National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

# John Muir National Historic Site

## *Geologic Resources Inventory Report*

Natural Resource Report NPS/NRSS/GRD/NRR—2021/2333

**ON THE COVER**
**Photograph of a trail passing through an oak woodland in the Mount Wanda Unit of the historic site. Bedrock composed of sandstone, siltstone, and clay underlies the landscape. Slope movements such as landslides and debris flows occur in the area. Steep, convex slope profiles and trees developing curved trunks (as shown in the photograph) are indications of soil creep, another type of slope movement.**
**NPS photograph by Will Elder (Golden Gate National Recreation Area).**

**THIS PAGE**
**Photograph of the Muir House. Built in 1882, John Muir lived in this Victorian-era, Italianate-style home for the last 24 years of his life. John Muir's father-in-law, John Strentzel, contracted to have the house built on a knoll with a commanding view of the Alhambra Valley.**
**Photograph by Katie KellerLynn (Colorado State University).**

# John Muir National Historic Site

*Geologic Resources Inventory Report*

Natural Resource Report NPS/NRSS/GRD/NRR—2021/2333

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All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.



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# Executive Summary

*Comprehensive park management to fulfill the NPS mission requires an accurate inventory of the geologic features of a park unit, but park managers may not have the needed information, geologic expertise, or means to complete such an undertaking; therefore, the Geologic Resources Inventory (GRI) provides information and resources to help park managers make decisions for visitor safety, planning and protection of infrastructure, and preservation of natural and cultural resources. Information in the GRI report may also be useful for interpretation.*

On 31 August 1964, John Muir National Historic Site (referred to as the "historic site" throughout this report) was authorized as "a public national memorial to John Muir in recognition of his efforts as a conservationist and a crusader for national parks and reservations" (National Park Service 1991, appendix 1). The historic site interprets the entirety of John Muir, beyond his legacy in conservation, and preserves the home and a portion of the land where he lived with his family in Martinez, California, from 1880 until his death in 1914. Muir is buried onsite.

The historic site's resources—including a palatial Victorian home, landscaped grounds, remnant orchards, rolling hills such as Mounts Wanda and Helen, and the thought-provoking Strentzel-Muir gravesite—represent aspects of John Muir that contrast with the popular image of him as a solitary wanderer who rejected modern society. The historic site's resources speak to Muir's deep ties to family and friends as well as to the burgeoning agricultural economy of California.

The historic site's resources also speak to the political and social currents of the Progressive Era—a period of widespread social activism and political reform across the United States from the 1890s to the 1920s. Composed at that time, Muir's writings inspired Americans to protect the nation's most spectacular landscapes and introduced new ideas about the meaning and value of wilderness, the negative impacts of industrialization, and the rights of nature (Johnson 2019). John Muir and his writings influenced the composition of the modern conservation movement and ignited the development of the National Park System.

The historic site's foundation document (National Park Service 2015) explains that, given John Muir's pivotal role in the founding of the National Park System, the historic site is uniquely positioned to explore how inequities of class, race, ethnicity, sex, and gender from Muir's time were woven into the system from its origins and why they continue today. Understanding this history and its ramifications is critical in helping the National Park Service to chart a just and egalitarian direction for the future. The historic site provides many opportunities for the public to connect with and critically examine Muir's life, stories, and evolving legacy.

For generations, people have connected to John Muir and his writings, and the GRI is no exception. This report highlights connections between John Muir and geology, including his legacy as part of America's geologic heritage. The name "Muir" is embedded in this heritage. From the mineral "muirite" (Alfors et al. 1965; International Mineralogical Association 2021) to mountains—as well as a spring, rapids, cape, lake, waterfall, stream, glacier, beach, and valley—geologic features honor John Muir (see Geographic Names Information System [GNIS] in "Additional References, Resources, and Websites").

Notable for this GRI report is that John Muir's public career as a nature writer began with geology and glaciology as his subjects (Dean 1995). Furthermore, 14 of Muir's publications are listed in the US Geological Survey (USGS) bibliography, *Geologic Literature on North America, 1785–1918* (Nickles 1923). This accomplishment is remarkable for someone who neither held a degree in geology nor worked as a geologist in a professional capacity.

Muir's geologic publications addressed the effects of earthquakes in and the origin of Yosemite Valley (Muir 1872b, 1874b), glaciers of California and the Sierra Nevada (Muir 1872a, 1873, 1874c, 1875a), mountain building and mountain sculpture in the Sierra Nevada (Muir 1874a, 1875b, 1875c), glacial and postglacial denudation in the Sierra Nevada (Muir 1874d, 1874e), formation of soils in the Sierra Nevada (Muir 1874f), postglacial history of *Sequoia gigantea* (Muir 1877), Pacific coast glaciers (1902), and glaciation in the Arctic and subarctic (Muir 1884, 1917). Seven of these publications are the well-known "Studies in the Sierra" (Muir 1874a–f and 1875c), which were originally published in *Overland Monthly*. The Sierra Club republished these studies in the *Sierra Club Bulletin* following Muir's death.

In addition to Muir's writings and legacy, many other resources at the historic site are part of America's geologic heritage. The historic site's bedrock and landscape, for example, are part of the "puzzle" of plate tectonics, which geologists have been piecing together for the past six decades. Plate tectonics is the unifying theory of how Earth works. It provides the context for why continents move, seafloors spread, mountains rise, volcanoes erupt, and earthquakes happen.

The GRI team compiled four maps by the California Department of Conservation, Division of Mines and Geology (now, California Geological Survey) into the GRI GIS data for the historic site. These maps, referred to as "plates," are from a project by Haydon (1995).

Geologic map units in the GRI GIS data are referenced in this report using map unit symbols. Table 1 shows all the map units within the historic site in a context of geologic time. Geology is a complex science with many specialized terms. This report provides definitions of geologic terms at first mention, typically in parentheses following the term.

The GRI follows the interpretation provided by Haydon (1995), which mapped the Cretaceous rocks (deposited between 145 million and 66 million years ago) at the historic site as the Great Valley sequence. This interpretation corresponds to the current geologic understanding of the geology of the San Francisco Bay Area. With respect to the Paleocene rocks (deposited between 59.2 million and 56 million years ago) at the historic site, Haydon (1995) mapped the Martinez Formation, lower member. The GRI follows this interpretation. However, the current understanding of the Paleocene rocks at the historic deems an interpretation by Graymer (2000) as more in line with current understanding of Bay Area geology. Graymer (2000) mapped these Paleocene rocks as the Vine Hill Sandstone. This change is discussed in the "Martinez Formation" section of this GRI report.

This report contains the following chapters:

Introduction to the Geologic Resources Inventory—This chapter provides background information about the GRI, highlights the GRI process and products, and recognizes GRI collaborators. A geologic map in GIS format is the principal deliverable of the GRI. This chapter highlights the source maps used by the GRI team in compiling the GRI GIS data for the historic site. It also calls attention to the poster that illustrates these data.

Geologic Heritage—This chapter highlights significant geologic features, landforms, landscapes, and stories of the historic site preserved for their heritage values. It draws connections between geologic resources and other park resources as well as connections between John Muir and geology.

Geologic Features and Processes—This chapter describes the geologic features and processes of significance for the historic site and highlights them in a context of geologic time. The features and processes are discussed in order of geologic time, oldest to youngest. The historic site's geologic story began between about 145 million and 56 million years ago when sediments that would become the historic site's bedrock were deposited. Geologic processes such as tectonism and fluvial activity continue to alter the landscape to the present day.

Geologic Resource Management Issues—This chapter discusses management issues related to the historic site's geologic resources. The issues, which are discussed in order of management priority, are (1) erosion and downstream flooding at the Mount Wanda Unit; (2) slope movements; (3) condition of the Martinez Adobe; (4) bank erosion at the Gravesite Unit; (5) faults and earthquakes; (6) climate change and geologic resources; (7) flooding on Franklin Creek; and (8) paleontological resource inventory, monitoring, and protection.

Guidance for Resource Management—This chapter is a follow up to the "Geologic Resource Management Issues" chapter. It provides resource managers with a variety of ways to find and receive management assistance with geologic resources.

Literature Cited—This chapter is a bibliography of references cited in this GRI report. Many of the cited references are available online, as indicated by an Internet address included as part of the reference citation. If historic site managers are interested in other investigations and/or a broader search of the scientific literature, the NPS Geologic Resources Division has collaborated with—and funded—the NPS Technical Information Center (TIC) to maintain a subscription to GEOREF (the premier online geologic citation database). Multiple portals are available for NPS staff to access this database. Historic site staff may contact the GRI team or the NPS Geologic Resources Division for instructions to access GEOREF.

# Introduction to the Geologic Resources Inventory

*The Geologic Resources Inventory (GRI), which is administered by the Geologic Resources Division (GRD) of the NPS Natural Resource Stewardship and Science (NRSS) Directorate, provides geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. The GRI is funded by the NPS Inventory and Monitoring Program.*

## GRI Products

The GRI team—which is a collaboration between the National Park Service Geologic Resources Division and Colorado State University Department of Geosciences—completed the following tasks as part of the GRI process for John Muir National Historic Site (referred to as the "historic site" throughout this report): (1) conducted a scoping meeting and provided a scoping summary (KellerLynn 2008), (2) provided geologic map data in a geographic information system (GIS) format, (3) created a poster to display the GRI GIS data, and (4) provided a GRI report (this document). These products are available on the GRI products webpage and through the NPS Integrated Resources Management Applications (IRMA) portal (see "Access to GRI Products" in the "Guidance for Resource Management" chapter).

Ground-disturbing activities should neither be permitted nor denied based on the information provided in GRI products. Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features in the GRI GIS data and on the poster. Based on the source map scale (Haydon 1995; 1:24,000) and US National Map Accuracy Standards, geologic features represented in the GRI are horizontally within 12 m (40 ft) of their true locations.

### *Scoping Meeting*

On 24 September 2007, the National Park Service held a scoping meeting at the historic site in Martinez, California. The scoping meeting brought together historic site staff, other NPS staff, and geologic experts who reviewed and assessed available geologic maps, developed a geologic mapping plan, and discussed geologic features, processes, and resource management issues to be included in the final GRI report. A scoping summary (KellerLynn 2008) summarizes the findings of the scoping meeting.

### *GRI GIS Data*

Following the scoping meeting, the GRI team compiled the GRI GIS data for the historic site. These data are the principal deliverable of the GRI. The GRI team did not conduct original geologic mapping but compiled existing geologic information (i.e., paper maps and/or digital data) into the GRI GIS data (fig. 1). Scoping participants and the GRI team identified the best available source maps with respect to coverage (area mapped), map scale, date of mapping, and compatibility of the mapping to the current geologic interpretation of an area.

At the time of scoping, Graymer et al. (1994) seemed a likely choice as a source map for the GRI GIS data, and the discussion in the scoping summary (KellerLynn 2008) reflects this. Since scoping, however, the GRI team in consultation with the California Geological Survey determined that the project by Haydon (1995), which is at a scale of 1:24,000, would better serve resource management at the historic site than the 1:75,000-scale mapping by Graymer et al. (1994) (Tim Connors, NPS Geologic Resources Division, geologist, email communication, 11 April 2008).

The project by Haydon (1995) consisted of compilation of a geologic map (plate 32C) with local modifications primarily from Jones and Graymer (1992) as well as Pease (1953) and Saul (1973); collection of data on soils, which were taken from Welch (1977); interpretation of geologic and slope stability features on aerial photographs; field mapping; and evaluation of relative landslide and debris-flow susceptibility of the study area.

The GRI GIS data for the historic site compiled the following four maps/plates from Haydon (1995):

- Plate 32C: "Geologic Map of the Martinez-Orinda-Walnut Creek Area, Contra Costa County, California."
- Plate 32B: "Landslides and Related Slope-Failure Features Map of the Martinez-Orinda-Walnut Creek Area, Contra Costa County, California."
- Plate 32D: "Relative Debris-Flow Susceptibility Map of the Martinez-Orinda-Walnut Creek Area, Contra Costa County, California."
- Plate 32A: "Relative Landslide Susceptibility Map of the Martinez-Orinda-Walnut Creek Area, Contra Costa County, California."

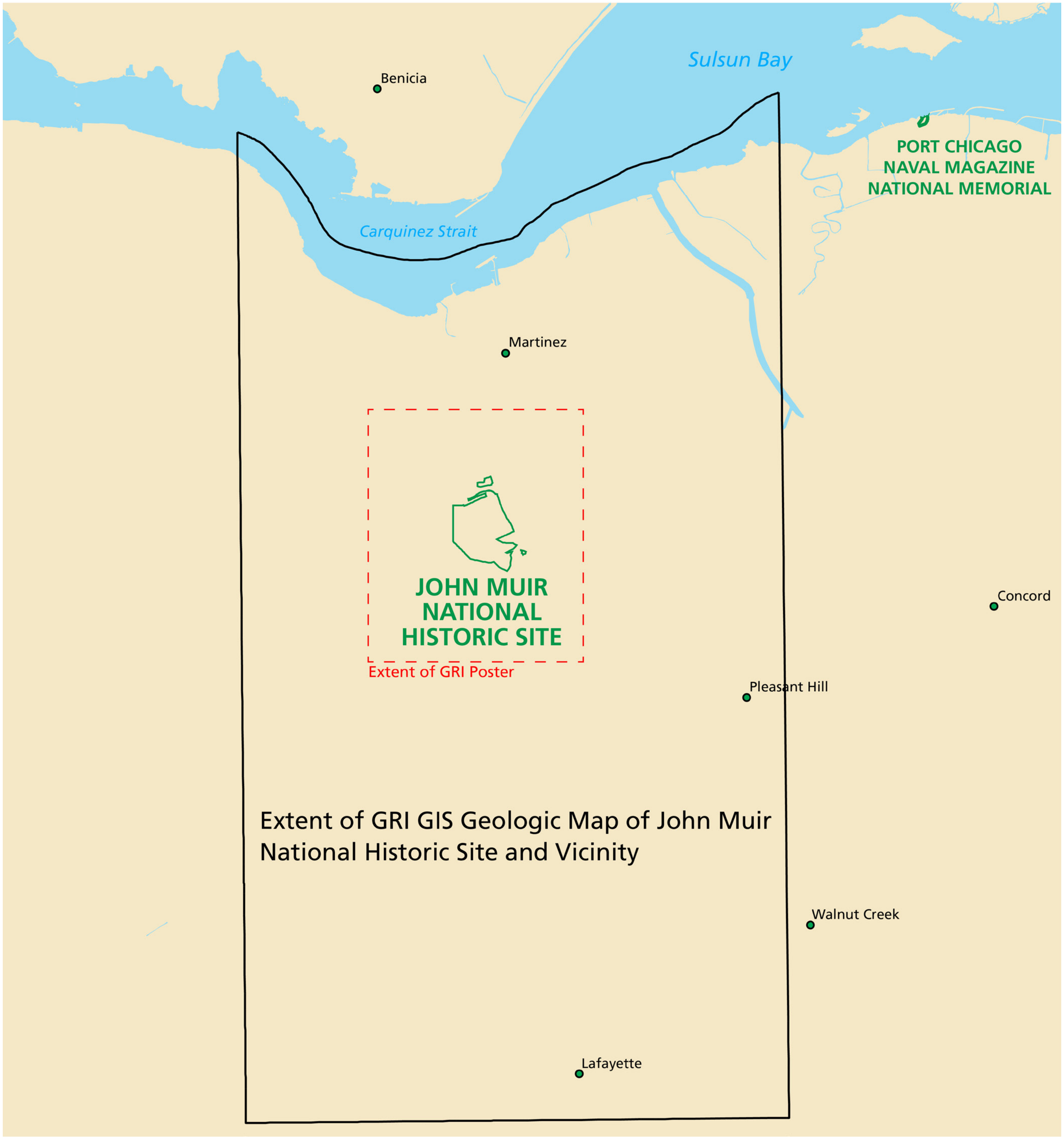


**Figure 1. Index map for the historic site's GRI GIS data.**
**The GRI team compiled geologic data in a GIS format from a mapping project by Haydon (1995). The scale of the data is 1:24,000. The black outline on the figure shows the extent of the data. The red hashed outline indicates the extent of the poster. The boundary of the historic site is outlined in green. Graphic by Stephanie O'Meara (Colorado State University) modified by Rebecca Port (NPS Geologic Resource Division).**

Each of these plates is part of *Landslide Hazards in the Martinez-Orinda Walnut Creek Area, Contra Costa County, California*, which is Open-File Report OFR-95-12 published by the California Department of Conservation, Division of Mines and Geology (now California Geological Survey).

The area of the source map (and GRI GIS data) is centered approximately 35 km (22 mi) northeast of San Francisco in the East Bay Hills. It consists of about 197 $km^2$ (76 $mi^2$) of grassy, brushy, or wooded rolling hills, low rugged mountains, and small to large alluvial valleys and terraces. The data cover all or parts of the following cities: Martinez, Pleasant Hill, Walnut Creek, and Lafayette, and span between the Carquinez Strait on the north and the Lafayette Reservoir on the south (see fig. 1). The area covered comprises portions of four USGS 7.5-minute (scale 1:24,000) quadrangles: (1) the east half of Briones Valley, (2) the west half of Walnut Creek, (3) the southeast quarter of Benicia, and (4) southwest quarter of Vine Hill. The historic site is situated primarily on the Briones Valley quadrangle, though the Gravesite Unit is on the Walnut Creek quadrangle.

In addition, the GRI GIS data contain mapping by Boucher (1990), which provided mine point features (i.e., "dry holes" [non-producing oil and gas wells]). Also, Rogers and Halliday (1992a, 1992b) provided the names of faults (i.e., Briones, Calaveras, Concord, Franklin, Las Trampas, Pinole, and Southampton) used in the GRI GIS data.

### *GRI Poster*

A poster of the GRI GIS data draped over a shaded relief image of the historic site and surrounding area is the primary figure referenced throughout this GRI report. The poster is not a substitute for the GIS data but is supplied as a helpful tool for office and field use and for users without access to GIS. The poster does not show the full extent of the GRI GIS data and not all GIS feature classes are included on the poster. Geographic information and selected park features have been added. Digital elevation data and added geographic information are not included in the GRI GIS data but are available online from a variety of sources.

### *GRI Report*

In anticipation of preparing the GRI report for the historic site, the GRI team hosted a follow-up conference call for historic site staff and interested geologic experts on 8 July 2020. The call provided an opportunity to get back in touch with staff at the historic site, introduce "new" (since the 2007 scoping meeting) staff to the GRI process, and update the list of geologic features, processes, and resource management issues for inclusion in the GRI report.

The GRI report is a culmination of the GRI process. It synthesizes discussions from the scoping meeting in 2007, the follow-up conference call in 2020, and additional research. The selection of geologic features highlighted in the report was guided by the previously completed GRI GIS data. Moreover, writing reflects the data and interpretation of the source map author (i.e., Haydon 1995).

## Acknowledgements

The lists of names in the "Acknowledgements" are in alphabetical order by last name except for those under "GRI GIS Data Production" and "GRI Poster Design," which are listed with respect to relative contribution to those projects. The following lists of participants reflect the names and affiliations of participants at the time of the 2007 scoping meeting and/or the 2020 follow-up conference call. Notably, staff members at John Muir National Historic Site also are the stewards of resources at Eugene O'Neill National Historic Site, Rosie the Riveter/World War II Home Front National Historical Park, and Port Chicago Naval Magazine National Memorial, as well as Pinnacles National Park.

The GRI team thanks the participants of the 2007 scoping meeting and 2020 follow-up conference call for their assistance in this inventory.

Because the GRI team does not conduct original geologic mapping, we are particularly thankful for the California Department of Conservation, Division of Mines and Geology (now California Geological Survey), for its maps of the area. This report and accompanying GIS data could not have been completed without them.

Thanks to Marc Delattre (California Geological Survey, senior engineering geologist) for his input on the use of "Martinez Formation" in this GRI report. Thanks to Vincent L. Santucci (NPS senior paleontologist and Paleontology Program coordinator) and Victoria Bones (John Muir National Historic Site, museum curator) for their help in verifying the paleontological resources in the historic site's museum collection. Thanks to GRI team members Victoria Crystal, Michael Barthelmes, Rebecca Port, and Jason Kenworthy for their thoughtful input on this report's "Historic Timeline"; resources regarding relevancy, diversity, and inclusion; and the challenges and opportunities associated with John Muir's legacy. Thanks to Trista Thornberry-Ehrlich (Colorado State University) and Rebecca Port (NPS Geologic Resources Division) for creating many of the figures in this report.

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# Geologic Heritage

*This chapter draws connections among the historic site's geologic resources and other park resources and stories, specifically, the legacy of John Muir. The geologic heritage of the historic site is twofold. First, geology serves as the foundation of the landscape (see "Geologic Features and Processes"). Second, many connections can be made between John Muir and geology.*

*The historic site is the best place to learn about John Muir as a multifaceted individual, including family man, businessman, conservationist, and writer. Muir also was a man of science, specifically, a glaciologist, who was the first to recognize and report that the "glaciers" in the Sierra Nevada were indeed glaciers—that is, moving bodies of ice, not simply stagnant snowfields. He referred to glaciers as "living" (Muir 1872a).*

## Historic Timeline

A story focused on John Muir's life in Martinez begins in 1880. For a timeline covering Muir's entire life and ongoing legacy, see Wood (2019) and NPSHistory.com (2021). The geologic and human histories of the Martinez area, however, extend much farther back in time. In the "Geologic Features and Processes" chapter, a geologic time scale (see table 1) highlights the geologic story, which includes deposition of the historic site's bedrock between 145 million and 56 million years ago. The following timeline highlights the more than 17,000 years of human history of California and the Martinez area:

Starting about 17,500 years ago—Humans migrate to the west coast of North America. A coastal route along what is now British Columbia, Canada, becomes ice-free about 17,500 years ago (Wood 2021).

About 13,000 years ago—An inland, ice-free corridor between the Cordilleran ice sheet on the west and the Laurentide ice sheet on the east opens, allowing human migration southward (Wood 2021).

About 11,700 years ago—The most recent ice age ends (exact timing varies from place to place).

1542 CE—Sailing under the Spanish flag, Portuguese-born Juan Rodriquez Cabrillo is the first European to explore California, which he claims for Spain (see GRI report about Cabrillo National Monument by KellerLynn 2018).

1579—Sir Francis Drake, an Englishman, sails into California. Empowered by the "right of discovery," Drake claims the whole territory for the English Crown.

Within the first 40 years of European colonization in California, thereby, two countries claim the land but neither acknowledges the rights of the Native people who have resided on it for thousands of years. Like all other Indigenous (term used in Canada) and Native (term used in the United States) peoples in North America, California's Native population has a tragic and tumultuous history (e.g., Dutschke 2004; California Courts 2021). Before the missionary, fur trapping, and gold rush era migrations, an estimated 200,000 people live in what is now California. The Karkin Ohlone, Bay Miwok, and Muwekma Ohlone peoples are associated with the historic site (Native Land Digital 2021; Gretchen Stromberg, John Muir National Historic Site, Resource Management and Planning lead, email communication, 9 September 2021).

1760s to 1820—Native ways of life end through cultural assimilation, disease, and genocide. As many as 16,000 Native Californians die in the genocide, which takes place from the 1840s through the 1870s. Most of the deaths occur during hundreds of massacres when state and local militias encircle and murder Native peoples. The genocide is facilitated by discriminatory California laws and the outright support of state officials and federal authorities who condone the attacks (Blakemore 2019). In 1820, mission records show no Native people remaining in the Carquinez Strait area (National Park Service 2005b).

1769—The Spanish found the first mission in California—San Diego—on 16 July 1769. This mission system spreads and persists for 65 years.

1775–1776—Spanish Lt. Juan Bautista de Anza leads an expedition from Nogales, Arizona, to San Francisco Bay, where he establishes the first non-Native settlement in the area (see "Martinez Adobe").

1834—Mexico, which encompasses California, gains independence from Spain. The mission system collapses. Land ownership and economy shift from the mission approach to private enterprise in which large land grants are given to wealthy Mexican citizens. Powerful landholding families, such as that of Don Ignacio Martinez, direct political, cultural, and economic development, including the emergence of a merchant class, the establishment of the first towns, and the furtherance of international trade and cultural exchange (National Park Service 2015).

1838—John Muir is born on 21 April 1838 in Dunbar, Scotland. Because John Muir continues to inspire environmental consciousness and action, his birthday is commonly celebrated in conjunction with Earth Day, which is 22 April.

1846–1848—The United States and Mexico engage in armed conflict—known in the United States as the Mexican–American War or the Mexican War, and in Mexico as the Intervención Estadounidense en México ("US Intervention in Mexico"). In 1848, California becomes the property of the United States as one of the spoils of this war.

1850—California becomes a state.

1880—John Muir's life in Martinez, California, begins. He marries Louisa "Louie" Wanda Strentzel on 14 April 1880.

1881—Muir takes over running the Strentzel fruit ranch in 1881. The Muirs' daughter Wanda is born 25 March 1881. Daughter Helen is born on 23 January 1886.

1914—Muir dies on 24 December 1914.

1916—Congress creates the National Park Service.

1964—John Muir National Historic Site is established.

2015—The foundation document published for John Muir National Historic Site (National Park Service 2015) formalizes the historic site's role in examining and interpreting the inequities of race, ethnicity, sex, gender, and class that influenced the composition of the modern conservation movement as well as the development of the National Park System.

2019—The State of California apologizes for the genocide it carried out against Native people.

2020s onward—Conservation organizations and land management agencies encourage discourse and reexamination of history and key historical figures, including John Muir, and push for more relevancy, diversity, and inclusion (see "Additional References, Resources, and Websites"). The Sierra Club executive director, Michael Brune, publicly confronts the complex past of the Sierra Club (Brune 2020). Brune's depiction of John Muir's views is controversial and triggers a thorough, ongoing reexamination (e.g., Colman 2021; Mair et al. 2021).

## Park Background and Establishment

The historic site is in Martinez, California, in Contra Costa County (fig. 2). It preserves the home where John Muir lived during the last 24 years of his life. From this place, Muir changed the way a country viewed its wilderness—not as a resource to be harvested, but as a treasure to be preserved (National Park Service 2005a).

Muir's life in Martinez began at the age of 42 when he married Louie Strentzel, the daughter of John and Louisiana Strentzel. John Strentzel was a physician and noted horticulturist who, along with Strentzel's brother Henry, experimented with many imported and native fruits and vines to determine which varieties grew best in the Martinez area. The Strentzel fruit ranch produced California's first Muscat grapes and raisins, as well as pears, apples, cherries, figs, olives, oranges, peaches, pecans, plums, quinces, and walnuts. The ranch also grew vegetables and hay and raised cattle and hogs. In addition, Strentzel helped establish a wharf at Martinez. From there, produce was shipped to local and eastern markets using Strentzel's innovative shipping techniques. In the gentlemen farmer tradition, Dr. Strentzel promoted the benefits of fruit growing to his fellow farmers and often gave away cuttings and advice to get them started (Killion and Davison 2005).

Louie Strentzel and John Muir met as a result of the encouragement of friends, namely Jeanne Carr, whose husband Ezra had been one of Muir's professors at the University of Wisconsin. Carr enjoyed a close relationship with Muir and took it upon herself to find him a suitable wife (Johnson 2019). Louie and John were married in 1880, between Muir's first and second trips to Alaska.

The birth of the Muirs' first daughter, Wanda, in 1881 prompted the peripatetic Muir to give greater attention to domestic life, but only after a third trip to Alaska at the urging of Louie, who worried that separation from wild nature had degraded her husband's health (Johnson 2019). Upon Muir's return, the couple settled into their first home together—Alhambra ranch house—located near the existing Strentzel-Muir gravesite. Muir then devoted himself to improving the profitability of the ranch. His efforts benefited from a booming market for land and fruit in California (Johnson 2019). Muir took over the responsibility of running the fruit ranch in 1881 in response to the declining health of Dr. Strentzel.

By the late 1880s, Muir's worries about the ill health of his second daughter, Helen, who was born in 1886, and years of laboring and toiling at the ranch were beginning to affect his own health. Aware of her husband's love of wilderness and his role in preserving it, Louie successfully convinced John to begin writing

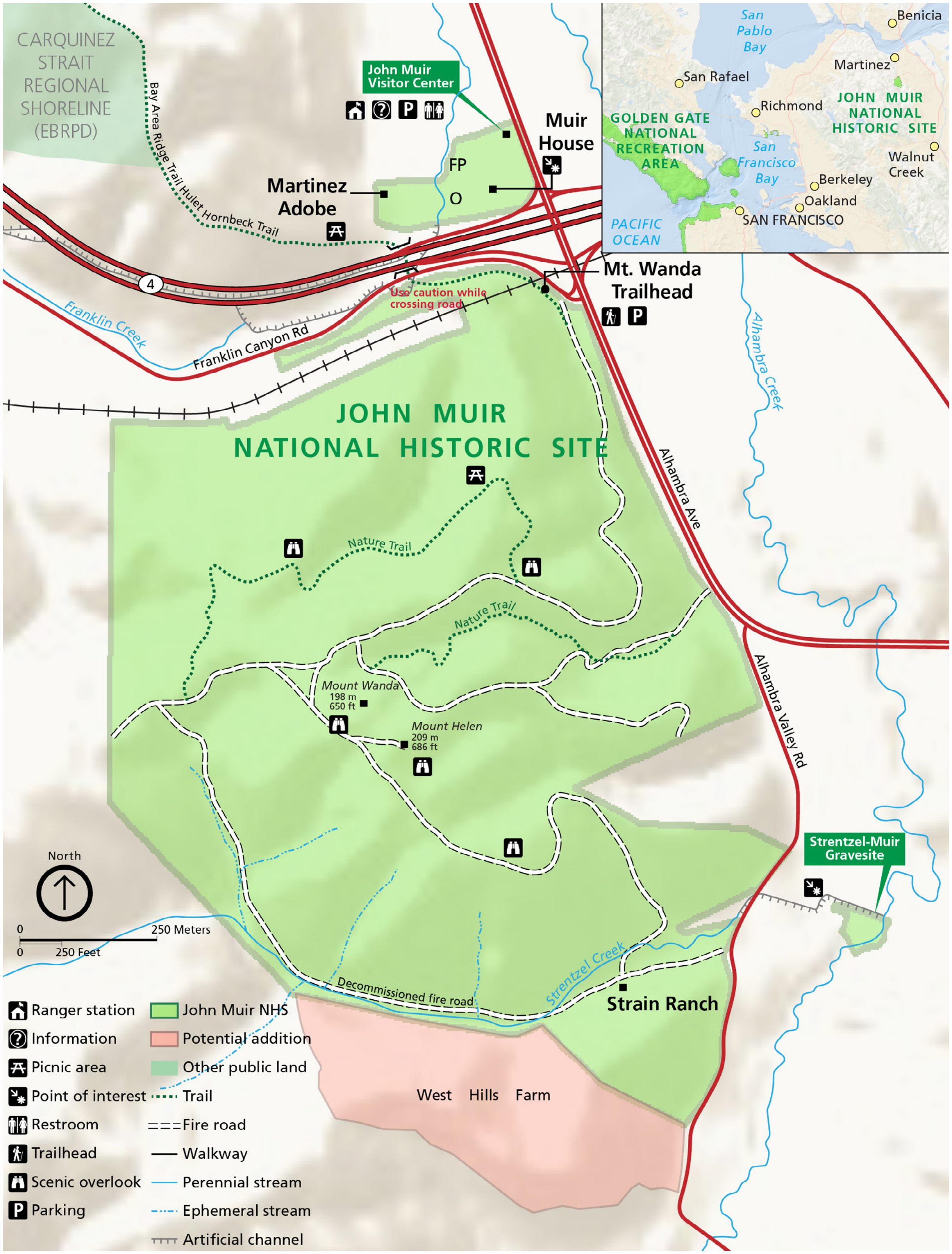


**Figure 2. Location map.**
**John Muir National Historic Site covers approximately 138 ha (341 ac) and consists of three, noncontiguous units: House Unit, Mount Wanda Unit, and Gravesite Unit. The historic site is about 50 km (30 mi) northeast of San Francisco. It is south of the Carquinez Strait and downtown Martinez, California. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after National Park Service (2015, inside front cover).**

and traveling again. To help fund this venture, the couple began to sell and lease much of the ranch lands. Combined with profits earned from the adept management of the fruit ranch, Muir was able to save enough money to largely retire at the age of 51 whereby he pursued writing and traveling for the balance of his life.

While living in Martinez, Muir accomplished many things—both at home and away from home. In addition to the aforementioned trips to Alaska in 1879, 1880, and 1881, Muir was part of the Harriman Expedition in 1899 (see "John Muir and Earthquakes"); he was one of the founders and served as the first president of the Sierra Club; he played a role in the creation of several national parks, including Petrified Forest (see GRI report by KellerLynn 2010), Grand Canyon (see GRI report by Graham 2020), Sequoia and General Grant (now Kings Canyon; see National Park Service 2002), Glacier Bay (see GRI scoping summary by KellerLynn 2009), and Mount Rainier (see GRE [now GRI] report by Graham 2005); he was instrumental in the creation and expansion of national forest reserves, including groves of coast redwood (*Sequoia sempervirens*) and giant sequoia (*Sequoiadendron giganteum*) in California; and he battled (unsuccessfully) to prevent Yosemite National Park's Hetch Hetchy Valley from being dammed. Muir received honorary degrees from Harvard and Yale Universities and the Universities of Wisconsin and California for this work.

Although Muir once complained that "writing is like the life of a glacier; one eternal grind," he was highly prolific, producing more than 300 journal or magazine articles and 12 books. These publications expound the virtues of conservation and the natural world. Works like *Our National Parks* (Muir 1901a) were greatly responsible for the creation of the aforementioned national parks and for the establishment of the National Park Service. Two years after Muir's death, Congress created the National Park Service to preserve America's treasures for future generations. Muir so profoundly influenced the NPS mission that he is called the "father of the National Park Service" (National Park Service 2005a).

The historic site was established on 31 August 1964. Prior to this, the Muir House, Martinez Adobe (see "Geologic Connections to Park Resources"), and lands in between these two structures were listed as a national historic landmark on 29 December 1962. The historic site was listed on the National Register of Historic Places on 16 October 1966 and updated on 22 May 1978. Additional lands were added to the historic site in 1993 (Mount Wanda Unit), 2000 (Gravesite Unit), and 2016 (former Stain Ranch property). West Hills Farm may be transferred to the National Park Service in the future (see fig. 2).

The historic site encompasses 155.6 ha (384.6 ac) and is composed of three noncontiguous properties: House Unit, Mount Wanda Unit, and Gravesite Unit. Together, these lands preserve important pieces of the Strentzel-Muir ranch, which originally encompassed about 930 ha (2,300 ac; Killion 2005).

- House Unit—The House Unit includes the Muir House, Martinez Adobe, and remnants of orchards that John Muir and his father-in-law, Dr. John Strentzel, maintained.
- Mount Wanda Unit—Covering 132 ha (326 ac), the rolling hills of the Mount Wanda Unit make up most of the historic site's land area. During Muir's life in Martinez, the primary use of what is now the Mount Wanda Unit was taking walks and being in nature; it remains so today. A small network of footpaths and fire roads runs through the area. From sunrise to sunset, on any given day, visitors can explore the woodlands and grasslands where the Muir girls took nature hikes with their "papa" (National Park Service 2020b).
- Gravesite Unit—The Gravesite Unit encompasses a small family cemetery, including the gravesite of John Muir. The Gravesite Unit also contains specimen trees such as incense cedar (*Calocedrus decurrens*), California laurel (*Umbellularia californica*), and eucalyptus (*Eucalyptus globulus*). Although the vines planted by Muir no longer survive at the historic site, fruit trees at the Strentzel-Muir gravesite harken to the larger orchard planted and grown during Muir's life. The remnant pear orchard at the Gravesite Unit was one of Strentzel's first plantings (Johnson 2019).

## Geologic Connections to Park Resources

Many interesting connections exist between the geologic and other resources at the historic site, including the following:

### *Muir House*

The "Muir House," as it is now called (see inside-front cover of this report), is a fundamental resource and value of the historic site (National Park Service 2015). Elements of the house illustrate many of the roles John Muir served throughout his lifetime, including family man, businessman, conservationist, and activist (National Park Service 2015). The house and adjacent grounds are the focal point of the historic site (Killion 2005).

The Muir House was built in 1882. The Strentzels contracted to have their home built on a knoll with a commanding view of the Alhambra Valley. The house was designed by architects Wolfe and Son of San Francisco and built by contractors Sylvester and Langabee also of San Francisco. The 17-room, two-story structure, composed of wood in the Italianate style of the late Victorian period, is topped by a cupola/bell tower, has a full basement and attic, 4-m- (12-ft-) high ceilings, and more than 900 $m^2$ (10,000 $ft^2$) of floor space. The occupants of the house enjoyed many modern conveniences, including running water, electricity, and telephone service.

In 1890, with the death of Dr. John Strentzel, the Muirs (John, Louie, Wanda, and Helen) moved into the "Big House" (as it was then called) where they could more easily care for Louie's mother, Louisiana Erwin Strentzel. The family home became the unlikely center of an emerging environmental movement—a movement whose primary voice was that of John Muir (National Park Service 2005a). The "Scribble Den" on the second floor of the house was where Muir produced many of his most important writings (National Park Service 2015). The desk in that room is one of the few original pieces of furniture in the house. From the north window of the Scribble Den, Muir could see across the ranch's orchards to Martinez and the Carquinez Strait.

Geologic connections of the Muir House are the underlying geology, which is composed of younger alluvium (**Qal**; see poster and "Fluvial Features and Processes"), and the house's building stone. A focused inventory of all the stone contained within, under, and immediately surrounding the Muir House is not known to have taken place, but cultural resource investigations contain scattered information applicable to a geologic inventory of building stone.

Building stone in the Muir House includes white marble (possibly imported from Italy; fig. 3) and black marble for the fireplaces, a white onyx mantel (in the west parlor, which was broken by vandals in the 1950s during a time when the house was empty; see Grassick 2006), and a marble lavatory (Grassick 2006). Geologically, marble is metamorphosed limestone. Onyx is gemstone-quality chalcedony (a cryptocrystalline [crystals not seen with the naked eye] variety of quartz). The basement walls and foundation, as well as the intermediate load-bearing columns, are constructed of red fired brick; the concrete slab basement floor was added in 1969 (Johnson 2019).

Exterior stonework (e.g., steps, curbs, and paving stones), which is commonly flagstone (a type of thin-layered sandstone), may be composed of the Great Valley sequence (see "Great Valley Sequence"), though this needs to be verified in the field by a geologist. In addition, walkways and retaining walls also may have been constructed of locally sourced material.

**Figure 3. Photograph of marble fireplace. Geologic resources at the House Unit include building stone such as this marble fireplace in the Muir House. Although the provenance of much of the building stone in the house is unknown, the white marble of this fireplace may be from Italy. Of the seven original fireplaces in the Muir House, three remain: two were converted to brick (by John Muir himself) and two were removed. NPS photograph by Luther Bailey.**

A geologic inventory of the Muir House building stone would make an interesting project. A researcher could trace the stones' commercial origins (i.e., quarries) then based on these locations determine the geologic formations (fundamental rock-stratigraphic unit; see "Martinez Formation") of the extracted materials. Connections could then be made to regional, national, and global geologic stories as well as other National Park Service areas; for example, pure-white Yule Marble from Colorado was used in making the Tomb of the Unknown Soldier in Arlington National Cemetery and the Lincoln Memorial (Matthews et al. 2003). Moreover, following the 1906 San Francisco earthquake (discussed below), John Muir replaced a damaged fireplace in the west bedroom and embedded a piece of petrified wood (fig. 4) into it (Grassick 2006). Muir probably collected this specimen during his travels to Petrified Forest in Arizona (see "John Muir and Fossils"). Such discoveries illustrate the potential for more paleontological materials as part of building stone and within museum collections (see "Paleontological Resource Inventory, Monitoring, and Protection").

Receiving geologic expertise for an inventory and research project of building stone may be possible through the Scientists in Parks (SIP) program (see "Guidance for Resource Management"). A building-stone inventory could be combined with and help address a data need for general research associated with the historic site's museum collections that is expressed in the historic site's foundation document (National Park Service 2015).

**Figure 4. Photograph of petrified wood embedded in fireplace.**
**The fireplace in the west bedroom of the Muir House was damaged during the 1906 San Francisco earthquake. While replacing the damaged fireplace, John Muir embedded a piece of petrified wood as an adornment. He collected the specimen during his travels to the Petrified Forest in Arizona. NPS photograph by Virginia Bones (John Muir National Historic Site).**

### *Martinez Adobe*

The Martinez Adobe (fig. 5), which is an "other important resource and value" of the historic site (National Park Service 2015), offers an opportunity to examine a way of life in the Alhambra Valley before the time of the Strentzels and Muirs. The primary importance of the building, which was designated a California registered historic landmark in 1955, is representing California's Spanish Colonial and Mexican history.

The historic site is an official "stop" on the Juan Bautista de Anza National Historic Trail. The 1,900-km (1,200-mi) national historic trail connects history, culture, and outdoor recreation from Nogales, Arizona, to San Francisco Bay. In 1775–1776, Spanish Lt. Juan Bautista de Anza—the so-called founder of San Francisco—led an estimated 240 men, women, and children on an epic journey to establish the first non-Native settlement at San Francisco Bay. Located within the grounds of the historic site, the Martínez Adobe provides interpretation of the passage of the Anza expedition and the subsequent Spanish and Mexican periods. The Martinez Adobe contains exhibits featuring bilingual displays about the national historic trail; it also provides storage space for the historic site (see "Condition of the Martinez Adobe"). Interestingly, Guadalupe Moraga, the wife of Vicente Martinez who built the Martinez Adobe, was a great-granddaughter of Juan Bautista de Anza (National Park Service 2020a).

The Martinez Adobe was constructed in 1849 under the direction of Vincente Martinez, for whom the town of Martinez is named. Don Vicente Martinez lived in the structure for only four years before he sold it to Edward Franklin, who was the first of a series of owners. Dr. Strentzel purchased the building from Thomas Redfern in 1874. Strentzel used the building for storage and as a residence for his foremen. Contrary to legend, John and Louie Muir never lived in the Martinez Adobe, but it was once the home of their elder daughter, Wanda, and her husband, Tom Hanna. John Muir would often eat meals at the Martinez Adobe and play with his grandchildren there (National Park Service 2017). The National Park Service acquired the Martinez Adobe in 1966.

The Martinez Adobe stands at the western end of the House Unit. Like the Muir House, the Martinez Adobe is underlain by younger alluvium (**Qal**; see poster and "Fluvial Features and Processes").

The architectural vernacular of the Martinez Adobe is classic California–Mexican style ranchero (Burke et al. 1992). The footprint of the two-story building is roughly 14 m × 6 m (45 ft × 20 ft) or 84 $m^2$ (900 $ft^2$) with walls constructed of adobe block surfaced with either stucco or sheathed with timber lap planks (see fig. 5). The long walls (east and west) run in a north–south direction. The main entrance is on the east side of the building, which has stucco coating for both the first and second floors. The rest of the exterior walls are covered with wooden horizontal lap planks, except the upper 0.9 m (3 ft) of the west wall where it meets the roof (Mason 2020).

Some preliminary information is known about the materials used in construction of the Martinez Adobe:

- The foundation of the Martinez Adobe is "rough stone" (National Park Service 2017). Kelly (1981) described the foundation as composed of sandstone masonry with individual stones bounded by a small amount of adobe mortar. Burke et al. (1992, p. 90) noted "sandstone cobbles" used in construction of the Martinez Adobe. The provenance of this stone is speculative: it could have come from marine bedrock exposed along the north and south sides of Carquinez Bay or along both sides of the foothills east and west of Alhambra Creek, or even from Franklin Creek (Burke et al. 1992). The foundation was apparently begun by layering rocks on a natural, unprepared earth surface (Kelly 1981). The framed additions on the west side of the building have a concrete foundation (Burke et al. 1992).
- The walls of Martinez Adobe are sun-dried adobe brick ranging in thickness from 60 to 80 cm (24 to 30 in; National Park Service 2017). Soil tests conducted on the existing adobe and samples taken on the site indicate that the Martinez Adobe was constructed of material found in the immediate area (Burke et al. 1992), possibly the banks of Franklin Creek (Fitzgerald and Dorrance 2004), but the exact location is unknown. Soils in the "immediate area" include Botella clay loam, which underlies the Martinez Adobe; Los Gatos loam, which underlies the Muir House; Los Osos clay loam, and Garretson loam (fig. 6).
- Some bricks under the porch of the Martinez Adobe have "CARNEGIE" or "CASCO" stamped into them. In the later 19th and early 20th century, stamping bricks with a manufacturer's name became the practice. Carnegie bricks were manufactured between the 1890s and 1906 by Carnegie Brick and Pottery Company, located at Carnegie, San Joaquin County, near present-day Tracy, California (Rensch et al. 1933). Casco bricks were likely from a local brick yard, but precise identification has not been made (Kelly 1981).

Similar to, or in association with, an inventory of building stone for the Muir House, an inventory of the Martinez Adobe could be conducted. Analysis of adobe pieces for pollen would help in the description of the environmental conditions of Martinez, California, during the 1840s (Kelly 1981). Palynology (the study of pollen and spores and their dispersal) is a useful tool in many applications, including geoarcheological (multidisciplinary approach that uses the techniques and methods of the earth sciences to examine topics that inform archeological knowledge and thought, and vice versa) and paleontological (see "Paleontological Resource Inventory, Monitoring, and Preservation") applications.

A preliminary search of the Web Soil Survey (Natural Resources Conservation Service 2019; see "Guidance for Resource Management") showed that Botella clay loam underlies the Martinez Adobe (see fig. 6). The Botella Series consist of moderately well-drained to well-drained soils on alluvial fans and floodplains. These soils are formed from clasts of sedimentary rock in alluvium (Burke et al. 1992).

**Figure 5. Photograph of Martinez Adobe.**
**Located on the grounds of the House Unit, the Martinez Adobe represents California's Spanish Colonial and Mexican history. The historic site is a "stop" on the Juan Bautista de Anza National Historic Trail because of proximity to the trail and the presence of the Martinez Adobe. During the Strentzel–Muir era, the Martinez Adobe served as the house for Dr. Strentzel's ranch foreman and the home of Wanda and Tom Hanna, but never John and Louie Muir. NPS photograph, photographer unknown.**

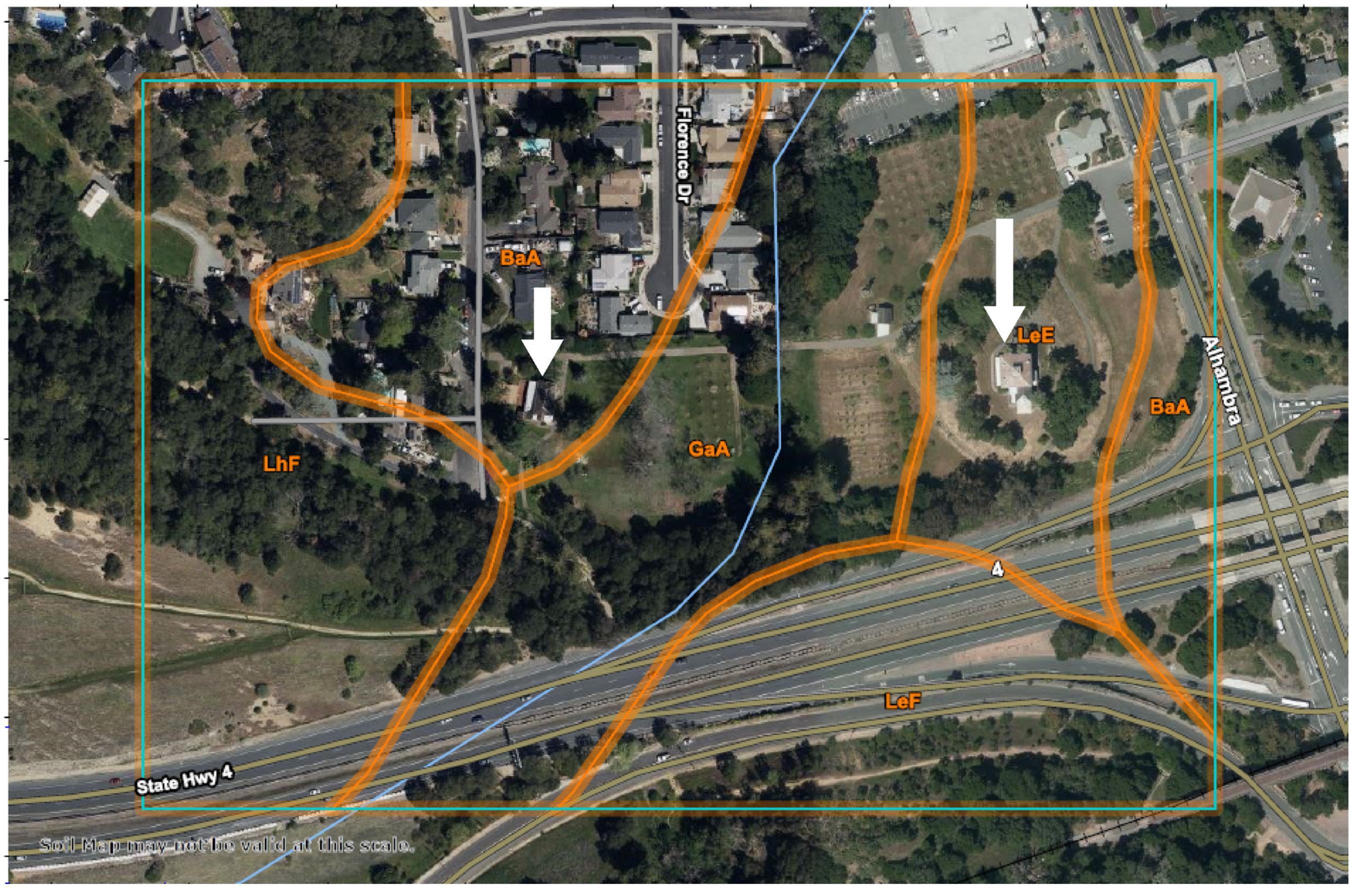


**Figure 6. Map of soils at the House Unit.**
**Marked by white arrows on the figure, the Muir House (on the right) is on LeE (Los Gatos loam, 15 to 30 percent slopes); the Martinez Adobe (on the left) is on BaA (Botella clay loam, 0 to 2 percent slopes). GaA = Garretson loam, 0 to 2 percent slopes. Lhf = Los Osos clay loam, 30 to 50 percent slopes. LeF = Los Gatos loam, 30 to 50 percent slopes. The green outline indicates the area of interest (AOI) selected in the Web Soil Survey. Orange lines delineate the area covered by a particular soil map unit. Graphic compiled by Katie KellerLynn (Colorado State University) using data from the Web Soil Survey (Natural Resources Conservation Service 2019).**

*Strentzel-Muir Gravesite*

In December 1914, John Muir caught a cold on a train ride on his way to visit his daughter Helen and her family in Daggett, California. The cold quickly turned to pneumonia, and Muir died in a Los Angeles hospital on 24 December 1914; he was 76.

Muir was buried next to his wife Louie, who died in 1905, at the family gravesite on the west bank of Alhambra Creek (technically Arroyo del Hambre; see "Fluvial Features and Processes"). His funeral service was held under the spreading branches of a eucalyptus tree that he had admired; the tree still stands at the site today.

In addition to the graves of John and Louie Muir, the Strentzel-Muir family gravesite (fig. 7) contains the graves of Louie's parents—John (died 1890) and Louisiana (died 1897) Strentzel—as well as John and Louie's daughter Wanda (died 1942) and son-in law Tom Hanna (died 1947). Also, the gravesite has markers for Jonnie (John Erwin, the Strentzel's son; died 1857), Lottie (the Strentzel's other daughter; date of death unknown), and Uncle Henry (Dr. Strentzel's brother; died 1865), though their bodies may not actually be interred here (Killion 2005; National Park Service 2015). John and Louie's daughter Helen (died 1964) is buried offsite, next to her husband, Buel Alvin Funk, at Bellevue Memorial Park in Ontario, San Bernardino County, California.

The gravesite, which is in the Gravesite Unit (see fig. 2), is a fundamental resource and value of the historic site (National Park Service 2015). A "quiet residential neighborhood" containing post–World War II era, single-family residences on 0.4-ha (1-ac) lots surrounds


**Figure 7. Photographs of the Strentzel-Muir gravesite.**
**Geologic resources at the Gravesite Unit include the stone of grave markers and the surrounding coping. Granite makes up various elements of the gravesite including the dark Black Academy granite of John Muir and Louie Strentzel Muir's grave markers and the light-colored Raymond granite of the Strentzel obelisk. The coping also is composed of Raymond granite. NPS photographs from National Park Service (2015, p. 8 [top] and 38 [bottom]).**

the Gravesite Unit (National Park Service 2015, p. 37). The geologic connection of the Gravesite Unit is fluvial; that is, the gravesite is situated on younger alluvium (**Qal**) and bounded on the southeast by Alhambra Creek.

Prior to establishment of the historic site, the gravesite served as a gathering place and memorial area for those inspired by Muir. His death from pneumonia little more than a year after the loss of Hetch Hetchy led to popular depictions of Muir as a martyr to the cause of environmental preservation and helped ensure that "Hetch Hetchy" would be a watchword for the conservation movement to the present day (Johnson 2019). The pear orchard and historic specimen trees at the gravesite bear witness to the years of pilgrimage by members of the Muir family, the Sierra Club, local historians, and the John Muir Memorial Association, who all fought for and achieved recognition of Muir's legacy through designation of John Muir National Historic Site as a unit of the National Park System (National Park Service 2015).

Like the Muir House and Martinez Adobe, the gravesite could benefit from a thorough geologic inventory of materials. The historic site's cultural landscape report (Killion and Davison 2005) provides some pertinent information for tracking down the origins of the grave markers, so a preliminary discussion is provided here. According to Killion and Davison (2005), "Raymond granite" (commercial name) composes the base of John Muir's grave marker, John Strentzel's grave marker (a three-tiered obelisk), the coping that surrounds the gravesite, and three small headstones (for Jonnie, Lottie, and Henry Strentzel). The Raymond Granite Company had quarries in Raymond, California, which is in the Sierra Nevada. In addition, Killion and Davison (2005) noted that the top stone of John Muir's grave marker is "Black Academy granite." A preliminary online search suggests that Black Academy granite comes from the Academy pluton—an igneous intrusion at the western edge of the Sierra Nevada (StonePly Co. 2020). It seems appropriate that the origins of Muir's grave marker are from his beloved Sierra Nevada. The small headstones of Wanda and Tom Hanna's graves are made of part of a granite millstone that had been used at the Hanna gold mine near Lundy, California. In 1916, Wanda and Tom Hanna moved to Crockett, California (west of Martinez); from there, they owned and operated the gold mine in Lundy, as well as a lumber yard in Berkeley (Ryan 1979; Killion and Davison 2005).

### *Windmills and Wells*

Today, the primary source of water for the 500,000 residents of the Contra Costa Water District is the Sacramento–San Joaquin Delta, which is at the confluence of these rivers, north of the historic site. Water originating from rivers within the Sierra Nevada flows into the Sacramento and San Joaquin Rivers and eventually finds its way into the delta (Contra Costa Water District 2020). In 1955, the historic site was "hooked up to city water" (Killion and Davison 2005, p. 496).

Historically, however, water used at the historic site—for irrigating fruit trees and vines, watering landscape plants, and supplying the buildings—was pumped from Franklin Creek and Alhambra Creek via windmills. Windmills and wells are part of the historic site's cultural landscape, which is a fundamental resource and value (National Park Service 2015).

The reconstructed "Franklin Creek windmill" (fig. 8) evokes historic character and stands on the property today (Killion 2005). The "Alhambra windmill"—constructed by 1898, probably to irrigate nearby fields and possibly to supply water to the Muir House and fill the water tank in the back addition—was located northeast of the Muir House at the bottom of the knoll. That windmill was dismantled in the early 1960s prior to establishment of the historic site, though the well was retained and in 1989 improved to provide water for irrigation (Killion 2005). Two additional windmills, and associated wells, stood on the property, but whether they served the Muir House is unclear (Killion and Davison 2005).

**Figure 8. Photograph of Franklin Creek windmill and well.**
**Windmills and wells provide a geologic–cultural connection at the historic site. Historically, the source of well water at the historic site was surface water (not groundwater) that was pumped from nearby creeks. The Strentzels and Muirs used water to irrigate orchards, vineyards, and landscape plants, as well as to supply the buildings for domestic uses. NPS photograph from National Park Service (2015, p. iv).**

Dr. Strentzel took special care to ensure a reliable water supply at the Muir House. In addition to a well dug in May 1882 west of the house near Franklin Creek and a 49,000-L (13,000-gal) cistern, a water tank was installed in the attic and was supplied either by rainwater or well water pumped by the windmill along Franklin Creek (Killion and Davison 2005).

Between 1907 and 1910, a 9-m- (30-ft-) deep well was dug a short distance northeast of the Martinez Adobe to supply water to the building and water plants. That windmill is no longer standing. At the time the well was dug, Wanda Muir Hanna and her husband Tom inhabited the Martinez Adobe. From 1915 to 1917, the well was covered with boards. The location of this feature, identified by a simple wood cover, shows the importance and convenience of having a well close by during this moment in history (Killion 2005).

### *Mount Wanda Unit*

Mount Wanda is named for John Muir's elder daughter, Annie Wanda Muir Hanna (US Board on Geographic Names 1995b). The summit is 198 m (650 ft) above sea level. South of Mount Wanda, but still in the Mount Wanda Unit (see fig. 2), Mount Helen is named for the Muir's younger daughter, Helen Lillian Muir Funk (US Board on Geographic Names 1995a). Standing 209 m (686 ft) above sea level, Mount Helen is taller than Mount Wanda. The Geographic Names Information System (GNIS; see "Additional References, Resources, and Websites") does not provide the Native names of these two summits.

The summits of both Mounts Wanda and Helen are composed of the Great Valley sequence, sandstone, siltstone, and clay shale (map unit **Kus**). Slopes are composed of the Great Valley sequence, sandstone (**Kcs**), as well as the Martinez Formation, lower member (**Tmzl**). The Great Valley sequence was deposited during the Cretaceous Period (145.0 million to 66.0 million years ago). The Martinez Formation was deposited during the late Paleocene Epoch (59.2 million to 56.0 million years ago). Both the Great Valley sequence and the Martinez Formation originated under marine conditions as part of the forearc basin of a subduction zone (see "Geologic Setting").

The convex profiles, narrow valleys, and steep slopes of the Mount Wanda Unit (fig. 9) are consistent with broad uplift that coincided with the land surface rising above sea level by 6 million years ago (Haydon 1995; Moore 2006). This change from marine to terrestrial conditions took place rather quickly in terms of geologic time (over 5 million years; Graham et al. 1983) between deposition of the upper Miocene Neroly Formation (see GRI GIS data; this map unit [**Tpn**] is not shown on the poster), which is the last marine unit near the historic site, and the upper Miocene Orinda Formation (see GRI GIS data; this map unit [**Tco**] is not shown on the poster), which is the first nonmarine unit near the historic site.

Although it does not crop out in the historic site, the Neroly Formation near the historic site yields abundant fossil clam shells, molds, and casts in fine to medium grained sandstone, and in places is almost a coquina (limestone composed almost entirely of cemented shell fragments; Haydon 1995). These features are indicative of its marine origin. Another interesting fact is that the volcanic-derived sediments of the Neroly Formation record the last of arc volcanism (subduction-related volcanic eruptions) in the Sierra Nevada (Graham et al. 1983; see "Geologic Setting").

The source of the nonmarine Orinda Formation is the local Franciscan Complex, which by that time had been accreted to the North American continent, lifted above sea level, and eroded to provide clastic material to the Orinda Formation (see "Geologic Setting").

The summit area of the Mount Wanda Unit is on the axis of an anticline (upward arching of rock layers), which explains the incongruity of older rock units (at the summits) above younger rock units (on the flanks). The anticline formed less than 3 million years ago (see "Anticline").

## Geologic Connections to John Muir

Principally known for the role he played in the protection and preservation of national parks and other natural areas, John Muir was also a man of science who enthusiastically shared his contemporaries' interest in the progress of scientific and technical knowledge (Collomb 2010). The following descriptions make connections to John Muir's geologic interests and experiences.

### *John Muir and Earthquakes*

Since 1700 CE, California has experienced at least 78 "significant" earthquakes, meaning an earthquake with magnitude (M) 6.5 or greater, or an earthquake that caused loss of life or more than $200,000 (not adjusted for inflation) in damage (California Geological Survey 2019). Two of these earthquakes took place while John Muir was living in California: the 1872 Owens Valley earthquake (M 7.4 with two M 6.8 aftershocks) and the 1906 San Francisco earthquake (M 7.8).

**Figure 9. Photographs of the Mount Wanda Unit.**
**Oak woodlands and grasslands cover the Mount Wanda Unit. An anticline runs through the unit, doming the landscape upward. The Great Valley sequence, sandstone, siltstone, and clay shale (map unit Kus) underlies the summit area. The Great Valley sequence, sandstone (Kcs), and Martinez Formation, lower member (Tmzl), make up the flanks of the anticline. Top: NPS photograph from Martin and Denn (2017, figure 3). Bottom: NPS photograph from National Park Service (2015, p. 33).**

### Owens Valley Earthquake

In his books, *Our National Parks* (Muir 1901a) and *The Yosemite* (Muir 1912), Muir described the spectacular rockfall triggered by the Owens Valley earthquake on 26 March 1872:

> In Yosemite Valley, one morning about two o'clock I was aroused by an earthquake; and though I had never before enjoyed a storm of this sort, the strange, wild thrilling motion and rumbling could not be mistaken, and I ran out of my cabin, near the Sentinel Rock, both glad and frightened, shouting, "A noble earthquake!" feeling sure I was going to learn something. The shocks were so violent and varied, and succeeded one another so closely, one had to balance in walking as if on the deck of a ship among the waves, and it seemed impossible the high cliffs should escape being shattered. In particular, I feared that the sheer-fronted Sentinel Rock, which rises to a height of three thousand feet, would be shaken down, and I took shelter back of a big Pine, hoping I might be protected from outbounding boulders, should any come so far. I was now convinced that an earthquake had been the maker of the taluses and positive proof soon came. It was a calm moonlight night, and no sound was heard for the first minute or two save a low muffled underground rumbling and a slight rustling of the agitated trees, as if, in wrestling with the mountains, Nature were holding her breath. Then, suddenly, out of the strange silence and strange motion there came a tremendous roar. The Eagle Rock, a short distance up the valley, had given way, and I saw it falling in thousands of the great boulders I had been studying so long, pouring to the valley floor in a free curve luminous from friction, making a terribly sublime and beautiful spectacle—an arc of fire fifteen hundred feet span, as true in form and as steady as a rainbow, in the midst of the stupendous roaring rock-storm. The sound was inconceivably deep and broad and earnest, as if the whole earth, like a living creature, had at last found a voice and were calling to her sister planets. It seemed to me that if all the thunder I ever heard were condensed into one roar it would not equal this rock roar at the birth of a mountain talus (from *Our National Parks*, chapter 8: "The Fountains and Streams of the Yosemite National Park," no page numbers in online version).

In later years, this account was used to determine the far-reaching impacts of the Owens Valley earthquake, as summarized in two USGS Professional Papers—160 (Matthes 1930) and 1551 (Wallace 1990). Matthes (1930) highlighted Muir's experience of the rockfall in a discussion of the postglacial history of Yosemite Valley. Muir was so impressed by the sight of the great avalanche of bounding rock fragments that he attributed most ("more than nine-tenths") of the talus in the valley to earthquake activity; Matthes (1930) agreed that a considerable part of the "waste rock" was of earthquake origin. Nearly eight decades after Muir's death, Wallace (1990) compiled knowledge about the San Andreas Fault system, incorporating some of Muir's observations.

### San Francisco Earthquake

The 1906 San Francisco earthquake was one of the costliest natural disasters in the history of the United States and the deadliest in California's history. The earthquake and resulting fire killed more than 3,000 people and destroyed more than three-quarters of that city. During the earthquake, the San Andreas Fault ruptured along approximately 477 km (296 mi) of its length, from San Juan Bautista, through Golden Gate National Recreation Area (see GRI report by Port 2016), to the Mendocino triple junction at Shelter Cove (see GRI report about Redwood National and State Parks by KellerLynn in review).

During the infamous San Francisco earthquake, which occurred on 18 April 1906, Muir was in Adamana, Arizona, with his daughter Helen, who was convalescing from a respiratory disorder in the dry heat of the desert. A letter written by Wanda to her father on 18 April 1906 noted that "At five o'clock this morning the worst earthquake ever known struck Alhambra Valley and left the houses in it a wreck. Every one of four of our five chimneys are down…The only house in the valley that is not hurt is the adobe" [in actuality, the chimney and north wall of the Martinez Adobe were damaged]. Wanda goes on to write, "Most all of Martinez is in ruins. There are rumors of awful things in San Francisco, but as all the telegraph wires are down and there are no trains running. I don't know how true they are" (Clark and Sargent 1983, p. 87).

Soon after the earthquake, Muir returned to Martinez to inspect the damage, and daughter Wanda travelled to Arizona to be with Helen, despite Wanda's upcoming wedding to Tom Hanna in June 1906. Once home, Muir determined that the damage to the Muir House was not as severe as Wanda had reported, though many of the chimneys were destroyed, especially on the east side of the house. Muir repaired the damaged chimneys and decided to use the opportunity to make some changes to the house, including the construction of a massive brick fireplace in the east parlor (fig. 10), where he could build a "real mountain campfire" (Killion and Davison 2005, p. 118). Muir also opened up the two first-floor parlors with large archways and a smaller one into the dining room (National Park Service 2017).

**Figure 10. Photograph of brick fireplace. As a result of damage caused by the 1906 San Francisco earthquake, John Muir replaced the original fireplace in the east parlor of the Muir House with a large, mission-style one. Photograph by Stephanie Wright Hession (author of "Bay Area Arts"; see Wright Hession 2013), used by permission.**

The north wall and chimney of the Martinez Adobe suffered extensive damage during the 1906 earthquake. Soon after, Wanda Muir and her husband Tom Hanna remodeled the building into a residence, replacing the north wall with wooden clapboards; building a new chimney and fireplace; installing electricity and an upstairs lavatory; and removing the lean-to, cistern, and other farm equipment that had accumulated around the building (Fitzgerald and Dorrance 2004).

Another connection between the San Francisco earthquake and John Muir is to a colleague, Groves Karl Gilbert. In 1899, Muir and Gilbert were both part of the Harriman Expedition in Alaska. Organized by wealthy railroad magnate Edward Harriman, the expedition explored the coast of Alaska—from Seattle to Alaska and Siberia and back—on the steamship SS *George W. Elder* for two months (31 May–30 July 1899). Harriman brought with him an elite community of scientists, artists, photographers, and naturalists to explore and document the Alaskan coast. The passengers on the ship were some of the most famous and influential people in America at that time.

As the top field geologist of his day, G. K. Gilbert was an obvious choice for the scientific team on the Harriman Expedition. He camped with John Muir during the expedition (PBS 2005). Gilbert used his time on the voyage to consider the physics of glacial geology and geomorphology. He took many photographs and set out to build a reliable set of data about Alaskan glaciers, which were useful at the time and for years to come. Based on a letter written in Portland, [Oregon], from Gilbert to Muir on 3 September 1899, it seems possible that Gilbert visited Muir in Martinez later that month (Gilbert 1899).

Following the San Francisco earthquake in 1906, G. K. Gilbert joined the investigation team that looked into the geologic causes of the disaster. Gilbert took a (now) well-known series of photographs documenting the damage along the San Andreas Fault from Inverness to Bolinas. His photographs, diagrams, and descriptions of the behavior of the San Andreas Fault during that earthquake are data that have been used repeatedly. Gilbert's studies of the earthquake stand out to present-day investigators as his principal contribution to the knowledge of earthquakes (Wallace 1990). Moreover, Gilbert's paper "Earthquake Forecasts" (Gilbert 1909) was the only paper about earthquake predictions listed in the USGS bibliography, *Geologic Literature on North America, 1785–1918* (Nickles 1923). The issues and concepts—earthquake prediction, earthquake engineering, land use, risk evaluation, and insurance—in Gilbert's paper anticipated many elements of the Earthquake Hazard Reduction Act of 1977 (Yochelson 1980).

One final example of Muir's connection to the San Francisco earthquake is that the earthquake and subsequent fire increased the City of San Francisco's determination to find a reliable source of water (Good 2000). Notably, interest was not only for fire safety but for developing hydroelectricity. Early efforts to build a dam in the Hetch Hetchy Valley—the glacial valley in the northwestern part of Yosemite National Park drained by the Tuolumne River—were denied by Congress. Following the devastation caused by the 1906 earthquake and fire, however, a sympathetic Congress passed, and President Woodrow Wilson signed, the

Raker Act in 1913, which allowed the City of San Francisco to build the water project it had long sought (Rosekrans 2017). In short, the 1906 San Francisco earthquake is linked to Muir's most famous and perhaps most frustrating conservation battle—the damming at Hetch Hetchy.

### *John Muir and Fossils*

After the death of his wife Louie in 1905, John Muir traveled to the dry desert climate of Arizona to assist his daughter Helen's recovery from a respiratory disorder. As a student at the University of Wisconsin, Muir completed courses in geology, and he used this knowledge to undertake excavations of fossils near Adamana, Arizona (fig. 11). Muir captured his observations of the Petrified Forest in his correspondence, notebooks, and sketchbooks but never published an article about his findings (Elder et al. 2008).

**Figure 11. Photograph of John Muir in the Petrified Forest of Arizona (ca. 1905–1906).**
**Although Muir never published an article about the Petrified Forest of Arizona, his observations are recorded in correspondence to others as well as his own notebooks and sketchbooks. NPS photograph (JOMU 3268.168) courtesy of John Muir National Historic Site.**

Muir's most important contribution to come out of his travels in the Petrified Forest was the recognition and naming of the Blue Forest (now Blue Mesa; fig. 12), a rich deposit of petrified logs exposed approximately 10 km (6 mi) south of Adamana (Lubick 1996). The Blue Mesa Member is part of the well-known Triassic Chinle Formation. The Blue Mesa Member contains most of the known fossil leaf localities of the Chinle Formation. Additionally, the Blue Mesa Member yields abundant petrified wood and other plant remains, as well as fungi, invertebrate body and trace fossils, and vertebrate body and trace fossils.

After his departure from Adamana and the Forest Hotel in August 1906, John Muir contacted paleontologist John C. Merriam of the University of California. Muir presented Merriam with a small collection of vertebrate fossils he had collected from the Petrified Forest. These remains were identified as phytosaur and placed in the university's paleontology collection (Elder et al. 2008).

With respect to vertebrate remains, the historic site has a single tusk cataloged in its collection. John Muir collected the tusk in 1881 in Kotzebue Sound, Eschscholtz Bay, Alaska. Muir discussed the find in his book *The Cruise of the Corwin* (Muir 1917). The tusk is a 30 cm (12 in) section at the alveolar end (closest to the jawbone) with the other end sawed flat. It appears to be from a woolly mammoth (*Mammuthus primigenius*; Mead et al. 2020).

Based on John Muir's behavior (e.g., collecting this tusk in Alaska and fossils in the Petrified Forest), it seems likely that he collected other specimens. Consequently, a paleontological inventory of the historic site's museum collection is warranted. In addition, an investigation of other repositories (e.g., University of California) may yield additional specimens collected by Muir during his travels (see "Paleontological Resource Inventory, Monitoring, and Protection").

### *John Muir and Glaciers*

John Muir is well known as a mountaineer, naturalist, and writer, but less well known as a glaciologist. Muir spent five summers, beginning in 1869, meticulously cataloging the glaciers of the Sierra Nevada, ultimately documenting 65 (Muir 1873).

John Muir was the first to point out that the glaciers of the High Sierra were "true glaciers" (moving bodies of snow and ice), not simply snowfields (Matthes 1930). He gathered evidence of glacial movement, borrowing a technique from his predecessors. By placing a straight row of stakes across the surface of McClure Glacier, for example, and returning seven weeks later, Muir was able to show that the stakes (and therefore the glacier) had moved (Dean 1995).

In addition, Muir recognized various landscape features as deposited by the direct action of glaciers. He wrote about moraines (ridges or other distinct accumulations

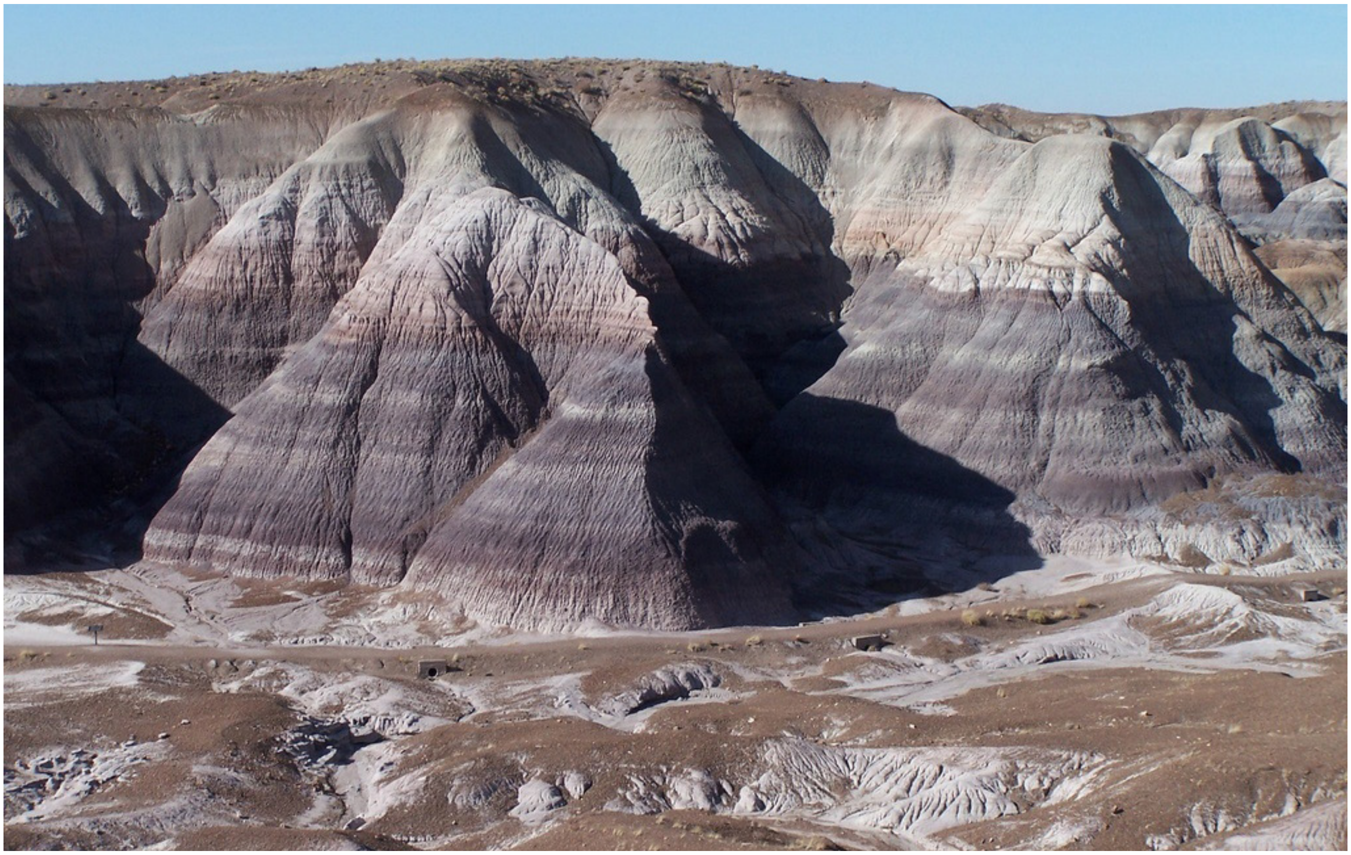

**Figure 12. Photograph of the Blue Mesa area at Petrified Forest National Park, Arizona. The colorful hills, flat-topped mesas, and sculptured buttes of the park's badlands are composed of the Upper Triassic Chinle Formation, named for the Chinle Valley north of the park. The horizontal bands are paleosols (ancient soil layers). The area, originally named "Blue Forest" by John Muir, is now called "Blue Mesa." NPS photograph by Marge Post.**

of unsorted and unstratified rock material [clay, silt, sand, gravel, and boulders]) as documenting glacial activity and extent. He also noted certain sand-and-gravel deposits as indicative of temporary glacial lakes (Matthes 1930).

Muir also studied the effects of glacial scouring and quarrying and was convinced that glacial ice (rather than fluvial activity) was responsible for features such as rugged mountains, rounded domes, pointed spires, steep-sided canyons, U-shaped valleys, and concave lakes in the Sierra Nevada (Dean 1995). "It was John Muir, the keen student and ardent lover of nature, who first saw clearly that the glaciers themselves had done most of the excavating" (Matthes 1930, p. 4).

Muir took his thinking about glacial excavation and applied it to the entire Yosemite Valley, which was a controversial step at that time because the prevailing scientific hypothesis was catastrophic; that is, "the valley had come into existence suddenly as the result of a violent convulsion of the earth, its bottom dropping out, so to speak, leaving the sheer walls standing" (Matthes 1938, p. 9). At the age of 30, Muir dared to oppose the dictum of Josiah Dwight Whitney, one of the foremost geologists of his time. Whitney was the state geologist of California (1860–1874) and professor of geology at Harvard University (1865–1896). Mount Whitney—4,413 m (14,478 ft) above sea level and the highest point in the lower 48 states—is named in his honor. Whitney ridiculed Muir's ideas as "the wild fantasies of an ignorant shepherd" (Matthes 1938, p. 9). Whitney had seen and noted glaciers and glacial features in California, so his repudiation of observable facts and Muir's ideas is rather astounding. Perhaps "Whitney's intense pique that a geologist with his reputation should have been proved wrong on so important a matter as the valley's origin" (Colby 1950, p. 4) explains his rejection of Muir's ideas. Whitney's theory, when announced, had been quite generally accepted as providing a plausible and satisfactory explanation. "To have it undermined must have been gall and wormwood to his proud nature, unduly sensitive to criticism as he was" (Colby 1950, p. 4).

Because of Whitney's doubts and diatribes, John Muir was naturally anxious to fortify his own views (Colby 1950). Thus in 1879, Muir headed to Alaska where large glaciers were performing the same sort of work that had taken place in the geologic past in the Sierra Nevada. In his book, *Travels in Alaska*, published posthumously in 1915, Muir tells of his various trips to the northwest coast, which were in large part devoted to an intimate and detailed study of Alaskan glaciers. He was a pioneer in these explorations, the first to map parts of this rugged coast, and a keen observer and recorder of fiords and the actions of tidewater glaciers. In 1893, Muir visited Switzerland and the fiords of Norway, searching for—and finding—further confirmation of his views (Colby 1950). Heacox (2014) argued that the glaciers of Alaska inspired Muir's fiercest passion for wilderness and animated his efforts to protect wild places.

Muir's painstaking study of glacial features, cogent reasoning based on observation, and published findings of "Studies in the Sierra" (Muir 1874a–f, 1875c) ultimately convinced the scientific community of the glacial origin of Yosemite Valley. Joseph LeConte, a distinguished geologist who along with his brother John LeConte, organized the University of California (Sierra Club 2020), was one of the first to recognize the accuracy of Muir's observations. In the paper, "On Some of the Ancient Glaciers of the Sierra Nevada," which appeared in the *American Journal of Science*, LeConte (1875) referenced "Studies in the Sierra" and credited Muir for his discoveries. Muir and LeConte became long-time friends, as illustrated in "Reminiscences of Joseph LeConte" (Muir 1901b).

Notably, at the time of the Harriman Expedition, one of the largest glaciers in Glacier Bay was already named for Muir (fig. 13). It was Muir's expertise in glaciology, along with his broad background in nature study, that prompted Edward Harriman to invite Muir to join the expedition (PBS 2005). Muir had traveled to Alaska on previous trips and was a recognized authority on glaciers there. Despite Muir's lack of formal education, the other participants of the expedition considered him the group's "foremost investigator" of glaciers (Dean 1995).

**Figure 13. Repeat-photography images of Muir Glacier in Glacier Bay National Park, Alaska. Top: The black and white photograph of the calving face of Muir Glacier was taken in 1899 by G. K. Gilbert of the US Geological Survey while on the Harriman Expedition. John Muir also was on that expedition. Bottom: The color photograph depicting the modern ice-free conditions of Muir Inlet was taken by Ron Karpilo in September 2003. Today, Muir Glacier is less impressive as it has retreated onto land and is no longer a calving, tidewater glacier (Ron Karpilo, Colorado State University, research associate, email communication, 16 April 2020).**

# Geologic Features and Processes

*The geologic features and processes highlighted in this chapter are significant for the historic site's landscape and history. Selection of these features and processes was based on input from scoping and conference-call participants, analysis of the GRI GIS data, and research of the scientific literature and NPS reports. These features and processes are discussed more-or-less in order of geologic age (oldest to youngest). A geologic time scale (table 1) shows the chronology of geologic events (bottom to top) that led to the historic site's present-day landscape; this story covers more than 145 million years.*

This report links the geologic features discussed to the GRI GIS data by using map unit symbols. The bedrock at the historic site, for example, consists of the Great Valley sequence, sandstone, siltstone, and clay shale (map symbol **Kus**); the Great Valley sequence, sandstone (**Kcs**); and the Martinez Formation, lower member (**Tmzl**). "**K**" in a map unit symbol represents the Cretaceous Period (~145.0 million to 66.0 million years ago). "**T**" stands for Tertiary, which is a widely used but obsolete term for the geologic period from 66.0 million to 2.6 million years ago. Following Haydon (1995), GRI products use the term and symbol (**T**). In current geologic nomenclature, the Paleogene (66.0 million to 23.0 million years ago) and Neogene (23.0 million to 2.6 million years ago) Periods have replaced the Tertiary. The Paleocene rocks discussed in this report correspond to the Paleocene Epoch (66.0 million to 56.0 million years ago), which is the oldest epoch of the Paleogene Period. A geologic time scale, which lists all the map units in the historic site, is provided as table 1.

**Table 1. Geologic time scale.**

The geologic time scale puts the divisions of geologic time in stratigraphic order, with the oldest divisions at the bottom and the youngest at the top. For a geologic history of the historic site, read the "Geologic Events" from bottom to top. Figures 14, 15, 17, and 19 help to illustrate "Geologic Events." GRI map abbreviations for each time division and map unit symbols are in parentheses. With the exception of landslides (Qls), only geologic units mapped within the historic site are included in the table. Boundary ages (Years Ago) follow the International Commission on Stratigraphy (2020).

| Geologic Time Units | | Years Ago | Map Unit in the GRI GIS data | Geologic Event |
|---|---|---|---|---|
| Quaternary Period (Q) | Holocene Epoch (H) | 11,700–today | Faults | Ongoing seismicity serves as evidence of continued tectonic activity. Historic earthquakes take place, including the 1906 San Francisco earthquake. |
| Quaternary Period (Q) | Late Pleistocene (PE)–Holocene (H) Epochs | 126,000–today | Younger alluvium (**Qal**) | • Historic flooding takes place in 1915, 1937, and 1958.<br>• In the past 126,000 years, modern floodplains and stream channels develop. |
| Quaternary Period (Q) | Late Pleistocene (PE)–Holocene (H) Epochs | 126,000–today | Faults | Less than 126,000 years ago, initial rupturing of the Concord fault (east of the historic site) occurs. |
| Quaternary Period (Q) | Pleistocene (PE) and Holocene (H) Epochs | 2.6 million–today | Landslides *Note*: No large landslide deposits (**Qls**) are found in the historic site, but many smaller landslides, debris flows, areas of mass movement, and gullies occur. | Slope movements become prominent on the landscape. |

**Table 1, continued. Geologic time scale.**

| Geologic Time Units | | Years Ago | Map Unit in the GRI GIS data | Geologic Event |
|---|---|---|---|---|
| Quaternary Period (Q) | Pleistocene (PE) and Holocene (H) Epochs | 2.6 million–today | n/a | • Outflow of the Sacramento and San Joaquin Rivers through the Carquinez Strait develops about 800,000–650,000 years ago (Will Elder, Golden Gate National Recreation Area, visual information specialist, written communication, 11 February 2021).<br>• Over the past 2.6 million years, rivers and tributary streams develop and flow across the landscape. |
| Quaternary Period (Q) | Pleistocene Epochs (PE) | 2.6 million–11,700 | Faults and folds | • About 2 million years ago, Mount Diablo rises up (Dawson 2015); uplift continues to the present day.<br>• Less than 3 million years ago, folding and faulting associated with compression along major faults takes place. Older strata are turned up along the flanks of present ranges (Christensen 1965). The historic site's anticline forms (see fig. 19). |
| Tertiary (T) or Neogene Period (N) | Pliocene Epoch (PL) | 5.3 million–2.6 million | Faults and folds | • About 4 million years ago, the San Andreas Fault becomes the principal element of the transform plate boundary (see fig. 14), and modern landscape development ensues.<br>• The San Andreas Fault system (see fig. 17) has been developing in this area for some millions of years (see Miocene Epoch below), but a shift in plate motion around 4 million years ago causes more compression on the transform boundary, and uplift and folding increase. |
| Tertiary (T) or Neogene Period (N) | Miocene Epoch (MI) | 23.0 million–5.3 million | Faults | • By 6 million years ago, tectonic forces have lifted the landscape above sea level, and conditions have shifted from marine to nonmarine (Haydon 1995).<br>• About 8 million to 6 million years ago, initial wrenching on the Calaveras fault (south of the historic site) takes place (Graham et al. 1983).<br>• Between about 10 million and 7 million years ago, initial rupturing of the Hayward fault (east of the historic site) takes place (Graham et al. 1983).<br>• About 10 million years ago, the Coast Ranges are submerged. Starting in the south and progressing northward, emergence begins as the Mendocino triple junction migrates northward (Lock et al. 2006).<br>• Between 15 million and 12 million years ago, volcanism in the East Bay Area indicates movement of the Mendocino triple junction through the area and establishment of the transform plate boundary (Will Elder, Golden Gate National Recreation Area, visual information specialist, written communication, 11 February 2021).<br>• About 15 million to 7 million–5 million years ago, transition from a convergent plate boundary (subduction zone; see fig. 15) to a transform plate boundary takes place (Buising and Walker 1995; Atwater and Stock 1998; McLaughlin et al. 2012). |

**Table 1, continued. Geologic time scale.**

| Geologic Time Units | | Years Ago | Map Unit in the GRI GIS data | Geologic Event |
|---|---|---|---|---|
| Tertiary (T) or Paleogene Period (PG) | Oligocene Epoch (OL) | 33.9 million–23.0 million | n/a | About 28 million years ago (Atwater 1970, 1989), the East Pacific rise (spreading center between the Farallon plate and Pacific plate) makes contact with the western margin of the North American plate and begins to subduct beneath it. Also, the Mendocino triple junction (where the Gorda, Pacific, and North American plates meet) forms in southern California and begins to propagate northward. |
| Tertiary (T) or Paleogene Period (PG) | Eocene Epoch (E) | 56.0 million–33.9 million | n/a | At 36 million years ago, subduction continues; the subduction margin of the coast of western North America is intact (Blakey and Ranney 2018). |
| Tertiary (T) or Paleogene Period (PG) | late Paleocene Epoch (EP) | 59.2 million–56.0 million | Martinez Formation, lower member (sandstone; **Tmzl**) | Sediments, including the historic site's bedrock, accumulate in a forearc basin associated with the subduction zone (see fig. 15). |
| Tertiary (T) or Paleogene Period (PG) | early and middle Paleocene Epochs (EP) | 66.0 million–59.2 million | n/a | Unconformity (see "Unconformity"). |
| Cretaceous Period (K) | Early and Late Epochs | 145.0 million–66.0 million | Great Valley sequence<br>• sandstone, siltstone, and clay shale (**Kus**)<br>• sandstone (**Kcs**) | • About 70 million years ago the Laramide Orogeny (mountain-building event that forms the Rocky Mountains) commences (Page and Engebretson 1984) and the forearc basin uplifts (Dickinson and Snyder 1979; Moxon and Graham 1987).<br>• Starting at least 140 million years ago (Blake et al. 1967), plate collision and subduction associated with accretion of the Franciscan Complex (including marine sediments and ocean crust) begins.<br>• Between 145 million and 66 million years ago (Haydon 1995), sediments, including the historic site's bedrock, accumulate in a forearc basin associated with the subduction zone (see fig. 15). |
| Jurassic Period (J) | Early, Middle, and Late Epochs | 201.3 million–145.0 million | n/a | • Between about 163 million and 66 million years ago (Delattre and Rosinski 2012), marine sediments (Franciscan Complex) accumulate in a trench on the seafloor. The trench is associated with the subduction zone. Some trench sediments are subducted enough to become slightly metamorphosed.<br>• Between about 164 million (Orr and Orr 1999) and 145 million years ago, the overriding continental plate scrapes against the top of the oceanic plate, and layers of oceanic crust (e.g., Coast Range ophiolite) peel off and plaster against the leading edge of the North American plate.<br>• As collision between the North American plate and Farallon plate continues, the continental crust of the North American plate rides over the oceanic crust of the Farallon plate, which plunges below Earth's surface, creating a subduction zone.<br>• Seafloor spreading takes place at the East Pacific Rise. The North American plate moves westward and collides with the Farallon plate. |

**Table 1, continued. Geologic time scale.**

| Geologic Time Units | | Years Ago | Map Unit in the GRI GIS data | Geologic Event |
|---|---|---|---|---|
| Triassic Period (TR) | Early, Middle, and Late Epochs | 251.9 million–201.3 million | n/a | About 200 million years ago, the supercontinent Pangea begins breaking up. The North American and Eurasian continents, previously joined, rift apart; the rift between these two continents becomes the Atlantic Ocean. |
| Paleozoic Era | • Permian Period (P)<br>• Pennsylvanian Period (PN)<br>• Mississippian Period (M)<br>• Devonian Period (D)<br>• Silurian Period (S)<br>• Ordovician Period (O)<br>• Cambrian Period (C) | 358.9 million–251.9 million | n/a | The supercontinent Pangea assembles between 340 million and 300 million years ago. |
| Proterozoic Eon | • Neoproterozoic Era (Z)<br>• Mesoproterozoic Era (Y)<br>• Paleoproterozoic Era (X) | 2.5 billion–541.0 million | n/a | n/a |
| Archean Eon | • Neoarchean Era<br>• Mesoarchean Era<br>• Paleoarchean Era<br>• Eoarchean Era | ~4.0 billion–2.5 billion | n/a | Oldest rocks preserved on Earth are about 4.0 billion years old (not present at the historic site). |
| Hadean Eon | No subdivisions | 4.6 billion–4.0 billion | n/a | About 4.6 billion years ago, Earth forms. |

## Geologic Setting

The initial geologic setting reflected in the historic site's bedrock is of an evolving marine basin located at the western margin of the North American continent. Sediments that now compose the historic site's bedrock, which consists of the Great Valley sequence and Martinez Formation (discussed below), were deposited in this basin between 145 million and 56 million years ago (Haydon 1995).

At that time, the oceanic Farallon plate and the continental North American plate were colliding at the latitude of the historic site. This convergent plate boundary (fig. 14, first panel) differs markedly from the transform plate boundary that exists today (see fig. 14, last panel; see "San Andreas Fault").

Where plates converge, the one with thinner oceanic crust will subduct beneath the one with thicker (more buoyant) continental crust, creating a subduction zone (fig. 15). The following are features of the subduction zone:

- Magmatic arc—A magmatic arc forms above the region where the descending plate gets hot enough to "sweat" fluids and trigger melting in the mantle (layer of Earth below the crust). The gray granitic rocks so familiar to travelers in the Sierra Nevada (fig. 16) represent the magmatic arc. At the time of subduction, an arc-shaped chain of volcanoes, similar to today's Cascade Range, erupted, giving rise to the Sierra Nevada. While some molten rock erupted at the surface as lava, most of the material solidified deep below ground as plutons (deep-seated igneous intrusions).

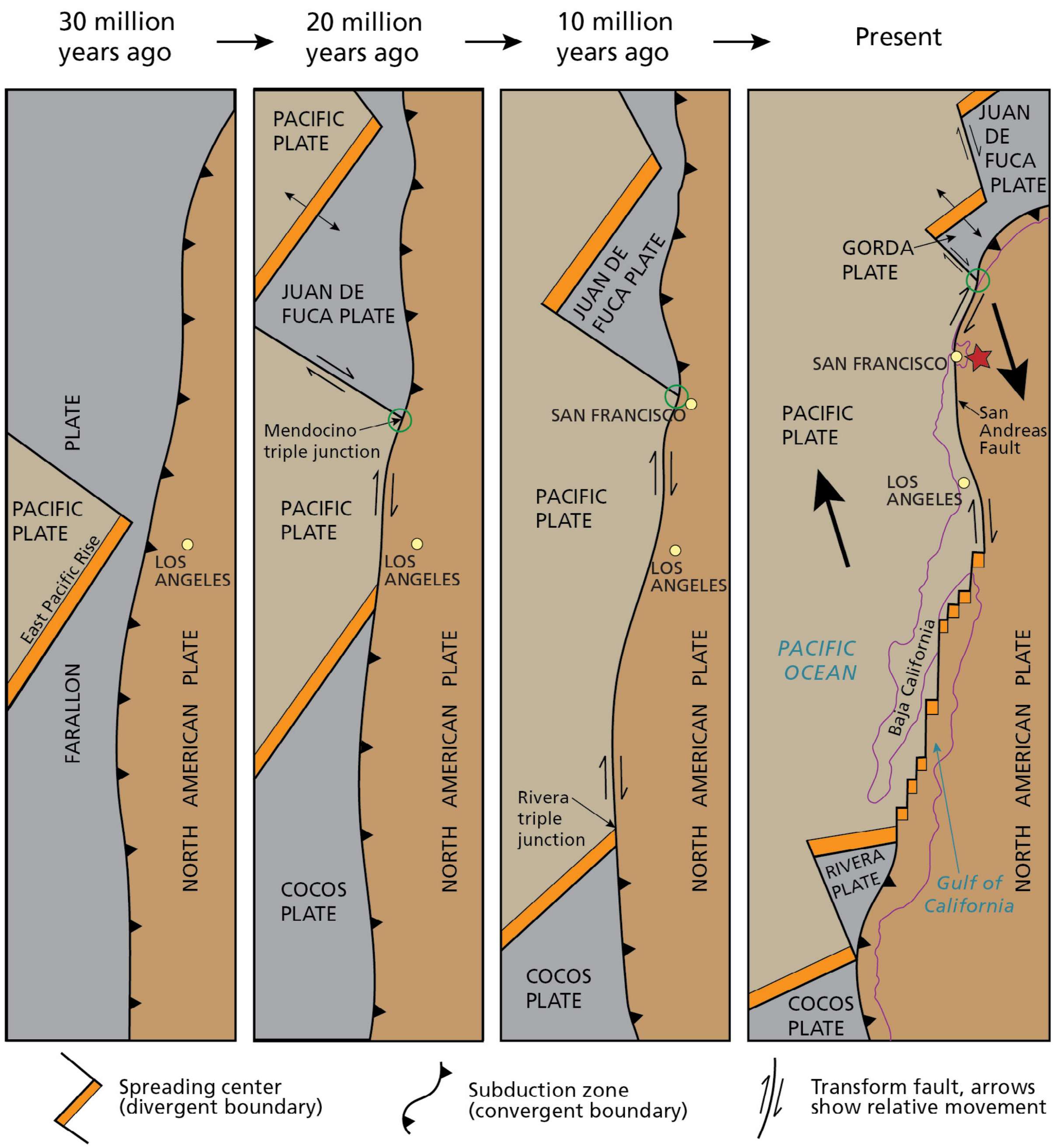


**Figure 14. Illustration of a part of the North American plate boundary over time.**
**The four panels illustrate subduction of the Farallon plate as it was progressively consumed beneath the North American plate. As the East Pacific Rise and North American plate make contact (about 28 million years ago), the Farallon plate east of the rise begins to fracture into smaller plates (e.g., Juan de Fuca). The Mendocino triple junction forms where the North American, Pacific, and Juan de Fuca plates intersect (green circle). Farther south, the Rivera triple junction forms where the Pacific, North American, and Cocos plates intersect. The migration of the Mendocino triple junction northward corresponds to the progressive cessation of subduction, propagation of the transform fault system, and movement and eventual shut-off of arc volcanism in the Sierra Nevada (farther east, not shown on figure). About 10 million years ago, the Mendocino triple junction was at the latitude of San Francisco (Graham et al. 1983); today it is off the coast of Cape Mendocino. About 4 million years ago, the San Andreas Fault becomes the principal element of the transform plate boundary. Large, black arrows show the sense of relative motion between the Pacific and North American plates. The red star on the last panel depicts the location of the historic site. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Dickinson (1981, figure 1-12), Wallace (1990, figure 3.12), and Kious and Tilling (1996, p. 7).**

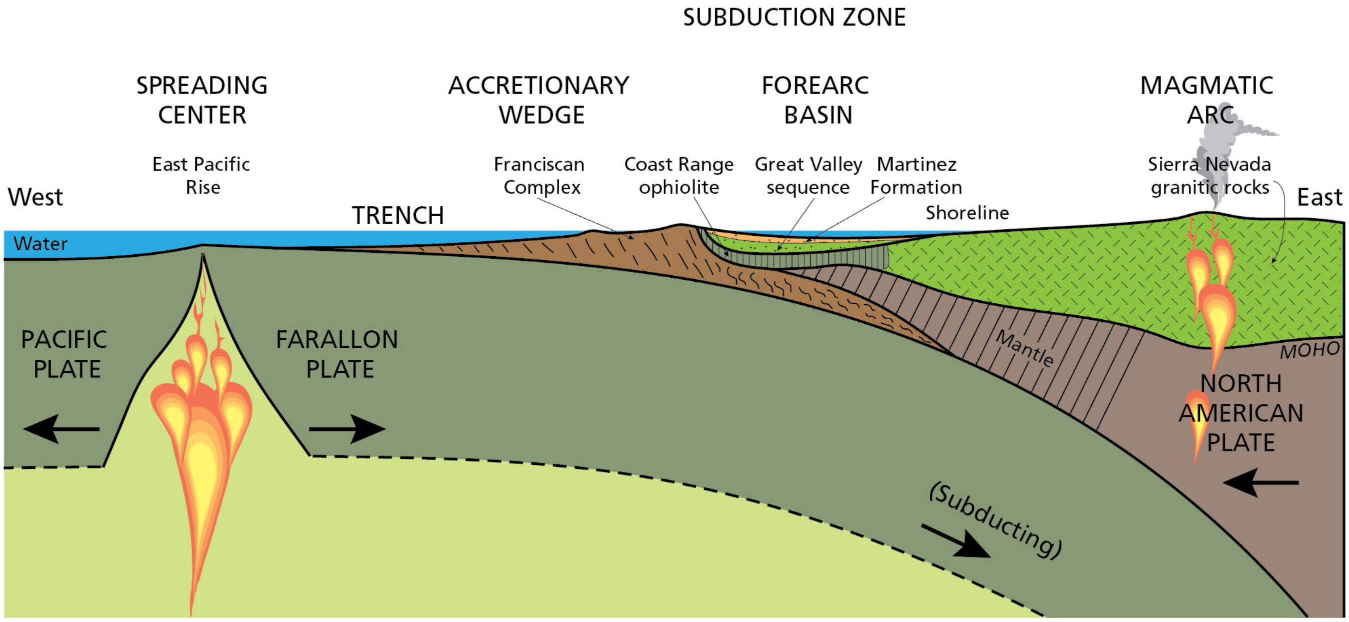


**Figure 15. Generalized cross section of a subduction zone.**
**Before about 28 million years ago, the oceanic Farallon plate spread eastward from the East Pacific Rise (a spreading center/mid-ocean ridge) and subducted beneath the continental North American plate. Subduction of the Farallon plate ended when the East Pacific Rise made contact with the North American plate (see fig. 14). Major features of subduction were a magmatic arc (represented by granitic rocks in the Sierra Nevada), a forearc basin (represented by the Great Valley sequence and Martinez Formation at the historic site and elsewhere), and an accretionary wedge (represented by the Franciscan Complex, which underlies many parts of coastal California). The Great Valley sequence was deposited on the Coast Range ophiolite (seafloor), which was uplifted when the Franciscan Complex was thrust underneath it; some of the Franciscan Complex was subducted. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Crouch and Suppe (1993, figure 2) and Lillie (2005, figure 7.6).**

- Forearc basin—A forearc basin forms in the region between the descending plate and the magmatic arc. The "surface expression" of the descending plate is a trench (narrow, elongate depression on the ocean floor). From the Late Jurassic Period to Paleocene Epoch (163.5 million–56.0 million years ago), sediments—including the historic site's bedrock (see "Great Valley Sequence" and "Martinez Formation")—accumulated in the forearc basin. The source of these sediments was the Sierra Nevada magmatic arc.
- Accretionary wedge—An accretionary wedge develops where oceanic material is scraped off the descending plate (see fig. 15). The accretionary wedge of material is composed of the widely recognized and widespread Franciscan Complex, which accumulated at the same time as sediments in the forearc basin (Bailey et al. 1964). The Franciscan Complex consists of former offshore sediments, some of which underwent metamorphism (low temperature and high pressure; Blake et al. 1967), as well as fragments of oceanic crust that were accreted (tectonically emplaced) onto the western edge of the North American continent during plate collision and subduction (e.g., see Ernst 1983; McCrory 1989; Harden 1998). The San Francisco Bay Area is known for the world-famous Franciscan Complex (Sloan 2006; see GRI reports about Golden Gate National Recreation Area by Port 2016 and Redwood National and State Parks by KellerLynn 2021).

## Great Valley Sequence

The Great Valley sequence (map units **Kus** and **Kcs** in the historic site; see table 1) accumulated in an ancient forearc basin, which was part of a subduction zone that existed on the western margin of the North American continent between 163.5 million and 56.0 million years ago. Deposits of the Great Valley sequence represent a range of depositional systems: from fluvial-deltaic and shallow marine on the east to deep-sea fan and basin plain in the west (Ingersoll 1979; Cherven 1983; Bartow and Nilsen 1990). Today, the Great Valley sequence underlies much of the historic site (see poster).

The rocks of the Great Valley sequence are as much as 12,000 m (40,000 ft) thick (Bartow and Nilsen 1990). The enormous thickness of clastic detrital material

**Figure 16. Photograph of John Muir in Yosemite. In the photograph, John Muir sits on an outcrop of exfoliated (concentric rock layers are spalled away) granite, which is ubiquitous in the Yosemite Valley. The granite developed as part of the magmatic arc of a subduction zone. It makes up sheer cliffs and domes, underlies pristine alpine meadows and deep glacial valleys, and provides the backdrop for spectacular waterfalls and expansive vistas of the majestic High Sierra. For more information about the geology of Yosemite National Park, see the GRI report by Graham (2012). Library of Congress photograph from National Park Service (2015, p. 3).**

is believed to have largely originated from erosion of the ancestral Sierra Nevada (Irwin 1990), that is, the magmatic arc to the east. Sediments that eroded from the magmatic arc were transported westward and southwestward and accumulated in the forearc basin as layers of sand, silt, and mud in a marine setting (Payne 1962; Bartow and Nilsen 1990), which became a sequence of interlayered sedimentary rocks such as sandstone, siltstone, and shale. The material was eroded from the arc and then quickly transported to the basin, leaving little time for the sediments to "mature," that is, alter to clays and be sorted by size and type (Will Elder, Golden Gate National Recreation Area, visual information specialist, written communication, 12 February 2021).

The name "Great Valley sequence" was introduced by Bailey et al. (1964) for the rocks that crop out along the west side of the Great Valley of California. The Great Valley sequence and the Franciscan Complex (accretionary wedge) are largely coeval. Strata of the Great Valley sequence range in age from Late Jurassic (Bailey et al. 1964) to early Paleocene (Goudkoff 1945; Payne 1951).

One of the principal problems in making sense of the Great Valley sequence is the plethora of lithostratigraphic names (Bartow and Nilsen 1990). The Great Valley sequence includes units known as Knoxville (Upper Jurassic), Paskenta and Horsetown (Lower Cretaceous), Chico (Upper Cretaceous), and many other names applied locally (Bartow and Nilsen 1990). Although these terms have been widely applied in the past, they are based mainly on faunal criteria and are not acceptable as formal names of rock units, referred to as "lithostratigraphic names" (Bartow and Nilsen 1990). Moreover, the US Geologic Names Lexicon (Geolex)—the national compilation of names and descriptions of geologic units (see "Additional References, Resources, and Websites")—does not formally recognize "Great Valley sequence." As such, the term "sequence" is not capitalized in this GRI report. Yet, because the Great Valley sequence represents an archetypal forearc basin, the term is widely used (Orme and Surpless 2019).

## Unconformity

Layers of rock are referred to as "conformable" where they are found to have been deposited essentially without interruption. Although particular sites may exhibit conformable beds representing significant spans of geologic time, no place on Earth contains a full set of conformable strata. Breaks in conformable strata are called "unconformities." Each unconformity represents a period when deposition ceased or where erosion removed previously formed rocks.

Regionally, an unconformity separates the Great Valley sequence from late Paleocene or younger strata (Bartow and Nilsen 1990). The unconformity was probably the result of either en echelon (overlapping or staggered elements, collectively forming a zone) folding associated with movement on the proto–San Andreas Fault (Harding 1976) or thrusting associated with emplacement of a Franciscan accretionary wedge (Namson et al. 1990). The unconformity also correlates with a drop in eustatic (worldwide) sea level, suggesting that sea-level change was a contributing factor in the development of the unconformity (Bartow 1991); this lowering of sea level occurred about 62 million years ago (Vail and Hardenbol 1979).

## Martinez Formation

Like the Great Valley sequence, rocks designated as part of the Martinez Formation, lower member (**Tmzl**) have a marine origin and accumulated in a forearc basin (see fig. 15). Additionally, like the Great Valley sequence, these sediments derived from the Sierran magmatic arc and were transported into the forearc basin by turbidity (sediment-laden, underwater, density) currents (Elder 2013). Today, these strata form the northeastern and southwestern flanks of the historic site's rolling hills and underlie the Strentzel Creek drainage (see poster).

At the time of scoping, Graymer et al. (1994) seemed a likely choice as a source map for the GRI GIS data (see "GRI Products"), and the discussion in the scoping summary (KellerLynn 2008) reflected this. Graymer et al. (1994) divided the bedrock of Contra Costa County, including the historic site, into assemblages bounded by faults; the historic site is part of Assemblage IV of the Martinez Area.

In Assemblage IV, the Tertiary rocks that are stratigraphically above the Great Valley sequence are the Vine Hill Sandstone. In other words, Graymer et al. (1994) mapped the historic site's Tertiary strata as the Vine Hill Sandstone, not the Martinez Formation, lower member (**Tmzl**). This interpretation by Graymer et al. (1994) was based on mapping by Weaver (1953), which applied the name "Vine Hill Sandstone" to these rocks. However, the GRI GIS data, and in turn the poster and this report, were based on the map by Haydon (1995), which interpreted these Tertiary (upper Paleocene) rocks as the Martinez Formation, lower member (**Tmzl**) instead of the Vine Hill Sandstone.

Newer mapping projects (e.g., Graymer 2000; Graymer et al. 2002), which cover parts of Contra Costa County, use Vine Hill Sandstone of Weaver (1953) rather than Martinez Formation for the following reasons: (1) the differences in lithological and paleontological character of the rocks near the town of Martinez vs. rocks also designated Martinez Formation on the north flank of Mount Diablo and (2) because of the confusion of stratigraphic ranking associated with the name (i.e., Martinez "group"), which investigators (e.g., Gabb 1869; Arnold 1906) have previously used (Marc Delattre, California Geological Survey, senior engineering geologist, written communication, 5 February 2021). Note: In geologic terminology, a formation is the fundamental rock-stratigraphic unit, meaning it is mappable (at a particular scale), lithologically distinct (with respect to rock type and other characteristics such as color, mineral composition, and grain size) from adjoining strata, and has a definable upper and lower contact. A formation can be divided into "members" or combined into a "group."

As mentioned in the GRI scoping summary (KellerLynn 2008), Paleocene rocks are a "unique geologic resource" because of their rarity in California. Geolex lists 41 Paleocene formations—from Alberhill Clay to Yager Formation—for California. For comparison, Geolex lists 178 Jurassic formations in California and 332 Cretaceous formations in the state. Because of the rarity of Paleocene rocks in California, further study of the historic site's Paleocene bedrock seems warranted. A field comparison of the Paleocene rocks in the historic site to the type localities (place where a geologic feature was first recognized and described) of the Vine Hill Sandstone and the Martinez Formation could be an interesting Scientists in Parks (SIP) project. Such a project would help to clarify the geologic story of the historic site as well as enhance statewide geologic understanding of the events that took place during the Paleocene Epoch.

Field work by an SIP participant could be combined with a field survey of the historic site's archeological resources, which was identified as a planning and data need in the historic site's foundation document (National Park Service 2015). A third aspect of this field work could be a survey of in situ paleontological resources at the historic site (see "Paleontological Resource Inventory, Monitoring, and Protection"). Field reconnaissance can yield fossil discoveries (see the GRI report by KellerLynn 2016 about Aztec Ruins National Monument).

With respect to field work, the three type localities—one for the Vine Hill Sandstone and two for the Martinez Formation—are quite close to the historic site. The type locality of the Vine Hill Sandstone consists of cuts along the Santa Fe Railway immediately east of Pacheco Road (now "Boulevard") near Martinez (Weaver 1953). The type localities of the Martinez Formation are exposures south of Martinez and on the north flank of Mount Diablo (Gabb 1869; Stewart 1949).

This SIP project could address some of the confusion associated with the Paleocene rocks in the Martinez area. Confusion relates to nomenclature, as discussed above, as well as to the lithology of these Paleocene rocks. For instance, Weaver (1953) described the Paleocene rocks of the Martinez area as consisting of massive medium- to coarse-grained brown to reddish brown glauconitic sandstone and minor amounts of interbedded silty shale. By contrast, Haydon (1995) described these same rocks as light red-brown weathered sandstone consisting of fine- to medium-grained sand with little coarse-grained material. Besides grain size and rock type, a difference in these two descriptions is that Weaver (1953) identified these rocks as glauconitic whereas Haydon (1995) did not. Thus, verifying the existence of glauconite, which serves as an indicator of very slow sedimentation, seems important for understanding the depositional history of the historic site's bedrock. Glauconite is a greenish silicate (silicon + oxygen) mineral, $(K,Na)(Fe,Al,Mg)_2(Si,Al)_4O_{10}(OH)_2$, characterized by a micaceous structure (capable of being easily split into thin sheets), commonly interstratified with smectite (a clay mineral).

Another aspect of the Martinez Formation is its historical context and connection to John Muir. In 1869, the California Geological Survey published *Palaeontology, Volume II: Cretaceous and Tertiary Fossils* (Gabb 1869), which provided the first description of these rocks in the Martinez area. Coincidentally, when William M. Gabb was doing reconnaissance of California's geology and collecting Cretaceous and Tertiary fossils, John Muir was studying glaciers in the Sierra Nevada. Interestingly, the timing of both Gabb's and Muir's work coincides with the "controversy" between John Muir and Josiah D. Whitney (see "John Muir and Glaciers"). From his office in Cambridge, Massachusetts, where he was a professor at Harvard University, Whitney wrote the preface of Gabb (1869); Whitney was serving as the state geologist of California at that time. In the preface (p. xiii), Whitney provisionally proposed that the Tertiary rocks in the Martinez area be called the "Martinez Group" and include the series of beds of small geographic extent found at Martinez and on the northern flank of Mount Diablo. In short, while Whitney was disparaging Muir's work about glaciers and the Yosemite Valley, he was proposing an interpretation of the rocks in the Martinez area that continues to feed confusion to the present day. Thus, for more than 150 years, J. D. Whitney has caused angst for John Muir, though in this case for "the place" and its geology, not "the man."

## San Andreas Fault

The San Andreas Fault is a relative newcomer on the geologic scene. The fault is the tectonic expression of a transform plate boundary where the Pacific plate is sliding northwestward along the western margin of the North American plate. The transform boundary known as the San Andreas Fault has been a prominent tectonic feature for at least the past 10 million years but became responsible for most of the displacement within the system about 4 million years ago. Movement on the San Andreas Fault caused both the 1906 San Francisco (M 7.8) and the 1989 Loma Prieta (M 6.9) earthquakes (see "Faults and Earthquakes").

The San Andreas Fault is commonly referred to as a "system" because of the widespread network of faults associated with it. In the East Bay Area alone, more than a dozen faults are part of the San Andreas Fault system that makes up the transform plate boundary (fig. 17). All the faults included in the GRI GIS data are associated with this system.

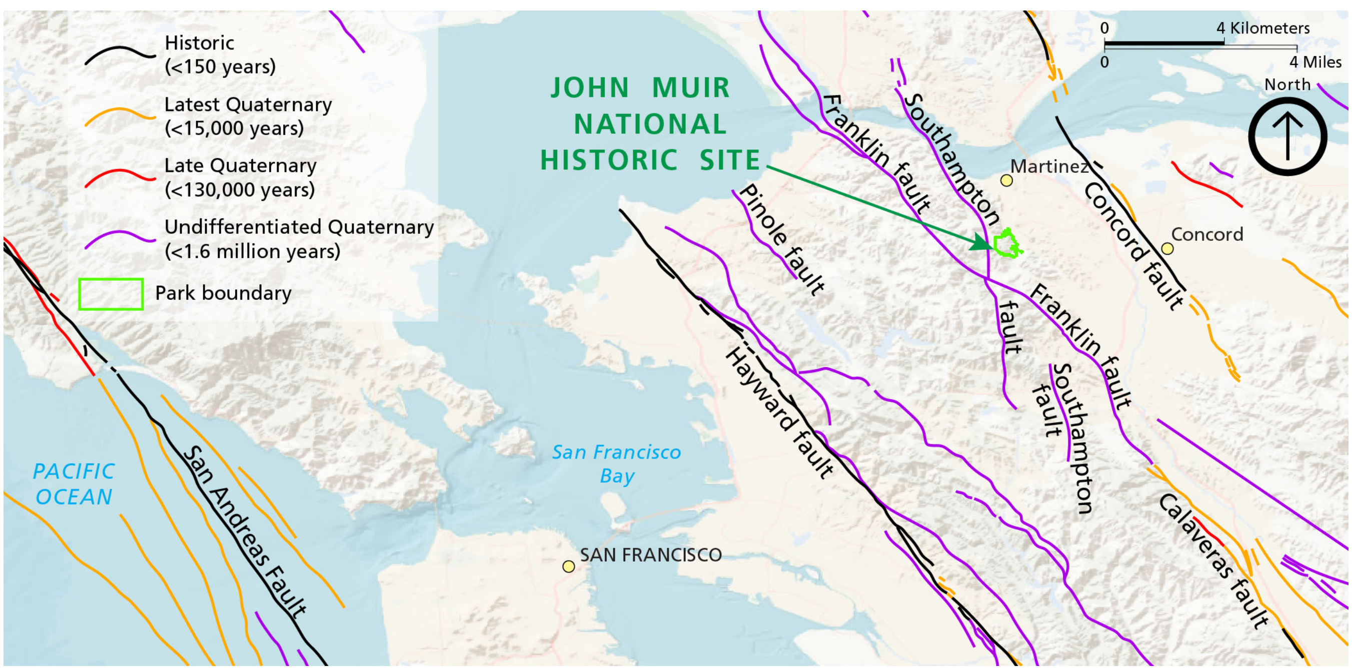


**Figure 17. Map of faults in the San Francisco Bay Area.**
**Near the historic site, faults that have moved in the past 150 years (delineated in black) include the San Andreas, Hayward, and Concord. These are active faults. The Calaveras fault, which moved in the past 15,000 years (delineated in orange), also is active. The Franklin, Southampton, and Pinole faults, which are potentially active, moved in the past 1.6 million years (delineated in purple). Graphic by Trista Thornberry-Ehrlich (Colorado State University). The faults are from the USGS Quaternary faults database (US Geological Survey 2021). Base imagery is ESRI ArcGIS World Imagery.**

Additionally, the San Andreas Fault is commonly referred to as a "zone" because of its length and width. The fault zone extends for 1,200 km (800 mi; Southern California Earthquake Data Center 2013), having both onshore and offshore segments. At the latitude of San Francisco, the zone is approximately 80 km (130 mi) wide; at the latitude of San Diego, it is approximately 150 km (90 mi) wide (Wallace 1990).

Today, the topography of western California is controlled by the San Andreas Fault zone (Vigil et al. 2000). The faults composing the San Andreas Fault system have predominantly right-lateral strike-slip movement (fig. 18), which collectively accommodates most of the relative motion between the North American and Pacific plates. About 10% of the present plate motion is compressional (Vigil et al. 2000); shortening and wrinkling of Earth's crust creates the parallel northwest–southeast-oriented mountains of the California Coast Ranges. Compression also created the anticline that runs through the Mount Wanda Unit (see poster).

## Anticline

A notable geologic feature—an anticline (upward fold of rock layers; fig. 19)—runs through the historic site and gives the landscape a dome-like appearance. The anticline, like the faults and mountain ranges in the area, trends northwest–southeast and is associated with the San Andreas Fault system. As such, the anticline formed quite recently (i.e., less than 3 million years ago; see table 1).

Between faults, the landscape and underlying structure is dominated by compression that is normal (perpendicular) to the major faults, which are primarily strike-slip (see fig. 18). Folds, including the historic site's anticline, form as compression wrinkles and shortens Earth's crust. As a result of this ongoing process, uplift continues, and major faults move closer together (Graymer 1995).

The compliment to an anticline is a syncline (downward fold of rock layers). Like the anticlines in the region, synclines trend northwest–southeast and are associated with the San Andreas Fault system. No synclines occur in the historic site, but the GRI GIS data include five named synclines (Bear Creek, Briones, Happy Valley, Lafayette, and Pacheco), in addition to four named anticlines (Miner Ranch, Orinda, Pinole, and Sobrante). The data also have 57 unnamed synclines or anticlines, two of which are subaqueous. The anticline in the historic site is unnamed.

### *Oil and Gas Exploration*

An understanding of anticlines helped to advance oil and gas exploration in the Bay Area. In the late 19th century and early 20th century, the "anticlinal theory" was developed by early exploration geologists who were convinced that most oil could be found in the upward folds of anticlines because oil and gas, which are lighter than water, would migrate upward and be captured by these folds (Gries 2018). Large oil fields were found in the southernmost San Joaquin Valley and along

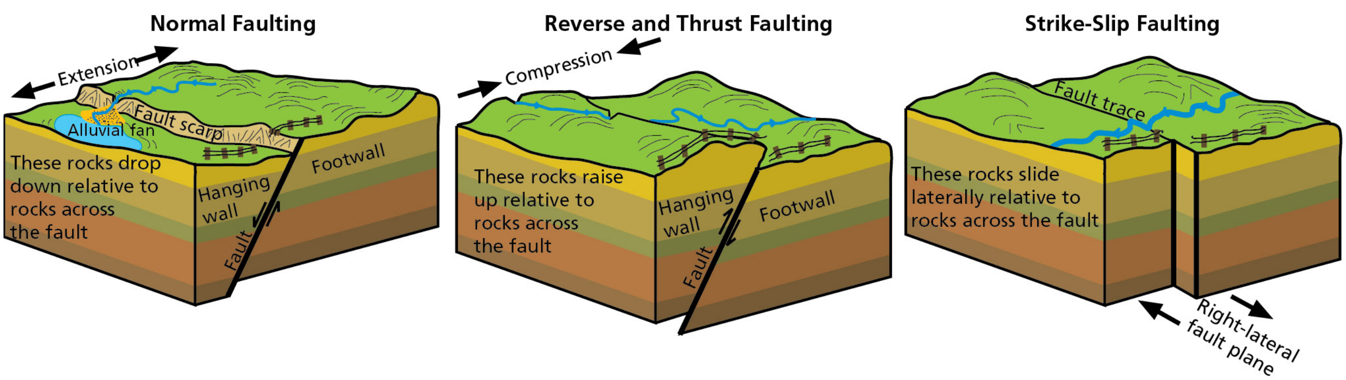


**Figure 18. Block diagrams of fault types.**
**Movement occurs along a fault plane. Footwalls are below the fault plane, and hanging walls are above. In a strike-slip fault, movement is horizontal. When movement across a strike-slip fault is to the right, it is a right-lateral strike-slip fault, as illustrated above. When movement is to the left, it is a left-lateral strike-slip fault. A strike-slip fault between two tectonic plates is called a transform fault. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is a type of reverse fault that has a dip angle of less than 45°. Both strike-slip and thrust faulting occurs in and near the historic site. Graphic by Trista Thornberry-Ehrlich (Colorado State University).**

anticlinal uplifts on its southwestern margin (California Geological Survey 2002). Notably, three exploration wells (Almond #2, #5, and #6) were drilled in what is now the Mount Wanda Unit (see GRI GIS data); the last one in 1954 (Killion 2005). Three other wells (Almond #1, #3, and #4) were drilled near, though south of, the historic site's southern boundary (Boucher 1990). All were "dry holes" (no gas produced) and were later capped (Killion 2005).

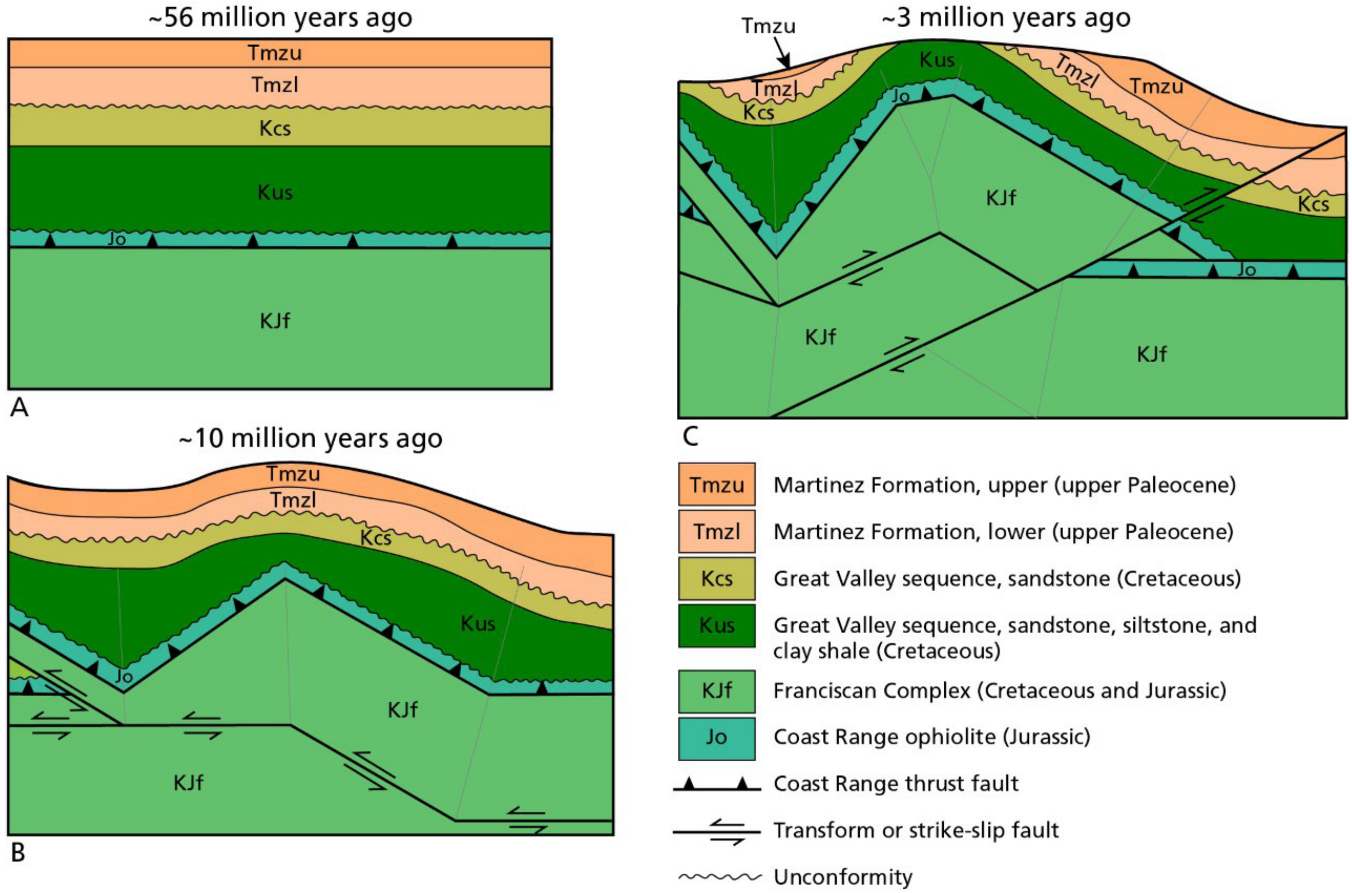


**Figure 19. Generalized cross sections of landscape evolution and anticline formation. (A) The slowly subsiding Great Valley forearc basin is located between the Franciscan subduction complex to the west and the Sierra Nevada magmatic arc to the east (see fig. 15). Cretaceous sediments shed from the magmatic arc accumulate unconformably (with a break in deposition) on the Coast Range ophiolite (Jo), which lies structurally above the Franciscan Complex (KJf). The Coast Range thrust fault (see legend for symbol) separates the Franciscan Complex from the Coast Range ophiolite. A period of regional uplift creates an unconformity (see legend for symbol) between the Cretaceous rocks of the Great Valley sequence (Kus and Kcs) and the Paleocene Martinez Formation (Tmzl and Tmzu). (B) The East Pacific Rise approaches then makes contact with the North American plate about 28 million years ago; the Mendocino triple junction forms (see fig. 14). The plate boundary transitions from subduction to transform (see legend for symbol). The forearc basin is deformed to create local basins and highs in a marine setting. The modern San Andreas Fault system begins to rupture the landscape about 10 million years ago and dominates by 4 million years ago. Nonmarine conditions prevail by about 6 million years ago. (C) Transpression (transform fault motion plus compression) causes folding (wrinkling and shortening), including the anticline in the historic site, which developed about 3 million years ago. Stratigraphically older rocks are at the core of the anticline. Strike-slip faults of the San Andreas Fault system cut Paleocene and younger rocks and deposits. Colors on the figure correspond to those in the GRI GIS data and on the poster. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Namson et al. (1990, figure 6.5).**

## Fluvial Features and Processes

When Louisiana Strentzel, John Muir's mother-in-law, settled in Martinez in the 1880s, she renamed the valley "Alhambra Valley" because she disliked the name "Cañada del Hambre," meaning "Hungry Valley" (Sierra Club 2021). Spanish soldiers, who had been unable to find food and nearly starved, named Hungry Valley. Mrs. Strentzel renamed it for the popular story published in the mid-1800s by Washington Irving about the Alhambra palace in Spain. As indicated by its usage today, as well as a formal listing by the US Geological Survey and US Board on Geographic Names (1981), "Alhambra Valley" stuck.

The etymology and usage of the name of the creek that runs through the valley, including alongside the Gravesite Unit (see fig. 2), is trickier than the valley itself. The entire creek—from headwaters to mouth—is commonly referred to as "Alhambra Creek," though technically, Alhambra Creek is only the upper 3 km (2 mi) of the river (south of the historic site). US Board on Geographic Names (1941) formalized "Arroyo del Hambre" as the name for the lower creek (east of the historic site and flowing northward into the Carquinez Strait). Furthermore, two USGS 7.5-minute quadrangles (Briones Valley and Walnut Creek) confirm the name as "Arroyo del Hambre." Nevertheless, "Alhambra Creek" predominates in everyday usage.

The other named stream associated with the historic site is Franklin Creek, which bisects the House Unit. During the time of John Muir, Franklin Creek was the source of water for the Muir House (see "Windmills and Wells").

All the smaller drainages in the historic site are unnamed, though the ephemeral stream on the southern flank of Mount Wanda, which is the main fluvial feature in the Mount Wanda Unit (Moore 2006), is referred to as "Strentzel Creek" by the National Park Service and Martinez residents (see fig. 2 and poster). The watershed management report by Moore (2006) referred to the basin drained by Strentzel Creek as the "Strentzel watershed" and the drainage itself as "Strentzel Canyon." Martin and Denn (2017) referred to it as the "Strentzel Creek watershed." The Contra Costa County Flood Control District refers to this watershed as "sub-drainage zone no. 1167." Using USGS nomenclature, it is the "unnamed west tributary to Arroyo del Hambre in the vicinity of Strentzel Lane."

The so-called "Strentzel Creek watershed" drains eastward into the so-called "Alhambra Creek" (see "Erosion and Downstream Flooding at the Mount Wanda Unit"). The watershed is generally described as open oak woodland on deeply dissected hills (Inglis 2000). It encompasses about 107 ha (264 ac). The National Park Service owns less than half of the watershed or about 47 ha (117 ac); the remainder or about 59 ha (147 ac) is in private ownership (Martin and Denn 2017). The non-NPS portion (south side of the catchment basin) consists of private cattle pastures and residential lots (Inglis 2000).

Within the historic site (i.e., the north side of the drainage basin), the Strentzel Creek channel is oriented south and southeast. The channel exits the uplands area near the former Strain Ranch and forms a sizable and active alluvial fan (a low relief, gently sloping fan-shaped deposit of stream sediment). Beyond the former ranch property, the Strentzel Creek channel is not defined, so discharge passes as sheet flow (overland flow) before collecting in a detention basin and leaving NPS property at Strentzel Lane through a buried culvert (fig. 20).

Within the Mount Wanda Unit, the upper Strentzel Creek channel is underlain by Great Valley sequence, sandstone (**Kcs**), and Martinez Formation, lower member (**Tmzl**) (see poster). The lower portion of channel is underlain by younger alluvium (**Qal**; stream-deposited sand, silt, clay, and gravel) that has been reconfigured through human occupation and reworked by recent flows and sediment deposition. A ditch, levee, and large pads of fill direct flow to an artificial channel north of the former Strain Ranch.

Younger alluvium (**Qal**) also underlies the House and Gravesite Units. The material was deposited primarily during floods (Haydon 1995). Although younger alluvium (**Qal**) underlies the Muir House, and the house is located near the Franklin Creek channel, Dr. Strentzel ensured that the house was secure from high water. The Muir House, which is situated some 9 m (30 ft) above Franklin Creek (Killion and Davison 2005), has remained higher than any floodwaters to date (see "Flooding on Franklin Creek"). The Martinez Adobe, which also is underlain by younger alluvium, is out of the floodplain. Fluvial features and processes at the Gravesite Unit are further discussed in the "Bank Erosion at the Gravesite Unit" section of this report.

**Figure 20. Photographs of culvert at the mouth of Strentzel Creek.**
**Starting at its headwaters near Mount Wanda, the channel of the informally named "Strentzel Creek" (an ephemeral stream) cuts across the landscape for about 1,500 m (5,000 ft). The channel exists the upland area and forms an alluvial fan at the former Strain Ranch property. A ditch, levee, and large pads of fill direct flow to an artificial channel. Beyond the former ranch, the channel is not defined, so discharge passes as sheet flow (overland flow) before collecting in a detention basin and leaving NPS property at Strentzel Lane through a buried culvert. NPS photographs from Denn and O'Neil (2005, photos 8 and 9).**

# Geologic Resource Management Issues

*Some geologic features, processes, or human activities may require management for human safety, protection of infrastructure, and preservation of natural and cultural resources. The NPS Geologic Resources Division provides technical and policy assistance for these issues (see "Guidance for Resource Management"). The issues are ordered with respect to management priority.*

## Erosion and Downstream Flooding at the Mount Wanda Unit

In response to significant floods in the 1980s and 1990s, the Alhambra Watershed Council (formerly the Alhambra Creek Watershed Planning Group) formed in 1997 and produced the Alhambra Creek Watershed Management Plan in 2001. The National Park Service is an active participant on the council. Other partners include Contra Costa County, Friends of Alhambra Creek, Muir Heritage Land Trust, Martinez residents, Martinez Planning Commission, and Alhambra Valley Improvement Association.

NPS attention has focused on the Strentzel Creek watershed of which the Mount Wanda Unit is a part. Flooding at the confluence of Alhambra and Strentzel Creeks, which affected the Strentzel Lane neighborhood in the vicinity of the Gravesite Unit, is an area of concern (see fig. 2). Gullying (channel incision) is the primary geologic process that has raised concern (Stoms et al. 2014).

The National Park Service's response to the community's concern about flooding is highlighted by the following four NPS reports:

Inglis (2000)—This watershed condition assessment was intended to guide managers at the historic site to the best combination of land management practices to improve watershed condition and reduce flooding. This assessment computed model simulations to compare alternative management scenarios and their reduction of peak flows. Building a stormwater retention pond was modeled to reduce peak flows by 88%. Adding wetlands was modeled to reduce peak flows by 58%. Changing vegetation type was modeled to reduce peak flows by 27%. Reconstructing existing ponds was modeled to reduce peak flows by 17%. Improving vegetation condition was modeled to reduce peak flows by 10%. Reconditioning the diversion channel (at the former Strain Ranch) was modeled to reduce peak flows by 3%. Improving channel condition was modeled to reduce peak flows by 2%. Mitigating the effects of fire roads was modeled to reduce peak flows by 2%. In anticipation of future storm events and associated flooding, revisiting Inglis' findings may provide a means to produce visual aids for community outreach, which was suggested by conference-call participants. Expertise to produce such a product, potentially using updated computer modeling methods, may be available through the Scientists in Parks (SIP) program (see "Guidance for Resource Management").

Moore (2006)—This watershed management report was intended to guide management of the Strentzel watershed. It identified many potential factors that might account for a high erosion rate, including the following: soils and their erodibility, slope, climate, vegetative cover, land use impacts, grazing, nonnative annual plants, wetland destruction, and dam breaches. In the process of completing this watershed management report, a geomorphic survey of the watershed was conducted (Moore et al. 2006); the resulting chart (scale 1:1,000) details the locations and extent of the most notable erosion points in the watershed. Analysis of sediment sources by Moore (2006) revealed that the expanding and deepening network of gullies is the primary source of sediment, and slumping (slope failures) is secondary. A tertiary source of sediment is linked directly to human activities and includes dam failures (where the dam itself is eroded, and decades of impounded sediment are released), the road network (especially the old fire road that runs along the creek), and stormwater drainage from residential areas in the upper, non-NPS part of the watershed. This watershed management report developed a prioritized list of 25 recommended actions to restore natural watershed conditions, monitor watershed health, research best management strategies, and improve community outreach (see table 6 *in* Moore 2006). Lawliss (2007) summarized these recommended actions.

Stoms et al. (2014)—This natural resource condition assessment identified erosion in the Strentzel watershed and its possible contribution to flooding and sedimentation in Alhambra Creek as one of the most pressing resource management issues at the historic site. The assessment investigated some of the potential stressors proposed by other investigations such as Moore (2006). The assessment considered soil types; post-fire erosion potential; trends in annual precipitation; changes in extreme precipitation events; grazing history; invasion of nonnative annual grasses, which replaced perennial species that have deeper roots; culverts; the network of fire roads and trails in the watershed; failure of small dams, which may have allowed a surge of water to rush downstream and cut channels deeper; and the loss of wetlands, which would have released water gradually. Stoms et al. (2014) did not identify any obvious factors that would make Mount Wanda unique or at unusually high risk for erosion compared to the overall East Bay region.

Martin and Denn (2017)—This channel and floodplain assessment of Strentzel Creek was completed by the NPS Water Resources Division in response to a technical assistance request. The assessment concluded that channel incision (referred to as “gullying” by Stoms et al. 2014) will likely continue through the middle and upper reaches of Strentzel Creek, possibly propagating to the upper elevations of the watershed. Channel incision will generate sediment and possibly increase the flood peak and response time of the watershed to precipitation events. Although direct channel stabilization does not appear to be a practicable treatment under current conditions, revegetation or other types of “soft” treatments may improve watershed processes in specific locations in the watershed. Martin and Denn (2017) concluded that a more thorough assessment of the Strentzel Creek watershed with a focus on identifying zones of erosion or instability would be necessary to develop specific plans. Notably, the 1:1,000-scale chart completed by Moore et al. (2006) and the location of gullies and slope failure areas in the GRI GIS data (see poster) may be applicable to this need. Like previous studies, this assessment noted that the Strentzel Creek drainage forms an alluvial fan at its mouth, which is on the former Strain Ranch, but this assessment introduced an additional factor, that is, the entire area should be considered a floodplain because of the flooding conditions associated with an alluvial fan. Therefore, any type of NPS action in or potentially affecting a floodplain requires a floodplain review and possibly a floodplain statement of findings. The NPS Water Resources Division is currently providing technical support regarding floodplain hydraulics and compliance with NPS floodplain policy (Director’s Order #77-2; see “Guidance for Resource Management”).

One potential or even highly likely stressor (for this location), which seems to have been mostly overlooked by previous studies, is tectonic activity. In terms of channel hydraulics, even a slight increase in channel slope can push a “stable” channel past an erosion threshold and lead to substantial channelization. A similar relationship exists for slope stability, where tectonic activity can lead to slope instability (Mike Martin, NPS Water Resources Division, hydrologist, written communication, 10 February 2021).

In the absence of a watershed management plan, which the historic site’s foundation document (National Park Service 2015) identified as a medium-priority need, managers at the historic site continue to work with local government entities and other community partners to mitigate erosion and flooding associated with Strentzel Creek. For instance, in 2004, the National Park Service collaborated with the City of Martinez and Contra Costa County Flood Control District to install a detention basin that drains into a large culvert routed under the downstream neighborhood and into Alhambra Creek (see figs. 2 and 20). In anticipation of the impending lease expiration of the Strain Ranch property in 2017, planning for the long-term management of the watershed was delayed. Now under full NPS management, historic site managers have an outstanding opportunity to align the management of the parcel at the mouth of Strentzel Creek with watershed management objectives, as suggested by Moore (2006). Restoration of the former Strain Ranch back to a functioning alluvial fan is perhaps the most cost-effective watershed improvement. The meandering channel constructed in 2003 is the appropriate concept but quite limited in the space available. To gain the full benefit of a natural alluvial fan, restoration efforts could extend to the distal end of the fan near the road crossing (Moore 2006).

Moore (2006) noted that the highly visible site of the now-former Strain Ranch would present an excellent opportunity to share a restoration project with the community. In light of this suggestion, the National Park Service and Friends of Alhambra Creek (volunteer group) have collaborated on community projects (e.g., planting native plants) at the former Strain Ranch that promote natural processes, reduce flooding in the surrounding neighborhood, improve water quality, and provide wildlife habitat.

### Slope Movements

The historic site’s foundation document (National Park Service 2015) identified a comprehensive site management plan for the Mount Wanda Unit, including the former Strain Ranch, as a high-priority need and a roads and trails management plan for the entire historic site as a medium-priority need. Because consideration of slope-movement hazards is applicable to both these management plans, the locations of landslides, debris flows, and gullies—mapped by Haydon (1995)—are pertinent for these planning efforts. The locations of landslides, debris flows, and gullies are contained in the GRI GIS data for the historic site and shown on the poster. Knowing the locations of these deposits is also pertinent for future land use (e.g., trails and infrastructure) and flood and erosion control efforts.

Haydon (1995) mapped the following types of slope movements within the historic site: landslides (masses of rock, soil, and debris that have been displaced downslope by sliding, flowing, or falling), debris flows (short-lived phenomena resulting from the rapid failure of surficial slope materials), and gullies (upland drainage channels where colluvium [deposited by gravity] and alluvium [deposited by streamflow] underlying that channel floor have been incised). Haydon (1995) also mapped earthflows (relatively shallow deposits of soil or other colluvial material that have moved downslope, commonly at a rate too slow to observe except over long duration), though none were mapped in the historic site.

Haydon (1995) also mapped relative landslide and debris-flow susceptibility (fig. 21) and provided an evaluation of the slope-stability characteristics for each geologic map unit (**Kus**, **Kcs**, **Tmzl**, and **Qal**).

Although not mapped by Haydon (1995), another type of slope movement is soil creep. According to Moore (2006), the presence of steep, convex slope profiles—even in valley bottoms—may indicate that soil creep is a significant process at the historic site. As evidence of soil creep, trees can develop curved trunks (see photograph on cover). This process is most active in the topmost layer of soil and diminishes with depth. It is a gradual process caused by repeated wetting and drying of soil coupled with gravity.

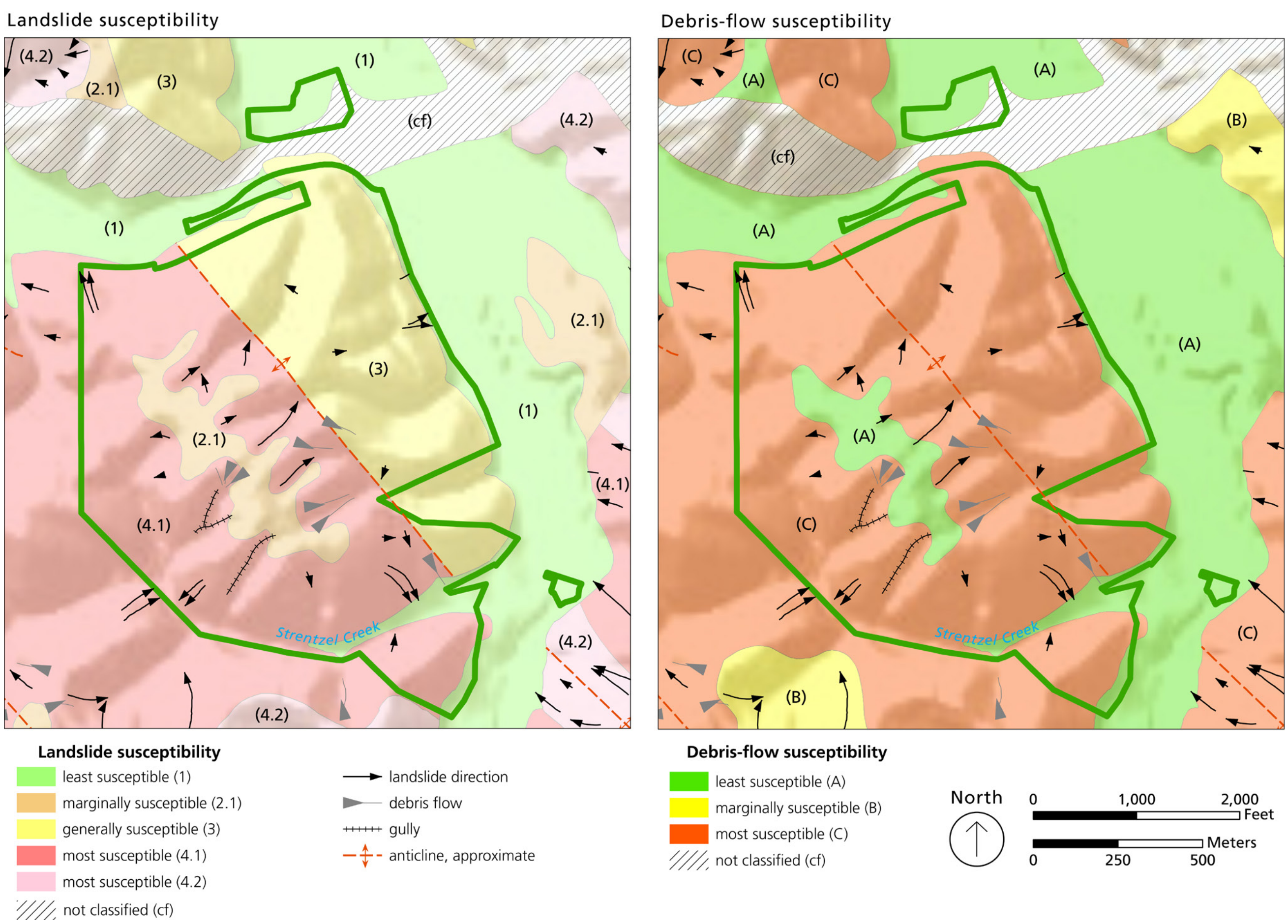


**Figure 21. Maps of landslide susceptibility and debris-flow susceptibility at the historic site. The green outline represents the historic site's boundary. Left: Haydon (1995) mapped areas of landslide susceptibility—least susceptible (1 and green), marginally susceptible (2 and tan), generally susceptible (3 and yellow), and most susceptible (4 and red). The western portion of the Mount Wanda Unit is most susceptible to landslides, though the summit area is marginally susceptible to landslides. The former Strain Ranch is also deemed most susceptible. The eastern side of the Mount Wanda Unit is generally susceptible to landslides. The floodplain east of the historic site is least susceptible to landslides. Right: Haydon (1995) mapped areas of debris-flow susceptibility—least (A and green), marginally (B and yellow), and most (C and orange). Aside from the summit area in the Mount Wanda Unit and the lower segment of Strentzel Creek, which are least susceptible, much of the historic site is most susceptible to debris flows. Graphic by Rebecca Port (NPS Geologic Resources Division) using the GRI GIS data and a shaded relief base map.**

Past slope deposits are prone to reactivation, so the GRI GIS data are useful in identifying areas of potential future movement. Only selected large landslides (**Qls**) are shown on the geologic map (plate 32C) of Haydon (1995); none of these occur in the historic site. However, the landslide and related slope failure features map (plate 32B) of Haydon (1995) identified the following within the historic site: one debris flow in the Great Valley sequence (**Kus**), one area of small mass movement in the Great Valley sequence (**Kus**), 20 landslides in either in the Great Valley sequence (**Kus** and **Kcs**) or the Martinez Formation (**Tmzl**), three gullies in either in the Great Valley sequence (**Kus** and **Kcs**) or the Martinez Formation (**Tmzl**), and one small landslide deposit that terminates in the younger alluvium (**Qal**) of Strentzel Creek near the southern end of the historic site (see poster).

With respect to specific areas of concern in the historic site, Franklin Canyon Road runs along the northern boundary of the Mount Wanda Unit (see fig. 2 and poster). As mentioned during the follow-up conference call, NPS land adjacent to this road could serve as a future location for expanded parking (for the Mount Wanda Trailhead) or additional NPS facilities, though no plan is presently under consideration. From west to east, the road along the historic site's boundary runs through an area mapped by Haydon (1995) as "least susceptible" then "generally susceptible" for debris flows and landslides. In the event of planning for NPS infrastructure along the Franklin Canyon Road, a site-specific investigation by a geologist would be needed to avoid cutting the toe (downslope edge) of a landslide deposit or building on such a deposit, which would likely result in ongoing maintenance or possibly hazardous conditions for users of the road, parking lot, or other facility. Managers at the historic site are encouraged to contact the NPS Geologic Resources Division about the Unstable Slope Management Program (see "Guidance for Resource Management").

## Condition of the Martinez Adobe

Cracks in the Martinez Adobe, which indicate physical distress, have been a concern for decades (e.g., Burke et al. 1992). Although the scoping summary of the 2007 scoping meeting (KellerLynn 2008) did not mention these cracks, the 2020 conference-call participants discussed them briefly. The cracks of primary concern occur at the northeast corner of the building along the east wall.

Various causes for the cracks have been suggested, for example, settlement due to erosion of lower adobe bricks, but the primary cause appears to be seismic shaking. The Martinez Adobe sustained damage during the 1906 San Francisco earthquake (see "John Muir and Earthquakes") and during the 1989 Loma Prieta earthquake (Burke et al. 1992).

The historic site's foundation document (National Park Service 2015) identified management, use, and preservation of the Martinez Adobe as a key issue and a comprehensive condition assessment of it as a high-priority data need. In August 2020, such an assessment, including suggested repairs, was conducted by a structural engineer from the NPS Vanishing Treasures Program, and a condition assessment was completed by Mason (2020).

The assessment showed that in its current condition, the Martinez Adobe would not withstand a major earthquake on the Concord or Hayward faults (see "Faults and Earthquakes"). The building will likely sustain major damage during a large earthquake with the potential for complete collapse. In addition, human safety in the west addition of the Martinez Adobe during a large earthquake is significantly jeopardized because the potential is great for the building to fall off the foundation, exploding upon impact and crushing anything within the fall zone (Mason 2020). Hence, access to the Martinez Adobe was blocked off for visitors and staff immediately after receiving the Vanishing Treasures report and will remain closed until the structure is stabilized (Bentley 2020).

The stability of the chimney is another concern. The fireplace foundation is composed of flat tile bricks that are glued together by Portland cement mortar. This system is bearing directly on unconsolidated soils. The combination of over-stressed soils (by the chimney and even more so by the adobe walls) and an unstable foundation introduces stability problems for the life of the chimney (Mason 2020).

Mason (2020) suggested actions for both short-term and long-term stabilization projects. Analysis indicated that the 1993 seismic retrofit of the Martinez Adobe followed proper methods and sequencing and most structural strengthening detailing was correctly implemented, but several critical details were not properly investigated to realize issues with their design. These include the connection details of the corners of the exterior adobe walls, the interface of the exterior perimeter adobe walls with the rubble stone foundation for bearing (compression capacity) and sliding (shearing action and resistance), and the stability of the rubble stone foundation.

Mason (2020) recommended that a concerted effort occur in the very near future to prevent the destruction of this national heritage site and building. Currently, managers at the historic site are using "Repair and Rehabilitation" funding to implement temporary stabilization of the building while going through the Great American Outdoors Act/Legacy Restoration Fund (GAOA/LRF) and "Line-Item Construction" (LIC) project submittal process for permanent stabilization (Gretchen Stromberg, John Muir National Historic Site, chief of Resource Management and Planning, written communication, 13 May 2021).

As evidenced by the thorough condition assessment (Mason 2020), the Martinez Adobe is in "good hands" with the NPS Vanishing Treasures Program with respect to historic preservation. If historic site managers would like a geologic perspective to inform future planning, however, they are encouraged to contact the NPS Geologic Resources Division (see "Guidance for Resource Management"). GRD staff can provide technical and policy support for geologic resource management issues or direct historic site managers to other sources of assistance such as the Natural Resources Conservation Service (NRCS), California Geological Survey, or US Geological Survey.

## Bank Erosion at the Gravesite Unit

Because of proximity to Alhambra Creek, scoping participants (see scoping summary by KellerLynn 2008) identified bank erosion at the Gravesite Unit as a resource management concern, namely the potential for the Strentzel-Muir gravesite to be eroded out of the bank as a result of further deepening of the creek and associated loss of the slope's integrity. The closest corner of the gravesite is 11 m (35 ft) northwest from the top of the bank (fig. 22).

Alhambra Creek is a low-gradient stream (less than 2% slope) with a low width/depth ratio, low to moderate sinuosity (single thread), and bed material of erodible silt and clay (map unit **Qal**). The channel bed has been augmented with concrete blocks, presumably placed by local landowners in attempts to retard downward erosion of the bed. The creek is entrenched (carved downward into the creek bed) along the length of the Gravesite Unit. Entrenchment is likely a consequence of increased surface-water runoff caused by impervious surfaces associated with the low-density residential development (Inglis 2002); that is, rainwater quickly runs off pavement and roofs rather than infiltrating into the soil.

Evidence of ongoing creek bed incision at the Gravesite Unit includes a narrow channel, over-steepened banks, and a lack of bedrock control (Inglis 2002). "Bedrock control" relates to the influence that underlying bedrock has on channel processes; bedrock control would reduce further erosion.

**Figure 22. Photograph at the Gravesite Unit. The amount of buffer space between the gravesite fence and the bank of Alhambra Creek is minimal, allowing for little adaptive management. At its closest point, the southeast corner of the fence is 11 m (35 ft) north of the edge of the stream channel. The ground surface at this corner post is 5 m (16 ft) above the deepest part of the creek. Note the fence on the right, which surrounds the gravesite. The creek bank is at the left-hand side of the photograph. Photograph by Katie KellerLynn (Colorado State University) taken 24 September 2007.**

A monitoring update in 2005 (Denn and O'Neil 2005) noted that the gravesite is not at immediate risk of erosion due to its location on an inside bend of the creek and a large mass-wasting site (area of slope movement) downstream of the NPS property. Mass wasting is contributing sand to the creek and keeping the bed level high (Denn and O'Neil 2005). The exact location of this mass-wasting site is unknown, but the GRI GIS data show several possibilities.

Additionally, a monitoring update in 2013 (Denn and Villalba 2013) noted that the riparian forest at the Gravesite Unit stabilizes the upper elevations of the banks. The forest consists of mature sycamore (*Platinus racemosa*), bay laurel (*Umbellularia californica*), eucalyptus (*Eucalyptus* sp.), and ponderosa pine (*Pinus ponderosa*) with an understory consisting of California blackberry (*Rubus ursinus*), English ivy (*Hedera helix*), and poison oak (*Toxicodendron diversilobum*). If one (or more) of the largest trees fall, however, uprooting could destabilize the bank and channel. Denn and Villalba (2013) suggested that the historic site's horticulturist inspect the riparian forest annually, ideally before the beginning of the storm season. If/when any of the larger trees die, historic site managers should consider cutting the stump near the ground to prevent the tree from falling over and dislodging its roots. The historic site's horticulturalist may recommend replacement of the dead tree with native riparian vegetation if the absence of the dead tree leaves a portion of the bank without root structure (Denn and Villalba 2013).

Dumping of concrete rubble by private landowners on the opposite side of the channel to the gravesite is a concern for at least two reasons. First, the Contra Costa County Floodplain Management Program has guidelines for construction within the floodplain in the unincorporated parts of the watershed (Alhambra Creek Watershed Planning Group 2001), and this segment of the creek is a regulatory floodway (fig. 23). Thus, the addition of concrete blocks, which equates to building in the channel without a permit, is a violation of county ordinances as well as state and federal laws (Inglis 2002). Second, in 2002, channel blockage from the artificial rubble and the bank protection on the opposite (private) side of the creek appeared to be causing undercutting of the bank near the gravesite.

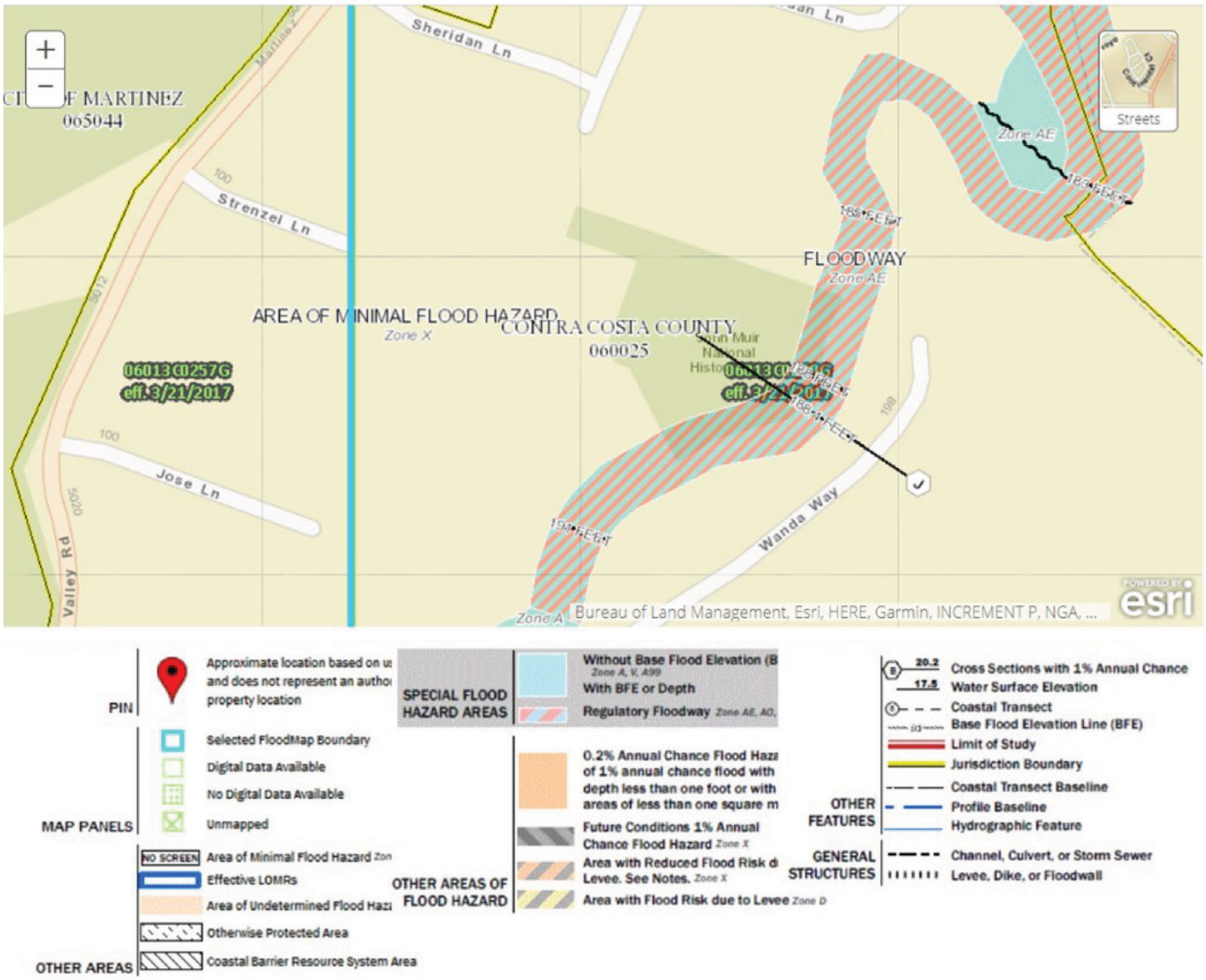


**Figure 23. Flood map of the Gravesite Unit and surrounding area.**
**The Gravesite Unit is situated on the northwestern side of Alhambra Creek (technically, Arroyo del Hambre). The Federal Emergency Management Agency (FEMA) designated this segment of the creek as a "regulatory floodway." Consequently, the river channel and adjacent land areas must be reserved (i.e., not developed) to ensure that no increases in upstream flood elevations take place. Graphic produced by Katie KellerLynn (Colorado State University) using FEMA Flood Map Service Center (Federal Emergency Management Agency 2021).**

As of 2013, however, the channel appeared to be aggrading rather than eroding through the entire reach bordering the NPS property (Denn and Villalba 2013). Coarse sediment appeared to have accumulated behind concrete blocks on the channel bed immediately adjacent to the gravesite, and new sediment mounds were supporting herbaceous perennial wetland vegetation (*Juncus* sp. and *Schoenoplectus* sp.). Aggradation may be associated with the grade control structure installed downstream of the gravesite in 2004 as a part of the Strentzel Lane stormwater drainage project. Notably, the accumulated sediment and plants could be scoured out during a large winter storm. After particularly large storms, therefore, historic site staff may wish to inspect the channel, looking for potentially destabilizing scour.

A technical report by Inglis (2002), a memo about monitoring Alhambra Creek morphology (Denn and O'Neil 2005), and the cultural landscape report (Killion 2005) recommended that erosion on the steep bank separating the gravesite from the creek be closely monitored, especially after storm events. If change is detected in the channel, streambank, or riparian forest (including mature trees and the ground surface), proactive measures may be needed to protect the gravesite. Moreover, necessary response time could be short if certain changes (e.g., the formation of tension cracks between the gravesite fence and the creek bank) are detected. Under these circumstances, NPS managers would need to take quick and decisive action to prevent damage to the gravesite. The NPS Geologic Resources Division has the expertise to assist park managers in making informed decisions (see "Guidance for Resource Management").

According to the historic site's foundation document (National Park Service 2015), the National Park Service regularly monitors the Alhambra Creek stream profile to keep track of bank erosion and accretion. The last known survey took place in 2013 (i.e., Denn and Villalba 2013).

### Faults and Earthquakes

Dozens of faults cross the San Francisco Bay region (see fig. 17). All these faults are part of the San Andreas Fault system (see "San Andreas Fault"), though many have been named individually. Of these faults, three have moved—and thereby produced earthquakes—in historic times (the past 150 years); these faults are, from west to east, the San Andreas (see "John Muir and Earthquakes"), Hayward, and Concord. Of these, the Concord fault is the closest to the historic site (see fig. 17). Named for Concord, California—the largest city in Contra Costa County—the fault is about 6 km (4 mi) northeast of the historic site at its closest point.

The Hayward fault (west of the historic site) is the most prominent fault in the East Bay Area. It is marked for much of its length by landslides, fault-related springs, offset streams, and linear valleys (Sloan 2006). The Hayward fault provides the major shaking potential for the area (Herd 1978; Lienkaemper 1992) and has the greatest likelihood of rupturing in the next 30 years (Association of Bay Area Governments 2014). The Hayward fault, which is named for Hayward, California, is beyond the coverage of the GRI GIS data (see fig. 1). At its closest point, the Hayward fault is about 21 km (13 mi) west of the historic site (see fig. 17).

The following are potential impacts to the historic site from shaking on the Hayward fault. An earthquake produced on the Hayward fault, which has a probable magnitude of 6.7 or greater, will cause damage to roads and utilities in the East Bay Area. Also, shaking will cause many homes to become uninhabitable. During shaking, houses can move off foundations and tall chimneys can fall; adobe walls can turn to dust. The cripple wall (a short wooden wall framed between the foundation and floor) of the Muir House could collapse (KellerLynn 2008). Additionally, liquefaction (transformation of loose, water-saturated silt and sand into fluid material) is likely to take place along San Francisco Bay near the city of Richmond (west of the historic site) and in East County along the Sacramento–San Joaquin Delta (Association of Bay Area Governments 2014). At depth, liquified sediments lose their strength and cease to support buildings and other structures built on them. Liquefaction in the Sacramento–San Joaquin Delta is notable because the delta is the source of the historic site's water supply (see "Windmills and Wells").

Seven named faults are in the vicinity of the historic site (i.e., they appear in the GRI GIS data): Concord, Calaveras, Franklin, Southampton, Pinole, Briones, and Las Trampas (table 2). The Concord and Calaveras faults, which moved in the past 150 years and 15,000 years, respectively, are considered active and have the potential to generate strong ground shaking and surface rupture during an earthquake. The Franklin and Southampton faults are potentially active (Marc Delattre, California Geological Survey, senior engineering geologist, written communication, 5 February 2021), having moved in the past 130,000 years (see fig. 17 and poster). In addition, the Pinole fault is potentially active. At its closest point, the Pinole fault, named for Pinole, California, is about 10 km (6 mi) southwest of the historic site (see fig. 17). Neither the Briones nor the Las Trampas faults is considered active or potentially active because neither has moved in the past 1.6 million years (see table 2).

**Table 2. Named and unnamed faults in the GRI GIS data.**

[1]As indicated by occurrence in the US Quaternary faults online database (US Geological Survey 2021) or input from Marc Delattre (California Geological Survey, senior engineering geologist, written communication, 5 February 2021).

[2]As mapped and interpreted by Haydon (1995). See fig. 18 for an explanation of fault types.

| Name | Active?[1] | Age[1] | Fault Type[2] |
|---|---|---|---|
| Briones | No | Older than Quaternary | Likely pure strike-slip (horizontal) to mostly strike-slip displacement with limited to no vertical displacement |
| Calaveras | Yes | Latest Quaternary, <15,000 years old | Right-lateral strike-slip |
| Concord | Yes | Historic, <150 years old | Likely pure strike-slip to mostly strike-slip displacement with limited to no vertical displacement |
| Franklin | Potentially | Undifferentiated Quaternary, <1.6 million years old | Thrust |
| Pinole | Potentially | Undifferentiated Quaternary, <1.6 million years old | Likely pure strike-slip to mostly strike-slip displacement with limited to no vertical displacement |
| Las Trampas | No | Older than Quaternary | Likely pure strike-slip to mostly strike-slip displacement with limited to no vertical displacement |
| Southampton | Potentially | Undifferentiated Quaternary, <1.6 million years old | Thrust, right-lateral strike-slip |
| Unnamed (589 segments in the GRI GIS data) | Unknown | Unknown | Left-lateral or right-lateral strike-slip with vertical displacement unknown or unknown offset/displacement |

## Climate Change and Geologic Resources

John Muir identified his first glacier in the Sierra Nevada in 1871 (see "John Muir and Glaciers"). Later, he wrote, "How much longer this little glacier will live will, of course, depend upon climate and the changes slowly effected in the form and exposure of its basin" (Muir 1875a, p. 773). Ever the student of nature, Muir was aware of dynamic change (see "John Muir and Earthquakes"), but the accelerated changes we are witnessing today as a result of climate change were probably not something he envisioned. A compelling illustration of climate change for the historic site is Muir Glacier in Alaska, which was named for John Muir ca. 1880. Today, the glacier is only a fraction of the size that Muir would have seen during the Harriman Expedition in 1899 (see fig. 13).

Although the glacier that carries Muir's name may be much diminished, Muir himself remains larger than life—an inspiration to those who work to combat the effects of climate change (French 2015). Notably, the historic site became a "Climate Friendly Park" in 2008 and developed an action plan that identifies steps to reduce greenhouse gas emissions (National Park Service 2019). The action plan includes ways to adapt to current and future impacts of climate change. Along these lines, the historic site's foundation document (National Park Service 2015) identified a climate change vulnerability assessment as a medium-priority data need.

Although climate change planning is beyond the scope of this GRI report, a discussion of climate change is included because of the potential disruption it may cause to the historic site's resources, including geologic resources. Park managers are directed to the NPS Climate Change Response Program (CCRP; see "Guidance for Resource Management") to address climate change planning. The CCRP helps park managers develop plausible science-based scenarios that inform strategies and adaptive management activities that allow mitigation or adjustment to climate change effects. Some information and findings specific to the historic site are included in "Guidance for Resource Management."

Possible associations between climate change and geologic features and processes at the historic site include the following:

- More intense drought cycles—Drought-related geologic impacts are a result of a complex interplay among fire frequency and magnitude, vegetation composition and structure, precipitation events, streamflow, stream-channel morphology, sediment transport, erosion of surficial deposits, and slope movements. Of potential interest and use for climate-change planning at the historic site are the GRI reports for Bandelier National Monument (KellerLynn 2015) and Tonto National Monument (KellerLynn 2020), which provide detailed discussions of the interplay among these factors.

A warmer, drier landscape will mean a decrease in water resources, which are important for sustaining the existing ecological systems and cultural landscape at the historic site. A decrease in water also will impact park operations, including visitor services and irrigation water to maintain vegetation. Extended periods of drought have the potential to increase wildfire frequency and magnitude (discussed below); alter the vegetation composition and structure of the cultural landscape; and accelerate weathering, deterioration, and loss of archeological and cultural resources such as the Martinez Adobe. Any widespread loss of vegetation can affect slope stability (discussed below). Likewise, changes in vegetation type and distribution may change landslide processes and distribution.

- More intense storms—As discussed in the previous bullet item, climate change may result in an overall decrease in average annual precipitation, causing drought. By the same token, however, climate change may cause more intense storms. Gullying is associated with high-intensity storm events (Stoms et al. 2014). Consequently, an increase in storm intensity could exacerbate gullying and accelerate the following: erosion and sedimentation rates, weathering of trails, weathering and structural damage of Martinez Adobe, and bank erosion at the Gravesite Unit.
- Increased frequency and magnitude of fires—The frequency of large fires in this area is predicted to increase 16%–41% by the end of the century depending on the emissions and urban growth scenario (Stoms et al. 2014). Wildfires are a geologic concern because of the accelerated erosion and sedimentation that follow them, as well as the connection between wildfires and slope stability.
- Slope stability—Although the type of underlying bedrock or other geologic material is a primary factor in slope stability, various types of slope movements respond differently to changes in precipitation. For example, bank failures (slumps) are more likely to be triggered by extended rainfall events than isolated, large floods (Moore 2006). Swanston et al. (1983) found that progressive creep responded to annual increments of precipitation whereas earthflows responded to seasonal precipitation during the rainy season. Consequently, changes in precipitation patterns induced by climate change will influence the type and timing of slope movements.

### Flooding on Franklin Creek

Franklin Creek, which flows through the House Unit (see fig. 2), is prone to flooding. The two main features of the House Unit—the Muir House and the Martinez Adobe—have not experienced flooding, however. The Muir House was built on a knoll that has stood higher than any floodwaters to date (see "Fluvial Features and Processes"), and the Martinez Adobe is out of the floodplain.

Flooding along Franklin Creek (and Alhambra Creek) gradually increased in frequency as land use in the valley transitioned from agricultural to suburban (Killion and Davison 2005). In the mid-1960s, part of Franklin Creek just south of the House Unit was channelized into a culvert under State Route 4 (see fig. 2). A small check dam was built downstream under the Franklin Creek Bridge to maintain a minimum pool of water. Later, concrete stabilization structures were added to curb bank erosion near the culvert outfall (Killion and Davison 2005).

Flooding associated with Franklin Creek has impacted the following areas within or near the historic site:

- House Unit, orchard area—During the scoping meeting in 2007 (see scoping summary by KellerLynn 2008), participants identified flooding on Franklin Creek as a management concern because flooding occurs in the orchard area (on either side of Franklin Creek between the Martinez Adobe and Muir House; see fig. 2). Floodwaters, in turn, transport debris, which generally requires some maintenance and cleanup, but could potentially include hazardous materials.
- Franklin Creek Bridge—In 1915, the wooden bridge across Franklin Creek was washed out. During flood events in 1937 and 1958, the Muir House was an island surrounded by water and cut off from Franklin Canyon Road, but the bridge along the main farm road apparently held. In 1965, however, a sudden flood washed the bridge out because gophers had dug behind the abutments. Flooding problems again plagued the bridge and creek in 1970 (Killion and Davison 2005).
- Fish pond (northwest of the Muir House, near Franklin Creek; see fig. 2)—During Muir's life in Martinez, floodwaters from Franklin Creek likely filled a low area, which became known as the "fish pond," next to the Franklin Creek Bridge. By 1887, a low earthen berm was built along the north side of the fish pond; the berm was probably constructed to protect a young peach orchard from floodwaters. Today, the ground in the fish pond is mostly bare and is commonly muddy after rain events (Killion and Davison 2005).

## Paleontological Resource Inventory, Monitoring, and Protection

In situ (i.e., in rocks or unconsolidated deposits) paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). They may be body fossils (any remains of the actual organism such as bones, teeth, shells, or leaves) or trace fossils (evidence of an organism's activity such as nests, burrows, tracks, or coprolites [fossil feces]). Fossils also may occur in museum collections and other cultural contexts, as discussed below. All fossils are nonrenewable.

Elder et al. (2008) provided a baseline paleontological resource inventory for NPS areas in the San Francisco Area Network, including the historic site. A field-based survey at the historic site has not been conducted. The historic site's foundation document (National Park Service 2015) identified an archeological survey of the Mount Wanda Unit as an "opportunity"; a paleontological survey could potentially be combined with that effort.

### *In Situ Fossils*

The Cretaceous Great Valley sequence at the historic site has the potential to yield fossils. No fossils are yet known from the Cretaceous rocks exposed in the historic site, but rocks of similar age nearby have produced diverse invertebrate fossils and microfossils. North of the historic site, for example, Weaver (1949) listed several localities with diverse molluscan assemblages. These fossil localities may be in the Great Valley sequence, sandstone, siltstone, and clay shale (**Kus**), which is the historic site's oldest bedrock unit, though these localities and fossils need to be reviewed and modern nomenclature applied before an accurate determination can be made (Elder et al. 2008).

Rocks of Paleocene age are rare in California, and the rocks of this age in the Martinez area provided important fossil material. Although no fossils are known from the Paleocene rocks at the historic site, Elder et al. (2008) reported the potential of these rocks to yield fossils, especially of invertebrate faunas. The Paleocene rocks of the Martinez area are included in pivotal early studies of the first fossils known from the Paleocene Epoch on the West Coast (Elder et al. 2008). These studies date back to Gabb (1869) and include White (1889), Stanton (1896), Dickerson (1914), Nelson (1925), Watson (1942), Weaver (1949), and Parker (2003).

As discussed in the "Martinez Formation" section of this report, various investigators (Graymer et al. 1994, 2002; Haydon 1995; Graymer 2000) have mapped the Paleocene rocks in the historic site differently and identified them as Martinez Formation or Vine Hills Sandstone. Moreover, various other investigators have assigned rocks of the Martinez Formation to other formations, for example, Yerkes and Campbell (1979) assigned them to the Coal Canyon Formation (in the Santa Monica Mountains). Closer to the historic site, in the San Joaquin basin, various studies have assigned the Martinez Formation to the upper part of the Moreno Formation (e.g., McGuire 1988a, 1988b; Bartow 1991) or to the lower part of the Lodo Formation (Goudkoff 1945; Mallory 1959). According to Johnson and Graham (2007), however, the Martinez Formation likely constitutes a depositional sequence distinct from the Lodo Formation based on well-log character (Bloch 1991).

Future paleontological resource investigations or inventories of the historic site's Paleocene rocks will need to take these past studies into consideration when researching fossil potential. An inventory that includes a field survey seems warranted. Such an inventory could be conducted at the same time as a field survey of these rocks with respect to lithology, stratigraphy, and sedimentology, clarifying the inconsistencies between the descriptions by Weaver (1953) and Haydon (1995) (see "Martinez Formation").

### *Fossils in the Historic Site's Museum Collection*

The historic site has one of the world's largest museum collections of artifacts, archives, and natural history specimens related to John Muir. Additionally, items in museum collections at other parks, including Yosemite National Park, Golden Gate National Recreation Area, and Petrified Forest National Park, also relate to John Muir (National Park Service 2015).

A paleontological inventory of the historic site's museum collection has not been conducted. Yet, some pertinent information is known. During the GRI review process, email correspondence between Vincent L. Santucci (National Park Service, senior paleontologist) and Virginia Bones (John Muir National Historic Site, museum curator) revealed several "fossil discoveries" (discussed below). Santucci compiled that email correspondence into a memo to file (dated 10 February 2021). The NPS Paleontology Program maintains memos to file in the NPS paleontology archives. This documentation captures information (e.g., personal communication, email communication, or other sources of information) that can be ephemeral in nature, easily lost, or hard to obtain. It is a way to preserve important and interesting paleontological information that is otherwise unpublished and not recorded elsewhere (Vincent L. Santucci, National Park Service, senior paleontologist, email communication, 27 February 2021).

In addition to a piece of petrified wood that is embedded in the fireplace in the west bedroom (see "Muir House"), which was part of Muir's personal collection, at least six other specimens of Triassic petrified wood (JOMU 1535, 1538, 1539, 1540, 4258, and 4259) have been part of the historic site's collection. In 1973, these specimens were transferred from Petrified Forest National Park to the historic site for use in interpretive exhibits. These specimens are representative of the year-long venture that John Muir and his daughters made to Arizona between the summers of 1905 and 1906. Lubick (1996) provided an account of Muir's visit to the Petrified Forest before establishment of the national monument in 1906. The area was designated a national park in 1962 (see GRI report about Petrified Forest National Park by KellerLynn 2010).

One of the petrified wood specimens (JOMU 1540, originally PEFO 2426) was transferred back to Petrified Forest National Park in 2013 because it was a portion of the holotype specimen. A holotype specimen is the specimen upon which the original, formal description of a species or taxon is based, and park staff at Petrified Forest wanted it back (Virginia Bones, John Muir National Historic Site, museum curator, email communication, 26 April 2021). The other five specimens of petrified wood are displayed in the Scribble Den of the Muir House.

Another fossil in the historic site's collection is a "sunfish." This specimen (JOMU 679) was not owned by John Muir, rather by a private citizen in Oakland, who donated the specimen in 1967 to help furnish the Muir House in a Victorian style. The fossil was on display in the house for many years, but in 2013–2014, a new interpretive plan was created. Objects that did not resemble those owned by Muir were removed from display to create a more authentic presentation of what the home looked like while Muir lived there (Virginia Bones, John Muir National Historic Site, museum curator, email communication, 11 February 2021). Nevertheless, the specimen has geologic interest and ties to the National Park System: Living during the Eocene Epoch (56 million–33.9 million years ago), the specimen is of the genus *Priscacara* from the Green River Formation. *Priscacara* is an iconic and recognizable fossil fish from Eocene lake deposits preserved in Colorado, Utah, and Wyoming. The distinctive entrance sign at Fossil Butte National Monument in Wyoming, for example, displays *Priscacara*. Fossil Butte National Monument was established to preserve the fossiliferous lake deposits of one of three Eocene lakes, Fossil Lake (Vincent L. Santucci, NPS Geologic Resources Division, senior paleontologist, email communication, 11 February 2021). The specimen remains in the historic site's collections.

Exhibitions of collections in the Muir House rotate on a regular basis, providing repeat visitors with varying perspectives on Muir's history and legacy (National Park Service 2015). Such an exhibit could take a geologic theme, showcasing photographs of John Muir in geologic contexts (e.g., see figs. 11 and 16); his collection of fossils, rocks, and minerals; his writings about geology; and his connection to famous geologists of the time (see "Geologic Connections to John Muir").

### *Fossils in Cultural Contexts*

Cultural contexts include archeological sites, prehistoric structures, historic structures, ethnographic stories and legends, and historic records and archives. Kenworthy and Santucci (2006) provided an overview of NPS paleontological resources in cultural resource contexts, though no examples in that publication were from the historic site. As explained by Kenworthy and Santucci (2006, p. 70):

> Fossils are found as tools, jewelry or other spiritual items in National Park Service archeological sites. Ethnographic stories and legends told by American Indians and "mountain men" of the American West also incorporate fossils found within areas now administered by the National Park Service. Many building stones found in prehistoric and historic structures of the National Park Service display fossils including body fossils, trace fossils and petrified wood. In addition, various archives, journals, memoirs and photographs include numerous other historical accounts of fossils in areas of the National Park Service.

The petrified wood embedded in the fireplace in the west room of the Muir House is an example of a fossil in a cultural context (see fig. 4). Santucci et al. (2021), which highlighted the petrified wood in the fireplace at the historic site, documented the occurrence of fossils and fossiliferous stone within historic and prehistoric structures. Many historic structures were constructed, faced, or ornamented with sedimentary rocks that contain fossils.

A geologic inventory of building stone at the historic site has the potential to discover other fossils in a cultural context. Receiving geologic expertise for an inventory of building stone may be possible through the Scientists in Parks (SIP) program (see "Guidance for Resource Management").

# Guidance for Resource Management

*These references, resources, and websites may be of use to managers at the historic site. The laws, regulations, and policies apply to NPS geologic resources. The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (§ 204), National Park Service 2006 Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75).*

### Access to GRI Products

- GRI products (scoping summaries, GIS data, posters, and reports): http://go.nps.gov/gripubs or https://www.nps.gov/subjects/geology/geologic-resources-inventory-products.htm
- GRI products also are available through the NPS Integrated Resource Management Applications (IRMA) portal: https://irma.nps.gov/. Enter "GRI" as the search text and select a park from the unit list.
- Additional information regarding the GRI, including contact information: https://www.nps.gov/subjects/geology/gri.htm

### Four Ways to Receive Geologic Resource Management Assistance

- Contact the NPS Geologic Resources Division (https://www.nps.gov/orgs/1088/contactus.htm). GRD staff members provide technical and policy support for geologic resource management issues in three emphasis areas: (1) geologic heritage, (2) active processes and hazards, and (3) energy and minerals management. GRD staff can provide technical assistance with resource inventories, assessments, and monitoring; impact mitigation, restoration, and adaptation; hazards risk management; law, policy, and guidance; resource management planning; and data and information management.
- Formally request assistance at the Solution for Technical Assistance Requests (STAR) webpage: https://irma.nps.gov/Star/ (available on the Department of the Interior [DOI] network only). NPS employees (from a park, region, or any other office outside of the Natural Resource Stewardship and Science [NRSS] Directorate) can submit a request for technical assistance from NRSS divisions and programs.
- Contact the program manager and/or submit a proposal to receive geologic expertise through the Scientists in Parks (SIP) program: https://doimspp.sharepoint.com/sites/nps-scientistsinparks (available on the DOI network only). Proposals may be for assistance with research, interpretation and public education, inventories, and/or monitoring. Formerly the Geoscientists-in-the-Parks (GIP) program, the SIP program (https://www.nps.gov/subjects/science/scientists-in-parks.htm) places scientists (typically undergraduate students) in parks to complete geoscience-related projects that may address resource management issues. A partner of this program is the Geological Society of America.
- Refer to *Geological Monitoring* (Young and Norby 2009), which provides guidance for monitoring vital signs (measurable parameters of the overall condition of natural resources). Each chapter covers a different geologic resource and includes detailed recommendations for resource managers, suggested methods of monitoring, and case studies. Chapters are available online at https://www.nps.gov/subjects/geology/geological-monitoring.htm.

### Assistance with Water-Related Issues

Although water is a geologic agent, some water-related issues are best addressed by the NPS Water Resources Division (WRD), rather than the NPS Geologic Resources Division. Such issues include water quality, water supply, floodplains, wetlands, and water rights. Park managers are directed to the WRD website (https://home.nps.gov/orgs/1439/index.htm) for program specifics and contact information (https://home.nps.gov/orgs/1439/contactus.htm). Park managers can formally request assistance from the Water Resources Division via https://irma.nps.gov/Star/ (available on the DOI network only).

### Park-Specific Documents

The historic site's cultural landscape report (Killion and Davison 2005; Killion 2005), watershed management report (Moore 2006), natural resource condition assessment (Stoms et a. 2014), and foundation document (National Park Service 2015) are primary sources of information for resource management within the historic site. These documents guided the writing of this GRI report. In addition, the historic site has a general management plan and environmental assessment (National Park Service 1991).

### NPS Resource Management Guidance and Documents

- National Parks Omnibus Management Act of 1998 (S. 1693): https://www.congress.gov/bill/105th-congress/senate-bill/1693
- Director's Order #77-2 (Floodplain Management): https://npspolicy.nps.gov/DOrders.cfm [webpage for all director's orders and related documents]
- NPS-75: Natural Resource Inventory and Monitoring Guideline: https://irma.nps.gov/DataStore/Reference/Profile/622933
- NPS Management Policies 2006 (chapter 4: Natural Resource Management): https://www.nps.gov/subjects/policy/upload/MP_2006.pdf
- NPS Natural Resource Management Reference Manual #77: https://irma.nps.gov/DataStore/Reference/Profile/572379

### Geologic Resource Laws, Regulations, and Policies

The following table (table 3), which was developed by the NPS Geologic Resources Division, summarizes laws, regulations, and policies that specifically apply to NPS minerals and geologic resources that may be present at the historic site. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available.

**Table 3. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
|---|---|---|---|
| Paleontology | **Archaeological Resources Protection Act of 1979, 16 USC §§ 470aa – mm Section 3 (1) Archaeological Resource—**nonfossilized and fossilized paleontological specimens, or any portion or piece thereof, shall not be considered archaeological resources, under the regulations of this paragraph, unless found in an archaeological context. Therefore, fossils in an archaeological context are covered under this law.<br><br>**Federal Cave Resources Protection Act of 1988, 16 USC §§ 4301 – 4309 Section 3 (5) Cave Resource—**the term "cave resource" includes any material or substance occurring naturally in caves on Federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems. Therefore, every reference to cave resource in the law applies to paleontological resources.<br><br>**National Parks Omnibus Management Act of 1998, 54 USC § 100701** protects the confidentiality of the nature and specific location of paleontological resources and objects.<br><br>**Paleontological Resources Preservation Act of 2009, 16 USC § 470aaa et seq.** provides for the management and protection of paleontological resources on federal lands. | **36 CFR § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof.<br><br>**Prohibition in 36 CFR § 13.35** applies even in Alaska parks, where the surface collection of other geologic resources is permitted.<br><br>**43 CFR Part 49** (in development) will contain the DOI regulations implementing the Paleontological Resources Preservation Act. | **Section 4.8.2 requires NPS to protect geologic features from adverse effects of human activity.**<br><br>**Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria. |

**Table 3, continued. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
|---|---|---|---|
| Recreational Collection of Rocks Minerals | **NPS Organic Act, 54 USC. § 100101 et seq.** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law.<br><br>**Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone). | **36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units.<br><br>**Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown.<br><br>**Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment. | **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. |
| Common Variety Mineral Materials (Sand, Gravel, Pumice, etc.) | **Materials Act of 1947, 30 USC § 601** does not authorize the NPS to dispose of mineral materials outside of park units.<br><br>**Reclamation Act of 1939, 43 USC §387**, authorizes removal of common variety mineral materials from federal lands in federal reclamation projects. This act is cited in the enabling statutes for Glen Canyon and Whiskeytown National Recreation Areas, which provide that the Secretary of the Interior may permit the removal of federally owned nonleasable minerals such as sand, gravel, and building materials from the NRAs under appropriate regulations. Because regulations have not yet been promulgated, the National Park Service may not permit removal of these materials from these National Recreation Areas.<br><br>**16 USC §90c-1(b)** authorizes sand, rock and gravel to be available for sale to the residents of Stehekin from the non-wilderness portion of Lake Chelan National Recreation Area, for local use as long as the sale and disposal does not have significant adverse effects on the administration of the national recreation area. | None applicable. | **Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and:<br>-only for park administrative uses;<br>-after compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment;<br>-after finding the use is park's most reasonable alternative based on environment and economics;<br>-parks should use existing pits and create new pits only in accordance with park-wide borrow management plan;<br>-spoil areas must comply with **Part 6** standards; and<br>-NPS must evaluate use of external quarries.<br><br>Any deviation from this policy requires a written waiver from the Secretary, Assistant Secretary, or Director. |

**Table 3, continued. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
|---|---|---|---|
| Soils | **Soil and Water Resources Conservation Act, 16 USC §§ 2011–2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources.<br><br>**Farmland Protection Policy Act, 7 USC § 4201 et. seq.** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS). | **7 CFR Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. **Part 610** governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. **Part 611** governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements. | **Section 4.8.2.4** requires NPS to<br>-prevent unnatural erosion, removal, and contamination;<br>-conduct soil surveys;<br>-minimize unavoidable excavation; and<br>-develop/follow written prescriptions (instructions). |
| Climate Change | **Secretarial Order 3289** (Addressing the Impacts of Climate Change on America's Water, Land, and Other Natural and Cultural Resources) (2009) requires DOI bureaus and offices to incorporate climate change impacts into long-range planning; and establishes DOI regional climate change response centers and Landscape Conservation Cooperatives to better integrate science and management to address climate change and other landscape scale issues.<br><br>**Executive Order 13693** (Planning for Federal Sustainability in the Next Decade) (2015) established to maintain Federal leadership in sustainability and greenhouse gas emission reductions. | None Applicable. | **Section 4.1** requires NPS to investigate the possibility to restore natural ecosystem functioning that has been disrupted by past or ongoing human activities. This would include climate change, as put forth by Beavers et al. (in review).<br><br>**Policy Memo 12-02** (Applying National Park Service Management Policies in the Context of Climate Change) (2012) applies considerations of climate change to the impairment prohibition and to maintaining "natural conditions".<br><br>**Policy Memo 14-02** (Climate Change and Stewardship of Cultural Resources) (2014) provides guidance and direction regarding the stewardship of cultural resources in relation to climate change.<br><br>**Policy Memo 15-01** (Climate Change and Natural Hazards for Facilities) (2015) provides guidance on the design of facilities to incorporate impacts of climate change adaptation and natural hazards when making decisions in national parks. |

**Table 3, continued. Geologic resource laws, regulations, and policies.**

| Resource | Resource-specific Laws | Resource-specific Regulations | 2006 Management Policies |
|---|---|---|---|
| Upland and Fluvial Processes | **Rivers and Harbors Appropriation Act of 1899, 33 USC § 403** prohibits the construction of any obstruction on the waters of the United States not authorized by congress or approved by the USACE.<br><br>**Clean Water Act 33 USC § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US [including streams]).<br><br>**Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also **D.O. 77-2**)<br><br>**Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also **D.O. 77-1)** | None applicable. | **Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems.<br><br>**Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks, unless directed otherwise by Congress.<br><br>**Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety.<br><br>**Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding.<br><br>**Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams.<br><br>**Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes.<br><br>**Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue. |

### Additional References, Resources, and Websites

*California Geology*

- California Geological Survey (CGS): https://www.conservation.ca.gov/cgs/
- CGS Notes (short pamphlets with answers to commonly asked questions about California's geology): https://www.conservation.ca.gov/cgs/publications/cgs-notes
- Geological Gems of the California State Parks (Fuller et al. 2015; online and/or downloadable PDF): https://www.parks.ca.gov/?page_id=29631
- Geological Gems of the California State Parks (online map): https://maps.conservation.ca.gov/cgs/sr230/

*Climate and Climate Change*

- The historic site is within the Mediterranean-type climate zone of central and southern California and northern Baja California. This climate type only occurs in four other locations around the world: (1) the area bordering the Mediterranean Sea, (2) central Chile, (3) the Cape region of South Africa, and (4) southwestern and southern Australia. These areas are distributed between roughly 30° and 40° latitude—north and south—and are located along the western edges of continents where cold ocean currents moderate the climate.
- Due to the historic site's proximity to the coastline, its climate is heavily influenced by the Pacific Ocean, which creates mild, wet winters and warm, dry summers. Over the past 50 years, temperatures averaged 15°C (59°F) and total annual precipitation averaged 50 cm (20 in; Stoms et al. 2014).
- Davey et al. (2007) conducted a weather and climate inventory for NPS areas in the San Francisco Bay Area Network, including the historic site. No weather or climate stations were identified within the boundaries of the historic site, but the urban setting of much of the San Francisco Bay Area Network hosts many non-NPS sources of weather and climate data. Davey et al. (2007) reported 69 weather or climate stations within 20 km (12 mi) of the historic site and noted that a station does not have to be within a park unit's boundaries to provide useful data and information regarding a given park unit. The closest active station to the historic site is the COOP (Cooperative Observer Program) station Martinez Water Plant, which is 3 km (2 mi) northeast of the historic site.
- A natural resource condition assessment (Stoms et al. 2014) evaluated the threats and stressors, including climate change and increasing fire frequency, that act on the natural resources at the historic site.
- A climate change resource brief (Monahan and Fisichelli 2014) reported that one of 14 temperature or precipitation variables was "extreme" (i.e., having a mean percentile less than the 5th percentile or greater than the 95th percentile) compared to the historical range of conditions. The variable—minimum temperature of the coldest month—was "extreme warm." Notably, when a threat from climate change falls far outside the contemporary experience of natural and human systems, such conditions may present a substantial challenge to adaptation (Cook et al. 2015). In addition, Monahan and Fisichelli (2014) noted that climate change will manifest itself not only as changes in average conditions but also as changes in particular climate-related events (e.g., more intense storms, floods, or drought).
- A park-specific brief (Fisichelli and Ziesler 2015) examined how future warming may alter visitation patterns. Modeling found no significant relationship between visitation and temperature, including annual visitation, peak-season visitation, low-season visitation, or shoulder-season visitation at the historic site. Although the findings by Fisichelli and Ziesler (2015) do not support a relationship between temperature and visitation, this does not necessarily mean that visitors are not responding to climate. Visitors to the historic site may be responding to other aspects of climate, such as precipitation, or to shorter-term weather patterns such as storms and heat waves. Non-climate factors may also be significant drivers of visitation. Furthermore, visitor response to climate may shift or strengthen with ongoing climate change.
- *Climate Change in the National Parks of the San Francisco Bay Area, California, USA* (Gonzalez 2016) presented the results of spatial analyses of historical and projected climate change. Average annual temperature from 1950 to 2010 increased at statistically significant rates of 2.4 ± 0.7°C (4.3 ± 1.3°F) per century (mean ± standard error), with the greatest increases in spring. Total annual precipitation from 1950 to 2010 showed no statistically significant change. With continued emissions of greenhouse gases, projections under the four emissions scenarios of the Intergovernmental Panel on Climate Change (IPCC) indicate an increase of 3.8 ± 0.8°C (6.8 ± 1.4° F) (mean ± standard deviation) for the average annual temperature by 2100. Climate models project total annual precipitation increases of 5% to 10% on average, but increased temperatures may still increase aridity.
- Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

- NPS Climate Change Response Program: http://www.nps.gov/subjects/climatechange/resources.htm
- NPS climate change, sea level change: https://www.nps.gov/subjects/climatechange/sealevelchange.htm/index.htm
- NPS sea level rise (map viewer): https://maps.nps.gov/slr/
- US Global Change Research Program: http://www.globalchange.gov/home

### *Faults and Earthquakes in California*

- CGS, earthquakes and faults: https://www.conservation.ca.gov/cgs/earthquakes. *Note*: The website has links to information about recent earthquakes, historical earthquakes, faults, earthquake probabilities, earthquake shaking hazard, and earthquake loss estimation.
- CGS Map Sheet 48 (Branum et al. 2016; earthquake shaking potential for California): https://gis.conservation.ca.gov/server/rest/services/CGS/MS48_ShakingPotential/MapServer
- CGS Note 31 (California Geological Survey 2003; faults and earthquakes in California): https://www.conservation.ca.gov/cgs/publications/cgs-notes [webpage with links for all CGS Notes]
- California Integrated Seismic Network (CISN; real-time earthquake map of California): https://www.cisn.org/
- CISN ShakeMaps (depict the intensity of ground shaking for earthquakes of magnitude 3.5 and higher): https://www.cisn.org/services/shakemap.html
- ShakeAlert: An Earthquake Early Warning System for the West Coast of the United States: https://www.shakealert.org/
- USGS Earthquake Hazards Program unified hazard tool: https://earthquake.usgs.gov/hazards/interactive/
- Working Group on California Earthquake Probabilities: http://www.wgcep.org/

### *Geologic Maps*

- American Geosciences Institute (provides information about geologic maps and their uses): http://www.americangeosciences.org/environment/publications/mapping
- *General Standards for Geologic Maps* (Evans 2016)
- National Geologic Map Database: https://ngmdb.usgs.gov/ngmdb/ngmdb_home.html
- Online geologic map of California: https://maps.conservation.ca.gov/cgs/gmc/

### *Geological Surveys and Societies*

- American Geophysical Union: http://sites.agu.org/
- American Geosciences Institute: http://www.americangeosciences.org/
- Association of American State Geologists: http://www.stategeologists.org/
- California Geological Survey: https://www.conservation.ca.gov/cgs/Pages/Index.aspx
- Geological Society of America: http://www.geosociety.org/
- US Geological Survey: http://www.usgs.gov/

### *Slope Movements*

- The NPS Geologic Resources Division employs three rockfall management strategies: (1) an Unstable Slope Management Program (USMP) for transportation corridor risk reduction, (2) quantitative risk estimation for specific rockfall hazards, and (3) monitoring of potential rockfall areas. Park managers can contact the Geologic Resources Division to discuss these options and determine if submitting a technical assistance request is appropriate.
- CGS landslide inventory: https://maps.conservation.ca.gov/cgs/lsi/app/
- CGS Note 50 (California Geological Survey 2013; factors affecting landslides in forested terrain): https://www.conservation.ca.gov/cgs/publications/cgs-notes [webpage with links for all CGS Notes]
- *Geological Monitoring* chapter about slope movements (Wieczorek and Snyder 2009): https://www.nps.gov/articles/monitoring-slope-movements.htm
- *The Landslide Handbook—A Guide to Understanding Landslides* (Highland and Bobrowsky 2008): http://pubs.usgs.gov/circ/1325/

### *Natural Hazards*

- Association of Bay Area Governments, online hazard viewer: https://abag.ca.gov/our-work/resilience. *Note*: The website includes wildfire, tsunami, FEMA flood hazard, landslide hazard, earthquake fault zones, earthquake shaking hazards, earthquake shaking scenarios by fault name, and liquefaction susceptibility.

### *NPS Geology*

- America's geologic heritage: https://www.nps.gov/subjects/geology/americas-geoheritage.htm
- NPS Geologic Resources Division: http://go.nps.gov/geology
- NPS Geologic Resources Inventory (GRI): http://go.nps.gov/gri
- NPS geodiversity atlas: https://www.nps.gov/subjects/geology/nps-geodiversity-atlas-link.htm

- NPS geoscience concepts: https://www.nps.gov/subjects/geology/geology-concepts.htm

*NPS Reference Tools*

- NPS Technical Information Center (TIC; repository for technical documents and means to receive interlibrary loan materials): https://pubs.etic.nps.gov/
- GEOREF. The GRI team collaborates with TIC to maintain an NPS subscription to GEOREF (the premier online geologic citation database) via the Denver Service Center Library interagency agreement with the Library of Congress. Multiple portals are available for NPS staff to access these records. Park staff can contact the GRI team or GRD staff for access.
- NPS Integrated Resource Management Applications (IRMA) portal: https://irma.nps.gov/. *Note*: The GRI team uploads scoping summaries, maps, and reports to IRMA. Enter "GRI" as the search text and select a park from the unit list.

*Relevancy, Diversity, and Inclusion*

- NPS Office of Relevancy, Diversity and Inclusion: https://www.nps.gov/orgs/1244/index.htm
- John Muir: racist or admirer of Native Americans? (Barnett 2020): https://vault.sierraclub.org/john_muir_exhibit/life/racist-or-admirer-of-native-americans-raymond-bennett.aspx
- Changing the narrative in science & conservation: an interview with Sergio Avila (Sierra Club, Outdoor Program coordinator). Science Moab radio show/podcast: https://sciencemoab.org/changing-the-narrative/
- The racist legacy many birds carry: the birding community faces a difficult debate about the names of species connected to enslavers, supremacists and grave robbers (Fears 2021): https://www.washingtonpost.com/climate-environment/interactive/2021/bird-names-racism-audubon/

*Soil*

- Web Soil Survey (WSS) provides soil data and information produced by the National Cooperative Soil Survey. It is operated by the USDA Natural Resources Conservation Service (NRCS): https://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm

*US Geological Survey Reference Tools*

- Geologic Names Lexicon (Geolex; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/search
- Geographic Names Information System (GNIS; official listing of place names and geographic features): https://www.usgs.gov/core-science-systems/ngp/board-on-geographic-names/domestic-names
- GeoPDFs (download PDFs of any topographic map in the United States): http://store.usgs.gov (click on "Map Locator")
- USGS Publications Warehouse: http://pubs.er.usgs.gov
- Tapestry of Time and Terrain (descriptions of physiographic provinces): http://pubs.usgs.gov/imap/i2720/

*Writings by John Muir*

- Sierra Club (magazine articles, books, journals, letters, writings/tributes/eulogies about other people by John Muir): https://vault.sierraclub.org/john_muir_exhibit/writings/
- University of the Pacific (special collection: John Muir Papers): https://www.pacific.edu/university-libraries/find/holt-atherton-special-collections/john-muir-papers
- University of the Pacific (John Muir's original journals): https://scholarlycommons.pacific.edu/jmj-all/

# Literature Cited

*These references are cited in this report. Contact the Geologic Resources Division for assistance in obtaining them.*


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