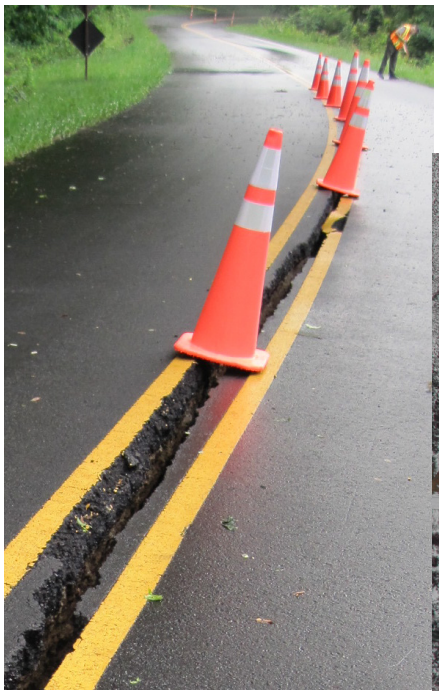
National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Summary and Categorization of Documented Geologic Hazards of the National Park System

Natural Resource Report NPS/NRSS/GRD/NRR—2014/813











ON THIS PAGE
Dump truck crushed by rockfall at Zion National Park, Utah, on November 23, 1947. NPS Photo.

ON THE COVER
Top left: Slope failure closes section of the road at Blue Ridge Parkway, North Carolina, July 2013. NPS Photo: John Otten
Top right: Aerial imagery of landslide at Denali National Park & Preserve, Alaska, Oct. 2013. NPS Photo: Rob Burrows
Bottom left: Rockfall impact in Mount Rainer National Park, Washington, May 2014. NPS Photo: Scott Beason
Bottom right: Old Fall River Road landslide, Rocky Mountain National Park, Colorado, Sept. 2013. NPS Photo: Kirsten Hardin

Summary and Categorization of Documented Geologic Hazards of the National Park System

Natural Resource Report NPS/NRSS/GRD/NRR—2014/813

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The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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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.

Data in this report were collected and analyzed using methods based on established, peer-reviewed protocols and were analyzed and interpreted within the guidelines of the protocols.

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Executive Summary

Geologic hazards are naturally occurring, dynamic geologic processes which have the potential to cause damage, loss of property, and/or injury and loss of life. These processes include: avalanches, cave and karst incidents, coastal and shoreline hazards, flooding, geothermal risks, glacial activity, mass wasting events, rockfalls, seismic activity, and volcanic hazards.

Although servicewide data on geologic hazards is far from comprehensive, the study found that 72 people were killed and at least 124 injured. There have been 141 incidents damaging or destroying park facilities and 31 that affected irreplaceable cultural resources.

Of the geologic hazard categories, rockfalls are the most commonly reported incident (27%) followed by flooding (16%) and mass wasting (14%). These hazards often occur repeatedly in the same locations and carefully planned preventative measures could prevent future damages and injuries. Damages to facilities are most common (67%) followed by incidents affecting people (38%) and damage to cultural resources (38%). These numbers add up to more than 100% because events often cause damage to more than one category (facilities, people, cultural resources). Due to an under-reporting of incidents and lack of a centralized database for collecting these events, the results presented in this report far under-represent the true extent of geologic hazards impacting the National Park System.

This project is a collaborative effort between the National Park Service (NPS) Geologic Resources Division (GRD) and the Public Risk Management Program (PRMP). It stresses the importance of a servicewide reporting system for geologic hazard incidents and is a first effort to compile servicewide geologic hazard information.

Background work for this report involved the review of 225 documented geologic hazards in 83 NPS areas and itemization of those incidents resulting in injury or damage. This effort lays the foundation for establishing a queryable geologic hazard and incident database for the NPS to maintain geologic hazard incident data, add new incidents, analyze trends, and identify areas of high-risk. These data may help guide NPS management decision-making around park planning, injury and resource damage prevention, and to identify future areas of needed research. We recommend the development of a reporting method to collect geologic hazard incidents and capture retrospective incidents not currently itemized. This would allow the National Park Service to more proactively identify geologic hazard areas and investigate mitigating actions. We also recommend the identification of a few high-risk parks to undergo a detailed hazard analysis and develop preventative solutions to recurring issues.

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This study was performed under a cooperative mission of two directorates of the U.S. Department of the Interior, National Park Service: the Geologic Resources Division (GRD) and Public Risk Management Program (PRMP). The GRD works to integrate geologic resources management into established NPS natural resource activities and improve the Service's ability to gather, analyze and use geoscience information. The PRMP is a science-based program that provides park units with the necessary policies, guidelines, information, training, and assistance to evaluate their unit's public risk and to establish risk management and injury prevention programs that will minimize the potential for suffering or loss and enhance the visitor experience within our National Park System.

We thank GRD staff Rebecca Beavers, Rebecca Port, and Jason Kenworthy for providing insight on content items. Input from National Cave and Karst Research Institute executive director, George Veni, was much appreciated for caving accident source materials. Many thanks to Jon James, Luis Teran, and Bernard Spencer-Bey of George Washington Memorial Parkway for their availability and insight on rockfall issues. The staff of Walnut Canyon National Monument, Diane Chung, Paul Whitefield, Lisa Leap, Lisa Baldwin, Theodore Tsouras, and Nicole Arendt, was extremely accommodating and willing to help with the forward motion of this project. Thanks to Grand Canyon National Park staff, Deanna Greco, Colleen Hyde, Kim Besum, and Carl Bowman for their help in the data-gathering phase.

1 - Introduction

1.1 - Background

A geologic hazard is a naturally occurring, dynamic geologic process capable of causing damage, loss of property, and/or injury and loss of life. Geologic hazard processes can happen slowly over days or years, or have a sudden onset occurring in seconds or minutes. Engineering solutions, such as stabilizing hillslopes or building flood walls, can mitigate some serious hazard-related safety issues, but many naturally occurring hazards are more difficult to mitigate, such as a rockfall or sinkhole formation. These hazards may pose a threat to the safety of visitors and employees, the structural integrity of facilities, and the preservation of irreplaceable cultural resources. Hazard and risk awareness is the foundation for hazard mitigation. The efforts put forth in this report are the important first steps toward building the servicewide awareness so crucial to hazard assessment and mitigation.

The National Park Service currently maintains 401 units across a wide variety of geologic settings. In fact, every kind of geologic hazard can be found in at least one park, and typically many parks. This represents an enormous challenge to NPS employees in charge of risk management, public and employee safety, and the protection of cultural and natural resources, as well as infrastructure. Although the magnitude and timing of future geologic hazards are difficult to forecast, we strive to understand hazards and, subsequently, minimize their potential impact on visitors, staff, and developed areas as outlined by the NPS Management Policies (2006) §4.8.1.3. In the context of naturally occurring hazards, it is important to understand the distinction between “hazard” and “risk”. The level of “hazard” (low, medium, high) refers to the likelihood that an event will occur. “Risk” refers to the consequences of the hazard event (Holmes, et al. 2013). Identifying geologic hazards, assessing the likelihood of occurrence, and defining potential risks to infrastructure or people can assist the National Park Service with the management of these hazards.

1.2 – Problem Statement

Prior to this effort, the NPS has not maintained a servicewide dataset of geologic hazards and incidents in the parks. A few parks, which regularly experience geologic hazard events, maintain records for these incidents that impact visitor/employee safety and damage facilities or cultural resources. For example, Yosemite National Park (YOSE) employs a full-time geologist and Geoscientists-In-Parks program participants, who develop maps of areas with the highest geologic hazard threats and conduct cliff-face and rockfall research and monitoring (Stock et al. 2013).

Most parks have at least one geologic hazard, although many have multiple hazards. Minor geologic hazard incidents occur frequently and are more easily managed and mitigated. Larger and more significant geologic hazard events, although less frequent, can cause more severe damage. These large events—volcanic eruptions, major mass wasting events, or even tsunamis —are much harder to mitigate and cannot always be predicted.

This first attempt at compiling a servicewide database for geologic hazards entailed a preliminary analysis of the impacts of geologic hazards on park resources and people. The effort in compiling this database also highlighted the lack of standardized methods for collecting and reporting incidents

related to geologic hazards. For example, YOSE receives more than 3.5 million visitors per year and experiences regular rockfalls, mass wasting events, flooding, and avalanches. The search of servicewide documentation found nine reported incidents of rockfalls impacting people and facilities at the park. By contrast, Stock et al. (2013) compiled rockfalls from all historic written documents (the first was in 1857) to recent reports and the results totaled more than 510 rockfall incidents.

1.3 - Project Description

This project, a collaborative effort between the NPS GRD and PRMP, involved the review of documented geologic hazards and the itemization of those incidents resulting in injuries or damages. These park hazards are compiled in a spreadsheet (Appendix A) where they can be sorted, organized, and analyzed. This information enables the evaluation of data associated with the scope, significance, and distribution of geologic hazards throughout the NPS. The analysis of basic geologic hazard data helps NPS management in decision-making, identifying future research, and aiding in hazard mitigation planning.

This effort also involved the development of case studies for George Washington Memorial Parkway and Walnut Canyon National Monument. These studies highlight the availability of incident documentation at parks. The efforts provide a detailed analysis of historic and current geologic hazards and offer recommendations on potential damage prevention strategies at the two parks that may be applicable to parks servicewide.

2 - Methods

2.1 - Geologic Hazard Categories

The first step of the geologic hazard analysis of the National Parks was to define categories of hazards. Listed below are the categories and descriptions of the specific dangers associated with each hazard. Although flooding is a form of coastal/shoreline hazard, it was made a separate category because the weather and geomorphic conditions contributing to reported flood events are different than those affecting coast/shoreline events. Rockfalls are technically a form of mass wasting, they were kept in separate categories because of their frequency and modes of failure. Avalanches are also a form of mass wasting, but very different in material composition, seasonality, and trigger mechanisms so as to be categorized separately.

2.1.1 – Avalanche

A flow of snow, ice, rock, and other material that occurs as a result of thawing or agitation (can be started by the weight of skiers), are called avalanches. These events occur mostly late in the snow season when the snowpack is deep and the thaw is just beginning. Especially common are avalanches from steep slopes with a deep snow cover. Fast-moving, deep snow-flows and rapid burial are the biggest danger to people and facilities.

2.1.2 - Cave/Karst

A karst landscape is characterized by sinkholes, caves, sinking streams, and springs. These features typically develop in limestone terrain, but can also be found in areas with abundant evaporate deposits. Dissolution of these subsurface layers can lead to surface failures. The major dangers in caves are rockfalls, falling, or getting lost. In karst topography, the biggest danger, though unpredictable, is the sudden formation of sinkholes.

2.1.3 - Coastal/Shoreline

Numerous hazards face parks located on ocean coasts and lake shores. The regions of our country with these types of parks are the Atlantic coast, Gulf coast, Great Lakes parks, and Pacific Rim locations. Major hazards that make up this broad category include: tropical storms, hurricanes, coastal flooding, tsunamis, beach erosion, ship groundings, and submarine landslides (within park boundaries). Storms and floods can cause widespread facility damage as well as expose harmful or toxic components from debris. Tsunamis are extremely dangerous events, sending a large wave or series of large waves toward the shore as a reaction to a coastal landslide or submarine earthquake. Massive damages can result from a tsunami and only some of them give advanced warning. Those waves that propagate from long distances can be prepared for, but in the case of small, nearly-closed basins, little can be done to reduce risks.

2.1.4 – Flooding

Flooding is an overflow of water onto land. Floods at parks can occur on the floodplains of any body of water or as a result of major storm events, spring snowmelt, or rain-on-snow events. Coastal flooding is also an issue at parks, but has been categorized as a coastal/shoreline hazard for this study.

2.1.5 – Geothermal

At volcanically active parks and those with heat at depth in their geologic strata, geothermal hazards become a concern for visitor and employee safety. Boiling mudpots, geysers, steam-vents and hot springs are all geothermal hazards present at certain parks. Most of these hazards are well mapped and serious injury can generally be avoided if warning signs are followed. Simply staying on the trail or boardwalk and using handrails could have prevented many injuries and fatalities. The biggest dangers posed by geothermal hazards are severe skin burns which can lead to hospitalization and often fatal injuries.

2.1.6 – Glacial

Glacial hazards are common in the high-elevation, mountainous regions of the country. The major hazards to people are accidental slips into crevasses and glacial outburst flood events (or jökulhlaups). A crevasse is a deep crack in an ice sheet or glacier. Although a range of sizes and shapes exist, the deepest crevasses can be up to 45 meters deep. Falling into a crevasse while on a backcountry hike or climb could prove fatal to both visitors and rescuers alike. A glacial outburst flood is any large and abrupt release of water from a subglacial or proglacial lake. These flooding events can have disastrous results for homes and facilities downstream.

2.1.7 – Mass Wasting

Landslides, mudflows, and debris flows are all forms of mass wasting that can cause severe facility damage and endanger lives. Often lubricated by rainfall or agitated by seismic activity, these events occur very rapidly and move as a flow. The runout of a mass wasting event depends on the volume of material, water content, and slope steepness. Buildings, trails, campgrounds, and cultural resources can be deeply covered with debris, damaging them beyond repair. Lahars, avalanches, and rockfalls (all forms of mass movement) are categorized as different hazard types for this study because they occur under very unique conditions.

2.1.8 – Rockfall

Although rockfalls are technically a form of mass wasting, they are unique because either their volume or viscosity prevents them from behaving as a flow. Fragments of rock that fall off vertical or sub-vertical cliffs and travel down slope, by bouncing or sliding, can pose a serious threat in our parks. Those parks in mountainous terrain or with any kind of steep, sheer cliffs have rockfall dangers. Roads and facilities built along cliffs or below cliffs are most sensitive.

2.1.9 – Seismic

Seismic waves are generated from slips and sudden releases of energy at depth in the Earth's crust. The surficial expression of this energy is called an earthquake and can range widely in severity. Strong earthquakes can destroy buildings and roads, start landslides or rockfalls, and can even cause wide-spread flooding. Earthquake events are tightly linked to geographic location, focused mostly around the Pacific Basin and on major fault lines.

2.1.10 – Volcanic

Violent eruptions are only one of the hazards associated with volcanic hazards. Volcanic mudflows, called lahars, carry a mixture of hot or cold water and volcanically-derived debris down the flanks of

a volcanic feature. They vary in size and speed which, in turn, varies their destructive power. A pyroclastic flow is a high-density mixture of rock fragments and hot gases that move away from the volcanic vent at high speeds. Eruptions can cause lava flows, clouds which rain down hot rock (tephra deposits), seismic activity, and poisonous ash and gas. All these hazards can prove very dangerous to park visitors and staff as well as the facilities and cultural resources that may be located near a volcanic field.

No eruption is necessary for cracks in the ground to allow gases to reach the surface. More than 90% of all gas emitted by volcanoes is water vapor (steam), most of which is heated groundwater. Other common volcanic gases are carbon dioxide, sulfur dioxide, hydrogen sulfide, hydrogen, and fluorine. Sulfur dioxide gas can react with water droplets in the atmosphere to create acid rain, which causes corrosion and harms vegetation. Carbon dioxide is heavier than air and can be trapped in low areas in concentrations that are deadly to people and animals. Fluorine, which in high concentrations is toxic, can be adsorbed onto volcanic ash particles that later fall to the ground, poisoning livestock and domestic water supplies.

2.2 – Hazard Data Collection

The two main components of this research included: identifying actual and potential hazards, and specific geologic hazard incidents in parks that resulted in injury to people or damage to park facilities or resources. We captured incidents associated with or caused by geologic hazards between 1927 and October 2013 and entered data into a spreadsheet for analysis.

A variety of sources were used to capture incidents by the type of geologic hazards in parks including: park web pages, particularly the "Plan Your Visit" and "Things to Know Before You Come" sections, InsideNPS Morning Reports, case incident reports, newspaper articles, NPS Geologic Resource Inventory reports, institutional knowledge such as seasonal flooding conditions, current volcanic gas emissions, trail closures, and weather advisories provided on park websites. Additional sources of information we relied on included scenery photos, topographic maps, geologic maps, and past park news alerts to capture additional cases and potential hazards. We also utilized the National Speleological Society (NSS) annual caving incident reports, GRD Technical Assistance Reports (TARs), concessioners' websites, technical journal articles, various print sources, and personal communication with GRD and other NPS staff. Refer to the "References" section for a selection of sources used.

Site visits to parks yielded additional incident information, including personal details from witnesses of the events. Data captured from incidents include geologic hazard category, a brief description, specific damages observed, and whether the incident affected people (P), facilities (F), cultural resources (R), or a combination.

An important distinction made in the data organization was to determine whether each incident was caused by a dynamic geologic process or a human behavior. This is denoted in a column labeled "Causal Factors" and incidents can either be process (P) or non-process (NP). Non-process incidents are those that occurred in relation to a geologic hazard but were more directly related to the interaction of the person with the environment. This interaction and resultant incident occurs, for

example, when an individual is unaware or ignores the dangers around them and, even if not participating in a high-risk recreational activity, becomes injured by geologic conditions. For example in 2006, a visitor to Haleakala National Park (HALE) dislodged a boulder that then rolled on top of him; he did not survive this incident. Although the geologic hazard for this event is labeled as a rockfall, it is also marked as "NP" in the causal factor column. Human judgment and behavior are the causal factor in "NP" incidents whereas the geologic process is the causal factor of "P" incidents.

2.3 - Park-Specific Geologic Hazard Reports

This study also included case studies focused on the rockfall hazards and incidents at George Washington Memorial Parkway (GWMP, Appendix B) and Walnut Canyon National Monument (WACA, Appendix C). Although there are historic issues with flooding and seismic activity at GWMP, the main geologic hazards are rockfalls and mass wasting incidents. Data were collected via interviews directly with park staff with significant knowledge about past geologic incidents. Rockfall reporting at WACA was extensive, highlighting many more incidents at the park than were previously identified from widely distributed sources.

3 - Results

3.1 – Servicewide Hazard Types, Frequency, and Locations

Although data collected in this study are not comprehensive, they provide an important first step in the description of the actual and potential risks to people and resources caused by geologic hazards across the National Park System.

We identified geologic hazards at 196 parks, but only 83 parks have reported geologic hazard incidents. Not surprisingly, those parks with the greatest number of geologic hazards all are located in steep mountainous terrain. Katmai National Park and Preserve (KATM) and Wrangell-St. Elias National Park and Preserve (WRST) have experienced the greatest number of hazards, and each has avalanche, coastal/shoreline, flooding, glacial, mass wasting, rockfall, seismic, and volcanic hazards. The parks with the next highest number of documented geologic hazards are Yellowstone National Park, Mount Rainier National Park, Hawaii Volcanoes National Park, and Klondike Gold Rush National Historical Park. These should be considered minimum numbers as actual incidents have far surpassed reported incidents.

Of the ten geologic hazard categories, rockfalls occur most often followed by flooding, coastal/shoreline hazards, and finally mass wasting (Figure 1). If rockfall and mass wasting were to be combined into one category (technically a rockfall is a specific type of mass wasting), it would be the most common geologic hazard, at 41%.

There are distinct regional trends in types of geologic hazards. Flood, geothermal, seismic, and volcanic hazards dominate the Pacific West Region and the Alaska Region because they are located near tectonic plate boundaries. The Intermountain Region had the most mass wasting and rockfall hazard parks due to the number of parks with steep, rocky terrain. Alaska Region NPS units also had the significant glacial hazards because of its location in the lowest latitudes of the country. The Southeast Region had most coastal and shoreline hazards because of the number of coastal park units. Cave/karst hazards were most common in the Intermountain and Pacific West Regions, while avalanche hazards were common in equal numbers of parks in the Alaska and Pacific West Regions.

3.2 - Impacts to Park Facilities, People, and Cultural Resources

Our study found more than 200 geologic hazards documented between 1927 and October 2013 that caused human, facility, and/or cultural resource damage. Because no standard system for tracking incidents exists in the NPS and there has been inconsistent reporting of events throughout the years, these incidents are by not comprehensive. Since 2000, however, record keeping and the distribution of NPS incidents has improved and more data has been available to researchers. Of the collected incidents, the majority (67%) resulted in damages to facilities, followed by people (38%), and cultural resources (15%). These values add up to more than 100% because many incidents cause damage to more than one category (F, P, R). By number of reported incidents, rockfalls most frequently impacted facilities and humans, while both flooding and rockfalls were the most reported threat to cultural resources.

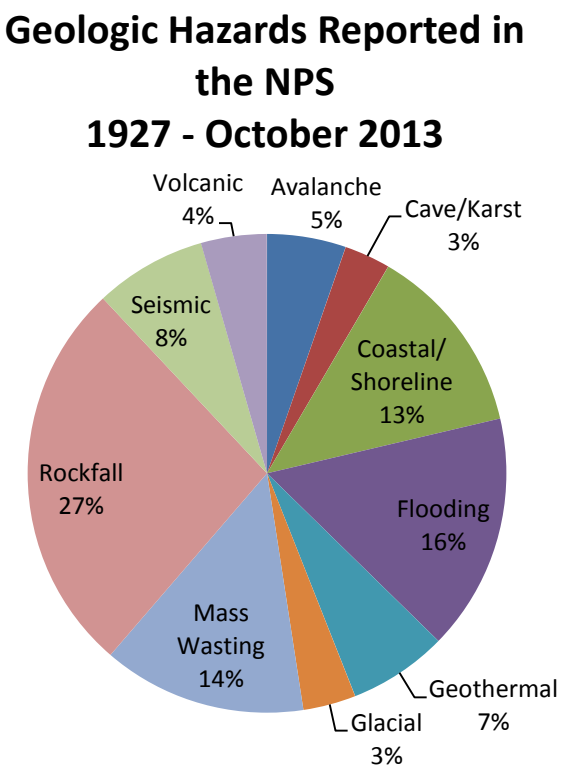


Figure 1. Chart showing the frequency of the different geologic hazards reported in the NPS from 1927 to October 2013. Total number of incidents is 225.

3.2.1 - Facility Damages

The facility damages reported range from inexpensive trail damage, to catastrophic flooding and destroyed park buildings. The majority of facility damage was caused by rockfalls, followed by flooding and coastal/shoreline hazards (Table 1). Rockfalls damaging facilities were reported in every region, except the Alaska Region (likely because of the limited infrastructure and vast geographic extent of Alaskan parks). Half of the coastal and shoreline incidents were in the Southeast Region, known for frequent hurricanes and tropical storms as well as an extensive coastline containing many park units. Like flooding and coastal/shoreline hazards, seismic and mass wasting events cause wide-spread damage due to their diffuse or far-reaching effects.

Table 1. Incidents Affecting Facilities

Type of hazard	Number of incidents	Percentage
Rockfall	40	28%
Flooding	32	23%
Mass Wasting	26	18%
Coastal/Shoreline	25	18%
Seismic	11	8%
Volcanic	5	4%
Cave/Karst	2	1%
Avalanche	1	1%
TOTAL	**142**	

3.2.2 – Geologic Hazards and Injury to People

From 1927 to October 2013, at least 124 people have been injured, 72 of whom were killed, in NPS sites due to geologic hazards. These numbers only represent incidents reported to resources we searched. These events are not spread evenly through the 86 year timespan indicated (Figure 2). In recent years, reporting methods have improved as well as communication between parks and headquarters. The last 34 years in particular have the richest data in this category. Rockfalls, geothermal incidents, and avalanches caused 65% of the recorded visitor and employee injuries (Table 2).

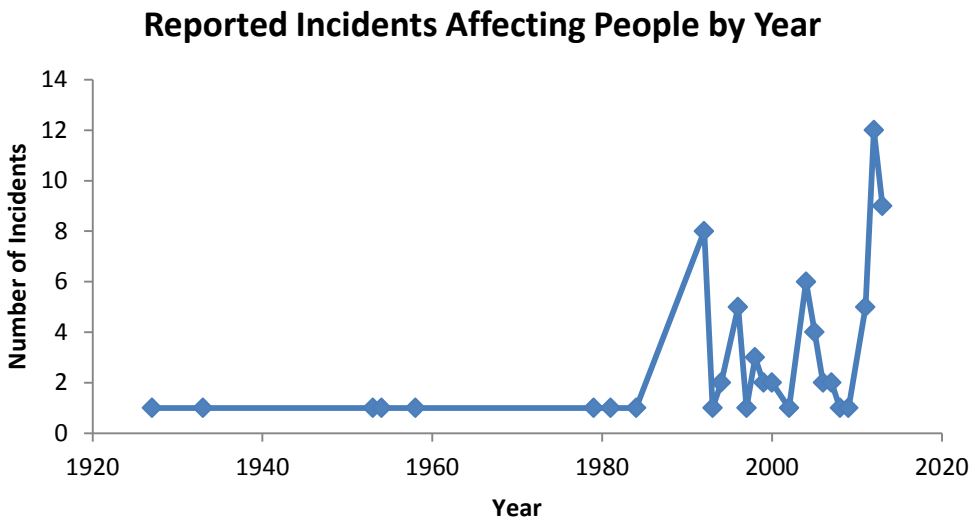


Figure 2. Graph showing number of incidents affecting people by year. Although it appears that geologic hazards are occurring with more frequency, this is likely that reporting practices have improved over the years and as a result more data was available to us recently (specifically the last 30 years).

Table 2. Incidents Affecting People

Type of hazard	Number of incidents	Percentage
Rockfall	23	30%
Geothermal	13	17%
Avalanche	12	16%
Glacial	7	9%
Flooding	6	8%
Coastal/Shoreline	5	7%
Volcanic	4	5%
Cave/Karst	4	5%
Mass Wasting	2	3%
TOTAL	**76**	

3.2.3 – Geologic Hazard Impacts on Cultural Resources

Although far fewer geologic hazard incidents affected cultural resources (15% of total incidents), these events can have a devastating and costly impact on irreplaceable objects or structures preserved for cultural and historic purposes. Prehistoric artifacts, ruins, burial mounds, historic structures, and

rock art are all examples of cultural resources that, when damaged, may be impossible to restore to their original condition. The major causes of damage to cultural resources in the NPS are flooding and rockfall, followed by, coastal/shoreline, and volcanic hazards (Table 3). Rockfall are particularly dangerous because they occur instantaneously and often without warning. While also extensively damaging, flooding and other coastal or shoreline hazards may have more warning (e.g. hurricanes or tsunamis). Due to their expansive scale, coastal/shoreline hazards (tropical storms, hurricanes, coastal flooding, tsunamis, beach erosion, ship groundings, and submarine landslides), much like flooding, can impact many cultural sites in a single event.

Table 3. Incidents Affecting Cultural Resources

Type of hazard	Number of incidents	Percentage
Flooding	9	28%
Rockfall	8	25%
Coastal/Shoreline	5	16%
Volcanic	4	13%
Mass Wasting	3	9%
Seismic	2	6%
Geothermal	1	3%
TOTAL	**32**	

3.3 - Park Hazard Reports

Because rockfalls are a serious threat to safety, facilities, and cultural resources in 82 parks, the park-specific reports prepared for George Washington Memorial Parkway and Walnut Canyon National Monument provide models for other units to consider. Through the findings of park literature reviews, it was decided that rockfall geologic hazards were the single most important hazard to focus on. Incident reports stored at the parks were far more complete than the information gathered in the servicewide incident spreadsheet for those parks. Several parks have complied extensive reports documenting all reported hazards at their parks. Excellent examples were completed at Yosemite National Park (Stock et al. 2013) and Zion National Park (Lund et al. 2010), where park records and research far surpassed the widely distributed incident reports.

4 - Conclusions and Next Steps

This unique collaborative project between the NPS GRD and PRMP stresses the importance of a servicewide reporting system for geologic hazard incidents. The project also represents the first effort to compile hazard information for the entire System and highlights the inconsistencies in reporting. Many parks have detailed records of past geologic hazard incidents that would be incredible resources at the national level. Analysis of these hazard trends and easy methods of reporting future incidents could help NPS management in decision-making, identifying future research, and aiding in hazard mitigation planning.

Preliminary data interpretation shows that data collection and availability has improved drastically over the last 30 years, yet many incidents go unreported. We are only able to analyze the frequency of those incidents that are reported, a list that is not comprehensive. It is also the first attempt at putting together a searchable list of incidents from across the entire System. This project offers a solid foundation for future geologic hazard projects and recommendations for NPS management.

Of the ten hazard categories, rockfalls are the most commonly reported incident (27%) followed by flooding (16%) and mass wasting (14%). These hazards often occur repeatedly in the same locations and carefully planned preventative measures could prevent future damages and injuries. Damages to facilities are most common (67%) followed by incidents affecting people (38%) and damage to cultural resources (38%). These numbers add up to more than 100% because events often cause damage to more than one category.

The following are recommendations we offer the NPS:

- The spreadsheet containing geologic hazards and corresponding incidents should be converted to a database to allow the continued collection and analysis of hazard data.
- Any categories of data that may be deemed valuable in the future should be added. This will keep the database current and the contents more valuable.
- We recognize that this geologic hazard list is not comprehensive; therefore we recommend that the NPS consider the development of a procedure to capture servicewide geologic hazard incident data and collect retrospective data not previously recorded. The development of such a resource will increase the value of these data and make future management and mitigation projects more relevant.

References

References listed in this section include both reference cited in the text of this report and sources of information not cited in the text used to gather statistics about National Park Service geologic hazard incidents.

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Appendix A - List of Geologic Hazards at Each Park

Unit Name	Type of Unit	Acronym	Region	I&M Network	Avalanche	Caves/Karst	Coastal/ Shoreline	Flooding	Geothermal	Glacial	Mass Wasting	Rockfall	Seismic	Volcanic	Totals
Acadia	NP	ACAD	NER	NETN	1		1			1		1	1		**5**
Ala Kahakai	NHT	ALKA	PWR	PACN			1	1	1				1	1	**5**
Alagnak	WR	ALAG	AKR	SWAN			1	1			1				**3**
Aleutian World War II	NHA	ALEU	AKR	SWAN			1					1			**2**
American Memorial	Park	AMME	PWR	PACN			1	1			1				**3**
Aniakchak	NM & Pres	ANIA	AKR	SWAN			1	1					1	1	**4**
Apostle Islands	NL	APIS	MWR	GLKN			1	1							**2**
Appalachian	NST	APPA	NCR	NETN				1			1	1			**3**
Arches	NP	ARCH	IMR	NCPN				1			1	1	1		**4**
Assateague Island	NS	ASIS	NER	NCBN			1	1							**2**
Badlands	NP	BADL	MWR	NGPN				1			1				**2**
Bandelier	NM	BAND	IMR	SCPN				1			1	1			**3**
Bering Land Bridge	NPres	BELA	AKR	ARCN			1	1	1	1					**4**
Big Bend	NP	BIBE	IMR	CHDN				1	1		1	1			**4**
Big Cypress	NPres	BICY	SER	SFCN			1	1							**2**
Big South Fork	NRRA	BISO	SER	APHN				1			1				**2**
Big Thicket	NPres	BITH	IMR	GULN			1	1			1				**3**
Biscayne	NP	BISC	SER	SFCN			1	1							**2**
Black Canyon Of The Gunnison	NP	BLCA	IMR	NCPN				1			1	1			**3**
Blue Ridge	PKWY	BLRI	SER	APHN							1	1			**2**

Appendix A - List of Geologic Hazards at Each Park (continued)

Unit Name	Type of Unit	Acronym	Region	I&M Network	Avalanche	Caves/Karst	Coastal/ Shoreline	Flooding	Geothermal	Glacial	Mass Wasting	Rockfall	Seismic	Volcanic	Totals
Boston	NHP	BOST	NER	NETN			1	1							2
Boston Harbor Islands	NRA	BOHA	NER	NETN			1	1			1				3
Bryce Canyon	NP	BRCA	IMR	NCPN							1	1			2
Buck Island Reef	NM	BUIS	SER	SFCN			1	1							2
Cabrillo	NM	CABR	PWR	MEDN			1						1		2
Canaveral	NS	CANA	SER	SFCN			1								1
Cane River Creole	NHP	CARI	SER	GULN			1	1							2
Canyon De Chelly	NM	CACH	IMR	SCPN				1			1	1			3
Canyonlands	NP	CANY	IMR	NCPN				1			1	1	1		4
Cape Cod	NS	CACO	NER	NCBN			1	1							2
Cape Hatteras	NS	CAHA	SER	SECN			1	1							2
Cape Krusenstern	NM	CAKR	AKR	ARCN			1	1							2
Cape Lookout	NS	CALO	SER	SECN			1	1							2
Capitol Reef	NP	CARE	IMR	NCPN							1	1			2
Capulin Volcano	NM	CAVO	IMR	SOPN									1	1	2
Carlsbad Caverns	NP	CAVE	IMR	CHDN		1						1			2
Castillo De San Marcos	NM	CASA	SER	SECN			1	1							2
Castle Clinton	NM	CACL	NER	NCBN			1	1							2
Chaco Culture	NHP	CHCU	IMR	SCPN								1			1
Channel Islands	NP	CHIS	PWR	MEDN		1	1	1			1	1	1		6
Charles Pinckney	NHS	CHPI	SER	SECN			1								1
Chesapeake & Ohio Canal	NHP	CHOH	NCR	NCRN			1								1
Chiricahua	NM	CHIR	IMR	SODN				1			1	1	1		4

Appendix A - List of Geologic Hazards at Each Park (continued)

Unit Name	Type of Unit	Acronym	Region	I&M Network	Avalanche	Caves/Karst	Coastal/ Shoreline	Flooding	Geothermal	Glacial	Mass Wasting	Rockfall	Seismic	Volcanic	Totals
Christiansted	NHS	CHRI	SER	SFCN			1	1							2
Colonial	NHP	COLO	NER	NCBN			1								1
Colorado	NM	COLM	IMR	NCPN				1			1	1			3
Congaree	NP	CONG	SER	SECN				1							1
Coronado	NMem	CORO	IMR	SODN		1		1			1				3
Crater Lake	NP	CRLA	PWR	KLMN			1	1			1	1	1	1	6
Craters of the Moon	NM	CRMO	PWR	UCBN	1	1					1	1	1	1	6
Cumberland Island	NS	CUIS	SER	SECN			1	1							2
Cuyahoga Valley	NP	CUVA	MWR	HTLN		1		1				1			3
De Soto	NMem	DESO	SER	SFCN			1	1							2
Death Valley	NP	DEVA	PWR	MOJN				1			1	1			3
Delaware Water Gap	NRA	DEWA	NER	ERMN				1			1				2
Denali	NP & Pres	DENA	AKR	CAKN	1			1			1	1	1		5
Devils Postpile	NM	DEPO	PWR	SIEN								1	1	1	3
Devils Tower	NM	DETO	IMR	NGPN								1			1
Dinosaur	NM	DINO	IMR	NCPN							1	1	1		3
Dry Tortugas	NP	DRTO	SER	SFCN			1	1							2
Ebey's Landing	NHR	EBLA	PWR	NCCN			1	1							2
Effigy Mounds	NM	EFMO	MWR	HTLN				1							1
El Malpais	NM	ELMA	IMR	SCPN		1						1	1	1	4
El Morro	NM	ELMO	IMR	SCPN								1			1
Everglades	NP	EVER	SER	SCPN			1	1							2
Fire Island	NS	FIIS	NER	NCBN			1	1							2

Appendix A - List of Geologic Hazards at Each Park (continued)

Unit Name	Type of Unit	Acronym	Region	I&M Network	Avalanche	Caves/Karst	Coastal/ Shoreline	Flooding	Geothermal	Glacial	Mass Wasting	Rockfall	Seismic	Volcanic	Totals
Fort Caroline	NMem	FOCA	SER	SECN			1	1							2
Fort Frederica	NM	FOFR	SER	SECN			1	1							2
Fort Matanzas	NM	FOMA	SER	SECN			1	1							2
Fort McHenry	NM & HS	FOMC	NER	MIDN			1	1							2
Fort Monroe	NM	FOMR	NER	MIDN			1	1							2
Fort Point	NHS	FOPO	PWR	SFAN			1	1							2
Fort Pulaski	NM	FOPU	SER	SECN			1	1							2
Fort Raleigh	NHS	FORA	SER	SECN			1	1							2
Fort Sumter	NM	FOSU	SER	SECN			1	1							2
Fort Vancouver	NHS	FOVA	PWR	NCCN			1	1							2
Fossil Butte	NM	FOBU	IMR	NCPN							1		1		2
Gates Of The Arctic	NP & Pres	GAAR	AKR	ARCN	1					1	1	1			4
Gateway	NRA	GATE	NER	NCBN			1	1							2
George Washington	Mem PKWY	GWMP	NCR	NCRN				1			1	1	1		4
George Washington Birthplace	NM	GEWA	NER	NCRN			1								1
Gila Cliff Dwellings	NM	GICL	IMR	SODN								1			1
Glacier	NP	GLAC	IMR	ROMN	1			1		1	1	1			5
Glacier Bay	NP & Pres	GLBA	AKR	SEAN			1	1		1	1	1	1		6
Glen Canyon	NRA	GLCA	IMR	SCPN							1	1			2
Golden Gate	NRA	GOGA	PWR	SFAN		1	1	1					1		4
Governors Island	NM	GOIS	NER	NCBN			1								1

Appendix A - List of Geologic Hazards at Each Park (continued)

Unit Name	Type of Unit	Acronym	Region	I&M Network	Avalanche	Caves/Karst	Coastal/ Shoreline	Flooding	Geothermal	Glacial	Mass Wasting	Rockfall	Seismic	Volcanic	Totals
Grand Canyon	NP	GRCA	IMR	SCPN		1		1			1	1			**4**
Grand Portage	NM	GRPO	MWR	GLKN			1	1			1	1			**4**
Grand Teton	NP	GRTE	IMR	GRYN	1			1			1	1	1		**5**
Grant-Kohrs Ranch	NHS	GRKO	IMR	ROMN				1			1				**2**
Great Basin	NP	GRBA	PWR	MOJN		1		1			1	1			**4**
Great Smoky Mountains	NP	GRSM	SER	APHN							1	1			**2**
Guadalupe Mountains	NP	GUMO	IMR	CHDN							1	1			**2**
Gulf Islands	NS	GUIS	SER	GULN			1	1							**2**
Hagerman Fossil Beds	NM	HAFO	PWR	UCBN				1			1				**2**
Haleakala	NP	HALE	PWR	PACN			1	1			1	1	1	1	**6**
Harpers Ferry	NHP	HAFE	NCR	NCRN			1	1			1	1			**4**
Hawaii Volcanoes	NP	HAVO	PWR	PACN			1	1	1		1	1	1	1	**7**
Hot Springs	NP	HOSP	MWR	HTLN				1	1						**2**
Indiana Dunes	NL	INDU	MWR	GLKN			1	1			1				**3**
Isle Royale	NP	ISRO	MWR	GLKN			1	1			1				**3**
Jean Lafitte	NHP & Pres	JELA	SER	GULN			1	1							**2**
Jewel Cave	NM	JECA	MWR	NGPN		1					1	1			**3**
John Day Fossil Beds	NM	JODA	PWR	UCBN				1			1	1			**3**
John Muir	NHS	JOMU	PWR	SFAN			1						1		**2**
Joshua Tree	NP	JOTR	PWR	MOJN							1	1	1		**3**
Kalaupapa	NHP	KALA	PWR	PACN		1	1	1					1	1	**5**

Appendix A - List of Geologic Hazards at Each Park (continued)

Unit Name	Type of Unit	Acronym	Region	I&M Network	Avalanche	Caves/Karst	Coastal/ Shoreline	Flooding	Geothermal	Glacial	Mass Wasting	Rockfall	Seismic	Volcanic	Totals
Kaloko-Honokohau	NHP	KAHO	PWR	PACN			1	1	1				1	1	**5**
Katmai	NP & Pres	KATM	AKR	SWAN	1		1	1		1	1	1	1	1	**8**
Kenai Fjords	NP	KEFJ	AKR	SWAN	1		1	1		1	1	1			**6**
Klondike Gold Rush	NHP	KLGO	AKR	SEAN	1		1	1		1	1	1	1		**7**
Kobuk Valley	NP	KOVA	AKR	ARCN				1			1	1			**3**
Lake Clark	NP & Pres	LACL	AKR	SWAN			1	1						1	**3**
Lake Mead	NRA	LAKE	PWR	MOJN							1	1			**2**
Lake Meredith	NRA	LAMR	IMR	SOPN							1	1			**2**
Lassen Volcanic	NP	LAVO	PWR	KLMN	1			1	1			1	1	1	**6**
Lava Beds	NM	LABE	PWR	KLMN					1			1	1	1	**4**
Lewis and Clark	NHP	LEWI	PWR	NCCN			1	1			1				**3**
Little River Canyon	NPres	LIRI	SER	CUPN				1			1				**2**
Mammoth Cave	NP	MACA	SER	CUPN		1						1			**2**
Mesa Verde	NP	MEVE	IMR	SCPN							1	1			**2**
Mojave	NPres	MOJA	PWR	MOJN				1			1	1			**3**
Montezuma Castle	NM	MOCA	IMR	SODN				1			1	1			**3**
Moores Creek	NB	MOCR	SER	SECN			1	1							**2**
Morristown	NHP	MORR	NER												
Mount Rainier	NP	MORA	PWR	NCCN	1			1		1	1	1	1	1	**7**
Muir Woods	NM	MUWO	PWR	SFAN			1	1					1		**3**
Natchez	NHP	NATC	SER	GULN			1	1							**2**

Appendix A - List of Geologic Hazards at Each Park (continued)

Unit Name	Type of Unit	Acronym	Region	I&M Network	Avalanche	Caves/Karst	Coastal/ Shoreline	Flooding	Geothermal	Glacial	Mass Wasting	Rockfall	Seismic	Volcanic	Totals
National Capital Parks-East	–	NACE	NCR	NCRN			1	1			1	1			**4**
National Mall	_	NAMA	NCR	NCRN			1	1							**2**
National Park of American Samoa	–	NPSA	PWR	PACN			1	1					1		**3**
National Parks of New York Harbor	–	NPNH	NER				1	1							**2**
Navajo	NM	NAVA	IMR	SCPN							1	1			**2**
New Bedford Whaling	NHP	NEBE	NER	NETN			1	1							**2**
New Orleans Jazz	NHP	JAZZ	SER	GULN			1	1							**2**
New River Gorge	NR	NERI	NER	ERMN			1	1			1	1			**4**
Nez Perce	NHP	NEPE	PWR	UCBN							1	1			**2**
North Cascades	NP	NOCA	PWR	NCCN	1					1	1	1			**4**
Olympic	NP	OLYM	PWR	NCCN	1		1	1		1	1	1			**6**
Oregon Caves	NM	ORCA	PWR	KLMN		1						1			**2**
Organ Pipe Cactus	NM	ORPI	IMR	SODN				1				1			**2**
Padre Island	NS	PAIS	IMR	GULN			1	1							**2**
Palo Alto Battlefield	NHP	PAAL	IMR	GULN			1								**1**
Perry's Victory & International Peace	Mem	PEVI	MWR	GLKN			1								**1**
Petersburg	NB	PETE	NER	MIDN			1	1							**2**
Petrified Forest	NP	PEFO	IMR	SCPN							1	1			**2**
Pictured Rocks	NL	PIRO	MWR	GLKN			1	1			1	1			**4**
Pinnacles	NM	PINN	PWR	SFAN		1		1			1	1	1		**5**

Appendix A - List of Geologic Hazards at Each Park (continued)

Unit Name	Type of Unit	Acronym	Region	I&M Network	Avalanche	Caves/Karst	Coastal/ Shoreline	Flooding	Geothermal	Glacial	Mass Wasting	Rockfall	Seismic	Volcanic	Totals
Point Reyes	NS	PORE	PWR	SFAN			1	1					1		3
Port Chicago Naval Magazine	NMem	POCH	PWR	SFAN			1								1
Pu`uhonua O Honaunau	NHP	PUHO	PWR	PACN			1	1	1				1	1	5
Pu`ukohola Heiau	NHS	PUHE	PWR	PACN			1	1	1				1	1	5
Redwood	NP	REDW	PWR	KLMN			1	1			1		1		4
Richmond	NBP	RICH	NER	MIDN				1							1
Rock Creek	Park	ROCR	NCR	NCRN			1	1			1	1			4
Rocky Mountain	NP	ROMO	IMR	ROMN	1			1		1	1	1			5
Rosie the Riveter WWII Home Front	NHP	RORI	PWR	SFAN			1	1					1		3
Russell Cave	NM	RECA	SER	CUPN		1						1			2
Sagamore Hill	NHS	SAHI	NER	NCBN			1	1			1				3
Saint Croix Island	IHS	SACR	NER	NETN			1	1			1				3
Salem Maritime	NHS	SAMA	NER	NETN			1	1							2
Salt River Bay	NHP & EPres	SARI	SER	SFCN			1	1							2
San Francisco Maritime	NHP	SAFR	PWR	SFAN			1						1		2
San Juan	NHS	SAJU	SER	SFCN			1	1							2
San Juan Island	NHP	SAJH	PWR	NCCN			1	1			1				3
Santa Monica Mountains	NRA	SAMO	PWR	MEDN			1	1			1	1	1		5
Saugus Iron Works	NHS	SAIR	NER	NETN			1	1							2
Scotts Bluff	NM	SCBL	MWR	NGPN							1	1			2
Sequoia & Kings	NPs	SEKI	PWR	SIEN				1			1	1			3

Appendix A - List of Geologic Hazards at Each Park (continued)

Unit Name	Type of Unit	Acronym	Region	I&M Network	Avalanche	Caves/Karst	Coastal/ Shoreline	Flooding	Geothermal	Glacial	Mass Wasting	Rockfall	Seismic	Volcanic	Totals
Canyon															
Shenandoah	NP	SHEN	NER	MIDN							1	1			**2**
Sitka	NHP	SITK	AKR	SEAN			1	1							**2**
Sleeping Bear Dunes	NL	SLBE	MWR	GLKN			1	1			1				**3**
Statue Of Liberty	NM	STLI	NER	NCBN			1	1							**2**
Sunset Crater Volcano	NM	SUCR	IMR	SCPN		1						1	1	1	**4**
Theodore Roosevelt	NP	THRO	MWR	NGPN				1			1	1			**3**
Timpanogos Cave	NM	TICA	IMR	NCPN		1		1				1			**3**
Timucuan	Eco & HPres	TIMU	SER	SECN			1	1							**2**
Tonto	NM	TONT	IMR	SODN		1		1			1	1			**4**
Vicksburg	NC	VICK	SER	GULN			1	1							**2**
Virgin Islands	NP	VIIS	SER	SFCN			1	1							**2**
Virgin Islands Coral Reef	NM	VICR	SER	SFCN			1								**1**
Voyageurs	NP	VOYA	MWR	GLKN				1			1				**2**
Walnut Canyon	NM	WACA	IMR	SCPN				1			1	1			**3**
War In The Pacific	NHP	WAPA	PWR	PACN			1	1							**2**
Washington	Mon	WASH	NCR	NCRN									1		**1**
White Sands	NM	WHSA	IMR	CHDN				1			1				**2**
Wind Cave	NP	WICA	MWR	NGPN		1						1			**2**
World War II Valor in the Pacific	NM	VALR	PWR	PACN			1	1							**2**
Wrangell - St Elias	NP & Pres	WRST	AKR	CAKN	1		1	1		1	1	1	1	1	**8**

Appendix A - List of Geologic Hazards at Each Park (continued)

Unit Name	Type of Unit	Acronym	Region	I&M Network	Avalanche	Caves/Karst	Coastal/ Shoreline	Flooding	Geothermal	Glacial	Mass Wasting	Rockfall	Seismic	Volcanic	Totals
Wright Brothers	NMem	WRBR	SER	SECN			1	1							**2**
Wupatki	NM	WUPA	IMR	SCPN				1				1	1	1	**4**
Yellowstone	NP	YELL	IMR	GRYN	1			1	1		1	1	1	1	**7**
Yosemite	NP	YOSE	PWR	SIEN	1			1			1	1			**4**
Yukon - Charley Rivers	NPres	YUCH	AKR	CAKN				1							**1**
Zion	NP	ZION	IMR	NCPN				1			1	1	1		**4**
Totals					**17**	**19**	**110**	**144**	**11**	**13**	**89**	**87**	**47**	**22**	**559**

Appendix B - GWMP Geologic Hazard Report

GWMP Park Visit and Interviews
Rockfall Research

Elizabeth Schaller
NPS/SCA Intern
October 26, 2012

On July 17th, 2012, I spoke with George Washington Memorial Park (GWMP) superintendent, Jon James about rockfall issues, causes, repairs, and engineering strategies. Major areas we discussed were Spout Run, an active rockfall site along the roadway and the hiking trail at Windy Run. On July 23, I visited areas of GWMP to have a look at the active rockfall and past landslide areas. Luis Teran, civil/structural engineer, showed me rockfall sites and explained recent stabilization work. We looked at the Spout Run area and hiked around Windy Run, where a portion of the Potomac Heritage Trail was covered by a rockfall. I also spoke with Bernard Spencer-Bey, occupational health and safety specialist, on October 24th about the parkway's visitor protection efforts.

Spout Run

The Spout Run area features a long, steep rock face along the parkway. Rocks here are heavily faulted from historic quarrying, winter/spring freeze-thaw action, tree root invasion, and recent seismicity. Due to the proximity to the road, rockfalls present a major hazard both to visitor safety and facility integrity.

Very expensive recent stabilization work has been done along the face involving scaling (removing loose material, netting with stainless steel cables (Figures B-1, B-2), and long bolts drilled deep into the rock (to hopefully anchor the loose outer rocks to stable bedrock). Future steps involve a glue-like epoxy material to be applied to fractures.

A second area of Spout Run is closer still to the roadway and work there presented more challenges. All weekend traffic had to be stopped for three or four weeks while efforts were underway.

Both areas have seen fewer rockfalls and overall improved slope stability since the engineering efforts were completed. This gives the parkway hope for the prevention of future incidents at Spout Run and the NPS confidence as to the effectiveness of efforts conducted at other park locations.

Windy Run

The Windy Run area of GWMP is home to a path called the Potomac Heritage Trail that is popular with local hikers. The trail, which falls under the jurisdiction of GWMP, leads down to the Potomac River and crosses under the parkway. In 2004, a large rockfall occurred near the trail's end. The original handrails still lead down to the river, but now parts of the trail and stone steps are covered by large tire-sized boulders (Figure B-3). Luis Teran showed me how visitors can still reach the river, but are advised against this by several signs posted by the NPS (Figure B-4). As discussed with Bernard Spencer-Bey, the rock-covered part of the trail likely receives higher visitation than previously. Many visitors enjoy the challenge of rock scrambling, but do not consider the

vulnerability of the area to rockfalls. The area appeared relatively stable at the time of my visit, but the cliffs had the same faulted appearance as at Spout Run. Freeze/thaw action and long periods of rain seems to be the biggest threat to the stability of the bedrock blocks.

Recommendations

The park has done extremely well in responding to incidents that affect visitor safety and the functionality of the parkway and trails. The solution at Spout Run was a very expensive, large-scale engineering project which aimed to remove loose material and stabilize the steep cliffs. The project has worked very well so far, but needs to be closely monitored for potential areas of weakness that may emerge. Due to spring freeze/thaw action, that may be the time to implement the most monitoring and be ready to enforce a road closure, should that become necessary.

At Windy Run the park chose to warn visitors of the 2004 rockfall incident and the dangers in proceeding along the trail. The scary reality here is that many visitors pay no heed to the official signage and continue down the trail, scrambling over rocks down to the Potomac River. The parkway might consider having someone inspect the rocks these hikers walk over for stability as well as the above cliffs. The rock face above the slide has many deep fractures and may, with spring freeze/thaw, heavy rains, and root invasion, produce another large rockfall. Educating visitors on the dangers they face is the best method for now, but a thorough inspection might be a useful next step.

Figures



Figure B-1. Spout Run rock wall along the parkway with stainless steel netting. Plant growth is from this season as netting was installed last fall.



Figure B-2. Closer view of stainless steel netting.



Figure B-3. Remnants of the 2004 landslide still cover the end of the Potomac Heritage Trail.



Figure B-4. The sign visitors encounter before the landslide area at Windy Run. The trail beyond this point is considered “at own risk.”

Appendix C - WACA Geologic Hazard Report

Walnut Canyon National Monument
Rockfall Hazard Research

Elizabeth Schaller
NPS/SCA Intern
November 9, 2012

Project Purpose

The NPS Public Risk Management Program (PRMP) and the Geologic Resources Division (GRD) paired up to conduct a risk assessment of geologic hazards in the National Parks to provide the first report that documents the scope and impact of geologic hazards on humans, park facilities, and cultural resources Service-wide. The purpose of this project was to compile baseline data on geology-related incidents in NPS units which resulted in injuries, fatalities, and damages (to both facilities and cultural resources). After completing the initial Service-wide data collection phase, I conducted a geologic hazard assessment research project at Walnut Canyon National Monument (WACA). The purpose of this effort was to gather information on historic rockfall incidents at the monument, to identify current high risk areas and to provide recommendations on potential mitigation strategies.

Methods

To gather data on both historic and current geologic hazard incidents throughout the NPS, I relied on various sources of data. I conducted a literature review, face-to-face interviews, and site observation to carry out a thorough assessment of hazards at WACA.

Literature Review

WACA staff pulled together a wealth of historical resources, both on area geology and on specific rockfall incidents. Many historic rockfalls are only mentioned in the texts, but more recent (last ten years) major incidents have occurred that affected visitor safety, facilities, and cultural resources. The park documented these major incidents in great detail and explained all the repair activities. Step-by-step photos accompanied many of these accounts. Staff also provided me with a map that plots rockfall locations and proximal archeological sites.

The oldest reports on file are June and July 1936 geologic reports on Walnut Canyon written by V. W. Vandiver and Chas. N. Gould, respectively. These documents contain descriptions of the rock types and features mapped in the canyon, as well as the geological and archeological significance of certain sites. Both men were regional geologists and spent extensive time in the canyon, mapping and documenting their observations.

Jon Alan Benfer wrote his Master's thesis for the Northern Arizona University (NAU) geology department in January of 1971. This work was entitled, "The Petrology of the Eastern Phase of the Toroweap Formation, Walnut Canyon, Arizona." He describes field work in the canyon and other northern Arizona locations. Although the outcrops of Toroweap in Walnut Canyon were the main focus of the report, he also made many other geologic observations to provide a more complete picture of Walnut Canyon stratigraphy.

A large report on 'rock motion hazards' was published in 1978 for a number of parks and monuments, including: El Morro National Monument, Bandelier Monument, Chaco Culture National Historical Park, Wupatki National Monument, Mesa Verde National Park, Tonto National Monument, Canyon de Chelly National Monument, Navajo National Monument, Walnut Canyon National Monument, and Montezuma Castle National Monument. The Walnut Canyon section is extremely thorough in its assessment of rockfall hazards (both in general and specific sites) and its future maintenance/mitigation recommendations.

- Identified hazards included:
    - Massive ledges overhanging the trails with motion apparent on propagating cracks
    - Massive ledges overhanging the trail with minor motion indicated by 'strain slabbing' at pivot points
    - Massive, precariously balanced float blocks beside the trail
    - Unstable cliff faces
    - Random falling, rolling rocks
- A 500-ton scale float block at the far southeast end of the Island Trail seems to overbalance its center of gravity, hanging over a 0.5-1 meter gap adjacent to the trail
    - No motion has been observed by Monument staff, but preventative reinforcement is desirable
- Recommendations:
    - Most of the slopes and faces above the trail area at WACA are accessible. They should be carefully and methodically policed for loose rock.
    - Remove rock that is loose to touch or to light prying with a bar.
    - Also, some engineering thought should be given immediately to stabilizing the worst overhangs and the large float block.

The majority of WACA records contain information from a series of rockfalls that occurred on November 30th and December 7th, 2007 in separate areas on the Island Trail, the primary interpretive trail at the monument. These events were thought to have been triggered by prolonged heavy rainfall, snow storms, and strong winds the preceding month. The November 30th, 2007 rockfall blocked the lower loop section of the trail (between sites 159 and 160) and moderately damaged 15 feet of trail surface and the adjacent retaining wall. Repair efforts were able to remove the largest blocks and arrange smaller blocks along the footpath. No cultural resources were damaged by this incident.

More damaging than the November 2007 event, was the 49-ton boulder that fell across the Island Trail on December 7th, 2007 (Figures C1-C4). Guardrails, benches, and the CCC-era trail were damaged and the entire loop trail was blocked. For nine months (until September 2008) the Island Trail was closed for repairs, although the monument and Rim Trail remained open to visitors. Challenges during the repairs included:

- Work was constrained to a narrow ledge in a steep, switchback trail system. The rockfall incident occurred about 150' below the rim, with about 284 stairs. Concrete rubble from the damaged trail and steps had to be hand-carried back up to the canyon rim. Some native limestone rock was disposed of on the canyon slopes below the trail, but care was taken not to damage any cultural sites or ruin the scenic views for visitors.
- The NPS consulted with the U.S. Fish & Wildlife Service under the Endangered Species Act on the use of explosives to clear the trail as Walnut Canyon is a nesting habitat of the Mexican spotted owl. After consultation, use of explosives was permitted however, the project team found a "noiseless" alternative with the use of a chemical expansion compound. This "noiseless" method was the safest because rock fragments could be controlled as produced instead of being blasted all at once.
- The incident moved materials exposing a prehistoric Sinagua burial site. The site contained one, potentially two, human burials. More than ten pieces of human skeletal remains and several pottery shards were discovered in the hillslope soil deposit above the boulder's original location. It is unknown whether there was a burial pit due to the rockfall and heavy root infiltration.

In late summer 2008, archeologists Bernie Natseway and Ted Tsouras were eating lunch under the overhang of WACA 203 during a typical, but intense, mid-day monsoon thunderstorm. While the archeologists were eating, a large boulder fell from a ledge above the site, striking the occupied ledge and breaking apart. The boulder was approximately the size of a grand piano and pulverized a small pinyon tree about fifteen feet away from Tsouras, who was showered with splinters from the tree, but was uninjured. Some of the boulder remained on the ledge containing WACA 203 and other portions of the boulder continued tumbling down the canyon wall.

In the spring 2010, a large boulder fell down through the Valley of Daggers, damaging several portions of a prehistoric masonry retaining wall that supports WACA 476 (Figure C-5). The boulder (or several boulders) fell and bounced down the slope breaking apart as it traveled. Substantial rain and repeated freeze-thaw cycles were likely the contributing factors. No retaining walls were severely damaged, but several wall stones were displaced or broken apart.

In the early spring 2011, archeological crews noticed a fresh rockfall between WACA 212 and WACA 213. The rock-fall occurred in a small drainage and obliterated several trees and a portion of the game trail used by monument employees for backcountry travel between sites. The boulder originated from somewhere above the level of known cliff dwellings, spreading debris and large pieces of rock from that level to the canyon bottom below.

Another recent rockfall event recorded in WACA's literature was on March 7, 2011. It was reported that three large rocks fell onto the Island Trail (Figure C-6). No one was injured and the only facility damages were to the trail (less than 15' impacted) and handrails. There are several cultural sites located very near the rockfall location, but were unaffected by the movement. In this incident, six tons of rock fell in total (as compared to 49-ton boulder in the 2008 incident).

Interviews

To begin this project, Vincent Santucci (NPS Senior Geologist) and I held a brief introductory meeting with Walnut Canyon staff at the Flagstaff Area National Monuments office. We met with monument Superintendent Diane Chung, Resource Management Specialist Paul Whitefield, Chief of Resources Lisa Leap, and Lisa Baldwin, the Cultural Resources Program Manager. Our goal was to explain this geologic hazard risk management project in the context of Walnut Canyon and gain the monument staff's support. We received great support from all meeting participants and I began work the following week.

WACA's major geologic hazard is rockfall incidents, both large and small, which put visitors, employees, facilities, and cultural resources at risk. After delving into the modern and historic rockfall literature and geological reports, I spoke to monument staff about incidents. During our introductory meeting I learned about the large rockfalls of 2007 (described in greater detail in the literature review section) that necessitated a nine month Island Trail closure and costly repairs.

Archeologist and facility management software specialist Nicole Arendt witnessed the most recent Walnut Canyon rockfall on July 23, 2012. She and other members of the archeology crew were surveying a site off the Ranger Ledge Trail, near site 155, during a summer rain storm. Water falling over the ledge above them was likely the cause of a roughly "desk-sized" rock to fall into the canyon.

Before our site visit to the Ranger Ledge Trail, I spoke with archeologist Ted Tsouras about the nature of rockfalls at the monument. He informed me that although some rockfalls are similar in nature to the December 2007 event, a large free-standing boulder toppling over, most events are not. The majority of rockfalls in the canyon are due to spalling, rock fragments dislodging due to fine (often undetectable) cracks. Many such cracks are covered with vegetation or are very small until widened by freeze-thaw action. Only a very labor-intensive, and dangerous, investigation that covered every ledge would discover all the threats from spalling. Annual freeze-thaw action in the canyon makes spring a high risk season for visitors and employees alike. Temperature variations can swing from 10^0F at night to the 50s during the day. These temperature conditions in conjunction with water can cause rapid erosion.

Site Visits

I made three visits to Walnut Canyon over the course of this research project. The first was immediately following the introductory meeting at the Flagstaff Area Monuments office. Paul Whitefield, Lisa Leap, and Lisa Baldwin took Vince Santucci and I to the site of the December 7th, 2007 rockfall incident on the Island Trail. They showed us the repairs (replaced handrails, newly poured concrete walkway and stairs, and the stone retaining wall containing the impacted cultural site) and current position of the massive boulder that toppled during that event.

On October 5, 2012 I conducted a site visit of the popular Island Trail to observe and photograph areas of risk. Although it is nearly impossible to know when rockfalls will occur, I did note the areas that appeared more vulnerable than others and identified a few areas I found to be at the highest risk.

- The first area of concern is the large boulder perched right above the site of the December 7th, 2007 rockfall incident (Figure C-7). Although this rock has been in place since before the opening of the monument, it looks to be quite precariously balanced on a talus slope. This area also sees higher traffic than most areas of Walnut Canyon because of its location on the switchbacks leading down the Island Trail. Any slip of this rock could harm visitors, destroy pathways and railings, and also do further damage down-slope on the trail and saddle.
- Another concern area is immediately adjacent to the previously mentioned site. This precariously balanced boulder is on the Island Trail just beyond the first area of concern (Figure C-8). This highly faulted block of limestone sits angled steeply toward the trail. If it were to fall, it would do major damage to the trail, railings, and cultural sites or visitors downslope. Another serious threat with regard to this particular rock is the potential to trigger movement of the adjacent boulder. If this rock were to strike the corner of the rock next to it (the aforementioned area of concern), both would fall, and serious damage would occur.

On October 10th, 2012 I made a third visit to Walnut Canyon to look at the recent rockfalls with archeologist Ted Tsouras. The sites we explored were along the Ranger Ledge Trail, one that the public can only visit with a ranger. This path took us right by numerous cultural sites and very old rockfall scars. I saw first-hand the impacts rockfalls can have on cultural sites. Although most cultural sites are protected by the bedrock ledges they were built under, the prehistoric people built a number of masonry wall structures and switchback trail systems that are fully exposed. Falling rocks strike a prehistoric masonry feature and knock blocks off, exposing surfaces that haven't been seen since the wall's creation.

- An area of concern we saw on the October 10th visit was visible directly across the canyon from WACA 156 on the Ranger Ledge Trail (Figure C-9). This event, noticed in early spring 2011, is described in the literature review section of the report, as interpreted by Ted Tsouras. It was obvious to them that a recent rockfall had occurred in the drainage they were crossing. The large boulder likely fell from the ledge above the area, tumbling down the chute, gaining speed and hitting trees and rocks with force. Walking in steep drainages can be very dangerous; should any rock become dislodged, there is nowhere to gain cover.

Recommendations

As one of the main outputs of this research project, I share the following recommendations regarding hazard mitigation of rockfalls at the monument. I realize that the park must make any decisions regarding safety in concert with resource protection issues as well as other factors; these are recommendations that take into account only the geologic hazard safety factors.

- In northern Arizona the spring has high rockfall risk due to snow-melt saturated soils and rapid (often daily) freeze-thaw cycles. Temperatures can be well below freezing at night and as high as the mid-50s during the day. This, in combination with the high moisture levels characteristic of the season, contributes to high rockfall risk. In order to protect employee safety, it might be prudent to limit work in the canyon that requires ledge traverses and areas with unstable slopes during the spring season. Crack widening and rock weakening during this season is unpredictable.

- These seasonal factors also present a risk to visitors. It would be wise to warn hikers of the risk of rockfall during this time of year, that loud noises could be a warning sign of impending rockfall, and that it is not safe to touch rock walls while passing by. Visitors might be especially warned to carefully follow the paths and not go off-trail.
- The monument might find it useful to assemble a multi-disciplinary team (safety officer, cultural and natural resources experts, facilities management, visitor services, etc.) to plan for a targeted geologic hazard assessment of sites most vulnerable to damages. Rock faces directly above sensitive cultural sites and high-traffic visitor areas, are places monument staff might consider having inspected site-by-site and tested for stability. An intern, geoscientist-in-parks, or seasonal hire could examine areas of highest risk in the canyon. With my literature review and interviews as a guide, the perched boulders have been documented and future assessments can focus on areas where spalling might occur.
    - Park management might also consider how to approach future rockfall issues.
        - Education: Information for visitors regarding rockfalls could be on the park website, on waysides, in the visitor center, and incorporated into the interpretation talks.
        - Engineering: Some protection measures can be implemented at the park to protect visitors, cultural resources, and facilities. These options include removing loose rocks, gluing cracks, netting bedrock ledges, or installing bolts into rock faces.
        - Enforcement: On days of high rockfall risk, trails might need to be closed for visitor safety or employee projects put on hold.
    - Additional information resources for these techniques can be made available from the NPS Office of Risk Management by request.
- The large perched boulder near the December 7th, 2007 site might be the ideal candidate for an optical rock movement monitoring system. A permanent photo mount could be installed on the railing shown in Figure C-10 and angled toward the boulder. Photos taken once each month (or more frequently) can be uploaded into movement detection software. The slightest movements or rotation of the block would be recorded and alert monument staff of a potentially destructive slide. Early warning at this high-traffic, high-risk area of the canyon would be extremely valuable.

Figures



Figure C-1. The December 7th, 2007 rockfall resulted in a massive boulder on the Island Trail, a trail popular with visitors.



Figure C-2. Overview of December 7th, 2007 rockfall on the Island Trail. Arrow shows fallen boulder on trail.

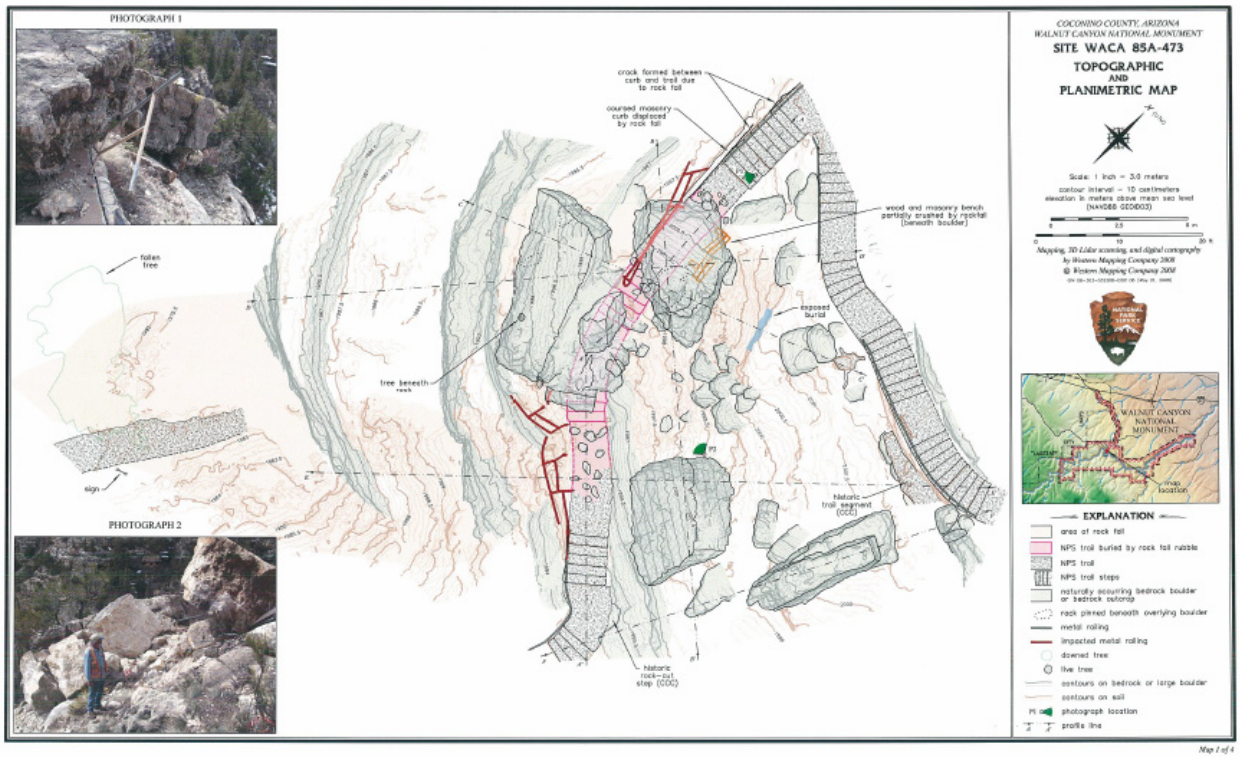


Figure C-3. 3D LIDAR scanning and digital cartography were used to make this map of the December 7th, 2007 rockfall event. Scans were made in 2008. Objects of note include all the damaged areas, the exposed archeological site, and the placement of the boulder after the fall.



Figure C-4. Handrail, trail, and vegetation damages done on the switchbacks below the December 7, 2007 rockfall site (visible at top of photo).



Figure C-5. Part of boulder fall in the Valley of Daggers in the spring of 2010. The boulder (or several boulders) fell and bounced down the slope breaking apart as it traveled. Minor damages were done to a prehistoric masonry retaining wall feature. Pictured also is NPS archeologist Kristen Carlson.



Figure C-6. Three large rocks fell onto the Island Trail loop on March 7th, 2007. No visitors were injured, nor were any cultural resources impacted. The guard rail was taken out as well as damage to 15’ of trail.



Figure C-7. This image shows the first area of concern for future rockfall. This precariously balanced boulder is directly above the lower switchback section of the Island Trail. Visitor and employee safety is a major concern at this location. Failure could also result in pathway, handrail, and stair damages, as well as damage down in the canyon.



Figure C-8. The circled boulder is a potential rockfall hazard on the Island Trail and sits directly next to another precariously balanced boulder (to the left of the circle).



Figure C-9. This rockfall was found in early spring 2011, and occurred between WACA 212 and WACA 213. The photo location was directly across the canyon from the Ranger Ledge Trail. Circled is the drainage gully that channeled a tumbling boulder and directed it down the canyon. Note the damaged trees and visible rubble.



Figure C-10. Location of proposed photo-mount installation. All photos of the high risk boulder would be taken from this point and analyzed with software to detect its slightest movements.

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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