ARCTIC
VOL. 66, NO. 2 (JUNE 2013) P. 147–158

Application of 3D Laser Scanning to the Preservation of Fort Conger, a Historic Polar Research Base on Northern Ellesmere Island, Arctic Canada

PETER C. DAWSON,[1] MARGARET M. BERTULLI,[2] RICHARD LEVY,[3] CHRIS TUCKER,[4] LYLE DICK[5] and PANIK LYNN COUSINS[6]

(*Received 28 June 2012; accepted in revised form 19 October 2012*)

ABSTRACT. Fort Conger, located in Quttinirpaaq National Park, Ellesmere Island, is a historic landmark of national and international significance. The site is associated with many important Arctic expeditions, including the ill-fated Lady Franklin Bay Expedition of the First International Polar Year and Robert Peary's attempts to claim the North Pole. Although situated in one of the most remote locations on earth, Fort Conger is currently at risk because of the effects of climate change, weather, wildlife, and human activity. In this paper, we show how 3D laser scanning was used to record cultural features rapidly and accurately despite the harsh conditions present at the site. We discuss how the future impacts of natural processes and human activities can be managed using 3D scanning data as a baseline, how conservation and restoration work can be planned from the resulting models, and how 3D models created from laser scanning data can be used to excite public interest in cultural stewardship and Arctic history.

Key words: laser scanning, heritage preservation, Arctic exploration, inorganic contamination, virtual reality, computer modeling

RÉSUMÉ. Fort Conger, situé dans le parc national Quttinirpaaq, sur l'île d'Ellesmere, est un lieu historique d'importance nationale et internationale. Ce site est lié à de nombreuses expéditions arctiques importantes, dont l'infortunée expédition de la baie Lady Franklin relevant de la première année polaire internationale et les tentatives de revendication du pôle Nord par Robert Peary. Bien qu'il se trouve dans l'un des endroits les plus éloignés du globe, Fort Conger subit actuellement les risques découlant des effets du changement climatique, des conditions météorologiques, de la faune et de l'activité humaine. Dans cette communication, nous montrons comment un scanneur laser 3D a permis de répertorier les caractéristiques culturelles avec rapidité et précision malgré les conditions difficiles qui ont cours à ce site. Nous discutons de la manière dont les incidences futures des processus naturels et de l'activité humaine peuvent être gérées à l'aide des données 3D comme données de base, comment les travaux de conservation et de restauration peuvent être planifiés à partir des modèles qui en résultent et comment les modèles 3D créés à partir des données de scannage laser peuvent rehausser l'intérêt du grand public à l'égard de la gérance culturelle et de l'histoire de l'Arctique.

Mots clés : scannage laser, préservation du patrimoine, exploration de l'Arctique, contamination inorganique, réalité virtuelle, modélisation informatisée

Traduit pour la revue *Arctic* par Nicole Giguère.

INTRODUCTION

Various natural and human agents of destruction currently threaten many heritage sites of national and international significance. Even sites located in some of the most remote regions of the world have not been spared. Erosion, weather, earthquakes, chemical contamination, looting, and warfare pose significant hazards to heritage sites in such far-flung regions as the deserts of Jordan (Al-Kheder et al., 2009), Turkmenistan (Barton, 2009), Antarctica (Bathow and Breuckmann, 2011; Gibb et al., 2011), and the North American Arctic (Arnold, 1988). The use of 3D laser scanning is emerging as an effective method for rapid and accurate recording of cultural features at archaeological sites (Zheng, 2000; Ahmon, 2004; Al-Kheder et al., 2009; Barton, 2009; Rüther et al., 2009; Armesto-González et al., 2010; Martin Lerones et al., 2010; English Heritage, 2011). However, the sensitivity of scanning equipment to extremes

[1] Corresponding author: Department of Archaeology, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada; pcdawson@ucalgary.ca
[2] Parks Canada, 145 McDermot Avenue, Winnipeg, Manitoba R3B 0R9, Canada
[3] Faculty of Environmental Design, University of Calgary, 2500 University Drive NW, Calgary, Alberta T2N 1N4, Canada
[4] SarPoint Engineering Ltd., #6, 3530–11A Street NE, Calgary, Alberta T2E 6M7, Canada
[5] Lyle Dick History and Heritage, #103–1055 Harwood Street, Vancouver, British Columbia V6E 1R5, Canada
[6] Nunavut Field Unit, Parks Canada, Box 278, Iqaluit, Nunavut X0A 0H0, Canada

in temperature, humidity, and violent jostling during transport to field sites, as well as a multitude of operational challenges associated with battery charging, sensitivity to lighting, dust, and wind, make using 3D laser scanning in remote areas with harsh environments extremely challenging (Barton, 2009; Dawson et al., 2009; Bathow and Breuckmann, 2011; Gibb et al., 2011). Paradoxically, it is in such areas of the world where heritage sites are often at greatest risk. Nowhere is this more evident than in the Arctic and Antarctic regions, where the effects of climate change and human activity are destroying culturally significant sites at an alarming rate.

Over the past decades, increases in global temperatures have accelerated the erosion and biodegradation of archaeological sites in polar regions (Barr, 2004). Much of this destruction is due to the effects of two interrelated processes. First, the melting of permafrost and permanent snowpack is thawing organic materials and artifacts at many archaeological sites, causing biodegradation through microbial activity and exposure to the elements (Osterkamp and Romanovsky, 1999; Camill, 2005; Blanchette et al., 2008). Second, rising sea levels and the effects of large storm surges caused by changing weather patterns and depletion of sea ice are destroying significant numbers of coastal archaeological sites through wave impacts and coastal erosion (Arnold, 1988; Friesen and Hunston, 1994). Human activities occurring at these sites, both past and present, are also reason for concern. Inorganic contaminants such as mercury and arsenic, which were brought to these sites by explorers and scientists during the Heroic Age of Exploration, pose a significant risk to heritage sites like historic polar research bases (Snape et al., 2002; Reisinger et al., 2005; Laing et al., 2008). The rise of polar tourism in Antarctica and the North American Arctic also has the potential to damage heritage sites through foot traffic, vandalism to fragile buildings and other structures, and the removal of surface artifacts (Blanchette et al., 2008; Stewart et al., 2010).

Fort Conger is an excellent example of a remote heritage site that is currently at risk. Located at the north end of Discovery Harbour in Quttinirpaaq National Park, Ellesmere Island, this fort features prominently in the annals of polar exploration (Dick, 2001). It is associated with the Lady Franklin Bay Expedition, one of the most famous expeditions of the First International Polar Year (Greely, 1884, 1885; Pavy, 1886). American polar explorers Robert Peary and Matthew Henson also used it in their attempts to claim the North Pole (Dick, 2001). Like many polar heritage sites, Fort Conger is threatened by erosion, weathering of site materials, and the on-site activities of animals and humans (Laing et al., 2008; Blanchette et al., 2008; Bertulli, 2010). However, recent analysis of soils at the site by the Environmental Sciences Group, Royal Military College of Canada, reveals that inorganic contamination is also of concern. These contaminants, which include unexpectedly high levels of arsenic, copper, lead, and zinc, as well as some cadmium, chromium, nickel, and mercury, are largely attributable to the activities of the Lady Franklin Bay Expedition (ESG, 2009). The potential uptake of these elements into the terrestrial food chain, as well as the possibility that they may migrate into the marine environment via an eroding bank, resulted in Fort Conger's current categorization on the National Classification System for Contaminated Sites as Class 1 – High Priority for Action (CCME, 2008). Risk minimization may require the removal of contaminated soils from targeted areas of the site. As many surface artifacts, building foundations, and standing structures remain, the potential removal of contaminated soils threatens the integrity of Fort Conger.

In this paper, we discuss how 3D laser scanning was used to manage these threats by rapidly and accurately documenting the artifacts and cultural features present at Fort Conger. We outline the challenges of using scanners in polar regions, where temperatures, wind speed, logistics, and access to clean power can cause problems. Finally, we discuss the uses of the 3D scanning data obtained from Fort Conger. In addition to creating a baseline of data from which the future effects of natural and cultural agents can be monitored, we explore how 3D data can be used to create models and virtual heritage environments that can excite interest in heritage sites, which are often far removed from the public eye.

Heritage Under Threat

During the past century, many important heritage sites have been destroyed through the effects of natural and human agency. The creation of world heritage sites—places listed by UNESCO as locations of outstanding importance to the common heritage of humanity—has made it illegal to commit acts of hostility directly against historical monuments associated with cultural or spiritual heritage (UNESCO, 2007). However, as the destruction of the Buddhas of Bamiyan by Afghani Taliban in 2001 dramatically illustrates, acts of vandalism perpetrated through warfare or clashes of ideology can occur unexpectedly. Natural agents of destruction such as earthquakes, tsunamis, erosion, and flooding can also destroy important heritage sites without regard for their legal status as designated sites (Emberling and Hansen, 2008; Shmuel, 2008).

CyArk, located in Oakland, California, is an organization founded in recognition of such threats to world heritage. Since 2003, CyArk has partnered with government, industry, and universities to capture and store digital data on important heritage sites, often in the form of 3D point clouds recorded by laser scanners (http://archive.cyark.org/). A point cloud is a three-dimensional coordinate system that represents the external surfaces of a building or artifact. The work of CyArk has prompted us, as well as other researchers, to explore how laser scanners might be used to document archaeological sites at risk. Ancient buildings are especially susceptible to destructive processes because they were frequently made from such materials as rammed earth, rough-hewn stone, wood, and plaster (Barton, 2009; Armesto-González et al., 2010). The appearance of longitudinal cracks in the walls of Umayyad desert palaces in Jordan, apparently caused by the vibrations of nearby traffic, prompted the use of laser scanning and photogrammetry to document the affected structures (Al-Kheder et al., 2009). Similarly, laser scanning has been used to monitor the deterioration of earthen architecture at the Merv Oasis in Turkmenistan (Barton, 2009).

As heritage sites often attract tourist activity, researchers have also employed laser scanning for the purposes of site conservation and development. The scanning of Wonderwerk Cave in South Africa, for example, proved useful in determining new routing for tourists visiting the site, as well as in positioning a pedestrian bridge to improve access (Rüther et al., 2009). Likewise, the tomb of Egyptian ruler Seti I in the Valley of the Kings has been subject to vandalism over the centuries. Visitors and trophy hunters have engaged in graffiti, taken wax impressions from tomb walls, and removed wall fragments as trophies (Ahmon, 2004). High-resolution 3D laser scans used to record the tomb were later combined with industrial fabrication techniques to reproduce a 16 m^2 section of wall in the burial chamber (Ahmon, 2004). This replica was placed on display at the Museo Arqueológico Nacional in Madrid in 2002 (Ahmon, 2004). Threats to important paleontological sites have also been managed using laser scanning. The National Research Institute of Cultural Heritage in Korea has digitally preserved dinosaur footprints, many of which have been damaged by prolonged weathering, development, and tourists (Ahn et al., 2010).

CyArk uses a Hazard Map, located on its website, to identify heritage sites throughout the world that are currently at risk of damage or destruction. Conspicuously absent are heritage sites located in the world's polar regions, for example, those associated with the cultures of Inuit or Eskimos and their ancestors or those of Western explorers, whalers, missionaries, and traders. This omission is likely due to several factors. First, there is a perception that heritage sites in remote regions are protected from acts of vandalism by virtue of their inaccessibility. Second, cold temperatures and harsh environmental conditions were thought to impede agents of biodegradation such as wood rot (Blanchette et al., 2008; Gibb et al., 2011). Third, the challenges of operating sensitive instruments like laser scanners in harsh polar environments, along with the complexities and expense of moving equipment and operators to remote sites, may have made some of CyArk's high-tech approaches to recording heritage seem impractical in polar contexts (Gibb et al., 2011).

As it turns out, polar heritage sites are not immune to harm. Studies undertaken at historical polar bases in both the Canadian Arctic and Antarctica, for example, reveal deterioration caused by strains of polar fungi that are extremely resilient to harsh site conditions (Blanchette et al., 2008; Gibb et al., 2011). Many of the wooden structures at these bases also contain different microclimates that vary in temperature and humidity, thereby promoting instances of soft wood rot and other forms of fungal growth (Barr, 2004; Blanchette et al., 2008; Mattssen and Flyen, 2008). Warming temperatures in polar regions will likely accelerate these forms of biological damage in the years to come. Other non-biological agents have also proven destructive to wooden buildings. Examples of such destruction are wind ablation of exterior building surfaces, damage caused by wildlife, presence of inorganic contaminants introduced by expedition activities, and vandalism by tourists and other visitors (Barr and Chaplin, 2008; Blanchette et al., 2008; Bertulli, 2010). Finally, the success of laser scanning projects in other remote regions of the world challenges the idea that laser scanning is impractical in harsh environments, where conditions often exceed operational limits recommended by manufacturers (Al-Kheder et al., 2009; Barton, 2009; Dawson et al., 2009; Gibb et al., 2011). The caveat here is that researchers must understand the different categories of laser scanners and how they might be affected by on-site environmental conditions.

CATEGORIES OF LASER SCANNERS

Laser scanners are active remote-sensing tools that emit a source radiation that is reflected from a target object. The returned beam is then sensed at or near the source and used to produce an image at varying levels of resolution. High-resolution scanners usually have very short ranges of only a few centimeters and operate at .00002 mm accuracy. They are either hand-held or fixed to a bench and used under very controlled conditions. Mid-resolution scanners, which include the Minolta Vivid 910 scanner used in this project, have ranges of about 5 m or less and provide resolutions of .03 mm. Scanners of this type will not operate in bright light, making them challenging to use outdoors. Long-range scanners have a range of more than 100 m and use advanced techniques such as echo digitization and online waveform processing to achieve better resolutions. They have two advantages: they can scan objects the size of buildings and operate under a wide variety of lighting conditions.

Laser scanners can be further broken down into three main technological categories: time-of-flight (tof), phase (continuous wave), and triangulation scanners.

Time-of-Flight Scanners

Time-of-flight scanners are perhaps the simplest to understand. These scanners emit a pulse of radiation from a laser, and the time the pulse takes to travel to the target and return is measured. The travel time is multiplied by the speed of light (a constant) and then divided by two, providing the distance from the scanner to the target. The planar coordinates of the target are determined by monitoring the rotation and orientation of mirrors or the scanner itself. Compiling the angular and range data creates a 3D point on the target object. Time-of-flight scanners may be used for a variety of applications, but they are comparatively slow relative to phase scanners, with collection speeds seldom above 100 000 points/second. Depending on the distance from the scanner to the target surface, the accuracy may range from a few millimeters to a few centimeters.

Phase Scanners

Phase-based or continuous wave scanners operate on a slightly more sophisticated principle. The scanner laser emits a continuous, smoothly oscillating waveform. The timing of the waveform cycle is constant. Therefore, a constant known as the ambiguity interval is expressed in distance. The onboard sensor measures the phase differential from the reflected wave, which is then translated into a range measurement. Again, the planar coordinates are determined by angular measurement with the scanning mirror and rotating head of the scanner. Phase scanners do not have the distance measurement capabilities of long-range time-of-flight scanners. However, higher levels of accuracy, falling in the range of a few millimeters, offset this issue. The introduction of self-rotating laser-emitting heads has greatly increased the speed of data acquisition.

Triangulation Scanners

Triangulation scanners have the sensor offset from the source. The source radiation is directed towards the target and the offset camera sensor detects the reflected radiation. As the travel time is monitored, the offset from source to sensor is known, and the location of the reflected light on the target is determined in the sensor camera. Consequently, all the requirements for determining the positioning triangle of the target location are known. Most triangulating scanners operate at distances of less than 5 m and are capable of sub-millimeter accuracies. As they are able to acquire data at speeds greater than 300 000 points per second, these scanners offer the archaeologist the ability to acquire highly accurate 3D images of artifacts and architectural details. Older triangulation scanners, such as the Minolta Vivid Series, usually require light levels to be in a specific range. If light levels exceed the manufacturer's parameters, the camera will not function properly. In addition, surfaces that are very reflective under bright lighting will result in holes in the data set. Thus these scanners can be especially problematic in Arctic environments, where the reflective surfaces of permafrost and ice encountered during excavation might cause issues. Single camera versions work on the principle used by range finders: a known baseline distance between the mirror and camera lens allows triangulation on a point. Triangulating scanners that employ a double camera are similar to the single-camera scanners, but feature a light projector that produces a moving strip or static pattern. These patterns, when viewed by the camera at a fixed distance from the light source, can provide data used to determine the shape of the object. Though not capable of capturing data over a large area, they do provide accuracy in a range of 0.1 to 0.6 mm, depending on the distance to the object and the design of the unit. Bench-mounted versions of this type of scanner make it possible to automate data acquisition. Unlike other types of long- and mid-range scanners, triangulation scanners also have the advantage of having few moving parts. They are very stable and operate on a "point and shoot" principle, much like a digital camera.

Operating Laser Scanners in Extreme Environments

Environmental controls are much easier to manage under lab conditions than in the field, where dust and vibration, excessive heat and cold, and lack of clean power mean operating the instrument outside of normal parameters. Ordinarily, scanners will not work in environments that are dusty, wet, or excessively hot or cold. Though some scanners have been designed to minimize the impact of dust entering the unit by replacing fans with heat sinks that dissipate heat into the surrounding air, most units are sensitive to heat above 40˚C and below freezing 0˚C. Laptop computers, which are commonly used in the field to process and store data downloaded from the laser scanner, also have difficulties charging, rebooting, waking from sleep mode, and transferring data outside of normal operating temperature ranges (Barton, 2009; English Heritage, 2011; Gibb et al., 2011).

Proximity to sea ice, snow or rock cover, and prevailing winds are just a few of the climatic factors that can influence laser-scanning surveys in polar regions (Dawson et al., 2009; Gibb et al., 2011). Wind speeds, for example, can create havoc with these sensitive instruments by stirring up particles of dust and grit. In extreme cases, the laser can pick up windblown particles and even clouds of insects, resulting in scanner noise (Barton, 2009; Dawson et al., 2009). High winds require that scanners be operated on fixed and stable platforms to minimize vibration of the instrument during recording. Excessively bright light levels, caused by extended periods of daylight at high latitudes, as well as the reflectivity of snow, ice, and bleached wood or timber, also create problems for time-of-flight scanners, which are especially sensitive to light. In order to reduce ambient light levels, scanners in this category need to be enclosed within a tent, shielded by a tarp, or operated at night (Barton, 2009; Dawson et al., 2009; Bathow and Breuckmann, 2011; Gibb et al., 2011). Operating in the rain is not advised or recommended for any scanner, which is again problematic for laser scanning in Arctic regions, where rain, snow, and persistent fog are common during summertime.

Finally, the logistics required to transport delicate scanning equipment to remote locations can become a serious issue. Only a few scanners are small and light enough to fit in the overhead compartment or under the seat of an airplane. This problem is even more challenging in the Canadian Arctic, where smaller fixed-wing aircraft service smaller communities. The use of G-force cases, though they are reliable, will likely not guarantee that the unit will avoid damage while being handled by cargo and airport baggage personnel. In addition, ancillary equipment such as targets, digital camera, laptop computer, connecting cables, uninterrupted power supplies, generators, tripods, tarps, and tents must also be transported to the site. Consequently, being self-sufficient in the field may require the transport of several hundred pounds of equipment, which easily exceeds the normal cargo allowance for northern commercial airlines.

While these factors may appear formidable to those considering laser scanning in extreme settings, a growing number of projects undertaken in recent years have successfully overcome changing weather, burning sunshine, freezing cold, high humidity, sand, thunderstorms and even dangerous animals (Bathow and Breuckmann, 2011). In many of these cases, scanners have proven remarkably reliable in temperatures far above (Dawson et al., 2009; Gibb et al., 2011) and below (Barton 2009) the optimal range. Success at the extreme ends of such a spectrum indicates it is feasible to conduct laser scanning of objects in Arctic regions of North America.

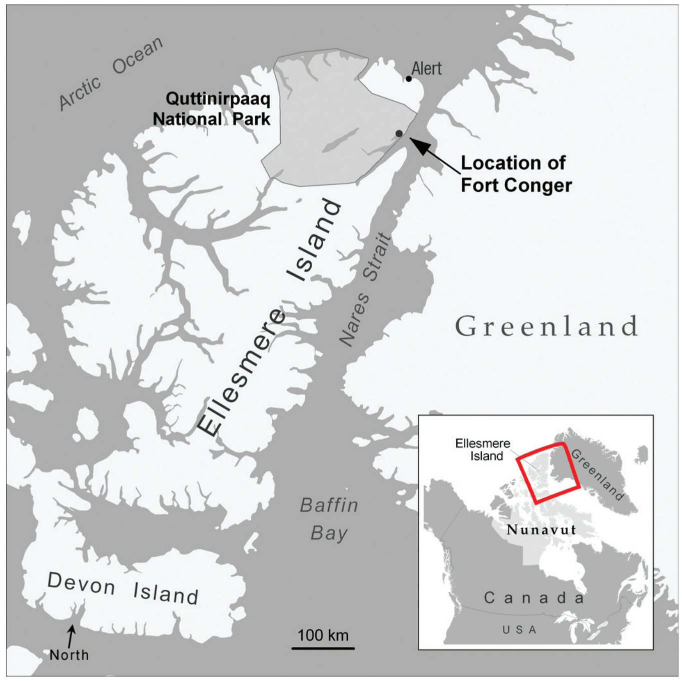

FIG. 1. Location of Fort Conger, Quttinirpaaq National Park, Ellesmere Island.

HISTORIC BACKGROUND OF FORT CONGER

Fort Conger is located in Quttinirpaaq National Park, Ellesmere Island, Nunavut (Fig. 1). Aptly called "the crossroads of the High Arctic" (Christie, 1968:31), Fort Conger has seen 19th- and 20th-century expeditions of geographic and scientific discovery as well as numerous 20th-century visits by government and military personnel, researchers, and travelers (Dick, 2001). Among the most famous are the Lady Franklin Bay Expedition (1881–84) and the North Pole attempts of Robert Peary and Matthew Henson (1899, 1905, 1908).

The site was initially visited by British explorer George Nares, who overwintered at Discovery Harbor in 1875–76, as part of the British Arctic Expedition (Dick, 2001). It was partially due to Nares' voyage that the United States government selected this location for the Lady Franklin Bay Expedition. This expedition formed part of the First International Polar Year (1882–83)—a scientific initiative led by nations around the world to advance knowledge of polar areas. Led by First Lieutenant Adolphus Greely, this expedition is known both for its scientific achievements and for the planned retreat of its 25 members, of whom only six would survive (Dick, 2001). Greely and his men transported a prefabricated building to the site, along with provisions, scientific equipment, and other items to last them for a period of two years (Greely, 1885; Dick, 2001). The building measured 18.5 m × 5.2 m, with double walls of tongued and grooved boards that enclosed an air space of 32 cm (Dick, 2001). Tar paper was used to seal the inside and outside surfaces of the shelter, as well as the single-layered roof constructed of boards. The interior was divided into three rooms. At the north end was a room 5.2 m by 4.6 m that housed the officers; at the south end was a room approximately double in size that housed the enlisted men. In between were an entry hall, kitchen, bathroom, and small observatory (Dick, 2001). Canvas lean-tos were constructed at either end of the house to store meteorological equipment. While the house was being built, the expedition members lived in tents, the outlines of which are still visible on the site today (Bertulli, 2010).

Following the abandonment of Fort Conger by Greely and his men, the site remained unoccupied until the arrival of Robert Peary in 1899. Peary was an intelligent, driven man who had paid close attention to the tragic events of the Lady Franklin Bay Expedition. He argued that a new form of exploration needed to be developed—one that was not dependent upon multiple ships, which, if stuck, could prove disastrous to expedition members awaiting rescue (Dick, 2001:234). Instead, he advocated including Aboriginal workers—in his case, the Inughuit or Polar Inuit of Greenland—on expedition teams. Peary paid close attention to Inuit technology. He learned about the use of skin clothing, traditional shelters (snowhouses), caches, and sledging (Dick, 2001:349–354). Although the equipment and provisions left behind by the Lady Franklin Bay Expedition constituted a veritable emporium to Peary, he felt the expedition house was ill suited to his needs. The structure was dismantled and its materials used to build three smaller structures. Inspired by Inuit architecture, these dwellings were low-lying, semi-subterranean structures with low entrance passages that would have been connected via snow tunnels in winter (Dick, 2001, 2004). They were sealed with tar paper and insulated using silt and gravel. Peary himself slept in a double-walled tent attached to one of the structures, the walls of which were insulated using the mattresses recovered from Greely's house (Dick, 1991). Although warm and cozy while at the fort, Peary and his men spent most of the time living in far less comfortable shelters while hunting muskoxen in the interior areas of Ellesmere Island (Dick, 2001). Peary used Fort Conger only during his 1898–1902 expeditions. While the site was briefly occupied by Donald B. MacMillan to take a month of tidal readings in 1909, Peary never visited it again.

ESTABLISHING THE HISTORICAL SIGNIFICANCE OF FORT CONGER

The legacies of these two expeditions, along with earlier visits by George Nares aboard HMS *Discovery* during the British Arctic Expedition (1875) and later stopovers by explorers like Godfred Hansen (1919), have left behind a great deal of material culture. The most obvious of these artifacts include the remains of a post office cairn built by the men of the Nares expedition, which now presents as a mound surrounded by a concentration of rusted tin cans; two wooden boards commemorating the deaths of two men of HMS *Discovery*; the house foundation of the Lady Franklin Bay Expedition, along with the remains of a thermometer observatory, barrel hoop ring, brick pedestal and numerous artifacts; American explorer Robert Peary's three huts, and the berm outlining Peary's tent quarters (Fig. 2) (Bertulli, 2010).

During the 1970s, there was growing concern over the unauthorized removal of artifacts from historic sites across Canada's Arctic. In 1978, the Government of the Northwest Territories declared Fort Conger a site of Territorial Historic Significance under the Historical Resources Act, a designation continued by the Government of Nunavut. As well, the three standing structures erected by Peary's expedition in 1900 have achieved the highest level of designation made by the Federal Heritage Buildings Review Office as Classified Federal Heritage Buildings, the same level accorded Canada's Parliament Buildings in Ottawa. The site is also one of two places in the Arctic at which the Historic Sites and Monuments Board of Canada commemorates the First International Polar Year of 1882–83 as a National Historic Event, specifically relating to the United States Lady Franklin Bay (Greely) Expedition. Fort Conger is likewise under consideration by the International Polar Heritage Committee of the International Council on Monuments and Sites (ICOMOS) as a site of international significance for inclusion on a list of 30 significant cultural heritage sites in the North and South Polar regions. Within Quttinirpaaq, Fort Conger has been accorded Zone 1 status, which gives it special wilderness protection and reflects its status as a unique, threatened, or endangered cultural feature. Despite this recognition, it is clear that past and current factors—degradation of the wooden structures, bank erosion, visitation, and inorganic contamination—pose threats of varying degrees to Fort Conger's longevity and survival.

FIG. 2. Peary huts as they appeared in 2010 at Fort Conger.

DESCRIPTION OF EXTANT REMAINS AND MANAGEMENT CONCERNS

Because of the historical significance of Fort Conger, many attempts have been made to systematically record the cultural features and materials present there. Geologist R.L. Christie mapped the site in 1965 and, with prescience, opined that preserving Fort Conger carried the conflicting risks of over-protecting it and allowing natural processes to take their course (Christie, 1968). At the same time, retired mineralogist and artist Maurice Haycock painted Peary's huts (Haycock, 2007); one of these paintings now hangs near the Speaker's offices of the Nunavut Legislative Assembly in Iqaluit. More recently, work at Fort Conger has focused on monitoring and recording the extant structural and surface remains (Blanchette et al., 2008; Bertulli, 2010). As the major standing structures, the Peary huts have received the most attention. By 1935, they had taken their modern appearance (Shackleton, 1937:250), with the roof and west wall of the western hut absent and only one ceramic chimney pipe remaining on the northeast hut. As-found or measured drawings and photographs of the Peary huts (Broodhagen et al., 1979) provided a baseline for documenting structural changes. The exterior walls of each hut were largely missing, but interior walls were intact except for the entire west wall of the west hut. Door and window openings were present, but the doors and windows themselves were lacking except for two glass panes in the northeast hut (since lost). Traces of tar paper and canvas adhered to the structures, as well as vestiges of the gravel and silt intended as an insulating layer between the interior and exterior walls (Philips Parmenter et al., 1978:235–243).

Biodegradation and Deterioration

Ice, snow, and water, accumulating in each hut's interior according to the season, foster moss growth in warmer temperatures. The roofless hut that originally housed the Inughuit during Peary's sojourn at Fort Conger is in the worst condition, with one wall falling in and separations occurring between the walls. Blanchette et al. (2008) note critical deterioration of the wood of the Peary huts (mainly white pine with some hard pine and possibly southern yellow pine, as well as birch and oak wood). The exterior surfaces of many boards have a grooved appearance due to wind ablation, as well as indications of limited salt damage. Most seriously, soft rot caused by fungi (*Cadophora* species) has decayed the boards. These soft rot fungi are active in moist conditions and temperatures above the freezing mark. Consequently, boards in contact with the ground surface are particularly vulnerable, and the interior boards are often so affected as to be "soft to the touch." Further, defibration, the mechanical separation of wood into fibers or fiber bundles, resulting in a fuzzy appearance, is occurring on some boards of the Peary huts, as well as other wooden objects across the site. The chemical (salt) attack and cell detachment on wood surfaces renders these loosened fibers easily removable by strong winds, and this deterioration process contributes to the gradual thinning of the historic woods (R.A. Blanchette, pers. comm. 2012).

Erosion

Fort Conger sits on a tableland bounded on its north and west sides by a 2.5 m bank that is eroding into Discovery Harbour. A protocol to monitor bank erosion was designed and implemented in 2007 and expanded in 2010. It involves measuring from the site's original north-south grid line to the first major break in the bank edge. Greely (1885) states that the distance from his station house to the bank was 30 yards. Phillips' 1979 site map shows a distance of 12.7 m from the northwest corner of the Greely House to the eroding bank. The results of recent monitoring show that the distance from the northwest corner of the Greely House to the eroding bank was 11.7 m in 2007 and 9.4 m in 2010. The most serious concern is for the post office cairn of the Nares expedition, which is only about 1 m from the bank; artifacts (barrel hoops and cans) have been removed from the bank edge and relocated a few meters inland.

Destruction by Wildlife and Vandalism

A photographic monitoring protocol, implemented in 1990 by Parks Canada and based on photographs of general views of the Peary huts and surface artifacts, indicates that the Peary huts have sustained damage from polar bears. Loss and movement of numerous artifacts and animal bones, particularly skulls and a bowhead whale rib, have also occurred across the site. On 13 April 1994, a chartered fixed-wing aircraft, intending to establish a fuel cache, mistakenly landed on the snow-covered site rather than at the airstrip about 1 km to the north. On takeoff, the plane's wing clipped a seven-coursed brick instrument pier associated with the Greely expedition, knocking it off its base and tumbling it several meters downslope, where it remains today. A geomagnetic survey point, mounted in place in 1982 to observe the 100-year anniversary of Greely's scientific work, was likely damaged at this time (PWGSC, 2002:11).

Inorganic Contamination

Inorganic contamination of soils and their potential remediation pose the gravest threat to Fort Conger and its cultural resources. Investigations by the Environmental Sciences Group (ESG) of the Royal Military College, Queen's University, Kingston, Ontario, have detected unexpectedly high levels of arsenic, copper, lead, and zinc in soil samples, as well as some cadmium, chromium, nickel, and mercury, although natural levels of arsenic, nickel, and copper are elevated in this area (ESG, 2009). Contamination is spread across the site, but is concentrated around the Peary huts, Nares' post office cairn, and particularly in and around the remains of the Greely House. Probable sources of these contaminants, attributed largely to the requirements of the Greely expedition's scientific work, include the use of arsenic trioxide to preserve natural history specimens and samples; mercury from weather recording instruments; lead from tin can solder; and copper and zinc from batteries (Laing et al., 2008; ESG, 2009). Polycyclic aromatic hydrocarbons (PAHs) from tar paper used in building construction are likewise present. ESG also assessed the potential for uptake of these elements into the terrestrial food chain, as well as the plausibility of their migration into the marine environment via a natural drainage ditch and the bank slumping into Discovery Harbour (ESG, 2009). Plants growing in contaminated earth were found to contain inorganic elements, posing a risk to collared lemmings, but not to animals higher in the food chain, such as Arctic foxes and predatory birds. The possibility of future contaminant migration into the sea was assessed as likely because of bank collapse (ESG, 2009). Such contamination is of particular concern as the discharge of harmful substances into water bodies may be harmful to fish and marine life forms. These assessments have resulted in Fort Conger's current categorization as Class 1—High Priority for Action on the National Classification System for Contaminated Sites (CCME, 2008), indicating that further research and risk management or remediation are required to address existing concerns. Predictably, Class 1 sites are seen to have suffered from quantified, multifactorial impacts. Remediation work may require the removal of contaminated soils from the site, placing the extant cultural features and artifacts on the site at significant risk.

Laser Scanning of Fort Conger

For our project, we selected two scanners to record the site: a Zoller+Fröhlich Imager 5006i phase-based scanner (Fig. 3) and a Minolta Vivid 910 triangulation scanner (Fig. 4). The Z+F scanner was used for long-range scanning of terrain and large cultural features such as the Peary huts, while smaller artifacts were scanned with the Minolta scanner at higher levels of resolution. Upon arriving at

FIG. 3. Zoller+Fröhlich Imager 5006i phase-based scanner.

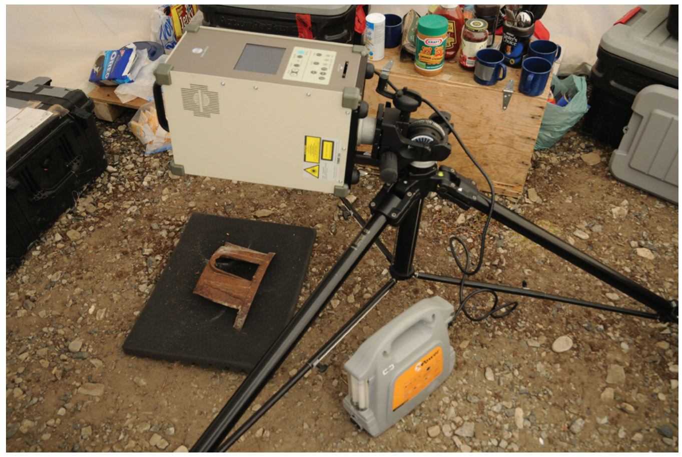

FIG. 4. Minolta Vivid 910 triangulation scanner.

Fort Conger, the existing north-south/east-west baseline established during an earlier survey in the late 1970s was re-established for the purpose of tying the laser scanning data to existing maps of the site. The baseline was also useful in establishing the coordinates of the targets required for registering the many point clouds created as the scanner was moved around the site to capture cultural features and objects. Like a standard camera, laser scanners have a field of view, meaning that other entities can occlude objects being scanned. The clustered positions of the Peary huts, for example, meant that the wall of one building might obscure portions of another. Subsequently, targets were affixed to the Peary cabins, as well as placed atop survey tripods, which were then distributed around the structure and geo-referenced. Once scanning had been completed, the data sets (point clouds) were downloaded onto a laptop computer. Zoller+Fröhlich Laser Control software was then used to register the various point clouds by identifying targets common to multiple scans.

Our original intentions were to use the Minolta scanner, which provides higher-resolution scans at sub-millimeter levels of accuracy, to scan selected artifacts at Fort Conger. However, weight concerns, coupled with difficulties associated with using the scanner under conditions of natural versus artificial light, required us to revise our plans. In the end, we used the Minolta scanner to scan three artifacts, primarily as a means of demonstrating the utility of this scanner for future research.

RESULTS AND DISCUSSION

All laser scanning was completed over a period of 12 days during July 2010. A total area of 34 500 m^2 was recorded from 43 scanner locations, and the resulting 3D point clouds captured all of the cultural features present at the site. In Figure 5, an overhead view of the site shows each scanner set-up location as a yellow triangle. It should be noted that only 11% of the detail captured during the scanning process was used because of limitations in current desktop and mobile computer processing power. As more powerful processors become available in future years, the remaining 89% of the data will become useful, thereby adding a legacy dimension to our project. Even at 11%, the scans revealed such details as the staining caused by nails on the wallboards of the Peary huts. Figure 6 presents an image of the registered point clouds of the Peary huts and associated artifacts at Fort Conger.

One of the advantages of laser scanning is that the point clouds can be used to support existing on-site conservation efforts at Fort Conger. Using Leica Geosystems Truview, a web-enabled panoramic point cloud viewer, accurate measurements of various cultural features can be obtained. By way of illustration, wallboards that had become detached from one of Peary's huts, either through weathering or by polar bear activity, were reattached in 2010 with metal screws to maintain the structural integrity of the huts. Should it be determined that other missing wallboards pose similar threats, conservators could use measurements of damaged areas obtained from the point cloud data to fabricate replacement boards in advance of any future trip. Restoration carpentry work could then be carried out rapidly at the site.

In much the same way, the laser scanning data from Fort Conger can be used to monitor the effects of soft rot fungi, wind ablation, and salt attack on wooden structures at the site. For example, laser scanning has recently been used to examine the effects of different storage environments on the morphology of wet-preserved wooden objects from archaeological sites (Lobb et al., 2010). The fact that diachronic changes to these wooden objects were identified and detected at sub-millimeter levels of accuracy suggests that conservators could monitor the deterioration of exterior wooden surfaces at Fort Conger using high-resolution scanners like the Minolta 910 Vivid. As mentioned previously, historic polar buildings often contain discrete microclimates that can influence where deterioration occurs (Blanchette et al., 2008). While exposed to similar agents of biodegradation, the interior and exterior surfaces of Peary's huts at Fort Conger seem to have been affected in different

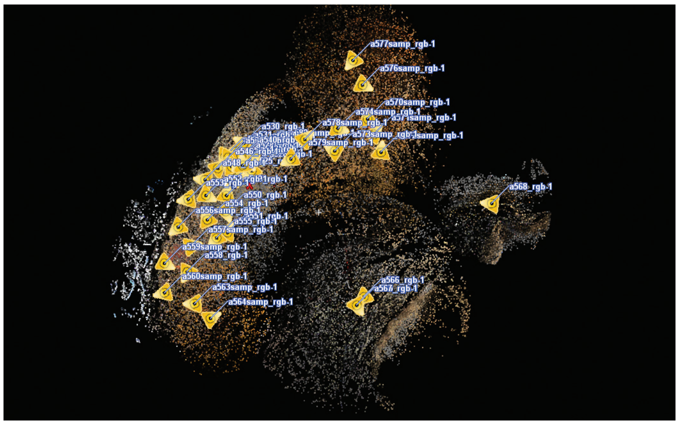

FIG. 5. A bird's-eye view of the Fort Conger point cloud, representing a total area of 34 500 m^2 recorded from 43 scanner locations (scanworlds). Some sea ice was also captured by the scanner (lower left). Each scanworld is represented by a yellow triangle.

FIG. 6. Point cloud showing two Peary huts and associated artifacts.

ways. Ice, snow, and water accumulating in each hut's interior according to the season foster moss growth in warmer temperatures, which may lead to even more favorable conditions for decay. In contrast, wind ablation has given the exterior surfaces of many boards a grooved appearance that is often missing from the more protected interior surfaces. As both the interior and exterior areas of the huts were scanned, the resulting data may prove useful in determining how and why different areas inside and outside the huts degenerated.

The laser scanning data can also be used to supplement earlier measured drawings and photographs of Fort Conger that have been used to monitor the site. Many of these photographs contain general and specific views of the Peary huts and surface artifacts. Researchers visiting Fort Conger since 1990 have photographically replicated these views. The panoramic images of the surrounding landscape, captured as point clouds by the laser scanner at each set-up location, are called scanworlds. The large number of scanworlds at Fort Conger (43) allows us to reproduce the field of views captured during these earlier photographic monitoring protocols (Fig. 5). They can even be used to replicate

FIG. 7. Untextured mesh model of the Peary huts at Fort Conger.

the views of historic photographs taken by the Lady Franklin Bay and Peary expeditions and by Godfred Hansen's 1919 expedition to lay caches for Roald Amundsen. Perhaps most importantly, the 43 scanworlds at Fort Conger dramatically increase the extent of visual coverage for future monitoring of changes to the site (Fig. 5).

In addition to supporting conservation management of the site, the point cloud data have also been used to create photorealistic models of structures and artifacts. Using Polyworks, developed by InnovMetric Software, Inc., the point clouds from Fort Conger were converted into mesh files, each a collection of vertices, edges, and faces that define the shape of an object, to which surface texture and colour can later be added (texture mapping). Figure 7 presents an untextured image of the completed model of the Peary huts, created using data obtained from the Z+F Imager 5006i. Figures 8 and 9 are images of the textured Peary hut model rendered in 3D Studio MAX software. Two cast iron stove parts, scanned using the Minolta Vivid 910 scanner, are presented as textured models in Figures 10 and 11. When imported into 3D Studio MAX software, these and other mesh models were used to create animations and QuickTime Virtual Reality (QTVR) movies (http://www.fortconger.ca). Virtual reality environments were also produced using Virtools 5.0 SP1 by Dassault Systèmes. Ultimately a website will host the images, movies, and virtual worlds generated from this project. This virtual heritage environment will be used to educate the public about the significance of Fort Conger and the roles played by various expeditions in advancing polar science.

LIMITATIONS AND CONSTRAINTS

While the use of laser scanning to document Fort Conger was carried out successfully, many challenges were encountered. First, high winds and precipitation occasionally prevented us from collecting data, thereby slowing down the survey. Second, lighting conditions at the site were often extremely bright because of the 24-hour pattern

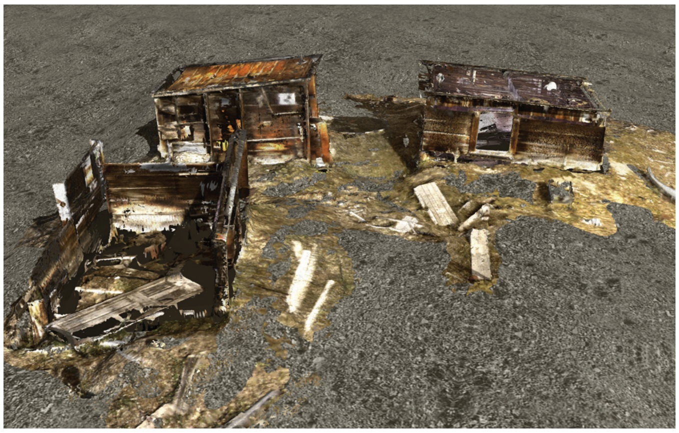

FIG. 8. Textured mesh model of Peary Huts, Fort Conger.

FIG. 9. The textured model seen from a second perspective.

of daylight and reflection off sea ice and wallboards. The Minolta Vivid scanner is sensitive to light levels above 500 lux, requiring that the scanner be used inside a tent, where light levels could be reduced to an acceptable level. Acquiring accurate colour information also presents a unique set of challenges in 3D imaging. Though it is possible to capture colour data with all types of scanners, very controlled lighting conditions of the target or site are required to capture consistent and accurate colour data. This is often difficult when working under natural lighting conditions in polar regions. With laser scanners, colour values (RGB) are recorded for each point acquired from the surface of the object. To improve colour capture, a high-resolution digital camera was used to supplement data collected with the Z+F Imager 5006i laser scanner. Using a software solution based on photogrammetric principles, it was then possible to select colour values from the digital image for every point in the 3D image or point cloud. This allowed us to create 3D models of buildings and objects that were colour correct. Third, the use of Twin Otter aircraft for travel to and from the site placed limits on cargo weight, requiring us to fly the Minolta Vivid scanner back to Resolute Bay earlier than originally intended. As a result, we were able to scan only a small sample of artifacts on the surface of the site.

FIG. 10. Textured model of a cast-iron stove part.

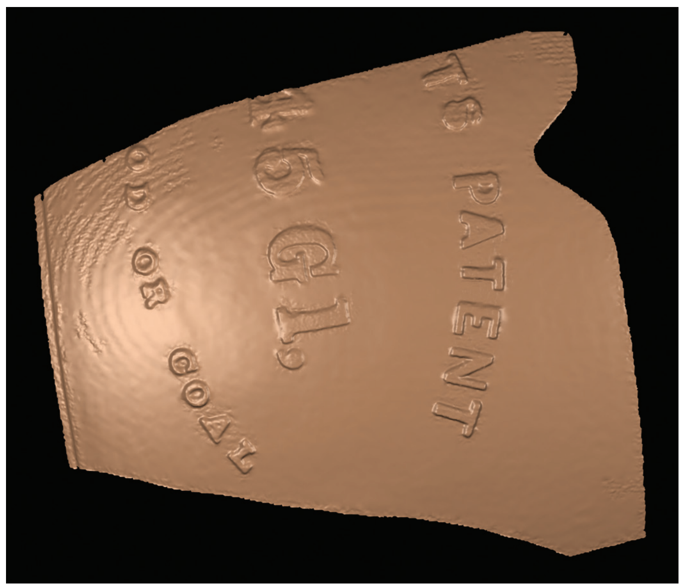

FIG. 11. Textured model of a second cast-iron stove part, showing maker's mark.

CONCLUSIONS

Laser scanning is an extremely complex process that uses sensitive equipment and requires relatively fixed and predictable environmental conditions. Shipping cargo to remote areas like the Canadian Arctic can also be prohibitively expensive, and the chances that a key piece of equipment will be lost or damaged are always high. As a consequence, researchers planning similar projects need to recognize that success is far from guaranteed. Nevertheless, the results reported here demonstrate the feasibility of using laser scanning to document important cultural heritage sites in remote areas of the world like the Canadian High Arctic, where conditions often exceed recommended operational limits for these instruments. Advantages of laser scanning over more traditional survey methods include its capacity for rapid collection of data at extraordinarily high levels of detail. The resulting 3D point clouds provide excellent baseline information for establishing monitoring protocols, as well as producing a range of animations, movies, and virtual objects to excite public interest. Given that the impacts of climate change are being felt most keenly in polar regions, the use of laser scanning may prove extremely useful in recording other archaeological sites under threat. The lesson learned from Fort Conger is that inaccessibility neither protects heritage sites from destruction nor prevents them from being recorded and protected. Instead, steps can be taken to document and preserve such sites before they are lost forever.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to Parks Canada's Nunavut Field Unit, the Polar Continental Shelf Program, and Z+F USA, Inc.

REFERENCES

Ahmon, J. 2004. The application of short-range 3D laser scanning for archaeological replica production: The Egyptian tomb of Seti I. The Photogrammetric Record 19(106):111–127.

Ahn, J., Wohn, K.-Y., and Kong, D.-Y. 2010. 3D digital documentation of dinosaur footprints. Presented at the 16th International Conference on Virtual Systems and Multimedia (VSMM), 20–23 October 2010, Seoul, Korea. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc. 340–345.

Al-Kheder, S., Al-Shawabkeh, Y., and Haala, N. 2009. Developing a documentation system for desert palaces in Jordan using 3D laser scanning and digital photogrammetry. Journal of Archaeological Science 36(2):537–546.

Armesto-González, J., Riveiro-Rodríguez, B., González-Aguilera, D., and Rivas-Brea, M.T. 2010. Terrestrial laser scanning intensity data applied to damage detection for historical buildings. Journal of Archaeological Science 37(12):3037–3047.

Arnold, C.D. 1988. Vanishing villages of the past: Rescue archaeology in the Mackenzie Delta. The Northern Review 1:40–58.

Barr, S. 2004. Polar monuments and sites – An introduction. In: Barr, S., and Chaplin, P., eds. Cultural heritage in the Arctic and Antarctic regions. Monuments and Sites 8. Paris: ICOMOS, International Polar Heritage Committee. 18–23.

Barr, S., and Chaplin, P., eds. 2008. Historical polar bases – preservation and management. Monuments and Sites 17. Oslo: ICOMOS, International Polar Heritage Committee.

Barton, J. 2009. 3D laser scanning and the conservation of earthen architecture: A case study at the UNESCO World Heritage Site Merv, Turkmenistan. World Archaeology 41(3):489–504.

Bathow, C., and Breuckmann, B. 2011. High-definition 3D acquisition of archaeological objects: An overview of various challenging projects all over the world. Paper presented at the 23rd CIPA Symposium, 12–16 September, Prague, Czech Republic.

Bertulli, M. 2010. Cultural resource management at Fort Conger, Quttinirpaaq National Park in 2010. Unpubl. report. Parks Canada, 145 McDermot Avenue, Winnipeg, Manitoba R3B 0R9.

Blanchette, R.A., Held, B.W., and Jurgens, J.A. 2008. Northumberland House, Fort Conger and the Peary huts in the Canadian High Arctic: Current condition and assessment of wood deterioration taking place. In: Barr, S., and Chaplin, P., eds. Historical polar bases – preservation and management. Monuments and Sites 17. Oslo: ICOMOS, International Polar Heritage Committee. 30–37.

Broodhagen, V., Parmenter, C., and Konotopetz, L. 1979. Fort Conger, Ellesmere Island, NWT, As Found Recording. Unpubl. report, drawings, and photographs. Parks Canada, 145 McDermot Avenue, Winnipeg, Manitoba R3B 0R9.

Camill, P. 2005. Permafrost thaw accelerates in boreal peatlands during late-20th century climate warming. Climatic Change 68(1-2):133–152.

CCME (Canadian Council of Ministers of the Environment). 2008. National classification system for contaminated sites: Guidance document. Winnipeg: CCME. http://www.ccme.ca/assets/pdf/pn_1403_ncscs_guidance_e.pdf.

Christie, R.L. 1968. Fort Conger: Crossroads of the High Arctic. Musk-ox 34:29–34.

Dawson, P.D., Levy, R.M., Oetelaar, G., Arnold, C., Lacroix, D., and Mackay, G. 2009. Documenting Mackenzie Inuit architecture using 3D laser scanning. Alaska Journal of Anthropology 7(2):29–44.

Dick, L. 1991. The Fort Conger shelters and vernacular adaptation to the High Arctic. Bulletin of the Society for the Study of Architecture in Canada 16(1):13–23.

———. 2001. Muskox Land: Ellesmere Island in the age of contact. Calgary: University of Calgary Press.

———. 2004. Robert Peary's North Polar narratives and the making of an American icon. American Studies 45(2):5–34.

Emberling, G., and Hanson, K., eds. 2008. Catastrophe! The looting and destruction of Iraq's past. Publication 28. Chicago: The Oriental Institute Museum of the University of Chicago.

English Heritage. 2011. 3D laser scanning for heritage: Advice and guidance to users on laser scanning in archaeology and architecture. Swindon: English Heritage Publishing.

ESG (Environmental Sciences Group). 2009. Human health and ecological risk assessment of Fort Conger, Quttinirpaaq National Park, Ellesmere Island. Unpubl. report. Royal Military College, Kingston, Ontario K7K 7B4.

Friesen, T.M., and Hunston, J. 1994. Washout – the final chapter: 1985–86 NOGAP salvage excavations on Herschel Island. In: Pilon, J.-L., ed. Bridges across time: The NOGAP Archaeology

Project. Canadian Archaeological Association Occasional Paper 2. 39–60.
Gibb, R., McCurdy, D., Farrell, R.L., Bathow, C., and Breuckmann, B. 2011. Use of multi-resolution laser scanning/ white light scanning and digital modelling of the historic huts of Scott and Shackleton in Antarctica. Archaeology in New Zealand 54(2):131–143.
Greely, A.W. 1884. Arctic meeting at Chickering Hall, November 21st, 1884. Reception of Lieut. A. W. Greely, U. S. Army, and his surviving companions in the exploration of the Arctic. Journal of the American Geographical Society of New York 16:311–344.
———. 1885. The scientific results of the Lady Franklin Bay Expedition. Science 5(115):309–312.
Haycock, K. 2007. On site with Maurice Haycock, artist of the Arctic: Paintings and drawings of historical sites in the Canadian Arctic. Campbellville, Ontario: Edgar Kent Publishers.
Laing, T., Koch, I., Zeeb, B., Reimer, K., and Bertulli, M. 2008. Ecological risk assessment at a northern historical site – Fort Conger, Ellesmere Island. Paper presented at the RPIC (Real Property Institute of Canada) Federal Contaminated Sites Workshop, 8–10 October, Vancouver, British Columbia.
Lobb, M., Krawiec, K., Howard, A.J., Gearey, B.R., and Chapman, H.P. 2010. A new approach to recording and monitoring wet-preserved archaeological wood using three-dimensional laser scanning. Journal of Archaeological Science 37(12):2995–2999.
Martin Lerones, P., Llamas Fernández, J., Melero Gil, Á., Gómez-Garcia-Bermejo, J., and Zalama Casanova, E. 2010. A practical approach to making accurate 3D layouts of interesting cultural heritage sites through digital models. Journal of Cultural Heritage 11(1):1–9.
Mattssen, J., and Flyen, A.-C. 2008. Biodeterioration in buildings in Svalbard. In: Barr, S., and Chaplin, P., eds. Historical polar bases – preservation and management. Monuments and Sites 17. Oslo: ICOMOS, International Polar Heritage Committee. 23–29.
Osterkamp, T.E., and Romanovsky, V.E. 1999. Evidence for warming and thawing of discontinuous permafrost in Alaska. Permafrost and Periglacial Processes 10(1):17–37.
Pavy, L.M. 1886. Dr. Pavy and the polar expedition. The North American Review 142(352):258–269.
Philips Parmenter, C., Burnip, M., and Ferguson, R. 1978. Preliminary report of the second season (1977) of historical archaeological investigations in the High Arctic, 2 vols. Restricted Manuscript Series. Ottawa: Environment Canada, Parks Canada.
PWGSC (Public Works and Government Services Canada). 2002. Fort Conger, Quttinirpaaq National Park of Canada, heritage recording report, July 2002. Unpubl. report. Western and Northern Service Centre, Parks Canada, Winnipeg, Manitoba R3B 0R9.
Reisinger, H.J., Burris, D.R., and Hering, J.G. 2005. Remediating subsurface arsenic contamination with monitored natural attenuation. Environmental Science and Technology 39(22):458–464.
Rüther, H., Chazan, M., Schroeder, R., Neeser, R., Held, C., Walker, S.J., Matmon, A., and Horwitz, L.K. 2009. Laser scanning for conservation and research of African cultural heritage sites: The case study of Wonderwerk Cave, South Africa. Journal of Archaeological Science 36(9):1847–1856.
Shackleton, E. 1937. Arctic journeys: The story of the Oxford University Ellesmere Land Expedition 1934–5. London: Hodder and Stoughton Limited.
Shmuel, M. 2008. Recognition of earthquake-related damage in archaeological sites: Examples from the Dead Sea fault zone. Tectonophysics 453(1-4):148–156.
Snape, I., Riddle, M.J., Stark, J.S., Cole, C.M., King, C.K., Duquesne, S., and Gore, D.B. 2002. Management and remediation of contaminated sites at Casey Station, Antarctica. Polar Record 37(202):199–214.
Stewart, E.J., Draper, D., and Dawson, J. 2010. Monitoring patterns of cruise tourism across Arctic Canada. In: Lück, M., Maher, P.T., and Stewart, E.J., eds. Cruise tourism in polar regions: Promoting environmental and social sustainability? London: Earthscan Ltd. 133–145.
UNESCO. 2007. Climate change and world heritage: Report on predicting and managing the impacts of climate change on world heritage and strategy to assist states parties to implement appropriate management responses. Paris: UNESCO World Heritage Centre.
Zheng, J.-Y. 2000. Virtual recovery and exhibition of heritage. Multimedia, IEEE 7(2):31–34.