AN EVALUATION OF HISTORIC CEMENT STUCCO USING CONDITIONS ASSESSMENT METHODOLOGY AND DIGITAL VISUALIZATION TOOLS, GRAND TETON NATIONAL PARK, USA

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I am a gentle reminder of man's past
A time when he was not afraid to dare
And hoped the evidence of his works would last
To prove he had the decency to care.

from "I bear bleak witness," a poem by Lester May
a Mormon Row homesteader

"Were I obliged to live in a log-house,
I would have it plastered and whitewashed that it might be neat and pleasant."

Brigham Young
June 12, 1860
Journal of Discourses*, 8:297*

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ABBREVIATIONS

ACL— Architectural Conservation Laboratory at the University of Pennsylvania

ASR— Alkali Silica Reaction

GIS— Geographic Information System

IRT— Infrared Thermography

JMH— 'John Moulton Homestead' code for stucco samples

NPS— National Park Service

PCA— Portland Cement Association

PLASTER TERMINOLOGY [1]

- Plaster (n): a portland cement-based cementitious mixture. Referred to as stucco (n) in exterior locations.
- Cementitious material (n): a material that, when mixed with water and with or without aggregate, provides the plasticity and the cohesive and adhesive properties necessary for placement and the formation of a rigid mass.
- Admixture (n): a material other than water, aggregate, or basic cementitious material added to the batch before or during job mixing.
- Set (n): the chemical and physical change in plaster as it goes from a plastic state to a rigid state.
- Coat (n): a thickness of plaster applied in a single operation.
- Three coat work (n): application of plaster in three successive coats with time between coats for setting.
- Scratch coat (n): the first coat of plaster applied to a plaster base or lath.
- Brown coat (n): the leveling coat in a plaster system; second coat of plaster applied over the scratch coat.
- Finish coat (n): the final layer of plaster applied over base coat.
- Metal reinforcement (n): expanded metal lath; also called wire cloth, metal plaster base, or hardware cloth.
- Scoring, or scratching (n): the grooving of the surface of an unset plaster coat to provide a key for a subsequent coat.
- Key (n): plaster that physically surrounds to lock onto the perforations or irregularities of the plaster base or previous coat of plaster.
- Texture (n): any surface appearance as contrasted to a smooth surface; similar to rustication (n).
- Cement paint (n): A paint consisting of white portland cement and water; pigments, hydrated lime, water repellents, or hygroscopic salts can be added to impart qualities or characteristics.
- Coarse aggregate: aggregate retained on the 4.75 mm sieve (No. 4).
- Fine aggregate: aggregate retained on the 75 mm sieve (No. 200).

[1] ASTM C926-17, Standard Specification for Application of Portland Cement-Based Plaster, 2-3. ACI Concrete Terminology, 2013.

1.0 INTRODUCTION

The John Moulton homestead, located in Grand Teton National Park, is likely to be the most intact structure which can be accessed by the public within the Mormon Row Historic District. The homestead complex is one of six building complexes that constitute the historic district, which was inscribed on the National Register of Historic Places in 1997.[1] Commonly known as "the Pink House," the homestead stands out amidst the plethora of rugged lodgepole log cabins for its principle characteristic: its pink-painted cement stucco. The stucco skin is presumed to be shedding from the structure, exhibiting cracking, loss at the foundation of the structure, displacement, and detachment of the system from the wooden sheathing underneath. To date, there has been no substantial inquiry into the overall condition of the cement stucco or the mechanisms of its decay.

The presumed causes of deterioration of the stucco, which call into question the stability of the cement as a material as well as its method of attachment, may be unfounded. This thesis takes a step further to test the use of non-destructive digital tools as an innovative method to investigate the extent of deterioration present in an attempt to support this argument. First, the condition of the stucco and its attachments will be discussed through the findings of a site survey of the John Moulton homestead and a laboratory analysis of the stucco; this research mirrors that of a traditional conditions assessment and materials testing methodology so as to establish the visually evident existing conditions and to substantiate the pathologies. However, field limitations hindered a full examination of the breadth of deterioration which can ultimately lead to assumptions based on unknowns. This thesis uses a methodology which incorporates three independent digital techniques to analyze the spatial distribution of data which builds upon the information ascertained during conditions assessment. These tools provide complimentary information which ultimately renders a more thorough assessment, while minimizing the use of invasive assessment techniques that conflict with good preservation practice.

The principle goal for the Moulton property is to determine the cause of the cracking in the exterior stucco, as well as the extent of detachment. Geographic information system (GIS) software, infrared radiation thermography (IR), and Structure from Motion (SfM)

[1] No single structure on the row is individually designated.

Figure 1.1 The John Moulton homestead, also popularly known as the Pink House. (Photo by author, 2017)

Figure 1.2 Primary deterioration concerns at the John Moulton homestead center on the evident cracking and loss of the exterior stucco. (Photos by author, 2017)

photogrammetry are tools which have the potential to supplement more traditional modes of documentation by furthering spatial understandings and three dimensional characteristics that are difficult to calculate or record by hand. Patterns based on the comparison of the resulting graphics suggest that unseen or misunderstood conditions could be more extensive than what is observed in the field or can be communicated through typical conditions drawings. Each of these techniques provide a different and unique approach of enhancing the typical methods of condition survey. The goal of this thesis is to see if the findings from these graphics will indicate areas of interest for further investigation. The success of this experiment hinges on the degree to which these techniques can clarify the evidences of deterioration conditions beyond traditional documentation, ultimately rendering the analysis more robust.

The continued survival of this iconic landmark in Grand Teton National Park depends on this proposed initial study of the material, its system, and its condition. The National Park Service cultural resource managers contracted the Architectural Conservation Laboratory (ACL) at the University of Pennsylvania to 1) analyze the condition of the exterior stucco at the Moulton homestead and 2) examine the mechanisms of deterioration. While this thesis begins to satisfy some of these requirements, a full conditions assessments and treatment recommendations report is forthcoming. Since this thesis is meant to be part of a larger overall assessment and conservation plan for the structure, some critical information related to the final report may be omitted because it is not relevant to the outcome of this thesis. While focused primarily on the discussion of modern digital techniques of survey, an additional outcome of this thesis is the production of base line condition documentation consisting of a series of annotated drawings and laboratory testing results. In the conclusions, future steps for field research will be discussed based on analyses with digital tools as well as discussion of other factors impacting the longevity of the building, including a prioritized list of stabilization interventions. In addition, recommendations for site management will also be addressed.

2.0 BACKGROUND

The John Moulton homestead is one of four structures in the Mormon Row Historic District which stands out for its high degree of integrity, and is the most accessible for present visitors; the significance of the cement stucco on the Moulton homestead extends beyond its distinctiveness in the context of the local vernacular style. The cement building material is critical to expressing the meager success of a late homesteading family, particularly in the Jackson Hole Valley where any modicum of success for farmers was uncommon. But the mouldering ruins of neighboring dwellings which once surrounded this house redouble its significance through its rarity.

2.1 Historic Context

The Jackson Hole Valley, located in northwest Wyoming, was part of the late period of frontier homesteading of the Western United States. Since its settlement in the 1890s, the major industry in the area has been tourism. While rich in natural beauty, the Teton area is resource poor in terms of minerals and viable land for agriculture. By the beginning of the twentieth century, Jackson Hole had a small population who attempted to homestead and cultivate federal land grants. This was the case of John Moulton, who migrated to the burgeoning Mormon Row community just north of Jackson in 1908 *(Figure 2.1, 2.2)*. John Moulton, along with his brother Thomas Alma and other emigres from Idaho and Utah, claimed land grants to the north of Blacktail Butte which had a fortuitous combination of deep, well-drained soils with access to seasonal streams and shelter from the prevailing winds *(Figure 2.3)*. The Mormon Row inhabitants were the primary local agricultural resource and therefore critical to the early Jackson Hole economy, and they provided fresh dairy products for the local community and dude ranches alike.[2, 3]

2.2 The John Moulton Homestead and Vernacular Style in Jackson Hole

Most of the structures in Jackson Hole reflect the available natural resources in the region. The local vernacular building style utilized lodgepole pine, a tall and straight growing pine, sourced from Timbered Island at the foot of the Tetons and Shadow Mountain to the

[2] Ann Hubber and Janene Caywood, “Grand Teton National Park Multiple Property Submission; National Register of Historic Places Multiple Property Documentation Form” (United States Department of the Interior National Park Service, June 1991), 53.
[3] Robert W. Righter, *Crucible for Conservation: The Creation of Grand Teton National Park* (Colorado Associated University Press, 1982), 64.

Figure 2.1 The Moulton homestead and Mormon Row are located within Grand Teton National Park, north of Jackson, Wyoming.

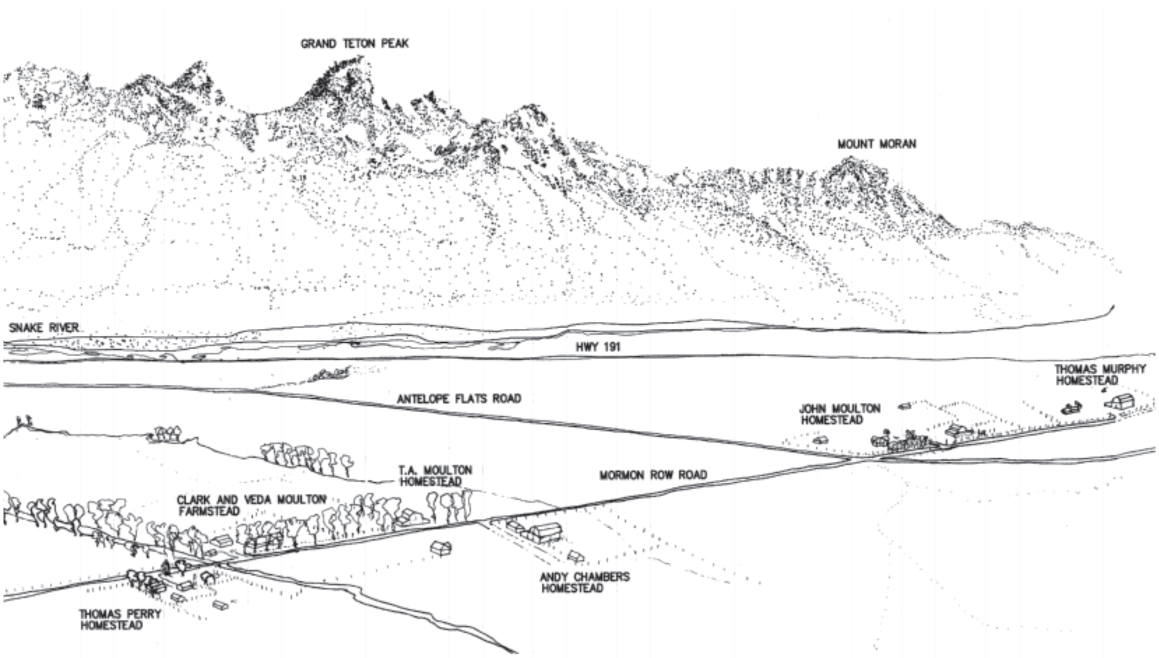

Figure 2.2 Contextual perspective illustration of the Mormon Row Historic District, which shows the extant structures on the row. (Historic American Building Survey, WY-152-A).

Figure 2.3 View of the historic district, looking southwest. The Mormon Row community was situated on the Jackson Hole valley floor on the leeward side of Black Tail Butte (left). Traces of the Moulton homestead's pink finish is visible through the aspen screen on the left. (Photo by author, 2017)

northeast of Mormon Row. Indeed, most of the first structures built by homesteaders were 12 x 12 ft log cabins to satisfy the requirements of the Homesteading Act of 1862. The log cabin was the primary architectural style in the area, likely because hardware and tools required for frame construction had to be transported by train to western Idaho and driven over the Teton Pass.[4] The first noted instance of frame construction is an addition to Bill Menor's store in 1900, which indicates that milled wood was available in the valley as early as the turn of the century.[5] Frame structures were more common in the 1910s due to the availability of lumber produced at local commercial saw mills, although transporting other building materials via the Teton Pass Road was still considered to be treacherous until the road was widened in 1932.[6] Until that point, hardware and building materials could be purchased from mercantile stores in Jackson at a higher cost.[7]

[4] The Oregon Short Line (Union Pacific) reached as far as Rexburg, Idaho, by 1899. The line was extended to Victor in 1912, a town 25 miles from Jackson via the Teton Pass.

[5] John Daugherty, "Life on the Homestead," in A *Place Called Jackson Hole: The Historic Resource Study of Grand Teton National Park*, First (Moose, Wyo.: Grand Teton National Park, National Park Service, 1999), 127.

[6] John Daugherty, "The Transportation Frontier," in *A Place Called Jackson Hole*, 193.

[7] John Daugherty, "The Pioneers: Homesteading in Jackson Hole, 1884-1900," in *A Place Called Jackson*

After cultivating their plots of land, it was generally accepted that the cabins initially built by homesteaders to satisfy the Homesteading Act would be replaced with more finished and refined structures given time and resources. A few of the Moultons' neighbors quickly upgraded their homes in the 1910s; even his brother built a frame structure in 1915. John, by contrast, waited nearly thirty years to construct his second home. After moderate success for their farm and dairy in the 1920s and 1930s, the J. Moultons had the resources to build a two story frame house stuccoed with cement in 1938. The house was one of two stuccoed structures on Mormon Row, and the first structure on the row built by a professional.[8] The John Moulton homestead exterior is decorated with a pink-tinted cement paint and the foundation line has a decorative 'water table', in which the stucco has been scored to represent stone and painted a darker purple to distinguish it from the rest of the elevation. The wooden window frames were painted a dark green, and the rest of the wooden elements painted were white. The whimsical style of the house may derive from traditions of domestic styling in the western Mormon cultural sphere, which favored durable and highly processed materials to connote expression of human power and refinement.[9] Hearsay among the NPS staff and Jackson community places intention with John Moulton himself, who purportedly elected to paint the house pink because it was his wife's favorite color. In all, the new vibrant house would have stood out dramatically on the flat valley floor amongst the log cabins and nearby frame structures alike.

2.3 Preservation Philosophy

Of the several homesteads in Mormon Row community during the 1910's and 1920s, only six families remained on the row into the next generation.[10] Although Jackson and its surrounding communities had flourished during wartime as the result of higher prices for agricultural goods, the following decade brought drought, falling beef prices, and two devastating floods. Homesteaders in the valley could barely subsist on the meager products of

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Hole, 93.

[8] Ann Hubber and Janene Caywood, "National Register of Historic Places Multiple Property Documentation Form," 49.

[9] Thomas Carter, "Frontier Fashion: Domestic Architecture and Individual Display," in *Building Zion: The Material World of Mormon Settlement* (University of Minnesota Press, 2015), 102.

[10] Ann Hubber and Janene Caywood, "National Register of Historic Places Multiple Property Documentation Form," 53-54.

their land;[11] during the 1930s, several families sold their land to the Snake River Land Company.[12] In 1943, the majority of the valley floor surrounding Mormon Row was incorporated into the Jackson Hole National Monument; these areas were consolidated into the expanded Grand Teton National Park in 1950. And while those few families succeeded in maintaining their residency, most of them sold their land to the Grand Teton National Park after 1950 under leases to lessen the economic strain of agricultural life in the valley. John Moulton sold his land to the park in 1953[13] after reaching an agreement with the park to lease back the land for the rest of his lifetime. John resided in the house for another forty years with help from family members to maintain the structure.[14, 15] After John's death in 1991 the Moulton family relinquished the property to the National Park Service.

The Moulton homestead is the most intact of any existing historic complex on the Mormon Row.[16] Life tenant caretakers typically had little interest in modernizing their structures because they knew that their properties would not be inherited by succeeding heirs, so most structures remained in their historic condition.[17] Caretakers typically let their property fall into disrepair in the later years of tenancy. By contrast, the substantial amount of intact historic fabric at the John Moulton homestead complex indicates that the Moultons fastidiously maintained the house *(Figure 2.4)*. In 1997, Mormon Row was inscribed on the National Register of Historic Places. The National Park Service has since mothballed the structure; no maintenance has been completed since 1991 aside from boarding up the accessible windows. Volunteer projects in partnership with the NPS have addressed maintenance of the grounds and outlying structures, but not the main house. [18]

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11 Maxwell Struthers Burt, "Homestead and Desert Claims," in *The Diary of a Dude-Wrangler* (New York,: C. Scribner's sons, 1924), 124-125.

12 The Snake River Land Company was pressured by local business people and the state legislature to put a moratorium on purchasing land from the Mormon Row in , as it was the only viable agriculture in the valley. Following the hardships of the late 1920s, a number of settlers wrote to the governor of Wyoming to appeal the decision. By late 1930, the Mormon Row area was reinstated in the SRLC purchasing program.

13 Candy Vyvey Moulton, *Legacy of the Tetons*, 2nd rev. ed. (Cheyenne: La Frontera Pub., 2007), 92.

14 Ann Hubber and Janene Caywood, "National Register of Historic Places Multiple Property Documentation Form," 54.

15 Candy Vyvey Moulton, *Legacy of the Tetons*, 94.

16 Ann Hubber and Janene Caywood, "National Register of Historic Places Multiple Property Documentation Form," 31.

17 M. Curran, "Mormon Row Historic District, Grand Teton National Park; National Park Service Cultural Landscapes Inventory" (National Park Service, Department of the Interior, 2006), https://www.nps.gov/grte/learn/historyculture/upload/Mormon-Row-CLI.pdf, 17.

18 https://www.bestofthetetons.com/2014/08/13/preservation-begins-on-the-john-moulton-homestead/.

Figure 2.4 A comparison of photographs from the early 1960s to the present confirms that the John Moulton homestead still has high integrity. The historic photo also shows how the visible the structure would have been during the period of significance when the aspens in the front yard were much smaller. (Source: Best of the Tetons, https://www.bestofthetetons.com/2014/04/08/the-moulton-barns-1963-1965/)

In summary, the singularity of the structure and its stucco derives from a number of concurrent sources. First, its flamboyant architectural style and use of commercial construction materials represent a rare instance of successful homesteading in the Jackson Hole Valley where the concept of 'proving up' came to fruition. Its persisting integrity redoubles its significance, particularly against the backdrop of the nearly empty Mormon Row. If the ruined state of the historic district is any indication, this is the pivotal moment for NPS cultural resource managers to step in and proactively invest in preserving what remains of the stucco feature and structure. According to the Secretary of Interior's Standards, to which the NPS is beholden: "Preservation is defined as the act of applying measures necessary to sustain the existing form, integrity, and materials of an historic property."[19] This philosophy is the most appropriate when the feature in question is important for that property's interpretive value and maintains a high degree of physical integrity. While concise, this brief history demonstrates that the stucco is key to conveying the structure's significance. What remains at issue is the physical condition of the stucco, and its ability to maintain integrity as a decorative and protective finish on the John Moulton homestead. The next section will parse deterioration theories and briefly discuss the results of field investigation and laboratory analysis of the stucco in order to verify, or call into question, the condition of the stucco.

[19] Anne E. Grimmer, *The Secretary of the Interior's Standards for the Treatment of Historic Properties with Guidelines for Preserving, Rehabilitating, Restoring and Reconstructing Historic Buildings* (Washington: U.S. Department of the Interior, 2017), 2, https://www.nps.gov/tps/standards/treatment-guidelines-2017.pdf.

3.0 PRELIMINARY ASSESSMENT

While this thesis focuses primarily on the potential use of digital tools for investigation a thorough understanding of all the means of failure— both known as well as presumed— is critical to the argument. Without considering all of the possible causes of failure, the non-destructive analysis could easily be drawn into doubt. This investigation of pathologies includes physical and historical investigations, as well as laboratory analyses. The information gained from testing is relevant as it can contribute to the documentation and condition assessment of any conservation report as well as inform about the material, both as it was originally applied and as it is in its present state. In this instance, analyzing the stucco can substantiate or dismiss the initial pathology hypotheses that call into question the condition of the cement matrix and the embedded ferrous metal reinforcement.

Several NPS employees and conservation professionals, each of whom have a unique and intimate knowledge of the structure, were asked for initial opinions about the primary factors contributing to the deterioration of the stucco.[20] The installation and assembly of the stucco is called into question by two of the hypotheses put forth.[21] The phenomena include the mechanisms of failure which affect the cement material, metal attachment system, frame structure, and site. *Figure 3.1* lists these hypotheses, along with tests or methods required to confirm them as primary contributors to deterioration.

Literature research, field survey, conditions graphics, and laboratory material analysis can substantiate or dismiss the majority of these theories, and additional monitoring may be able to confirm the results. These methods, however, cannot fully establish the area of detachment, deformation, and weathering damage— the extent of which are critical to determine in order to estimate risk of failure. Probing or exposing the interface of the stucco and frame could begin to confirm these conditions, but due to the high integrity of structure it is imperative to use methods which minimize damage to the historic fabric as much as possible. Other non-destructive methods, including ultrasonic testing and laser scanning, could potentially benefit the surveys in the future; however, these are not currently available to the ACL and can be cost prohibitive.

[20] Respondants included Shannon Denison (NPS), Betsy Engles (NPS), Jeff Olsen (NPS), Jim McDonald, Matt Morgan, Michael Henry, and Frank Matero.
[21] Improper installation of the lath and the use of undersized nails to attach the lath to the sheathing.

	Hypothesis	Evidence(s)	Method of Confirmation
Structural *Foundation*	Relic roots on the east side of the structure had undermined the foundation.	Diagonal cracking, detachment	Historic research
	Rodents undermining the foundation.	Diagonal cracking, detachment	Observation, monitoring
	Uneven settlement of the foundation.	Diagonal cracking, detachment	Research, monitoring
Attachment	Mesh is butted rather than overlapping.	Rectilinear cracking	Survey
	Undersized nails used to attach metal reinforcement.	Detachment	Survey
	Differential thermal expansion between metal reinforcement and cement and/or wood frame.	Rectilinear cracking	Research on material properties
	Differential expansion of furring strips.	Rectilinear cracking	Survey, literature research
	Corrosion of metal reinforcement.	Cracking, loss	Sample examination, field confirmation
Cement	Damage due to exposure; thermal cycling, hygric cycling, freeze-thaw cycling.	Cracking, particularly on the south and west elevations.	Laboratory analysis
Environment	Earthquake damage.	Diagonal cracking	Literature research

Figure 3.1 Theories of deterioration collected from site managers and knowledgeable preservation professionals.

3.1 Comparison to Contemporary Product Literature

Aside from a National Register nomination and documentation from the Historic American Building Survey, no relevant resources were found which discuss the building of the John Moulton homestead in detail nor its condition when it entered into the care of the National Park Service. Contemporary sources which discuss the installation of exterior cementitious stucco are essential in this case, as they can help to elucidate errors in application or installation which may be contributing to the deterioration of the stucco. Several theories in this vein had been put forward by professionals as a potential contributors in *Figure 3.1*, and these will be called out in this section. The following section compares the observations of the stucco assembly at the Moulton homestead to that which was prescribed in the literature of the period. Descriptions and illustrations regarding the system of construction are based on common construction details for frame structures, with some details added based on observations from the field.

In the first half of the twentieth century, hydraulic cements were considered to be the only material acceptable for exterior plastering due to their durability, appearance, and effective waterproofing. Industrially produced cement was increasingly accessible in the late nineteenth and early twentieth centuries due to the development of the continental rail network and expanding domestic production in the United States.[22] By the 1920s, Jackson Hole was still relatively isolated. Goods, like the cement used on the Moulton homestead, were carried via railroad and driven over the Teton Pass to Jackson to be sold at one of the general stores in town.[23] Cement products were accompanied by craft treatises[24] and product literature,[25,26] which dictated the techniques, tools, and materials necessary to apply cement stucco and anticipate potential pitfalls.

[22] Robert Whitman Lesley, *History of the Portland Cement Industry in the United States* (American Cement Company, 1900), https://books.google.com/books?id=owtHAAAAYAAJ&printsec=frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false., 12-16.

[23] By 1912, the Union Pacific Oregon Short Line railroad spur was extended to terminate at Victor, Idaho, on the west side of the Teton Mountain Range; this would have been the closest contemporary railroad.

[24] Whether or not the Moultons would have had access to these resources is not known, but these are documents contain clarifying details which are sometimes absent from product literature. *The Modern Plasterer*, by W. Verall, published in 1927 was particularly useful for this research. *Plastering* by J. T. Sawyer, which was first published in 1951, includes helpful techniques to improve the durability and workability of exterior stucco.

[25] "Plasterer's Manual for Applying Portland Cement Stucco and Plaster,"1929, and "Portland Cement Stucco," 1927, both distributed by the Portland Cement Association.

[26] These documents also mention the components incorporated into cement mixtures, which helps to explain the results from laboratory testing, particularly petrographic analysis.

a. System Examination

Despite the relative difficulty in procuring building materials in rural Jackson Hole, the reinforcement substrates and stucco at the John Moulton homestead appears to meet recommended specifications in the literature, with one critical exception. Contemporary Portland Cement Association literature describes the ideal installation of stucco on a frame structure as, in order of assembly: wooden sheathing nailed to wall studs; a moisture barrier attached to the sheathing surface; woven wire lath reinforcement panels attached to the sheathing, offset from the surface by furring nails *(Figure 3.2)*. This provides the substrate reinforcement for the cement stucco to be applied in a three coat system. As evidenced by the area of loss on the south elevation, the structure has diagonal sheathing to support the stucco system *(Figure 3.3)* with a vapor barrier attached to the sheathing *(Figure 3.4)*. Furring nails were placed at a distance from one another to avoid cracking, although the pattern is difficult to discern from this small area of observation (see *Figure 3.3)*.[27, 28] Furring devices at the homestead match a device advertised in a Portland Cement Association manual from 1929, which successfully offset the nail heads and wire reinforcement 1/4 in. from the surface of the sheathing allowing the cement to thoroughly coat and protect the ferrous metal from corrosion *(Figure 3.5)*.[29] While the nails were not measured in person, a photo taken from behind an area of displacement with a rigid borescope shows that the nail is likely 1 ⅜ in. in length which matches the length of nails recommended in product literature, disproving that the nails may be undersized and contributing to detachment of the system.

The flaw in construction is not the attachment of the metal reinforcement to the sheathing, but rather the installation of the mesh. Based on field observation, it appears that the woven wire lath panels were not overlapped the recommended 1 in. but butted together, perhaps in an attempt to economize the materials *(Figure 3.6)*. To form a rigid surface on which the plaster can cure, the reinforcement should have been lapped at least 1 in. at the edges to

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[27] Nails were preferable to furring strips, which can cause weaknesses along these portions of the stucco which results in cracking.
[28] "Plasterer's Manual for Applying Portland Cement Stucco and Plaster" (Portland Cement Association, 1929), 7.
[29] A furring device was present in a sample of detached concrete sent by the NPS staff to Philadelphia. The stucco comes from the area of major loss on the south elevation.

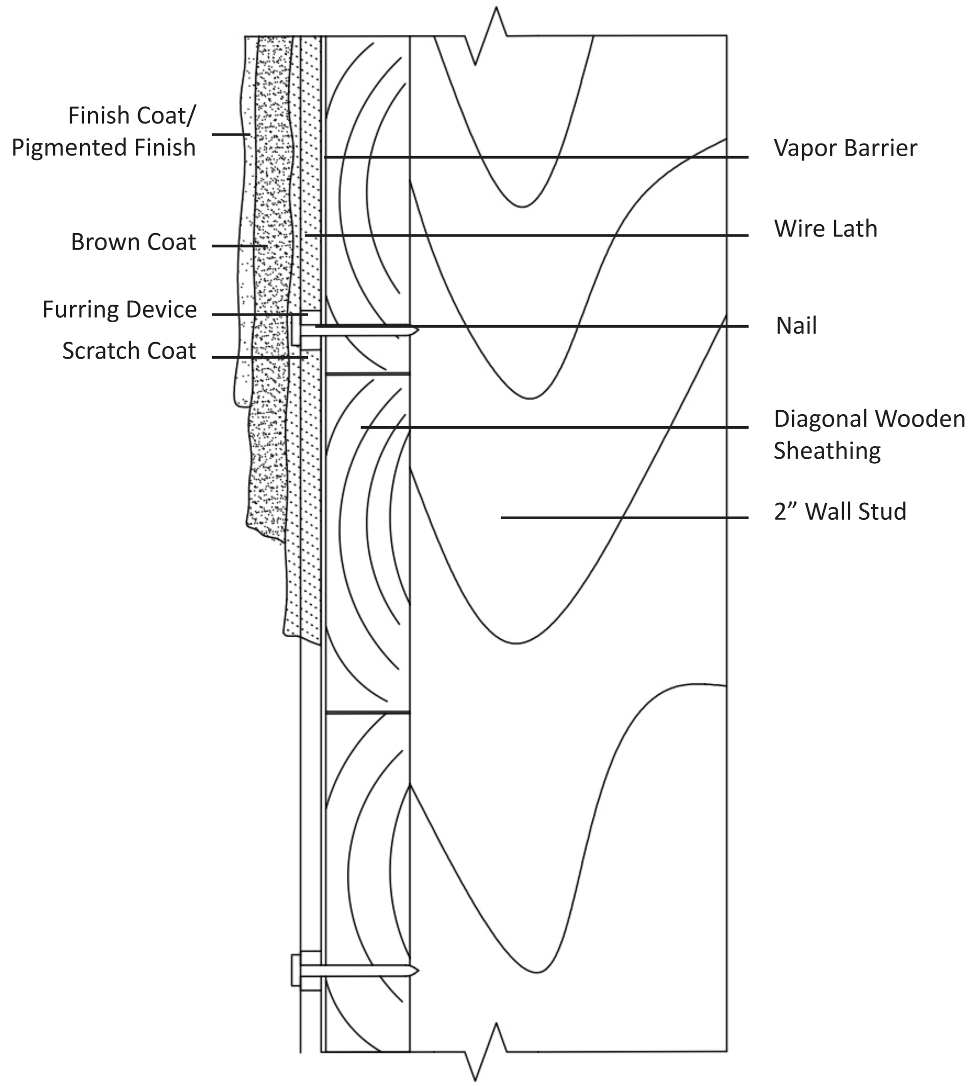

Figure 3.2 Section detail, based on product literature and observations at the site; this system provides a suitable substrate reinforcement for the stucco to be applied. (Drawn by author, 2018)

Figure 3.3 Section detail, based on product literature and observations at the site; this system provides a suitable substrate reinforcement for the stucco to be applied. Haphazard holes from the furring nails indicate that the lath was not attached using furring strips. (Photo by author, 2017)

Figure 3.4 Evidence of the underlying vapor barrier, visible through a crack on the south elevation. (Photo by author, 2017)

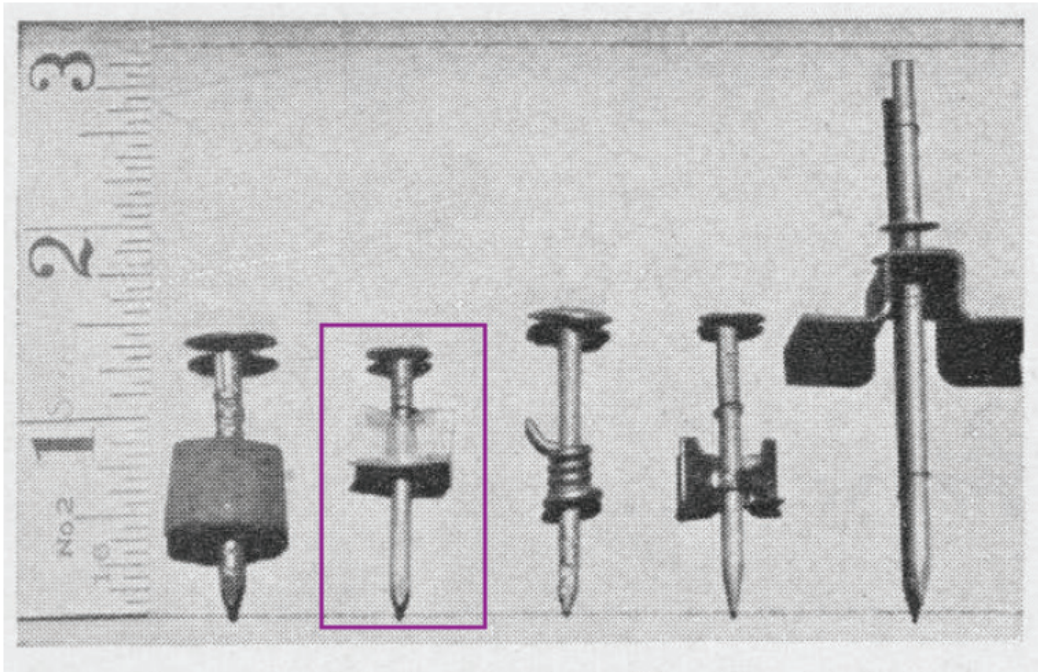

Figure 3.5 Image from 1929 PCA literature exhibiting acceptable furring devices as well as nail sizes for furring out lath. The device indicated matches that found at the Moulton homestead. (from "Plasterer's Manual for Applying Portland Cement Stucco and Plaster.")

Figure 3.6 Only one layer of reinforcement is visible in cross section along the vertical edge of a crack. (Photo by author, 2018)

form a continuous network across the entire surface.[30] Metallic laths were often secured at the edges of the sheets to the joists, whether with wire, fixing nails, or staples; the extent to which this was done is unknown, but it may not be sufficient enough to secure the panels together.[31] Therefore, the mesh panels may act as independent fields that expand and contract under thermal conditions rather than acting as a continuous surface, likely the cause of at least some, or possibly all, of the fine orthogonal cracks on the south and west elevations.

3.2 Materials Characterization

a. Test Selection and Sampling Methodology

For the purposes of this project, laboratory testing and analysis is confined to:

- Optical microscopy (petrographic examination and cross sectional analysis) to characterize the weathered condition of cement matrix and possibly identify the source of the aggregate in the stucco.
- Porosity characterization to establish the available pore space in a volume of material.
- Mechanical testing to determine the ability of the stucco to resist brittle failure through three-point bending.
- Testing to determine the presence and relative amount of salts (nitrates, sulfates, and chlorides) in a sample.[32]

Sample locations were chosen to ensure at least one representative from each elevation. To minimize the visual impact of missing material, samples were taken largely from the base of the structure near areas that were already exhibiting damage, cracking or loss. As a result, the data obtained in testing may represent the most damaged condition rather than a general overall condition of the cement stucco due to proximity to ground moisture, snow accumulation, and exposure to weathering.

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[30] "Plasterer's Manual for Applying Portland Cement Stucco and Plaster" (Portland Cement Association, 1929), 24.
[31] Ibid, 7.
[32] This was added to testing after preliminary photomicrographs revealed possible sub florescence beneath the paint finish; salt efflorescence was not visible during field investigation.

Figure 3.7 J. Hinchman detaches a sample from an area of existing damage on the east elevation using a hammer and chisel. (Photo by author, 2017)

Once locations were identified, samples were detached from the structure mechanically using a hammer and chisel *(Figure 3.7)*. Each sample was numbered sequentially with locations annotated in field notes. Photographs were taken at each sampling location and these locations are marked on *Appendix Biii. Appendix C* has an index of each sample, with bulk sample photographs, a detailed description and primary keywords, and a notation is included that indicates the test applied.

b. Testing Results

Both the cementitious material and the metal reinforcement, individually and as a composite unit, are in relatively good condition. Many of the laboratory testing results show that the stucco is still robust, both physically and chemically. In extreme environments, cement as a material will inevitably lose its material integrity and these conditions must be treated seriously. Some of these future pathologies can be extrapolated by the observations made in these tests. These are not presently so serious that they are contributing to the present failure of the stucco.

Figure 3.8 Cross section of a subsurface void directly connected to a surface crack, which shows that moisture can percolate through hairline cracks and exert force on the material with cycling temperatures. Magnification 50x. (Photo by M. C. Boileau, 2018)

Figure 3.9 Cross section of furring device which shows some evidence of ferrous corrosion. Despite eighty years of exposure, the metal still has a significant amount of heathy cross section. Magnification 20x. (Photo by M. C. Boileau, 2018)

In all, despite eighty years of exposure, the cement still is well adhered to the aggregate and does not show significant damage due to thermal or hygric cycling. There is evidence of surface micro cracks on both the exterior and posterior surfaces; these areas are more thoroughly carbonated than the surrounding matrix.[33] In some cases, these cracks also aligned with small underlying voids likely the result of moisture infiltration and freeze-thaw cycling *(Figure 3.8)*.[34, 35] The cement matrix surrounding the woven wire lath does not show significant physical stress which accompanies expansive corrosion products or thermal cycling. Voids evident near the metal reinforcement are likely from errors in application rather than damage. The results from the mechanical tests suggest that the stucco is quite durable in flexural bending, which means that the composite material is in good condition and a significant amount of force would have been required to cause the cement to rupture and displace, as is evidenced by the base of the structure where there is loss.[36] In samples that demonstrate a modulus of elasticity below the average, it is possible that the adhesion of the cement matrix to the wire cloth was more influential than the actual condition of the stucco itself, as voids diminished the tensile strength imparted by the wire.[37]

The embedded woven wire lath reinforcement dates to the 1930s, before the advent of galvanized steel and corrosion resistant coatings; as the system was originally designed, the alkalinity of the cement should inhibit corrosion products from forming. Over time, however, the process of cement carbonation takes place whereby the cement matrix combines with atmospheric carbon dioxide to form calcium carbonates. In a neutral environment the metal elements are more susceptible to corrosion: this is concerning, as the metal becomes more susceptible to breaking, and may induce spalling of the cement material due to corrosion jacking. The Moulton homestead cement samples demonstrate variable depths of carbonation in petrographic examination, which may be related to the degree of exposure. The metallic reinforcement system shows some evidence of ferrous corrosion but this does not appear to

33 Further information in *Appendix Diii*.
34 No crystalline salt was found in these areas.
35 Concluded in cross section and petrographic analysis.
36 See *Appendix Dv*.
37 Conversation with Dr. Alex Radin, of the Laboratory for Research on the Structure of Matter.

be inducing physical damage to the surrounding cement matrix. Where observable, the furring devices and wire lath look to have viable cross section *(Figure 3.9)*. The relatively low levels of corrosion and cement carbonation could be due to the low levels of porosity in the cement.[38, 39]

In the future, however, the cement material should be monitored for signs of deterioration relating to thermal cycling and its related pathologies.[40] One such pathology is corrosion jacking, in which the ferrous corrosion products can swell in volume and exert force on the surrounding concrete, stone, masonry, etc., which are reinforced with metal components which ultimately leads to damage.[41] Carbonation, for example, is an inevitable phenomenon for cement and will eventually leave the metal reinforcements exposed to deterioration. While salt attack was not posited as a potential contributor to the deterioration of the stucco, salt testing strips indicate that the stucco contains moderate amounts of nitrites (25 to 50 mg/L) and sulfates (>1500 mg/L).[42] Evidences of crystalline salt, however, were not observed in petrographic examination nor do the samples demonstrate damage patterns consistent with salt attack, although in a few instances sub fluorescence was observed within the cement matrix and on the building paper. Soluble salts can readily undergo crystallization cycles in environmental conditions with varying humidities and temperatures as is the case in Jackson Hole.[43]

Other potential pathologies which can affect cement, but which were not mentioned, include inappropriate aggregate which is physically or chemically incompatible with cement. For exterior stucco, river sand is typically the best aggregate due to its low clay content.[44] In Wyoming, decomposed granite and tufa rock was considered to be a suitable substitute.[45] Subangular grains were preferred for exterior plaster work, as the shape deters shrinkage from occurring.[46] The aggregate observed in the samples is a coarse, subangular mixture of stable and

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38 Conversation with Michael Henry, lecturer at PennDesign.

39 Inferred from the rate of water absorption and percent porosity calculations; see *Appendix Div.*

40 Particularly spalling due to freeze-thaw and salt crystallization.

41 David Watt, *Building Pathology: Principles and Practice*, 2nd ed. (Oxford ; Blackwell Publishing, 2007), 120-21.

42 See *Appendix Dvi*.

43 Dissolved salts can crystallize and exert pressure on pore walls, inducing mechanical damage; when relative humidity increases, the salts redissolve and can be transported further into the material due to utilizing the mechanical damage as an extended pore network.

44 J. T. Sawyer, *Plastering* (Shaftesbury : Donhead, 2007), 31.

45 Portland Cement Association., Proportioning Concrete Mixtures and Mixing and Placing Concrete. (Chicago: Portland cement association, 1916), 9, https://catalog.hathitrust.org/Record/100029668.

46 Jeremy P. Ingham, “Mortar, Plaster, and Render,” in *Geomaterials Under the Microscope* (London: Manson Publishing Ltd., 2013), 137–62, https://www.sciencedirect.com/science/book/9780124072305, 154.

inert alluvium, which is likely to be locally sourced either from the Snake or Gros Ventre River. No evidence of alkali silica reaction (ASR) or other deterioration pathologies affecting the aggregate were observed.

3.3 Structure and Environment

The building context is critical to analyzing the present condition of the stucco and the structure as it can clarify deterioration phenomena. Site conditions which have destabilized part of the foundation were put forth as a major contributor to the diagonal cracks and detachment of the stucco from the underlying sheathing. Other environmental factors, such as weather conditions and seismic activity also fall under this category of investigation.

a. Historic and Contemporary Uses

Although the foundation is not part of the stucco, its overall condition has a direct impact on the longevity of the entire building. In fact there is some evidence that suggests that the largest problems with the stucco may be directly linked to the condition and construction of the foundation, supporting the notion that the extent of the damage to the stucco may not be as egregious as once believed. While briefly touched upon here, this issue with the foundation will be discussed further in the conclusions as it has both a direct impact on the future of treatment and also helps to support some of the ideas put forward about the conclusions of the non-destructive testing analysis.

The condition of the foundation can be inferred from a number sources. This report does not purport to be a comprehensive or finalized analysis of the conditions affecting the foundation but discusses the inferences that can be made regarding its condition. According to the National Register nomination, other structures in the Mormon Row district are built on foundation walls made of concrete or native stone, but these are typically shallow enough that the entire structure can buoyantly rest on top of the alluvial clays. The J. Moulton house is similarly built on a concrete wall foundation, but a cellar under the southwest portion of the structure which extends below the frost line renders that part of the house rigid. The north and east parts of the house are cantilevered and move differentially to the southwest, likely causing the large diagonal cracks evident on the south and north elevations *(Figure 3.10)*. The Reed

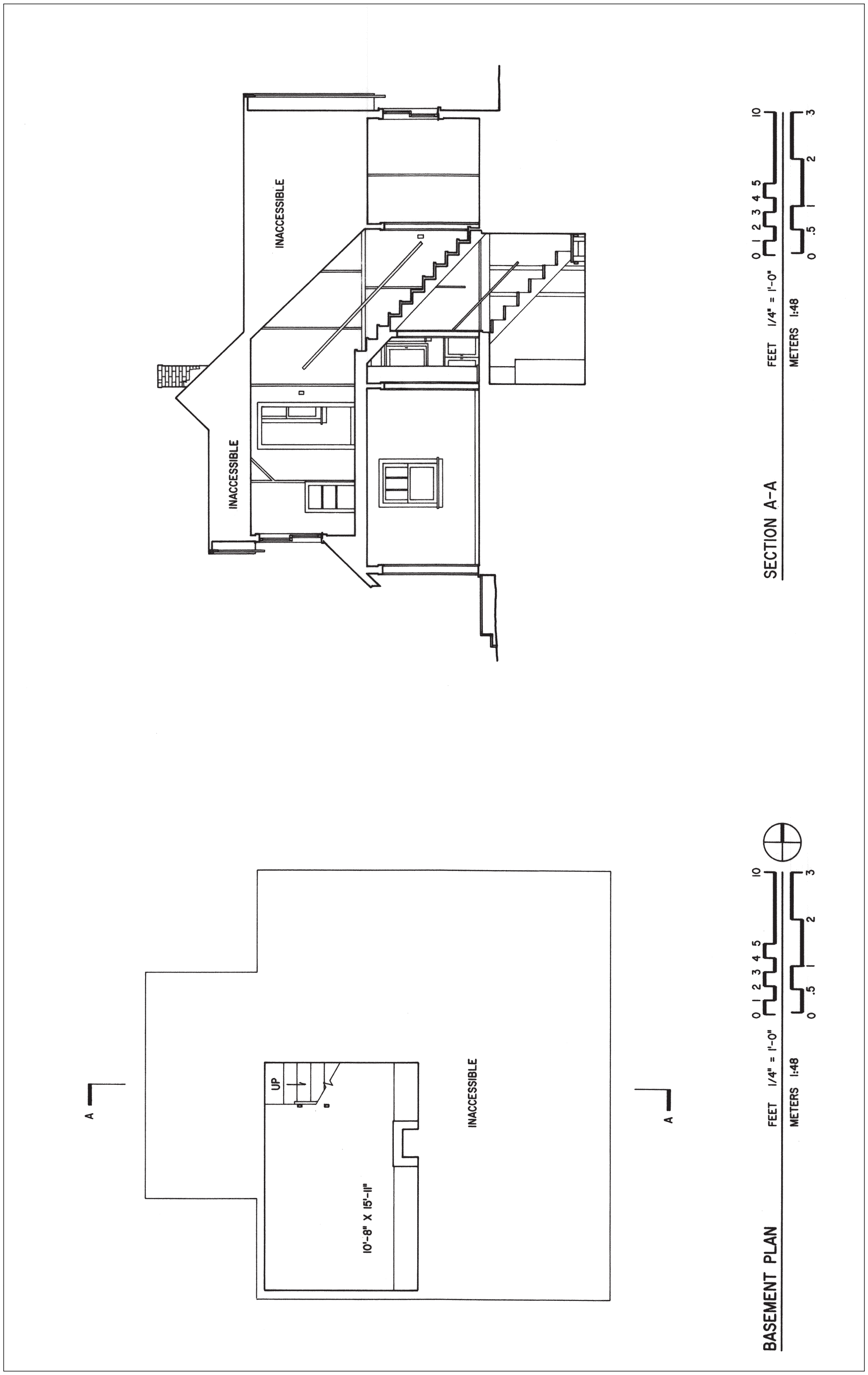

Figure 3.10 Plan of the John Moulton Homestead basement. (Historic American Buildings Survey, WY-152-A)

Figure 3.11 HABS photos from 1997 reveal trees and bushes encroaching on the east and south sides of structure, potentially impacting the stability of the foundation. (Historic American Buildings Survey, WY-152-A)

Moulton House, which is located to the north of the John Moulton property on the Jackson Moran Road, is an excellent comparison for this point. The house does not appear to have a deeper foundation or cellar than a cement foundation wall and therefore its exterior stucco does not exhibit the same diagonal cracks. But whether this motion is the result of freeze-thaw of the soil or subsidence should be determined with further monitoring.

Historic photos are used to analyze previous conditions of the house, including landscaping and contemporary uses. Proximity of trees and bushes to the base of the structure may contribute to destabilization of the foundation due to root jacking, whereby the root system undermines and destabilizes the foundation wall . The role of the relic tree roots on the east side of the structure similarly requires further research: it was suggested in one comment that the tree roots could have actually stabilized the east side of the foundation and deterred movement,

Figure 3.12 The stuccoed exterior of the Reed Moulton home does not exhibit diagonal cracking, as would be expected from earthquake damage or foundation subsidance. There is evidence of similar orthagonal cracking on the south and north (pictured here) elevations of the R. Moulton home. (Photo by author, 2017)

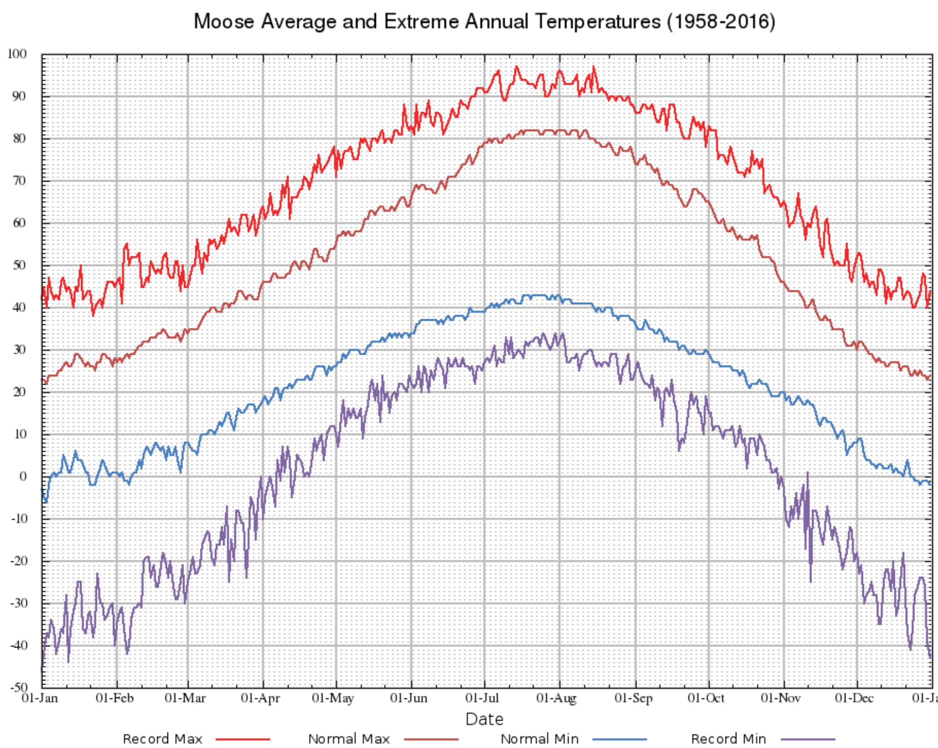

Figure 3.13 The average temperatures on the valley floor demonstrate extreme seasonal variations; a normal daily temperature cycle can exhibit 25-40 degrees change. (Source: Wyoming Water Resources Data System/State Climate Office)

but now that the tree is gone,[47] the roots are disintegrating and the foundation is free to subside *(Figure 3.11)*. A thorough structural investigation is needed to corroborate the precise cause of foundation movement, as it means the difference between movement which is stable and cycling and movement which is worsening; both of which would greatly affect the conservation treatments implemented.

b. Seismic Activity

Records of local seismic activity is also presented in this research, as ground disturbances may be contributing to deterioration conditions. Indeed, the Teton-Yellowstone region has a high level of seismicity due to faults in the surrounding region and the Yellowstone hotspot.[48] In the Teton region, several thousand small to moderate magnitude earthquakes have been recorded in the last thirty years;[49] these rarely exceed magnitude 2.5.[50] It is possible that loads from mild seismic tremors could be contributing to the cracking phenomena at the John Moulton homestead. The Reed Moulton residence, north of the John Moulton homestead, does not exhibit similar displaced or diagonal cracking in its exterior stucco characteristic to lateral loads induced by earthquakes *(Figure 3.12)*.[51] Either the stucco at the other house was installed after damage occurred to the stucco at the John Moulton homestead or, if the R. Moulton stucco is contemporaneous, the large cracks at the Pink House are likely not the result of seismic activity.

c. Climate

Thermal expansion and moisture gradients are the most common causes of cracks in concrete. Initial strain is induced as the cement cools and dries, but subsequent fluctuations in temperature and moisture can cause the different materials in the assembly to expand and contract.[52, 53] These discontinuities are typically 1-2mm wide and have little to no effect on the durability or the strength of the concrete.

47 The tree is evident in the 1997 HABS photos and has been cut down by 2014, according to the date stamp on photos found online.
48 Bonnie J. Pickering White et al., "Seismicity and Earthquake Hazard Analysis of the Teton-Yellowstone Region, Wyoming," Journal of Volcanology and Geothermal Research 188 (2009): 277.
49 Ibid, 783.
50 "Search Earthquake Catalog", accessed 12 April 2018, https://earthquake.usgs.gov/earthquakes/search/.
51 The National Register nomination is unclear as to when the stucco was applied to the structure. The house was likely built by previous owners in the 1910s or 1920s, before the John Moulton homestead.
52 Concrete typically contracts 0.37 mm/m during set.
53 David Odgers, ed., *Concrete*, vol. 8, Practical Building Conservation (London: English Heritage, 2012), 75-76.

The Jackson Hole valley displays extreme temperature variations. Teton County is classified as ASHRAE 169-2006 Climate Zone Number 7 Subtype B, very cold and dry, (43.666065, -110.664857). During both the summer months and winter months, the average daily temperature can fluctuate between thirty and forty degrees Fahrenheit *(Figure 3.13)*.[54, 55] Freezing conditions and temperature fluctuations may induce damage to the cement, which leaves the underlying ferrous metal reinforcements exposed to atmospheric conditions potentially causing corrosion. The R. Moulton home is again a good comparison; the exterior of the structure is likewise covered by hairline and small cracks, which confirms that the cementitious material forms small cracks under the strain of thermal cycling.

Mean annual snowfall in the valley can reach 13 to 16 ft.[56] A study of snow drifts observed at the Bar BC Dude Ranch in Grand Teton National Park found that snow tended to flow with the wind and accumulate on the north side of the structure, but this was less dramatic for gable ends that are perpendicular to wind direction.[57] Because the gable end of the structure faces the wind perpendicularly, some snow accumulation likely occurs on the north side of the Moulton homestead at the base and on the roof, but the differential accumulation is not greatly unequal between the north and south of the structure if Beckman's observations from the Bar BC ranch hold true on the other side of the valley. Photographic documentation in the winter would be useful to appreciate how high the snow accumulates against the stucco on the north elevation. Wherever snow accumulates at the base of the structure, the stucco is in contact with a source of moisture and therefore exposed to related damage.

The prevailing winds in the Jackson Hole Valley flow from south to north, although Blacktail Butte should shield the John Moulton homestead.[58] The stucco is completely exposed on all sides to weather, with little protection afforded by the aspen trees immediately to the

54 "Temperature Extremes, Annual, Moose (486428) - Wyoming State Climate Office," accessed April 2, 2018, http://www.wrds.uwyo.edu/temperature/extremes/486428-Annual.html.

55 Average summer temperatures vary between lows of 37-40°F and average highs of 75-80°F. In the winter, by contrast, the average daily high temperature is between 22 and 30°F and the average low can reach 0 to 10°F.

56 Christopher A. Davey, Kelly T. Redmond, and David B. Simeral, "Weather and Climate Inventory, National Park Service, Greater Yellowstone Network" (Fort Collins, CO: National Park Service, 2006), 13.

57 Christine L. Beckman, "Evaluating the Displacement Modes and Associated Risks of Stacked Log Structures" (University of Pennsylvania, 2013), https://repository.upenn.edu/cgi/viewcontent.cgi?article=1547&context=hp_theses.

58 The leeward side of Blacktail Butte was purportedly chosen to be the location of the Mormon Row for this reason.

	Hypothesis	Method of Confirmation	Contributing?
Structural *Foundation*	**Relic roots on the east side of the structure had undermined the foundation.**	Historic research	Potentially
	Rodents undermining the foundation.	Observation, monitoring	Potentially
	Uneven settlement of the foundation.	Research, monitoring	Potentially
Attachment	**Mesh is butted rather than overlapping.**	Survey	Likely
	~~Undersized nails used to attach metal reinforcement.~~	~~Survey~~	
	Differential thermal expansion between metal reinforcement and cement and/or wood frame.	Research on material properties	Likely
	~~Differential expansion of furring strips.~~	~~Survey, literature research~~	
	~~Corrosion of metal reinforcement.~~	~~Sample examination, field confirmation~~	
Cement	~~Damage due to exposure; thermal cycling, hygric cycling, freeze-thaw cycling.~~	~~Laboratory analysis~~	
Environment	~~Earthquake damage.~~	~~Literature research~~	

Figure 3.14 Revised list of deterioration hypotheses.

east. The surface of the south elevation receives both the brunt of solar gain as well as winter storms. A combination of direct sunlight and exposure to the wind are the cause of dramatic paint loss and fading on the south elevation.

3.4 Summary of Assessment

Based on these preliminary analyses, half of the original hypotheses have been fully eliminated while others have also been drawn into question (*Figure 3.14*). While these do not approximate the areas in which the stucco is at risk, it is critical in a conditions assessment to determine the causes of pathologies and whether or not they are active and worsening. Treating afflicted areas when the causes of deterioration are still active can risk accelerating damage and wasting resources on interventions which are ultimately ineffective. Conservators, like doctors, are taught to treat the cause and not the symptom of deterioration. Treatment is ineffective and potentially harmful if the mechanism of failure is not understood. All of these issues discussed above are important to systematically consider as potentially contributing factors, although they may not seem to be related to the non-destructive testing investigation. Those which remain are each a potential candidate for the cause of failure and yet the question remains of how to identify if any or all of these are the culprit. Most of the conclusions which have been reached so far have been based on investigations that limited the amount of destructive contact with the stucco. Without doing more damage, alternatives need to be considered to help this process of narrowing down the contributing factors and this is where the use of non-destructive testing should be considered.

4.0 DIGITAL ANALYSES

A set of three tools were selected to analyze the distribution of cracks and to contribute to the observations from the condition assessment. Each of these techniques are common tools that are readily available, and can be relatively easy to use with a condition assessment but have not commonly been used in tandem. Since each of these techniques is a non-invasive and non-destructive method, absolutes from the data can be difficult to identify. Non-destructive tools (NDT) are typically used to further the understanding of unseen conditions; however, there are few instances where visualization based NDT are utilized together in order to reduce the uncertainties or errors in analyzing data.[59,60] Combining and overlaying these approaches together can strengthen the case for areas of likely deterioration.[61]

4.1 Description of Tools

Photogrammetry, geographic information system (GIS), and infrared thermography (IRT) have been used in the past twenty years to supplement the recording and evaluation of historic structures to detect and record attributes of structures. Because photogrammetry and IRT are more commonly utilized in conditions assessment for cultural heritage, this section will briefly introduce them, their capabilities, and limitations in the capacity of assessing cultural heritage. Geographic Information Systems (GIS) is not a standard tool in conditions assessment, although it has been used in limited instances to analyze unique patterns where observable deterioration is restricted and where the relationship of these patterns may suggest pathologies and/or identify vulnerable areas. The discussion of GIS, its functions, and applications in architectural conservation will be more lengthy for this reason, but it carries the same utility in this methodology as the other tools described in this section.

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[59] D. Breysse et al., "How to Combine Several Non-Destructive Techniques for a Better Assessment of Concrete Structures," *Cement and Concrete Research* 38, no. 6 (June 2008): 783–93, https://doi.org/10.1016/j.cemconres.2008.01.016.

[60] Ch. Maierhofer et al., "Investigating Historic Masonry Structures with a Combination of Active Thermography and 3D Laser Scanner," *Quantitative InfraRed Thermography Journal* 8, no. 1 (June 2011): 115–18, https://doi.org/10.3166/qirt.8.115-118.

[61] R. Krankenhagen et al., "Quantification of Damage Processes at Surfaces and Interfaces of Building Structures Using Optical Methods and Active Thermography," in *Proceedings of the European Conference on Non-Destructive Testing* (Moscow, 2010), 10, http://www.ndt.net/article/ecndt2010/reports/1_05_10.pdf.

a. Photogrammetry

Photogrammetry is a technology whereby reliable metric information can be constructed for an object or surfaces based on photographs. Photogrammetric software establishes matching tie points from a series of overlapping photos to deduce camera orientations; for close-range photogrammetry, this involves instances where the camera is located and operated from the ground.[62] For a long time, photogrammetric softwares relied on referenced coordinates to reconstruct the position of the camera; more recently, however, new processing algorithms can use photographs taken with a common point and shoot or SLR camera to produce drawings, 3D models, measurements or point clouds.[63] The introduction of automatic reconstruction methods, called Structure from Motion (SfM), have rendered what was once restricted to experts more accessible for a broad range of audiences. A typical approach for the softwares creates a dense point cloud consisting of all the possible matches between the images. A series of outputs can be produced from the dense point cloud based on the project objective. Meshes are generated using triangulated irregular networks based on the dense point cloud, meaning that much of the original shape and texture is retained.

This method has become increasingly popular in architectural conservation for a number of reasons. As photogrammetry has become more efficient and less expensive, professionals can experiment with three dimensional representations to understand sophisticated construction more easily and accurately. The precision of SfM and other photogrammetry techniques are high in case studies which compare methods of 3D data acquisition; the results showed little variation from laser scanned models, which have long been considered to be the most accurate tool.[64] Photogrammetry, for its diminished cost, high portability, and convenience, has become a popular alternative to terrestrial laser scanning to capture and construct accurate models

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[62] Historic England, "Photogrammetric Applications for Cultural Heritage. A Guidance for Good Practice" (Swindon: Historic England, 2017), 4-8.

[63] Fabio Remondino and Fabio Menna, "Image-Based Surface Measurement for Close-Range Heritage Documentation," *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 37, no. B5 (2008): 199.

[64] A. M. Manferdini and M. Galassi, "Assessments for 3D Reconstructions of Cultural Heritage Using Digital Technologies," *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-5/W1 (February 13, 2013): 173, https://doi.org/10.5194/isprsarchives-XL-5-W1-167-2013.

of cultural heritage.[65] The technique is particularly attractive for its versatility, as it can be used without direct interaction between the structure and the operator to quickly record the morphology and volume of complex structures, both large and small.

The literature concerning photogrammetry and cultural heritage shows that the technology has yet to be capitalized upon for the purposes of answering research questions, or for monitoring and conditions assessment; there are by far more published case studies in which photogrammetry is used to create interpretive products, in which historic buildings are rendered in virtual and augmented reality models, or to document and archive endangered heritage.[66] While conservators have tended to utilize the software for archiving and distributing complex three dimensional models, its use in architectural conditions assessment is limited but growing.

b. Infrared Thermography

Infrared Thermography (IRT) cameras sensors detect the infrared radiation emitted from a surface and produce images which show temperature patterns present. IRT has long been used to detect the presence of air or moisture flow in structures based on differential thermal signatures to assess energy efficiency. Similar approaches can be applied to examining historic structures and artistic works for moisture retention or areas where voids are present.[67, 68]

While the thermal images are easy to capture, translating the significance of the thermal patterns proves to be more difficult. Differential signatures, for example, can be due to either material characteristics or indicate internal flaws.[69, 70] Moist areas, for example, tend to be cooler than dry areas because evaporation takes energy and lowers the surface temperature.

65 Paolo Salonia et al., "Multi-Scale Cultural Heritage Survey: Quick Digital Photogrammetric Systems," *Journal of Cultural Heritage* 10S (2009): e59–64, https://doi.org/10.1016/j.culher.2009.09.004.
66 Fiona Cameron and Sarah Kenderdine, "Introduction," in T*heorizing Digital Cultural Heritage: A Critical DIscourse*, ed. Sarah Kenderdine (Cambridge: MIT Press, 2007), 1–15, http://ebookcentral.proquest.com/lib/upenn-ebooks/detail.action?docID=3338737.
67 Elisabetta Rosina and Elwin C. Robison, "Applying Infrared Thermography to Historic Wood-Framed Buildings in North America," *APT Bulletin* 33, no. 4 (2002): 37–44, https://doi.org/10.2307/1504807.
68 E. Z. Kordatos et al., "Infrared Thermographic Inspection of Murals and Characterization of Degradation in Historic Monuments," *Construction and Building Materials* 48 (2013): 1261–65, http://dx.doi.org/10.1016/j.conbuildmat.2012.06.062.
69 N.P Avdelidis and A Moropoulou, "Applications of Infrared Thermography for the Investigation of Historic Structures," *Journal of Cultural Heritage* 5, no. 1 (January 2004): 120, https://doi.org/10.1016/j.culher.2003.07.002.
70 Ch. Maierhofer et al., "Investigating Historic Masonry Structures with a Combination of Active Thermography and 3D Laser Scanner," *Quantitative InfraRed Thermography Journal* 8, no. 1 (June 2011): 115, https://doi.org/10.3166/qirt.8.115-118.

Cooler temperatures can also indicate areas which are insulated. For the purposes of building investigation, this does not mean that one can 'see' the presence of the location of studs within a wall assembly;[71] instead, once can infer their presence because they affect the transfer of energy, resulting in a pattern of differential temperatures visible on the thermal image. The patterns of temperature differences, therefore, cannot identify the exact cause of these patterns but simply displays the presence of irregularities.[72] Field observations and other means of detection are required to further investigate these areas in order to confirm causes.

Infrared thermography has been applied in investigating subsurface conditions and moisture in a variety of historic materials, including assemblies on wood frame structures, dimensional stone, and masonry. In one case, the technique was sensitive enough to distinguish the presence of mosaic tesserae beneath a plastered surface;[73] these conclusions, however, can only be put forth as probable conditions as no supplemental testing was reported to confirm this. In an interesting case, Maierhofer et al. utilized an investigative methodology which combined infrared and three dimensional data to substantiate conclusions from thermal imagery for a damaged sandstone column in Madgeburg, Germany.[74][75] The researchers initially used these two tools in conjunction in order to make the thermal data reliable; a secondary benefit, they found, was the ability to discern between thermal patterns which are the result of irregular surface geometries and internal faults. These studies utilize active thermography, which intentionally induces heat transfer on the material being studied through the use of heat or halogen lamps.[76] Their methodology was unique in that they combined the 2D thermograms with 3D point clouds, thereby interpolating the thermal information onto its corresponding 3D point(s). The resulting graphics can correlate areas with notable thermal signatures and

[71] Timothy Woerner, "Infrared Thermography," *Exterior Building Envelope Inspections Using Thermal Infrared Imaging: A Report to the Public Building Service of the General Services Administration* (U.S. General Services Administration, 2006), https://static1.squarespace.com/static/52ed80f1e4b0354340039c-3c/t/55ee252ae4b0d8cb34180937/1441670442295/GSA_IR+Inspec_Protocol.pdf, 6.
[72] Ibid, 9.
[73] N.P Avdelidis and A Moropoulou, "Applications of Infrared Thermography," 125–26.
[74] Ch. Maierhofer et al., "Investigating Historic Masonry Structures," 115–18.
[75] R. Krankenhagen et al., "Quantification of Damage Processes at Surfaces and Interfaces of Building Structures Using Optical Methods and Active Thermography," in *Proceedings of the European Conference on Non-Destructive Testing* (Moscow, 2010), 10, http://www.ndt.net/article/ecndt2010/reports/1_05_10.pdf.
[76] Passive thermography utilizes changes in the natural changes in ambient temperature or amount of insolation to induce heat.

anomalous physical features and these areas were prioritized in succeeding investigations. While this study focuses on a substantially smaller feature than the stucco at the Moulton homestead, the methodology promises interesting advantages in isolating areas that are anomalous for further investigation when there is little visible information to indicate damage.

c. Geographic Information Systems (GIS)

A geographic information system is a highly popular software category in which users can manipulate and examine data with a spatial component. While principally developed in the field of geography and geospatial information, GIS can be used to organize information to create two and three dimensional visualizations. Presently, most GIS work employs softwares such as ESRI's ArcGIS or the open source equivalent, QGIS. While the capabilities offered by each software may differ slightly, these programs typically have tools and extensions that allow users to query, manage, and portray the trends within a set of data. Such statistical and querying capabilities available in GIS programs go beyond the capacity of Computer Aided Design (CAD) programs which have been primarily developed to display, rather than analyze, spatial information.

GIS data can exist in both raster and vector formats. A raster-based format consists of a grid of pixels that store and display information, while a vector format utilizes three fundamental information types: point, line, and polygon shapes. Information can be easily transferred from CAD based softwares, almost exclusively in vector formats, into GIS programs to create a series of graphical representations of spatial data which allow conservators to correlate data based on queries, statistics, and spatial analysis.

This section describes three projects which underscore the use of GIS in architectural conservation conditions assessments. In these projects GIS softwares were used as a tool to analyze the spatial distribution of cracks in resources of historic or artistic significance. The methodologies, interpretations, and results of these projects have been reviewed as case studies for this thesis. While these case studies differ from the John Moulton homestead in practical dimensions, such as materials or building system, they show that GIS can be used to parse and interpret visual data that conservators typically gather.

i. GCI Assessment of David Siquieros' América Tropical (1997)[77]

In 1990, the Getty Conservation Institute (GCI) undertook a $9 million conservation project to document and restore *América Tropical: Oprmida y Destrozada for los Imperialismos*(1932), a large exterior mural in Downton Los Angeles by Mexican muralist David Alfaro Siquieros. During the course of producing a condition assessment to direct treatment recommendations, researchers used GIS to highlight spatial relationships between a number of conditions, including cracks and salt efflorescence.

This is an early published instance of GIS software used in a conditions assessment, although, from the brief article, its use in the project appears to be limited to rendering the field drawings and notes into a queryable visual database. The article focuses more on the relative ease of transferring information into GIS from CAD softwares, rather than conveying a description of the workflow or tools used within the ArcGIS. The researchers utilized the edit function for the attribute table, in which numerical and textual data may be added to individual features— a process possible in CAD but often overlooked. One could, for example, query to highlight 'severe' cracks or where sodium chloride was found. The researchers also employed proximity analyses and, judging from the illustrations, made rasters to highlight areas of higher incidence of particular conditions. This study is prevalent in that it names initial tools that can prove useful for architectural conservation. It is still true that conservators can easily translate their work from field annotations to GIS through AutoCAD, and that CAD has no equivalent function to the attribute table or similar way to attach and store information to data. In the use of spatial analysis tools, however, the study was overall lacking in concrete evidence or analysis for the usefulness of the GIS software in succeeding assessment and treatment phases of the project.

ii. ACL Ceiling Plaster Assessment at Drayton Hall, Charleston (2001)

The Architectural Conservation Laboratory (ACL) at the University of Pennsylvania conducted an intensive assessment to characterize the condition of the decorative plaster ceiling in the Great Hall at Drayton Hall in Charleston, South Carolina. Adjacent to field recording and

[77] Gaetano Palumbo, "Beyond CAD: A Look at Data Integration and Analysis Using GIS," in *GraDoc: Graphic Documentation Systems in Mural Painting (Rome: International Centre for the Study of the Preservation and Restoration of Cultural Property* (ICCROM), 2000), 114–23.

digitizing of conditions, researchers John Hinchman and Kyu-Bong Song experimented with using the Spatial Analyst extensions in ArcMap and regression analysis to look for statistical correlations between the cracks and the supporting structures.[78] The researchers produced a series of maps using a combination of these methods, providing the successive treatment campaigns with extensive numerical data regarding the conditions and a visual map that illustrates and quantifies the extent of areas with high risk.

This study is significant as it uses regression models to study the relationships between data inputs in order to predict areas where damage could be unseen, and uses this "risk" notion to guide treatment. Regression models are relevant tools in two regards: they can indicate which factors (independent variables) are statistically significant in the influencing the location of a particular outcome (dependent variables), and these relationships can be used to predict values in other places. The latter use was used in the case of Drayton Hall, and it was interpreted as a "risk" map to indicate areas where deterioration was incipient but unseen. Creating the inputs for these models, however, is ultimately imprecise. The independent variables are each assigned a regression coefficient which describes the relationship of that variable on the dependent variable. In the case of deterioration conditions and structural features, the values assigned in this case were subjective and left to the interpretation of the researchers. While this threat map did successfully guide the conservation of the ceiling at Drayton Hall, no alternative methods of investigation were used to evaluate or confirm the results of the map nor were other regression analyses tested.

iii. Ceiling Plaster Assessment at the Wagner Free Institute of Science, Philadelphia (2008)

In her 2008 thesis, Marlene Goeke examined the efficacy of GIS analyses as a tool to enhance a condition assessment of the plaster ceiling at the Wagner Free Institute of Science in Philadelphia, Pennsylvania.[79] After a portion of plaster fell from the Exhibit Hall in 2003, the site managers were worried that the condition of the plaster was actually more severe than previously assumed. The lime-based plaster on the ceiling had exhibited significant cracking and

78 Frank Matero and John Hinchman, "Analysis and Conservation of the Great Hall Ceiling," Treatment Report (Architectural Conservation Laboratory and Research Center, University of Pennsylvania, 2003), http://www.conlab.org/acl/dray/Reports/2003%20Great%20Hall%20Report%20%28full%29.pdf.

79 Marlene Lauren Goeke, "Assessment and Analysis of the Plaster Exhibit Hall Ceiling at the Wagner Free Institute of Science, Philadelphia, PA" (University of Pennsylvania, 2008), http://repository.upenn.edu/

other conservation issues, but the building managers were concerned that the delaminating areas posed a safety risk for visitors to the historic museum and warranted replacing the whole feature. Goeke based GIS analyses on information from an assessment conducted in 2007 in which the location and size of cracks were recorded, as well as displacement and loss of the plaster.

Based on these drawings, Goeke tested the utility of GIS as a diagnostic method by examining statistical relevance of possible causal relationships between patterns of deterioration in the plaster ceiling and other external factors. Goeke separates her analyses into: 1) quantitative calculations, to compare data about crack distribution, location, and orientation and begin to speculate on potential diagnoses based on these contextualized in understandings of the underlying structure; and 2) visual representations, which encompass raster-based density and distance data and regression analysis. To supplement this study, the conservation team had hoped to use nondestructive testing techniques (NDT), but this was not completed at the time of the published thesis because the viability of the available methods were unsubstantiated for plaster on wooden lath. Ultimately, however, Goeke's method of analysis is well thought through and derives its usefulness in the absence of alternatives. Her thorough interpretation of GIS-based analyses she produced and their usefulness in answering research based questions pushes forward the use of GIS software beyond black-box regression models or superficial spatial database uses.

4.2 Summary

These studies differ significantly from the cementitious stucco at the John Moulton homestead, but several factors intrinsic to a plaster or stucco of any kind make these methods worthwhile to explore despite several practical differences. Observations and assumptions made for each study cannot be directly translated to this thesis project. For one, the situation of the resource varies amongst all of the studies. Both Drayton Hall and the Wagner Institute projects are indoor and therefore experience little to no weathering, whereas the patterns of deterioration at the América Tropical and the exterior stucco at the John Moulton homestead

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must be analyzed in the context of regular exposure to their respective environments. The shape, orientation and structures underlying each feature is also highly varied, from the Great Hall's overlying floor, the Wagner's barrel vaulted ceiling, and the exterior brick masonry supporting the *América Tropical*.

GIS is principally concerned with mapping. Conditions on a wall or a ceiling can be mapped in a similar way that roads or forests can be mapped on the landscape. While each of the techniques discussed above differ in their physical reality, they are all attempting to find correlation between conditions through the relationship of patterns. In each of these cases, GIS was used principally because it is a non-destructive form of testing that relies on information already gathered in the field and it had the potential to yield other interpretations that could help the conservators identify conditions and diagnose causes of deterioration. This point is particularly important where the outer surface of the plaster is the only observable plane, as at the John Moulton homestead where the interface of the plaster and the wooden sheathing is impossible to examine without doing significant damage to interior finishes or to the stucco itself. The decorative ceiling at Drayton Hall faced a similar issue: the overlying floor had been filled with plaster of Paris as part of an attempt to stabilize the plaster in the 1978 meaning that the backside of the plaster feature was inaccessible without serious risk of damaging the decorative plaster. At the Wagner Institute, by comparison, correlations could be made between areas where it was known that the plaster had not been properly keyed into the lath and resulted in observable patterns.

Based on these published conditions assessment projects which use GIS software, the following tools have proven to be the most useful for the purposes of analyzing field data:

- Attribute Table: The tabular Attribute Table feature in GIS allows conservators to attach data, both numerical and textual, to the vector data. Its usefulness is demonstrated by the Getty Conservation Institute study of the *América Tropical* in 1997.
- Querying: GIS softwares can selectively display data based on attributes of that data (for example, selecting "small" and "medium" cracks) without requiring separate layers for each type, as one would do with AutoCAD. The Field Calculator tool in the attribute table enables

the user to look at numerical and statistical data about the selected attributes; for example, the total length of cracks for a single attribute, like "small" cracks, or combined attributes like "small" and "medium" cracks. Goeke utilizes these values to create charts, independent from their source maps, in order to compare raw data about crack lengths and the distribution of crack sizes in different areas of the ceiling at the Wagner Institute.

- Spatial Analyses: The Spatial Analyst extensions also represent a potential benefit to conservators; as Palumbo points out in the case of *América Tropical*, these tools are the statistical versions of what conservators typically interpret qualitatively.[80] With GIS, however, these relationships are analyzed quantitatively and then rendered into visually simplified (but striking) graphic forms, particularly with the aid of graphs and colored raster layers. Three tools within the spatial analysis toolbox include:
    - The proximity analysis tool which highlights those features which fall within a certain distance from a specified file, vector or raster.
    - The distance analysis tool, which creates a raster overlay based on the distance from cells in a selected file to a particular feature.
    - Density tools which convert the input vector (point or line) layer into a density raster based on concentrations of occurrences for a selected feature. Where there is a clustering of points, that area will have a higher value compared to fewer points in other areas, producing an image of hotspots based on the statistical analyses of the spatial relationships between points.
- Raster Calculator: The Raster Calculator tool, which executes Map Algebra expressions to create a raster based on input variables combined according to mathematical operators (addition, subtraction, etc.) selected.

[80] Palumbo, "Beyond CAD," 115-116.

5.0 METHODOLOGY

A conditions assessment typically consists of a brief site and structural survey, followed by systematic documentation and assessment of the physical condition of the resource based on accepted definitions of conditions and their pathologies. Photography, graphic conditions documentation, technical geophysical and structural reports are used to supplement these evidences and bolster conclusions. Historical research is pursued to confirm, or challenge, as well as supplement interpretation of the feature's present condition.

5.1 Field Survey

A condition survey was conducted over the course of three days, from October 20 to October 22, 2017. Once on site, the team conducted a brief preliminary survey of the site to identify the primary deterioration conditions and strategize how to best document them in spite of a number of disadvantages in the field.[81] Assessment was carried out from the ground around the structure. The interior of the building was not accessible during the field survey.

Upon investigation, the team identified that the primary deterioration condition affecting the cement stucco is cracking. Secondary conditions, including biological growth and discolored or deteriorating finishes, were present on the surface of the stucco but were very infrequent. Some note has been made of these on elevation drawings as part of the conditions assessment.

a. Limitations

Field survey was limited by a number of factors which relate to unexpected practical difficulties in the field. Weather conditions, including freezing rain, snow, and gusty wind, made the field assessment process less than ideal. All observations were made from grade because scaffolding and ladders were not practical in the given weather conditions *(Figure 5.1)*. Conditions of the stucco itself made assessment difficult. The stucco was too thick to reliably identify voids through a tap test. Finally, the survey consisted of two people completing the assessment over the course of three days. The number of limitations forced the researchers to prioritize recording of primary conditions in the field, and take other forms of documentation which could subsequently be analyzed upon return to the University of Pennsylvania.

[81] These will be further discussed in a succeeding limitations section.

Figure 5.1 Access to the upper part of the south, west and north elevations was limited due to poor conditions. A ladder was used to collect samples and make close range observations. (Photos by author, 2017)

The high integrity of the stucco also acted as a hindrance for field investigation. While conditions like cracking, discoloration, and paint loss are visible and can be easily recorded using traditional means, other conditions such as detachment and corrosion of the metal reinforcements would not have been possible to thoroughly examine without significant interventions. Due to high integrity of both the stucco and the interior finishes, for example, it was not ethical to blindly probe or expose the underside of the stucco in order to examine the attachments or detect detachment from the underlying sheathing.

b. Condition Drawings

Independent drawings were created to depict the extent of conditions for each elevation. For this field project, field condition drawings serve two purposes. They allow for better synthesis of information in subsequent analyses as well as standing as a baseline for future conservation. For the John Moulton homestead, it is particularly pertinent to diminish or mute unnecessary visual information which stand out in photography— such as large cracks, and the variation in surface texture and color— in order to better understand the spatial relationship and pattern of conditions.

Figure 5.2 Preliminary conditions drawings were confirmed in the field; all observations were made from grade. (Photo by C. Magill, 2017)

Figure 5.3 Cracks were confirmed and then annotated according to size, extra small to extra large; those which were not evident in photos were traced onto elevations in the field.

Due to the environmental factors, initial conditions drawings were made off site using rectified elevation photos to draw visible cracks.[82] These drawings were then taken into the field to be confirmed and annotated based on visual field inspection *(Figure 5.2)*. Along each crack, or portions of line segments, a 'size' note was added to characterize the approximate width of the discontinuity *(Figure 5.3)*. The team members agreed upon general categories to depict size, ranging from extra-small to extra-large or abnormal, information which is included in the conditions glossary.[83] The extents of loss were traced and hatched. Displacement, or areas where either side of the crack are not on a level plain, were also noted. Secondary conditions were also noted, which are detailed in a general glossary with photos and definitions as a companion to the drawings. These include:

- Discoloration and staining of the plaster, due to moisture or animal activity.
- Biological growth, including mosses and lichen, on the stucco surface.
- Loss of painted finish, however the degree to which this had progressed was unique to each elevation, ranging from most deteriorated on the south elevation to most intact on the east elevation.

To create the final digitized conditions drawings, the field-annotated architectural elevations were scanned and the new digital files were re-rectified. These files were then attached to the existing line drawing files using AutoCAD. Polylines were then traced over the field-corroborated cracks, each assigned to different layers according to the size annotation accompanying the crack segment. A final set of drawings are included in *Appendix Bii*.

c. Photography

Photos were useful primarily to illustrate the conditions observed in the field. In architectural conservation, photography can support the analyses and suggestions that are made by the conservator but also can enhance other kinds of documentation in this report, as well as be used as a baseline from which to judge deterioration in the future.

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82 Based on architectural elevation line drawing files created by A&E Architects of Missoula.

83 See *Appendix A*.

A series of photographs were taken during field survey to document the conditions of the structure and site. The purpose of these photographs can be broadly sorted into five categories:

- Architectural survey photographs: These photographs capture elevations and the oblique relationships between them, as well as the details of the site context which can affect the preservation of a structure.
- Conditions photography: Detail photos that exhibit a variety of different conditions and modifications[84] for the purposes of building a visual glossary; some of these are also keyed on drawing sheets.
- Infrared radiation thermography (IRT) photos: Thermal images taken with a FLIR C2 Compact Camera of each elevation, as well as closeup partial photos to be stitched together later to improve resolution.
- Photogrammetry: This process which relies on a series of overlapping photographs which are subsequently aligned and converted to a dense point cloud in post-processing to capture the three dimensional shape of the elevations in order to detect detachment of the stucco.

5.2 Survey Results

Based on the survey, the primary deterioration conditions affecting the stucco include cracking, loss, displacement, and detachment of the system from the wooden sheathing underneath; secondary conditions, such as discoloration and loss of the paint, were infrequent and determined to be superficial and not contributing to risk. Based on preliminary diagnostics and research, the cracks fall broadly into two categories. First are cracks with discernible likely causes, which are typical to failure of cementitious materials or develop in response to installation or structural movements. Other cracks, like the series of fine cracks in an orthogonal pattern on the west and south elevations, are likely the result of errors in installation. A dramatic crack on the south elevation indicates that the stucco system is coming off from the wooden sheathing beneath, but the extent of this condition is not apparent. Loss has occurred at the

[84] Examples of intentional modifications such as alterations (patching, vents) and artifacts of application (distinct paint strokes, paint splatters) are visible in photographs, and noted where apparent.

Figure 5.4 Fine orthogonal cracks evident on the south elevation are likely the result of differnetial thermal expansion of the metal reinforcements. What is unseen is the extent of detachment around the large crack extending from the corner of the east window. (Photo by author, 2017)

base of the structure, where the tensile strength of the stucco has been surpassed. Whether the causes of these conditions are static, dynamic, or worsening can be surmised at this time based on complementary analyses, but must be confirmed in the field with monitoring protocols.

The result of the survey is a set of drawings with the extents of conditions drawn and keyed photographs which indicate the severity of deterioration phenomena. These are typical documentation for architectural conservation, and can be easily read by a resource manager or professional. They are useful in that they are comparable: this drawing set provides baseline documentation against which succeeding assessments can be compared to determine if the condition is worsening or static. But as previously suggested, these drawings by themselves do not indicate the extents of unseen conditions, like detachment or areas where damage to the cement is likely to occur or incipient.

6.0 DIGITAL ANALYSES

Developing a methodology to compare the results produced by the three different non-invasive approaches of assessment chosen for this thesis requires understanding the value of their synergy. Geographic information system (GIS), infrared thermography (IRT) image analysis, and photogrammetry each have their strengths and limitations to indicate areas of unseen damage. The graphics produced by each software can show the spatial distribution of conditions, whether cracks, temperature, or three dimensional shape but none of the results are absolute, or can independently indicate damage. An individual graphic by itself is often not sufficient to corroborate the presence of a condition due to a variety of limitations of that tool. Overlaying the resultant graphics from each of the three systems together can help substantiate (or call into question) areas of presumed deterioration by showing the similarities or differences between the results of the tests.

6.1 Graphics Description

a. Geographic Information System

As previously discussed, GIS softwares are designed to store, manipulate, and present spatial data. Information about the shape and distribution of the cracks were exported from AutoCAD as polylines and opened in ESRI ArcMap[85] as unreferenced vectors. These were used to produce the following representations of the data:

i. Density Rasters

A series of raster maps based on the distribution of selected conditions. Ultimately, the density tools in the Spatial Analyst extension proved to be the most useful for this project. In order to generate comparable density maps, the same cell size and radius parameters were used across all elevations. Two types of graphics were produced using the kernal density tool: one based on all of the cracks recorded (XS, S, M, L, XL) and the other based only on the bigger cracks (M, L, XL) *(Figure 6.1)*. In the All Cracks graphic, the value for each crack is equal ('1') as it is not possible to objectively apply differing values to different sizes of cracks. Therefore, the density of all cracks is meant to show an approximate risk of exposure to moisture intrusion. This

[85] Software product used: ESRI ArcMap 10.4.1.

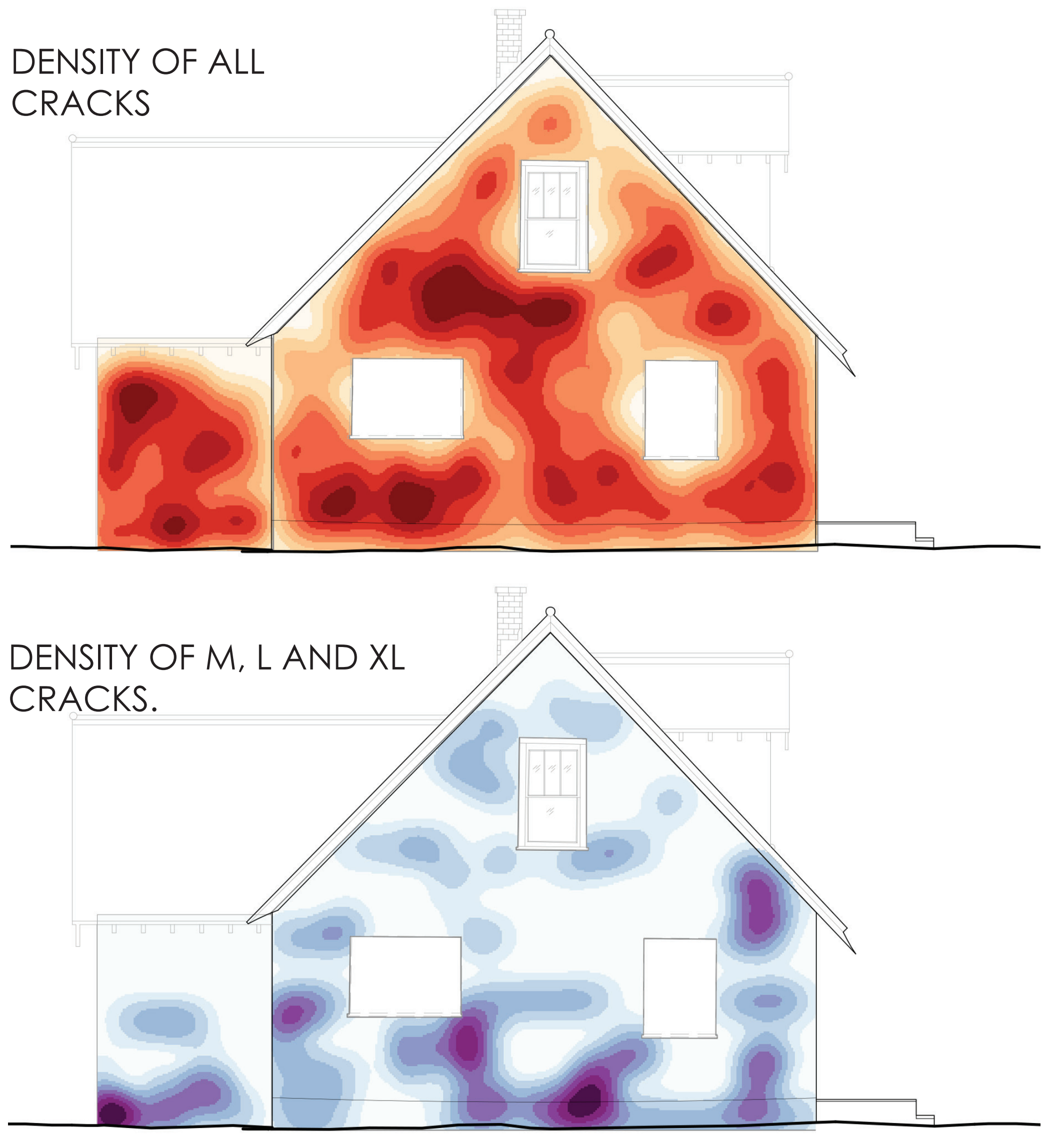


Figure 6.1 Density graphics for the south elevation produced using the Kernal Density Tool in Spatial Analyst. The area of each pixel is 1 in., and the search radius is 25 in. (Graphics by author, 2018)

interpretation is generalized, as GIS can only represent the surface where cracks are visible; it cannot approximate the depth of hairline or small cracks, which may only be superficial. Based on the findings of the laboratory testing, micro cracks demonstrate the effects of water and carbonation, so this is not a gross exaggeration. The bigger cracks map can show the distribution of cracks which are associated with structural movement and shear forces on the stucco; these tend to occur at the base and corners of the structure, as well as corners of openings.

ii. Distance Toolset and Raster Calculator

A series of rasters generated using the distance toolset in the Spatial Analyst extension which can be combined and overlaid to predict where damage is likely to occur. The points of origin and the values assigned are based on generalities about structures and their movements (*Figure 6.2*). While this method was helpful in assessing both Drayton Hall and the Wagner Free Institute, these analyses were not successful in this case. While the Raster Calculator proved useful in previous studies, it was not used in this project for both its grey box qualities and potential for confirmation bias. Following the model set by Goeke in 2008, a series of rasters were made based on the proximity to architectural features; these commands are interpreted according to generalizations typically used by conservators to anticipate damage and deterioration. Using the south elevation for an initial test, rasters were generated according to the following table. The values for these rasters were reclassified to be of equal weight and values, 1-10, and then combined using addition in the Raster Calculator. The resulting map was then compared to the present extents of cracking, but there was no obvious correlation between these graphics.

Several factors could account for the lack of correlations at the John Moulton Homestead, where previous studies had success. Exposure to weathering at the John Moulton homestead means that the cracks are not just the result of structural movements, installation problems, and/or material characteristics, as was the case at the Wagner Institute and Drayton Hall. Secondly, both of the previous studies had more parameters to compare: at Drayton Hall,

Eaves (-) to mid-level (+)	Exposure to weathering
Foundation (+) to mid-level (-)	Proximity to foundation movement, basal moisture, faunal activity.
Corners of elevation (-) to middle (+)	Proximity of cracks to relatively static members.
Corners of windows (+) outward (-)	Area of weaker stucco.

Figure 6.2 Explanation of distance rasters generated based on architectural features, increasing or decreasing value from the input feature based on straight line (Euclidean distance).

for instance, the researchers had the benefit of comparing data to known positions of underlying supports as well as a map of internal voids. At the John Moulton homestead, these are unknown or could not be produced in the course of the limited field survey. It might have been possible to compare the cracks to areas highlighted by the thermal images but, as previously mentioned, the interpretation of whether these areas actually indicate detachment or another condition is difficult to draw only from the thermal image.

iii. Crack and Loss Statistics

Statistics about the total length of cracks and their distribution over each elevation. Elements were queried using the Select by Attribute and their lengths calculated using the Field Calculator tools to compare the proportions of cracks by size, normalized by the total surface area, for each elevation; the results of this function is detailed in *Appendix Bv*.[86]

b. Infrared Thermography (IRT)

Infrared thermography, while a potent tool, can be onerous for two reasons: higher resolution cameras are expensive, and the method of active IR requires the skillful operation of external heat sources. Neither feature is desirable when working in rugged, exterior site conditions. A FLIR C2 Compact camera[87] was used for this project, which has a lower resolution compared to other products, but its lower cost and portability make it ideal for rugged conditions assessments and travel to site, as well as making it approachable for use by almost anyone doing building assessment. Infrared thermographs were taken at midday to ensure that some of the surfaces had been warmed. Solar radiation is typically used as a passive way to induce temperature differences due to the differential rates of heat diffusion on the surface of the structure; it is these differences which are subsequently registered by the thermal camera and parsed for information regarding the internal or geometrical deviations of the surface.[88] In FLIR Tools, thermal images can be individually manipulated to have regularized temperature spans, thus rendering a series of photos for better comparison between several images taken of the same elevation.

[86] Page 96-97.
[87] Products used: FLIR C2 Compact Camera ($499), FLIR Tools (Free with product serial number).
[88] F. Mercuri et al., “Active Infrared Thermography Applied to the Investigation of Art and Historic Artefacts,” Journal of Thermal Analysis and Calorimetry 104, no. 2 (May 2011): 475–85, https://doi.org/10.1007/s10973-011-1450-8.

There are inherent limitations at the John Moulton homestead which can affect the thermal imagery. Warming a surface in question, whether passively or actively, is key in thermal imaging to induce differential patterns. Using the sunlight to passively heat the surfaces of the structure means that each surface will receive differing amounts of energy; at the Moulton homestead, the elevations are cardinally oriented so the resulting thermal images will likely be more successful for some than others. While the cement is presumed to be uniform over the surface of the structure, there could be small thermal variations due to the variable thickness of the cement. Cross sections from the image-based models can differentiate these from areas with actual internal structural deficiencies which are out of plane. While offering a view of a building unlike that which is recorded by a standard camera, the resulting images can be difficult to interpret for a variety of reasons.[89]

c. Photogrammetry

Photogrammetry is principally used in this project to identify areas which may be out of plane. To estimate the extent of detachment, one can compute cross sections from a constructed mesh with which to compare to an ideal plumb surface. First, Agisoft PhotoScan is used to generate a three dimensional dense point cloud using a series of triangulated photographs. Photogrammetry softwares, while drastically less expensive nowadays, can still be a limiting factor for assessment; for example, an Agisoft PhotoScan Professional Edition standalone license costs $3499, while other open source and free softwares could also produce suitable models. In this particular application, the less expensive version of the software was sufficient to provide all that was needed.[90] The software can use non-referenced photographs to create models with varying degrees of resolution (low, medium, and high density). It utilizes a grey box method, in which input photographs can subsequently be manipulated and re-aligned. Once generated, dense point clouds can be easily exported from PhotoScan with an .obj file extension into Meshlab, an open source software for three dimensional mesh processing. The software offers tools oriented for editing, rendering, and inspecting large data sets. Meshes were constructed from dense point clouds for each elevation in order to compute planar sections. The cross sections consist of several hundred points and can be imported into AutoCAD to be plotted.

[89] Refer back to *4.1.b*, which discusses some of the difficulties that may arise.
[90] Agisoft PhotoScan Standard Edition ($179/license).

Photogrammetry can offer a view of a building in ways that a single standard view of an elevation cannot: the three dimensional information can aid in identifying anomalies in the dimensions of a surface. Variations in the cross section, however, should not be automatically assigned as areas of potential detachment or deformation. False positives can arise due to the uneven application of the stucco. Sizable deviations from the flat plane which correspond to thermal variations in IRT imagery should be further investigated.

6.2 Analysis Results

Initial research questions for each elevation are twofold: 1) to identify the extent of deformation and detachment, and 2) to analyze the potential risk that exposure to weather could pose for deterioration of the cement and/or its ferrous metal reinforcements.

The results which follow are based on a comparison of the resulting graphics, which are then interpreted through material behaviors and/or structural observations from the field: these are included in *Appendix Biv*. The success of these graphics and sources of potential error depend on the deterioration conditions, quality of data gathered in the field, and field limitations unique to each elevation. For this reason, the following discussion is organized according to elevation. The south, west and north elevation are discussed and have corresponding illustrations. Thermal images for east elevation, however, did not show sufficient variations to be useful for comparison. Following a brief description of the evident patterns is a discussion of the likely causes or contributors to these phenomenon and an analysis of potential deterioration risks.

a. South Elevation

The process of information collection for photogrammetry and infrared thermography in the field was quite thorough, as the south elevation had previously been identified as an area for significant concern. A photogrammetric model was constructed from a series of 96 photos taken both straight on and at an angle to the elevation; the resulting model, therefore, has high detail and is more likely to accurately portray shape of the stucco. Limitations which could have impacted the resulting model are those which have affected the entire conditions assessment process; namely, photographs had to be taken from grade. The photos for the top of the elevation were taken from a poor angle and, as a result, will be of lower resolution and disposed for error than the base of the structure. For optimal photogrammetry work, several overlapping photos are required which show both details and broader swaths of area as well as head on and angled photographs. The south elevation faces directly south and is unobstructed, so the majority of the elevation's surface can receive direct sunlight.[91]

From a comparison of these graphics, anchored by observations in the field, we can make the following hypotheses:

1. *Areas of likely attachment and detachment, according to relative temperature.[92]* The area below the left corner of the eastern window on the first story is known to have detached stucco; in the infrared thermograph, this area is notably cooler than the adjacent plaster. It was determined in the course of field investigations that the plaster to the left and above this area, alongside the window frame, appeared to be better attached to the underlying sheathing. The temperature gradient runs from cooler to warmer where the stucco is better attached. Therefore, it could be assumed that areas which have a higher surface temperature may be the result of thermal transfer from the sheathing and the interior of the structure. While this assumption is well framed, there are other factors in house construction, which could also produce color variation in the thermal image, including changes in the thickness of the stucco, variations in insulation due to settling or improper installation, and moisture penetration just to name a few.
2. *Correlating bigger crack sizes with possible areas of detachment.[93]* Crack patterns can offer suggestions about the failure of the stucco and those patterns can easily be exploited in ArcMap where running densities is a relatively easy process. The density maps patterns of cracks from the GIS graphics could be used to correlate areas that are detached through temperature and crack size distribution. Areas with cooler temperatures on the south elevation that are coincident with areas that have a high density of medium, large and extra-large cracks. While this system works for the south elevation, it does not seem to apply

[91] The only exception is the area directly under the eaves.
[92] Refer to *Appendix Biv,* page 89.
[93] Refer to *Appendix Biv,* page 89.

as well for the other three elevations where thermal variation seems to be much smaller. The end result is that the comparison of the IR and GIS can show that there is a possible correlation but it fails to explain why this correlation is not consistent on the other sides of the house. These areas were further investigated using the photogrammetric model; several cross sections were cut in these areas and overlaid in order to see if displacement was occurring and the extent of this condition. It was through the use of photogrammetry, and the usefulness of 3D data, that provides a possible clue as to why the patterns described above don't seem to be consistent when comparing the south with the other three elevations. While the south elevation shows a significant shift out of plane in several locations, the other three sides do not. It is through the comparison of the three different types of digital assessment that the pattern can be uncovered.

3. *Surface areas with a higher density of cracks and warmer temperature are likely still attached to the sheathing.*[94] Based on the first observation, warmer areas of the stucco surface are likely better attached to the underlying sheathing. A comparison of the infrared thermograph to the GIS density graphics reveals that these highlighted areas are strikingly similar to areas where there is a high density of extra small and small cracks. This pattern would imply that areas which have a higher density of cracks are better attached to the underlying sheathing. Therefore, it could be possible that attachment of the stucco to the sheathing induces or encourages the formation of small cracks. While not as alarming as the large cracks or detachment, it is important to consider the implications of micro cracks for the fabric and its potential for deterioration, based on the observations from the laboratory testing section. While these smaller cracks are likely confined to the surface and expose less cross section to water infiltration, both the cross section and thin section samples reveal that mico-cracks are often accompanied by evidence of atmospheric and water infiltration. Materials sampled from exposed areas revealed surface micro cracks and much deeper carbonation than less exposed counterparts.[95] Once concrete has carbonated, the material is no longer sufficiently alkaline to deter corrosion of metal reinforcements. While these areas could be better attached to the sheathing beneath, the reinforcement in these areas could

[94] Refer to *Appendix Biv,* page 90.
[95] See petrographic analysis section in *Appendix Diii*.

be more predisposed to corrosion and loss of viable section. These are also areas with a greater potential for water transmission and therefore are more likely to experience damage due to freeze-thaw cycling and salt crystallization.

Two conclusions result from these patterns. First, the similarities in the distribution of cracks and temperatures, corroborated by sections cut from the photogrammetric model, imply that detachment could be more extensive than previously presumed. This appears to be the case for the bottom of the south elevation, where a gradient of decreasing temperature extends from the displaced crack below the east window across to the west window. The corresponding area of the model shows stucco that is out of plane.[96] Utilizing the same combination of thermal cues and crack densities, an area above the first story windows was indicated and subsequently cross sectioned. The resulting photogrammetric cross sections, however, did not prove to reveal the same geometrical abnormalities. If detachment does exist in this second area, three possible phenomena could be occurring: the photogrammetric model does not have high detail at higher points on the elevation and if the detachment were too subtle to be detected by the photogrammetric model then the results would be inconclusive. One other possible explanation of this is that the area is detached, but skewed in an even plane from the sheathing; this is hard to detect, however, as photogrammetry can only demonstrate the geometrical shape of the visible materials. Further thermal imagery would be needed to determine if an underlying void exists.

Second, based on the laboratory analysis results, it is possible to infer that high density of cracks areas are more exposed to moisture and atmospheric infiltration, and therefore more likely to display early signs of physical damage due to thermal cycling and corrosion of the underlying reinforcements. If the visible cracks can be correlated with the micro cracks observed in the laboratory testing, it would suggest that these areas are prone to water infiltration and deeper carbonation of the cement; both factors pose an increased risk of corrosion and loss of section for the metal reinforcements, as well as irreversible damage to the cement itself. For the south elevation, this is particularly concerning as the crack densities seem to coincide with areas that are likely to still be attached to the sheathing. Areas with a higher crack density could also

[96] Refer to *Appendix Biv,* page 91.

indicate instances where it is more likely that moisture will breech the concrete and reach the underlying wood sheathing, a serious condition which could go undetected behind the stucco and result in rotting of wooden elements.[97] The GIS density of cracks graphic cannot suggest the depth of the cracks, as these are based only on observations of the surface; using a higher resolution IR in these areas could assist in determining the depth of cracks and better evaluate the risk of moisture intrusion in these areas.

b. West Elevation

The thermal images have good quality and show good details of the distribution of surface temperatures. However, it should be noted that the data could be skewed due to position of the ell with respect to the sun and the time at which the photos were taken. While the west elevation of the ell had not received direct sunlight at the time of the IR photographs, half of the elevation appears to have been warmed due to thermal transfer from direct sunlight on the south elevation.[98] The highest density gradient falls into areas that have a lower temperature; this is opposite to observations from the south elevation where higher densities coincided with higher temperatures. The high densities of larger cracks occurs near the foundation of the structure, areas which are distributed across a gradient of warmer and cooler temperatures in the infrared thermograph.

The lack of strong correlation between the resulting thermal image and crack density graphics could be due to a few phenomena. First, the geometry of the ell could be encouraging an uneven warming of the surface which would skew the results from the infrared thermographs. Another possibility is that detachment, seen through the use of photogrammetry on the south elevation, does not occur on this particular elevation; displacement of the south corner demonstrates that the plaster is still attached to the sheathing, and that the sheathing and possibly the frame itself, is moving away from the foundation. In contrast to the south elevation, however, its graphic signature is unknown and the lack of correlation between the crack densities and thermal images means that it is difficult to postulate where it could be occurring.

[97] Deterioration and rot of the wood is a primary concern, as it could threaten the integrity of the structure. Wetting of the sheathing could also weaken the grip of the attachment nails and lead to further detachment of the stucco.
[98] Refer to *Appendix Biv,* page 92.

A photogrammetric model was constructed using 14 photos, consisting of both oblique and straight-on photographs of the west elevation of the ell. Rather than using a directed approach to select areas,[99] the plaster above and below the windows was selected to create two cross sections to look for possible deformation of the stucco. As the drawing indicates, neither section reveals significant deflection or detachment of the stucco. A slight bending is apparent on the right side, but this is more likely the result of a poorly built model than actual damage to the structure.[100] A comparison of the crack density map to the infrared photo does not reveal a strong correlation between the densely cracked areas and surface temperature suggesting that the relationship between the GIS and thermal image seen on the south side may be coincidental. The fact that the plane of the west elevation is nowhere near as discorded as the south elevation again supports the argument in favor of using these three different methods to assess the unseen conditions and reasserts the notion that the relationships seen on the south elevation may in fact have merit.

c. North Elevation

The distribution of crack densities for two sets of cracks calculated in the GIS are not concentrated in a few locations as they were on the south elevation.[101] These include both the entirety of the cracks and as well as only the bigger cracks (Medium, Large, and Extra Large). Instead, the cracks appear to be well distributed across the surface of the elevation in both graphics. Bigger cracks are also more prevalent on the north elevation than on others, as several of the coincident densities between the All Cracks and Bigger Cracks graphics suggests. This is to be expected as the cracking is more likely the result of structural movement rather than thermal or hygric cycling. There does not appear to be a correlation between the crack density graphics and thermal images. It is critical to consider again the environment and exposure for this part of the structure. The north elevation had received no direct exposure to sunlight, so the thermal transfer predominantly comes from the structure's interior, the ambient exterior air, and the ground. The thermograph shows a distinct cooler gradient at the base of the structure which is likely the result of snow accumulation.

[99] As was the case in examining the south elevation.
[100] Refer to *Appendix Biv,* page 93.
[101] Refer to *Appendix Biv,* page 94.

A high density point cloud was constructed using 7 photos, all taken directly facing the main north elevation; it can be expected that this model has the poorest resolution of the set and is less accurate. The resulting cross section appears to be concave,[102] which is likely due to a lack of photos taken from oblique angles. Nonetheless, the section does not reveal significant irregularities that would suggest detachment of the stucco.

6.3 Discussion of Results

The process of graphics overlay was the most successful for the south elevation, where the analysis followed a series of suppositions, established using known areas of deterioration and confirmed in the field. An examination of this area in the digital graphics establishes a series of visual correlations. From these, a series of further deductions are made, which can be rationalized by observations from the field investigation and/or knowledge of architectural conservators. This initial proof of concept process of analysis was neither straightforward nor strictly scientific, while possible to do so, and relied on the iterative process of visually correlating similarities and then using knowledge of deterioration causes and effects to interpret the patterns. Ultimately, this analysis did not indicate areas of unseen deterioration with certainty, but rather guides future investigations.

One thing which has become apparent through the digital analysis is that there appears to be inconsistencies when comparing the results of the south facade with the results of the other three elevations. If there were to be any other elevation that might be comparable to the south, it would be the west. Based on the collected data and the results of the analysis, the west has a higher proportion of loss as well as a displaced crack on the southwest corner of the ell. Even with this stated, though, the south elevation has proven to be the most unique as well as successful as far as the digital analysis. While it is easy to draw conclusions about why the comparison of all four sides is inconsistent and therefore not successful, let's first consider evidence with might suggest that the digital analysis for the full structure was in fact a success. Many people, prior to the conditions assessment, had assumed that the pattern of cracks across the entire house was evidence of a failing stucco as well as physical evidence of a uniform

102 Refer to *Appendix Biv,* page 95.

problem with the entire house, requiring a large scale treatment. Since treatment is irreversible, and can introduce damage to the feature through invasive applications, a cautious approach is often the best solution.

The inconsistent results of the south elevation, when compared to the other three elevations, may show that the south side of the building is in fact anomaly and that true failure— failure which compromises the survival of the survival of the stucco— is not reflected in the smaller cracks but instead is only associated with the largest cracks which display shear displacement. When comparing the results of the north, west, and east sides, which have no large cracks that have displacement, they all seem to have similarities to each other but not to the south. The conclusions of the analysis, which invoked not just the digital, but also the historic research, and the laboratory analysis, suggests that the cracks across the entire house are not indications of a failing system but may be due to the thermal expansion and contraction cracks similar to monolithic concrete. A review of the historic literature shows that the installation process was consistent with the manufacturer's guidelines of the day, and laboratory analysis shows that the stucco is well made and displays limited decay. If the hundreds of smaller cracks are not a threat to the longevity of the house, then perhaps the evidence found in the digital assessment supports a more focused plan for conservation which limits initial treatment to only the largest cracks on the south elevation. The foundation shifting poses a greater threat to the stucco, as it induces detachment and loss of section to support the weight of the system as it peels away from the wooden surface. The small, yet extensive, cracking pattern seen across all elevations has little to do with this more deleterious phenomenon.

The possibility of this digital comparison system not working is very plausible. This method was less successful on the other elevations for two potential reasons. First, the overlay of conditions is diminished due to inferior thermal and photogrammetric data. The poor input data could be remedied in the course of future investigation, thereby improving resolution and confidence parameters for inferences to be established. In fact, the hope is to do additional thermal imaging on the structure using a much higher resolution IR camera which was not initially used in the 2017 assessment as it is both more expensive and difficult to transport. Another barrier in establishing patterns may also be attributed to a lack of known areas of detachment; in the case of the south elevation, this was critical for creating inferences. Although detachment is what is being sought out in this analysis, a proof of concept approach such as this requires something on which to base the results. Neither the north, east, or west elevations demonstrate observable instances of this condition since the surfaces are not openly compromised and tap testing has proven highly inconclusive. An area of detachment could be established through limited probing in a future site visit if there was strong evidence to suggest a candidate area where molesting the historic fabric would be worthwhile.

With that said, drilling would be required for the purposes of treatment. Without outward evidence of detachment, alternatives are always well accepted, especially if there is some basis for their success. The notion that the system did not work at all on the other three elevations is not without merit. The process, as applied to the north, east, and west elevations would simply need to be more nuanced and depend on unknowns but evidence could be drawn based on using the same process. The end result is that areas on the other three elevations could be identified and subsequently further investigated. Blindly drilling to detect this condition is not an option, as it recklessly introduces damage to the feature. Further NDT analysis is needed to begin to identify areas of possible detachment on these elevations, or confirm that this condition does not affect these areas of the structure.

7.0 SUMMARY

The task agreement between Grand Teton National Park and the Architectural Conservation Laboratory at the University of Pennsylvania addresses the character-defining pink stucco on the exterior of the John Moulton Homestead. Principal objectives include establishing the composition of the cementitious material, its application, and causes of failure in order to begin to develop stabilization recommendations and a pilot treatment plan to preserve the exterior stucco. This thesis addresses the first of these goals through a variety of avenues which are common to condition assessments. Site investigations and laboratory analysis prove that the stucco presently has good physical integrity despite the number of cracks evident on the surface of the structure. A comparison of the contemporary product literature to the stucco system demonstrates that the most deleterious pathologies affecting the stucco do not emanate from the feature or system itself. From a long list of site- and structural-based hypotheses initially put forth as potentially contributing to the failure of the stucco, a few likely phenomena have been selected to investigate further. These include:

1. Foundation movement and subsidence, which contribute to the formation of large diagonal cracks and displacement of the stucco, and
2. Differential thermal expansion of the stucco and embedded metal reinforcements, which cause small and hairline cracks to form; the orthogonal pattern likely relates to improper installation of the woven wire lath, but this will be confirmed in further field examination.

The second part of this thesis focused on analyzing and comparing digital graphics to approximate the extent of unseen conditions that pose a risk to the continuing integrity of the stucco. Detachment of the stucco system from the sheathing is only observable on the south elevation, and when this area was probed with a borescope during field assessment it had been assumed that the expanse of detachment was limited to the immediate area surrounding the crack. Using a methodology which combines Geographic Information System (GIS) analyses, infrared thermography (IRT), and photogrammetry, the extents of detachment, at least for the south elevation, appear to be much larger than previously observed in the field. Similar analyses were attempted on the west and north elevations, but the results were inconclusive due to environmental factors, information collection, and the lack of known deterioration; it is possible, however, that detachment does not affect these areas of the structure. Moving forward, test probe locations will be selected on the base of the south elevation to confirm detachment in the areas suggested by this methodology. Further study of the other elevations should take place to look for detachment on other elevations. These measures could include using a higher resolution IR camera and a protocol of active sensing with controlled external heat sources.

The density graphics, coupled with laboratory analysis of the composite stucco, also can indicate areas of potential risk where the stucco is more likely to be affected by water and atmospheric intrusion. In the future, deterioration in these areas could be substantiated with other non-destructive tools, including a high resolution thermal camera. These graphics provide a prioritized map with which to start future investigation.

8.0 NEXT STEPS

The following is a preliminary outline of the recommended interventions; these are organized by the deterioration mechanism addressed.

a. Detachment

Before any stabilization of the plaster begins, the movement of the foundation needs to be examined by an engineer. Any stabilization or conservation interventions performed on the stucco should only take place after an engineer has confirmed that the foundation is stable. If differential movement is still occurring (either cyclically with the freeze-thaw of soils or due to subsidence) the movement could render the interventions ineffective and detachment could progress, or the introduced interventions might cause further damage to the stucco.

Once the foundation has been stabilized, the detachment of the stucco needs to be addressed. As it was initially installed, the furring nails would have had enough bite into the underlying sheathing to support the weight of the stucco system. Because some of the nails in the system have disengaged from the sheathing, it is possible that the gravity load on the stucco could exceed the shear strength of the nails. The conservation plan should include methods with which the stucco could be supported and reintegrated into the underlying frame.

b. Moisture and Solar Protection

While it may take some time to get to funds to contract an engineer and introduce stabilization measures, moisture control interventions are more minimal. In the meantime, measures should be taken to weatherize the areas of loss where wooden elements are exposed. The primary function of the stucco, after all, is to waterproof the exterior of the structure to protect the underlying wooden frame from moisture and other environmental impacts which could compromise the structural integrity of the building. The most obvious instance is the south elevation, where loss and detachment has exposed the sheathing underneath. The corners of the structure where loss has occurred should be checked for exposed end grain, and similarly treated.

A pilot treatment program could include testing materials to fill the cracks in more exposed areas where there is a high density of fine cracks to deter water intrusions and potentially slow carbonation of the cement and corrosion of the metal reinforcements. Further research will be conducted to find a physically compatible material that will be minimally invasive and not disrupt the visual aesthetic of the stucco.

Indirect moisture control measures also include altering the site elements which retain moisture and contribute to the deterioration of the stucco. A french drain system should be installed around the base of the structure, ideally after all foundation stabilization has been completed. This includes laying a trench which would direct water away from the base of the structure to an irrigation ditch.

9.0 REFERENCES

Avdelidis, N.P, and A Moropoulou. "Applications of Infrared Thermography for the Investigation of Historic Structures." *Journal of Cultural Heritage* 5, no. 1 (January 2004): 119–27. https://doi.org/10.1016/j.culher.2003.07.002.

Beckman, Christine L. "Evaluating the Displacement Modes and Associated Risks of Stacked Log Structures." Master's Thesis, University of Pennsylvania, 2013. https://repository.upenn.edu/cgi/viewcontent.cgi?article=1547&context=hp_theses.

Breysse, D., G. Klysz, X. Dérobert, C. Sirieix, and J.F. Lataste. "How to Combine Several Non-Destructive Techniques for a Better Assessment of Concrete Structures." *Cement and Concrete Research* 38, no. 6 (June 2008): 783–93. https://doi.org/10.1016/j.cemconres.2008.01.016.

Burt, Maxwell Struthers. *The Diary of a Dude-Wrangler*. New York,: C. Scribner's sons, 1924.

Carter, Thomas. "Frontier Fashion: Domestic Architecture and Individual Display." In *Building Zion: The Material World of Mormon Settlement*. Minneapolis: University of Minnesota Press, 2014.

Curran, M. "Mormon Row Historic District, Grand Teton National Park; National Park Service Cultural Landscapes Inventory." National Park Service, Department of the Interior, 2006. https://www.nps.gov/grte/learn/historyculture/upload/Mormon-Row-CLI.pdf.

Daugherty, John. *A Place Called Jackson Hole: The Historic Resource Study of Grand Teton National Park*. First. Moose, Wyo.: Grand Teton National Park, National Park Service, 1999.

Davey, Christopher A., Kelly T. Redmond, and David B. Simeral. "Weather and Climate Inventory, National Park Service, Greater Yellowstone Network." Fort Collins, CO: National Park Service, 2006.

Cameron, Fiona, and Sarah Kenderdine. "Introduction." In *Theorizing Digital Cultural Heritage: A Critical Discourse*, edited by Sarah Kenderdine, 1–15. Cambridge: MIT Press, 2007. http://ebookcentral.proquest.com/lib/upenn-ebooks/detail.action?docID=3338737.

Goeke, Marlene Lauren. "Assessment and Analysis of the Plaster Exhibit Hall Ceiling at the Wagner Free Institute of Science, Philadelphia, PA." University of Pennsylvania, 2008. http://repository.upenn.edu/hp_theses/106.

Grimmer, Anne E. *The Secretary of the Interior's Standards for the Treatment of Historic Properties with Guidelines for Preserving, Rehabilitating, Restoring and Reconstructing Historic Buildings*. Washington: U.S. Department of the Interior, 2017. https://www.nps.gov/tps/standards/treatment-guidelines-2017.pdf.

Historic England. "Photogrammetric Applications for Cultural Heritage. A Guidance for Good Practice." Swindon: Historic England, 2017.

Hubber, Ann, and Janene Caywood. "Grand Teton National Park Multiple Property Submission; National Register of Historic Places Multiple Property Documentation Form." United States Department of the Interior National Park Service, June 1991.

Ingham, Jeremy P. “Concrete.” *In Geomaterials Under the Microscope*, 75–120. London: Manson Publishing Ltd., 2013. https://www.sciencedirect.com/science/book/9780124072305.
———. “Mortar, Plaster, and Render.” In *Geomaterials Under the Microscope*, 137–62. London: Manson Publishing Ltd., 2013. https://www.sciencedirect.com/science/book/9780124072305.

Kordatos, E. Z., D. A. Exarchos, C. Stavrakos, A. Moropoulou, and T. A. Matikas. “Infrared Thermographic Inspection of Murals and Characterization of Degradation in Historic Monuments.” *Construction and Building Materials* 48 (2013): 1261–65.

Krankenhagen, R., M. Röllig, Ch. Maierhofer, R. Mecke, and M. Schiller. “Quantification of Damage Processes at Surfaces and Interfaces of Building Structures Using Optical Methods and Active Thermography.” In *Proceedings of the European Conference on Non-Destructive Testing*, 10. Moscow, 2010. http://www.ndt.net/article/ecndt2010/reports/1_05_10.pdf.

Lesley, Robert Whitman. History of the Portland Cement Industry in the United States. American Cement Company, 1900. https://books.google.com/books?id=owtHAAAAYAAJ&printsec =frontcover&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false.

Maierhofer, Ch., R. Krankenhagen, M. Röllig, J. Schlichting, M. Schiller, Th. Seidl, R. Mecke, U. Kalisch, Ch. Hennen, and J. Meinhardt. “Investigating Historic Masonry Structures with a Combination of Active Thermography and 3D Laser Scanner.” *Quantitative Infrared Thermography Journal* 8, no. 1 (June 2011): 115–18. https://doi.org/10.3166/qirt.8.115-118.

Manferdini, A. M., and M. Galassi. “Assessments for 3D Reconstructions of Cultural Heritage Using Digital Technologies.” *ISPRS - International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* XL-5/W1 (February 13, 2013): 167–74. https://doi.org/10.5194/isprsarchives-XL-5-W1-167-2013.

Matero, Frank, and John Hinchman. “Analysis and Conservation of the Great Hall Ceiling.” Treatment Report. Architectural Conservation Laboratory and Research Center, University of Pennsylvania, 2003. http://www.conlab.org/acl/dray/Reports/2003%20Great%20Hall%20 Report%20%28full%29.pdf.

McCoy, Jill, Steve Kopp, Kevin Johnston, and Environmental Systems Research Institute (Redlands Calif.). *Using ArcGIS Spatial Analyst: GIS by ESRI.* Environmental Systems Research Institute, 2001.

Mercuri, F., U. Zammit, N. Orazi, S. Paoloni, M. Marinelli, and F. Scudieri. “Active Infrared Thermography Applied to the Investigation of Art and Historic Artefacts.” *Journal of Thermal Analysis and Calorimetry* 104, no. 2 (May 2011): 475–85. https://doi.org/10.1007/s10973-011-1450-8.

“Mormon Row Historic District, Grand Teton National Park.” National Park Service Cultural Landscapes Inventory. National Park Service, 2006. file:///Users/Stratte/Downloads/GRTE_ Mormon_Row_Historic_District.pdf.

“Mormon Row Historic District National Register of Historic Places Registration Form.” National Register of Historic Places Registration Form. United States Department of the Interior National Park Service, 1997.

Moulton, Candy Vyvey. *Legacy of the Tetons.* 2nd rev. ed. Cheyenne: La Frontera Pub., 2007.

Odgers, David and Catherine Croft, eds. *Concrete.* Vol. 8. Practical Building Conservation. London:

English Heritage, 2012.

Palumbo, Gaetano. “Beyond CAD: A Look at Data Integration and Analysis Using GIS.” In *GraDoc: Graphic Documentation Systems in Mural Painting*, 114–23. Rome: International Centre for the Study of the Preservation and Resotration of Cultural Property (ICCROM), 2000.

Salonia, Paolo, Serena Scolastico, Andrea Pozzi, Andrea Marcolongo, and Tommaso Leti Messina. “Multi-Scale Cultural Heritage Survey: Quick Digital Photogrammetric Systems.” *Journal of Cultural Heritage* 10S (2009): e59–64. https://doi.org/10.1016/j.culher.2009.09.004.

Pickering White, Bonnie J., Robert B. Smith, Stephan Husen, Jamie M. Farrell, and Ivan Wond. “Seismicity and Earthquake Hazard Analysis of the Teton-Yellowstone Region, Wyoming.” *Journal of Volcanology and Geothermal Research* 188 (2009): 277–96.

“Plasterer’s Manual for Applying Portland Cement Stucco and Plaster.” Portland Cement Association, 1929. https://archive.org/details/PlasterersManualForApplyingPortland CementStuccoAndPlaster.

Portland Cement Association. “Portland Cement Stucco.” Portland Cement Association, 1927. http://archive.org/details/PortlandCementStucco_616.

Portland Cement Association. “Proportioning Concrete Mixtures and Mixing and Placing Concrete.” Chicago: Portland Cement Association, 1916. https://catalog.hathitrust.org/Record/100029668.

Remondino, Fabio, and Fabio Menna. “Image-Based Surface Measurement for Close-Range Heritage Documentation.” *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* 37, no. B5 (2008): 199–206.

Righter, Robert W. *Crucible for Conservation: The Creation of Grand Teton National Park.* Colorado Associated University Press, 1982.

Rosina, Elisabetta, and Elwin C. Robison. “Applying Infrared Thermography to Historic Wood-Framed Buildings in North America.” *APT Bulletin* 33, no. 4 (2002): 37–44. https://doi.org/10.2307/1504807.

Sawyer, J. T. *Plastering*. Shaftesbury : Donhead, 2007.

“Temperature Extremes, Annual, Moose (486428) - Wyoming State Climate Office.” Accessed April 13, 2018. http://www.wrds.uwyo.edu/temperature/extremes/486428-Annual.html.

Verrall, W. *The Modern Plasterer*. Shaftesbury, Dorset : Donhead Pub., c2000.

Watt, David. *Building Pathology: Principles and Practice*. 2nd ed. Oxford ; Blackwell Publishing, 2007.

Weyer, Angela, Pilar Roig Picazo, Daniel Pop, JoAnn Cassar, Aysun Özköse, Jean-Marc Vallet, and Ivan Srša. *EwaGlos: European Illustrated Glossary of Conservation Terms for Wall Paintings and Architectural Surfaces.* 2nd ed. Petersberg, Germany: Michael Imhof Verlag, 2015. http://193.175.110.9/hornemann/doi/2016ewa2a.pdf.

Woerner, Timothy. “Infrared Thermography.” *Exterior Building Envelope Inspections Using Thermal Infrared Imaging: A Report to the Public Building Service of the General Services Administration.* U.S. General Services Administration, 2006. https://static1.squarespace.com/static/52ed80f1e4b0354340039c3c/t/55ee252ae4b0d8cb34180937/1441670442295/GSA_IR+Inspec_Protocol.pdf.

JOHN MOULTON HOMESTEAD

Appendix A: Conditions Glossary

1. Sources of Deterioration Definitions
2. Condition Definitions

- Primary
    - Cracks
- Secondary
    - Biological Growth
    - Darkening
    - Detachment
    - Fading
    - Loss
    - Modification
    - Soiling

JOHN MOULTON HOMESTEAD

Appendix A: Conditions Glossary[1]

Source: Intrinsic Cause

Deterioration due to internal properties of a material, such as chemical composition and/or physical properties. The weakness of a material usually manifests due to the combination of intinsic properites and extrinsic causes, which include freeze-thaw cycles, soluble salts, etc.

Source: Extrinsic Cause

External factors bringing about deterioration, either natural or anthropogenic. May include air pollution, soluble salts, rising damp, freeze-thaw cycles, environmental fluctuations.

Source: Environmental Deterioration

Deterioration triggered or exacerbated by climatic factors such as temperature and humidity extremes, and their fluctuations. Repeated changes in environmental parameters can bring about deterioration by physical, chemical, and/or biolodical means. Wind erosion can also be considered as a factor.

1 Conditions definitions based on "Deterioration Sources" and "Deterioration Phenomena" in *EwaGlos European Illustrated Glossary of Conservation Terms for Wall Paintings and Architectural Surfaces* (2016) edited by Angela Weyer (Spangenberg: Michael Imhof Verlag GmbH & Co.)

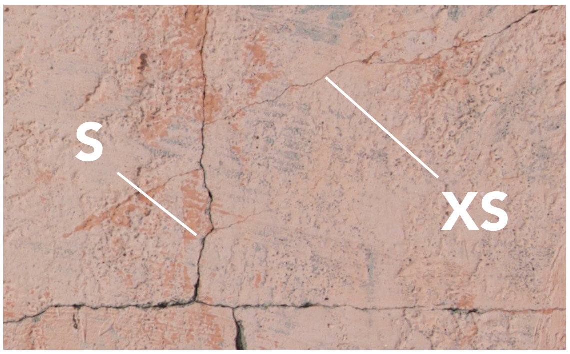
JOHN MOULTON HOMESTEAD

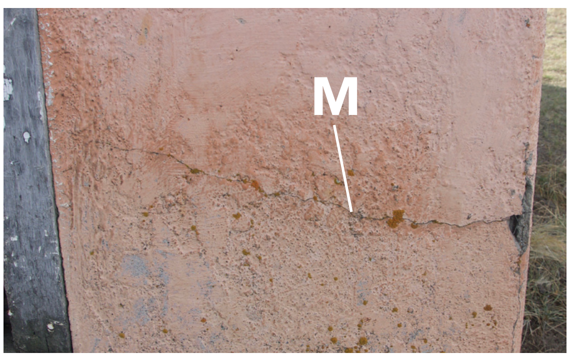
Appendix A: Conditions Glossary

PRIMARY CONDITION

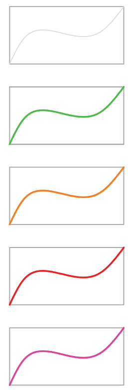
Condition: Crack

A discontinuity in an architectural surface or wall painting, resulting in a visible separation of one part from another, that extends through one or more layers.





Graphic:



Extra Small (XS) (<0.005 in.)

Small (S) (<0.025 in.)

Medium (M) (<0.050 in.)

Large (L) (>0.050 in.)

Extra Large (XL)
(Cross section exposed)

SECONDARY CONDITION

Condition: Biological Growth

Colonization by living organisms on an object which can lead to damage and deterioration. Growth can include simple bacteria and lichens as well as more complex plants and animals.

JOHN MOULTON HOMESTEAD

Appendix A: Conditions Glossary

SECONDARY CONDITION

Condition: Darkening

A change in the surface color due to a decrease in hue. Darkening can be the result of a local presence of humidity.

Condition: Detachment

Separation of the plaster system from the wood substrate, visible along cracks where displacement is occuring.

Graphic:

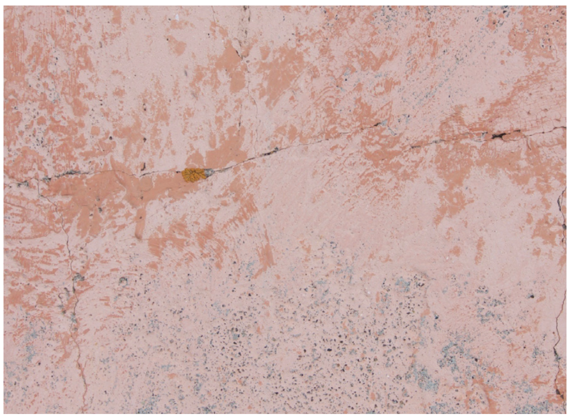
+ Positive

− Negative

SECONDARY CONDITION

Condition: Fading

A chromatic alteration manifested as the weakening of color (pigment) saturation and which is generally the result of chemical reactions or exposure to direct sunlight.



Condition: Loss

A missing part of an architectural surface which affects its integrity.

Graphic:

Loss

SECONDARY CONDITION

Condition: Modification
Non-original material, historic or contemporary, which shows subsequent modification.

Condition: Soiling
Accumulation of extraneous material on a surface leading to discoloration.

0 1 5 10

SCALE IN FEET
1/4" = 1'-0"

SHEET IDENTIFICATION:
Appendix Bi
Rectified Photo-elevations

DESCRIPTION
Rectified photo of east elevation.

JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming

0 1 5 10

SCALE IN FEET
1/4" = 1'-0"

JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming

DESCRIPTION
Rectified photo of south elevation.

SHEET IDENTIFICATION:
Appendix Bi
Rectified Photo-elevations

0 1 5 10

SCALE IN FEET
1/4" = 1'-0"

SHEET IDENTIFICATION:
Appendix Bi
Rectified Photo-elevations

DESCRIPTION
Rectified photo of west elevation.

JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming

0 1 5 10

SCALE IN FEET
1/4" = 1'-0"

SHEET IDENTIFICATION:
Appendix Bi
Rectified Photo-elevations

DESCRIPTION
Rectified photo of north elevation.

JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming

0 1 5 10

SCALE IN FEET
1/4" = 1'-0"

Windows obscured by plywood

Condition: Crack Sizes

Extra-Small

Small

Medium

Large

Extra-Large

Loss

SHEET IDENTIFICATION:
Appendix Bii
Conditions

DESCRIPTION
Crack conditions on east elevation.

JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming

0 1 5 10

SCALE IN FEET
1/4" = 1'-0"

Windows obscured
by plywood

Condition:
Crack Sizes

Extra-Small

Small

Medium

Large

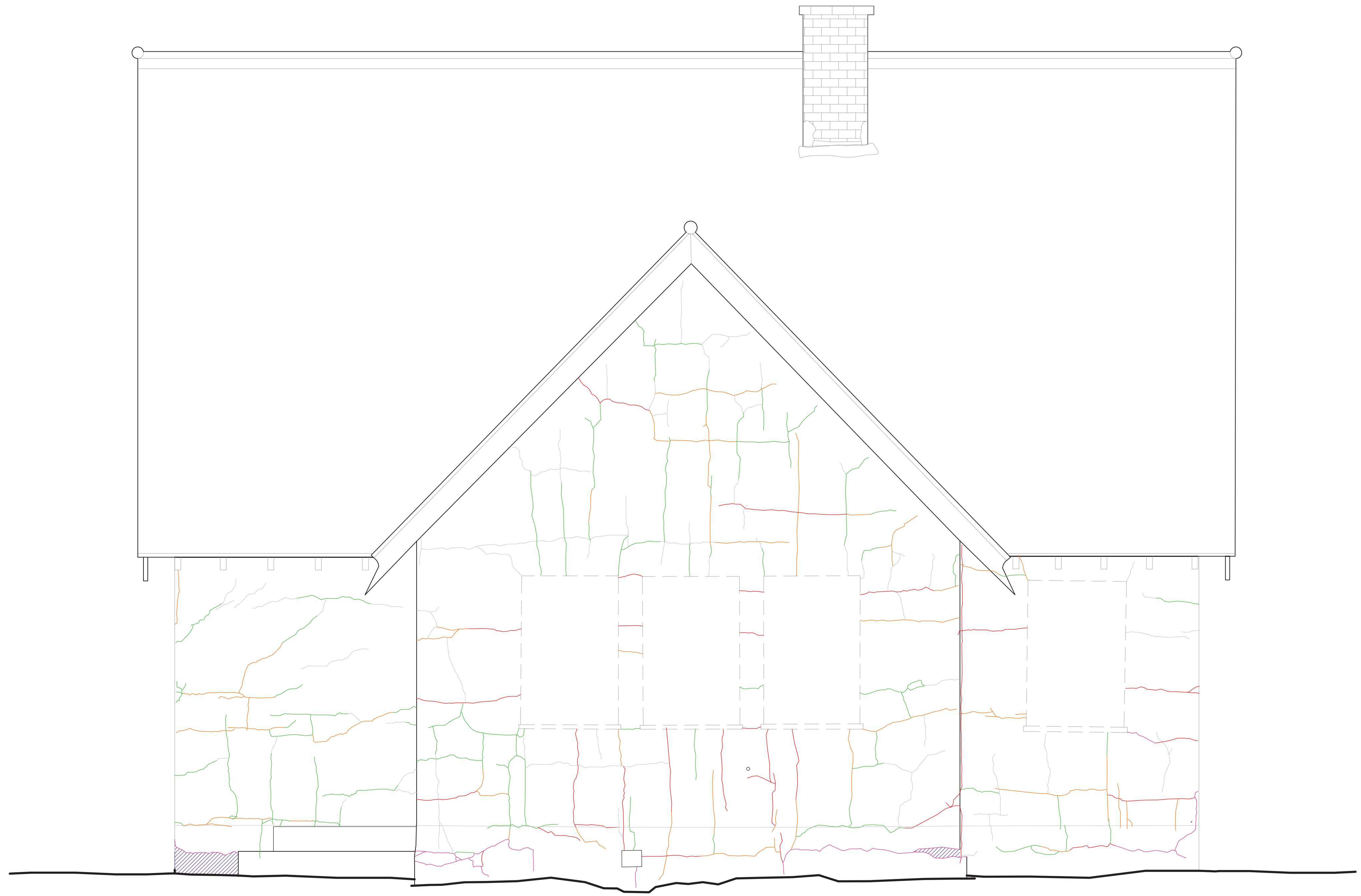
Extra-Large

Loss

SHEET IDENTIFICATION:
Appendix Bii
Conditions

DESCRIPTION
Crack conditions on south elevation.

JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming



0 1 5 10

SCALE IN FEET
1/4" = 1'-0"

Windows obscured
by plywood

Condition:
Crack Sizes

Extra-Small

Small

Medium

Large

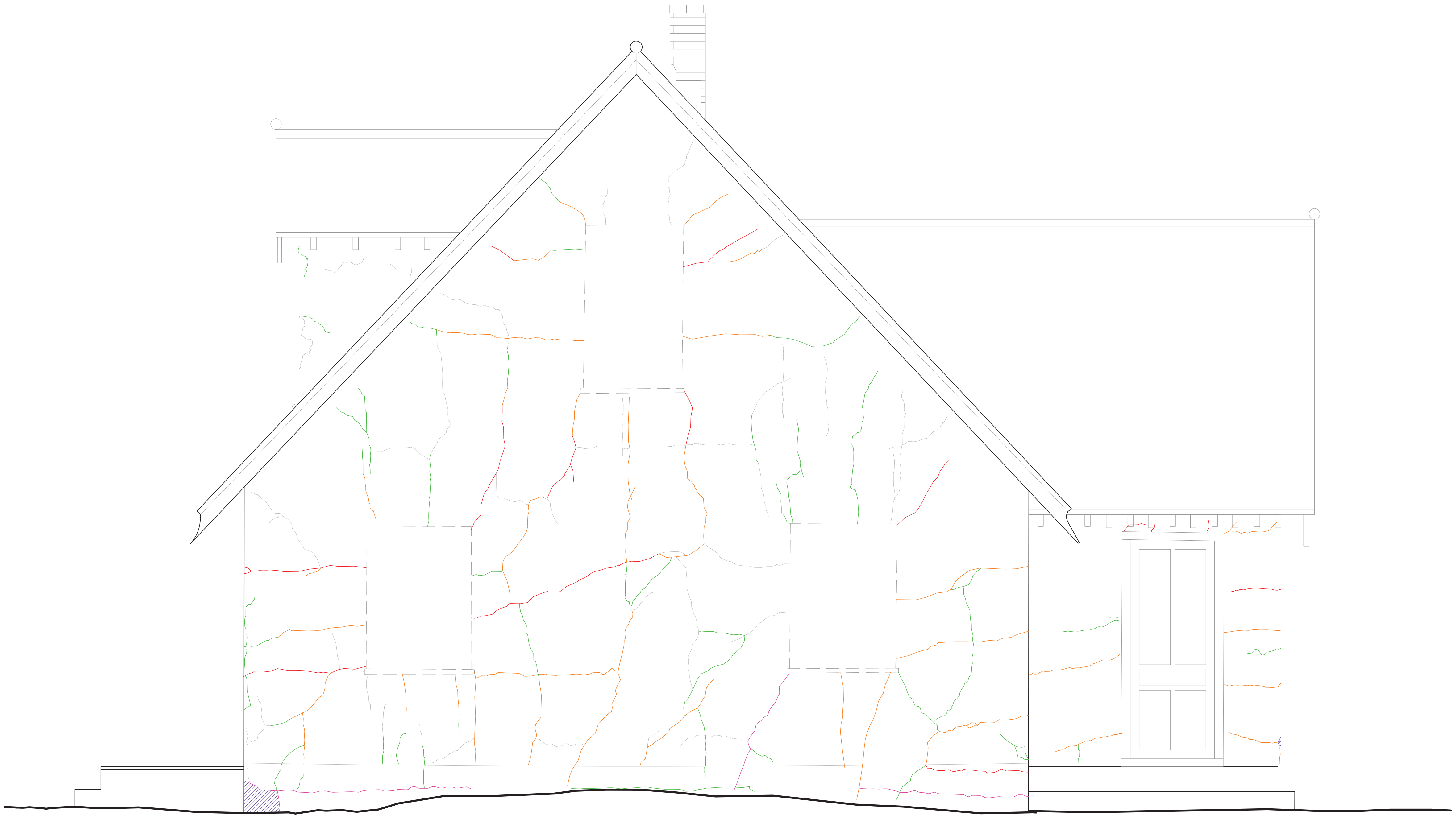
Extra-Large

Loss

SHEET IDENTIFICATION:
Appendix Bii
Conditions

DESCRIPTION
Crack conditions on west elevation.

JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming



0 1 5 10

SCALE IN FEET
1/4" = 1'-0"

Windows obscured
by plywood

Condition:
Crack Sizes

Extra-Small

Small

Medium

Large

Extra-Large

Loss

SHEET IDENTIFICATION:
Appendix Bii
Conditions

DESCRIPTION
Crack conditions on north elevation.

JOHN MOULTON HOMESTEAD
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Grand Teton National Park, Moose, Wyoming

0 1 5 10

SCALE IN FEET
1/8" = 1'-0"

Petrographic Analysis

Mechanical Testing

Paint Analysis

Hollow markers indicate samples that come from the junction of two elevations.

Paint analysis will be part of a succeeding report to be completed in the fall of 2018.

SHEET IDENTIFICATION:
Appendix Bii
Sample Locations

DESCRIPTION
Sample locations for each elevation.

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JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming

DESCRIPTION
Sample locations for north elevation.

SHEET IDENTIFICATION:
Appendix Bii
Sample Locations

SHEET IDENTIFICATION:
Appendix Bii
Sample Locations

DESCRIPTION
Sample locations for south elevation.

JOHN MOULTON HOMESTEAD
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JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming

DESCRIPTION
Sample locations for east elevation.

SHEET IDENTIFICATION:
Appendix Bii
Sample Locations

SHEET IDENTIFICATION:
Appendix Bii
Sample Locations

DESCRIPTION
Sample locations for north elevation.

JOHN MOULTON HOMESTEAD
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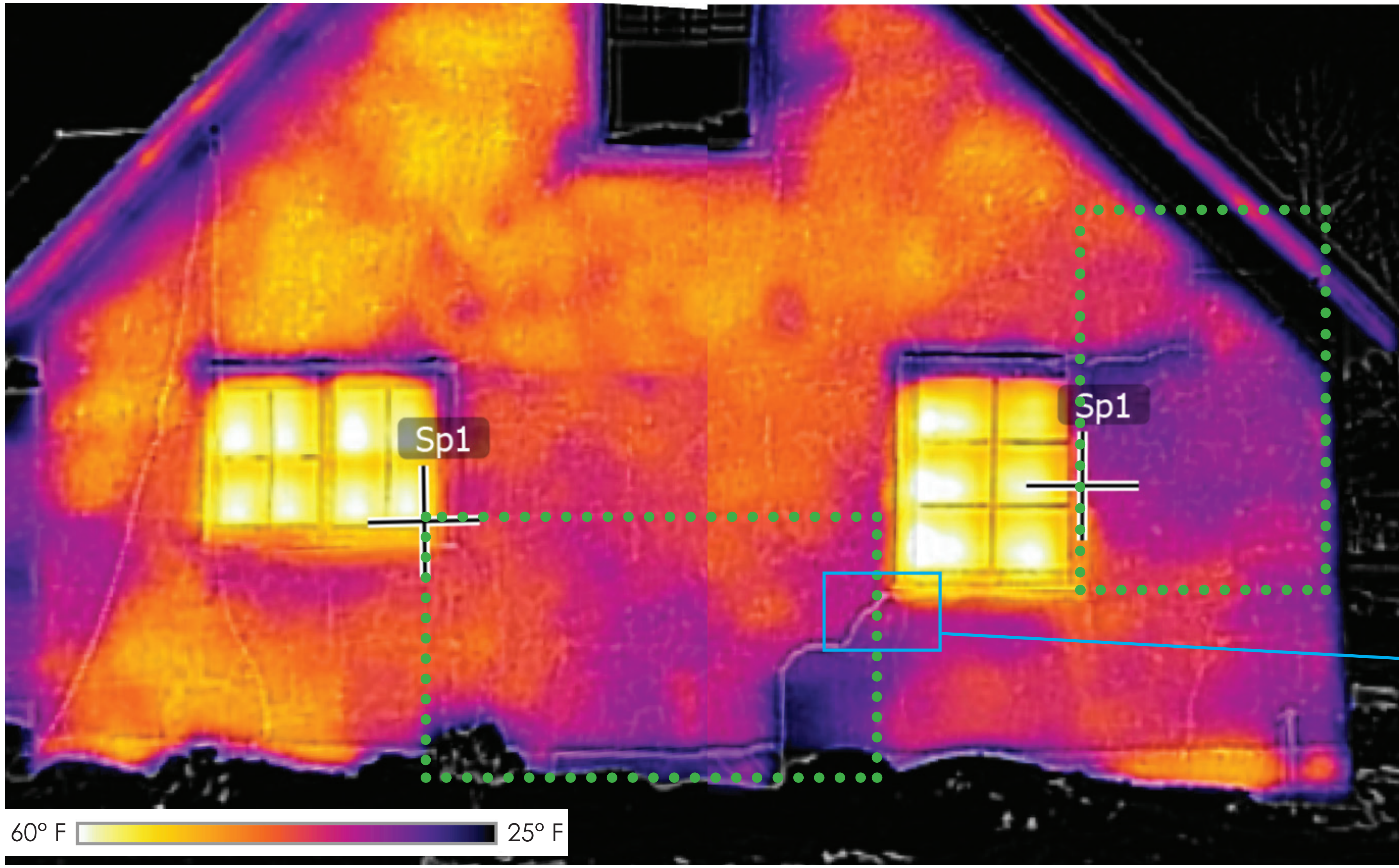
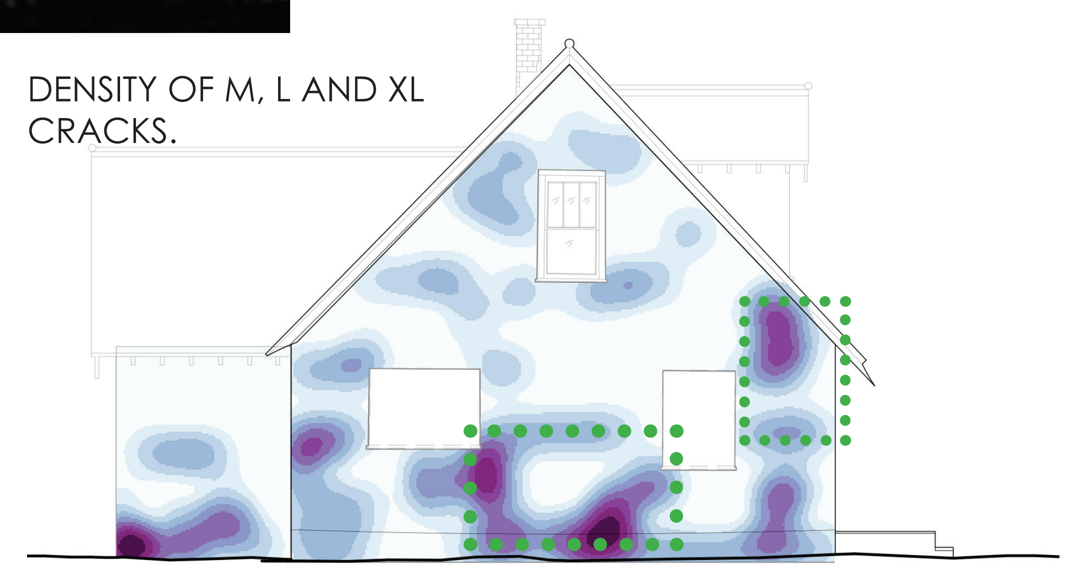
Grand Teton National Park, Moose, Wyoming



Hypothesis:
Areas that have lower temperature are associated with detachment. Bigger cracks and areas of cooler surface temperature are associated with or indicative of unseen detachment.

Risk Implied:
- Areas where the weight of the stucco is not adequately supported by nails.
- Possibility of water intrusion through the crack to wet the nails, vapor barrier, and wood sheathing; deterioration could be obscured by the stucco.

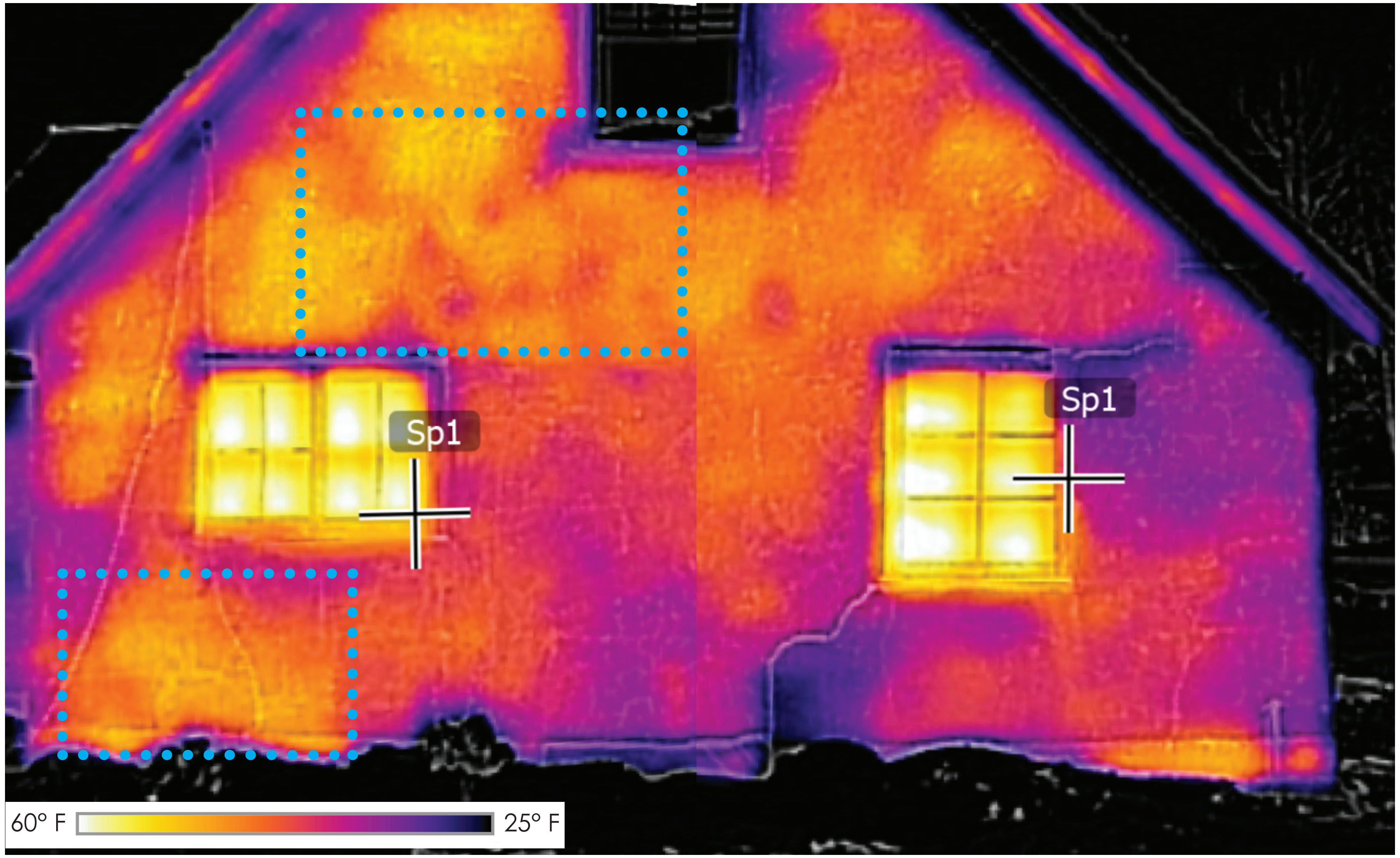
DENSITY OF M, L AND XL CRACKS.

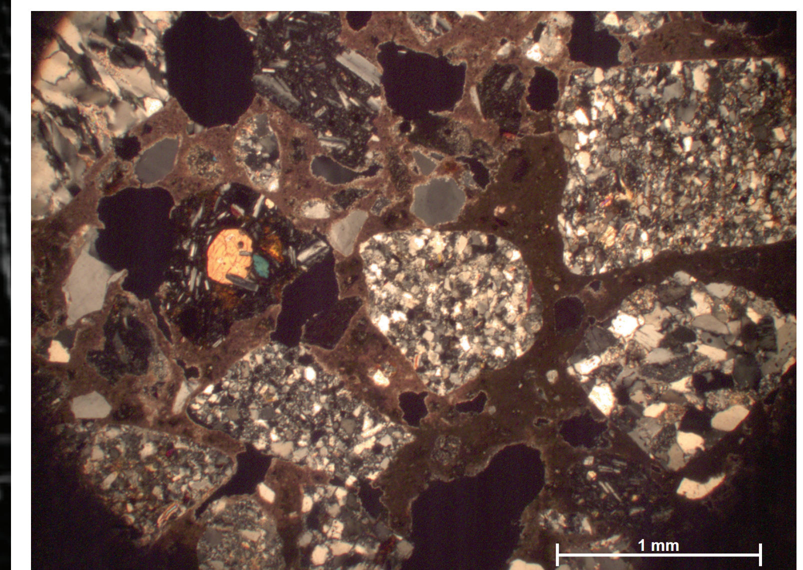


SHEET IDENTIFICATION:
Appendix Biv
Digital Analyses

DESCRIPTION
Digital analyses for south elevation.

JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming



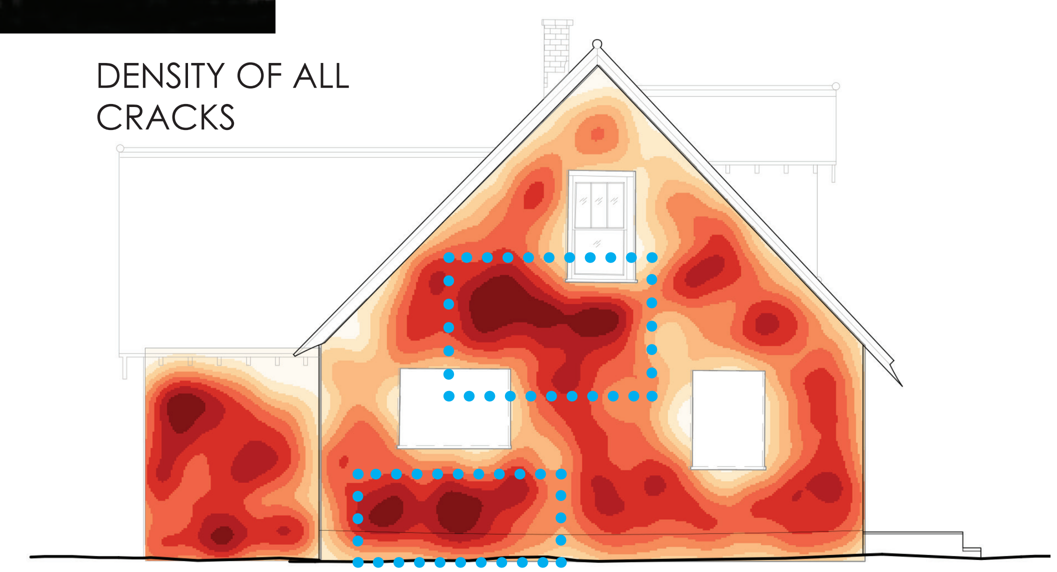


Carbonation of the cement matrix extends through the brown coat in JMH 12 in XPL, 25x magnification.

Hypothesis:
Areas with a higher density of cracks could indicate areas where stucco is still attached to the sheathing. *Alternative: Differential moisture gradients.*

Risks Implied:

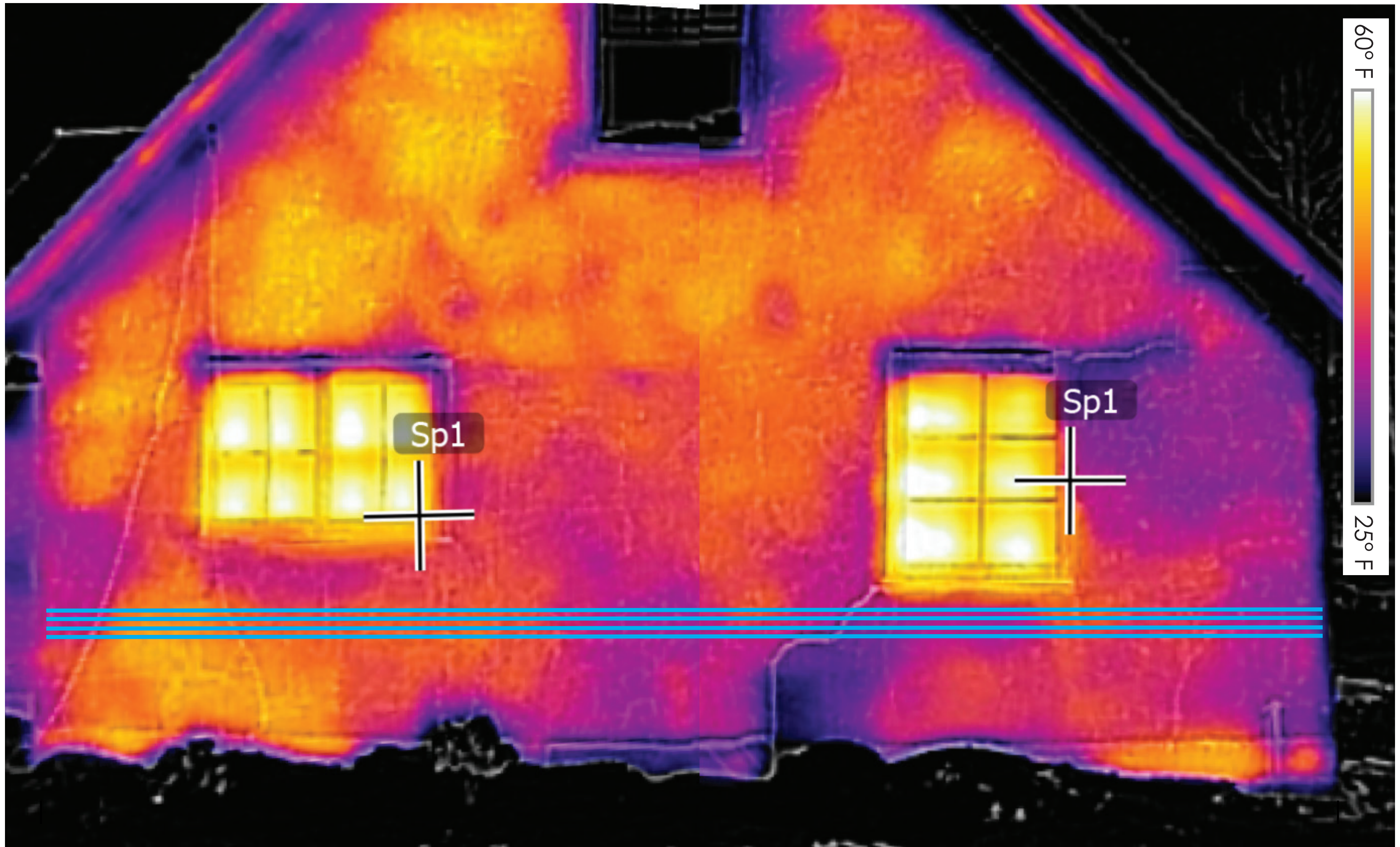
- Possible areas where ferrous reinforcement is corroding, as microcracking and surface cracking are correlated with deeper carbonation of the cement.
- Freeze thaw action and salt efflorescence, due to greater potential of water intrusion.



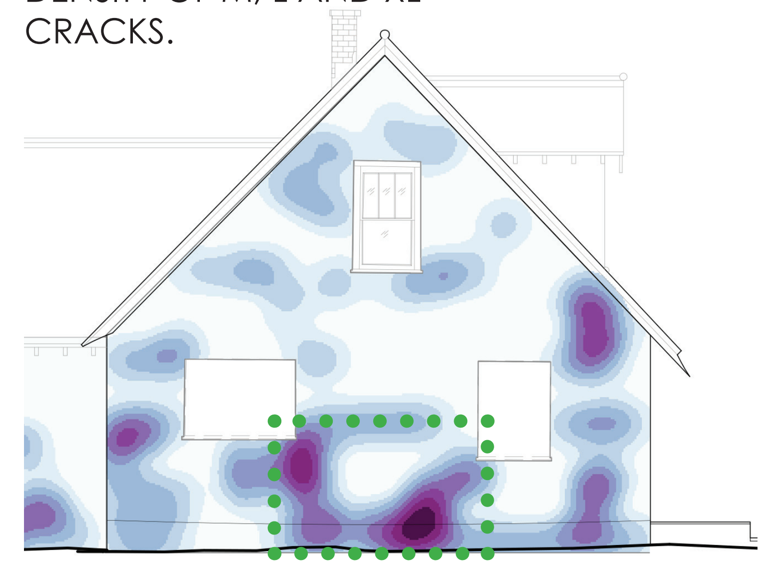
SHEET IDENTIFICATION:
Appendix Biv
Digital Analyses

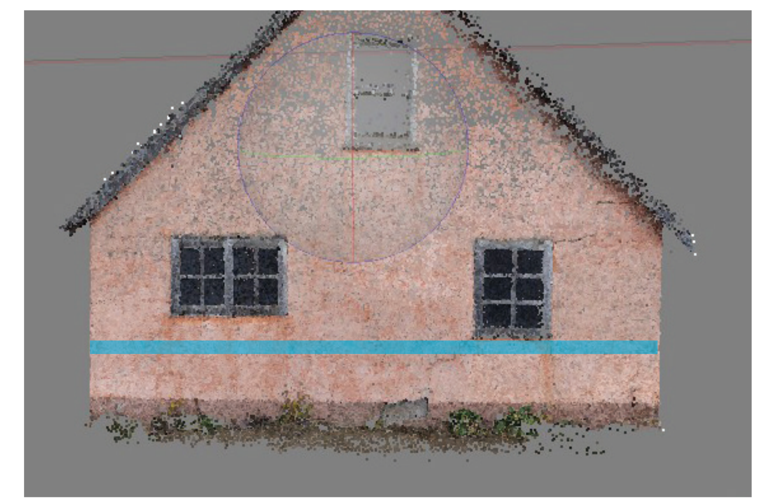
DESCRIPTION
Digital analyses for south elevation.

JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming



DENSITY OF M, L AND XL CRACKS.





Still of photogrammetric model with area of cross section indicated.

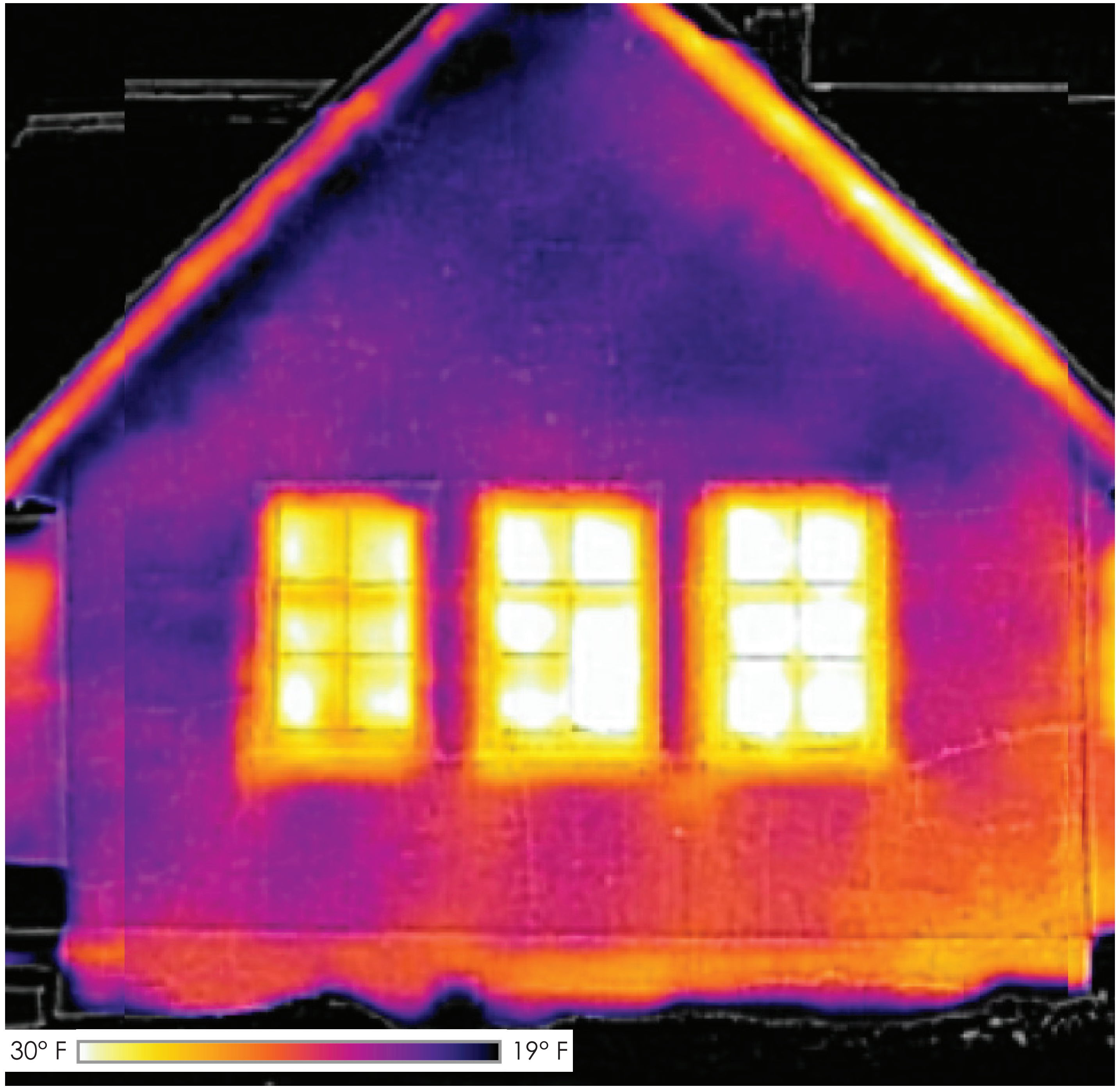
Areas of adjacent to the known area of detachment show:
1) cooler temperatures in IRT and
2) is indicated by the bigger cracks (M, L, XL) density map.

Cross section from photogrammetric model shows that detachment on the south elevation could be more extensive than previously observed.

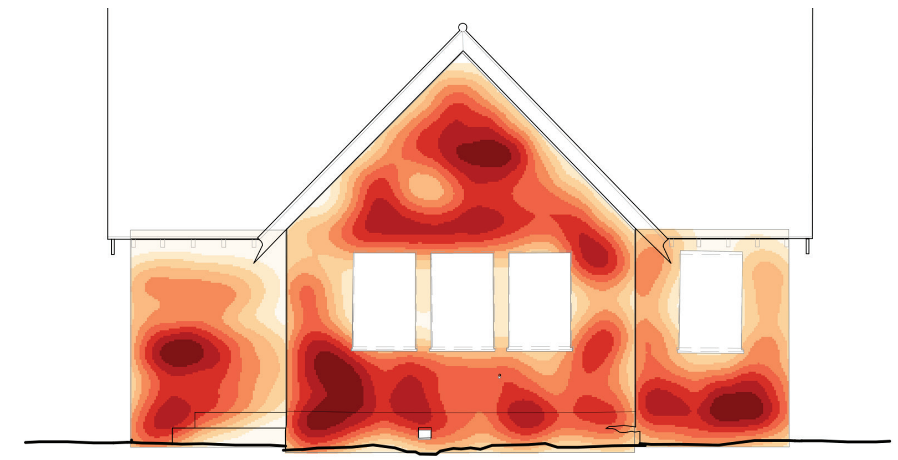
SHEET IDENTIFICATION:
Appendix Biv
Digital Analyses

DESCRIPTION
Digital analyses for south elevation.

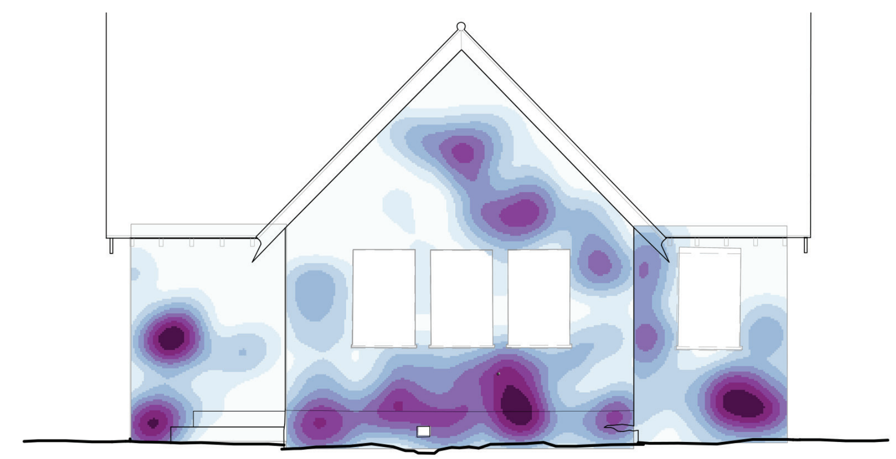
JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming



DENSITY OF ALL CRACKS



DENSITY OF M, L, AND XL CRACKS



NO EVIDENCE OF VISUAL CORRELATION
IR thermographs were taken at midday, when solar raditation had only warmed the south elevation of the west ell. The result is a potentially misleading distribution of temperatures across the surface of the west elevation. Warmer temperatures emanating from the lower right corner could be indicative of the condition of stucco, or simply warmed by the sun while the rest has been in shadow in the preceding hours.

SHEET IDENTIFICATION:
Appendix Biv
Digital Analyses

DESCRIPTION
Digital analyses for west elevation.

JOHN MOULTON HOMESTEAD
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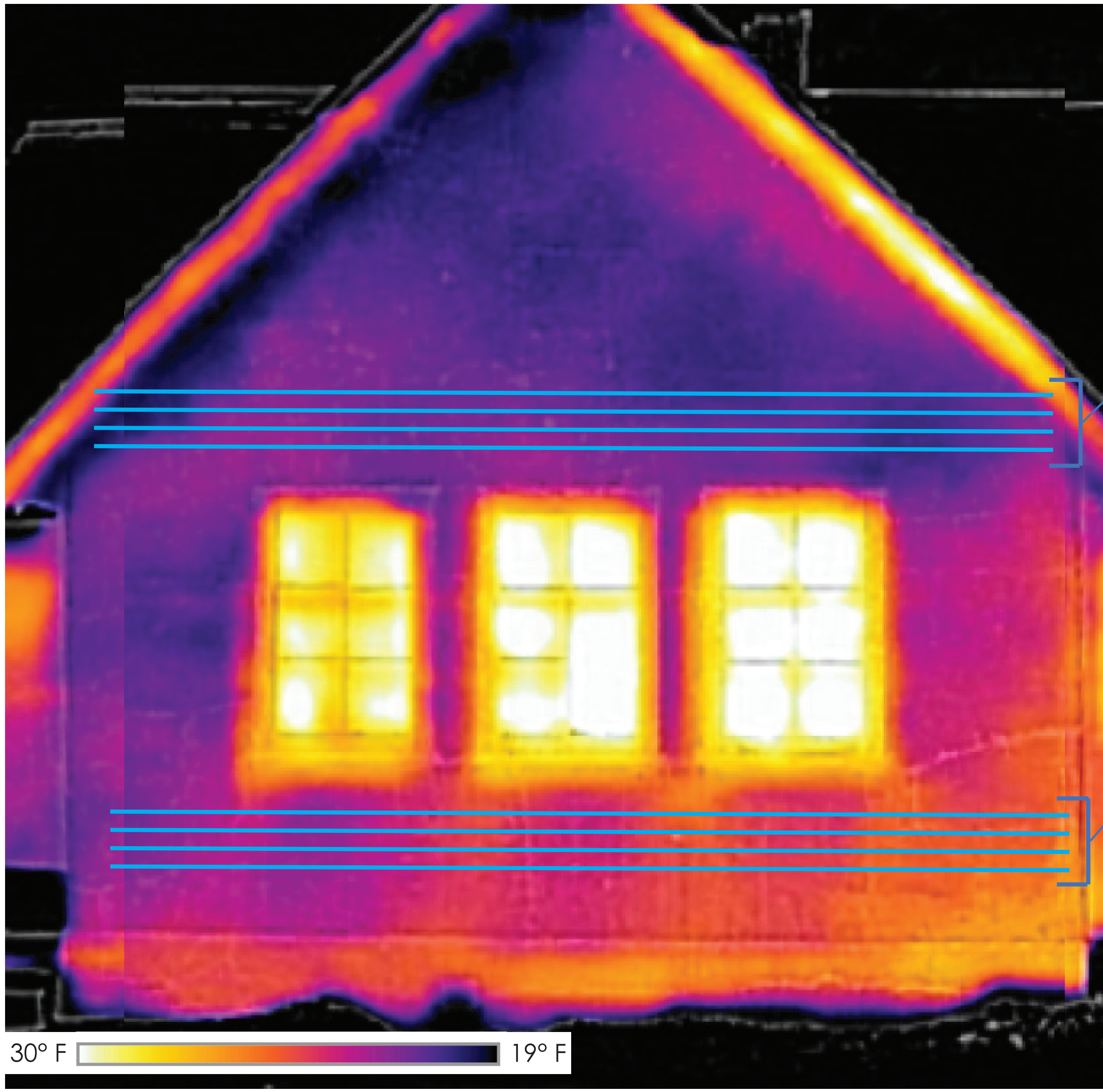
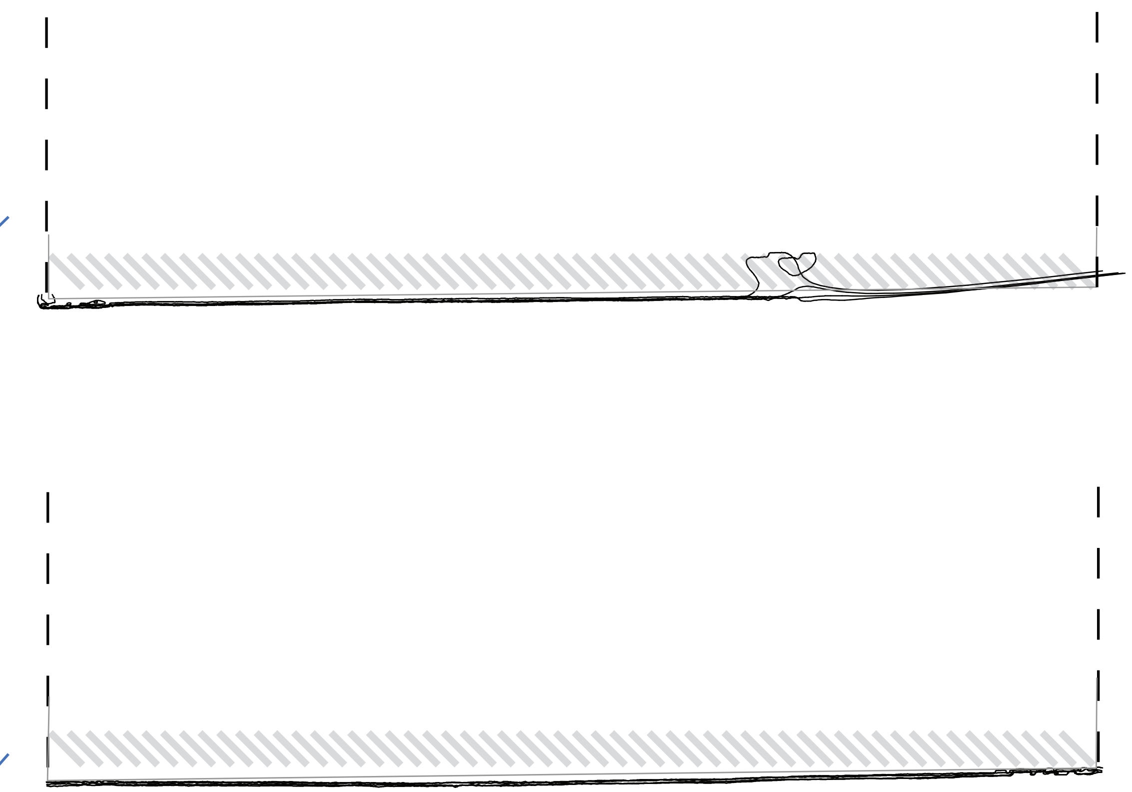


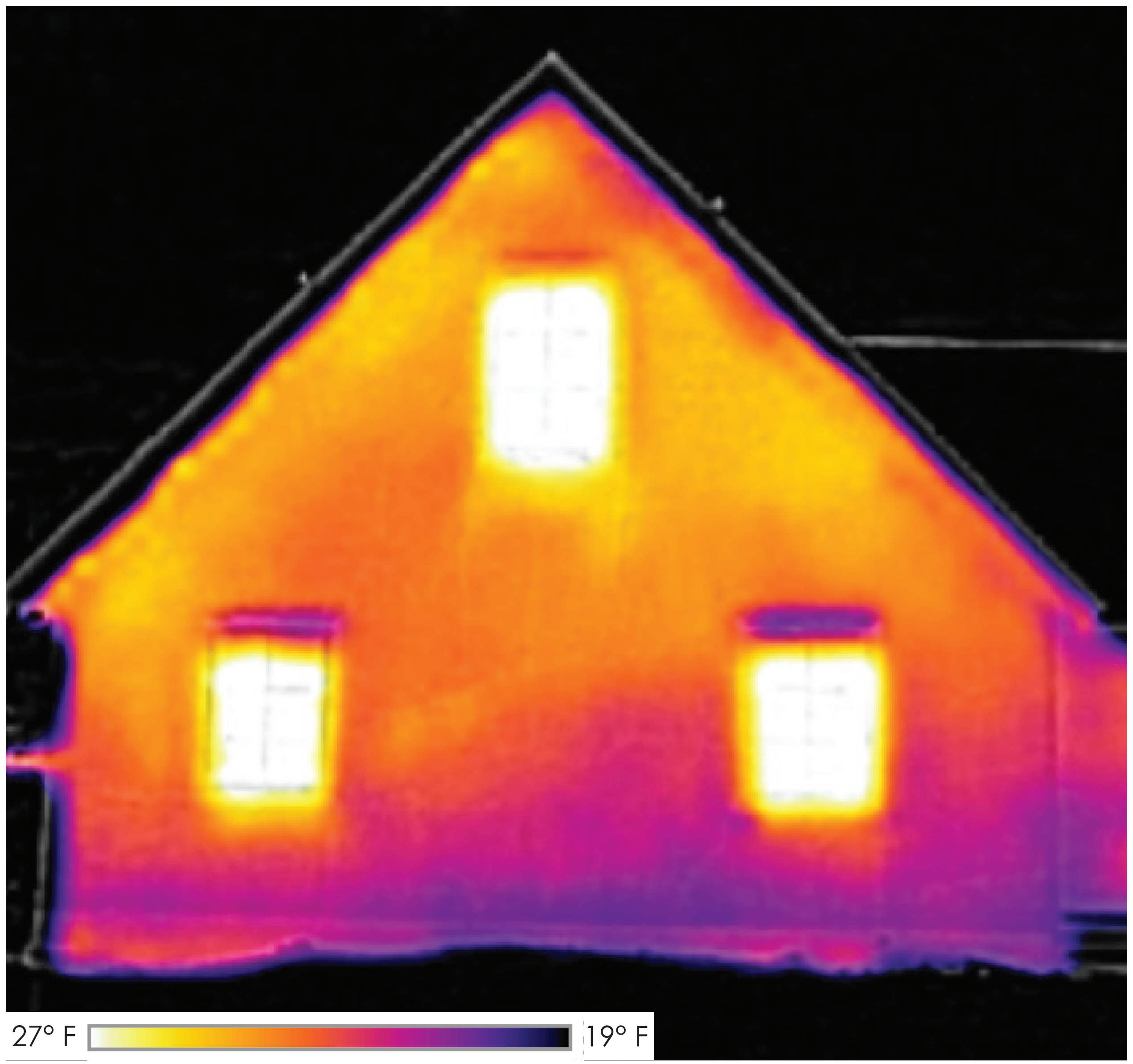


COMMENTS
Cross sections from the west elevation appear to be plane. The stucco on the west elevation of the ell is likely to be in good condition and not detached because it may not be undergoing the same amount of movement as the main structure. Further testing with a higher resolution IR camera will be required to confirm this condition.

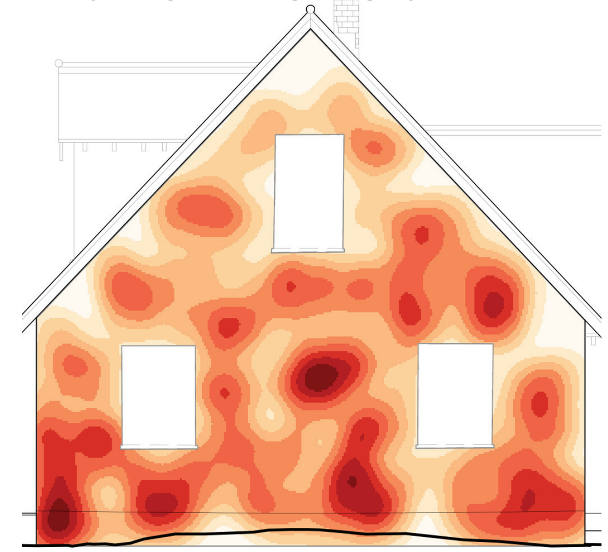
SHEET IDENTIFICATION:
Appendix Biv
Digital Analyses

DESCRIPTION
Digital analyses for west elevation.

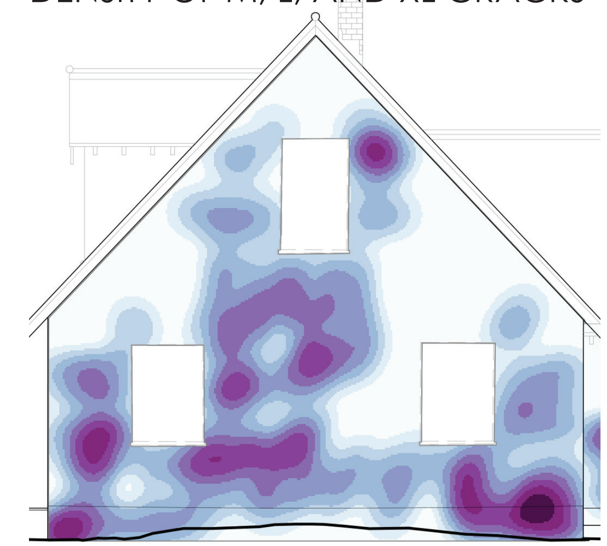
JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming



DENSITY OF ALL CRACKS



DENSITY OF M, L, AND XL CRACKS



COMMENTS

The north elevation is the least exposed to direct sunlight and wind; therefore, it may be expected there are fewer small cracks on this surface. The similarity between the density graphics for all cracks and bigger cracks confirms that failure on this elevation is result of structural movement rather than thermal or hygric cycling. The thermal image, however, does not show a strong relationship with either graphic due perhaps to environmental factors.

SHEET IDENTIFICATION:
Appendix Biv
Digital Analyses

DESCRIPTION
Digital analyses for north elevation.

JOHN MOULTON HOMESTEAD
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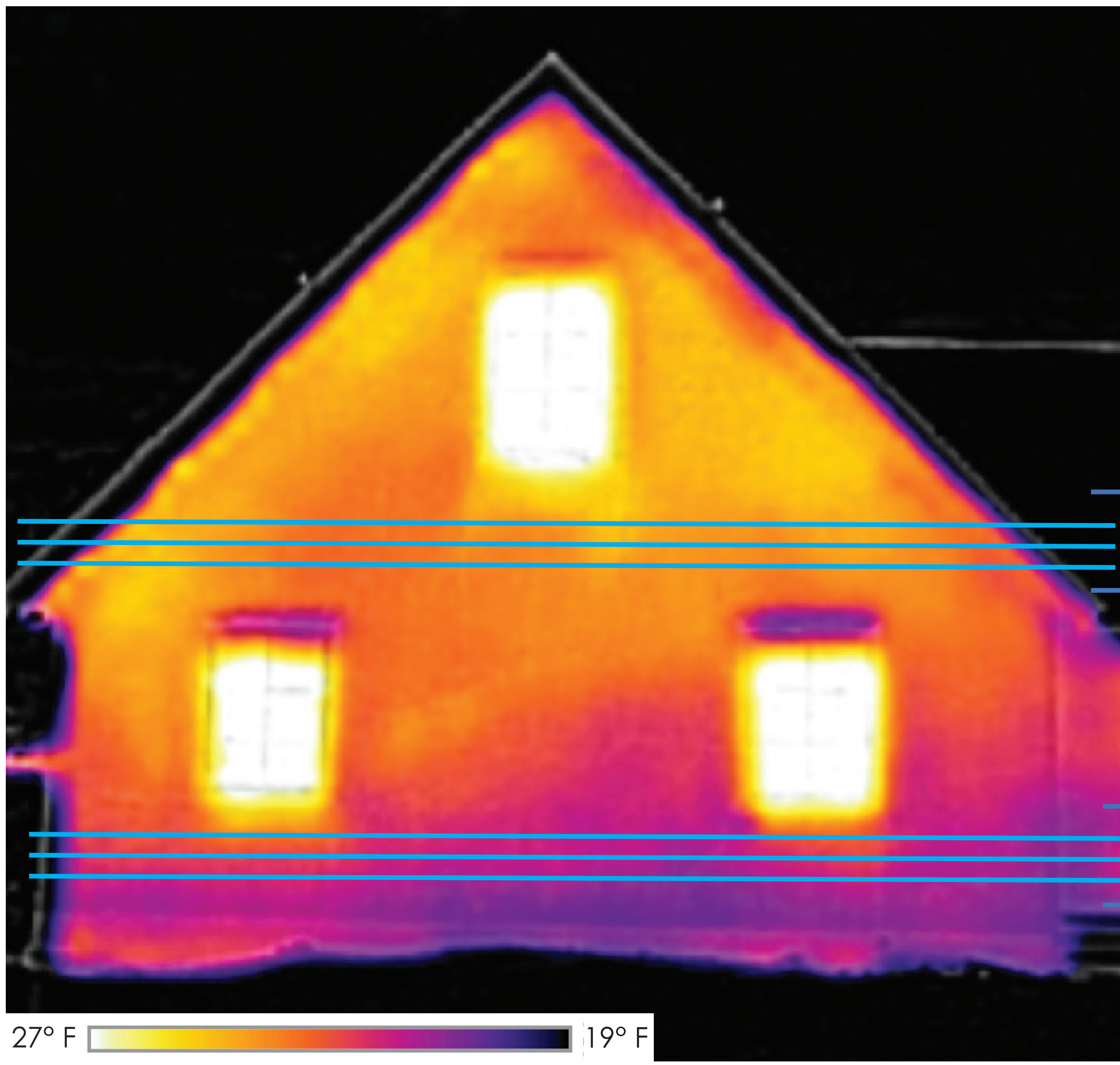
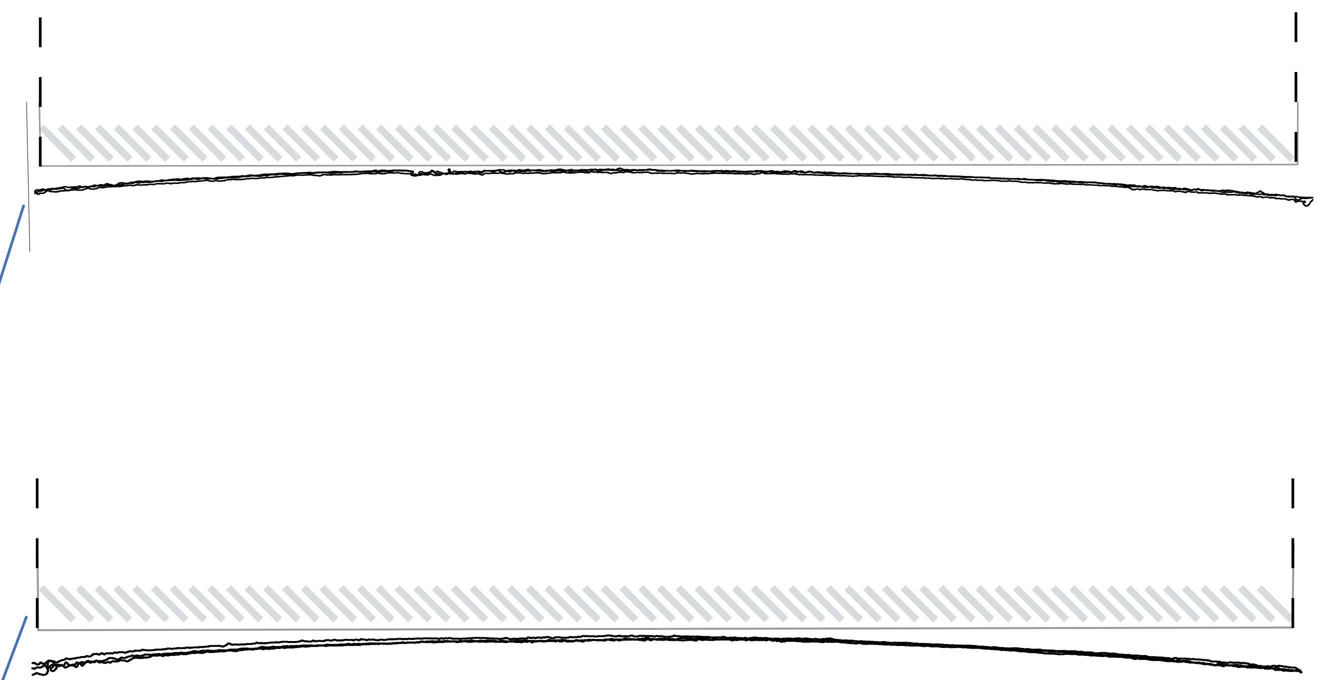




COMMENTS

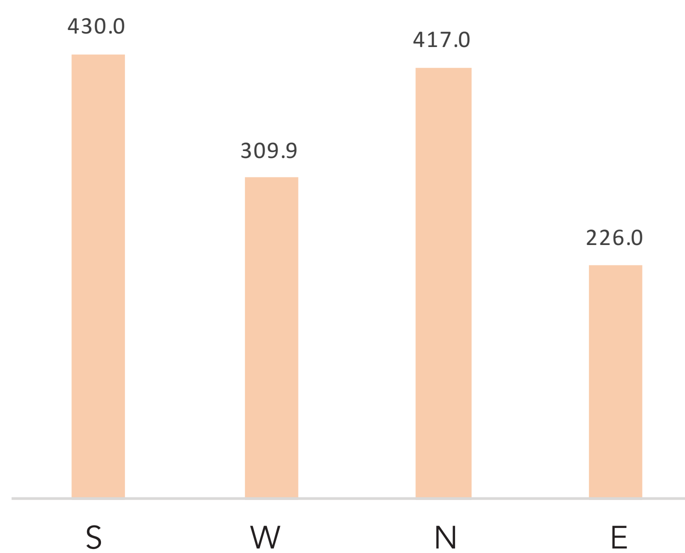
The photogrammetric model for the north elevation has the poorest resolution of the set and is less accurate. The resulting cross section appears to be concave, which is likely due to a lack of photos taken from oblique angles. Nonetheless, the section does not reveal significant irregularities that would suggest detachment of the stucco. The thermal signatures are more likely to be the result of external environmental factors than revealing characteristics about the stucco.

SHEET IDENTIFICATION:
Appendix Biv
Digital Analyses

DESCRIPTION
Digital analyses for north elevation.

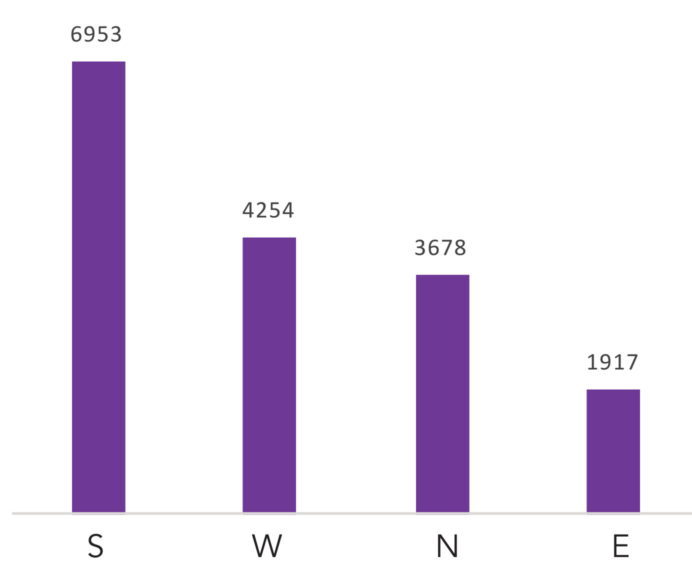
JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming

TOTAL SURFACE AREA (SQ FT)
PER ELEVATION



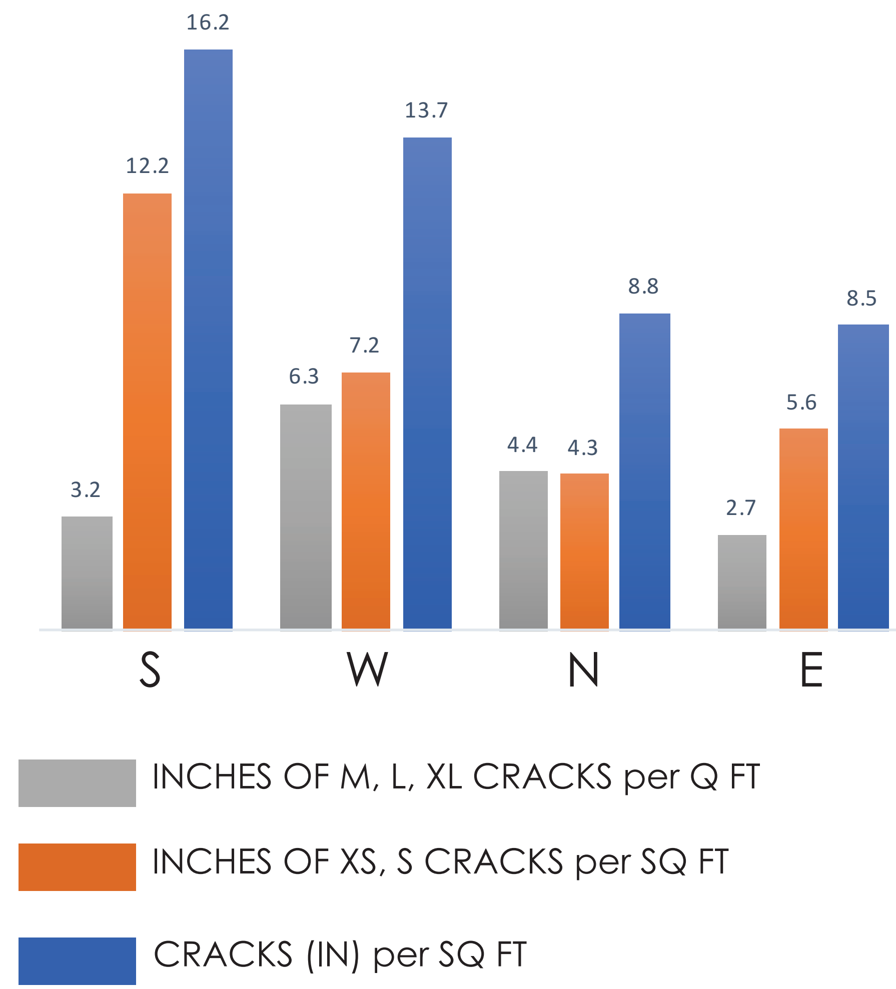
Based on all elevations except the dormers, measured in AutoCAD.

CRACKS, LINEAR INCHES
PER ELEVATION



All cracks selected and quantified in ArcGIS.

DISTRIBUTION OF CRACKS
NORMALIZED BY SURFACE AREA



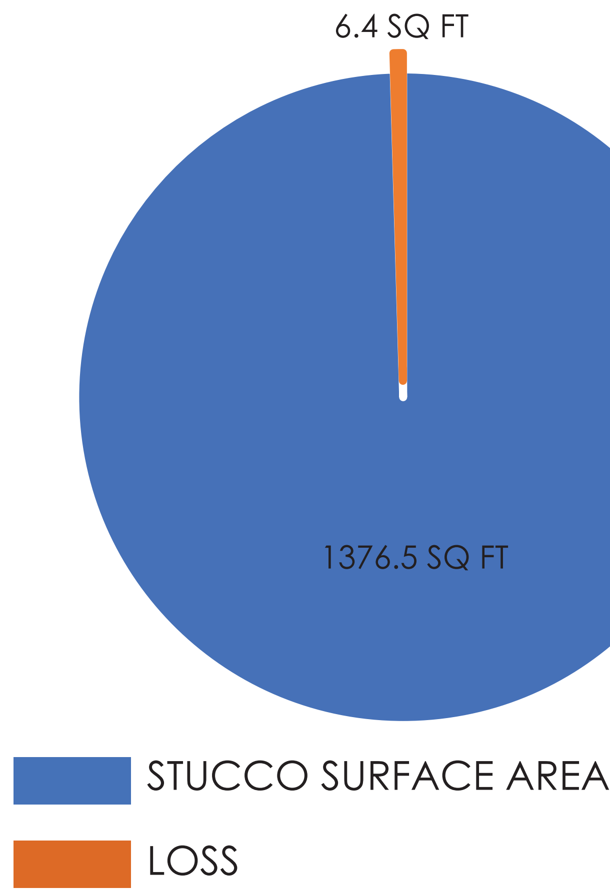
COMMENTS
Numerical data regarding the distriution of sizes and linear inches of cracks on each elevation is advantageous as it can draw out new inferences which indicate how pathologies may be affect each elevation. These observations are based on generalizations with relate crack size to deterioration cause.

SHEET IDENTIFICATION:
Appendix Bv
Crack Statistics

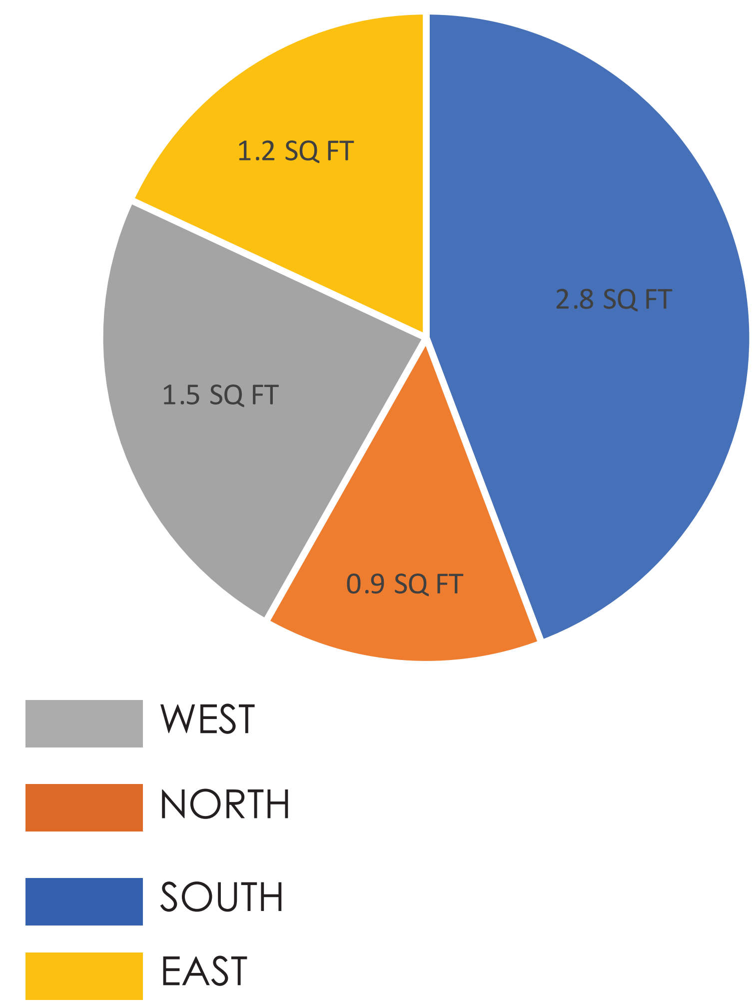
DESCRIPTION
Distribution of crack sizes/elevation.

JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming

AREA OF LOSS
PER ELEVATION



DISTRIBUTION OF LOSS
PER ELEVATION

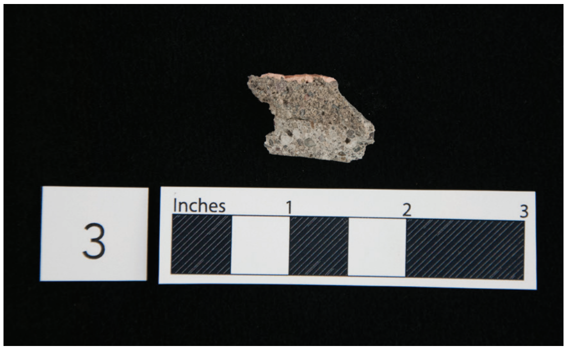


COMMENTS
Loss is a highly worisome condition, but the area of loss is relatively low in comparison to the total surface area. The south elevation is the most affected by loss, which contributes to the theory that the south is the most affected by movement of the foundation. The west elevation is likewise affected, but to a lesser extent, because of the openings on that elevation and the ell. The degree to which the west elevation is affected by detachment is warrented.

SHEET IDENTIFICATION:
Appendix Bv
Crack Statistics

DESCRIPTION
Distribution of loss per elevation.

JOHN MOULTON HOMESTEAD
13040 Antelope Flats Road
Grand Teton National Park, Moose, Wyoming



JMH 3 taken from displaced crack (+) below left corner of east window on south elevation.

Characterization of stucco from an exposed area which should demonstrate condition of cement with eposure to weather and thermal cycling. Photo by author, 2017.

JMH 12 taken from the base of the north elevation near the east corner. Photo by author, 2017.

JMH 16 taken from base of the south elevation near east corner. Photo by author, 2017.

JMH 17 taken from base of the east elevation near the south corner. Photo by author, 2017.

JMH 18 taken from the northwest corner of the L addition. Photo by author, 2017.

Sample is curved and has a thicker finish coat paint layer, likely the result of application.

JMH 20 taken from corner of north and east elevation under the eave. Photo by author, 2017.

The bulk sample has poor interlayer adhesion, perhaps due to faulty application/installation. Sample taken to characterize unexposed cement matrix.

JMH 22 was found detached from the structure and collected from the ground adjacent to the southwest corner of the west L addition. Sample taken in July 2017 by J. Hinchman. Photo by author, 2017.

JMH 23 was found detached from the structure and collected from the ground adjacent to the south corner of the east elevation. Sample taken in July 2017 by J. Hinchman. Photo by author, 2017.

Smp No.	Location Description	Elevation(s)	Paint color	Testing	Date Collected	Collected by
JMH 03	Below left corner of east window.	South	Pink	Petrographic Examination	10/21/2018	J. Hinchman, S. Stratte
JMH 12	Base course stucco from corner.	North	Purple	Petrographic Examination	10/21/2018	J. Hinchman, S. Stratte
JMH 16	Base course stucco from corner.	South	Purple	Petrographic Examination	10/21/2018	J. Hinchman, S. Stratte
JMH 17	Base course stucco from deteriorated area at SE corner.	East	Purple	Petrographic Examination, Salt Testing	10/21/2018	J. Hinchman, S. Stratte
JMH 18	NW corner of the ell.	North, West	Pink	Petrographic Examination	10/21/2018	J. Hinchman, S. Stratte
JMH 20	NE corner, under eave.	East, North	Pink	Petrographic Examination	10/22/2017	J. Hinchman, S. Stratte
JMH 22	SW corner of the ell.	West	Purple	Petrographic Examination	Summer 2017	J. Hinchman
JMH 23	Base course stucco from deteriorated area at SE corner.	East	Purple	Petrographic Examination, Water Absorption	Summer 2017	J. Hinchman
JMH 24	Area of significant loss at base of south elevation.	South	Pink	Three point bending	Spring 2018	B. Guild (GRTE)

i. Test Selection

ASTM C1764-12, *Standard Test Methods for Non Metallic Plaster Bases (Lath) Used with Portland Cement Based Plaster in Vertical Wall Applications*, contains a series of basic tests which can approximate the performance and mechanical limitations of a Portland Cement Based Plaster under a variety of test conditions and exposures. These include measuring the ability of the plaster to withstand transverse and vertical loads, as well as characterizing the embedded lath or furring within the plaster and ability of the fasteners to withstand failure. The scale of the tests in this standard was designed for testing commercial market rather than historic materials. Some of the tests employed to characterize the cement stucco have been adapted from standards developed for other materials, as the standard requires fabricating large test frames and panels of cement stucco not suitable or realistic for testing small sample.

ii. Potential Sources of Error

For water absorption and three point bending tests a single large piece of stucco, already detached from the structure, was divided into sample coupons.[1] Both tests traditionally require a large volume of materials, but obtaining samples from a variety of locations would damage the integrity of the stucco and is not in keeping with preservation ethic. Conducting tests on stucco from a single source rather than multiple sources introduces a degree of potential error as the test results are not representative of the stucco for the whole structure. This point is of particular importance as the mechanical and chemical character for cement on each elevation could be different due to field-mixing. Additionally, both samples are taken from near grade so it can be expected that these materials may have a higher degree of damage than other stucco materials on the structure due to proximity to ground moisture, faunal activity, and visitors.

[1] Samples for water absorption were cut from JMH 23, a large stucco piece from base of the east elevation which was found already detached from the structure. Material for mechanical testing was sent to the University of Pennsylvania by Grand Teton National Park staff in March 2018; the piece had fallen off of the south elevation and been stored in the kitchen of the John Moulton homestead.

iii. Thin Section

ASTM C856-17, *Standard Practice for Petrographic Examination of Hardened Concrete*, describes the methodology for preparing and examining cement samples with a stereomicroscope and polarized light microscope. Thin section analysis can characterize the physio-chemical composition and deterioration state of a cement material, typically for engineering and construction-related investigation. For historic preservation, these tests can serve a number of useful purposes:

- Determining the number of layers and their thicknesses.
- Identifying the type of source of aggregate
- Identifying the type of binder: Description of the cementitious matrix, including qualitative determination of the kind of hydraulic binder used, degree of hydration, degree of carbonation if present, evidence of unsoundness of the cement, presence of supplementary cementitious materials, and the nature of hydration products.
- Identifying the presence of mineral additions, such as pigments.
- Quantifying the materials present to estimate the mix proportions.
- Assess workmanship. Determination of effects of use of different concrete making materials, forming, and molding procedures, types of reinforcement, embedded hardware, etc.
- Identifying defects.
- Diagnosing decay mechanisms and assessing the level of deterioration. Determination of whether the concrete has been subjected to a sulfate attack or to early freezing, or other harmful effects of freezing and thawing. Alkali reactivity of the constituent parts, either with carbonate or siliceous aggregate.

Eight samples were sent to National Petrographic Service, Inc., along with annotated photographs and descriptions for how to cut and prepare samples; a description of these samples and their locations is in *Figure Diii.1*. The orientation of the thin sections was determined by visual and stereo microscopic examination to be perpendicular to plaster layers. Areas where metal plaster backing was evident were noted, and some of the samples were ordered to be cut on or near these features to examine the structure of cement materials in proximity to the metal mesh. Samples were cut and polished using an oil-based lubricant to ensure salt efflorescence, if present, would not be damaged during sample preparation. Standard thin sections were prepared for petrographic examination with a polarized light microscope. The sections were mounted onto glass slides with clear epoxy; five received glass cover slips, which improve optics during examination. Three samples did not receive glass cover slips for SEM testing at a later date.[2]

The samples examined are all similar in terms of arrangement plaster coat layers. The samples follow the prescribed three coat system typically used in plastering: coarse or scratch coat, followed by the brown coat, and then the finish coat. Only JMH 18 and 20 were anomalous, as they are both missing a distinct coarse coat layer; this is likely due to error in application and the respective locations of each sample.The mineralogy for the brown and coarse coats is similar, but the spacing of the grains is larger for the coarse coat. In two cases, the embedded wire woven lath was evident in thin section.[3]

Despite despite the harsh climate to which it is exposed, the weathered cement is remarkably well preserved. The cement matrix is still well adhered to the aggregate in the finish and brown coats, and the carbonation depth varies *(Figure Diii.2)*. In only a few instances, there was evidence of micro cracks which are lined with either carbonated cement or calcified free lime *(Figure Diii.3)*. While salt sub florescence had been observed in cross section, no crystalized salt was found in thin section examination. The cement matrix was mostly well adhered to the embedded metallic reinforcement. The metallic elements show some evidence of ferrous corrosion in cross section and rust deposits were visible in thin section, but this does not appear to be inducing physical damage to the surrounding cement matrix *(Figure Diii.4)*. The matrix surrounding micro-cracks on the exterior and posterior surfaces of samples were more thoroughly carbonated than the surrounding matrix. The finish coats are composed of white portland cement with mineral pigments added, which color the cement matrix. The individual minerals were too small to bee discerned in thin section so further chemical testing will required to identify these components.

[2] JMH 03, 17, and 23.
[3] JMH 12 and 15.

Test Sample No.	Location	Notes
JMH 03	South	Sample taken from displaced crack (+) on south elevation. Pink finish.
JMH 12	North	Stereomicrograph shows an anomalous white substance under and within the paint layer, possibly salts. Nitrate strip testing might confirm, along with thin section examination. Purple finish (base).
JMH 16	South	Sample contains ferrous mesh; thin section taken adjacent to wire. Purple finish (base).
JMH 17	East	Purple finish (base).
JMH 18	North, West	Curved sample, taken from the northwest corner of the ell addition. Pink finish.
JMH 20	North, East	Sampled from under the eave on the east elevation. The bulk sample has poor interlayer adhesion, perhaps due to faulty application/installation. Pink finish.
JMH 22	West	Sample was found detached from the structure and collected from the ground adjacent. Purple finish (base).
JMH 23	East	Sample was found detached from the structure and collected from the ground. Contains ferrous wire mesh; thin section taken adjacent to wire. Stereomicrograph shows that there may be a reddish brown layer underlying the purple paint. Purple finish (base).

Figure Diii.1. Petrographic samples, along with notes about the location and sample features.

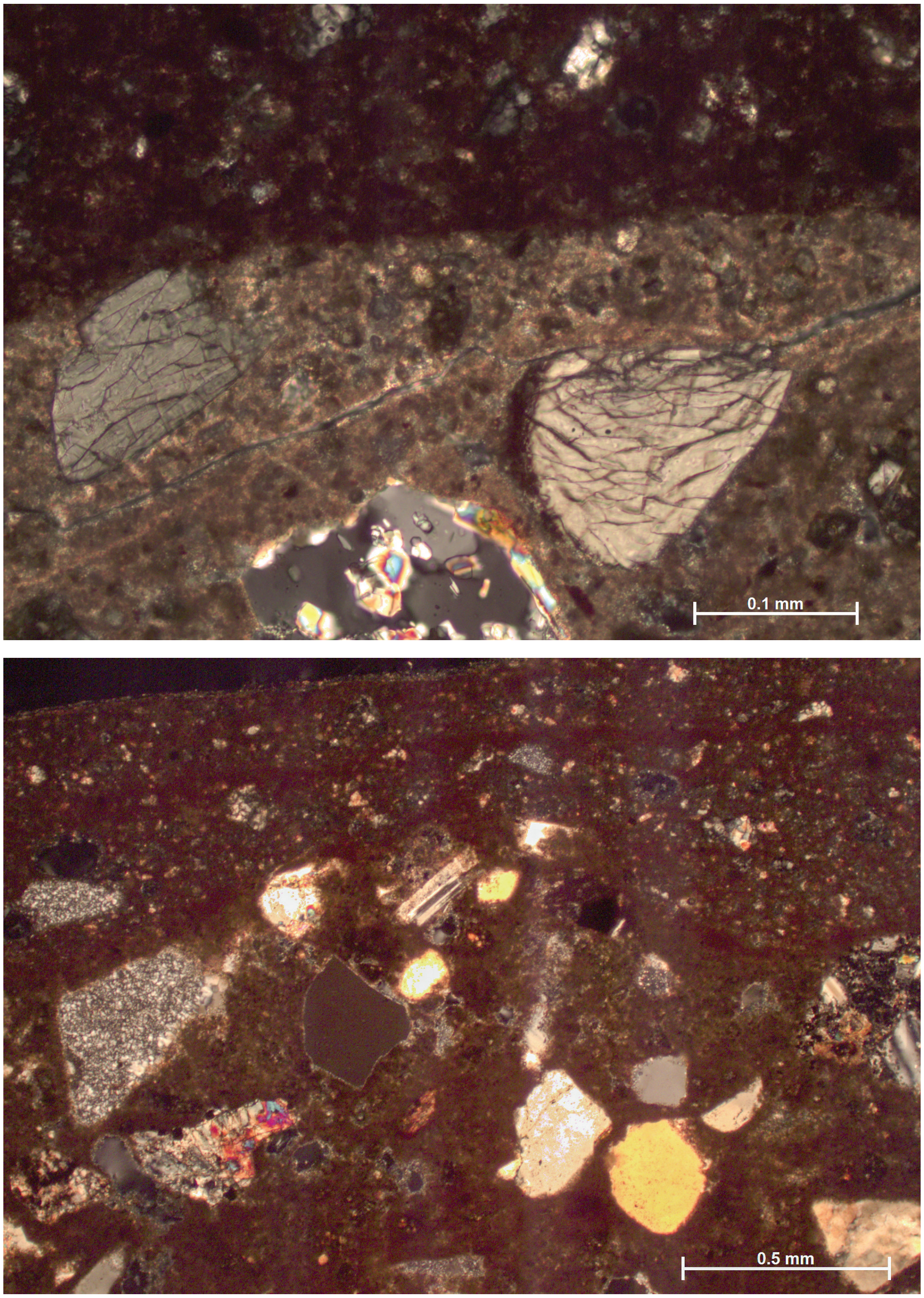


Figure Diii.2 Samples show differing depths of carbonation. JMH 16 (top) has carbonated cement matrix extending into the brown coat, while JMH 18 (bottom) demonstrates little carbonation. (XPL, 50x magnification)

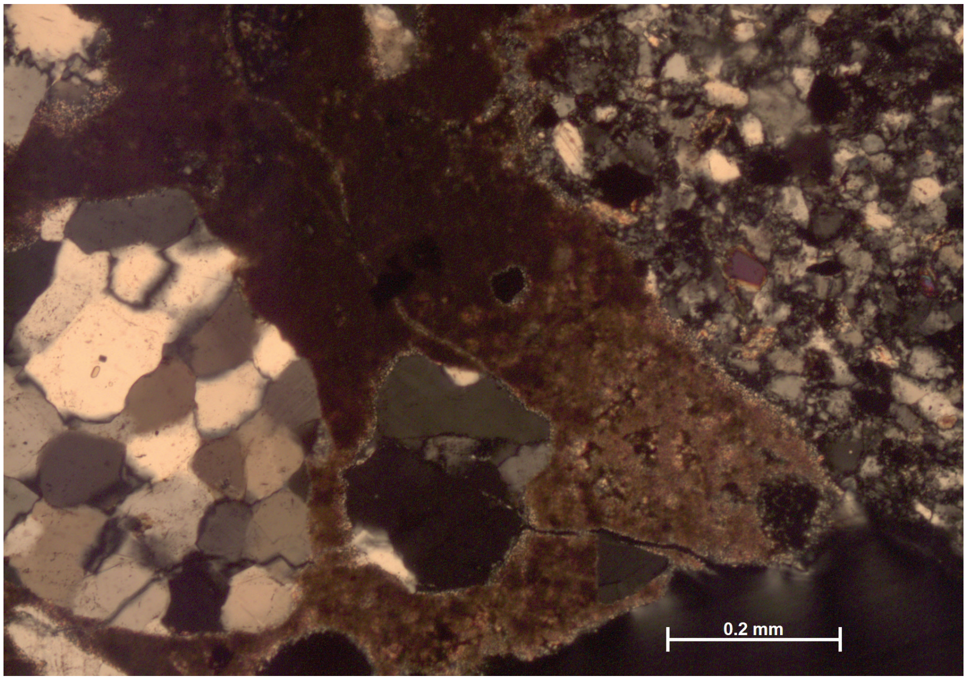


Figure Diii.3 Some microcracking was evident in some samples on the posterior surface of the coarse coat; in these cases carbonation was affecting both the exterior and interior faces of the stucco. (JMH 16, XPL, 100x magnification)

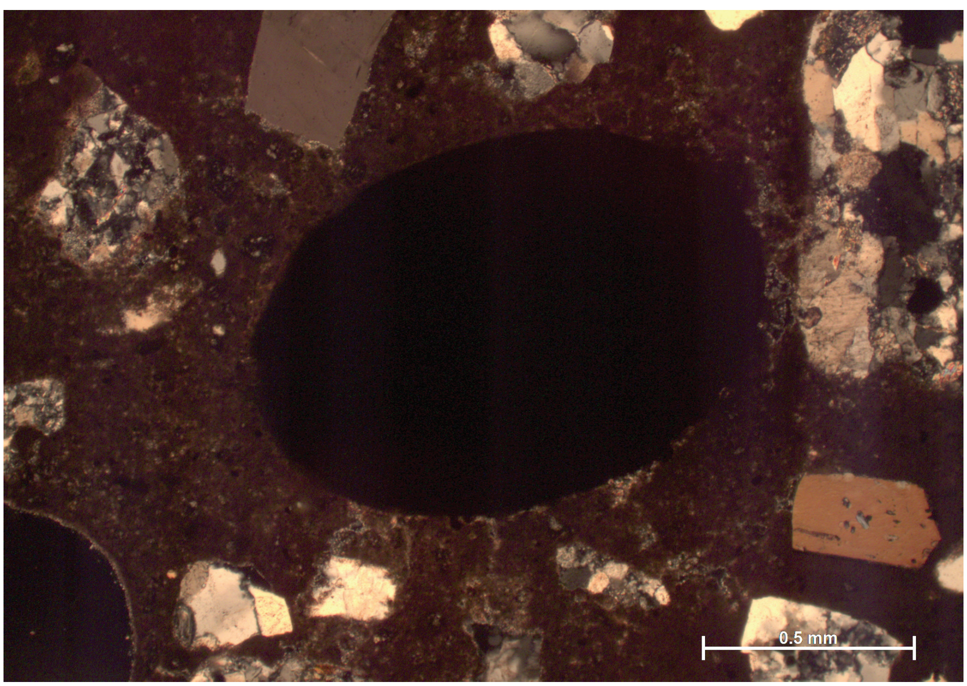


Figure Diii.4 The cement matrix surrounding the metal wire (opaque, center of image) appears to only have minor microcraking and carbonation of the cement matrix. No rust deposits were observed. (JMH 16, XPL, 100x magnification)

iv. Water Absorption

ASTM C97/C97M-15, *Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone*, is useful for indicating the differences in absorption between various stone materials; the variability in stone characteristics and quality is typically controlled by using as many samples as are necessary for determining gate range of properties. For the cement stucco, this means using multiple test samples in order to determine an average rate of absorption. Due to the limitations of available material, the dimensions recommended in ASTM C97/C97M-15 were not possible. Instead, the sample material was divided into 0.75 x 0.75 x 0.75 in. cubes using a RIGID 7 in. tile saw with a continuous-rim diamond blade.

The samples were conditioned prior to testing according to ASTM C97/C97M-15; the samples being dried for 48 hours in a ventilated oven at a temperature of 140 ± 4°F. At one hour intervals in the last three hours, the specimens were weighed to ensure stable weight. Prior to submersion, the samples were cooled in a room for 30 minutes and then weighed. The sixteen samples were divided into two groups based on the whether planes were plane (Group A) or intersected voids (Group B) *(Figure Div.1)*.[4] Following initial preparation, the samples were submersed in distilled water at 72 ±4°F *(Figure Div.2)*. The samples were then removed from the water bath at intervals, surface dried with a damp cloth, and each weighed. The absorption for each specimen was calculated as follows:

$$\text{Absorption (weight \%)} = [\ (B-A)/A] \times 100$$

where:
A = weight of the dried specimen, oz., and
B = weight of the specimen after immersion, oz.

These value are plotted according to time for each sample in *Figure D.iv.3*.

The percent porosity is calculated as follows:

$$\% \text{ Porosity} = (V_p / V_a) \text{ X } 100$$

V_p = volume of pores (cm³)
V_a = volume apparent (cm³).

[4] Presumably, cubes with planes that intersect existing voids could have a more accessible pore network.

These results are in *Figure Div.4.*

Ultimately, both Group A and Group B had similar results. The average water absorption for all samples was approximately 6% and the average percent porosity of the samples is 12.98% ± 1.47%. This figure is similar to results for commercially available building limestone (0.95 to 17%) and sandstone (1.9 to 22%), suggesting that the cement has a similar capacity to absorb water as stones deemed durable in exposure.[5]

Figure Div.1 Samples for water absorption testing, devided into Groups A and B based on the characteristics of the sample faces.

[5] D. W. Kessler and W. H. Sligh, "Physical Properties of the Principal Commercial Limestones Used for Building Construction in the United States.," Technological Papers of the Bureau of Standards (Washington: Government Printing Office, 1927), 519-520.

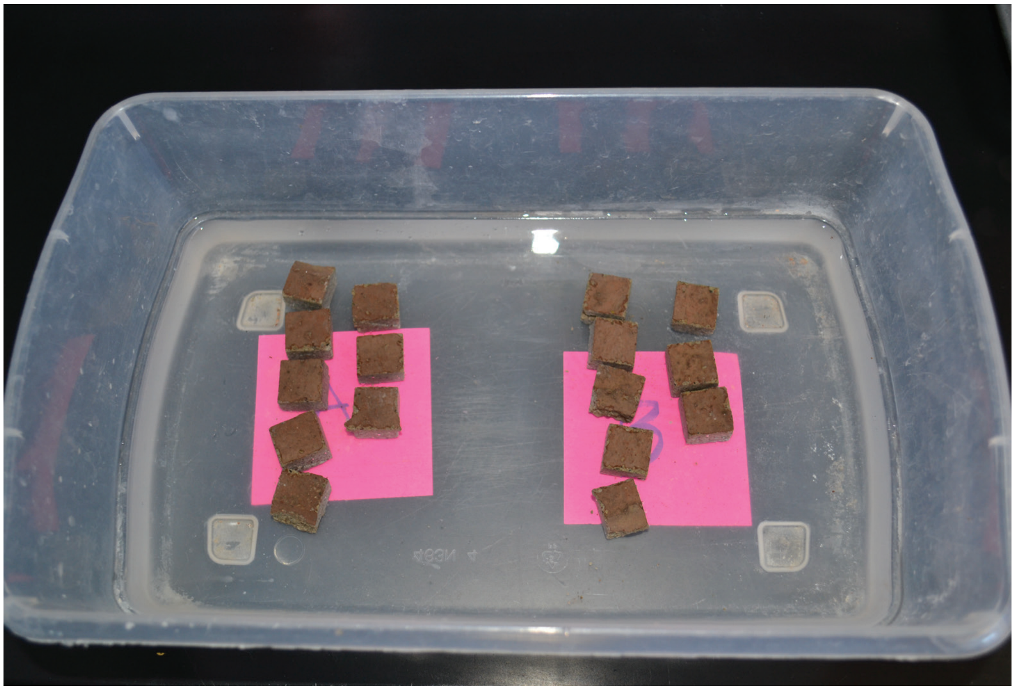


Figure Div.2 Sample Groups A and B submersed in water.

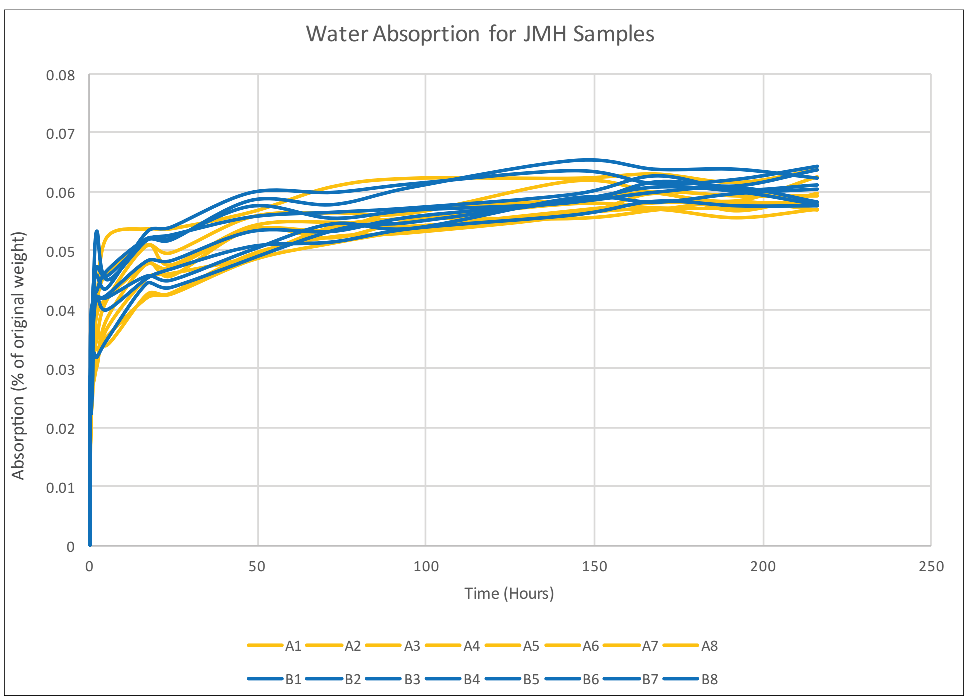


Figure Div.3. Water Absorption Rate for Samples. The rate of absoprtion did not differ between Group A (yellow) and Group B (blue).

Test Sample No.	M_0 (g)	M_s (g)	V_p (cm^3)	V_a (cm^3)	% Porosity
A1	13.99	14.88	0.89	7	12.71
A2	13.9	14.69	0.79	6	13.17
A3	13.78	14.58	0.8	6	13.33
A4	15.16	16.04	0.88	10	8.80
A5	14.74	15.66	0.92	8	11.50
A6	13.59	14.40	0.81	6	13.50
A7	13.86	14.68	0.82	6	13.67
A8	13.83	14.62	0.79	6	13.17
B1	13.51	14.38	0.87	6	14.50
B2	13.54	14.36	0.82	6	13.67
B3	13.33	14.16	0.83	6	13.83
B4	13.03	13.78	0.75	6	12.50
B5	12.03	12.73	0.7	6	11.67
B6	12.89	13.68	0.79	6	13.17
B7	14.59	15.52	0.93	6	15.50
B8	13.51	14.29	0.78	6	13.00

Figure Div.4. Percent Porosity for Water Absorption Samples.

v. Mechanical Testing

The methodology for this test is based on ASTM C580-02, *Standard Test Method for Flexural Strength and Modulus of Elasticity of Chemical-Resistant Mortars, Grouts, Monolithic Surfacings, and Polymer Concretes*, which specifies dimensions, method, and calculations for evaluating concrete mortars. However, because this specification is designed for samples that are formed rather than cut, reference to ASTM C 99M15, *Standard Test Method for Modulus of Rupture of Dimension Stone*, is useful in that it dictates that dictates the faces of each sample should be as near to plane as possible, and rough materials may be ground to a smooth finish to avoid point loading.[6]

The samples were cut into thirteen rectangular prisms measuring 6.0 in. x 1.0 in. x 11/16 in. ± 1/32 in. Each sample contained wire mesh, as demonstrated in cross section and one sample had a nail head and furring device.[7] Each sample received force tangential to the direction of the wire mesh and the stucco layers. An area of one square inch was leveled in the middle of the finished surface for each sample by passing the sample back and forth under the same continuous rim diamond blade *(Figure Dv.1)*.[8] The thickness for the sample population was 0.67 ± 0.07 in., based on one measurement taken at the center of the leveled area for each sample before testing.

An Instron 4206 testing machine at the Laboratory for Research on the Structure of Matter (LRSM) was used for three point bending tests. Specimens were placed flatwise on support blocks, spaced to a 4 in. span. The supports were then adjusted to ensure that length of the center loading nose was flush to the surface of the sample *(Figure Dv.2)*. Force was applied until the sample broke. The flexural strength of the material is equal to the stress calculated at maximum load, where

$$S = 3\,FL/2\,bd^2$$

where:

S = Stress in the specimen at midspan, psi

F = the maximum load at or prior to the moment of crack or break, lbf

[6] ASTM C580-02 also recommends that the underside of the samples are ground to plane to ensure that the sample is level when placed on the testing supports. This was not applied because the bottom of samples were nearly plane, and excessive grinding could potentially introduce micro cracks to the sample.
[7] The shank had been removed before shipment to Philadelphia by NPS staff.
[8] Variance from ASTM C580-02; grinding the entire surface was determined to not be desirable as the mechanical action and vibrations could have introduced micro cracks to the structure of the fabric, artificially reducing the strength of the material.

L = span, in.

b = width of the beam tested, in., and

d = depth of the beam tested, in.

With a couple of exceptions, the behavior of failure conformed to expectations for brittle materials *(Figure Dv.3)*. The Modulus of Rupture for samples tested varied widely; the average value was 1493.96 psi with a standard deviation of 376.83 psi *(Figure Dv.4)*. This figure is similar to the lower range obtained for architectural limestone and sandstone. The thickness of the sample had no discernible correlation to its modulus of rupture; it is possible that the adhesion of the cement matrix to the wire cloth within the sample contributes to strength of the material in bending.[9]

Figure Dv.1. The thirteen stucco prisms prepared for three point bending; one inch square was levelled in the center to prevent point loading. (Photo by author, 2018)

[9] Conversation with Dr. Alex Radin, of the Laboratory for Research on the Structure of Matter.

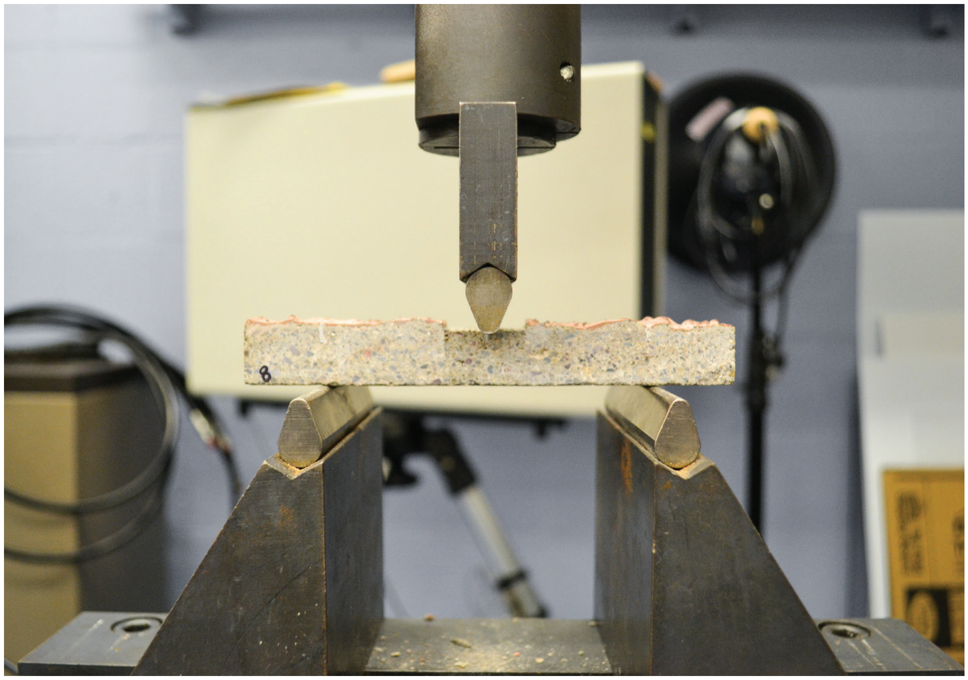


Figure Dv.2. Stress-Strain Curves derived from three point bending data. (Photo by author, 2018)

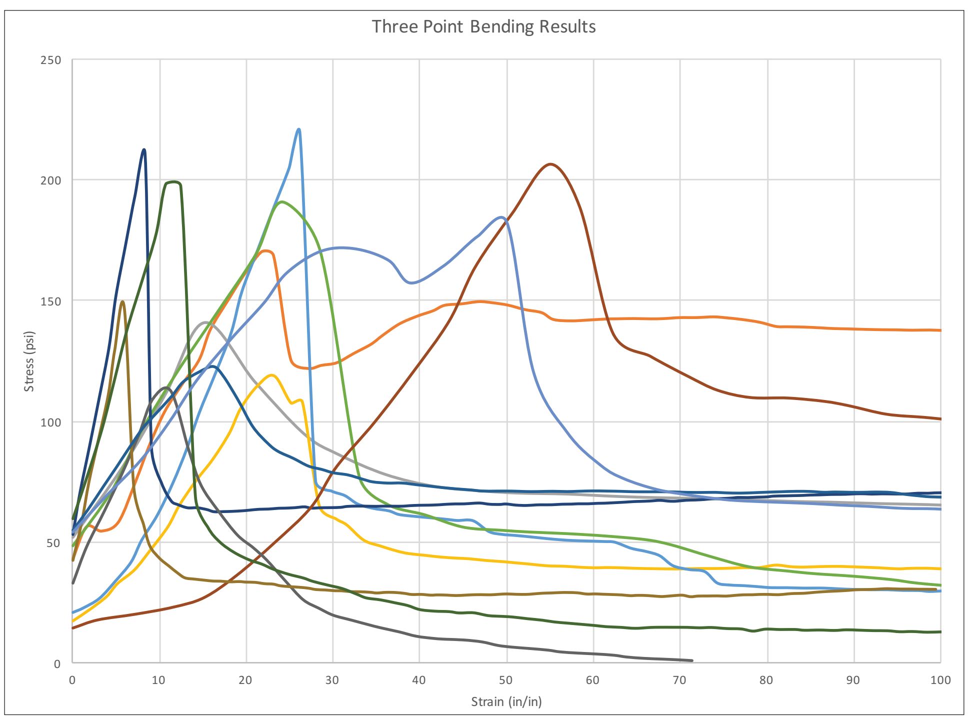


Figure Dv.3. Stress-Strain Curves derived from three point bending data.

Test Sample No.	Breaking Load (lbs)	Prism Dimensions	Modulus of Rupture (psi)
MT 1	N/A**	6 in. x 1 in. x 0.60 in.	N/A
MT 2	119.35	6 in. x 1 in. x 0.70 in.	1478.27
MT 3	101.31	6 in. x 1 in. x 0.72 in.	1189.03
MT 4	82.03	6 in. x 1 in. x 0.69 in.	1036.78
MT 5	149.04	6 in. x 1 in. x 0.68 in.	1919.78
MT 6	116.38	6 in. x 1 in. x 0.61 in.	1849.21
MT 7	126.18	6 in. x 1 in. x 0.60 in.	2078.68
MT 8	146.65	6 in. x 1 in. x 0.71 in.	1733.26
MT 9	78.89	6 in. x 1 in. x 0.70 in.	955.05
MT 10	104.51	6 in. x 1 in. x 0.71 in.	1254.50
MT 11	80.96	6 in. x 1 in. x 0.66 in.	1111.78
MT 12	138.95	6 in. x 1 in. x 0.70 in.	1703.86
MT 13	122.09	6 in. x 1 in. x 0.67 in.	1617.34

** MT 1 was subjected to a series of preliminary tests to calibrate the settings for the Instron. The results were abnormally low likely due to fatigue imposed by repeated force applied to the sample in these preliminary trials.

Figure Dv.4. Breaking Load and Modulus of Rupture for mechanical testing samples.

vi. Salt Testing

Salt efflorescence was not visible on the structure during field investigation, however photomicrographs of cross sections revealed large white minerals between the brown coat and finish layer in a number of instances *(Figure Dvi.1)*. For salt testing, a sample was submerged in deionized water and then the solution was tested to determine the presence of salt ions in the solution. Nitrite, chloride, and sulfate test strips were used because the potential source of the salt was unknown. A small sample was detached from JMH 17 with a hammer and chisel. The sample fragment was ground to a powder with a mortar and pestle to ensure that any salt content in a sample would be dissolved in the water.[10] The powdered sample was added to a glass beaker with 50 ml deionized water, and agitated with a magnetic stirring hotplate for five minutes *(Figure Dvi.2)*. Once the portion of powder appeared to be dissolved in the water, the strips were dipped into the solution and then left to dry. The strips indicate that the sample contains moderate amounts of nitrites (25 to 50 mg/L) and sulfates (1500 mg/L) *(Figure Dvi.3)*.

The presence of salt is worrisome, as the repeated crystallization and dissolution in the pores can cause cracking and spalling of the surfaces.[11] To approximate the risk that these materials pose in the cement, it is essential to determine whether the salt content is likely to increase or remain the same. The sulfate originates either from external or internal sources. Soil surveys in the area indicate that there is a low likelihood that components within the soil may contribute to electrochemical and physical deterioration of concrete; these are based on evaluations of sulfate and sodium content and acidity of the soil.[12] The primary internal source for sulfate is a high content of gypsum included in the initial portland cement mixture to deter early set. A second possibility is the mineral content of the water used to mix the concrete, likely from the Kelly Warm Spring via the Mormon Ditch. Further testing is required to identify the source of the sulfate.

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[10] It is preferable to grind the sample to a powder rather than submerge a solid volume with disconnected pores.

[11] David Odgers, ed., Concrete, vol. 8, Practical Building Conservation (London: English Heritage, 2012), 97.

[12] Web Soil Survey, https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx.

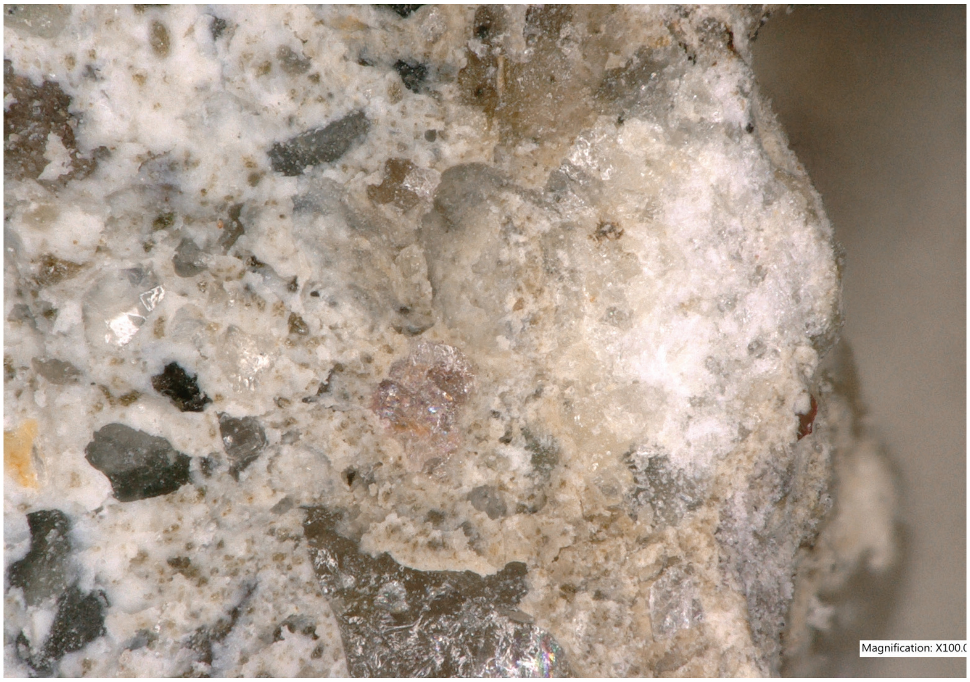

Figure Dvi.1 Photomicrograph of JMH 17 reveals white substance at the interface of the brown coat and finish coat. Magnification 100x (Photo by M.-C. Boileau, 2018)

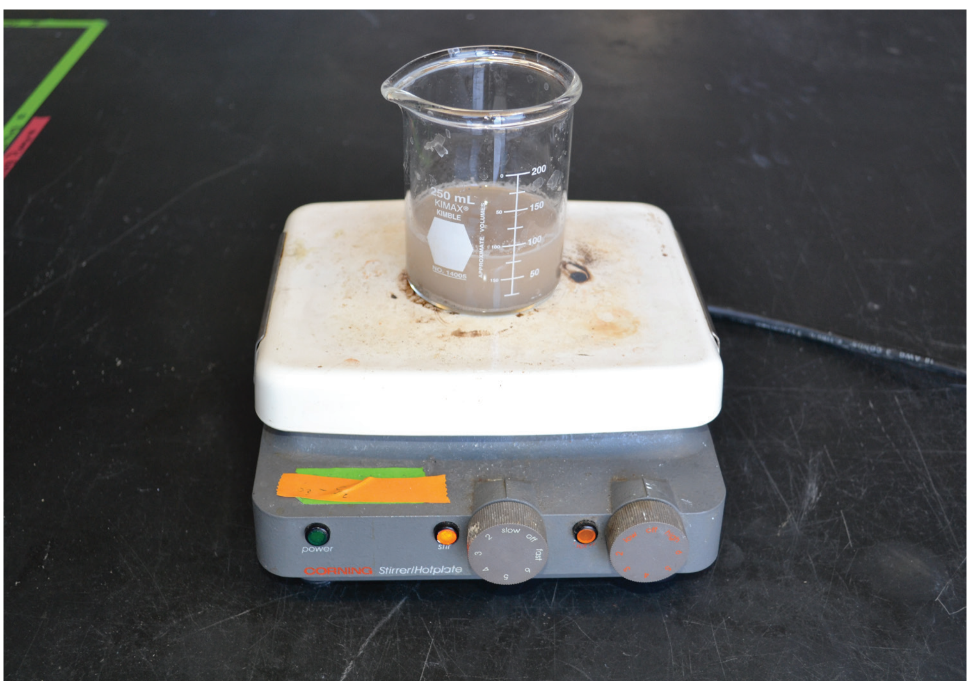

Figure Dvi.2 The powdered fraction was combined with deionized water using a magnetic stirrer hot plate (Photo by the author, 2018).

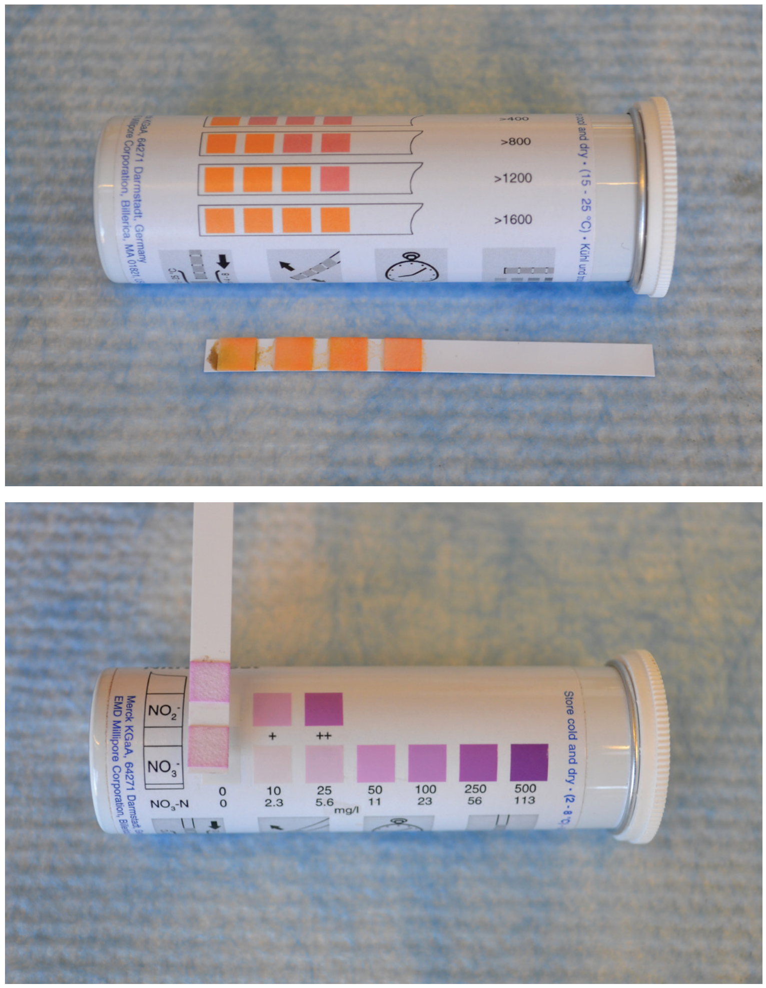

Figure Dvi.3 Test strips indicate that the sample contains both sulfates (top) and nitrates (below). (Photo by the author, 2018)

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