transform in northwestern Syria along the Missyaf fault segment to between 4.9-6.3 mm/yr. Further, with the goal of producing a refined assessment of the seismic hazards of the region, the findings of Sbeinati et al. (2010) suggest that the recent seismic quiescence along the Missyaf fault segment of the DST implies that a large earthquake is overdue and may result in a major catastrophe to the population centers of Syria and Lebanon in the near future. This archaeoseismic approach to seismic hazard analysis is particularly applicable in this region and especially important along the Dead Sea transform since it corresponds to a major tectonic plate boundary (Meghraoui et al., 2003; Sbeinati et al., 2010).

Sites like Ateret in Israel, Qasr Tilah in Jordan, and Al Harif in Syria are unique in that information about past earthquakes can be obtained from measurements collected from directly offset structures and from careful recording of the stratigraphy across the fault trace. While many archaeological sites have been damaged from earthquakes in the historical past, few sites are able to demonstrate such strong evidence of faulting and rupture of the site so clearly. The vast majority of archaeological sites damaged by earthquakes, like the site of Early Islamic Ayla (7th-12th C.) to be discussed herein, were damaged as a result of ground-shaking, and may show signs of earthquake damage in the form of subsidence, liquefaction at the site, and/or failure of walls, columns, or other structures that were present at the time of the event.

Previous Archaeological Excavations and Work at Early Islamic Ayla

Historian and archaeologist Dr. Donald Whitcomb of the Oriental Institute at the University of Chicago excavated the archaeological site of Early Islamic Ayla from 1986 to 1995, and unearthed a large portion of the city near the modern shoreline in Aqaba. His excavations revealed the original rectangular city wall, a mosque, and numerous commercial and residential structures in and around the ancient city. Archaeological evidence shows that the city of Ayla was a fishing port likely occupied from the mid-seventh century to the twelfth or thirteenth centuries (Khouri and Whitcomb, 1988; Whitcomb, 1986, 1987, 1988a, 1988b, 1989a, 1989b, 1992, 1993a, 1993b, 1994a, 1994b, 1995a, 1995b). Donald Whitcomb's extensive excavations at Ayla over the course of nearly a decade ultimately illuminated the organization of an early Islamic city.

In 2000, S.T. Parker excavated a trench (R1) across the alignment of the city wall of Early Islamic Ayla as a part of the Roman Aqaba Project. The specific purpose of this excavation was to determine once and for all whether the site's origin was the legionary fort of the *Legio X Fretensis*. The trench was placed underneath the bridge of Corniche Road (al-Istiqlāl) in the wadi that now runs through Ayla in a section of the site referred to as Area R (Parker, 2002) because it was an area of lower elevation that would allow the deeply buried layers to be more easily exposed. Parker's R1 trench exposed a portion of the city wall that was found to be in good condition with no apparent earthquake damage. Pottery collected from at and beneath the wall foundation confirmed Whitcomb's hypothesis of an A.D. seventh century construction date for the Islamic city wall (Parker, 2002).

In an attempt to better understand the history of the Islamic city and the seismicity of the region, the Wadi ‘Arabah Earthquake Project (WAEP), led by Dr. Tina Niemi, has excavated several locations along the outer walls of the site, looking for evidence that the Dead Sea transform (DST) fault offset the city walls of Ayla. Whitcomb (1993a) hypothesized that the DST fault trends directly through the city, along the trend of the wadi that crosses the site. Excavations conducted by the WAEP in 2001 and 2003 focused on articulating several portions of the city wall leading to the east corner tower, as well as the corner tower itself, which is situated in the wadi under the same bridge where Parker (2002) excavated. Based on these excavations, Rucker and Niemi (2005) proved conclusively that there is no evidence of faulting offset through this section of Islamic Ayla. They do not rule out the hypothesis presented by Galli and Galadini (2001), however, that the DST fault may trend inland from the Gulf of Aqaba NNE-SSW from the Sea Gate to the reconstructed wall NW of the Egyptian Gate, although further excavation is required to examine this hypothesis (Rucker and Niemi, 2005).

Kristoffer Damgaard also excavated portions of Islamic Ayla starting in 2008 as a part of the Islamic Aqaba Project, directed by Dr. Johnny De Meulemeester from the University of Ghent, in an effort to investigate further the town’s occupational phases and morphology. A trench was laid out out specifically to investigate the possible marketplace expansion of Ayla outside of the city walls near the Egyptian Gate, as well as a trench positioned within a previously unexcavated portion of the southwestern quadrant of the city (Damgaard, 2008). This preliminary excavation revealed that at least the southwestern quadrant of Ayla remained occupied for the entire lifespan of the city (Damgaard, 2008).

Further, the expansions made along either the inner or outer walls of the city were found to have been constructed in-line with earlier structures despite those earlier structures being buried by a fill layer and presumably hidden from view during each new phase of construction. As such, Damgaard (2008) suggests that the inhabitants of Ayla understood the previous construction plan of the city in many respects and were able to carry on this plan through the centuries. In 2010, Damgaard returned to excavate at Ayla as director of the Aylah Archaeological Project (AAP) after Dr. De Meulemeester's untimely passing in 2009. This season focused again on determining the extent and location of mercantile facilities related to the Red Sea trade, as well as further defining the morphology of occupation and urban planning from the seventh through the eleventh centuries (Damgaard and Jennings, 2010; Damgaard et al., 2010; Damgaard, 2011).

Cultural History of Aqaba, Jordan

Much of what we know about the history of the region comes from the archaeological excavations in and around the city of Aqaba. Buried by sand until the mid-1980s when Donald Whitcomb first rediscovered the Islamic settlement through well-placed archaeological probes (Whitcomb, 1994a), Ayla has become one of best examples of an early Islamic city anywhere, and is unique in the country of Jordan (Whitcomb, 1986). In terms of conducting archaeological research, the Aqaba region is easily accessed because of its position at the head of the Gulf, although until rather recently it was archaeologically unexplored. While there are accounts of western travelers passing through the Aqaba coastal zone in the early 19th - 20th centuries and noting the strewn ancient ruins, it was not until the 1930s that archaeological research on the region was conducted and published.

Ayla is a walled city with a rectangular plan approximately 170 m x 145 m (Figure 3.1), now situated between the Mövenpick Hotel and Aqaba Yacht Club along the Gulf of Aqaba. As is the case with the majority of historical events that took place at Islamic Ayla, there is no documentary evidence for dating the foundation of the city. Whitcomb (1995a), however, places the establishment of Ayla within the caliphate of ‘Uthman ibn ‘Affan in A.D. 650, the third of the Rashidun Caliphs after the death of the Prophet Mohammad in A.D. 632 (Table 3.1), based on data collected from archaeological excavations.

Today, Aqaba functions as both a growing tourist resort and vital commercial port, providing invaluable access to the Red Sea, as it has since antiquity. The port of Ayla was a very important route of trade and cultural connections because it lies at the critical junction of both land and sea routes uniting Asia, Africa, and Europe (Khouri and Whitcomb, 1988). During the medieval period this region also served as an important commercial center based on the pottery assemblages, which are the primary dating tool used at this site, as well as other archaeological materials and artifacts recovered from medieval Aqaba (Khouri and Whitcomb, 1988).

With a settlement pattern of southern migration down the coast (Parker, 1997), in the municipality of Aqaba proper three individual settlements dating from the 1st century and later have been identified from ancient ruins and detailed archaeological excavation (Figure 3.2). Located approximately 250 m to the northwest of Islamic Ayla is the Roman/Byzantine town of Aila (2nd - 7th C.), which is largely built upon 1st century Nabataean ruins, and

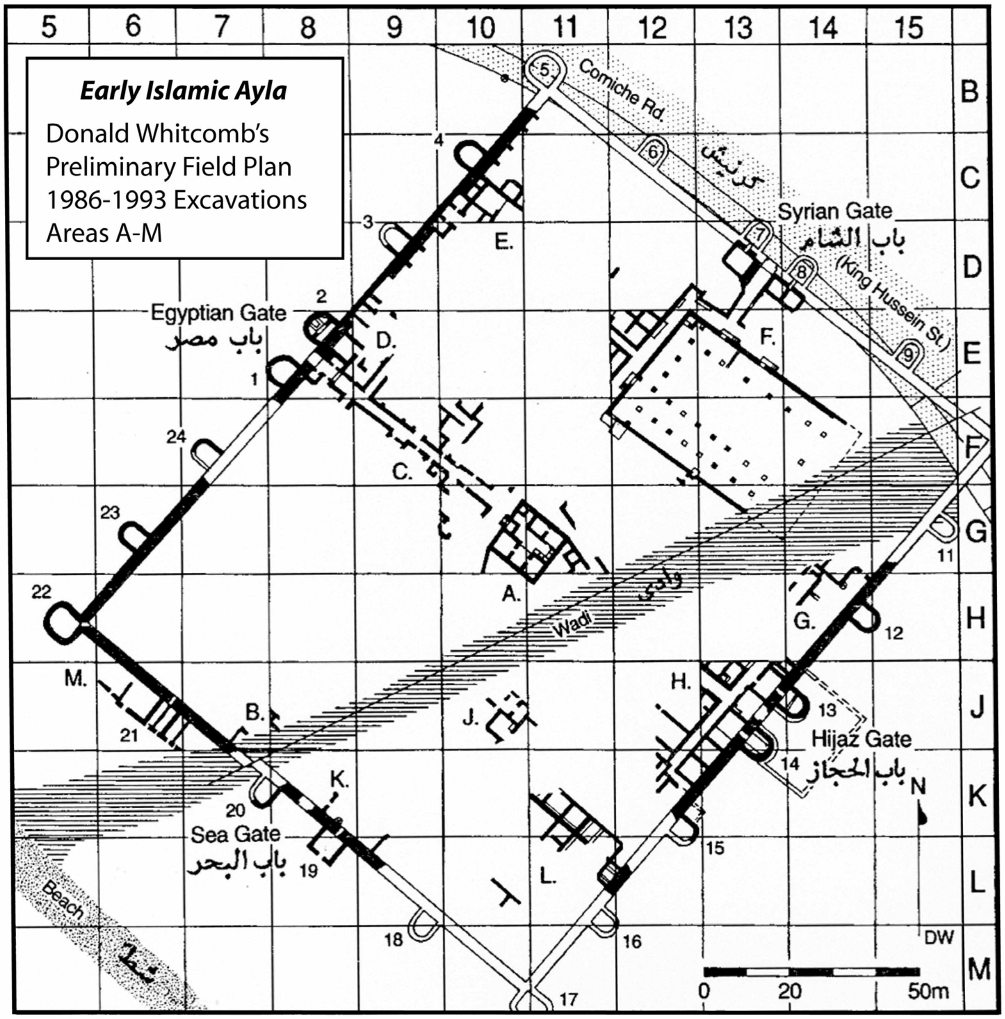

Figure 3.1 Top plan of Early Islamic Ayla, 7th-12th C. (modified after Whitcomb, 1994a).

TABLE 3.1

HISTORICAL CHRONOLOGY OF JORDAN

HISTORICAL PERIOD/EVENT	CALENDAR YEAR
Modern	A.D. 1918-Present
Ottoman	A.D. 1516-1918
Mamluk	A.D. 1260-1516
Ayyubid	A.D. 1173-1260
Crusaders	A.D. 1099-1187
Fatimid	A.D. 969-1099
Abbasid	A.D. 750-969
Umayyad	A.D. 661-750
Arab Conquest	A.D. 636-661
Death of the Prophet Muhammad	A.D. 632
Byzantine	A.D. 324-636
Roman	A.D. 63-324
Nabataean	312 B.C.-A.D. 106

(After Saunders, 2006)

TABLE 3.1 -- Continued.

HISTORICAL CHRONOLOGY OF JORDAN

HISTORICAL PERIOD/EVENT	CALENDAR YEAR
Hellenistic	332-63 B.C.
Persian	539-332 B.C.
Iron Age	1200-539 B.C.
Bronze Age	3600-1200 B.C.
Chalcolithic	5000-3600 B.C.
Pottery Neolithic	5500-5000 B.C.
Pre-Pottery Neolithic	8,200-5500 B.C.
Epi-Paleolithic	20,000-10,000 BP
Paleolithic	1.7/1.5 million-20,000 BP

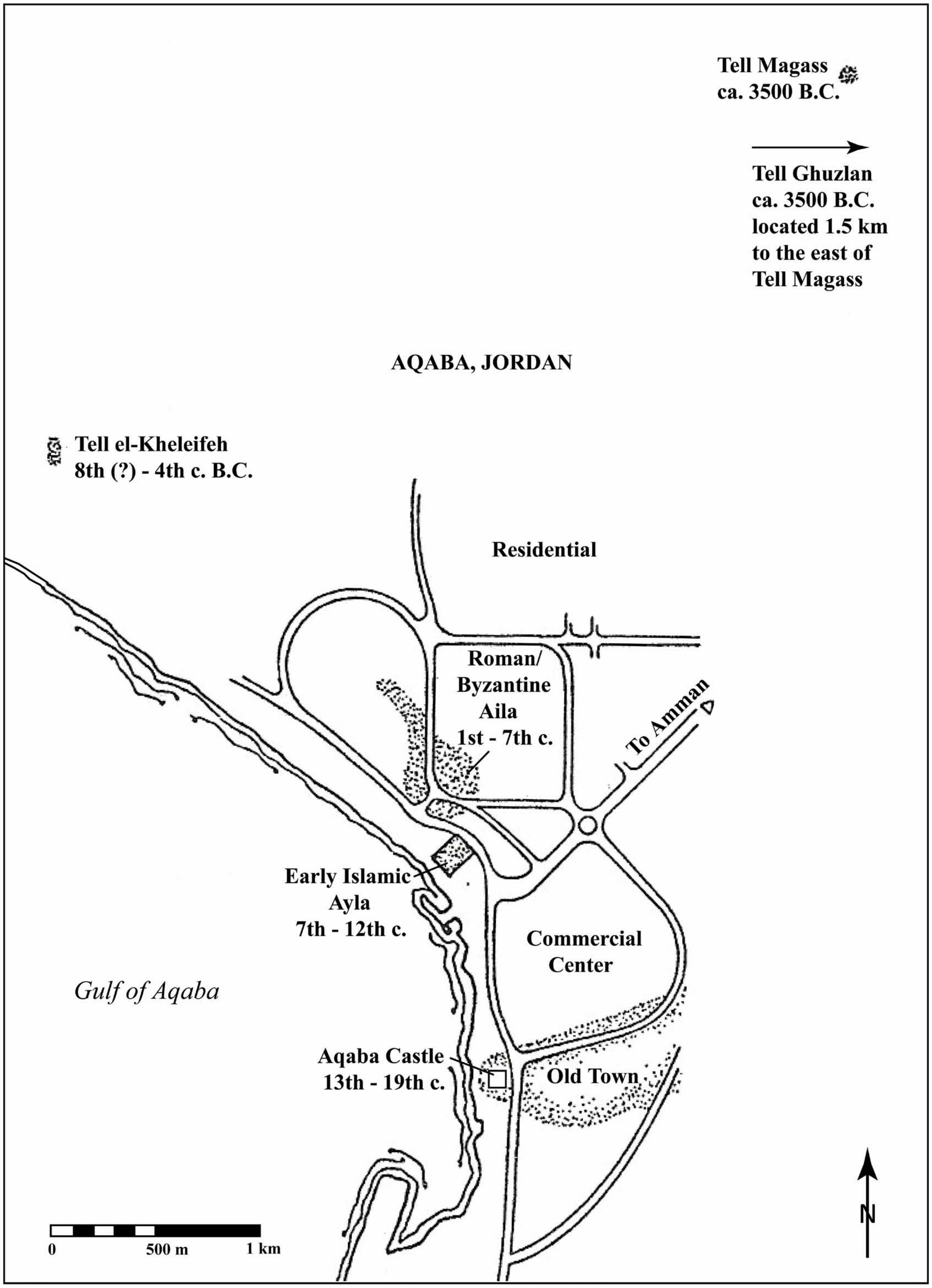

Figure 3.2 Map of archaeological sites in greater Aqaba, Jordan area showing southern migration down the coastline (modified from Parker, 1997).

located some 850 m to the south of Islamic Ayla is the Aqaba Castle dated to the Mamluk and Ottoman periods (e.g. Khouri and Whitcomb, 1988; Parker, 1997).

The ancient town of what is now referred to as Roman/Byzantine Aila is thought to have been founded by the Nabataeans, and was a center of trade and industry starting in the late 1st century B.C. (Parker, 2007). The most important early evidence about Aila is in Strabo's 1st century *Geography*, according to Parker (1997). Strabo confirms that the area was inhabited by Nabataean Arabs, and mentions that frankincense and myrrh as well as other aromatics from south Arabia were sold to merchants (Jones, 1930), which is quite significant because items like these, which would have been expensive commodities, often do not survive in the archaeological record or in the historical record as being bought or sold (Parker, 1996). This evidence supports the idea that Aila was an important town along the spice trade route during antiquity (Parker, 1996). Although there is little direct evidence of such, Aila would have made a likely and logical location for a Nabataean port because of its close proximity to the Nabataean capital of Petra, but the port has yet to be discovered in Aqaba (Khouri and Whitcomb, 1988). After the annexation of the Nabataean Kingdom in A.D. 106 by Roman Emperor Trajan, Aila fell under Roman control and became the southernmost extent of the Roman province along the *via nova Traiana* ("Trajan's new road"), which was extended from Syria in the north all the way to Aila between A.D. 111-116 (e.g. Khouri and Whitcomb, 1988; Parker, 1996). Around the start of the 4th century, the *Legio X Fretensis* (10th Legion Fretensis) from Jerusalem was stationed in Aqaba to secure the region militarily, which they then called Ailana (Khouri and Whitcomb, 1988). The transition from this to the Byzantine period seems smooth in the archaeological record, but relatively little about this shift is known. The legionary presence in the city remained until at least the 5th century, and Aila is believed to have prospered during the Byzantine period, likely because of this military presence (Parker, 2007).

The reason for the collapse of Roman/Byzantine Aila and the move to Islamic Ayla is a matter of debate, but based on recent excavations the city is believed to have been damaged and/or ruptured by no fewer than seven earthquakes since the second century A.D. (Thomas et al., 2007). Multiple repairs have been documented at what is referred to as the Monumental Building at Aila, and after the A.D. 363 earthquake during the Byzantine period, there was a notable reduction in occupation and a change in function of the structure to a more domestic capacity based on artifacts recovered (Thomas et al., 2007). It is clear that the seismic activity of the region played an ongoing role in functional and social changes at Aila, likely resulting in its decline and eventual collapse somewhere between the mid-7th to mid-8th centuries (Thomas et al., 2007). It is also likely that when the earthquake damage became too severe to make repairs any longer worthwhile, most people started moving away from the dilapidated town, and Islamic Ayla was newly constructed. A small population of people, however, must have remained at Aila to some extent or re-inhabited the site because there is evidence of construction and reuse of earlier Umayyad structures as determined from archaeological deposits dating to the mid- to late 8th century at the site (Thomas et al., 2007).

Muslim rule, the start of the Islamic period, began in A.D. 630 when Yuhanna ibn Ru’ba, a representative or possible bishop of Roman/Byzantine Aila, personally negotiated the city’s surrender to Prophet Mohammad at Tabuk in present-day northwestern Saudi

Arabia (e.g. Guillaume, 1955; Zayadine, 1994; Parker, 1996). As a part of this arrangement, the Prophet guaranteed the protection of Roman/Byzantine Aila's ships and caravans on both land and sea, implying that trade and commerce were of great importance to the city of Aila right up until the Muslim conquest (e.g. Guillaume, 1955; Zayadine, 1994). Very soon after the conquest, which was not accompanied by widespread destruction (Avner and Magness, 1998), the new fortified city of Ayla was founded by the Muslims, beginning a new of chapter of development in Aqaba (Whitcomb, 1994a).

It is important to clarify that the cities of Islamic Ayla and Roman/Byzantine Aila, are both pronounced the same way, and because a variety of spellings have been used for both sites, this can be confusing in the historical record and even in modern publications at times. Roman/Byzantine Aila, excavated from 1994-2002 by S. Thomas Parker, has also been referred to as Ailana, Aelana, Elana, Haila, Ailath, and even Ayla (e.g. Parker, 1996; Whitcomb, 1997). Islamic Ayla, because it was founded centuries after classical Aila in the 7th century, was also called "Wayla" by Shams ad-din Muqaddasi, the first Arab geographer to study the area as he traveled through the region during the 10th century (de Goeje, 1906; Whitcomb, 1997). "Wayla" is thought to mean "diminutive little Aila," and was presumably introduced by Muqaddasi to reduce confusion about the two similar city names, although the name seems to have remained idiosyncratic to him and his writings (Whitcomb, 1997). Referring to this perceived naming problem, Muqaddasi wrote, "The city is usually called Ayla, but the true Ayla is in ruins nearby…ask them concerning the town by the sea" (e.g. de Goeje, 1906; Khouri and Whitcomb, 1988). Interestingly, until 1986 this quote could not be understood by modern historians and archaeologists because the ruins of Islamic Ayla and most of Roman/Byzantine Aila were completely buried by sand by the time Whitcomb first visited Aqaba in the early 1980s. According to Khouri and Whitcomb (1988), however, Muqaddasi's 10th century observations, coupled with a few scattered sherds found on the surface above where Islamic Ayla was buried, are the reasons that Whitcomb dug a few small excavation probes, eventually finding the Islamic city once again.

In A.D. 661, Damascus became the new capital of the Arab-Muslim Umayyad caliphate. Jordan prospered during the Umayyad period (A.D. 661-750), likely because of its proximity to Damascus. With walls preserved up to 4.5 meters tall, Early Islamic Ayla, an example of this Umayyad prosperity, contains four gates or entrances leading into the city: the Egyptian Gate, the Syrian gate, the Hejaz (Hijaz) Gate, and the Sea Gate (Whitcomb, 1995a). Once established, the city flourished from A.D. 650 until A.D. 746 or 749 when a large earthquake struck Ayla, requiring that substantial repairs be made to its walls and towers (Whitcomb, 1995b). The extensive damage documented by excavation records and the likely weakened infrastructure of Ayla may have contributed to the defeat of the Umayyads by the Abbasids in A.D. 750 (Whitcomb, 1995b). This earthquake event, and all others that may have affected the city of Ayla and the greater Aqaba coastal zone, will be discussed in the next chapter in a section that will summarize the known seismic activity of the region.

Following this mid-8th C. earthquake, the city experienced a serious investment of capital in the form of rebuilding, expansion, and reorganization of architectural space (Cobb, 1995). This post-Umayyad re-build can be seen, most readily, in the restructured Abbasid mosque, and in the extramural expansion associated with this period, according to Cobb

(1995). Also, the city of Ayla is marked by axial streets dividing the town into four quadrants, and at this central meeting place stood a tetrapylon, referred to as the "Central Pavilion" (Whitcomb, 1994a). At this central crossing, another change in the administration of the city can be seen through the modification of the function of the Central Pavilion from that of an administrative center to what appears to be a domestic residence in the Abbasid period. Khouri and Whitcomb (1988) suggest this may have been turned into the home of a governor or other city official. The city was possibly damaged yet again by another earthquake only a few years later in A.D. 757, but because these earthquakes happened in such a close period of time, they are not individually distinguishable in the archaeological record.

Islamic Ayla, originally built as a "misr," or fortified camp town, seems to have been an economic center located along the trade route, as well as an oasis of sorts to weary pilgrims making their way to the city of Mecca in the south (Whitcomb, 1995a). After recovering from at least one, if not two, mid-8th century earthquakes and the change to Abbasid rule, it seems that the town of Ayla enjoyed relative prosperity based on the varied pottery collected through Whitcomb's numerous excavations, which continues to show extensive trade throughout the region, albeit under increasing political destabilization (Cobb, 1995).

Egyptian Fatimid rule in the mid-10th century began a period of adversity as hinted at by geographer Muqaddasi when he writes that, "… in Wayla there is disagreement among the people of Syria, the Hejaz, and Egypt…but I join it to Syria because its customs and measures are Syrian. It is the port of Palestine, from which come its imported goods" (e.g.

de Goeje, 1906; Khouri and Whitcomb, 1988). Starting in A.D. 961, a garrison was stationed at Ayla in order to contend with the local tribesmen and other unruly outsiders who were becoming increasingly prevalent, and who would eventually succeeded in sacking the city in A.D. 1024 (Khouri and Whitcomb, 1988).

The city of Islamic Ayla took another major hit when, according to historical sources, and as cited by the earthquake catalogs of Guidobini and Comastri (2005) and Ambraseys (2009), the city of Ayla was severely damaged in the large March 18, 1068 earthquake with an epicenter believed to be in or very near the Gulf of Aqaba. This catastrophic earthquake resulted in the buildings at Ayla being destroyed and all its inhabitants killed, except for twelve residents who were out fishing on the Gulf at the time of the earthquake (e.g. Makdisi, 1956; Guidobini and Comastri, 2005; Ambraseys, 2009). The historical record also shows another earthquake occurred just two months later on May 29, 1068 that is said to have destroyed the city of Ramla in Palestine along with at least 15,000 inhabitants. The effects of these two events are not, however, altogether separable because some locations may have felt both earthquakes. Unfortunately, the close occurrence of these seismic events within the same year caused confusion in the historical record, and sources often combine these two major seismic events into one event (e.g. Guidobini and Comastri, 2005; Ambraseys, 2009).

Destroyed by this large seismic event, the city of Islamic Ayla was eventually captured in A.D. 1116 by King Baldwin I of Jerusalem, and he was not thought to have been met with much resistance as most of the city’s residents had either died or relocated as a result of the A.D. 1068 earthquakes (Whitcomb, 1994a). While a few people had come from other cities like Ramla (Guidoboni and Comastri, 2005) to try and carve out a living in the damaged city, the archaeological record indicates that Islamic Ayla was never fully inhabited nor fully functional again (Whitcomb, 1994a). After the attack by Baldwin I, the Crusaders built a small fort for their garrison, which is thought to be the Aqaba Castle located 850 m south of the collapsed city of Islamic Ayla. Whitcomb (1997) suggests that this move by the Crusaders to a new location down the coastline, rather than repairing or building on top of the old city, can be compared to that of rundown modern inner cities -- that at some point it is just easier and less expensive to construct new buildings at a new location than to restore and reconstruct damaged or dilapidated buildings. The city of Ayla changed hands again when Saladin took the city for Muslim rule from the Crusaders in A.D. 1170, only to have Crusader Renaud de Chatillon briefly occupy the city about a decade later (e.g. Khouri and Whitcomb, 1988).

Whitcomb believes that it is best to turn to the Arab geographers of the 9th and 10th centuries for first-hand descriptions of the development of the town of Ayla, including Ya'qubi who in the late 9th century wrote, "The city of Ayla is a great city on the shores of the Salt Sea, and in it gather the pilgrims of Syria, Egypt and the Maghreb. There are numerous merchants and common people…" (e.g. de Goeje, 1892; Khouri and Whitcomb, 1988). This personal account from geographer Ya'qubi (de Goeje, 1892) attests to the commercial prosperity of the town at that time and, combined with Muqaddasi's (de Goeje, 1906) insight a century later, it also reveals that multiple sets of ruins were present and visible. Despite the collapse of Roman/Byzantine Aila, the younger Islamic Ayla was prospering (Khouri and Whitcomb, 1988).

Several westerners are known to have visited the Islamic city of Ayla throughout the 19th century. Travelers who visited the area in the first half of this century include John Lewis Burckhardt in 1816, German geographer and naturalist Eduard Rüppell and surgeon Michael Hay in 1822, French explorers Leon de Laborde and Linant de Bellefonds in 1826, and British Navy lieutenant J. Raymond Wellsted in 1833 (e.g. Burckhardt, 1822; Rüppell, 1829, 1840; de Laborde, 1838; Wellsted, 1837, 1978). The Aqaba area was also visited by a number of Western travelers in the second half of the 19th century, including English theologian Arthur Stanley in 1852-1853, English scholar Charles Doughty in 1876, English diplomat and orientalist Richard Burton in 1877, and Czech theologian and orientalist Alois Musil visited the area in 1898 and again in 1902 and 1910 (e.g. Musil, 1907, 1908, 1926; Stanley, 1910; Burton, 1913a, 1913b; Doughty, 1921).

One of the earliest 20th century visitors to the city was T.E. Lawrence in 1913 while on his trek through the region with C. Leonard Woolley. In describing what seemed to be the ruins of Islamic Ayla, Lawrence suggested the ruins and scattered artifacts represent "an Arab settlement of some luxury in the early Middle Ages" (Woolley and Lawrence, 1936). He then mentions that "there are ruins a little farther inland, and these represent probably a small village outside the gates of the larger place," which, based on geographic placement, must have been the even older ruins of classical Aila (Woolley and Lawrence, 1936). These early accounts of Islamic Ayla and Roman/Byzantine Aila are particularly interesting and important because by the time archaeologist Donald Whitcomb visited the region in the 1980s, these ruins were either buried in the sand and out of sight, or partially built on by the expanding modern city of Aqaba. As mentioned, Whitcomb based the location of his first small trenches at Islamic Ayla on a very small surface scatter of sherds he found, as well as the primary source accounts of early geographer Muqaddasi (Khouri and Whitcomb, 1988). But the historical accounts throughout the centuries, such as Woolley's and Lawrence's, also reaffirmed that there were indeed numerous sets of archaeological ruins along the southern coast of modern-day Jordan.

During Whitcomb's first excavation along the Egyptian wall and gate at Ayla in 1986, he identified several occupational phases as the site, Phases A-E, which included the Umayyad, Abbasid, and Fatimid periods (Table 3.2) (Whitcomb, 1987, 1994a). Ceramic sherds from these trenches, and those from the rest of his archaeological field seasons, testify to an international commerce at Ayla, and include imports from Iran, Iraq, Egypt, and China (e.g. Whitcomb, 1987, 1994a). Exports from Ayla to eastern Africa and the Far East also suggest broad commercial contacts during the Umayyad and Fatimid periods (Whitcomb, 1994a).

Damgaard (2011) published a site plan for Islamic Ayla showing the archaeological phasing of the site based on Whitcomb's excavations of the city and his own work at Ayla (Figure 3.3). Damgaard's phasing of the site includes occupational Phases 1-5, and can be roughly divided into a chronological framework based on the ceramic horizon of associated deposits and the morphology of the architecture (Damgaard, 2011). This updated phasing correlates very closely to Whitcomb's phasing of Ayla (Phases A-E), although there are differences. To summarize these two phasing schemes, Damgaard's Phase 5 (mid 7th - mid 8th C.) corresponds to Whitcomb's Phase A (A.D. 650-750) and encompasses the same

TABLE 3.2

OCCUPATIONAL PHASES EARLY ISLAMIC AYLA 7th-12th C.

Whitcomb Phasing	Whitcomb Approx. Dates/ Historical Period(s)	Damgaard Phasing	Damgaard Approx. Dates/ Historical Period(s)	Islamic Ayla Life History	Archaeological Evidence
Phase E	A.D. 1050-1116	Phase 1	11th to early 12th C.	Continued decline and collapse of city; taken by Baldwin I in A.D. 1116	Increase in mudbrick suggests decline in construction quality; increase in handmade pottery (Tupperware); destruction layers from 1068 EQ
	Fatimid		Fatimid		
Phase D	A.D. 950-1050	Phase 2	Mid to late 10th C.	Disruptions and decline of city	Sacked by Banu Jarrah in 1024; two hoards of gold coins lost; intensification of housing, and narrowing of streets; increase in trash; many Chinese sherds and Ayla Tupperware first appears
	Late Abbasid or Fatimid		Late Abbasid to Early Fatimid		
Phase C	A.D. 850-950	Phase 3	9th to early 10th C.	Continued periods of growth and prosperity of city	Archaeologically uneventful; excavations reveal a clean, orderly town; refined pottery from Iraq, but few ceramics overall
	Middle Abbasid		Abbasid		

(Table 3.2 continued)

TABLE 3.2 -- Continued.

OCCUPATIONAL PHASES
EARLY ISLAMIC AYLA
7th-12th C.

Whitcomb Phasing	Whitcomb Approx. Dates/ Historical Period(s)	Damgaard Phasing	Damgaard Approx. Dates/ Historical Period(s)	Islamic Ayla Life History	Archaeological Evidence
Phase B	A.D. 750-850	Phase 4	Mid 8th to early 9th C.	Periods of growth and prosperity	746/749 earthquake repairs result in the reconstruction and growth of the city; "mall on the beach" constructed; city mosque enlarged
	Early Abbasid		Early Abbasid to Tulunid		
Phase A	A.D. 650-750	Phase 5	Mid 7th – mid 8th C.	Foundation of city	Early occupational layers buried by thick overburden; probes reveal transformation from late Byzantine to Islamic pottery; ends with A.D. 746/749 earthquake
	Rashidun and Umayyad		Rashidun and Umayyad		

(After Whitcomb, 1994a, and Damgaard, 2011)

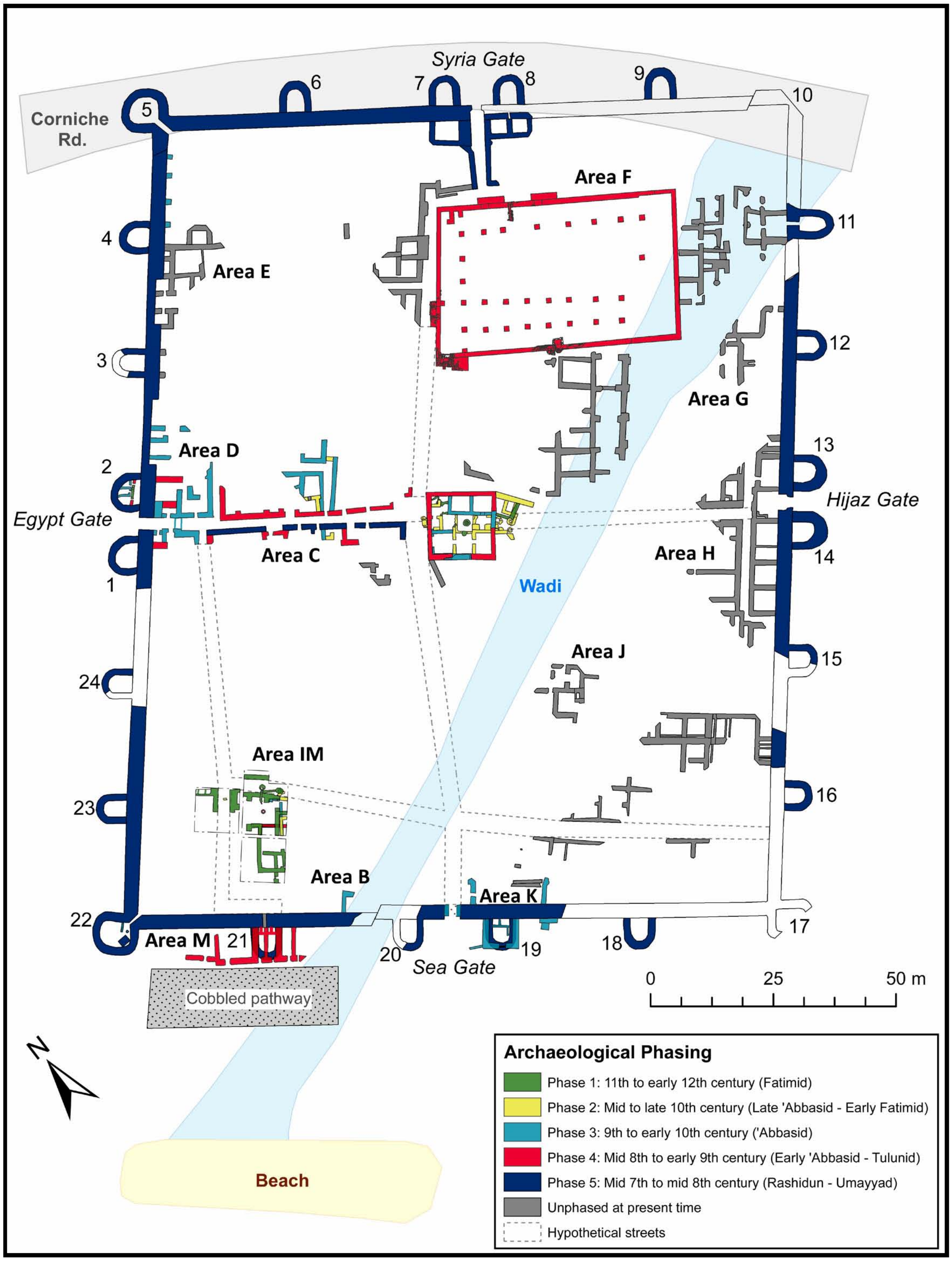

Figure 3.3 Archaeological phasing of Early Islamic Ayla (Damgaard, 2011).

period of time during the Rashidun and Umayyad periods, the foundation and approximately the first one hundred years at the site (Whitcomb, 1994a; Damgaard, 2011).

The phasing differs slightly between Whitcomb's Phase B, which spans the years A.D. 750-850, and Damgaard's Phase 4, which encompasses the mid 8th C. to the early 9th C. (Whitcomb, 1994a; Damgaard, 2011). Whitcomb (1994a) describes these years at Ayla as showing periods of growth and prosperity. Next, according to Whitcomb (1994a), Phase C at Ayla includes the years A.D. 850-950 during the middle Abbasid period and represents continued periods of growth and prosperity. Phase C correlates to Damgaards's Phase 3 of Ayla, which is described as the Abbasid period from the 9th to the early 10th C. (Damgaard, 2011).

Moving forward in the life of the city, Whitcomb defines Phase D as A.D. 950-1050 during the late Abbasid or Fatimid periods, and Damgaard's corresponding phase, Phase 2, is described as occurring in the mid-to late 10th C. during the late Abbasid to early Fatimid periods (Whitcomb, 1994a; Damgaard, 2011). It is during this period of time that disruptions and decline start to appear in the archaeological record at Ayla (Whitcomb, 1994a).

Finally, the most recent occupational phase at Islamic Ayla as identified by Whitcomb, Phase E, encompasses the years A.D. 1050 during the Fatimid period to A.D. 1116 when the city is finally taken by Baldwin I during the Crusader period. Damgaard's earliest phase, Phase 1, spans the 11th C. to the early 12th C. (Damgaard, 2011).

Whitcomb continued to excavate at Islamic Ayla until 1995, and in the process unearthed a good portion of the city and revealed much about the economy and trade happening at Ayla and in the surrounding region. Despite nearly a decade of excavation, however, much of the original city still remains buried, including the majority of the earliest Umayyad occupational layers. The Umayyad materials remain largely unexcavated primarily due to a deep overburden of younger material, a shallow water table which makes accessing the earliest deposits difficult, and limited excavation time each season. Seismic activity at the site has also likely contributed to the overall subsidence of Ayla, making these oldest archaeological remains challenging to access (e.g. Whitcomb, 1987).

Ceramics and the Archaeological Record at Early Islamic Ayla

Besides a very limited number of primary sources available concerning the site, the majority of what is known about Early Islamic Ayla comes from the previous archaeological excavations conducted, as mentioned. As far as pottery is concerned, each of the periods represented at Ayla tends to have its own characteristic style of pottery, and with tight stratigraphic control, pottery recovered from excavations can be used to better understand the history of the region. Depending on the degree of preservation, artifacts can provide clues and act to illuminate the culture of the people who once lived at a site (Khouri and Whitcomb, 1988). Most pottery recovered from an excavation typically consists of undecorated body sherds which are non-diagnostic pieces of a broken ceramic vessel that may give a ceramicist clues to its age. What is preferential to find during an excavation, however, are indicator sherds which reveal a diagnostic aspect of the vessel that is useful for the purposes of reconstruction and dating. A diagnostic sherd can consist of anything from the rim, base, or handle of a vessel, to a diagnostic glaze, paint, or incised pattern specific to a certain time period, for example. It should also be noted that even though an indicator sherd may be found, it may not be specific enough or well enough preserved to be dated accurately by a pottery expert. Still, indicator sherds inevitably reveal more information about the vessel as a whole than do body sherds.

As with any material manufactured throughout history, changes in the production of ceramic pottery occur through time. The ceramics at Ayla most certainly vary through the Islamic period, century to century, and have been found throughout the region signifying extensive trade at the city of Islamic Ayla (Khouri and Whitcomb, 1988). Changes in pottery can occur for several reasons -- as a result of a need for a specific function and/or form (e.g., water vessel vs. container for dry goods), because the available clay source or manufacturing technique of the pottery changes from wheel-made to hand-made, or vice versa, because the firing process changed, or because stylistic changes, which naturally occur in anything man-made, evolve through time as styles still do today. The analysis of pottery on the basis of vessel form, however, is typically not as common as analysis based on stylistic attributes (Sharer and Ashmore, 1979). Paint on the outside of a vessel, for example, served no function for that particular vessel, other than to be aesthetically pleasing or potentially to signify cost or societal status. The decorative paint and patterns used, however, become associated with specific periods and can be traced to determine the extent of trade, which can provide insight into the economics and politics of a historical period.

There are currently two ceramic typologies for the site of Islamic Ayla: the 1986 typology devised by Whitcomb, and a 2009 typology developed by Damgaard (2011). Starting with his excavation in 1986, Whitcomb categorized pottery recovered from stratified loci on the basis of vessel form and, in part, the surface treatment of the ceramics (e.g. Whitcomb, 1987). Rather than creating an entirely different typology, Damgaard (2011) augmented Whitcomb's 1986 field typology and combined it with the ceramic types collected from the single 2008 Islamic Aqaba Project campaign (Damgaard, 2011). The 2009 ceramic typology, however, categorizes pottery on the basis of ware and fabric instead of form. This change in sorting principles from vessel form to ware was intended to help trace mercantilism at Ayla by distinguishing between locally produced wares and imports (Damgaard, 2011). A complete ceramic typology for the site has not been published, but in his dissertation Damgaard (2011) published the first comprehensive catalog of ceramic wares and types at Ayla, and also included Whitcomb's 1986 typology for reference.

Since Ayla was founded in or around A.D. 650, the earliest (oldest) pottery found *in situ* at the site of Islamic Ayla dates to the early Umayyad period (Whitcomb, 1987). The pottery from this period represents the transition from Byzantine to Islamic material culture (Whitcomb, 1989b). Although difficult to reach in a stratigraphic section, as discussed previously, during the 1993 field season Whitcomb was alerted to the fact that there were building foundations that exposed supposed ancient pottery kilns in the modern Radwan neighborhood near Islamic Ayla. After an initial investigation, his planned excavation for the season was expanded to include the excavation of two 7th century kilns, the larger of which was almost 4 m in diameter (Melkawi et al., 1994). This find constituted one of the most important ceramics discoveries made in Aqaba, indicating a vital increase in occupation and commerce, and confirming industrial manufacturing of pottery at Islamic Ayla (Melkawi et al., 1994). Within the pottery found *in situ* in and around the two kilns at this new site, for instance, were Egyptian imports and the occurrence of ceramics with

Coptic attributes, clearly borrowed from Egyptian pottery known as Coptic-glazed ware (Melkawi et al., 1994).

Interestingly, a number of identifiable types of pottery found at Ayla are found nowhere else in the region, and thus, “do not have ready or even vague parallels” (Melkawi et al., 1994). The findings at the 7th century kiln site actually suggest that this medieval city was a separate regional pottery center marked by strong new tradition, and is a feature that may be readily associated with the experience of early Islamic times, according to Melkawi et al. (1994). As discussed, the Red Sea was a route of trade and cultural connections in the early Islamic period, and a special type of 7th century amphora (“Ayla-Axum ware”) was used as a cargo container by the merchants because they were sturdy enough and large enough for carrying quantities of goods some distance (Whitcomb, 1994b). This expansion in Red Sea commerce after the Arab conquest in the 7th century increased the need for such amphorae, which have been found near Aden in present-day Yemen and even as far as Axum in modern Ethiopia (Whitcomb, 1994b). Whitcomb (1994b) also found what he considered to be “startling evidence” of this Ethiopian connection in an Axumite coin, the second recovered from his archaeological excavations.

Starting in A.D. 750, a change of political power from the Umayyads to the Abbasids also resulted in a change of pottery from the amphora mentioned to what is known as “Mahesh ware.” Identified and named by Whitcomb (1989b), Mahesh ware is characterized by cream-colored ware and is easily identified by a wavy pattern of incised combing that circles the vessel near the rim and/or middle of the vessel. While it is not the style of the pottery that is important, Mahesh ware is the pottery most readily associated with the

Abbasid period, and it allows archaeologists to study the distinct beginning of new Abbasid traditions (Whitcomb, 1989b).

Whitcomb (1988a) has also identified at Ayla a type of handmade pottery, very utilitarian in nature, dated to the early- to mid-11th century (or perhaps very late 10th C.) for which he coined (or rather borrowed) the name "Tupperware" because it represents an everyday type of pottery that a family might use. The Tupperware also seems to have been made to nest one inside the other. Whitcomb (pers. comm., 2011) suggests that the Ayla Tupperware can act as a gauge of cultural stresses indicative of industrial, economic, and political change. Rautman (1998) explains that the adoption of wheel-based pottery-making in this part of the world is generally considered to reflect rising craft specialization and social complexity, and that the re-emergence of handmade pottery could reflect times of "dramatic cultural change." Found alongside the handmade pottery in the late 10th - early 11th centuries in the archaeological record at Ayla are also fine luxury ceramics, including imported Chinese wares, as well as an increased trash accumulation pointing to economic disparity, and perhaps population pressures (e.g. Whitcomb, 1994a; Cobb, 1995).

Whitcomb hypothesizes that the Ayla Tupperware was produced at home by women, and perhaps by helpful children (Whitcomb, pers. comm., 2011), unlike most other pottery at Ayla that was wheel-made and produced in bulk, as was evidenced at the 7th century kiln site (Melkawi et al., 1994). Impressions of reed mats are often found on the base of the Tupperware, and some vessels were found to have been repaired (Whitcomb, 1988a). Tupperware pottery was most predominantly recovered from archaeological layers leading up to the A.D. 1068 earthquake, after which ashy destruction layers are commonly found

(Whitcomb, 1988a). These handmade rich pottery assemblages indicate, therefore, that even before the city was destroyed by the earthquake of A.D. 1068, times were difficult and making pottery at home was a necessity because the ceramic industry at Ayla had been interrupted or collapsed. The Ayla Tupperware is also sometimes referred to as "abandonment pottery" because it is also found in archaeological deposits after the A.D. 1068 earthquake, although to a lesser extent (Whitcomb, pers. comm., 2011).

One of the most significant archaeological discoveries ever made at Islamic Ayla was a hoard of thirty-two gold dinars (medieval coins), minted primarily in North Africa by rulers loyal to Muslim Spain, found buried only a meter beneath the surface just inside the Syrian Gate (Whitcomb, 1992). This find acts to further illustrate the importance of the port of Ayla as a site of trade and commerce during the early Islamic period. As Whitcomb points out, this financial loss would have constituted a personal tragedy for someone, and he has hypothesized that this coin purse belonged to either a merchant or traveler, perhaps someone on his way to Mecca (Whitcomb, 1992). Further, based on the stratified evidence and the shallow depth of burial near the Syrian Gate, which is one of the four main entrances to the city, Whitcomb (1992) has postulated that the coin purse could have been dropped or temporarily hidden during the sacking of Ayla by Bedouin in A.D. 1024, never to be collected by the owner.

Political turmoil most certainly interfered with the yearly pilgrimage to Mecca along both the Nile and Red Sea routes. Peters (1994) refers to the Crusaders entering the area at this time as "Western intruders" who at the beginning of the 12th century held Jerusalem, large areas of coastal Syria, and even areas east of the Jordan River. As discussed, Ayla is known to have finally fallen when King Baldwin I took the city in A.D. 1116 (Khouri and Whitcomb, 1988). By this year, the Seigneurie of Montreal extended down through the Gulf of Aqaba and included the “fortress of Ayla” (Peters, 1994).

Given the long history of ancient Aqaba, it is telling that modern Aqaba functions in much the same way today as it has throughout the centuries -- it is still primarily a town that people visit on vacation or to pass through on their way to Israel to the west or to Saudi Arabia in the south. Known for very hot summers and temperate winters, it is located in an oasis-like setting with date palm trees and the stunning Gulf of Aqaba as a backdrop, Jordan’s only access to the Red Sea and Indian Ocean. The Gulf of Aqaba also functions as a vital port for the import and export of goods. So while the number of permanent residents in Aqaba continues to grow as the city itself expands, the city swells significantly on the weekends and during the holidays with tourists, and also with visitors from Amman and other near-by cities looking for a place to relax.

The archaeological evidence of the Islamic periods at Ayla in Aqaba provides important information on the sequence of the cultural changes that happened between late antiquity and the formation of early Islam, as well as the development between the Abbasid and the Fatimid periods (Whitcomb, 1988b). The pottery assemblages at Ayla, combined with Muqadassi’s first-hand 10th century accounts of the port, also provide evidence of the prosperity of Ayla and its extensive trade connections with North Africa, Palestine, the Hejaz, and the Far East, including China (e.g. de Goeje, 1906; Khouri and Whitcomb, 1988). More than anything, it was Ayla’s geographic location at the head of the Gulf of Aqaba at the intersection of the land and sea routes (namely the North African/Egyptian and

Palestinian/Syrian roads), as well as the abundant freshwater sources (Whitcomb, 1994b), that turned Ayla into a wonderful stop-over town for Muslim pilgrims on their way to Mecca (Khouri and Whitcomb, 1988).

Liquefaction Susceptibility

Work at Islamic Ayla and in the city of Aqaba has also included an evaluation of the liquefaction susceptibility of the site and region. The phenomenon of liquefaction is an earthquake hazard usually associated with granular sediments like sand and some gravels, although finer-grained sediments such as silts and clays can liquefy as well (McCarthy, 2002; Boulanger and Idriss, 2006). Especially susceptible where the water table is shallow, seismic ground shaking can cause sediment grains to push apart and shift, settling past one another in an attempt to move into a denser and more compact arrangement as the groundwater rises to the surface acting to reduce the load capacity of the affected sediment (Marshak, 2009). The presence of pore water interferes with the cohesion and subsequent rearrangement of grains, however, and much of the soil's shear strength is also temporarily lost during seismic ground shaking (McCarthy, 2002). As the once-sturdy ground weakens because of the rising groundwater and sinking sediment, structures built on the surface of the affected region can sustain damage ranging from toppled chimneys, cracked foundations, and leaning or sinking walls to the complete failure and loss of a structure (Ambraseys, 2009).

Determined to be highly susceptible to liquefaction in studies conducted by Mansoor (2002) and Mansoor et al. (2004), the modern city of Aqaba, Jordan is currently at risk of liquefaction should a sizeable earthquake occur within the region. Islamic Ayla lies in an area of especially high liquefaction susceptibility due to the presence of saturated sands at shallow depth and its close proximity to the Gulf of Aqaba (Mansoor, 2002; Mansoor et al., 2004). The water table at the site of Islamic Ayla is approximately 3 m below the ground surface except in the wadi that now runs through the site where the water table is at a depth of 2 m (Al-Homoud and Tal, 1998). The city was also built on top of primarily unconsolidated alluvial sediments washed down from the large Wadi ‘Arabah and Wadi Yutim drainages located to the north of the city (e.g. Al-Homoud and Tal, 1998). Allison and Niemi (2010) conducted a drilling campaign in the so-called Circular Area, a portion of the Aqaba coastal plain located approximately 200-800 m inland from the Gulf, in order to reconstruct the paleoenvironment of ancient Aqaba. Thirteen sediment cores drilled to a depth of 10 m in the Circular Area define a basal marine transgression overlain by a regressive sequence of coastal lagoon deposits and backshore lake, sand dune, and distal alluvial fan deposits (Allison and Niemi, 2010). Brückner et al. (2002) also report the stratigraphy of a core recovered from the Mövenpick Hotel construction site, located 50 m from the shoreline and just north of our study site at Islamic Ayla. This core revealed that a 6-m-thick alluvial sequence overlies littoral sands encountered at a depth of 1.35 meters below sea level.

Al-Homoud and Tal (1998) conducted geotechnical investigations at Islamic Ayla where three borings were made to a depth of 12 m in order to obtain a soil profile with depth. They found that the archaeological site is underlain by relatively uniform subsurface conditions, and that the archaeological sediments are supported by up to 5.5 m of medium dense silty and clayey sand. The basal sediments located even further underneath Ayla are fluvial granitic gravels and sands (Al-Homoud and Tal, 1998). Two types of fill layers were found at Islamic Ayla: (1) a non-homogeneous fill lacking texture and structure and containing remnants of ash and other unidentified objects, and (2) poorly-stratified silt, sand, and gravel flood deposits from the wadi that cuts through the site (Al-Homoud and Tal, 1998). Al-Homoud and Tal (1998) also reported tilting and sinking of exterior walls that they interpreted as slumping due to horizontal ground acceleration in an earthquake.

Al-Tarazi and Korjenkov (2007) also studied the liquefaction of the Aqaba area during an archaeoseismic investigation of the city of Islamic Ayla and determined that Ayla has been damaged by liquefaction due to seismic ground shaking in the historic past and that repairs were made as a result, as has been documented by Whitcomb (1994, 1997). They confirmed that an earthquake damaged the city in the 8th century at the end of the Umayyad period, which was likely the January 18, 746/749 earthquake, although Al-Tarazi and Korjenkov (2007) cite this event as A.D. 748. They also report observing substantial damage including the tilting of walls from the A.D. 1068 earthquake during the Fatimid period. Finally, they found that the modern November 22, 1995 earthquake in Nuweiba, Egypt, which had a $M_w = 7.1\text{-}7.3$ (e.g. Klinger et al., 1999; Hofstetter, 2003) and was the largest to affect the area since the A.D. 1068 event, also left clear traces of liquefaction damage in the excavated buildings at Ayla. The 1995 Nuweiba epicenter was located at least 100 kilometers from the Islamic city, and a Modified Mercalli Intensity (MMI) of VIII was observed by Al-Tarazi (2000) along the beach in the Aqaba coastal zone for that event.

Finally, evidence of liquefaction typically includes sand blows and leaning or toppled structures on the surface, and dikes of fluidized sediment (usually sand) in cross-section. Noller (2001) discusses how the compactness of archaeological deposits and floors can actually lead to greater overpressure in areas with seismically accelerated sand, causing it to liquefy and form dikes and sills in cross-section. At Islamic Ayla in 1992, Whitcomb actually identified a small sand dike in cross-section as it was exposed in a trench wall during the course of his excavation of Area G near the wadi (Figure 3.4). In addition to the studies by Al-Homoud and Tal (1998), Mansoor (2002), Mansoor et al. (2004), and Al-Tarazi and Korjenkov (2007) which have shown that the Aqaba area and the site of Ayla are liquefiable, this photograph (Figure 3.4) and associated excavation log are evidence that liquefaction has occurred in the historic past in the city of Ayla, and that the strata upon which the modern city of Aqaba is built are capable of being liquefied in the future.

2009 Archaeoseismic Excavation at Early Islamic Ayla

The purpose of this current archaeoseismic research is to use archaeological excavation and geological mapping techniques to document evidence for the history of earthquakes occurring during late antiquity in the region south of the Dead Sea in Wadi ‘Arabah with special focus on the site of Early Islamic Ayla in Aqaba, Jordan. As discussed in previous sections, portions of the Islamic Ayla site were first excavated during the late 1980s and early 1990s by Dr. Donald Whitcomb of the Oriental Institute at the University of Chicago. In addition to his numerous archaeological finds, his excavations at Ayla revealed

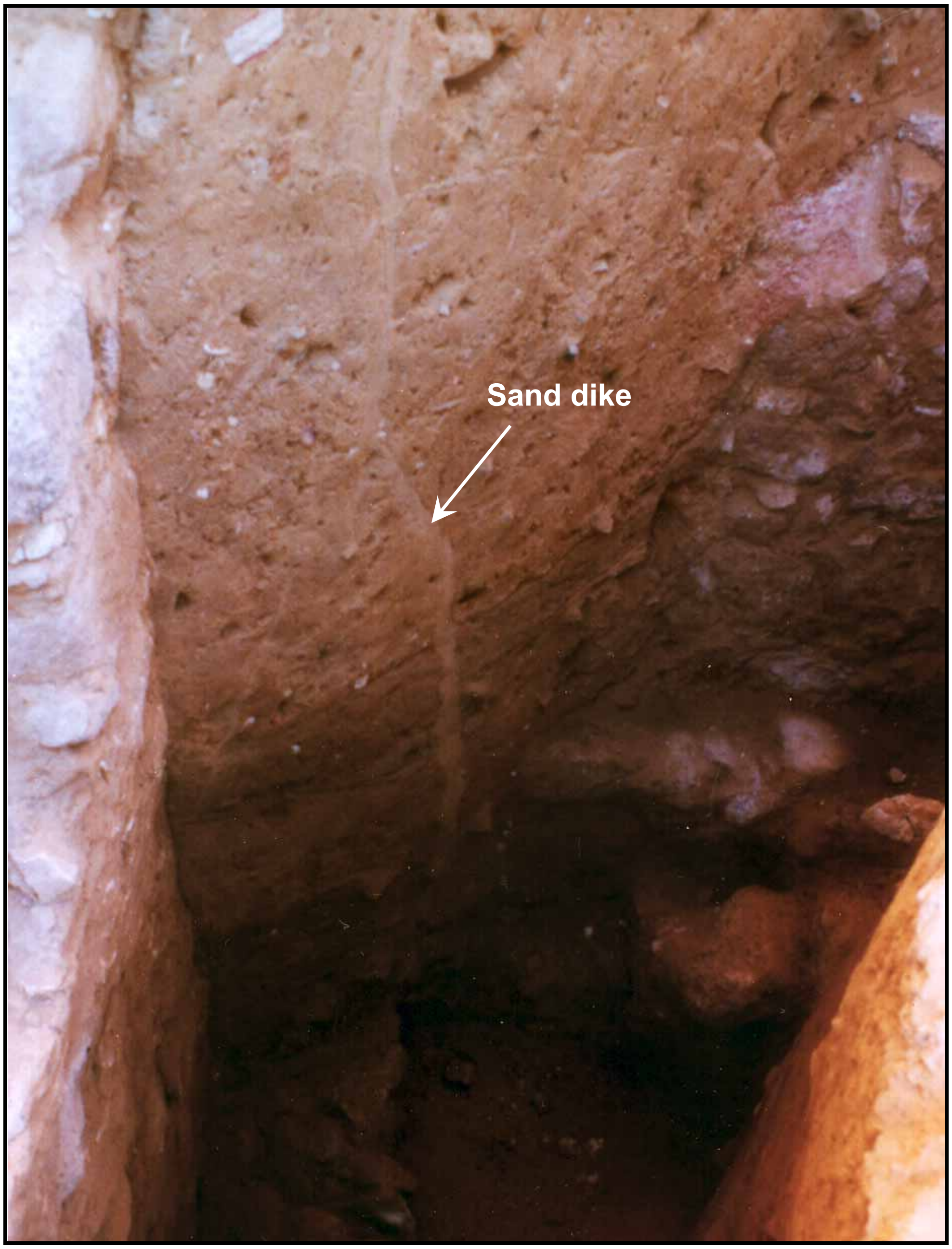

Figure 3.4 Small sand dike exposed in Area G trench at Early Islamic Ayla during Whitcomb's 1992 excavation near the wadi that now runs through the archaeological site. Photograph courtesy of D. Whitcomb.

evidence of seismic activity at the site, including the extant leaning southern wall of the city of Ayla (Whitcomb, 1994a).

In 2001, Dr. Sawsan Fakhri of the Department of Antiquities in Aqaba also conducted limited excavations along the southern wall (usually called the ‘sea wall’ because it faces the beach) as part of a project to reconstruct the dilapidated eastern and southern walls of Ayla for both archaeological and historical preservation purposes. The Department of Antiquities excavations revealed that large segments of the sea wall lean outward, and in an area of the Islamic town highlighted by this study, the leaning city wall was found to have been repaired by the construction of a 3.5 m-long revetment wall or buttress built to support the damaged wall (Figure 3.5).

The structural damage of the Ayla city wall is recognized from several distinct features. The exposure of the western edge of the revetment and leaning city wall revealed that the wall is still intact in that the stones are still stacked one on top of the other, but this portion of the sea wall is clearly leaning forward and has sunk into the ground indicating a loss of underlying support. The damaged section of the city wall also seems to have been somewhat shaken apart so that the most substantially constructed outer course of stones pulled away from the main part of the structure, thus necessitating the construction of a revetment wall. With the objective of excavating this earthquake damaged wall in a future season of the Wadi ‘Arabah Earthquake Project (WAEP), Niemi requested that this section of the leaning city wall and revetment be left *in situ* and not removed during the reconstruction process. Fortunately, Dr. Fakhri was able to leave these structures in place as she worked to reconstruct the city wall of Ayla, allowing for this current study to take place.

Figure 3.5 Section of the damaged leaning city wall and revetment wall at Early Islamic Ayla revealed during the 2001 Department of Antiquities restoration project (Rucker and Niemi, 2005). View toward the southeast.

In February and March of 2009, archaeoseismic excavations were conducted at the site of Early Islamic Ayla with the goal of investigating the section of the original city sea wall that is hypothesized to have been damaged due to liquefaction as a result of seismic activity in the region and then repaired with a buttress shortly thereafter (Figure 3.6). One of the primary goals for this excavation was to obtain pottery and charcoal fragments for radiocarbon analysis, if possible, from within and beneath the revetment wall, with the goal of dating the revetment construction, and thus constraining the age of the earthquake that caused the subsequent liquefaction damage. Dating this earthquake damage and the repair construction is very important to understanding the occupational history of the site of Early Islamic Ayla as well as the seismic history of the region.

Methodology

Archaeological excavation techniques were employed at this site in order to study the damaged portion of the Islamic Ayla city wall in a detailed and methodical fashion, with special attention paid to the construction and condition of the architecture present. In order to constrain the construction date of the revetment wall, with the objective of thereby constraining the date of the seismic damage sustained by the Ayla city sea wall, two trenches, AY1 and AY2, were excavated along the outside of the city wall closest to the beach over the course of twelve days (Figure 3.7). Both trenches were aligned with the standing architecture at the site, the original (buried) and reconstructed city walls of Ayla. The reconstructed wall of Ayla was built by the Department of Antiquities so as to be positioned directly over the original Ayla city wall where possible, with the objective of

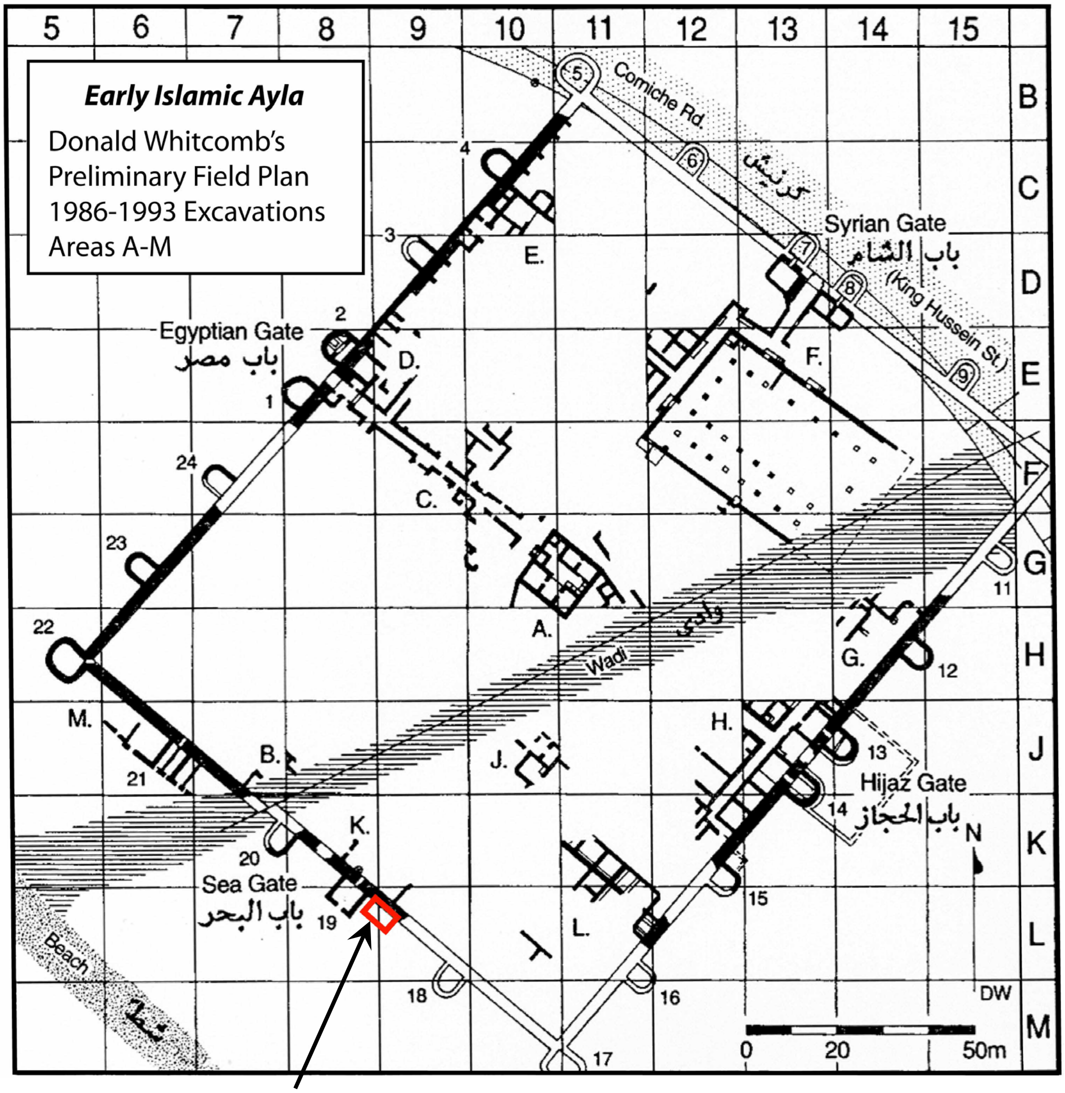

Figure 3.6 Trench site locations along the city sea wall of Early Islamic Ayla. Both trenches, AY1 and AY2, are located within the parameters of the excavation area outlined in red (modified after Whitcomb, 1994a).

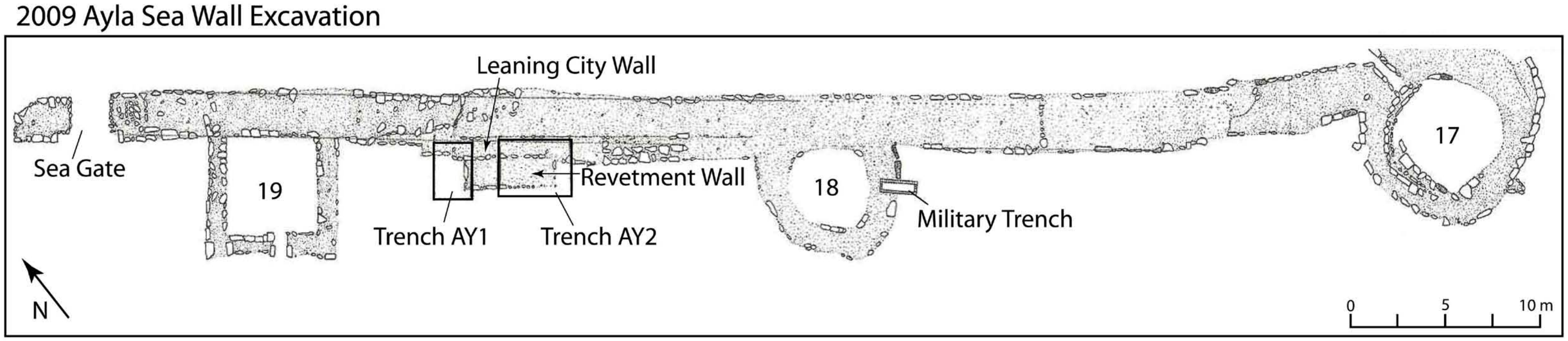

Figure 3.7 Location of trenches AY1 and AY2 along the city sea wall at Early Islamic Ayla. Numbered structures (17-19) correlate to numbered structures (towers) on the top plan by Whitcomb (1994a) (see Figure 3.6). The Ayla city wall was surveyed and drafted by Maisoon Fakhri as part of the Department of Antiquities excavations in 2001 (Dr. Sawsan Fakhri, unpublished data).

keeping the original plan of the Islamic city intact and preserving the ancient wall from further deterioration. This choice of trench alignment, as opposed to aligning the trenches based on standard cardinal directions as is often the practice during an archaeological excavation, was made primarily because it was our intention to include within each trench both the original and reconstructed city walls. The reconstructed sea wall trends roughly N53˚W, and both trenches were aligned perpendicular to this at N37˚E.

Investigation of the site followed standard archaeological excavation practices in that the site was excavated carefully and slowly, centimeter by centimeter from the top soil layer down, paying special attention to changes in sediment type, color, texture, degree of compaction, unit thickness and placement within the trench. Each time a change in the sediment was observed in one of the trenches, a new "locus" or layer was assigned and recorded in order to maintain stratigraphic control over the site and excavation. Sediment color was determined from a Munsell® soil color chart and recorded for each locus. Artifacts such as pottery, glass, and shell fragments, among other items unearthed, were collected from each locus for analysis and dating purposes. The extant architecture exposed in trenches AY1 and AY2 were also assigned a specific locus. Top plans and cross-sections of each trench were drawn throughout the various stages of the excavation process, and each trench and the site itself were photographed in detail. Following the completion of the excavation of the leaning city wall and revetment at Ayla, a final report was submitted to the Jordanian Department of Antiquities detailing the excavation process and the artifacts recovered, as well as a preliminary analysis of the excavation findings.

Two dating methods were used in this archaeoseismic study: radiocarbon dating and ceramic analysis. Samples of charcoal fragments were collected from sediment in both trenches, and the Center for Accelerator Mass Spectrometry (CAMS) at the Lawrence Livermore National Laboratory in California performed the C-14 analysis. Radiocarbon dates were calibrated to a two sigma probability using the CALIB Radiocarbon Calibration 7.0 program and included the IntCal13 curve selection (Reimer et al., 2013). The pottery recovered as a result of this excavation was dated by Donald Whitcomb from the Oriental Institute at the University of Chicago. Several other archaeologists and ceramicists who specialize in the Islamic period in Jordan, including Kharieh Amr, Yvonne Gerber, and Bethany Walker, provided expertise on pottery identification and dating.

Archaeological excavations, by their nature, are destructive. One of the most important considerations when conducting an excavation is the conservation of the site itself. It is important that the site be disturbed as little as possible during the actual excavation, and that the original condition of the site is preserved as much as is feasible for the work that must be conducted. In the interest of conservation, both trenches AY1 and AY2 were backfilled completely with the excavated sediment to prevent further deterioration of the architecture. Thick sheets of plastic were also placed at the bottoms of both trenches to alert future excavation teams of the excavation efforts in this specific location outside of the city sea wall.

Excavation Results

The city wall, eight to nine courses high, is primarily composed of large, limestone and sandstone ashlars. The 3.5 m-long section of damaged wall is leaning uniformly at an angle of approximately 30° out toward the Gulf of Aqaba, with the upper course of stones leaning the furthest forward. The wall is described as ‘leaning’ and not as fallen or collapsed because the building stones present at the time of this excavation are still stacked one on top of the other in an organized fashion, as would have been the case when the wall was in use, although the entire damaged section tilts toward the beach as though it lacks underlying structural support.

Trench AY1

Trench AY1 was laid out as a 2 m by 3 m trench at the northern end of the study site, positioned to intersect the visible northwestern edge of the revetment and leaning city wall within its parameters. Excavation of trench AY1 began with the removal of locus AY1:1, a lightly compacted, 20 cm-thick layer of light-brown, silty sand containing a few cobbles, from over the entirety of the trench. This unit was followed by the removal of locus AY1:2, a lightly compacted, 35 cm-thick layer of light-brown, silty sand with a slightly higher concentration of cobbles, also excavated from across the majority of trench AY1. One large sandstone boulder was left pedestaled in this locus, but as the excavation continued it proved to be unassociated with any of the existing architecture in the trench so it was eventually removed. Beneath locus AY1:2 there was an obvious and significant change in the sediment, and a layer of loosely consolidated, light-gray, medium-grained sand with a few pebbles, designated as locus AY1:7, was located along the northeastern balk of the trench where the trench intersects the original buried city wall. This locus was not fully excavated because it does not come into contact with either the leaning wall or revetment wall, so a total unit thickness is not available.

Each of the four walls exposed in trench AY1 was also designated as a separate locus for the purposes of this excavation. These are: (1) the reconstructed city wall built by the Department of Antiquities, locus AY1:3, (2) the revetment wall, locus AY1:4, (3) the damaged and leaning portion of the original city wall, locus AY1:5, and, (4) the portion of the original city sea wall that was buried underneath the reconstructed city wall, locus AY1:6. Locus AY1:6 was only visible once exposed by the complete removal of loci AY1:1 and AY1:2 in this trench. Unlike the large limestone ashlars used to construct the upper portion of the leaning city wall section, the lower portion of the original city wall that was exposed beneath the reconstructed wall during excavation was comprised of blocks of red sandstone which were found to be deteriorating (Figure 3.8).

Sealed by locus AY1:2, locus AY1:8 is a light-brown, silty sand with granules that covers the entirely of the trench, except for where the unconsolidated pebbly sand (locus AY1:7) was located across the northeastern balk of the trench. Excavation efforts were then concentrated in a 1 m square probe in the south corner of trench AY1. In this corner, what seemed to be the same loosely consolidated, medium-grained, pebbly sand layer identified along the northeastern balk (locus AY1:7) was uncovered, although at a slightly lower elevation, and was designated as locus AY1:9. The average thickness of locus AY1:9 was 32 cm. Upon removal of this locus within the trench probe, a layer of silty sand with a small

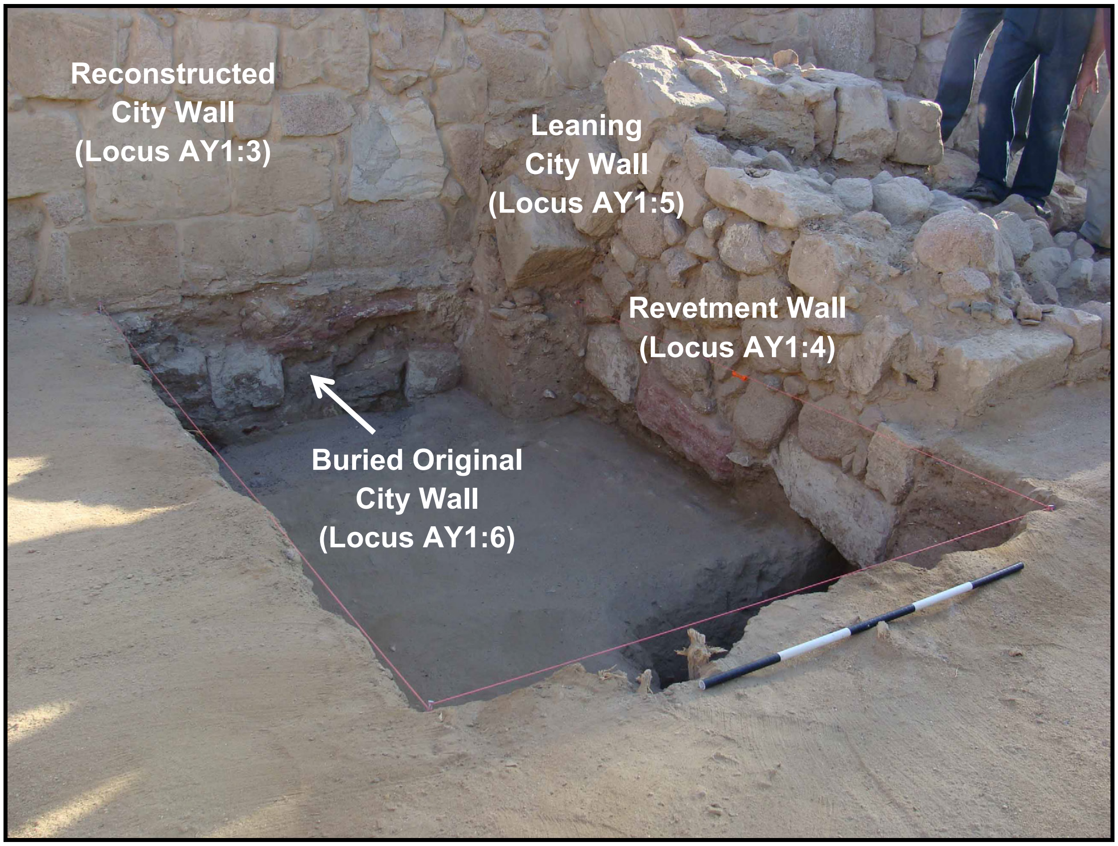

Figure 3.8 Photograph showing relationship of all architecture in Trench AY1 including the leaning city wall, revetment wall, the reconstructed city wall, and the buried original (non-leaning) city wall. View toward the east. Meter stick for scale in the foreground.

percentage of clay was revealed and designated as locus AY1:10. At its deepest point in this probe, the trench was excavated to a total of 1.3 m. Further excavation of locus AY1:10 was unnecessary based on the specific goals of this trench to fully expose the northwestern edge of the leaning city wall and revetment and to collect dateable materials from beneath the revetment wall itself.

These excavation goals were achieved as the southeastern balk of trench AY1 fully exposed the northwestern edge of the extant leaning wall, as well as the revetment wall (Figure 3.9). The revetment wall was revealed to be a relatively shallow structure, approximately six courses high, with the base of the revetment located roughly 55 cm beneath the current ground surface. As exposed in cross-section along its northwestern edge, the revetment wall measured 1.30 m tall at its northern corner, and 1.25 m at its western corner, and is up to 1.95 m wide (measured NE to SW) as exposed in this trench. This excavation revealed that the revetment wall is composed of several different types of materials including locally sourced granitic cobbles, blocks of red sandstone, blocks of worked and unworked limestone, and a few cobble-sized pieces of coral (Figure 3.10). As will be discussed through the excavation of trench AY2, it became apparent that larger stones, both worked and unworked, were primarily used to outline the revetment wall's outer courses, while the center of the buttress was comprised of a rubble fill. Based on its rough and uneven surface configuration, which is visible in both top plan view and in cross-section, it is assumed that the revetment was once composed of additional stones and likely stood several courses higher than it does it its current state. Exposure of the northwestern

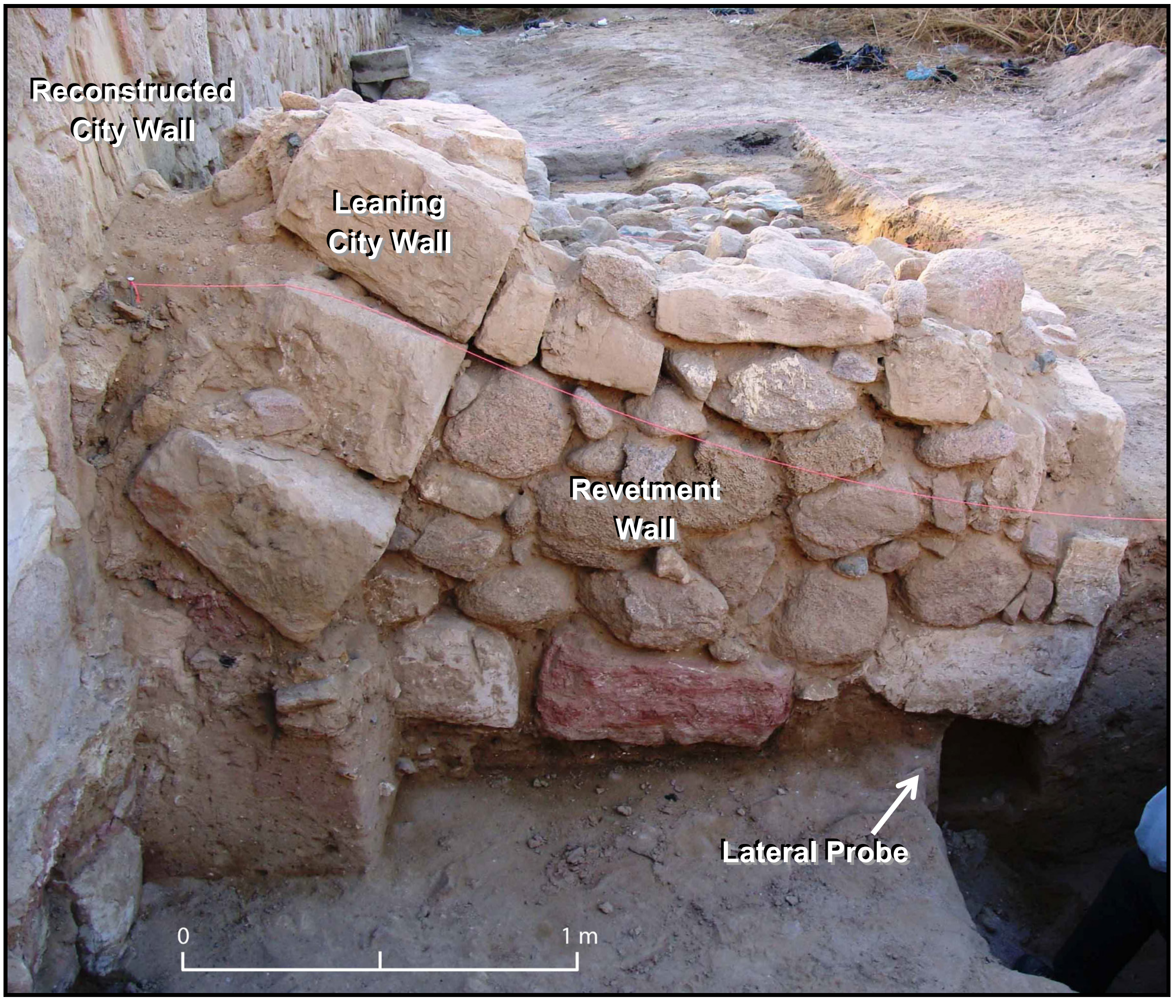

Figure 3.9 Photograph of the visible northwestern edge of the leaning city wall and revetment wall as exposed in the southeastern balk of Trench AY1. Pottery was collected from beneath the revetment wall in this trench via the small probe visible on the right side of the photo. View toward the southeast.

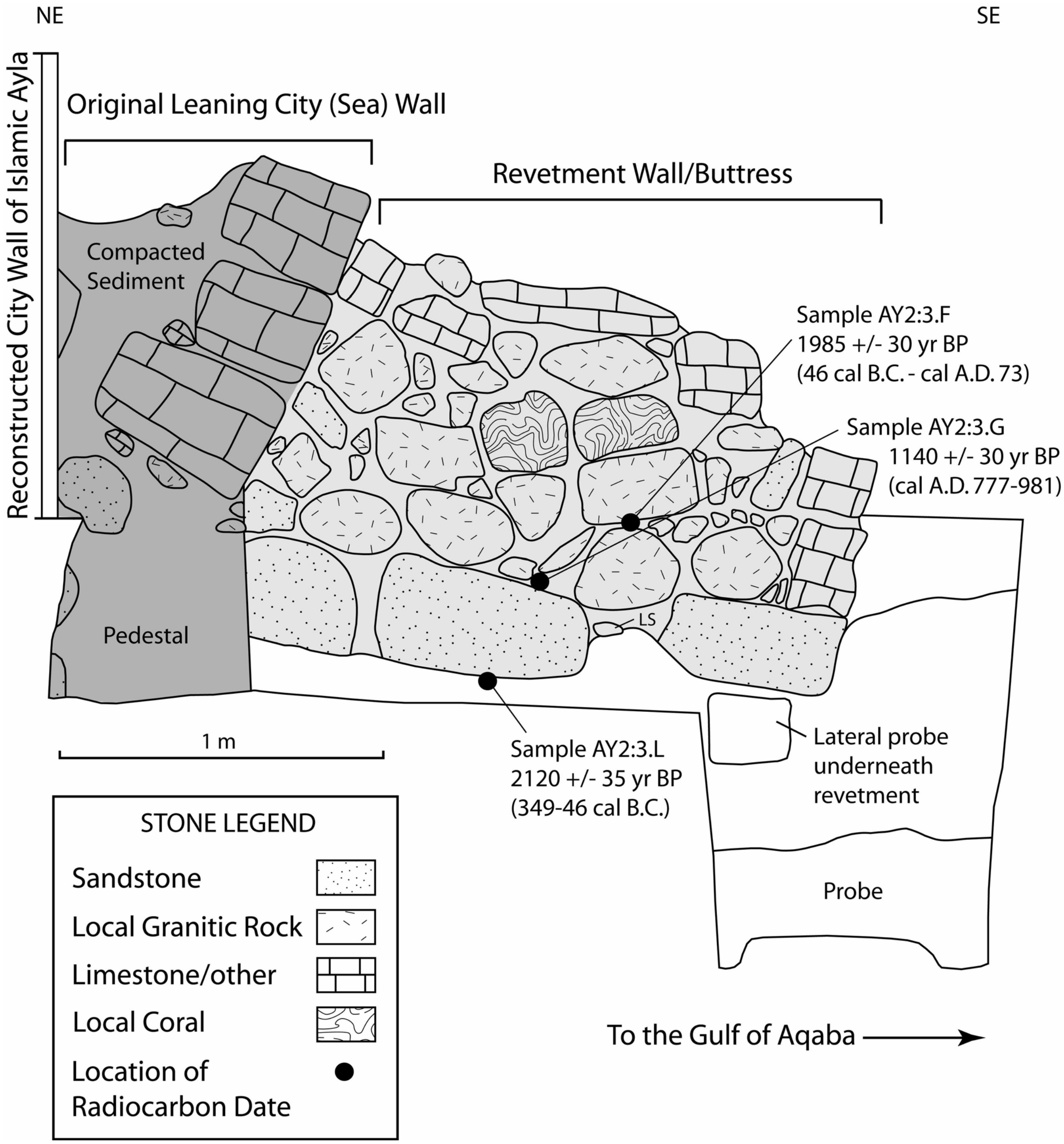

Figure 3.10 Cross-section of the visible northwestern edge of the leaning city wall and revetment wall as exposed in the southeastern balk of trench AY1 at Early Islamic Ayla. Radiocarbon dates from charcoal samples collected from trench AY2 are projected here into cross-section.

edge of the buttress also revealed that this wall, like the damaged portion of the city wall it was built to support, is also now leaning out toward the Gulf of Aqaba.

Finally, a small probe was extended laterally into the southeastern balk of trench AY1 underneath the revetment wall in order to obtain datable material from beneath the construction. A small amount of pottery was collected from within this probe which included one indicator sherd and ten body sherds. In all, 490 sherds were collected from the AY1 trench during the course of excavation.

Trench AY2

Trench AY2 was initially laid out as a 2 m by 3 m trench and was aligned with the extant architecture at N37˚E as previously described. The removal of the first locus in this trench, locus AY2:1, a loosely compacted, light-brown, silty sand with a few cobbles, approximately 20 cm thick, helped to define more clearly the extent of the underlying architecture. Trench AY2 was quickly extended 2 m to the northwest in order to more thoroughly include the revetment wall and leaning city wall within the trench parameters, and locus AY2:1 was removed from the remainder of the now 4 m by 3 m trench. Locus AY2:2, a loosely consolidated, pebbly gravel with an approximate thickness of 20 cm was the next unit excavated. This locus was interpreted to be a fill layer of some sort rather than an archaeological soil layer based on its homogeneity, particle size, loose compaction, and complete lack of artifacts. This fill layer was most likely deposited as a result of the Department of Antiquities reconstruction project of the southern Ayla city wall in 2001.

Excavation through most of this trench was limited to exposing and articulating the top and outer face of the revetment wall. After the removal of the overlying soil layers, both the revetment and leaning city wall, loci AY2:3 and AY2:5 respectively, were clearly exposed within the trench (Figure 3.11). Along the northwestern balk of the trench, a 1 m wide section was laid out trending NE-SW across the revetment wall, locus AY2:3, with the goal of sectioning down through the revetment in an effort to collect organic material for radiocarbon dating from sealed loci from within and beneath the revetment (Figure 3.12).

Upon excavation of the 1 m-wide revetment wall section, the portion of the revetment situated within this trench was revealed to be even shallower than the portion of the revetment exposed in trench AY1, and perhaps more loosely constructed as well. This section of the revetment wall was found to be a total of four courses high in its present state, and 1.5 m wide and 0.75 m tall. The outer course of the revetment wall is composed of large, limestone ashlars. The center of the buttress is filled with an interlocking rubble core of cobbles and pebbles with incidental discarded pottery sherds (Figure 3.13). Thin, uneven layers of light brown, sandy silt, approximately 1-4 cm thick, separate the individual stones that comprise the revetment wall. This sediment may have originally been a thick mud-slurry of sorts that was used to help set the building stones in place. The outer course of revetment wall stones was not removed in order to maintain the general configuration of the wall during excavation. As each stone was removed from within the center of the sectioned portion of the revetment, both pottery sherds and charcoal fragments were collected from beneath the various courses and labeled accordingly to maintain stratigraphic control of recovery location within the buttress.

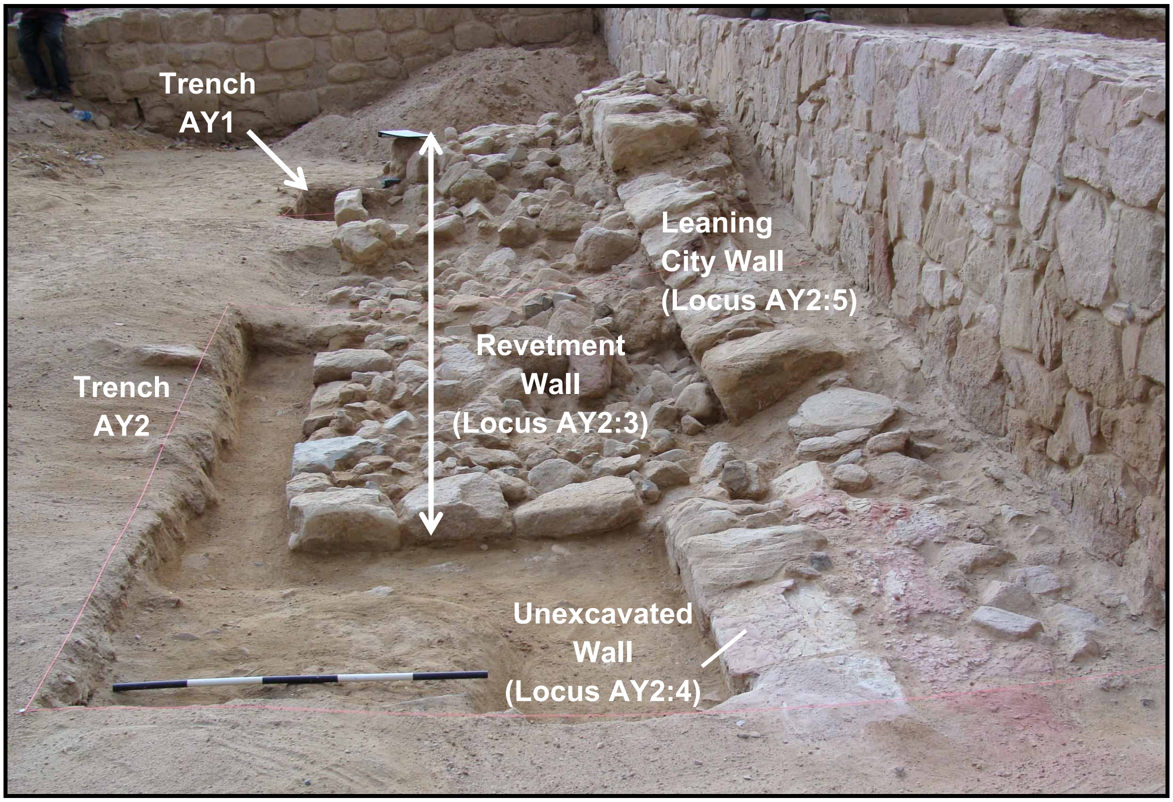

Figure 3.11 Photograph of trench AY2 (foreground) looking northwest prior to the sectioning of the revetment wall. Trench AY1 is visible at the top of the photo. Meter stick for scale.

Figure 3.12 Top plan of trench AY2 showing the relationship between architecture in the trench, including the leaning city wall of Ayla and the revetment wall. The sectioned portion of the revetment is shown in gray.

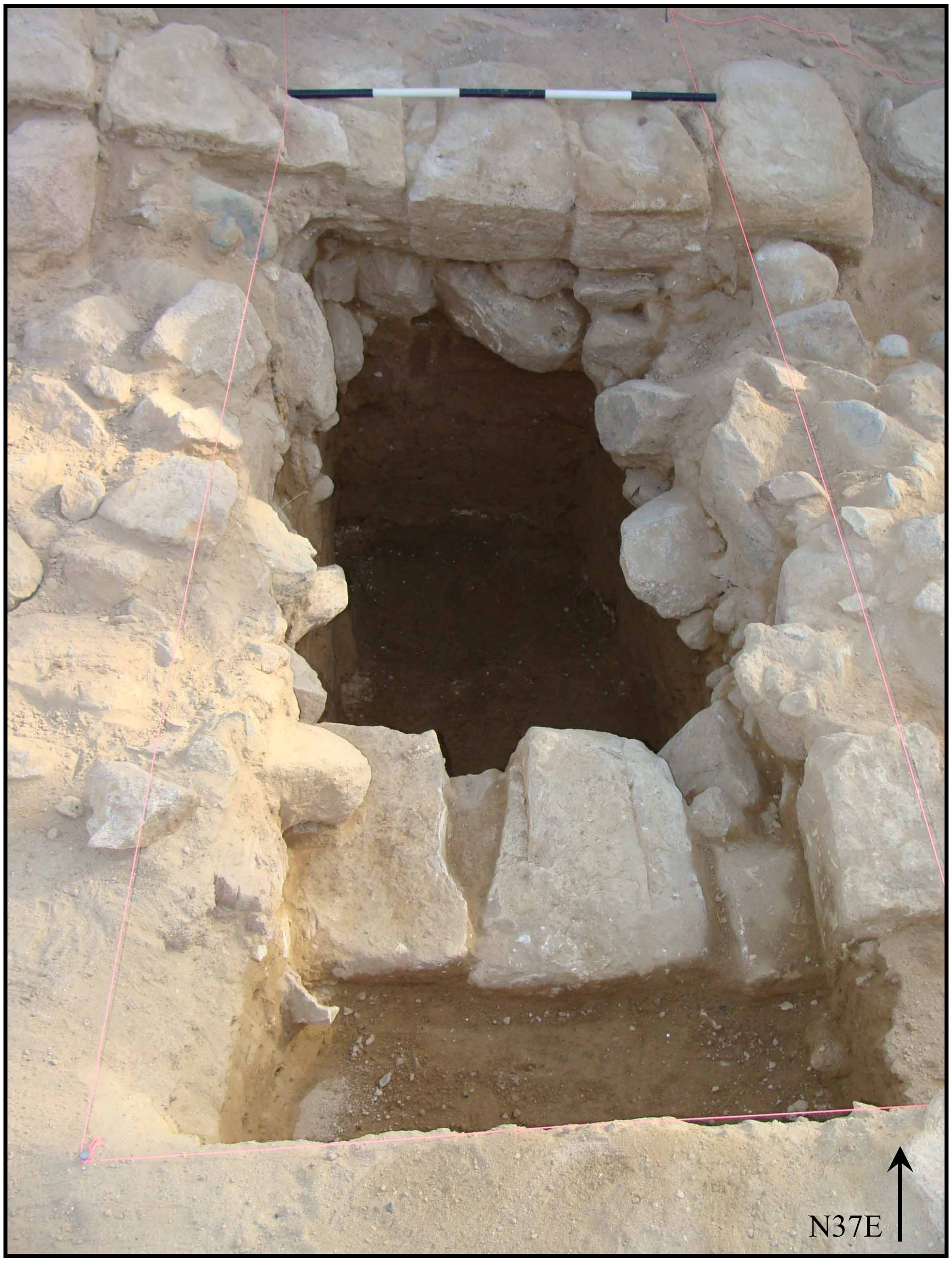

Figure 3.13 Photograph of sectioned portion of the revetment wall as exposed in trench AY2. This photograph correlates to the gray outlined portion of the revetment wall shown in Figure 3.12. Meter stick for scale.

After the fourth course of stones was removed, the excavation continued deeper to determine the composition of the sediment upon which the revetment was originally built, and to confirm that the bottom of the revetment wall was reached. The first locus below the fourth course of revetment stones was locus AY2:7, a light brown, medium-grained, silty sand layer, 37-40 cm thick. At a depth of approximately 40 cm below the bottom of the stone revetment wall, a lightly compacted, 2-3 cm-thick layer of off-white plaster and plaster debris was identified and designated as locus AY2:8. Locus AY2:8 was excavated completely, and beneath it lay locus AY2:9, a medium-grained, light brown, silty sand with medium compaction. The depth of this locus is unknown since it was not fully excavated.

Designated as locus AY2:5 in this trench, and previously only visible in cross-section along the eastern balk of trench AY1, the outer course of the leaning city wall is constructed of large, limestone ashlars. The city wall also contains a rubble fill that is visible because of the damage incurred as it leaned and separated from the rest of the city wall, likely as a result of liquefaction of the site due to seismic ground shaking. Other architecture present in trench AY2 included locus AY2:4, which is a small stone wall located to the southeast of the leaning city wall and revetment at this site. Other than cleaning and articulating the uppermost course of the limestone ashlars that comprise this wall, this locus was not excavated any further. Based on its configuration, however, this wall may represent an earlier revetment or even a portion of the original city sea wall (see figure 3.11 and 3.12).

Locus AY2:6, a lightly compacted, medium-grained, silty sand unit, approximately 35 cm wide as exposed in the top plan view, was located between the revetment wall and the southwestern balk of trench AY2. One copper alloy coin was excavated from just beneath the surface of locus AY2:6. In the same locus and at the same depth as this coin, modern Styrofoam was also present, so the coin is interpreted as having been found in a secondary context rather than primary. Locus AY2:6 was not fully excavated since it was not related to the excavation of the buttress, and thus the thickness of this unit is unknown.

The last locus recorded in trench AY2 was the reconstructed city wall of Ayla, locus AY2:10, which was located just inside the parameters of this trench along the northeastern balk. While not excavated in any way, the reconstructed wall was included in this trench in order to show the relationship between it and the leaning city wall. In all, trench AY2 produced a total of 111 pottery sherds, which is significantly fewer than were recovered from trench AY1, due in part to the fact that the majority of loci in trench AY2 were stone walls rather than soil loci where artifacts are most readily buried.

Ceramic Analyses

The majority of the 602 sherds recovered from this excavation at Early Islamic Ayla were so-called surface finds, and thus were not considered to have been unearthed in their primary context because modern materials were commonly found within the same locus. Surface traffic at the site and previous excavations carried out near this current excavation location have also helped to increase the mixing and contamination of these uppermost units. Overall, of the 602 sherds collected from this excavation, 153 of those are classified as indicators, just over 25% of all the ceramics recovered. However, only 13 of these indicator sherds were unearthed in their primary context, and the remaining indicators were either part of the surface finds mentioned or were located in loci designated as modern.

The majority of the pottery recovered from trench AY1 was composed of scattered surface finds collected from either locus AY1:1 or AY1:2, which were determined to be consistently Abbasid (A.D. 750-969) in age, according to Dr. Donald Whitcomb (pers. comm., 2011). Within this same trench, trench AY1, the small lateral probe excavated into the southeastern balk and underneath the revetment wall produced a total of eleven sherds, one of which was an indicator. This indicator sherd, sherd # 477, appears to be the handle of a whole-mouth jar and possibly dates to the early Umayyad period (Whitcomb, pers. comm., 2011). The Umayyad period in Jordan spans the years A.D. 661-750, so this rim collected from underneath the revetment wall was likely produced sometime during the mid-7th C. to the mid-8th C.

During the excavation of loci AY1:2 and AY1:6 within trench AY1, several pottery sherds were found oriented vertically and positioned up against the buried original city wall of Ayla along the northeastern balk of the trench. The sherds were tightly pressed into position against the buried city wall, but it is unclear whether they were intentionally placed there or whether natural processes may have moved them into this unusual arrangement. During the pottery analysis for this locus, Whitcomb (pers. comm., 2011) made special mention that over the course of nearly a decade of excavation he never found vertically oriented pottery sherds at Islamic Ayla. Two indicator sherds from this vertical assemblage, one decorated with red paint (sherd #437) and one Mahesh ware base (sherd #429), date to the Umayyad (A.D. 661-750) and the Abbasid (A.D. 750-969) periods, respectively (Whitcomb, pers. comm., 2011). Mahesh ware is a cream ware or cream-colored pottery that typically contains an incised wavy combed pattern around either the center of the vessel and/or near the rim, and is characteristic of the Abbasid period in Jordan, the mid-8th to the mid-10th C. (Whitcomb, 1989b). Despite the fact that both indicators were excavated from loci containing modern material, their unusual vertical arrangement up against the buried city wall makes these sherds noteworthy.

In trench AY2, ceramics were recovered during excavation from outside and adjacent to the revetment wall as well as from within and underneath the revetment. From locus AY2:6 located outside of the revetment wall along the southwestern balk of trench AY2, three body sherds were collected (#493, #502, and #523) which all date to the early Abbasid period (A.D. 750-969) (Whitcomb, pers. comm., 2011). These were the only datable sherds in trench AY2 that were excavated from outside and adjacent to the revetment wall construction, and thus they provide some context for loci adjacent to the buttress at Ayla.

In trench AY2, several indicator sherds were collected from within the revetment wall, locus AY2:3, during the excavation (sectioning) of this structure. In general, most of the pottery collected from within the buttress consisted of red ware and cream ware body sherds. From underneath the first course of revetment wall stones, Whitcomb (pers. comm., 2011) identified one of the indicators, sherd #511, as a glazed bowl rim of an Iraqi import that dates to the early Abbasid period (A.D. 750-969). Also from beneath the first course of revetment wall stones, a very small fragment of a cream ware vessel with green glaze was recovered during excavation. This glazed sherd also dates to the Abbasid period (Whitcomb, pers. comm., 2011). From beneath the fourth course of revetment wall stones, the rim of an Abbasid jar with a black-brown ware was also identified (Whitcomb, pers. comm., 2011). In terms of typology, this pottery sherd is most similar in form to the 1986 Ayla type 86-48 (Whitcomb, 1987) and to the 2009 Aylah type 201d (Damgaard, 2011). The remaining body sherds collected from locus AY2:3 at the bottom of the wall were given a general date of late Umayyad to early Abbasid, 8th - 10th C. (Whitcomb, pers. comm., 2011).

The largest assemblage of pottery in trench AY2, composed of 55 sherds in all, was collected from beneath the revetment wall within locus AY2:7, although the majority of these ceramics were body sherds rather than indicators. This locus contained an overall predominance of Umayyad (A.D. 661-750) ribbed wares, relatively thick body sherds (1.5 - 2 cm wide) with heavy, lateral ribbing around the circumference of the vessel (Whitcomb, 1987; Whitcomb, pers. comm., 2011). Locus AY2:7 also contained 10 indicator sherds which are shown in Figures 3.14 and 3.15. Each indicator sherd from this locus, with the exception of glazed sherds, was also drawn in cross-section (Figure 3.16).

Several 10th century sherds, the latest sherds recovered from this excavation, were collected from beneath the revetment wall. Sherd #549, the base of a late Abbasid (early- to mid-10th C.) jar hypothesized by Whitcomb (pers. comm., 2011) to have been used to carry milk products, most closely matches the 1986 Ayla typology form 86-235 (Whitcomb, 1987). Sherd #549 also appears most similar to type 202d from the 2009 Aylah typology (Damgaard, 2011). This 10th C. jar base is a red-orange ware and contains a small inclusion of granite (5 mm wide) within the overall fine-grained fabric of the vessel. This granite inclusion suggests that the materials used to create this vessel were of local origin, likely sourced from the nearby granitic mountains located to the east and north of Islamic Ayla.

Figure 3.14 Indicator pottery sherds (showing outside of vessel) collected from beneath the revetment wall in trench AY2, locus AY2:7.

Figure 3.15 Indicator pottery sherds (showing inside of vessel) collected from beneath the revetment wall in trench AY2, locus AY2:7.

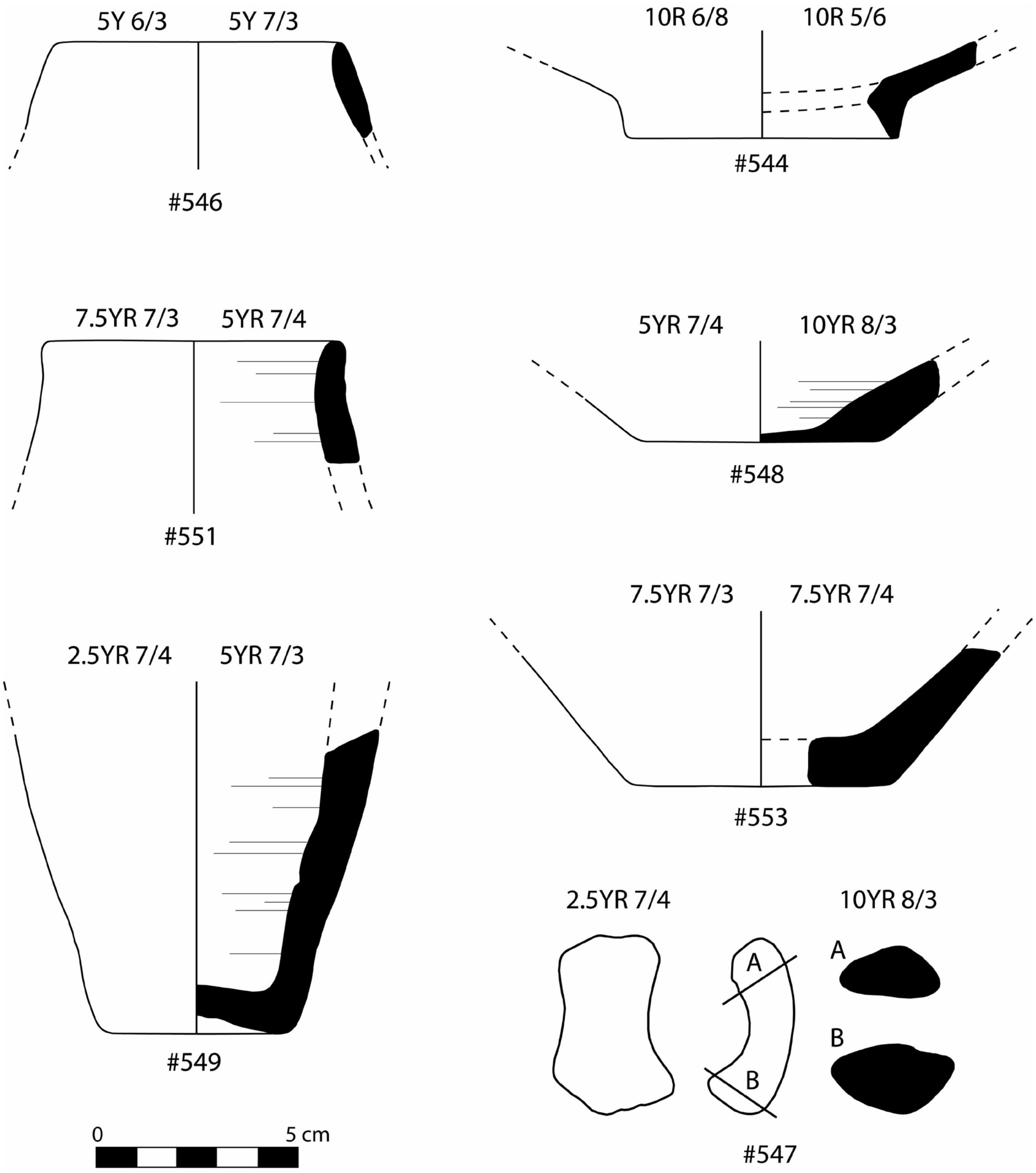

Figure 3.16 Cross-section illustrations of indicator sherds collected from beneath the revetment wall in trench AY2, locus AY2:7. Munsell color values are listed above each sherd indicating the color of both the exterior (left side of illustration) and interior (right side of illustration) of each vessel.

Three glazed sherds, #545, 550, and 555, recovered from beneath the revetment wall within locus AY2:7 also date to the 10th C. in the late Abbasid period (Whitcomb, pers. comm., 2011). Sherd #545 is part of a lightly ribbed, cream ware vessel coated in a yellow-green monochromatic glaze containing very fine-grained sand. This glaze is most similar to the glaze on pottery type 115b from the 2009 Aylah typology (Damgaard, 2011). The two other glazed sherds in this locus which date to the 10th C., #550 and 555, are both from the same partially ribbed, red ware vessel. They are covered with a cream-colored glaze that appears iridescent when viewed through a hand-lens, and patterned bands of black and olive-colored glaze appear to encircle the vessel.

Two other indicator sherds also located within locus AY2:7 (sherds # 544 and 546) range in age from the late Byzantine (A.D. 324-636) or early Umayyad (A.D. 661-750) periods to the early Abbasid period (A.D. 750-969). Sherd #544 is the base of an African Red Slip (ARS) plate or large, shallow bowl that dates to either the late Byzantine or early Umayyad periods, likely sometime between the 6th - 7th C. (Whitcomb, pers. comm., 2011). This base is most similar in form to the 1986 Ayla type 86-134 (Whitcomb, 1987) and to the 2009 Aylah type 203a (Damgaard, 2011). The 2009 Aylah typology dates form 203a to the Abbasid period, while sherd #544 is several centuries older according to Whitcomb (pers. comm., 2011), however the vessel forms themselves are similar and thus the 203a type is provided for the sake of comparison. Likewise, the 1986 form 86-134 is considered a Nabataean (312 B.C. - A.D. 106) fine-ware (Whitcomb, 1987), which is centuries older than sherd #544, but this is the ceramic form most similar to sherd #544 within the 1986 Ayla typology.

Sherd #546 is a rim from a green-gray ware jar or juglet with medium- to coarse-grained sand inclusions that dates to the early Abbasid period (Whitcomb, pers. comm., 2011). This sherd was likely over-fired since ceramics that are exposed to intense and prolonged heat typically end up having a strong greenish sheen and a uniform green-gray colored fabric. The sheen is a result of the vitrification of the sand temper in the clay which can sometimes appear as a light glaze (Damgaard, 2011). Considering the simple in-turned rim shape and the relatively narrow opening of this vessel (~7-8 cm wide), this sherd is most similar in form to the 1986 Ayla type 86-54 (Whitcomb, 1987) and also has attributes similar to the 2009 Aylah type 111c (Damgaard, 2011).

Other locus AY2:7 indicators recovered from the site, sherds #547, 548, 551, and 553, were less diagnostic and thus were not dated by Whitcomb during the ceramic analysis of this trench. Based on the 1986 and 2009 typologies from Ayla, however, similarities to form and ware can be drawn for each sherd. Sherd #547, for instance, is a portion of a handle likely from a large jar, jug, or bowl, and is a medium- to coarse-grained, cream surface ware with red-orange fabric. This sherd is most similar in form to the 1986 Ayla type 86-127 (Whitcomb, 1987) and to the 2009 Aylah type 202h (Damgaard, 2011). Sherd #548 is a vessel base with cream surface ware and red fabric. This sherd is most similar in form to the 1986 Ayla type 86-132 (Whitcomb, 1987) and to the 2009 Aylah type 202b (Damgaard, 2011). Sherd #551 is a red ware rim which is most similar in form to the 1986 Ayla type 86-264 (Whitcomb, 1987) and to the 2009 Aylah type 112h (Damgaard, 2011). Finally, sherd #553 is a vessel base with cream surface ware and red fabric. This sherd is most similar in form to the 1986 Ayla type 86-254 (Whitcomb, 1987) and to the 2009 Aylah type 114v (Damgaard, 2011).

To summarize these ceramic finds, the majority of pottery collected from outside of and adjacent to the revetment wall in both trenches at this site, AY1 and AY2, dates predominately to the Abbasid period, with the greater part of these ceramics being surface sherds. The pottery recovered from within and underneath the revetment wall dates to the late Byzantine or early Umayyad periods (the 6th - 7th C.) through the late Abbasid period (mid-10th C.). The latest pottery collected from within a sealed locus in either trench, which in this case was locus AY2:7 situated underneath of the revetment wall in trench AY2, dates to the mid-10th C. Therefore, based on the pottery collected from this excavation and considering the principle of superposition, the revetment wall at Islamic Ayla must be of late Abbasid age or later since this structure was built on top of locus AY2:7 in the historic past.

Radiocarbon Dating

In order to support the ceramic dating analysis of the pottery collected during excavation, radiocarbon dating analysis was also conducted at this site. Several charcoal fragments were collected from both trenches AY1 and AY2 during the course of this archaeoseismic excavation. With the specific research goal of determining the date of the revetment wall construction in order to constrain the date of seismic damage sustained by the leaning city wall, the revetment was sectioned in order to collect datable material from within this structure. Three charcoal fragments collected from inside of the revetment wall, locus AY2:3, were selected for radiocarbon dating. These dates are reported in Table 3.3.

TABLE 3.3

RADIOCARBON DATING RESULTS:
EARLY ISLAMIC AYLA,
AQABA, JORDAN

Field Sample No.	Collection Location in Trench AY2	Lab Sample No.	Measured Radiocarbon Age	δ13C	Conventional Radiocarbon Age	Tree-ring Calibrated Age
AY2:3.F	Beneath 2nd course of stones in revetment	CAMS 158892	1985 ± 30 yr BP	-24.4	1985 ± 30 yr BP	46 Cal B.C.- Cal A.D. 73
AY2:3.G	Beneath 3rd course of stones in revetment	CAMS 158952	1140 ± 30 yr BP	-26.7	1140 ± 30 yr BP	Cal A.D. 777-981
AY2:3.L	Beneath 4th course of stones in revetment	CAMS 158891	2120 ± 35 yr BP	-25	2120 ± 35 yr BP	349-46 Cal B.C.

Radiocarbon ages have been calibrated to calendar years with the CALIB 7.0 online calibration program using a 2 sigma range probability and IntCal13 curve selection (Reimer et al., 2013).

Charcoal sample AY2:3.F was collected from beneath the 2nd course of stones that comprise the internal portion of the revetment wall construction in trench AY2. Sample AY2:3.F returned a conventional radiocarbon date of 1985 ± 30 yr BP and a tree-ring calibrated date of 46 Cal B.C. - Cal A.D. 73. The second sample of charcoal radiocarbon dated from this excavation, Sample AY2:3.G, was collected from beneath the 3rd course of stones in the revetment wall in trench AY2. Sample AY2:3.G produced a conventional radiocarbon date of 1140 ± 30 yr BP and a tree-ring calibrated date of Cal A.D. 777-981. Finally, from beneath the 4th and most deeply buried course of stones inside of the revetment wall, sample AY2:3.L yielded a conventional radiocarbon date of 2120 ± 35 yr BP and a tree-ring calibrated date of 349-46 Cal B.C.

All three of the charcoal samples collected from inside the revetment wall are interpreted as being remobilized and deposited inside the wall sometime after they were created elsewhere. Each sample chosen for dating was collected from directly underneath a revetment wall building stone and not from between stones where the charcoal could have possibly filtered in from above over time. The dates of each charcoal sample, therefore, represent inherited ages and help to provide a maximum age for the revetment wall construction. Based on the law of inclusions, the wall can be no older than the youngest sample of charcoal collected from within its construction.

Discussion

In order to determine the age of the earthquake that damaged Ayla, thereby expanding our knowledge of the paleoseismicity of the region, we can work to determine the age of the buttress built to support the seismically damaged city wall, the repair of which most likely occurred relatively soon after the structure was damaged. Radiocarbon dates from charcoal samples collected from within and below the revetment wall suggest that this secondary support wall must have been built sometime after a charcoal fragment dated to A.D. 777-981 was deposited or placed inside the wall under the third course of revetment stones. Since the buttress appears to have been built fairly quickly, using primarily unworked stones mixed with a rubble core of cobbles, pebbles, and discarded pottery sherds, the charcoal fragments were probably mixed in with the rubble and sediment that was added to fill the revetment wall during construction. The radiocarbon data, however, ultimately suggests that the revetment wall was likely constructed any time during or after a date of A.D. 777-981, but not before.

Analysis of the ceramics recovered from this excavation at Islamic Ayla helped to further refine the date of revetment construction. Based on the age of the most recent pottery collected from inside the revetment wall, locus AY2:3, and from within sealed locus AY2:7, which was located beneath the revetment wall, the revetment must have been constructed in the mid-10th C. or later. The analysis of the ceramics recovered from these two loci, therefore, supports the radiocarbon date of A.D. 777-981 from the charcoal fragment found inside the revetment construction.

With these pieces of dating evidence acting to constrain the revetment construction, we must consider historic earthquakes that are known to have affected the region at this time that could have caused the Ayla city sea wall to partially fail and lean as a result of liquefaction from ground shaking. As was reviewed in an earlier chapter, the only earthquakes known to have affected the southern Wadi ‘Arabah region since the foundation of Islamic Ayla in approximately A.D. 650 are the seismic events of A.D. 659, 746/749, 757, 1033, 1068, 1212, 1293, 1458, 1546, and 1588. Based on the late Abbasid period pottery found underneath the revetment wall, however, none of the earthquakes that struck the region prior to the late 10th century are possible seismic candidates for this earthquake damage and repair. Furthermore, historical sources report that Ayla was catastrophically destroyed by the March 18, 1068 event with an epicenter in the Gulf of Aqaba and was likely further damaged by the May 29, 1068 event in Ramla (Guidoboni and Comastri, 2005; Ambraseys, 2009). Destroyed by these earthquakes, the city was largely abandoned sometime shortly after this date because by the time Baldwin I decided to take Ayla in A.D. 1116 he was met with little to no resistance (Khouri and Whitcomb, 1988; Whitcomb, 1994a). It is highly unlikely, even if the damage to this 3.5 m-long section of wall was caused by a post-1068 earthquake, say the 1212 or 1258 events, that anyone would have made the effort to make such a repair since the city was considered unoccupied.

Based on correlation with the major earthquake catalogs of Ambraseys (2009) and Guidoboni and Comastri (2005), the only two historic earthquakes that could have damaged the wall of Ayla in the Fatimid period or later while the city was still inhabited were the earthquakes of A.D. 1033 and A.D. 1068. As discussed, the earthquakes that occurred in March and May of 1068 were so devastating to the city, however, that it is also very unlikely that this city wall repair would have been a priority, and perhaps not even possible considering the level of death and destruction the region experienced. Taking into account the date of the latest pottery recovered from underneath the sectioned revetment wall (mid-

10th C.), and the date of the latest charcoal sample collected from within the revetment (A.D. 777-981), the most likely date of revetment construction is sometime in the Fatimid period prior to the catastrophic A.D. 1068 earthquake that destroyed Islamic Ayla. It seems most probable, therefore, that the southern city wall of Ayla was damaged due to seismic ground shaking from the December 1033 earthquake which had an epicenter in the Jordan Valley.

The A.D. 1033 event affected the cities of Ramla, Nablus, Jericho, Baniyas, and Acre the most significantly, as discussed in an earlier chapter (Guidoboni and Comastri, 2005; Ambraseys, 2009). As a result of this early 11th century earthquake, one-third to one-half of the houses in Ramla fell down, half the buildings in Nablus collapsed killing at least 300 people with the surrounding country destroyed, and structures fully collapsed in Jerusalem where damage was also widespread (Guidoboni and Comastri, 2005; Ambraseys, 2009). This damage included portions of the Aksa Mosque, the Dome of the Rock, and a part of the Mihrab of Dawud which were all badly damaged or ruined. A tsunami was reported to have caused people in the city of Acre to drown as a result of inland flooding, ground motions in the low-lying plains around Lake Tiberias (Sea of Galilee) were reported to cause trees to sway and water cisterns to slosh, and the aftershocks went on for many days (Guidoboni and Comastri, 2005; Ambraseys, 2009). A landslide is also reported to have buried the village of al-Badan along with all of the people who lived there and their livestock, and other near-by villages suffered the same fate (Ambraseys, 2009). In all, the A.D. 1033 earthquake was felt from Egypt to the Negev desert, and from the mountains of Galilee to Syria in the north. While not specifically described in the aforementioned earthquake catalogs as having been felt at Islamic Ayla, seismic ground shaking from the

A.D. 1033 event that was felt in Egypt would have also most likely been felt in southern Jordan, especially within a coastal city situated along the Dead Sea transform.

Guidoboni and Comastri (2005) estimate the maximum Modified Mercalli Intensity (MMI) of this earthquake was IX – X. Despite the approximately 250 km distance from the epicenter of the A.D. 1033 earthquake to the city of Ayla, it is likely that seismic ground-shaking along the beach at the head of the Gulf of Aqaba would have been significant enough to have resulted in liquefaction of the unconsolidated beach sands and alluvial sediments upon which the city of Ayla is constructed. This hypothesis is based on both the estimated MMI values and the extent of the reported seismic damage throughout the southern Wadi ʻArabah region for the A.D. 1033 event.

One other possible explanation for the seismic damage incurred by the leaning city wall at Ayla is that it was damaged by an earthquake that was not recorded in the historical record, but that still occurred sometime between the late-10th C. and the large A.D. 1068 Gulf of Aqaba earthquake. While this is a possibility that should be considered, it is not the most likely scenario since the A.D. 1033 and 1068 earthquakes were both well recorded events with numerous reports from in and around the region.

An early 11th century date for both the earthquake and the revetment construction is also supported by fact that out of more than 600 sherds, none of the so-called Tupperware or handmade “abandonment pottery” was recovered from this excavation. As discussed previously, this type of handmade pottery is dated to the 11th century and is believed to act as a gauge of cultural stresses indicative of industrial, economic, and political change (Whitcomb, pers. comm., 2011). Whitcomb (1988a, 1994a) reports that Tupperware was most predominantly recovered from the archaeological layers associated with occupational Phase E leading up to the A.D. 1068 earthquake. The Tupperware sherds recovered by Whitcomb (1994a) at Ayla indicate that even before the city was destroyed by the A.D. 1068 earthquake, times were difficult and making pottery at home was a necessity because the commerce-based production of ceramics at Ayla had been interrupted or failed. The lack of Tupperware in the ceramics recovered as a part of this archaeoseismic excavation, therefore, supports the hypothesis that the leaning city wall was damaged and then buttressed prior to the mid-11th C. when this type of handmade pottery is much more common in the archaeological record.

As mentioned previously, the revetment wall itself is now also leaning toward the Gulf of Aqaba. This could have happened as a result of any of the subsequent earthquakes that affected the area, although the March 1068 and the May 1212 events are the most likely historical candidates to create any additional liquefaction of the site since their epicenters are thought to have been centered in or very near the Gulf and in close proximity to the site of Islamic Ayla. The fact that the walls of Ayla were affected by the 1995 Nuweiba earthquake (Al-Tarazi, 2000) supports the hypothesis presented here that a distant source earthquake like the A.D. 1033 event could have caused liquefaction damage at the site of Ayla.

Further, in order to create ground shaking substantial enough to cause sediment to become liquefied, a MMI value of at least VII is generally the lowest value required to produce liquefaction-induced features in locations where highly susceptible deposits are present (e.g. National Research Council, 1985; Obermeier, 2009), as is the case along the beach at Ayla. However, liquefaction effects have also occurred at MMI values as low as V and VI, according to Keefer (1984). An earthquake capable of producing MMI values of XI-X like the A.D. 1033 event (Guidoboni and Comastri, 2005), makes the possibility of liquefaction at the site of Early Islamic Ayla quite feasible. In addition, any earthquake intense enough to cause liquefaction and/or subsidence damage at Ayla would also most likely be an event that would have been significant enough for someone to record, so again this evidence suggests that the damage to the leaning city wall was caused by a known historic earthquake.

Lastly, the wall partially exposed as a result of this excavation that has yet to be thoroughly investigated is the stone wall designated as locus AY2:4 located at the southeast end of trench AY2. One possible interpretation for the configuration of this stone wall (see Figures 3.11 and 3.12) is that it could be a part of an earlier revetment that pre-dates the A.D. 1033 damage and repair highlighted in this study. If this is the case, then there are at least two phases of earthquake repair present in trench AY2 along the Ayla sea wall, with the excavated revetment (locus AY2:3) likely being the most recent repair.

Another possible interpretation for this structure is that the unexcavated stone wall (locus AY2:4) may be a portion of the original city wall that was damaged in an earthquake that occurred sometime after the A.D. 1033 damage and repair. Visible in Figures 3.11 and 3.12 is an apparent misalignment of the buttressed leaning city wall (AY2:5) and the unexcavated stone wall (AY2:4). If locus AY2:4 is indeed part of the original city wall, this section of wall may have leaned out toward the Gulf of Aqaba sometime after the A.D. 1033 damage and repair to locus AY2:5, which could explain this misalignment. Since only a portion of the top course of stones comprising locus AY2:4 was exposed during this excavation, however, it is very difficult to determine whether this buried wall is damaged in any way, or how this wall may relate to the adjacent leaning city wall and buttress. The excavation of this stone wall, and especially the intersection where locus AY2:4 comes into contact with the revetment and leaning city wall, loci AY2:3 and AY2:5, is necessary to determine whether this wall is an earlier revetment built at the site, part of the original city wall, or whether it perhaps served some other function at Islamic Ayla.

Conclusions and Future Excavation at Islamic Ayla

Radiocarbon dating evidence, ceramic analysis, and relative dating data collected from the excavation of Ayla, as well as an evaluation of the regional historic earthquakes and earthquake catalogs, suggests that it was likely the A.D. 1033 earthquake that caused the failure of the city wall at Ayla, causing it to lean seaward as a result of liquefaction and possible differential subsidence of the site. This archaeoseismic excavation was very successful in that it provided new information about the earthquake history of the region that would have affected the people living in and around the city of Ayla during the early 11th C.

Prior to this study, there was no correlation of the A.D. 1033 event to the city of Early Islamic Ayla, and while the damage to the Ayla city wall highlighted by this study was neither catastrophic nor severe, there were likely other repercussions from the earthquake in the city of which we are currently still unaware. Referring to Whitcomb's occupational phases of Ayla, it is known that even prior to the large A.D. 1068 earthquake that the city was starting to decline, and disruptions in the economic flow of the city are seen in the handmade pottery in these later periods, for example (Whitcomb, 1994a). It is likely that damage from the A.D. 1033 earthquake at Ayla, and any economic losses that occurred as a result, only added to the stresses already being exerted upon the city, which would soon experience devastation only thirty-five years later before ultimately collapsing.

The site of Early Islamic Ayla is fertile ground for further archaeological investigation, and such work can only act to increase the value and interest of the site as a tourist attraction as a part of the long history of Aqaba. Many areas in Ayla are of interest for future excavation, including the more deeply buried structures associated with the Umayyad period (A.D. 661-750), since they represent the foundation of the city, and because we know the least about this transitional time period in Aqaba.

CHAPTER 4

TABA SABKHA

Introduction

The goal of this study is to more thoroughly characterize the behavior and rupture pattern of the Dead Sea transform (DST) fault through time. Due to the difficulty of exposing the main fault within the city of Aqaba, another strand of the DST, the Wadi ‘Arabah (Evrona) fault, was investigated north of the city in the Taba (Yotvata) Sabkha as a part of this paleoseismic study. The Wadi ‘Arabah fault, exposed through trenching in the Taba Sabkha, was studied in order to find paleoseismic evidence for ground rupture of major earthquakes along the southern portion of the Dead Sea transform over the last two millennia.

The trench location in the Taba Sabkha provides a unique opportunity to conduct paleoseismic studies along the Wadi ‘Arabah fault segment of the DST fault zone in an area that is both uninhabited and geographically accessible. Proper military permission is required to work in this location, however, because of the sensitive position of the Taba Sabkha which straddles the international Jordanian-Israeli border. This international border, which roughly follows the Wadi ‘Arabah Valley northward, is likely one of the primary reasons this segment of the DST has not been studied in greater detail across the entire width of the valley. The focus of this research, therefore, is to determine the timing of ancient earthquakes occurring along this segment of the Dead Sea transform. To accomplish this goal, detailed mapping and radiocarbon dating of the subsurface stratigraphy as exposed in a trench that bisects the Wadi ‘Arabah fault was used in order to understand more thoroughly the seismic behavior of this transform plate boundary through time.

Description of Taba Sabkha Trench Site

The trench site in this paleoseismic study is located 35 km north of the city of Aqaba, Jordan in the Taba (Yotvata) Sabkha, a 55 km^2 continental sabkha situated in the southern portion of the Wadi ‘Arabah Valley (Figure 4.1). The term ‘sabkha’ is an Arabic word that means ‘salt flat,’ regardless of its geographic position relative to the sea (Abed, 1998). There are two types of sabkhas: 1) coastal or supratidal, and 2) inland or continental sabkhas. Evaporites formed within coastal sabkhas are related to sea water (e.g. Gavish, 1974; Butler et al., 1982; Kendall and Warren, 1988). In a continental sabkha like Taba, evaporites and sediments are related to meteoric waters only, or those waters derived directly from precipitation, and form well away from seas or oceans (e.g. Kinsman, 1969; Amiel and Friedman, 1971; Handford, 1988). More specifically, Kinsman (1969) describes coastal sabkhas as supratidal surfaces developed by depositional offlap of marine sediments in which evaporites precipitate from seawater-derived brines. Continental sabkhas, in contrast, are composed of continental or earlier cycle marine sediments in which the evaporites are precipitated from evaporated meteoric waters. Abed (2002) explains that this area is most properly referred to as a sabkha and not a playa, as may be expected, based on the surrounding geology. This is because the majority of the basin that does periodically flood

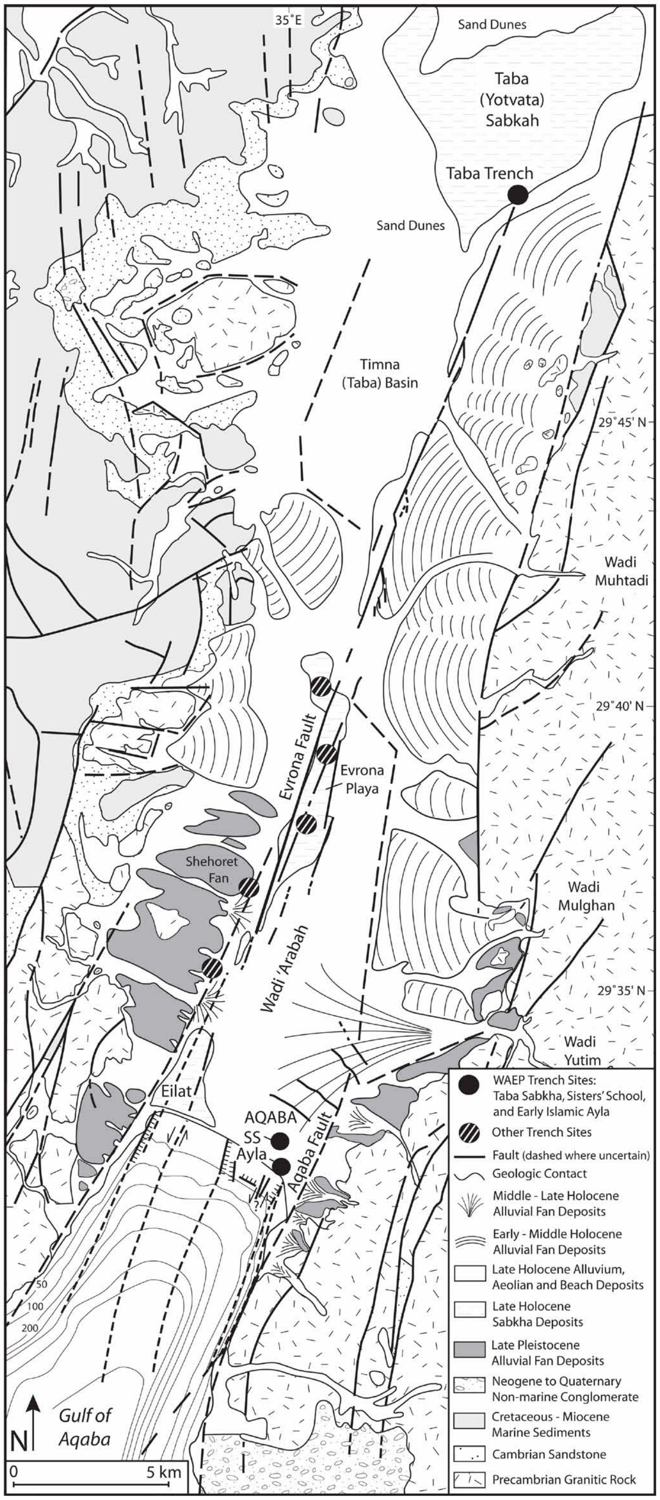

Figure 4.1 Geologic map of the southern Wadi ʻArabah. The Taba Sabkha trench location is shown at the top of the map (modified after Garfunkel, 1970). DST faults in Gulf of Aqaba from Hartman, 2012.

only holds water for a few days unlike playas which tend to hold water for longer periods of time (Abed, 2002).

The Taba Sabkha is a deflation hollow in a sand-dominated landscape (Amiel and Friedman, 1971; Abed, 1998). Kinsman (1969) describes continental sabkhas as equilibrium deflation surfaces through to the local water table, where the capillary fringe above the water table marks the base-level of wind deflation. Sediments located stratigraphically above the capillary fringe, therefore, are subject to wind removal, which results in the formation of a relatively flat land surface that is related to the local groundwater table (Amiel and Friedman, 1971). Precipitation draining down mountains located to both the east and west of the sabkha and the subsequent alluvial fans created from such drainage, as well as flood waters draining down the Wadi ‘Arabah Valley itself, all contribute to the local groundwater table in the Taba Sabkha. In particular, an important amount of groundwater flow is postulated to originate from the large Wadi Darba fan located 3-6 km NNE of Taba (Abed, 1998). Abed (1998) also reports groundwater at a depth of only one meter at the toe of one of the eastern alluvial fans nearest the Taba Sabkha, with the groundwater table deepening westward toward the center of the sabkha. Historically, local Bedouin have used wells dug into this shallow water table on the eastern side of the sabkha to water their camels and goats, and this practice continues to the present-day. In winter months, the groundwater of this fan system actually emerges on the surface some 200 m west of these wells where a palm tree oasis is supported (Abed, 1998). In the concrete-lined well located near the trench site, the water table was approximately 3-3.5 m beneath the ground surface at the time of this study in February 2009, and was not encountered during trenching.

Abed (1998) excavated seventeen shallow pits up to 1.5 m deep and drilled 8 boreholes up to 17 m deep at various locations in the Taba Sabkha in order to study the sedimentology and mineralogy. The eastern side of the sabkha laterally interfingers with several alluvial fans where wadis have cut across the Precambrian basement rocks. Sand dominates the eastern, northern, and northeastern fringes of the Taba Sabkha, while massive clays that form the vast center of the sabkha are found at the distal part of the alluvial fans (e.g. Inci, 1991; Yagmurlu and Helvaci, 1994; Abed, 1998, 2002). The clay minerals present in the Taba sediments include kaolinite, smectite, illite, chlorite, and sepiolite; these minerals form up to 60% of the sediments in the center of the sabkha (Abed, 1998, 2002). Detrital minerals such as quartz, feldspars, and micas all decrease westward with distance away from the granitic source mountains located to the east. North of the sabkha, however, sand dunes are present for a distance of approximately 35 km, and as a result sand is often blown south into the sabkha by prevailing northerly winds (Abed, 1998, 2002).

Surface water that is periodically present in the sabkha precipitates halite, giving the ground a whitish appearance in places where a thin (about 1 cm thick) mineral crust has formed. These areas are often covered by desiccation cracks of various sizes, but the cracks involve only the upper 3 mm of the surface and do not penetrate deeper (Abed, 1998). Brownish areas within the Taba Sabkha are of a slightly higher (1-3 cm) elevation, and represent older desiccation cracks where holes several centimeters deep and 2-7 cm in diameter have formed in the halite-rich crust as a result of dissolution. Salt-rich “cakes” are found underlying these dissolution holes (Abed, 1998, 2002). Gypsum (and sometimes anhydrite), also an evaporitic mineral, dominates in the eastern portion of the sabkha and also contributes to the sometime whitish appearance of the sabkha sediments. Calcite, much of it wind-blown from the Mesozoic limestone strata on the western side of the Wadi ‘Arabah, and authigenic dolomite, are also present in the Taba Sabkha, but to a lesser degree (Abed, 1998, 2002).

Ameil and Friedman (1971) also studied the Taba Sabkha stratigraphy and mineralology, but focused primarily on the western, Israeli side of the sabkha. They excavated a total of 330 sample pits at 250 m intervals along traverse lines and collected samples every 30 cm down to the water table (Ameil and Friedman, 1971). Based on the sediment composition, distribution of vegetation, salinity, and depth to groundwater, these authors identified three distinct zones within the Taba Sabkha: (1) the central barren zone, (2) the transitional zone, and (3) the outer vegetated zone with halophytic vegetation.

The central barren zone, as its name implies, was found to be devoid of any vegetation and is composed of silty and sandy clay with strips of aeolian sand that cut across the zone, covering the sabkha to a depth of 30-100 cm in places. The halitic crust found throughout the Taba Sabkha is most pronounced in this central area (Amiel and Friedman, 1971). The transitional zone was the second zone identified in the study and was found to have sparse vegetation, primarily tamarisk. These shrubs act as a barrier to the movement of sand in the sabkha by trapping wind-blown particles that accumulate in small, irregular hillocks. According to Amiel and Friedman (1971), the sedimentation in this zone varies. Along the far western margin of the central barren zone, the sediment of the transitional zone is generally a silty sand. It becomes predominantly sandy silt northwest of the central barren zone. In both cases, the sediment is alluvial in origin and is derived from the wadis that drain the slopes of the mountains to the east and west (Amiel and Friedman, 1971). This zone differs mineralogically from the central barren zone in that gypsum is the dominant authigenic mineral in the sediment profile. Finally, the outer vegetated zone is the marginal zone of the sabkha that interfingers with the alluvial sediments of the fans. It is the largest zone in the Taba Sabkha, and sediments here consist primarily of silt and fine-grained sand, although sedimentation can also be coarse-grained and pebbly in places. Vegetation in this outer zone is mainly halophytic in nature, and thus capable of growing in salty soil (Amiel and Friedman, 1971).

Abed (2002) also identified vegetation zones within the Taba Sabkha, except he identified four zones present on the sabkha periphery, and found the vast area occupied by the sabkha center to be completely barren. The four zones of vegetation as determined by Abed (2002) include: 1) the *Acacia* zone on the alluvial fans, 2) the palm zone, 3) the *Nitratia retusa* and *Tamarix* sp. zone, and 4) the *Cressa cretica* cf. zone, although this zone is patchy.

Active Structure of the Wadi ‘Arabah Fault

The Wadi ‘Arabah fault, or Evrona fault as it is referred to on the Israeli side, trends up the Wadi ‘Arabah Valley at approximately N15˚E and is recognizable to about 35 km north of Aqaba. It terminates under sand dunes located just north of the Taba Sabkha. The Wadi ‘Arabah fault is complex and consists of several sub-parallel fault traces. In the south, the fault crosses unconsolidated recent alluvium and playa deposits in a belt approximately 1 km wide on the western side of the valley, and in the north, the Wadi ‘Arabah fault has displaced alluvial fans by *en-echelon* faulting (Garfunkel et al., 1981). The geometry of small, rhomb-shaped grabens indicates left-lateral slip along this north portion of the Wadi ‘Arabah fault. Active normal faulting is also present along the western mountains that flank the southern Wadi ‘Arabah (e.g. Zak and Freund, 1966; Garfunkel et al., 1981).

In all, there has been an estimated post-Eocene displacement of 107 km across the Dead Sea transform (e.g. Quennell, 1959; Freund, 1965; Freund et al., 1970; Bartov, 1974; Steinitz et al., 1978; Garfunkel and Ben-Avraham, 1996). This left-lateral movement occurred in at least two major stages as indicated by the palinspastic reconstruction of offset geological formations and structural features. According to earlier studies, 62 km of offset occurred along the DST by the early Miocene, with another 45 km of offset occurring since the late Miocene or Pliocene to present (e.g. Quennell, 1958, 1959; Garfunkel, 1981). Hatcher et al. (1981) also conducted geophysical studies that served to verify this displacement amount. The late Quaternary slip-rate of the DST has been estimated in multiple studies to be about 3-5 mm/yr. (e.g. Zak and Freund, 1966; Freund et al., 1968; Garfunkel et al., 1981; Jestin et al., 1994; Zhang, 1998; Klinger et al., 2000a; Niemi et al., 2001; Le Béon et al., 2010).

Garfunkel (1970) notes that north of the large, active fan of the Wadi Yutim there are older alluvial fans, as indicated by their dark patina-covered surface, which are truncated by what is probably a fault extending south to the northeastern shore of the Gulf of Aqaba. Strike-slip faults in the region tend to affect very young to recent sediments, while the marginal normal faulting events are apparent only in the older parts of the rift fill (Garfunkel et al., 1981). Le Béon et al. (2010) mapped offset Quaternary alluvial fans at the sites of

Jebal al-Muhtadi and Hamrat al-Fidan, and Le Béon et al. (2012) mapped offset Quaternary alluvial fans at the sites of Al-Risha, Al-Dhawi, and Mazla, in order to study early Holocene and late Pleistocene slip-rates along the DST in Wadi ‘Arabah. Le Béon et al. (2012) calculated that the slip-rate along the Dead Sea transform for the last 300 ka (late Pleistocene) was between 5-12 mm/yr with preferred values of 5-7 mm/yr, very similar to the Holocene DST slip-rate. The concurrence between slip-rates across timescales (during the Pleistocene and Holocene epochs) supports a constant-over-time fault kinematics scenario (Le Béon et al., 2010) for the Dead Sea transform, at least for time periods longer than approximately 10 ka (Le Béon et al., 2012).

Previous Geophysical Survey of the Taba Sabkha

The subsurface stratigraphy in the Taba Sabkha was previously imaged using geophysical methods. Ground penetrating radar (GPR), a non-invasive ground survey technique that uses electromagnetic waves, offers a unique high-resolution image of subsurface soil and rock conditions down to a depth of several tens of meters (Basson, 2002). Abueladas (2005) conducted a ground penetrating radar survey across the Wadi ‘Arabah fault where it enters the south end of the Taba Sabkha along the margins of a pressure or shutter ridge. Four buried fault strands were identified across an area of 12 m in the GPR section within the sabkha. A change in reflector intensity (peak amplitude) and a mismatch of reflectors suggest that the faults identified in the Taba Sabkha are strike-slip faults. The increase in reflector mismatch with the depth also indicates repeat motion on the buried faults. Along the section of the Taba Sabkha surveyed by Abueladas (2005), the fault traces are buried by approximately 1 m of sediment which is an indication that these faults have not ruptured to the ground surface for some centuries.

Basson et al. (2002) also used ground penetrating radar imaging to map faults to a depth of 25 m in the Evrona playa approximately 20-25 km south of the Taba Sabkha. The study revealed a dense, inhomogeneous distribution of subsurface discontinuities along the Wadi ‘Arabah fault. The GPR images show dense sets of fractures and faults located at various depths within the ground (Basson et al., 2002). GPR observations for this study also indicated that the density of faults increases as a function of depth at the first 25 m, and the apparent dips of the faults also suggest that they merge at a depth of a few tens of meters (Basson et al., 2002). Shallow seismic reflection (SSR) data (Shtivelman et al., 1998) were also used to identify a parent fault below the group of faults detected by the shallower GPR profile data collected by Basson et al. (2002). A comparison of the SSR and GPR data confirmed that the faults are merging at depth. According to Basson et al. (2002), a typical single fault traced through the top hundred meters along this section of the Dead Sea transform abruptly changes its characteristics as it reaches a depth of approximately 35-20 m below the ground surface. As it approaches the surface, the fault tends to fan out in a series of splays through the soft sediment, and the tectonic displacement that accumulates along a plane of a parent fault is dispersed towards the surface as a result (Basson et al., 2002).

An analysis of the faults detected by this GPR study by Basson et al. (2002), coupled with the dating of samples collected from excavated trenches, enabled an evaluation of the relative level of tectonic activity of the Wadi ‘Arabah fault zone. The GPR record indicates that tectonic activity peaked somewhere between 18,000-27,000 yr BP. It was also found that the recent period (0-9000 yr BP) can be characterized by a relatively low level of seismicity. Basson et al. (2002) found that this level of activity is approximately only 70% of the average seismic activity seen throughout the last 45,000 years in the region, and only about 50% of the determined peak activity.

Previous Paleoseismic Studies in Southern Wadi ‘Arabah

While the cumulative lateral displacement and slip-rate of the active Dead Sea transform have been well documented, the earthquake recurrence interval of the DST fault is poorly understood. Several studies in the last few decades have focused on the paleoseismicity of the Wadi ‘Arabah (Evrona) fault north of the Gulf of Aqaba (e.g. Gerson et al., 1993; Enzel et al., 1994, 1996; Amit et al., 1995, 1996, 1999, 2002; Porat et al., 1996, 2009; Zilberman et al., 2005). Previous paleoseismic work in the southern Wadi ‘Arabah has occurred in primarily two locations: along the normal faults of the Nahal Shehoret alluvial fan and strike-slip faults within the Evrona playa, both of which are located on the Israeli side of the valley (see Figure 4.1).

Twelve trenches up to 30 m long were excavated across normal fault scarps and other lineaments at the Shehoret site by Gerson et al. (1993). Located off of the main strike-slip fault of the Dead Sea transform, this site is situated 7 km north of Eilat, and approximately 28 km south of the Taba Sabkha. The presence of buried soils on the downthrown block at the fan site studied by Gerson et al. (1993) suggested a hiatus in the depositional record and was interpreted as a reliable indicator of periods of tectonic quiescence. In all, nine seismic events were identified as having occurred within the last

100,000 years along this section of the fault, with a recurrence interval of 1000-3000 years (Gerson et al., 1993). Working within the Nahal Shehoret fan site, Enzel et al. (1994) also calculated a 1000-3000 year recurrence interval by comparing the stratigraphy, sedimentology, and soils of colluvial and alluvial deposits on the fault scarps and near-by faulted terrace risers.

Infrared-stimulated luminescence ages of buried colluvial wedge deposits suggest that four surface faulting events occurred sometime between 35 ka and 14 ka with vertical displacements of 1.5 m (Amit et al., 1995, 1996; Porat et al., 1996). Smaller earthquakes are thought to have followed and continued until recent times. The mean recurrence interval for earthquakes of $M \geq 6.2$ on this specific fault in the Shehoret fan was calculated as approximately 4000 years by Porat et al. (1996). Leonard et al. (1998) concluded that smaller, more frequent fault displacements in Holocene deposits within the Nahal Shehoret fan indicate a potential change in the seismic activity and behavior of the Wadi ‘Arabah fault around 14 ka. Enzel et al. (1996) suggested that at least one large seismic event ($M > 6.5$) occurred along the Wadi ‘Arabah fault within the last 1000-2000 years based on luminescence dating and fault scarp degradation modeling. Enzel et al. (1996) also point out that since so few fault scarps have been studied in the area, these scarps represent a minimum estimate for large ($M > 6.5$) earthquake events in the region.

A study by Porat et al. (2009) conducted within the Shehoret alluvial fan site dated single grains of quartz collected from colluvial wedges deposited shortly after each faulting event. Porat et al. (2009) determined that the most recent earthquake took place a short time before 500-1300 years ago, and that this chronological framework agrees with the geomorphic age of the fault scarp which was modeled to be less than 2000 years old.

A study by Amit et al. (2002) investigated both the Shehoret fan and the Evrona playa toward the center of the valley. Paleoseismic evidence shows that the southern Wadi ‘Arabah (Evrona) fault system has generated at least fifteen earthquakes of M > 6 during the Pleistocene and Holocene (Amit et al., 2002). Using the maximum displacement method for estimating paleoearthquake magnitudes, Amit et al. (2002) found that throughout the Pleistocene, earthquakes occurring along the Evrona fault within the Shehoret fan site had magnitudes of between M 6.7 and M 7. The recurrence interval was calculated as 2.8 +/- 0.7 ka. Holocene fault motion at the Shehoret fan site had both a higher frequency and higher recurrence rate of 1.2 +/- 0.3 ka as compared to activity during the Pleistocene (Amit et al., 2002). The vertical fault displacements during the Holocene were smaller (0.2 -1.3 m), and therefore the earthquake magnitudes were also smaller, M 5.9 - M 6.7. This study also suggests that these smaller earthquakes were likely not substantial enough to activate the marginal faults along the western side of the valley (Amit et al., 2002).

Paleoseismic studies that focused on the main strike-slip fault located in the southern Wadi ‘Arabah Valley at sites within the Evrona playa (Amit et al., 1999, 2002; Zilberman et al., 2005) indicate that at least six M > 6 seismic events have ruptured the fault within the last 14,000 years. Amit et al. (1999) have concluded that the last significant seismic event occurred within the last 1000 years based on the limiting age of the sequence studied, as well as the extent of soil development in the Evrona playa. This earthquake is understood to have been an event significant enough to change the morphology of the Evrona playa from a closed system with internal drainage to an open basin, which ultimately resulted in relief inversion of the playa sediments (Amit et al., 1999).

A study by Zilberman et al. (2005) presents archaeological evidence of a water irrigation system, known as a qanat, located in the western part of the Evrona playa that was deformed because of movement along the Evrona fault. The qanat system once irrigated an early Islamic farm that dates to the 11th C. and that likely supplied the city of Early Islamic Ayla with fresh agricultural products (Avner, 1993). The farm was irrigated by a network of water canals connected to a central reservoir. The water reservoir was fed by the qanat, an underground tunnel system connected to the surface by rows of vertical shafts, which collected groundwater from alluvial fans located along the western margin of the valley (Zilberman et al., 2005). Topographic profiles of the roofed water canal show that the inlet of the canal to the water reservoir is 1 m higher than the qanat outlet, and the canal itself is deformed at three separate points along its length. The uplift of the reservoir, therefore, resulted in an inversion in the gradient of the qanat system (Zilberman et al., 2005).

The destruction of this irrigation system caused the farm to be abandoned in the 11th C. at the same time the city of Early Islamic Ayla was destroyed by an earthquake (Avner, 1993). Zilberman et al. (2005) conclude that the faulting event that destroyed the qanat system at the Islamic farm site is likely the same seismic event described by Amit et al. (1999, 2002) that occurred in the last 1000 years, and most likely represents the catastrophic A.D. 1068 earthquake (e.g. Guidoboni and Comastri, 2005; Ambraseys, 2009). In all, by combining data from studies at both the Shehoret fan site and the Evrona playa, the recurrence interval for large M > 6 earthquakes during the Pleistocene and Holocene periods along the Wadi ‘Arabah fault is estimated to fall somewhere between 1200-2000 years (e.g. Gerson et al., 1993; Enzel et al., 1994, 1996; Amit et al., 1995, 1996, 1999, 2002; Porat et al., 1996, 2009; Zilberman et al., 2005).

Submarine paleoseismology has also been conducted along the Dead Sea transform fault within the Gulf of Aqaba in an effort to more thoroughly understand the behavior and pattern of rupture along the DST along this southern segment of the fault. In a study by Makovsky et al. (2008), submerged relict coastline features were identified in the Gulf by using high resolution sub-bottom profiles of the northwestern tip of the Gulf of Aqaba down to a water depth of approximately 120 m.

Along the northern shelf of the Gulf, Makovsky et al. (2008) identified a relict reef in 65 m of water that is vertically offset by 10 +/- 1 m and sinistrally offset by 30 +/- 10 m across the offshore Evrona fault. Assuming that the reef was formed when sea level was approximately 65 m lower than today, these authors suggest the reef developed at around 11 +/- 2 ka. Measured offset and age of the 65-m reef, therefore, were used to estimate the slip-rate along this section of the fault as 2.7 +/- 1.5 mm/yr (Makovsky et al., 2008).

Tibor et al. (2010) conducted a high-resolution marine geophysical study in the Gulf of Aqaba that produced the first multibeam imaging of the seafloor across the entire gulf head spanning both Jordanian and Israeli waters. Analyses of the seafloor morphology indicate that the Gulf of Aqaba transform basin is asymmetrical and can be divided into the Aqaba and Eilat sub-basins separated by the north-south trending Ayla high. They also found seafloor lineaments, which suggest that the Eilat Canyon and the boundaries of the Ayla high align along NNW-striking faults -- the Wadi ‘Arabah (Evrona) Fault zone to the west and the Ayla Fault zone to the east -- as suggested by slope gradient analyses (Tibor et al., 2010). The 100-m shelf-slope break in the Eilat sub-basin and the shallower 70-m shelf-break in the Aqaba sub-basin, which are correlated to the last glacial period approximately 21 ka, are offset by approximately 150 m along the eastern edge of the Ayla high, which Tibor et al. (2010) suggest may be the result of horizontal and vertical movements along the Ayla Fault on the east side of the structure. It also appears from this work that a lack of active fault morphology across fan deltas suggests that the Aqaba Fault has not been active recently or has been rapidly buried by sediment, and that the Eilat side of the Gulf is more tectonically active (Tibor et al., 2010).

Hartman (2012) studied the Quaternary evolution of the Gulf of Aqaba transform basin using high-resolution geophysical data, including seismic profiles, full multibeam bathymetric and acoustic backscatter, and sidescan imaging, which revealed six systems of relict reefs situated within transgressive depositional systems. Originally identified by Makovsky et al. (2008) and Tibor et al. (2010) as >1 km-long linear terraces, the two youngest reefs exposed along the northwest corner of the Gulf of Aqaba on the seafloor at depths of 15 m and 60 m were interpreted as being related to two decelerations in sea-level rise during the last two deglaciations, and portray a repeating pattern of stratigraphic reef development (Hartman, 2012). The results of this research were correlated with rates of sea-level change, climatic events, and reef generation phases to produce an age model for these reefs, which from high-resolution seismic profiles were also found to be offset by active fault strands (Hartman, 2012). The reefs and overlying sedimentary layers were deformed by a total of six NNE-SSW trending faults as well as one E-W trending transverse fault, and based on the measured offset and ages of the 15-m and 60-m reefs, 8.4-8 ka and 12.9-11.7 ka, respectively, slip-rates and fault activity were calculated (Hartman, 2012). Of these fault strands, the Wadi ‘Arabah (Evrona) fault was found to be the most active fault crossing the reef system, with an average slip-rate of 0.5 +/- 0.1 mm/yr through the late Quaternary and 4 +/- 2.3 mm/yr during the Holocene, acting to absorb the majority of the left-lateral slip within the Gulf of Aqaba transform basin (Hartman, 2012).

Paleoseismic Investigation of the Taba Sabkha

Methodology

The geological investigation for this study was conducted over the course of two field seasons in 2009 and 2010. The specific trench location for this study was chosen due to clear geomorphic expression of the active Wadi ‘Arabah fault in the Taba Sabkha. The active fault lies along the base of a linear pressure ridge at the southeastern end of the Taba Sabkha and continues northward under the sabkha without topographic expression. A bulldozer (front-end loader) was used to excavate a 15 m long and 4 m wide trench northwest of the visible pressure ridge in order to bisect the *en-echelon* faulting pattern of the DST present in the Wadi ‘Arabah (Figure 4.2).

This paleoseismic trench, excavated to a maximum depth of 2.3 m, is located on the far eastern side the sabkha and is orientated at N80˚W. A grid system was laid out on both the north and south trench walls, and nails were positioned at one-meter intervals horizontally and at half-meter intervals vertically. Both trench walls were mapped in detail using photomosaic trench logging techniques (McCalpin, 2009), and each individual digital

Figure 4.2 Paleoseismic trench excavated in the Taba Sabkha, southern Wadi ‘Arabah, Jordan. The trench is 15 m long and approximately 4 m wide. View is toward the northwest.

photograph was photo-rectified to remove any angle distortion present before being digitally stitched together to create a photo-rectified mosaic of the trench walls. Trench log linework including stratigraphic units, contacts, and fault lines were described and drawn on top of the corrected photo-mosaic in the field. Stratigraphic units were differentiated and described on the basis of grain size, sorting, lithology, type of boundary, degree of cohesion, structure, and color as determined from a Munsell® soil chart. Sediment samples were also collected at 10 cm intervals to a depth of 2.3 m from the center section of the south trench wall for sediment characterization.

Samples of charcoal were collected from both the north and south trench walls in the Taba Sabkha for radiocarbon analyses by the Center for Accelerator Mass Spectrometry (CAMS) at the Lawrence Livermore National Laboratory in California. Radiocarbon dates were calibrated to a two sigma probability using the CALIB Radiocarbon Calibration 7.0 program and included the IntCal13 curve selection (Reimer et al., 2013). Further, in an effort to date a relevant stratigraphic unit that did not contain obvious fragments of organic material, a bulk sediment sample collected from above the most recent seismic event was dated based on bulk organic content. Currently, seven charcoal samples and one bulk sediment sample have been dated, and these dates are reported in Table 4.1.

Results

Sedimentological and Faulting Sequence of Taba Sabkha Deposits

Paleoseismic events in the Taba Sabkha trench were identified on the basis of primary coseismic evidence including upward-terminating faults, fissures, offset

TABLE 4.1

RADIOCARBON DATING RESULTS:
TABA SABKHA TRENCH, JORDAN

Sample No.	Depth in Trench	Stratigraphic Unit/Wall	Lab Sample No.	Measured Radiocarbon Age	$\delta^{13}C$	Conventional Radiocarbon Age	Tree-ring Calibrated Age
Bulk Sediment	0.4 m	TS-3, South	CAMS 158896	1960 ± 110 yr BP	-25	1960 ± 110 yr BP	348 Cal B.C. - 331 Cal A.D.
TSSW-28	0.52 m	TS-5, South	CAMS 158894	12230 ± 140 yr BP	-25	12230 ± 140 yr BP	Cal B.C. 12870-11808
TSSW-20	0.7 m	TS-5, South	CAMS 152241	280 ± 20 yr BP	-25.06	280 ± 20 yr BP	Cal A.D. 1521-1661
TSSW-22	1.0 m	TS-10, South	CAMS 152242	1055 ± 40 yr BP	-25	1055 ± 40 yr BP	Cal A.D. 893-1030
TSSW-1	1.4 m	TS-12, South	CAMS 158895	1170 ± 20 yr BP	-26.02	1170 ± 20 yr BP	Cal A.D. 774-943
TSSW-5	1.5 m	TS-12, South	CAMS 152239	865 ± 35 yr BP	-25	865 ± 35 yr BP	Cal A.D. 1045-1256
TSNW-17	1.32 m	TS-12, North	CAMS 152240	1535 ± 25 yr BP	-24.36	1535 ± 25 yr BP	Cal A.D. 428-591
TSNW-18	1.28 m	TS-13, North	CAMS 158893	2110 ± 35 yr BP	-25	2110 ± 35 yr BP	Cal B.C. 345-43

Radiocarbon ages have been calibrated to calendar years with the CALIB 7.0 online calibration program using a 2 sigma range probability and IntCal13 curve selection (Reimer et al., 2013).

stratigraphic units, offset channel deposits, and rotated pieces of clay identified in the trench wall exposures (e.g. McCalpin and Nelson, 2009) (Figure 4.3). The stratigraphic expression of primary postseismic evidence at this site consists of fissure fills present in both trench walls to be discussed herein. An examination and analysis of the Taba Sabkha trench stratigraphy suggests that exposed in the Taba Sabkha trench walls there is evidence for as many as four separate faulting events and as few as two faulting events. The identified paleoseismic events are numbered sequentially with EQ I being the most recent event (MRE) exposed within the Taba trench. Various earthquake event scenarios will be discussed in a later section.

The stratigraphic sequence in the Taba Sabkha consists primarily of interbedded fine-grained units of sand, silt, and clay (Figure 4.4) that were washed into the Wadi ‘Arabah basin from distal alluvial fan runoff originating from the Precambrian granitic mountains located to the east of the study site. Also present in the trench stratigraphy are channel deposits of medium- to coarse-grained sands, which indicate that small flooding events occur periodically within the sabkha.

At a depth of 2.3 m, the basal sedimentary units in the Taba trench include alternating beds of fine-grained, tannish-brown, silty sand (units TS-18, TS-16, TS-14) and units of interbedded medium-grained, gray sand and sandy silt (units TS-17, TS-15). Units TS-17 and TS-18 are only exposed in the north trench wall because earthquake faulting in the sabkha has caused the strata to dip slightly to the south in this trenching location. Unit TS-13, a bed of light brown sandy silt some 10-40 cm thick, then caps these basal units. All of these units were faulted by EQ IV, the most strongly expressed paleoseismic event in the

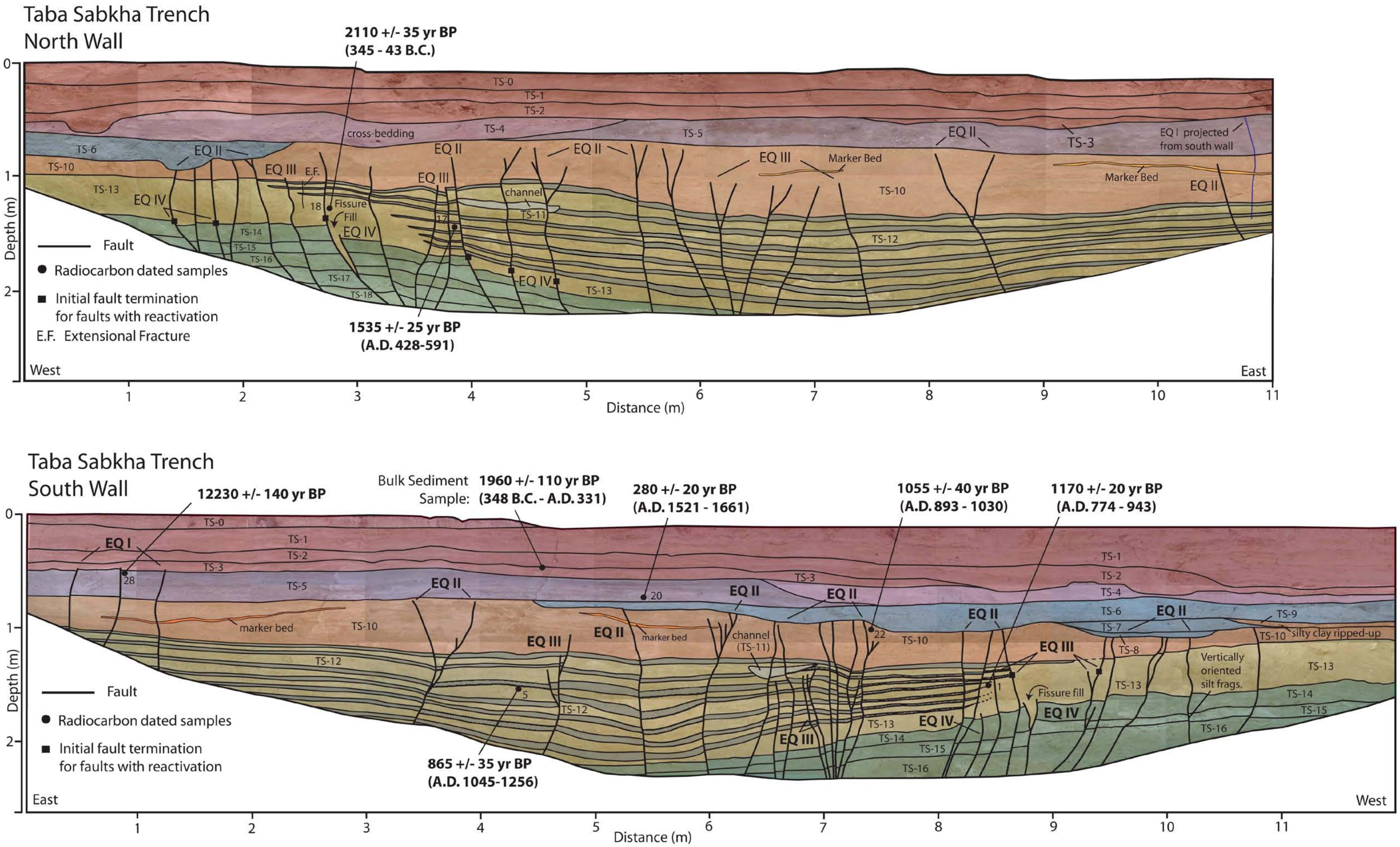

Figure 4.3 Cross-section of both the north and south Taba Sabkha trench walls showing faulting, stratigraphic offset, and radiocarbon dates of charcoal samples collected.

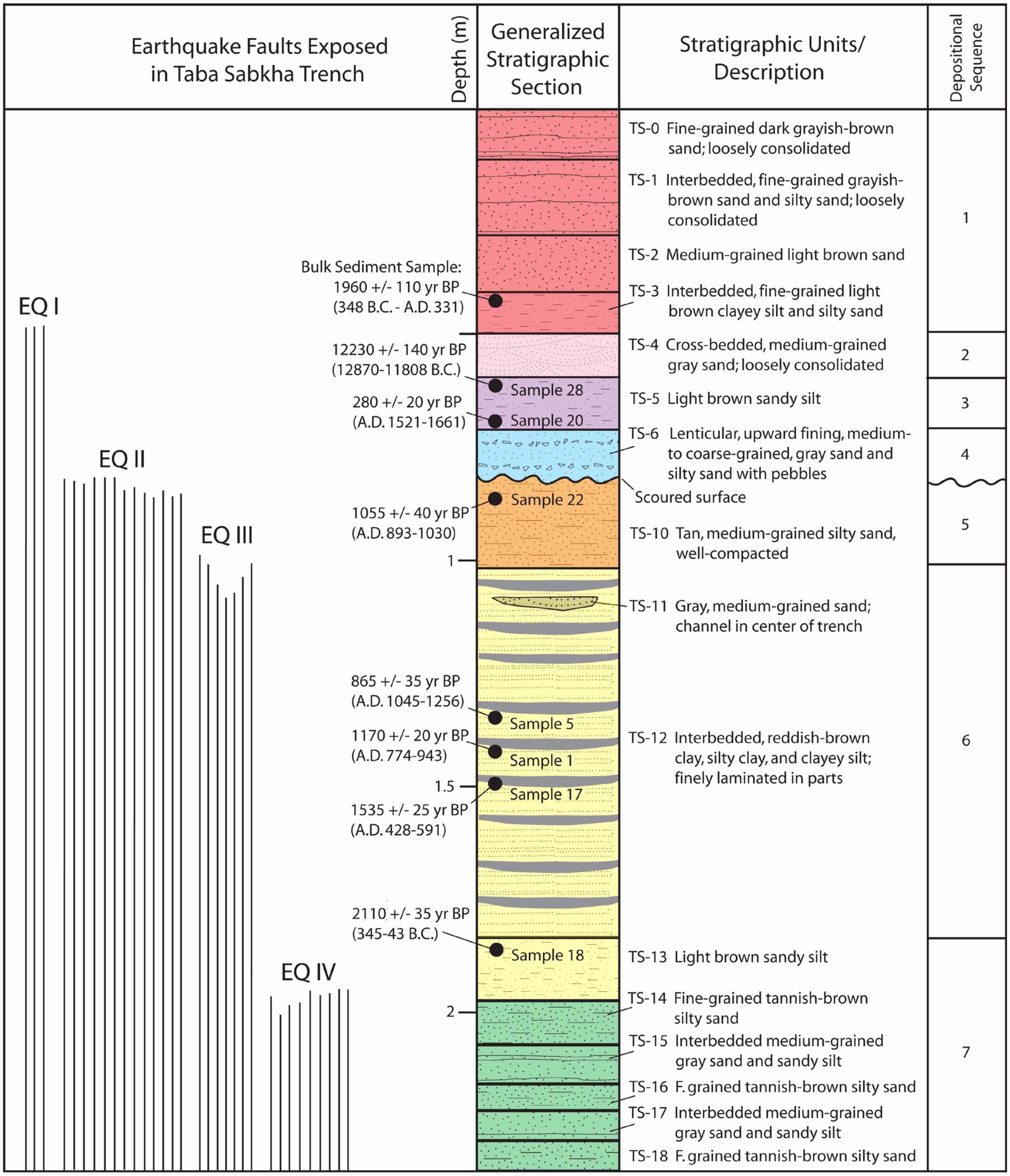

Figure 4.4 Paleoseismic faulting and stratigraphic correlation in the Taba Sabkha trench, Wadi ‘Arabah, Jordan. Colored stratigraphic units correlate to colored cross-sections of trench walls (see Figure 4.3).

Taba trench, and stratigraphic mapping of the trench sediments indicates that TS-13 was the unit exposed on the surface at the time of this earthquake. A component of normal slip resulted in the down-to-the-east movement of sabkha sediments and also produced a fissure, a coseismic and geomorphic expression of this tectonic event. The fissure, visible in both the north and south trench walls, is filled in with the silty sand of unit TS-13. This unit also continued to be deposited after this faulting event occurred. One of the faults from the EQ IV seismic event trends N12˚E. Some fault lines that were first created during the rupture of this fourth earthquake event were later reactivated during either or both EQ III and EQ II.

Overlying the lower silty and sandy strata (TS-18 – TS-13) is a 1 m-thick package of interbedded reddish-brown clay, silty clay, and clayey silt (unit TS-12) which is finely laminated in parts. The individual layers of this sedimentary package thicken toward the center of the Taba trench and then pinch out toward the east and west. Subsidence of the eastern side of the trench due to the coseismic dip-slip of EQ IV created a shallow depression where runoff periodically pooled, allowing fine-grained sediments to settle out, thereby creating numerous alternating beds of clayey strata 0.25 – 2.5 cm thick. Some of the layers in this unit are partially mottled. One relatively thin channel deposit, a medium-grained gray sand (unit TS-11), cuts through the upper section of unit TS-12 toward the center of the trench.

Stratigraphically situated above these clayey strata is a well-compacted bed of fine- to medium-grained tan, silty sand (unit TS-10). This bed is faulted by EQ III, although some upward fault terminations for this event only cut to the upper portion of the TS-12 package and do not propagate into unit TS-10, depending on the location within the trench. Faulting evidence for EQ III includes vertically offset strata (2-3 cm), mismatched unit thicknesses across fault lines as a result of strike-slip motion, and upward fault terminations. Unit TS-10 continued to be deposited and was later faulted again by EQ II. All upward fault terminations for EQ II are found at the top of unit TS-10. Several EQ III faults were also reactivated by EQ II. This second seismic event is recognized by the 3-4 cm of vertical offset present, as well as evidence of strike-slip motion apparent from the differing thicknesses of stratigraphic units across a fault. Ground shaking at the site caused unit TS-10 to be largely homogenized in places, and this lack of structure is particularly visible in the northern wall where this unit is thicker. EQ II also offset the narrow sand channel (TS-11) found toward the top of unit TS-12.

After the penultimate event (EQ II) occurred, the uppermost portion of unit TS-10 in the south trench wall, and thus the majority of EQ II upward fault terminations in the same wall, was largely scoured away by the fluvial deposition of units TS-8, TS-7, and TS-6. Unit TS-8 is a thin, localized deposit of coarse-grained sand with pebbles that is overlain by a thin, localized deposit of sandy silt, unit TS-7. Overlying both of these layers is unit TS-6, a 0.10-0.26 m-thick bed of lenticular, upward-fining, medium- to coarse-grained, gray sand and silty sand that also contains pebbles. Unit TS-6 is present along the western end of the Taba exposure and stretches across two-thirds of the trench to the east where it pinches out, although units TS-8 and TS-7 are only present on the far western end of the trench. This fluvial package (TS-8, TS-7, and TS-6) is also much more prominent in the south wall than in the north wall. The majority of the faults associated with EQ II on the north wall have not been scoured away as a result. Due to the depth of the erosional surface created by these fluvial units toward the far western end of the trench, it is also possible that some of the faults that were scoured away may represent EQ III, although none of them can represent EQ I due to the overlying stratigraphic relationships of units TS-5 and TS-4.

Unit TS-5, a 0.20-0.30 m-thick bed of light brown sandy silt, caps the previously described graded fluvial sequence. It is itself partially overlain by a loosely consolidated and cross-bedded, medium-grained gray sand, unit TS-4. The TS-4 fluvial sand, 0.10-0.28 m-thick, scoured off any of the underlying sandy silt from unit TS-5 on the western half of the trench exposure that may have been present at one time, and in cross-section is thickest on the north wall. EQ I, the most recent seismic event (MRE) present in the Taba Sabkha trench, is visible on the far eastern end of the south trench wall. In all, three upward terminating faults associated with the MRE cut completely through unit TS-5 and are capped by an interbedded, fine-grained, light brown clayey silt and silty sand, unit TS-3. The upper termination of this earthquake event is buried only 50 cm beneath the ground surface. The uppermost portion of the Taba trench stratigraphy is composed of a medium-grained, light brown sand (TS-2), a loosely consolidated, interbedded, fine-grained grayish-brown sand and silty sand (TS-1), and a loosely consolidated, fine-grained, dark grayish-brown sand (unit TS-0). Unit TS-0 is the present ground surface in the sabkha at the Taba site.

Earthquake events I, II, and III show relatively little vertical displacement as compared to the observable dip-slip associated with EQ IV, but it is clear that the three most recent seismic events exposed in the trench do offset the strata they have faulted. As mentioned, many of the faults exposed in the Taba trench also show accumulated slip as strata toward the bottom of the trench are progressively more offset than the younger overlying units. Each time a specific fault line is reactivated by a new faulting event, the more deeply buried stratigraphic layers become increasingly offset, thus creating non-uniform displacement. Certain EQ III and IV faults contain evidence of accumulated slip, and thus provide evidence of reactivation along the same fault line.

Numerical Dating of Seismic Events

Numerous charcoal samples were collected from within the Taba Sabkha trench walls, although the trench otherwise contained little other obvious organic material. In order to properly bracket the timing of individual paleoearthquakes, radiocarbon ages are needed for the youngest datable unit deformed by the earthquake, and for the oldest datable unit that caps or buries evidence of the seismicity in question (e.g. McCalpin et al., 2009). The stratigraphic location of the eight dated samples is illustrated on the north and south wall trench logs (Figure 4.3), as well as on the Taba Sabkha stratigraphic section (Figure 4.4).

Collected from unit TS-5 in the south wall, the uppermost unit faulted in the trench, charcoal sample 20 produced a radiocarbon date of 280 +/- 20 yr BP (A.D. 1521-1661). All faults from EQ I cut through unit TS-5. Therefore, the most recent seismic event (MRE) occurred sometime after the deposition of this layer in the 16th or 17th century, and has subsequently been buried by 0.5 m of sand, silty sand, and clayey silt. Another charcoal fragment, sample 28, was collected from the uppermost portion of unit TS-5 and produced a very old date of 12230 +/- 140 yr BP (12870-11808 B.C.) which correlates to the Pleistocene epoch. Despite the fact that sample 28 was located stratigraphically above sample 20 within the same sedimentary unit (TS-5), this particular charcoal fragment is clearly much older than the unit from which it was collected. Considering that charcoal is detrital, this sample is interpreted as being remobilized from another much older deposit located elsewhere before being deposited in unit TS-5. Further, in an attempt to date the unit that caps the MRE, we dated organic material from within a bulk sediment sample collected from the upper portion of unit TS-3, a clayey silt and silty sand unit located stratigraphically above the EQ I terminations at a depth of 40 cm. This sediment sample was selected for bulk dating due to the absence of charcoal fragments or other datable organic materials in the TS-3 capping unit. However, with a reported date of 1960 +/- 110 yr BP (348 B.C. - A.D. 331), which is a date out of sequence with the rest of the radiocarbon dated materials considering stratigraphic placement and depth, this organic matter is also interpreted as being remobilized from an older deposit or deposits elsewhere in the region. This inherited radiocarbon date is therefore unusable toward the determination of the Taba seismic chronology.

Sample 22, a charcoal fragment dated to 1055 +/- 40 yr BP (A.D. 893-1030) was collected from sediment deposited just below the faulted erosional surface toward the center of the trench in unit TS-10, thus at least two earthquakes, EQ I and II, occurred along this section of the Wadi ‘Arabah fault after this date. The youngest date located stratigraphically below sample 22 in this trench is sample 5 collected from within unit TS-12, which dates to 865 +/- 35 yr BP (A.D. 1045-1256). Thus, since charcoal sample 5 is younger than sample 22, this suggests that charcoal sample 22 was remobilized from elsewhere and deposited in unit TS-10 prior to the scouring of this silty sand by unit TS-6. The tree-ring calibrated dates for samples 5 and 22 do not overlap, but in considering the high and low range of each date, A.D. 1030 for sample 22 and A.D. 1045 for sample 5, these samples may potentially be separated by as few as 15 years. EQ II, therefore, most likely occurred sometime between the 11th century, but before the deposition of layer TS-5 dated to the 16th - 17th century (sample 20) when EQ I likely occurred.

Based on the radiocarbon dating of charcoal samples 1 and 5 from unit TS-12 in the south wall, as well as charcoal sample 17 collected from unit TS-12 in the north wall, the timing of the third seismic event exposed in the Taba trench can also be constrained. EQ III occurred sometime after layers dated to 1170 +/- 20 yr BP (A.D. 774-943), 865 +/- 35 yr BP (A.D. 1045-1256), and 1535 +/- 25 yr BP (A.D. 428-591) respectively, but before a layer (unit TS-5) dated to 280 +/- 20 yr BP (A.D. 1521-1661). The timing of this earthquake can be further constrained since the youngest date collected from stratigraphic units faulted by EQ III is sample 5 with a date of 865 +/- 35 yr BP (A.D. 1045-1256). EQ III must have occurred between this date and 280 +/- 20 yr BP (A.D. 1521-1661), which is the uppermost radiocarbon date available in the Taba trench.

Finally, the faulted stratigraphy and radiocarbon dates were studied in order to determine the paleoseismic chronology of EQ IV in the Taba Sabkha trench. The highest stratigraphic unit cut by EQ IV is unit TS-13. Charcoal sample 1, collected from unit TS-12 located stratigraphically above and near the fissure fill from this earthquake in the south trench wall, provided a radiocarbon date of 1170 +/- 20 yr BP (A.D. 774-943) and is the latest date situated above an EQ IV event horizon. This sample acts to help constrain the youngest possible age of the EQ IV event. Sample 18, a charcoal fragment collected from above the EQ IV horizon in unit TS-13 on the north wall, provided a radiocarbon date range of 2110 +/- 35 yr BP (345-43 B.C.). Since both charcoal samples 1 (A.D. 774-943) and 18 (345-43 B.C.) were collected from approximately the same depth within the trench and are located so closely together stratigraphically, it is very likely that sample 18 is a piece of remobilized charcoal with an inherited age that is older than the horizon or sedimentary unit in which it was deposited. Thus, stratigraphic evidence indicates that the fourth seismic event back occurred in the Taba Sabkha sometime prior to a date of 1170 +/- 20 yr BP (A.D. 774-943).

Discussion

As detailed in Chapter Two, several historical earthquakes are recorded for the southern Wadi ‘Arabah region between the Dead Sea and the Gulf of Aqaba from the 2nd - 16th C. These include the earthquakes of A.D. 110-114, 363, 418/419, 554, <597-598, 634, 746/749, 757, 1033, March and May 1068, 1212, 1293, 1458, 1546, and 1588 (Guidoboni, 1994; Guidoboni and Comastri, 2005; Ambraseys, 2009). In the following section, these seismic events are considered as several earthquake scenarios are discussed based on trenching data collected from the Taba Sabkha paleoseismic excavation.

Earthquake Scenarios and Earthquake Correlation

Detailed analysis of the faulted stratigraphy in the Taba Sabkha trench indicates that between two and four paleoseismic events are recorded in the trench wall sediments. Based on the trenching data discussed, there are three probable earthquake scenarios or models that would explain the stratigraphic and radiocarbon evidence present in the Taba Sabkha exposure: a four-earthquake event scenario, a three-earthquake event scenario, and a two-earthquake event scenario. In order to discuss the earthquakes within each of these event models, they will continue to be referred to as EQ I - IV since it is possible that there are as many as four events exposed in the trench, although as few as two earthquake events may also be represented.

In a four-earthquake event model, earthquake events I-IV are all individual events, as discussed in the previous section. The oldest earthquake exposed in the trench is EQ IV, followed by EQ III, then EQ II, and finally EQ I. The available radiocarbon dates that partially constrain EQ IV are 1170 +/- 20 yr BP (A.D. 774-943) from sample 1, and a radiocarbon date of 2110 +/- 35 yr BP (345-43 B.C.) from sample 18, a remobilized charcoal fragment. This data suggests that EQ IV occurred sometime before A.D. 774-973 and may likely be attributed to either the A.D. 746/749 event or the A.D. 757 event, both thought to have originated on the Dead Sea transform in the Jordan Valley (Guidoboni, 1994; Ambraseys, 2009). Controversy surrounds the seismic events that span the A.D. 746-757 time period in the historic record, and Ambraseys (2009) acknowledges that it is difficult to separate out various seismic events during this narrow eleven year window. While the earthquake catalogs of both Guidoboni (1994) and Ambraseys (2009) agree that there was an earthquake along the DST on A.D. March 9, 757, they disagree about the year of the large A.D. 746/749 event. Guidoboni (1994) cites this event as occurring on January 18, 749 and Ambraseys (2009) cites it as a January 18, 746 event. However, archaeological evidence from an excavation at the site of Bet Shean in Israel strongly supports the A.D. 749 date (Tsafrir and Foerster, 1992). Excavations of a collapsed commercial street at Bet Shean revealed a small hoard of artifacts including several coins, the latest of which was dated to A.D. 748 (Tsafrir and Foerster, 1992). The earthquake that destroyed the city, therefore, must have occurred after this date, likely in A.D. 749 and not in 746 as Ambraseys (2009) suggests.

It is also possible, since there is no lower capping date associated with the EQ IV rupture, that this earthquake represents an older seismic event such as those that occurred in A.D. 659 and A.D. 634, both of which were also centered in the Dead Sea region (Guidoboni, 1994; Ambraseys, 2009). Based on the close proximity of collected charcoal samples 1 and 18 to the event horizon of EQ IV, however, it is not likely that this rupture represents an event much older than those earthquakes proposed here, based on the type of depositional environment found in the Taba Sabkha. There is also a general lack of historic earthquakes in the 9th century that are known to have affected locations along and within the southern Wadi ‘Arabah Valley. Considering the range of years provided by the sample 1 radiocarbon date (A.D. 774-943), which was collected from a unit overlying EQ IV fissures, the faulting and stratigraphic evidence points most strongly toward a mid-8th century event for EQ IV.

Within the four-earthquake event model, EQ III is the next oldest seismic event represented in the Taba trench. If this event does represent a separate earthquake event as this model would suggest, the third seismic event occurred sometime after layers dated to 1170 +/- 20 yr BP (A.D. 774-943), 865 +/- 35 yr BP (A.D. 1045-1256), and 1535 +/- 25 yr BP (A.D. 428-591), samples 1, 5, and 17 respectively. EQ III must have also occurred before a layer dated to 1055 +/- 40 yr BP (A.D. 893-1030), as determined from the stratigraphic position of Sample 22 in the south trench wall. Sample 22 was collected from the uppermost portion of unit TS-10, which was deposited stratigraphically above all possible EQ III terminations as determined from detailed paleoseismic mapping. However, since the calibrated date from sample 22 (A.D. 893-1030) is actually older than sample 5 (A.D. 1045-1256), which was collected from unit TS-12 located stratigraphically underneath unit TS-10, charcoal sample 22 is interpreted having been remobilized from elsewhere in the Wadi ‘Arabah Valley. This suggests that the age of sample 22 is an inherited age and does not accurately date unit TS-10. All EQ III faulting, therefore, must have occurred sometime after the A.D. 1045-1256 date, but before the deposition of sample 20 (280 +/- 20 yr BP or A.D. 1521-1661), the uppermost date available in the Taba trench. This event cannot be further constrained at this time based on the radiocarbon dates available.

In the four-event model, it follows that EQ II, which ruptures to the top of unit TS-10, must have also occurred after EQ III which happened sometime after a date of A.D. 1045-1256 based on the youngest radiocarbon dated sedimentary unit these faults rupture (TS-12), and prior to the deposition of sample 20 (280 +/- 20 yr BP or A.D. 1521-1661) in unit TS-5. Like EQ III, EQ II can only be constrained as occurring sometime between the mid-11th century and the 16th - 17th centuries based on the uppermost available radiocarbon date, sample 20, deemed to be in proper sequence in the Taba trench. Considering the historical earthquakes known to have affected the southern Wadi ‘Arabah region from the 11th - 16th century based on the earthquake catalogs of Guidoboni and Comastri (2005) and Ambraseys (2009), the EQ III and EQ II events likely represent either the catastrophic A.D. March or May 1068 events, the 1212 event, the 1293 event, the 1458 event, the 1546 event, or the 1588 event. The 1293, 1546, and 1588 events, however, can likely be ruled out as options for EQ III and EQ II. The 1293 and 1546 earthquakes both had epicenters closer to the Dead Sea and likely would not be very strongly expressed in the Taba Sabkha. The 1588 event was centered near the Gulf of Aqaba and thus was relatively close in proximity to Taba, but because this is the most recent historic earthquake on record for the southern Wadi ‘Arabah region, this event likely represents a more recent rupture present in the Taba trench rather than EQ III or EQ II. Of the remaining possible historic earthquakes, the two most likely to represent the EQ III and EQ II faults mapped in the Taba trench are the A.D. March 1068 and 1212 events, respectively. They both had epicenters in or near the Gulf of Aqaba, located approximately 35 km south from Taba, while the May 1068 event and the 1458 events both had epicenters located further north up the Wadi ‘Arabah (Guidoboni and Comastri, 2005; Ambraseys, 2009).

Finally, EQ I represents the most recent earthquake event visible in the Taba Sabkha trench stratigraphy in the four-earthquake event model presented here. The age of this earthquake is only partially constrained by radiocarbon dating since sample 20 (280 +/- 20 yr BP or A.D. 1521-1661) was collected from slightly beneath the EQ I horizon, but there are no useable radiocarbon dates that cap the most recent seismic event (MRE). Therefore, the MRE occurred sometime after the deposition of the layer containing sample 20 (unit TS-5) in the 16th or 17th centuries, and these terminations have subsequently been buried by 0.5 m of sediment. Based on the known historical earthquakes that occurred in the region of the southern Wadi ‘Arabah during the medieval period, EQ I could potentially represent either the A.D. 1546 event that is known to have affected the Holy Land or the A.D. 1588 event that had an epicenter in or around the Gulf of Aqaba or the northern Red Sea, according to Ambraseys (2009). While both seismic events are possibilities, because of the proximity of the 1588 event epicenter to the Taba trench, this earthquake is probably more likely to have ruptured Taba in the 16th C. than the 1546 event.

It is possible that only three earthquake events are actually present in the Taba Sabkha trench stratigraphy. In a three-earthquake event scenario, the same data presented previously concerning the four-earthquake model still holds true, with one major exception. In this modified scenario, the EQ III and EQ II terminations are considered to represent the same event, not two separate earthquakes as previously postulated. Thus, under this scheme, EQ IV still occurred first and likely represents either the A.D. 746/749 or 757 earthquake events. The next earthquake that occurred is represented by combining the stratigraphic and radiocarbon evidence from both EQ III and EQ II, since in this scenario they are interpreted as representing the same seismic event. This model suggests, therefore, that not all of the upward terminations associated with this event (those originally assigned to EQ III) propagated as high or as close to the ground surface as those originally designated as EQ II terminations. Using the radiocarbon dates provided from sample 5 (865 +/- 35 yr BP or A.D. 1045-1256) and sample 20 (280 +/- 20 yr BP or A.D. 1521-1661) as guidelines, EQ III and EQ II together likely represent the A.D. March 1068 event, as postulated previously in the four-earthquake event scenario. This is the most probable historical earthquake considering the large number of faults present in the Taba trench, and the proximity of the trench to the March 1068 event epicenter in the Gulf of Aqaba. As discussed with the four-earthquake model, the second most likely earthquake represented by this faulting evidence is the A.D.

1212 event, which also likely had a Gulf of Aqaba epicenter. Under this three-earthquake scenario, EQ I is the third and most recent seismic event visible in the Taba trench stratigraphy. From the historical earthquakes known to have affected the southern Wadi ‘Arabah within this time frame, EQ I likely corresponds to either the A.D. 1546 or A.D. 1588 events. This chronology is based on the radiocarbon date of 280 +/- 20 yr BP (A.D. 1521-1661) produced from the sample 20 charcoal fragment collected within unit TS-5 that was situated approximately 20 cm beneath the EQ I event horizon.

Finally, the last earthquake event scenario concerning the paleoseismicity of the region is explained by a two-earthquake model. In this particular scenario, EQ IV is still a single seismic event that likely represents an 8th century earthquake, perhaps either the A.D. 746/749 or 757 events, and faults associated with EQ III and EQ II are still interpreted as a single seismic event, as presented in the three-earthquake event scenario. The EQ III/EQ II event can most likely be attributed to the catastrophic 11th century earthquake that occurred in March of 1068, as was also suggested by the three-earthquake event model. However, unlike the other seismic scenarios discussed concerning the Taba trench, the two-earthquake event model does not recognize the EQ I faults (there are only three in all) to be evidence of an earthquake, but simply as faulting as a result of sympathetic slip due to an earthquake located along another nearby fault line. Under this two-event interpretation, the EQ III/EQ II event is recognized as the MRE, or most recent seismic event, present in the Taba Sabkha trench stratigraphy, and still likely represents the March 1068 event as discussed in the three-earthquake event scenario.

Based on detailed mapping of trench stratigraphy and radiocarbon dating of charcoal fragments, all three of these earthquake-event scenarios are reasonable interpretations for the paleoseismology of the southern Wadi ʻArabah. The most probable and thus the preferred seismic model presented here, however, is the three-earthquake event scenario, where EQ IV and EQ I are independent events, but EQ III and EQ II faulting evidence is combined and thus interpreted to represent a single earthquake.

Evidence of Earthquake Faulting

As stated by McCalpin and Nelson (2009), the paleoseismic record, in general, is a record of large ($M > 6.5$) to great ($M > 7.8$) earthquakes because geologic evidence of small- to moderate-sized events is typically not created nor preserved near the ground surface. Thus, it is assumed that all of the faults identified in the Taba Sabkha trench are considered to have been the result of $M > 6.5$ earthquakes because they ruptured up to or very near the ground surface (McCalpin, 2009).

Earthquakes are identified in exposures of strike-slip faults based on a variety of types of faulting evidence. Faulting evidence can include upward termination of fault displacement, abrupt changes in vertical separation of strata as faults are traced up- or down-section, abrupt changes in the thickness of strata across a fault, fissures and sand blows in the stratigraphic sequence, angular unconformities produced by folding and tilting, and colluvial wedges shed from small scarps (McCalpin et al., 2009). While upward fault terminations tend to be the most cited form for faulting evidence, this type of evidence must be interpreted very carefully since many faults do not actually rupture all the way to ground surface (e.g. Bonilla and Lienkaemper, 1991; McCalpin et al., 2009). Bonilla and Lienkaemper (1991) found that where the ground surface was known at the time of the earthquake, some 73% of faults died out before rupturing to the surface. The depth at which faults can die out before propagating to the ground surface, even for large M > 6.5 earthquakes, ranges from between just a few centimeters to > 2 m, with a mode of approximately 15-30 cm below the ground surface (Bonilla and Lienkaemper, 1991). While upward fault terminations are a valid and useful form of evidence to identify earthquakes, they should only be used when the terminations are consistent at numerous locations in the trench (when ruptures end within the same stratigraphic horizon). They may also be used in association with other earthquake indicators, like fissures or colluvial wedges which are both considered to be strong evidence of earthquake faulting (McCalpin et al., 2009).

In the Taba Sabkha trench, EQ IV was identified from down-faulted strata and a fissure visible in both the north and south trench walls. Upward fault terminations were used in this study, in part, to identify earthquake events III, II, and I, along with other faulting evidence present, such as abruptly offset stratigraphic units on either side of a fault, mismatched unit thicknesses across faults, and strata that are increasingly offset down-section indicating reactivation of the same fault line through time. All of the seismic events identified at Taba produced at least three upward terminating faults which terminate at the same stratigraphic horizon, such as with EQ I, while EQ IV, III, and II each produced numerous faults that terminate within the same horizon, respectively.

Faults also propagate differently through the ground depending on the material through which they are traveling, and this is especially true as a fault nears the ground surface where overlying pressures are greatly reduced. While faults resulting from large (M > 6.5) earthquakes will generally rupture to the ground surface (McCalpin and Nelson, 2009), faults propagating through softer sediments, such as the sand, silt, and clay present in the Taba trench, may splay or create “flower structures” as they approach the surface (e.g. Shtivelman et al., 1998; Basson et al., 2002). A seismic flower structure is created when a parent fault breaks into two or more branches as the fault nears the surface. This can complicate paleoseismic trench interpretations because it is possible that one single earthquake event can produce faults that terminate at or beneath the ground surface at different depths, particularly within soft-sediment environments. In the Taba Sabkha trench, therefore, earthquake events III and II may very well represent the same seismic event, as suggested in both the preferred three-earthquake event model and the two-earthquake event model.

Earthquake Recurrence Interval

The seismic recurrence interval, or return period, is the average time interval between earthquake events along a particular fault (Keller and Pinter, 1996). Considering the earthquake scenarios presented to explain the faulting evidence identified within the Taba trench, a four-, three-, and a two-earthquake event scenario, recurrence intervals are calculated for each model (Table 4.2). In the four-event model, the oldest earthquake, EQ IV, represents a mid-eighth century event, likely either the A.D. 746/749 or 757 events. The most recent seismic event visible in the trench walls at Taba is a likely a mid- to late-sixteenth century earthquake, either the A.D. 1546 or the 1588 event. Because EQ I could

TABLE 4.2

EARTHQUAKE EVENT MODELS AND RECURRENCE INTERVALS TABA SABKHA, SOUTHERN WADI ‘ARABAH, JORDAN

Four-Earthquake Model	*Three-Earthquake Model*	*Two-Earthquake Model*
EQ I A.D. 1546 or 1588	EQ I A.D. 1546 or 1588	Sympathetic slip from A.D. 1546 or 1588 event
EQ II A.D. 1212	EQ II A.D. March 1068	EQ I A.D. March 1068
EQ III A.D. March 1068		
EQ IV A.D. 746/749 or 757	EQ III A.D. 746/749 or 757	EQ II A.D. 746/749 or 757
Average Recurrence Interval = 316 years between EQ events	Average Recurrence Interval = 421 years between EQ events	Average Recurrence Interval = 632 years between EQ events

represent one of two possible historic seismic events (1546 or 1588 event), and because EQ IV could represent one of three different events (the 746, 749, or 757 earthquakes), the average of each of these possible earthquake years was calculated as A.D. 1567 for EQ I and A.D. 751 for EQ IV. Therefore, the total number of years between EQ IV (using A.D. 751 as the average event age for EQ I) and EQ III (likely the A.D. March 1068 event) was determined to be 317 years. The total number of years of quiescence between EQ III (A.D. 1068) and EQ II (A.D. 1212) under this model was calculated as 144 years. A total of 355 years was calculated as the length of time between EQ II (A.D. 1212) and EQ I (using A.D. 1567 as the average event age for EQ I). Finally, the last known historical earthquake in the Taba trench occurred 446 years ago (calculated by subtracting the current year of A.D. 2013 from the A.D. 1567 average for EQ I). The average recurrence interval for the four-earthquake model, therefore, is estimated to be approximately 316 years.

The three-earthquake model is very similar to the four-earthquake model, with the primary difference being that this scenario suggests that the EQ III and EQ II events are actually the same seismic event, and in this model they are referred to together as EQ II. Like the four-event model, EQ I is likely one of the A.D. 746/749 or 757 events (with a calculated average of A.D. 751), EQ II is likely the large March 1068 event with a Gulf of Aqaba epicenter only 35 km away from Taba, and the third earthquake acknowledged in this trench, EQ III, is likely the 1546 or 1588 event (averaged to A.D. 1567). Thus, this seismic scenario also spans as much time as the four-earthquake scenario, 1262 years in all (A.D. 2013 - A.D. 751), but suggests that only three earthquakes ruptured the Taba Sabkha in as many years. The recurrence interval for the three-earthquake scenario is estimated to be approximately 421 years.

Finally, a recurrence interval for the two-earthquake scenario in the Taba Sabkha was calculated. Again, the oldest earthquake event identified through faulting in the Taba trench, EQ II, is dated to a mid-eighth century event in either 746/749 or 757 (average of A.D. 751). This scenario then dates the last earthquake to have ruptured the Taba Sabkha, EQ I, as the catastrophic A.D. March 1068 event. Considering that it has been 945 years since the Wadi ʻArabah fault ruptured under this model (A.D. 2013-1068), and that 317 years passed between EQ I and II, the recurrence interval for the two-earthquake scenario is estimated to be approximately 632 years.

Comparison to Previous Paleoseismic Studies in Southern Wadi ʻArabah

Considering the earthquake scenarios discussed as a part of this paleoseismic research, possible average recurrence intervals of 316 years, 421 years, and 632 years were calculated for the earthquake events present in the Taba Sabkha trench. As summarized in an earlier section, numerous paleoseismic studies were conducted along the Dead Sea transform at both the Shehoret fan site and in the Evrona playa in southern Israel over the last couple of decades. Taken together, these studies suggest a recurrence interval for large M > 6 earthquakes during the Pleistocene and Holocene epochs along the Wadi ʻArabah/Evrona fault is estimated to fall somewhere between 1200-2000 years (e.g. Gerson et al., 1993; Enzel et al., 1994, 1996; Amit et al., 1995, 1996, 1999, 2002; Porat et al., 1996, 2009; Zilberman et al., 2005). Amit et al. (1999, 2002) also suggest that the last large seismic event in the Wadi ‘Arabah occurred about 1000 yr BP, and propose that the most recent event exposed in their trenches is likely the large A.D. 1068 event that destroyed Early Islamic Ayla.

This model most closely agrees with the two-earthquake scenario presented here as a part of this dissertation research, where EQ III represents a mid-8th C. event, EQ II represents the A.D. March 1068 event, and what is referred to as EQ I is a result of sympathetic slip from movement along another fault in the region rather than another individual earthquake at Taba. However, the three-earthquake scenario is the preferred model presented here as being the most likely earthquake sequence for this section of the Wadi ‘Arabah fault, based on detailed paleoseismic trenching data from Taba. Thus, this suggests that the 16th C. earthquake that likely ruptured the Taba Sabkha either did not rupture the Evrona playa, or it ruptured a fault that has yet to be studied as the zone of active faulting is quite wide. There is also no evidence of a 16th C. rupture of the marginal faults present in the Shehoret fan. The large A.D. March 1068 earthquake, however, was significant enough to rupture the Wadi ‘Arabah Valley from Eilat to as far north as the Taba Sabkha. Further, the mid-8th C. event present in all three of the Taba Sabkha earthquake models discussed is also not specifically recognized in the paleoseismic trenches south of Taba, although a mid-8th C. event is recognized to have ruptured in the Jordan Valley to the north at the Galei Kinneret site in Israel (Marco et al., 2003). Marco et al. (2003) attribute the seismic damage at this site to the A.D. January 18, 749 earthquake, although because there is more than one mid-8th C. earthquake known to have affected the region, it is difficult to determine if this is the same earthquake that ruptured the Taba Sabkha.

Evidence of much older seismic events dating further back into the Holocene and even into the Pleistocene, however, is reported for paleoseismic trench sites south of Taba (e.g. Gerson et al., 1993; Enzel et al., 1994, 1996; Amit et al., 1995, 1996, 1999, 2002; Porat et al., 1996, 2009; Zilberman et al., 2005).

Paleoseismic differences between trenches can be explained, in part, by considering the various trenching locations within the DST fault zone. The 1200-2000 year seismic recurrence interval suggested by Amit et al. (1999, 2002) is a calculation based on combined data collected from numerous paleoseismic trenches within both the Evrona playa and along the Shehoret fan located on the western side of the Wadi ʻArabah Valley. The Taba site, meanwhile, consists of a single trench located approximately 20-28 km north of these Israeli paleoseismic sites, and is located on the far eastern side of the Wadi ʻArabah. Further, Keller and Pinter (1996) suggest that it is not uncommon to find that recurrence intervals between seismic events vary considerably for different fault segments within the same fault zone. They also cite a general lack of uniformity in earthquake frequency for fault zones composed of different fault segments (Keller and Pinter, 1996), as is the case with the Dead Sea transform. Based on their geographic locations and the distance between these paleoseismic sites within the complex DST fault zone, it is not surprising that earthquake events have ruptured various fault segments at different times, creating discrepancies in the paleoseismic record. McCalpin and Nelson (2009) also point out that historical records of large earthquakes, in particular, tend to show a substantial amount of variability in their spatial and temporal patterns of recurrence. Since any fault that ruptures up to or near the ground surface is considered to be the result of a large ($M > 6.5$) seismic event (McCalpin, 2009), all of the earthquakes present in the Taba Sabkha, the Evrona playa, and in the Shehoret fan paleoseismic trenches are subject to this variability. However, despite the paleoseismic differences between sites, these calculated recurrence intervals can still provide useful guidelines for land use planning, building codes, and engineering designs (Keller and Pinter, 1996) for structures within the southern Wadi ‘Arabah region.

Conclusions

The ability to evaluate present and future earthquake hazards is rooted in understanding seismogenic (earthquake producing) faults. This study has revealed evidence of the paleoseismicity of the Taba Sabkha which was poorly understood until now. Analysis of the paleoseismic data from the Taba trench suggests that there is faulting evidence for between two and four earthquakes occurring between the 8th century and 16th century in the southern Wadi ‘Arabah. Earthquake evidence exposed within the Taba trench also represents seismic events that are not easily observable in the city of Aqaba, Jordan located 35 km to the south of this trenching site as a result of urbanization. As urbanization continues to expand within the municipality of Aqaba, which has dramatically increased in recent years, it will be very important to be able to study locations outside of the city that can act as an analog for Aqaba seismicity.

The data collected from this study suggests that large ground rupturing earthquakes may occur more frequently along the Wadi ‘Arabah segment of the Dead Sea transform fault in the Taba Sabkha than previously understood. While seismic recurrence intervals for the southern section of the DST in the Evrona playa and Shehoret fan are estimated at approximately 1200 to 2000 years, radiocarbon dates and stratigraphic data within the Taba trench suggest a more frequent recurrence interval of between 632-316 years, at least along this portion of the complex DST fault. This new data from the Taba trench highlights an increased seismic hazard for the southern Wadi ‘Arabah Valley, particularly for the coastal cities of Aqaba, Jordan and Eilat, Israel.

Future work at this site will include the further elucidation of the uppermost faults present in the trench -- EQ I in the preferred three-earthquake model. Due to the trend of the Wadi ‘Arabah fault relative to the placement of the Taba trench, EQ I faults are currently only visible in the south trench wall, but not in the north wall. Since DST faulting in the Wadi ‘Arabah is arranged *en-echelon*, faults are often discontinuous and difficult to locate. It would be prudent, therefore, to conduct a ground penetrating radar investigation at this site prior to the excavation of additional trenches in order to non-invasively locate this most recent fault as it steps over. Contingent on the depth of the water table, continued excavation of the Taba trench to a greater depth would also allow older, more deeply buried seismic events to be investigated, ultimately lengthening the paleoseismic record for the Wadi ‘Arabah fault in the Taba Sabkha.

CHAPTER 5

SISTERS' SCHOOL TRENCH

Introduction and Motivation for Research

The second paleoseismology study conducted as a part of this dissertation research consisted of a geological survey of the Aqaba region in Jordan in order to locate and identify exposed segments of the Dead Sea transform fault. With construction and growth within the city of Aqaba at an all-time high, there were many newly opened building foundation trenches present at the time of this study in 2009 and 2010. With the permission of the on-sight construction crews, several of these trenches were examined in search of evidence of earthquake faulting. Open foundation trenches dug for the construction of a new building are large exposures that typically contain numerous cuts into the earth at various angles, which can allow for a quick assessment of whether or not a particular tract of land contains fault strands of the Dead Sea transform. Digging trenches in search of earthquake faulting is a time consuming and expensive process, and as discussed in an earlier chapter, within the city of Aqaba this is also becoming increasingly problematic as a result of intense urbanization (Rucker and Niemi, 2005). By being allowed to tour numerous foundation trenches and exposures, it was possible to more quickly narrow down locations where the DST has ruptured in the past and also where it has not.

While several foundation trenches were examined, earthquake faulting was identified within only one trench during the course of this study. At a site referred to herein as the

"Sisters' School" site, multiple earthquake faults were identified in the foundation trench walls, as was evidence of paleoliquefaction in the form of clastic sand and silt dikes. At the time of this survey, this trench had been seemingly abandoned by the construction crew, perhaps due to the large number of faults present at the site, or perhaps because funding for the construction project was pulled or had been exhausted. In the absence of any construction crew or land owner at the site, the Department of Antiquities of Jordan granted the Wadi 'Arabah Earthquake Project permission to conduct a paleoseismic survey within the Sisters' School trench since this geologic study was of a non-invasive nature.

Understanding exactly where and how often the Dead Sea transform has ruptured in the historic past within the now densely populated city of Aqaba is of the utmost importance for seismic hazard analysis and building code development. Even though the Dead Sea transform is seismically active, and the city of Aqaba is built directly along this major tectonic boundary, it is still difficult to identify exactly where the faults are located within the city. As discussed in Ch. 3 Early Islamic Ayla, the exact location where the Aqaba fault comes onto land is still unknown. Modern buildings, asphalt roads, and landscaping hide the seismic scars of the past, temporarily burying them out of sight. Thus, the motivation for this study is to further elucidate these faults within the city of Aqaba, to determine the last time they ruptured and how often they tend to do so, and to increase awareness of this active seismic zone with city officials and city planners. Dating the faults exposed at the Sisters' School site is also very important to understanding the history and chronology of earthquake faulting in the greater southern Wadi 'Arabah region.

Local Setting of Aqaba, Jordan

Located in the far southwestern corner of Jordan, the city of Aqaba lies approximately 320 km south of the capital city of Amman and is situated at the head of the Gulf of Aqaba/Eilat. Aqaba lies within the geographic coordinates of 29˚30' – 29˚40' N and 34˚59' – 35˚03' E, and is influenced by a relatively wet Mediterranean climate to the northwest, and a hot, arid climate to the south and east. As described in a previous chapter, Jordan typically has a short rainy winter, while the remainder of the year is warm and dry with temperatures often exceeding 40º C in the summer months. According to data from the Aqaba Meteorological Station (1955-2002), the average annual rainfall in Aqaba is less than 50 mm, yet despite the aridity there is a large freshwater aquifer only a few meters beneath the surface.

There are several drainage basins in the Aqaba region, but the largest drainage basin in the southern ʻArabah Valley is Wadi Yutim which reaches the furthest into the eastern plateau and covers over 4,545 km^2 (Foote et al., 2011). There are also several branches of the Wadi Yutim drainage basin that flow to the south toward the Gulf of Aqaba. Niemi and Smith (1999) mapped the alluvial fans of Aqaba and of the Wadi ʻArabah and identified three cycles of fan alluviation, entrenchment, and soil development. The two Holocene-aged fan progradations mapped as a part of this study correlate well with the archaeological record at 6 ka and 2-3 ka (Niemi and Smith, 1999).

Geological studies of the Aqaba area conducted by Mansoor (2002) and Slater and Niemi (2003) show the so-called "Aqaba fault" emerging from the Gulf of Aqaba on the far eastern side of the Gulf head and trending northeast underneath the city. The Aqaba fault borders the Gulf's east side in Jordan and dies out under the city of Aqaba where it is currently covered by rapidly growing urban development. Offshore, high resolution geophysical surveys conducted by Tibor et al. (2010) and Hartman (2012) also mapped several segments of the DST that are present within the Gulf of Aqaba (Figure 5.1). From the known location of the Aqaba fault, the DST steps west approximately 0.5 km to the West Aqaba fault. In the middle of the Gulf, the East Ayla fault and the Ayla fault are truncated by the Holocene surface suggesting they are not active (Hartman, 2012). The segments of the Dead Sea transform on the Israeli side of the Gulf of Aqaba include the Evrona fault (or Wadi ‘Arabah fault as it is called on the Jordanian side) along northwest-striking, normal-to-oblique slip faults (e.g. Amit et al., 1999), and the Eilat fault located on the far western side of the head of the Gulf (Hartman, 2012). The goal of this research is to further elucidate the various segments of the Dead Sea transform beneath the city of Aqaba, which will ultimately act to improve the earthquake catalogs for the region.

Paleoseismic Investigation of the Sisters’ School Trench

Methodology

The geological investigation for this study was conducted over the course of three field seasons in 2009 and 2010. The Sisters’ School site is so named because it is located adjacent to the Rosary Sisters’ School, an elementary school situated within the city of Aqaba, Jordan. This site is located approximately 1 km northeast of the head of the Gulf of Aqaba and approximately 1.3 km north of the archaeological site of Early Islamic Ayla (Figure 5.2). Each wall in the approximately 140 m by 100 m Sisters’ School trench was evaluated for faulting evidence using seismic indicators such as vertically offset stratigraphic units, units that mismatch abruptly across a fault line, the presence of sand-

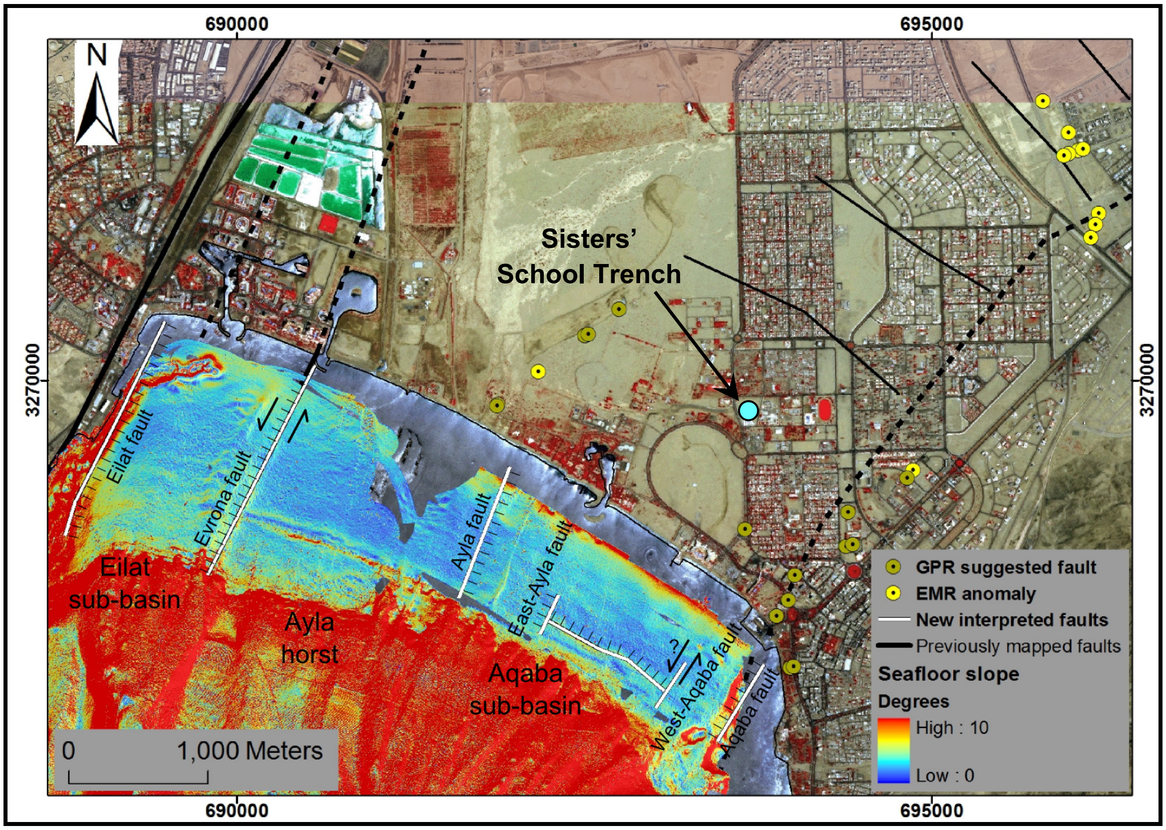

Figure 5.1 Location of Dead Sea transform faults mapped both offshore in the Gulf of Aqaba (white lines) and on land (dashed black lines). The solid back lines indicate transverse cross-faults mapped throughout the city of Aqaba, Jordan. Map from Tibor et al., 2010.

Figure 5.2 Location map of the Sisters' School site within the city of Aqaba, Jordan located at the head of the Gulf of Aqaba (Google Earth, 2013b).

filled fissures, and evidence of paleoliquefaction in the form of clastic dikes. The majority of faults present at this site were concentrated along the southern end of the trench, with half of these faults concentrated within only the southwest wall. Due to the sheer size of the site, the southwest wall became the primary trench wall of focus for this paleoseismic study (Figure 5.3), although all visible faults exposed in the trench were mapped and photographed.

In order to study the exposed faults at the Sisters' School site systematically, a grid system was first laid out on the southwestern wall of the site, and nails labeled both alphabetically and numerically were positioned at one-meter intervals horizontally and at half-meter intervals vertically. The main SW trench wall mapped at the site measures 27 meters in length and varies in height between 5 and 6 meters. This trench wall was first mapped in detail using photomosaic trench logging techniques (McCalpin, 2009). Each individual digital photograph was photo-rectified to remove any angle distortion present before being digitally stitched together to create a photomosaic of the trench wall. Trench log linework including stratigraphic units, contacts, and fault lines were described and drawn on top of the corrected photomosaic image in the field. Stratigraphic units were differentiated and described on the basis of grain size, sorting, lithology, type of boundary, degree of cohesion, structure, and color as determined from a Munsell® soil chart.

Although the southwest wall was mapped in the greatest detail, all faults and fractures in the exposed trench walls were mapped in an effort to better understand the seismicity of the region. A top plan of the entire site was also drawn to scale (Figure 5.4). The fault terminations and sedimentary units that could not be reached from the ground or by using a ladder were photographed and mapped using a "bucket truck" which allowed the stratigraphic units located highest up on the wall to be reached. All arrangements to use

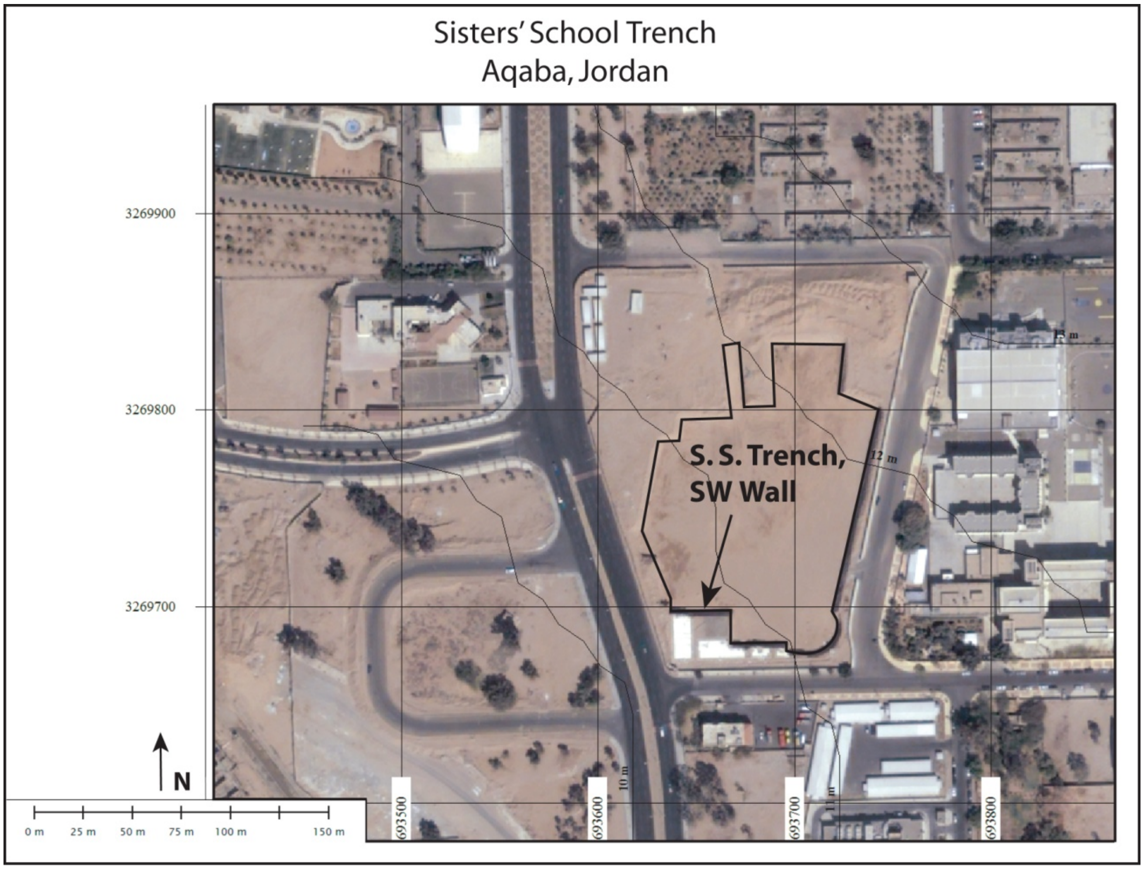

Figure 5.3 Location map of Sisters' School trench within the city of Aqaba, Jordan. The building foundation trench is outlined in black and the arrow points toward the southwest wall which contains the majority of faults identified at the site. Topographic contour lines, trending generally NW-SE, are shown with a 1 m contour interval.

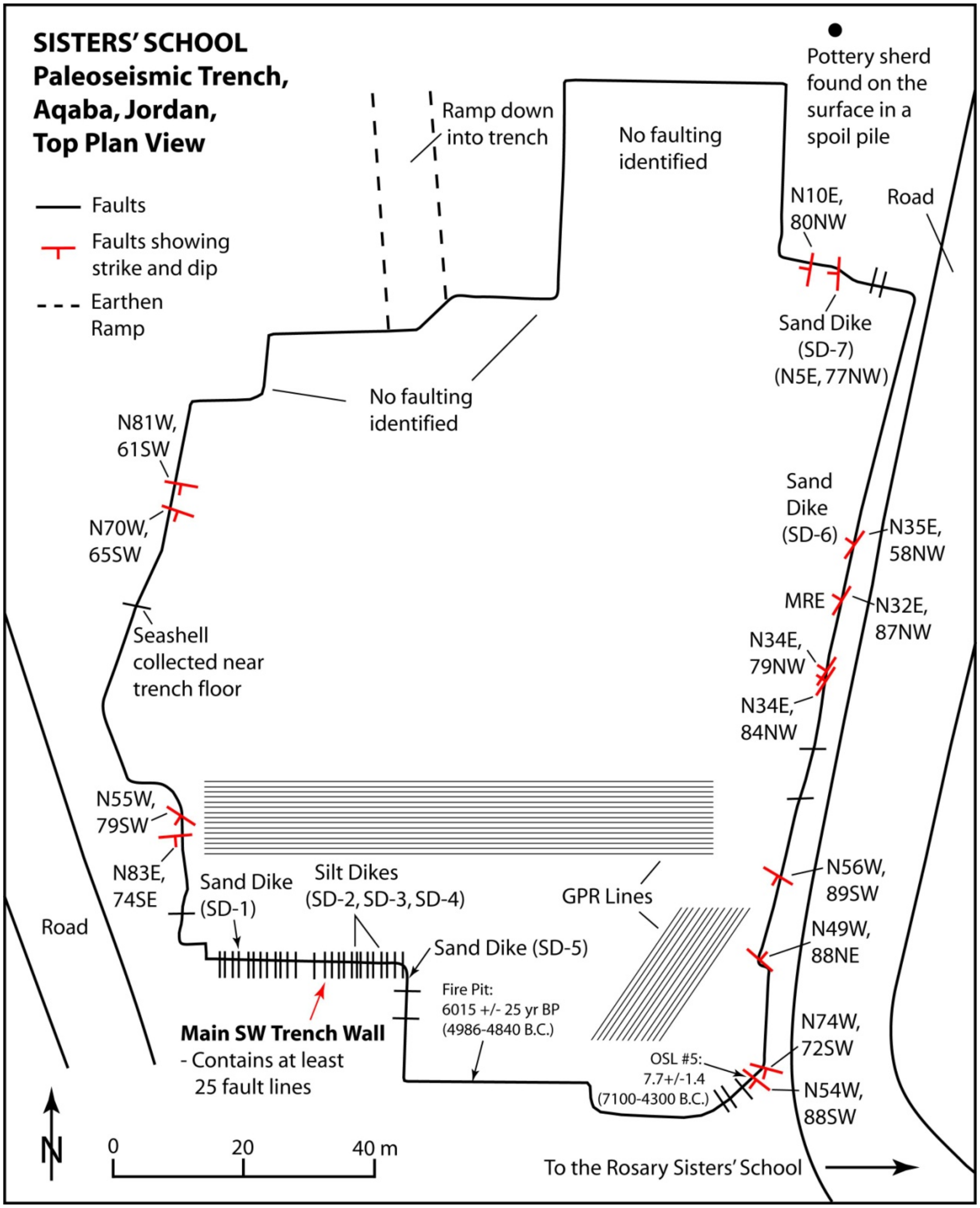

Figure 5.4 Top plan map of the Sisters' School trench within the city of Aqaba, Jordan. The building foundation trench is outlined in black, and a red arrow points toward the southwest wall that contains approximately half of all the faults identified at the site. Faults and dikes identified in the trench walls are marked with either a short black line or a red strike and dip symbol where available and where space would allow. Fault lines in black are drawn perpendicular to their respective trench wall for uniformity and do not indicate direction of strike.

this equipment, as well as all other logistical support required to work at this site, was facilitated by Dr. Sawsan Fakhri of the Department of Antiquities in Aqaba. Her assistance was paramount to the geological research success at this site.

Optically Stimulated Luminescence Dating

The Sisters' School site contains very little organic matter suitable for radiocarbon dating purposes. Therefore, in an effort to date the seismic events present in the Sisters' School trench, sediment samples were collected from within relevant stratigraphic horizons to be dated using optically stimulated luminescence (OSL). OSL is a dating technique that is useful for establishing the depositional age of sediments, and thus for determining the age of a capping stratigraphic unit, in the absence of datable organic material. OSL dating is a form of geochronology that measures the energy of photons being released from individual silicate mineral grains, primarily quartz and potassium feldspar (Aitken, 1998). As sediment is transported by wind, water, or ice, it is exposed to sunlight, bleached, and zeroed of any previous luminescence signal. Once this sediment is deposited and subsequently buried, it ceases being exposed to sunlight and is exposed to low levels of natural radiation (U, Th, Rb) in the surrounding sediment (Aitken, 1998). Through geologic time, quartz and feldspar minerals accumulate a luminescence signal as ionizing radiation excites the electrons within parent nuclei in the mineral grain's crystal lattice. A certain percentage of the freed electrons become trapped in defects or holes in the crystal lattice and accumulate over time (Aitken, 1998). This stored radiation dose can be "evicted" with stimulation and released as luminescence. The calculated age of an OSL date is the time since the last exposure of that sediment to sunlight. As time passes, the luminescence signal increases through exposure to the ionizing radiation and cosmic rays. Luminescence dating is based on quantifying both the radiation dose received by a sample since its zeroing event, and the dose rate which it has experienced during the accumulation period after deposition.

OSL samples are light-sensitive and must be collected in a dark, controlled environment. In order to insure that sediment samples were not contaminated by sunlight exposure during collection, samples were carefully collected from beneath layers of dark sheets using a 20 cm-long and 7 cm-wide PVC tube cut to length (Figure 5.5). Once the protective sheets were hung over the area to be sampled, the sediment was cleaned back approximately 5-6 cm into the trench wall. The PVC tube was then hammered into the specific stratigraphic unit to be sampled, forcing sediment into the sample tube. Lastly, layers of duct tape were placed over each end of the tube before being removed from beneath the protective cover.

In the lab, the portion of each sediment sample used for OSL dating purposes was collected from the center of the tube in a darkroom environment by Dr. Naomi Porat at the Geological Survey of Israel in Jerusalem. Quartz samples (88-125 µm) were etched by soaking in concentrated hydrofluoric acid for forty minutes. The De value, or equivalent dose, was obtained by using the single aliquot regeneration (SAR) dose protocol, using preheats of 10 seconds at 220-260 ˚C. The moisture content of each sample collected from the site was estimated at 2%. At first, thirteen 5 mm aliquots were measured for samples SS-1 through SS-5. Aliquots, as far as OSL dating is concerned, are the portion of a sediment sample taken or collected for analysis. All samples had a typical fluvial dose distribution, with some of the older aliquots indicating incomplete bleaching of the quartz grains.

Figure 5.5 Collecting sediment samples to be dated using optically stimulated luminescence (OSL) along the southwest trench wall using a bucket truck supplied by the Department of Antiquities in Aqaba, Jordan. OSL samples were collected from beneath layers of dark sheets to avoid contamination (bleaching of sediment grains) by exposure to sunlight.

The more scattered samples, SS-2, SS-4, and SS-5, were measured again using twenty-four 2 mm aliquots to isolate the younger population of sediment grains. For those samples, the 5 mm aliquots were not used in age calculations. Samples SS-6 and SS-8 were measured at first using 3 mm aliquots. Sample SS-6 had a clear population containing 60% aliquots, and this was used for age calculation. Sample SS-8 had ages that measured as high as 17 ka, which indicates that the measured sample contained both old and unbleached grains. In this case, the youngest age population was used. Currently, seven OSL samples have been dated and are reported in Table 5.1.

Radiocarbon Dating

An ashy sediment sample containing fragments of charcoal, sample RC-SS #1, was collected from a fire pit exposed in cross-section in the south trench wall (Figures 5.6 and 5.7) for radiocarbon analyses by the Center for Accelerator Mass Spectrometry (CAMS) at the Lawrence Livermore National Laboratory in California. This single radiocarbon date was calibrated to a two sigma probability using the CALIB Radiocarbon Calibration 7.0 program and included the IntCal13 curve selection (Reimer et al., 2013). This radiocarbon date is reported in Table 5.1.

TABLE 5.1

GEOCHRONOLOGY OF SISTERS' SCHOOL TRENCH, AQABA, JORDAN: OPTICALLY STIMULATED LUMINESCENCE (OSL) DATING RESULTS

Sample No.	Location in Trench	Strat. Unit	Depth (m)	Total Dose (μGy/a)	Age (ka)	Calendar Age (B.C.)
OSL-1	SW Wall, Meter 4	SS-7	2.25	2522 ± 39	7.6 ± 0.6 (8200-7000)	6200-5000
OSL-2	SW Wall, Meter 21	Dike SD-1	6.0	2711 ± 48	6.9 ± 1.7 (8600-5200)	6600-3200
OSL-3	SW Wall, Meter 14	SS-5	2.25	3108 ± 42	6.0 ± 0.3 (6300-5700)	4300-3700
OSL-4	SW Wall, Meter 18	SS-10	3.0	2894 ± 44	6.6 ± 1.6 (8200-5000)	6200-3000
OSL-5	SE Wall, Corner	SS-7	3.5	2786 ± 43	7.7 ± 1.4 (9100-6300)	7100-4300
OSL-6	SW Wall, Meter 8	SS-3	1.5	3198 ± 41	3.3 ± 0.6 (3900-2700)	1900-700
OSL-8	SW Wall, Meter 1	SS-2	1.0	2779 ±38	5.2 ± 1.1 (6300-4100)	4300-2100

RADIOCARBON DATING RESULTS

Sample No.	Location in Trench	Laboratory Sample No.	Measured Radiocarbon Age	δ13C	Conventional Radiocarbon Age	Tree-ring Calibrated Age
RC-SS #1	Ash from Fire Pit in South Wall	CAMS 152243	6015 ± 25 yr BP	-16.22	6015 ± 25 yr BP	4986-4840 Cal B.C.

The radiocarbon age has been calibrated to calendar years with the CALIB 7.0 online calibration program using a 2 sigma range probability and IntCal13 curve selection (Reimer et al., 2013).

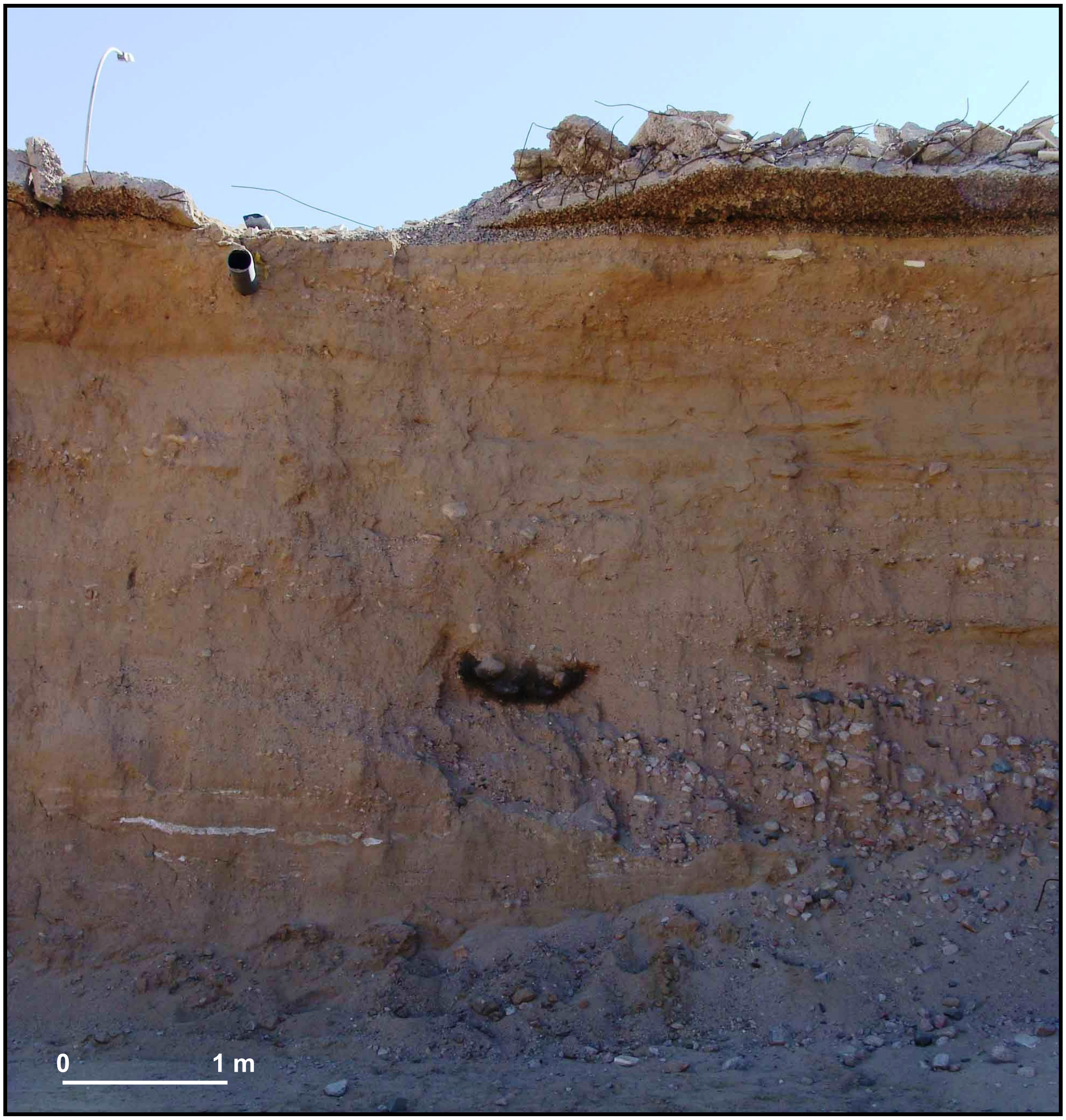

Figure 5.6 Fire pit exposed in cross-section in the south wall of the Sisters' School trench.

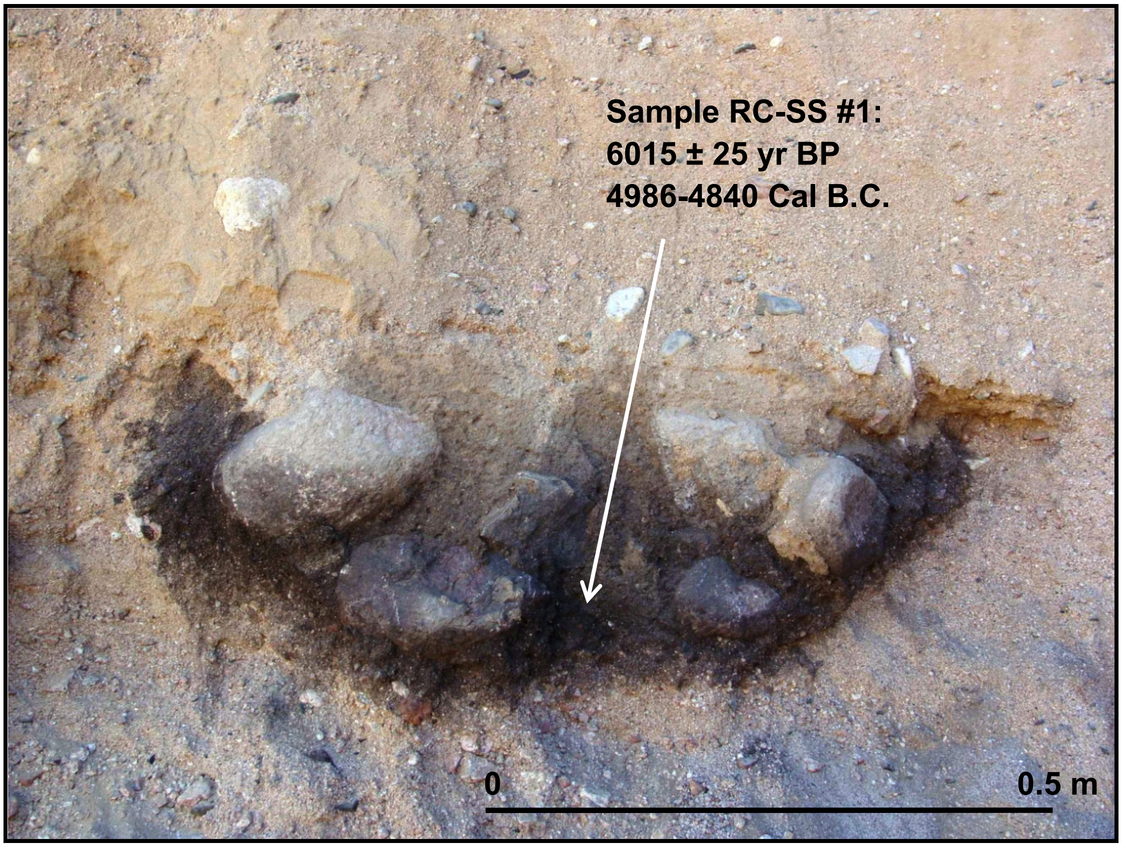

Figure 5.7 Close-up of the fire pit exposed in cross-section in the south wall of the Sisters' School trench showing the location of charcoal collected for radiocarbon dating.

Results

Sedimentological and Faulting Sequence of Sisters' School Deposits

Paleoseismic events in the Sisters' School trench were identified on the basis of primary coseismic evidence including upward-terminating faults, fissures, offset stratigraphic units, and offset channel deposits identified in the trench wall exposures (e.g. McCalpin and Nelson, 2009) (Figure 5.8). The stratigraphic expression of primary post-seismic evidence at this site consisted of a fissure fill present in meter 1 and 2 of the southwest trench wall where a fault ruptured the ground surface. An examination and analysis of the trench stratigraphy suggests that exposed in the Sisters' School trench walls there is evidence for at least five separate faulting events. The identified paleoseismic events are numbered sequentially with EQ I being the most recent event (MRE) exposed within the Sisters' School trench and EQ V as the oldest.

The lower stratigraphic sequence at the Sisters' School site (Figure 5.9) consists primarily of interbedded fine- to medium-grained units of sand and silt that were washed down the Wadi 'Yutim basin from distal alluvial fan runoff originating from the Precambrian granitic mountains located to the northeast and east of the study site. The upper stratigraphic units at the site are much more coarse-grained in nature. They largely consist of upward fining sequences of fluvial deposits that consist of cobbles, pebbles, granules, coarse-, medium- and, in places, fine-grained sands. Also present in the trench stratigraphy are numerous smaller channel deposits of medium- to coarse-grained sands and pebbles with some cobbles. The presence of channels and the larger fluvial deposits in the upper section of the trench wall indicate that both small to substantial flooding events occurred periodically at this location in the past.

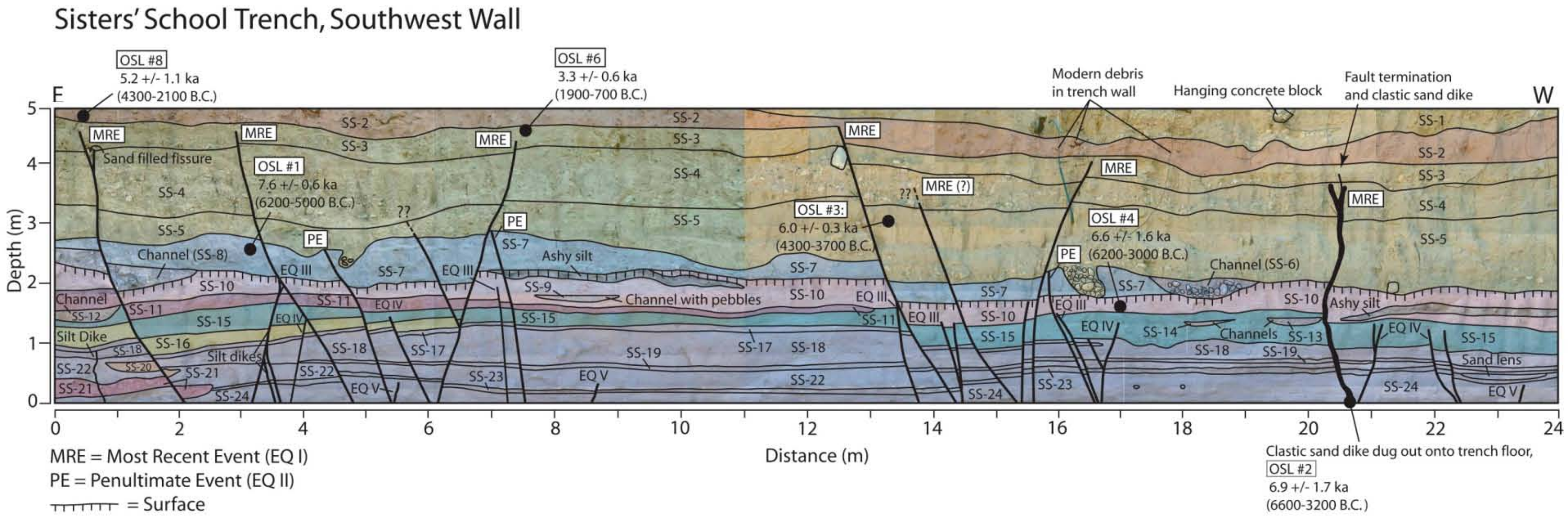

Figure 5.8 Cross-section of the southwest trench wall at the Sisters' School site in Aqaba, Jordan showing faulting, stratigraphic offset, OSL dates, and evidence of paleoliquefaction in the form of sand and silt dikes.

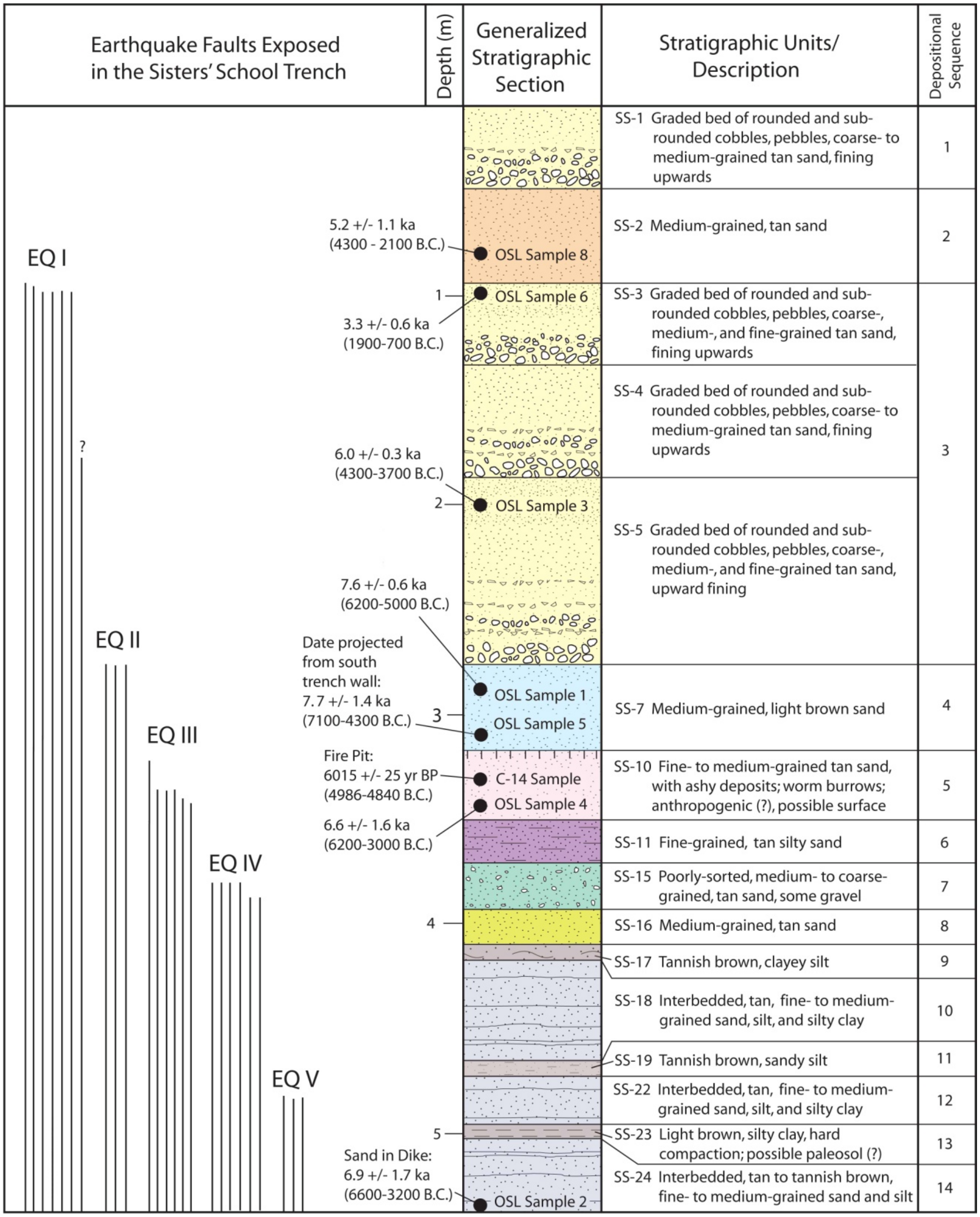

Figure 5.9 Paleoseismic faulting and a generalized stratigraphic section of the Sisters' School southwest trench wall in Aqaba, Jordan. Colored stratigraphic units correlate to the colored cross-section of the SW trench wall (see Figure 5.8).

At a depth of 5.5 m, the basal sedimentary units in the Sisters' School trench include alternating beds of tan to tannish-brown, fine- to medium-grained sand, silt, and silty sand (units SS-24, SS-22, SS-18), a unit of light brown silty clay (SS-23), and units of tannish-brown sandy silt or clayey silt (units SS-19, SS-17). Unit SS-23 has a particularly hard compaction and has been interpreted as a possible paleosol. The oldest of the faulting events identified at the Sisters' School site, EQ V, ruptures as high as unit SS-22 in the southwest wall and is capped by unit SS-19. Unit SS-16, a bed of tan, medium-grained sand then caps all of these basal units, but is only present toward the eastern side of the southwest trench wall. Situated stratigraphically above unit SS-16 is unit SS-15, a tan, poorly-sorted, medium- to coarse-grained sand containing gravel in places. Unit SS-15 contains a lens of fine-grained sand, unit SS-14, and two small channels, units SS-13 and SS-12. Channels SS-13 and SS-12 contain coarse-grained sand and pebbles, and SS-13 also contains a few cobbles. After deposition, all of these lower stratigraphic units, SS-24 though SS-15, were faulted by EQ IV. Faulting evidence for both EQ V and EQ IV includes vertically offset stratigraphic units, mismatched unit thicknesses across fault lines due to strike-slip motion, and upward fault terminations.

Unit SS-11 is a tan, fine-grained silty sand that is present in the eastern half of the southwest trench wall but pinches out at the boundary between meter 13 and 14. This sand acts to cap EQ IV faults on the eastern end of the trench wall. This layer is then overlain by unit SS-10, a tan, fine- to medium-grained ashy sand that contains concentrated lenses of ashy silt throughout. This particular stratigraphic layer also contains numerous worm burrows, and a small channel (SS-9) with pebbles and coarse-grained sand runs through the center of this layer around meters 8-9 in the trench wall. Unit SS-10 is interpreted as an "anthropogenic layer" because it contains a visible component of ash across the length of its exposure, presumably ash deposited from camp or cooking fires built in antiquity. Unit SS-10 can also be traced further to the east, past the edge of the southwest trench wall, to the south trench wall at the Sisters' School site. At a depth of approximately 3.5 m from the ground surface, a clearly defined fire pit is exposed in cross-section within unit SS-10 (see Figures 5.6 and 5.7), helping to explain the abundance of ash in this layer. The upper boundary of unit SS-10, as can be seen on the trench cross-section (Figure 5.8), is interpreted as a possible archaeological surface. A charcoal sample collected from the fire pit was radiocarbon dated and will be discussed in an upcoming section.

All EQ III faults terminate within the lower to middle portion of unit SS-10, the anthropogenic layer, which is capped by unit SS-7, a light-brown, medium-grained sand, likely aeolian in nature. Layer SS-7 is cut by cobble-rich channels and either pinches out naturally or was scoured away on the western end of the trench wall starting in meters 18 and 19. Stratigraphically situated above these finer-grained deposits, unit SS-5 is an upward fining, graded bed of rounded and sub-rounded cobbles, pebbles, coarse-, medium-, and fine-grained sands. This layer is more than a meter thick in places, particularly toward the western end of the trench wall, and thins to the east. All EQ II faults terminate at the contact between unit SS-7 and the overlying fluvial unit SS-5. It appears that a portion of unit SS-7 was scoured away during the higher energy depositional phase of unit SS-5, along with the upper fault terminations of EQ II, because the faults now abruptly stop at the SS-7/SS-5 contact.

Overlying unit SS-5, layer SS-4 is also an upward fining, graded bed of rounded and sub-rounded cobbles, pebbles, and coarse- to medium-grained sands, but it does not contain any fine-grained sand. Unit SS-3 is very similar to unit SS-5 and consists of an upward fining, graded bed of rounded and sub-rounded cobbles, pebbles, coarse-, medium-, and fine-grained sands. Most MRE (most recent event) or EQ I faults, six in all, terminate within stratigraphic unit SS-3. The one exception to this is the fault found in meter 14 in the southwest wall that cuts up into the lower portion of unit SS-4 and terminates at a depth of approximately 1.5 m from the top of the trench wall. This fault is either an EQ I fault that did not rupture as close to the ground surface as all of the other MRE faults, or it represents a different faulting event altogether that is represented nowhere else in the Sisters' School southwest trench wall. This fault cannot be categorized as an EQ II fault as previously described because it cuts much high than the EQ II terminations, which all seem to have been partially scoured away by the deposition of unit SS-5 over unit SS-7.

Units SS-5, SS-4, and SS-3 are clearly fluvial in nature based on their upward fining depositional sequence, and because they are composed of individual clasts ranging in size from large cobbles to fine-grained sand. Together these units represent a significant change in the type of deposition for this coastal region in antiquity. Unit SS-2, a tan, medium-grained sand, approximately 0.5 m thick, overlies this fluvial sequence and is likely aeolian. Layer SS-2 caps all EQ I (MRE) faults and is the oldest unit not faulted in the southwest trench wall. Finally, overlying SS-2 is unit SS-1, the uppermost stratigraphic unit exposed in the southwest trench wall at the Sisters' School site. Layer SS-1 is another fluvial deposit of upward fining, rounded and sub-rounded cobbles, pebbles, and coarse- to medium-grained sands.

Paleoliquefaction Evidence

Seven clastic dikes were identified in the stratigraphy of the Sisters' School trench walls and are interpreted as evidence of paleoliquefaction. As discussed in an earlier chapter, liquefaction is a process by which unconsolidated sediments temporarily behave as a liquid as ground water rises to the surface because of an increase in pore pressure in the ground due to intense seismic shaking (e.g. McCarthy, 2002; Boulanger and Idriss, 2006). The largest dike exposed in the main southwest wall, SD-1, is a clastic sand dike located in meter 21. Dike SD-1 is 2.5-6 cm wide in cross-section and reaches to a height of 3.8 m above the trench floor. This fluidized sand migrated up along the EQ I fault line in the same meter and terminates a few centimeters below this EQ I fault termination (Figures 5.10, 5.11). The layered fabric of SD-1, with fine- to medium-grained sand along the outside edges of the dike and medium-grained sand in the center, suggests there may have been two injection events within this dike, and likely a reactivation of the associated fault (Figure 5.12).

Three smaller clastic dikes composed of silt and sandy silt are also exposed in the southwest trench wall. Two of these silt dikes, SD-2 and SD-3, are located in meter 4 and are 1-2 cm wide and up to 2 m tall as measured from the bottom of the trench floor. These dikes follow the EQ III fault line also present in the same meter. The fourth dike, SD-4, is a small silt dike located in meter 1 of the southwest trench wall. At 1-1.5 cm wide and only 0.85 m tall as measured from the foundation trench floor, dike SD-4 is the smallest dike identified at the Sisters' School site. All of these liquefaction features were mapped and photographed in detail (Figure 5.13).

Three other sand dikes were also identified within the remaining trench walls at the Sisters' School site. Around the corner and to the east of the main southwest trench wall,

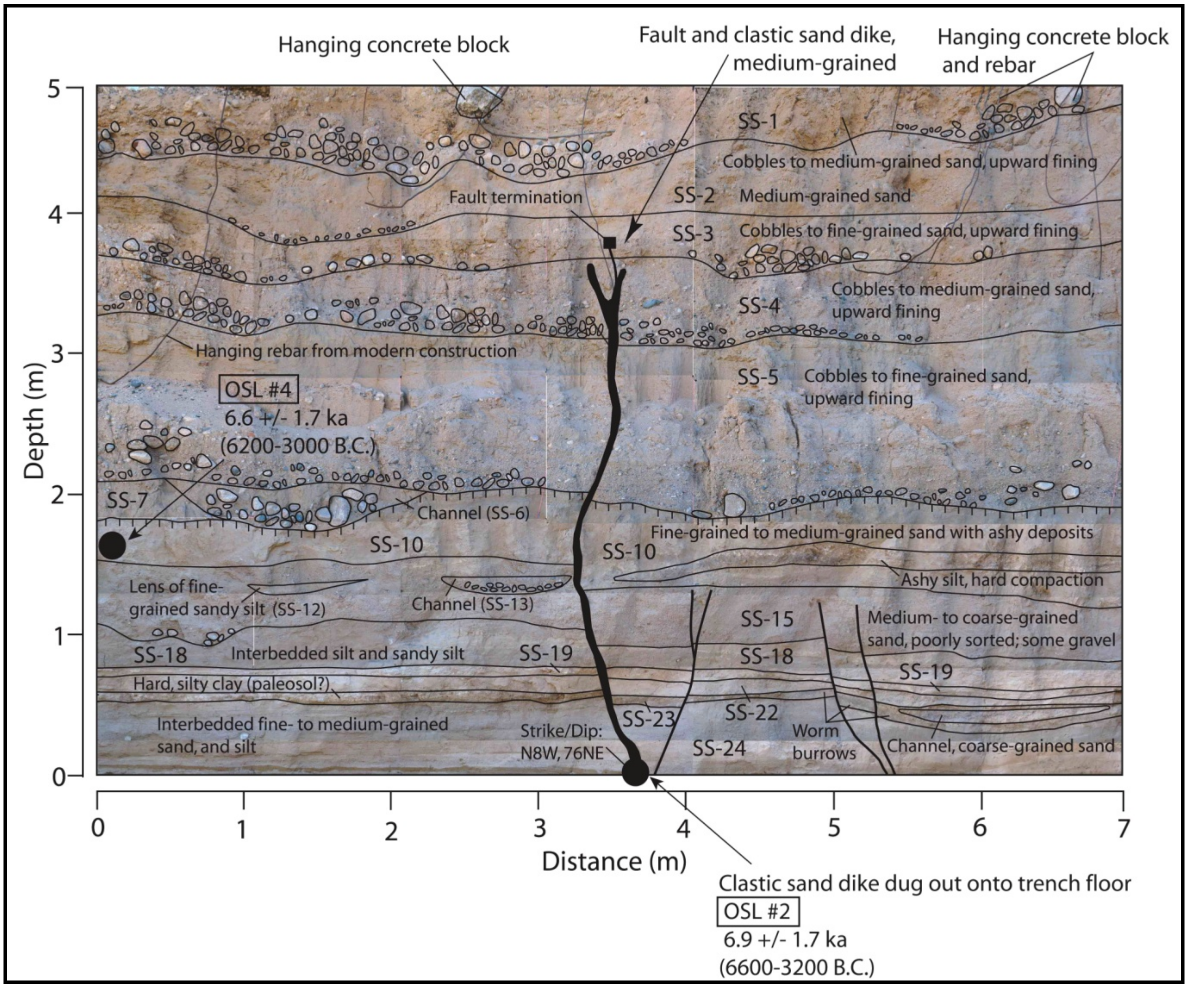

Figure 5.10 Clastic sand dike SD-1 and associated EQ I (MRE) fault located in the southwest wall of the Sisters' School trench. The dike is 2.5-6 cm wide in cross-section and reaches approximately 3.8 m above the ground surface of the trench floor.

Figure 5.11 Photograph of clastic sand dike SD-1 located in meter 21 of the southwest wall of the Sisters' School trench.

Figure 5.12 Photograph of clastic sand dike SD-1 showing the fluidization of sand as it moved toward the surface from depth. Note the layered composition of sand within SD-1 (fine- to medium-grained sand present along the outside edges of the dike and medium-grained sand in the center) which suggests there may have been two injection events within this dike in antiquity.

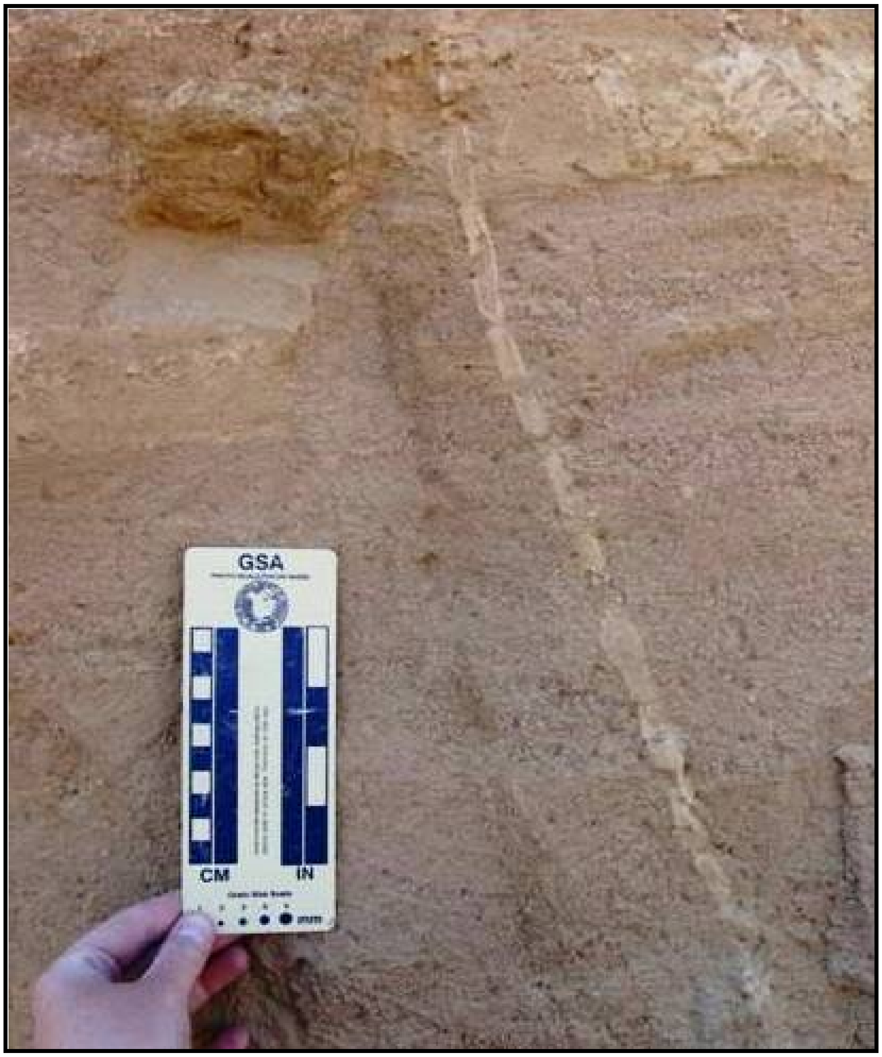

Figure 5.13 Photograph of clastic silt dikes SD-2 and SD-3 located in meter 16 of the southwest wall of the Sisters' School trench. Both dikes are 1-1.5 cm wide as exposed in cross-section and reach 2 m above the surface of the trench floor.

sand dike SD-5 was documented during the geologic survey of this site. Dike SD-5 is approximately 10-15 cm wide and 3 m in height as measured from the surface of the trench floor. This dike is difficult to photograph as it trends approximately N-S in the same direction as the cut of the wall in which it is situated. Dike SD-6 is a sand dike, approximately 5-6 cm thick, located toward the center of the east trench wall at the Sisters' School site. Like dike SD-5, this dike also trends roughly in the same direction as the cut of this wall, and is difficult to measure and photograph as a result. Based on the geometric configuration of this paleoliquefaction feature, for example, excavating approximately 0.3 to 0.5 m further (deeper) into the eastern trench wall of the site in this location would expose this sheet dike in planar view.

The last clastic sand dike identified at the Sisters' School site, SD-7, is located in the far northeast trench wall. At approximately 20-25 cm wide as exposed in cross-section, dike SD-7 is the largest dike documented at the site. It measures 3.5-4 meters in height from the surface of the foundation trench floor and trends N5˚E.

Numerical Dating of Seismic Events

Due to a lack of obvious organic material within the Sisters' School trench walls, the majority of the stratigraphic units at the site were dated using optically stimulated luminescence (OSL). One charcoal-rich sediment sample, however, was collected from the fire pit exposed in cross-section in the south trench wall for radiocarbon dating. As discussed in the previous chapter, in order to properly bracket the timing of individual paleoearthquakes, an age is needed for the youngest datable unit deformed by the earthquake and for the oldest datable unit that caps or buries evidence of the seismicity in question (e.g.

McCalpin et al., 2009). The stratigraphic locations of the six dated OSL samples and the single radiocarbon dated charcoal sample acquired from the site are illustrated on the Sisters' School trench log and on the generalized stratigraphic section (Figures 5.8 and 5.9).

Collected from unit SS-2 in the southwest trench wall, the oldest capping unit overlying all EQ I (MRE) faults, OSL sample #8 produced a date of 5.2 +/- 1.1 ka (4300-2100 B.C.). All faults from EQ I cut through unit SS-3 located stratigraphically below SS-2, with the single exception of the fault present in meters 14 and 15 in the southwest wall, which terminates within the lower portion of unit SS-4. This fault is likely an EQ I fault that did not rupture all the way to the surface. It could, however, potentially represent an entirely separate faulting event, but since no other faults rupture to this same stratigraphic horizon in the SW wall, this scenario is less likely. Also collected from above the MRE in the southwest wall, OSL sample #6 is a sediment sample from the upper portion of unit SS-3 that dates to 3.3 +/- 0.6 ka (1900-700 B.C.). However, considering the remaining dated OSL samples collected from the trench wall, and the age of the overlying OSL sample #8 (4300-2100 B.C.) which should be younger than OSL #6 based on superposition, the OSL #6 date is out of sequence with the rest considering stratigraphic placement and depth. Based on the sensitive nature of OSL samples to light-exposure, this particular sample could have potentially been contaminated during either collection or analyses. Therefore, based solely on OSL sample #8, it seems most likely that the MRE or most recent seismic event that ruptured the Sisters' School in antiquity occurred prior to a date of 4300-2100 B.C. when unit SS-2 was deposited.

The next seismic event visible in the trench wall is EQ II which cuts as high as unit SS-7. All three EQ II fault terminations were scoured away by the deposition of unit SS-5, an upward fining fluvial sequence that yielded a date of 6.0 +/- 0.3 ka (4300-3700 B.C.), based on OSL sample #3. The penultimate event (EQ II) at the Sisters' School site, therefore, occurred prior to a date of 6.0 +/- 0.3 ka (4300-3700 B.C.) when unit SS-5 was deposited. OSL sample #3 also helps to constrain the possible date range for EQ I since the MRE occurred after units SS-5 (with an age of 6.0 +/- 0.3 ka or 4300-3700 B.C.), SS-4, and SS-3 were all deposited. Below unit SS-5, a sediment sample (OSL #1) collected from unit SS-7 was dated to 7.6 +/- 0.6 ka (6200-5000 B.C.). Since all EQ II faults ruptured to the top of unit SS-7, at least to as high as the portion of this unit that remains after the scouring depositional event of fluvial unit SS-5, EQ II must have occurred after a date of 6200-5000 B.C. (OSL #1), but before a date of 4300-3700 B.C. (OSL #3).

EQ III, the next earthquake event visible in the SW trench wall, can be constrained by considering the OSL dates acquired from sediment samples collected from unit SS-7, the oldest unit capping EQ III, and from unit SS-10, the youngest unit deformed by EQ III. Since all EQ III faults rupture into unit SS-10, this earthquake must have occurred after a unit SS-10 was deposited around 6.6 +/- 1.6 ka (6200-3000 B.C.) based on OSL sample #4, but before unit SS-7 was deposited which dates to 7.6 +/- 0.6 ka (6200-5000 B.C.) based on OSL sample #1. However, since unit SS-7 overlies SS-10, and since they have age ranges that overlap, OSL sample #1 (6200-5000 B.C.) from unit SS-7 can be used to constrain the large age range of the sediment dated in unit SS-10 from OSL sample #4 (6200-3000 B.C.). Given that the youngest possible age of unit SS-7 is 5000 B.C., and the youngest possible age of unit SS-10, which is positioned stratigraphically below unit SS-7, is 3000 B.C., unit SS-10 cannot be younger than this overlying unit based on superposition. No major tectonic folding or upheaval has occurred at this site to overturn the strata since these units were deposited. Unit 10, therefore, must be constrained to the same age range (or very near the same age range) as unit SS-7. Likewise, unit SS-7 cannot be older than unit SS-10 for the same reason, and thus the possible age range of unit SS-10 is constrained to 6200-5000 B.C. rather than 6200-3000 B.C. based on the OSL dates provided. Given this modified age range for OSL sample #4, units SS-7 and SS-10 could have potentially been deposited as many as 1200 years apart to as closely as months, weeks, or even days apart, depending on the specific depositional environment at the Sisters' School site at the time.

The single radiocarbon date collected from the Sisters' School site, RC-SS #1, also helps to constrain the age of unit SS-10, as well as unit SS-7. The dated charcoal fragments were collected from the bottom of a fire pit exposed in cross-section that was discovered in the south wall of the foundation trench. While the south trench wall was not mapped in extensive detail like the southwest wall, this anthropogenic feature was traced to the west and correlates to unit SS-10, the ashy, anthropogenic layer mapped in the main SW wall at the site. This charcoal-rich sediment sample yielded a radiocarbon date of 6015 +/- 25 yr BP (4986-4840 B.C.), which is in agreement with the original OSL sample #4 date range (6200-3000 B.C.), and agrees even more closely to the unit SS-10 constrained date which was determined to be 6200-5000 B.C. Therefore, as far as the seismicity in question is concerned, EQ III must have occurred sometime after the deposition of unit SS-10, dated to 6200-5000 B.C. based on both radiocarbon and OSL dates, but before unit SS-7 was deposited. Since unit SS-7 post dates both the deposition of the fire pit in 4986-4840 B.C., it must be younger than this date or very close in age, likely ~5000 B.C., given the OSL sample #1 range of 6200-5000 B.C. Since both the last unit cut by EQ III (SS-10) and the oldest overlying non-deformed unit (SS-7) date to approximately the same age range (although SS-7 has to be at least slightly younger), unit SS-7 was likely deposited shortly after EQ III occurred in or around 5000 B.C.

This dating information also acts to constrain the date of EQ II even further. Since OSL sample #1 (6200-5000 B.C.) collected from within unit SS-7 must be closer in age to 5000 B.C. considering the radiocarbon date of the underlying fire pit in unit SS-10, EQ II must have occurred after the deposition of unit SS-7 in or around 5000 B.C., but before unit SS-5 was deposited in 4300-3700 B.C.

One other OSL sample, OSL #5, collected from above a fault in the southeast corner of the Sisters' School trench located to the east of the main SW wall, also dates unit SS-7. OSL sample #5 was dated to 7.7 +/- 1.4 ka (7100-4300 B.C.), and while this date does agree with the age determined by OSL sample #1 (7.6 +/- 0.6 ka or 6200-5000 B.C.) collected from unit SS-7 in the SW wall, it provides an age range of nearly 3000 years for this sedimentary unit. As just discussed, OSL #1 likely dates closer to 5000 B.C., so this should be the case for OSL sample #5 as well based on its stratigraphic position. Therefore, while OSL #5 does not further refine the date of the seismicity in question, it does serve to corroborate the possible age of unit SS-7.

Finally, the faulted stratigraphy and OSL dates were studied in order to determine the paleoseismic chronology of both EQ IV and EQ V identified in the Sisters' School trench. The highest stratigraphic unit ruptured by EQ IV is unit SS-15, which is overlain by unit SS-10. This fourth seismic event can be partially constrained by OSL sample #4 (collected from unit SS-10) since this sediment sample dates the oldest overlying stratigraphic unit not deformed by EQ IV. Considering the constrained date range discussed previously for OSL sample #4 (6200-5000 B.C.), as well as the radiocarbon dated charcoal

(RC-SS #1) collected from the south wall within the same stratigraphic horizon as SS-10 in the southwest wall (6015 +/- 25 yr BP or 4986-4840 B.C.), EQ IV must have occurred prior to a date of 6200-5000 B.C.

The only other OSL sediment date that is currently available to help provide a lower boundary age range for this earthquake event is OSL sample #2. This sediment sample was collected from the base of the 3.8 m tall sand dike (SD-1) located in meter 21 of the SW trench wall as it was traced out onto the floor of the trench. This OSL sample returned a date of 6.9 +/- 1.7 ka (6600-3200 B.C.), and represents the age range of a buried, medium-grained sand unit that is currently not exposed in the southwest wall, other than within the sand dike itself. During the MRE (EQ I) event, sand from depth was forced to the surface as it became liquefied as a result of seismic ground shaking. Considering the previous discussion concerning the constrained age of OSL sample #4, OSL sample #2 must be older than 5000 B.C., and at least the same age or younger than 6600 B.C., the lower age range determined from the OSL analysis of sample #2. Further, considering the number and type of stratigraphic units situated stratigraphically above the sand unit that once fed the SD-1 dike, primarily fine-grained sands and silts with a possible paleosol, it is likely that the age of this buried sand unit is toward the middle or lower (older) end of the constrained 6600-5000 B.C. age range. EQ IV, therefore, occurred before unit SS-10 was deposited in approximately 5000 B.C., and after the deposition of a buried sand unit with a possible age range of 6600-5000 B.C.

Similarly, the age of the fifth seismic event (EQ V) mapped within the Sisters' School southwest trench wall, which ruptures as high as unit SS-22, can only be approximated as happening sometime before EQ IV occurred, but after the deposition of the buried sand unit that was brought up from depth in the form of the SD #1. Again, the sand dike dates to 6.9 +/- 1.7 ka (6600-3200 B.C.) based on OSL sample #2, but can be constrained to approximately 6600-5000 B.C. because of younger, overlying layers and the fire pit radiocarbon date of 6015 +/- 25 yr BP (4986-4840 B.C.) in unit SS-10.

Strike and Dip Measurements

Strike and dip measurements were collected along fault lines where it was possible to expose a suitable fault plane, primarily within the finer-grained, lower stratigraphic units exposed in the Sisters' School trench, as opposed to the coarser, fluvial sediments located further up in the stratigraphic section. Out of the approximately fifty faults identified within the Sisters' School trench, twenty-five strike and dip measurements were collected over the course of three field seasons (see Figure 5.4). A rose diagram was constructed to visually represent the direction of strike for these various faulting events (Figure 5.14). An evaluation of these measurements indicates that the primary direction of strike for the faults that ruptured through this site in antiquity trend within a few degrees either to the east or west of north. Eighteen of the twenty-five strike measurements collected fall between N10˚W and N35˚E. This data suggests that these particular faults follow the general NE-SW trend of the DST, usually reported to be approximately N15˚E or so. The remaining measurements of strike collected from the Sisters' School trench, six of which fall between N50˚W and N81˚W indicate the presence of a transverse cross-fault trending through the site roughly perpendicular to the NE-SW trending strike-slip faults of the DST.

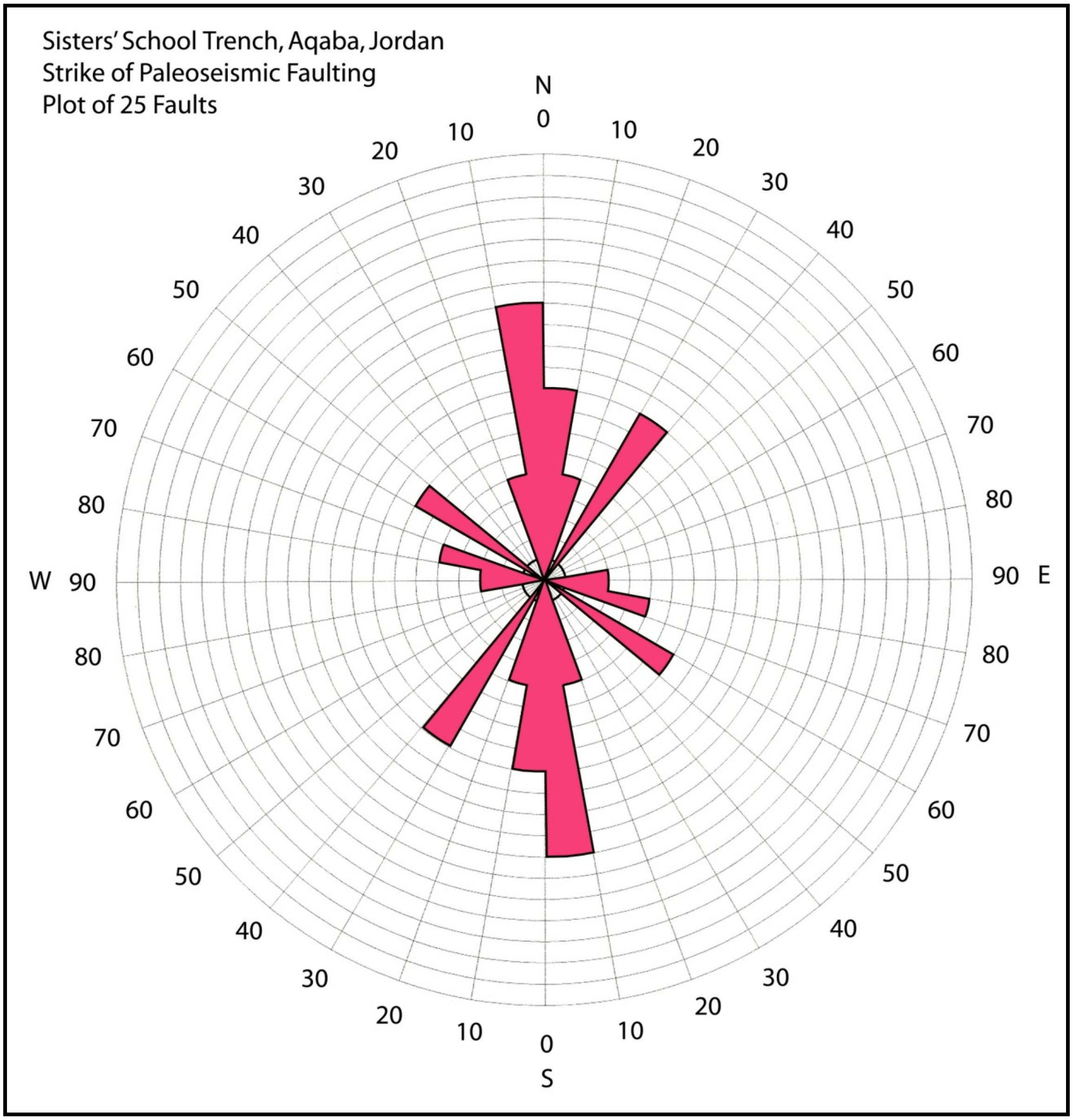

Figure 5.14 Rose diagram depicting the direction of strike as measured from twenty-five paleoseismic faults identified within the Sisters' School trench. Locations of faults providing strike and dip measurements are mapped on the site top plan (see Figure 5.4).

Discussion

Faulting and Depositional Environments

Detailed analysis of the faulted stratigraphy in the Sisters' School trench suggests that at least five seismic events ruptured the site in antiquity. With at least fifty individual faults identified within the Sisters' School trench, this geographic location, at only 1 km north of the head of the Gulf of Aqaba, is clearly a location through which the Dead Sea transform has ruptured numerous times. It is also an area that could be quite seismically hazardous in the future.

Air photo interpretation of the regional surficial geology in the Aqaba area suggests that the Aqaba fault comes onto land from the Gulf of Aqaba in the south, and that the energy is then transferred to the cross-faults trending northwest through the city (Niemi and Smith, 1999; Slater and Niemi, 2003; Mansoor et al., 2004). Five cross faults were also mapped trending northwest through the city of Aqaba, including a cross fault that trends through Area J-East at the archaeological site of Roman-Byzantine Aila (Thomas et al., 2007) (Figure 5.15). Several geologic trenches (T1-T5) were excavated across four northwest-trending cross faults (CF 1-4) that are responsible for producing tectonic subsidence at the head of the Gulf of Aqaba (Mansoor, 2002; Slater and Niemi, 2003). According to Slater and Niemi (2003), the location of the Aqaba fault is likely constrained to the south and/or to the east of the cross faults identified in Aqaba since these linear cross faults are not offset. Based on this description of where the Aqaba fault likely trends inland, as well as research discussed in Chapter 3 from the archaeoseismic excavation conducted at Islamic Ayla that suggests the Aqaba fault lies to the east of trenches AY1 and AY2 at Ayla, the faults exposed in the Sisters' School trench are most likely not associated with the Aqaba

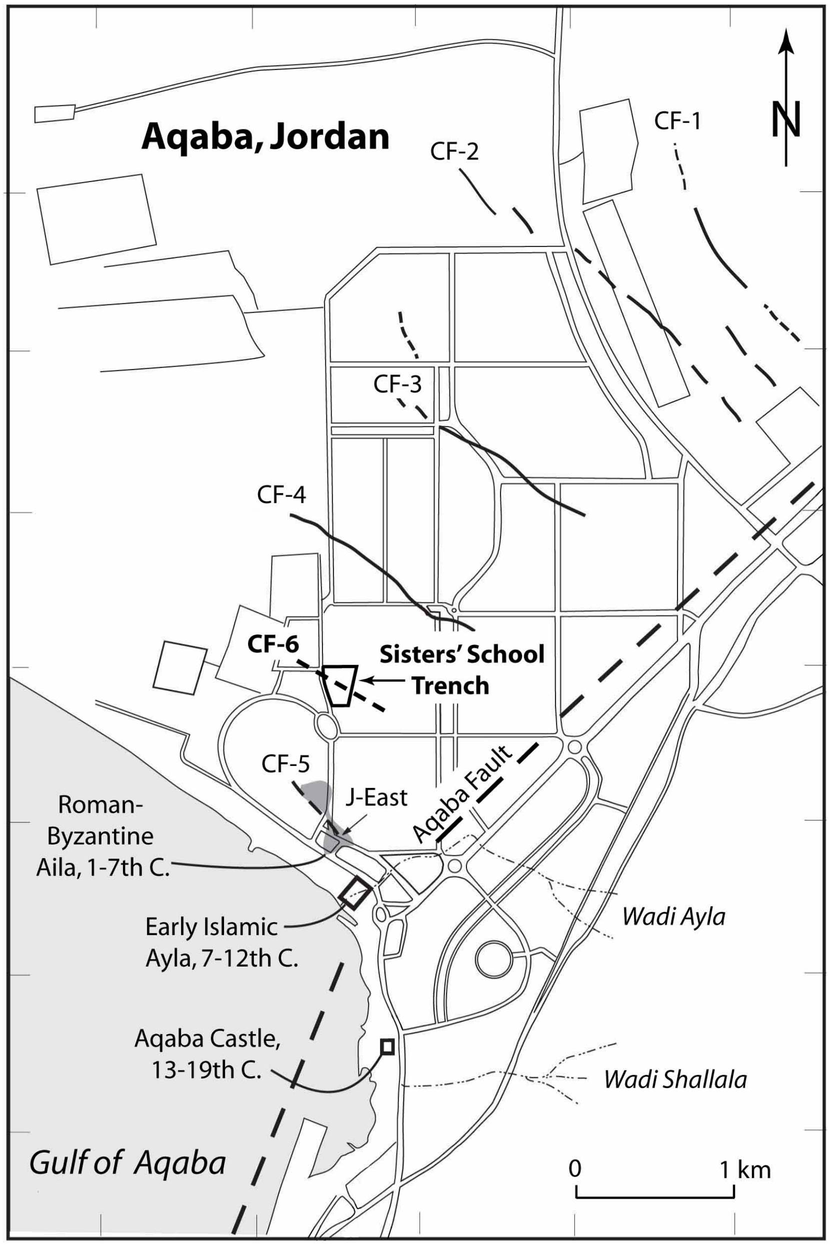

Figure 5.15 Map of the city of Aqaba showing locations of the active cross faults (CF 1-5) mapped from aerial photos and discovered during the archaeological excavations of J-East in Roman-Byzantine Aila. The proposed location of cross fault 6 (CF-6) was determined as a result of this paleoseismic study at the Sisters' School site. Locations of other major archaeological sites in the city are also shown (after Thomas et al., 2007).

fault, but likely with the West-Aqaba fault located to the west of the Aqaba fault strand (See Figure 5.1).

The faulting in the Sisters' School foundation trench shows evidence of both strike-slip motion in the form of NE-SW trending faults, as well as normal faulting. This normal faulting was likely caused by a cross-fault trending NW-SE through the site, roughly perpendicular to the strike-slip motion. The rose diagram constructed for this site depicts the direction of strike for twenty-five faults measured within the Sisters' School trench. Strike and dip measurements were only able to be collected for approximately 50% of the faults identified at the Sisters' School site. This is mainly because the fault plane for many of these faults was difficult to expose in order to take proper strike and dip measurements. The strike measurements plotted on the rose diagram, therefore, may be biased toward one type of faulting more than another based on the configuration of the trench walls and whether a measurement could be acquired from a specific fault.

Regardless of how many additional NW-SE trending faults may be present in the trench, the sheer volume of faulting evidence collected from the various exposures in the Sisters' School trench is substantial. Considering the cross faults that are already mapped in the city of Aqaba, it seem likely that another cross fault, Cross Fault 6 in this case, trends northwest through this site as is shown on Figure 5.15. Further, as discussed in the previous chapter on the Taba Sabkha, the paleoseismic record is essentially a record of large (M > 6.5) to great (M > 7.8) earthquakes because geologic evidence of small- to moderate-sized earthquakes is typically not created nor preserved near the ground surface (McCalpin and Nelson, 2009). It is assumed, therefore, that all of the faults identified in the Sisters' School trench are the result of M > 6.5 earthquakes because they ruptured up to or very near the ground surface (McCalpin, 2009).

The depositional environment of the Aqaba coastal zone has also changed over time in this location. The Sisters' School trench, in general, consists of primarily fine-grained sediments in the lower half of the trench with several stratified fluvial packages located toward the upper portion of the trench. As discussed by Hartman (2012), the two main terrestrial sediment sources bringing material into the head of the Gulf of Aqaba in antiquity were likely the paleo-Wadi ‘Arabah and the paleo-Wadi Yutim. Since the Sisters' School site is situated closely to Wadi Yutim, it was likely Yutim that primarily washed sediments down to this site in antiquity. Yutim drains large parts of the Edom Mountains and joins the Wadi ‘Arabah Valley about 5 km north of the head of the Gulf (Hartman, 2012).

Based on the change in trench stratigraphy from fine-grained sands, silts, and clays to very coarse-grained flood deposits, however, it appears that the drainage path of Wadi Yutim has migrated over time resulting in these significant sedimentary differences. Hartman (2012) cites a possible directional change of Wadi Yutim from the eastern Wadi ‘Arabah Valley to the western Wadi ‘Arabah Valley during the early to mid-Holocene. The OSL dated sediment samples in the Sisters' School trench agree with this suggested transitional time period for Wadi Yutim drainage. Unit SS-7, the latest fine-grained sedimentary unit from the lower half of the SW trench wall dates to 7.6 +/- 0.6 ka (6200-5000 B.C.), and unit SS-5, the earliest of the fluvial packages that characterize the upper portion of this foundation trench dates to 6.0 +/- 0.3 ka (4300-3700 B.C.), for example. This depositional change would have had a great effect on the people living in or working around the Sisters' School site at the time, and likely resulted in specific human migrations as locals tried to avoid the flood waters.

Historical Chronology of Seismic Events

Based on the ages returned from the OSL dating of sediment samples, it is clear that all of the seismic events in the trench occurred several thousand years ago during the early to middle Holocene epoch. More specifically, based on the historical chronology of Jordan (Table 5.2), all of the earthquakes mapped at the Sisters' School site occurred sometime during either the Pre-pottery Neolithic period (8200-5500 B.C.), the Pottery Neolithic period (5500-5000 B.C.), the Chalcolithic period (5000-3600 B.C.), or during the Bronze Age (3600-1200 B.C.) .

The most recent seismic event (EQ I) occurred before unit SS-2 was deposited approximately 5.2 +/- 1.1 ka (4300-2100 B.C.), a timeframe that encompasses a portion of both the Chalcolithic and Bronze Age periods, but after the deposition of unit SS-5 dated to 6.0 +/- 0.3 ka (4300-3700 B.C.) during the Chalcolithic. EQ I, therefore, could have occurred anytime from the middle Chalcolithic period to the middle Bronze Age based on the available OSL #8 and OSL #3 dates. The penultimate event, EQ II, occurred after unit SS-7 was deposited in 6200-5000 B.C., according to OSL #1, but before a date of 4300-3700 B.C. (OSL #3) when unit SS-5 was deposited during the Chalcolithic period. Since the date of unit SS-7 was constrained to approximately 5000 B.C. based the radiocarbon date of 4986-4840 B.C. from the underlying unit SS-10, EQ II must have occurred anytime between ~ 5000-3700 B.C. during the Chalcolithic period.

TABLE 5.2

HISTORICAL CHRONOLOGY OF JORDAN

HISTORICAL PERIOD	CALENDAR YEAR
Iron Age	1200-539 B.C.
Bronze Age	3600-1200 B.C.
Chalcolithic	5000-3600 B.C.
Pottery Neolithic	5500-5000 B.C.
Pre-Pottery Neolithic	8200-5500 B.C.
Epi-Paleolithic	20,000-10,000 BP
Paleolithic	1.7/1.5 million-20,000 BP

The third seismic event identified in the Sisters' School trench occurred before unit SS-7 was deposited (OSL #1: 6200-5000 B.C.) and after unit SS-10 was deposited (OSL #4: 6200-3000 B.C.). The single radiocarbon date (4986-4840 B.C.) collected from the fire pit in the south trench wall within unit SS-10 constrains the OSL #4 date of 6200-3000 B.C. to approximately 6200-5000 B.C. Since unit SS-7 overlies unit SS-10, this radiocarbon date also acts to constrain OSL sample #1 to approximately 5000 B.C., given the original 6200-5000 B.C. possible age range. Because both the last unit cut by EQ III (SS-10) and the oldest overlying non-deformed unit (SS-7) date to approximately the same age range, EQ III likely occurred in or around 5000 B.C. during the early Chalcolithic period.

The fourth seismic event at the Sisters' School site occurred prior to the deposition of unit SS-10 dated by OSL sample #4, and after the deposition of the sand layer that liquefied during the MRE and created dike SD-1 which dates to 6.9 +/- 1.7 ka (6600-3200 B.C.) (OSL #2). The age range for this date is again constrained (6600-5000 B.C.) by the date of the fire pit charcoal in SS-10, which is located stratigraphically above the buried sand layer. EQ IV, therefore, occurred sometime between the Pre-Pottery Neolithic and the start of the Chalcolithic period. Similarly, EQ V, which ruptures only as high as unit 22, can only be estimated as occurring sometime between the Pre-Pottery Neolithic and the start of the Chalcolithic period, based on OSL dates #2 and #4, and prior to EQ IV, but cannot be further constrained.

Earthquake Recurrence Interval

The average time interval between earthquake events along a particular fault is known as the seismic recurrence interval, or return period (Keller and Pinter, 1996). An analysis of the faulting events and offset stratigraphy present in this trench, along with an analysis of the OSL dates and single radiocarbon date, suggest that within the Sisters' School trench, at least five earthquakes occurred after a date of 6.9 +/- 1.7 ka (6600-3200 B.C.) (OSL #2), which can be more tightly constrained to 6600-5000 B.C., and before a date of 5.2 +/- 1.1 ka (4300-2100 B.C.) (OSL #8). Considering both the oldest and youngest ranges of these two dates, the possible recurrence interval along this segment of the Dead Sea transform may be as high as 900 years (6600-2100 B.C.), or as few as 140 years (5000-4300 B.C.). The median recurrence interval is 520 years for this site if both of the oldest dates (6600-4300 B.C.) and both of the youngest dates (5000-2100 B.C.) are considered and averaged.

The particular fault segment trending through the Sisters' School trench, which is most likely the West-Aqaba fault based on offshore fault mapping by Hartman (2012), showed seismic activity dating from as early as the Pre-Pottery Neolithic up until perhaps as late as the Bronze Age. However, this fault is currently in a period of seismic quiescence since it has been more than 4100 years since any of the faults mapped within the SW trench wall have ruptured. The seismic quiescence of the site could mean that a large earthquake is possible in the not-so-distant future, since this is still considered an active fault segment of the Dead Sea transform in that it has ruptured one or more times within the last 10,000 years (e.g. McCalpin, 2009). This seismic quiescence could also be an indicator that this is a dead fault strand and therefore unlikely to rupture again in the future, especially if the motion has been transferred to another fault strand. Considering the range of possible recurrence intervals for the Sisters' School trench, this 4100-year quiescent period is more than four times as long as the highest recurrence interval (900 years) calculated for the site, and suggests that this fault is dead.

Paleoliquefaction

The fault exposures in the Sisters' School trench are unique in the city of Aqaba because they display obvious evidence of paleoliquefaction. While the liquefaction susceptibility of the city has been studied (e.g. Mansoor, 2002; Mansoor et al., 2004), field evidence of paleoliquefaction has not been documented within the region. The liquefaction evidence documented in the Sisters' School trench, clastic dikes SD-1 through SD-7, confirms that this seismic phenomenon occurred in the Aqaba coastal zone in antiquity.

According to Kramer (1996), three conditions must exist for liquefaction to occur: (1) the presence of a soil type susceptible to liquefaction, (2) the presence of a shallow water table, and (3) strong ground shaking. All of these conditions are met within the city of Aqaba, based on historical accounts and on the recent ground motion during the November 22, 1995 Nuweiba earthquake (e.g. Dziewonski et al., 1997; Baer et al., 1999; Husein Malkawi et al., 1999; Klinger et al., 1999; Al-Tarazi, 2000). Based on the paleoseismic evidence presented as a part of this study, it is clear that the unconsolidated alluvial sediments of this coastal city are susceptible to liquefaction. In addition to the abundance of fine-grained, sandy and silty sediments at the Sisters' School site, the ground water table is also relatively shallow at approximately 10 m, and continues to shallow toward the Gulf head. Lastly, large ($M > 6.5$) earthquakes have most certainly ruptured the region in the past, as is evidenced by the catastrophic A.D. 1068 earthquake that destroyed Early Islamic Ayla (Guidoboni and Comastri, 2005; Ambraseys, 2009), for example. Also, with a moment magnitude $M_W = 7.3$ and a local magnitude $M_L = 6.2$, the 1995 Nuweiba earthquake was the most sizeable earthquake to occur in the region of the southern Wadi ‘Arabah in the last century, and it produced strong ground shaking as a result (e.g. Dziewonski et al., 1997; Baer et al., 1999; Husein Malkawi et al., 1999; Klinger et al., 1999; Al-Tarazi, 2000).

In general, liquefaction most commonly occurs at a depth of between 2 and 5 m, but can originate at depths of up to 20 m or more (Seed and Idriss, 1982). Since the depth of the sand and silt units that fed the three small dikes (SD-2, SD-3, and SD-4) and the large sand dike (SD-1) in the southwest trench wall is unknown, this is useful information to help approximate the depth of the source sediments that comprise these paleoliquefaction features. For example, based on the age of the sand dike in meter 21 of the SW trench wall, 6.9 +/- 1.7 ka (6600-3200 B.C.) compared to the other OSL dated sedimentary units in the trench, the sand unit that fed this dike is most likely buried only a meter or two beneath the trench floor. Since both this dike and the associated MRE fault in meter 21 ruptured to a height of approximately 3.8 m above the floor of the trench (at or near the theoretical ground surface at the time of the earthquake), this would mean that liquefaction for this event originated at a depth of approximately 4.8 to 5.8 m if these estimations are correct.

Further, modern seismicity studies have shown that in order to liquefy sediments at depth during an earthquake, a minimum earthquake magnitude of $M > 5$ is required, and these features become relatively common at magnitudes of $M > 5.5$-6 (Obermeier, 2009). Since the minimum magnitude necessary to rupture up to or close to the ground surface is $M > 6.5$, it is possible that some of the liquefaction features documented at the Sisters’ School site occurred as a result of one or more earthquakes that were not large enough in magnitude to rupture to the ground surface, but that were capable of inducing liquefaction in the underlying unconsolidated sediments. As discussed, sand dike SD-1 actually migrated up one of the EQ I fault lines, and both the fault and dike terminate in very close proximity. Dikes SD-2 and SD-3 located in meter 4 are also associated with a fault, this time from the EQ III event. Dike SD-4, however, is not associated with any one particular fault and thus may or may not have occurred as a result of one of the five seismic events mapped in the SW trench wall. It is possible that this small silt dike (SD-4), which ruptured to a height of only 0.9 m above the trench floor, could represent a completely separate earthquake event that occurred within some close proximity of the Sisters' School site, but that is not directly observable in the trench walls. Located stratigraphically closest to the EQ IV event horizon, dike SD-4 may also represent liquefaction associated with EQ IV based on its upper termination in unit 18.

With the city of Aqaba, Jordan found to be highly susceptible to liquefaction (Mansoor, 2002; Mansoor et al., 2004), the evidence of paleoliquefaction in the Sisters' School trench corroborates this geotechnical work, and also calls attention to the elevated seismic hazard potential for all construction efforts at the head of the Gulf of Aqaba.

Anthropogenic Evidence

The city of Aqaba, Jordan has a very rich cultural history as is evidenced by the large number of archaeological ruins in the region. The history of the Aqaba coastal zone was largely detailed in chapters 2 and 3, although the archaeological and anthropogenic finds in the Sisters' School trench pre-date the majority of archaeology discussed in those sections.

Evidence of human occupation at the Sisters' School site was first identified in the southwest trench wall in the form of an ashy, fine- to medium-grained sand unit, layer SS-

10. This sand unit contains lenses of silt so concentrated with ash that they are visible from a distance because of the contrast in color between the ash and the surrounding tan-colored sediment. This ashy unit was quickly identified as being anthropogenic in nature, and it was hypothesized that this ash must have been deposited at a time when there was an abundance of cooking or camp fires in the immediate area. An OSL sample collected from this anthropogenic layer, OSL #4, dates this unit to 6.6 +/- 1.6 ka (6200-3000 B.C.), which correlates to the historical periods ranging from the Pre-Pottery Neolithic (8200-5000 B.C.) to the Bronze Age (3600-1200 B.C.) in Jordan.

Given the abundance of pottery typically found during an excavation in the city of Aqaba, it was at first surprising that no pottery was found *in situ* in the trench walls, especially considering the number of walls and cuts present in the Sisters' School trench. A single pottery sherd was identified at the site, but it was found laying on the surface of a spoil pile at the northeastern end of the trench (see Figure 5.4), and thus is not useful for dating purposes. The older age of unit SS-10, along with the other OSL dates discussed previously, explains the lack of ceramics at the site, since pottery was not used in the area until at least the Pottery Neolithic (5500-5000 B.C.) and is typically not found in abundance until later historical periods. Unit SS-10 is interpreted as a possible archaeological surface, as is indicated on the main SW wall cross-section (Figure 5.8).

While this ashy, silty sand unit is strong evidence of human activity at the Sisters' School site, a well-preserved fire pit exposed in cross-section in the south trench wall largely confirms this human presence at the site (see Figures 5.6 and 5.7). The fire pit, approximately 0.8 m wide and 0.5 m deep, is lined with cobbles and contains an extremely ashy medium- to coarse-grained sand throughout. A sample of this carbon-rich sediment, sample RC-SS #1, was collected for radiocarbon dating and represents the only charcoal dated from within the Sisters' School trench. Sample RC-SS #1 was dated to 6015 +/- 25 yr BP (4986-4840 B.C.), which correlates to the early Chalcolithic period (5000-3600 B.C.) in Jordan. The sedimentary unit containing the fire pit, which was also ashy in nature, was able to be traced over to the southwest trench wall and was correlated with unit SS-10. As discussed in earlier sections, the radiocarbon date of the fire pit charcoal substantiates the OSL #4 date, and most importantly, helps to constrain the large date range of OSL #4 (6200-3000 B.C.) to closer to 6200-5000 B.C.

There are a few other sites in the Aqaba region that also date to the Chalcolithic period, including Tell Hujayrat al-Ghuzlan and Tell al-Magass, both located on the northern outskirts of the city and built on the alluvial fan sediments of Wadi Yutim. Both of these sites date to between the Chalcolithic and late Chalcolithic period (Khalil, 1987, 1988, 1992, 2009). Tell al-Magass was previously found to contain the earliest evidence of sedentary occupation discovered thus far in the Aqaba region, and is interpreted to have been an industrial site for copper smelting during the Chalcolithic period. Tell Hujayrat al-Ghuzlan is interpreted as the residential site for the Tell al-Magass workers (Khalil, 1987, 1992, 1995, 2009; Khalil and Riederer, 1998; Hauptmann et al., 2009). While these sites are both well documented through archeological excavation, they are younger than both the ashy, anthropogenic layer (SS-10) constrained to 6200-5000 B.C. and the fire pit documented at the Sisters' School site that dates to 6015 +/- 25 yr BP (4986-4840 B.C.). There is strong evidence, therefore, that the Sisters' School site contains some of the oldest signs of human occupation in southern Jordan dating to around 5000 B.C., the transition between the end of the Pottery Neolithic period and the start of the Chalcolithic period.

Conclusions

In a city undergoing such rapid change as a result of urbanization, locating an open foundation trench the size and depth of the Sisters' School provides a unique window into the paleoseismic history of the Aqaba coastal zone. Data collected from this study suggests that there is evidence for at least five earthquakes to have ruptured this site in antiquity – from as early the Pre-Pottery Neolithic to as late as the Bronze Age – with a median recurrence interval of 520 years.

The earthquake faults and paleoliquefaction evidence exposed at the Sisters' School site provide a wealth of information and shed light on the seismology of the region. Since the Dead Sea transform is not one single linear trace that can be followed from end to end, it is extremely important to study and map any exposed portions of the DST fault where available to help better characterize the motion and, thus, the long-term behavior of this major tectonic boundary. Even within this major seismic zone, both the number of faults and the paleoliquefaction documented at this site are unprecedented in the city of Aqaba.

What originally began as a paleoseismic investigation evolved to include archaeological evidence discovered in the Sisters' School trench, most significantly some of the oldest evidence of human activity in the city of Aqaba. Future research at this site will include working to further elucidate any additional archaeological ruins or artifacts within the Sisters' School trench, and to continue mapping the remaining trench walls and faults in greater detail. Considering the incredible amount of earthquake faulting discovered, and that this site revealed the first evidence of paleoliquefaction documented anywhere in the city of Aqaba, the Sisters' School site is one of the most dynamic locations for study in the Aqaba coastal zone.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

This archaeoseismic and paleoseismic research has worked to elucidate the seismic events that occurred in and around the municipality of Aqaba, Jordan and up to 35 km north of the Gulf of Aqaba over the course of the last several millennia. All three sites that comprise this dissertation research, Early Islamic Ayla, the Taba Sabkha trench, and the Sisters' School trench, have yielded important paleoseismic and/or archaeoseismic data which has contributed to the overall understanding of this very important tectonic boundary, the Dead Sea transform.

At the site of Early Islamic Ayla, a 3.5 m long section of the original city wall was determined to have partially failed and leaned seaward due to liquefaction damage as a result of ground shaking from an 11th C. earthquake, and was buttressed shortly thereafter. Pottery and charcoal fragments collected from within and beneath the revetment wall helped to constrain the possible timeframe of revetment construction. Based on the known historical earthquakes detailed within the regional earthquake catalogs (Guidoboni and Comastri, 2005; Ambraseys, 2009), the Ayla city sea wall was most likely damaged during the historic earthquake of A.D. 1033. This is the first time that any damage at the site of Early Islamic Ayla has been attributed to the A.D. 1033 seismic event, and this research acts to extend the damage range for this particular event further to the south than previously documented. It is also likely that liquefaction from this early 11th C. earthquake damaged other portions of the city as well, perhaps damaged sections of the city previously attributed to the A.D. 1068 earthquake. Although this paleoseismic damage was not caused by the catastrophic A.D. 1068 event that is known to have destroyed the town of Early Islamic Ayla, the A.D. 1033 earthquake may have been the one of the more significant catalysts contributing to the overall decline of Ayla that is seen in the archaeological record in the years leading up to the large A.D. 1068 earthquake (e.g. Khouri and Whitcomb, 1988; Whitcomb, 1994a).

There is no shortage of future archaeological and archaeoseismic work at this site, especially since a large portion of the city still remains unexcavated. Specific to this excavation, further archaeoseismic research needs to be conducted on the buried architecture at the southeast end of trench AY2, locus AY2:4, to further expose what may be another, likely even earlier, revetment wall situated along the outside of the sea wall at Islamic Ayla (See Figures 3.11, 3.12). Only the uppermost section of this structure was cleaned off to articulate the stones exposed during the course of this work, but the wall was not further excavated since this particular structure did not directly relate to the leaning wall and revetment at the core of this research. Based on the current configuration of the length of the Ayla sea wall, which appears to be misaligned and slightly rotated, it is possible that the Aqaba fault trends inland from the Gulf of Aqaba and ruptured to the east of this current excavation site, dragging the city wall with it as it moved in a left-lateral fashion. Locating exactly where the DST emerges on land in the city of Aqaba is very important for seismic hazard analyses and for future land use planning purposes at the head of the Gulf.

Some 35 km north of the municipality of Aqaba in the Taba Sabkha, a paleoseismic trench aligned to intersect the Wadi ‘Arabah fault revealed evidence that between two and four seismic events ruptured this portion of the southern Wadi ‘Arabah Valley between the

8th and 16th centuries. However, detailed fault mapping of the trench walls coupled with the analyses of several radiocarbon-dated charcoal fragments collected from within the Taba trench, suggest that a three-event model is the most likely seismic scenario. The seismic events attributed to these three ruptures includes the A.D. 746/749 or 757 earthquakes (EQ IV), the A.D. 1068 earthquake (EQ II/III), and either the A.D. 1546 or the 1588 earthquake (EQ I). The faulting present in the Taba trench suggests a recurrence interval ranging from between approximately 316 to 632 years, which is significantly shorter than the 1200-2000 year recurrence interval previously estimated within the Shehoret fan and Evrona playa paleoseismic sites located 20-25 km southwest of Taba (e.g. Gerson et al., 1993; Enzel et al., 1994, 1996; Amit et al., 1995, 1996, 1999, 2002; Porat et al., 1996, 2009; Zilberman et al., 2005). The recurrence interval suggested by the faulting in the Taba Sabkha trench points to a higher level of seismicity along this particular section of the DST situated along the eastern side of the Wadi ‘Arabah Valley, at least within the last 1200 years or so. Further, this research has shown that when an earthquake occurs in the region, not all fault segments of the Dead Sea transform typically move at the same time since neither the 8th C. nor the 16th C. earthquakes identified at Taba have been found to rupture within the Shehoret fan or Evrona playa, at least not within the trench sites excavated. The A.D. 1068 earthquake, however, has been identified in trenches located on both sides of the Wadi ‘Arabah Valley, confirming how significant of a seismic event this earthquake was for the southern Wadi ‘Arabah in the 11th C. (e.g. Gerson et al., 1993; Enzel et al., 1994, 1996; Amit et al., 1995, 1996, 1999, 2002; Porat et al., 1996, 2009; Zilberman et al., 2005).

Future seasons of paleoseismic research in the Taba Sabkha will entail excavating this current trench to a deeper depth, with the intention of determining what even earlier earthquakes also ruptured this section of the DST fault zone prior to the 8th C. Ideally, excavating additional trenches further to the north of this current site would also extend knowledge of paleoseismic faulting in the Wadi ‘Arabah, and hopefully allow for a more comprehensive examination of the MRE (EQ I) faults identified on the far eastern side of the Taba trench. Because this fault trends up the Wadi ‘Arabah in an *en echelon* pattern, it would be prudent to conduct a ground penetrating radar investigation at this site prior to the excavation of additional trenches in order to non-invasively locate this most recent fault as it steps over.

The final paleoseismic investigation comprising this dissertation research entailed a study of the abandoned Sisters’ School foundation trench within the city of Aqaba, situated just 1 km north of the Gulf. This trench contained at least fifty fault ruptures with approximately 50% of these concentrated within the southwest trench wall. Seven OSL dates and one radiocarbon date from this site suggest that at least five earthquakes have ruptured the trench site since antiquity, with the most recent event occurring sometime shortly before a layer dated to 5.2 +/- 1.1 ka (4300-2100 B.C.). Paleoseismic mapping of the trench walls suggests evidence for a previously undetected NW-SE trending cross-fault through this location in the city of Aqaba. This trench also contains the first documented occurrence of paleoliquefaction anywhere in the city of Aqaba, as is evidenced by seven sand and silt dikes identified in the Sisters’ School trench walls. An ashy sand unit (SS-10) dated to 6.6 +/- 1.6 ka (6200-3000 B.C.) and a fire pit dated to 6015 +/- 25 yr BP (4986-4840 B.C.) exposed in cross-section at the southern end of the trench also provide evidence for some of the earliest human occupation near the head of the Gulf of Aqaba. Interpreted as anthropogenic indicators, the dates of the ashy sediments and charcoal collected from the fire pit constrain the boundary of this human activity to between the very late Pottery Neolithic (5500-5000 B.C.) and the early Chalcolithic (5000-3600 B.C.) periods. Further, the implications of seismic quiescence exemplified by the research conducted at all three sites is of concern since, in general, the longer it has been since there has been an earthquake, the more likely there is to be a significant seismic event along a particular fault. At the Sisters' School site, however, it is possible that the faults observed, which can likely be attributed to the West-Aqaba fault segment, may represent a dead fault since they have not been reactivated in more than 4000 years.

Future work at the Sisters' School site, assuming the site remains open and accessible, will entail a more comprehensive archaeological/archaeoseismic investigation, and will focus on continued mapping efforts of faults exposed in the walls outside of the main SW wall mapped as a part of this research. At each of the three research sites detailed as a part of this dissertation, Early Islamic Ayla, the Taba Sabkha trench, and the Sisters' School trench, there is certainly no shortage of work to be carried out in the future. Data collected from future trenching and excavation efforts will be combined with the data presented here in an effort to continue further defining the rupture behavior and pattern of the Dead Sea transform, with the ultimate goal of better characterizing the future seismic hazard potential of the southern Wadi 'Arabah region.

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VITA

Alivia Janeil Allison was born in Independence, Missouri on February 22, 1977. She was educated in Independence public schools and graduated from Harry S. Truman High School in 1995. She attended the University of Missouri-Kansas City and received her Bachelor of Arts in English with an emphasis in Creative Writing and minors in Political Science and Geology in 1999, and earned her Bachelor of Science degree in Geology in 2004. During her final year as an undergraduate geology student, she worked as a teaching assistant for the General Geology laboratories in the Geosciences Department at UMKC. Ms. Allison continued her education in geology at UMKC, and graduated with a Master's of Science degree in Urban Environmental Geology in 2007. Ms. Allison worked as a graduate teaching assistant while earning her M.S. and Ph.D. degrees. The classes she taught at UMKC as a graduate student and doctoral candidate included a graduate Geotechnics laboratory course, Field Methods in Earth and Environmental Science, and the General Geology lecture and laboratory courses.

Ms. Allison has received numerous scholastic awards during the course of her academic career, including the Oliver Rudolph Grawe award for the most outstanding undergraduate student in the state of Missouri (2003), the Superior Graduate Teaching Assistant Award from UMKC (2006-2007), as well as research grants from the Geological Society of America, the Association of Engineering Geologists, the Graduate Assistance Fund from the UMKC Women's Council, the Earth Science Clubs of Greater Kansas City, and UMKC's SEARCH program (Students Engaged in Artistic and Academic Research).

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