CHAPTER

14

A Geologic Assessment of Historic Saint Elizabeth of Hungary Church Using the Cultural Stone Stability Index, Denver, Colorado

Casey D. Allen[*], *Stacy Ester*[**], *Kaelin M. Groom*[†], *Roderick Schubert*[**], *Carolyn Hagele*[**], *Dana Olof*[**], *Melissa James*[**]

***The University of the West Indies, Cave Hill Campus, Barbados;**
****University of Colorado Denver, Denver, CO, United States; †Arizona State University,**
Tempe, AZ, United States

OUTLINE

Urban Geomorphology. http://dx.doi.org/10.1016/B978-0-12-811951-8.00014-X

14.1 INTRODUCTION AND BACKGROUND

This chapter outlines a recent technique for assessing the geologic stability of cultural stone (e.g., buildings, monuments, bridges) based on observable forms and processes found in rock/stone decay science (weathering[1]). While techniques exist across disciplines to assess building stone, most are costly, time-consuming, and require special expertise and training to execute (Bruthans et al., 2014; Fitzner et al., 1992, 1997; Giesen et al., 2013; Griffin et al., 1991; Groom, 2014; Janbade et al., 2016; Janvier-Badosa et al., 2016; Jo et al., 2012; McKinley et al., 2006; Paradise, 1999; Smith et al., 2013; Thornbush, 2012; Warke et al., 2003). Further, even though geomorphology (and by natural extension, stone decay) undoubtedly plays an important role (Pope et al., 2002), aside from Fitzner et al. (2002); Fitzner (2004); and Fitzner's and Heinrich's (2001) work that hyperfocuses on stone decay minutiae, requires (expensive) specialized equipment and testing procedures, and remains difficult to translate into common vernacular more useful for everyday analyses, these assessments pay scant attention to *specific* stone decay (weathering) forms and processes—or worse, misinterpret and/or misrepresent specific decay processes (Kurtz et al., 2001; Lee and Chun, 2013; Siedel and Siegesmund, 2014). Building on the successes of Cerveny's (2005) and Dorn et al.'s (2008) pioneering work on the Rock Art Stability Index (RASI), its subsequent successes (Allen, 2008; Allen et al., 2011; Allen and Groom, 2013a, b; Allen and Lukinbeal, 2011; Cerveny et al., 2016; Groom, 2016), and following in the steps of Groom's (2017) adaptation of RASI for assessing hewn monuments in Petra, Jordan, the case study presented here utilizes the Cultural Stone Stability Index (CSSI) to assess the geologic stability of a significant historic building on the Auraria Campus (Denver, Colorado, USA): Saint Elizabeth of Hungary Roman Catholic Church.

Beginning with a brief historical synopsis of the Auraria Campus, including the structure in question, a basic overview of the CSSI technique is offered before expounding on findings that assess the geologic stability of Saint Elizabeth's, offering particular insight into major and minor stone decay forms and processes contributing to its deterioration. This section is offered in "technical report" style, giving the reader a feel for how the CSSI may be used in professional settings. The chapter concludes by noting some implications surrounding CSSI analyses, including perceived shortcomings, transferability across rock types and architectural styles, and other potential uses.

14.1.1 Auraria Campus

In the winter 1959 issue of the *Georgia Review*, Meaders (1959) wrote:

> In a manner of speaking, the godmother of Denver and Colorado, now celebrating their centennial year, was a Georgia lady and my wet nurse. My earliest memories of Auraria, Georgia, (for which the first white settlement in Colorado was named) are associated with a great consuming thirst, quenchable only by frequent draughts of water drunk from a gourd dipped into the only old oaken, moss-covered bucket in my experience and drawn by benefit of a creaking, groaning windlass from the far and icy depths of a North Georgia well (p. 406).

---

[1] Like Hall et al. (2012); Dorn et al. (2013); and others, we subscribe to the use of rock or stone decay in lieu of "weathering." Stone deterioration or rock deterioration are also acceptable. These terms more accurately reflect the breakdown of rock; and dispel the common weather-is-responsible-for-rock-breakdown misperception.

More than 40 years after her departure from Georgia to New Mexico, Meaders provides an apt starting point to introduce Colorado's Auraria. Settlement started in the waning quarter of 1858, after placer gold deposits were discovered in Cherry Creek, and a mining camp named Auraria was founded on its shores. Initially, three sites were originally plotted based on the gold's location: Auraria, Denver City, and Highlands (Fig. 14.1). After much protest and some financially driven campaigns, Auraria residents voted to merge with Denver City in April 1860.

At present, the Auraria space is a higher education center that provides an environment nurturing the human intellect—a space to slake a thirst for knowing through academic support, sustenance, and mental invigoration. Auraria's name belies its roots in the Latin signifier for gold, *aurum*. It seems even in the present-day, the notion of finding your dreams—that most personal gold—and then bringing the evasive glints to a knowable shimmering reality remains prevalent.

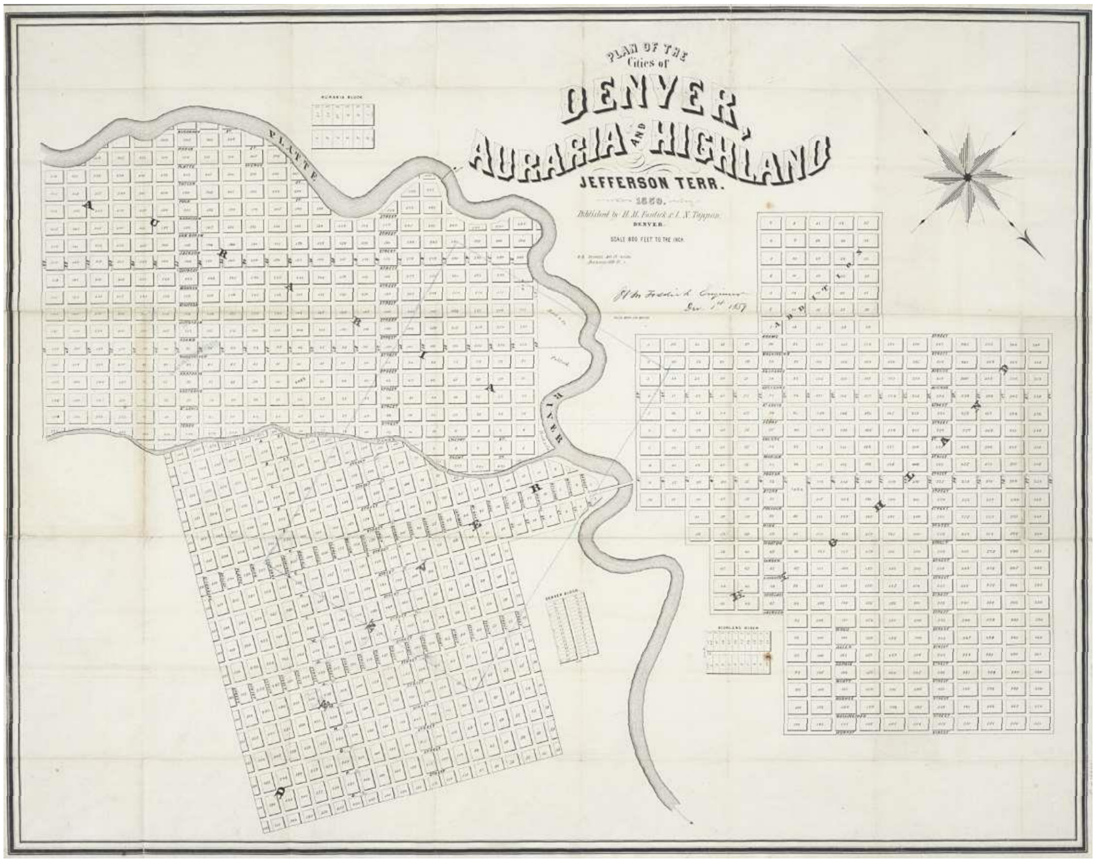

FIGURE 14.1 **Map of Denver, Auraria, and the "Highlands" in 1859 by H.M. Fosdick.** Highlands is to the right of the (large) Platte River, with Auraria (top-left), and Denver (angled, bottom-left), divided by Cherry Creek, where gold was first discovered in Colorado. *Source: Denver Public Library.*

By the mid-1920s, Auraria had become both a manufacturing area and distribution hub in addition to a growing Hispanic population, becoming a thriving walking-type of urban area, where shops, housing, manufacturing spaces, and warehouses all shared space and place (Page and Ross, 2015). Once America's Great Depression hit in the early 20th century, however, fortunes changed dramatically. For more than a quarter century after the Great Depression, Auraria saw an ensuing shift to other manufacturing and large warehousing areas specifically, leading to Auraria's decline and public perception of a blighted and shabby urban area (Page and Ross, 2015, 2016).

Beginning with the creation of Metropolitan State College of Denver in 1963, and the subsequent expansion of the University of Colorado's Denver Extension Center into an independent campus, the Denver Urban Renewal Authority and State of Colorado's Commission on Higher Education joined forces to find a suitable location for a center of higher education to serve the burgeoning downtown. In 1969, $12.6 million were provided by the US Department of Housing and Urban Development for purchase of the 169-acre Auraria urban renewal project. The result of this effort, the Auraria Higher Education Center, now hosts three distinct institutions of higher education, each serving a specific purpose: the Community College of Denver (offering 2-year degrees), Metropolitan State University of Denver (offering degrees at the baccalaureate level as well as a few professional Master's degrees), and University of Colorado Denver (a Tier I Carnegie Research Institution offering degrees at all levels). Together, these three campuses serve more than 50 000 students during any given semester and consist of the most diverse student body of any other higher education institution in the state (Page and Ross, 2015, 2016).

Today, like many campuses around the US, the Auraria Campus seems perpetually under construction, with seemingly a new building or remodeling project completed every year. Yet, the present campus configuration is the result of many design and urban planning ideas, with the final choice preserving a few extant and historical structures (Page and Ross, 2015, 2016). A few legacy structures remain, including the desanctified Saint Cajetan's Church and an unnamed rammed earthen sculpture as well as the structure assessed in this chapter: Saint Elizabeth of Hungary's Roman Catholic Church.

14.1.2 Saint Elizabeth's

By 1870, Denver's German immigrant population had grown to sufficient size to warrant a petition for a priest to address its community needs. The region's leadership, led by Bishop Machebeuf, established Denver's second parish in 1878 to serve the Auraria and southwest Denver area neighborhoods and a modest church of brick construction was erected. In 1887, "two Franciscans, Francis Koch, O.F.M. (order of Friars Minor) and Venatius Eder, OFM" responded to Machebeuf's additional request "to found a Franciscan House at Saint Elizabeth's." This was followed in 1890 by the building of a "two-story brick school" and, 1 year later, a rectory (Saint Elizabeth Church, 2017).

During the 19th century's last quarter, Saint Elizabeth's became "the German national church" and spiritual home for all of Denver (Noel and Wharton, 2016). The initial church soon became overcrowded, however, to the point that the old building was razed in 1898 to allow for the construction of the present Saint Elizabeth's structure (Noel and Wharton, 2016). A German Franciscan, Brother Adrian, had been assigned to the Parish and assisted the present structure's architect with the church's design. This new structure follows the Romanesque Revival style, and used locally sourced "rough-cut Castle Rock rhyolite..." with "...a dominant single corner spire soaring 162 ft...." (Noel and Wharton, 2016, p. 127). In 1936, a curved arcade, fountain, and friary were added. Included in the design by Jules Jacques Benoit Benedict was a private chapel and library, which retained "samples of the German stained glass and ornate woodwork gone from the modernized church sanctuary," and constructed through the beneficence of the May Bonfils Trust (Noel and Wharton, 2016, p. 127).

At present Saint Elizabeth's maintains its long tradition of direct community service "for the poor and hungry," which started with collections from grammar school children in 1890, who collected food and money for their community and its needy. In late 1907, Father Leo Heinrichs, OFM, extended this to providing daily sustenance each morning. Starting in the late 1970s, the pastor at that time reinvigorated this "tradition of feeding the hungry by organizing a bologna sandwich breadline behind the [C]hurch" (Saint Elizabeth Church, 2017). This continues at present 7-days-a-week from 11:00 a.m. until noon.

The structure, as it stands today, was consecrated as a sacred space on June 8, 1902, by Bishop Matz. Saint Elizabeth's Franciscans and generous German Catholics helped this community become the first in Colorado to be debt-free (Saint Elizabeth Church, 2017). In 1973, Saint Elizabeth's was added to the National Register of Historic Places. Today, due to a shortage of priests, Saint Elizabeth's serves as a mission church for the Denver Roman Catholic Cathedral, with Masses held daily and Sunday mornings.

14.2 METHODS: BASICS OF THE CULTURAL STONE STABILITY INDEX

Rock decay remains universal, as a finite number of processes yield a finite number of forms, regardless of the rock's creation, composition, structure, or use. A straightforward scientific index that efficiently assesses rock decay then, such as the RASI (Dorn et al., 2008), serves as a valuable analytical tool. Accounting for more than three-dozen forms of rock decay spread across six overarching categories, with only a few changes in terminology to reflect architecture vernacular, RASI can be adapted to a cultural/worked stone context, allowing for assessment of any stone type: bridges, sculptures, headstones, building stone, and others (Groom, 2017). When performing RASI, the trained researcher makes a quick drawing and takes a photograph of the facade (panel) to be assessed and then ranks each of the rock decay parameter on a scale of 0–3. The ratings for each element are then tallied and doubled, resulting in a final score for the facade in question with the risk for deterioration increasing with score (Table 14.1).

While the overall score remains useful for gaining a snapshot of general decay danger, each element can also be individually assessed by the site manager for its degree of decay contribution. For example, if a particular pillar or column has experienced severe deterioration, but the adjacent pillars remain in "good condition," the site steward can make an informed recommendation regarding repairs for one pillar, instead of spending unnecessary time and money on stone that does not need any maintenance. Like its cousin RASI, the CSSI was devised as an easily accessible tool for nonrock decay specialists to quickly assess stone architectural and monument features that may be geologically at risk, using nothing more

TABLE 14.1 The CSSI Scoring System with Accompanying Qualitative Interpretation

CSSI score range	Score interpretation
<20	Excellent condition
20–29	Good condition
30–39	Problems that could cause erosion
40–49	Urgent possibility of erosion
50–59	Great danger of erosion
60 and above	Severe danger of erosion

In reports, scoring ranges are often color-coded: from green (most stable, lowest CSSI score, and lowest decay risk) to yellow, orange, light red, and dark red (least stable, highest CSSI score, and highest decay risk), giving a qualitative value to the quantitatively-derived score. Panels assessed for this study follow this color-coding scheme to demonstrate its applicability for site managers.

than a writing utensil, paper, camera, and time. The CSSI is used in much the same manner as RASI and has been since before its inception (Groom, 2011).

As Groom (2017) noted, terminological changes in the CSSI from RASI do not include any additional rock decay processes as a general rule, but instead serve to widen the index's range to include cultural/worked stone. Specifically, Groom (2017, pp. 129-130) suggested that RASI's "Rock Coatings" category be modified "... due to the different roles of rock coatings between rock art and other cultural stone" because, as also noted by Dorn (1998), often rock coatings on rock art panels are beneficial, enhancing the rock art's stability. Groom (2017, pp. 129-130) explained that:

> Most petroglyphs, for example, are created by pecking or scraping through rock coatings to reveal the raw stone beneath the surface (Whitley, 2005). The contrast between the coated exterior and newly-exposed interior makes the art possible. Therefore, in RASI, two of the four rock coating elements have negative scores—indicating them as stabilizing agents. Alternatively, stone building [facades] and most other cultural stone are created with freshly quarried material, so any rock coating accumulation takes place after the stones are already in situ and beginning to decay. Also, since historic buildings and cultural stone often exist within cities and populated areas, as compared to the relative isolation of rock art sites, they may experience higher exposure to air pollution and urban traffic exhaust, leading to the development of harmful toxic rock coatings.

Because of the perceived need to include pollution and other factors that can negatively influence rock stability in urban settings (Inkpen et al., 2012a, b; Thornbush, 2012; Warke et al., 2003), the CSSI also, for example, has researchers rank the host stone's "carbonate coating" and "oxidation" with positive (i.e., detrimental) scores. Such additional inclusions do not affect the reliability or validity of the index, but serve to increase its applicability (Groom, 2017).

The point behind assessment tools like RASI and CSSI rests in their field-based, rapid, noninvasive, and cost-effective nature. They also promote flexibility in both scale (i.e., size and number of "panels" to assess) and personnel (i.e., nonspecialists can be trained quickly). Specifically, in this instance, a cadre of five researchers were trained in the CSSI following previously established protocols for RASI (Allen, 2008; Allen and Lukinbeal, 2011; Dorn et al., 2008), and assessed Saint Elizabeth of Hungary Roman Catholic Church located on the Auraria Campus in downtown Denver (USA). Following Groom's (2017) lead for hewn monuments, each edifice was divided into "panels" for ease of assessment. While each researcher was assigned a particular set of panels to assess, analysis of each panel as well as the overall structure was completed as a group. While CSSI has been used for years informally, this study marks just the second time it has been put into practical use, yielding the first geologic stability assessment of a historic building *in an urban setting*.

14.3 SAINT ELIZABETH'S CSSI ANALYSIS

Given the church's size, smaller sections based on the edifice's architecture were selected for analyses, following Groom's (2017) work. Saint Elizabeth's, like many churches, was built in relation to the Cardinal directions. For assessment ease (after Groom, 2017), panels were numbered according to their aspect (i.e., north, south, east, or west), and selected based on their architectural features. This resulted in 42 separate panels: 14 for the north aspect, three for the south aspect, 16 for the east aspect, and 9 for the west aspect.

Overall, and at first glance, the church presumably looks just like it did more than 100 years ago when construction was completed (Fig. 14.2). Closer inspection by a more trained eye, however, reveals several rock decay forms contributing to its overall deterioration. Although the entire edifice earned a CSSI rating of 26 (a "Good" status, average of 42 panels), some panels revealed very specific decay features, which should warrant a conservator's or site steward's attention. Although the building stone may be rough-hewn in appearance and contains small natural tafoni consistent with the Castle Rock rhyolite's explosive genesis, it has been expertly masoned and dressed. The church personnel do appear, however, to be doing a reasonably diligent job of monitoring the main decay and erosional concerns. Still, as newer cleaning techniques become available and parish funds permit, they would be a worthwhile investment for the building's maintenance. The following subsections offer a detailed analysis of each facade, highlighting potential weaknesses that could eventually lead to extreme degradation if left unaddressed.

14.3.1 North-facing Panels

With an average score of 26 (14 panels total), the north face of Saint Elizabeth's remains in "Good condition" (Fig. 14.3). The most dominant decay features are a combination of tafoni, flaking, and crumbly disintegration, which pervade the surfaces of both the stairs and the facades. Other notable decay features on the church's facades include oxidation, pollution, and a few small scaling (spalling) events. Still, most concerns with the north-facing facade remain relegated to the bottom couple of meters, with a few specific outliers. The single set of stairs on this aspect (N1), for example, show significantly more signs of decay than the rest of the church facade, including serious decay between mortar joints, resulting in 1–3 cm gaps between many of the stairs (Fig. 14.4).

Panel N1 (the stairs) also has obvious past and impending splintering, which contributed to large scaling events on the tops of several steps. These problems are likely exacerbated because of the difference in building materials: the main walls of the church are Castle Rock rhyolite and the stairs are sandstone.

FIGURE 14.2 **Saint Elizabeth of Hungary Roman Catholic Church as viewed from the southeast corner (looking northwest) showing the church's south-facing side and front entryway (east-facing, with the white statue, center).** While the overall building is structurally sound, decay processes are occurring on all four sides.

From afar, N9 (Fig. 14.5) clearly displays a darker color relative to the adjacent panels, as it did not receive recent cleaning like the other panels. The west-face of N10's column also hosts a pair of long, darkly colored vertical stripes, which appear to be an imprint left by a previously attached conduit of some sort (Fig. 14.6). Perhaps the conduit was attached during a cleaning event and later removed to reveal a stripe of darkened stone. Most concerning on N10, however, is that each base of its two columns show signs of potential future loss with precarious fissures at the corners adjacent to other panels, with N9 displaying the same feature. Other significant fissures stem from the vent openings at the bases of N9 and N11

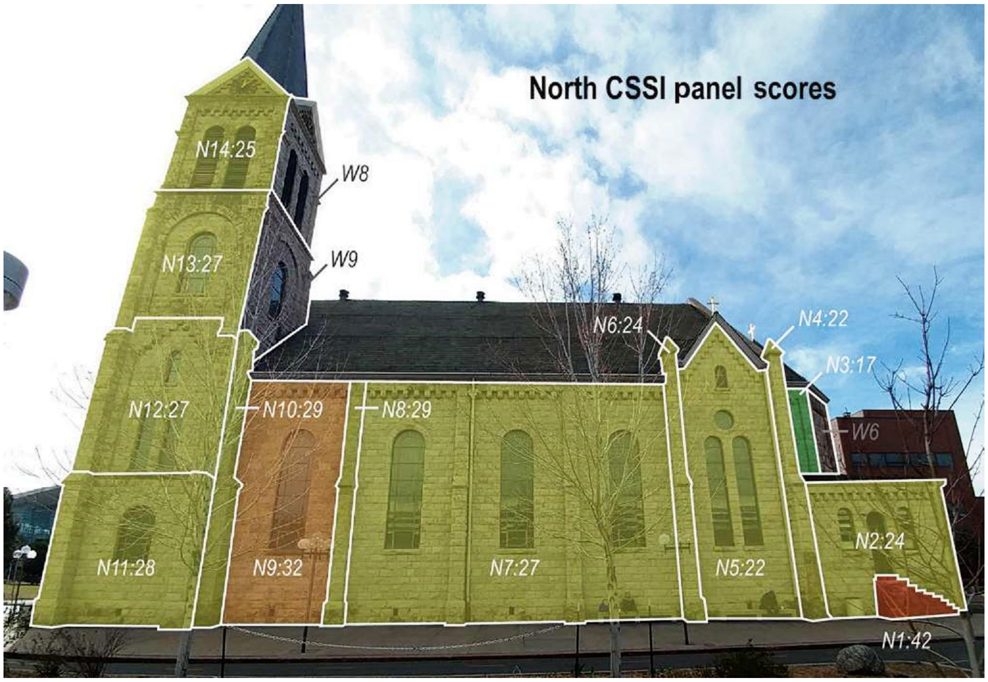

FIGURE 14.3 **The north-facing facade of Saint Elizabeth.** Most of the aspects retain "Good condition" (*yellow color*) as measured by the CSSI, but several panels exhibit specific decay processes that have already occurred or will occur in the near future, especially N1 and N9.

FIGURE 14.4 **Panel N1, covered with a heavy (anthropogenic) coating.** Notice also the missing mortarwork above the vent, creating a gaping fissure as well as other multiple cracks in the mortar.

FIGURE 14.5 **Not cleaned like its neighboring panels, N9 hosts a much darker color (rock coating).** Most rock coatings enhance stability (Dorn, 1998) and removing them improperly can be detrimental to the host stone, opening the door for fiercer decay processes.

(Fig. 14.7) and flaking events having already occurred on the underside of N11's window arch (Fig. 14.8).

While seemingly stable overall, the north-facing facades also exhibit continuing decay forces that require constant attention and maintenance vigilance. Fissures in the sidewalk-level stones remain most apparent and offer great potential for exacerbated decay. Indeed, especially during the colder months, when deicing chemicals are used, the rock's internal individual structural integrity can be altered, increasing decay potential. Also of concern is the weakening of internal stone structure through the entry of moisture and Colorado's rapid freeze/thaw cycles. Further, while the north facade does not appear to be load-bearing, its

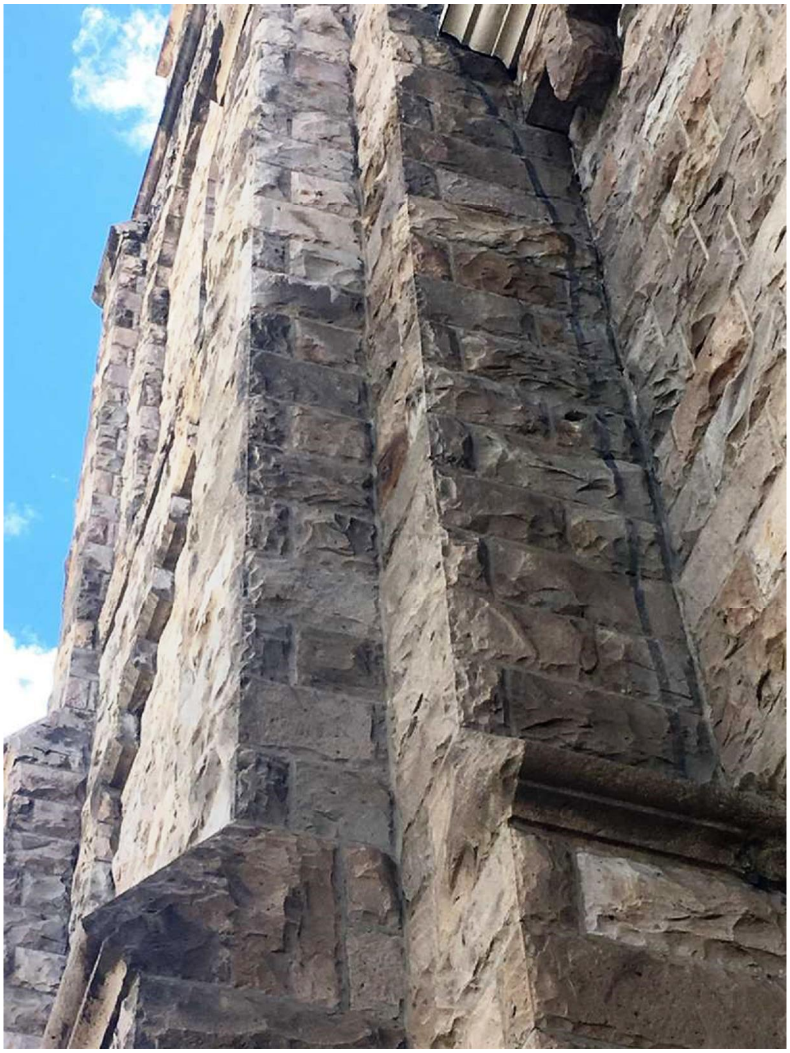

FIGURE 14.6 **Dark-color vertical stripes on the side of N10, perhaps from old piping.** Notice the difference in coloration between the portion of N10 that hosts the stripes and that to its immediate left. The left-side portion of N10 has been recently cleaned.

lowest level stones do bear the weight of above stones and this could be a contributing factor to the multiple column fissures.

14.3.2 East-facing Panels

While mostly stable with an overall score of 25 (Fig. 14.9), three "panels" on the east-facing facade scored particularly high: E5, E7, and E8, with average scores of 46, 49, and 52,

FIGURE 14.7 **An example of fissures around air vents. In this example from N11, fissures around the vent are visible.** Note also the scaling event—a small chunk of rock missing in the middle of a fissure independent of lithification on the stone to the left of the vent's grate.

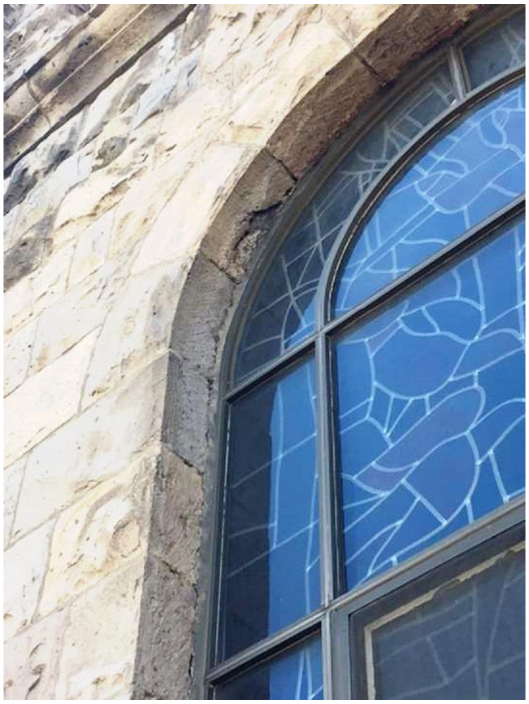

FIGURE 14.8 **Flaking events already occurred and impending around N11's arched window.** Similar forms were also observed on the upper windows of N12 and N13.

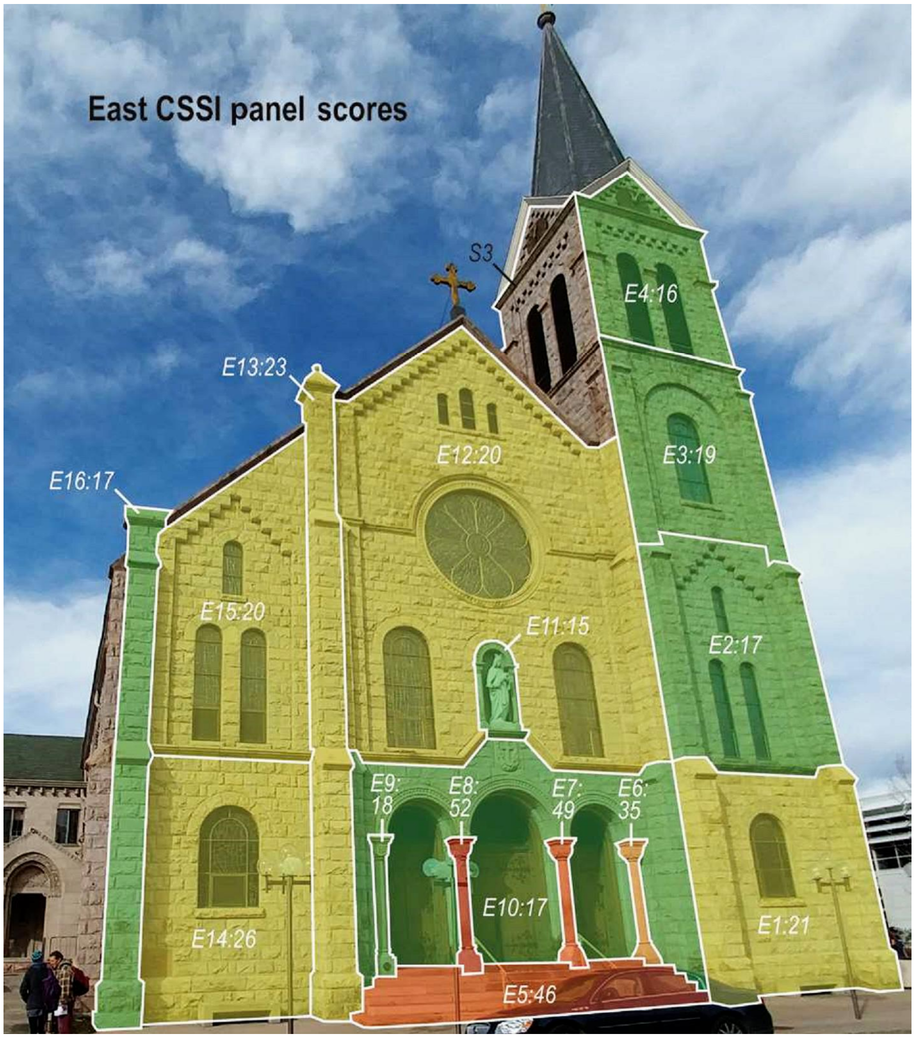

FIGURE 14.9 **Saint Elizabeth's east-facing facade.** Earning an overall score of 25 ("Good condition" status), the east facade has some looming problems that, if not addressed promptly, may result in large stone loss and the need for very costly repairs. In particular, E5, E7, and E8 remain at high risk, especially E7 and E8—the highest scoring panels on the entire structure and in "Urgent danger of erosion," specifically, at their bases (compare with Figs 14.13–14.16).

respectively, earning a ranking of "Urgent possibility of erosion" (E5 and E7) and "Great danger of erosion" (E8).

These three "panels"—stairs (E5, Fig. 14.10) and two main columns on either side of the main doors (E7 and E8) that comprise Saint Elizabeth's main parishioner entryway—host the bulk of decay concerns. This is perhaps no surprise, as Saint Elizabeth's holds regular Mass.

Still, decay on the stairs and columns show significantly more signs of deterioration than the rest of the church's east-facing facade. Differing rock type may also play a role in the

FIGURE 14.10 **The stairs of Saint Elizabeth's main entryway on the east-facing facade.** As Saint Elizabeth is still a functioning church, it is no surprise that these stairs remain in "Urgent danger of erosion." Specifically, notice the impending splintering of individual stairs and loose/cracked mortar, similar to N1 (compare Figs 14.4 and 14.5).

entryway's decay because the stairs (E5) are comprised of the same weakened sandstone as N1 and the columns (E7 and E8) were hewn from Pikes Peak granite, but never "polished" (Fig. 14.11A), and the columns' bases were originally Castle Rock rhyolite, but deteriorated portions have been replaced with concrete fashioned to look like the original stone (Fig. 14.11B). This mismatching of stone type, although perhaps aesthetically and architecturally pleasing, leaves inherent weaknesses exposed, especially at the bases of the columns where different rock types are in contact with each other, promoting strong differential decay.

For example, where different rock types come into contact with each other, such as column bases and capitals, erosion of the stones has necessitated the use of concrete repairs to create and in some instances replace the original carved stone surfaces (Fig. 14.11). These repairs have bonded with mixed results to the underlying Castle Rock rhyolite. While newer additions, they still exhibit significant surface decay and decomposition, most likely due to the use of pavement-clearing salts during winter months. The newer encasements may protect at first, but they also allow the decay agents to collect on the Castle Rock rhyolite surfaces, since the bond between underlying stone and repaired surface remains less than absolute. Additionally, Denver's extreme seasonal climate shifts, especially in terms of precipitation fluctuation and rapid temperature changes, create cyclical conditions that are challenging for any building material, but perhaps more so for rough-hewn and nonpolished rock joined together with a coarse-grained mortar and concrete.

Small future scaling (spalling) on the base of E9 (a column) was also observed; and the main entrance hosts many fissures at each base (Fig. 14.12). This is a high-traffic area with continual use of the stairs, and stair-railing installation sites also seem to be contributing to

FIGURE 14.11 (A) Flaking of E7 (the column) accompanied by crumbly and granular disintegration. Note the small pieces of granite strewn across the steps at the column's base. The columns, while made of usually strong Pikes Peak granite, have only been smoothed, not polished or veneered, leaving them exposed to the elements. Indeed, the rock's matrix has been weakened so much that even someone casually leaning against this column exacerbates the crumbly and granular disintegration process. Notice also the fissure at the stair railing's base (bottom-center of image), perhaps brought on by the rail's oxidation, extending into the mortar of the steps (E5). (B) Examples of scaling, flaking, crumbly disintegration, and granular disintegration around E8. The lighter-colored stone is concrete, poured and sculpted to fit the original column base specifications. The replaced concrete area includes faux-tafoni as part of the stone dressing in an attempt to generate the same "feel" of Castle Rock rhyolite.

oxidation and fissures, which may eventually lead to larger events than crumbly and granular disintegration, ultimately compromising the railings as well as the staircase itself (Fig. 14.11). Additionally, the stones closest to the ground (within ~2 m of the ground), show more signs of decay than upper areas, with the stairs showing serious decay in their mortar work as well as splintering.

Higher up, as well as away from the entryway, most panels remain in "Good" or "Excellent" condition. Some fissures independent of stone lithification, such as the ledge over the main entrance remain present (Fig. 14.13), but with that exception and window cavities (Fig. 14.8), the upper and side panels of the east aspect remain considerably more stable than those near to the ground and around the entryway.

Of particular note on the church's east-facing aspect, is the statue of Saint Elizabeth herself. For the CSSI assessment, this beautifully carved statue (and its accompanying alcove) was given its own panel number (E11) due to the cultural significance. Although this statue (and her alcove)

FIGURE 14.12 **An example of fissures independent of stone lithification around column bases.** This particular fissure (with a pencil for scale) occurs on E8. Just to the right of the pencil is a very light discoloration (*the white areas*) where salt efflorescence and subflorescense is occurring. Often occurring through capillary action, efflorescence, and subfloresence exert pressure on pore spaces, exacerbating interior vulnerabilities of the rock.

earned a low CSSI score, there are still concerns about the amount of basal flaking, discoloration (possibly due to oxidation) around her wreath, and a missing pendant from her crown (Fig. 14.14). Still, for a century-old painted concrete statue, the condition remains remarkable.

In all, while the immediate east-facing facade appears stable, any impending losses around the main entrance must be taken seriously. For example, the most dominant decay features—a combination of tafoni, flaking, crumbly and granular disintegration, and (impending) fissures—pervade the surfaces of both the stairs and the facades. Other minor, but notable, decay features include missing and disintegrated mortar, oxidation, pollution (especially

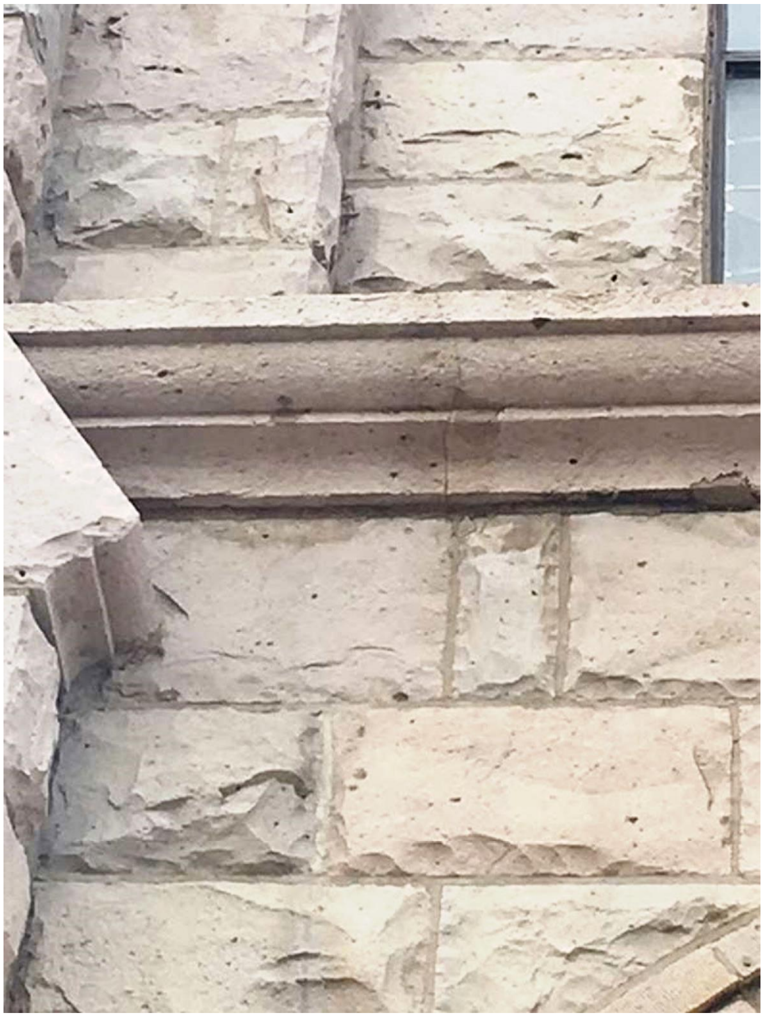

FIGURE 14.13 **Fissure independent of lithification extending through a ledge on E10.** Left untreated, this fissure will only widen, leading to (small) flaking and subsequent scaling. This ledge also exhibits flaking (right-center and far-right-center).

near the facade's base), and some small scaling (both impending and already occurred) as well as flaking (impending and already occurred) and anthropogenic coatings (most likely pollution) at higher levels.

14.3.3 South-facing Panels

Of the four aspects, the south-facing scored the lowest CSSI rating (23, Fig. 14.15). This may be due to the aspect itself, where continual sun, even during the winter months, serves as a buffer in keeping away snow and ice better than the other, nonsun-facing aspects.

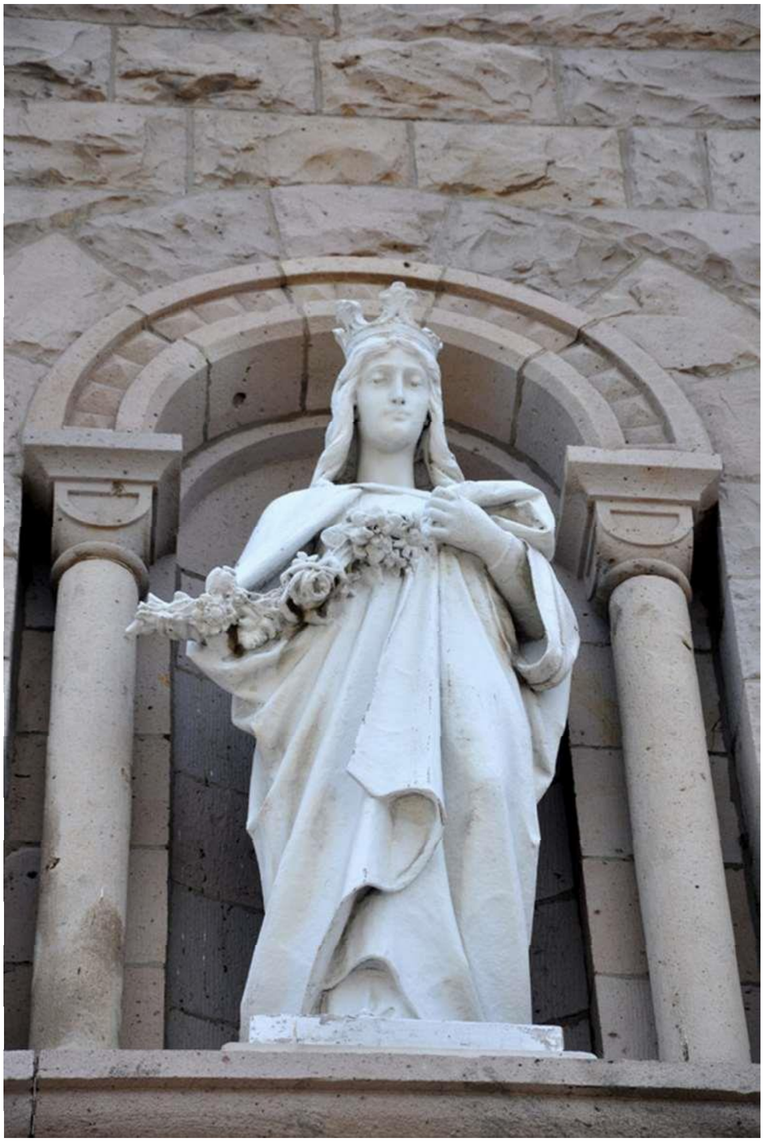

FIGURE 14.14 **The statue of Saint Elizabeth adorning the alcove above the church's main entrance.** This statue, now over 100 years old, is made of what appears to be concrete (no reference could be found of any records on its creation, even after questioning church personnel, other than its relative age), and is regularly painted to keep its brilliant white color. A close examination via telephoto lens reveals paint chipping off the sculpture, especially around its base. Notice also the missing crown prong.

As with other facades, however, minor areas of decay remain, such as tafoni, flaking, and granular and crumbly disintegration. Darkened spots of discoloration, likely the result of pollution, also span the south-facing facade, and in some areas the (likely protective, Dorn, 1998) coating has been removed. Small plants also line the base of S1, but do not pose any immediate decay threat.

FIGURE 14.15 **Saint Elizabeth's south-facing facade, displaying "Excellent" and "Good" CSSI scores.** While very stable overall, the church's south aspect did have a few minor concerns, such as fissures, flaking on the underside of window arches, and very small plant growth at the facade's base.

Similar to other facades on adjoining aspects, mortar separation—including whole chunks of missing mortar—remains a key deterioration factor on the south-facing facade. Indeed, the separating and missing mortar in doorway and window cavities on this side of the church appear to be worse than other facades, especially as they occur on several archways. The most conspicuous of these on panel S1, is a vertical fissure extending (upward) from the easternmost window arch's keystone along the mortar line of four separate stone layers (Fig. 14.16). A similar event has occurred adjacent to S1's window (Fig. 14.17).

Panel S2 is well-protected by a semicircular exterior hallway structure, so the base was inaccessible, but there was little evidence of the same mortar separating/disappearing as on panel S1. Panel S3 was difficult to assess from the ground and required use of high-magnification binoculars to assess. Still, similar to S2, no mortar separation/disappearing

FIGURE 14.16 **Beginning at the top of S2's highest window and extending across four bricks, missing mortar creates a gap in the masonry.** The open space increases the probability of fissure formation and its resultant flaking and scaling events. This area remains perhaps the most at-risk section of S1.

was observed, although a rock coating was present on some of the decoration, likely from pollution. Additionally, unlike the other three sides of the church, some stones during the earlier morning hours exude condensate (i.e., appear moist to the eye and damp to the touch) that, when coinciding with the inherent tafoni in Castle Rock rhyolite, could prove to be a future decay culprit, especially during winter months when temperatures can range from below freezing to well above freezing in a given 24-h period. While a few minor problems exist, overall, the south-facing aspect appears to be in very stable condition, aligning with the CSSI's "Good condition" status.

14.3.4 West-facing Panels

While earning a "Good condition" score of 28, the west facade still exhibits minor decay concerns (Fig. 14.18). The most obvious and contributing factor to the west facade's deterioration rests in its location, next to a high-traffic and delivery road even though it remains a bit more secluded than the other facades at first glance. This leads to the main overarching

FIGURE 14.17 **Creating similar conditions as seen on the underside of other window arches (compare Figs 14.10 and 14.17), the missing mortar along S1's window edge will ultimately lead to flaking and scaling events if left untreated.** Specifically, note the large crack between the stone of the arch and the windowpane, extending from the old mortar work (bottom-center) all the way to the beginning of the curve of the archway.

decay-contributing factor: constant vehicular interaction. As west panels remain adjacent to a frequently used road, pollution becomes a major issue, and a dark coating up to 1-m high from the base is present all along the west facade (Fig. 14.19). The presence of asphalt, and its subsequent need to be repaired regularly in the sometimes-extreme Colorado climate, may also affect the future stability of the stone as it abuts against the panels' bases.

As with other panels' aspects, mortar cracking also remains an issue, but here, owing to the more secluded location, garbage (e.g., cigarette butts) is often stuffed into the Castle Rock rhyolite's inherent tafoni by passersby. Another minor decay feature that affects the west facade are fissures independent of stone lithification, resulting in future flaking and scaling events like those found on other facades around the church.

14.3.5 Overall Assessment

From a rock-decay perspective, although small problems potentially affecting the building stones' future do exist, each facade appears to be overall stable. Judging from the building size and pervasive use of mortar for sealing the space between stones and repairing broken/missing pieces of decorative and dressed stone, the parish community most likely engages in significant

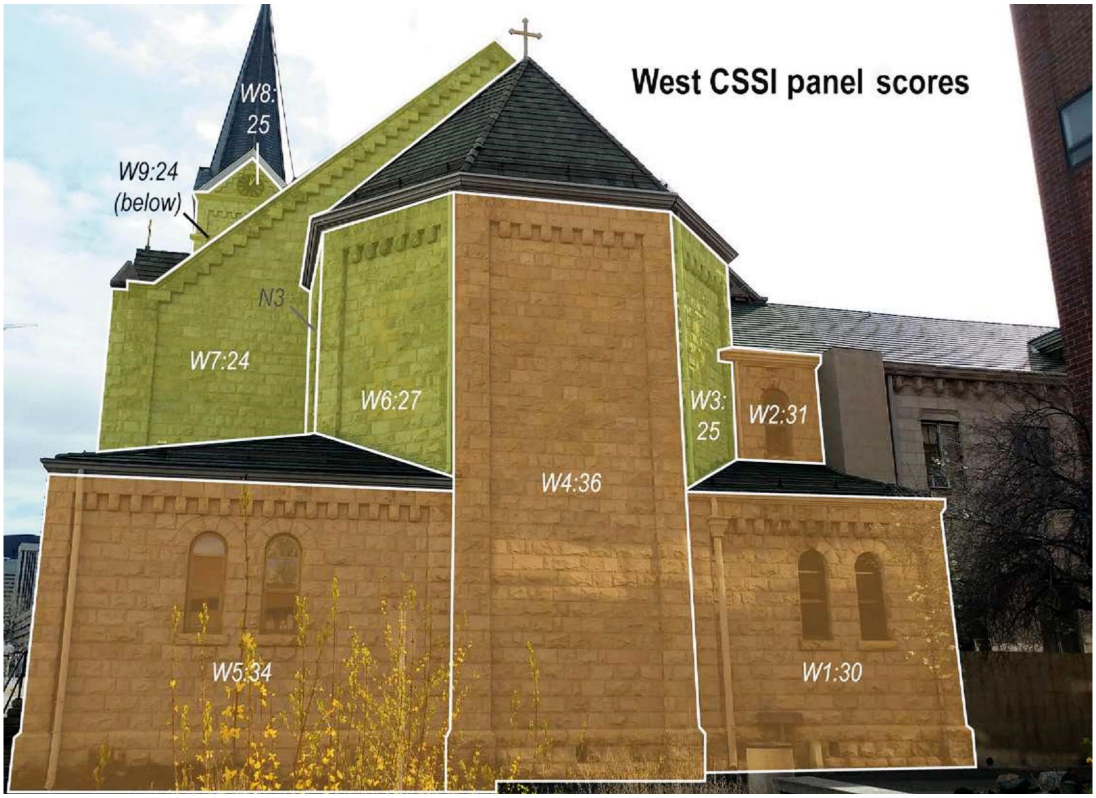

FIGURE 14.18 **Saint Elizabeth's west facade.** Although the west aspect earned the highest average CSSI score (28), panels with aspects offset slightly to the north or south did not display as high a ranking as those facing directly west, revealing that aspect may play a role in stone decay processes (Groom, 2014).

repairs when funds are available. That said, missing mortar work scattered across each facade needs attention. Continued monitoring of any decay will aid in deterring deterioration events at Saint Elizabeth's; and it is recommended that repairs occur in a timely manner.

14.4 IMPLICATIONS AND CONCLUSION

The RASI has been proven as a noninvasive, cost-effective, and easy-to-understand field-based research and assessment tool over the past decade (Allen et al., 2011; Allen and Groom, 2013a, b; Allen and Lukinbeal, 2011; Cerveny, 2005; Cerveny et al., 2016; Dorn et al., 2008; Groom, 2016, 2017); and the CSSI follows suit. Even so, RASI's strengths come with accompanying shortcomings (see Groom, 2017, especially Chapter 3.2.1, for a comprehensive overview). Similarly, although the CSSI remains the same as RASI with the exception of few terminological differences, it nonetheless exhibits specific benefits and challenges, the largest being its underlying conditional assumptions. Groom (2017, p. 130) elaborated:

FIGURE 14.19 **Panels W1 (two windows), W2 (singular window, above W1), part of W3 (to the left of W2), and W4 (left of drainpipe).** This image shows the thick, dark, and continually present anthropogenic coating of Saint Elizabeth's west facade. The coating extends the aspect's entire length and about 1 m above ground level.

Unlike RASI, CSSI compares current conditional statuses against assumed non-decayed baselines, since most cultural stone resources were created from "new" material. With RASI, researchers need to recognize that there will be a certain degree of "inherited decay"—rock decay that took place before the rock art was created—in their final scores since most rock art exists on preexposed surfaces. In contrast, the "virgin surfaces" of built monuments and building facades foster the assumption that all decay present has occurred after the completion of the resource. This assumption provides researchers with a controlled timeline of decay—allowing them to estimate factors such as rates of decay and date of decay initiation, which are much more difficult to calculate in natural settings. That said, the possibility remains that assumed baselines can skew results if the original surface was different than presumed (e.g., if stone dressings imitating textural deterioration were applied intentionally).

Additionally, panel definition remains distinct between RASI and CSSI. For example, when using RASI, panels are assigned by the researcher based on previously identified records or following the protocol established by the entity in charge (e.g., archaeological staff). Further, rock art tends to be found on fairly flat surfaces, such as cliff faces and boulder facets, which allows for panel division based on Cardinal direction (i.e., aspect—the direction the panel faces) or where motifs are most abundant (Groom, 2016). In the CSSI's case, because it is used to assess any built stone structure, including not just buildings but bridges, monuments, statues, and even gravestones, field preparation and site mapping to determine "panels" can be complicated but also flexible, as Groom (2017, p. 131) has suggested:

> When dealing with large building [facades], statues, or other more detailed cultural stone, site mapping and preparation can be a little more complicated, but also more flexible. CSSI researchers have the ability to define panels/features in whatever way best suits allotted field time, available resources, or desired precision. For example, a square building could be divided into four panels by aspect (i.e., "north side," "east side," "south side," "west side") or the same building could be divided by feature (e.g., "north side window arch 1," "north side window arch 2"). That same building could be assessed by aspect first, and then any specific characteristics of particular interest or importance can be analyzed individually. A large building [facade] could be just as easily divided into a handful of quadrants or dozens of individual elements, depending on the design and intention of the research. While studies with more panels will provide a more detailed analysis, they are much more time intensive and risk becoming counterproductive.

Groom (2017, p. 131) continued: "The intention of techniques like RASI and CSSI are to provide cost-effective rapid field assessments. If a building were divided into too many elements, a CSSI investigation would be prohibitively slow and potentially defeat the purpose of the work." In the case of Saint Elizabeth's, panels were defined based on architecture, but limited also by feasibility. For example, assessing the higher panels required finding different vantage points—on the tops of other buildings, on various floors of adjacent buildings—and nearly always required binoculars. Additionally, panel division for Saint Elizabeth's could have been brick-by-brick or horizontally, rather than vertically. Therein lies a benefit of the CSSI: the scale and intensity of assessment can be determined by the site manager based on need. That is, if a brick-by-brick assessment is needed—on the entire structure or just a single part—then the CSSI can be adjusted to accommodate. Indeed, one key to the CSSI's success rests in this situational adaptability.

Using the case study of a historic building in downtown Denver, CO, USA, this chapter focused on outlining the CSSI as a new technique for assessing the inherent geologic weaknesses in stone as well as highlighting its application for site managers. In a single afternoon, a research team of six people were able to assess Saint Elizabeth of Hungary Roman Catholic Church for its geologic stability (based on current and impending stone decay forms and processes) and then expound upon the findings in a succinct report, offering the site manager insight into areas most in need of monitoring and repair. Although other rock/stone decay assessments exist, most remain expensive, time-consuming, invasive (which can be detrimental to the host stone), and require a specialist to perform the assessment and interpret the results. The CSSI—like its RASI cousin (Dorn et al., 2008)—exhibits the opposite of these traits. As a technique for rapid, field-based assessment of rock deterioration, both the RASI and the CSSI have proven themselves valuable. Add to that the straightforward terminology/vernacular and quick training times for nonspecialists and a powerful tool emerges. With future assessments planned in the US, Europe, and the Middle East, the CSSI sets itself apart as a useful, cost-effective, and adaptable technique that, with appropriate training, can be used by almost anyone to evaluate current and impending rock weaknesses for any stone structure, regardless of size, building material, or location.

References

Allen, C.D., 2008. Using Rock Art as an Alternative Science Pedagogy. Arizona State University, Tempe, AZ.

Allen, C.D., Groom, K.M., 2013a. Evaluation of Grenada's "Carib Stones" via the Rock Art Stability Index. Appl. Geogr. 42, 165–175.

Allen, C.D., Groom, K.M., 2013b. A geologic assessment of Grenada's carib stones. Int. Newslett. Rock Art 65, 19–24.

Allen, C.D., Lukinbeal, C., 2011. Practicing physical geography: an actor-network view of physical geography exemplified by the Rock Art Stability Index. Prog. Phys. Geogr. 35 (2), 227–248.

Allen, C.D., Cutrell, A.K., Cerveny, N.V., Theurer, J., 2011. Advances in rock art research. La Pintura 37 (1), 4–6, 13.

Bruthans, J., Soukup, J., Vaculikova, J., Filippi, M., Schweigstillova, J., Mayo, A.L., Masin, D., Kletetschka, G., Rihosek, J., 2014. Sandstone landforms shaped by negative feedback between stress and erosion. Nat. Geosci. 7 (8), 597–601.

Cerveny, N., 2005. A weathering-based perspective on rock art conservation. Dissertation, Geography, Arizona State University, Tempe, AZ.

Cerveny, N.V., Dorn, R.I., Allen, C.D., Whitley, D.S., 2016. Advances in rapid condition assessments of rock art sites: Rock Art Stability Index (RASI). J. Archeol. Sci. Rep. 10 (2016), 871–877.

Dorn, R.I., 1998. Rock Coatings (Developments in Earth Surface Processes, number 6), first ed. Elsevier, Amsterdam, The Netherlands.

Dorn, R.I., Whitley, D.S., Cerveny, N.V., Gordon, S.J., Allen, C.D., Gutbrod, E., 2008. The Rock Art Stability Index: a new strategy for maximizing the sustainability of rock art as a heritage resource. Herit. Manag. 1 (1), 37–70.

Dorn, R.I., Gordon, S.J., Allen, C.D., Cerveny, N., Dixon, J.C., Groom, K.M., Hall, K., Harrison, E., Mol, L., Paradise, T.R., Sumner, P., 2013. The role of fieldwork in rock decay research: case studies from the fringe. Geomorphology 200, 59–74.

Fitzner, B., 2004. Documentation and evaluation of stone damage on monuments. In: Proceedings of the 10th International Congress on Deterioration and Conservation of Stone. June 27–July 2, 2004, Stockholm, Sweden. .

Fitzner, B., Heinrichs, K., 2001. Damage diagnosis at stone monuments: weathering forms, damage categories and damage indices. Acta-Univ. Carol. Geol. 45 (1), 12–13.

Fitzner, B, Heinrichs, K, Kownatzki, R, 1992. Classification and mapping of weathering forms. In: Proceedings of the 7th International Congress on Deterioration and Conservation of Stone. June 15–18, 1992, Lisbon, Portugal. .

Fitzner, B., Heinriches, K., Kownatzki, R., 1997. Weathering forms at natural stone monuments: classification, mapping and evaluation. Int. J. Restor. Build. Monum. 3 (2), 105–124.

Fitzner, B., Heinrichs, K., la Bouchardiere, D., 2002. Damage index for stone monuments.

Giesen, M.J., Ung, A., Warke, P.A., Christgen, B., Mazel, A.D., Graham, D.W., 2013. Condition assessment and preservation of open-air rock art panels during environmental change. J. Cult. Herit. 15 (1), 49–56.

Griffin, P., Indictor, N., Koestler, R., 1991. The biodeterioration of stone: a review of deterioration mechanisms, conservation case histories, and treatment. Int. Biodeterior. 28 (1–4), 187–207.

Groom, K.M., 2011. Historical assessment of rock decay on Dry Wash Bridge, Petrified Forest National Park. National Park Service, Rocky Mountain Cooperative Ecosystem Study Unit Project Summary Report.

Groom, K.M., 2014. Analysis of environmental influences on dressed stone decay: a case study of tafoni development on a hewn Djinn block in Petra, Jordan. Thesis, University of Arkansas.

Groom, K.M., 2016. Fading imagery: a mixed method analysis of rock art deterioration in the Arkansan Ozarks. Int. Newslett. Rock Art 74 (1), 14–20.

Groom, K.M., 2017. Rock art management and landscape change: mixed field assessment techniques for cultural stone decay. Dissertation, University of Arkansas.

Hall, K., Thorn, C., Sumner, P., 2012. On the persistence of 'weathering'. Geomorphology 149, 1–10.

Inkpen, R., Viles, H., Moses, C., Baily, B., 2012a. Modelling the impact of changing atmospheric pollution levels on limestone erosion rates in central London, 1980–2010. Atmos. Environ. 61, 476–481.

Inkpen, R., Viles, H., Moses, C., Baily, B., Collier, P., Trudgill, S., Cooke, R., 2012b. Thirty years of erosion and declining atmospheric pollution at St Paul's Cathedral. Atmos. Environ. 62, 521–529.

Janbade, P., Thakur, N., Tandon, B., 2016. Quantifying the damage and decay for conservation projects: identification, classification and analysis of the decay and deterioration in stone. Science and Art: A Future for Stone. p. 343.

Janvier-Badosa, S., Brunetaud, X., Beck, K., Al-Mukhtar, M., 2016. Kinetics of stone degradation of the Castle of Chambord in France. Int. J. Archit. Herit. 10 (1), 96–105.

Jo, Y.H., Lee, C.H., Chun, Y.G., 2012. Material characteristics and deterioration evaluation for the 13th century Korean stone pagoda of Magoksa temple. Environ. Earth Sci. 66 (3), 915–922.

Kurtz, J., Harry, D., Netoff, D.I., 2001. Stabilization of friable sandstone surfaces in a desiccating, wind-abraded environment of south-central Utah by rock surface microorganisms. J. Arid Environ. 48 (1), 89–100.

Lee, C.H., Chun, Y.G., 2013. Effect of climate conditions on weathering of stone cultural heritages in Korea. Int. J. Digit. Content Technol. Appl. 7 (12), 451.

McKinley, J.M., Warke, P.A., Lloyd, C.D., Ruffell, A.H., Smith, B.J., 2006. Geostatistical analysis in weathering studies: case study for Stanton Moor building sandstone. Earth Surf. Process. Landf. 31 (8), 950–969.

Meaders, M.I., 1959. Auraria was my friend. Georgia Rev. 13 (2), 402–408.

Noel, T.J., Wharton, N.J., 2016. Denver Landmarks and Historic Districts. University Press of Colorado, Boulder, CO.

Page, B., Ross, E., 2015. Envisioning the urban past: GIS reconstruction of a lost Denver district. Front. Digit. Humanit. 2 (3), 1–18.

Page, B., Ross, E., 2016. Legacies of a contested campus: urban renewal, community resistance and the origins of gentrification in Denver. Urban Geogr. 38 (9), 1293–1328.

Paradise, T.R., 1999. Analysis of sandstone weathering of the Roman theater in Petra, Jordan. Ann. Dept. Antiq. Jordan 43, 353–368.

Pope, G.A., Meierding, T.C., Paradise, T.R., 2002. Geomorphology's role in the study of weathering of cultural stone. Geomorphology 47 (2), 211–225.

Saint Elizabeth of Hungary Roman Catholic Church, 2017. Saint Elizabeth's website. Available from: http://stelizabethdenver.org/welcome/.

Siedel, H., Siegesmund, S., 2014. Characterization of stone deterioration on buildings. Stone in Architecture: Properties, Durability. Springer, 349-414.

Smith, B., Curran, J., Warke, P., Adamson, C., Stelfox, D., Savage, J., 2013. Stone-built heritage inventory and "performance in use" condition assessment of stonework. Quart. J. Eng. Geol. Hydrogeol. 46 (4), 391–404.

Thornbush, M.J., 2012. A site-specific index based on weathering forms visible in Central Oxford, UK. Geosciences 2 (4), 277–297.

Warke, P.A., Curran, J.M., Turkington, A.V., Smith, B.J., 2003. Condition assessment for building stone conservation: a staging system approach. Build. Environ. 38, 1113–1123.

Whitley, D.S., 2005. Introduction to Rock Art Research. Left Coast Press, Walnut Creek, CA.