



# **PRESERVATION PLAN**

## **ACEQUIA AND COMPUERTA**

### **TUMACÁCORI NATIONAL HISTORICAL PARK**

Drachman Institute | Heritage Conservation  
College of Architecture, Planning, and Landscape Architecture  
The University of Arizona

In conjunction with:  
Desert Southwest Cooperative Ecosystem Studies Unit (DS-CESU)  
June 2014



**COLLEGE OF ARCHITECTURE, PLANNING  
& LANDSCAPE ARCHITECTURE**  
Drachman Institute





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## PROJECT INFORMATION

This project was carried out between the National Park Service and the University of Arizona through a Joint Ventures Agreement administered by the Desert Southwest Cooperative Ecosystem Studies Unit (DSCESU).

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Project References:

Cooperative Agreement No. H1200100001  
Task Agreement Order No. P12AC10882  
Project Number UAZDS-393  
UA Account No. 3002140

## EXECUTIVE SUMMARY

The historic acequia at Tumacácori National Historical Park was likely constructed by 1774, channeling surface flow from the Santa Cruz River to mission fields and orchard. Historic documents and aerial photography suggest use of the feature continued into the late 1930s. Shortly thereafter, natural and man-made changes on the landscape buried or obscured a large portion of the feature. Recent archaeological and geophysical testing has provided evidence of intact acequia stratigraphy buried within the Park.

The *compuerta* or *lavandaría* (referred to in the body of this report as the compuerta) was re-exposed in 1993. This feature provides a tangible point of reference for the largely buried acequia, as well as insight into the techniques and materials used in its construction and use. The remaining acequia swale that extends to the north and south of the compuerta provides further insight into the morphology of the feature. Together, the compuerta and extant swale provide a locus for onsite interpretation of the larger acequia feature.

A condition assessment conducted within the Park found the acequia to be in fair condition. Primary issues affecting the condition include material loss and deterioration due to weathering and disturbance resulting from rodent and insect activity, impacts from Park development and past research, as well as vegetation encroachment. Low visibility within the landscape, combined with a lack of detailed information pertaining to the morphology and use of the feature, has impacted the Park's ability to increase its interpretation.

In order to address issues affecting the acequia's condition and visibility, this report recommends a two-part approach to treatment:

- **Preservation maintenance** of the compuerta and extant swale to maintain the integrity and long-term stability of the historic materials.
- **Rehabilitation** of the buried acequia alignment as a pedestrian trail to increase visibility of the feature's location and linear nature within the landscape, while preserving the archaeological data associated with the buried stratigraphy.

This report recommends that rehabilitation of the acequia alignment be conducted in coordination with ongoing landscape restoration and maintenance with the Park. As such, the recommendations in this report should be incorporated into a Cultural Landscape Report for the Park unit.

## PROJECT BACKGROUND AND NEED

The historic acequia at Tumacácori National Historical Park (TNHP) was a significant feature in the mission community's economy and lifeways, and continued to be used by subsequent inhabitants of the land now incorporated into the Park. Despite its importance and long history of use, the feature was largely buried or obscured through land modifications following its functional period. Because the feature was considered to be largely destroyed, it has received little in the way of preservation maintenance under National Park Service stewardship. Recent research has revealed evidence that portions of the acequia alignment remain intact and shallowly buried, but more information is needed to understand the morphology and use of the feature, as well as to develop strategies for its management.

This project was initiated to synthesize prior research and documentation associated with the historic acequia and compuerta, assess current feature conditions, and provide recommendations for preservation maintenance and further research. This synthesis provides a baseline of information that is required for informed management decisions and preservation measures. Furthermore, the acequia is an important cultural and economic feature that is underrepresented within the Tumacácori cultural landscape. The information in this report serves as an initial plan for preservation measures, as well as increased interpretation and visibility of the acequia within the Park.

The scope of work required to fulfill the project objectives required an interdisciplinary approach. Data were gathered and analyzed using archaeological, geophysical and remote sensing, geomorphological, materials conservation, and historic preservation methodologies. The range of disciplines represented was possible through a collaborative approach between the National Park Service and the University of Arizona. The project was initiated by Jeremy Moss, former Chief of Resources and Archaeologist for TNHP and Alex Lim, TNHP Architectural Conservator and Exhibit Specialist served as the project ATR. Brooks Jeffery, Director of the University of Arizona's Drachman Institute, served as the Principal Investigator. Steve Gastellum, TNHP Chief of Maintenance, provided expertise on resource maintenance needs and procedures. Consultations with geomorphologist Fred Nials provided contextual information on the acequia stratigraphy, as well as critical information on the potential and procedures for further research on the feature and the associated landscape. Consultations with Sarah Studd and Steve Buckley from the Sonoran Desert Network provided information on the historical and current ecological conditions associated with the cultural landscape at TNHP, as well as key information pertaining to landscape restoration. Treatment recommendations were developed through these consultations. Barry Price Steinbrecher of the University of Arizona's Drachman Institute served as a graduate student researcher and contributing author. Laura Jensen of the University of Arizona's Drachman Institute produced GIS and CAD drawings included in this report.





**PART ONE**  
**BACKGROUND AND CONTEXT**

## HISTORICAL BACKGROUND

Tumacácori National Historical Park is located in the Santa Cruz River Valley in Southern Arizona. The Park preserves three Spanish colonial mission sites, including Los Santos Ángeles de Guevavi San Cayetano de Calabazas, and San Jose de Tumacácori, each forming separate units of the Park. This report will focus exclusively on the site of San Jose de Tumacácori (AZ DD:8:3 [ASM]; Tumacácori Unit) founded at its current location in the mid-eighteenth century. The Santa Cruz River Valley is located within the region described by Spanish colonists as the Pimería Alta. The Pimería Alta is located within the Sonoran Desert and consists of the territory roughly defined by the Magdalena River in the south to the Gila River in the north and from the Colorado River in the west to the San Pedro River in the east (McIntyre 2008: 27).

### PREHISTORY

Evidence of human occupation within the Pimería Alta region date back as far as the Paleoindian period beginning approximately 11,500 B.C. Agriculture in the Santa Cruz River Valley began roughly around 3500 B.C. with cultivation of maize, beans, and squash at the mouths of tributary streams within the floodplain, (Bossler and Johnson 2012:22). Evidence of Late Archaic inhabitants of the lower Santa Cruz Valley utilization of irrigation canals to cultivate domesticated crops dates to circa 1200 B.C. (Mabry 1998). By the Hohokam Pioneer period (ca. A.D. 650-750), the populations of dispersed villages, or *rancherías* were supported by maize agriculture irrigated by earthen and caliche-lined diversion canals. In addition to Hohokam settlements, sites associated with trincheras groups of northwestern Mexico extended into the region, including the mountains to the west of TNHP. “The area between Nogales and Tumacácori on the Santa Cruz River became a contact zone between these two cultures, and archaeological sites in this area exhibit traits characteristic of each culture, with the notable absence of canal irrigation” (Bossler and Johnson 2012: 22-23).

Beginning around A.D.1400, large Classic Period Hohokam communities began to disperse, and the Pimería Alta has been inhabited by the descendants and/or northern-migrating ancestors of the Akimel and Tohono O’odham peoples (Sheridan 2006:25, Bossler and Johnson 2012: 23). O’odham inhabitants of the Santa Cruz River valley continued to cultivate crops in the floodplain using flood waters and diversion canals, but also subsisted on wild plant and animal resources.

### COLONIAL PERIOD

During the sixteenth century, there was limited physical contact between Spanish colonial entities and the local population. The exploration expedition and reconnaissance mission that led Franciscan priest Fray Marcos de Niza in 1539, and later Francisco Vasquez de Coronado between 1540 and 1542, into the Pimería Alta resulted in the earliest known written documentation of the area and its inhabitants. However, there is no evidence that either party spent time in the Santa Cruz Valley (Sheridan 2006: 28).

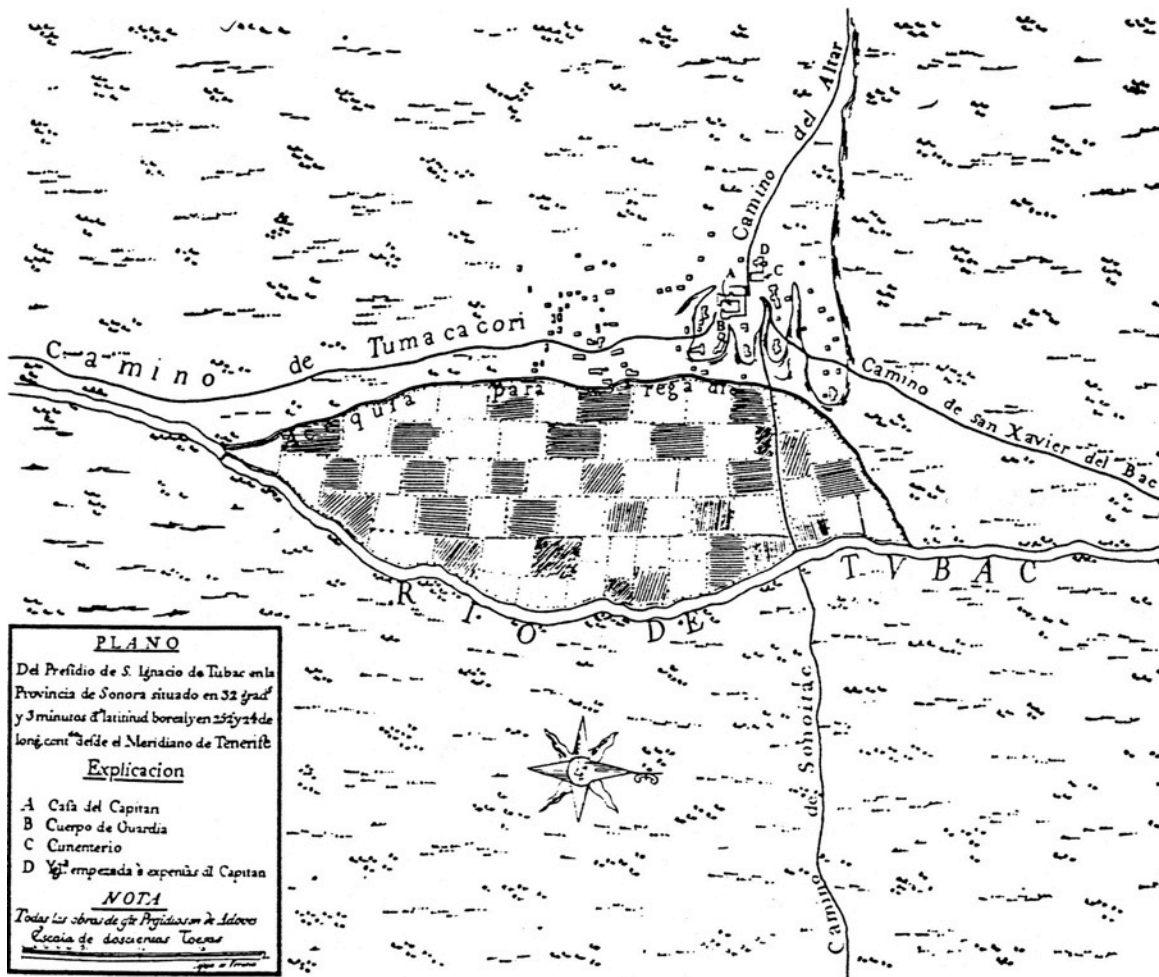
Little documentation of the Pimería Alta followed that from the Coronado expedition until the late seventeenth century when Jesuit priest Father Francisco Eusebio Kino began keeping records of his

travels and communications within the area. By that time, Kino had established a chain of mission church communities along the Altar and Magdalena Rivers, presently in Sonora, Mexico. In 1691, Kino described an invitation by the Pima (O'odham) for him and his superior, Father Juan Maria Salvatierra, to visit the rancherías located within the Santa Cruz and San Pedro Valleys. Kino traveled with military escort Juan Mateo Manje north into the Pimería Alta, both men recording the land and local populations they encountered.

In 1691, Kino made note of two rancherías settlements within the Upper Santa Cruz Valley, including Guevavi and "Tumagacori" (sic.), the latter he dedicated to San Cayetano. In his account, the settlement at San Cayetano de Tumacácori consisted of over forty houses clustered on the east bank of the river and the community there built three structures in which the visitors could conduct their domestic and religious activities (Sheridan 2006: 28, Bossler and Johnson 2012: 60). Kino and Salvatierra established the site of Guevavi as the *cabecera*, the head mission church with a resident missionary, and San Cayetano de Tumacácori as a *visita*, a secondary site where the priest only visited.

By 1753, the Tumacácori community had relocated downstream to the west side of the Santa Cruz River, just south of the newly constructed (1751) Tubac presidio. Previously distinct Piman (O'odham) communities of Tubac and San Cayetano de Tumacácori were congregated in this new location and the site. A new adobe church was constructed and dedicated to a new patron, San Jose (Bossler and Johnson 2012: 24-25, Moss 2006:10).

In 1766, Marqués de Rubí, a Spanish nobleman, led a survey documenting the presidios of the northern frontier of New Spain. The Tubac presidio and surrounding features were mapped by Joseph de Urrutia, a member of the survey expedition (Figure 1.1). The map includes the irrigation infrastructure associated with the presidio, including a structure that diverted water from the river into an *acequia* that gravity fed water into the fields on the west bank of the river (Bossler and Johnson 2012: 63).



From the British Museum (courtesy Arizona State Museum)

Figure 1.1: Map of Tubac, prepared by Lieutenant Joseph de Urrutia in 1766, depicting a town site, *acequia* system, and circulation features. The checker-board pattern between the *acequia madre* and the Santa Cruz River channel indicates cultivation fields (reproduced in Bossler and Johnson 2012: 226).

The 1766 map of Tubac is one of several maps drawn by Urrutia that depict the nature of the agricultural space in Spanish colonial communities in Sonora. Bossler and Johnson (2012) suggest that the layout of the various colonial settlements documented in Urrutia's maps provide insights into the layout of Tumacácori (p 63). Regulations guiding the development of Spanish colonial settlements were promulgated in 1680 by the crown in the legal documents referred to as the Law of the Indies. While many factors, such as topography and hydrology, affected the location and layout colonial settlements, compliance with the regulations in the Law of the Indies created a predictable structure for the organization of communities. The Piméria Alta mission communities faced related influences and limitations which resulted in similarities regarding their spatial organization, including the agricultural components of each community.

In 1774 stipulations concerning water use were established between the Tumacácori community and the colonial settlers downstream at Tubac. The agreement suggests that a significant amount of water was being diverted at Tumacácori, most likely through the *acequia* system, by this time (Logan 2002:51). Observations in 1793 describe wheat, corn, and "abundant" squash among the

crops grown at Tumacácori. “Eighteenth- and nineteenth-century accounts of the mission attribute the beauty and prosperity of the mission gardens and orchard, and the high state of cultivation of the farm fields, to the mission’s irrigation network,” (Moss 2006, 19).

Archaeological evidence, combined with documentation of irrigation infrastructure at other Sonoran colonial communities, helps to define the layout of the cultivated land at Tumacácori. The initial intake of the *acequia madre* was located just downstream from Rock Corral Canyon, (Bossler and Johnson 2012: 63). This was likely the site of a diversion structure created to form a reservoir to facilitate intake of surface flow from the main channel of the Santa Cruz River. The main irrigation ditch was likely extended out as far as possible from the river to maximize the use of the floodplain, diverting water through gravity flow. The compuerta acted as a weir which slowed and lifted the water, potentially allowing for distribution to up-slope fields (F. Nials, personal communication). While no other distribution features have been found in association with the Tumacácori *acequia*, colonial irrigation systems in the region were often divided further into *sangrias*, or lateral canals, using small diversion structures referred to as *adzudes* for distribution into cultivated fields (Bossler and Johnson 2012: 89).

The fields were likely divided into recessed units bounded by berms that could be flooded periodically. A large portion of the cultivated area were communal fields, referred to as *labores*, that provided general subsistence and economic commodities for the mission community, Smaller parcels, or *milpas*, were held and maintained by individuals or families (Ibid.).

Mission Period of Significance and  
Homestead Era Irrigation Scheme

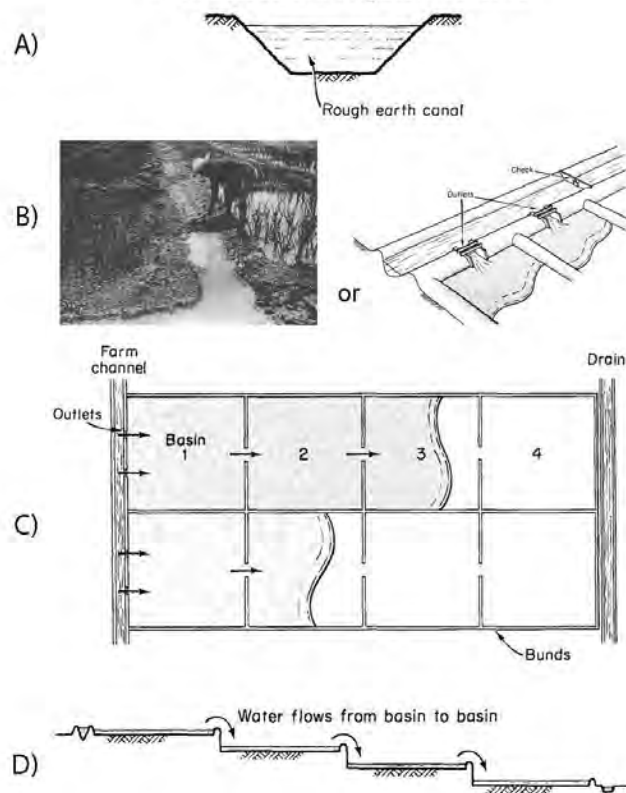


Figure 1.2. Examples of possible irrigation system structures: A) Cross section of typical earthen irrigation canal; B) Illustration of check dam or weir used to slow water for distribution through outlets within canal banks; Plan view (C) and cross section (D) of water distribution through field cells using gravity flow, overflow may be channeled back to main river channel within a drainage canal (after Bossler and Johnson 2012:147).

The social organization of the missions required that the indigenous community perform manual labor, such as working in fields, tending to livestock, or maintaining structures (Crosby 1985: 2). The successes of many missions and the monopoly the missionaries had on Indian land and labor led to tensions between the Jesuits and colonial settlers (Sheridan 2006: 42). These tensions led, in part, to the expulsion of the Jesuit order from New Spain in 1767. The Franciscan order succeeded the Jesuits arriving in the Pimería Alta in 1773, and the new priests designated San Jose de Tumacácori the regional cabecera (Moss 2006: 10).

The Franciscans oversaw a major building campaign and restructuring of the mission grounds between approximately 1770 and 1800. During this time, a large adobe wall was constructed around the garden where fruits, vegetables, and herbs were cultivated, adding a protective element for the garden species. The garden wall was constructed to allow the acequia to pass through within the southwest and northwest corners (Moss 2006). The northwest corner of the wall was constructed on a diagonal in relation to the other walls. A bend in the acequia within the orchard walls, combined with the angle of the northwest orchard wall, may indicate that the natural topography of the site was a factor in the construction techniques associated with the feature.

## **MEXICAN PERIOD**

Six years after the Mexican Revolution in 1821, the Franciscan order was officially expelled from Mexico and all Spanish-born missionaries were forced to leave the country. The resident priest at Tumacácori, Fray Ramon Liberos, who had advocated for the land rights of the mission community, was removed. After Liberos' removal, the land was administered by local O'odham governors. In 1828, half of the mission's wheat fields were leased to rancher Ignacio Ortiz (Sheridan 2006: 98-99). Secularization in 1834 removed mission lands from the control of the Catholic Church, greatly reducing its involvement in the affairs of the mission communities (Crosby 1985: 6, Bossler and Johnson 2012: 29).

In addition to changes in the political environment, changes in the natural environment and climate in the 1830s affected the Tumacácori community. Correspondence from Fray Rafael Díaz, who served communities between the presidios at Santa Cruz and Tucson, to the vice governor of Sonora in 1832, described the drought at Tumacácori as "so complete that we have not raised a grain from a single seed" (quoted in Kessell 1976: 288). Further environmental changes may have affected the use of the acequias. Correspondence from Juan Batista Elías, justice of the peace at Tubac, described the river channel as having moved "a long way away" from the presidio (Kessell 1976:288). The channel upstream at Tumacácori may have been similarly affected. Increased conflict with the Apache at this time compounded the stress on the mission community. In 1841, the final priest to reside at Tumacácori moved to Magdalena (Moss 2006:10).

"By 1843, the Tubac justice of the peace described a fallen and crumbling *convento* building, a standing church and two former communal fields, south of the mission and across the river which was, "unfenced and abandoned, to be full of mesquite and other bushes," (Quoted in Bossler and Johnson: 65). Other accounts suggest there was "only enough water for some Indians to irrigate their meager sowings," (Quoted in Sheridan 2006: 100). However, in October of 1848, US Army lieutenant Cave Coats passed through the Santa Cruz Valley on a reconnaissance mission following the treaty of Guadalupe-Hildago and accounted for the Indian settlement at Tumacácori and described the church as being well kept. Two months later, after a serious Apache attack, the people of Tumacácori took the church furnishings and joined the O'odham at San Xavier del Bac, near Tucson (Crosby 1985: 7).

## **AMERICAN TERRITORIAL PERIOD**

In 1849, the gold rush led many travelers en route to California through southern Arizona. Several travelers who passed through the Santa Cruz Valley wrote their observations of the Tumacácori mission site. In October of 1849, John Robert Forsyth described the well-preserved nature of the church and mission grounds. He wrote: "The garden was well filled with full grown fruit trees and they had been heavily laden with peaches, pomegranates, quinces, etc..." (Quoted in Crosby 1985: 8). Forsyth described the compuerta within the mission acequia as one of the "beautiful baths," indicating there may have been more than one such feature at the site. "Only one has been found to date, but it is probable that numerous diversion boxes would have been needed along the *acequia madre* to feed lateral ditches for wheat and corn fields." (Moss 2006: 20).

Between 1851 and 1855, Manuel María Gándara, one of the most powerful men in Sonora (Sheridan 2006: 100), established a large sheep and goat ranch and farming operation, using the Tumacácori mission compound as the headquarters. “Fields of maize and wheat, and fruit trees were also cultivated during this time,” (Bossler and Johnson 2012: 30). Gándara’s claim to the land was a product of a seemingly unscrupulous auction in Guaymus, Sonora in 1844 (Sheridan 2006: 101).

An un-authored account in 1857 described multiple irrigation canals at Tumacácori (Bossler and Johnson 2012: 31). In 1860, William Wrightson of the Santa Rita Mining Company described how the acequia passes through the mission garden wall and the remains of a “washing vat and bathing place,” which is understood to refer to the compuerta. “Although its function is unknown, the feature probably served to impound water, by constricting and slowing ditch flow, in order to create sufficient head for lateral ditches that fed gardens and orchard trees. The compuerta may have also served as a *lavandaria*, or laundry tank, a common element of mission gardens in the Pimería Alta and Alta California,” (Moss 2006:20).

### **TRANSITION TO NATIONAL PARK SERVICE STEWARDSHIP**

In 1908, President Roosevelt designated the Tumacácori National Monument, after homesteader Carmen Mendez deeded 10 acres containing the mission church to the federal government. The site was administered by the U.S. Forest Service until 1914, when the U.S. Supreme Court ratified the Baca Float No. 3 and the government lost the title to the mission grounds. Homesteaders in the area were evicted from their plots. The Bouldin family, grantees of the Baca Float No. 3, subsequently deeded 10 acres containing the Tumacácori church grounds back to the government in 1917 and the newly formed National Park Service (NPS) took on administration of the property (Sheridan 2006:175, Bossler and Johnson 2012: 34-35).

Few changes were made to the landscape immediately surrounding the Monument until the 1930s when the lands associated with Baca Float No. 3 were developed into the Baca Float Ranch, which also came to be known as the Pendleton Ranch, after Talbot “Tol” Pendleton purchased the land grant in 1929. While an account by a Junior Landscape Architect for the Park suggests that the fields surrounding the Monument were under cultivation in 1930, the agricultural practices likely maintained some continuity with the agricultural traditions of the homesteaders (Bossler and Johnson 2012: 66-67).

As mechanized plowing equipment was adopted on the Pendleton Ranch, the fields to the north and south of the Monument were expanded. Between 1934 and 1936, fields that had been cultivated during the mission periods were re-graded and planted with cotton and a variety of vegetables. The historic acequia continued to irrigate a portion of the Pendleton Ranch fields and the orchard, but new wells were constructed to accommodate the increased acreage under cultivation. Increased groundwater pumping within the property and surrounding area contributed to a significant decrease in the surface flow of the Santa Cruz River. By 1938, the historic *acequia* was no longer diverting water from the river and pumped well water was required to irrigate the orchard and garden.



By 1940, the use of the historic acequia had ceased and the mission garden was no longer being irrigated. The “last of the Mission Period cultivars, including the ‘sixteen peaches, one pomegranate, one walnut, one or two cottonwoods and two willows’ that comprised the ‘trees along the old canal,’ were perishing,” (Bossler and Johnson 2012: 70).

Between the late 1950s and 1979, the property to the south and east of the mission complex changed hands twice. During this time the land were used as pasture for horses and cattle. In 1979, George Binney bought the property and continued to operate an active ranch. Between the mid-1980s and 1992, fields were re-graded and the irrigation system was overhauled. (Bossler and Johnson 2012: 76, 83).

In 1978, Tumacácori National Monument acquired six acres of previously cultivated land to the north to of the mission complex. The land had been used to accommodate the growing participation in the Tumacácori fiesta, a celebration of the variety of cultures that are associated with the site’s history. This portion of the current monument grounds continues to be referred to as the fiesta grounds. In 1990, Congress created Tumacácori National Historical Park (TNHP)<sup>1</sup> that includes the old monument land and the missions of Guevavi and Calabazas. The Park acquired additional land in 2004, extending the park’s land holdings to include 310 acres. The expanded boundaries include the full extent of the mission garden, the acequia, agricultural fields to the north and south of the church grounds, and a stretch of the Santa Cruz River channel (Bossler and Johnson 2012: 81, 85).

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<sup>1</sup> Throughout this document, the term “Monument” is used to refer to the original mission building and the administrative unit managing it from 1908-1990 consistent with historical documents referenced in this report. The term “Park” is used to refer to the administrative unit and entire landscape managed by the National Park Service since 1990.

<sup>2</sup> The measurements recorded for the swale are approximate. The measurements were taken from the inner edges

## PREVIOUS ARCHAEOLOGICAL RESEARCH

Early archaeological research related to the acequia was conducted in association with larger projects that were predominantly focused on architectural features within the central church complex. Small compliance projects have yielded additional information on the acequia. Recently new interest in identifying the extent of the acequia and its condition has resulted in more focused research on the feature.

The 1934 Federal Emergency Relief Act program funded a large-scale archaeological investigation within the Monument. Walter G. Atwell, a NPS engineer, started the investigations and Paul Beaubien, a park ranger and student archaeologist, took over in December of that year, directing work until March 27, 1935. The objective of the project was to uncover the structures within the central mission complex to create a comprehensive map that would guide future management (Figure 1.3). The walls of the convento rooms and their internal features were exposed and then backfilled after mapping. Under Atwell, the crew had exposed the Jesuit church complex. In total, 79 rooms and areas within the mission complex were documented. The compuerta/lavandaria of the mission acequia was recorded as Area 75 (Figure 1.4) and was described as:

“a problematical structure of burned brick with plastered walls and floors. It was located in an irrigation ditch, about 14’ inside south wall of orchard. The constricted outlet would serve to raise the level of a stream slowing through this structure. The raise in water level might be desired to provide a “washing vat” or to introduce the water to another irrigation ditch. A 3” dip in the floor at the south end with a corresponding 3” rise at the north end suggests a secondary purpose for which I cannot account” (Beaubien 1935: 215).

The ambiguity surrounding the compuerta/lavandaria during the 1934-1935 excavations suggests that the feature was no longer actively utilized according to its original function.

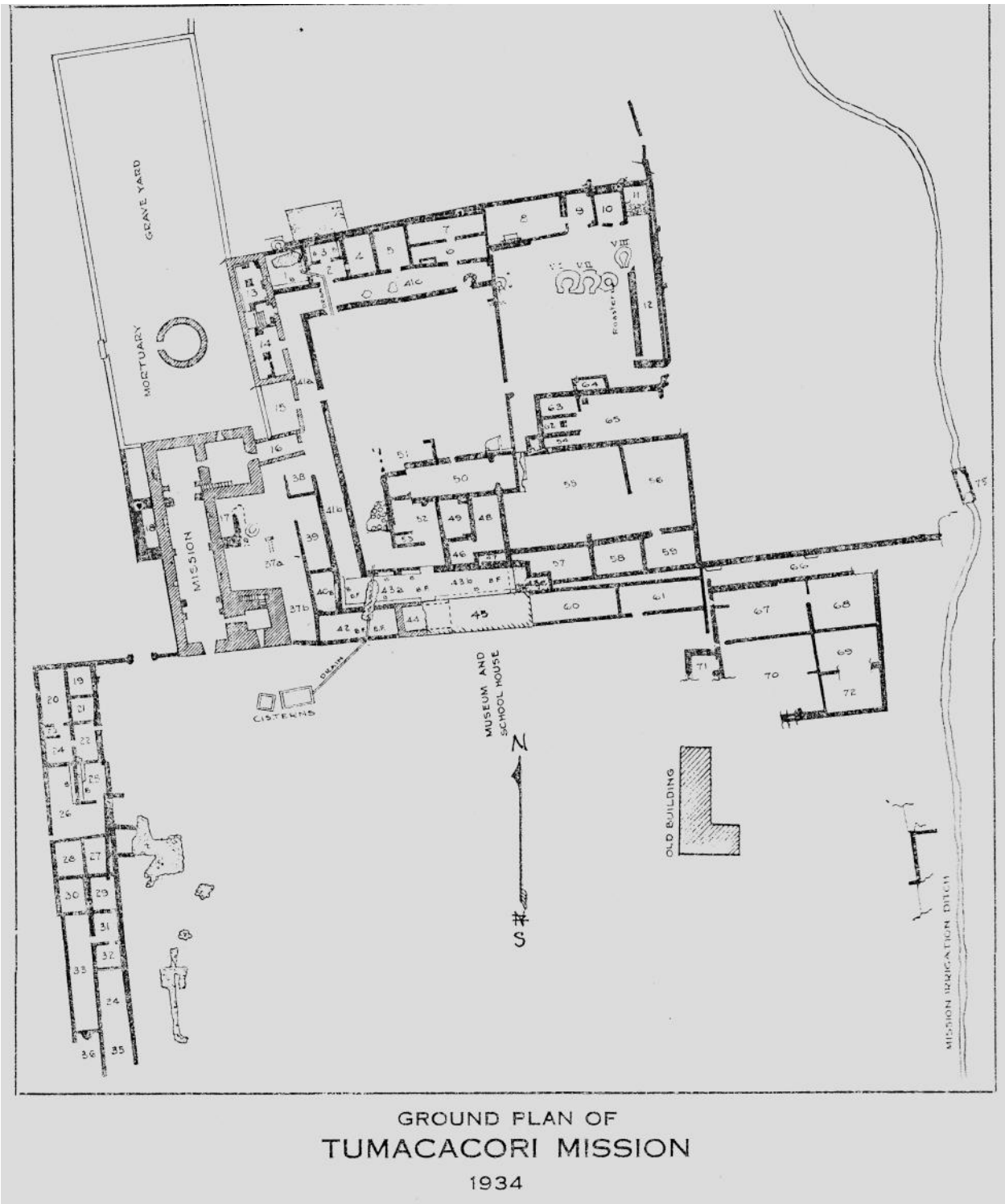


Figure 1.3. Plan of the Tumacacori mission complex drafted as a result of the 1934-1935 excavations conducted by Atwell and Beaubien. Note "mission irrigation ditch" with compuerta on the eastern edge of the map (insert in Beaubien 1935).

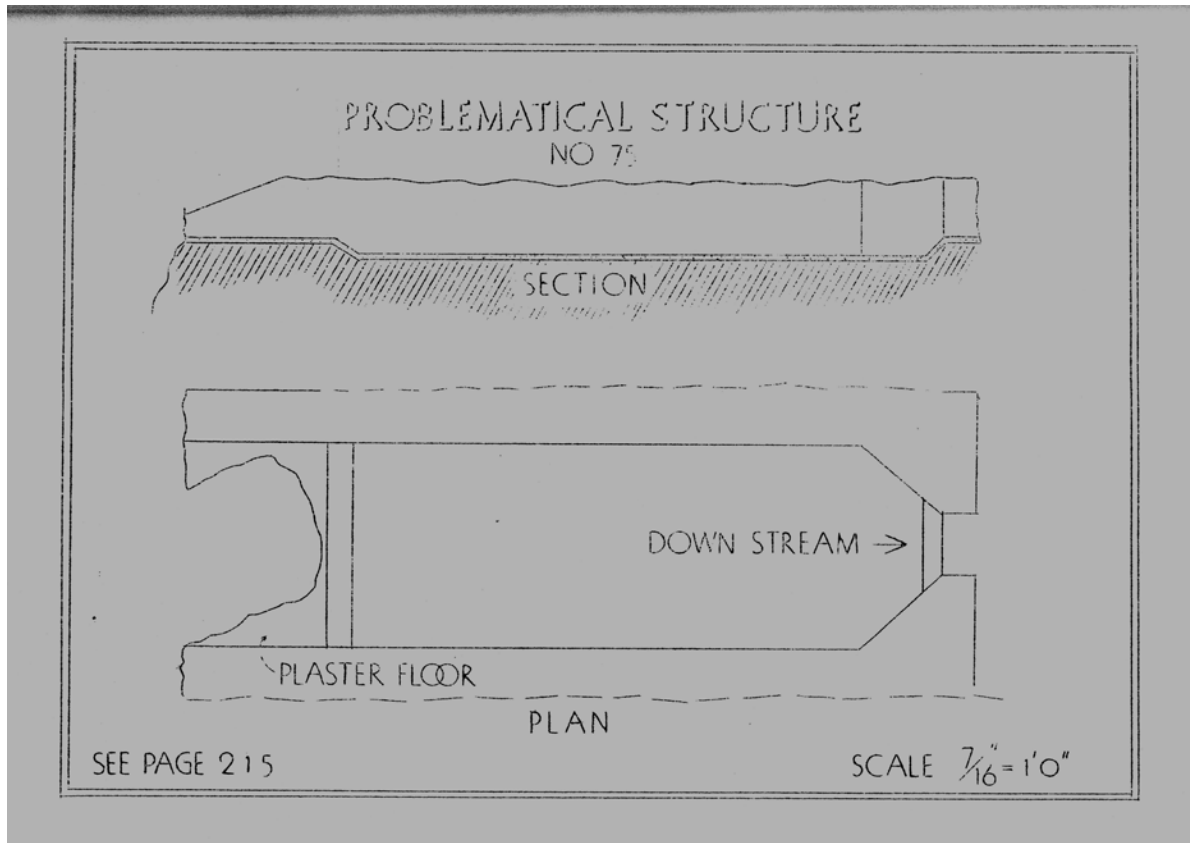


Figure 1.4. Plan and cross section of compuerta (Area 75) from 1934 excavations directed by Paul Beaubien; compuerta described as a “problematical structure.” (Beaubien1935: 214).

In September of 1994, Jeffery Burton from the Western Archaeological and Conservation Center (WACC) and David Yubeta, a member of the Tumacácori National Historic Park staff, conducted a testing project to investigate three areas of soil subsidence adjacent to the church and within the plaza. Six units were mechanically excavated within the areas of subsidence and within the historic acequia. Prior to the testing project, David Yubeta had exposed the compuerta (see Figures 1.7, 1.8, and 1.9). It is unclear as to whether the compuerta had been buried due to grading and land modification or sediment deposition as a result of flooding. Most likely, a combination of the two factors caused the compuerta to be buried over time after it was abandoned in the late-1930s.

To further investigate the historic acequia feature, a backhoe trench (Unit 6) was excavated through the alignment approximately 6 m south of the compuerta. The trench measured 11.5 m in length and 1.5 m in depth. In a memo report to the WACC Division of Archaeology Chief, Burton describes a 1-m-wide basin-shaped stratum of laminated soils located just below the modern ground surface (see Figure 1.10). Burton suggests this may represent a modern channel due to the shallow nature of the feature in relation to the modern ground surface (1994:3). However, the profile drawn during the testing project shows a possible channel filled with grayish-brown silt with laminated clay inclusions located immediately below a slight dip in the topography that may represent the remnants of the acequia swale. The laminated soils may represent stratigraphy associated with use of the acequia.



Figure 1.5. Archaeological crew recording Unit 6 during 1994 testing project directed by Jeffery Burton of WACC (NPS TNHP Archives).



Figure 1.6. Unit 6 from 1994 archaeological testing project directed by Jeffery Burton of WACC (NPS TNHP Archives).

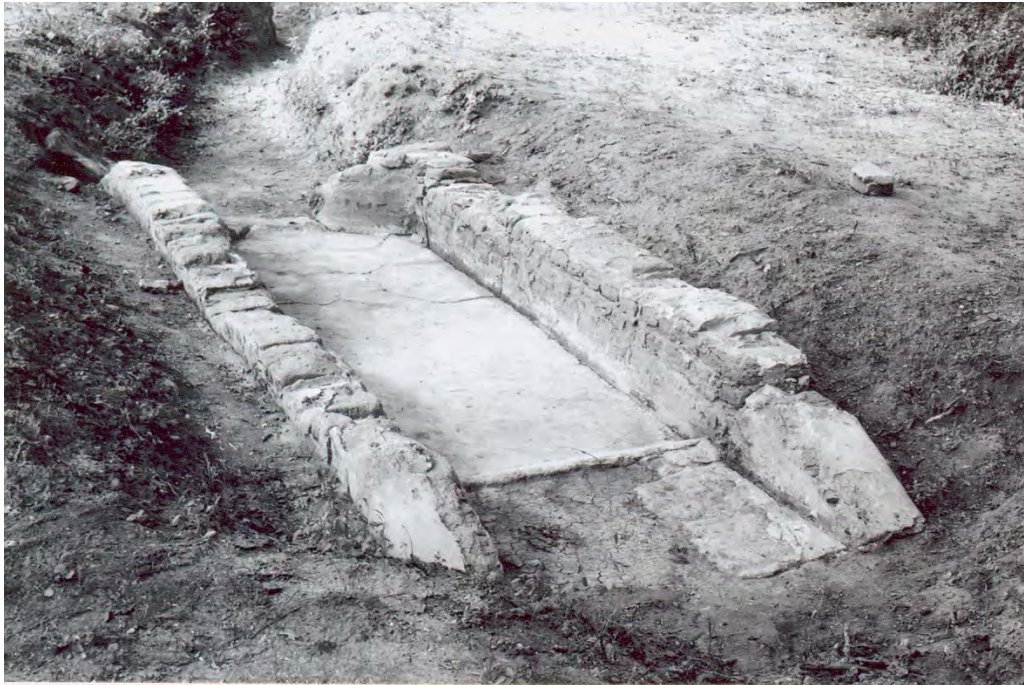


Figure 1.7. Photograph of compuerta during 1994 archaeological testing project directed by Jeffery Burton of WACC, looking northeast (NPS TNHP Archives).



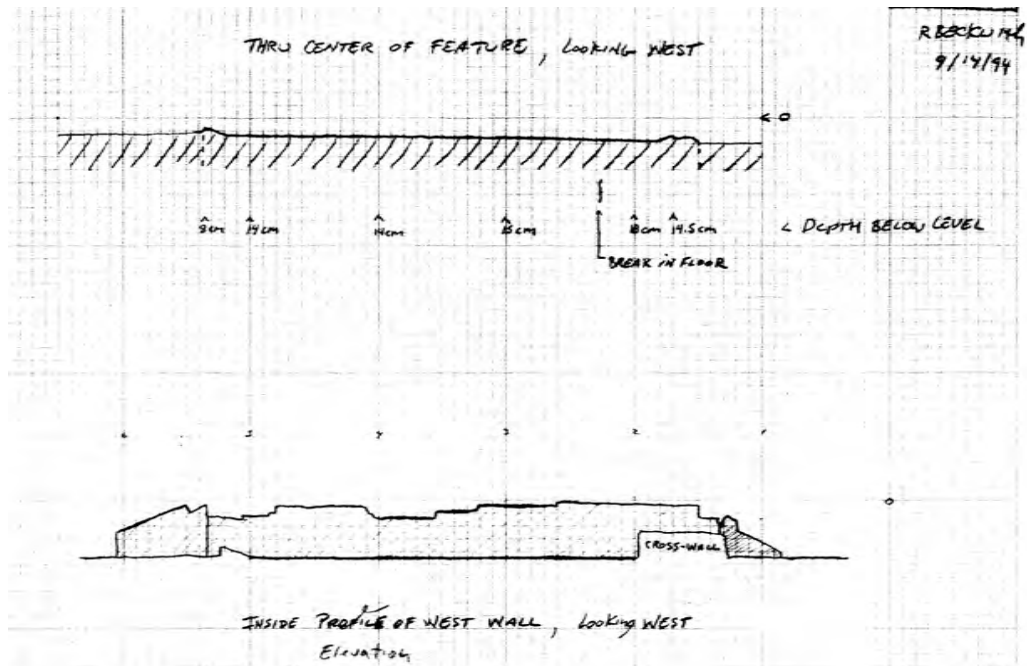


Figure 1.9. Measured cross section drafted by R. R. Beckwith in 1994 after the feature was exposed by D. Yubeta (NPS TNHP Archives).

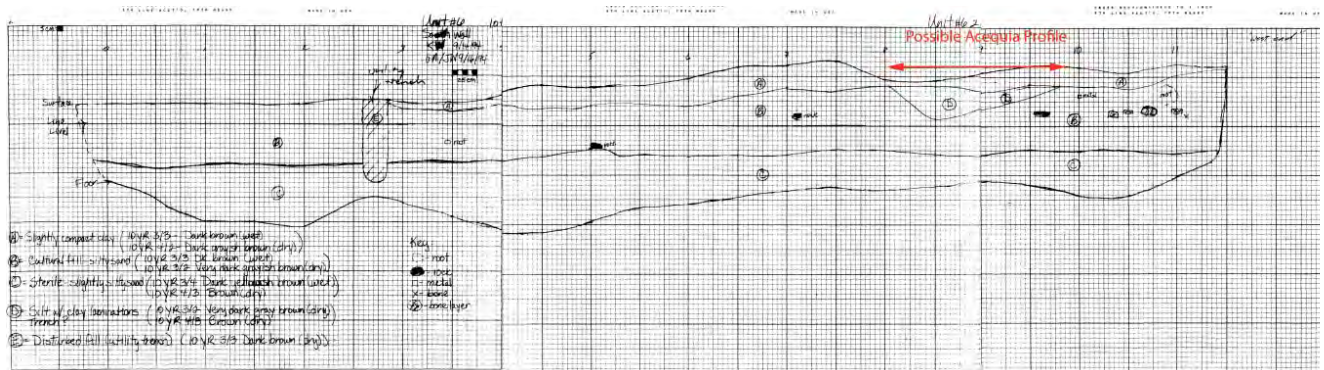


Figure 1.10. Profile of south wall of Unit 6, 1994 WACC archaeological testing project. Note location of laminated soils possibly representing acequia channel indicated in red (NPS TNHP Archives).

In 2004, the Park boundaries were officially expanded to include 310 acres. Investigations to identify and document archaeological resources within the expanded Park boundaries were completed between 2004 and 2005. During this project, a test unit was excavated south of the compuerta, just south of the extant swale. The test trench revealed the acequia stratigraphy in profile (Figures 1.11 and 1.12). The acequia stratigraphy was most clearly delineated within the southern profile of the trench. Within the southern profile, a slightly irregular basin-shaped lens of yellowish-brown silt, ranging from 1 to 4 cm thick, delineated the bottom of the acequia channel. This lens was located 36 cm below the modern ground surface with approximately 5 cm of fill having been added over a portion of the southern unit wall in 2005 to cover low areas in the



vicinity of the feature. This lens measured approximately 80 cm across and represents an early depositional event within the channel. A smaller, less distinct basin-shaped silt lens was observed at approximately 28 cm below the modern ground surface. This top lens was substantially smaller, measuring approximately 40 cm across. This lens appears to be from a later depositional event or a later iteration of the channel. The stratum between the two silt lenses was disturbed by rodent runs and roots, making it hard to distinguish from the surrounding matrix. Only one silt lens was recorded within the north profile of the test unit. Within the north profile, the acequia channel was delineated by a yellowish-brown silt lens that measured between 1 and 3 cm thick. The bottom of the silt lens was approximately 28 cm below the modern ground surface. This lens appeared to correspond to the lower, earlier lens within the south profile (the difference in elevation is attributed to the addition of modern fill, raising the ground surface on the south side of the unit). Bank deposits were not visible in either the north or south profiles and details on the feature's construction, maintenance and use require further investigation.

In order to help reconstruct environmental vegetative conditions associated with the acequia, four soil samples were collected from the south wall of the test trench. One sample was taken approximately 6 cm above the uppermost silt lens of the acequia channel. Two samples were collected from within the acequia stratigraphy, one from the sediment between the two visible silt lenses and the other from within the lower silt lens. A fourth sample was collected from an underlying stratum, approximately 48-50 cm below the modern ground surface. The pollen content within the soils samples was analyzed by Nicole Arendt at the University of Arizona School of Anthropology. All of the samples contained a similar pollen profile, which was similar to the profile of pollen samples taken from other locations within the mission grounds, including from the orchard wall and from an adobe brick and surfaces between bricks within a nineteenth-century structure on site. There was a slight increase in the taxa represented within the samples collected from this unit, particularly from the samples collected from within the acequia stratigraphy. The most prevalent type of pollen found in all of the samples was amaranth (*Chenopodiaceae-Amaranthus*). A number of common agricultural weeds and other weedy plant varieties were found within the acequia deposits (see Figure 1.13 for all taxa represented). Pollen from several types of trees and shrubs was found, with pine (*Pinus*) most common. A few riparian varieties identified within the acequia deposits, including hackberry (*Celtis*), willow (*Salix*), and fern (*Pteridophyta*). *Sporomiella*, a dung fungal spore, was found within the acequia deposits and the sediment above the silt lenses. Two taxa found within each sample from the test trench were considered potential cultigens, including prickly pear (*Opuntia*) and Poaceae pollen with grains larger than 40 µm that may represent Old World grains such as wheat. The similarity of the pollen profiles in the samples collected from the test unit with those taken from other areas of the site, as well as the taxa identified, shows evidence of both agriculture and environmental disturbance. This is consistent with the grading and plowing that has been described in the historical documentation. The riparian taxa were most prevalent in the acequia deposits, which underscores the long-term presence of water within this feature (Arendt 2006).

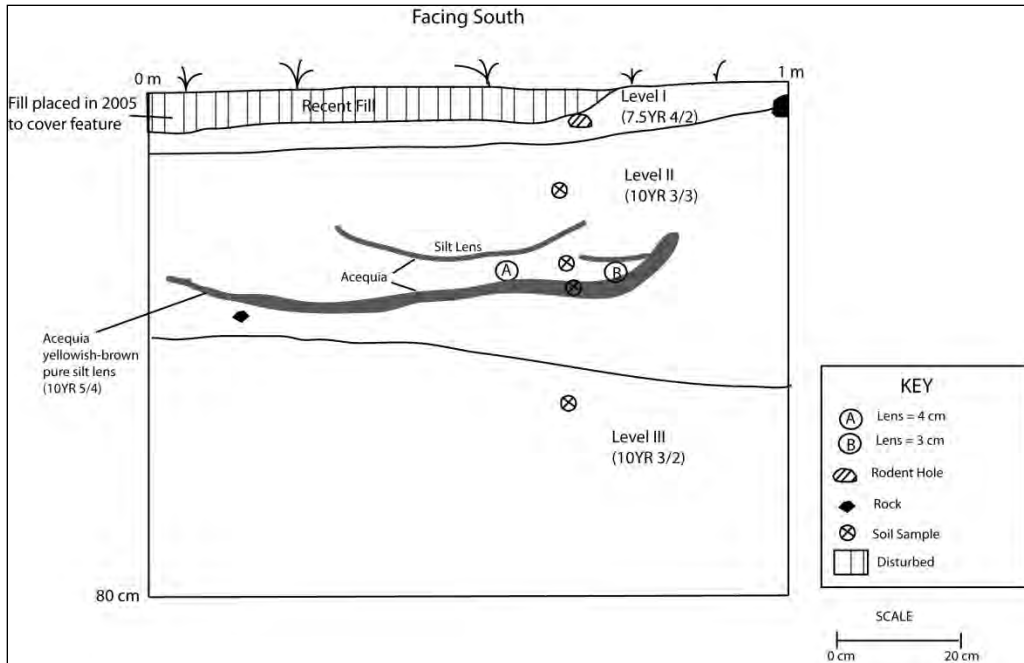


Figure 1.11. Profile of south wall from 2005 testing unit excavated south of the compuerta documenting acequia stratigraphy (reproduced in Conyers and Moss 2013).

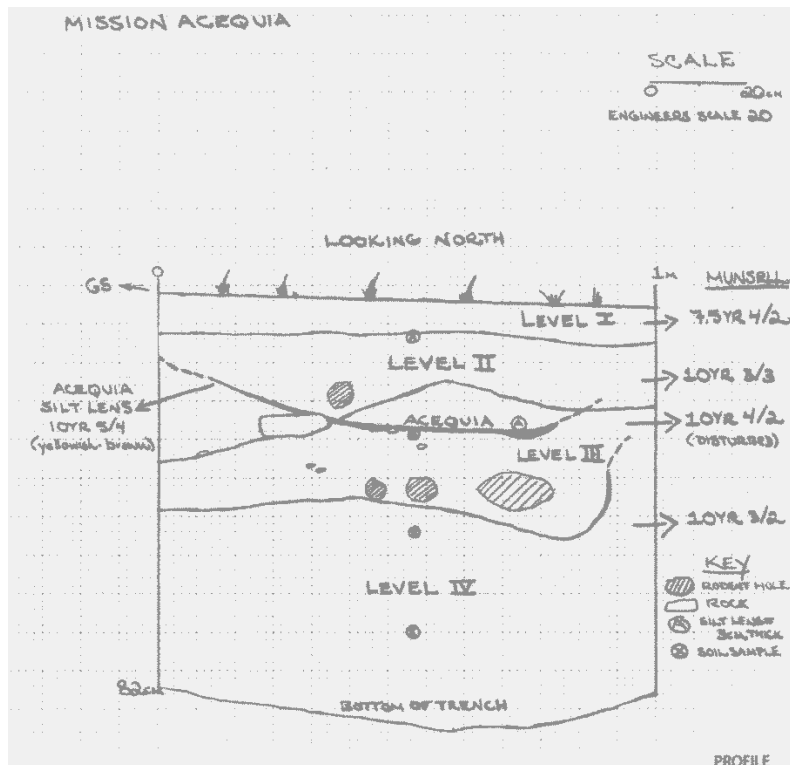


Figure 1.12. Profile of north wall from 2005 testing unit excavated south of the compuerta documenting acequia stratigraphy (NPS TNHP Archives).

# Tumacacori

## Acequia

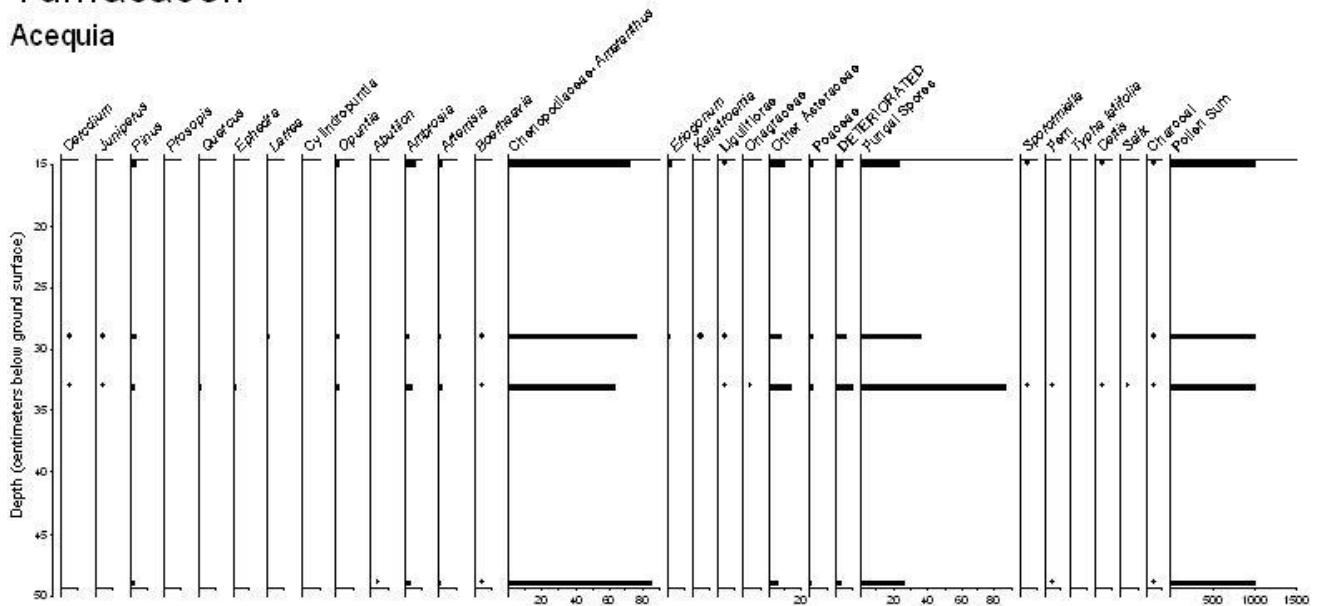


Figure 1.13. Chart illustrating the pollen profile of each sample collected from south wall of 2005 test trench that exposed acequia (from Arendt 2006:11).

Between 2004 and 2006, the Park performed investigations of the mission garden in conjunction with WACC. A series of test units were excavated along the south and east sections of the garden wall, revealing the construction materials and techniques. The construction techniques differed between the south and east wall, reflecting construction at different times or representing repair episodes, which may have been necessary due to flood damage. While sections of the wall may date to the Jesuit period, the investigation concluded that the wall was likely constructed during the subsequent Franciscan period building campaign (Moss 2006). Based on the accommodations made to work around the acequia channel during construction of the north and south garden walls, it is likely that the acequia was constructed first.

In 2010, a new sewage utility line was placed along the north end of the Ranger’s Residence and crosses the road to the new leach field. It presumably crossed the acequia, although a profile could not be confirmed. A soil change that was initially thought could mark the acequia was noticed in the trench just east of the residence on the western edge of the road. Park staff debated what it was and that it is still uncertain whether the acequia was identified here (it’s referred to as a possible acequia remnant). If it is a portion of the acequia, it’s further to the east than what was identified by the Conyers survey, perhaps identifying a different parallel acequia remnant but one that was never adequately confirmed (Jeremy Moss, personal communication, June 2014).

In February of 2012, archaeological testing was conducted prior to construction of an ADA-accessible trail located to the east of the church complex. The trail was designed to cross the acequia alignment just north of the visible swale. A test trench (TT2) was excavated in the estimated location of the intersection of the trail segment and the acequia, approximately 16 m north of the compuerta (see Figure 1.14). The trench ran east-west and measured 4 m in length by

0.8 m in width by 0.85 m in depth. A poorly defined profile of the acequia channel was exposed in the eastern end of the trench. While the profile was visible in both walls of the trench, it was most clearly delineated within the southern wall (see Figures 1.15, 1.16, and 1.17).

The top of the channel appeared to be truncated and was capped by a shallow (less than 5 cm in depth) stratum of light grayish-brown fine sandy loam at the modern ground surface. The acequia channel was defined by a basin-shaped, 1-to-3 cm thick lens of light yellowish-gray to pale brown fine laminated silt with clay films. The channel above the silt lens was filled with grayish-brown silty clay loam with subangular blocky texture and hard to very hard compaction (Level II). The channel fill was similar in color and texture to the underlying stratum into which it was excavated (Level III); however, there were fine silt lenses and clay microfilms throughout the channel fill that were not present throughout Level III. Level III consisted of a band of hard to very hard compacted medium gray-brown silty clay loam that was approximately 30 cm thick. The bottom contact of Level III with the underlying stratum (Level IV) sloped upward below the western edge of the channel and became irregular and less distinct, terminating just below the modern ground surface approximately 70 cm west of the acequia edge. Level IV was similar in color to Level III, but contained less clay, was less compact, and was not blocky in structure. A thin band of slightly hard medium brown silty loam (Level V) was exposed at the bottom of the trench in the western end of the unit.

The bottom of the channel exposed in the southern profile of TT2 was 23 cm below the modern ground surface (993.003 meters above sea level). The bottom of the channel was found to be slightly higher (0.055 m) higher than the bottom surface of the compuerta (992.948 meters above sea level). Because the elevation of the acequia base should decrease in the downstream direction, it is possible that the profile exposed in TT2 reflects a later iteration of the channel. Alternatively, the canal may have been constructed in such a manner as to maintain a relatively slow flow of water when a head gate within the compuerta was opened, releasing water downstream. The top of the acequia appears to be truncated within the southern profile in TT2 as a result of ground surface modification through grading and/or erosion (see discussion in Progression of Condition below), removing the berms on both sides of the channel.

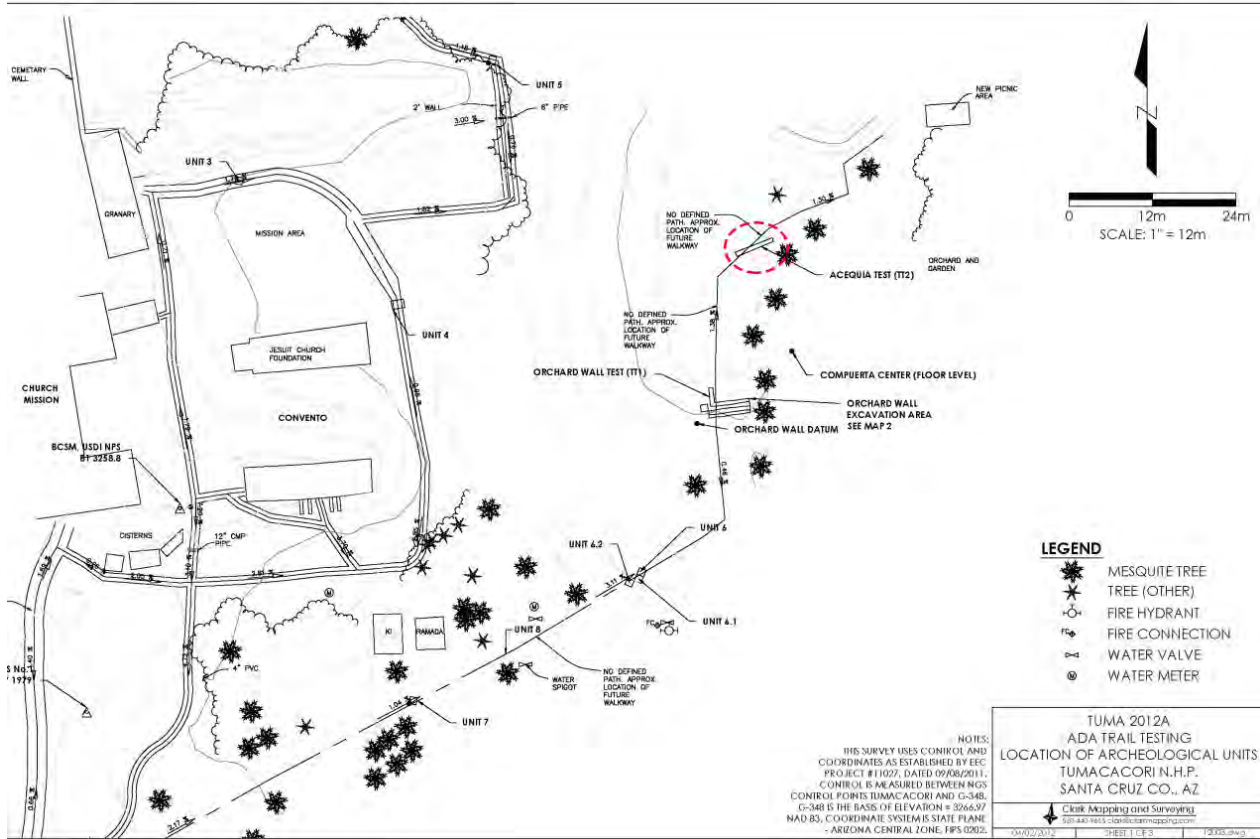


Figure 1.14. Map detailing the proposed 2012 ADA-accessible trail alignment and associated archaeological test units. Test Trench 2 is circled in red (Moss and Burghardt 2012).

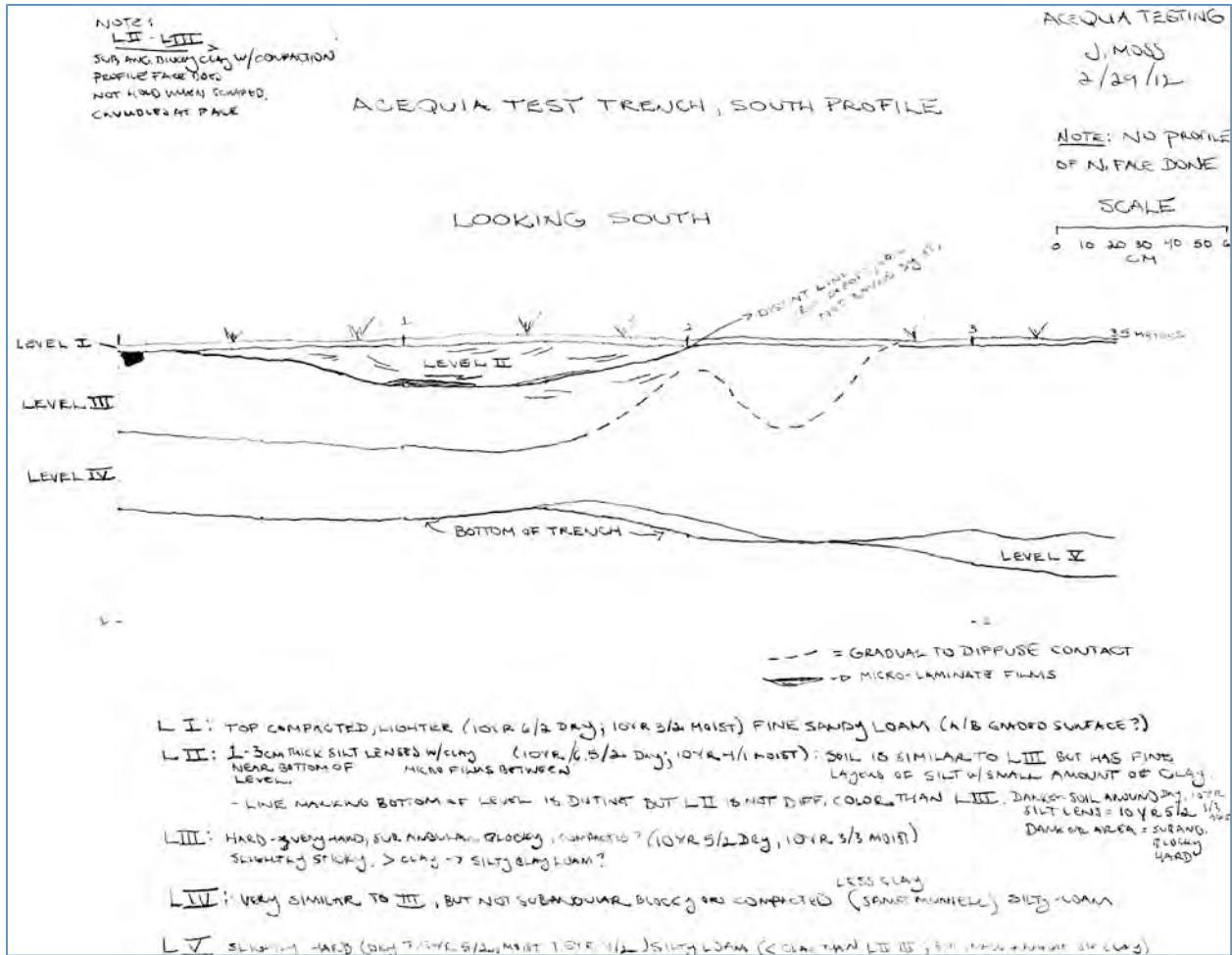


Figure 1.15. Profile map documenting the acequia stratigraphy exposed in the south wall of Test Trench 2 during 2012 test excavations (Moss and Burghardt 2012).



Figure 1.16. Acequia profile in south wall of Test Trench 2 during 2012 test excavations (Moss and Burghardt 2012).



Figure 1.17. Additional view of acequia profile in Test Trench 2 during 2012 test excavations (Moss and Burghardt 2012).

CONTROL POINTS						
DESCRIPTION	NORTHING ffeet	EASTING ffeet	ELEVATION ffeet	NORTHING M	EASTING M	ELEVATION M
BCSM, NPS No.1	207738.5154	969650.3488	3267.02	63318.699	295549.426	995.788
BCSM, USDI NPS	207834.656	969694.4858	3268.13	63348.003	295562.879	996.126
UNIT 1, S.W. CORNER	207835.272	969699.6004	3267.97	63348.191	295564.438	996.079
UNIT 2, S.W. CORNER	207936.8548	969690.088	3266.70	63379.153	295561.539	995.690
UNIT 3, S.W. CORNER	207987.6324	969720.4646	3264.98	63394.630	295570.798	995.165
UNIT 3, CENTER OF EXCAVATION	207989.0248	969722.2743	3264.28	63395.055	295571.349	994.954
UNIT 4, S.W. CORNER	207928.3825	969794.8026	3264.78	63376.571	295593.456	995.105
UNIT 4, CENTER OF EXCAVATION	207931.2568	969797.2022	3263.77	63377.447	295594.187	994.797
UNIT 5, S.W. CORNER	208044.6607	969840.0795	3263.49	63412.013	295607.256	994.710
UNIT 6.0, EXCAVATION DEPTH	207804.7106	969912.1146	3260.47	63338.876	295629.213	993.792
UNIT 6.0, UPPER LEVEL EXCAVATION	207802.0527	969910.8672	3261.60	63338.066	295628.832	994.135
UNIT 6.1, EXCAVATION DEPTH	207800.2516	969910.6056	3261.10	63337.517	295628.753	993.984
UNIT 6.2, N.W. CORNER/ UNIT 6.1 S.W. CORNER	207800.6015	969908.9465	3261.92	63337.623	295628.247	994.233
UNIT 6.2, EXCAVATION DEPTH	207800.1229	969907.3644	3261.51	63337.477	295627.765	994.108
UNIT 6.2, S.W. CORNER	207798.7834	969904.5297	3262.24	63337.049	295626.901	994.330
UNIT 7, S.W. CORNER	207742.604	969802.7382	3263.68	63319.946	295595.875	994.768
ORCHARD WALL DATUM	207874.601	969938.6357	3260.45	63360.178	295637.296	993.784
COMPUERTA CENTER	207908.6888	969983.4422	3257.70	63370.568	295650.953	992.948
ACEQUIA TEST (IT2) DATUM	207954.2187	969959.3189	3258.36	63384.446	295643.600	993.148
ACEQUIA TEST (IT2), N.E. CORNER	207962.1666	969974.1417	3258.29	63386.868	295648.118	993.126
ACEQUIA TEST (IT2), EAST EDGE OF SOUTH STRATUM	207959.7193	969973.1173	3258.38	63386.122	295647.806	993.155
ACEQUIA TEST (IT2), WEST EDGE OF SOUTH STRATUM	207958.2445	969969.1423	3258.45	63385.673	295646.595	993.174
ACEQUIA TEST (IT2), LOWEST POINT OF SOUTH STRATUM	207959.2276	969970.6658	3257.88	63385.973	295647.059	993.003
ACEQUIA TEST (IT2), EAST EDGE OF NORTH STRATUM	207961.9227	969972.7032	3258.33	63386.794	295647.680	993.140
ACEQUIA TEST (IT2), WEST EDGE OF NORTH STRATUM	207960.9579	969969.7259	3258.45	63386.500	295646.772	993.174
ACEQUIA TEST (IT2), LOWEST POINT OF NORTH STRATUM	207961.1058	969971.6056	3257.88	63386.545	295647.345	993.002

NOTES:  
 THIS SURVEY USES CONTROL AND COORDINATES AS ESTABLISHED BY EEC PROJECT # 111027, DATED 09/08/2011. CONTROL IS MEASURED BETWEEN NGS CONTROL POINTS TUMACACORI AND G-348. G-348 IS THE BASIS OF ELEVATION = 3266.97 NAD 83. COORDINATE SYSTEM IS STATE PLANE - ARIZONA CENTRAL ZONE, FIPS 0202.

TUMA 2012A  
 ADA TRAIL TESTING  
 LOCATION OF ARCHEOLOGICAL UNITS  
 GARDEN WALL EXCAVATION  
 TUMACACORI N.H.P.  
 SANTA CRUZ CO., AZ

Clark Mapping and Surveying  
 320-440-9165 clark@clarkmapping.com

04/02/2012 SHEET 3 OF 3 12003-2.dwg

Figure 1.18. Table of elevations taken during 2012 archaeological testing. Elevations related to the acequia are highlighted in yellow (Moss and Burghardt 2012).

## DISCUSSION

Archaeological investigations have exposed profiles on both north and south sides of the compuerta. The profile exposed on the south side of the compuerta in 2005 had distinct silt lenses and two depositional events or iterations of the acequia channel were identified. The distinct silt lenses clearly delineated the acequia channel from the underlying matrix into which it was excavated. In contrast, the profile exposed in 2012 on the north side of the compuerta did not contain distinct silt lenses, but rather thin silty laminae were dispersed throughout the channel fill. Additionally, the channel boundary was less clearly defined within the unit excavated to the north of the compuerta, with the channel fill similar in color and texture to the surrounding matrix. A recent ground-penetrating radar (GPR) study (discussed below) produced similar results, with the acequia more clearly defined in reflection profiles produced from transects on the southern side of the compuerta and more limited feature visibility in profiles from transects north of the compuerta. The higher visibility of the feature in reflection profiles indicates that there is higher contrast among the strata within the channel fill south of the compuerta.



The inconsistency between the sedimentation on the north and south sides suggests that the flow of water may have been slowed or stopped using a head gate within the compuerta. The slowed flow of water would have allowed for more silt and clay to settle south (upstream) of the compuerta, whereas the more rapid flow of water to the north (downstream) of the compuerta when the head gate was opened would have allowed for less silt and clay to be deposited within this portion the channel. The increased silt and clay deposition to the south of the compuerta may have resulted in the need for periodic maintenance or clean-out episodes to sustain the functionality of the feature, resulting in multiple basal surfaces within this portion of the acequia. Alternatively, the channel deposits to the north of the compuerta may have been more significantly affected by erosion and disturbance factors, allowing this portion of the channel to fill with the surrounding soil.

While the variation in the stratigraphy of the acequia at different locations along the alignment may provide information about how the water was controlled or distributed, as well as post-use erosion and deposition processes, the stratigraphic variability has an impact on the identification of the feature. Data that indicate the location, elevation, and size of the feature are critical to and directly impact the management and preservation of the feature. Further investigation of the acequia through re-exposing the profiles documented in 2005 and 2012, as well as new units providing additional exposures of the feature on both sides of the compuerta (guided by the results of the GPR study), is needed to evaluate the differences in the nature of the acequia identified in past investigations. New data could be used to assess whether variations in the stratigraphy are a result of intentional water control measures during active use of the acequia, or whether they can be attributed to disturbance or natural processes that occurred after the acequia was no longer in use. A more comprehensive understanding of the acequia stratigraphy may also provide insights into the larger irrigation system that could be used to enhance the feature's interpretation, as well as provide a foundation for the identification of additional portions of the feature in the future.

## **INTERPRETATION AND PARK PLANNING**

The mission acequia is a significant feature within the San Jose de Tumacácori cultural landscape. The extant portion of the feature provides a tangible link to the larger agricultural component of the mission complex that is essentially imperceptible on the ground today. Interpretation of acequia provides the public with a more complete understanding of the mission community layout and lifeways. The interpretive measures outlined below are described on a thematic basis along with suggested steps to take to provide such thematic information to the public.

### **THE IMPORTANCE OF WATER**

The availability of water was a critical component in the lifeways and survival of the mission community, and most likely factored significantly into the establishment of the mission in its current location. The engineered irrigation system that allowed for the cultivation of crops on a large scale was important for the subsistence of the community as well as the mission's economy. The water delivered by the acequia not only watered the fields and garden, but was likely used for gathering drinking water, washing, and many other everyday activities within the community. Thus, the location of the compuerta likely served as a focal point for such activities and therefore would have been a central feature in everyday mission life. The installation of an interpretive wayside at the compuerta, describing its role in irrigation and daily life among the mission community would provide Park visitors with new insights on the significance of this feature. A map of the mission-period complex that indicates the location of the compuerta on the wayside would provide visitors with a link to a tangible landmark within the wider cultural landscape.

### **IRRIGATION TECHNOLOGY**

Irrigation technology had been used in the Santa Cruz Valley prior to the arrival of the European-influenced technology. The agricultural practices of Spanish colonists and missionaries interacted with the traditions in place among the Native American communities with whom they intermingled. Information describing the long history of irrigation in the Santa Cruz Valley, from Hohokam canal irrigation to O'odham dry-farming techniques to more recent practices of groundwater pumping, provides a backdrop to the technology reflected in the Tumacácori acequia. A brochure summarizing the deep history of crop cultivation in the Santa Cruz Valley, highlighting the mission acequia, would provide context for the feature. The brochure could be offered at the wayside associated with the compuerta.

Constructed without the aid of modern machinery, the builders of the acequia system needed to be familiar with principles of engineering and irrigation technology in order for the feature to function. The community that constructed and used the acequia system needed to be keenly aware of the conditions of their environment, including the topography of the site and the natural cycles of the river. Highlights of the irrigation technology used at the mission site could be featured on Park's website within the "Nature and Science" subsection.

## CONNECTING TO THE LARGER LANDSCAPE

The acequia is a linear feature, which has implications for its interpretation to the public. By delineating the alignment of the acequia on the ground as an interpretive trail, the increased visibility would provide a more tangible connection to the feature. Increased pedestrian traffic would impact the feature in both beneficial (mitigation of new destructive vegetation) and potentially adverse (erosion and impacts to potentially preserved banks) ways. More information about the relationship of the feature to the modern ground surface would need to be obtained before the effects of increased foot traffic could be predicted. Should the projected effects be determined adverse, the trail could be offset to minimize impacts.

The Juan Batista de Anza National Historic Trail runs through the park. A segment of the trail runs from the northeast corner of the restored mission garden to the Santa Cruz River to the east. Park interpretive staff offer guided “Anza Trail River Walks” periodically during the cool season. The acequia could be included as a waypoint on the guided tour in the Park before linking up to the Anza trail (see Figure 1.19).



Figure 1.19. The Juan Batista de Anza Trail (indicated with red dashed line) runs through TNHP. A section runs east-west from the northeast corner of the mission garden east to the Santa Cruz River (amended screenshot from Juan Batista de Anza National Historic Trail website: <http://www.anzahistorictrail.org/visit/explorer>).



**PART TWO**  
**FEATURE LOCATION, ATTRIBUTES, AND RESEARCH**

## LOCATING THE ACEQUIA MADRE

Historical documentation, maps, and aerial photos of the Tumacácori mission site are valuable resources that have yielded information pertaining to the historic location and use of the acequia system, as well as how its condition has changed over time. “Archeological investigations at the park have identified few irrigation features. The original acequia has been largely obliterated by modern farm fields, although some segments were straightened and reinforced with concrete for modern use,” (Moss 2006:19). While the location of the acequia madre, or main canal, can be inferred with some degree of confidence due to historic aerial photos, documentation of nearby acequias (i.e. Tubac), and the topography of the site, it is likely that it was only one part of a more complex irrigation system that watered extensive fields. Thus, the main channel provides a point of departure for further understanding the irrigation system and how it related to the greater mission landscape.

### PROGRESSION OF CONDITION

The degree to which the acequia system was used by the community at Tumacácori after secularization in 1834 is unclear. Despite drought conditions and movement in the Santa Cruz River channel described in correspondence in the 1830s (Kessell 1976:288), there is evidence that the mission orchard and garden continued to be irrigated using the historic acequia. The irrigation infrastructure in place during the Mission period may have had several lapses in use. However, accounts of cultivated fields in the immediate area of the mission, paired with the survival of the orchard fruit trees into the late 1930s, indicates that the acequia was revived and reused over the course of nearly a century after the O’odham community at Tumacácori relocated to Bac.

During the first half of the 1930s, the fields surrounding the mission continued to be cultivated, mostly growing corn. A 1936 aerial photograph (Figures 2.1 and 2.2) of the mission site and surrounding area shows the full extent of the acequia madre, the remaining outline of the garden/orchard, and their spatial relationship relative to the contemporary agricultural fields under cultivation. By 1936, the Pendleton Ranch fields to the north and south of the mission were reconfigured and planted with cotton and several types of vegetables. “This expansion likely removed much of the remaining landscape evidence of the homesteading era, such as adobe homes, barbed wire fences, and earthen canals, since mechanized equipment allowed for larger-scale fields. With the expansion of the fields, groundwater use also increased. While the historic acequia continued to irrigate the orchard, and presumably the southern fields of the Pendleton Ranch, additional fields extending to the west of the historic acequia alignment and north of the monument were likely irrigated by gravity flow from a well located directly north of the church,” (Bossler and Johnson 2012: 68-69). The cotton fields extended into the land formerly used for the mission garden and orchard (Moss 2006:13).

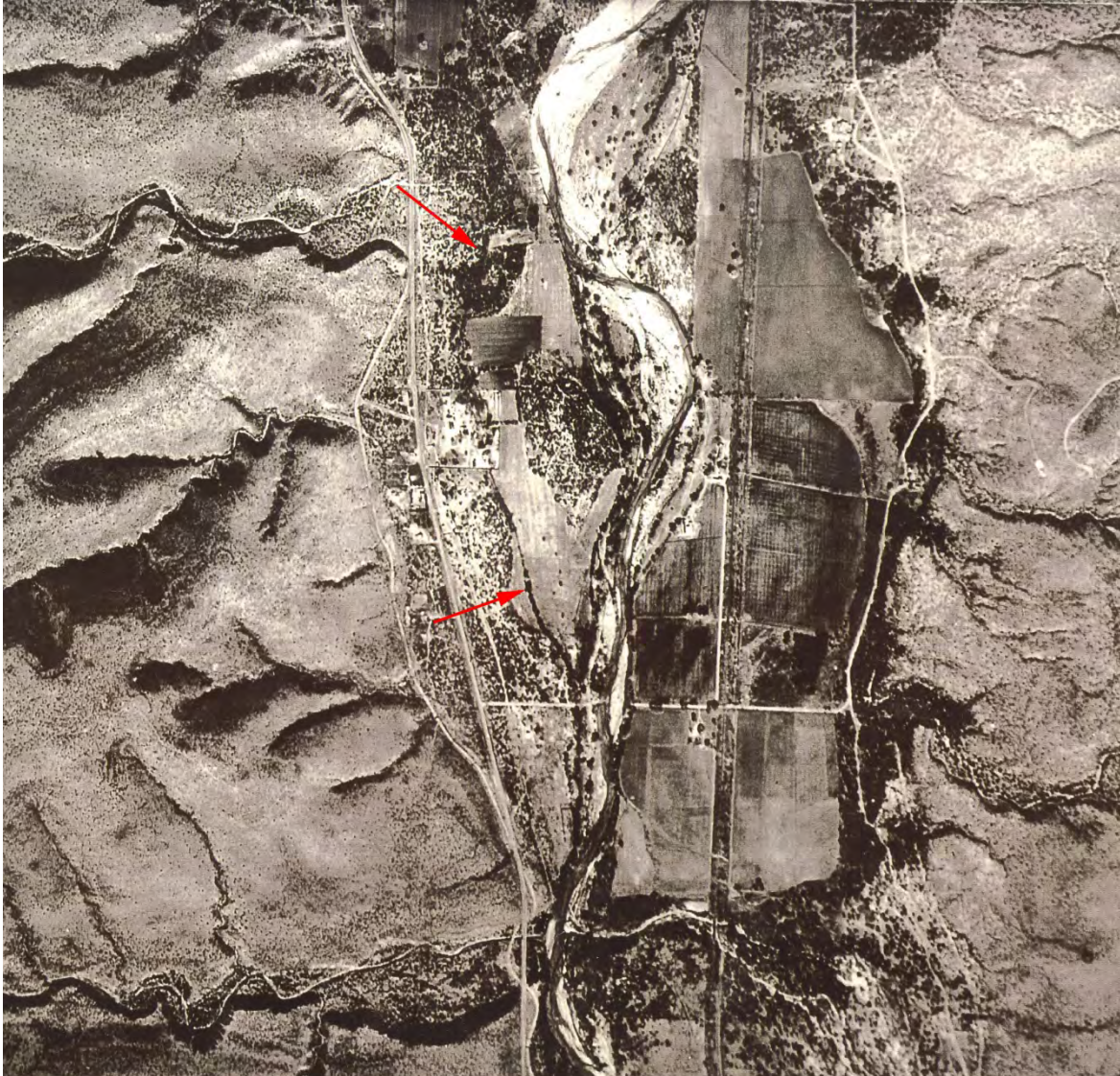


Figure 2.1. Aerial photograph of San Jose de Tumacácori showing the full extent of the mission acequia, 1936 (NPS TNHP Archives). See Figure 2.2 for further annotations.

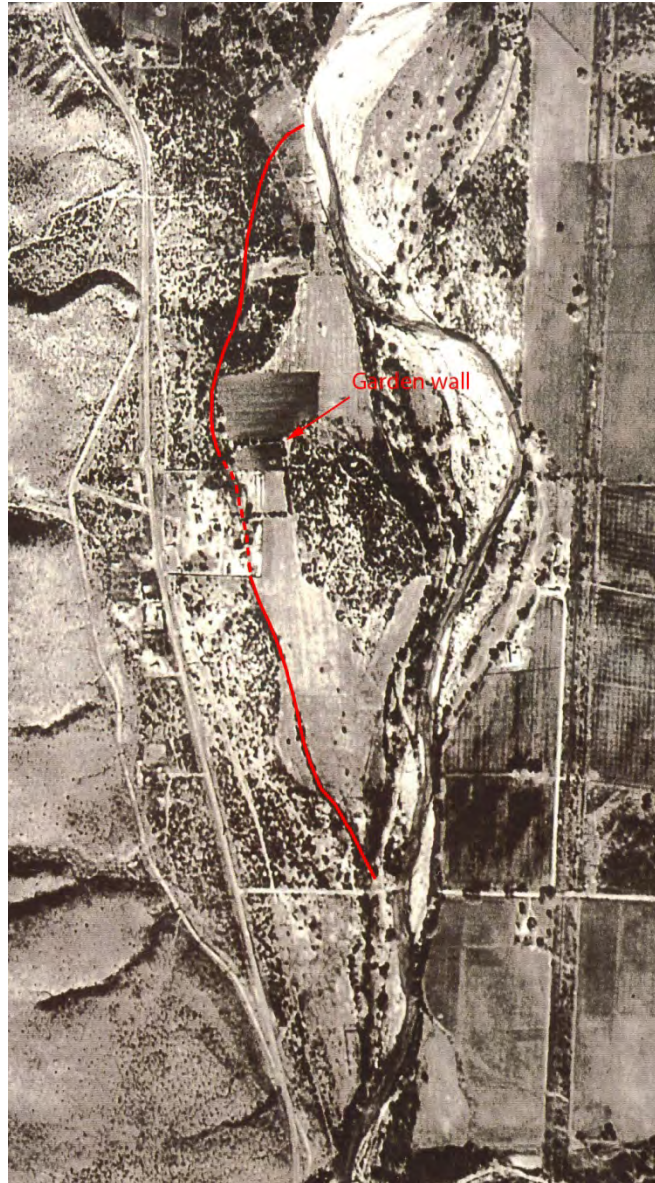


Figure 2.2. Detail of 1936 aerial photo; red line indicates approximate location of acequia alignment.

By the late 1930s, increased use of well water for irrigation had contributed to a significantly decreased water table. In addition, severe drought conditions had set in by 1934 (Bossler and Johnson 2012:37). The surface flow of the Santa Cruz River was reduced to the extent that the acequia was no longer functional by 1938. The fruit trees that had thrived within the walled orchard were no longer irrigated and died.

Several additions were made to the built environment during the 1930s, including a home for the Park custodian, a ranger's residence, and a garage in the southwestern portion of the Monument. The ranger residence and garage were constructed approximately 40 feet west of the acequia alignment (see Figure 2.3). Subsequent additions in 1954 connected the ranger's residence and garage and expanded the footprint of the combined building (Bossler and Johnson 2012:43). A paved parking area constructed to the south and east of the residence by 1967 and a walled yard



extending from the northeast corner of the building were likely built over the acequia alignment (see Figure 2.4).

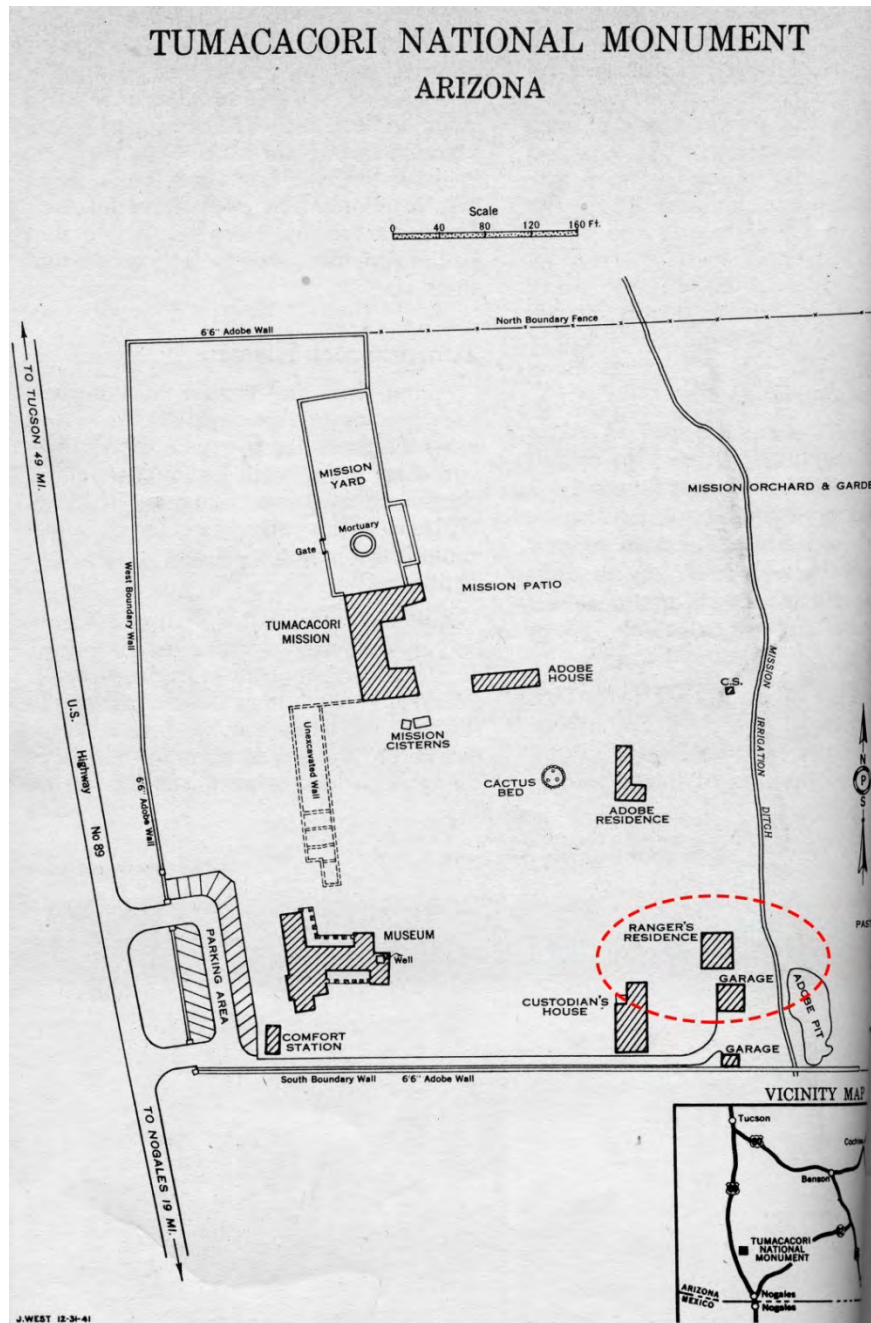


Figure 2.3. Map from mid-1930s monument brochure showing layout of major buildings and features. Note location of ranger's residence and garage just east of 'mission irrigation ditch' or acequia (after Bossler and Johnson 2012:126).



Figure 2.4. 2012 aerial photo depicting the amended footprint of combined ranger’s residence and garage, as well as walled yard and paved parking area, in relation to the projected acequia alignment (denoted with blue line segment). Red boxes with grid designations denote units from ground-penetrating radar study discussed below (amended after Moss and Conyers 2013:16).

Evidence of significant transformations within the landscape surrounding the mission can be identified in a 1967 aerial photograph of the area. The fields to the south and southeast of the mission core had been plowed and cultivated, grading over a large portion of the historic acequia alignment (Figures 2.5 and 2.6). There appears to be a remnant of the original acequia alignment preserved in the cultivated field south of the church complex. To the north of the mission, the historic alignment had been straightened and reinforced with concrete. While the acequia alignment can be traced within the ungraded area immediate to the east of the convento, a two-track road trace had formed over portions of the feature (Figure 2.6). A dirt road running parallel with the northern garden wall had been graded over the feature.

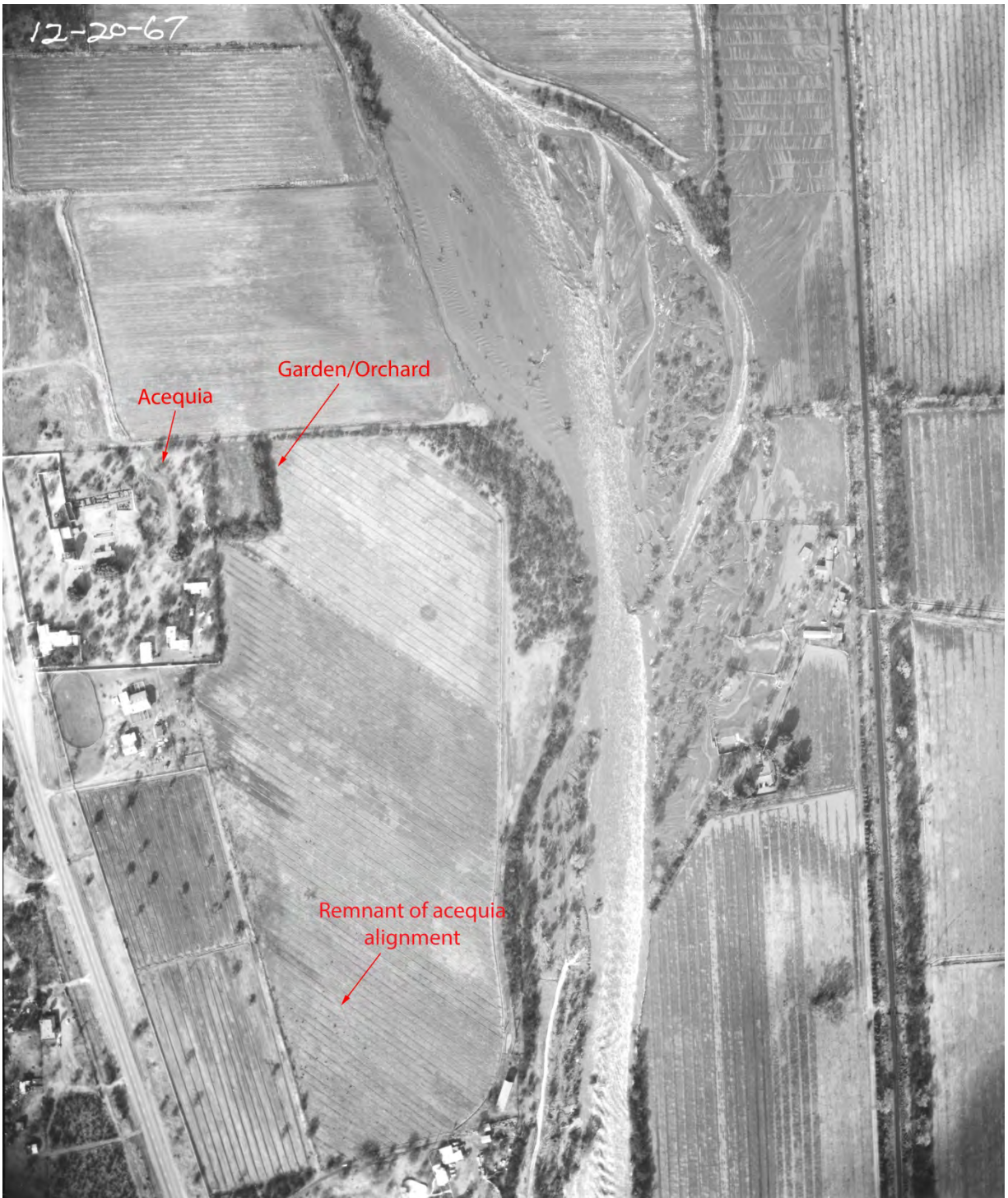


Figure 2.5. 1967 aerial of Tumaçácori area showing significant transformation of the cultivated fields surrounding the monument grounds. See Figure 2.6 below for detail (NPS TNHP Archives).



Figure 2.6. Detail of 1967 aerial photograph showing location of remaining acequia alignment indicated with red arrow. Note two-track road trace over feature (NPS TNHP Archives).

By 1977, the area of the historic acequia had been flattened and increased vegetation had accumulated over the alignment. NPS had built a series of adobe test walls over the feature just south of the dirt road paralleling the northern garden wall (Figure 2.7). Vegetation encroachment increasingly affected the visibility of the feature in the 1980s, including the straightened and cemented portion of the feature north of the mission core. An aerial photograph taken in 1983 (Figure 2.8) shows that a dirt road had been built over the feature, roughly following a segment of the alignment through the adobe test walls to the fiesta grounds. The fields to the south of the mission continued to be cultivated, while the fields to the north had been allowed to naturalize.



Figure 2.7. Detail of 1977 aerial photograph showing the condition of the acequia and the alterations within the mission landscape (NPS TNHP Archives).



Figure 2.8. 1983 aerial photo illustrating the development of the landscape and the condition of the acequia adjacent to the mission core complex. Red arrows indicated road trace between NPS test walls follows approximate acequia alignment south of the raised dirt road to the fiesta grounds (NPS TNHP Archives).

Conditions within the vicinity of the acequia appeared to stabilize in the 1980s as there are few visible changes between aerial photos including the feature taken in 1983 (Figure 2.8) and 1993 (Figure 2.9). However, in 1994, a utility line was excavated through a section of the acequia alignment (Figure 2.10). The installation of additional utility lines over time may have damaged or removed sections of the buried channel.



Figure 2.9. 1993 aerial photograph illustrating the landscape within and surrounding the mission site (NPS TNHP Archives).



Figure 2.10. 1994 aerial photograph illustrating the location of an excavated utility-line trench within the acequia alignment (NPS TNHP Archives).

The condition of the compuerta cannot be discerned from the aerial photos, but likely was buried along with a majority of the extant channel. An article published in *Nogales International* on September 23, 1994 reported that David Yubeta (TNHP Facilities Manager at the time) had recently uncovered the compuerta while digging in the area of the acequia.

It is likely that by the 1990s very little evidence of the acequia remained visible from the ground surface and that the location of the feature was largely inferred from maps and aerial photographs. The feature was likely considered to have mostly deteriorated, precluding the development and implementation of preservation measures before that time. Since the mid-1990s, the dirt road trace just north of the compuerta has been allowed to revegetate and the adobe test walls have deteriorated in place. The compuerta has remained exposed since 1994 and continues to provide a valuable reference point for the location of the historic acequia.



## GROUND PENETRATING RADAR STUDY SUMMARY

In 2012, plans for a plant restoration project included ground disturbance within the vicinity of the mission acequia. As mentioned above, a majority of the land in the vicinity of the historic acequia alignment had been disturbed by activities such as plowing, grading, vehicular traffic, and utility line excavation. The modern ground surface within the alignment was up to 20 cm below the base of the intact compuerta, which suggested that the previous land modification had removed the strata associated with the acequia (Moss 2012:1). However, archaeological work in 2005 and 2012 provided evidence that portions of the channel remained intact, just below the modern ground surface. TNHP Chief of Resources Management and Archaeologist, Jeremy Moss, initiated a ground-penetrating radar (GPR) study to evaluate the extent and condition of the intact acequia and to assess the potential effects of the plant restoration project more completely. GPR has been used successfully to map buried prehistoric earthen irrigation features within the Tucson basin, suggesting it would be an effective method to provide more information about the location of the acequia without destructive measures. The complete report from the GPR study with detailed descriptions of data procurement and processing procedures is included in Appendix B. Below is a summary of that report.

### METHODS

The GPR fieldwork was conducted over two sessions. The first session was completed on December 3, 2012 by Dr. Lawrence B. Conyers (Geophysical Investigations, Inc.) and Jeremy Moss. The second session was conducted on March 2013 by Dr. Conyers and Jeremy Moss, who were assisted by Andrew Perew and Alyssa Cunial from the University of Arizona. Radar reflection data was collected over the approximate acequia alignment, visible in aerial photographs as late as 1967. Equipment used to gather the data included a GSSI SIR-3000 geophysical data acquisition system with a 400 MHz dipole antenna, and a survey wheel with an encoder device on the radar antennas to georeference the transects. The data collected were used to produce horizontal amplitude slice maps that illustrate the alignment in plan view and vertical linear reflection profiles that illustrate the channel in cross section at a given point along the alignment (Conyers and Moss 2013: 1).

The initial study area investigated in December 2012 consisted of a 62 m by 18 m grid unit located immediately north of the compuerta and extending north-northwest toward the adobe test walls. Reflection profile data were collected from 41 transects spaced every 2 m within the unit. In March 2013, the study area was expanded to include three additional grid units, extending the investigated area both north and south of the compuerta (Figure 2.11). Similar procedures were used with each unit divided into transects to collect reflection profile data spaced 2 m apart. Grid 1 measured 66 m by 22 m and extended south from the compuerta to just north of the walled yard of the NPS residence (formerly the 'ranger's residence'). Grid 2 measured 13 m by 14 m and was located southeast of the NPS residence beyond the paved parking area, abutting a tall wall that divides the residence area from the maintenance garage and office grounds. Grid 3 was located in approximately the same location as the unit investigated in December 2012 that extended north of the compuerta, although it was offset slightly to the north. Grid 4 measured 18 m by 14 m,

extending north from Grid 3 past the dirt road to the fiesta grounds (which runs perpendicular through the unit).



Figure 2.11. Location of March 2013 GPR study grid units. Note “Grid 3” reflects approximately the same unit investigated in December 2012 (from Conyers and Moss 2013).

## RESULTS

The initial work completed in December of 2012 produced well-defined reflection profiles from the data collected in 15 of the 41 transects, with traces of the feature evident in profiles produced from a number of additional transects. There was variation in the visibility of the feature, even among the most well-defined reflection profiles. In many cases, one feature attribute, such as the channel berms, was clearly visible in the reflection profile, while other attributes were not defined (see Figure 2.12). As stronger reflection signals are detected when there is a high degree of contrast in the physical properties of the buried materials being tested, the degree of visibility within the reflection profiles depends on the presence of contrasting strata interfaces, such as clay and sand. The limited visibility within a number of the profiles suggested that the sediments within the channel fill were similar in texture to the surrounding matrix. This is consistent with the observations made on the profile exposed in 2012 in Test Trench 2.

While several transects in this unit yielded inconclusive profiles, the results indicated that the acequia channel had not been completely removed by land modification and was buried by up to 20 cm of topsoil. By mapping the visible profiles within the grid unit, the alignment of the acequia could be delineated (Figure 2.13). The results of the initial work in December 2012 demonstrated that the buried feature could be investigated and mapped using such geophysical surveying methods, providing initial data on the location, size, and depth of the channel. Such information is vital to effective management and preservation of the feature, which warranted further study outside the initial area scheduled for replanting. Further, as the results indicated that the acequia was preserved subsurface, the revegetation plans were amended to including only species that would result in minimal root disturbance.

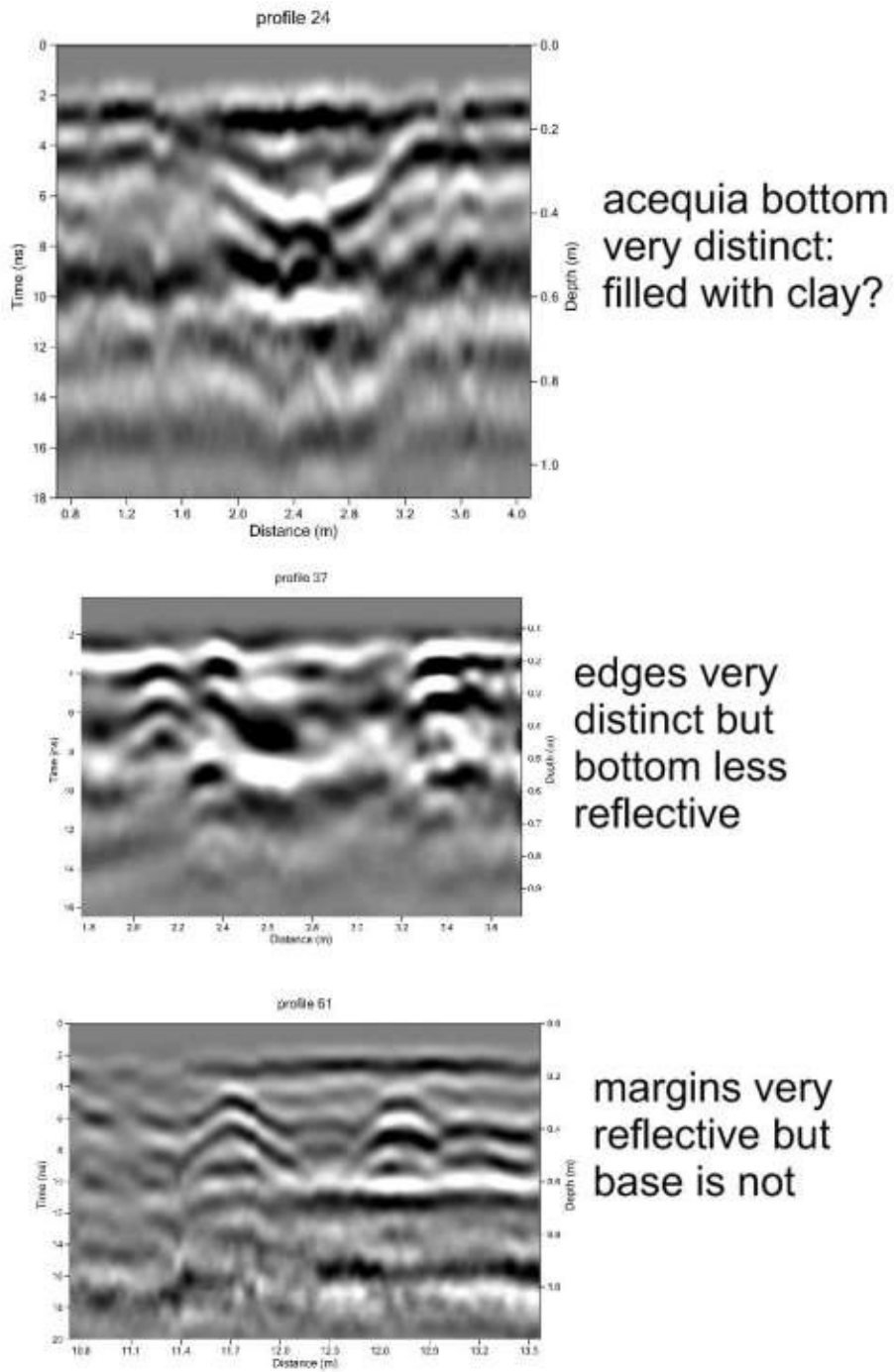


Figure 2.12. Reflection profiles from data collected in December 2012. Profiles display high visibility but illustrate variability in reflection patterns and attributes represented (from Conyers 2013).

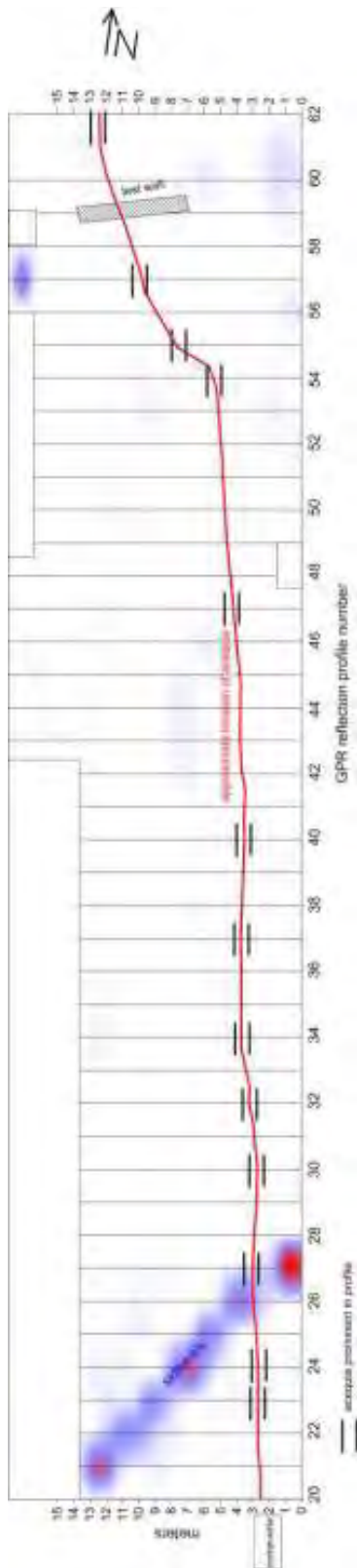


Figure 2.13. Manual interpretation alignment map produced from data collected in December 2012 reflecting location of buried acequia channel north of the compuerta. Note location of cement sidewalk and adobe test wall (from Conyers 2013:5).

Additional data gathered in March of 2013 yielded new reflection profiles, raising the total number of transects recorded to 154. The new data provided a more complete overview of the channel alignment, extending both north and south from the compuerta.

### Grid 1

Data were collected from 34 transects within this unit. However, only 18 transect produced visible reflection profiles (Figure 2.14). Reflection profiles indicate the channel is located approximately 15 cm below the modern ground surface and is approximately 40 cm in depth. The horizontal amplitude maps and manual interpretation of profile alignments produced from data collected in this unit suggested that the channel alignment is fairly straight within this segment, with slight undulations. Multiple disturbances, including metal pipes were detected in this unit. The margins appear to be much wider along a portion of the channel in the in the southern half of the unit, indicating possible erosion or disturbance (Figure 2.15).

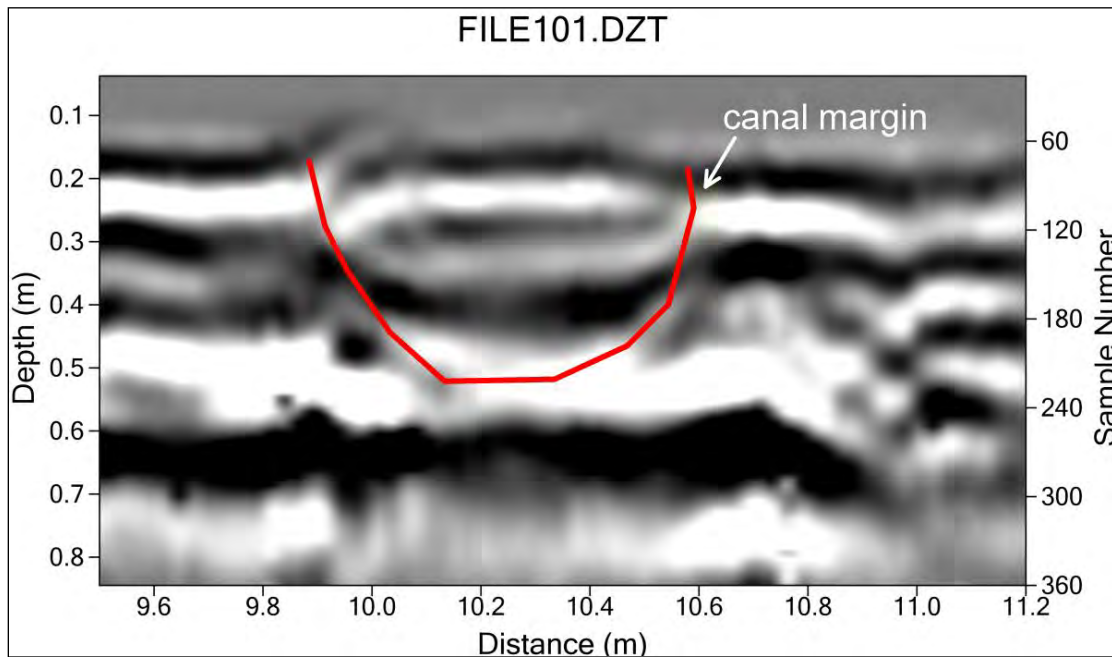


Figure 2.14. Reflection profile from Grid 1 with well-defined margins (from Conyers and Moss 2013:9).

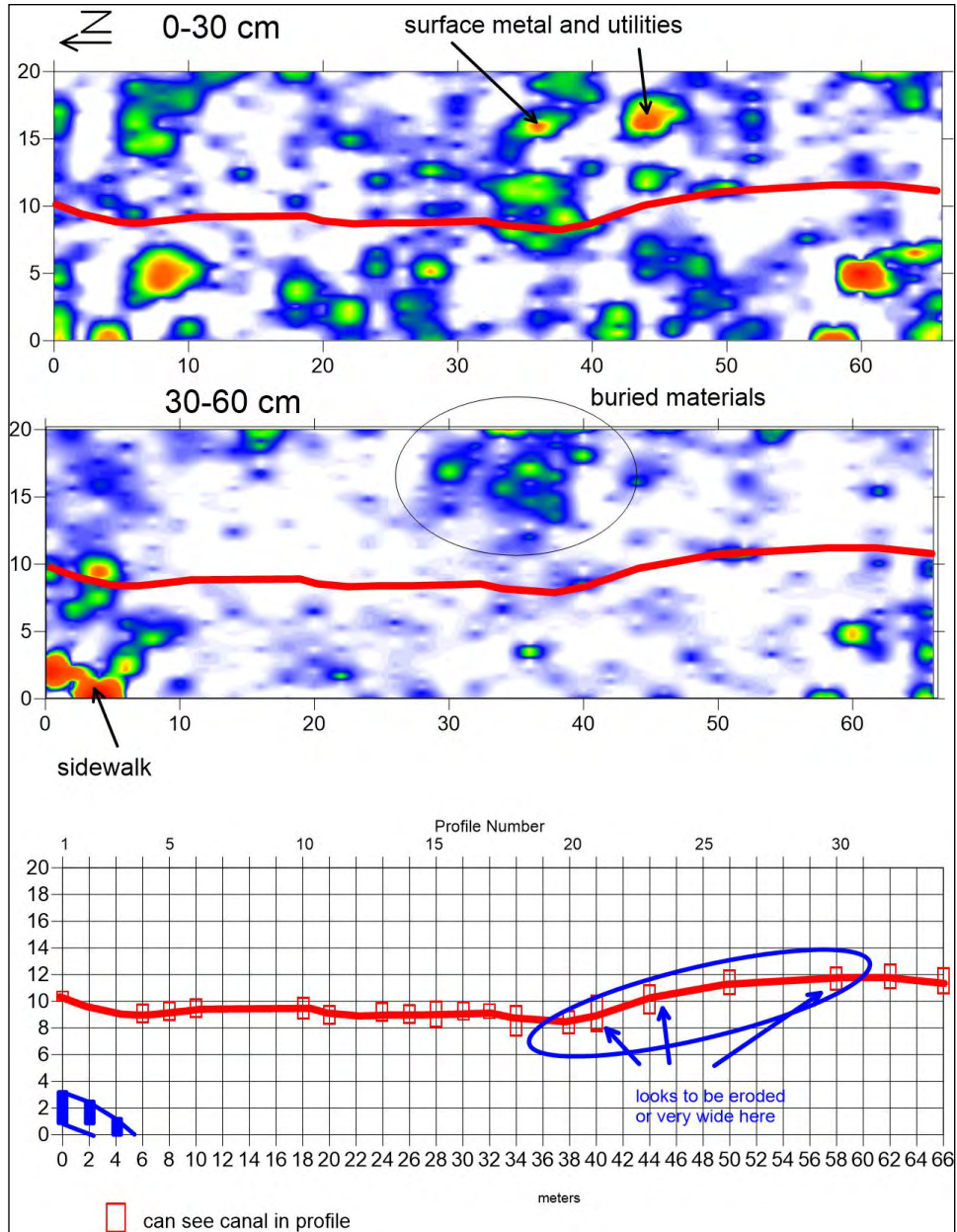


Figure 2.15. Horizontal amplitude maps (top and middle) and alignment map (bottom) showing the plan view location of the channel within Grid 1. Note location of potentially disturbed or eroded section in southern half of the unit (from Conyers and Moss 2013:11).

## Grid 2

Data were collected from a total of eight transects within this unit. Less than half (three out of eight) of the reflection profiles from transects within this unit showed evidence of the acequia channel. The top of the feature appears to be truncated in this area, with intact portions of the channel located immediately below the modern ground surface (Figure 2.16). This unit is located adjacent to a paved parking area and is transected by a dirt road trace. The development of both modern features may have impacted the acequia, truncating the top of the feature. The base of the

acequia was not clearly visible in the profiles collected from this unit. The alignment appears to be fairly straight in this unit, though only a small segment was identified (Figure 2.17).

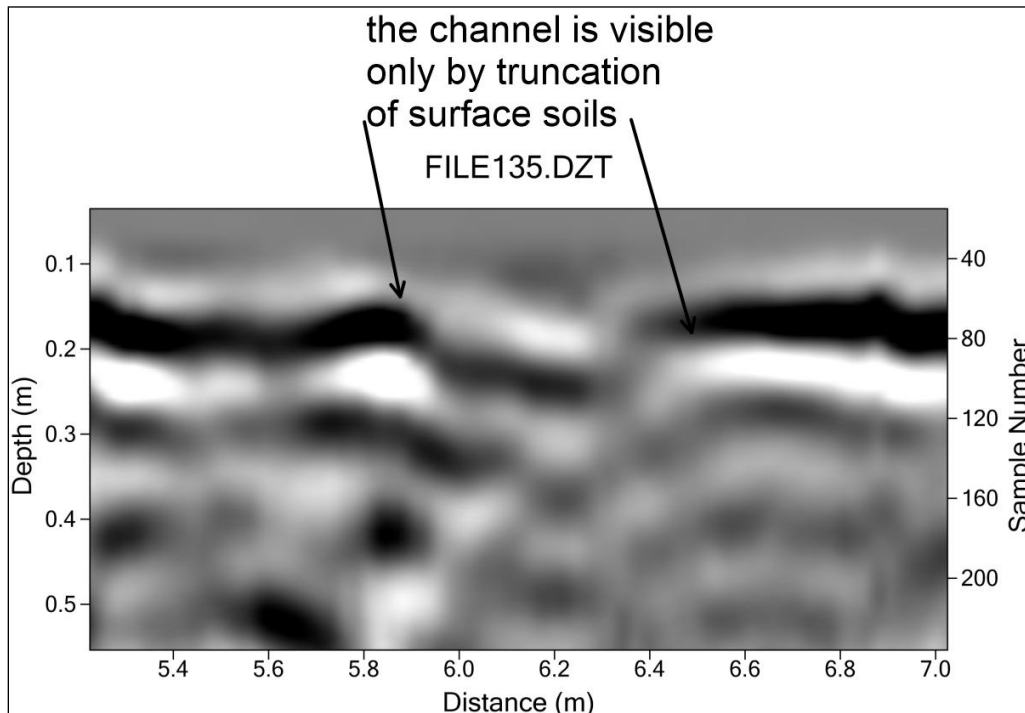


Figure 2.16. Representative reflection profile from Grid 2, showing the channel truncating the stratum just below the modern ground surface (from Conyers and Moss 2013:12).

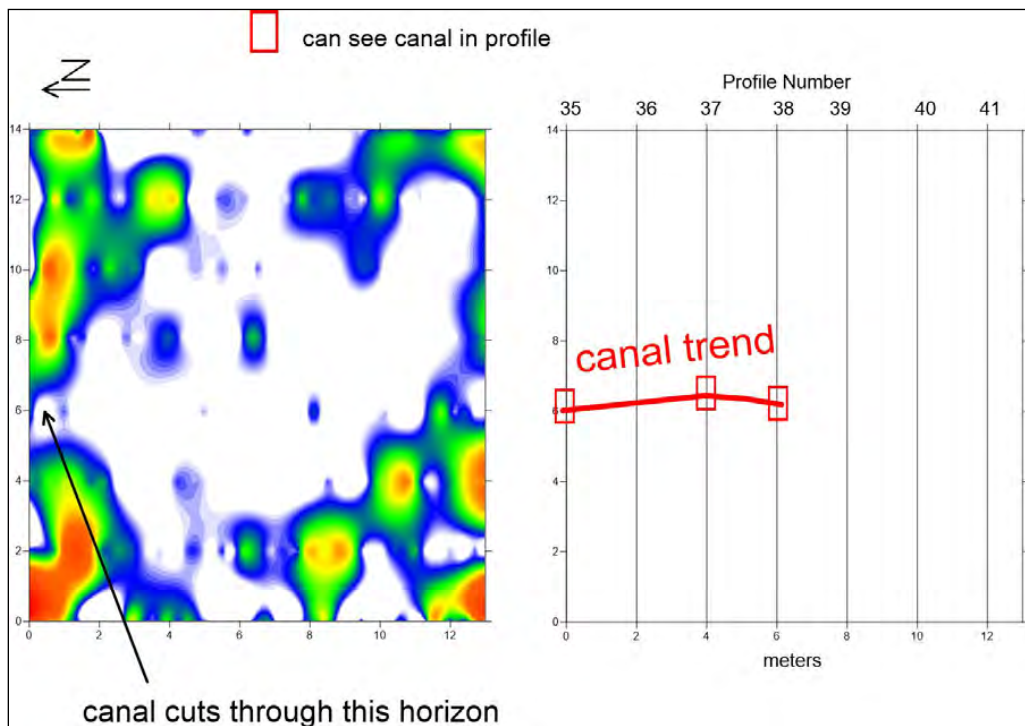


Figure 2.17. Horizontal amplitude map (left) and alignment map (right) showing location of acequia channel in plan view within Grid 2 (from Conyers and Moss 2012:13).

### Grid 3

This grid unit corresponded to the area initially tested in December 2012 that had yielded 15 profiles in which the acequia was highly visible with additional profiles with limited visibility. During the second field session only 11 of 41 profiles successfully documented the acequia, many of which were located in segments that had not previously produced visible profiles. Despite the inconsistency in visibility within this unit between the first and second sessions, horizontal amplitude maps produced from data gathered during both sessions suggest that the channel alignment meanders to the east toward the northern end of the unit (see Figure 2.18). This pattern corresponds to the alignment visible in historic aerial photographs dating from 1936 (Figures 2.1 and 2.2) and 1967 (Figure 2.5).

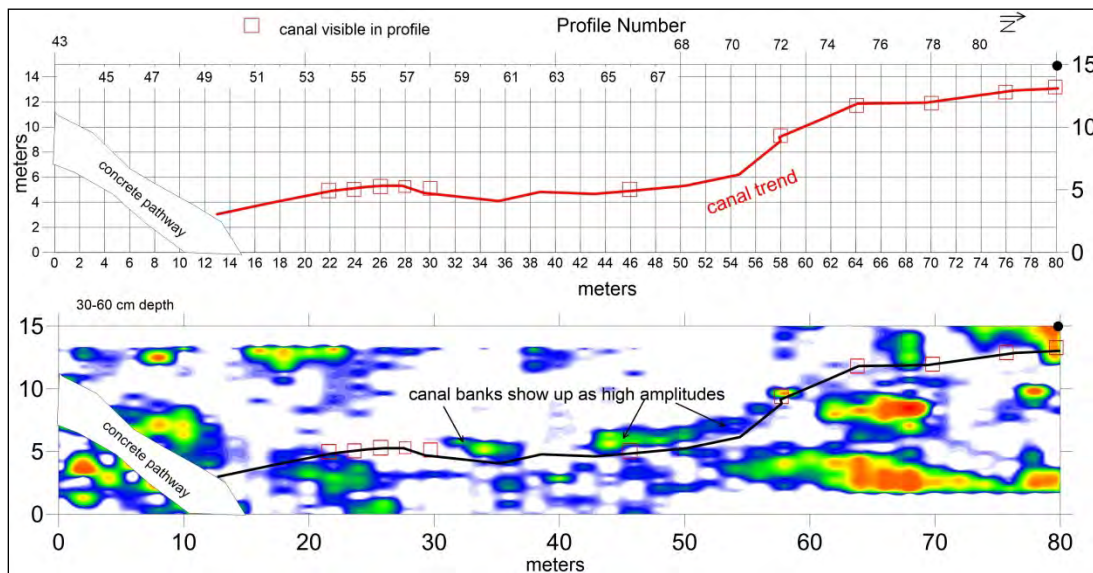


Figure 2.18. Alignment map (top) and horizontal amplitude map (bottom) showing the plan view location of the channel within Grid 3 (from Conyers and Moss 2013:14).

### Grid 4

Data were collected from a total of 12 transects within this unit. Data were not collected from the central part of this grid unit due to thick vegetation. Only four profiles depicting the channel were generated within this unit, predominantly within the southern half. The location of the profiles suggests that the channel undulates slightly in the central part of the unit, turning from northwest to north (Figure 2.19). No horizontal amplitude map was published for this unit, as there was too much interference from the compacted dirt road that transected the unit.



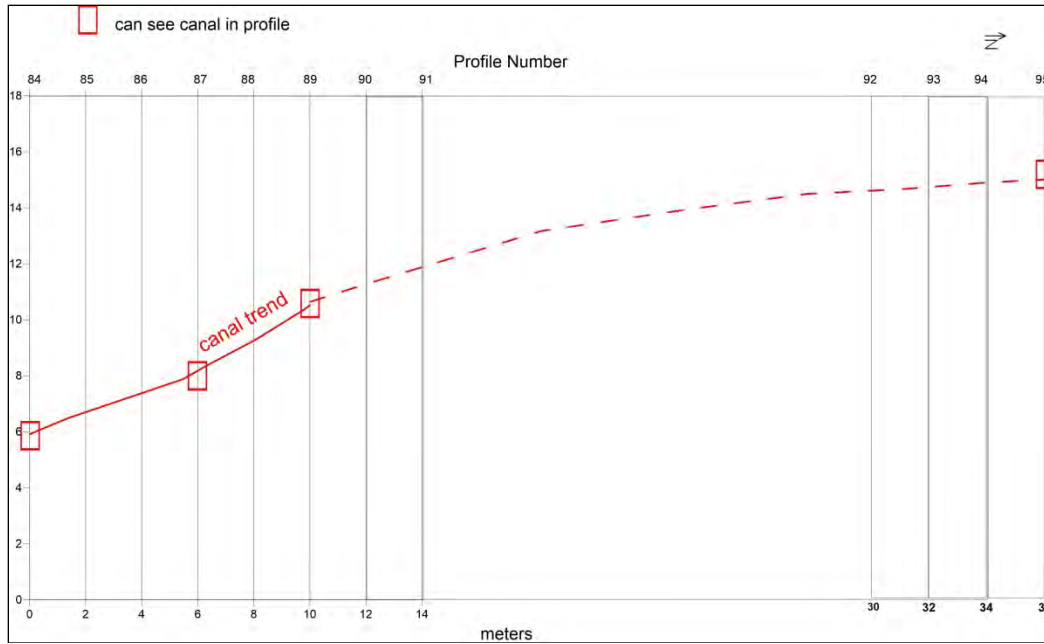


Figure 2.19. Alignment map showing the location of the channel in plan view within Grid 4; note portion of grid unit where data was not collected (from Conyers and Moss 2013:16).

## DISCUSSION

While only 49 reflection profiles out of 154 total transects showed evidence of the buried acequia channel, the study provided valuable information about the extant portions of the feature, including location and depth. The location of reflection profiles could be manually interpreted to produce approximate alignments for all four grids investigated (see Figure 2.20).



Figure 2.20. Overview of grid locations with projected alignment of acequia based on results of both December 2012 and March 2013 field sessions (from Conyers and Moss 2013:16).

The results of the geophysical survey were subject to limitations, including environmental conditions that affect visibility of buried materials and strata. As mentioned above, contrasting properties among buried strata, such as the contrast between clay and sand, result in greater

visibility of features within reflection profiles. The difference in texture among the strata is compounded by the capacity of clay to retain water content, while coarser-grained silt and sand dry out more quickly. During the second field session in March of 2013, recent rains had saturated the ground, which may have resulted in similar water content among the different strata within the channel fill, canal banks, and surrounding matrix. This may account for the decrease in visibility with the area of Grid 3 as compared to the results of the initial field session in December 2012 when the ground was dry.

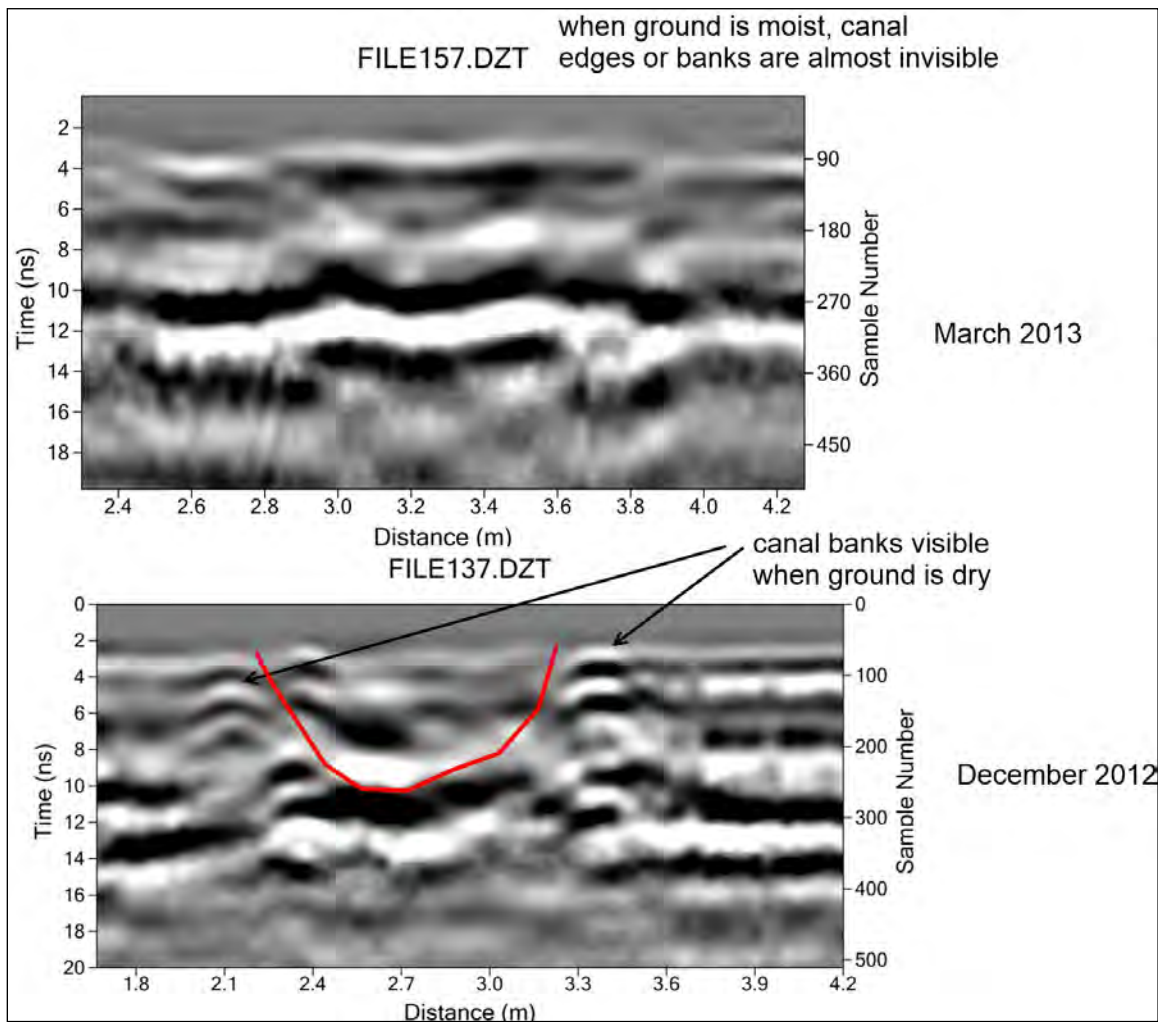


Figure 2.21. Example of variability in feature visibility within profiles from the same transect in Grid 3 generated during the two different field sessions (from Conyers and Moss 2013:8).

The GPR results were also affected by differential compaction caused by roads and road traces, as well as areas impacted by other construction, such as utility line trenches and paved surfaces (such as that adjacent to Grid 2). While soil conditions may account for visibility limitations, it is also possible that transects that did not produce visible profiles represent areas where disturbance or erosion has significantly impacted or destroyed the feature.

While visibility was not consistent, the results of the GPR study underscore trends that had been previously identified. The location of the acequia alignment, including a prominent undulation north of the compuerta defined through the GPR study, aligned with the location visually documented in historic aerial photographs. Furthermore, a higher percent of transects south of the compuerta produced visible reflection profiles than in areas investigated north of the compuerta. The higher visibility among grids south of the compuerta suggests that there is higher contrast among the strata within the channel fill in this portion of the feature. This is consistent with the results of previous archaeological investigations, which revealed the acequia in profile in units to the north and south of the compuerta. The profile exposed to the south of the compuerta showed distinct fine-grained silt lenses up to 4 cm thick that appeared to delineate two use-episodes. The silt lenses defined the acequia fill within the surrounding coarser-grained matrix. The profile exposed in the unit north of the compuerta contained thin silty laminae, but was much less distinctly defined from the surrounding sediments.

The variation in acequia stratigraphy may be the result of a head gate within the compuerta that slowed or stopped the flow of water downstream (or north), allowing more silt and clay to accumulate on the base of the canal upstream (south) of the compuerta. Additional exposures are needed to assess this hypothesis and account for all of the factors that have contributed to the variation in the acequia stratigraphy, including erosion and disturbance.

## QUESTIONS FOR FURTHER STUDY

While the results of the GPR study provided valuable information suggesting the acequia is buried and in better condition than previously thought, additional information is needed to confirm and expand on the findings. While remote sensing studies, such as GPR, provide non-destructive methods for data collection, ground-truthing of the location and an in-depth analysis of the stratigraphy associated with the acequia may help resolve inconsistencies among the GPR data. Further investigations may seek to address questions associated with practicalities that aid in preservation and management activities, assess the condition, and/or examine feature attributes. Such questions may include:

1. Are the GPR results accurate in terms of the location of the alignment and the depth of the channel below the modern ground surface?
2. What conditions account for the variability or absence of detectable geophysical data? Similar physical properties among channel deposits and the surrounding sediment? Significant disturbance?
3. Are channel deposits intact? If so, can different use-episodes be identified?
4. Are different sedimentation patterns identified between the north and south sides of the compuerta consistent? If so, are such patterns the result of intentional water control measures such as a head gate in the compuerta?
5. Are channel berms intact? If so, is there evidence of canal maintenance?
6. Is the acequia alignment identified in aerial photographs and in GPR reflection profiles associated with Mission-period construction and use? Are there earlier or later iterations that reflect different generations of the channel?

Further analysis of the acequia stratigraphy should involve a geologist, geomorphologist, or geoarchaeologist to ensure nuanced microstrata are identified, documented, and interpreted. Further investigation of the agricultural landscape associated with the acequia madre may yield information that informs upon the larger irrigation system, such as the presence of lateral canals. A more in-depth understanding of the feature's morphology may lead to supplementary research questions, such as whether cultural influences on the technology represented can be identified. A preliminary research design for further archaeological investigation is provided in Appendix A.

**PART THREE**  
**CONDITION ASSESSMENT**

## CONDITION ASSESSMENT

The following section describes the existing conditions of the extant segment of the acequia madre that is visible from the modern ground surface (See figure 3.1), as a continuation of and supplement to the preceding discussion on the overall condition of the acequia over the past 75 to 80 years. While a large portion of the acequia can only be detected through excavation or remote sensing methods, the extant swale and compuerta provide a tangible sample of the feature that can easily be assessed from the modern ground surface. As such, current conditions, deficiencies, disturbance factors, and preservation issues can be more readily detected and addressed.



Figure 3.1. Location of condition assessment (outlined in red).

A description of the physical features associated with the compuerta and swale is outlined, along with a description of the current condition. The physical condition of the acequia features was determined in consultation with the standardized criteria outlined in the *Preservation and Management Guidelines for Vanishing Treasures Resources* (Barrow 2009). The condition of each feature or section of the acequia is described as Good, Fair, or Poor. The criteria for the condition description are:

**Good Condition:** The site (or feature within the site) shows no clear evidence of major negative disturbance and deterioration by natural and/or human forces. The site's archaeological values remain well preserved, and no site treatment actions are required to maintain its condition.

**Fair Condition:** The site (or feature within the site) shows clear evidence of minor disturbance and deterioration by natural and/or human forces and some degree of corrective action should be carried out fairly soon to protect the site.

Poor Condition: The site (or feature within the site) shows clear evidence of minor disturbance and rapid deterioration by natural and/or human forces and stable immediate corrective action is required to protect and preserve the site.

### **ACEQUIA SWALE**

While a majority of the acequia alignment has been buried primarily by land modification activities since the feature was abandoned in the 1930s, a segment of the channel is visible from the modern ground surface extending both north and south from the compuerta. The current surface condition of the historic acequia swale was assessed on November 5, 2013, with additional observations made January 29, 2014 (see Figure 3.2). The physical assessment consisted of general observations and documentation of existing conditions from the modern ground surface, including measurements, vegetation encroachment, and evidence of disturbance. The integrity of (potentially) intact channel stratigraphy was not assessed at this time.





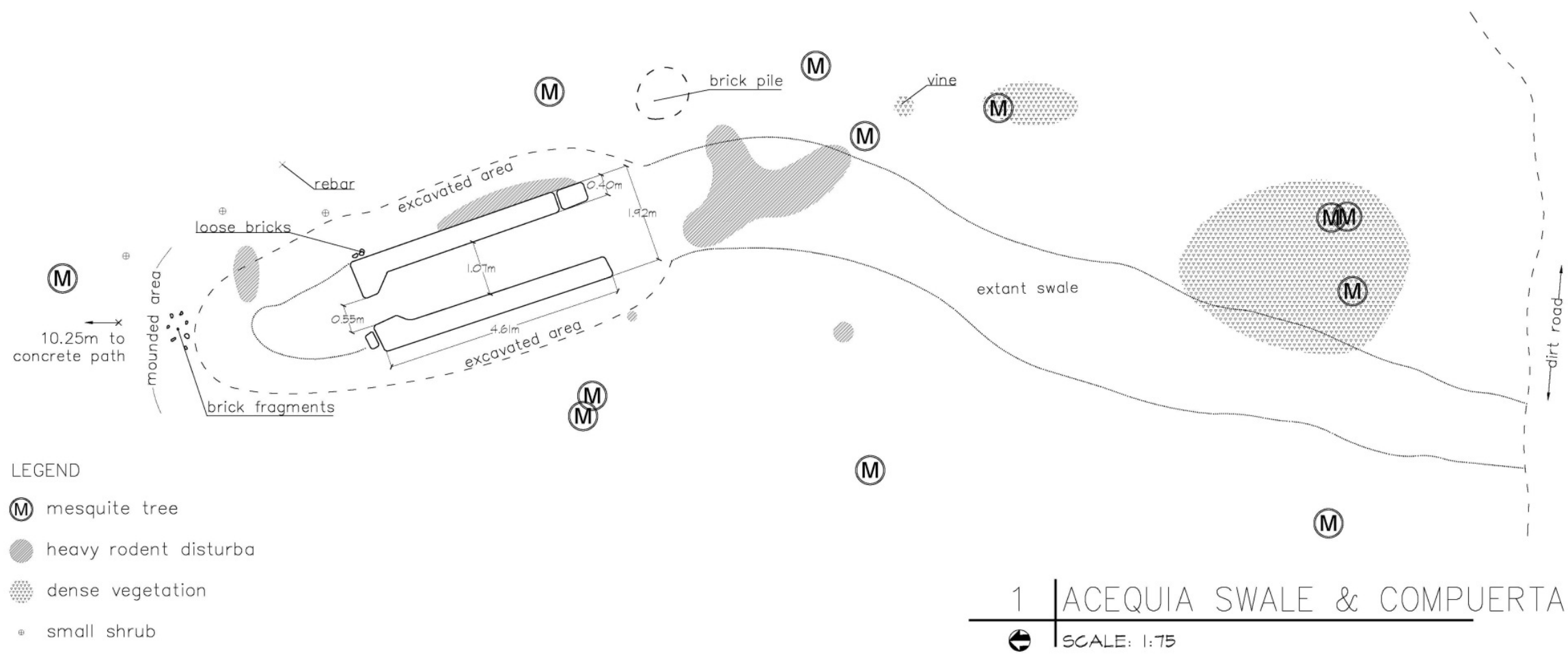


Figure 3.2. Schematic plan map of compuerta and visible swale. Deficiencies and preservation issues associated with the swale are outlined.



## Physical Description

The extant swale visible at the modern ground surface is confined to the area immediately surrounding the compuerta and predominantly extends to the south. The swale consists of the linear earthen canal alignment that would have channeled the surface flow from the Santa Cruz River to distribution points for the orchard and field plots before curving back toward the main river channel. The swale is aligned roughly north-south and curves toward the northwest immediately south of the compuerta. The swale extends approximately 18 m to the south of the compuerta before being obscured by an unpaved road bed. The southern portion of the swale ranges from 1.5 m to 2.5 m in width.<sup>2</sup> The widest portion of the swale to the south of the compuerta may correlate to the area tested by Burton in 1994. The increased width may be a result of mechanical excavation of a backhoe trench through this portion of the swale (Unit 6; see Figure 1.6 and 1.7).

The swale extends approximately 3 m to the north of the compuerta. This short section of the swale is also the widest, with a maximum width of approximately 3.5 m. The width of the swale in this corresponds to the width of the recessed area around the compuerta, which likely represents the limits of excavation performed by NPS personnel in 1994 when the compuerta was re-identified (see Figure 1.8). The northern end of the extant swale was likely affected by the excavations that revealed the compuerta.

At the northern terminus of the existing swale, the modern ground surface is mounded. Within this mounded area, small brick fragments are visible from the surface. The mounded dirt may represent secondary fill or, more likely, back-dirt associated with investigation of the feature by the NPS, including work completed by Yubeta and Burton in 1994. An additional concentration of brick fragments was observed on the east side of the swale approximately 1.5 m southeast of the compuerta, which may have been reserved from excavated fill.

While the acequia swale is no longer actively maintained, the convex shape provides a tangible link to the former conditions of the buried alignment and thus acts as a character-defining feature of the overall alignment.

Several large trees and shrubs are growing along the banks of the acequia along the visible section of the alignment, including mesquite, hackberry, and catclaw acacia. There are patches of dense vegetation along the edges of the alignment, with smaller shrubs and vines, especially along the southeast portion of the extant swale. The presence of dense vegetation along the edges of the acequia alignment is representative of the historic conditions of the feature, illustrated by the 1936 aerial photo showing the extent of the feature (Figure 2.1). Bossler and Johnson suggest that during the colonial period “(t)rees, commonly cottonwood (*Populus fremontii*) and netleaf hackberry (*Celtis reticulata*), were likely grown along these *acequias* for shade and windbreaks,” (2012:90). Thus, the alignment of vegetation along the edges of the acequia can be considered part of the landscape historically associated with the acequia.

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<sup>2</sup> The measurements recorded for the swale are approximate. The measurements were taken from the inner edges of the berm where the channel reaches maximum height.

Located just off of a paved ADA-accessible trail, the swale (along with the compuerta) functions as an interpretive feature. This section of the acequia is marked with a small sign to help self-guided visitors locate the feature. The acequia is also included in many tours given by the Park interpretive Staff.

**Overall Condition**

The swale is currently in fair condition. The feature currently does not appear to be significantly impacted by depositional or erosional processes. Ephemeral ground cover vegetation contributes to the overall stability of the swale and berms, holding the existing top soil in place, mostly with minimal potential for root disturbance. Subsurface deposits and feature attributes were not assessed for their condition (as in stratigraphic integrity, degree of bioturbation, etc.), but effects of bioturbation observed from the surface indicates that ongoing moderate impacts could be significantly impacting the integrity of the subsurface deposits over time.

**Condition Assessment**

Specific condition issues were identified during the in-field assessment. Definitions for the condition assessment terms are provided in the table below.

<b>Condition Term</b>	<b>Definition</b>
<i>Vegetation encroachment</i>	Growth of plants upon or within historic materials; also includes nearby plants with potential indirect or direct effect on structural or visual integrity
<i>Disturbance</i>	
Rodent disturbance	Removal, redeposit, or destruction of historic materials due to burrowing rodents
Insect disturbance	Removal, redeposit, or destruction of historic materials due to burrowing insects
Excavation	Manual or mechanical removal of historic materials
<i>Additions/Modifications</i>	Modification of the material that does not necessary imply a worsening of its characteristics from the point of view of conservation (ICOMOS-ISCS 2008:8)

Table 3.1. Definitions of terms used in the condition assessment for the extant swale.

Vegetation encroachment. While the trees along the edges of the acequia have deeply buried root structures, their initial growth patterns may have affected the acequia stratigraphy. Further, the thick understory and encroachment of saplings and shrubs pose a threat to the integrity of the buried berms and channel deposits. The stratigraphic record of channel use and maintenance is a critical source of information about the nature of the acequia, and bioturbation as a result of root growth may have a deleterious effect on portions of the buried stratigraphy. Numerous large mesquite trees are growing along the swale, as well as smaller shrubby trees such as catclaw acacia. There are patches of dense vegetation along the acequia banks, especially at the southeast edge of the extant swale.

In addition to the threat of disturbance due to root activity, the thick understory that has accumulated in the vicinity of the swale reduces the feature’s visibility within the landscape. The reduced visibility has a negative effect on interpretation, as the swale is less “readable” from the

ground surface and its connection to other features on the landscape (including the orchard) is more difficult to discern.

The mature mesquite trees, however, form an over story that may help reduce the amount of rainfall exposure, providing a beneficial impact on the feature. Limiting the amount of direct rainfall on the swale may help prevent erosion.

Native grasses and ephemeral ground cover accumulate within the swale, flourishing after rains and receding during dry months. The accumulation of ground cover may interrupt the visual integrity and increase deposition accumulated from storm water runoff. However, the grass cover reduces erosion, potentially protecting subsurface stratigraphy related to the acequia.



Figure 3.3. Overview of vegetation encroachment: areas of heavy vegetation circled in dashed line; looking south (photographed January 29, 2014).

Rodent and insect disturbance. The swale shows signs of active rodent and insect disturbance, especially along the channel's berms. Like root activity, bioturbation from rodent and insect activity can significantly affect the integrity of buried archaeological strata. Rodent activity was most notable along the bermed edges of the extant swale during the November 2013 assessment, while a large swath of fresh rodent activity was observed running through the channel south of the compuerta the following visit in January 2014. Small, localized evidence of insect activity (likely ant, cicada, and/or termite) was observed on the ground surface during both visits, but surface evidence burrowing was minimal at the time of assessment.



Figure 3.4. Overview of rodent disturbance; areas of fresh or significant activity outlined in red (photographed January 29, 2014).



Figure 3.5. Heavy concentration of rodent disturbance south within the swale south of the compuerta (photographed January 29, 2014).

Excavation. As mentioned above, NPS personnel investigated the acequia in 1994, uncovering the compuerta and excavating a backhoe trench through the channel alignment. The excavations likely had an impact on the condition of the swale in localized areas. The northern end of the swale appears to have been widened during excavation of the compuerta and back-dirt piled at the northern terminus (see Figure 3.6-Schematic Map). Approximately 7 m south of the compuerta, the swale widens and the eastern edge dips for a length of 3 m to nearly the same elevation as the base of the extant channel (see Schematic Map). The presence of several rebar datum stakes in the immediate vicinity of this portion of the swale suggests that this may be the location of the backhoe trench (Unit 6; Figures 1.6 and 1.7) from Burton’s 1994 investigations or references for the 2013 GPR survey. The full extent of impacts on the acequia stemming from this investigation is not clear, in the absence of a report of its methods, procedures, and findings.

NPS Additions/Modifications. An approximately 2.5 m wide concrete path has been paved over the acequia alignment 10.5 m north of the compuerta. Archaeological testing prior to the construction of the path showed that the acequia alignment in this location is extremely shallow and the top portion of the feature was likely adversely affected during construction of the concrete path. Furthermore, the concrete path interrupts the visually linear nature of the feature. Additionally, a dirt road trace has been constructed over the acequia alignment south of the compuerta, further obscuring the linear feature. The addition of Park infrastructure, including a 6-inch water line and a buried fire pump control cable, may have damaged buried portions of the acequia (see Figure 3.6).



Figure 3.6. Schematic map of Park utility infrastructure produced in 2001. Note existing 6-inch waterline and underground fore pump control cable in vicinity of acequia alignment (NPS TNHP Archives).

## COMPUERTA

The condition of the compuerta was assessed on November 19, 2013. The narrative that follows describes the preservation issues observed during the condition assessment, which were also recorded visually as color-coded annotations on photomontage images. The original annotated photomontages are on file with TNHP and digitized copies are included below.

### Physical Description

The compuerta is composed of two brick and mortar walls, spaced 1.2 m apart, that run northwest to southeast. The walls are constructed of fired bricks that are of uniform dimensions (12' in length, 5.5' in width, and 3' in height) up to 6 courses in height. The bricks are set with bedding mortar composed of lime tempered with coarse volcanic sands. The inner surface of the brick walls and base of the compuerta are finished with lime plaster. The exterior surface of the plaster was finished with a light wash, resulting in the light reddish to pink hue on the surface. A majority of the remaining plaster finish is preserved at the base of the walls with inner surface of the upper two to three brick courses mostly exposed.

Petrographic analysis of the plaster and mortar samples, performed by Meadors, Inc. in 2012, concluded that both materials are composed of similar proportions of lime and volcanic sand



aggregate temper. Brick dust was identified on the exterior surface of the plaster, indicating it had been applied as part of a surface wash. This surface treatment may have added to the hydraulicity and strength of the plaster at the surface, rather than specifically for aesthetic value.

Approximately 5% of the volcanic sand aggregate temper was composed of siliceous fines which appears to have added to the pozzolanic strength of both the mortar and plaster; it is unclear whether the fines were originally part of the sand aggregate or intentionally added to enhance strength. While the tendency of volcanic aggregates to dissolve in highly alkaline materials suggests that there would be a pozzolanic reaction with lime, the plaster had a higher than normal compression strength, suggesting further reaction beyond lime carbonization. The full report documenting the materials testing and analysis is included in Appendix C.

The brick walls protrude inward on the northern end, creating a weir that originally constricted the width of the channel to approximately 40 cm. The bottom floor surface of the compuerta, between the two walls, is prepared with smoothed hydraulic lime plaster. A majority of the floor surface is recessed, sloping downward 7 cm at the southern end and rising back up to the original elevation at the northern end of the feature (see Figure 3.7).

An additional column of bricks extends the northwest end of the compuerta. In a 1994 plan of the compuerta produced shortly after it was exposed, several large rocks were noted flanking the channel immediately north of the compuerta. Only one such rock was visible from the modern ground surface during the current condition assessment, on the west side of the channel.

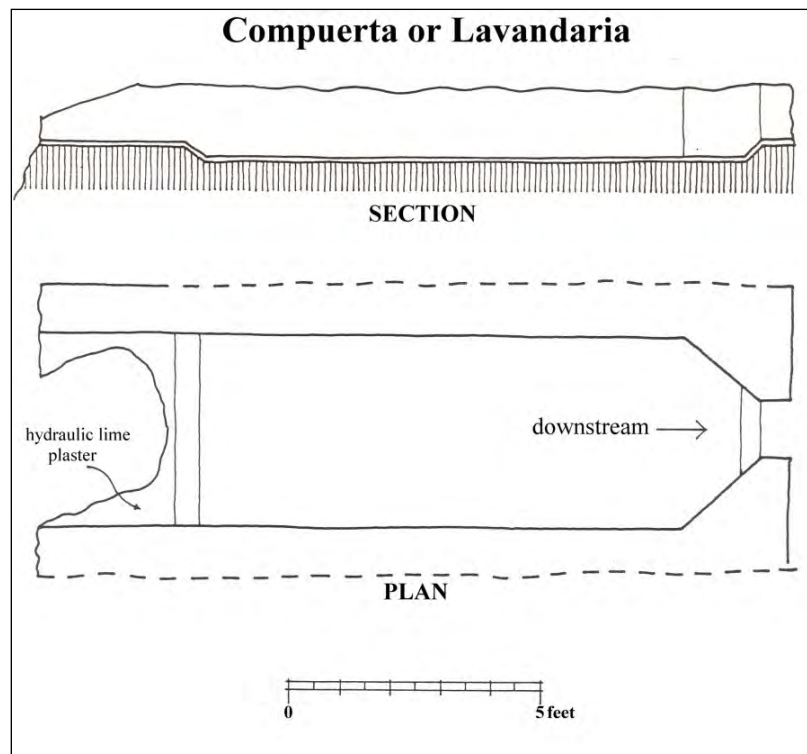


Figure 3.7. Stylized plan and cross-section of compuerta, showing the basic feature form (from Moss 2006:21).

## Overall Condition

The compuerta is currently in fair condition. Based on photographs taken shortly after it was exposed in 1994, the compuerta has experienced minor material loss. However, there are structural issues associated with movement, which may be exacerbated by vegetation encroachment and lateral pressure from accumulating sediment along the compuerta walls. Despite the preservation issues outlined below, the structure retains a high degree of integrity and is able to convey its historical form and function.

## Condition Assessment

Specific condition issues were identified during the in-field assessment. Definitions for the condition assessment terms are provided in the table below.

<b>Preservation Deficiency Term</b>	<b>Definition</b>
<i>Structural Issues</i>	
Crack/Fracture	Individual fissure, clearly visible by the naked eye, resulting from separation of one part from another (ICOMOS-ISCS 2008:10). Cracks can range from hairline (less than 0.1 mm) to fractures (which run completely through element).
Open joint	Joint of two distinct structural elements that has lost the formerly binding or adhesive agent, resulting in loss of structural integrity
Displacement	Movement of element or portion of structure from original location due to external forces (i.e. pressure from surrounding sediment )
<i>Material Loss</i>	
Complete loss of material	Empty space, obviously located in the place of some formerly existing element that is now completely lost (ICOMOS-ISCS 2008:36)
Spalling	Complete detachment of materials due to surface bursting or scaling; spalling may be a result of pressure from underlying efflorescence
Chipping	Loss of original material from the edge or surface due to human action.
Erosion	Loss of original surface, leading to smoothed shapes (ICOMOS-ISCS 2008:30) Erosion includes the loss of matrix within the bricks or plaster coating
<i>Vegetation encroachment</i>	Growth of plants upon or within historic materials; also includes nearby plants with potential indirect or direct effect on structural or visual integrity
<i>Loose materials</i>	
Detachment	General term to describe the separation of an element from structure due to an unknown cause; contributing forces may include structural fracturing, erosion of materials or disturbance
Spalling	Loss of material integrity due to partial surface bursting or scaling; spalling may be a result of pressure from underlying efflorescence
<i>Discoloration/Staining</i>	Change in color of historic materials at surface and/or within the matrix due to accumulation of exogenic material (ICOMOS-ISCS 2008:44). Dampness, salt efflorescence, and soiling may contribute to discoloration.

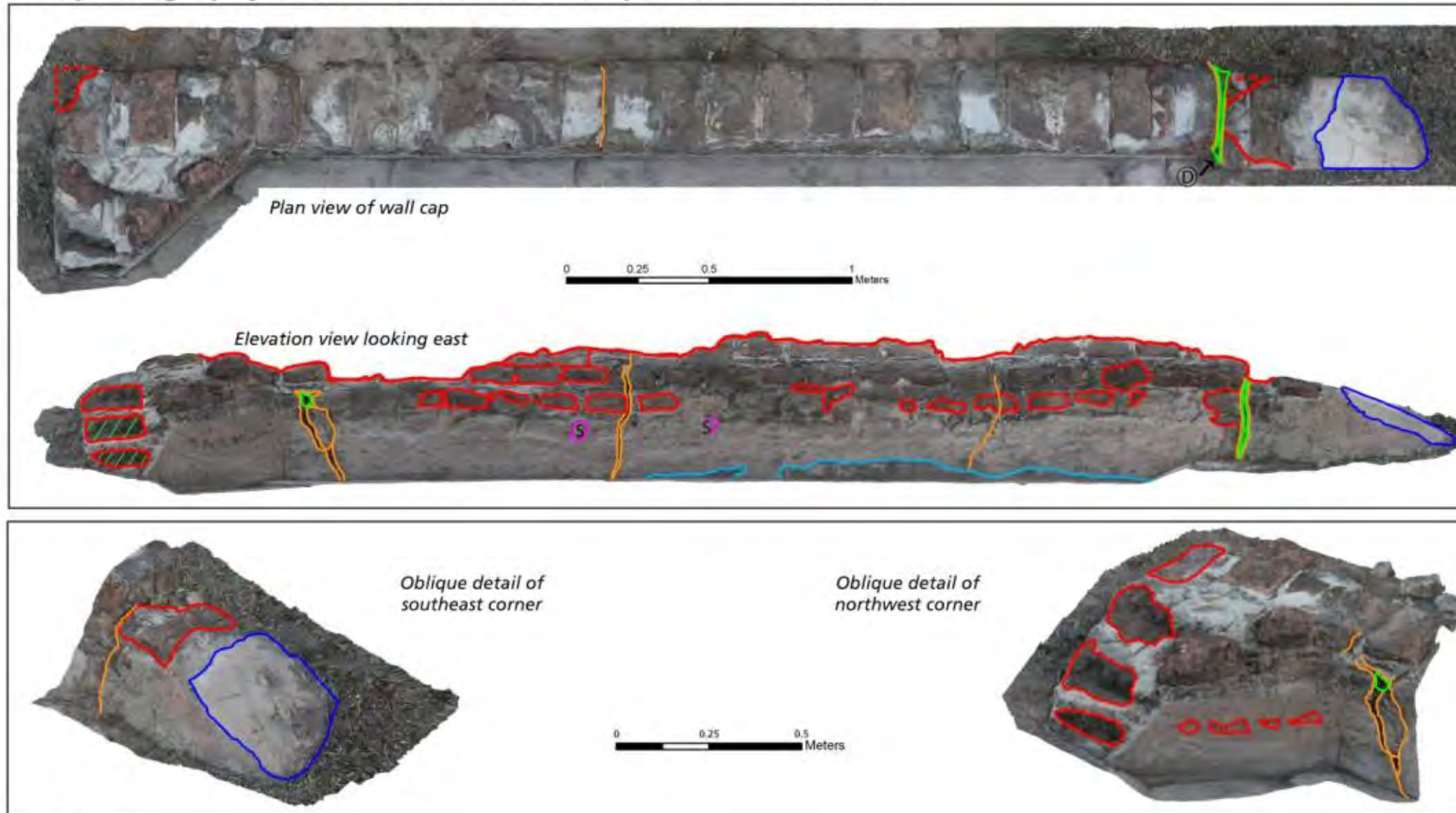
<i>Bio-organic growth</i>	
Lichen	“Vegetal organism forming rounded millimetric to centimetric crusty or bushy patches, often having a leathery appearance, growing generally on outside parts of a building. Lichen are most commonly grey, yellow, orange, green or black and show no differentiation into stem, root and leaf” (ICOMOs-ISCS 2008:68)
Moss	“Vegetal organism forming small, soft and green cushions of centimetric size. Mosses look generally like dense micro-leaves (sub- to millimetric size) tightly packed together. Mosses often grow on stone surface open cavities, cracks, and in any place permanently or frequently wet (masonry joints), and usually shady” (ICOMOS-ISCS 2008:70)
<i>Additions/Modification</i>	
Repair	Addition of non-historic materials to improve or retain structural integrity; may affect visual integrity

Table 3.2. Definitions of preservation deficiency terms used in the condition assessment for the compuerta.





### Orthophotography of the Tumacacori Compuerto - East Wall



Produced by SOAR Office

November 2013

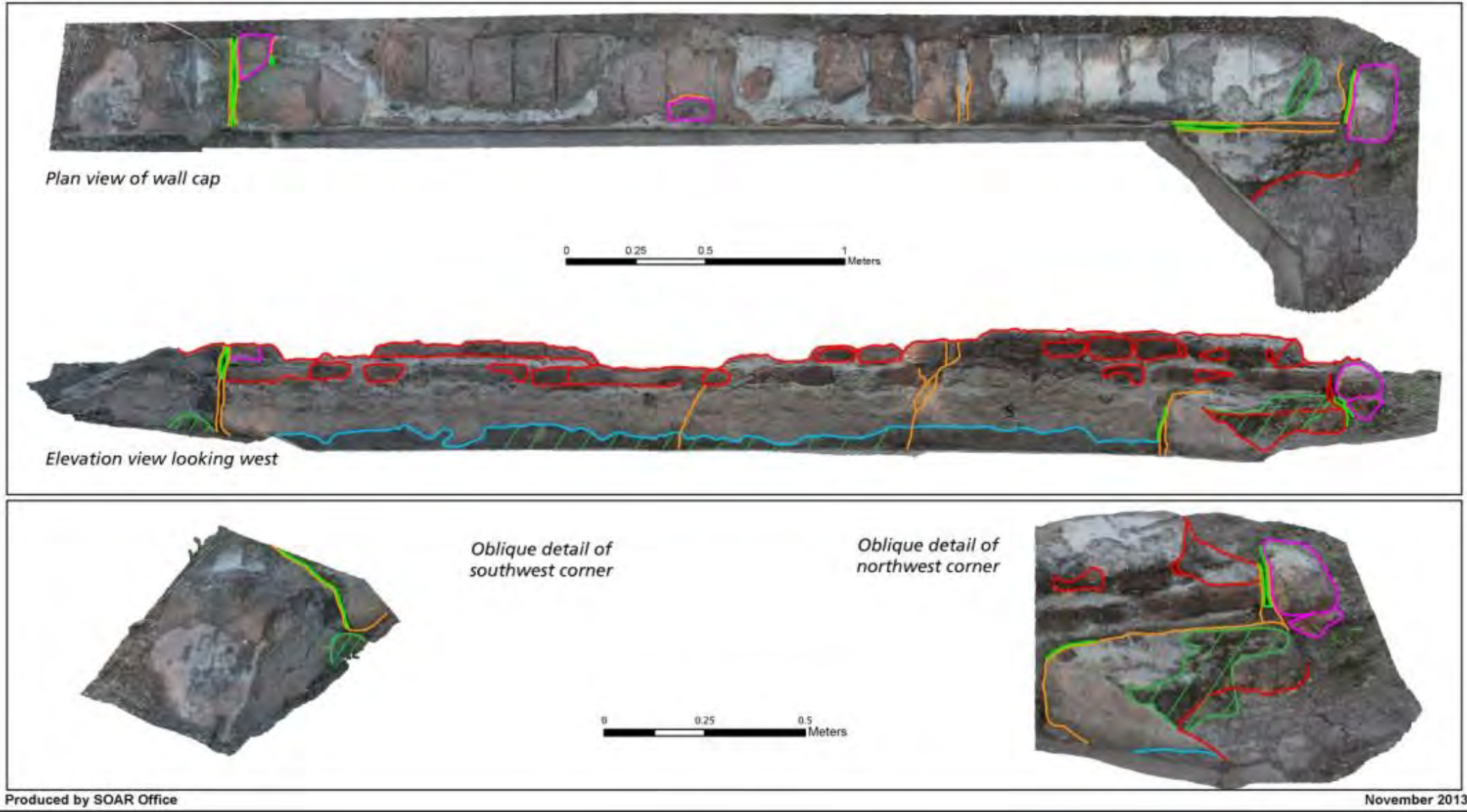
Condition Assessment Key:		
Material Loss	Vegetation Enroachment	Bio-Organic Growth
Structural Crack/ Open Joint	Discoloration/Staining	Displacement
Loose Material	Added Material/Repair	Spalling

Figure 3.8. Annotated photomontage illustrating comprehensive condition assessment evaluation for the east compuerta wall.





### Orthophotography of the Tumacacori Compuerto - West Wall



Produced by SOAR Office

November 2013

Condition Assessment Key:		
Material Loss	Vegetation Enroachment	Bio-Organic Growth
Structural Crack/ Open Joint	Discoloration/Staining	Displacement
Loose Material	Added Material/Repair	Spalling

Figure 3.9. Annotated photomontage showing comprehensive condition assessment evaluation for the west compuerta wall.





**Structural Issues.** Several structural cracks were observed in both east and west walls (Figure 3.10, 3.11, and 3.12). The most severe cracking in both walls was located near the southern ends where the wall begins to taper toward the swale. An open joint has resulted in separation of the wall extension forming the western half of the weir from the west wall in the northwest corner of the feature (Figure 3.13).

Slight displacement of the southern end of the eastern wall was noted, with movement of this section of wall toward the west. The displacement may be a result of disturbance factors such as root encroachment (Figure 3.14).



Figure 3.10. Structural cracks in southern ends of both east and west compuerta walls (traced in red); note vegetation encroachment in cracks (see detail in Figure 3.9) (photographed November 19, 2013).



Figure 3.11. Structural crack in southern end of west wall; vegetation encroachment within crack (photographed November 19, 2014).



Figure 3.12. Structural crack in north east corner of compuerta. Note root in the gap of the bedding mortar (photographed November 19, 2014).



Figure 3.13. Detail of open joint between the west wall of the compuerta and the west half of the weir at the northern end of the feature. Note vegetation encroachment within gap (photographed November 19, 2013).



Figure 3.14. Detail of southern end of east wall with displacement of section of wall toward the west (photographed November 19, 2013).

Material Loss. On both east and west walls, at least one course of bricks has been completely lost, as indicated by remaining brick joint imprints in the mortar along the top surface of the walls (Figure

3.15). Several sections of both walls have lost portions of lower brick course as well. Portions of additional bricks within the upper courses of both walls have been lost to chipping, erosion or melt, and spalling (Figures 3.16 and 3.17).

A portion of the wall extension forming the western half of the weir at the northern end of the compuerta has been lost. The eastern half of the weir is better preserved, providing a general idea of the extent of the loss (Figure 3.18).

The top portion of the plaster finish has eroded, leaving the inner surface of the top two to three courses of bricks exposed (Figure 3.19).

Cracking within the bedding mortar has resulted in localized material losses between the brick joints (Figure 3.20). Brick and mortar fragments associated with the compuerta are piled in two areas, which may represent both recent losses (Figure 3.21) and loose materials that were found during the initial excavation that uncovered the compuerta in 1994 (Figure 3.22).

The majority of the material loss, including the lost courses of bricks, appears to have occurred prior to 1994.



Figure 3.15. Evidence of lost course of bricks at top of compuerta walls, indicated by brick impressions in bedding mortar (photographed November 19, 2014).



Figure 3.16. Detail of spalled surface on brick, east wall of compuerta (photographed November 19, 2013).



Figure 3.17. Plan view of spalled brick, showing extent of material loss (photographed November 19, 2013).



Figure 3.18. Material loss on western portion of weir at northern end of compuerta. Estimated extant of original material lost outlined in red (photographed facing west, November 19, 2013).



Figure 3.19. Plaster finish on the interior surface of the compuerta has spalled and eroded (photographed November 19, 2013).



Figure 3.20. North end of east compuerta wall showing mortar loss within brick joints, outlined in red (photograph facing northeast, November 19, 2013).



Figure 3.21. Bedding mortar fragments piled near the eastern wall of the compuerta (photograph facing east, November 19, 2013).



Figure 3.22. Brick and bedding mortar fragments piled to the southeast of the compuerta (photograph facing east, November 19, 2013).

Vegetation Encroachment. Small shrubs are growing in several of the structural cracks, especially at the north and south ends of the walls (Figure 3.11). The vegetation growth and associated root structures are likely exacerbating the structural movement associated with the cracks. A large root was observed within a gap in the bedding mortar between bricks in northeast portion of the compuerta; the root appeared to have been cut back as part of vegetation maintenance associated with the feature (Figure 3.12).

Loose Materials. The remaining lime plaster finish on the bricks shows evidence of spalling with two loose sections of plaster near the center of the east wall (Figure 3.23). Spalls are likely a result of efflorescence in the underlying bricks or repeated wetting and drying cycles.

The corner brick at the northwestern edge of the compuerta is loose due to detachment of mortar and can be easily removed from its original location (Figure 3.24). Samples from the bedding mortar were taken from this location for material analysis testing by Meadors Conservation Laboratory in 2012-2013 (see Material Analysis in Appendix C).





Figure 3.23. Spalling plaster near center of the east compuerta wall (photograph facing east, November 19, 2013).



Figure 3.24. Loose brick at northwest corner of compuerta, outlined in red (photograph facing southeast, November 19, 2013).

Discoloration/ staining. Further evidence of prolonged water exposure was observed at the base of both compuerta walls. The plastered surface at the base of the walls exhibits discoloration from soil and salt deposits, likely due to water pooling in the depressed portion of the compuerta floor (Figure 3.25).

**Bio-organic Growth.** A light, patchy layer of lichen has developed on the exposed surface of the bricks and bedding mortar. The lichen ranges from black to gray-green in color and is most prevalent at the northern end of the feature (Figure 3.26). Green, moss-like biological growth was observed at the base of the compuerta walls, which coincided with discoloration of the plaster surface. The moss-like growth indicates prolonged damp conditions due to water accumulating in the compuerta.



Figure 3.25. Overview of discoloration at base of west wall highlighted in red (photograph looking south, November 19, 2013)



Figure 3.26. Detail of bio-organic growth on the surface of brick and bedding mortar of west wall (photograph November 19, 2013).

NPS Repairs. A hydraulic lime plaster coating was added in 2010 on the southern end of the east wall, capping the top surface of the wall as it curves down toward the ground surface. The plaster coating was added as a test to evaluate the material and its effects on the historic fabric of the compuerta. The test material is composed of St. Astier 3.5 moderately hydraulic lime (Jeremy Moss, personal communication, April 2014).



Figure 3.27. Natural hydraulic lime plaster test material at southern end of east compuerta wall (photograph looking north November 19, 2013)



**PART FOUR**  
**TREATMENT RECOMMENDATIONS**

## PRESERVATION MAINTENANCE

The following section outlines general recommendations and specific treatments for the preservation maintenance of the existing surface features associated with the acequia. Treatments have been developed in consultation with Park management policies and priorities, outlined in planning documents such as the *General Management Plan*. The treatment recommendations are designed to encourage stabilization and in situ preservation of historic materials, as outlined by the *Secretary of the Interior's Standards and Guidelines for the Treatment of Historic Properties*. Preservation, generally using the least intrusive methods, is the preferred intervention for both the compuerta and the swale. The Secretary of the Interior defines preservation as:

The act or process of applying measures necessary to sustain the existing form, integrity and materials of a historic property. Work, including preliminary measures to protect and stabilize the property, generally focuses upon the ongoing maintenance and repair of historic materials and features rather than extensive replacement and new construction (National Park Service 2001).

The Park's List of Classified Structures lists the acequia as contributing to the significance of the Tumacácori Mission Historic District. Furthermore, the current General Management Plan for the Park list the remnants of the historic acequia as a "fundamental resource," (2011:13). While managed as a ruin, the historic integrity of the feature must be preserved for its continued contribution to the significance of the site. Preservation maintenance will ensure that the extant swale and compuerta can continue to function as primary interpretive features representing the form and function of the historic acequia.

Recommended treatments for the acequia may subsequently be integrated into a comprehensive Cultural Landscape Report that assesses and evaluates the greater landscape associated with the Tumacácori mission complex. The Cultural Landscape Report will allow the Park to collate and assess comprehensive Park planning and consider associated effects on the broad cultural landscape.

### ACEQUIA SWALE

The swale represents a character-defining element that illustrates the concave shape of the irrigation channel, which at one time extended along the length of the alignment. As a majority of the acequia alignment has been buried by land modification activities, the extant swale is a significant asset to visually illustrate the nature of the acequia. Treatment recommendations are based on the current condition as observed from the modern ground surface and supplemented by information on the basal elevation and buried stratigraphy recovered from limited archaeological testing. Additional testing to further assess the condition and nature of the subsurface stratigraphy will allow for increasingly effective management, providing additional insights on formation processes affecting the condition of the below-grade portion of the feature. See Appendix A for a preliminary archaeological research design.

**Preservation Issues and Considerations**

The swale is an archaeological feature that has the potential to yield important information about the history of the mission, including past environmental conditions, construction technology, use and maintenance practices associated with the feature, and cultural influences on such practices. As an earthen feature in a vegetated area, root damage is an inherent concern. However, vegetation is an element of the cultural landscape and historic conditions associated with the acequia. The trees and vegetation contribute to the integrity of the acequia landscape, including the setting, feeling, and association. Preservation of the acequia will require a balance of landscape maintenance and archaeological stewardship. Furthermore, as a fragile archaeological resource, the effects of future use and development may pose a threat to its integrity and should be considered further in a Cultural Landscape Report.

**Summary of Deficiencies and Recommendations**

The following table summarizes the disturbance and deterioration factors that were outlined in the condition assessment in Part Three of this report. The preservation maintenance treatments recommended for each deficiency are summarized within the table and described in narrative form below.

<b>CONDITION</b>	<b>TREATMENT RECOMMENDATION</b>
<b>Disturbance Factors/Bioturbation</b>	
Vegetation encroachment	Mitigate potential root disturbance and reduced visibility by clearing saplings, shrubs and thick understory in vicinity of swale.
Rodent and insect disturbance	Develop an Integrated Pest Management program for Park
<b>Human Impacts</b>	
Archaeological excavation through swale	No action recommended
Addition of concrete path (disturbance of physical and visual integrity)	No action recommended
Construction of dirt road over acequia alignment south of compuerta	No action recommended
Possible disturbance resulting from installation of Park infrastructure	No action recommended

**Recommended Maintenance and Improvements**

Mitigate vegetation encroachment. Vegetation maintenance should be completed according to three objectives: mitigation of vegetation-related disturbance factors, maintaining visibility of the feature from the ground surface so that it may continue to serve as an interpretive feature, and restoration/preservation of the cultural landscape.

The small hackberry saplings in the northeastern edge of the swale should be removed, employing methods that minimize soil displacement associated with root removal. Heavy vegetation at the

southeastern edge of the swale should be trimmed back and maintained as part of a regular maintenance. In general, the understory of the surrounding vegetation should be thinned.

Vegetation maintenance should use equipment and procedures that limit ground disturbance within the swale. As the acequia is an archaeological resource that has the potential to yield important information on the history of the mission, herbicides are generally not recommended. Herbicides may impact or invalidate radiocarbon dates of archaeological material subsequently recovered from the area (National Park Service 1998:12).

Assess root disturbance. The proximity of large trees and heavy vegetation has likely resulted in disturbance to the intact channel stratigraphy through root activity. While the roots of the large trees surrounding the extant swale may have contributed to disturbance affecting any intact stratigraphy within the extant swale, the deep root structures of mature trees does not likely pose a continuing threat to the integrity of the feature. Continued vegetation maintenance, including removing tree saplings and shrubs that propagate within the swale alignment will mitigate the disturbance of new root systems to intact acequia stratigraphy. Future archaeological testing exposing the swale in profile should include an assessment of disturbance factors, including active root systems.

Mitigate rodent and insect activity. Measures to reduce the damage to the swale caused by burrowing rodents and insects should be developed as a part of a site-wide pest management plan, so that effort to remove pests associated with the acequia do not result in increased pest activity in other equally sensitive areas of the greater Tumacácori unit.

The National Park Service advocates the development of an Integrated Pest Management Plan (IPM) to guide the mitigation of negative impacts of pests and ensure the health and safety of employees and the public. 7 U.S. Code § 136r-1 states:

Integrated Pest Management is a sustainable approach to managing pests by combining biological, cultural, physical, and chemical tools in a way that minimizes economic, health, and environmental risks... Federal agencies shall use Integrated Pest Management techniques in carrying out pest management activities and shall promote Integrated Pest Management through procurement and regulatory policies, and other activities.<sup>3</sup>

Furthermore, the NPS *Cultural Resources Management Guidelines* states: “*Management Policies* (4:13-14) makes clear that dealing with such pests is a balancing act requiring close cooperation between cultural resource and IPM specialists. The goal is always to avoid unacceptable harm to both cultural resources and their environment,” (NPS 1998:49).

Pest control measures should initiate by assessing the range of species present and the size of their populations, as well as behavioral traits such as seasonality. Initial efforts should include treatments that exclude pests, limiting access to sensitive areas, as well as limit potential safety

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<sup>3</sup> Accessed at <http://www.law.cornell.edu/uscode/text/7/136r-1>



issues, such as tripping hazards associated with rodent burrows. Material interventions, such as laying geotextile in archaeologically sensitive areas should be considered only after non-material methods have been tested and evaluated. Consult with National Park Service Integrated Pest Management personnel for further guidance.

## COMPUERTA

Despite minor to moderate loss of historic materials, the compuerta retains its historic form and integrity. While preserved as a ruin, the compuerta functions as the primary interpretive element of the larger acequia feature. Continued maintenance is required to support the stability of the structure and in situ preservation of its historic materials. Structural issues, including cracks and displacement of portions of the brick and mortar walls have developed over time. Vegetation encroachment contributes to and exacerbates overall structural issues. Moderate material losses, including portions of brick, bedding mortar, and plaster finish have occurred since the compuerta was exposed in 1994. The disturbance and deterioration factors outlined in the condition assessment of this report and treatment recommendations are summarized in the table below. Preservation maintenance recommendations have been developed to promote both retention of historic materials and the long-term stability of the feature.

CONDITION	TREATMENT RECOMMENDATION
<b>Structural Deficiencies</b>	
Structural cracks	Fill structural cracks with compatible* repair mortar and monitor for further movement
Open joints	Repoint open joints with compatible* bedding mortar
Wall displacement	Mitigate lateral pressure on compuerta walls by reduction of excess fill at external edges**
<b>Material Loss</b>	
Missing brick	No recommended treatments; reconstruction of lost brick courses with replacement bricks it not necessary for historic integrity
Brick spall, erosion, and melt	Replace lost plaster on interior wall surface in kind to prevent further degradation; consolidate spalling or friable brick surfaces left exposed with compatible agent (to be determined by architectural conservator)
Loss of bedding mortar	Replace lost mortar with compatible* replacement mixture
Plaster erosion	Remove disintegrated plaster; replace eroded plaster with compatible repair coating and surface wash
<b>Vegetation Encroachment</b>	
Vegetation growth in structural cracks, open joints	Remove vegetation; treat area to minimize regrowth in vicinity of compuerta walls; fill cracks and repoint open joints to inhibit in-wall encroachment

<b>Loose Materials</b>	
Spalling Plaster	Consolidate spalling plaster
Loose bricks	Repair or replace lost mortar around loose bricks
<b>Discoloration/Staining</b>	
Soil and salt deposits causing discoloration at the base of both walls	Dry brush surface discolorants; if additional treatments are required, a poultice may be applied; improve surface drainage away from compuerta to reduce prolonged moisture exposure
<b>Biological Growth</b>	
Lichen	Remove lichen from surface, starting with the least abrasive methods such as dry brushing first. Poultice surface if necessary to remove lichen
Moss	Dry-brush surface to remove moss accumulations
<b>Modifications/Repair</b>	
New plaster at southeast corner	N/A

\*Requires assessment of possible effects on archaeological resources (see Appendix A for preliminary testing program).

\*\*See below for notes on replacement material compatibility testing.

### **Recommended Maintenance and Improvements**

Repair structural cracks and gaps. Structural cracks should be cleared of any intrusive material and vegetation (see below) and filled/repointed with an appropriate mortar mixture.<sup>4</sup> Both repaired and unmitigated gaps and cracks should be monitored for further movement and cracking, which would indicate ongoing structural displacement.

Mitigate lateral pressure. Accumulation of fill along the external edges of the compuerta creates lateral pressure on the masonry walls, which may contribute to structural cracking and displacement. To counteract the lateral pressure, the fill along the external edges of feature should be reduced. As the compuerta is an archaeological resource, the fill removal should be preceded by an archaeological assessment to ensure the process will not destroy intact stratigraphy or construction evidence within the acequia. The fill removal should be monitored by an archeologist and screened for associated artifacts.

<sup>4</sup> Compatible replacement mortar should be compatible with the historic mortar regarding the color, texture, compression strength and elasticity. Recent (2012) material analysis testing by Meadors Conservation Inc. was completed to identify components for compatible replacement materials. The results of testing suggest replacement mortar should consist of the following components to ensure compatible color, texture, and compression strength:

- One part Chemstar Type S Hydrated
- Two parts crushed volcanic rock from Tumacácori Mountain
- 1/512 parts Yellow Iron Oxide Pigment- Red Shade (Yellow 6940 Pigment) (Bayferrox 940)

See Appendix C for the full Meadors Conservation Inc. material testing and analysis report.

Repair bedding mortar. Ensure open joints and cracks within the bedding mortar are free of vegetation and pests. Repoint open joints and fill cracks with compatible replacement material (discussed above). New material added during repairs should be structurally and aesthetically compatible with the existing historic materials and appropriately documented.

Consolidate deteriorated or damaged plaster. Assess underlying brick and bedding mortar surface for structural integrity and friability prior to reattaching loose plaster. Consolidate disintegrating or spalling plaster using a lime mortar with similar physical properties to the original plaster.

Mitigation of vegetation encroachment. Vegetation encroachment within cracks and gaps may further exacerbate the structural movement within the compuerta walls. Vegetation established in cracks and gaps should be removed, the immediate site of growth treated to prevent reoccurrence, and regularly monitored for subsequent vegetation encroachment. Vegetation along the edges of the walls should be removed in accordance with Park standards at regular intervals to prevent the introduction of new root systems.

Remove bio-organic growth. Surface cleaning should begin with the least invasive methods possible to address the bio-organic growth, starting with dry-brushing with soft bristled brush in a small patch to assess the impact on the brick and mortar surface. Brick and mortar surfaces should not be cleaned using abrasive brushing or power washing. Firmly adhered lichen may be removed using a poultice, which should be tested in a small patch to assess its impact on historic materials prior to use.

Remove surface discolorants. Pressure test the area of discoloration to ensure structural stability. After ensuring plaster surface is adhered to underlying brick and non-friable, dry brush surface to remove accumulated soil and salts. Should surface cleaning not be sufficient, a poultice may be applied to draw out discolorants. The poultice should be tested in a small area prior to use to assess its impact on the historic materials within the feature. Monitor cleaned area for reoccurrence or expansion of discoloration. Re-grading the surrounding ground surface to divert water away from compuerta will reduce water exposure at the base of the walls through capillary action and prolonged surface exposure, which should aid in limiting discoloration factors.

Improve surface runoff. Drainage patterns for storm water should be assessed and improved to divert surface runoff away from the compuerta. Grading of the ground surface to ensure adequate drainage conditions may be combined with treatments to reduce the lateral pressure on the compuerta walls described above. Any ground disturbance within or adjacent to the acequia should be assessed for impacts on the archaeological resources. Diversion of storm-water runoff will reinforce other preservation treatments associated with counteracting water exposure-related degradation.

## BURIED ACEQUIA ALIGNMENT<sup>5</sup> REHABILITATION

A recent ground penetrating radar (GPR) investigation has provided new information on the location of the buried acequia alignment, which was previously documented primarily through historic aerial photos (see “Locating the Acequia” within this report). The GPR analysis provided approximate dimensions and depth below the modern ground surface, in addition to the location of segments of the alignment within the landscape. The historic acequia contributes to the significance of the mission cultural landscape preserved within the Park. As such, increased visibility of the feature within the broad cultural landscape and increased opportunities for interpretive experiences for Park visitors is desired.

Recommended treatments and alternatives outlined below address the need for increased visibility while encouraging active stewardship of the buried archaeological resources associated with the acequia. The recommendations are integrated with ongoing efforts within the Park to revegetate areas of the landscape affected by social trails and old road traces. As part of ongoing renewal of natural resources in the park, rehabilitation treatments for the cultural landscape associated with the buried acequia alignment are outlined below. The Secretary of the Interior defines rehabilitation as “the act or process of making possible a compatible use for a property through repair, alterations, and additions while preserving those portions or features that convey its historical, cultural, or architectural values,” (National Park Service 2001).

Rehabilitation treatments primarily involve reducing vegetation along the buried acequia alignment through maintenance, as well as through increased foot traffic. When integrated with revegetation of the surrounding landscape, the rehabilitation of the acequia alignment will improve the visibility of the location of the buried alignment within the landscape and will increase opportunities for Park visitor interaction with and awareness of the feature. While the linear nature of the feature will be highlighted, the historic channel should not be reconstructed or restored. Buried archaeological resources associated with the channel should be preserved in situ.

The recommendations outlined below reflect the initial implementation for the rehabilitation of cultural landscape associated with the acequia and development of an interpretive trail. Implementation of landscape rehabilitation and trail development should coincide with the development of user capacity standards to monitor the effects of maintenance and use of the associated natural and cultural resources. The current Tumacácori National Historical Park General Management Plan describes the objectives and process of developing such standards: “(u)ser capacity decision making is a form of adaptive management...in that it is an iterative process in which management decisions are continuously informed and modified. Indicators are monitored, and adjustments are made as appropriate. As monitoring of conditions continues, managers may decide to modify or add indicators if better ways are found to measure important changes in

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<sup>5</sup> The buried acequia alignment refers to the portion of the feature that has been covered due to grading and other ground modification activities, located both north and south of the compuerta and visible swale. For the purposes of this report, the extent of the buried acequia alignment refers to the portion of the alignment that has been tested in the 2013 GPR survey, unless noted otherwise.

resource and social conditions,” (2011:76). Thus, standards developed prior to implementation of landscape rehabilitation and trail use should be reviewed and revisited as anticipated and unanticipated effects of treatments are monitored.

## **RECOMMENDED MAINTENANCE AND IMPROVEMENTS**

### **Implement Acequia Vegetation Maintenance Plan and Trail Development**

In 2013, the open area directly north of the compuerta and paved trail was partially reseeded as part of a larger effort to increase vegetation cover within parts of the Park. Shallow-rooted grasses and wildflowers were chosen for this area to limit the effects of root activity on the buried archaeological resources associated with the acequia. A 2013 Grounds Maintenance Plan (Welborn 2013) outlines the Park’s preferred actions to increase the visibility of the acequia within the revegetated landscape to the north of the compuerta. Within this plan, vegetation maintenance parallels the designation of the acequia alignment as an unpaved pedestrian trail. The stretch of trail following the acequia alignment to the north of the compuerta would act as a connector to the established Anza Trail that extends westward into the Park near the northern orchard wall. The acequia alignment to the south of the compuerta offers less interpretive opportunities and intersections with other Park features and is not recommended for inclusion in the trail development at this time. The area to the south of the compuerta could be developed in the future, should the popularity of the trail warrant expansion and Park staffing permit.

Prior to trail development, the GPR results should be ground-truthed through limited archaeological testing in collaboration with a geomorphologist. Testing should confirm the location, average dimensions, and depth below the modern ground surface, all information critical to assess the potential effects and development of the interpretive trail. A preliminary archeological research design is included in Appendix A.

Additional reseeding (or introduction of plugs) should be conducted in consultation with staff from the Sonoran Desert Network to identify biologically and historically appropriate species that can be introduced into the portion of the landscape associated with the acequia. Initial consultations with Sonoran Desert Network staff suggests panic grass (*Panicum*) and tobosa grass (*Pleuraphis mutica*) may be appropriate species for consideration. The level of effort required from Park personnel to maintain ideal conditions should also be considered prior to selecting additional species for reseeding.

Vegetation Maintenance planning should identify exotic, invasive, or otherwise inappropriate species, as well as methods for their removal and prevention within the vicinity of the acequia. Consultation with the Sonoran Desert Network staff should include suggestions for a vegetation monitoring schedule and proper removal procedures for unwanted species.

The 2013 Grounds Maintenance Plan outlines vegetation maintenance procedures for the proposed trail alignment to the north of the compuerta. The designated portion of the acequia alignment developed as a trail should be kept free of vegetation through regular mowing, weed-trimming, and pedestrian traffic. The corridor should be delineated annually by Resource Management personnel prior to the summer rainy season (Welborn 2013:5-6). Initial maintenance plans developed prior

to implementation should be reviewed as both effective and ineffective strategies are identified during the course of implementation.

While trail development along the acequia alignment south of the compuerta is not recommended at this time due to staffing limitations, similar preservation maintenance strategies should be employed to maintain the archaeological integrity of this feature. This includes regular vegetation maintenance to reduce root disturbance, along with use of plant species with low-impact root systems for any future vegetation restoration, within the vicinity of the acequia alignment to the south of the compuerta.

Trail development and implementation should incorporate strategies that limit hazards to the public and adverse effects on Park resources. Initial strategies include maintaining a buffer zone on the periphery of the trail to limit exposure of Park visitors' and staff to hidden wildlife, such as snakes. Further, the fine floodplain sediments that may be exposed on the trail alignment could become slick and muddy during rains. Muddy conditions could render the trail hazardous and potentially adverse effects on the shallowly buried channel could be sustained by pedestrian or small vehicular traffic during muddy conditions. In addition to considering drainage patterns along the trail alignment, the feasibility of preparing the trail with gravel or decomposed granite should be assessed to reduce the potential for muddy conditions (see Alternatives below).

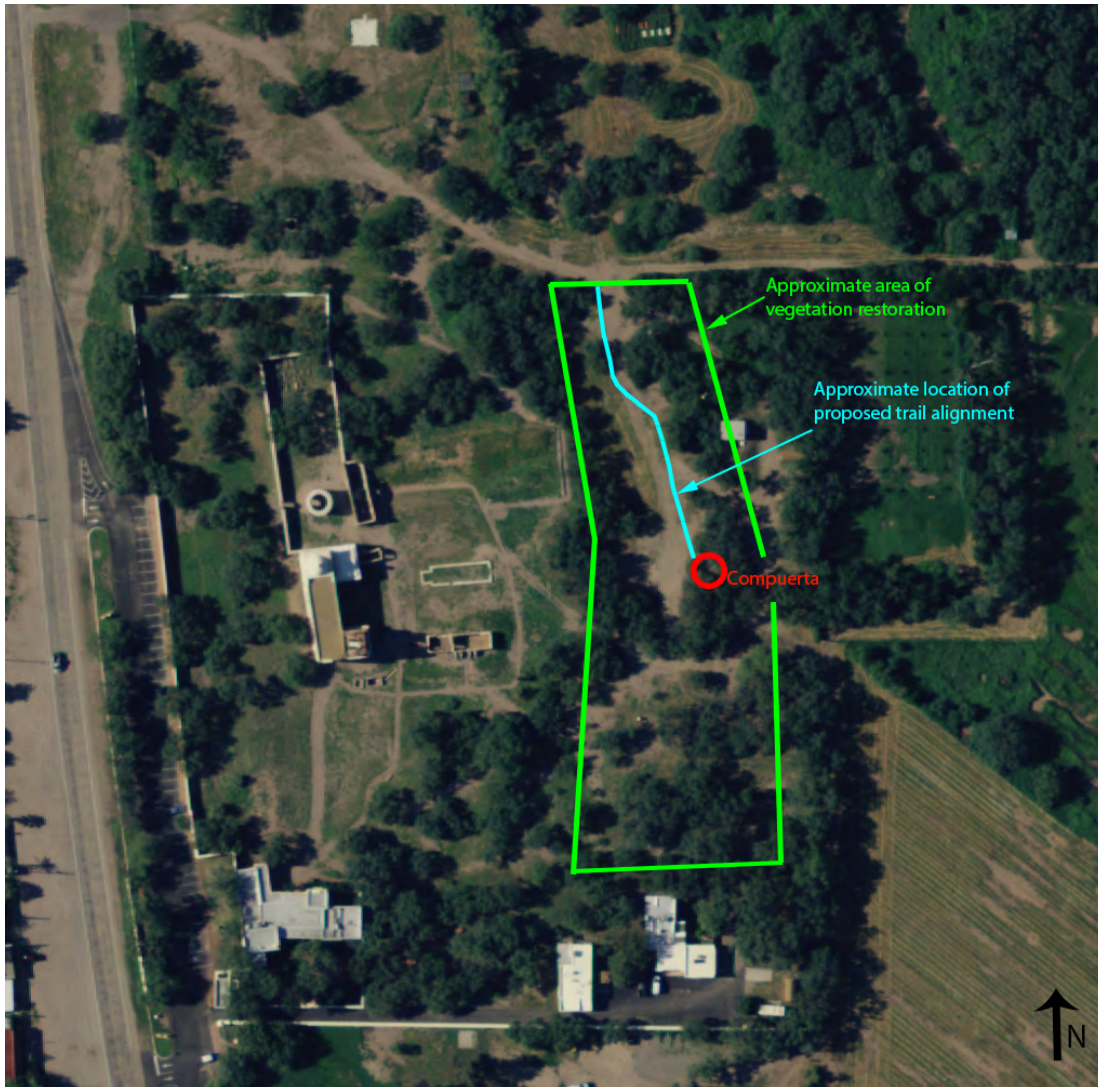


Figure 5.1. Overview of general area within the Park included in recommended cultural landscape rehabilitation. The area delineated in green represents the reseeding area associated with the acequia; the blue line represents the approximate location for the portion of the acequia alignment recommended for development as an interpretive trail.

### **Reduce the over-grown vegetation understory**

Revegetation efforts have introduced shallow-rooting grasses and wildflowers, which are designed to aid in increasing biological diversity and in the restoration of historic landscape conditions within the Park. To supplement the restoration of historic landscape conditions, the thick understory of shrubby vegetation that has accumulated among the mature trees surrounding the acequia alignment should be thinned. Removal of the understory within the vicinity of the acequia trail alignment will allow for greater visibility of other significant resources within the landscape, including the church and restored orchard. Regular removal of understory accumulation should be incorporated into the vegetation maintenance plan associated with the acequia.

### **Develop and Install Signage**

In order to inform Park visitors about the significance of the buried acequia alignment, as well as the archaeological sensitivity, appropriate signage and trail waysides should be developed and installed along the developed trail. Signage should orient Park visitors to the broad cultural landscape and provide information on the construction and use of the acequia, including its role in the lifeways of the mission community. Signage should also include information that informs visitors of the landscape rehabilitation, and the role that their presence on the trail plays in those efforts. Such information could include not only an explanation of why the trail was developed but also information on the surrounding vegetation involved in the landscape restoration.

Signage could be provided in critical locations to emphasize significant elements and relationships between key features on the landscape. Signage at the southern end of the trail alignment could emphasize the compuerta and the relationship of the acequia with the orchard. Signage at the north end could provide information on the acequia's function and water source, as well as direct attention to the view of the church to the west, illustrating the relationship of features within the landscape.

### **Monitor and Mitigate Erosion and Other Human Impacts**

Reduction of vegetative ground cover and increased pedestrian traffic associated with the development of an interpretive trail along the acequia alignment will increase the risk of top soil erosion. The top soil currently aids in the protection of the buried elements including channel berms and intact stratigraphy. The trail alignment should be monitored for erosion following a regular schedule that considers the local environmental and climate patterns (such as rainy seasons). See Alternatives for Treatment below for further discussion.

Increased pedestrian traffic may have additional impacts on the buried acequia alignment. Foot traffic could increase compaction, affecting the underlying acequia stratigraphy and increased use could expose the feature to vandalism.

The trail alignment should be inspected regularly for adverse impacts of its use. Maintenance and preservation treatments should be reevaluated based on such inspections.

### **Pest Management**

While not closely inspected for active insect and rodent burrowing at the time of the condition assessment, the buried acequia alignment, like the extant swale, is vulnerable to the destructive effects of bioturbation. A specific site-wide pest management plan should integrate measures to protect the portion of the acequia alignment that has been recorded within the 2012-2013 GPR investigation.

### **Integrate Recommendations into a Cultural Landscape Report**

The information in the Grounds Maintenance Plan (Welborn, 2013) as well as the landscape rehabilitation recommendations outlined above should be integrated into a Cultural Landscape Report (CLR) that considers the broad cultural landscape within the Tumacácori Unit of the Park. Further, a Draft Cultural Landscape Inventory (CLI) has been completed for the Park, but not finalized as of the completion of this report. The information and recommendations outlined in this



report should be integrated into the sections associated with the acequia in the CLI prior to its final submittal.

## **ALTERNATIVE TREATMENTS**

Because the development of an interpretive foot trail along the acequia alignment may result in adverse effects to the buried feature elements, mitigation strategies and alternative treatments should be considered in consultation with the State Historic Preservation Office as part of compliance with Section 106 of the National Historic Preservation Act.

### **Alternative A – Additional Top Soil**

In this alternative treatment, the recommendations for vegetation maintenance, trail use, and monitoring outlined above would be implemented with an additional treatment: in order to decrease the possible adverse effects associated with erosion and compaction, additional top soil or decomposed granite could be added over the modern ground surface along the alignment to provide an added layer of protection against wind and water exposure, as well as the effects of increased exposure to human use and foot traffic.

### **Alternative B – Offset Walking Trail**

As reduced ground cover and increased foot traffic may increase the risk of erosion, potentially resulting in adverse effects to shallowly buried acequia stratigraphy, the trail could be offset from the actual acequia alignment. However, the impact of root systems that result from vegetation restoration alongside the trail alignment would still need to be considered and adverse effects to the buried acequia stratigraphy would need to be avoided or mitigated using an alternative to trail development, including using shallow-rooted plant species and periodic vegetation maintenance to remove unwanted species from the area of the acequia alignment.

## **TREATMENT OPTIONS AND CONSIDERATIONS**

The recommendations outlined above were developed in consultation with the Park to address various needs: to integrate preservation with maintenance activities associated with the area around the acequia alignment, to increase the visibility of the acequia within the landscape, and to provide initial plans for increased interpretation of the acequia to the public. The recommendations incorporate Park plans that have been initiated prior to the completion of this report, including the vegetation restoration and maintenance activities that were outlined in the 2013 Grounds Maintenance Plan. Further, the recommendations reflect an attempt to improve visibility and public awareness of the significance and historic conditions of the acequia, while preserving the archaeological integrity of the feature. As such, options that include significant disturbance of the buried stratigraphy, such as restoration of water carrying capabilities, were not considered.

The option of extending the interpretive trail to the south of the compuerta was considered and rejected due to the limited size of the current maintenance staff. Further, the section of the acequia alignment to the north of the compuerta was found to have more potential for connecting with other features within the Park, including the restored orchard and the De Anza Trail. Should staffing

levels be increased and the popularity of the acequia trail warrant its extension to the south of the compuerta, this option should be reconsidered.

**PART FIVE**  
**SUMMARY AND CONCLUSIONS**

## SUMMARY AND CONCLUSIONS

This report has compiled a large body of historical and empirical information associated with the historic acequia at Tumacácori National Historical Park. The primary objective of this compilation is to provide a foundation for informed planning and preservation activities, as well as develop potential avenues for further research and interpretation. The following section provides a summary of the conclusions and recommendations that have been developed in the main body of the report.

The significance of the historic acequia as a contributing, but underrepresented, feature within the cultural landscape associated with the Park has prompted an increase in interest and activity intended to gain a better understanding of the feature. Several themes have emerged through the review of the historical background and archaeological investigations within the Park that are especially relevant to the interpretation of the feature. Such themes include:

- **The Importance of Water-** The availability of water was vital to the success and survival of the mission community, as well as to their predecessors and successors within the Santa Cruz River Valley region. As a conduit for such a critical resource, the acequia would figure as a focal point for many activities within the mission community.
- **Irrigation Technology-** The Santa Cruz River Valley ecosystem has supported a variety of irrigation technologies that span millennia between the Late Archaic Period (circa 2100 B.C. to A.D. 50) and the present day. The historic acequia provides a springboard for a discussion of the irrigation technology represented at the site and in the Santa Cruz River Valley as a whole.
- **Connection to the Larger Landscape-** The linear nature of the feature has been largely obscured by intervening land modification and changes within the landscape. Increasing the visibility of the acequia within the landscape offers an opportunity to boost engagement with the feature and increase connectivity with other features within the Park. Utilizing the linear acequia alignment as a pedestrian trail within the Park would allow visitors not only improved opportunities to conceptualize the feature as a whole but also to connect to other Park features, such as the De Anza trail.

Recent archaeological and geophysical testing completed to document the location and morphology, as well as initial information regarding the condition of the buried acequia alignment, have provided valuable data. However, the ephemeral nature of the acequia alignment, combined with inconsistent feature attributes (including the varied stratigraphic profiles and reflection profiles within the tested area), suggests further research should be completed to address inconsistencies in results. Initial questions that reflect data needed to address preservation issues and increase opportunities for interpretation include:

- Are the GPR results accurate in terms of the location of the alignment and the depth of the channel below the modern ground surface?

- What conditions account for the variability or absence of detectable geophysical data? Similar physical properties among channel deposits and the surrounding sediment? Significant disturbance?
- Are channel deposits intact? If so, can different use-episodes be identified?
- Are different sedimentation patterns identified between the north and south sides of the compuerta consistent? If so, are such patterns the result of intentional water control measures such as a head gate in the compuerta?
- Are channel berms intact? If so, is there evidence of canal maintenance?
- Is the acequia alignment identified in aerial photographs and in GPR reflection profiles associated with Mission-period construction and use? Are there earlier or later iterations that reflect different generations of the channel?

While a large portion of the feature is buried, the compuerta and the extant portion of the swale that extends north and south from the compuerta, remain exposed at the modern ground surface. The extant swale and compuerta are both in fair condition with evidence of minor to moderate disturbance or deterioration. Deterioration factors require preservation maintenance be completed within a reasonable time frame to prevent loss of integrity.

Disturbance factors affecting the extant swale consist primarily of bioturbation, with evidence of active rodent and insect disturbance. Vegetation encroachment suggests that there is potential for root disturbance as well. Human impacts consist of a dirt road trace constructed over the southern end of the swale, as well as disturbance associated with archaeological investigations in the 1990s. Additional disturbance from human impacts, including the construction of an ADA-accessible trail across the alignment and the archaeological testing that was completed prior to its construction, have affected the buried portion of the acequia alignment beyond the extant swale.

Deterioration and material loss due to weathering and structural movement were observed within the compuerta. Structural displacement may be a result of lateral pressure exerted by the surrounding sediment. Vegetation encroachment has occurred within structure cracks, while biological colonization has occurred on the brick, mortar, and plaster surfaces.

The recommended treatment for the swale and compuerta, which continue to function as the primary interpretive features associated with the acequia, is preservation. Preservation maintenance recommendations for the swale include development of an Integrated Pest Management Plan that coordinates with other features within the Park unit. Vegetation encroachment may be mitigated by removing saplings and shrubs that have taken root within the swale and by thinning the understory within the surrounding area. Further assessment of the impact of root activity associated with surrounding trees should be completed alongside future ground disturbing activity within the vicinity of the acequia, including future archaeological testing.

Treatment recommendations for preservation maintenance on the compuerta include mitigation of lateral pressure exerted by the surrounding bermed sediment and improvement of drainage paths for surface runoff. Removal of intrusive bio-organic and vegetative growth from the surface materials and structural cracks should be completed in preparation for repair of material loss, structural cracks, and surface deterioration. Repair mortar and plaster should be aesthetically and

structurally compatible with the historic materials used to construct the compuerta. Repair materials should be developed in consultation with the results of material analyses conducted by Meadors, Inc. in 2012 (the full report is included in Appendix C).

In order to increase the visibility of the acequia on the landscape and expand interpretation opportunities, as well as reduce vegetation encroachment, this report recommends rehabilitation of the buried acequia alignment. Recommendations outlined for rehabilitation integrate ongoing landscape restoration and grounds maintenance activities within the Park, coordinating with the 2013 Grounds Maintenance Plan. Reseeding of the areas to the north and south of the compuerta has been completed, increasing the density of shallow rooted ground cover within the area. This report recommends that reseeded activities continue, in consultation with ecologists from the Sonoran Desert Network. Consultation should identify additional appropriate species that add to the historic integrity of the landscape, as well as invasive or unwanted species and appropriate removal guidelines.

As part of the rehabilitation of the buried acequia alignment, this report recommends periodic vegetation maintenance that will delineate a clear path reflecting the location of the buried alignment. This will increase the overall visibility of the feature without direct disturbance of buried stratigraphy. The acequia alignment to the north of the compuerta should be developed into a pedestrian trail that incorporates interpretive signage that orients visitors to the significance of the feature and the activities involved in its preservation. Trail development to the south of the compuerta is not recommended at this time, given the current staffing levels, though periodic vegetation maintenance should be completed in this area. The feasibility for extending the trail south of the compuerta should be reassessed after the northern portion is in place.

Rehabilitation of the buried acequia alignment will require further research to confirm and expand on the results of initial geophysical and archaeological work documenting the location of the feature. A preliminary design for future research is included in Appendix A. Additionally, the potential effects of the trail development on the buried acequia alignment will need to be considered prior to, and periodically after, implementation.

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## **APPENDICES**

## APPENDIX A

### PRELIMINARY DESIGN FOR FURTHER RESEARCH ON THE ACEQUIA

The synthesis of past research and current conditions of the historic acequia provide a baseline for assessing deficiencies in existing data and opportunities for further investigation. This assessment shows that archaeological testing is required to inventory and document the subsurface condition and integrity of the acequia and to ensure accurate data is being interpreted to the public (via the proposed interpretive trail alignment). Several additional objectives of testing include further clarification of past research results, as well as the assessment of the potential effects of proposed preservation treatments and landscape rehabilitation. The testing requirements offer an opportunity to collect additional data associated with a wide range of research questions addressing the technology, use, and maintenance practices associated with the acequia. Such information may add to an understanding of the Colonial-period lifeways and subsequent reuse of the site.

Initial consultation with geomorphologist, Fred Nials, resulted in an extensive outline of research objectives and primary methods for investigation. This preliminary design for further research is based on questions and methods provided by Nials in consultations with Park personnel and Drachman Institute staff. The information outlined below should be integrated into a formal research design and treatment plan prior to further testing of the acequia.

#### RESEARCH ORIENTATION

Additional data are needed to confirm the location and condition of the buried acequia alignment are needed to proceed with recommended preservation treatments and interpretive trail development, the proposed archaeological testing plan includes destructive methods. Thus, it is critical to maximize the information gained from testing efforts. Several broad research themes and associated questions are outlined below that will guide the data collection.

#### Geological/geomorphic context

The geological setting of the mission site likely played a role in the site's selection and layout. The success of irrigated fields was contingent upon adequate availability of flood waters and surface flow within the Santa Cruz River. Further, erosion and deposition patterns from flooding and valley side runoff affect the integrity of the floodplain stratigraphy and the historic features buried within it. A comprehensive assessment of the geomorphic context will inform interpretations of past research results, guide the placement of archaeological test units, and provide needed context to investigate the remaining broad research questions.

Questions to be addressed include:

- What geological or geomorphic factors were involved in construction of the acequia?
- What are the primary formation processes affecting the acequia?
- How does the modern topography compare to the Colonial-period ground surface?
- What were environmental conditions during the construction and use of the acequia?
- How did irrigation affect the local environment (i.e. salinization, argilization, piping, nutrient depletion of soils)?

### **Location and design of irrigation system**

A ground penetrating radar study was completed for a section of the acequia madre between 2012 and 2013. Additional testing offers an opportunity to not only confirm but also expand on the results of this study. Historic documentation from other Colonial Period mission irrigation systems suggest that there is additional irrigation and field infrastructure beyond the acequia madre, most likely extending toward the Santa Cruz River (Bossler and Johnson 2012:89, see also Part One of this report).

While extensive plowing has graded the ground surface, it is unclear whether such ground disturbing activity completely destroyed the Colonial period irrigation infrastructure. High resolution topographic data can provide information regarding remaining patterns associated with buried historic irrigation infrastructure.

Questions to be addressed include:

- Does the location of the buried acequia alignment correspond with the mapped alignment produced by geophysical testing?
- Are lateral and distribution canals preserved? Are individual fields preserved?
- Does the design of the irrigation infrastructure reflect patterns associated with other Pimeria Alta colonial communities?

### **Construction, maintenance and use of the acequia madre**

Historic documents describing water use negotiations between the mission community at Tumacácori and the presidio of Tubac suggest that the acequia system was constructed by 1777 (Bossler and Johnson 2012:26). However, records that describe the construction of the irrigation infrastructure are lacking. Stratigraphic profiles (that include bank/berm deposits) have the potential to yield significant information reflecting the construction techniques, preparation of channel base and banks, functionality and use-episodes, maintenance practices, and associated environmental conditions. Furthermore, it is unclear whether the acequia channel was reused and/or remodeled during the course of the Colonial period and subsequent occupations of the site.

Questions to be addressed include:

- When was the acequia constructed?
- How was the acequia constructed?
- Is there evidence of preparation and/or maintenance? Can the frequency of maintenance activities be discerned?
- Is there evidence for remodeling or reconstruction episodes?
- Was the acequia modified during subsequent occupations of the site?

### **Cultural influences**

The mission community was characterized by cultural diversity. Specific canal traits, artifacts encountered, and age of use episodes can provide information about the cultural influences on the construction and use of the acequia. Historical records from Tumacácori and other Pimeria Alta missions may supplement the archaeological evidence in determining cultural traditions involving irrigation practice.

Questions to be address include:

- Is there evidence of irrigation at the site prior to the Colonial period?
- Are there morphological traits associated with the compuerta that correspond to historic and/or ethnographic data associated with a particular cultural group?

- Were different technologies and/or maintenance and use practices employed over time?
- Is there a relationship between the site topography, the dog-leg turn in the acequia alignment within the garden area, and the 45-degree angle of the northwest corner of the garden wall where the acequia leaves the garden area?

### **Chronology**

Several of the research questions presented above are contingent upon reconstructing temporal chronologies. Chronological data may be obtained through both relative and absolute means. In situ temporally diagnostic artifacts may be used to date the specific contexts in which they are found, providing relative temporal data for surrounding deposits. Absolute dating methods, including radiocarbon and archaeomagnetic dating can provide finer sequences for specific contexts. Chronological data will be critical should several iterations or remodeling episodes associated with the acequia be observed.

### **METHODS**

Due to the ephemeral nature of the acequia and its associated stratigraphy observed in previous research, further investigation and analysis should be conducted in collaboration with a geologist, geomorphologist, or geoarchaeologist.

#### **LIDAR mapping of site topography**

A high-resolution digital elevation model of the site can be produced using LIDAR. Patterns identified in the topography of the site may reflect extant irrigation infrastructure and can be investigated further through additional test excavation or non-destructive geophysical sensing methods.

#### **Test unit excavation**

In order to reconstruct the Mission-period ground surface associated with agricultural activities, a series of small test units should be excavated over a portion of the agricultural area within the site. Nials estimates that eight to ten units would be needed to document the paleosol associated with the Colonial period occupation of the site.

Burton's 1994 Unit 6 and Moss and Burghardt's 2012 Trench 2 (see Part Two of this report for descriptions) should be reopened and assessed by the project geomorphologist.

Four to five additional backhoe trenches should be widely spaced along the buried alignment in profile. The location of new test units should be determined by the project geomorphologist after an assessment of erosion and deposition patterns affecting the integrity of the site and feature is assessed. Ideally, the backhoe trenches should expose the full acequia channel, including preserved bank deposits, and a representative sample of the associated floodplain stratigraphy. Some backhoe trenches may be excavated beyond the known location of the acequia channel in order to assess or rule out the possibility of multiple iterations or reconstruction episodes.

An additional test unit should be placed on the exterior edges of both compuerta walls to expose the surrounding stratigraphy prior to preservation maintenance treatments outlined in Part Five of this report.

Geomorphic profiles of the floodplain stratigraphy, as well as feature profiles of the buried channel should be completed for each test trench. Profiles should be drawn by or in close consultation with the project geomorphologist or geoarchaeologist to ensure accurate and adequate detail is

included. Profiles should include description of sediment color, texture, compaction, and inclusions as the information would be a primary source of data used in analysis.

### **Sampling**

Soil samples for texture analysis and ostracod content should be collected by or in consultation with the project geomorphologist. Curated samples collected during previous investigations may be used in lieu of collecting new samples from the reopened units. Texture analysis and ostracod content would contribute to the reconstruction of water sources and rate of flow within the channel.

Radiocarbon samples could be collected on a judgmental basis from appropriate contexts to provide absolute dates for specific strata or identifiable use-episodes. If heavily burned or oxidized surfaces are identified within the acequia, archaeomagnetic dates could be obtained. The feasibility for thermoluminescence dating of buried sediments and location of appropriate sample contexts within the acequia stratigraphy should be assessed by the project geomorphologist. The location of all samples should be documented to allow for future reconstruction of the sample's context.



## APPENDIX B

### GROUND PENETRATING RADAR STUDY REPORT

#### Ground-penetrating Radar Mapping and Interpretation, Acequia Project Tumacácori National Historical Park, Arizona

March 19, 2013

Minor additions and modifications July 5, 2012

**Produced for:**

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**Introduction**

The purpose of this project was to map the historic acequia (irrigation canal) at the site, which is visible in a few locations at the site. Associated with this canal is a compuerta (weir) that is still visible on the surface and some linear depressions and tree alignments, which are likely showing the location of the canal. Ground-penetrating radar (GPR) is a geophysical method that has been shown to be excellent for this type of mapping elsewhere in Arizona (Conyers 2012).

Two sets of GPR data were collected. One grid of data was collected on Dec. 3, 2012 as a way to provide a first test the method and also to map the canal system in preparation for planting that was scheduled for the next day. A report on that project was sent to Jeremy Moss on January 4, 2013. The results of that pilot project showed that the canal was visible in many reflection profiles, but not all of the data. The canal fill appeared to be poorly differentiated from the surrounding sediment in some areas, and therefore was less visible in reflection profiles. Elsewhere the canal was very visible, probably clay was preserved in the channel and produced a distinct reflection surface.

A second set of GPR reflection data were collected on March 11, 2013. Four grids of data were collected at the direction of Jeremy Moss. Help in acquisition was provided by Andrew Perew and Alyssa Cunial from the University of Arizona. The reflection data in both surveys were collected using the GSSI SIR-3000 system with a 400 MHz dipole antenna. Grids

were laid out with tape measures and grid corners were identified with metal pins and nails with pink flagging tape for later surveying into the site grid system. All reflection data were placed into space using a survey wheel encoder device attached to the radar antennas. The corners of all grids were also measured to permanent landmarks as a back-up. These data were processed in several different ways to yield horizontal amplitude slice maps and vertical linear profiles. Amplitude slice maps allow for spatial analysis of buried materials in plan view, while profile analysis aids in determining vertical structure of layers in the ground, materials within those layers and their depth. The location of the 4 grids is shown in Figure 1. Grid 3 in this map is almost the same location as the single grid collected on Dec. 3, 2012. All grid corners were surveyed into space and the grid corner nails still remain visible as of July, 2013 (Jeremy Moss personal communication July 3, 2013).



**Figure 1:** Location of the GPR grids at the site. Grid 3 is in the same location as the single grid of data collected in Dec. 2012.

### **GPR: Use and Background**

Ground-penetrating radar data are acquired by transmitting pulses of radar energy into the ground from a surface antenna, reflecting the energy off buried objects, features, or bedding contacts and then detecting the reflected waves back at the ground surface with a receiving antenna. When collecting radar reflection data, surface radar antennas are moved along the ground in transects within a surveyed grid and a large number of subsurface reflections are collected along each line. As radar energy moves through various materials, the velocity of the waves will change depending on the physical and chemical properties of the material through which they are traveling (Conyers 2013, 2012). The greater the contrast in physical, electrical, and magnetic properties between two materials at an interface, the stronger is the reflected signal, and therefore the greater the amplitude of reflected waves. When travel times of energy pulses are measured, and their velocity through the ground is calculated, distance (or depth in the ground) can be accurately measured (Conyers and Lucius 1996). Each time a radar pulse traverses a material with a different composition or water saturation, the velocity will change and a portion of the radar energy will reflect back to the surface and be recorded. The remaining energy will continue to pass into the ground to be further reflected, until it finally dissipates with depth. The success of GPR surveys in archaeology is largely dependent on soil and sediment



mineralogy, clay content, ground moisture, depth of burial, surface topography and vegetation. Electrically conductive or highly magnetic materials will quickly attenuate radar energy and prevent its transmission to depth. The best conditions for energy propagation are therefore dry sediments and soil, especially those without an abundance of clay. The presence of mineralogical clays or salts in soil can attenuate radar energy very quickly, which affects how deep the energy can potentially resolve features of interest. In the area surveyed, the relatively dry sand and silt was found attenuate energy below about 1.2 meters, which was sufficient to resolve the historic canal. Resolution was moderate, with interfaces about 3-4 cm in thickness visible in many profiles, as long as there was sufficient chemical and physical difference between the layers. For example, interfaces where clay and either sand or silt are found are good at reflecting radar energy; probably because the clay retains moisture and the coarser grained sediments do not. It is the water retention differences that provide the differences, producing reflections (Conyers 2012). If these layers contained more similar percentages of retained water, the difference in reflection would be less, and therefore these units would be less visible with GPR.

### **Processing Procedures**

The initial data processing involved the generation of amplitude slice-maps (Conyers 2013, 2012). Amplitude slice-maps are a two-dimensional tool for viewing differences in reflected amplitudes across a given surface at various depths. Reflected radar amplitudes are of interest because they reflect the degree of physical and chemical differences in the buried materials. Strong, or high amplitude reflections often indicate dense buried materials, such as solid rock foundations or other historic features. Amplitude slice-maps are generated through comparison of reflected amplitudes between raw vertical profiles. This allows for spatial mapping and three-dimensional interpretation of radar data. These maps were good at mapping a portion of the canal in Grid 3 but had almost no utility in the other study areas for reasons discussed below.

In the amplitude map method, wave strengths (as measured by amplitude values) are recorded as digital values and analyzed at each location in a grid where there is a reflection recorded. The amplitudes of all traces are compared to the amplitudes of all nearby traces along that profile and between adjacent transects. A map is then produced that shows amplitudes in map view, but also with depth in the ground. The database can then be “sliced” horizontally and displayed to show the variation in reflection amplitudes at a sequence of depths in the ground. Often when this is done changes in the soil related to disturbances such as digging can become visible, making many features visible to the human eye as color changes in map view. Using the computer program *Surfer 9*, grid files were created and the data interpolated using the Minimum Curvature method. From the original .dzt files (raw data), a series of image files were created for cross-referencing to the amplitude slice maps that were produced.

Slicing of the data generally begins with the reversal of even numbered profiles, to compensate for the data collection technique. This is needed because the data are collected while moving up and back along transects. Since every other line is collected in the opposite direction, reversal is necessary prior to mapping the data. Following profile reversal, our protocol requires the creation of .xyz files. This step creates a Cartesian coordinate grid into which the data are eventually incorporated. The final step is the actual generating of amplitude slice-maps. Amplitude slice-maps are created in a program called *GPR Process* and saved in ASCII text

format. This is a three column text file containing X, Y, and amplitude value information. The Z coordinate for every point in a single file is the same, because each file represents a discrete depth unit. One text file is created for each grid at every depth that is sliced.

After slicing, the data are imported into *Surfer 9* where the areas between the regular grids of known values are statistically interpolated. Interpolation involves any of a number of techniques used to estimate an unknown value in a continuous dataset using the known values of nearby points. This is used to estimate points that lie between transects. The primary assumption in continuous data sets is that points close together will be more similar than those farther apart.

Following spatial interpolation, the data were rendered into horizontal slice maps depicting reflection intensity as a continuum of rainbow colors (ROYGBIV). The ROYGBIV scale begins with violet and white for low reflection amplitude and progress through the visual spectrum to red for very high intensities. To illustrate a greater contrast in physical, electrical, and magnetic properties between two materials at an interface, white was substituted in for violet; therefore, white represents the lowest reflections or no reflection at all. Because the intensities depicted on these maps are relative to the data in each grid, the colors do not indicate specific intensities, but rather a relative span from low to high.

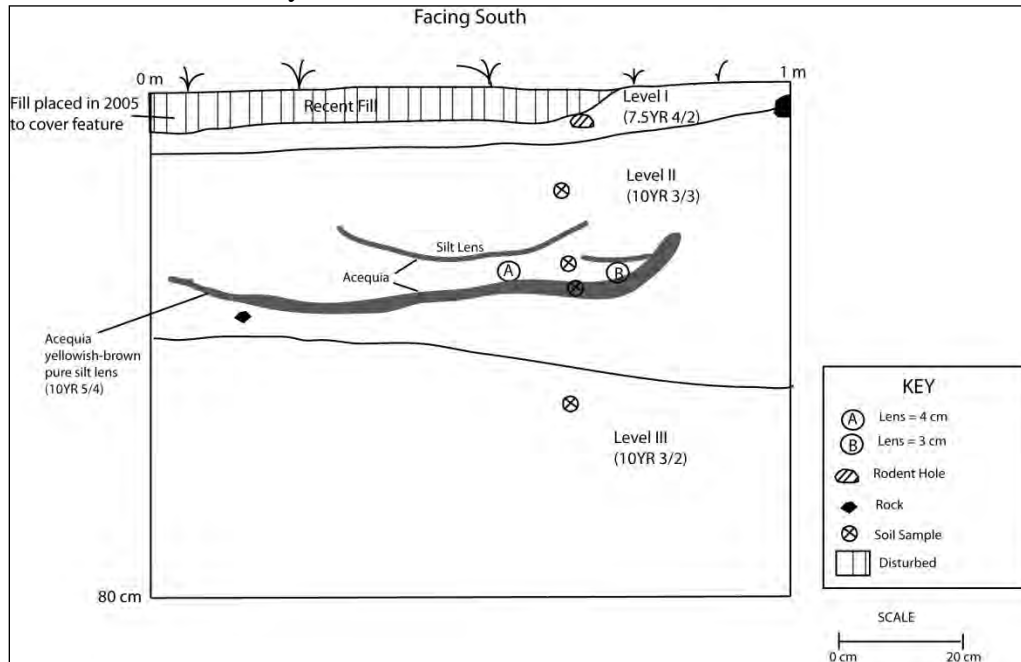
There are several criteria established as a rubric for the identification and classification of subsurface features at the site. Maps were considered in isolation and anomalous high and low intensities were selected for further investigation. The assumption being, that those intensities at or around the measures of central tendency of the data, represent site matrix and undisturbed stratigraphy. On the other hand, areas of anomalous high and low intensities are indicative of something intrusive in the ground that is different from the “background”, or matrix of the site. In addition, the radar profile through the potential feature had to show a truncation of horizontal stratigraphy over depth.

While amplitude-slice maps are a valuable aid in data interpretation, they are not always definitive. This was especially the case here as the amplitudes collected came from not only the canals, but from sediment along their edges, buried utilities, trash and debris dumped in this area in the past, and complex stratigraphy in general. For this reason all reflection profiles in all grids (a total of 154 profiles) was viewed and interpreted in two-dimensional vertical profiles. These interpretations were then correlated with the amplitude maps, which proved useful in some cases. For the most part it was a manual interpretation of the profiles that was best suited for mapping this irrigation canal.

It was also found after the March 2013 data were collected that there were a number of differences in reflection contrasts between those profiles and the ones collected in December 2012. The two grids of data were then overlaid and all profiles could be compared and contrasted.

Excavations of one canal area just south of the compuerta showed that there were only subtle variations in soil types, and no evidence of “clean out” sediments on the canal margins (Figure 2). This excavation information does not discuss detailed sediment types in this

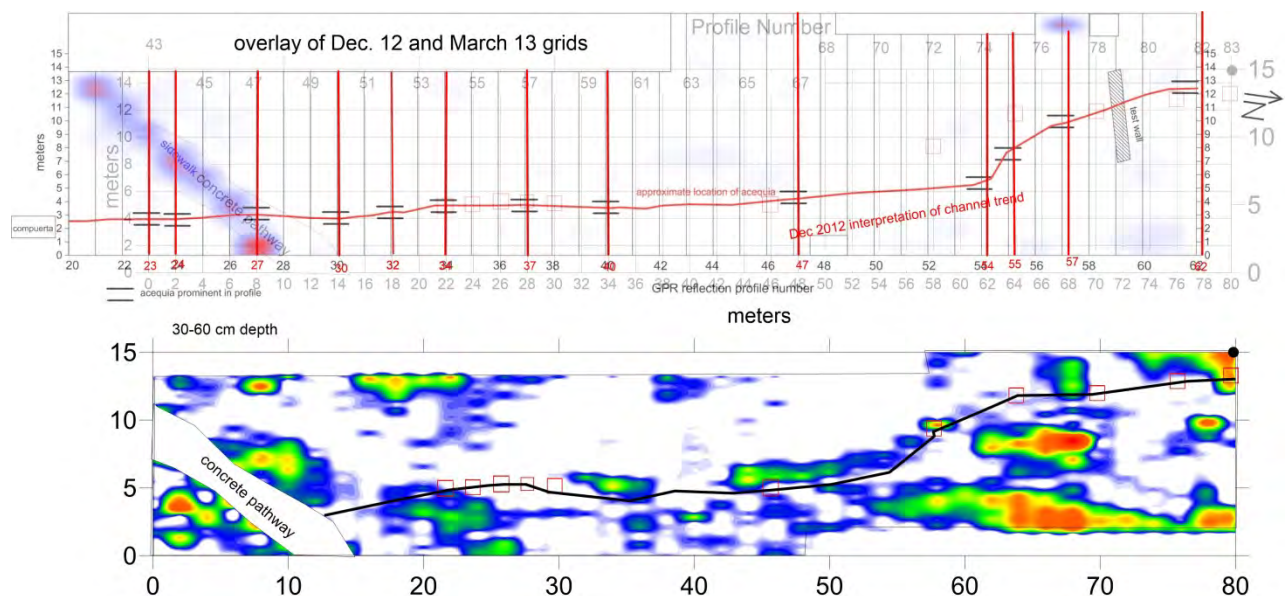
stratigraphic sequence, but does appear to show that sediment filled in the canals in at least two events, as there are two “silt layers” different from the other sediments in this excavation.



**Figure 2:** Excavation results of one area of the acequia just south of the compuerta. From Jeremy Moss report on 2004-2005 new lands testing.

### Comparison of Dec. 2012 data to those collected in March 2013

It was immediately apparent that the reflection data collected during the two different times was substantial. This phenomenon has been found elsewhere, especially when the ground has variable moisture content (Conyers 2012). The overlay of the two grids (the single grid collected in Dec. 2012 and Grid 3 in March 2013) is found in Fig 3.

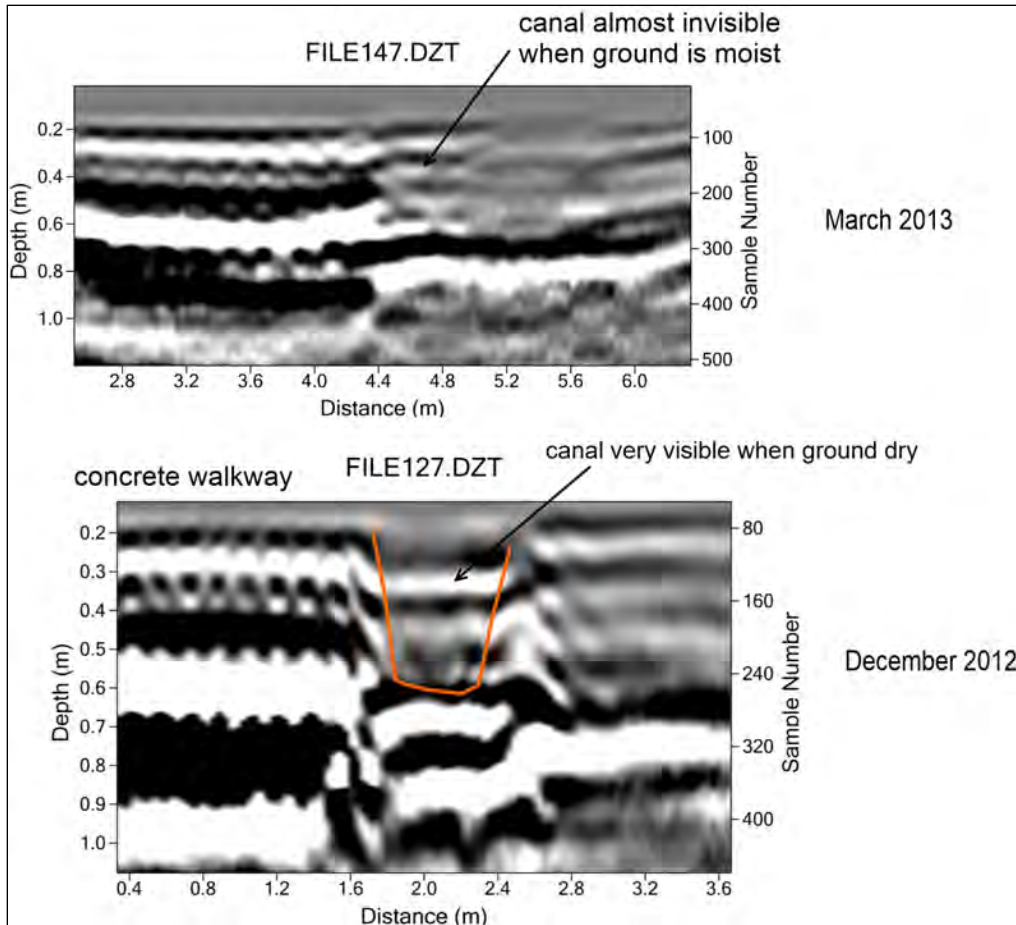


**Figure 3:** Overlay of the March 2013 and Dec. 2012 grids (upper map) with a comparison to the amplitude map from 30-60 cm depth in Grid 3. December profile numbers are shown at the top of the overlay. March profile number at bottom. Red profile lines show significant Dec. profiles.

All the reflection profiles were then compared between the two grids collected at two different times (and with inferred differences in moisture within buried layers). When the Dec. 2012 data were collected there had been .22 inches of precipitation at Tumacácori since Oct. 1, 2012 (TUMA Weather Station- Hobo chipset). The last significant rainfall was 2.49 inches in September. These data suggest that the late summer rains at Tumacácori had likely drained through the more permeable sediments (sand and sandy silt) by the time the GPR data were collected in early December. The only units that would have retained water by December, 2012 were the impermeable clays. In contrast from Jan. 1, 2013 until the GPR data were collected on March 11, 2013, 2.11 inches of rain had fallen at Tumacácori. Of the total precipitation, .42 inches of rain fell on March 8th and 9th, 2013, only two days before the March 11th survey. That significant precipitation was likely still retained in many of the sediment layers at the site. This would have led to less contrast in retained water within the various units at the time the March data were collected, and therefore lower amplitudes in the recorded radar waves.

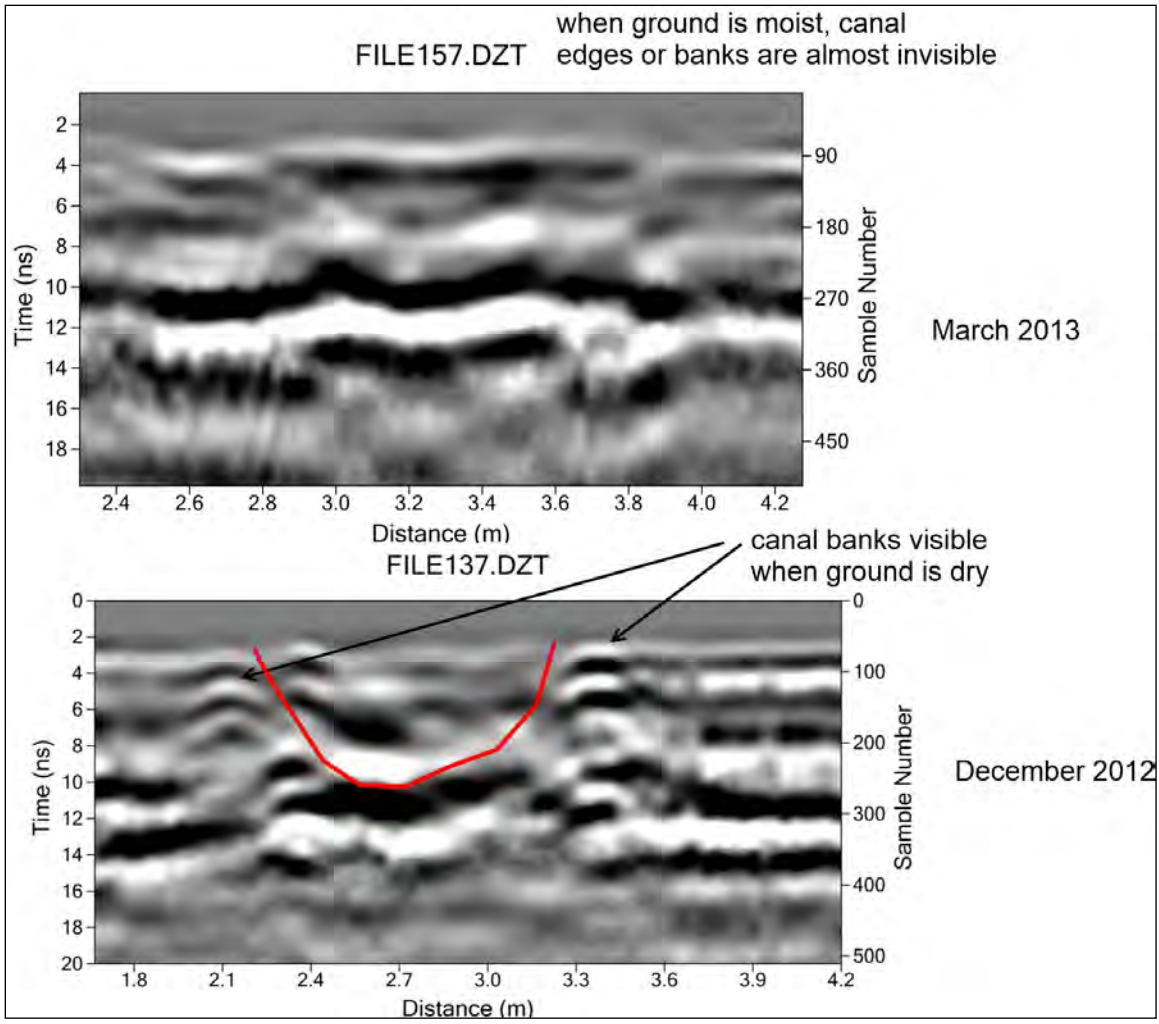
The lower reflection contrast in radar waves in the March, 2013 is exactly what can be seen in profiles. In Figure 4 a comparison of two reflection profiles in these two moisture regimes shows how the edges of the canal and its bottom produced high amplitude reflections in December, 2012 with the same feature is almost invisible in March, 2013.

In general, after about 2.1 inches of rain, the ground in March, 2013 would have contained sediments that were more similar in water saturation, as the layers had not yet had a chance to differentially drain. By December 3, 2012, with no rainfall for about 2 months or more, the only sediments that retained water were the units with more clay. This created a higher contrast between coarse and finer-grained sediment layers in December, and the canal was therefore more visible in GPR reflection profiles.



**Figure 4:** Comparison of March and December reflection profiles over the same feature in Grid 3. The canal is quite visible (especially its base) in Dec. but is almost invisible in March.

The canal edges are also more visible in reflection profiles collected in December (Figure 5). This is likely caused by clay in the “clean out” sediments deposited on the margins of the canals, which retains more moisture. While there is little sediment analysis at the site, canals usually contain finer-grained sediment deposition, which needs to be cleaned out periodically. That finer-grained material has a much lower permeability, and therefore retains more water. With more water retention in the clays layers, and less in the interbedded coarser grained sediment, the variation in the physical and chemical constituents that are responsible for radar wave reflection are more pronounced (Conyers 2012). The canal edges are therefore more pronounced in the December data. This is visible in many of the profiles. More analysis of sediments may help with interpretation of the GPR data.



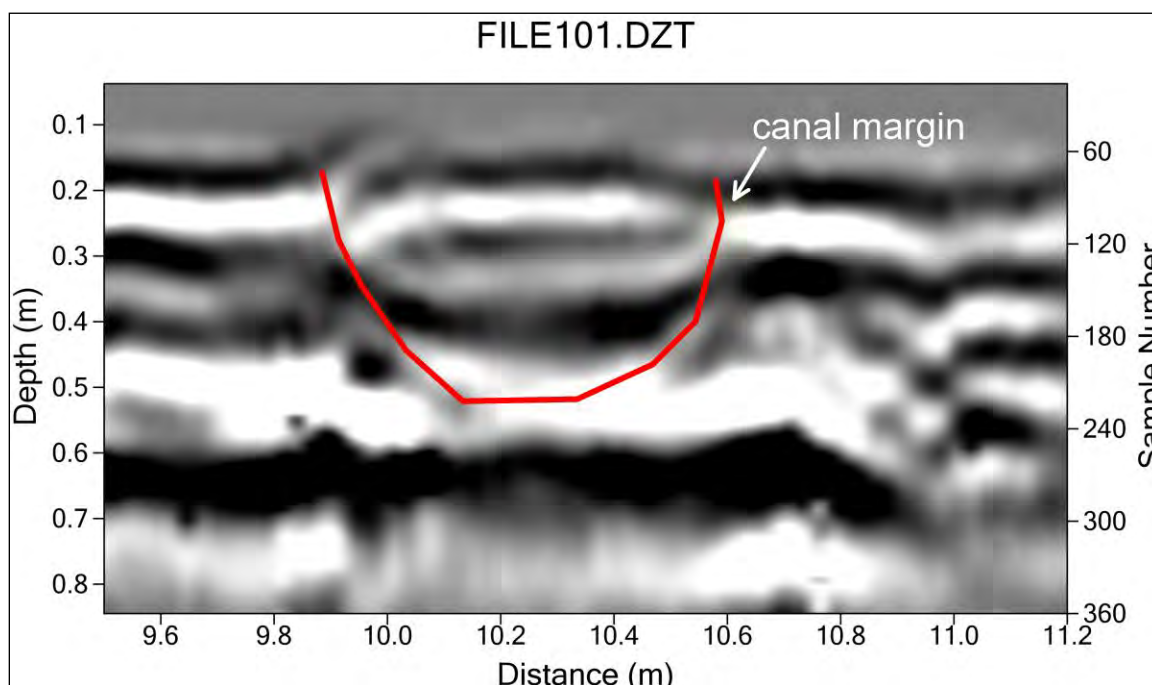
**Figure 5:** Comparison of profiles where the edges of the canals are more visible in December than in March. This is likely caused by the contrast in water saturation between canal clean-out sediments after 3 months of no rain.

## Data interpretation

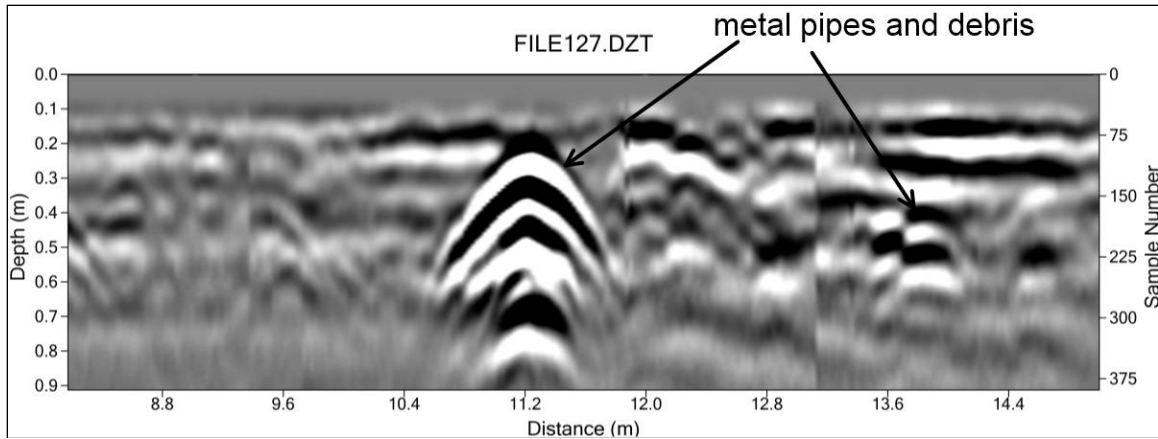
### Grid 1:

This grid of data consists of 34 reflection *profiles* separated 2 meters, within a 66x20 meter grid south of the *compuerta* to just north of the residence (Figure 1). A few of the profiles cross the concrete path in the northwest portion of the grid. The canal is visible in 18 of the 34 profiles. In some profiles the feature is very visible (Figure 6). The locations of canals such as these are shown in Figure 9. Many of the profiles show a plethora of metal, pipes and other debris, which obscures the canal (Figure 7). It is likely that trenches that were dug to emplace metal pipes might have destroyed the canal in some areas. There are also areas that appear to be very disturbed (Figures 7 and 9), and the canal is only visible in a few of the profiles in these areas. In many of the profiles in this grid the canal is very difficult to identify (Figure 8), which is likely caused by little differentiation in sediment types and therefore small variations in moisture content, or both.

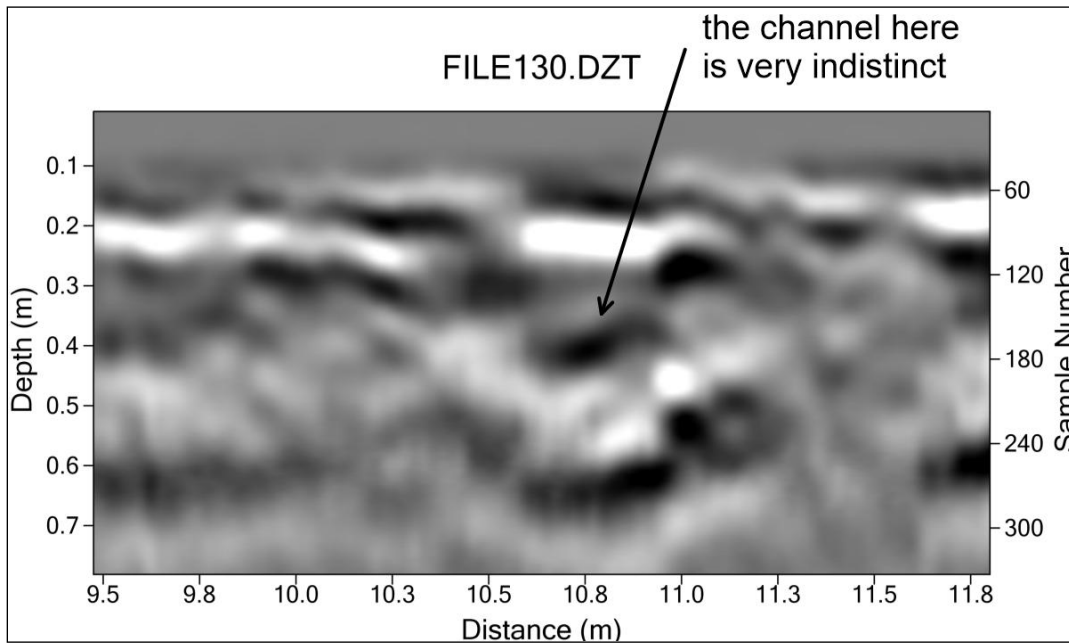
In the vicinity of the metal debris and other disruptions, the canal appears to be wider than elsewhere (Figure 9). Perhaps it was partially eroded here? Or am I seeing the results of digging and other excavations that have partially destroyed the canal in this area? It is difficult to know which. In Grid 1 the canal appears to be almost straight, and is only disturbed in the area where there is a good deal of metal and buried pipes (Figure 9). It trends directly into the walled backyard of the residence.



**Figure 6:** Canal in Grid 1 that shows a well-developed profile with high radar reflection amplitudes.

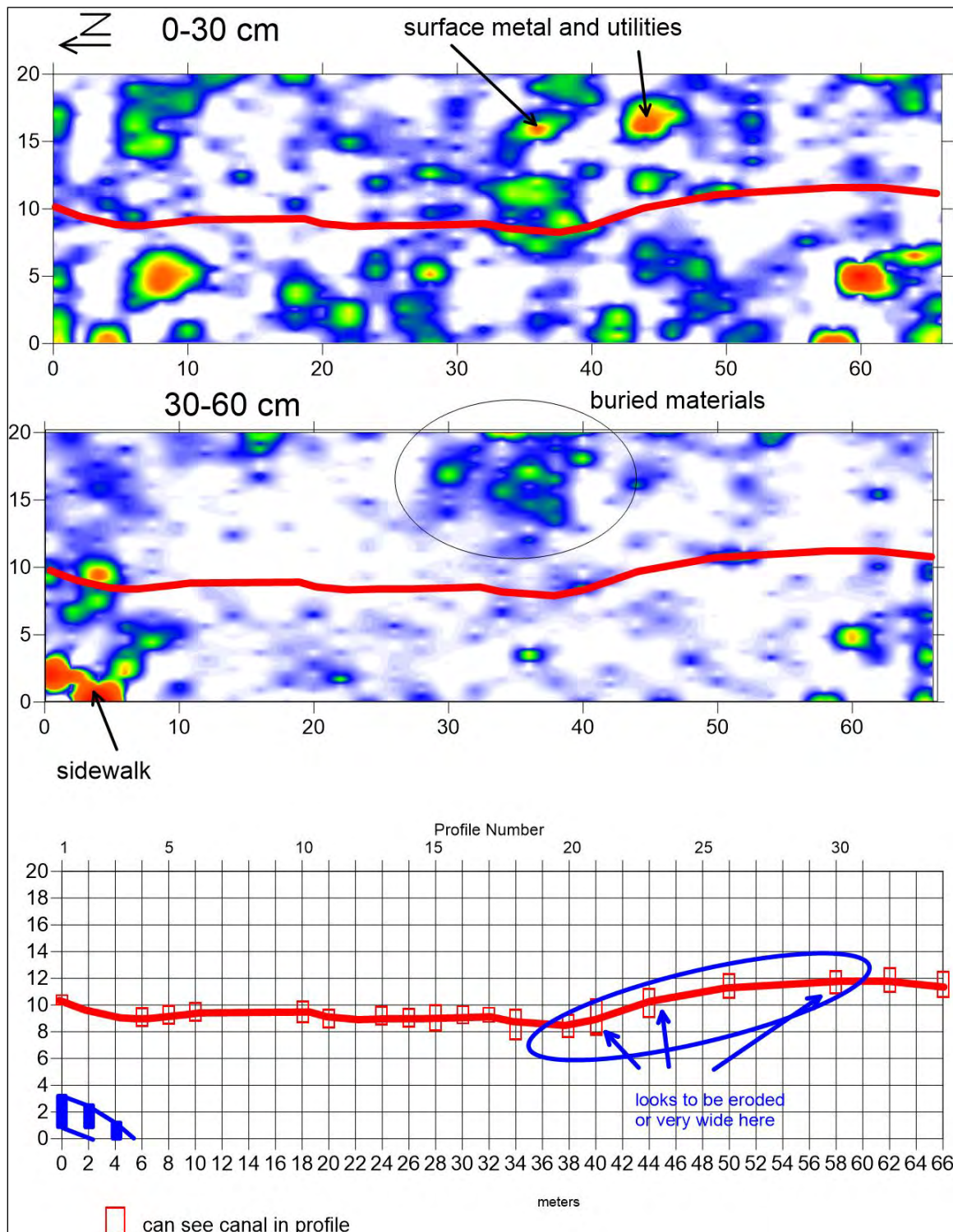


**Figure 7:** Example of buried metal pipes and other debris that obscures the canal in some of these profiles in Grid 1.



**Figure 8:** A very weakly reflective canal in Grid 1.

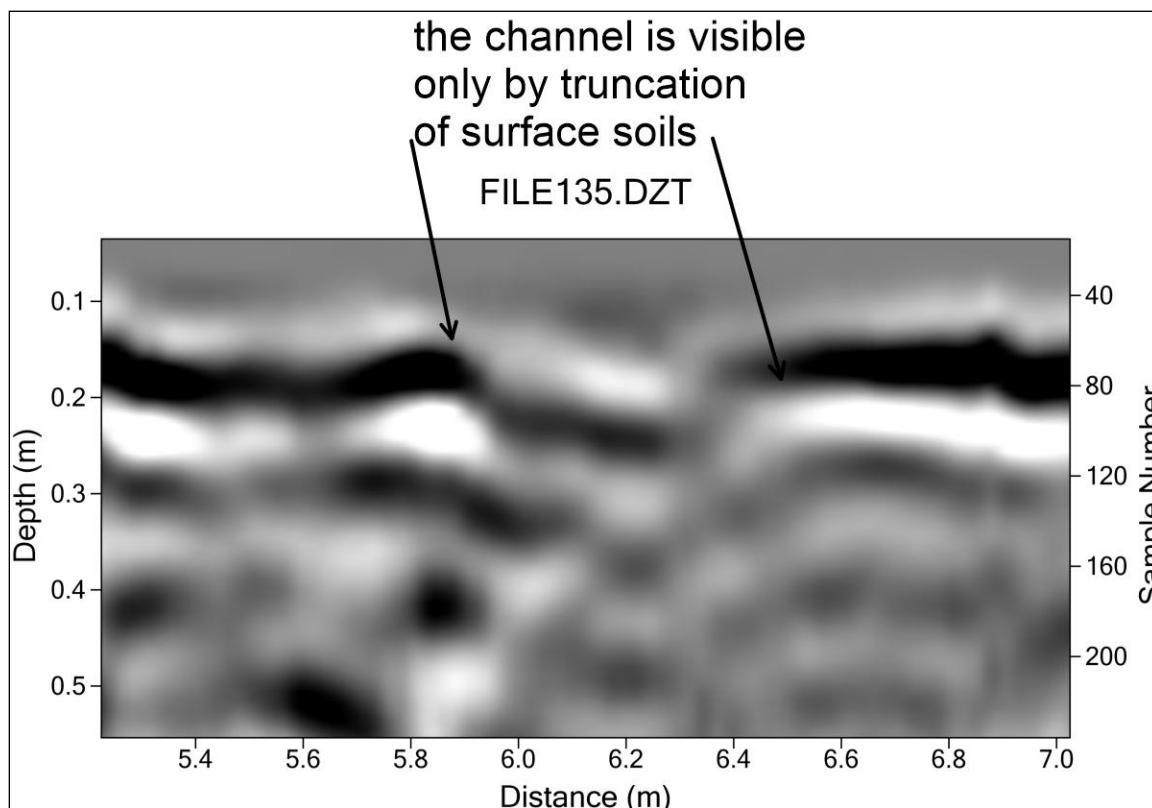




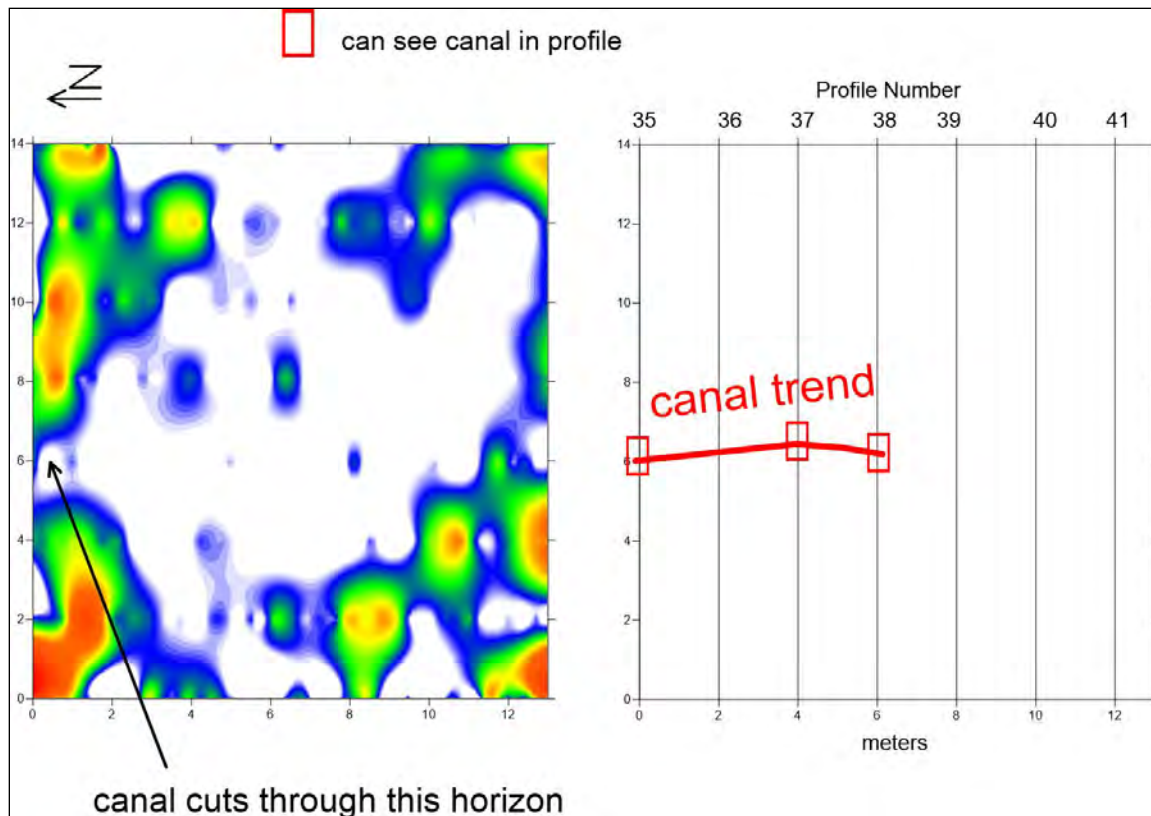
**Figure 9:** Amplitude maps and manual interpretation of profiles in Grid 1. The interpreted canal trend is shown in red.

## Grid 2:

This grid is located in an area south of the tall wall that bounds the residence area and the garage-maintenance area (Figure 1). The ground was very compacted here due to vehicle movement on the road and parking areas. The canal is only visible in 3 of the 8 profiles in this grid, which is 13x14 meters in dimension. The reflection profile closest to the wall along the north edge of the grid shows the canal much like those profiles collected in other grids (Figure 10). In this area of the grid a near-surface stratigraphic layer has been truncated by the canal excavation, and a “gap” in the amplitude map is visible there (Figure 11). Elsewhere in his grid the canal is not visible, or has been destroyed. The trend of this canal is directly toward the line of trees visible just to the south of the grid along the margin of the plowed field.



**Figure 10:** Reflection profile in Grid 2, showing it much like in other profiles in other grids. This profile was collected against the wall to the north, which bounds the maintenance area and the parking area for the RV.



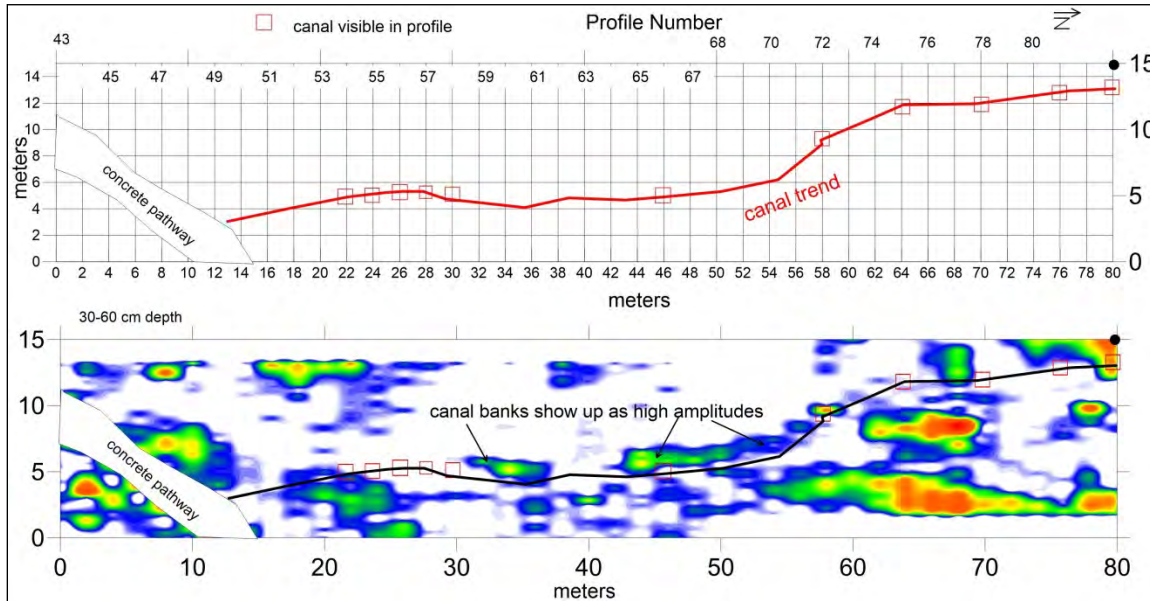
**Figure 11:** Grid 2 reflection amplitude map and a manual interpretation of the profiles in this grid.

### Grid 3:

Grid 3 was collected over top of the same grid collected in December, 2012, with a few minor variations in profile lengths (Figure 2). A total of 41 profiles were collected here in a grid that was 80x15 meters in maximum extent (Figure 12). In this area the canal is quite visible in both the data sets during different moisture regimes. It was very interesting how the banks or edges of some of the canal were visible in the amplitude map (Figure 12). In the March 2013 profiles only 11 of the profiles showed the canal. In the December, 2012 data set 13 of the profiles showed the canal, most in different areas of the survey area. When the two interpretations from the two grids are integrated, a trend line of the canal was made (Figure 12). This map shows a similar “jog” in the canal that Jeremy Moss sees in historic aerial photos of the area. The trend of the canal is also visible in the amplitude map, with the high amplitudes likely caused by canal-margin clean-out sediments.

The canal trend in Figure 12 is the most accurate interpretation of the canal’s reach. It is mostly the same as the trend interpreted in the Dec. 2012 data, with one small difference near the “jog” at between 54 and 64 meters (Figure 12). The earlier interpretation shows a much more drastic jog at this area of Grid 3 (Figure 3). That earlier interpretation is probably inaccurate due to slippage of the survey wheel or poor acquisition procedures when Jeremy Moss and I alone collected this grid under very rushed circumstances. An overlay of the canal trend in Figure 12

will probably match up very well with the color changes visible in an aerial photo shown me by Jeremy Moss, which was collected in the 1960s.



**Figure 12:** Manual interpretation and amplitude map of Grid 3 (March 2013). The canal trend can be seen in both images.

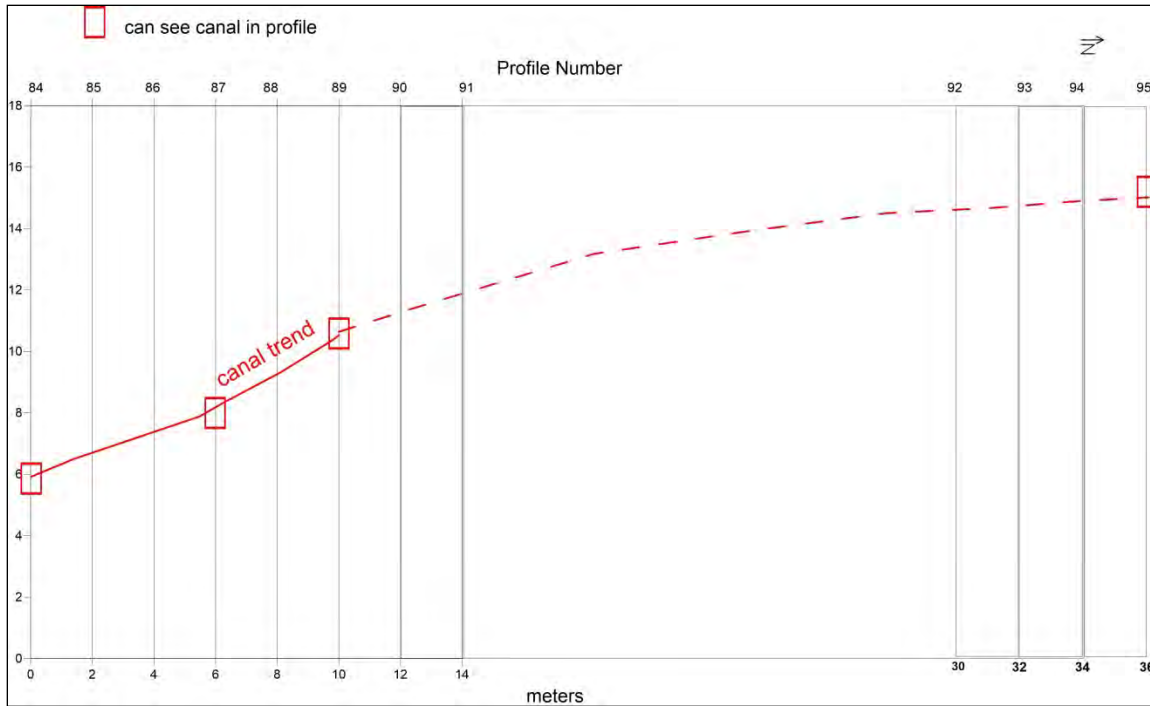
In 2012, archaeological testing was completed in the approximate location of the present concrete path shown in Figure 12. A test trench was placed just north of the compuerta mound in the projected location of the acequia. Profiles reveal the faint outline of a broad ditch filled with soil of the same composition as the surrounding soil with no layers or silt deposits visible (Figure 13). There was one thin silty-clay lens identified that could be a previous canal bottom, but there was a general lack of differentiation. This lack of soil differentiation could account for some of the inconclusive GPR results. It appears that in some locations the sediments/soils within and along the acequia differ, while in other locations sediments are too similar to be detected using GPR.



**Figure 13.** Profile of possible acequia remnant just north of the compuerta (TT2). Red arrow pointing at bottom contact (silty clay lens). More clayey soil above contact. South profile.

#### Grid 4:

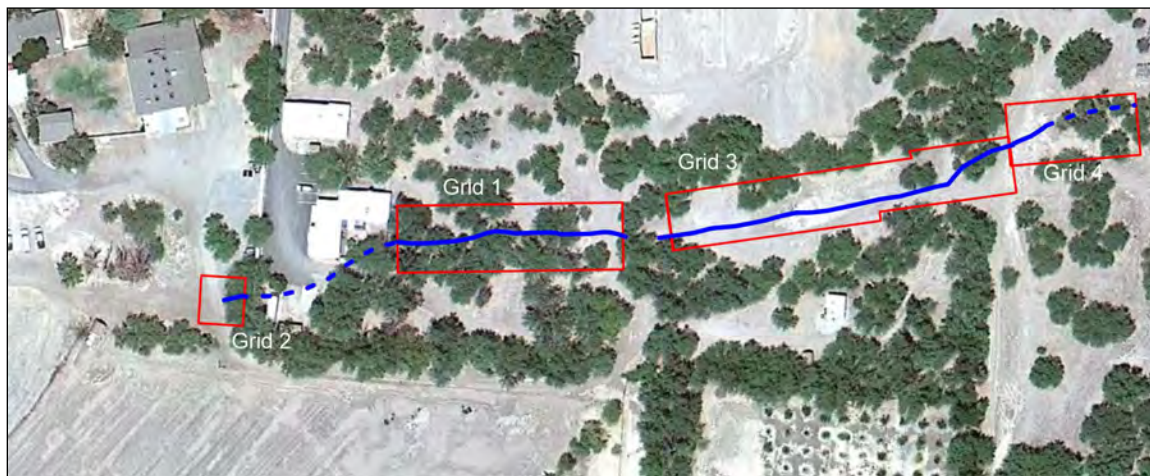
This grid is located north of Grid 3 in the open area along the dirt road leading from the picnic area toward the maintenance area to the south. Thick vegetation precluded GPR data collection in some of the grid (Figure 14) and only 4 individual profiles were collected there. A total of 12 profiles were collected here in a grid that was 18x14 meters in extent, with the 4 additional profiles to the north. The amplitude maps in this grid were not useful, likely due to the differential compaction along the dirt road, which affected energy coupling and produced anomalous features. Only 4 of the profiles exhibited the canal in cross-section. The projection of the canal from Grid 3 to the north shows an arc-trending toward the line of trees and the depression north of the grid.



**Figure 14:** Grid 4 profiles with a manual interpretation of canals.

### Overall Acequia Interpretation

The canal projection was placed on an aerial photo of the site in Figure 15. There are a few “jogs” in the canal, one within Grid 3, and another somewhere under the residence backyard between Grids 1 and 2. This trend nicely connects the line of trees to the south of Grid 2 and the line of trees north of Grid 4. The *compuerta* exposed on the surface is between Grids 1 and 3.



**Figure 15:** Composite interpretation of the GPR-mapped grid in the study area, with the grid locations shown.

In an attempt to delineate where in the grids the canal shows up “best” the following table was compiled to help place its trend into space (Table 1). All measurements in Table 1 were made from the base line of each grid (delineated in the detailed grids shown above).

**Table 1:** Location of the “best” canal locations in each grid. The first number in each line is the profile number, shown in Figures 9, 11, 12 and 13.

Grid 1:

1: 9.6-10.8  
4: 7.6-8.0: distance problems due to tree in profile  
5: 9.3-10.2  
11: 8.5-9.3  
13: hazy...eroded  
14: 8.6-9.8  
15: 8.7-9.7  
16,17,18,20,21,23,26,30: partially eroded but still vaguely visible  
32: 8.8-10  
34: 8.0-9

Grid 2:

35: 6.2-7.3  
37: 5.8-6.7  
38: 5.8-6.7

Grid 3:

54: 4.9-5.8  
55: 4.8-5.6  
56: 5.2-6  
57: 5.0-5.9  
58: 5.0-6.1  
66: 4.9-5.6  
72: 7.0-8.0  
75: 9.6-11.0  
81: 10.5-11.5  
83: 11.2-12.5: best of all profiles!

Grid 4:

84: 5.9-6.3  
87: 7.2-8.2  
89: 9.6-10.3  
95: 15.5-16.4

The “best” areas of canals in each grid is a little misleading, as these are GPR interpretations, not necessarily geological or archaeological interpretations. They are denoted as “best” in Table 1 because they were visible in GPR reflection profiles. To be visible in those

profiles there had to have been a significant amount of radar energy reflected from buried interfaces in the canal. Usually this is caused by changes in water saturation, which varies due to changes in porosity, permeability and bulk density. These variables may not be what is “visible” to the human eye in an excavation, but are physical and chemical changes only.

## **Conclusions**

Ground-penetrating radar was capable of showing the historic irrigation canal in 49 of the 154 reflection profiles collected. While this is only a 32% success rate in imaging the canal in individual profiles, the interpretations where it is visible are still capable of showing the trend of this linear feature. The 68% of the profiles that did not show the canal had the following possible problems:

1. The canal did not have sediments in it, or along it, which were different enough in chemistry or physical composition from those marginal to the canal. The lack of differences precluded the production of radar reflections along those indistinct interfaces.
2. The sediments associated with the canal both within it and adjacent to it retained water in different ways, which sometimes produced reflections and sometimes didn't. This was especially true when comparing the December, 2012 and March, 2013 data sets. The December data often showed the canals better because the clay units retained moisture after many months of no precipitation, which contrasted from the coarser units that had shed much of their moisture. In March the winter moisture had not yet drained from the coarser units, and therefore there was less contrast from which to reflect energy as the two both retained water.
3. Disturbances from excavations for utilities and perhaps debris burial in the past destroyed or impacted the canal in some other way, especially in portions of Grid 1.
4. Energy transmission coupling changed from compaction along the road and parking areas affected recorded reflections, making a subtle canal reflection signature almost invisible. This was the case in Grids 2 and 4.

Overall, the project was quite successful, and the historic acequia was visible and mapped across the study area.

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## **APPENDIX C**

### **MEADORS CONSERVATION INC. – LABORATORY TESTING REPORT**



# TUMACÁCORI NATIONAL HISTORICAL PARK TUMACÁCORI, AZ LABORATORY TESTING REPORT

PREPARED FOR:  
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DATE: 8.01.2013



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## ATTENTION:

Jeremy Moss, Chief of Resource Management  
Tumacácori National Historical Park  
P.O. Box 8067  
Tumacácori Arizona 85640

# INTRODUCTION

During the summer of 2012, Meadors Conservation was contracted by Tumacácori National Historical Park to design and perform a mortar testing program in order to evaluate replication mixes for the mission acequia located within the park. The acequia is a historically significant canal that once extended north to south through the mission to deliver water from the Santa Cruz River. This feature was largely responsible for the cultivation of the land and the prosperity of the mission gardens and orchard. Today, much of the acequia has been obliterated by modern farming techniques with only one known portion extant on the surface. Ground penetrating radar work performed at the site has located buried preserved sections which are not visible on the ground surface.

Original mortar was sampled from a remaining portion of the compuerta within the acequia in order to characterize and further understand the original construction materials. The goal of laboratory analysis was to characterize historic mortars through interpretation of petrographic analysis (provided by Highbridge Laboratories), and to formulate an appropriate repair mortar by testing the properties of various formulations. Two different types of local aggregate including gravel and volcanic rock were sent by the National Park Service to Meadors Conservation Laboratory to use in the evaluation testing. The local aggregates were chosen by the National Park Service as they were believed to be the most similar in composition to the local sands in the original mortar as determined by Highbridge Materials Consulting, Inc. Formulations determined by the petrographic analysis were utilized to create the replication mixes which were then made and cured in a laboratory setting. The testing methodology included analyzing setting time using the Vicat needle, understanding lime-pozzolanic strength development by compressive strength testing, and evaluating pozzolanicity through the lime combination test. Underwater setting tests were performed in order to confirm or negate the pozzolanicity of each aggregate studied. The data from each test was further analyzed and compared among the three formulations in order to determine the most compatible and appropriate replication formula.



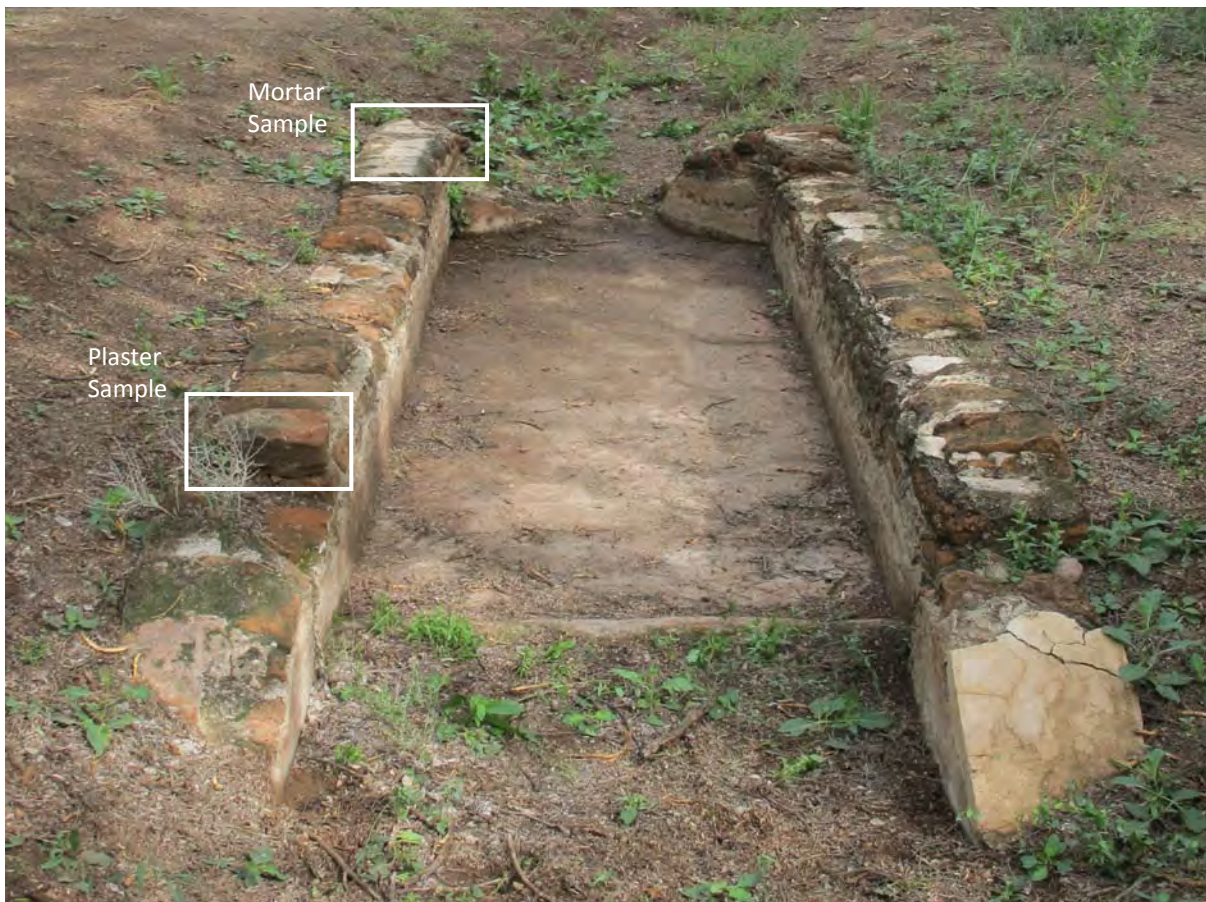
**Figure 1:** Photograph of compuerta . Image taken from the Northeast corner.

## SITE VISIT & SAMPLING

In September of 2012, Betty Prime of Meadors Conservation conducted a site visit to the acequia at Tumacácori National Historical Park. Samples were taken from the compuerta, located within the orchard walls (see site map in appendix p.39). The function of the site is currently unknown, although it is likely that the feature impounded water by restricting and slowing flow downstream from the acequia which then fed water into lateral ditches. The compuerta is also thought to have served as a laundry tank for the mission.

The compuerta structure is built of fired adobe bricks bonded together with bedding mortar and treated with a plaster finish on both the walls and floor of the structure. The plaster is finished with a wash that is pigmented with brick dust, giving the structure its pink-colored finish.

During the site visit Meadors Conservation worked in collaboration with representatives from the National Park Service (Jeremy Moss and Alex Lim) to select locations for the extraction of bedding mortar and plaster samples to be analyzed petrographically by Highbridge Materials Consultants, Inc. and then further tested by Meadors Conservation. The extraction sites of the plaster and bedding mortar samples are noted in the images below.



**Figure 2:** Photo of compuerta showing locations of sample extraction.

### Plaster Sample

The plaster sample was taken directly from the Southwest corner of the compuerta. The material selected for sampling had previously been dislodged and was found with the plaster surface lying down on the structure. The sample contained both the brick substrate and overlying plaster. The plaster sample was cut on site with a saw and half of the material was retained by the National Park Service for their records.

The sample analyzed by Meadors Conservation contained a plaster layer approximately 1.2" thick with a very thin and smooth red finish layer. A large portion of this sample was sent to Highbridge Materials Consulting, Inc. for further analysis.

### Bedding Mortar Sample

The bedding mortar sample was taken from the Northwest corner of the compuerta structure. The sample taken for analysis had a dark brown surface on the exposed faces of the mortar. When broken, the interior color of the mortar was light beige to gray. The mortar was well cohesive and did not easily crumble when touched. Small lime inclusions and brick fragments could be seen in the hand sample.

This sample was also chosen for analysis by Highbridge Materials Consulting, Inc. in order to gain a greater understanding of the mortar's original components.

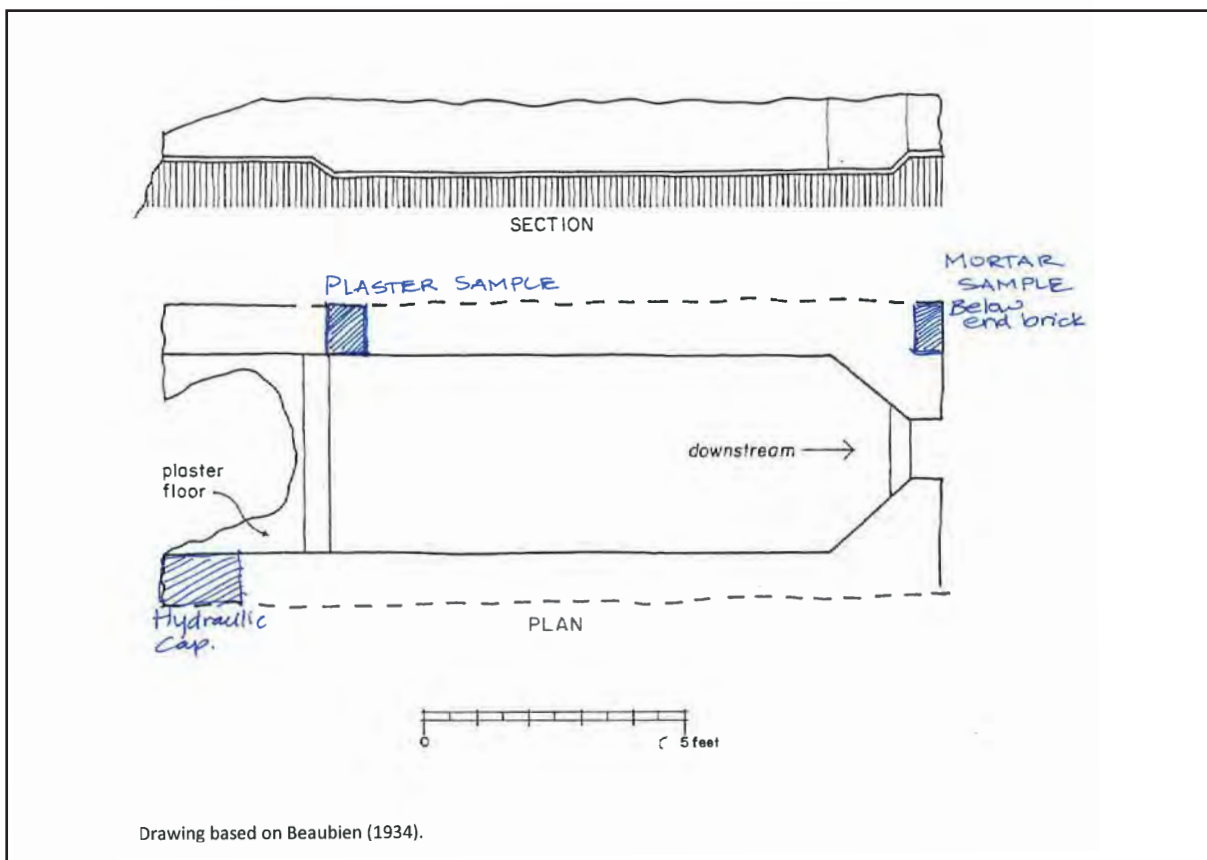


Figure 3: Plan of compuerta showing locations of samples and previous repair. (Map courtesy of NPS.)



## PLASTER SAMPLE



**Figure 4:** Photo of loose brick and plaster sample prior to removal.



**Figure 5A:** Photo of plaster sample after turning it over to expose the plaster finish.



**Figure 5B:** Close-up photo of plaster sample.

## BEDDING MORTAR SAMPLE



**Figure 6:** Photo of compuerta wall prior to removing the bedding mortar sample.



**Figure 7:** Photo of exposed bedding mortar after removing the brick above.



**Figure 8:** Photo of the bedding mortar extraction site after removal of the sample.



**Figure 9:** Photo of the compuerta wall after the mortar sample was removed.



**Figure 10:** Close-up photo of extraction site.



BULK SAMPLES



**Figure 11:** Photo of bulk bedding mortar sample. Photo taken from above.



**Figure 12:** Photo of bulk plaster sample. Photo taken from above.



**Figure 13:** Photo of bulk bedding mortar sample. Photo taken of sample section.



**Figure 14:** Photo of bulk plaster sample. Photo taken of sample section.



**Figure 15:** Photo of bulk bedding mortar sample.



**Figure 16:** Photo of bulk plaster sample.

## PETROGRAPHIC ANALYSIS

Petrographic analysis of mortar and plaster samples taken from the Tumacácori acequia in September, 2012 indicated that the mortar and plaster were composed of lime with volcanic sand aggregate. Although the aggregate component of the mortar and plaster is similar, the proportions of lime to sand and the individual sand gradation were different between the two samples. Brick dust was not detected as an additive to the mortar and plaster, as originally hypothesized, but was found as a component of the wash applied to the surface of the plaster. The brick dust particles are embedded into the lime paste at a depth of approximately 0.5 mm, indicating that this surface finish is original to the plaster installation. The brick dust may have reacted with the lime and slightly increased the hydraulicity and strength of the plaster, but as only a surface finish, it should not be considered a major pozzolanic component but likely more of an aesthetic treatment.

Although not determined conclusively, the volcanic sand aggregate used in the mortar and plaster potentially acted as a pozzolan, contributing to its strength and durability. Siliceous fines of volcanic origin were detected in both samples, accounting for approximately 5% of aggregate weight. These fines may have been a component of the unwashed sand aggregate, or they may have been added as a separate component for their strength-enhancing capabilities. Volcanic materials are known to have pozzolanic potential when combined with lime due to the presence of silica and alumina. Compressive strength testing and chemical analysis performed by Highbridge Materials Consulting, Inc. supports that there was a pozzolanic reaction between the volcanic sands and lime. Chemical analysis determined that the volcanic aggregate had a high solubility in alkaline material, suggesting its pozzolanic potential through its ability to combine with lime. The high compressive strength of the plaster sample also suggests that there is a reaction beyond normal lime carbonation responsible for the high strength of the plaster.

**Table 1:** Findings by Highbridge Materials Consulting, Inc.

	Proportions (lime:sand)	Compressive Strength (psi)	Hydraulicity Index (SiO <sub>2</sub> + Al <sub>2</sub> O <sub>3</sub> )/CaO)
<b>Bedding Mortar</b>	1:2.0	N/A	.07
<b>Plaster</b>	1:2.6	1300-1600	.09



## GOALS OF TESTING PROGRAM

The goal of the testing program was to produce a mortar mix that would replicate as closely as possible the original mortar material in terms of composition, physical properties and appearance. For the purposes of authenticity and compatibility, only pure lime and sand were to be used in the mix. The National Park Service expressed that Portland cement and additives were not acceptable for conservation mortars used on site. The petrographic and chemical analyses performed by Highbridge Materials Consulting, Inc. provided data regarding the material composition and proportions of the original mortar, which guided the selection of aggregates and proportioning. Due to the similarity between the proportions of plaster and mortar mixes determined by Highbridge (1:2.6 and 1:2), a representative 1:2 mix will be used for the experimental program. Because petrographic and chemical analysis suggested that the original mortar contained volcanic aggregate which may have been pozzolanic, the testing program was designed both to evaluate the properties of potential replication mortars and to determine whether the modern, local volcanic sands provided by the National Park Service would produce a pozzolanic reaction.

## POZZOLANIC VOLCANIC MATERIALS

The definition of “pozzolan,” according to ASTM C618 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete is “a siliceous or siliceous and aluminous material which, in itself, possesses little or no cementitious value but which will, in finely divided form in the presence of moisture, react chemically with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties.” Volcanic materials, particularly pumice and ash from volcanic eruptions, generally contain high proportions of silica and alumina in vitreous form which will readily combine with lime to form calcium silicate hydrate, the reaction product that is responsible for the modification of properties in pozzolan-lime mortars, including higher strength, decreased setting time, and ability to set in water and without exposure to carbon dioxide.

Since Antiquity, volcanic materials have been utilized by various civilizations to create pozzolanic mortars. In fact, the Romans used a volcanic material called pozzolana from the town of Pouzzili, Italy to make some of the earliest hydraulic mortars. It is from this material that the term “pozzolan” originates, although it is now applied more generally to a number of naturally-occurring and man-made materials that exhibit a pozzolanic reaction with lime. Volcanic pozzolans were also widely used during the 19th century in engineering works, particularly those in marine environments.



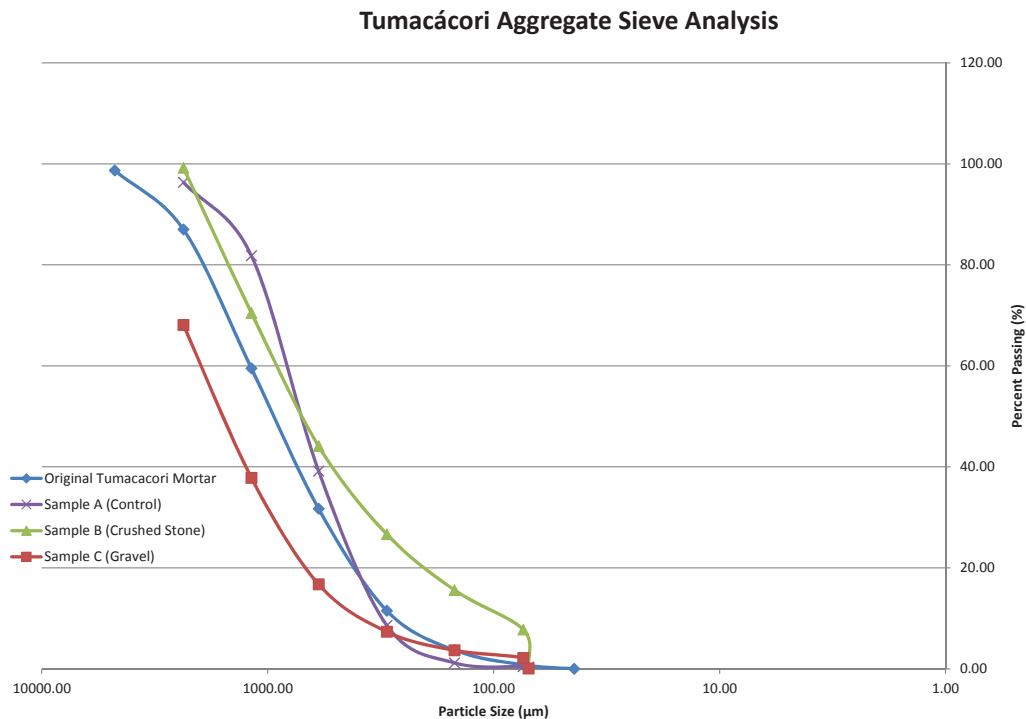
## MATERIALS & METHODOLOGY

### Materials

Two different types of aggregate including a gravel and a volcanic rock were selected by representatives at Tumacácori National Historical Park and sent to the Meadors Conservation Laboratory for testing. A corresponding map denoting sample locations can be found in the Appendix. A control sand, Sample A, was chosen from a Charleston sand mine as it had the closest gradation of local all the local sands to the original Tumacácori sand. 100 g of each sample were then sieved in order to determine the grain size distribution of each and compared with the distribution established by High-bridge Materials Consulting, Inc. from the original mortar.

The control sand was a concrete sand from the Murray Sand mine in Summerville, SC. This aggregate is a coarse angular sand composed mainly of white to gray silica quartz with very minor constituents of feldspar and magnetite. The control aggregate, Sample A, had a Munsell color code approximately 2.5Y 8/1 “White” and a nominal top aggregate size at the No. 8 (2.38mm) sieve. The peak abundance of grains was found to lie between the No 30 (0.595 mm) and No. 50 (0.297 mm) sieves. Approximately 90% of the grains within the aggregate lie above the No. 50 Sieve.

The volcanic rock, referred to as Sample B, was sampled from Tumacácori Mountain by the NPS. The rock is an extrusive rhyolite to rhyo-dacitic tuff that ranges from pink to yellow-pink. Large rock samples was crushed in the laboratory with a hammer and chisel into sizes that visually matched those of the gravel (Sample C). The crushed granite was highly angular and was composed of angular quartz and feldspars with possible biotite and hornblende. The samples has a Munsell Color code approximately 2.5 YR 8.5/1 “White” and a nominal top aggregate size at the No. 8 (2.38mm) sieve. The peak abundance lies between the No. 8 and No. 30 (0.595 mm) sieves.



**Graph 1:** Sieve analysis results for samples A-C in comparison with original aggregate

**Table 2:** Formulations and Proportions used in Testing

	Lime	Aggregate
<b>Formulation A</b>	1 part	2 parts control sand
<b>Formulation B</b>	1 part	2 parts crushed stone
<b>Formulation C</b>	1 part	2 parts gravel

Sample C was a unwashed sand-gravel mix sampled from alluvial deposits from the Tumacácori Mountains. This material was composed of small grains of rhyolite tuff, quartz particles, fragments of a variety of granitic rocks and organic matter. The sample was rounded to subangular in composition and had a nominal top size above the No. 8 sieve. This aggregate was further manipulated only retaining 50% of the aggregate retained the No. 8 sieve in order to approximate the original aggregate gradation. The peak abundance for the manipulated sediment was present between the No. 8 and No. 16 sieves with approximately 63% of the aggregate in this range. The sample had a Munsell color code of approximately 5YR 7/2 “Pinkish gray.”

All aggregate was tested for the presence of  $\text{Cl}^-$ ,  $\text{SO}_4^{4-}$ ,  $\text{NO}_3^-$ , and  $\text{NO}_2^-$  anions to indicate the presence of salts within the samples. No significant concentrations were discovered and the results can be found in the Appendix.

Lime chosen for sample mixing was a dry hydrate Chemstar Type S lime and was provided by NPS as it is not readily available in South Carolina. This lime was chosen because it is the type of lime that is typically used at Tumacácori National Historic Park for conservation projects, and is likely the type of lime that will be used for on site implementation.



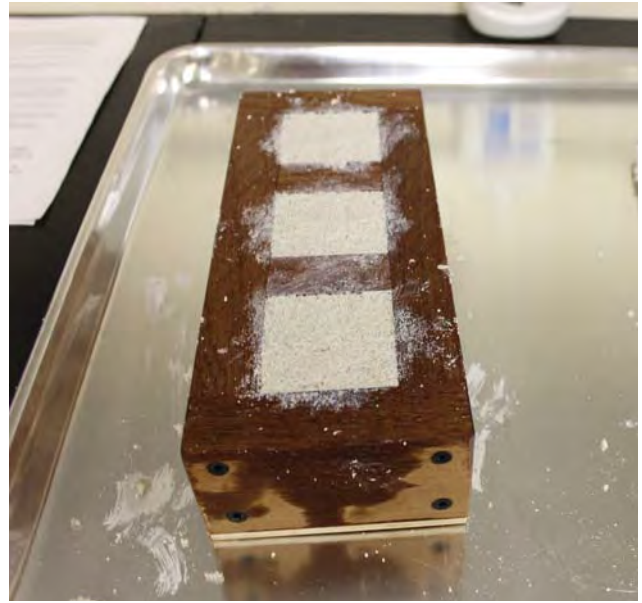
**Figure 17:** Volcanic Rock prior to crushing (Sample B)



**Figure 18:** Unwashed gravel aggregate (Sample C)



**Figure 19:** Dry mixing mortar ingredients.



**Figure 20:** Molding of Compressive Strength cubes

#### *Formulation*

As discussed previously, analysis by Highbridge Materials Consulting of original bedding mortar and plaster indicated the formulation to be a 1:2 mix by volume with lime equated to a dry hydrate for bedding mortar and 1:2.6 for plaster. All formulations made in the laboratory were made according to this determination, using the proportions of the original bedding mortar.

#### *Preparation of Samples*

Prior to sample mixing, all aggregate was dried in an oven at 110° for 24 hours and left to cool in a desiccator. Hydrated lime was pre-sifted through a sieve prior to use in order to remove all clumps. Samples for setting time and compressive strength tests were initially mixed dry by volume by hand using a trowel. Small amounts of deionized water were placed into the mix until a sufficient quantity had been added to form a workable consistency. The mortar was then mixed with a drill for five consecutive minutes. Mixing was completed when the mortar was able to remain on an inverted trowel, a test often used in the field to evaluate when a mortar has been properly mixed. The mass of each component was recorded in order to ensure the mix could be replicated. Samples were transferred into the molds and stored in the curing chamber as soon as possible.

Samples requiring specialized preparation methods, such as those for the lime combination and underwater setting time tests, were prepared following specific methods which are described in the individual testing section.

#### *Curing*

A modified relative humidity chamber was created for curing the mortar samples in between testing. 5 trays of deionized water were placed in a hooded baking rack and a digital hygrometer was placed inside to monitor the temperature and relative humidity. The relative humidity was kept as close to 90% as possible and additional water was added to the trays when needed. Compressive strength samples were cured for 30 days in a curing chamber at controlled at 90% relative humidity. Setting time samples were stored in the chamber until testing was complete. During the entire testing period, temperatures ranged within the chamber from 70.2 to 75.0 degrees Fahrenheit. This is an acceptable range for curing conditions.

## TESTING METHODOLOGY

### *Introduction*

The purpose of the testing phase was to formulate a replication mortar that matches the originals using local sands of known volcanic origin from the region, and to determine whether the sands provided are pozzolanic. The sands that were provided were characterized based on gradation, color, and texture. They were visually compared to the original sands extracted from the plaster and mortar samples in order to ensure their compositions were similar and would potentially produce compatible mortars.

As discussed previously, bulk samples of both Sample B & C contained aphanitic rhyolitic and rhyodacitic aggregate and are likely volcanic in origin. These compositions are similar to the natural volcanic sands, analyzed by Highbridge Materials Consulting, Inc, which were determined to be composed of dacite and rhyolite.

The pozzolanic potential of the volcanic fines was determined through a simple lime combination test in which the fines were combined with hydrated lime and water and observed for seven days. The ability of the mortars to set by the combined processes of carbonation and pozzolanic reactions



**Figure 21:** Formulation C arranged by gradation



**Figure 22:** Original plaster with embedded brick surface finish (bottom)



Figure 23: Preparation of Lime Combination Test Samples

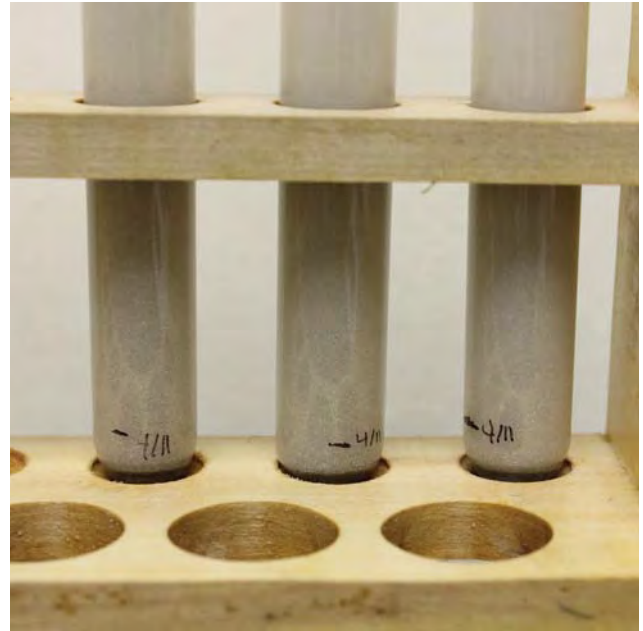


Figure 24: Sample C after agitation on Day 1

was measured through the setting time test. The underwater setting time test was used as a confirmatory experiment to identify pozzolanicity and measure the ability of the mortar to set underwater solely by the formation of cementitious compounds. Compressive strength tests were used to evaluate the strength imparted by the pozzolanic aggregate when compared to a non pozzolanic control. Overall, the data obtained from the testing program will help indicate the most appropriate aggregate to recommend for future replication mortars for the historically significant acequia.

#### *Lime Combination Test*

Lime combination test is used to evaluate the ability of a pozzolan to combine with lime and the test can indicate a pozzolan's respective reactivity. The lime combination test is a simple, chemical test that, while it yields little quantitative data, can indicate a pozzolanic reaction that can be detected through visual observation. The formation of calcium silicate hydrates (C-S-H) resulting from the reaction of lime and silica and/or alumina in the supposed pozzolanic material results in an increase in mass that can be detected visually. If no reaction occurs, there will be no changes in mass. This test was discussed in A.D. Cowper's book *Lime and Lime Mortars*, published in 1927, and has been successful in indicating pozzolanicity for brick dust. According to the simplified test, a quantity of raw material is combined with lime water in a test tube and is periodically shaken over 7 days. During testing, when a pozzolanic material is used, calcium silicate hydrate forms and increases the volume of solid matter and decreases the rate of settlement after shaking the tube. This test easily indicates the presence of a pozzolanic material and allows for comparison relative pozzolanicity among different materials.

The samples from each formulation were used for testing. Each aggregate sample was sieved and initially only the fines passing through the No. 200 (74 micron) sieve as required by the test. However, due to the limited amount of aggregate present within this range for all sample aggregate, aggregate



passing the No. 100 (149 micron) and retained on the No. 200 sieve were also used.

0.5 grams of fines, 0.3 grams of hydrated lime, and 20 mL of water was placed in each test tube. The tube was then stopped and sealed with electrical tape. Before photographs of each formulation were taken with a digital camera and the height of the solid matter was marked and recorded. Every 24 hours, each test tube was shaken and observed. Any change in the solid matter was recorded and photographed daily.

#### *Setting Time Test*

Setting time as measured by the Vicat is a standard method in accordance to ASTM to determine the speed of setting and hardening of a mortar. Using a Vicat apparatus, a needle is placed on the surface of a mortar and allowed to plunge into the material at various time intervals. Over time, as the mortar hardens the needle will penetrate less every recording interval until it cannot penetrate anymore. Initial setting time occurs when the paste becomes fully plastic, penetrating below 25 mm. Final setting time occurs when the mortar achieves hardening stage and the needle no longer penetrates into the paste.

Three samples of each formulation were created for the purposes of this test. Pre-tests with each formulation were made prior to final testing in order to establish a time testing interval for each respective formulation. Prior to molding, the inside of the conical Vicat molds were coated with petroleum jelly. Once the formulation was mixed and ready to be molded, a ball of mortar was made and tossed back and forth 6 times between gloved hands held approximately 6 inches apart as mandated by ASTM C-191. The ball of mortar was then pushed into the mold from the bottom (larger) end so that some of the mortar passed through the mold and sat proud on top. The filled mold was then placed on a plexiglass plate. A sharp trowel was used to remove excess material from the top of the mold in one swipe. The interface between the mold and plexiglass was then sealed with plumbers putty to ensure a secure base. Samples were then stored in the curing chamber following molding and between all readings. Testing was performed according to ASTM C-191 Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle. Penetration depth was recorded at each reading along with the current temperature and relative humidity within the chamber. Testing continued until all 3 formulations reached final set.

#### *Underwater Setting Time Test*

The underwater set test is a variation to the standard setting time test as performed in this experiment. This test is used to measure the setting time on a lime-pozzolan mortar that is submerged in water without access to carbon dioxide. This experiment is based on the assumption that active pozzolans will cause a lime-based mortar to set under water while non pozzolanic controls will not set in these conditions. This experiment was initially proposed by French chemist Feret who suggested modifying the standard set time test by placing the specimens underwater. According to his research, active pozzolans should reach initial set in less than 50 hours and final set in less than 100 hours. Poor and mildly pozzolanic materials will set after 100 hours and non pozzolanic materials will not set during this experiment (Morand & Gilliland 1950: 116).

One sample from each formulation was tested in this experiment. Samples were created with each aggregate using a 4:1 pozzolan: hydrated lime mix measured by weight. Only pozzolanic material passing the No. 100 (0.149 mm) sieve was used during this test. Dry lime and sand fines were hand mixed in a bucket with a trowel. Water was mixed until the mix formed a paste consistency. The amount of water used was recorded for each formulation.

Enough material was used to fill a cylindrical glass jar. The paste was formed into the jar by hand, and compressed to ensure there were no air bubbles. 100 mL of deionized water was used to cover the





Figure 25: Formulation A prior to testing.



Figure 26: Formulation B undergoing setting time testing.

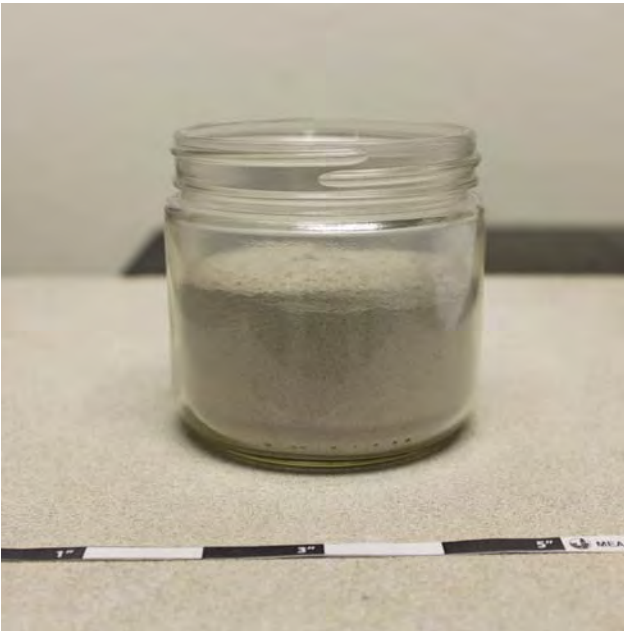


Figure 27: Preparation of underwater set samples.



Figure 28: Formulation C tested for underwater set.

paste followed by a layer of mineral oil to prevent the ingress of carbon dioxide. A lid was kept on the jar at all times between readings.

A Vicat needle was used to perform the setting time test according to ASTM C-191 Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle. Readings were taken once a day until initial set time was reached. Readings were increased at this point to obtain a precise calculation of final set time. Testing ended after 7 days if there was no indication of curing.

#### *Compressive Strength Test*

The compressive strength test is a common test used to quantify the pozzolanic reaction indirectly through strength enhancement. Theoretically, test samples containing pozzolanic material will have a higher strength than a specimen without active pozzolanic material. Additionally, the more reactive the pozzolanic material, the higher the strength of the mortar sample.

3 samples of each formulation were used for the purposes of this test. Fresh mortar was placed in specifically made 2 inch square sapele wood molds. The interior of each compartment was coated with mineral oil prior to molding. Mortar was packed into the molds using a trowel. The compartments within the mold were overfilled with mortar which was then pressed into the cubes as much as possible. A trowel was then held at a slight angle to slice off the excess mortar at the top and make it flush with the mold. Samples were then stored in their molds in the curing chamber to the next seven days. After seven days of curing, samples were removed from the molds and were returned to the bakers rack for curing. Samples were removed from the curing chamber at 30 days and tested according to ASTM 109 Standard Test Method for Compressive Strength of Hydraulic Cement Mortars. In preparation for testing, each sample was measured with calipers and brushed clean to remove loose sand grains or incrustations from the faces of the cubes.

Samples were tested in compression by Soil Consulting, INC at their laboratory in Charleston, SC. Mortar cubes were placed on the true plane surface of the testing machine. A constant force was applied from above until the cubes failed due to stresses. This force required to reach this was used to calculate the compressive strength.

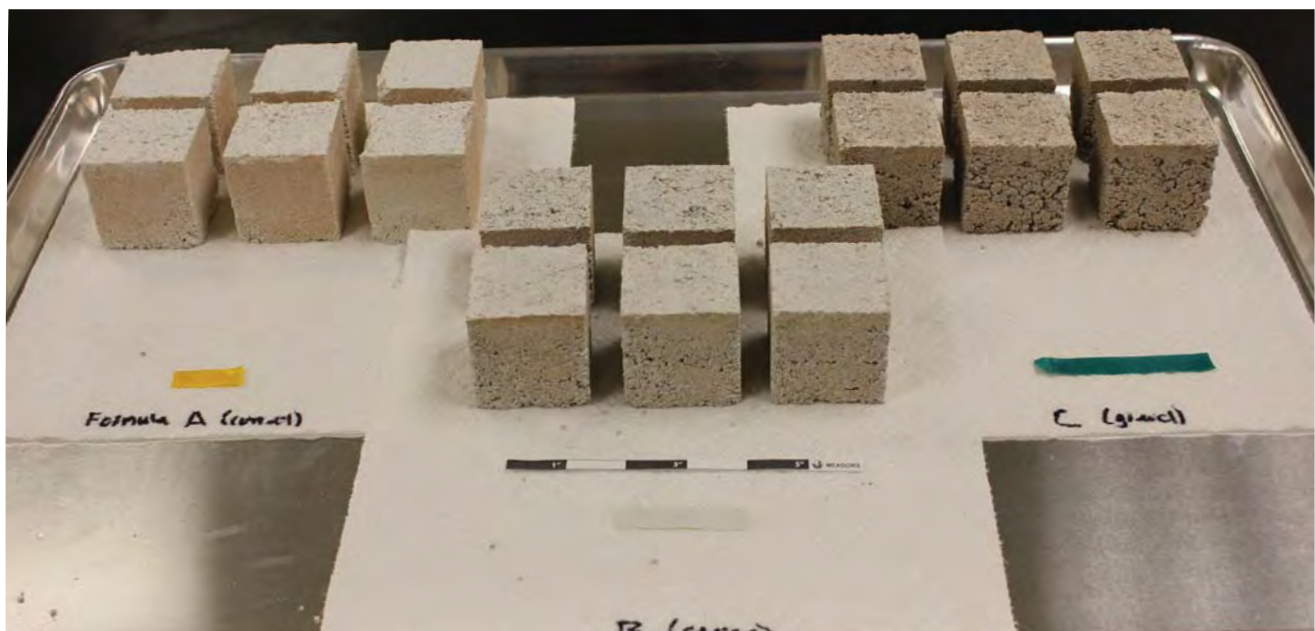
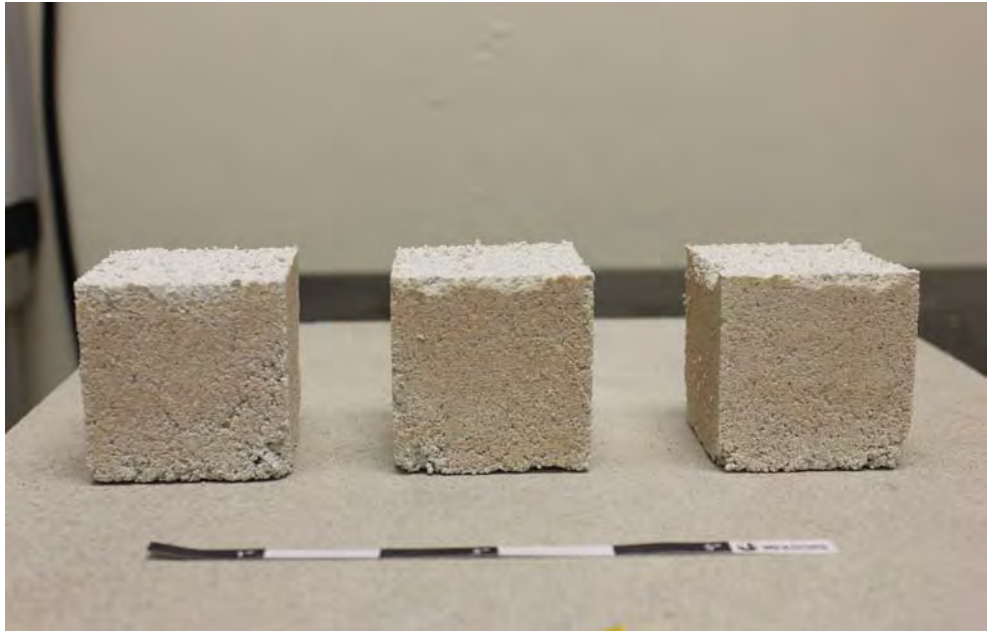


Figure 29: All compressive strength cubes after being carefully removed from the molds.



**Figure 30:** Formulation A compressive strength cubes after they were removed from the molds.

## TESTING RESULTS

### *Introduction*

Tests used for the purposes of this study were performed at the Meadors Conservation Laboratory between April and June 2013. The data and results are described below with the full data presented in an appendix attached to this report. Analysis of the data and final recommendations can be found in the following section.

### *Lime Combination Test*

The lime combination tests successfully indicated a pozzolanic reaction through the formation of calcium silicate hydrate in sample formulation B, the crushed volcanic rock, and Formulation C gravel. From the increase in solid matter and the formation of these reaction products, it can be implied that Formulation B and C are pozzolanic. Growth in solid matter was not visually detected in the control Formulation A. The test was able to provide some level of differentiation in the degree of pozzolanicity between Formulations B and C, which was consistent with the results of other tests. Formulation B showed the greatest increase in solid matter, with an average increase of approximately 148%, while Formulation C displayed an average increase of only 58.6%.

**Table 3:** Lime Combination Test Data

Formulation	Average Initial Height (mm)	Average Final Height (mm)	Increase (%)
A	11.3	11.3	0.0
B	9.7	24.0	148.3
C	9.7	15.3	58.6

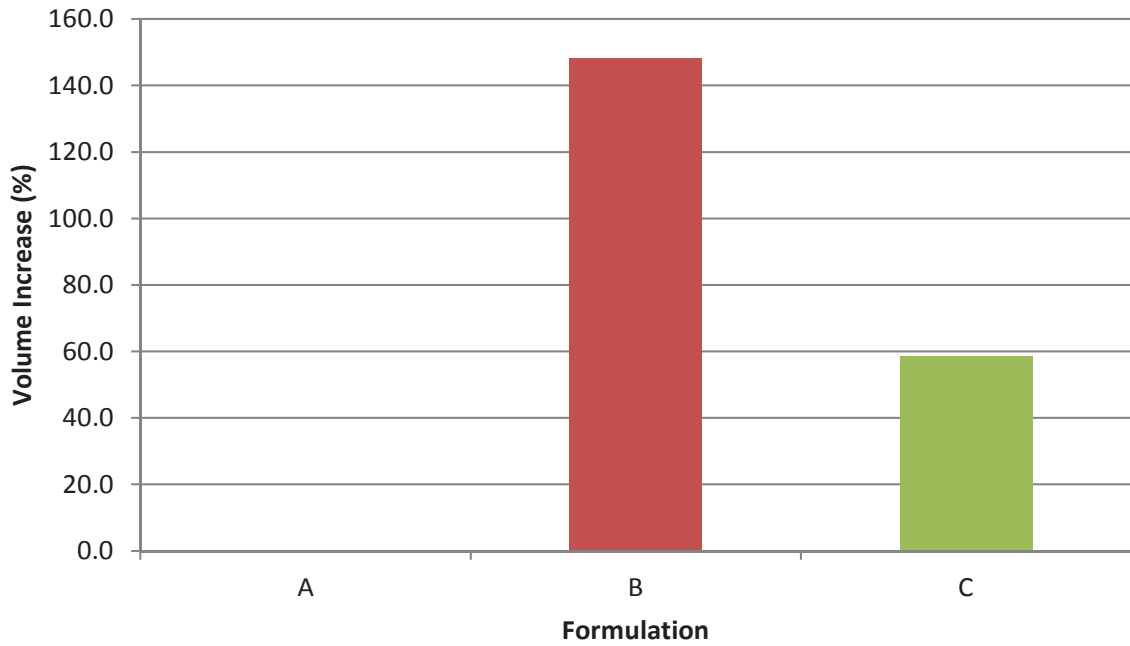
#### **Sample Key**

**Formulation A**                      Control- Concrete Sand  
**Formulation B**                      Crushed Volcanic Stone  
**Formulation C**                      Gravel

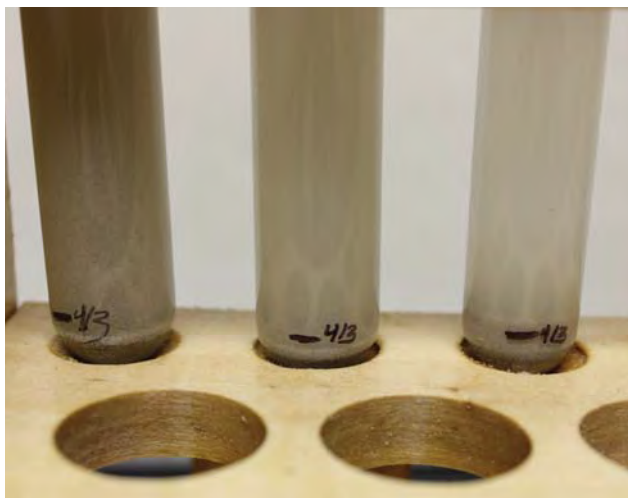
Note: Sample formulation 0.6:1 lime to aggregate



## Lime Combination Test



**Graph 2:** Lime Combination Test Results



**Figure 31:** Solid matter in Formulation B after day 1.



**Figure 32:** Solid matter Formulation B after day 7.

## TESTING RESULTS

### *Setting Time Test*

Setting time data for all formulations was in agreement with those determined by the Lime Combination Test. The initial and final set times were recorded for each formulation and is displayed below. Formulation B had the fastest initial and final set, with an elapsed average time of 3.67 and 26.08 hours, respectively. Formulation C, the gravel, followed with an initial set at 50 hours and a final set at 239 hours. Formulation A, the control took the longest time to set with an initial set at approximately 162 hours (7 days) and a final set at (2.5 weeks).

**Table 4:** Setting Time Test Results

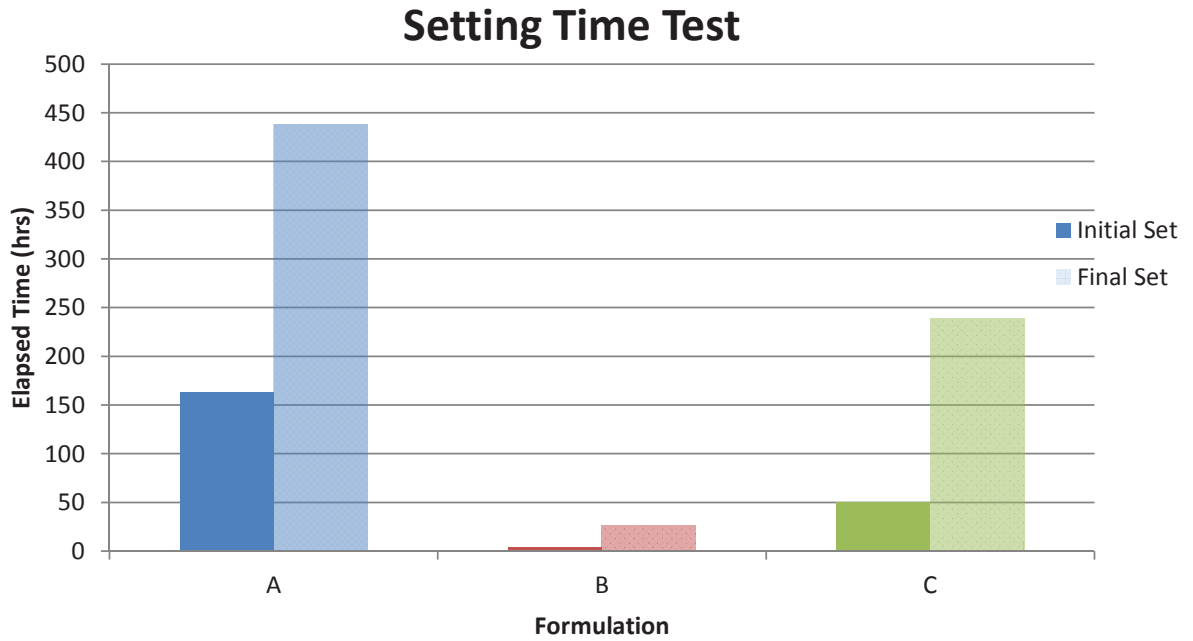
Formulation	Average Initial Set (hours)	Average Final Set (hours)
A	162.67	438.00
B	3.67	26.08
C	50.00	239

### **Sample Key**

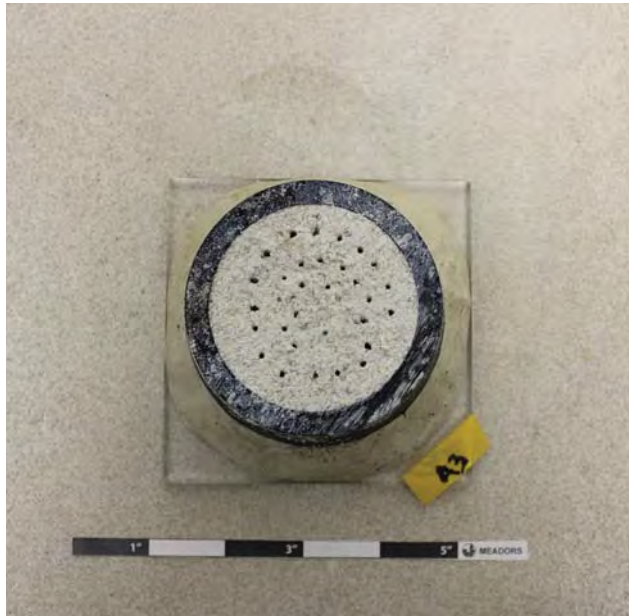
**Formulation A**                      Control- Concrete Sand  
**Formulation B**                      Crushed Volcanic Stone  
**Formulation C**                      Gravel

Note: Sample formulation 1:2 lime to aggregate

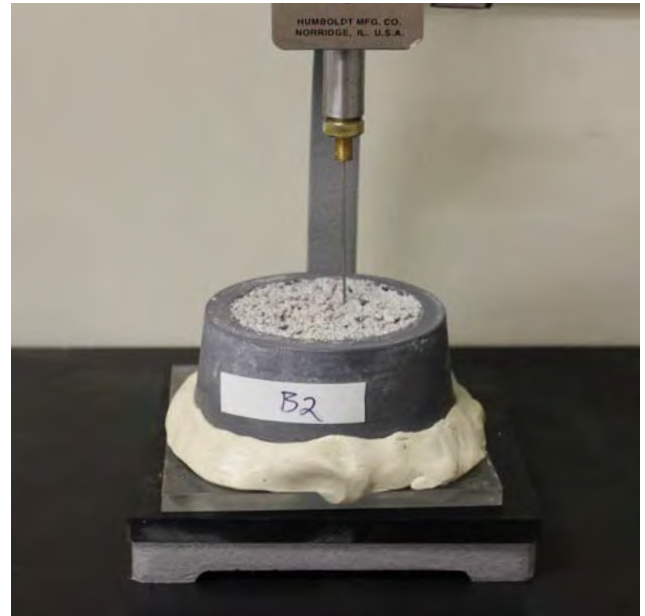




**Graph 3:** Results of Setting Time Test



**Figure 33:** Sample A following testing.



**Figure 34:** Sample B undergoing active testing.



## TESTING RESULTS

### *Underwater Set Test*

This test showed that only Formulation B, crushed volcanic rock, had the ability to set underwater. Formulation B reached initial set in approximately 51 hours and final set at approximately 123 hours. The control displayed no evidence of setting during the week testing period, after which the test was discontinued. Formulation C, gravel, initially showed a decrease in the needle's penetration depth, indicating that the sample was beginning to set. However, the sample did not show any further indication of reaching final set during the week testing period.

**Table 5: Underwater Set Test Results**

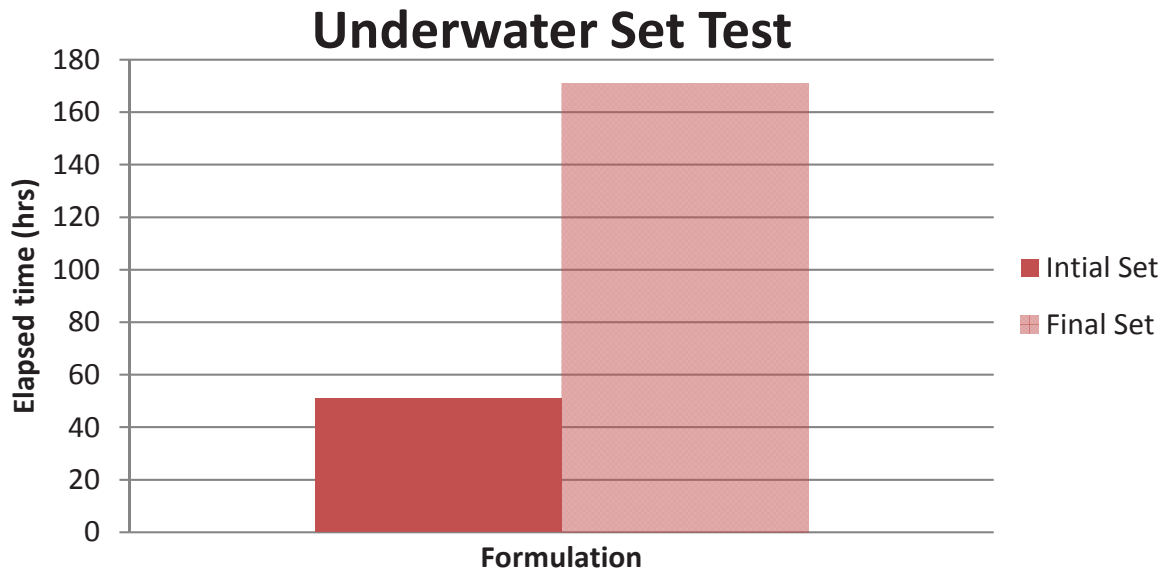
Formulation	Average Initial Set (hours)	Average Final Set (hours)
A	No Set	No Set
B	51	123
C	No Set	No Set

### **Sample Key**

**Formulation A**                      Control- Concrete Sand  
**Formulation B**                      Crushed Volcanic Stone  
**Formulation C**                      Gravel

Note: Sample formulation 1:4 lime to aggregate





Graph 4: Underwater Set Test Results



Figure 35: Formulation B undergoing Testing.



Figure 36: All prepared samples

## TESTING RESULTS

### *Compressive Strength Test*

Formulation B, the mortar containing the crushed volcanic rock, had a significantly higher compressive strength than Formulations A or C. Formulation A, the control, showed an average compressive strength of approximately 50. Formulation C showed an average compressive strength of approximately 83.3 psi. Formulation B had an average compressive strength of 225 psi, well above the other two formulations. The strength of Formulation B was 81.5% higher than that of the control and 64.0% higher than that for Formulation C, the mortar containing the gravel.

**Table 6: Compressive Strength Test Results**

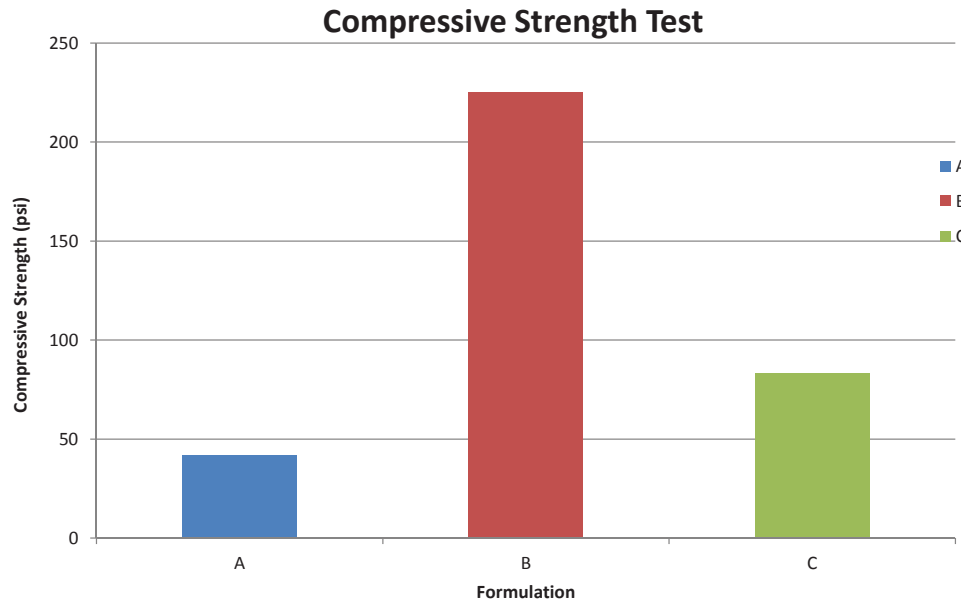
Formulation	Compressive Strength (psi)	Average Compressive Strength (psi)
A	25	41.7
	50	
	50	
B	175	225.0
	225	
	275	
C	100	83.3
	75	
	75	

#### Sample Key

**Formulation A**                      Control- Concrete Sand  
**Formulation B**                      Crushed Volcanic Stone  
**Formulation C**                      Gravel

Note: Sample formulation 1:2 lime to aggregate





**Graph 5:** Compressive Strength Test Results



**Figures 37 and 38:** Sample A undergoing compressive strength testing.

## DISCUSSION OF RESULTS

### *Introduction*

The testing methodology was able to provide varying amounts of information regarding each formulations individual pozzolanicity. The results are interpreted in the following section in order to make conclusions and recommendations.

### *Lime Combination Test*

The lime combination test indicated that Formulation B had the highest degree of pozzolanicity, with an increase in solid matter of over 148% indicating that the formation of calcium silicate hydrates is active and rapid. Formulation C, the mortar containing the gravel, showed a much lower degree of activity, but had an initial increase in solid matter amounting to 58%. Due to the lower increase in solid matter, it can be extrapolated that Formulation C formed less calcium silicate hydrate matter and is therefore less pozzolanic. For comparison purposes, Formulation A, displayed no increase in solid matter, and therefore test did not indicate any degree of pozzolanicity for this formulation.

It is important to note that this test does not necessarily measure any inherent property of each pozzolanic material, but simply indicates how reactive each respective material is under these experimental conditions. Ultimately, the degree of reactivity determined through the lime combination test was in direct agreement with the data determined by the setting time tests and compressive strength tests.

### *Setting Time Test*

The data obtained from the setting time test proved to be an excellent indicator of pozzolanicity. Pozzolans decrease the setting time of a mortar as the reactive silica and alumina within the material react with calcium hydroxide to produce calcium silicate hydrates. The setting of pozzolanic mortars occurs twofold by carbonation of the lime and the formation of these calcium silicate hydrates. This combined process allows for a more rapid setting time than mortars simply cured through carbonation.

Formulation A, a sand-lime mortar had the longest setting time as curing occurred only through carbonation. Formulation B, the most reactive formulation with the volcanic rock, had the most rapid set time of all formulations due to the pozzolanic volcanic aggregate. It can be assumed that the rapid setting time occurred mostly through the formation of the calcium silicate hydrates and with minor influence from carbonation. Formulation C, had a faster set time than the non pozzolanic Formulation A but was much more dependent on carbonation than Formulation B. As indicated by the lime combination test described above, the formation of calcium silicate hydrates likely occurred much slower in samples made with these formulations making it less pozzolanic than Formulation B. An important consideration when discussing this data is that the curing conditions of this mortar at 90% relative humidity greatly influenced the data presented in this report. It is likely that when mortars are mixed and laid in the field, temperature, relative humidity, and exposure to carbon dioxide in the atmosphere will greatly alter the setting times determined under laboratory conditions. However, it is likely that in these conditions that results would be consistent with the results of the controlled cure in terms of relative speeds at which the mortars set.



## DISCUSSION (CONTINUED)

### *Underwater Setting Time Test*

The underwater setting further indicated the pozzolanic nature of Formulation B and was agreement with the open air setting time data of the same formulation. During the testing program, only Formulation B set under water. As expected, the control did not set during the testing time period. Formulation C, despite showing some indications of pozzolanicity in other tests, did not set during the testing period. Initial readings indicated that setting was occurring, but this did not continue into for the week testing period. The behavior exhibited by this formulation is similar to that in the lime combination test, as there was initial increase in solid matter but did not continue throughout the test. Additionally, it is possible that the testing time period of one week was not sufficient time for the material to set solely by this type of reaction.

The behavior of Formulation B during this test is particularly notable as our data extends slightly beyond the range recommended by the French chemist Feret. According to Feret, active pozzolans should reach initial set at less than 50 hours and final set in less than 100 hours. Although Formulation B did not reach final set within the parameters established by Feret for a highly reactive pozzolan, the fact that it did set underwater, combined with the results of other tests, clearly indicates that is at least moderately pozzolanic. No mortar that does not contain hydraulic or pozzolanic components would be capable of setting under water.

### *Compressive Strength Testing*

The compressive strength testing data compliments the other data obtained from the aforementioned experiments. Formulation A displayed the lowest compressive strength as expected for lime-sand mortar. The differences of pozzolanic activity between Formulations B and C were very apparent in this experiment. Formula B with the highest activity out of the three formulations had the highest average compressive strength of 225 psi. Formulation C, with a relatively low pozzolanic activity had a compressive strength of 83, which was closer to the compressive strength of the control (43 psi) than that of Formulation B. In addition, Formulation B was 5.4 times stronger than the control A and 2.75 times stronger than C. Therefore this data when compared among all three formulations is in agreement with the results from the other tests.

However, the data is not in complete agreement with the compressive strengths determined by Highbridge Materials Consulting, Inc. The two samples (Highbridge samples # 1 and 2) of original plaster were determined to have a compressive strength of 1330 and 1660 psi. It should be noted that the compressive strength testing performed by Highbridge was done on non-standard test sizes and the data from which should be used as reference only. Curing time certainly influenced the results of compressive strength testing, making it difficult to compare the data of original samples with newly-created samples. It should be expected that the original mortar samples would have significantly higher strength than the freshly-created replication samples because complete carbonation would have likely occurred in the original samples, which have had many years to cure, whereas the newly-created samples only had 30 days to cure, and likely had not reached full carbonation. Furthermore, the samples tested by Highbridge included the original burnished finish, which has been thought to increase the hardness and overall strength of a material. In addition, as the samples were tested at 30 day cure time, there may have not been sufficient time for a pozzolanic reaction to develop to its greatest potential during this period. Research indicates that the pozzolanic reaction can be slow to occur. Due to this, low compressive strength results provided by the samples may not be indicative of the pozzolans' reactivity. It is likely that, if allowed a longer curing period not permitted by the time constraints of this project, all formulations would show a significant increase in strength.



## DISCUSSION (CONTINUED)

Also, it is possible that due to the low compressive strengths determined across all three formulations, there may exist an error in sample preparation that decreases the strength of the mortar being mixed and molded. Packing the molds for compressive strength samples and avoiding “deposit layers” within the cube was particularly difficult due to the large aggregate size. During the preparation of the samples, it was exceedingly more difficult to fully compress Formulations B & C into the molds than Formulation A. The presence of the large angular aggregate created voids within the sample that were not easily filled by the smaller grain sizes. These voids can decrease the compressive strength results as they offer no resistance during compressive strength testing.

Greater compressive strength results may be obtained by using more finely graded aggregate than those employed during this experiment. The aggregate gradation chosen for analysis was based upon the findings by Highbridge Materials Consulting, Inc. A slight change in the gradation of the original sands may produce the desired results without altering the compatibility of the replication materials.

Additionally, further testing with an increased water content could possibly improve the consolidation of the cubes. As mentioned previously, all the mortars made for testing prior to molding passed the inverted trowel test, which indicated that an adequate amount of water had been added to the mix. However, increased water content beyond that required for the trowel test may improve the immediate workability of the mortar and ensure that the mold are more successfully filled as the increased fluidity of the mix will allow voids to be more easily filled than previously tested. However, it is important to note that mortar with a high water content can have adverse affects on the workability and long term durability of the material.

### *Conclusions*

The results of all the tests showed that Formulation B, the crushed volcanic stone, was most pozzolanic based upon its behavior on the tested properties. All tests were able to confirm that this formulation has not only some degree of pozzolanicity, but also was highly reactive when compared among all formulations. Formulation C, the crushed gravel mortar, did show some indications of a mild pozzolanic reaction, but this cannot be determined conclusively from the data collected from these experiments .



## REPLICATION MORTAR

### *Replication Mortar*

Following the selection of Formulation B, prepared samples were compared with the Tumacácori bedding mortar to determine if there was a visual match between the replication and original materials. The original bedding mortar was described by Highbridge as light brownish gray in color with a Munsell color code approximately 10YR 6.5/2 “light gray” while the plaster was light buff to nearly white with a Munsell code 10YR 7.5-8/1 “light gray”. Sample discs of unpigmented Formulation B were bright white in color and have a Munsell color code of approximately N/9 “white”. This difference in color necessitated the creation of sample mortar discs with varying amounts of pigment in order to ensure visual continuity between the new and old materials.

1-1/2 inch circular sample discs were made of Formulation B with varying amounts of yellow iron oxide pigment (red shade). Due to the buff to gray color of the Formulation B aggregate, very small proportions of pigment were selected for replication trials which included samples made with 1/256, 1/512, and 1/1024 parts pigment. The samples were left to cure for several days and then visually compared to the original material in order to obtain the following recommendations. Laitance was removed from the replication discs prior to color matching using a bristle brush.



**Figure 39:** Original mortar (top) with unpigmented replication mortar (left), 1/1024 parts pigmented mortar (middle), and 1/512 parts pigmented mortar (right).



## REPLICATION MORTAR (CONTINUED)

### **Recommendation for Replication Bedding Mortar and Plaster**

- 1 part Chemstar Type S Hydrated Lime
- 2 parts Crushed Volcanic Rock from Tumacácori Mountain
- 1/512 parts Yellow Iron Oxide Pigment- Red Shade

### **Recommendations for Replication Mortar Materials**

- 1/512 Parts Yellow Oxide Pigment-Red Shade (Yellow 6940 Pigment) (Bayferrox 940)  
Available from Edison Coatings in 1 lb. and 5 lb. containers as Dry Color Pak, 3 Northwest Drive, Plainville, CT 06062 (860-747-2220), <http://www.edisoncoatings.com/store/>

The required volume of pigment necessary to achieve the desired color may vary when combined with the aggregate. Cured samples should be compared to the original to ensure an aesthetic match. All parts for each specified mortar mix should be mixed by volume and not by weight. Dry ingredients should be well mixed prior to the addition of a water.



**Figure 40:** Original mortar with selected 1/512 parts pigment replication mix.

## SURFACE FINISH

Highbridge Materials Consulting, Inc. concluded that brick dust particles were embedded in the lime plaster paste. Several different application methods were tested in order to determine if a similar finish could be replicated either through the application of limewash or a fresco on a hardened plaster surface.

### *Replication Limewash*

In an effort to further understand the brick particles embedded in the surface layer of the plaster Meadors Conservation researched available historic sources to gather information on the use of brick dust washes on plaster, historic recipes, and application methods. A combination of historic research and lab testing was used to develop a testing protocol for mixing and applying a replication brick wash.

### *Preparation*

Two bricks were sent to Meadors by the NPS for use during this phase of testing. Brick A (Figure 42) was a modern made brick from Mexico that is currently used at the park for repairs to the historic masonry. Brick B (Figure 41) was a Franciscan era historic brick. Both bricks were ground up using a mortar and pestle and sieved using the No 200 ( 0.074 mm) sieve as only the fines were retained for sample preparation. Four 1 : 4 lime to water washes of each brick type were made using each brick dust type in 5%, 10%, 15%, and 20% parts of brick dust by weight to the dry hydrate. When prepared, solutions had a consistency similar to milk.

### *Application*

Limewash samples were applied on 2 inch cubed samples that were not used during compression testing. One face of each cube was divided into two sections to allow for comparison between two different washes. Prior to application, the samples were thoroughly saturated with deionized water until it glistened but was not dripping. Each limewash solution was thoroughly agitated to ensure the solution was in suspension and then applied with a brush. Washes were applied twice a day for three days.

### *Results*

After 6 applications, it was apparent that all the limewashes imparted color to the original mortar to a varying degree. As expected, the wash with the highest proportion of brick dust caused the greatest change in chroma for both brick dust types. The 20% limewash formulation for brick dust A, the modern Mexican brick, was light pink in color and had a Munsell color code approximately 5YR 8/1 "white". The 20% limewash formulation of brick dust B, the historic Franciscan era brick, was also light pink in color and had a Munsell color code of 5YR 8/1 "white" (Figure 43). The applied washes did not match the original color of the plaster, which is light reddish brown in color with a Munsell color code approximately 2.5YR 6/3.

Therefore an additional test was made using a limewash with a darker red c. 1712 historic brick sampled from an archaeological site in Charleston, SC. The brick dust was prepared as described earlier in a 20% formulation and applied to the backside of one of the earlier cubes. After 2 applications, there was a noticeable difference in the color. Trials were also made with the Brick dust B in a 1:3 lime to water wash formulation in order to determine if a deeper color could be imparted to the surface of the mortar.



## SURFACE FINISH (CONTINUED)

### *Conclusions and Recommendations*

After several applications using the darker Charleston brick limewash, it was apparent that a deeper red to purple color was imparted to the mortar. It is likely that using a deeper and possibly more fired brick will allow for the recreation of a wash similar to the original. In order to replicate the finish exactly, it is recommended that further study be undertaken using a wider selection of potential brick dust sources.

Based on visual observation of the applied limewash it was apparent that the finish seen on the original plaster could not be replicated using this method of application.

Due to the visual appearance and behavior of the materials in the laboratory, it is likely the red finish coat was not a limewash, but likely imbedded into the surface of the freshly laid plaster. This is in agreement with the findings of Highbridge Materials Consulting, Inc. Additionally, the grainy aspect and visible aggregate of the surface wash indicate that a thorough carbonation process had occurred. The variable dispersion of the pigment throughout the grains highlights the fact that the pigment does not form a layer distinctive from the underlying plaster. These conditions are indicative of fresco finish.

Fresco is a method of painting in which pigments are ground up in suspension into liquid pigment dispersion and applied to an uncured lime substrate. The pigments are drawn in through capillary action. As the calcite crystallizes, the pigment is locked in the grain structure creating a durable surface. Lime stable water soluble natural pigments such as brick dust are commonly painted over a white lime plaster. Traditionally during this application, the less water used with the pigment, the more opaque the final fresco will be. This type of finish would be necessary for the structures such as the acequia as it was resistant to constant water action and ever changing environmental conditions.

Historically, fresh plaster, mortar, and fresco surfaces were often burnished to create a compact, hard, and smooth water proof surface. The act of polishing the surface creates a dense non porous structure at the surface of the material, decreasing the surface permeability while increasing the strength and hardening of the material. Burnished surfaces would allow for easier maintenance in areas prone to biogrowth and erosion, such as the acequia.

Literature from the early 18th century recommends the use of river cobbles or sheepskin in order to burnish the surface of the plaster. Burnishing has been used as early as 7000 BCE on the Mask of Jericho and in Mycenaean and Minoan settlements as early as 1500 BCE.

Based upon the available evidence and test samples prepared in the laboratory it is likely that the pigmented finish along the plaster surface was a burnished brick wash finish applied in a fresco fashion (Figure 44). The following recommendations are based upon historic research texts currently available and have not been extensively tested in the laboratory. However, locally based research not readily available to Meadors may provide more appropriate insight into historic surface finish techniques and regionally used application methods.

A full study of the embedded brick plaster finish has not been completed and therefore our results should only serve as an indication of potential application techniques. Meadors Conservation has not tested these application methods in large scale format and on all plaster formulations. The following recommendations have been selected from historic texts that detailed processes to create finishes similar to those seen at Tumacácori. It is strongly recommended that thorough testing is performed before a final formulation and application technique is chosen.



## SURFACE FINISH (CONTINUED)

### Preparation Methods:

Mix all dry materials and then add enough water to have a workable consistency. Care should be taken when using artificial pigments within this layer as certain pigments can be toxic when combined with lime. High magnesium or dolomitic lime is not recommended for this type of application and only high calcium lime should be used.

### *Recommendation for Limewater:*

1 part lime (powdered hydrated Type S)  
5 parts water

Mix the lime and water together until the lime is completely slaked. Stir and allow the mixture to separate. Repeat this process 2 times and retain the alkali water on top of this mixture. When using limewater for fresco application, avoid remixing the bottom of the bucket and only use the water on top.

### *Recommendation for Fresco:*

1 part brick dust  
3 to 5 parts lime water

Run a wet brush across the surface of the plaster after it has set. If the water is absorbed within 60 seconds, the plaster is ready to be painted. Ensure that the plaster surface is hard enough as to not deteriorate when brushed but not excessively dry as to inhibit adhesion of pigments and lime on the surface.

Apply the mixture with a synthetic bristle brush in a small workable area. Stir the mixture at each pass with the brush to ensure equal dispersion of the brick dust particles in every application. Do not apply in long strokes as this will result in streaking of the pigment.

Once the mixture has set, the surface can be burnished or polished with variety of materials in order to obtain the desired effect. This will require greater testing and experimentation in order to get the desired look. Generally, the thinner the pigmented layer, the more polished the surface appears. Following this, it is recommended that the area is protected from rain for 3 weeks in order to ensure proper carbonation.



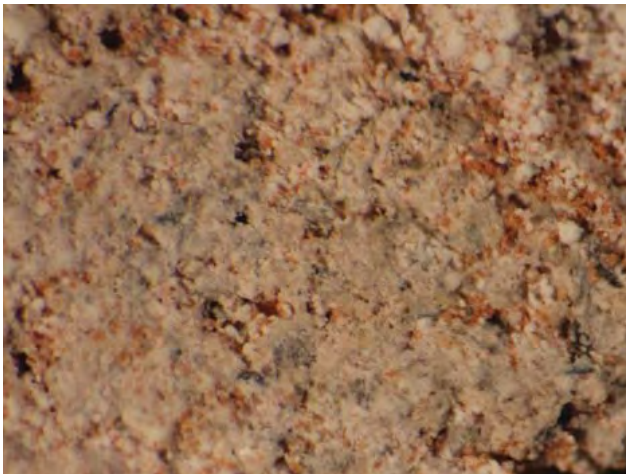
## WASH & FRESCO SAMPLES



**Figure 41:** Historic Franciscan period brick selected for study.



**Figure 42:** Modern Mexican brick selected for finish study.



**Figure 43:** Formulation B plaster with 20% Historic Franciscan period brick dust limewash applied after 5 applications. Samples using either brick were identical in color (Munsell color code of 5YR 8/1 “white”) and texture. Note: Light dispersion of brick dust with inconsistent deposition (upper right). (30x magnification, Reflected/Quartz Halogen)



**Figure 44:** Mexican brick fresco sample. Samples using either brick were identical in color (Munsell color code of 5YR 7/4 “pink”) and texture. Note: Even distribution of brick dust and darker appearance than limewash. (30x magnification, Reflected/Quartz Halogen)

## FINAL RECOMMENDATIONS

Based upon the data obtained through laboratory testing, Formulation B is the most pozzolanic mortar out of the samples tested. Formulation C displayed low to moderate pozzolanicity and should still be considered as a possible aggregate for a replication mix.

Through the previous analysis by Highbridge Materials Consulting, Inc, it was determined that the original bedding mortar (1:2) and plaster (1:2.6) were a mixture of lime to sand, using an aggregate of volcanic origin that likely served as a pozzolan. The grain size distribution and appearance of the original aggregate was closely matched to the volcanic aggregate provided by the National Park Service. The laboratory experiments employed by Meadors Conservation indicated that, out of the aggregate provided by the National Park Service, the crushed volcanic rock had the highest degree of pozzolanicity. Analysis by Highbridge indicated that the original mortar and plaster contained volcanic sands that served as a natural pozzolan. No studies to date have been able to ascertain the degree of pozzolanicity of the original volcanic sand used in the original formulation, or whether volcanic fines were added intentionally as a known pozzolanic additive or they were a components of the unwashed sands. However, as indicated in this study, use of formulation B as a replication mixture may serve as the most compatible formulation of those tested due to the volcanic origin and inherent pozzolanicity of the aggregate, particle size distribution and appearance of the aggregate, relatively low compressive strength, and overall mixture proportions.

At the conclusion of this testing, Formulation B appears to be an appropriate mortar mix as it closely imitates the properties and appearance of the original mortar and has shown pozzolanic reactivity. The pozzolanicity of the mix can provide greater strength and durability for the mortar without the necessity of incorporating any additives, Portland cement, or naturally hydraulic lime. The pozzolanic lime mortar may be physically compatible with existing original mortar and soft, adobe brick substrate while providing greater durability than a traditional lime and non-pozzolanic sand mortar. However the current pozzolanic strength development of this mortar past 30 days remains unknown and should be further investigated before this formulation is selected for use. It is possible that the compressive strength of this formulation may surpass that of the soft mortar and brick as time progresses, potentially creating a situation in which the repair material may cause further damage to the original fabric. Additionally, the strength development of Formulation C may increase as well, producing a final strength value similar to that of the original material.

Based upon further strength testing, a mix of hydrated lime to local crushed volcanic rock (Formulation B) or gravel (Formulation C) may be selected for the conservation treatment of the compuerta within the acequia at Tumacácori National Historical Park. The proportions of materials used for replicating the bedding mortar (1:2) and plaster (1:2.6) should adhere to the findings of Highbridge Materials Consulting, Inc (see report in appendix p. 67).



## RECOMMENDATIONS FOR FUTURE STUDY

As mentioned previously, further study should be conducted to perform additional compressive strength testing on cured Formulation B and C mortars. Testing these samples at different intervals beyond the 30 day mark will indicate the strength development over time of these pozzolanic materials. Pozzolanic reactions are known to be slow to develop and it is likely that the ultimate strength obtained by this material is higher than was recorded at 30 days. Ideally, further compressive strength tests would be conducted after curing for 6 months and 1 year. Testing during these periods will indicate the rate of strength development between Formulations B and C, and if the final compressive strength of highly reactive Formulation B will surpass that of the original material. Additionally, testing samples with a smaller aggregate gradation and increased water content may allow for increased strength results.

An additional recommendation for further testing would be for the characterization of cured pozzolanic Formulation B and C mortars and plasters through use of optical microscopy. This will allow the micro texture of the replication to be compared with the images and findings from Highbridge Materials Consulting, Inc. Visual microscopic similarities between the original and replication mixes will help to further assess the compatibility between these materials.

Once the final aggregate is selected, the application of the fresco needs to be studied on a larger scale. It is recommended that 2 by 2 foot mockups be created to test the application of this finish on the replication plaster. In addition to testing the application of the fresco, it is recommended the different burnishing techniques be evaluated as well, such as the use of river cobbles or sheep's skin to smooth the plaster surface. The creation of a test panel allows for the mock-up to be easily compared to the original plaster to ensure visual compatibility.



## REFERENCES

Moran, W.T., and Gilliland, J. L.,(1950). Summary of Methods for Determining Pozzolanic Activity, Symposium on Use of Pozzolanic Materials in Mortars and Concretes, ASTM Special Technical Publication No. 99, p. 116.

Moss, Jeremy. (2008) Of Adobe, Lime, and Cement: The Preservation History of the San José de Tumacácori Mission Church (Part III – Garden and Orchard), Tumacácori National Historical Park, National Park Service

Rogers, Sara B. (2011). Evaluation Testing of Brick Dusts as a Pozzolanic Additive to Lime Mortars for Architectural Conservation. (Masters Thesis). University of Pennsylvania, Philadelphia PA.

Shenwan, Al-Bashaireh, Khaled (2008) Chronology and technological production styles of Nabatean and Roman plasters and mortars at Petra (Jordan). (Ph.D.) University of Arizona, Tuscon AZ.

### Referenced Standards:

American Society for the Testing of Materials. "C109 Standard Test Method for Compressive Strength of Hydraulic Cement Mortars." Annual Book of ASTM Standards. West Conshohocken, PA: American Society for the Testing of Materials, 2000.

American Society for Testing of Materials. "C191-99 Standard Test Method for Time Setting of Hydraulic Cement by Vicat Needle." Annual Book of ASTM Standards. Vol. 04.01. West Conshohocken, PA, ASTM 2000.

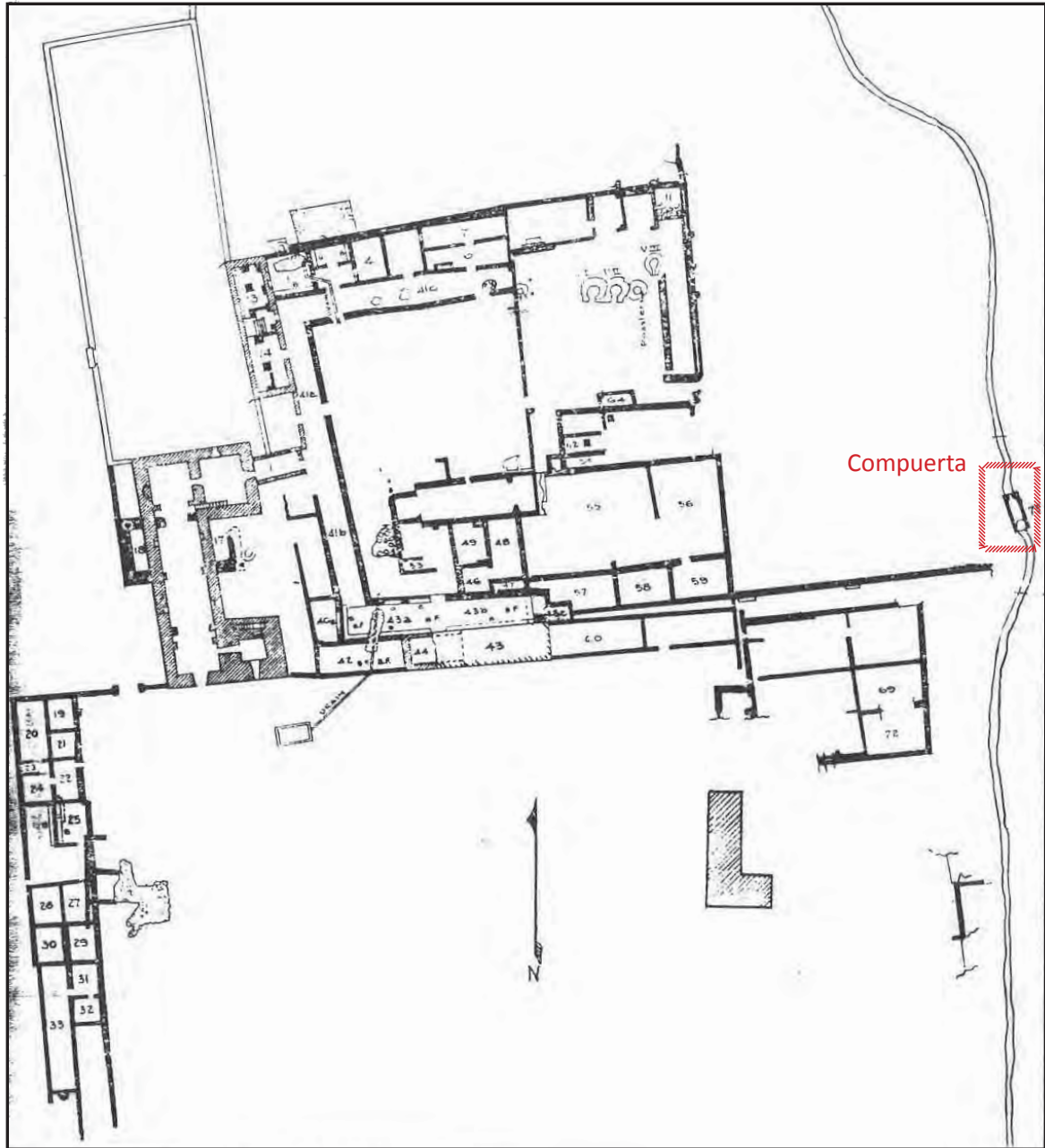




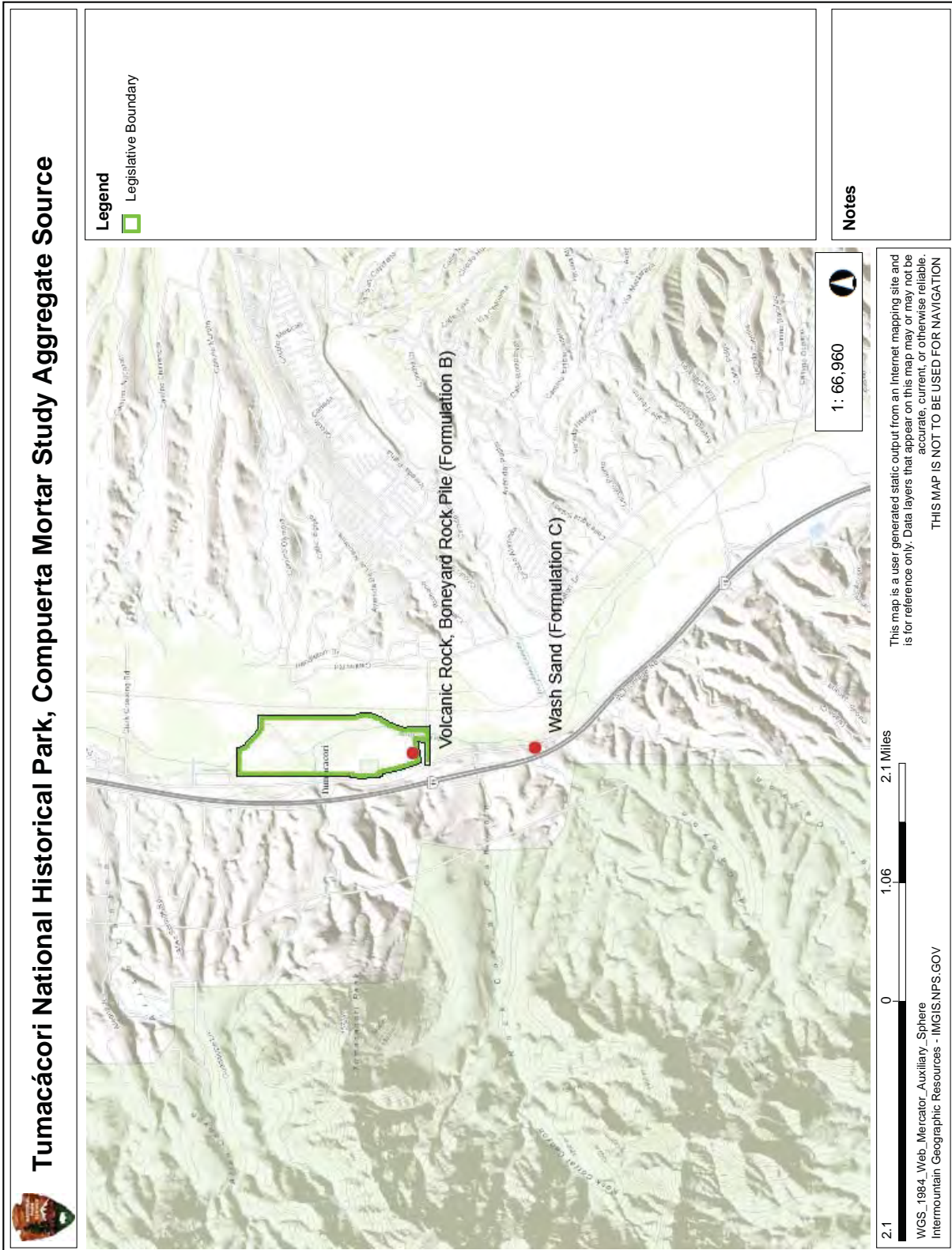
# APPENDIX



APPENDIX  
SITE MAP: GROUND PLAN TUMACÁCORI MISSION 1934



APPENDIX  
 MAP: ROCK AND GRAVEL SAMPLE LOCATIONS



APPENDIX  
SALT TESTS

ANION CONCENTRATIONS

Formulation	NO <sub>3</sub> <sup>-</sup> (mg/L)	NO <sub>2</sub> <sup>-</sup> (mg/L)	SO <sub>2</sub> <sup>4-</sup> (mg/L)	Cl <sup>-</sup> (mg/L)
A	0	Not Present	<200	50
B	0	Not Present	<200	0
C	10	Not Present	<200	0

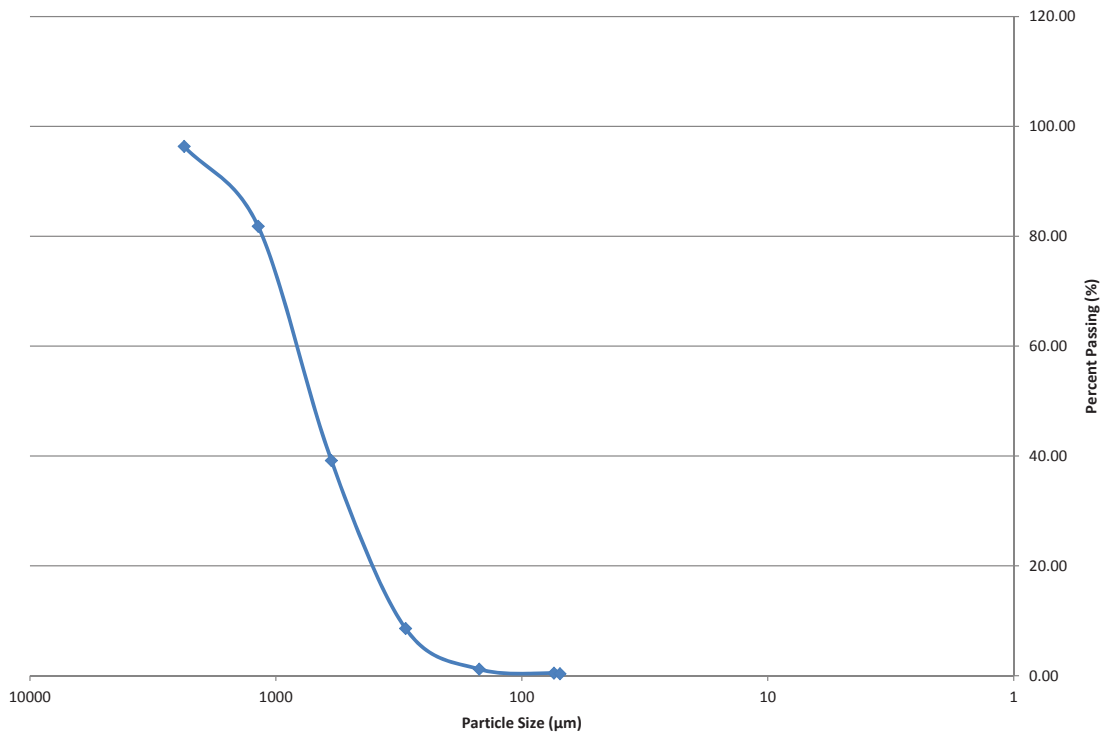


APPENDIX  
 PARTICLE SIZE DISTRIBUTION SAMPLE A (CONTROL)

SIEVE ANALYSIS DATA SAMPLE A

Sieve Number	Screen Size	M <sub>c</sub> (g)	M <sub>2</sub> (sample + cont.) (g)	M <sub>r</sub> (M <sub>2</sub> - M <sub>c</sub> ) (g)	%M <sub>r</sub> (M <sub>r</sub> / M <sub>s</sub> )*100%	%M <sub>rt</sub> Σ %M <sub>r</sub> (on or above)	%M <sub>pt</sub> 100% - M <sub>rt</sub> %
8	2360	1.54	4.94	3.40	3.65	3.65	96.35
16	1180	1.54	15.08	13.54	14.55	18.20	81.80
30	595	1.54	41.22	39.68	42.64	60.84	39.16
50	297	1.46	29.90	28.44	30.56	91.40	8.60
100	149	1.60	8.50	6.90	7.41	98.82	1.18
200	74	1.50	2.18	0.68	0.73	99.55	0.45
Pan	0	1.52	1.62	0.10	0.11	99.66	0.34

Sieve Analysis Sample A: Murray Mine Concrete Sand

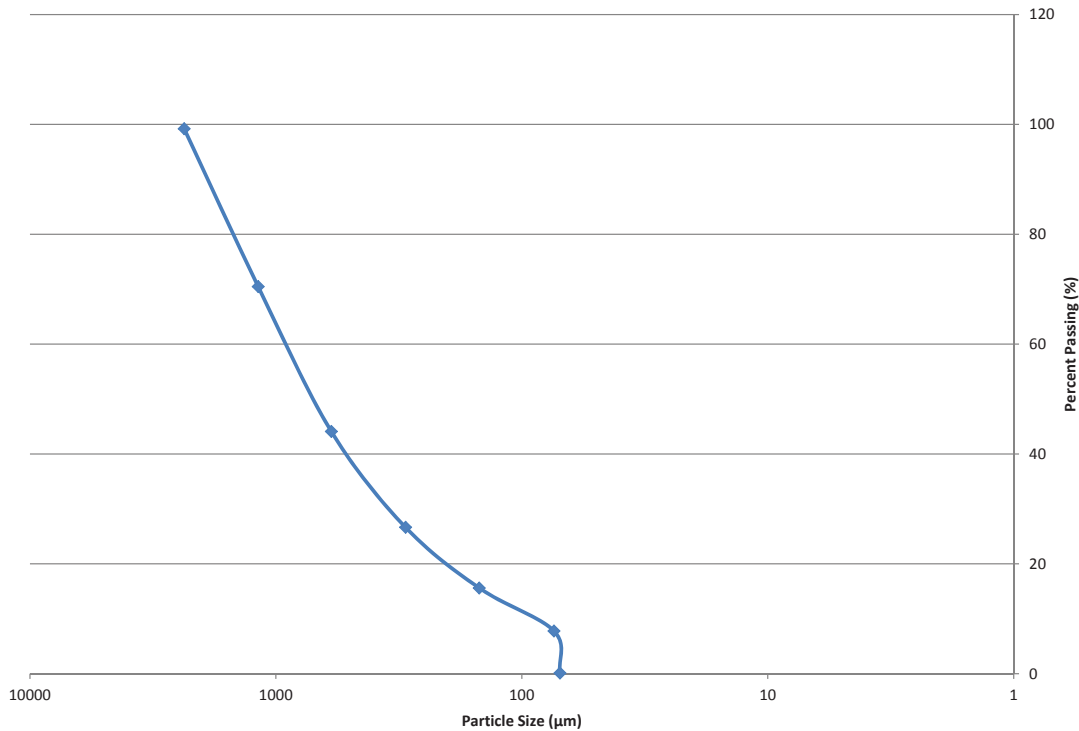


APPENDIX  
 PARTICLE SIZE DISTRIBUTION SAMPLE B (CRUSHED VOLCANIC ROCK)

SIEVE ANALYSIS DATA SAMPLE B

Sieve Number	Screen Size	M <sub>c</sub> (g)	M <sub>2</sub> (sample + cont.) (g)	M <sub>r</sub> (M <sub>2</sub> - M <sub>c</sub> ) (g)	%M <sub>r</sub> (M <sub>r</sub> / M <sub>c</sub> ) * 100%	%M <sub>rt</sub> Σ %M <sub>r</sub> (on or above)	%M <sub>pt</sub> 100% - M <sub>rt</sub> %
8	2360	1.52	2.32	0.80	0.78	0.78	99.22
16	1180	1.58	31.04	29.46	28.75	29.53	70.47
30	595	1.64	28.66	27.02	26.37	55.90	44.10
50	297	1.56	19.44	17.88	17.45	73.36	26.64
100	149	1.5	12.82	11.32	11.05	84.40	15.60
200	74	1.5	9.52	8.02	7.83	92.23	7.77
Pan	0	1.52	9.36	7.84	7.65	99.88	0.12

Sieve Analysis Sample B: Crushed Volcanic Rock

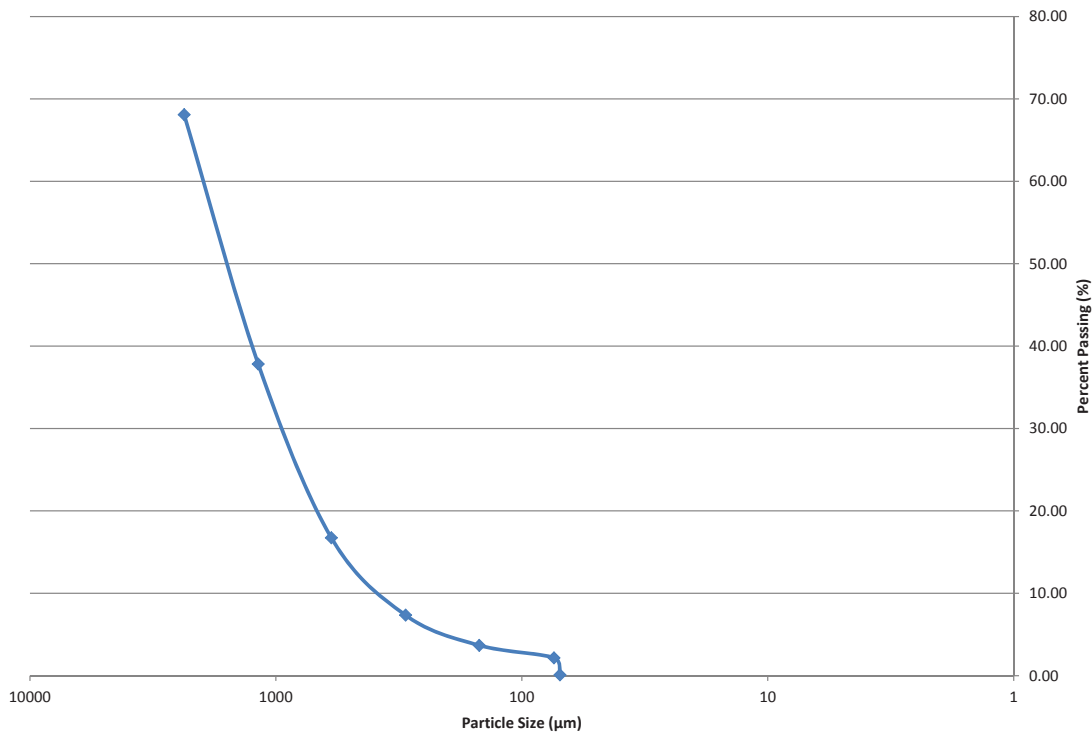


APPENDIX  
 PARTICLE SIZE DISTRIBUTION SAMPLE C (GRAVEL)

SIEVE ANALYSIS DATA SAMPLE C

Sieve Number	Screen Size	M <sub>c</sub> (g)	M <sub>2</sub> (sample + cont.) (g)	M <sub>r</sub> (M <sub>2</sub> - M <sub>c</sub> ) (g)	%M <sub>r</sub> (M <sub>r</sub> / M <sub>s</sub> )*100%	%M <sub>rt</sub> Σ %M <sub>r</sub> (on or above)	%M <sub>pt</sub> 100% - M <sub>rt</sub> %
8	2360	1.52	35.50	33.98	31.91	31.91	68.09
16	1180	1.58	33.80	32.22	30.26	62.17	37.83
30	595	1.64	24.10	22.46	21.09	83.26	16.74
50	297	1.56	11.56	10.00	9.39	92.66	7.34
100	149	1.50	5.40	3.90	3.66	96.32	3.68
200	74	1.50	3.12	1.62	1.52	97.84	2.16
Pan	0	1.52	3.72	2.20	2.07	99.91	0.09

Sieve Analysis Sample C: Gravel



APPENDIX

PROPORTIONS AND QUANTITIES OF COMPONENTS FOR SETTING TIME AND COMPRESSIVE STRENGTH

MIX PROPORTIONS BY VOLUME

Formulation	Hydrated Lime	Concrete Sand	Crushed Volcanic Rock	Mountain Gravel
A	1	2	--	--
B	1	--	2	--
C	1	--	--	2

MIX PROPORTIONS BY VOLUME

Tumacacori						
Mixing of Setting Time and Compressive Strength Samples						
	VOLUME			Mass		
	Lime (mL)	Aggr (mL)	Water (ml)	Lime (g)	Aggr (g)	Water (g)
Formulation A	1	2	509.72	370.46	2885.00	509.72
Formulation B	1	2	425.20	272.18	1580.68	425.20
Formulation C	1	2	424.78	279.78	1634.38	424.78





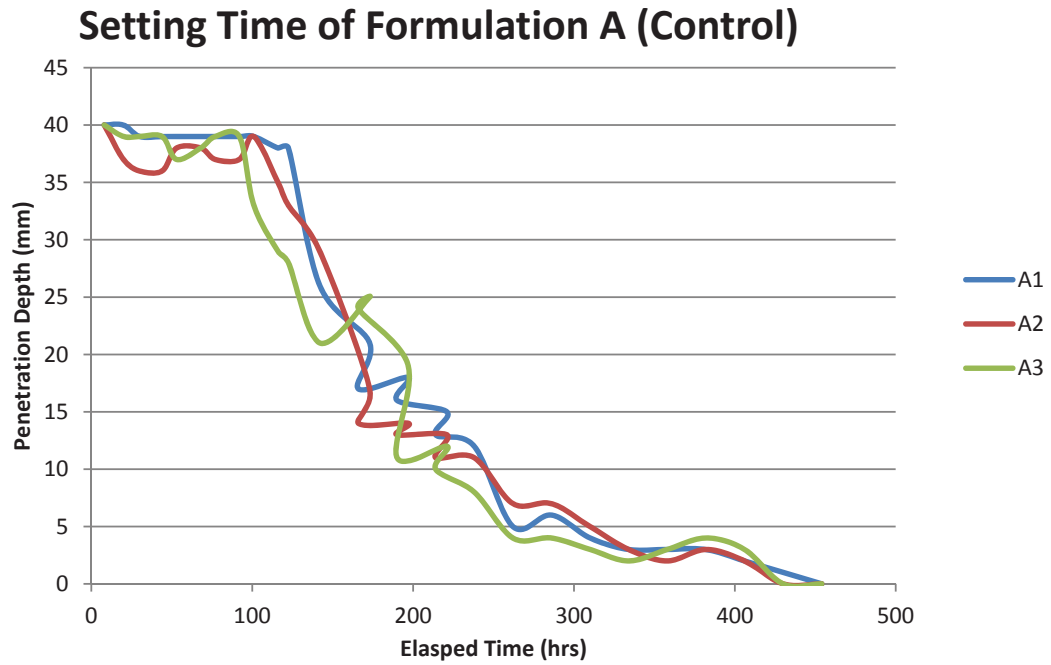
APPENDIX  
SETTING TIME DATA: FORMULATION A

SETTING TIME DATA FORMULATION A

Tumacacori: Setting Time							
Formulation A							
Date	Elapsed Time (hrs)	Temp	%RH	A1 (mm)	A2 (mm)	A3 (mm)	Average (mm)
4/8/2013	8	71.0	89	40	40	40	40.00
4/9/2013	20	71.0	89	40	37	39	38.67
4/9/2013	30	73.6	88	39	36	39	38.00
4/10/2013	44	72.0	89	39	36	39	38.00
4/10/2013	53	74.1	87	39	38	37	38.00
4/11/2013	68	72.7	89	39	38	38	38.33
4/11/2013	77	74.7	88	39	37	39	38.33
4/12/2013	92	73.0	89	39	37	39	38.33
4/12/2013	101	75.0	88	39	39	33	37.00
4/13/2013	116	72.0	89	38	35	29	34.00
4/14/2013	122.5	72.0	89	38	33	28	33.00
4/15/2013	142	72.9	89	26	29	21	25.33
4/15/2013	173	73.0	86	21	17	25	21.00
4/16/2013	166	73.2	86	17	14	24	18.33
4/16/2013	197	73.2	88	18	14	19	17.00
4/17/2013	190	75.2	88	16	13	11	13.33
4/17/2013	221	73.8	90	15	13	12	13.33
4/18/2013	214	73.8	90	13	11	10	11.33
4/19/2013	238	73.8	90	12	11	8	10.33
4/21/2013	262	73.4	90	5	7	4	5.33
4/22/2013	286	70.2	82	6	7	4	5.67
4/23/2013	310	71.8	90	4	5	3	4.00
4/24/2013	334	71.8	90	3	3	2	2.67
4/25/2013	358	71.8	90	3	2	3	2.67
4/26/2013	382	73.0	90	3	3	4	3.33
4/28/2013	406	73.4	90	2	2	3	2.33
5/1/2013	430	73.6	89	1	0	0	0.33
5/3/2013	454	73.4	89	0	0	0	0.00



APPENDIX  
SETTING TIME DATA: FORMULATION A



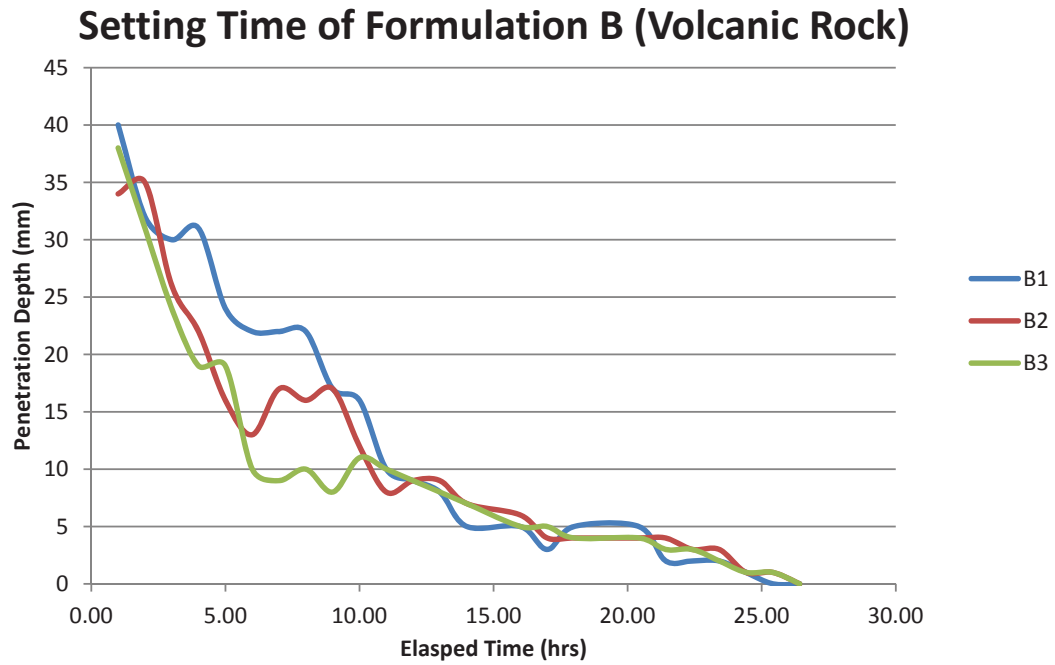
APPENDIX  
SETTING TIME DATA: FORMULATION B

SETTING TIME DATA FORMULATION B

Tumacacori: Setting Time							
Formulation B							
Date	Elapsed Time	Temp	%RH	B1 (mm)	B2 (mm)	B3 (mm)	Average (mm)
5/6/2013	1.00	73.5	83	40	34	38	37.33
5/6/2013	2.00	74.7	83	32	35	31	32.67
5/6/2013	3.00	75	84	30	26	24	26.67
5/6/2013	4.00	74.7	85	31	22	19	24.00
5/6/2013	5.00	74.5	85	24	16	19	19.67
5/6/2013	6.00	74.5	85	22	13	10	15.00
5/6/2013	7.00	74.7	85	22	17	9	16.00
5/6/2013	8.00	75	86	22	16	10	16.00
5/6/2013	9.00	74.8	86	17	17	8	14.00
5/6/2013	10.00	74.8	86	16	12	11	13.00
5/6/2013	11.00	74.8	86	10	8	10	9.33
5/6/2013	12.00	75	85	9	9	9	9.00
5/7/2013	13.00	75	85	8	9	8	8.33
5/7/2013	14.00	75	88	5	7	7	6.33
5/7/2013	16.00	74.5	87	5	6	5	5.33
5/7/2013	17.00	73.6	84	3	4	5	4.00
5/7/2013	18.00	74.1	82	5	4	4	4.33
5/7/2013	20.42	73.9	85	5	4	4	4.33
5/7/2013	21.42	73.8	86	2	4	3	3.00
5/7/2013	22.42	73.8	86	2	3	3	2.67
5/7/2013	23.42	73.8	86	2	3	2	2.33
5/7/2013	24.42	73.6	86	1	1	1	1.00
5/7/2013	25.42	73.6	86	0	1	1	0.67
5/7/2013	26.42	73.8	86	0	0	0	0.00



APPENDIX  
SETTING TIME DATA: FORMULATION B



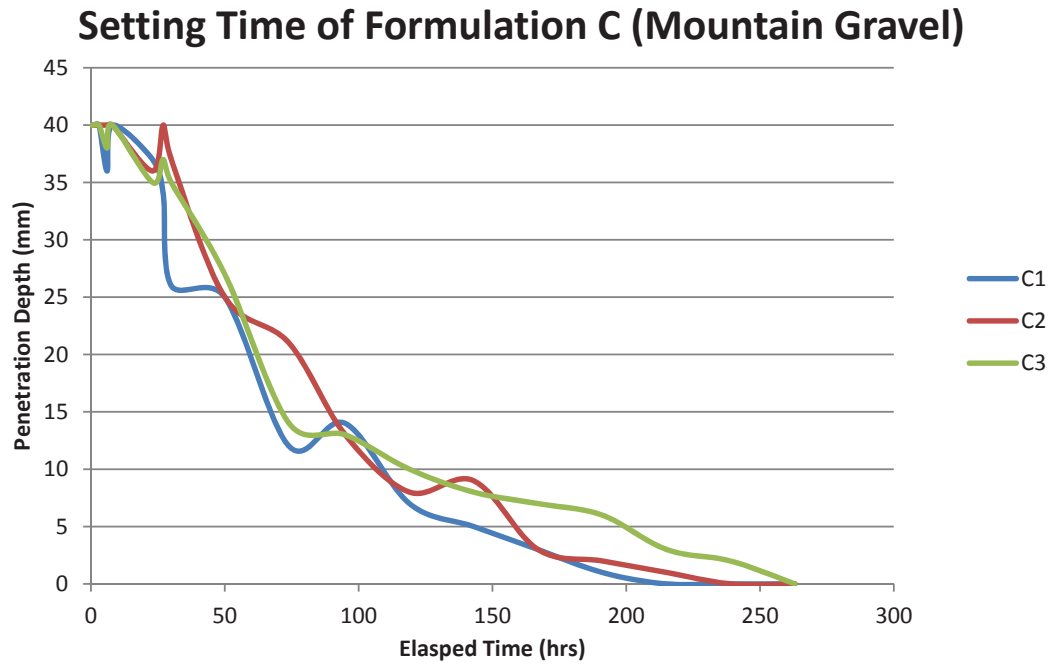
APPENDIX  
SETTING TIME DATA: FORMULATION C

SETTING TIME DATA FORMULATION C

Tumacacori: Setting Time							
Formulation C							
Date	Elapsed Time	Temp	%RH	C1 (mm)	C2 (mm)	C3 (mm)	Average (mm)
6/6/2013	0	72.0	82	40	40	40	40.00
6/6/2013	1	74.5	86	40	40	40	40.00
6/6/2013	3	74.7	87	40	40	40	40.00
6/6/2013	6	75.4	87	36	40	38	38.00
6/6/2013	8	74.7	86	40	40	40	40.00
6/7/2013	23	74.3	89	37	36	35	36.00
6/7/2013	27	75.4	88	34	40	37	37.00
6/7/2013	30	74.7	89	26	37	35	32.67
6/8/2013	50	74.1	89	25	25	27	25.67
6/9/2013	74	74.7	89	12	21	14	15.67
6/10/2013	95	75.0	91	14	13	13	13.33
6/11/2013	119	74.5	90	7	8	10	8.33
6/12/2013	143	73.9	88	5	9	8	7.33
6/13/2013	167	74.1	85	3	3	7	4.33
6/14/2013	191	75.0	89	1	2	6	3.00
6/15/2013	215	75.6	89	0	1	3	1.33
6/16/2013	239	75.6	89	0	0	2	0.67
6/17/2013	263	76.5	89	0	0	0	0.00



APPENDIX  
SETTING TIME DATA: FORMULATION C

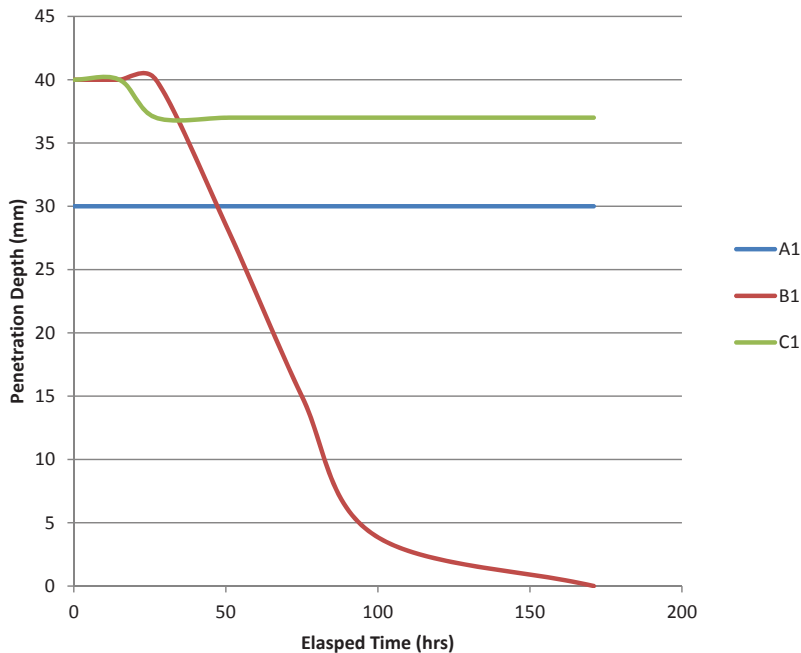


APPENDIX  
 UNDERWATER SETTING TIME DATA

UNDERWATER SETTING TIME DATA

Tumacacori					
UNDERWATER SET TEST (All Formulations)					
Date	Time	Elapsed Time	A1 (mm)	B1 (mm)	C1 (mm)
6-May	11:00 AM	0	30	40	40
7-May	2:00 AM	15	30	40	40
7-May	2:00 PM	27	30	40	37
8-May	2:00 PM	51	30	28	37
9-May	2:00 PM	75	30	15	37
10-May	2:00 PM	99	30	4	37
13-May	2:00 PM	171	30	0	37

Underwater Setting Time (All Formulations)



## APPENDIX LIME COMBINATION TEST DATA (FORMULATIONS A & B)

### LIME COMBINATION TEST DATA FORMULATION A

Tumacacori: Lime Combination Test								
Formulation A								
			Initial Reading (mm)			4 Minutes after Agitation (mm)		
Date	Time	Elapsed Time (hrs)	A1	A2	A3	A1	A2	A3
4/11/2013	8:00 AM	0	12	11	11	13	11	14
4/12/2013	8:00 AM	24	12	11	11	14	13	15
4/13/2013	1:00 PM	53	12	11	11	16	17	15
4/14/2013	1:00 PM	77	12	11	11	16	17	15
4/15/2013	8:00 AM	96	12	11	11	16	17	15
4/16/2013	8:00 AM	120	12	11	11	16	17	15
4/17/2013	8:00 AM	144	12	11	11	16	17	15
4/18/2013	8:00 AM	168	12	11	11	16	17	15

### LIME COMBINATION TEST DATA FORMULATION B

Tumacacori: Lime Combination Test								
Formulation B								
			Initial Reading (mm)			4 Minutes after Agitation (mm)		
Date	Time	Elapsed Time (hrs)	B1	B2	B3	B1	B2	B3
4/3/2013	3:30 PM	0.0	10	9	10	10	9	10
4/4/2013	3:30 PM	24.0	10	9	10	14	12	12
4/5/2013	3:30 PM	48.0	13	11	11	19	15	16
4/6/2013	1:00 PM	69.5	17	14	15	26	20	20
4/7/2013	8:00 PM	100.5	19	18	19	36	28	31
4/8/2013	3:30 PM	120.0	20	19	24	42	34	40
4/9/2013	3:30 PM	144.0	23	21	25	44	41	53
4/10/2013	3:30 PM	168.0	24	21	27	45	42	63





APPENDIX  
 LIME COMBINATION TEST DATA (FORMULATION C)

LIME COMBINATION TEST DATA FORMULATION C

Tumacacori: Lime Combination Test								
Formulation C								
			Initial Reading (mm)			4 Minutes after Agitation (mm)		
Date	Time	Elapsed Time (hrs)	C1	C2	C3	C1	C2	C3
4/3/2013	3:30 PM	0.0	10	9	10	10	9	10
4/4/2013	3:30 PM	24.0	10	10	11	11	17	18
4/5/2013	3:30 PM	48.0	11	17	18	11	17	18
4/6/2013	1:00 PM	69.5	11	17	18	11	17	18
4/7/2013	8:00 PM	100.5	11	17	18	11	17	18
4/8/2013	3:30 PM	120.0	11	17	18	11	17	18
4/9/2013	3:30 PM	144.0	11	17	18	11	17	18
4/10/2013	3:30 PM	144.0	11	17	18	11	17	18
4/11/2013	3:30 PM	168.0	11	17	18	11	17	18



APPENDIX  
COMPRESSIVE STRENGTH TESTING (FORMULATION A & B)



**Figure 1:** Formulation A prior to testing.



**Figure 2:** Formulation A undergoing compressive strength testing.



**Figure 3:** Formulation B prior to testing.



**Figure 4:** Formulation B undergoing compressive strength testing.

APPENDIX  
COMPRESSIVE STRENGTH TESTING (FORMULATION C)



**Figure 5:** Formulation C prior to testing.



**Figure 6:** Formulation C undergoing compressive strength testing.



**Material Safety Data Sheet  
Type S Hydrated Lime**

**SECTION 1: PRODUCT AND COMPANY IDENTIFICATION**

**Product Name:** Type S Hydrated Lime, Type SA Hydrated Lime  
**Synonym/s:** Dolomitic Hydrate; Hydrated Dolomitic Lime; Calcium Magnesium Hydroxide; Double Hydrated Dolomitic Lime  
**Chemical Name:** Calcium Magnesium Hydroxide **Chemical Formula:** CaOH<sub>2</sub>MgOH<sub>2</sub>  
**Product Use/s:** Construction, Water treatment, pH adjustment, FGT

<b>Manufacturer:</b>	<b>US Operations:</b> Lhoist North America 3700 Hulen St. Fort Worth, TX 76107 817-732-8164	<b>Canadian Operations:</b> Lhoist North America of Canada, Inc. 20303-102B Ave. Langley, BC V1M 3H1 604-888-4333
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**Emergency Phone:** Chemtrec 1-800-424-9300

**SECTION 2: HAZARDS IDENTIFICATION**

**Emergency Overview:** Type S hydrated lime is an odorless white powder. Contact can cause irritation to eyes, skin, respiratory system, and gastrointestinal tract.

**Hazard Pictograms:**



**Potential Health Effects**

- Eyes:** Contact can cause severe irritation or burning of eyes, including permanent damage.
- Skin:** Contact can cause severe irritation or burning of skin, especially in the presence of moisture.
- Ingestion:** This product can cause severe irritation or burning of gastrointestinal tract if swallowed.
- Inhalation:** This product can cause severe irritation of the respiratory system. Long-term exposure may cause permanent damage. Type S hydrated lime is not listed by MSHA, OSHA, or IARC as a carcinogen. However, this product may contain trace amounts of crystalline silica in the form of quartz or crystobalite, which has been classified by IARC as a Group I carcinogen to humans when inhaled. Inhalation of silica can also cause a chronic lung disorder, silicosis.

**Potential Environmental Effects:** This material is alkaline and if released into water or moist soil will cause an increase in pH.

**SECTION 3: COMPOSITION / INFORMATION ON INGREDIENTS**

Ingredient	Chemical Formula	Common Name	Conc. (%)	CAS
Calcium Hydroxide	Ca(OH) <sub>2</sub>	Portlandite	> 50	1305-62-0
Magnesium Hydroxide	Mg(OH) <sub>2</sub>	Brucite	> 35	1309-42-8
Magnesium Oxide	MgO	Periclase	< 3	1309-48-4
Calcium Carbonate	CaCO <sub>3</sub>	Limestone	< 3	1317-65-3
Crystalline Silica	SiO <sub>2</sub>	Quartz	< 1	14808-60-7

(Crystalline Silica is reported as total silica and not just the respirable fraction)





**Material Safety Data Sheet**  
**Type S Hydrated Lime**

**SECTION 4: FIRST AID MEASURES**

**Eyes:** Immediately flush eyes with generous amounts of water or eye wash solution if water is unavailable. Pull back eyelid while flushing to ensure that all Type S hydrated lime dust has been washed out. Seek medical attention promptly if the initial flushing of the eyes does not remove the irritant. Do not rub eyes.

**Skin:** Brush off or remove as much dry lime as possible. Wash exposed area with large amounts of water. If burned seriously or if irritation persists, seek medical attention promptly.

**Inhalation:** Move victim to fresh air. Seek medical attention. If breathing has stopped, give artificial respiration.

**Ingestion:** Do not induce vomiting. Seek medical attention immediately. Never give anything by mouth unless instructed to do so by medical personnel.

**Medical Conditions Aggravated by Exposure:** Contact may aggravate disorders of the eyes, skin, gastrointestinal tract, and respiratory system.

**SECTION 5: FIREFIGHTING MEASURES**

**Fire Hazards:** Type S hydrated lime is not combustible or flammable. However, it reacts vigorously with acids, and may release heat sufficient to ignite combustible materials in specific instances. Type S hydrated lime is not considered to be an explosion hazard, although reaction with acids or other incompatible materials may rupture containers.

**Suitable Extinguishing Media:** Use dry chemical or CO<sub>2</sub> fire extinguisher to extinguish the surrounding fire.

**Fire Fighting Instructions:** Keep personnel away from and upwind of fire. Avoid skin contact or inhalation of dust. Wear full fire-fighting turn-out gear (full Bunker gear), and respiratory protection (SCBA).

**Hazardous Combustion Products:** Not applicable

**SECTION 6: ACCIDENTAL RELEASE MEASURES**

**Spill / Leak Procedures:** **Do Not** use water on bulk material spills. Use proper personal protective equipment.

**Small Spills:** Use dry methods to collect spilled materials. Avoid generating dust. Do not clean up with compressed air. Store collected materials in dry, sealed plastic or non-aluminum metal containers. Residue on surfaces may be water washed.

**Large Spills:** Use dry methods to collect spilled materials. Evacuate area downwind of clean-up operations to minimize dust exposure. Store spilled materials in dry, sealed plastic or non-aluminum metal containers.

**Containment:** Minimize dust generation and prevent bulk release to sewers or waterways.

**Clean-up:** Residual amounts of material can be flushed with large amounts of water. Equipment can be washed with either a mild vinegar and water solution, or detergent and water.

**SECTION 7: HANDLING AND STORAGE**

**Handling:** Keep in tightly closed plastic or non-aluminum metal containers. Protect containers from physical damage. Avoid direct skin contact with the material. Avoid breathing any dust.

**Storage:** Store in a cool, dry, and well-ventilated location. Do not store near acids or other incompatible materials. Keep away from moisture. Do not store or ship in aluminum containers.





**Material Safety Data Sheet  
Type S Hydrated Lime**

**SECTION 8: EXPOSURE CONTROLS / PERSONAL PROTECTION**

Ingredient	OSHA PEL, TWA 8/40h (mg/m3)	ACGIH TLV, TWA 8/40h (mg/m3)	NIOSH REL, TWA 8/40h (mg/m3)	NIOSH IDLH (mg/m3)
Calcium Hydroxide	15 (total dust) 5 (respirable)	5	5	n/a
Magnesium Hydroxide	n/a	n/a	n/a	n/a
Magnesium Oxide	10	10	n/a	n/a
Calcium Carbonate	15 (total dust) 5 (respirable)	10	10 (total dust) 5 (respirable)	n/a
Crystalline Silica	10/(SiO <sub>2</sub> % + 2) (respirable)	0.025 (respirable)	0.05 (respirable)	50

- Engineering Controls:** Provide ventilation adequate to maintain PELs.
- Respiratory Protection:** Use NIOSH/MSHA approved respirators if airborne concentration exceeds PELs.
- Skin Protection:** Use appropriate gloves and footwear to prevent skin contact and the potential for burns. Clothing should fully cover arms and legs. Should lime get inside clothing or gloves, remove the clothing and the lime promptly.
- Eye Protection:** Use safety glasses with side shields or safety goggles. Contact lenses should not be worn when working with lime products.
- Other:** Eye wash fountain/stations and emergency showers should be available.

**SECTION 9: PHYSICAL AND CHEMICAL PROPERTIES**

<b>Appearance:</b> White free flowing powder	<b>Odor:</b> Odorless	<b>Physical State:</b> Solid
<b>Melting Point (°C/°F):</b> dec 580/ 1076	<b>Boiling Point (°C/°F):</b> n/a	<b>Bulk Density:</b> 22-35 lbs/ ft3
<b>Specific Gravity (g/cc)</b> 2.4 2.6		
<b>Vapor Pressure (mm Hg):</b> n/a	<b>Vapor Density:</b> n/a	<b>Evaporation Rate:</b> n/a
<b>pH (25°C/77°F):</b> 12.4	<b>Solubility in Water:</b> Slightly soluble in water at 1.02 g/L at 25 °C	

**SECTION 10: STABILITY AND REACTIVITY**

- Stability:** Chemically stable, but slowly reacts with CO<sub>2</sub> to form calcium carbonate. See also Incompatibility below.
- Hazardous Decomposition/ Products:** Does not occur
- Hazardous Polymerization:** Does not occur
- Incompatibility/ Conditions to Avoid:** Type S hydrated lime should not be mixed or stored with the following materials, due to the potential for vigorous reaction and release of heat:

Acids (unless in a controlled process)	Organic Acid Anhydrides
Reactive Fluoridated Compounds	Nitro-Organic Compounds
Reactive Brominated Compounds	Reactive Phosphorous Compounds
Reactive Powdered Metals	Interhalogenated Compounds





**Material Safety Data Sheet**  
**Type S Hydrated Lime**

**SECTION 11: TOXICOLOGICAL INFORMATION**

No LD50/LC50 have been identified for this product's components. Type S hydrated lime is not listed by MSHA, OSHA, or IARC as a carcinogen, but this product may contain trace amounts of crystalline silica, which has been classified by IARC as carcinogenic to humans when inhaled in the form of quartz or cristobalite.

Inhalation, skin and eye contact are the most likely routes of exposure. This material is irritating to the skin and severely irritating to the eyes.

**SECTION 12: ECOLOGICAL INFORMATION**

**Ecotoxicity:** Because of the high pH of this product, it would be expected to produce significant ecotoxicity upon exposure to aquatic organisms and aquatic systems in high concentrations (> 1 g/L).

**Environmental Fate:** This material shows no bioaccumulation effect or food chain concentration toxicity. High pH values will rapidly decrease over time as a result of recarbonation. This material may be used in soil stabilization or remediation and will show very little mobility in soils.

**SECTION 13: DISPOSAL CONSIDERATIONS**

Dispose of in accordance with all applicable federal, state, and local environmental regulations. If this product as supplied, and unmixed, becomes a waste, it will not meet the criteria of a hazardous waste as defined under the U.S. Resource Conservation and Recovery Act (RCRA).

**SECTION 14: TRANSPORTATION INFORMATION**

Type S hydrated lime is not classified as a hazardous material by US DOT and is not regulated by the Transportation of Dangerous Goods (TDG) when shipped by any mode of transport.

**SECTION 15: REGULATORY INFORMATION**

**U.S. EPA Regulations:** RCRA Hazardous Waste Number (40 CFR 261.33): not listed  
RCRA Hazardous Waste Classification (40 CFR 261): not classified  
CERCLA Hazardous Substance (40 CFR 302.4) unlisted specific per RCRA, Sec. 3001;  
CWA, Sec. 311(b)(4); CWA, Sec. 307(a), CAA, Sec. 112  
CERCLA Reportable Quantity (RQ), not listed  
SARA 311/312 Codes: not listed  
SARA Toxic Chemical (40 CFR 372.65): not listed  
SARA EHS (Extremely Hazardous Substance) (40 CFR 355): not listed, Threshold Planning Quantity (TPQ): not listed  
All chemical ingredients are listed on the US EPA TSCA Inventory List.

**OSHA/MSHA Regulations:** Air Contaminant (29 CFR 1910.1000, Table Z-1, Z-1-A): 5mg/M<sup>3</sup> TWA-8  
MSHA: not listed  
OSHA Specifically Regulated Substance (29 CFR 1910): not listed

**State Regulations:** Consult state and local authorities for guidance. Components found in this product may contain trace amounts of inherent naturally occurring elements (such as, but not limited to arsenic and cadmium) that may be regulated under California Proposition 65 and other States regulations.





**Material Safety Data Sheet**  
**Type S Hydrated Lime**

**Canada:** WHMIS Classification: "D2A" Materials Causing Other Toxic Effects  
 WHMIS Classification: "E" Corrosive Materials (listed due to corrosive effect on aluminum)  
 Canada DSL: [Listed](#)

**SECTION 16: OTHER INFORMATION**

**Prepared By:** Lhoist North America, Technical Services  
**Date Prepared:** August 6, 2012 **Revision:** 2012-3



**NFPA Hazard Class:** Health: 2 Flammability: 0 Instability: 0

**HMIS Hazard Class:** Health: 2\* Flammability: 0 Hazard: 0 Personal Protection: E

**Abbreviations:**  
 N/A Not Available or Not Applicable  
 IARC International Agency for Research on Cancer  
 IATA International Air Transport Association  
 ACGIH American Conference of Governmental Industrial Hygienists  
 TWA Time Weighted Average  
 PEL Permissible Exposure Limit  
 TLV Threshold Limit Value  
 REL Recommended Exposure Limit  
 dec Decompose

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# SOIL CONSULTANTS, INC.

ENGINEERS AND GEOLOGISTS  
SINCE 1951

P.O. Drawer 698 • CHARLESTON, SC 29402 • (843) 723-4539 • Fax (843) 723-3648  
[www.soilconsultantsinc.com](http://www.soilconsultantsinc.com)

Acct. No: ME018                      Project No: 131237                      Date Sampled: 04/08/2013  
Report Date: 05/08/2013                      Sampled By:  
Project: Tumacaori Project - Charleston, SC                      By Order Of: Kaylen McNab  
Location: Test Mixes                      Order Number:

Client: MEADORS CONSTRUCTION, INC.

REPORT: Grout, Cube Compressive Strength                      LAB NO: 28062-1  
Test Method: C780 A7 Cubes

### TEST RESULTS

Report No: 28062-1  
Page 1 of 3

Set: 1 of 3                      Material:                      Number of Specimens: 3  
Location: Test Mix A-1 thru A-3

Specimen Number	Age Tested (date : days)	Width X Width (in) (in)	Height (in)	Area (sq in)	Total Load (lbs)	Strength (PSI)	Average Strength (PSI)	Comments
1	05/08/13 : 30	2.00 2.00	2.00	4.000	100	25		
2	05/08/13 : 30	2.00 2.00	2.00	4.000	200	50		
3	05/08/13 : 30	2.00 2.00	2.00	4.000	200	50	42	

Type Curing:                      Transported By: Client  
Time Sampled:                      Time Picked Up:  
Ambient Temp:                      Date Received: 5/8/2013  
Mix Temp:                      Source:  
Type Mold: not given                      Truck No:  
Ticket No:

Remarks:

Test Method (As Applicable): C780-A7, C109

Orig: MEADORS CONSTRUCTION, INC.  
Attn: Mr. Kalen McNabb  
E-Mail: [Kalen@meadorsinc.com](mailto:Kalen@meadorsinc.com) (1-cc copy)

Respectfully Submitted,  
SOIL CONSULTANTS, INC.

Audrey Chubb, CM7 Manager

THIS REPORT APPLIES ONLY TO THE STANDARDS OR PROCEDURES INDICATED AND TO THE SAMPLE(S) TESTED AND/OR OBSERVED AND ARE NOT NECESSARILY INDICATIVE OF THE QUALITIES OF APPARENTLY IDENTICAL OR SIMILAR PRODUCTS OR PROCEDURES, NOR DO THEY REPRESENT AN ONGOING QUALITY ASSURANCE PROGRAM UNLESS SO NOTED. THESE REPORTS ARE FOR THE EXCLUSIVE USE OF THE ADDRESSED CLIENT AND ARE NOT TO BE REPRODUCED WITHOUT WRITTEN PERMISSION.





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Location: Test Mixes                      Order Number:

Client: MEADORS CONSTRUCTION, INC.

REPORT: Grout, Cube Compressive Strength

LAB NO: 28062-1

Test Method: C780 A7 Cubes

### TEST RESULTS

Report No: 28062-1

Page 2 of 3

Set: 2 of 3

Material:

Number of Specimens: 3

Location: Test Mix B-1 thru B-3

Specimen Number	Age Tested (date : days)	Width (in)	Width (in)	Height (in)	Area (sq in)	Total Load (lbs)	Strength (PSI)	Average Strength (PSI)	Comments
1	05/08/13 : 30	2.00	2.00	2.00	4.000	700	175		
2	05/08/13 : 30	2.00	2.00	2.00	4.000	900	225		
3	05/08/13 : 30	2.00	2.00	2.00	4.000	1,100	275	225	

Type Curing:  
Time Sampled:  
Ambient Temp:  
Mix Temp:  
Type Mold: not given

Transported By: Client  
Time Picked Up:  
Date Received: 5/8/2013  
Source:  
Truck No:  
Ticket No:

Remarks:

Test Method (As Applicable): C780-A7, C109

Orig: MEADORS CONSTRUCTION, INC.  
Attn: Mr. Kalen McNabb  
E-Mail: [Kalen@meadorsinc.com](mailto:Kalen@meadorsinc.com) (1-sc copy)

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LABORATORY MORTAR TESTING  
 Tumacácori National Historical Park  
 Tumacácori, AZ



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 Project: Tumacacori Project - Charleston, SC By Order Of: Kaylen McNab  
 Location: Test Mixes Order Number:

Client: MEADORS CONSTRUCTION, INC.

REPORT: Grout, Cube Compressive Strength LAB NO: 28062-1  
 Test Method: C780 A7 Cubes

**TEST RESULTS**

Report No: 28062-1  
 Page 3 of 3

Set: 3 of 3 Material: Number of Specimens: 3  
 Location: Test Mix C-1 thru C-3

Specimen Number	Age Tested (date : days)	Width X Width (in) (in)	Height (in)	Area (sq in)	Total Load (lbs)	Strength (PSI)	Average Strength (PSI)	Comments
1	05/08/13 : 30	2.00 2.00	2.00	4.000	400	100		
2	05/08/13 : 30	2.00 2.00	2.00	4.000	300	75		
3	05/08/13 : 30	2.00 2.00	2.00	4.000	300	75	83	

Type Curing: Transported By: Client  
 Time Sampled: Time Picked Up:  
 Ambient Temp: Date Received: 5/8/2013  
 Mix Temp: Source:  
 Type Mold: not given Truck No:  
 Ticket No:

Remarks:

Test Method (As Applicable): C780-A7, C109

Orig: MEADORS CONSTRUCTION, INC.  
 Attn: Mr. Kalen McNabb  
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## MORTAR AND PLASTER ANALYSIS REPORT

---

<b>Client:</b>	National Park Service	<b>Client ID:</b>	NATI002
<b>Project:</b>	Tumacacori National Historic Park	<b>Report #:</b>	SL0437-01
<b>Location:</b>	Tumacacori, AZ	<b>Date Received:</b>	09/17/12
<b>Sample Type:</b>	Mortar and plaster	<b>Report Date:</b>	11/21/12
<b>Delivered by:</b>	Client's representative B. Prime - Meadors, Inc.	<b>Chemist:</b>	M. Malaj
		<b>Petrographer:</b>	J. Walsh

---

**Page 1 of 22**

### Report Summary

- A bedding mortar sample (#1) and plaster sample (#2) from Tumacacori National Historic Park in Tumacacori, AZ are examined for this report.
- Both samples are identified as high calcium lime mortars containing a natural volcanic sand. The sands are similar in composition and texture though differ in gradation.
- Binder to sand ratios are estimated at 1 : 2.0 and 1 : 2.6 by volume with the lime equated to a dry hydrate.
- Brick dust is not detected as an addition to the lime. However, volcanic fines including siliceous glass account for about 5% of the total aggregate weight. These may simply represent an unwashed component of the sand or alternatively an intentional pozzolanic addition. The degree of reactivity is difficult to assess.
- The original materials are well mixed and mostly well consolidated though a higher abundance of voids is present in Sample #2 due to the higher sanding.
- The pigmented finish along the plaster surface is composed of brick dust embedded into the fresh lime paste.
- When freshly fractured, the mortars are mostly uniform in appearance and light-colored.
- Both samples are exceptionally cohesive and indurate though the paste is moderately soft and relatively permeable as is expected for lime-rich compositions.
- Carbonation is virtually complete in both samples. No deleterious effects of service are identified in either sample.
- A more detailed discussion of these findings may be found in the "Petrographic Findings and Discussion" sections on page 2 of this report.

## **1. Introduction**

On September 17th, 2012 Highbridge received two samples from Ms. Betty Prime of Meadors, Inc. on behalf of Jeremy Moss and Alex Lim of the National Park Service. Sample #1 is identified as a bedding mortar and Sample #2 is identified as a plaster. Both are reported to have been sampled from the Tumacacori National Historic Park in Tumacacori, AZ. At the client's request, compositional analysis is performed on both samples. The testing includes petrographic examination and chemical analysis in order to identify constituents, estimate proportions, and assess material quality. An acid digestion is also included in order to recover graded sand samples. An emphasis is requested on identifying the inclusion of brick dust or any other type of pozzolanic material.

Though not requested as part of the testing scope, two compressive strength tests are performed on cubes cut from the plaster sample. The testing does not include a formal analysis of the brick masonry or surface finishes or treatments. Nonetheless, some basic petrographic information is provided for these materials where possible. A chemical analysis is performed on an extracted sand sample to assess its reactivity and this is also an addition to the original testing scope.

## **2. Methods of Examination**

The petrographic examination is conducted in accordance with the standard practices contained within ASTM C 1324. Data collection is performed by a degreed geologist who by nature of his/her education is qualified to operate the analytical equipment employed. Analysis and interpretation is performed or directed by a supervising petrographer who satisfies the qualifications as specified in Section 4 of ASTM C 856.

Chemical analysis was conducted according to the procedures outlined in ASTM C 1324. Water, carbon dioxide and aggregate weight percentages are determined gravimetrically. Oxide weight percentages are determined by atomic absorption spectroscopy. The methods are modified when accounting for dolomitic lime. Rather than approximating lime through DTA with possible errors due to carbonated lime, dolomitic lime is instead calculated directly from the chemical analysis by simultaneous equations based on typical dolomitic lime chemistry.

Compressive strength is performed as a non-standard modification of ASTM C 109. The results should be used for reference only and the accuracy is expected to be less than that otherwise expected from the test method when performed in full compliance.

## **3. Petrographic Findings and Discussion**

### **3.1 - General Summary**

Both samples are identified as high calcium lime mortars containing a natural volcanic sand. The sands are similar in composition and texture. Gradations differ with Sample #1 having a coarser grain size than Sample #2. Binder to sand ratios are estimated at 1 : 2.0 and 1 : 2.6 by volume with the lime equated to a dry hydrate. The sand content approximately doubles with the lime considered in putty form. Brick dust is not detected as an addition to the lime. However, volcanic fines including siliceous glass account for about 5% of the total aggregate weight. These may simply represent an unwashed component of the sand or alternatively an intentional pozzolanic addition. Chemical arguments suggest that the volcanic sand as a whole is partly soluble in alkaline solution and may be expected to react with fresh lime as a natural pozzolan. The degree of reactivity is difficult to assess. Chemical analysis of the soluble binder does not indicate a significant reaction. In contrast, compressive strength testing of Sample #2 suggests a modest reaction with obtained results of 1330 and 1660 psi in oven-dried condition.

The original materials are well mixed and mostly well consolidated though a higher abundance of voids is present in Sample #2 due to the higher sanding. The pigmented finish along the plaster surface is composed of brick dust embedded into the fresh lime paste. When freshly fractured, the mortars are mostly uniform in appearance. Sample #1 is light brownish gray in color (Munsell color code approximately 10YR 6.5/2) and Sample #2 is light buff to nearly white (Munsell color code approximately 10YR 7.5-8/1). Both samples are exceptionally cohesive and indurate though the paste is moderately soft and relatively permeable as is expected for lime-rich compositions. Carbonation is virtually complete in both samples. No deleterious effects of service are identified in either sample.

### 3.2 - Materials (Aggregate)

The aggregate in the two examined samples is a natural volcanic sand of similar composition and texture but different gradation. The composition is fairly complex indicating that several bedrock sources may have contributed to the sediment. The rock types include mostly aphanitic and sometimes glassy materials of approximately intermediate to somewhat acidic composition. Many are composed of dacite and possibly andesite though rocks as alkaline as latite and trachyte appear to be present. Basalts are entirely absent. Rhyolites are not positively identified though some grain colors are consistent with the more acidic rock types. Refractive indices of approximately 1.50 seem to suggest higher silica compositions for glasses present in the fines. Porphyritic grains contain an extremely fine-grained feldspar groundmass with phenocrysts consisting of plagioclase, quartz, biotite, amphibole, and rare pyroxene. A low proportion of welded tuff is identified. Granitic grains are also present in minor amounts and these represent a non-volcanic component. No clay coatings or friable materials are detected and the sand is considered, hard, non-porous, and durable for use in lime-based mortars. The volcanic rocks might be considered deleterious in portland cement-based mortars due to their high potential for alkali-aggregate reactivity. However, this reactivity is considered a potential benefit in lime mortars.

Sands were extracted from both samples through acid digestion. The aggregate in Sample #1 is dull-lustered, opaque, and moderately variegated in appearance. The average color is reddish gray (Munsell color code approximately 5YR 6/0.5). Muted shades of orange, pink, purplish gray and minor green are apparent particularly in the coarser grains. The sand in Sample #2 is more uniform due to a lower quantity of coarse grains. The average color is a slightly richer reddish gray (Munsell color code approximately 2.5Y 6.5/1). There is a suspicion that the original sands may have been somewhat darker than those extracted through acid digestion. A caustic reaction between the sand and the lime before carbonation may have etched the aggregate surfaces resulting in more pastel tones in the recovered sample.

The sand in both samples is moderately soft-textured with equidimensional particles that are subrounded to subangular in shape. Extracted samples were graded through a standard sieve stack and details of the gradation profiles are presented in Section 4 below. The aggregate in Sample #1 is coarse-grained with a nominal top size at the No. 4 sieve. The peak abundance is distributed across two sieve intervals (the No. 8 to the No. 16 and the No. 16 to the No. 30). The aggregate in Sample #2 is medium grained with a nominal top size at the No. 8 sieve. The peak abundance lies between the No. 30 and No. 50 sieves. The gradation profiles for both samples drops off smoothly so that fines passing a No. 200 sieve represent only about 2% of the total extraction. However, approximately 5% of the recovered weight represents fines passing a No. 325 sieve. Microscopic examination of these powders indicates a relatively high content of volcanic glass as well as other fine-grained volcanic material. It could be argued that this material was separately added as a type of trass or natural pozzolan. However, it could also simply represent unwashed clay-sized material from the original sand source.

Once it was established that the sand consisted largely of volcanic material it was important to understand its solubility. This was desirable so that a chemical digestion procedure could be chosen that would not contaminate the binder signal with elements leached from the aggregate. A portion of Sample #2 was gently disaggregated without crushing the sand particles and digested in a dilute hydrochloric acid solution to remove all traces of binder. The sand was then rinsed and dried. The material was split and one half was ground to pass a No. 50 sieve using the same process normally used for the chemical analysis of hardened mortar. The other half was left intact. Both subsamples were then subjected to the normal mortar analysis procedure for major soluble elemental composition including a room temperature acid digestion followed by a hot base digestion in a 10 g/L NaOH solution. The filtrates were analyzed using atomic absorption spectroscopy and results of this analysis are presented in Table 5.1 below. Approximately 3.7% SiO<sub>2</sub> was leached from the unground sample and approximately 5% was leached from the ground sample. Though there are no benchmark values for this test, it is quite clear that the original volcanic aggregate has a high solubility in alkaline solution and therefore has inherent pozzolanic potential.

### **3.3 - Materials (Binder)**

The binder in both samples is a high calcium lime. The hardened matrix is homogeneously developed with only a minimum of polygonal shrinkage cracks typical of lime-based mortars. The capillary porosity is moderately high to high in Sample #1 and moderate to moderately high in Sample #2. Both are highly permeable and this is consistent with the lime-rich composition. Undispersed lime grains are observed in moderate abundance with most less than 0.5 millimeters in diameter. These are all fully carbonated and have diffuse boundaries with the adjacent cured lime paste. Most are internally non-descript though a few contain traces of partially combined quartz silt. Coarser-grained and incompletely burned lime grains are present in both samples and textures indicate the use of a similar lime rock. Grains consist of mildly deformed, high calcium limestone with a medium to coarse crystal size and few silicate inclusions. The lime rock tended to disaggregate along crystal boundaries and shear planes during firing and the calcination tends to have occurred from the edge of each calcite crystal inward. Grains best displaying this intermediate stage are detected in Sample #1. Unburned grains are more common in Sample #2.

It was possible to estimate the chemistry of the soluble portions of the binder and this estimate is presented in Table 5.3 below. The methods employed do not measure the bulk chemistry of the binder but only those components that are acid-soluble including carbonated lime and combined and hydrated species of silica and alumina. Unreacted pozzolanic material would not be included. To the first order, the similarity in chemical compositions suggests consistency in the source materials. The lime in both samples is a high calcium variety and no significant dolomitic component is indicated. The remainder of the chemistry is difficult to interpret as it cannot be determined if other elements were an original component of the lime or have been introduced as calcium silicate hydrates through pozzolanic reaction with volcanic dust. What is notable is that the hydraulicity index is calculated at below 0.1 for both samples. Aside from a slightly high alumina content, the total chemistry is comparable to many historical lean limes that are not reported to have been hydraulic. It is certain that the lime alone is nonhydraulic in character. Furthermore, any pozzolanic reaction that may have occurred appears to have produced only minor quantities of cementitious product.

The client has questioned whether brick dust may have been added to the lime mortars as a pozzolanic addition. There is no evidence found petrographically to suggest that brick dust was mixed with the bulk lime though some is found as a surface finish in the plaster sample. The insoluble material produced through acid digestion also exhibits an absence of larger brick fragments or reddish colored fines. Instead, it is believed that the sand itself was a source of pozzolanic material. As discussed above, the fines are base soluble and would be expected to release silica when exposed to caustic lime. Glass present in the fines has a refractive index in the range of 1.50 and this indicates a relatively high silica content. What is not clear is whether the volcanic fines represent a separate intentional addition or simply an unwashed component of the volcanic sand. Also undetermined is the degree of reactivity of the material. The chemical analysis suggests only minimal release of silica and this would argue for a very weak pozzolan. However, compressive strength testing performed on two cubes of Sample #2 suggests a modest hydraulicity. The non-standard strength tests were performed in oven-dried condition providing a maximum strength between 1330 and 1660 psi. Of course, a portion of the strength must also be attributed to the normal lime carbonation.

### **3.4 - Other Materials**

The brick is not the subject of the examination though a portion adhered to the plaster was observed petrographically. The brick is rich in temper consisting of volcanic sands not unlike those used in the mortar itself. There is a somewhat higher abundance of single biotite flakes. Traces of olivine are also found indicating some minor basalt in the source that is not present in the mortar aggregate. The temper is bound in a relatively compact fired clay with an orange-red color under plane light.

The plaster sample (Sample #2) is coated with a pink-colored finish material. Petrographic observations indicate that brick dust is the sole material responsible for the pigmentation. The fine particles are embedded into the lime to a maximum depth of approximately 0.5 millimeters indicating that the finish is original to the plaster installation.

### **3.5 - Component Proportions**

Chemical analysis was used to estimate the component proportions and these results are presented in Section 5 below. The total lime to sand ratio is estimated at 1 : 2.0 and 1 : 2.6 by volume for Sample #1 and #2 respectively with the lime given as the equivalent of a modern dry hydrate. It should be stressed that the lime is calculated in this report as the equivalent of a dry hydrate though it is certain that the lime was slaked on site. Calculating the lime weight in this manner is more accurate as it does not have to take into account the mix water used in a lime putty. If it is assumed that a volume of dry hydrate will lose approximately half its volume when water is added to produce a putty of stiff consistency, the ratios are recalculated at 1 : 4.0 and 1 : 5.1 for Samples #1 and #2 respectively.

It should also be noted that where volume proportions are given, these are based on estimated original bulk densities of the starting materials. Estimates are given for both dry hydrated lime and lime putty. However, limes are subject to great variation in volume due to factors such as settling or “fluffing” in dry powders and mix water content in putties. Table 5.4 presents the lime and sand as weight percentages of dry ingredients (dry lime hydrate and dry sand). These are more accurate as they represent direct measurements of material mass. In cases where in-kind replication is desirable, the most accurate method of achieving matching proportions would be to determine the unit weight of the new materials chosen for replication and to proportion their volumes so that these match the reported weights. It may be found that the resulting volumes are different than those estimated. This method becomes more complicated if premixed lime putty is chosen since the amount of water and dry hydrate in the mix will be unknown.

The proportioning of the bedding mortar (Sample #1) is considered reasonable if slightly oversanded. The coarseness of the aggregate coupled with the broad gradation requires less total binder to completely fill interstitial space. The adequate consolidation of the mortar reflects this and the total air content is estimated at about 6-8%. In contrast, the finer sand in the plaster sample (Sample #2) requires a greater quantity of binder yet the sand content is higher than that of the bedding mortar. Again, this is reflected in the consolidation of the material and a moderate abundance of consolidation voids are found at the interstitial spaces between sand grains. The total air content for this sample is estimated at approximately 10-12% by volume. Despite the incomplete consolidation at the microscopic scale, the plaster is well compacted overall.

It should be noted that the volcanic fines are not considered separately in the estimated proportions. The fines are simply included as part of the aggregate. If instead these are excluded, the sand volume per unit lime decreases only slightly and the error associated with including this material is considered negligible. The weight proportion of the fines may be of considerably greater importance if it was intentionally added as a separate pozzolanic addition. A rough calculation of the total weight percentage of the fines as a portion of the dry mortar ingredients is given in Table 5.4. This indicates that the fines would have represented a weight equivalent of approximately 20% to 30% of the lime weight in dry hydrate form. Mathematically converting the same amount of lime to a putty decreases these values in half to about 10% to 15% by weight.

### **3.6 - Condition and Service Performance**

Both samples examined are in relatively sound condition with no evidence for deleterious effects of service. The original components are well mixed and there are no sand streaks or excessive binder concentrations noted. The mix water was well incorporated into the paste of both samples with no heterogeneities in porosity caused by water variations. At the large scale, both samples are well compacted with no “clumpy” spots or other microvoidage. At the fine scale, consolidation is not thorough in Sample #2 due to a higher than desirable sand content. Still, the material is reasonably compact and cohesive. Microscopic consolidation is better achieved in Sample #1. The plaster sample (Sample #2) has a float-type finish resulting in a smooth, slightly sandy surface. Only one larger bughole is identified in the otherwise unbroken surface. No laitance or other defects are noted in the plaster finish. A wash of crushed brick dust is applied to the surface and the material is well embedded in the plaster. This indicates that the wash was applied while the lime paste was still plastic.

The hardened paste in both samples is relatively soft and both materials are considered moderately permeable. However, the mortar in bulk is exceptionally indurate in both samples and some of this may be attributed to a pozzolanic reaction between the fresh lime and the volcanic sand (particularly the fines). The brick dust wash may also have produced a pozzolanic reaction reducing the permeability of the plaster surface relative to the interior. Carbonation is complete for the full cross section of both samples and this is an expected and desirable consequence of long term curing. No recrystallization of the carbonate is identified in either sample. There is no evidence for leaching of the binder or mineralizations resulting from excessive water infiltration. Microcracking is minimal in both samples and includes only a minor amount of microscopic shrinkage cracking typical of lime-rich mortar compositions.



**4. Aggregate Sieve Analysis**

Aggregate analysis is performed by digesting the sample in an acid sufficient to dissolve the binder. The fines are examined petrographically to ensure that all recovered material represents sand rather than undigested binder components. In this case, the portions passing a No. 325 sieve include mostly volcanic fines and may be considered either unwashed sand or a separate addition. The gradation results are reported with this material both excluded and included for comparison. A qualitative description of the sands is given in the discussion above and the recovered samples provided with this report. The sample size is significantly smaller than would be required to perform a sieve analysis on fresh aggregate materials as per ASTM C 136 and some small errors should be expected.

**Table 4.1: Acid Digestion Data**

Sample ID	Raw Data - Weight Retained (g)			
	Fines excluded		Fines included	
	Sample #1	Sample #2	Sample #1	Sample #2
No. 4	0.34	0.56	0.34	0.56
No. 8	3.17	0.69	3.17	0.69
No. 16	7.45	2.34	7.45	2.34
No. 30	7.55	4.79	7.55	4.79
No. 50	5.46	8.32	5.46	8.32
No. 100	2.12	6.67	2.12	6.67
No. 200	0.77	1.99	0.77	1.99
No. 325	0.23	0.44	0.23	0.44
Pan	-	-	1.32	1.64

Sample ID	Cumulative Passing (wt. %)			
	Fines excluded		Fines included	
	Sample #1	Sample #2	Sample #1	Sample #2
No. 4	98.7	97.8	98.8	98.0
No. 8	87.0	95.2	87.6	95.4
No. 16	59.5	86.1	61.4	86.9
No. 30	31.7	67.5	34.8	69.5
No. 50	11.5	35.3	15.6	39.1
No. 100	3.7	9.4	8.2	14.8
No. 200	0.8	1.7	5.5	7.6
No. 325	0.0	0.0	4.6	6.0

Sample ID	Cumulative Retained (wt. %)			
	Fines excluded		Fines included	
	Sample #1	Sample #2	Sample #1	Sample #2
No. 4	1.3	2.2	1.2	2.0
No. 8	13.0	4.8	12.4	4.6
No. 16	40.5	13.9	38.6	13.1
No. 30	68.3	32.5	65.2	30.5
No. 50	88.5	64.7	84.4	60.9
No. 100	96.3	90.6	91.8	85.2
No. 200	99.2	98.3	94.5	92.4
No. 325	100.0	100.0	95.4	94.0
Pan	-	-	100.0	100.0
<b>Fineness Modulus</b>	<b>3.08</b>	<b>2.09</b>	<b>2.93</b>	<b>1.96</b>

**5. Chemical Analysis**

**Table 5.1: Sand Leachate Analysis**

A chemical analysis was performed on sand extracted from Sample #2 in order to determine whether the volcanic sand would interfere with the chemical measurements. A portion of the sample was gently disaggregated to ensure that none of the sand was crushed. The sample was digested in dilute hydrochloric acid just until all binder had decomposed. The residue was rinsed, dried, and split. One half of the split sample was left intact, the other was ground to pass a No. 50 sieve. Both were subjected to chemical analysis using digestion methods normally used for hydraulic lime. The solubilized elements were analyzed using atomic absorption spectroscopy.

SAMPLE ID	Sample #2	
	Unground	Ground
Preparation		
Component (wgt. %)		
SiO <sub>2</sub>	3.71	5.07
CaO	0.01	0.02
MgO	0.01	0.04
Al <sub>2</sub> O <sub>3</sub>	0.01	0.10
Fe <sub>2</sub> O <sub>3</sub>	0.01	0.10
<b>Measured Totals</b>	<b>3.75</b>	<b>5.34</b>

**Table 5.2: Chemical Analysis Results**

SAMPLE ID	Sample #1	Sample #2
Component (wgt. %)		
SiO <sub>2</sub>	0.41	0.36
CaO	13.45	11.08
MgO	0.41	0.41
Al <sub>2</sub> O <sub>3</sub>	0.59	0.63
Fe <sub>2</sub> O <sub>3</sub>	0.23	0.21
Insoluble residue	73.94	78.07
LOI to 110°C	0.96	0.91
LOI 110°C-550°C	2.51	2.62
LOI 550°C-950°C	9.26	7.33
<b>Measured Totals</b>	<b>101.77</b>	<b>101.62</b>

Notes:

1. The chemical procedure was modified to effectively partition the components identified petrographically. A room temperature acid digestion was used to ensure complete decomposition of the lime as well as any reacted pozzolan. The usual base digestion was excluded as it was determined that a significant leaching of the aggregate would occur. It should be noted that any unreacted volcanic glass is captured with the acid-insoluble residue and does not contribute to the elemental chemistry.

**Table 5.3: Estimated Soluble Binder Chemistry**

<b>SAMPLE ID</b>	<b>Sample #1</b>	<b>Sample #2</b>
<b>Component (wgt. %)</b>		
SiO <sub>2</sub>	2.7	2.9
CaO	89.1	87.3
MgO	2.7	3.2
Al <sub>2</sub> O <sub>3</sub>	3.9	5.0
Fe <sub>2</sub> O <sub>3</sub>	1.6	1.7
<b>CaO/MgO ratio</b>	<b>33.0</b>	<b>27.2</b>
<b>Hydraulicity Index</b>	<b>0.07</b>	<b>0.09</b>
<b>Cementation Index</b>	<b>0.14</b>	<b>0.16</b>

Notes:

- The soluble binder chemistry is estimated on a non-volatile basis assuming the five measured oxides represent 100% of the total. This chemistry includes elements from the lime as well as cementitious hydrates produced through pozzolanic reaction. Unreacted pozzolan is not included. Hydraulicity index is calculated by dividing the sum of SiO<sub>2</sub> and Al<sub>2</sub>O<sub>3</sub> by the measured CaO. Cementation index is calculated by dividing the “hydraulic elements” by the “lime elements” after multiplying each by coefficients normalizing them to their molecular rather than weight contribution.

**Table 5.4: Calculated Components**

<b>SAMPLE ID</b>	<b>Sample #1</b>	<b>Sample #2</b>
<b>Component</b>		
Lime expressed as dry hydrate (wgt. %)	20	16
Volcanic dust (wgt. %)	4	5
Sand (wgt. %)	76	79
Lime : sand ratio (by volume with lime as a dry hydrate)	1 : 2.0	1 : 2.6
Lime : sand ratio (by volume with lime as a putty)	1 : 4.0	1 : 5.1

Notes:

- The lime weight is calculated by mathematically reporting the measured CaO and MgO to their respective hydroxides by molecular weight conversion. The other measured elements are not totaled with the lime since much of this may have derived from pozzolanic reaction with components of the sand. The possible underestimation of the lime weight resulting from neglecting the other elements is considered negligible. The calculation presents the lime in dry hydrate form. The acid-insoluble residue is assumed to represent the sum of the sand plus the volcanic fines. The proportion of these components is determined by calculating the weight percentage passing the No. 325 sieve in the sample extracted through acid digestion. The proportion is then used to divide the acid-insoluble residue into its respective components by weight. All weights are then normalized to 100%.
- The contribution of the volcanic fines is ignored for the volume calculations and the total acid-insoluble residue is simply taken to represent the sand. Volumetric ratios are calculated assuming bulk densities for dry lime hydrate and damp, bulked sand of 40 lbs./ft.<sup>3</sup> and 80 lbs./ft.<sup>3</sup> respectively. Another volume ratio is estimated for the lime as a putty. This assumes a unit of dry lime hydrate will lose approximately half its volume when mixed to the consistency of a stiff paste. The sand volume then increases for the same weight of lime. This estimate should be considered less accurate.

**6. Compressive Strength Testing**

Sample #2 was provided as a large, intact plaster layer. After sectioning for compositional analysis, sufficient material remained to prepare two roughly cubic specimens for compressive strength testing. Specimens are just greater than 1” in all three dimensions. It should be understood that the testing is performed at non-standard test sizes and the results are provided as a general reference only. Loading surfaces were ground to plane parallelism by hand lapping to an 80-grit finish. No capping was necessary. Test cubes were oven-dried and the results should be considered the maximum obtainable. Specimens at ambient humidity levels would be expected to fail at lower values.

**Table 6.1: Compressive Strength Results**

<b>Specimen</b>	<b>Area Tested (in.<sup>2</sup>)</b>	<b>Max. Load (lbf)</b>	<b>Compressive Strength (psi)</b>
2A	1.42	1891	1330
2B	1.36	2267	1660

Respectfully submitted,

John J. Walsh  
President/ Senior Petrographer

*The interpretations and conclusions presented in this report are based on the samples provided.  
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**Appendix I: Visual Description of Samples as Received**

<b>Sample ID</b>	<b>Sample #1 (Bedding Mortar)</b>
Description	The sample consists of one large bedding mortar fragment with approximate dimensions of 5.5" x 4.5" x 2.5". The joint thickness is not obvious from the sample as provided. A few weathered brick fragments are adherent to portions of the sample.
Surfaces	It is difficult to observe the original masonry contact surface due to deep weathering. No tooled surfaces are apparent.
Hardness / Friability	The paste is moderately soft though the mortar on the whole is notably indurate.
Appearance	Fresh surfaces have a dull luster and are light brownish gray in color when freshly exposed (Munsell color code approximately 10YR 6.5/2). A muddy brown weathering color is common at the brick contact surfaces where brick is no longer attached.
Other Details	No cracks are visible in hand sample though a few weathered flakes dislodged in handling. No efflorescence or mineral deposits are visible. Coarse white binder inclusions up to approximately one centimeter in size are found in low abundance. A few dark ochre clay lumps are visible at approximately one millimeter diameter but these are not prevalent. The matrix is highly absorptive where fresh but not noticeably so where weathered.

<b>Sample ID</b>	<b>Sample #2 (Plaster)</b>
Description	The sample consists of one saw-cut plaster portion with underlying brick substrate. The sample is 6" x 4" in area with a 2" total thickness. The plaster is 1.2" thick on average. The base of the brick is cleanly saw-cut. The plaster is well bonded to the brick substrate.
Surfaces	The finished surface is smooth and planar with a very low relief, fine sand exposure (nearly flush). There is a thin but continuous colored finish with an average light reddish brown color (Munsell color code approximately 2.5YR 6/3). A few centimeter scale bugholes appear to contain the pigmentation as well.
Hardness / Friability	The paste is moderately soft though the mortar on the whole is notably indurate.
Appearance	Fresh surfaces have a dull luster and are buff to nearly white in color where fresh (Munsell color code approximately 10YR 7.5-8/1). A medium to dark brown soiling is apparent along the edges that are not saw-cut.
Other Details	No cracks, efflorescence, or mineral deposits are visible in hand sample. Both the brick and plaster are relatively fresh in appearance. White binder grains up to several millimeters in diameter are not uncommon. A few small red colored grains are visible but are not positively identified as brick particles. The matrix is highly absorptive where fresh but only slowly absorptive along the finished surface.

**Appendix II: Photographs and Photomicrographs**

Microscopic examination is performed on an Olympus BX-51 polarized/reflected light microscope and a Bausch and Lomb Stereozoom 7 stereoscopic reflected light microscope. Both microscopes are fitted with an Olympus DP-11 digital camera. The overlays presented in the photomicrographs (e.g., text, scale bars, and arrows) are prepared as layers in Adobe Photoshop and converted to the jpeg format. Digital processing is limited to those functions normally performed during standard print photography processing. Photographs intended to be visually compared are taken under the same exposure conditions whenever possible.

The following abbreviations may be found in the figure captions and overlays and these are defined as follows:

cm	centimeters	PPL	Plane polarized light
mm	millimeters	XPL	Crossed polarized light
µm	microns (1 micron = 1/1000 millimeter)		
mil	1/1000 inch		

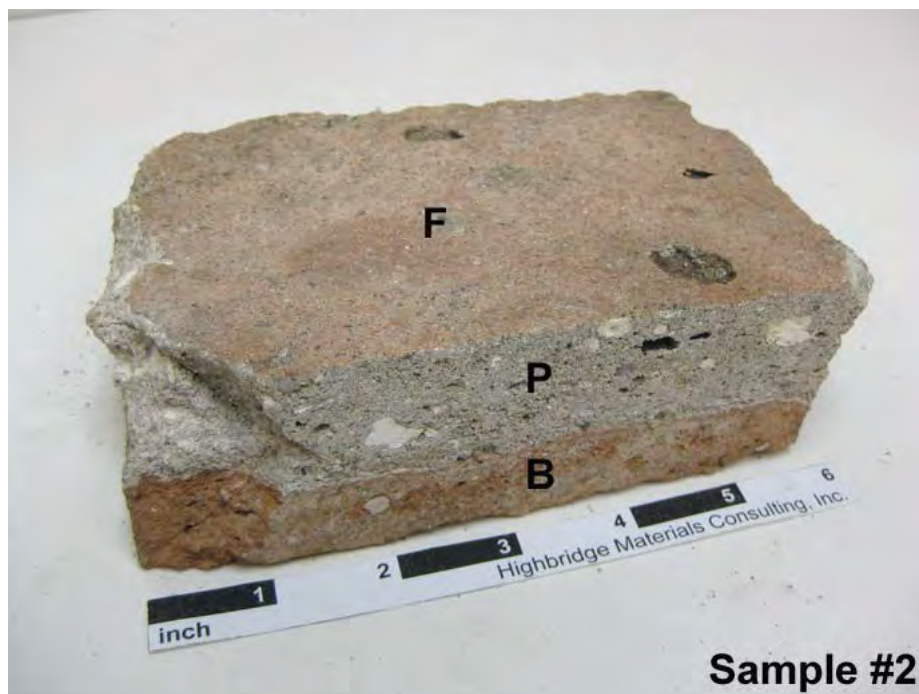
Microscopical images are often confusing and non-intuitive to those not accustomed to the techniques employed. The following is offered as a brief explanation of the various views encountered in order that the reader may gain a better appreciation of what is being described.

**Reflected light images:** These are simply magnified images of the surface as would be observed by the human eye. A variety of surface preparations may be employed including polished and fractured surfaces. The reader should note the included scale bars as minor deficiencies may seem much more significant when magnified.

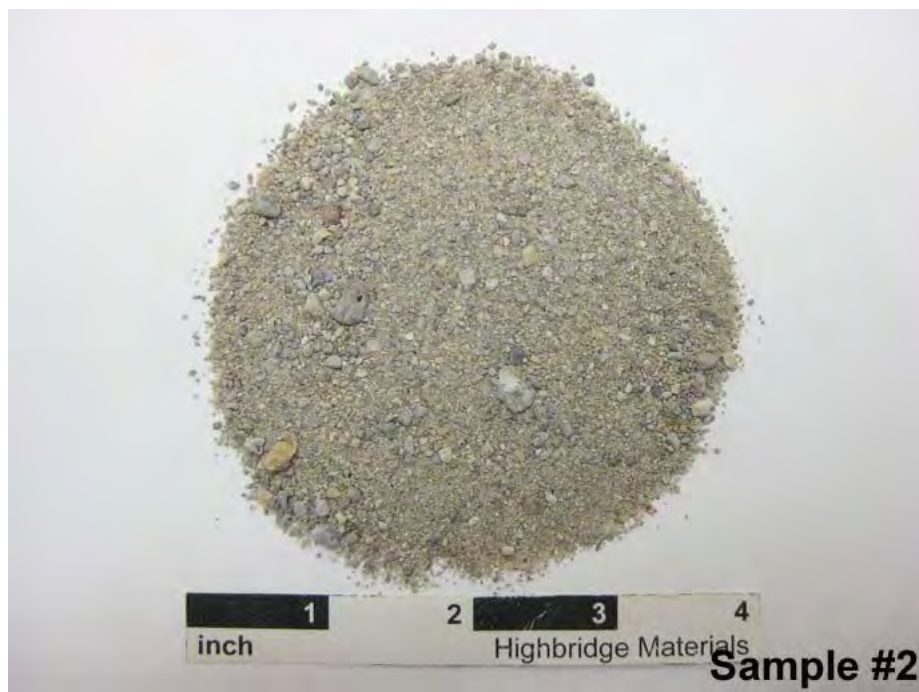
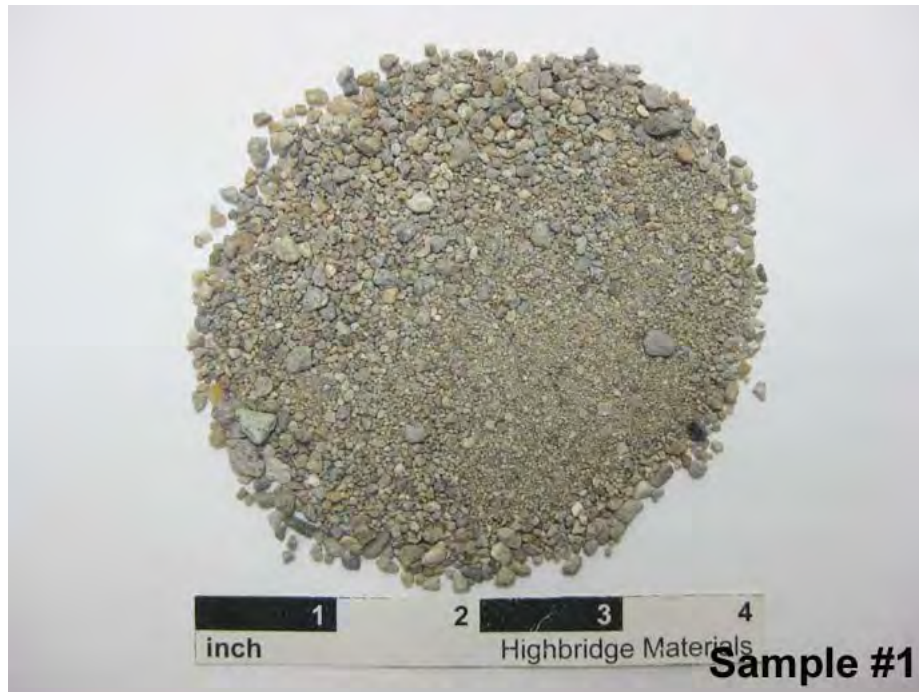
**Plane polarized light images (PPL):** This imaging technique is most often employed in order to discern textural relationships and microstructure. To employ this technique, samples are milled (anywhere from 20 to 30 microns depending on the purpose) so as to allow light to be transmitted through the material. In many cases, Highbridge also employs a technique whereby the material is impregnated with a low viscosity, blue-dyed epoxy. Anything appearing blue therefore represents some type of void space (e.g.; air voids, capillary pores, open cracks, etc.) Hydrated cement paste typically appears a light shade of brown in this view (with a blue hue when impregnated with the epoxy). With some exceptions, most aggregate materials are very light colored if not altogether white. Some particles will appear to stand out in higher relief than others. This is a function of the refractive power of different materials with respect to the mounting epoxy.

**Crossed polarized light images (XPL):** This imaging technique is most often employed to distinguish components or highlight textural relationships between certain components not easily distinguished in plane polarized light. Using the same thin sections, this technique places the sample between two pieces of polarizing film in order to determine the crystal structure of the materials under consideration. Isotropic materials (e.g.; hydrated cement paste, pozzolans and other glasses, many oxides, etc.) will not transmit light under crossed polars and therefore appear black. Non-isotropic crystals (e.g.; residual cement, calcium hydroxide, calcium carbonate, and most aggregate minerals) will appear colored. The colors are a function of the thickness, crystal structure, and orientation of the mineral. Many minerals will exhibit a range of colors due to their orientation in the section. For example, quartz sand in the aggregate will appear black to white and every shade of gray in between. Color difference does not necessarily indicate a material difference. When no other prompt is given in the figure caption, the reader should appeal to general shapes and morphological characteristics when considering the components being illustrated.

**Chemical treatments:** Many chemical techniques (etches and stains typically) are used to isolate and enhance a variety of materials and structures. These techniques will often produce strongly colored images that distinguish components or chemical conditions.

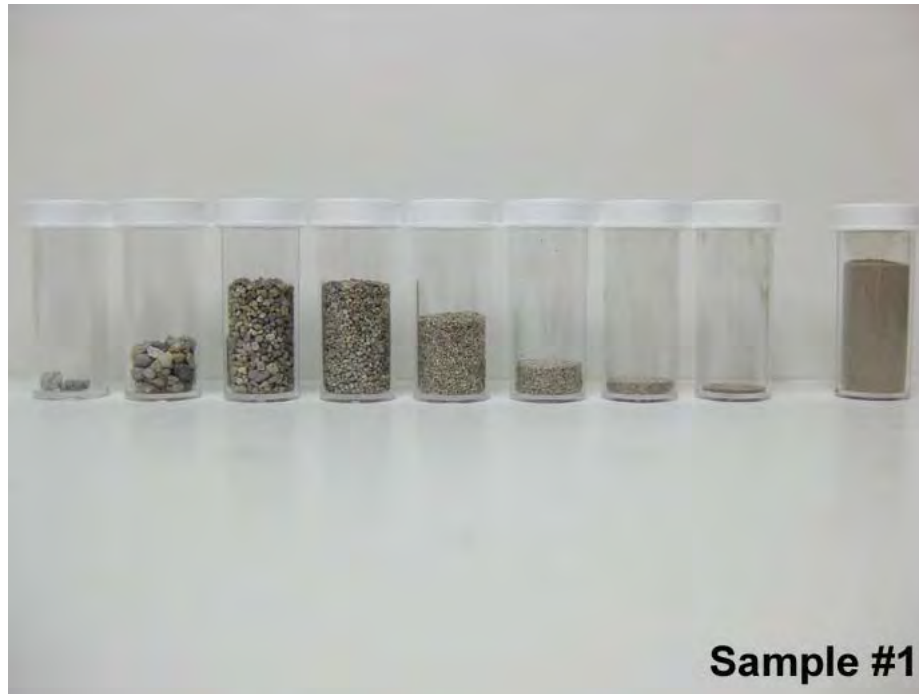


**Figure 1:** Photographs of the two as received by Highbridge for examination. Sample #1 consists of mortar (M). Several pieces of adherent brick (B) are included with the sample. Sample #2 consists of a thick plaster (P) well compacted against a brick substrate (B). The plaster has a float-type finish (F) and a pinkish pigmentation.

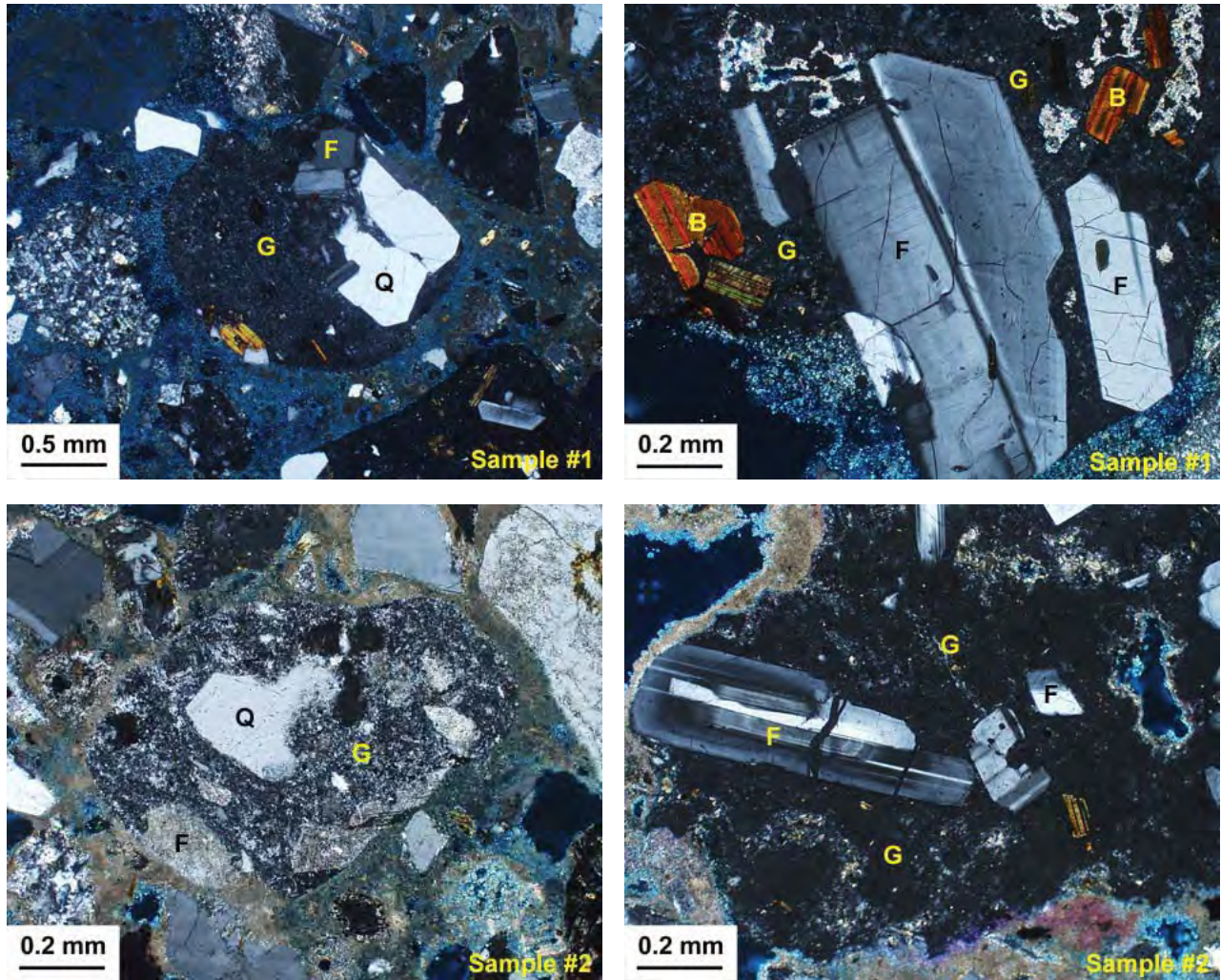


**Figure 2:** Photographs of the sand extracted from the two samples by acid digestion. Both are dull-lustered and opaque with a reddish gray color. The sand is composed largely of volcanic particles. The original sand may have been somewhat darker assuming that the surfaces have been etched due to reaction with the lime binder.

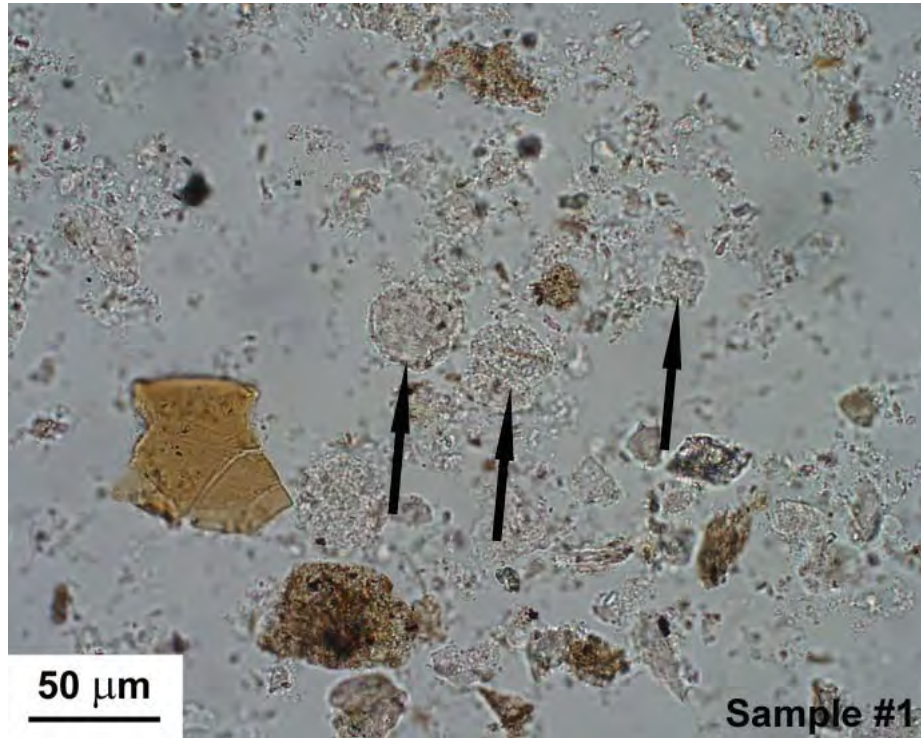




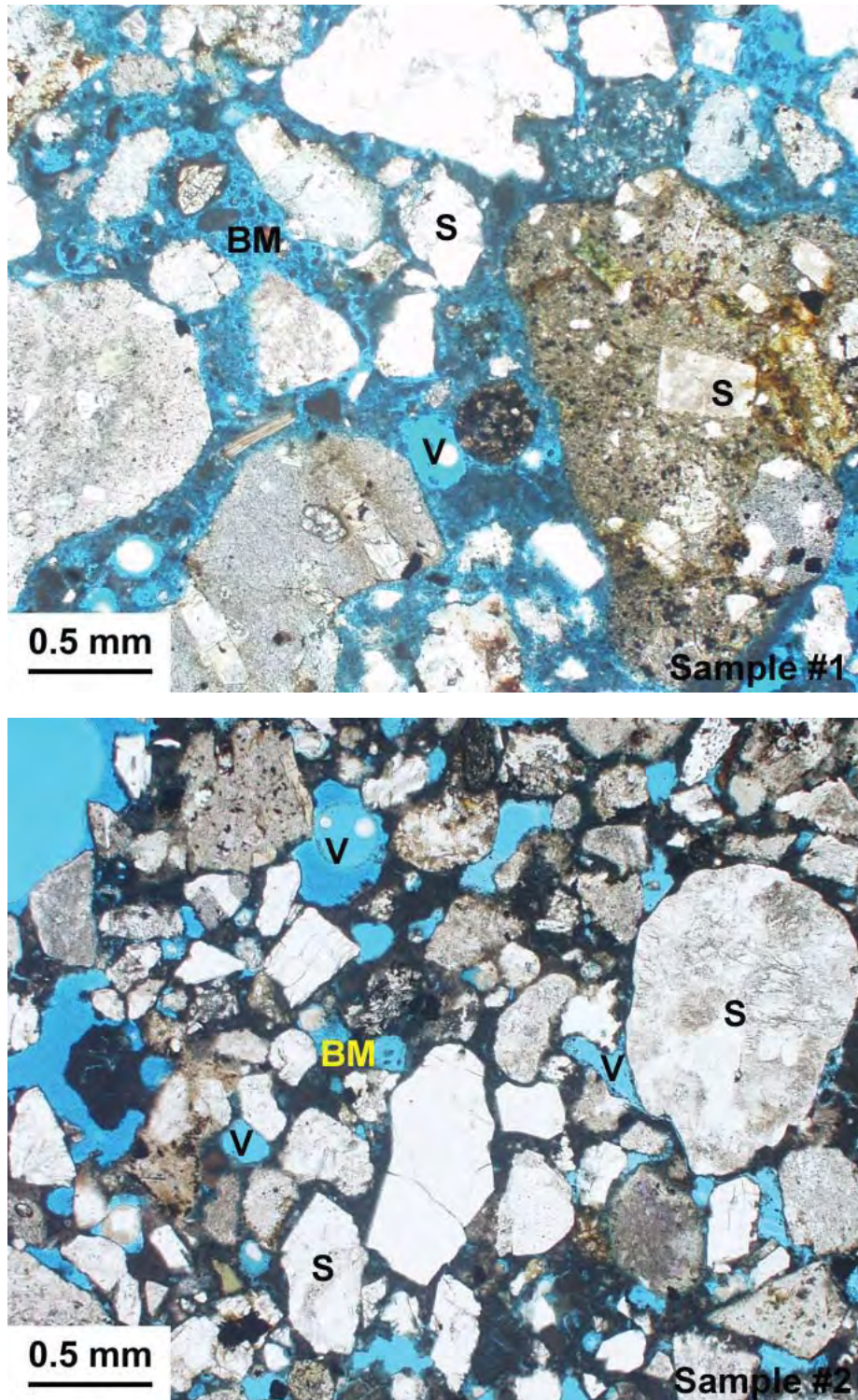
**Figure 3:** Photographs of the sand extracted from the two samples by acid digestion after gradation through a standard sieve stack. Particle size distributions are broad for both though the sand in Sample #1 is coarser-grained. The vials set aside to the right in each image represent fines passing a No. 325 sieve. Though some of this may represent undigested silica from the binder, much of it is volcanic rock fragments and glass. This may simply represent unwashed clay-sized fines from the sand source. Alternatively, these may represent a separate natural trass addition.



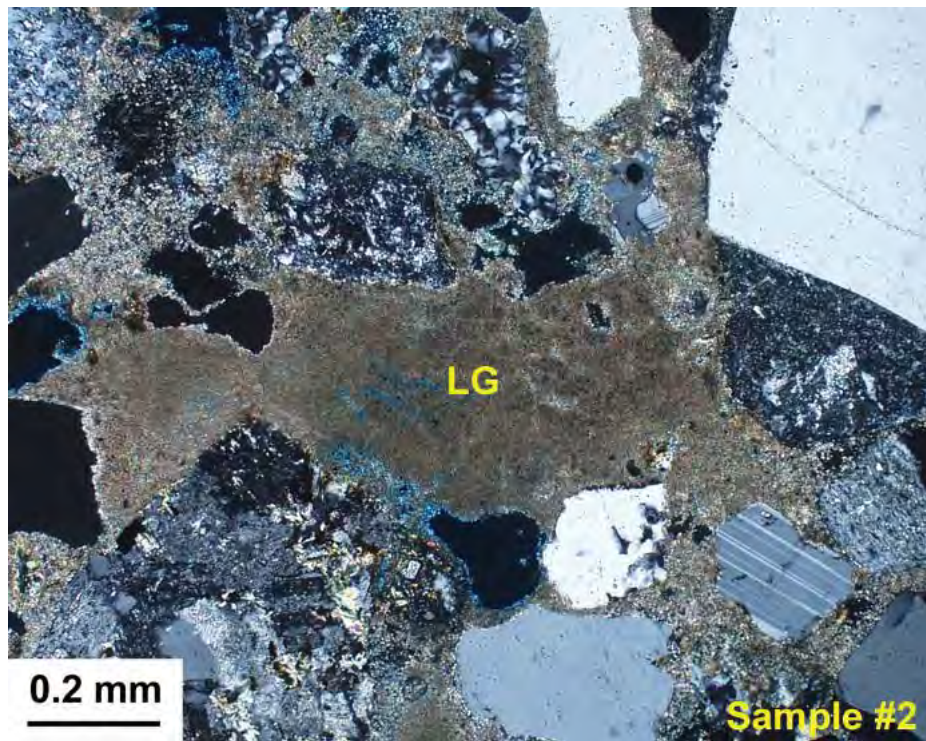
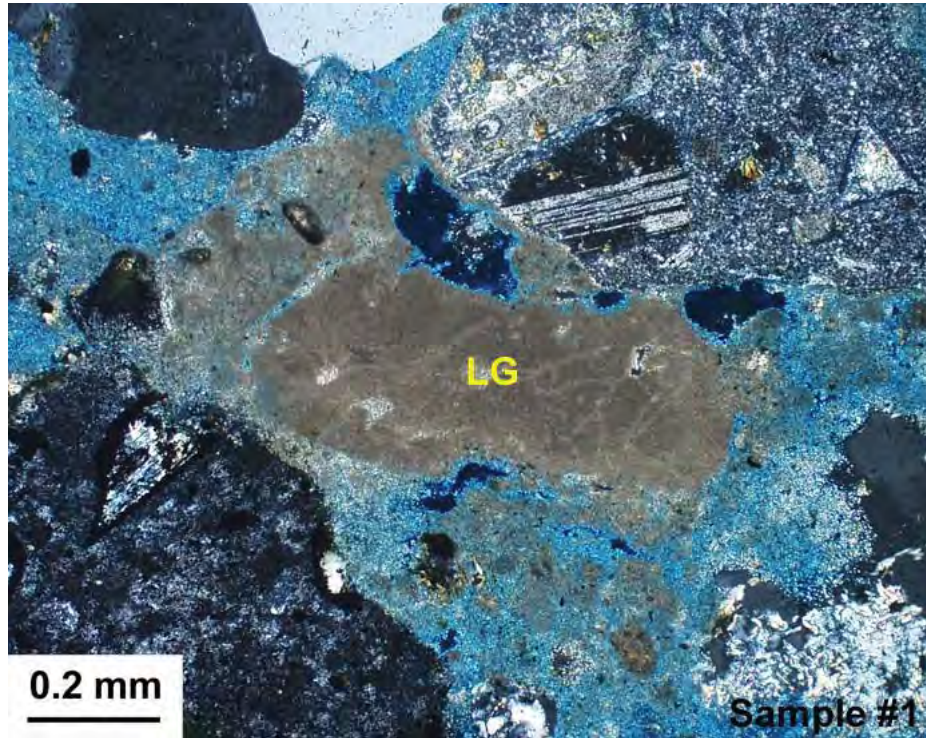
**Figure 4:** XPL photomicrographs. The sand in both samples is highly varied though most represent sediments derived from intermediate to somewhat acidic volcanic rocks. Dacite grains are shown at upper and lower left for each sample. The groundmass (G) consists mostly of very fine-grained feldspar though some glass is likely present. Phenocrysts include quartz (Q) and plagioclase feldspar (F). An andesite grain is shown at upper right for Sample #1. Again, a groundmass (G) of fine-grained feldspar is predominant. Phenocrysts include plagioclase feldspar (F) and biotite mica (B). The grain shown at lower right may also be andesitic rather than dacitic with feldspar (F) as the primary phenocrysts. In this case, the groundmass (G) is composed almost entirely of glass.



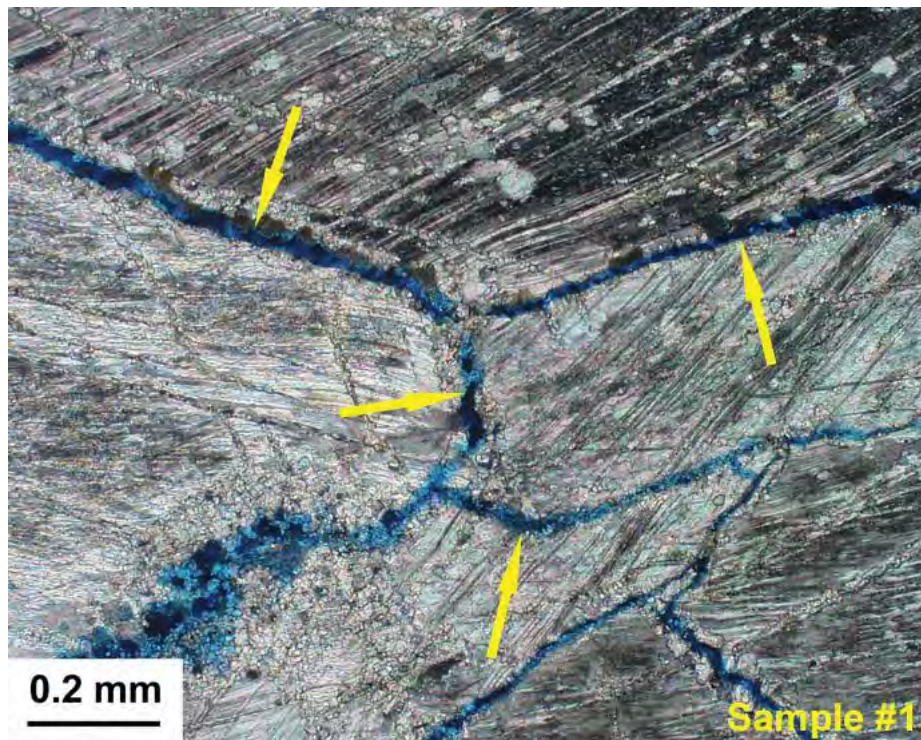
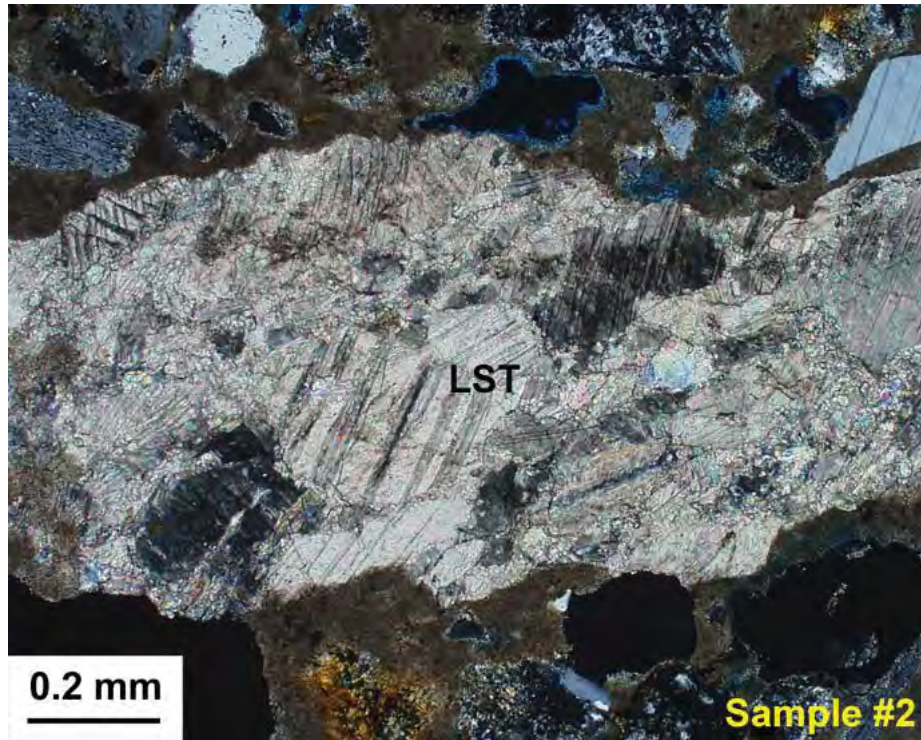
**Figure 5:** PPL photomicrographs of powder mount specimens prepared from the fines extracted through acid digestion. The arrows indicate fine particles of volcanic glass that represent a major portion of the finest fraction. Refractive indices are approximately 1.50 indicating a high silica content and this would be expected to result in a higher pozzolanic potential.



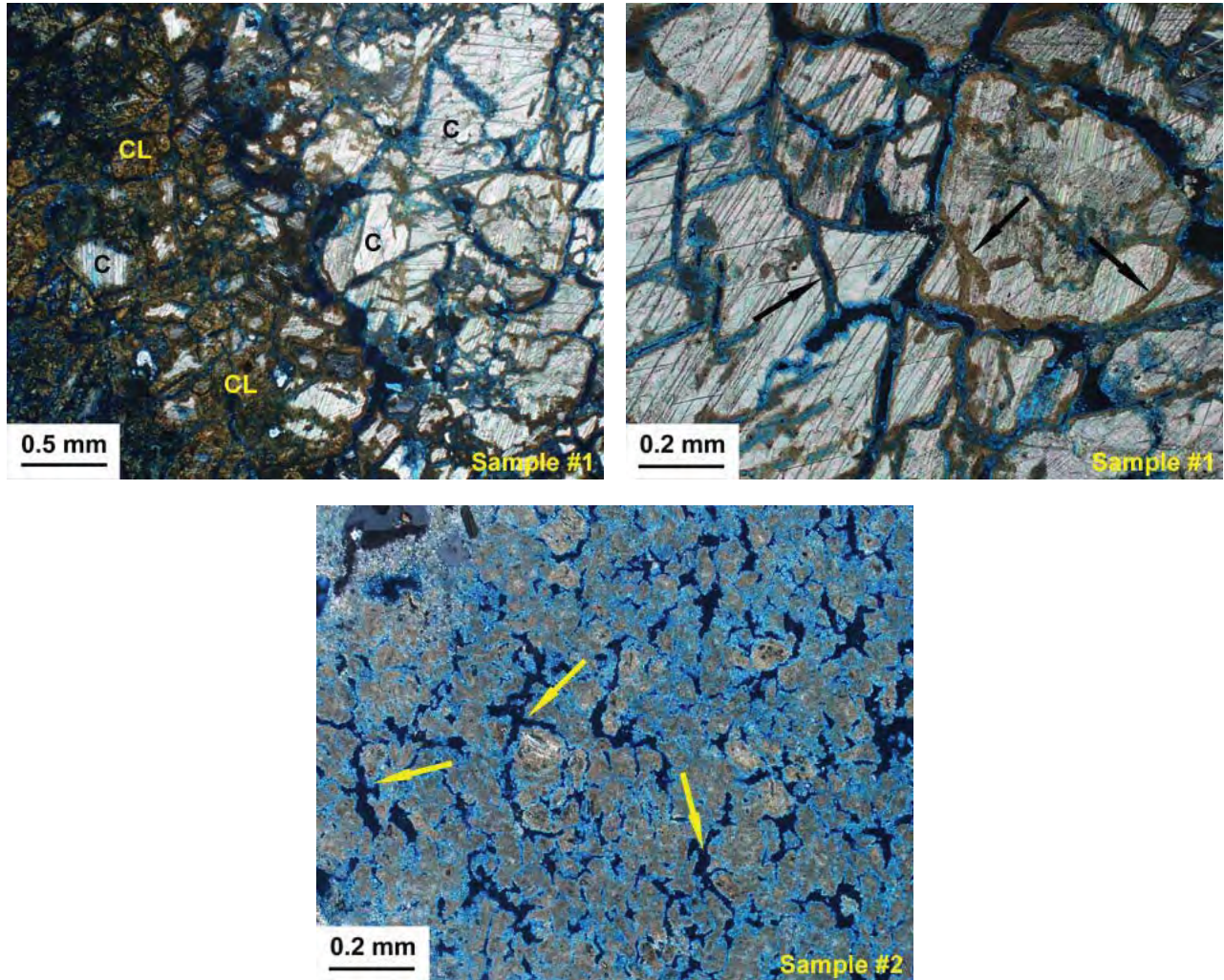
**Figure 6:** PPL photomicrographs illustrating the overall microtexture of the two examined samples. Both samples are impregnated with a low-viscosity, blue-dyed epoxy in order to highlight cracks, pores, and voids. The capillarity porosity of the binder matrix (BM) may be judged by the intensity of absorbed epoxy. Note that both have higher porosities typical of high lime mortars though Sample #2 is somewhat denser. Sand grains (S) are densely distributed in both samples reflecting the higher sand contents. Note the coarser grain size in Sample #1. The tight packing in Sample #2 leaves air-voids (V) at the interstitial space between some sand particles. Consolidation is not as well achieved in this sample. Voids are well distributed and not deformed between sand particles in Sample #1. The consolidation is more complete in this sample.



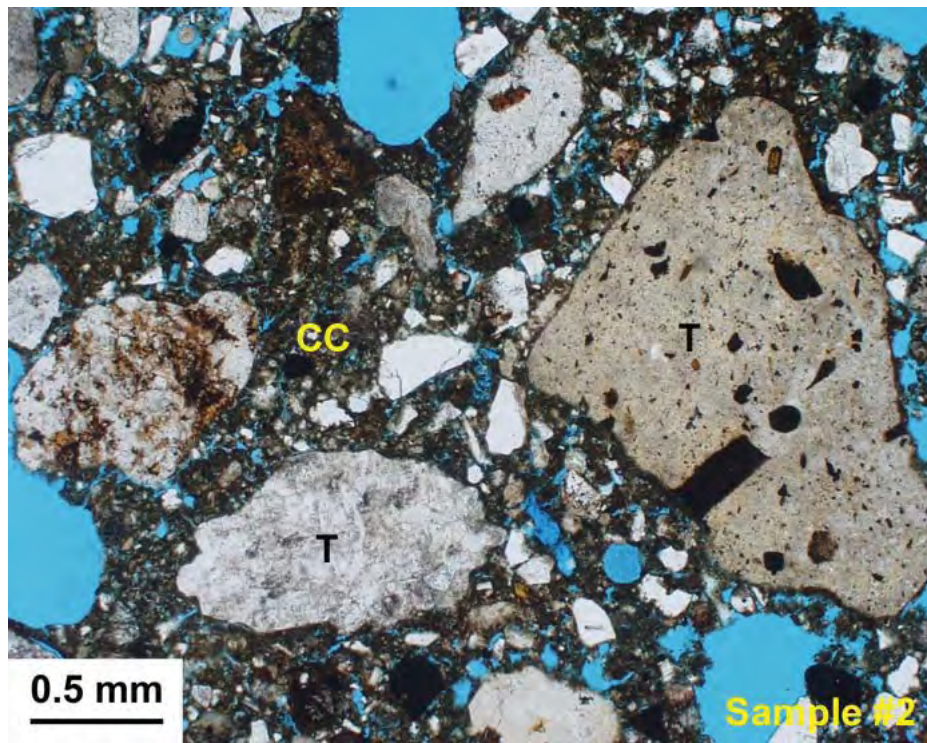
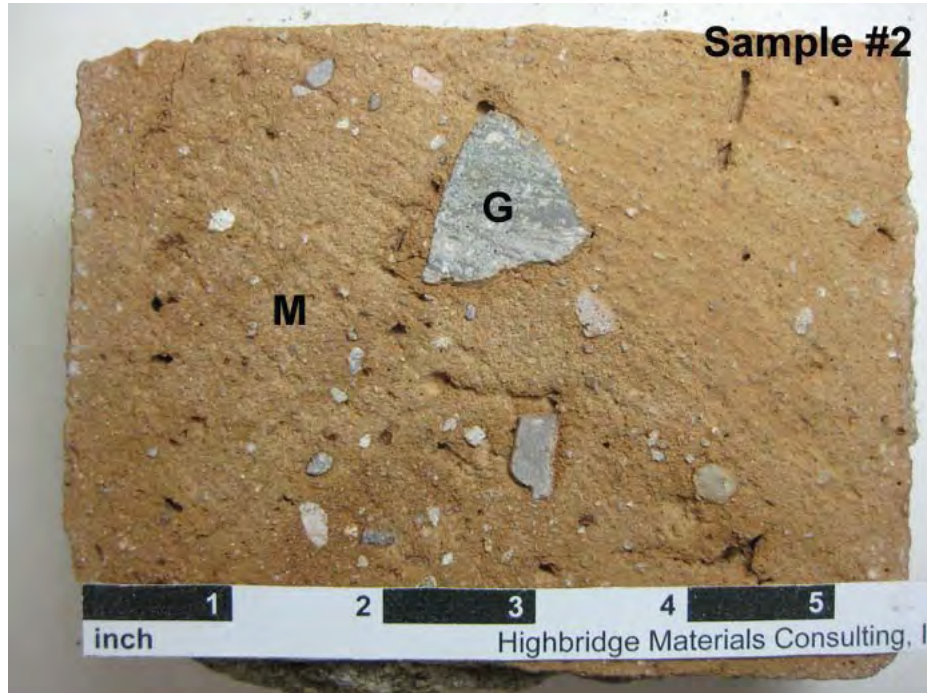
**Figure 7:** XPL photomicrographs illustrating the texture of most lime grains (LG) in both samples. The golden color indicates full carbonation of the lime. Most particles are non-descript and relatively fine-grained. The source of the lime is not revealed in these more abundant grains.



**Figure 8:** XPL photomicrographs illustrating grains revealing the lime source in both samples. (Upper image) A limestone particle (LST) is interpreted to represent an unburned portion of the lime. No burn texture is identified in this particular grain. The limestone consists primarily of calcite with trace quartz. The texture is indicative of mild geological deformation. (Lower image) A similar limestone grain is shown for Sample #1. Bent twin planes and subgrains along shear bands are again features related to geological strain. In this case, disaggregation has begun along grain boundaries and shear bands (arrows). This is produced by thermal expansion and this particular grain is determined to have been lightly burned.

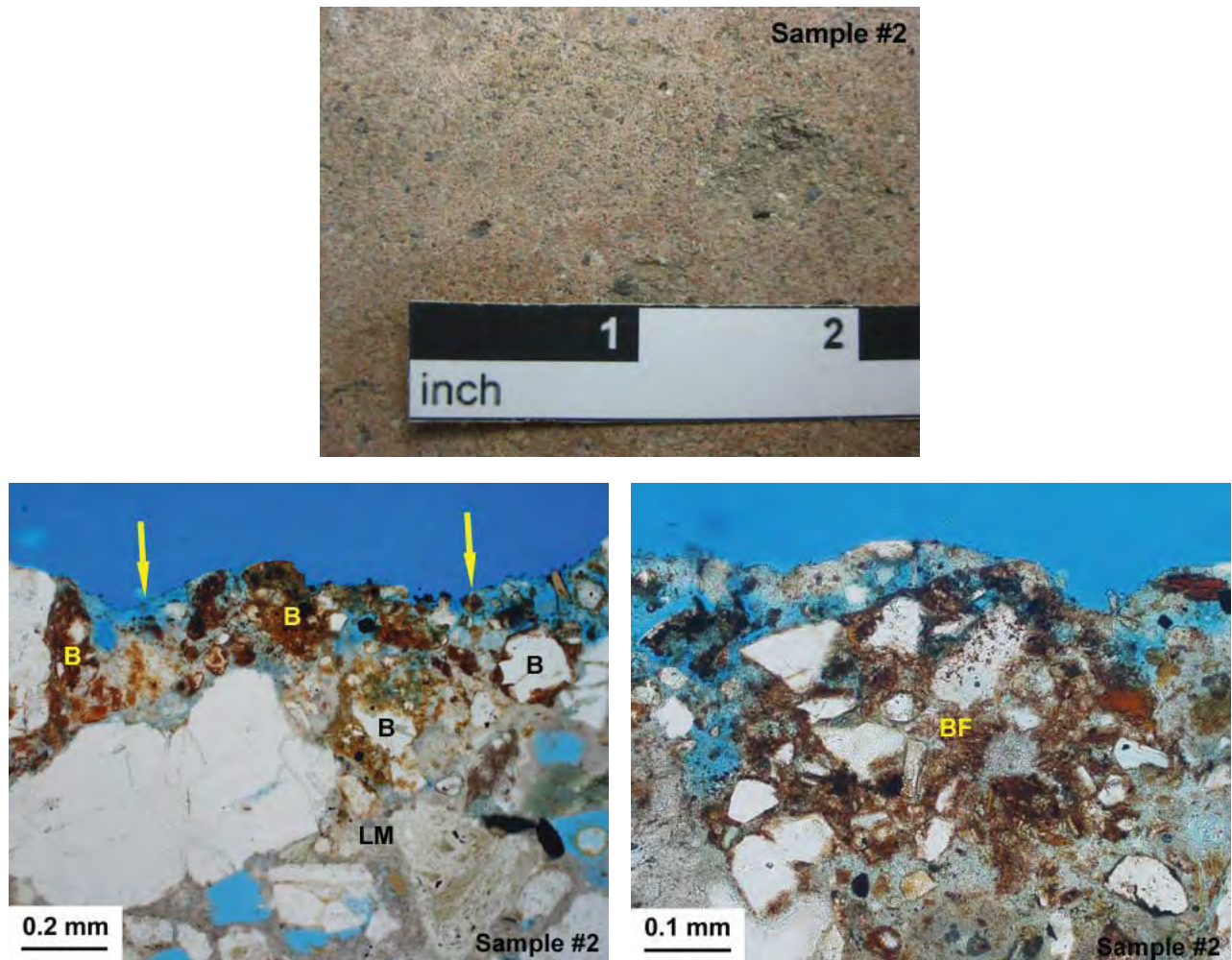


**Figure 9:** XPL photomicrographs illustrating lime grains that have undergone a greater degree of calcination than those shown in the last figure. (Upper left) The interior is shown of a large lime particle. Unburned calcite (C) appears cream-colored and carbonated lime (CL) appears a darker brown. Note that the left side of the grain was more completely calcined and this represents the outer core of the lime particle. Free lime was originally developed and this has since carbonated in situ. (Upper right) A close-up is shown of the less burned interior of the same grain. The arrows indicate disaggregation fractures formed during calcination along pre-existing grain boundaries and shear bands. Note that these fractures are lined with carbonated lime. Calcination has occurred first along the fracture openings. (Lower image) A completely burned and carbonated lime grain is shown. However, the original disaggregation fractures can still be observed (arrows). No unburned calcite is left within this particular grain.



**Figure 10:** (Upper image) The saw-cut brick surface underlying the plaster sample is shown. The brick has a reddish clay matrix (M) and a minor amount of coarse grog (G). (Lower image) PPL photomicrograph illustrating the brick microtexture in Sample #2. The brick contains an abundance of volcanic temper (T) encased in a matrix of calcined clay (CC). The volcanic grains are mostly similar to those observed in the mortar aggregate.





**Figure 11:** (Upper image) A close-up photograph illustrates the plaster finish surface. The finish has a slightly sandy, float-type texture and a pink pigmentation. (Lower left) PPL photomicrograph taken with a condenser lens inserted in the light path. The arrows indicate the outer surface of the plaster. Brick dust and fine fragments (B) are embedded in the lime mortar (LM). These brick fragments are responsible for the pigmentation and may also provide some weather-resistance assuming they have a pozzolanic property. (Lower right) PPL photomicrograph. A close-up is shown of one the coarser-grained brick fragments (BF) used for the plaster finish.







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