Grouting for Caesar: The Vault Complex and High Level Aqueduct at Caesarea After 20 Years

A Pilot Project Presented to the:

Israel Antiquities Authority
and
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By

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The Current Project

The ancient city of Caesarea has great historic and international importance, is a popular tourist attraction, a massive archaeological site, and a laboratory for conservation work. However, like many such projects in Israel and abroad, its conservation project has yet to publish a final report. The task is large and daunting and becomes more difficult with the passage of time, yet such a report is beneficial for the site, those involved in the project, decision makers, and conservation and related professionals around the world.

Conducted by the Israel Antiquities Authority (IAA) Conservation Department in the 1990s, the conservation and development of the archaeological site at Caesarea was the first large-scale conservation project in Israel. The conservation of the High Level Aqueduct (1991-1993) and Vault Complex (1993-1997) were particularly difficult engineering and architectural tasks that required multiple processes and utmost care. This report documents and analyzes the grouting method implemented at the Vault Complex and High Level Aqueduct. After 20 years, the effectiveness of the treatment is ripe for assessment. Furthermore, this report also serves as a pilot for the detailed implementation manual described in David Zell's (IAA) manual entitled פיילוט מפרטים לשימור: אפיון צרכים ותוכנית עבודה לקידום הפרויקט, which aims to standardize work reports in the field of conservation in Israel. Taken together, Zell's manual and this report present and embody a practical solution the problem of missing documentation and final reports.

This report uses research, documentation, analysis, and comparison to connect the dots between the condition of the Vault Complex and High Level Aqueduct at Caesarea upon excavation and their current state. Since the project was carried out many years ago, much data has been lost, scattered, or forgotten. Tangible documentation that remain comes from individuals who worked on the project and the IAA storage lockers at Caesarea. Without a final written report, oral communication with those involved in the archaeological and conservation projects is also a vital source of information.

Not only does this report recount and describe the grouting procedures at Caesarea, but it also analyzes their effectiveness via core drilling after 15-20 years. I compare the results of this testing on both Vault 1 and the High Level Aqueduct in respect to the effectiveness of grouting methods and longevity of treatment as they were evidenced on 26 June 2012, then propose possible reasons for the difference in results. Based on the analysis, this report concludes with recommendations for future grouting procedures and work on grouted areas, including the development and implementation of a maintenance plan for grouted areas that includes regular monitoring over an extended period of time.

1. History and Significance of Caesarea

Caesarea was a major commercial harbor that serviced the entire Mediterranean region for 1,000 years, from the 4-3rd centuries BCE until Arab invaders destroyed it in 641-42 CE. The city was revived on a smaller scale in the 9th century and became a Crusader principality from 1101-1265, but was abandoned when the Egyptian sultan Baybars damaged the site in 1291. The site, now known as Caesarea National Park, is located on Israel's Sharon coast, midway between modern Tel Aviv and Haifa (Figures 1-2).

Figure 1. Location of Caesarea in Mediterranean. (Google Maps)

The site was established as a small, fortified port town and commercial harbor named Straton's Tower (Στράτωνος Πύργος) sometime in the 4th or 3rd century BCE. The town was conquered by Alexander Jannaeus in the name of the Hasmonean Kingdom ca.100 BCE, then annexed by Pompey in the name of the Roman Empire in 63 BCE. When the site was returned to the Jews by Octavian in 31 BCE, it had fallen into disrepair.

Figure 2. Location of Caesarea in Israel. (Google Maps)

In the years 22 and 10-9 BCE, Herod the Great developed Straton's Tower and renamed it Caesarea in honor of Caesar Augustus, making this one of many Caesareas known throughout the Roman world. Among his many other building projects, Herod also built the port neighboring Caesarea and named it Sebastos, which is Greek for "Augustus". Ancient records, including Greek and Latin inscriptions, refer to this Caesarea as Caesarea of Sebastos, Caesarea of Straton, or, more commonly, Caesarea of Palestine (Holum and Raban, 1997). During Herod's reign over Israel (37-4 BCE), Caesarea developed into a traditional Greek polis with a temple to Roma and the Emperor, which often stood in contrast to Jewish Jerusalem. In 6 CE, it was named the administrative center of the provincial governor and remained the capital of the province of Judea throughout classical antiquity.

Caesarea is mentioned throughout the New Testament Book of Acts as a transportation hub (8:40; 9:30; 18:22; 21:8, 16), safe-haven from Jerusalem's religious extremists (9:30, 23:23), provincial capital (23:23, 33; 24:1; 25:1, 4, 6, 13), and the first center of gentile Christian life (10:1, 24; 11:11; 18:22; 21:8, 16).

During the First Jewish Revolt against Rome (66 CE), the tension between Roman and Jewish populations at Caesarea boiled over. According to historian Flavius Josephus, Caesarea's hellenistic population killed the city's Jewish minority (*War* II, 457). The city then became a center for Roman culture under the rule of Vespasian, the Roman commander. Caesarea continued to prosper under Roman rule, which led to the expansion of the aqueduct in order to transport more water to the bustling metropolis, where the famous Pythian games took place in the early 3rd century.

In the late 2nd century, both Christians and Jews moved to Caesarea and the surrounding towns. By the mid-3rd century, Caesarea was home to both a rabbinical academy and the Christian school of Origen, the scholar and theologian who housed a legendary library and composed the hexapla. In the early 4th century, Caesarea was also home to bishop Eusebius, the famous Christian historian and apologist, and Rabbi Abbahu, director of the famed rabbinic academy.

Caesarea reached its peak of prosperity in the sixth century, but was weakened by a Samaritan and Jewish revolt against the Christian majority in 529-30. It withstood the Perisan army in 614, but fell to the Arabs in 641-42. Caesarea was depopulated and fell into disrepair until the 10th century, when it reemerged on a small scale. From 1101-1265, it functioned as a Crusader principality, then was taken by the Egyptian sultan Baybars in 1291 after which it fell out of use until excavation.

The archaeological site of Caesarea was excavated off and on from the 1950s-2000s, by various teams from across the globe. The initial conservation project was carried out by the IAA in the 1990s and has been maintained by the IAA since.

2. Case Study 1: Vault 1

2.1 Location and Significance

The Vault Complex at Caesarea is centrally located within the site, between the Herodian and southern ports, just north of affluent Roman residences and theater (Figures 3-4).

The complex was excavated in two phases: by the Joint Expedition to Maritime Caesarea (1971-85), under the supervision of Robert Bull, Olin Storvick, and Edgar Krentz, and by the Combined Caesarea Expeditions (1988-2000), under the supervision of Avner Raban and Kenneth Holum, in conjunction with the IAA.

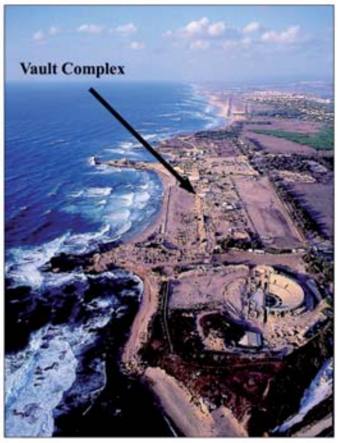


Figure 3. Location of Vault Complex. Aerial Photograph. (IAA)

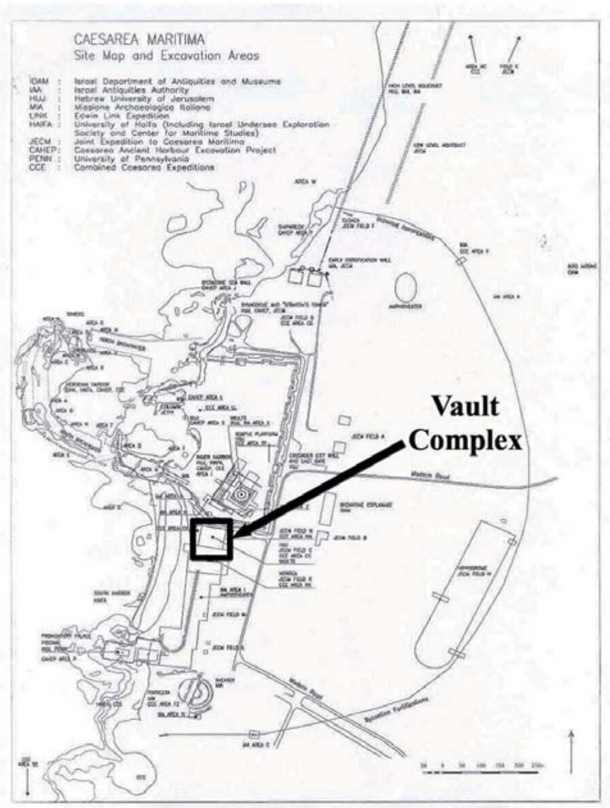


Figure 4. Location of Vault Complex. Archaeological Drawing. (Joint Expedition to Caesarea Maritima)

The vault complex was the first of several storage facilities located between Caesarea's two ports. Architecturally, this complex is categorized as a Roman *horrea*, or warehouse for commercial storage that was monitored by government officials and publicly owned. It is typical of other *horrea* found in the provinces of Asia Minor, Africa, and Judaea/Palastina, consisting of a single row of deep rooms, all of which open in the same direction (Patrich, 149; Figure 5). Vaults 1, 2, 11, and 12 were constructed and used as *horrea* from the late first century BCE to the mid first century CE. The vessels found in Vault 1 that date to this period originate from all over the Mediterranean world, including Spain, Italy, Rhodes, and Istria, in addition to vessels from the Negev and central Judaea/Palastina (Blakely, 149).

From the mid to late first century, vaults 1, 2, 11, and 12 were used as a Mithraeum, a sanctuary of the god Mithras, whose cult is well known for its bull sacrifice (See “2.2 Building Technology”). The vaults reverted back to warehouses in the late 3rd-7th centuries. Vault 1 in particular was used as an animal pen until the western 10m of the Vault Complex collapsed. Sometime during the Crusader period (11-12th centuries), 50 headless bodies were buried in the slope of the debris. The site as a whole was abandoned after Egyptian invaders took Caesarea in 1291.

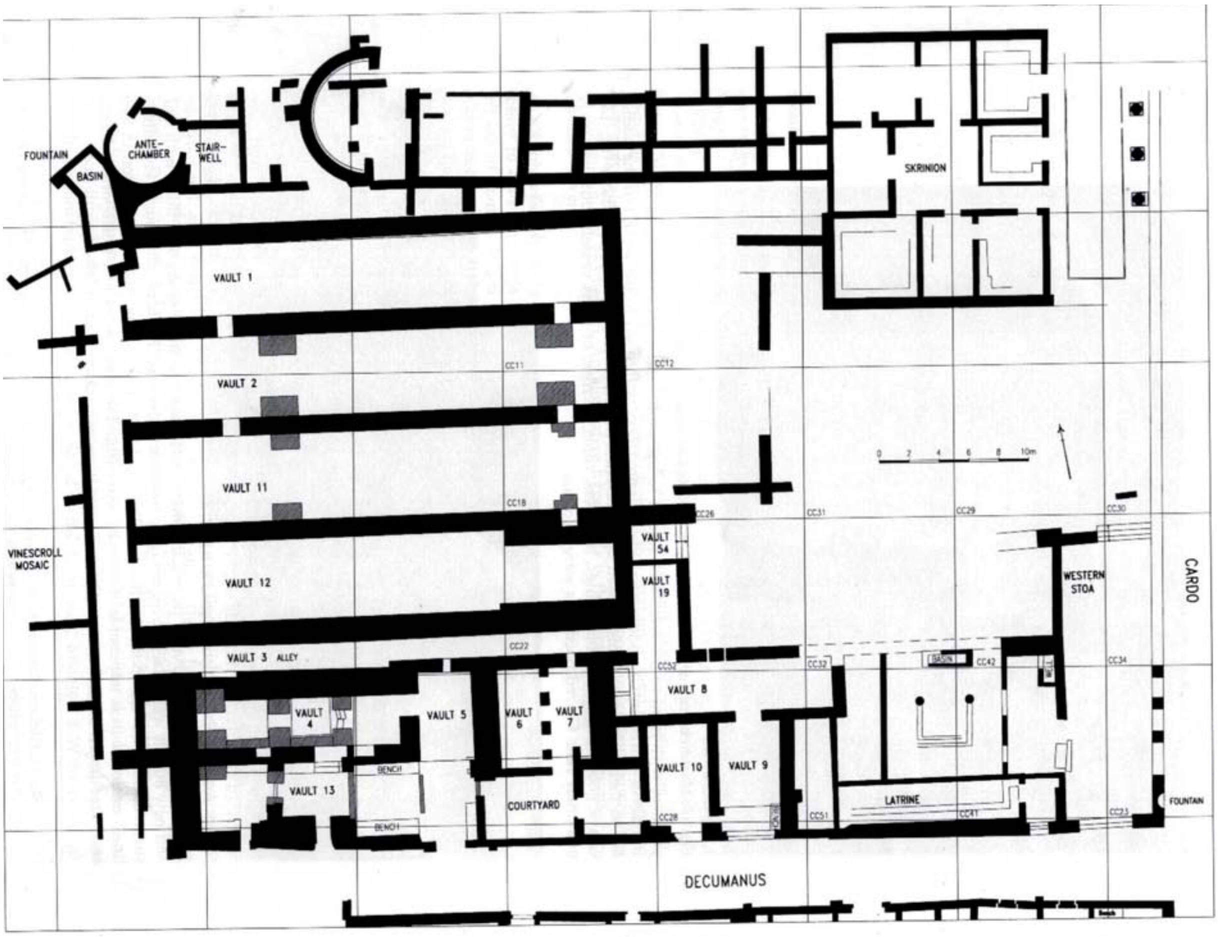


Figure 5. Plan of Vault Complex. (IAA)

2.2 Building Technology

Figure 6. Vault 1. Facing East. (IAA)

Vault 1 is part of the thirteen vault complex just south of Caesarea’s southern harbor (Figures 3-5). It is a typical barrel vault, built on sandstone bedrock, and faces a paved street to the west. Since the street level is 1m higher than the bedrock upon which the vault is built, a beaten earth ramp and sloped floor were built to facilitate entrance into the building (Blakely, 29-30).

The vault itself measures 31.30m long, 5m wide, and 5m high, and is constructed of well-hewn and fitted calcareous sandstone blocks of varying dimensions (70cm-1m long x 50-60cm wide x 30cm thick; Figure 8). The eastern (back) wall and lower seven courses of the northern and southern walls are made of rectangular ashlars (Figure 7). The remaining twenty-four courses of stone that make up the inner radius (2.50m) of the barrel vault are comprised of *voussoir*, or wedge-shaped stones that support arches by locking into place under pressure (Blakely, 29). A series of rectangular holes were cut into the stone work at 1.50-1.75m intervals, beginning 3.0m above bedrock. These may have been used as anchoring holes for supports to aid in the vault’s construction or for interior scaffolding related to Vault 1’s function as a warehouse (Blakely, 31). A small corridor was cut into the southern wall on the east end of the vault to connect vaults 1 and 2 (Figure 8).

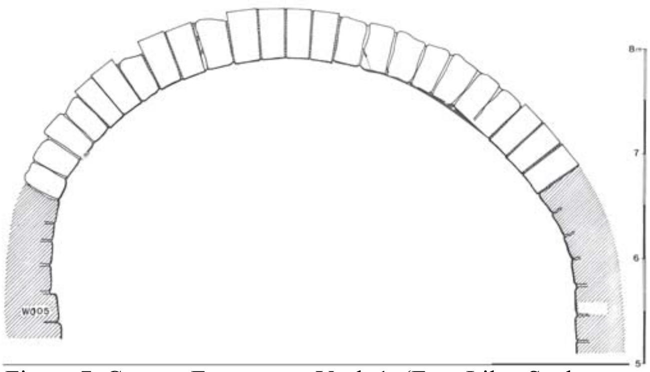


Figure 7. Current Entrance to Vault 1. (Eng. Lilya Suchanov, IAA)

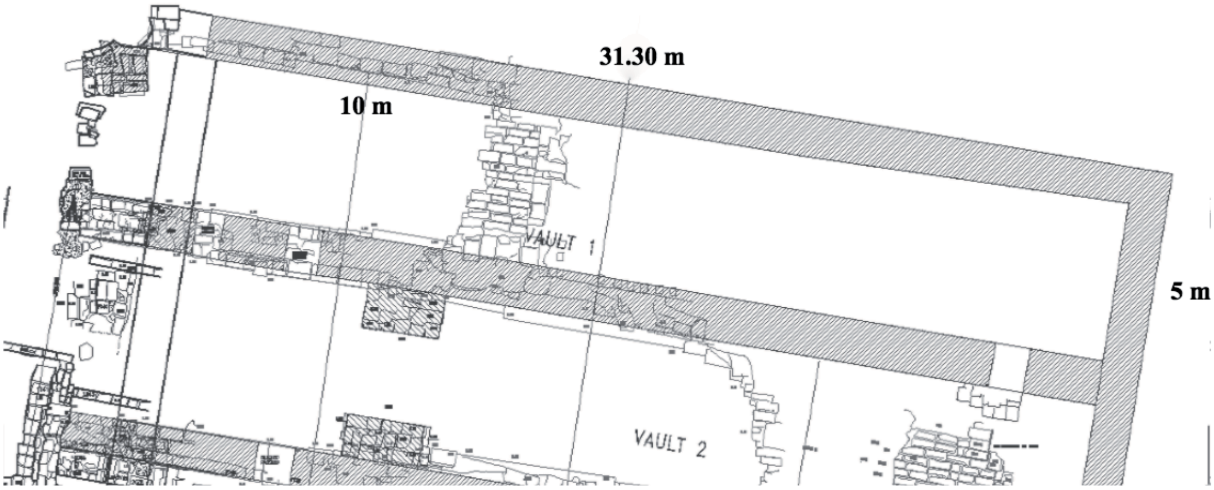


Figure 8. Plan of Vault 1. (Base CAD Drawing Courtesy of IAA)

When vaults 1, 2, 11, and 12 were converted into a Mithraeum (1st-3rd centuries), three benches and an altar were added to the eastern end of the Vault 1 and the walls were plastered with frescos depicting scenes from stories about Mithras. Lamps, ceramics, and numismatics also attest to the practice of the Mithra cult in this space.


Figure 9. Light Entering Eastern Scuttle, 23 June 2012.

In terms of building structure, the earlier support holes were covered during the Mithraeum period, a series of nineteen holes were added above the altar and to the east, and two scuttles were cut into the roof. The light that comes through the eastern scuttle hits the location of the altar at the time of the summer solstice (Blakely, 31-32; Figure 9). Other than the occasional resurfacing of the floor, the structure remained unaltered until its partial collapse and subsequent abandonment.

2.3 State of Preservation

The condition of Vault 1 between excavation and conservation varied from section to section. In general, all of the vaults suffer from varying degrees of deformation, cracked stone from the shift in the structure's geometry, and the collapse of the western 10m of the entire complex (Figure 8). The collapse of the second floor of the Vault Complex also stressed the stones of the vault below, contributed to its deformation, and drastically increased its exposure to natural elements from above. In addition to weakening the architecture and individual stones, these conditions also destabilized the mortar that both holds the stones in place and fills the core of the walls.

In order to consolidate these problems and stabilize the structure, several different interventions were carried out: stone replacement for stabilization (Figures 10-11), bracing (Figures 12-13), joint filling, drainage, and, finally, grouting.

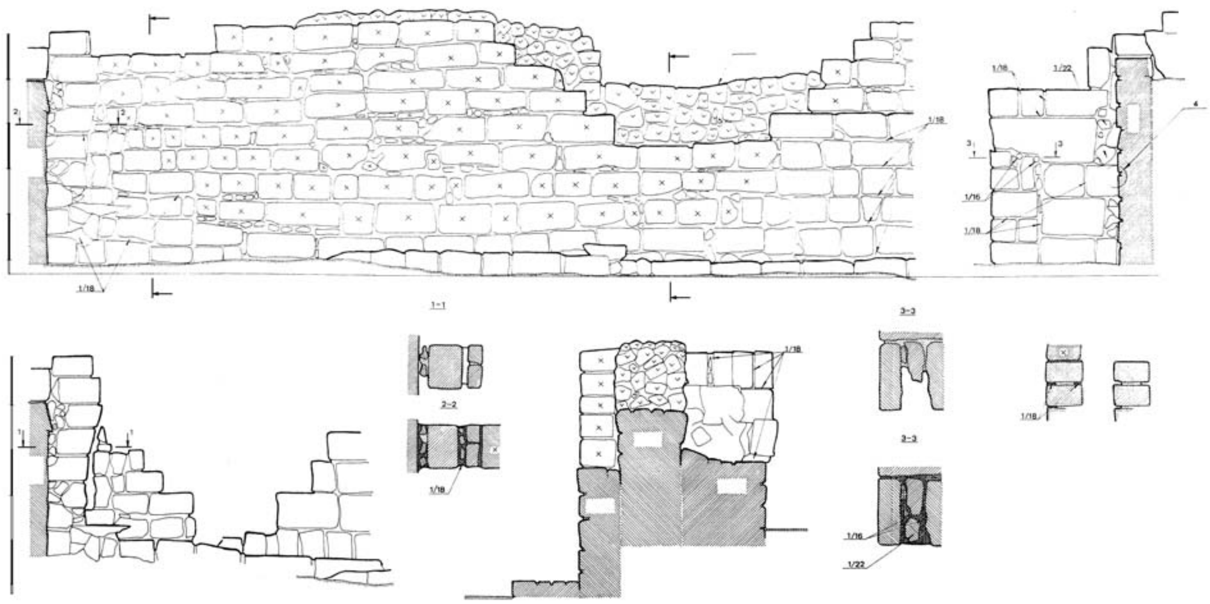


Figure 10. Stone Replacement, Vault 1. North Wall - West. Facing North. (Eng. Lilya Suchanov, IAA)

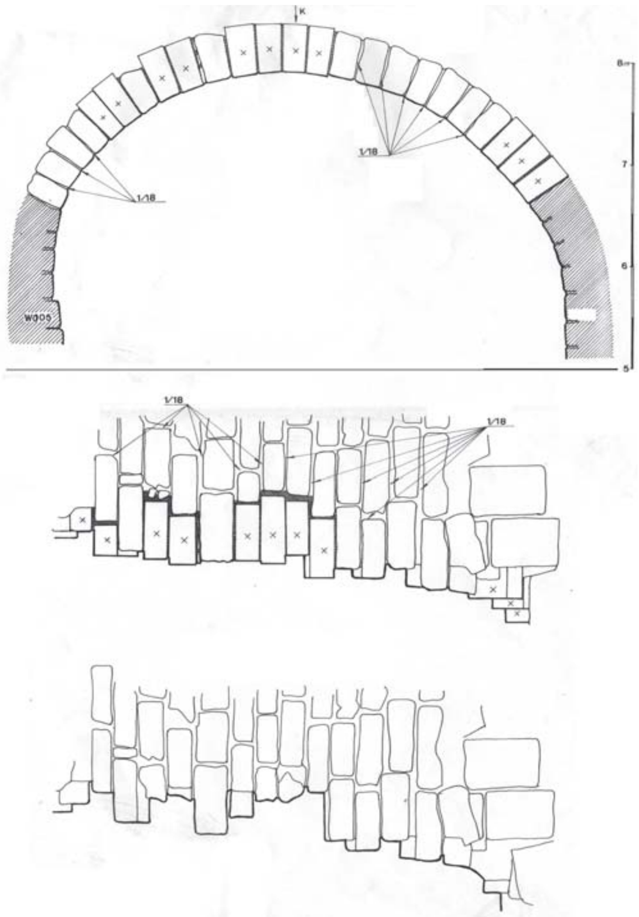


Figure 11. Stone Replacement, Vault 1. Modern Entrance. Facing East (above). Aerial View (below). (Eng. Lilya Suchanov, IAA)

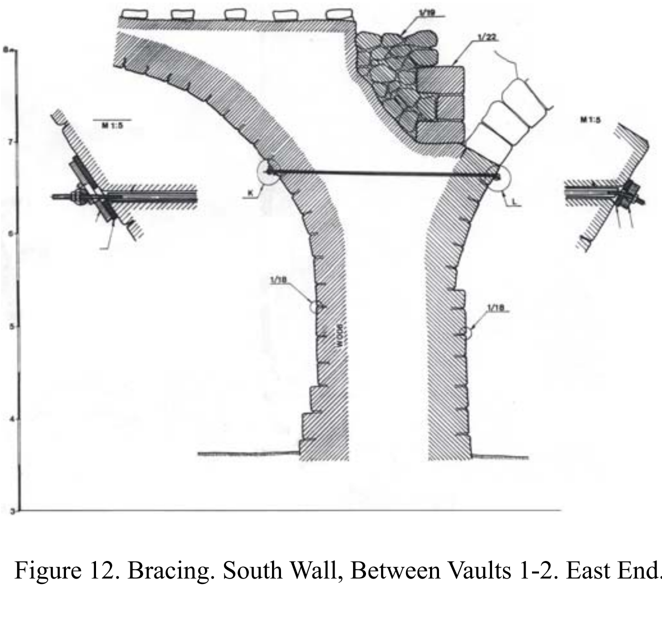


Figure 12. Bracing. South Wall, Between Vaults 1-2. East End. Facing East. (Eng. Lilya Suchanov, IAA)

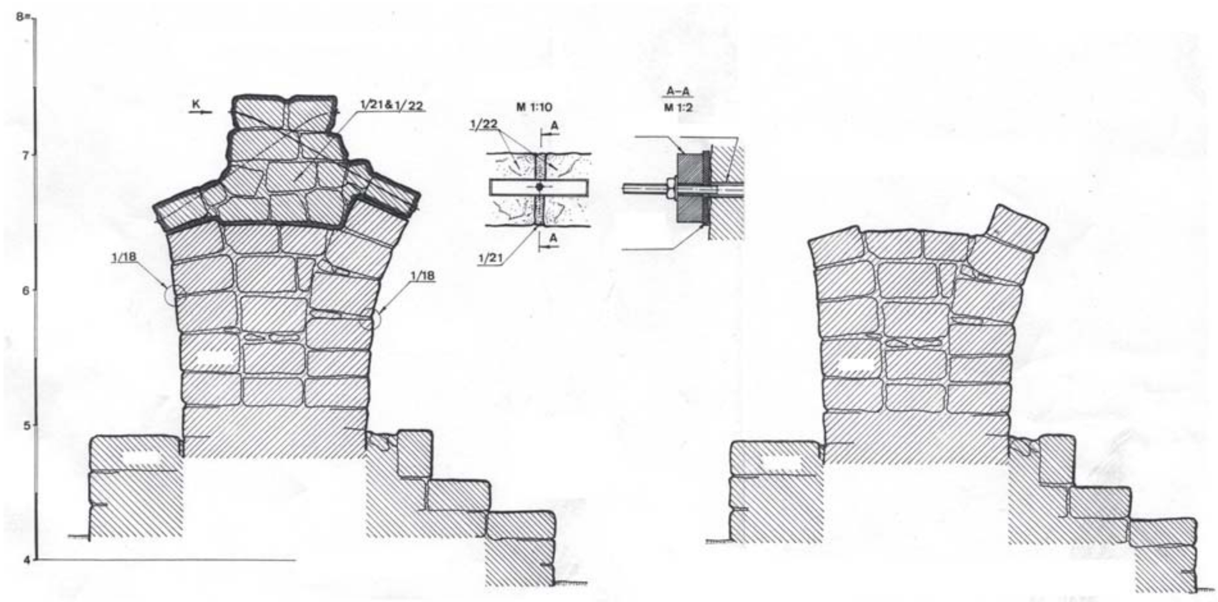


Figure 13. Bracing. South Wall, Between Vaults 1-2. West End. Facing East. (Eng. Lilya Suchanov, IAA)

2.4 Causes of Deterioration

The causes of deterioration for Vault 1 fall into three categories: environmental, structural, and material. The Vault Complex is just meters from the Mediterranean coast and Vault 1 itself is open to the west. As with any seaside location, environmental causes of deterioration include salts, humidity, water penetration, biological growth, coastal storms, and constant a wind that carries fine particles of abrasive sand and salt. All of these factors speed the natural deterioration process of the original sandstone and mortar materials, but salt is especially corrosive.

Figure 14. Biological Growth and Salt Crystallization. Vault 1. East Wall.

The structure of Vault 1 makes it particularly susceptible to environmental causes of deterioration. The 30m length of the windowless vault traps salty moisture and humidity, leading to large amounts of biological growth and a constant layer of fresh, wet salt to penetrate and corrode the stone (Figures 14-16). Water that penetrates the vault from above is also full of salt. After years of exposure to salt water, the natural lime and earthen fill that makes up the core of the wall degrades and becomes a breeding ground for biological organisms, such as mold. Water also causes old mortar to wash out of the joints between stones. The cracked stones, compromised mortar, and overall destabilization of the vault that occurred as a result of its shift in geometry make the structure even more vulnerable to water and salt penetration by increasing access to the core of the wall, as well as increasing the affected surface area.

Figure 15. Biological Growth and Salt Crystallization. Detail. Vault 1. East Wall.

Sandstone and natural lime mortar are porous materials, making them particularly susceptible to water and salt penetration. This is a common problem in this region because the majority of archaeological sites along Israel's northern coast are built of sandstone since it is the local building material. Evidence of quarrying can be seen throughout the region, including some areas of the shoreline.

Figure 16. Biological Growth and Salt Crystallization. Overview. Vault 1. East Wall.

3. Case Study 2: The High Level Aqueduct

3.1 Location and Significance

Figure 17. Location of High Level Aqueduct. Aerial Photograph. (IAA)

The water system at Roman Caesarea is one of the most intensive aqueduct projects evidenced in modern Israel. The system is comprised of two parallel aqueducts, the low level aqueduct and the High Level Aqueduct (Figure 18). The low level aqueduct drew water from a dam on the Zarqa River and transported it over 5km to the northern edge of the city, about 120m inland. The High Level Aqueduct at Caesarea carried water from the Springs of Shuni, down the coastline, to the northern edge of the city - a distance of over 9km. Given the water sources from which the Caesarea aqueducts drew, it is likely that the low aqueduct carried water for irrigation and agriculture, whereas water from the High Level Aqueduct was used for drinking and Caesarea's famous bathhouses (Negev, 274; Horton, 178-79).

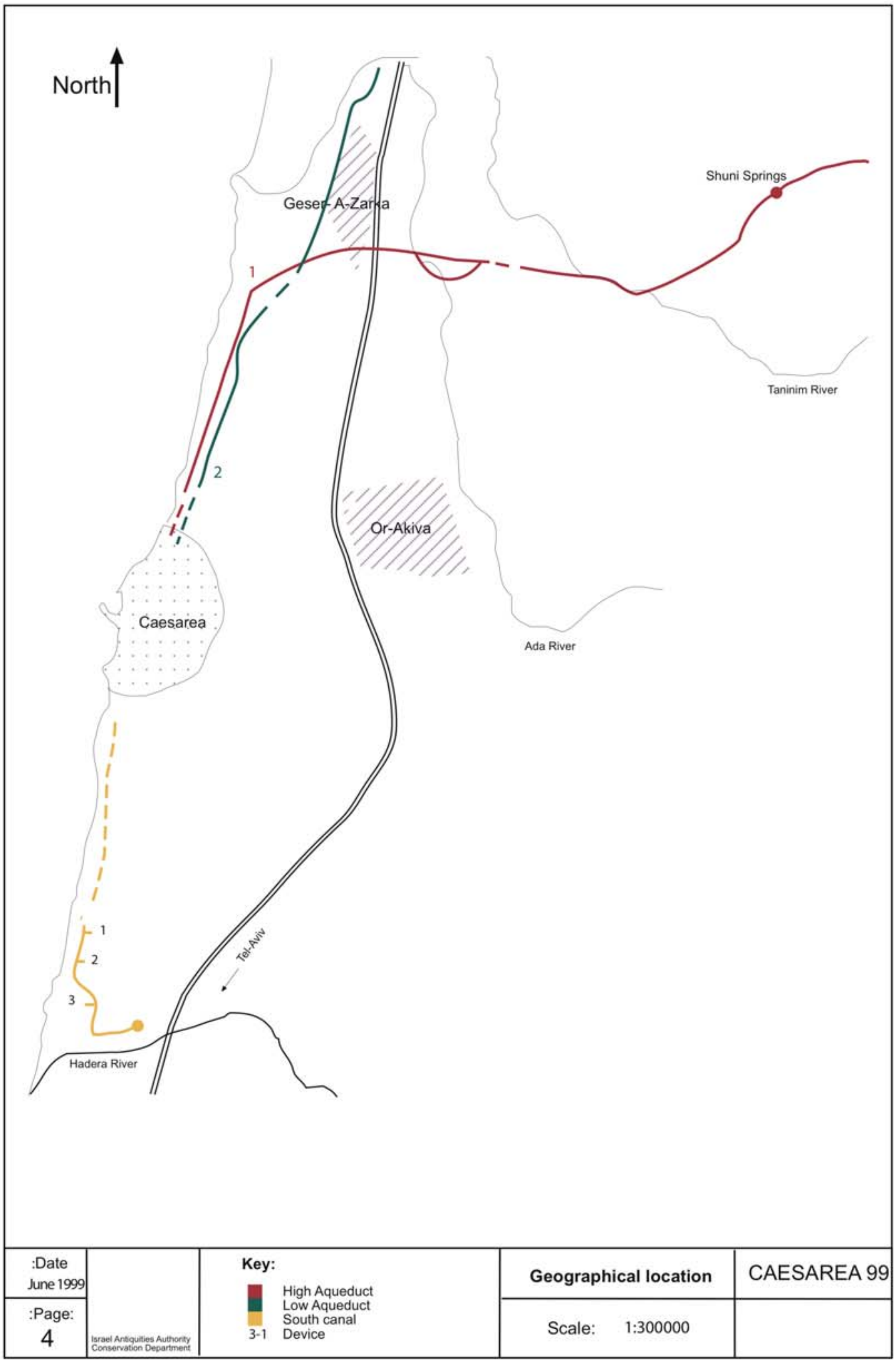


Figure 18. The Aqueducts and Canal Servicing Caesarea. Map. (IAA)

3.2 Building Technology

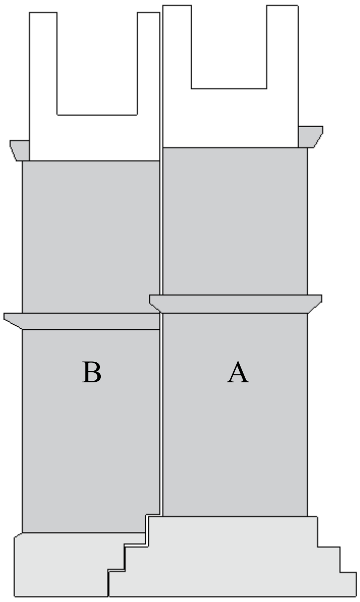


Figure 19. Building Technology. Schematic. Facing North.

Figure 20. Building Technology. Overview. Facing Northeast.

The High Level Aqueduct is built on a slight gradient so water flows from the Springs of Shuni to the city of Caesarea using gravity. Depending on topography, some sections of the aqueduct are underground while others are comprised of channels on top of arches.

The structure as it stands today was built in two main phases: the first phase, the eastern aqueduct (A), dates to the time of Herod (37-4 BCE) and the second phase, the western aqueduct (B), was built 130 years later (Figures 19-23). The western aqueduct was built on top of the stepped foundation of the eastern aqueduct and the walls of the two structures either touch or sit a few centimeters apart depending on the location (Figures 19-23). Many minor changes were made to the structure over centuries of use, including alterations to the upper channels, repairs, reinforcements, and reconstruction.

Both aqueducts are made of sandstone with stones and lime mortar making up the core of the pillars and arches (Figure 24). The channels on top of the arches are made of small kurkar stones set in ancient cement and coated with hydraulic plaster. A leveling course of clay or rubble sits between the arches and the

Figure 21. Building Technology. Facing North.

Figure 22. Building Technology. Facing Northeast.

Figure 23. Building Technology. Detail. Cornices of A and B. (IAA)

aqueduct (Everman, 189). The foundations of the structure are made of lime rubble set on bedrock and recovered by sand to a depth of approximately 2m (Figure 26).

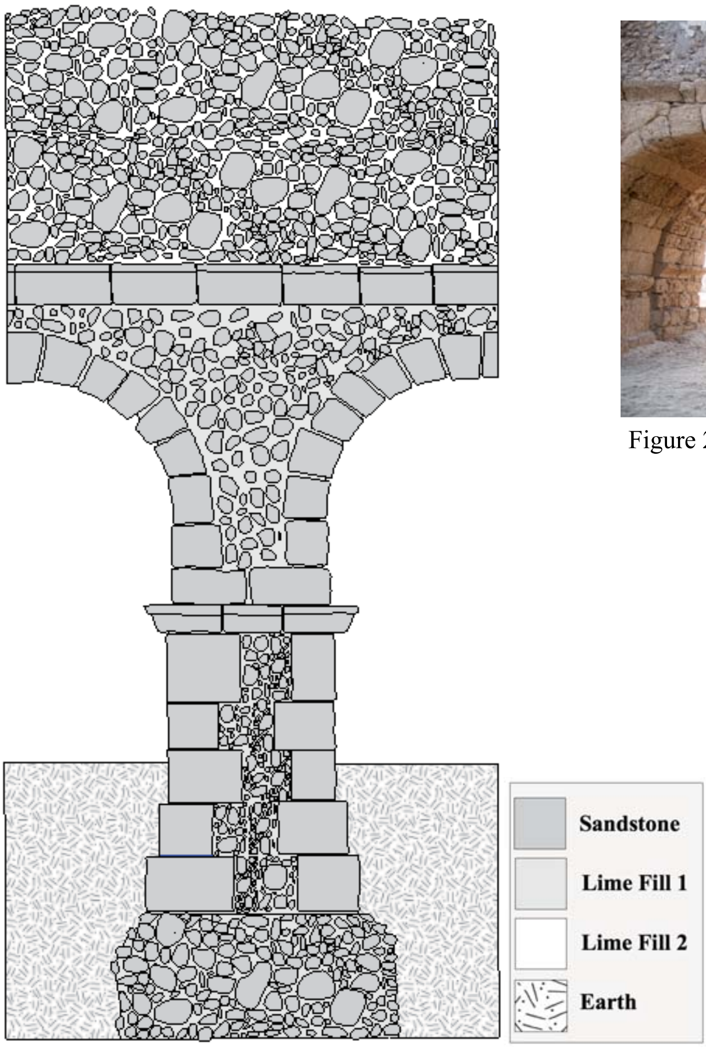


Figure 24. Building Technology. Section Drawing. Facing West or East.

Figure 25. Building Technology. Overview. Facing East.

Figure 26. Building Technology. Foundation. Facing East. (IAA)

3.3 State of Preservation

The High Level Aqueduct at Caesarea was built to be and still is a high quality building (Figure 27). It was repaired throughout its centuries of use, as is evidenced by the occasional difference in building style, numerous interventions, buttressing of the western arches (Figure 28), and even inscriptions. By and large, the eastern aqueduct (A) has remained stable throughout the centuries and has proven to be a much higher quality than the later western addition. This is largely due to the fact that the western aqueduct (B) protects the former from the effects of the sea, although it does cause structural problems in some areas. Since the western aqueduct is built against or a few centimeters away from the eastern aqueduct and overlaps the foundation of the earlier building, one structure's problems can drastically affect the integrity of the other structure, especially in cases where the western aqueduct leans on the eastern (Figure 29).

Figure 27. General Condition. (IAA)

Figure 28. Buttressing of Western Aqueduct. (IAA)

Figure 29. B Leaning on A, Causing Cracks. (David Zell, IAA)

Figure 30. Collapse. (IAA)

Figure 31. Exposed Rubble Fill and Foundation. (IAA)

Figure 32. Collapse of B.

Figure 33. Missing Mortar and Collapse of B. (IAA)

Figure 34. Joint Fill and Stabilization of Collapse of B. (IAA)

Figure 35. Restoration. (IAA)

Figure 36. Reinforcing Foundation, In Progress. (IAA)

Some areas of the High Level Aqueduct did suffer from collapse (Figures 30, 32-33), destabilization of the core of the structure or foundation (Figure 31), stone deterioration, and mortar decay (Figure 33) over time. These problems were consolidated through joint filling (Figure 34), restoration for stabilization (Figure 35), stabilization of foundations (Figure 36) and, of course, grouting.

3.4 Causes of Deterioration

The causes of deterioration of the High Level Aqueduct are in line with those in play at the Vault Complex. The environmental contributors that come with the coastal location - salt, water, wind, sand, humidity, biological growth, storms - all affect this site (Figures 37-38). In fact, a new series of repairs has been started on the High Level Aqueduct in recent months because a major storm in 2010 damaged the structure and exposed its foundations in several places. The issues with porous original materials (i.e., sandstone and lime mortar) are also the same as the Vault Complex, but because there was no catastrophic event parallel to the collapses at the Vault Complex, the aqueduct's materials show much less wear.


Figure 37. Salt Crystallization.


Figure 38. Salt Crystallization. Detail.

The main causes of deterioration are the deterioration of mortars and the occasional use of weak pieces of sandstone (Figures 39-40). As mortar deteriorates and falls away, more surface area of the stone and core of the structure is exposed to the elements, which speeds their deterioration. Since sandstone is a natural building material and particularly porous, its quality is variable. Sometimes this is evident only with the passage of time.


Figure 39. Deterioration of Mortar and Sandstone.


Figure 40. Deterioration of Mortar and Sandstone. Detail.

In terms of structure, the high aqueduct is well suited to the demands of its natural environment. The defining characteristic of aqueducts is that they are water resistant. The massive channels above the arches protect the core of the structure from both water penetration and the penetration of salts. Furthermore, the outer, vertical walls of the aqueduct, the cornices where the channels meet the vaults, the cornices midway down the pillars, and the sloped foundation all direct rain water away from the structure (Figures 24-25).

However, the structure is weakened as a result of the difference in engineering and craftsmanship between the higher quality eastern aqueduct (A) and the later, lower quality western aqueduct (B; See "3.2 Building Technology"). Interventions were made to remedy the situation while the aqueduct was still in use, but it has not been maintained in modern times. Since the aqueduct was excavated 40-50 years ago, little maintenance has been performed. This means that its exposure to the elements has dramatically increased as natural protection (i.e., sand covering) has disappeared.

4. Intervention

4.1 Principles and General Description of Grouting

Grouting is the non-reversible procedure of injecting large amounts of mortar into the core of a structure for the purpose of stabilization. The grouting project at the High Level Aqueduct was carried out from 1991-1993 and the project at the Vault Complex from 1993-1997. Since the process of grouting drastically changes the internal pressure of the structure, the procedure must be carried out with utmost care so as to avoid both human injury and structural collapse.

All procedures must be planned and executed in consultation with an engineer and the project manager. Every stone must be supported with temporary supports from the top down to avoid dislodging stones, particularly those that support the upper-courses. Grouting must be performed from the bottom up to guard against making the structure top heavy (Figure 41). Limitations in respect to how much mortar can be injected in a single treatment are determined by the on-site engineer.

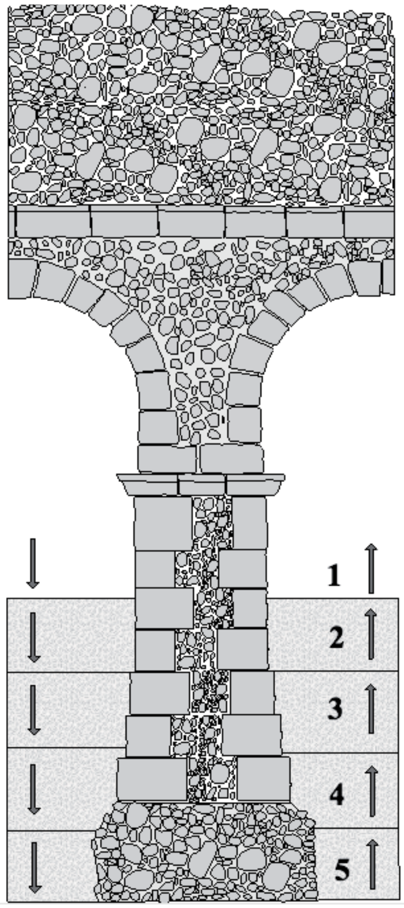


Figure 41: Stages of Washing (Left) and Grouting (Right).

In the case of the High Level Aqueduct, roughly 2m of the structure is underground. This means that the above ground portion was supported, washed, and grouted first, then the crew dug an additional 0.5m and performed the same procedures on the next lowest portion. This was repeated until the foundation was exposed (Figure 41). As for Vault 1, the conservators cannot alter the floor as it was uncovered by archaeologists, so the structure cannot be grouted down to its bedrock foundation. This means that the bottom 50cm or so are not grouted.

4.2 Detailed Description

Preparing the Area

Installation of Supports:

Using a combination of wooden beams, 4” metal piping, and 2” metal piping, support every stone from the top of the structure down. Since both the High Level Aqueduct and Vault 1 have varying states of preservation within the same structure and slightly irregular geometry, supports cannot usually be installed in a systematic, geometric pattern (Figures 41-45). Large problematic areas are supported using a temporary wall made of wooden beams and held in place with metal pipes (Figure 46). Wooden supports are most common because they are adjustable and absorb stress, which is why they are also used as a buffer between stones and metal piping (Figure 47). This prevents further damage to the stone.

Figure 42. Supports on Vault 1. Facing East. (IAA)

Figure 43. Supports on Vault 1. Facing Northeast. (IAA)

Figure 44. Metal Supports on Aqueduct. (IAA)

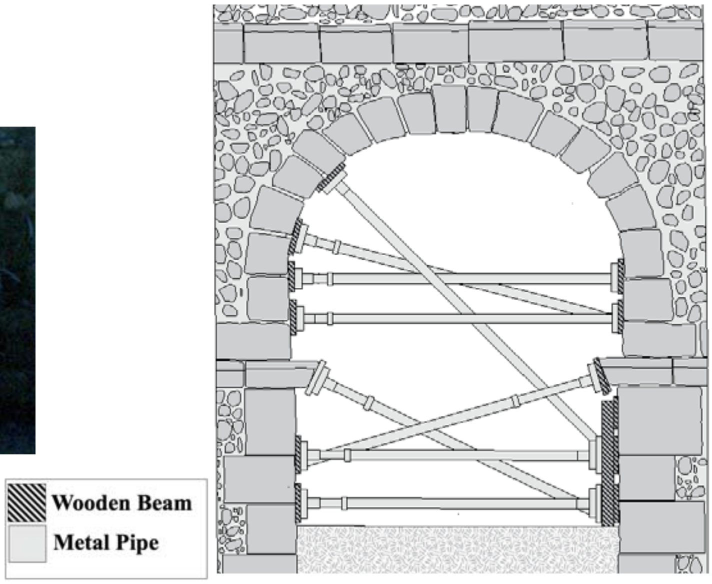


Figure 45. Supports on Aqueduct. Section.

Figure 46. Supporting Wall on Aqueduct. (IAA)

Figure 47. Metal Supports with Wooden Buffer on Aqueduct. Detail. (IAA)

Washing:

The quality of the grouting procedure is highly dependent on the quality of washing, as a clean, wet surface allows the mortar to adhere to the stones and other elements of the lime fill.

To ensure a thorough cleaning, washing must be completed from the top down and from every possible side of the structure. Insert copper pipes (5mm x 1m) into empty joints in the top most course of stones, from every accessible side of the structure, then begin filling the wall with water. Mark where water seeps out of the wall and insert a grouting tube in that location (Figures 48-49). This ensures that the channel between where the water enters and exits is filled with mortar upon injection. Continue washing from all possible sides until the water that exits is clean.

The water that exited the High Level Aqueduct was full of black earth with no lime inclusions and the water from Vault 1 had large amounts of black earth, ash, and little to no lime.

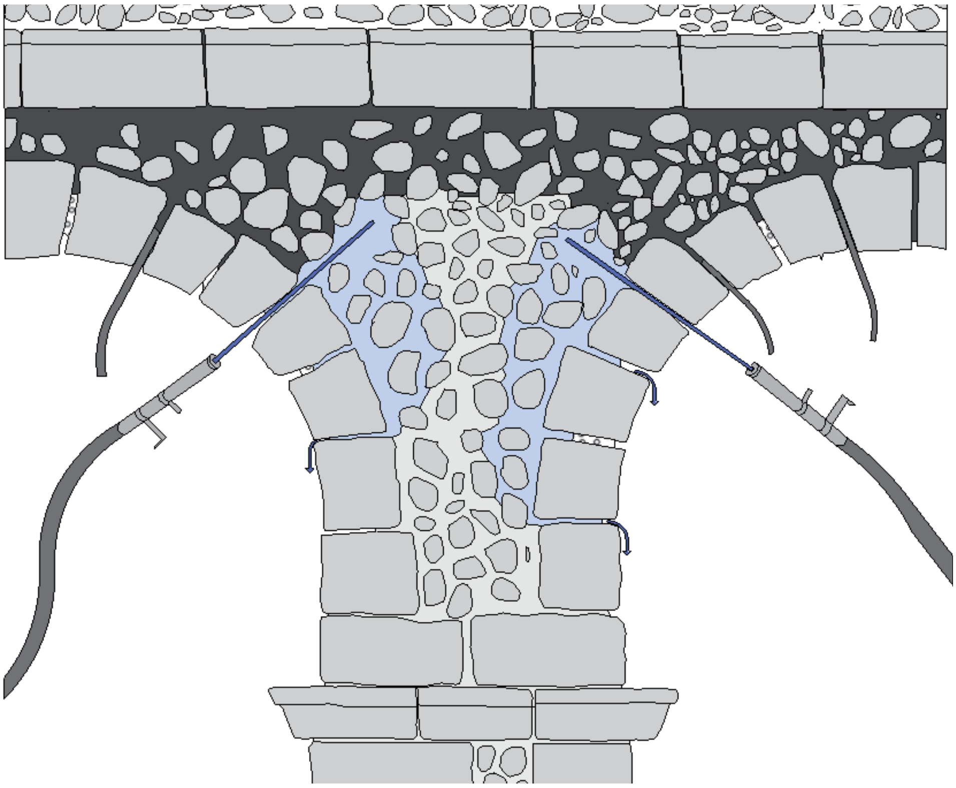


Figure 48. Washing. Overview.

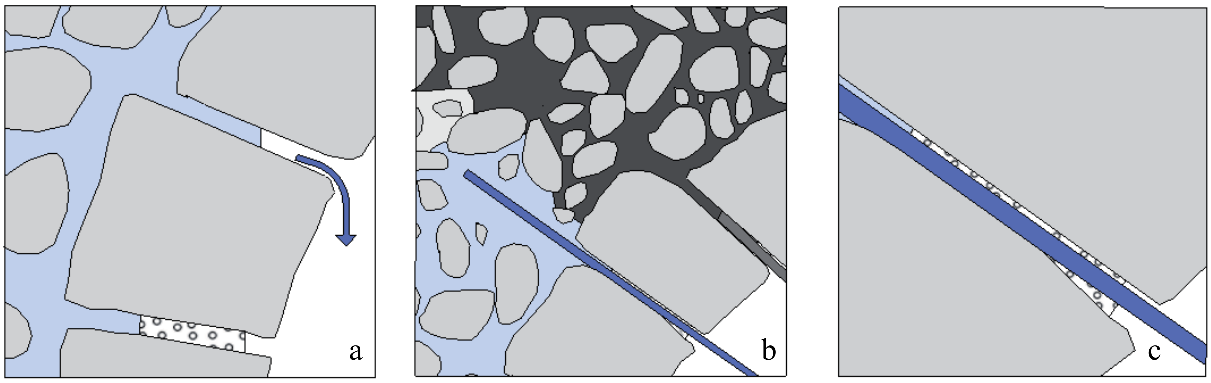
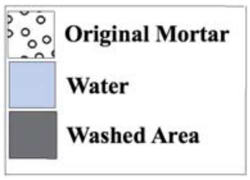


Figure 49. Washing. Detail. a) Water Leak, b) Stages of Washing with Grouting Pipe Inserted, and c) Pipe Insertion.



Joint Filling

Mortar:

1.25 part lime putty
0.25 part black cement
1.0 part Arad sand
1.0 part ceramic
1.0 part tuff
0.25 part ash

Since the IAA had yet to purchase a *mulazza* (Figure 50), a mortar mixer that grinds aggregates into a cohesive material, the Caesarea conservation team had to improvise. The need for something round, heavy, and smooth that could be put into the simple mixer led to the importation of two Napoleonic canon balls from the Old City of Akko (Figure 51). These were thrown into the mixer to achieve the desired effect. A *mulazza* replaced the canon balls midway through the project.

Figure 50. Mulazza at Caesarea.

Preparing the Area:

With the grouting tubes still in place, clean the section of wall to minimize contamination of the mortar and ensure proper adherence. This is done by removing vegetation, sediment, and old mortar. Use a handpick, chisel and hammer, trowel, brush, or any other suitable tool that will not damage the stone or cause further damage to the structure. Wet the area. This both cleans the stone and enables the mortar to adhere.

Figure 51. Canon Balls in Akko.

Pinning:

Before applying mortar to the facade, large holes must be filled with stone. Large sections of mortar crack over time, so it is best to use stones to fill such areas. This also helps mortar adhere and set properly. Line the hole with mortar, wet a stone of the appropriate shape and size, then insert it into the prepared hole (Figure 52). The area is then ready for joint filling.

Joint Filling:

Before applying mortar to the exposed joints, wet the area to both clean the stone and enable the mortar to adhere. Apply mortar with a trowel, spatula, and enough pressure to press it into the gaps between the stones and around the grouting pipes; repeat until mortar sits firmly 1-2 cm behind the stones (Figure 52-55). Sometimes it is necessary to allow the mortar to set for 5-10 minutes before pressing it into the gaps and adding another layer. After the mortar has set for 10-15 minutes, smooth with a spatula.

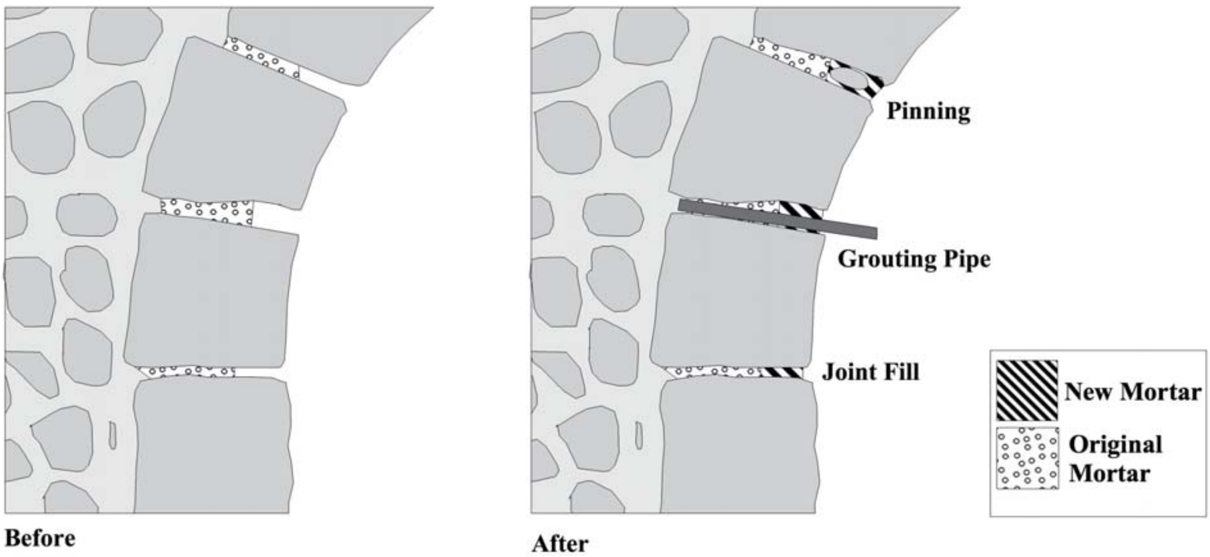


Figure 52. Pinning and Joint Filling.

Figure 53. Joint Filling Using Spatula and Trowel. (IAA)

Figure 54. Joint Filling Around Grouting Pipes. (IAA)

Figure 55. Joint Filling. Finished. (IAA)

Grouting

Mortar:

1.25 part lime putty
0.25 part black cement
1.5 part Arad sand
1.0 part tuff (0-2mm)
0.5 part ceramic (0-2mm)

Add water until mortar is the consistency of a creamy liquid. Small aggregates minimize the risk of separation of the mortar's elements and are easier on the pump used to inject the material.

Methods of Injection:

Two different methods of injection were used on the aqueduct and Vault 1 at Caesarea: gravitation and snail pump.

The first phase of the project used gravitation to fill the wall with mortar (Figure 56). In this method, a thick nylon sack is connected to a flexible pipe with a 4-5cm diameter, then filled with mortar. The sack is then lifted so the mortar will flow down into the wall.

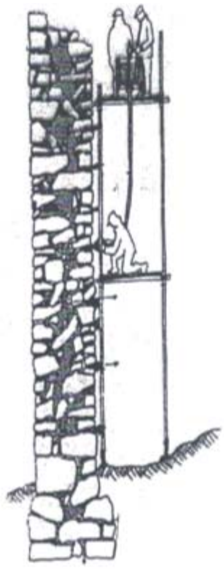


Figure 56. Gravitation. (IAA)

The second phase of the project used a worm (or "snail") pump attached to a TurboMalt L100 spiral mixer (Figure 57) to keep the aggregates from separating.

This mechanical method of injection uses a metal pipe (0.75" diameter) with a rubber and corkscrew filling. As the corkscrew twists, it pushes material through the pump, into the wall. The snail pump is very powerful and can push thick material, but is also expensive to maintain, as aggregates rapidly wear down the rubber filling and corkscrew.

Figure 57. TurboMalt L100. (IAA)

On the Vault Complex, the IAA experimented with an air pump that uses propellor technology but it was immediately abandoned when the high force dislodged a stone.

Preparation:

Wrap geotextile around the area where the grouting pipes meet the wall to prevent leaking. Set pieces of geotexile aside in a convenient location to quickly block any leaks that occur during the injection phase.

Injection:

Attach the gravitation hose or pump to the lowest grouting tube and begin to flood the interior of the wall with mortar. With a minimum of 2-3 people surrounding the structure to watch for leaks or signs of distress, continue to pump mortar into the wall until there is either a leak in the wall, or one of the grouting tubes fills and ejects mortar. Temporarily patch such leaks with geotextile. Pinch the grouting tube attached to the pump to stop the flow of mortar and plug it with geotextile. Check to see if the grout has reached each pipe up to the level of the leak or fill (Figures 58-59). In the case of Vault 1, sponges were also kept nearby for when high pressure dislodged the joint filling.

Repeat on the next lowest pipe and continue until the pressure is high according to the meter on the pump. Other indications of high pressure include: shaking grouting pipes, a popping noise indicating strain on the supports, and dislodged joint filling. In the case of the High Level Aqueduct at Caesarea, the crew was only permitted to fill 0.5m of the structure per day. The next day, continue where the previous day ended.

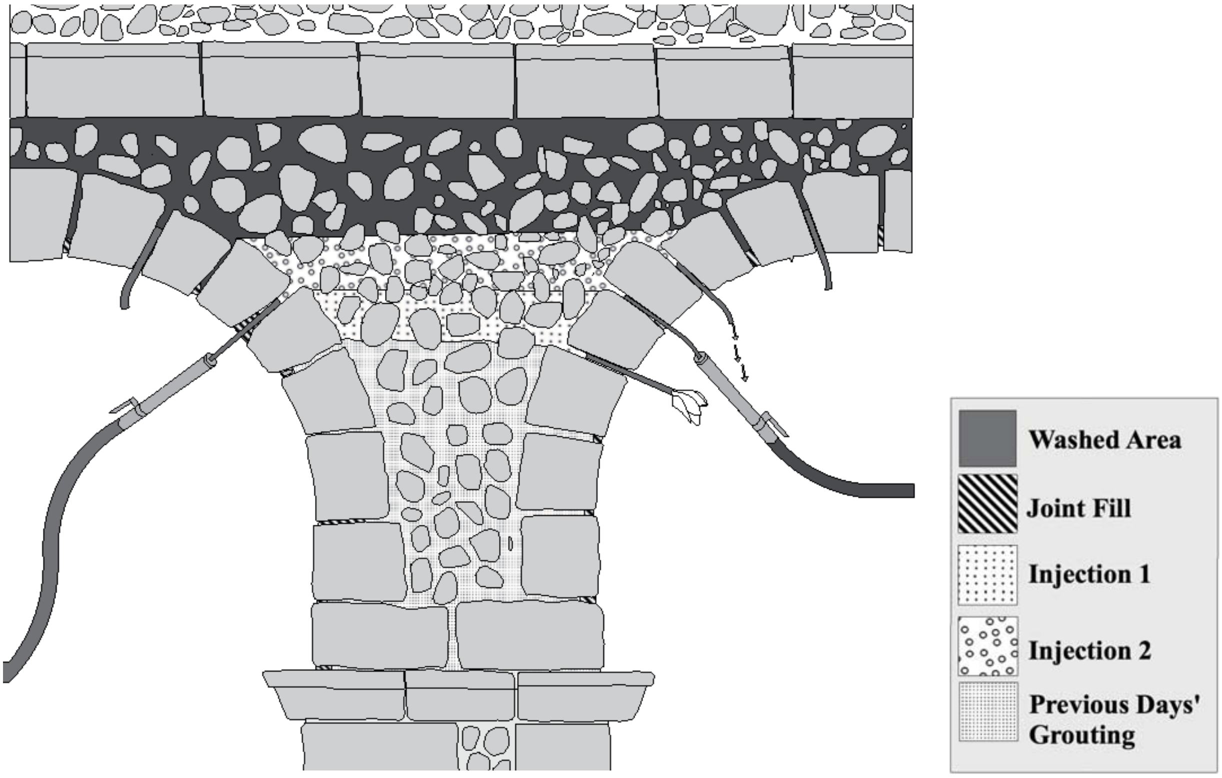


Figure 58. Injection. Overview.

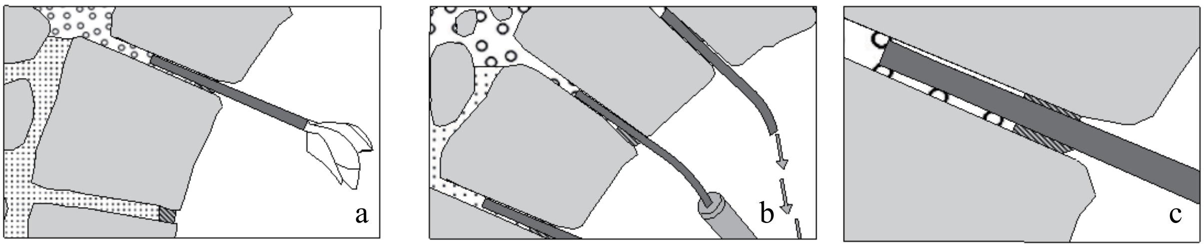


Figure 59. Injection. Detail. a) Completed Injection with Geotextile Plug, b) Second Injection with Mortar Leak, and c) Relation of Pipe to Mortar

Finishing:

Grouting pipes and geotextile plugs may be removed as soon as one day after injection. Fill the holes with mortar, making them flush with the newly applied joint filling (Figure 60). Supports may be removed a few days after the adjacent structures have also been grouted.

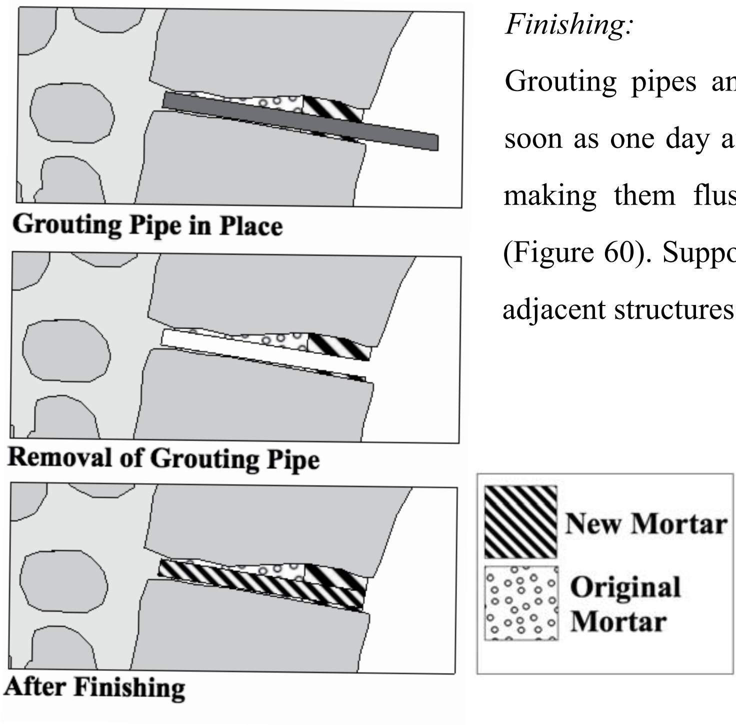


Figure 60. Finishing.

5. 2012 Analysis

5.1 Joint Fill

Monitoring the longevity of joint fill is important because its deterioration allows natural elements to penetrate the structure, causing further deterioration to its interior. Since the deterioration and subsequent destabilization of the core of a structure is what causes it to need grouting, periodically checking on the status of joint fill and maintaining it may delay the need for such an invasive and costly procedure. However, a direct correlation between the state of joint fill and the state of grouting should not be assumed since there are other environmental and structural factors at play.

5.1.1 Visual Inspection of Vault 1

Figure 61. Joint Fill. Vault 1, Ceiling.

After almost 20 years of exposure, the joint fill in Vault 1 is in very good condition, with little sign of deterioration (Figures 61-66). The structure and orientation of Vault 1 (See "2.2 Building Technology") protect the arch from abrasive winds, although salt accumulation and bio-attack are still problematic (Figure 64). Even the joint fill in sections of the north and south walls that are without covering is in good condition (Figures 65-66).

Fig 62. Joint Fill. Vault 1, North Wall (Covered).

Fig 63. Joint Fill. Vault 1, South Wall (Covered).

Fig 64. Joint Fill. Salt Deposits and Bio-Attack. Vault 1, North Wall (Covered).

Fig 65. Joint Fill. Vault 1, South Wall (Uncovered).

Fig 66. Joint Fill. Vault 1, North Wall (Uncovered).

5.1.2 Visual Inspection of High Level Aqueduct

Figure 67. Before Joint Filling. 1991-93. (IAA)

Figure 68. After Joint Filling. 1991-93. (IAA)

Figure 69. Joint Fill 2012. Example 1.

Figure 70. Joint Fill 2012. Example 2 (West Facade).

After 20 years of continued exposure to natural conditions common to life by the sea (See "3.4 Causes of Deterioration"), including a major storm that damaged parts of the High Level Aqueduct and other sites along coastline in 2010, the joint fill on the aqueduct at Caesarea is in various stages of disrepair. The western facade shows the most wear since it faces the sea and has maximum exposure to salt, water, wind, and blowing sand. The joint fill shows signs of weathering and deterioration but is mostly intact with gaps here and there (Figure 69-72). The joint fill on the facades that are protected, including the arches and eastern facade, is generally in better condition.

Figure 71. Joint Fill 2012. Example 3.

Figure 72. Joint Fill 2012. Example 4.

5.2 Testing Grouting Interventions via Core Drilling

To test the effectiveness and longevity of grouting interventions, core drilling was ordered for both Vault 1 and the High Level Aqueduct. Core drilling is the process of using a hollow diamond drill bit to extract a cylinder of material (Figure 73). The material inside the bit is referred to as a *core* or *core sample*, which is removed and laid flat in the order in which it comes out (Figures 74-77). This ensures that the sequence of materials remains clear. In this case, the core samples are a combination of stone, grout, and trace amounts of joint fill (Figures 74 and 78). The core sample is taken from between the stones to minimize damage (Figure 79).

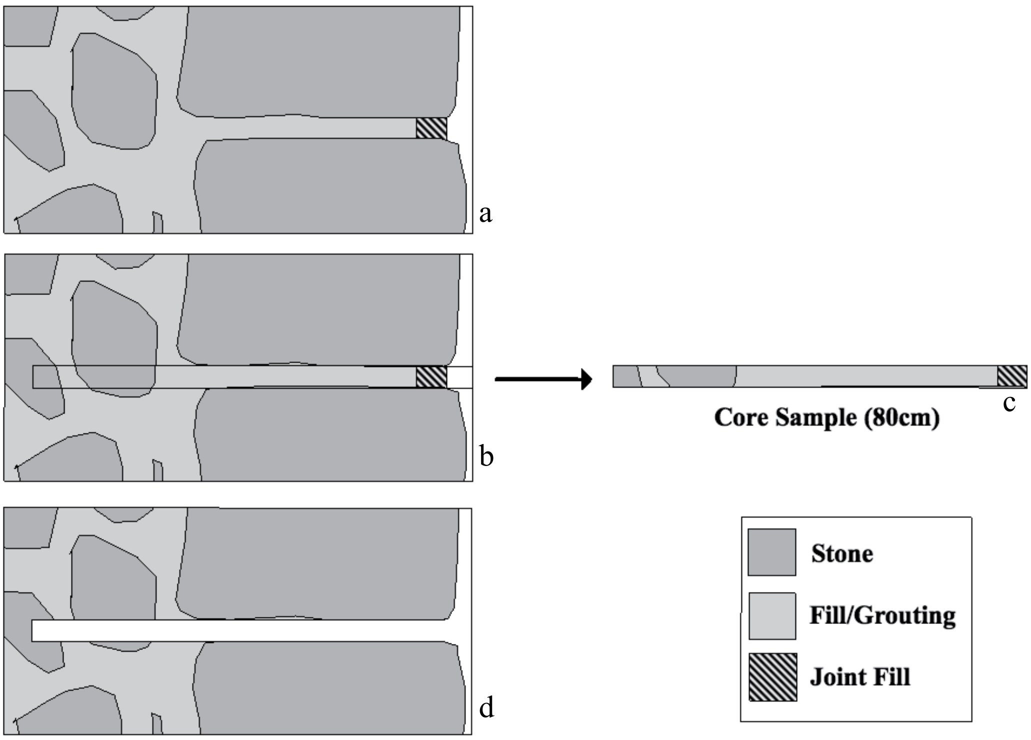


Figure 73. Core Drilling. Section Detail. a) Before, b) Path of the Core Drill Bit, c) Core Sample, and d) After Core Drilling.

Figure 74. Core Sample (80cm). Detail.

Figure 75. Extraction of Core Sample.

Figure 76. Extraction of Core Sample. Detail.

Figure 77. Extraction of Core Sample. Overview.

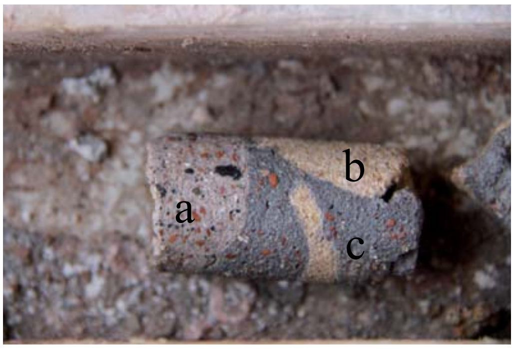


Figure 78. Core Sample. Detail. a) Joint Fill, b) Stone, and c) Grout.

Figure 79. Placement of Core Drill.

The drilling was completed using a Syrox CD160 drill with a 1m bit that produces core samples 80cm long (Figures 80-81). This particular type of core drill uses *wet drilling*, a method which sprays water through the drill bit as it penetrates in order to avoid both overheating the equipment and damage to the materials (Figure 82). The disadvantage of this method is that earth and sand are washed out, so an 80cm sample often does not produce 80cm of material. Plus, one cannot determine whether the absence of material is due to the wet drilling washing material out or reflects an actual void in the wall (Charts 1-2).

Figure 80. Syrox CD160.

Figure 81. Syrox CD160. Detail.

Figure 82. Wet Drilling.

5.2.1 Core Drilling Results for Vault 1

Of the eleven core samples pulled from Vault 1, six were collected from the covered portion of the southern wall and five from the northern wall (Figure 83). The samples also come from a variety of elevations spanning the breadth of the vault (Figure 84). A more complete and systematic set of samples is in order before further intervention is implemented, but this sample set is large enough to provide a snapshot of the condition of this particular vault.

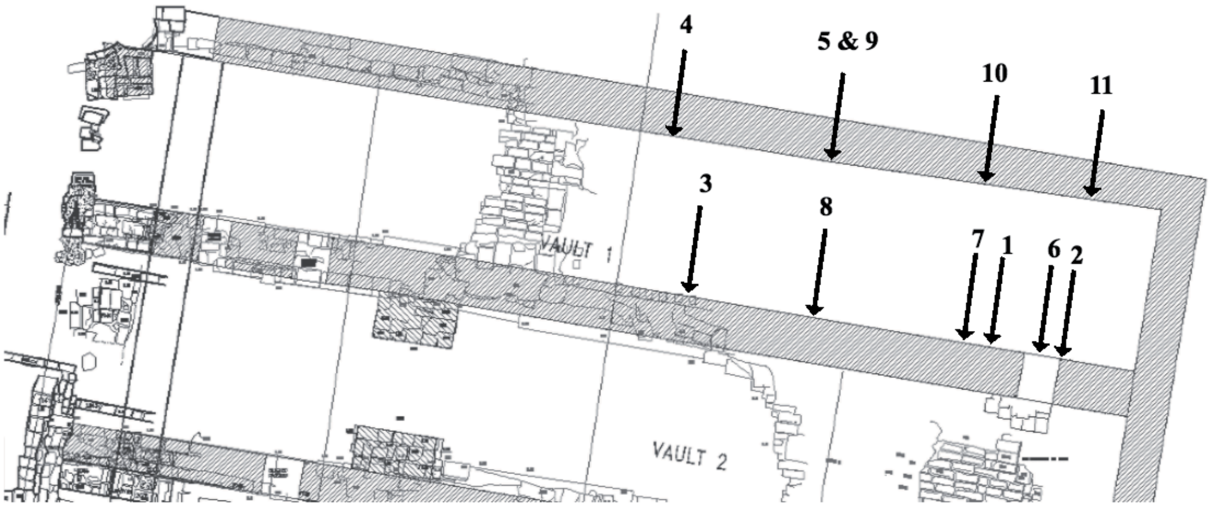


Figure 83. Locations of Core Drilling, Vault 1. Aerial View. (Base CAD Drawing Courtesy of the IAA)

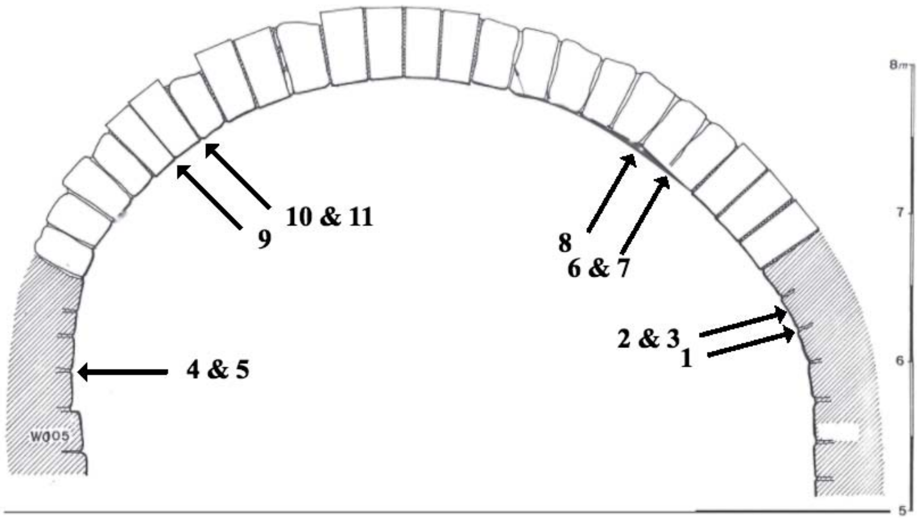


Figure 84. Elevations of Core Drilling, Vault 1. Modern Opening. Facing East. (Base Drawing Courtesy of Eng. Lilya Suchanov, IAA)

The eleven core samples suggest that Vault 1 may be in need of further intervention in the near future. On average, the walls are 74% earth or void and only 12% stone, 4% grout, and 10% stone and grout combined (Chart 1). The black or brown-red color of the water that came out during wet drilling suggests that those areas of the wall are filled with earth or sand, whereas clear water suggests a void in the wall (Chart 1; Figures 85-87). Sometimes the black or brown-red water was accompanied by a foul odor, possibly indicating the presence mold or some other form of biological growth in the core of the wall. The presence of earth or sand suggests that the washing procedures carried out before injection were only partially effective.

Figure 85. Black Water During Wet Drilling.

Figure 86. Brown-Red Water During Wet Drilling.

Figure 87. Clear Water During Wet Drilling.

Figure 88. Pouring Water into the Void, Drill #5.

Since drill #5 produced no stone or grout but was 100% void or washed out by wet drilling, we tested the sample area by pouring water into the hole with a hose. The water did not exit the wall in the 10 seconds we did so, which suggests a void in the core of the wall (Figure 88).

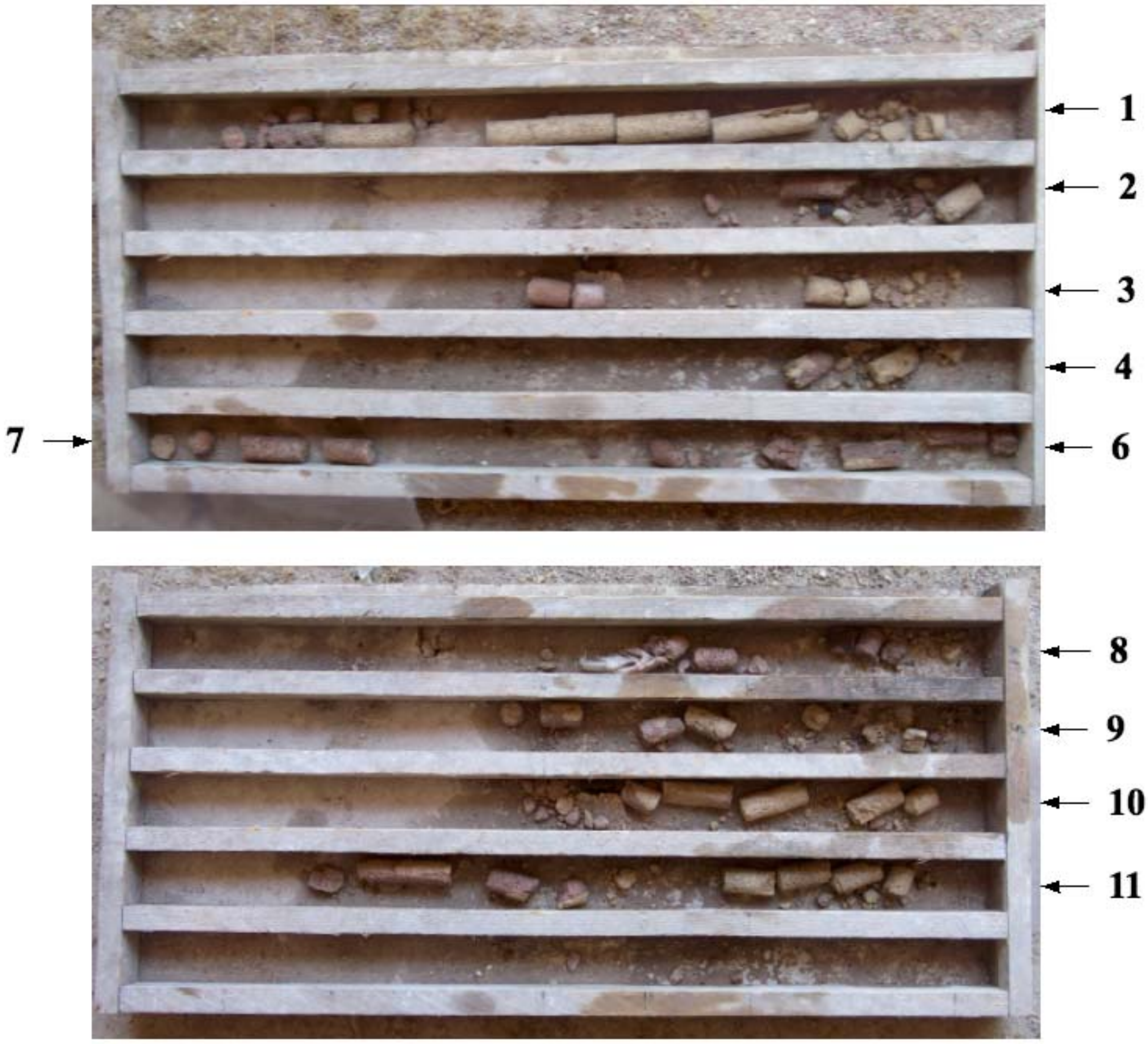


Figure 89. Core Samples, Vault 1 (No Material Extracted During Drill #5).

Chart 1: Results of Core Drilling, Vault 1

Drill: Number and Location	Stone	Grout	Both Stone & Grout	Washed or Void	Color of Water
1: South Wall; East End	68.75%	-	-	31.25%	Black
2: South Wall; East End	6.25%	8.75%	-	85.00%	Black
3: South Wall; Center	7.50%	8.75%	-	83.75%	Brown/ Red
4: North Wall; Center	8.75%	-	6.25%	85.00%	Black
5: North Wall; Center	-	-	-	100.00%	Black
6: South Wall - Arch; East End	-	-	25.00%	75.00%	Clear
7: South Wall - Arch; East End	1.25%	17.50%	-	81.25%	Clear
8: South Wall - Arch; Center	-	6.25%	13.75%	80.00%	Brown/ Red
9: North Wall - Arch; Center	5.00%	-	20.00%	75.00%	Clear
10: North Wall - Arch; East End	11.25%	-	22.50%	66.25%	Brown/ Red
11: North Wall - Arch; East End	23.75%	3.75%	21.25%	51.25%	Brown/ Red
Average	**12.05%**	**4.09%**	**9.88%**	**73.98%**	

5.2.2 Core Drilling Results for High Level Aqueduct

All six core samples that were pulled from the High Level Aqueduct came from the western structure (B; Figure 19) because it was the subject of most of the grouting interventions performed on the aqueduct (See “3.2 Building Technology”). The conservation team that worked on the High Level Aqueduct in the early 1990s numbered each arch, beginning at the southern most arch. We focused on arch #56 and its adjoining pillars because extensive grouting was performed in this general area (Figures 90-93). As with Vault 1, a more complete and systematic set of samples is in order before further intervention is implemented, but this sample set is large enough to provide a snapshot of the condition of this particular area.

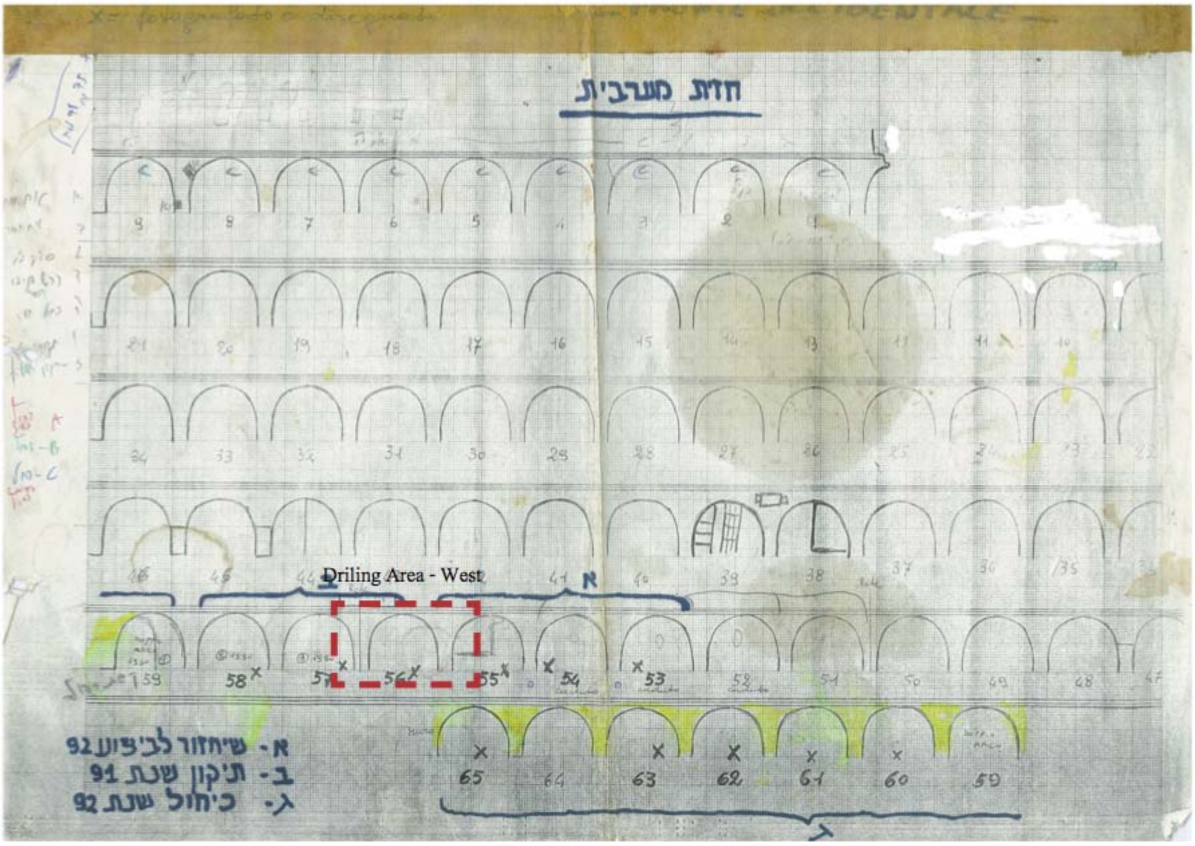


Figure 90. Numbering of the High Level Aqueduct, Western Facade. Drilling Area Outlined in Red. (Base Drawing Courtesy of the IAA, Conservation Department)

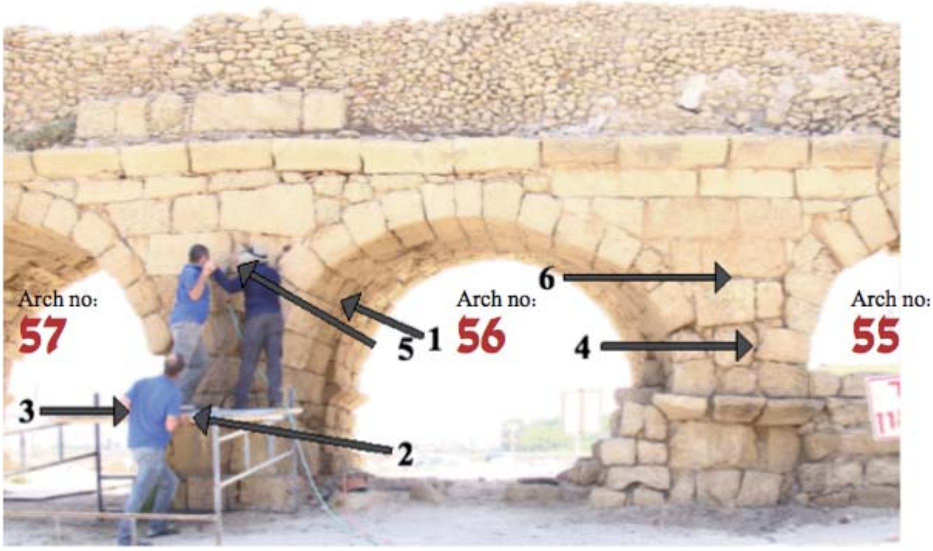


Figure 91. Locations of Core Drilling, High Level Aqueduct. Overview. Facing East.

Figure 92. Locations of Core Drilling, High Level Aqueduct. Detail of Drill #1. Facing Northeast.

Figure 93. Locations of Core Drilling, High Level Aqueduct. Detail of Drill #2-3. Facing Southeast.

The six core samples taken from arches 55-57 suggest that this particular area is in good condition but should be monitored at regular intervals. On average, the walls are 35% earth or void, with 14% stone, 18.5% grout, and 32.5% stone and grout combined (Chart 2). The clear water that came out of the wall during wet drilling suggests that the washing procedures performed on the western aqueduct were effective at removing the earthen material that had filled the wall in the centuries between its construction and conservation. The color of the water also suggests that the areas we tested were 15-47.5% void. In comparison to the results of drilling at Vault 1, which is an estimated 74% void, the aqueduct is in good condition. However, it should be monitored at regular intervals to insure that the structure remains stable.

Figure 94. Core Samples, High Level Aqueduct. Western Aqueduct.

Chart 2: Results of Core Drilling, High Level Aqueduct

Drill: Number and Location	Stone	Grout	Both Stone & Grout	Washed or Void	Color of Water
1: Arch 56; North Wall; Arch	11.25%	42.50%	-	46.25%	Clear
2: Arch 56-57; West Facade	25.00%	13.75%	18.75%	42.50%	Clear
3: Arch 57; South Wall; Pillar	11.25%	3.75%	66.25%	18.75%	Clear
4: Arch 55-56; West Facade	6.25%	22.50%	23.75%	47.50%	Clear
5: Arch 56-57; West Facade	12.50%	28.75%	20.00%	38.75%	Clear
6: Arch 55-56; West Facade	18.75%	-	66.25%	15.00%	Clear
Averages	**14.17%**	**18.54%**	**32.50%**	**34.79%**	

5.2.3 Comparing Results from Vault 1 and High Level Aqueduct

After 15-20 years, the grouting interventions at Caesarea have mixed reviews. The High Level Aqueduct, which was conserved from 1991-1993, is in a much better state than Vault 1, which was conserved from 1993-1997. An estimated 74% of the core of Vault 1 is either void or composed of earth or sand, whereas only 35% of the sampled area at the High Level Aqueduct can be described as void or filled with earth or sand (Chart 3). Furthermore, the samples from the aqueduct show a much higher level of both grout and the combination of stone and grout than the samples collected from Vault 1. If grouting interventions were performed using more or less the same work method, what accounts for the difference in test results? The answer is likely a combination of factors, both structural and human.

Chart 3: Comparing Averages of Core Samples from Vault 1 and the High Level Aqueduct

Structure	Stone	Grout	Both Stone & Grout	Washed or Void	Color of Water
Vault 1	12.05%	4.09%	9.88%	73.98%	36% Black 36% Brown/Red 27% Clear
High Level Aqueduct (B)	14.17%	18.54%	32.50%	34.79%	100% Clear

Structural Factors

In respect to the question of why one grouting intervention has faired better than the other, the issue of water penetration must be considered. The collapse of the second floor and eastern 10m of the vault in antiquity left the structure particularly vulnerable to water (See "2.3 State of Preservation"). Furthermore, the degree of biological attack on Vault 1, particularly the eastern end, and the odor that accompanied some of the drilling samples both point to a problem with water penetration (See "2.4 Causes of Deterioration"). The IAA did install a drain above the eastern wall of Vault 1 during its conservation, but the continued presence of mold, the foul odor, and a visual inspection of the drain itself strongly suggest that water continues to enter the vault from above, washing out the earthen core and transporting other environmental hazards. Since Caesarea is located by the sea, water penetration also means the penetration of salt and sand, both of which speed the process of deterioration. This is particularly problematic when it occurs in the core of a wall where there is no evaporation. Warm, wet, and dark earthen places tend to grow mold which affects the integrity of the structure. If salt is present, its deposits will continue to grow and deteriorate the stone and other materials from inside the wall, where the damage cannot be seen.

As for the High Level Aqueduct, its overall structure protects the core of the arches from water penetration. However, the same problems that affected the aqueduct in antiquity continue to affect it today (See "3.4 Causes of Deterioration"). Life by the sea, the structural weaknesses of the western aqueduct (B), and the effects of those weaknesses on the eastern aqueduct (A) all continue to contribute to the deterioration of the structure, as well the conservation efforts that were carried out upon it.

In respect to Vault 1, other structural factors include the fact that conservators cannot alter the floor as it was uncovered by archaeologists, so the bottom 50cm of Vault 1 are not grouted (See "4.1 Principles and General Description of Grouting"). Another potential factor may be differences in wall fill. Since the interior of the wall is not visible, it is uncertain whether the core of the High Level Aqueduct contains more stone than the core of Vault 1, as suggested by the core samples (Chart 3; See the "Both Stone and Grout" column). The presence of more stone versus more earth or sand would suggest a more stable wall since stone does not deteriorate as quickly as earthen fill.

Human Factors

Perhaps the biggest limitation of the grouting procedure is the fact that humans cannot see through walls. The only indication that the core of a wall has been thoroughly washed of earth and sand is if the water coming out of its cracks runs clear. The best indication that the injection of mortar is complete is a pressure gauge on the pump. Without seeing inside the wall, the conservator cannot be completely certain of the quality of his or her work.

In respect to the washing stage of the grouting process, the cleanliness of the water produced by the wet drilling on the aqueduct suggests a thorough washing. On the other hand, the presence of black and brown-red water in 72% of the wet drillings on Vault 1 suggests that the washing procedure was not nearly as effective on the vault as on the aqueduct. In respect to the injection of mortar, the 14.5% difference in the amount of grout and the 22.5% difference in the amount of stone and grout combined points to a more effective series of injections at the aqueduct than Vault 1 (Chart 3). Overall, the grouting performed on the High Level Aqueduct is currently at a much better state of preservation than that performed on Vault 1.

6. Recommendations

Based on visual examination of the joint fill and the results of core drilling, a few recommendations come to mind in regards to Vault 1, the High Level Aqueduct, joint fill, and grouted areas in general.

1. Perform a more systematic and extensive series of core drillings on Vault 1 and the High Level Aqueduct to fully assess the current states of preservation. Re-grout as necessary to ensure stability.
2. Reduce the amount of water that penetrates Vault 1 by 1) fixing the drainage system above, 2) regrading the flat, gravel surface that serves as a roof in order to direct water away from the Vault Complex (Figure 95), and 3) replacing joint fill between the stones above Vault 1.
3. Develop a maintenance plan for joint fill. Joint fill should be systematically checked at regular intervals and over extended periods of time. The joint fill should be maintained to avoid large scale projects at a later date.
4. Tend to other variables that effect the quality and longevity of grouting interventions, especially water penetration.
5. Develop a maintenance plan for grouted areas throughout Israel. This plan should include


Figure 95. Roof of Vault 1. Facing West.

a monitoring system for both joint fill and grouting. Visual inspection of the joint fill and core drilling of grouted areas should be performed systematically and at regular intervals over extended periods of time. Re-filling and re-grouting should be ordered as necessary.

7. Conclusion

This report has both documented and analyzed the grouting interventions that were performed at the High Level Aqueduct and Vault Complex at Caesarea 15-20 years ago. In light of this analysis, several practical recommendations have been made concerning monitoring, maintenance, and attention to variables that contribute to further deterioration. This report also serves as an example of the type of work David Zell describes in his manual פיילוט מפרטים לשימור: אפיון צרכים ותוכנית עבודה לקידום הפרויקט. The hope is that this report will encourage conservation professionals to produce final reports of their practical work so that other professionals, researchers, and other interested people will be able to connect the dots between a site's excavation and present state.

This is beneficial, not only for the individuals involved in conservation projects, but for the site, the bodies (e.g., government, private, third-party) that govern the site, decision makers, and, of course, the field of conservation as a whole. If the conservator's job is to pass heritage on to future generations, one should also explain *how* they do so. The act and process of conservation is part of the history of a place and its people, part of its narrative. This, too, must be maintained, passed on, and made accessible to future generations. As for the present, knowledge is gained through sharing. The field of conservation is fairly new in many parts of the world and has much to learn. Furthering the field means sharing processes of intervention and analysis with the conservation community at large so other conservators may benefit from one's work and, in turn, benefit the global community through the conservation of their particular sites.

8. Bibliography

Blakely, Jeffrey A. *The Joint Expedition to Caesarea Maritima Excavation Reports: The Pottery and Dating of Vault 1; Horreum, Mithraeum, and Later Uses.* Joint Expedition to Caesarea Maritima, Vol.4. Edited by Fred L. Horton. Lewiston, NY: Edwin Mellen Press, 1987.

Horton, Fred L. "A Sixth Century Bath in Caesarea's Suburbs and the Transformation of Bathing Culture in Late Antiquity." Pages 177-89 in *Caesarea Maritima: A Retrospective After Two Millenia.* Edited by Avner Raban and Kenneth G. Holum. Leiden: Brill, 1996.

Mart, Yossi and Ilana Perecman. "Caesarea: Unique Evidence for Faulting Patterns and Sea Level Fluctuations in the Late Holocene." Pages 3-24 in *Caesarea Maritima: A Retrospective After Two Millenia.* Edited by Avner Raban and Kenneth G. Holum. Leiden: Brill, 1996.

Patrich, Joseph. "Warehouses and Granaries in Caesarea Maritima." Pages 146-76 in *Caesarea Maritima: A Retrospective After Two Millenia.* Edited by Avner Raban and Kenneth G. Holum. Leiden: Brill, 1996.

Porath, Yosef. "The Tunnel of Caesarea Maritima's High Level Aqueduct at the Kurkar Ridge (Jisr ez-Zarqa)." *'Atiqot* 30 (1996):126-27.

Raban, Avner. *The Harbours of Caesarea Maritima, Results of the Caesarea Ancient Harbour Excavation Project 1980-1985. Volume 1: The Site and the Excavations.* Edited by John Peter Oleson. Oxford: BAR Oxford, 1989.