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Using Airborne LiDAR Survey to explore Historic-era archaeological landscapes of Montserrat in the Eastern Caribbean

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This article describes what appears to be the first archaeological application of airborne LiDAR survey to historic-era landscapes in the Caribbean archipelago, on the island of Montserrat. LiDAR is proving invaluable in extending the reach of traditional pedestrian survey into less favorable areas, such as those covered by dense neotropical forest and by ashfall from the past two decades of active eruptions by the Soufrière Hills volcano, and to sites in localities that are inaccessible on account of volcanic dangers. Emphasis is placed on two aspects of the research: first, the importance of ongoing, real-time interaction between the LiDAR analyst and the archaeological team in the field; and second, the advantages of exploiting the full potential of the three-dimensional LiDAR point cloud data for purposes of the visualization of archaeological sites and features.

Keywords: Montserrat, Caribbean, LiDAR, point cloud data, archaeological survey

Introduction

This article has as its focus the archaeological use of a relatively novel technology (LiDAR, or airborne laser scanning), applied in distinctly new ways, to the regional archaeological record of a rather out-of-the-way place (Montserrat) in the eastern Caribbean, where no such work has been attempted before. The contribution of iterative LiDAR analysis and the comprehensive integration of LiDAR remote sensing data to survey and landscape archaeology, as well as historical archaeological research, is illustrated in the following discussion of results from three survey areas on the island of Montserrat. Since this is the 40th anniversary issue of *JFA* we begin by briefly framing our case study and specific research goals within the wider context of the development of regional survey, and how it has been impacted by technological changes over the past several decades.

Survey—by which we mean the systematically organized, thorough inspection of the ground surface for archaeological remains by teams of archaeologists—became a significant part of standard archaeological practice in many parts of the world only in the years immediately before the launch of *JFA* in 1974.

Over the course of the ensuing half century, the extent to which survey in this sense has been conducted has varied tremendously, for a number of reasons. In some areas of the world challenging environments beyond the arable zone make field walking difficult and artifact visibility problematic. In other areas, archaeological regulations and the terms of permits actually impede pedestrian-based survey. Differing disciplinary traditions of archaeology have also resulted in variable degrees of interest in the types of regional-scale research questions that survey is best suited to address. Nonetheless, in those parts of the world where archaeological survey has been adopted with enthusiasm, it has emerged today as an inherently multi-method, holistic enterprise, often carried out in the context of regional or landscape archaeology research frameworks. Large-area geophysics, the acquisition and interpretation of aerial or satellite imagery and topographic data, and the study of historical cartography and contemporary data on land-use, soils, and hydrology are all part of an integrated approach to the landscape. The analysis of field walking results, and of topographic and monuments survey data, are carried out within this framework.

Pedestrian survey encompasses a variety of means for identifying, characterizing, and quantifying archaeological remains on the ground. Quite divergent traditions have emerged in different parts of

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the world. For example, in the Mediterranean—arguably the region that has witnessed the most experimentation with method (especially in Greece and Italy)—the canonical means of pedestrian survey, particularly in the contemporary agricultural landscape, is closely-spaced field walking within precisely defined areas to count or collect artifacts and record the full range of anthropogenic features. It has tended to be intensive in nature, covering areas of at most a few dozen sq km, as well as being fully diachronic in scope and comparative in outlook (Alcock and Cherry 2004). The Americas, by contrast, enjoyed a brief flirtation with survey sampling (Mueller 1975), but have generally moved on to a consensus, despite some strong regional variations in field procedures, that best practice involves so-called “full-coverage” survey: very large swaths of the landscape are examined in their entirety, but inevitably at far lower levels of intensity of field walking and recording than their Mediterranean counterparts. Whether because of ground visibility problems, or the requirements of contract archaeology, shovel test-pitting is also a regular addition to the suite of standard approaches in North America and parts of the Caribbean. Within this mix of survey practices, it could in general be said that the Americas remain strongly oriented to the site as a fundamental unit of analysis, while European and Mediterranean archaeologists have moved more clearly toward the landscape approach, with individual features or even artifacts as the basic element of analysis. A third methodology in survey practice has emerged in England and Scotland (and indeed much of temperate Europe), where topographic survey and the recording of upstanding monuments are key components of pedestrian survey, particularly for the study of pasture and upland landscapes, as well as other areas outside the plough zone. The Middle East likewise mixes methods, and has become notable for use of satellite data, including declassified archival scenes, notably CORONA, to guide prospection, particularly in Egypt, Iraq, and Turkey (Parcak 2007; Ur 2003). Archaeology in other parts of the world, such as Africa, Asia, and Australia, also often feature approaches to large-scale landscapes guided by remote sensing.

The Caribbean, the focus of the present article, does not fit comfortably within any of these generalized scenarios. Archaeology in this region developed slowly and relatively late, by comparison, although it has progressed remarkably in recent years (see, e.g., Keegan *et al.* 2013; Reid and Gilmore 2014). Multi-period, regional, or full-scale survey, as discussed above, can hardly be said to exist in the region as a standard and well-developed component of archaeological practice. Throughout the Caribbean,

there still exists a very strict division of academic interests and fieldwork activity on either side of the “Columbian divide,” and truly diachronic projects are virtually unknown. Surveys conducted by prehistorians generally involve prospecting for particular coastal locations thought to be suitable for Amerindian settlements, guided by the fact that previous surveys on other islands have reported a dominantly coastal site-distribution; while this may be so, it is obvious that this strategy is self-fulfilling and cannot serve as a test of where prehistoric sites do or do not exist throughout an island’s landscape. Conversely, most island-wide studies by historical archaeologists involve minimal field walking, and rather focus on locating and recording sites known from standing remains, historical maps and documents, or oral histories.

The discussion so far has been limited to survey of the ground surface by pedestrian techniques. In the wider sense of prospection for archaeological sites and features, however, it also embraces survey from space (satellite imagery), from lower altitude (aerial imagery), beneath the ground (geophysical survey), and on the sea-bed (underwater survey). It has been a notable feature of archaeology’s development in the past generation that there have been remarkable advances in the technologies for all these types of prospection, as well as their much wider deployment as a routine component of most archaeological projects. Survey has come to be a more hybrid technique. For example, there now exists a dizzying array of sensors mounted on space platforms, providing an ever-wider variety of archaeologically useful imagery, at ever-finer resolution and increasing affordability (Parcak 2009). Likewise, autonomous underwater vehicles have been revolutionizing maritime archaeology by moving the field beyond its focus on individual coastal shipwrecks in waters accessible to human divers, to the systematic and closely controlled survey of hundreds of square kilometers of the seabed at depths previously unreachable (Foley and Mindell 2002). With regard to aerial prospection for survey purposes, the two technologies that have had the most impact in recent years are airborne laser scanning (ALS) and drones; in fact, the two are converging, since there now exist drone-mounted light detection and ranging (LiDAR) systems with digital cameras, advanced computer processing, and GPS making it possible to create a remotely-piloted aerial LiDAR scanner.

This article, then, provides an example of the application of one of these newer technologies to landscape archaeology, in a region that has no strong tradition of survey. ALS was first employed in an archaeological context by UK researchers studying the landscape of Loughcrew in Ireland (Shell and Roughley 2004),

followed quickly by a LiDAR-based regional study in the Forest of Dean in England (Devereux *et al.* 2005). The emergence of archaeological LiDAR in this context implies an inheritance of the British tradition, best exemplified in the work of O. G. S. Crawford and J. K. St. Joseph, of integrated topographic surveys employing both aerial and field data. ALS's integration into archaeological prospection and landscape archaeology accelerated quickly, promoted by—among other means—work presented at the 2006 Aerial Archaeology Research Group (AARG) conference (Doneus *et al.* 2006; Opitz 2006), and it quickly gained traction within the core group of archaeologists engaged with aerial methods in both research and heritage management contexts. Those archaeologists working with ALS developed their practice within a community that emphasizes air-photo reading, interpretive mapping, landscape context, and mutually informed airborne and ground-based surveys.

Pedestrian survey has traditionally been informed by landscape remote-sensing data, and this contextualized approach to the reading of the landscape is integral to the character of this survey method. The fieldwork on Montserrat, discussed below, thus operates within these twin traditions, and it also shares similarities with the topographic and monuments survey traditions now practiced in the UK and Continental Europe. Technology facilitates this tighter integration between remotely sensed and pedestrian survey data, as the proliferation of tablets, hand-held computers, lightweight GIS programs, and increasingly affordable GPS devices allows archaeologists to bring the remotely sensed data into the field and work with both perspectives in tandem. GPS both facilitates the accurate recording of the locations and extent of individual features and aids the conduct of pedestrian surveys led by remotely-sensed data through enabling navigation in the field. We explore and exemplify these advantages in the following case-study.

Survey and Landscape Archaeology on Montserrat

Over the past 4000 years, natural disasters, environmental exploitation, and migrations have continuously transformed landscapes and social relations on the island of Montserrat in the Lesser Antilles (FIG. 1). Since 1995, Montserrat has been drastically transformed by volcanic eruptions, displacing two-thirds of the island's population and destroying or damaging most of its landscape in the south (Wadge *et al.* 2014). Archaeological research on the island prior to the start of volcanic activity was confined to just a handful of excavation-based projects, notably at the Saladoid-period settlement and manufacturing center of Trants (Watters 1994; Watters

and Petersen 1995; Petersen 1996; Watters and Scaglione 1994; Bartone and Crock 1993), and the historic-period Galways Plantation sugar mill and residences, among others (Goodwin 1982, 1987; Howson 1995; Pulsipher 1982; Pulsipher and Goodwin 1999, 2001). These and countless other archaeological sites and cultural landscape features in the Exclusion Zone have been destroyed or severely damaged by volcanic eruptions (Watters and Norton 2007). Several archaeological sites on the safe side of the Exclusion Zone boundary have also been impacted by heavy ash fall, earthquakes, and lahars (Cherry *et al.* 2012).

Since 2010, the Survey and Landscape Archaeology on Montserrat (SLAM) project has studied long-term landscape transformations on Montserrat by documenting historic, prehistoric, and multi-period archaeological sites and their environs across the island's safe zone. Influenced by scholars working on other islands in the Greater and Lesser Antilles (Callaghan 2007; Cooper and Sheets 2012; Curet 2005; Deagan 2004; Fitzpatrick and Keegan 2007; Hofman *et al.* 2007; Keegan *et al.* 2008), and with assistance from small field crews, SLAM has been examining the nature of the discursive relationships between communities and their environments on Montserrat throughout its human occupation. The project has now identified over 50 sites and over 300 landscape features, most of them unknown or long forgotten, and none previously well recorded (Ryzewski and Cherry 2013; Cherry *et al.* 2014; Cherry and Ryzewski 2014). These finds are generating new diachronic data essential for understandings of long-term settlement history, strategies for risk management, resource utilization, and consequences of migrations and colonization (both before and after the so-called "Columbian divide").

In 2013 the SLAM project team completed its comprehensive survey of archaeological resources in the mostly low-lying northern region of the island. This is a relatively arid part of the island characterized by poor soils, in many places now covered by a tangle of acacia scrub and manchineel forest. Such an environment makes quite impossible the type of systematic, intensive survey that is characteristic in many other areas of the world, where semi-arid, agricultural landscapes provide good conditions of surface visibility and accessibility. On Montserrat, a more extensive and opportunistic form of surface reconnaissance has been necessary, one that explores as carefully as possible all accessible open areas, trails, ridges, coastlines, and watercourses (known locally as *ghauts*), leaving aside areas of impenetrable dense vegetation and modern settlement.

The survey has now begun to extend into the Centre Hills, in the southern part of the research



Figure 1 Map of the Caribbean showing the location of Montserrat.

area and safe zone. Unlike the north of the island, which has been our main focus hitherto, the Centre Hills—a now-dormant volcanic complex—are comprised of steep slopes covered by dense neotropical mesic forest and (at the very highest altitudes) elfin woodland (Holliday 2009). At approximately 11.3 sq km, the area enjoys protection as a Forest Reserve mandated by the Government of Montserrat. Preliminary exploration of this region prior to 2014 indicated that our established methods of data acquisition through extensive and intensive pedestrian survey, mapping, and shovel-test excavations would be difficult and in most cases impossible to deploy in the Centre Hills where vegetation is dense, ground visibility is extremely low, and ash deposits are thick. Adding to these factors, prominent standing historic-period ruins are difficult to see even at close quarters. Historical research and archaeological evidence in the Montserrat National Trust collections nonetheless indicate that the Centre Hills comprised an area, over at least the past 2000 years, with extensive agricultural activity, water-management systems, fortified settlements, and, in more recent centuries, widespread jungle clearance for sugar production. Indeed, the most abundant archaeological remains in the Centre Hills are those of well-preserved, historic-period sugar estates, whose industrial-scale agricultural activities consumed the entire island between the late 17th and early 19th centuries (Ryzewski and Cherry 2015).

The challenges that the Centre Hills region poses to standard archaeological reconnaissance and data recovery forced us to think differently about our procedures.

With our research questions and field methodologies already well established, we realized that the recent LiDAR data commissioned by the Montserrat Volcano Observatory (MVO) could provide an invaluable research tool. An initial approach to the MVO resulted in the signing of a Memorandum of Understanding establishing a data-sharing agreement between SLAM and the MVO. As a result, we have recently begun to integrate airborne LiDAR data into our landscape approach, as a means of documenting archaeological land-use and settlement patterns within the Centre Hills region in a multi-scalar and time-efficient manner (FIG. 2). It needs to be emphasized that the project's essential questions and procedures were already well in place at the time we augmented them in 2014 by incorporating LiDAR data in order to be able to expand our survey work into areas less conducive to standard survey procedures.

In 2014, as part of an NSF-funded spatial archaeometry research collaboration (SPARC), the SLAM project began work with the Center for Advanced Spatial Technologies (CAST) at the University of Arkansas, in order to develop an iterative process for integrating airborne LiDAR and archaeological survey data on Montserrat. By integrating LiDAR visualizations into archaeological surveys of the Centre Hills region, we sought to identify the extent of modifications to the island's landscape that were caused by the colonial-period sugar industry. Such a large-scale understanding of the Centre Hills landscape is a necessary point of departure for understanding the spatial dynamics of historic sugar plantations and the scale on which they operated (Delle 2014). By implementing an iterative process

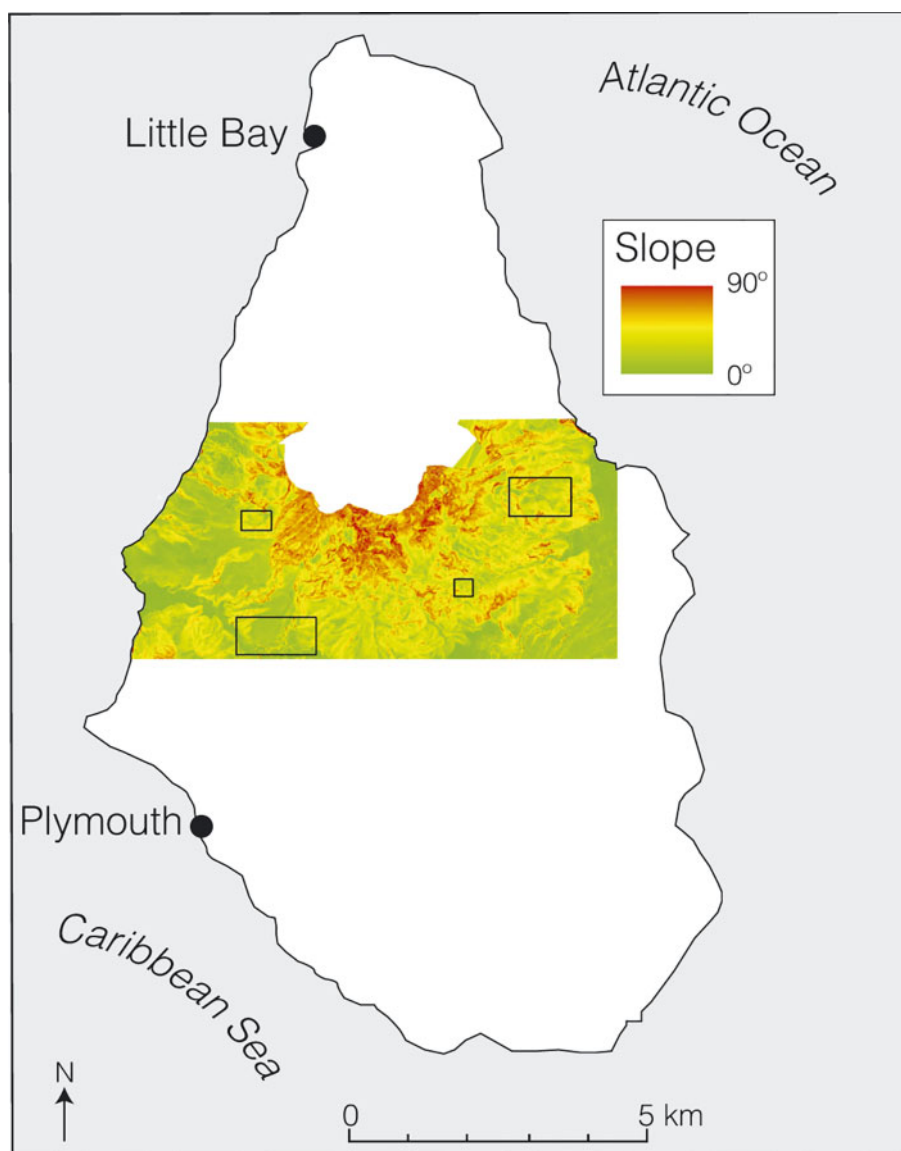


Figure 2 Map of Montserrat with an overlay of the LiDAR coverage for the Centre Hills region. Rectangular boxes encompass the four archaeological zones discussed in this study. Counter-clockwise from top left: The Cot (zone 1); Lower Waterworks Estate (zone 7); Bugby Hole Estate (zone 14); Locust Valley Estate (zone 12).

for working with LiDAR and pedestrian survey data, we also sought to address issues of access, intervisibility, and interpretation in rainforest environments that often challenge or elude archaeologists, both in the field and in processing LiDAR data. Using the MVO LiDAR data, this multi-step process has involved pre-fieldwork LiDAR analysis, survey and field assessment of the LiDAR data during the field season, in-field modifications of LiDAR visualizations, and post-fieldwork data classification at CAST based on earlier LiDAR and archaeological findings.

Initial inspection of the LiDAR imagery, prior to fieldwork, led to the identification of 15 zones of interest for potential analysis. Three of these, encompassing the sites of The Cot (zone 1), Locust Valley Estate (zone 12), and Lower Waterworks Estate (zone 7), were surveyed by SLAM and SPARC in 2014. Informed by the results from the field season's

finds at these three sites, LiDAR point cloud data were also reclassified, after fieldwork, to examine an additional zone in the now-inaccessible Exclusion Zone, the Bugby Hole Estate (zone 14). The following discussion details the process of integrating LiDAR with field survey as carried out in this project, with a focus on results from Locust Valley Estate, Lower Waterworks Estate, and Bugby Hole (FIG. 2).

The results from these three survey areas demonstrate the value of LiDAR integration to the processes of survey and landscape archaeological practices, as well as to historical archaeological research of the built environment in the Caribbean and elsewhere. This study emphasizes two aspects that we believe have been insufficiently evaluated in previous research projects of this kind. The first is the importance of iterative, real-time, reciprocal interchanges between the LiDAR analyst and the

archaeological team on the ground; such interaction allows the analyst to gain a close appreciation of how apparent features of interest in the LiDAR imagery relate to evidence on the ground, and field-work teams to be guided by more nuanced evaluations of the data. The second is the recognition of the importance of all information generated from LiDAR remote sensing data. Many previous archaeological applications have laid primary emphasis on “bare earth” digital elevation models, in some cases very effectively, but we aim to illustrate here that there are major advantages to be gained by making use of the entire point cloud generated from these remote sensing data (the term point cloud is explained more fully below).

Airborne LiDAR and Landscape Archaeology

Over the past decade, terrestrial and airborne LiDAR have become important archaeological survey techniques for gathering discrete, diachronic, and multidimensional information about cultural and natural land-use modifications (Opitz and Cowley 2013; Romero and Bray 2014). Airborne LiDAR (also referred to as ALS, or Airborne Laser Scanning) in particular offers the advantageous capability of surveying expansive regions, permitting visual access to ground surfaces under areas of thick vegetation, and producing three-dimensional point-cloud data that can be manipulated to examine the dimensions of particular topographic features or standing archaeological remains (Hesse 2013). In producing visualizations of man-made features of various sizes and construction materials across areas of considerable size, airborne LiDAR significantly expands the scope of practices and the scale of questions involved in studying archaeological landscapes (Chase *et al.* 2011; Mlekuž 2013; Pruffer and Thompson 2015; Risbøl 2013). To date, the majority of archaeological research projects involving airborne LiDAR have been undertaken in northern and western Europe (Opitz and Cowley 2013). However, the dramatic results of airborne LiDAR mapping at the Maya settlement of El Caracol in Belize and other Mesoamerican sites (Chase *et al.* 2011, 2014; Rosenswig *et al.* 2013), coupled with the increase in publicly-accessible USGS LiDAR data in the United States (Pluckhahn and Thompson 2012; Randall 2014), are certain to increase the pace of LiDAR integration internationally in the near future. This trend is already evident in the growing scope (Chase *et al.* 2014) and number of projects utilizing LiDAR in North, Central, and South America.

Based on a thorough review of the published literature, the integration of airborne LiDAR as part of the survey and mapping of Montserrat's

archaeological landscape is, to the best of our knowledge, the first application of airborne LiDAR for archaeological purposes anywhere in the Caribbean archipelago. Although the technique may be new to the region, the scope of regional analysis and the questions posed about the manipulation of landscapes in the Caribbean during the colonial period are not. Caribbean historical archaeologists have long been focused on mapping land-use patterns at regional and island-wide scales to understand relationships of control over social and economic spaces, as well as corresponding shifts in settlement patterns and social relations during and after the plantation era (Hauser 2009). On St. John, Armstrong and colleagues (2009: 96) have used Geographic Information Systems (GIS) to combine geospatial data with archival records and survey finds to identify two shifting land-use patterns across the island between 1780 and 1800. These shifts involved the consolidation of sugar estates in the island's north and the transition from industrial sugar production to provision agriculture in the smaller estates of the south. Through regional mapping, Armstrong charted the co-existence of enslaved and free Afro-Caribbean islanders and introduced new perspectives of colonial land-use by associating the changing spatial dimensions of parcels with increasing land ownership by free Afro-Caribbean islanders in the island's south before emancipation. Using similar island-wide geospatial and historical archaeological data, Delle has mapped the placement and expansion of plantation estates from the coastal to interior regions of Jamaica between the 17th and 19th centuries (1998, 2002, 2014). Delle contends that colonial planters' strict management of Jamaica's landscapes of sugar production facilitated their control over the surrounding environment and its inhabitants. Through his island-wide mapping project, Delle identified various mechanisms of control that Jamaican planters implemented to manage the wider landscape and local communities, including the strategic placement of buildings within plantation estates, lines of sight between estates, and inter-visibility between enslaved laborers' villages and estates (2002: 357).

Several studies exist from other geographic areas that productively inform our classifications and interpretations of the Montserrat point cloud data and archaeological landscape. Airborne LiDAR has achieved consistent success in detecting archaeological features under forest canopies in England, Norway, Belize, and the United States (Devereux *et al.* 2005; Risbøl 2013; Chase *et al.* 2011; Gallagher and Josephs 2008). Within the emerging studies of modern conflict archaeology, airborne LiDAR has been effective in detecting subtle traces of

earthworks, trenches, bomb craters, and weapons-testing areas dating to World War I in Belgium (Gheyle *et al.* 2013) and World War II in Germany (Hesse 2014). One of the earliest applications of airborne LiDAR to archaeology focused on the 18th-century plantation landscape of Maryland: the results of mapping at Tulip Hall and Wye Hall revealed traces of historical gardens, outbuildings, and pathways that conveyed a much more intricate landscape and dynamic built environment than previously detected by standard archaeological methods (Harmon *et al.* 2006). As in our own work on Montserrat, the combination of LiDAR analysis, pedestrian survey, and other archaeological data sources to locate previously unknown sites has been productive in the forests of southern New England (Johnson and Ouimet 2014), in the piedmont area surrounding the Mesoamerican site of Izapa in Chiapas, Mexico (Rosenswig *et al.* 2013), and in the investigation of archaic shell mounds on the St. John's River in Florida (Randall 2014). Recent adjustments to standard classification approaches in the Franche-Comte region of France have improved the ability to distinguish standing architecture from surrounding vegetation in LiDAR visualizations (Opitz and Nuninger 2014).

Finally, a number of airborne LiDAR surveys have been conducted in the Caribbean and elsewhere for non-archaeological purposes to monitor the effects of natural disasters, including lahars in Martinique (Clouard *et al.* 2013), landslide boundaries in Puerto Rico's National Rainforest Park (Wang *et al.* 2013), coastal erosion in San Diego and the effects of the Indonesian tsunami (Olsen *et al.* 2013); these studies in particular may offer useful data for future interpretations of the post-disaster archaeological landscape within Montserrat's Exclusion Zone. Terrestrial LiDAR was previously used on Montserrat to survey the active dome growth of the Soufrière Hills volcano and to monitor landslide activity as a predictive measure of future dome collapse (Jones 2006).

Working with Airborne LiDAR Data on Montserrat

On Montserrat, airborne LiDAR data, coupled with archaeological survey and archival research, demonstrates the extent to which similar land-use patterns existed on Jamaica, St. John, and other islands during the plantation era, but they also add an increased level of detail to understanding the island's socio-spatial landscape by revealing more subtle features of the landscape—e.g., terracing, trackways, water management systems, and building platforms—that are often invisible to the 'naked eye' in the Centre Hills environment.

Within challenging rainforest environments, like that of the Centre Hills of Montserrat, LiDAR offers the distinct advantage of efficiency in being able to target areas of interest, guiding pedestrian survey. In Montserrat's natural disaster setting, LiDAR data also serves as the only way to view archaeological remains in the inaccessible areas of the Exclusion Zone. Such access is not only important for our research interests in conducting a regional archaeological landscape survey, but also for informing cultural heritage preservation and management strategies across the island. The loss of archaeological resources in the Exclusion Zone has thus far been difficult to quantify, with the best estimate being that between 35 and 50 historic-period sites have been damaged or destroyed, as have all of the few previously-known prehistoric sites (Watters and Norton 2007; Miles and Munby 2006). As demonstrated by archaeologists working in other inaccessible or hazardous environments (Hesse 2014: 18), LiDAR data on Montserrat offer archaeologists an otherwise lost opportunity to evaluate systematically the remains in the Exclusion Zone that have survived the past 20 years of volcanic activity, and perhaps to identify previously unrecorded sites in the Exclusion Zone that it may now never be possible to investigate with pedestrian survey.

Airborne LiDAR offers promising prospects for increasing the speed, efficiency, and visibility of archaeological survey in the Caribbean and elsewhere, but there are challenges in integrating LiDAR with standard archaeological research that require critical awareness of the dataset's components, the filtering decisions that are applied during processing, visualization and interpretation, and the possible discrepancies between features visible in the LiDAR data and on the ground (Opitz and Cowley 2013).

While many of the challenges are those common to any data integration project, we highlight two key principles here. First, in order to combine these approaches to the landscape successfully, it is essential to accept that some features visible in the LiDAR are 'real' although not visible on the ground, and that some features apparent on the ground will not have a topographic expression in the LiDAR. Second, it is equally necessary to recognize the significant impact of classification routines which identify points as belonging to terrain, buildings, or vegetation. The effects and importance of different visualizations are broadly acknowledged in the archaeological LiDAR community, but the importance of classification is often overlooked. This is particularly pertinent in a historical archaeological context, where many of the expected features are standing structures rather than earthworks.

LiDAR Data and Methods

LiDAR Data

Discrete return, multi-echo airborne laser scanning (ALS) data were acquired by the Montserrat Volcano Observatory (MVO) in June 2010 and delivered in September 2010 for the purposes of monitoring volcanic risk on the island. The LiDAR survey was commissioned by MVO with funding from the UK Department for International Development (DFID) and was undertaken by Terrapoint Inc. on their behalf. These data were provided to SLAM by the MVO in March 2013, in the form of a Digital Terrain Model (DTM), a Digital Surface Model (DSM), and the original classified point clouds (.las files).

The metadata were not provided along with the data, but assessment indicates up to 7 returns per pulse, scan angles of 0–30 degrees, and 20% or better strip overlap. The .las files were tiled to facilitate loading and manipulation of the point cloud, while terrain model products were generated from the unified point cloud. We note that in the MVO reporting, the data are indicated as having a 1 m horizontal spacing and 15 cm vertical accuracy. However, assessment of the .las files reveals a nominal mean of 48 pts/sq m, and thus a DSM resolution of approximately 0.15 m. At typical ~20% vegetation canopy penetration rates, this equates to a nominal 10 pts/sq m, which can be interpolated over a 0.5 or 1 m grid.

Since the point cloud is central to the analyses that follow, some definition and explanation is required here. It is a collection of x,y,z values that represent spatial locations; in the case of ALS, these locations are the places where the laser pulse has encountered an object and the signal has been returned to the sensor. This collection of x,y,z values representing spatial locations may have other associated attribute values—for example, the return number, the classification, the GPS (global positioning system) time, the source flightline, the scan angle, and the intensity of the return. For archaeologists using LiDAR in their study of urban or rural landscapes, engaging with the point cloud data, rather than simply working with the derived terrain models, can be beneficial. In vegetated areas, and in particular where standing archaeological remains are present within the vegetated area, substantial classification errors are common. Working directly with the point cloud to separate standing remains and vegetation in mixed scenes is often the only means of reliably separating returns (points) from these two classes of objects. For projects such as SLAM that are targeting small and medium-scale standing architecture (e.g., a wall preserved to more than 1 m in height or a windmill tower with multiple discrete structural components), this means that working with the point cloud is

essential for reliable identification of the relevant archaeology. In areas of low, dense vegetation, moreover, engaging with the point cloud can lead to improved classification in areas with low earthworks, particularly those with sharp peaks or scarps. While working directly with the point cloud is essential for some applications, the visual inspection of the cloud through profile and 3D views is labor-intensive and requires a practiced eye, making it impractical over very large survey areas. The improvement of classification, segmentation, and interpolation algorithms for these conditions is a challenge to be met by archaeologists and their collaborators.

Methods of LiDAR Analysis

A series of basic visualizations, including a hillshade (a standard visualization based on projecting light from a single source across the terrain surface, with the light source located at an altitude of 35 degrees and an azimuth of 315 degrees), and a Sky View Factor (SVF) visualization (showing the portion of the sky visible from each raster cell), were generated using the DTMs provided by the MVO. A rapid visual assessment of these models at the locations of known archaeological features indicated that the classification carried out for the MVO had resulted in the removal of many archaeological features from the DTM, and that they were hidden by the canopy present in the DSM. This is unsurprising, as the classification parameters appropriate for modeling and visualizing relief and terrain features for geological, hydrological, or soil movement monitoring are rather different than those appropriate for detecting archaeological remains. Typical classification parameters used to generate DTMs for the former types of studies will identify more near-ground surface points as vegetation, resulting in a less detailed and smoother terrain model. For the purposes of identifying small-scale archaeological features, classification parameters resulting in a more detailed but noisier terrain model are preferred. Therefore, the original .las files were re-classified to create two new DTMs specifically for the purposes of archaeological analysis.

For the new DTMs, data in .las format were reclassified using Lastools, applying the “archaeology [deprecated] - fine” and “wilderness - fine” parameters. These parameter sets retain more points from the near surface band within the DTM, effectively including some noise in the terrain model in order to maintain the maximum number of terrain points and retain returns from near-surface structures, which might otherwise be removed through the filtering process. Notably, the archaeology parameter reintegrates points 20 cm above the general terrain surface, resulting in a DTM that is more

likely to contain traces of standing remains and earthwork features with small-scale ridges and peaks, which might otherwise be classified as low vegetation and removed from the set of points used to generate the DTM. The reclassified data were interpolated over a 0.5 m grid, using class 2 (terrain) points only to create DTMs for visualization generation.

Visualizations including hillshades calculated from the standard 315 azimuth, 35 degree altitude, SVF models, degree slope models, and elevation ramps were generated from the new DTMs. Two visualizations were used in parallel for the initial visual interpretation of the DTM: an elevation ramp with 70% transparency overlaid on the SVF model, and the slope model. On the basis of these visualizations, likely archaeological features were identified and marked. The features were then grouped into 15 zones spread across the study area, taking in a variety of geomorphological and ground cover conditions. Features identified included those at known archaeological sites, as well as a number in areas not yet explored by SLAM.

A booklet of maps showing the visualizations of each zone, with initial interpretations marked as vectors, was made available to the SLAM project in pdf and GIS formats. GPS coordinates along likely archaeological features were extracted to facilitate fieldwork planned for summer of 2014. Basic training in reading the LiDAR visualizations was provided to the SLAM project leaders and its GIS specialist, who in turn provided training to other members of the project team.

Process and Findings

Pre-Fieldwork Assessment

The initial assessment of the LiDAR data resulted in the identification of terraces, roads and paths, field boundaries, platforms, and a variety of undefined but probably anthropogenic features. In general, these features clustered together, creating defined zones of concentrations of anthropogenic remains, although in most cases the precise character and type of remains cannot be reliably identified from the LiDAR alone. The value of the initial assessment, therefore, was in providing a map of areas where fieldwork would be most profitable, and indications of the general type of remains to be expected.

It should be noted that the terrain models produced are visually quite noisy, as the parameters were set to include near-surface returns in order to capture indications of standing remains. At the pre-fieldwork stage no efforts at manual reclassification to produce a visually cleaner model or detailed characterization were made. Rather, these steps were planned for after the initial fieldwork.

Field Assessment

The summer 2014 fieldwork was intentionally brief and was conducted in three rather different zones, for the purpose of generating feedback for improving subsequent LiDAR classifications and visualizations. Guided by GPS data extracted from LiDAR zone maps, the SLAM survey team tested the practicalities of field assessment of the SPARC-analyzed data in three contrasting areas of the Centre Hills, two containing sites already known to the project (Locust Valley and The Cot), the third previously unexplored (Lower Waterworks) (Moloney *et al.* 2014). We found that GPS and the georeferenced LiDAR maps were able to guide us with great accuracy to features of interest, some so ephemeral as surely to have been missed by standard survey procedures. Nevertheless, the process of conducting LiDAR-informed survey differed considerably from the established extensive-tract survey strategy implemented by the field team during previous seasons (Cherry *et al.* 2012). In order to locate GPS points collected from the LiDAR, the field team engaged with the landscape in ways that more conventional survey methodologies would not, cutting through dense undergrowth, scaling steep ash-covered slopes, and relying more upon pathways dictated by GPS points of interest than those informed by terrain and surrounding conditions.

The field assessment and analytical process began with an examination of the LiDAR imagery. After confirming and adding points of interest to the LiDAR data in GIS, new point layers of waypoints were created in ArcGIS 10 to be located and checked on the ground during pedestrian survey. These waypoints included trail marks and potential archaeological landscape features identified during the initial LiDAR analysis and by project archaeologists prior to conducting survey. In selecting points of interest, the SLAM team paid particular attention to regular geometric and linear features that they thought might be roofless stone foundations, windmill-tower bases, terraces, stone walls, trackways, historic roads, and water-management features. The points of interest were re-plotted onto the LiDAR imagery in ArcGIS, and each point was assigned a number roughly in the order that they were expected to be approached on the ground. The predicted points were then transferred to the GPS (Garmin GPSmap 62stc) and loaded into the Garmin Basecamp software, so that they could be easily accessed, grouped, and renamed in the field. The point data for each zone were saved as both a GPX file and as a shapefile layer in ArcGIS.

During the surveys of each zone, the GPS guided the team to the location of predicted points of interest. Upon arriving at each such point, the team

verified the GPS' location by referencing printed copies of the LiDAR visualizations and the 1983 topographic map of Montserrat (edition 6 of the British Ordnance Survey 1962 "Tourist Map of Montserrat"). Additional GPS points were collected wherever a feature was observed, regardless of whether the feature was visible in the LiDAR predictions. New points were named in a way to differentiate them from the predicted waypoints. Whenever the team checked a predicted point or recorded new point data they also collected photographs, measurements of features, directional information for each point, notes on the material of features, the natural environmental conditions of the area (terrain, ground cover, vegetation, ash), and on visibility. This information was later entered into the attribute tables for the zone predictions and pedestrian survey data shapefiles.

After ground survey, the collected points were imported into the Garmin Basecamp software and grouped by zone. The grouping was imported as a GPX file into ArcMap. Shapefiles for each feature type were created so they could be layered over the GPS points and LiDAR imagery. In creating archaeological maps for each site, the shapes and dimensions of buildings, walls, and other features were corrected based on on-the-ground measurements of features. The GPS was not capable of sub-meter measurements, and thus manual correction of the feature dimensions was necessary for understanding the layout of each site.

In total, the 2014 LiDAR pedestrian survey covered an area of approximately 1.64 sq km. The archaeological team identified and recorded 33 landscape features from the LiDAR during pedestrian survey, ranging from prominent stone-built windmill towers to nearly invisible terracing, trackways and other earthworks. Both within and outside the Exclusion Zone, thick deposits of ash often cover archaeological features that were visible on the surface prior to 1995. In certain instances during the Locust Valley and Waterworks Estates surveys, LiDAR imagery seemed to detect shallow features such as stone boundary walls or historic trackways that were not visible on the surface due to ash cover. In other cases, large features detected in the LiDAR imagery turned out to be sizeable boulders that had travelled downhill during volcanic activities or expansive pig-wallows created by the feral pig population that has taken refuge in the Centre Hills in recent years. This iterative process of feature identification and correction of the interpretation following fieldwork is a normal and necessary part of integrating LiDAR and field surveys, particularly in the first investigations of a region's archaeology using these techniques in conjunction.

Results

The initial 2014 field assessment survey at Lower Waterworks Estate (zone 7) and Locust Valley Estate (zone 12) was quite successful and revealed a number of landscape and architectural features essential to the interpretation of these important and endangered archaeological sites.

Lower Waterworks Estate

The ruins and heavily modified landscape designated as Lower Waterworks Estate by the survey team are associated with the wider Waterworks Plantation complex, one of Montserrat's largest and oldest sugar and cotton estates. Waterworks dates to the late 17th century and, as its name implies, the industrial operations on the plantation were, unusually, powered by an extensive water management system that extends high up into the adjacent Centre Hills. The primary concentration of historical remains at Waterworks exists outside of the zone 7 survey area and consists of the original plantation manor house, manager's house, industrial buildings, and enslaved laborers' village. This portion of the plantation, which is still partially inhabited, is already well known and had been previously examined by SLAM. Prior to the analysis of the LiDAR data, however, no structural remains associated with Waterworks were known to exist beyond this central part of the estate.

The area of Lower Waterworks Estate is situated on the lower flanks of the Centre Hills between the Belham and Sappit Rivers downslope from the core industrial and residential area of the historic plantation. The landscape is heavily wooded with young trees and a thick forest canopy. Although the young trees afforded good visibility in some upslope areas of the survey zone (~20–30 m), the majority of the landscape is covered by interlocking low scrub trees and thorny acacia bushes, which severely obstruct visibility and hinder movement. Visibility in these conditions is often less than 2 m. Dense leaf litter and thick ash deposits totally obscure the area's ground surface. Lower Waterworks and the adjacent Belham River Valley have been subjected to heavy impact from ash-fall and pyroclastic flows over the past two decades of volcanic activity. Ash cover in the Lower Waterworks area was much heavier than at the other sites (over 1.5 m deep in places), covering one-course stone features (terrace walls, shallow foundations, etc.) of the kind that were visible on the ground at Locust Valley and The Cot.

LiDAR-based field assessment of Lower Waterworks resulted in the mapping of a hollow-way (a sunken historic track), stone walls, an outbuilding and the unexpected discovery of a previously unknown windmill, all located across the

Sappit River, downslope and to the east of the large mill complex. The team detected the hollow-way on the LiDAR imagery, and it was this feature that eventually led the survey team to the windmill. Near the Sappit River, the hollow-way was wide and flat and seems to be used as a modern trail. After crossing a second ghaut, however, the track seemed to disappear beneath heavy leaf litter and ash cover. Closer to the mill, the hollow-way became visible again as a raised roadbed defined by a large ridge of stone rubble on the downslope side with a sunken track on the upslope side. The visibility of this portion of the hollow-way was surprisingly good, given the area's dense ash and forest coverage. It led to what proved to be an 8-m tall stone windmill tower of probable 18th-century date, previously entirely unknown. Initially, the pre-fieldwork LiDAR imagery revealed this feature as a very faint, circular trace; but subsequent post-fieldwork manipulation of the three-dimensional point cloud data provided a dramatic cross-section of the tower, whose dimensions can be accurately measured (FIG. 3).

The survey team also located the remains of an outbuilding associated with this windmill tower, but was unable to access the area downslope due to the dense, tangled understory of thorny acacia trees. Ironically, the regrowth of secondary rainforest in the Lower Waterworks zone has likely preserved

entire archaeological landscapes more effectively here than in other parts of the island that have been impacted by agriculture and modern habitation. In total, survey guided by LiDAR located seven historic-period archaeological features in the accessible areas of Lower Waterworks: one water-management feature, two structural ruins, and four other landscape features (boundary walls and the hollow-way).

Locust Valley Estate

The ruins and heavily modified landscape of the Locust Valley sugar plantation date to the later 18th century, although little is known about the history of this archaeological site. Located in the upper elevations of the Centre Hills, on the boundary of the 2014 Exclusion Zone, the estate's landscape is heavily wooded with mature trees and the ground surface is entirely covered by leaves. Visibility among the trees was moderately good, generally 15 to 20 m, but all above-ground features have been covered by ash deposits (up to 1 m thick), due to the site's proximity to the active Soufrière Hills volcano. During previous exploratory visits to Locust Valley the SLAM team located an industrial and residential core in the uphill area of the site, consisting of a windmill tower base (preserved to a height of about 10 m, with the date 1773 or 1778 carved on the keystone of its main entry arch), well-preserved

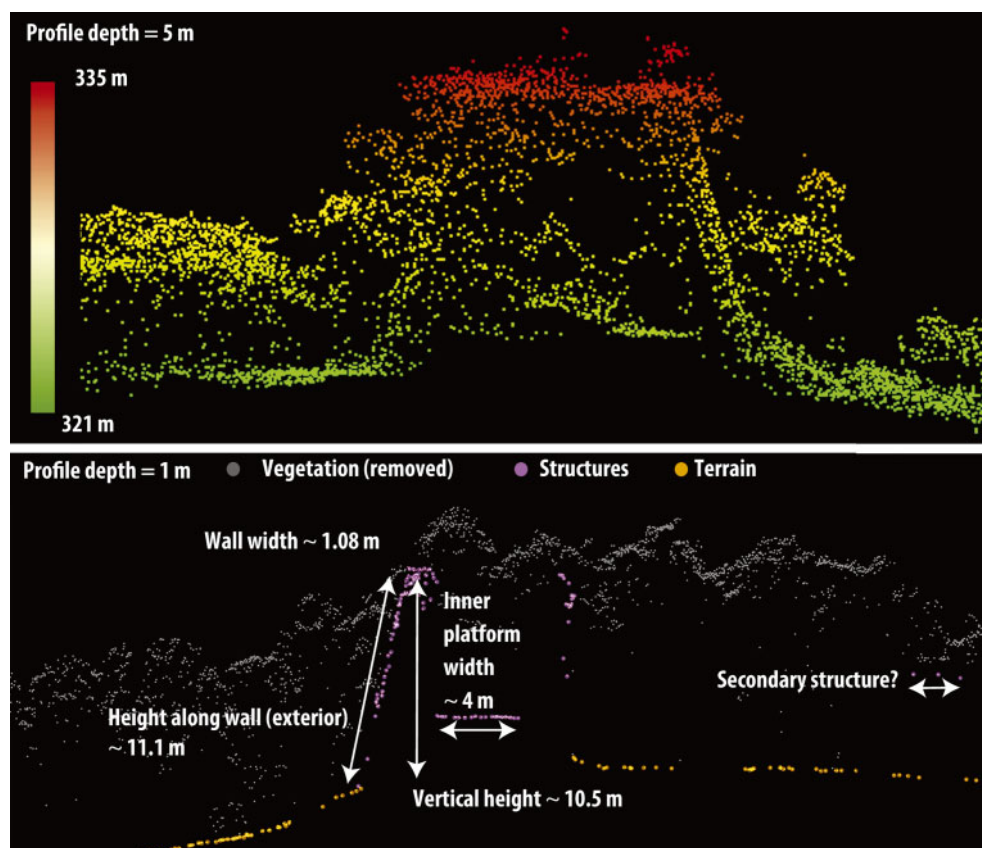


Figure 3 (Top) 5m point cloud profile showing the windmill tower base at Lower Waterworks Estate, colored by elevation. (Bottom) 1m point cloud profile with annotations for the dimensions of key structural elements.

structural remains, water-management features, and trackways. LiDAR imagery, assisted in identifying numerous previously unknown features, thereby increasing the known extent of the estate threefold (FIG. 4).

Guided by the LiDAR imagery, archaeologists located a secondary industrial complex with a second windmill tower and associated industrial buildings, agricultural fields, trackways leading between different areas of the estate, boundary walls, and potential house platforms, suggesting the location of laborer settlements. A number of earthwork features were visible in the LiDAR scene that would have been otherwise difficult to identify during conventional pedestrian survey. One of the most notable previously unrecognized features was an extensive sunken and now-buried hollow-way, 4.55 m wide, connecting the primary uphill industrial area of the estate with the secondary mill complex downhill. Other features clearly visible in the imagery, on the other hand, were not readily apparent during pedestrian survey, due to ash and vegetation coverage. These included the faint physical traces of an extensive terracing system along the steep slopes of the estate (FIG. 5).

In all, the field team located 18 archaeological landscape features from the LiDAR imagery during pedestrian surveys of the Locust Valley Estate: two

man-made ponds, 11 structural remains, and five other archaeological landscape features (boundary walls, hollow-way, trackways, terracing). Of the 120 GPS points marking potential features in the LiDAR imagery, 17 were not visible on the surface of the landscape, 45 were associated with modern features such as trails or modern structures, and 12 points turned out to be naturally-occurring features (e.g., pig wallows, large boulders). Additionally, 18 points were unchecked due to challenging conditions on the ground.

Post-Fieldwork Revisions and Extensions of the LiDAR Analysis

Further analysis following the summer 2014 fieldwork focused on providing more detailed information on the standing remains, especially those concentrated at the Locust Valley Estate and Bugby Hole Estate (zone 14). The information from the 18 archaeological features of various types that were located in the pre-fieldwork LiDAR assessment and confirmed by field survey was used to reclassify collected data from Locust Valley and to develop new classifications for visualizing the Bugby Hole Estate (zone 14) immediately south of Locust Valley.

Two approaches are practical for the task of identifying standing remains. The point cloud can be inspected visually and standing remains reclassified

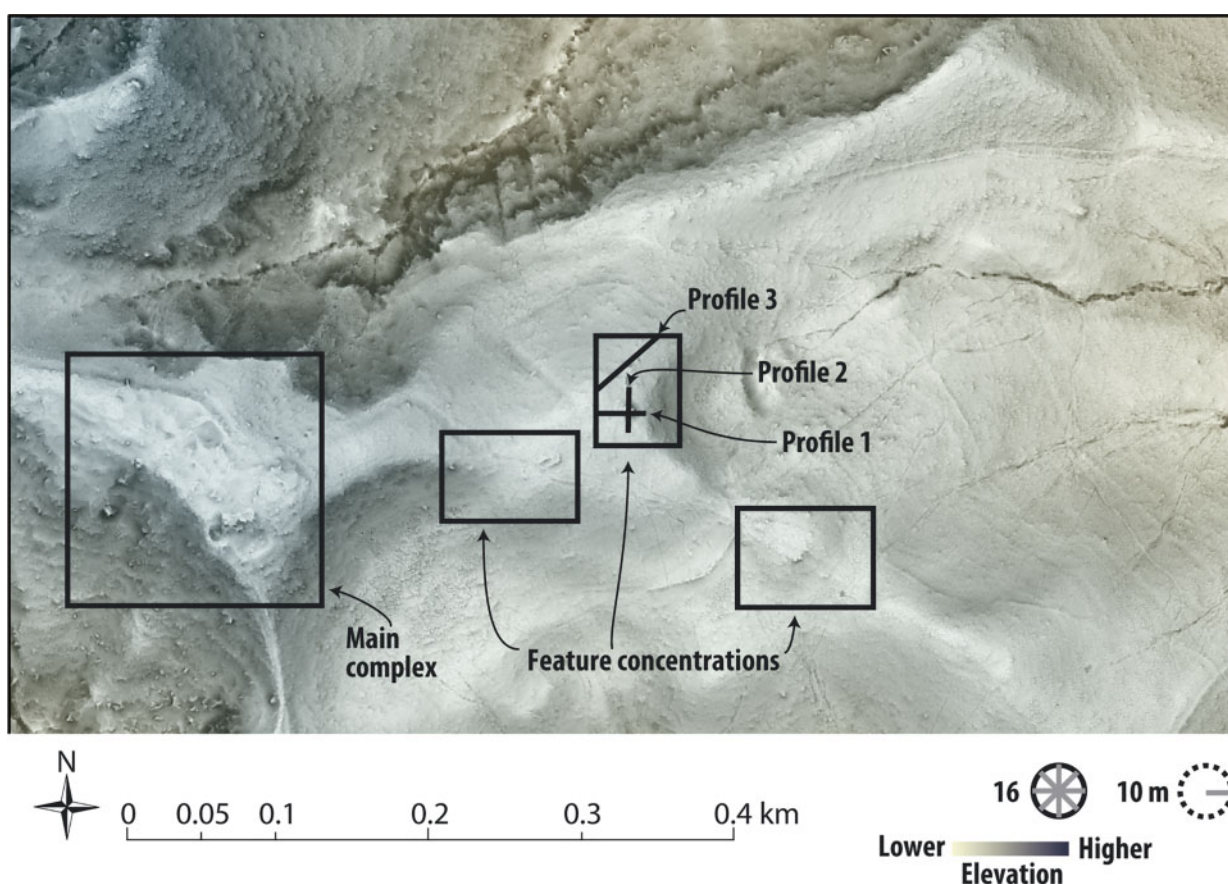


Figure 4 Locust Valley Estate landscape, with profile locations indicated.

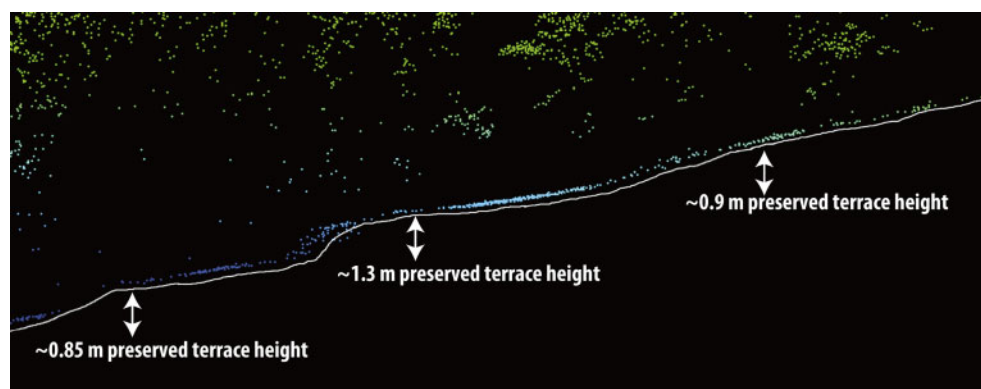


Figure 5 Terrace system along the slope of the upper processing complex at the Locust Valley Estate (Profile 3, FIG. 4).

in profile view, and subsequently measured and planned; or further automatic classification of the point cloud can be applied using algorithms developed to separate standing vegetation from walls, followed by the measuring and planning exercise. The automated classification of small sample areas demonstrated that it was not possible reliably to separate standing remains and fallen tree trunks through the currently available classifiers, since their morphology in the point cloud is quite similar. As these sites are dense with fallen or leaning trees (or were at the time of LiDAR data acquisition), a manual approach was taken. Starting at the locations of the features identified in the field or through the initial assessment of the terrain models, the point cloud was inspected through a series of profile slices and volumes. Returns identified as likely belonging to structures were reclassified while viewing the point cloud in profile slices; these points were classified as class 6 (building) based on the visual assessment of the point cloud, and the aggregate result of the reclassification was subsequently viewed as a cloud in making further interpretations about the character and preservation of the remains.

This interpretive exercise included taking a series of measurements directly on the point cloud, documenting the standing height and width of walls, and the dimensions of terraces, platforms, and other planimetric features. Rather than simply noting the presence of archaeological features, the aim was to produce an interpretive plan of the feature (or collection of features) based solely or primarily on the LiDAR data. Carrying out this task raises a set of methodological points. There are no extant conventions well suited for characterizing what is interpreted in a 3D point cloud that would serve as the parallel to hachure plans for an earthworks survey. It is possible to annotate on profile and plan views of the point cloud those groups of points that seem to form a structure, by coloring them differently, or to indicate preserved dimensions by adding CAD-style arrows and measurements; but

in practice movement of the point cloud is often needed to discern standing structures, and the combination of animated movements and CAD-style conventions is not entirely satisfactory. The strong dependence on the LiDAR point cloud to plan and interpret remains from sites in the Exclusion Zone, such as Bugby Hole, has highlighted the need for improved means of communicating interpretations based on visual assessment of point cloud data.

At the Locust Valley Estate, point cloud measurements were used to identify the dimensions of subtle and poorly visible landscape features, including the sunken hollow-way and the terracing system (see FIG. 5 above). Re-classifications of data collected from the lower complex's windmill tower base during survey was also used to demonstrate the capability of LiDAR to examine buildings accurately in three dimensions (FIGS. 6 a, b).

The classifications from the Locust Valley features informed interpretation of the nearby landscape of Bugby Hole Estate, a productive 18th-century sugar plantation situated on relatively flat terrain within the upper drainage of the Farm River. This represents a significant extension of the project's LiDAR research, because Bugby Hole is a place that, by virtue of its extremely dangerous position within the Exclusion Zone, is now — and will probably remain — totally inaccessible. Although located only 2.5 km north of the Soufrière Hills volcano, the estate was seemingly unaffected by direct volcanic impacts until the most recent major eruption and dome collapse in February 2010. During this event, pyroclastic flows surged at a speed of 50 m/second over the adjacent hills and into the Bugby Hole area, causing significant damage to the local geomorphology, by stripping vegetation and soil, and uprooting or shearing trees as large as 1.8 m in diameter (Stinton *et al.* 2014: 147–148; Wadge *et al.* 2014). But, remarkably, LiDAR imagery indicates that the stone-built ruins of this estate have survived fairly intact (FIG. 7).

In addition to the clearly visible compact complex of industrial sugar-plantation buildings, post-

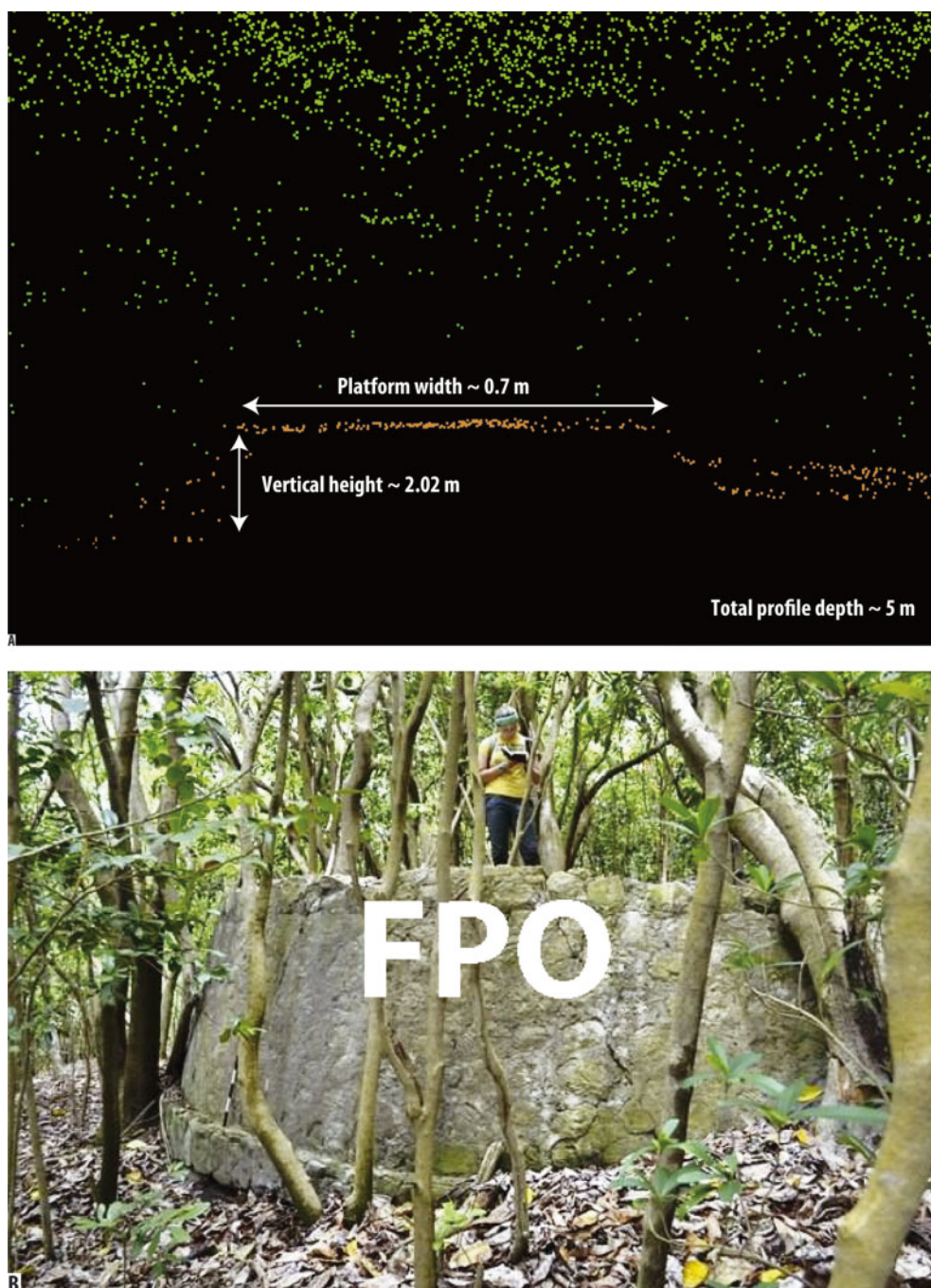


Figure 6 Post-fieldwork visualization of the point cloud data for the windmill-tower base in the lower processing complex of Locust Valley (6a), with a photograph of the feature during pedestrian survey (6b) (Profile 2, FIG. 4).

fieldwork LiDAR classifications revealed the existence of a building platform and the height of surviving structures at the site (FIGS. 8, 9). A visual inspection of the LiDAR point cloud in areas where anthropogenic features are visible in the DTM revealed standing remains, like that shown in FIG. 8, preserved to heights of more than 2m.

The identification of standing remains in medium-resolution ALS data, particularly in mixed scenes with dense, low vegetation, is always challenging, and the need for confidence in the interpretation of the point cloud is particularly important when it is not possible to visit the site on the ground. In the case of Bugby Hole, standing remains were identified

by a characteristic linear vertical distribution of returns over a planimetric (i.e., along the ground) distance of more than 2 m. In some cases, as in Figure 8, this is combined with a characteristic gap in the returns from the terrain, running parallel to the vertically distributed points, where a wall located at the edge of a swath (e.g. scan angles >20 degrees) blocks or distorts the location of returns.

The identification of multiple standing structures in areas of leveled terrain, and associated earthworks such as the raised and levelled platform seen in Figure 9 allow for a more detailed interpretation of the functioning of the site. The platform shown in Figure 9, of a size appropriate to have supported a

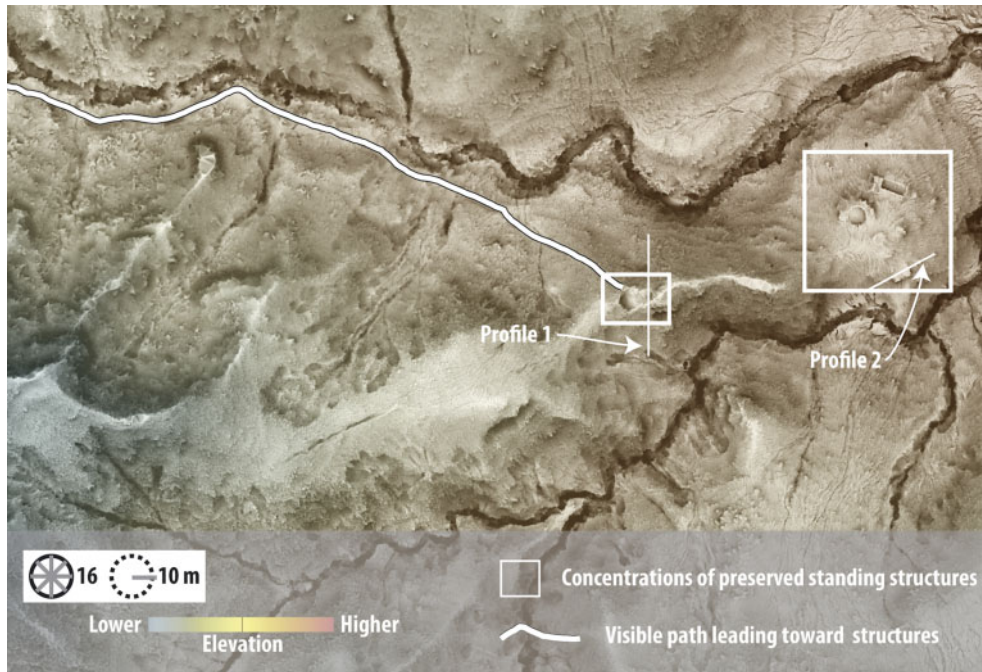


Figure 7 Bare-earth imagery of structures and access route at the Bugby Hole Estate in zone 14.

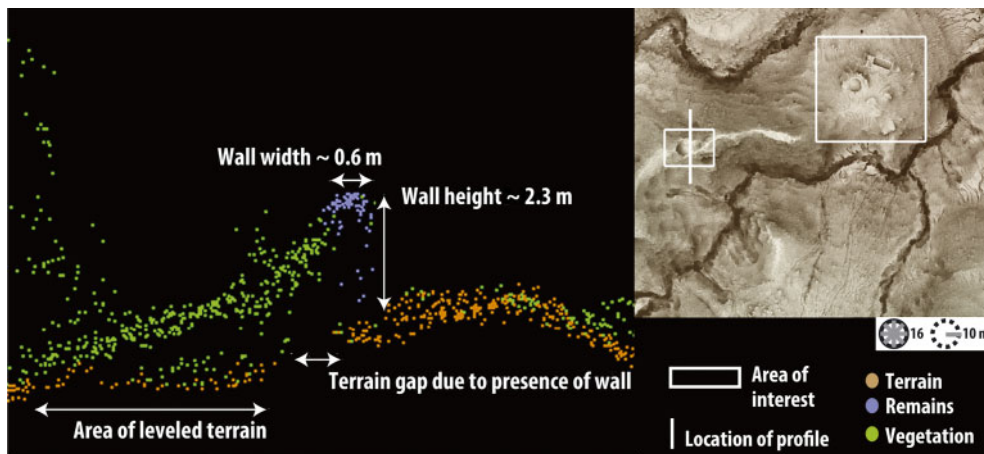


Figure 8 Profile of a wall at Bugby Hole Estate. Profile depth = 1 m (Profile 1, FIG. 7).

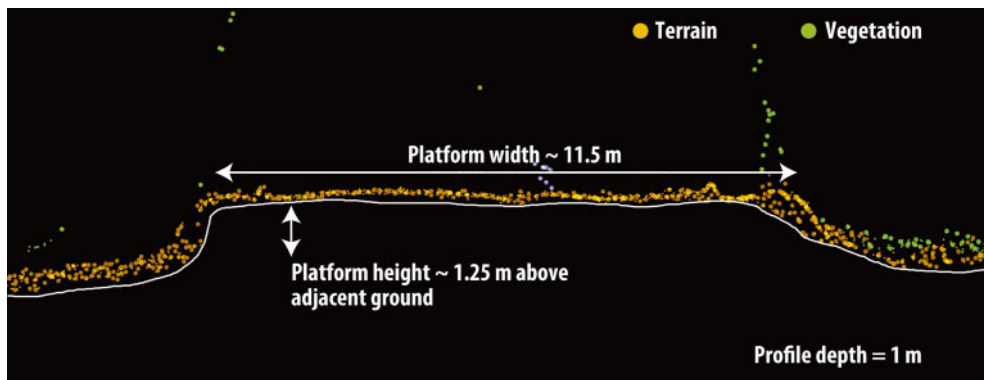


Figure 9 Platform base at Bugby Hole Estate (Profile 2, FIG. 7).

small structure, may also be the location of poorly preserved standing remains. These remains are represented as a concentration of points (purple - class 6) in the center of the platform.

Detailed assessments of standing remains' preserved dimensions, morphology, alignments and likely archaeological character is an intensive activity, requiring an experienced eye. In most

ALS-based prospection projects, the strategy at multi-element sites is to identify the dominant, and readily identified, earthwork features in the ALS and to undertake detailed planning of any standing remains in the field. As noted above, in truly inaccessible areas such as the Exclusion Zone of Montserrat, the need to carry out planning and interpretation solely through the airborne LiDAR data means that traditional visualizations of the terrain models are not sufficient and the point cloud data itself must be engaged with during the interpretation process, leading to a series of challenges in characterization.

Our results demonstrate the extent to which LiDAR data can contribute to archaeological landscape studies and regional analyses of totally inaccessible areas (cf. Hesse 2014). Naturally, the successful use of LiDAR to identify and interpret archaeological remains in areas not available for on-the-ground inspection remains dependent on a strong understanding of the region's archaeology and environment, including common feature types, geology, and vegetation patterns. The results at Bugby Hole, in the context of the broader SLAM project, show how the combination of LiDAR and field survey in yet broader areas can support the study of large-scale regional patterns without extensive pedestrian survey, opening the door to significantly more efficient surveys of large and challenging landscapes.

Conclusions

It is clear that LiDAR can be effectively integrated into the survey and landscape archaeological research program on Montserrat by contributing significantly to locating archaeological features, both minor (fragments of field walls and structures) and major (a previously unknown 8-m tall standing windmill tower), with an efficiency and range of interpretive possibilities quite impossible with standard survey techniques in the dense neotropical forest environment (see Shott 2014). We know from historic maps of the island that early planters conducted large-scale forest clearance and established estates at quite high altitudes. Indeed the Centre Hills LiDAR visualizations reveal a landscape that appears to bear many subtle traces of human modification. Ironically, it is the regrowth of secondary forest since the demise of sugar plantations in the late 18th and early 19th centuries (and lately heavy volcanic ashfalls) that have served to preserve and protect such remains. The conditions on Montserrat make critical the full use of LiDAR as a complementary source of information, guide for survey, and component of landscape archaeology data. The challenging vegetation cover on Montserrat, as well as its volcanic Exclusion Zone, mean that visits to many of

the archaeological features identified by LiDAR are difficult, if not impossible. Consequently, as an ongoing priority of the SLAM project we are making every effort to maximize the information gained from LiDAR data.

During the SLAM project's fieldwork (as is typical elsewhere), it has become clear that some features evident in the LiDAR terrain model are not recognizable in the field. Subtle changes in relief—typically a few centimeters of elevation difference over a large area—are not always apparent when viewed in a cluttered visual field, such as that created by the presence of neotropical forest vegetation. The acceptance of surface features not visible to the naked eye requires an intellectual leap of faith on the part of the archaeologists carrying out the survey, much as excavators sometimes need to rely on the reality of “ghost” features apparent in geophysical surveys, but invisible during excavation. Incorporating features visible (a) only in the LiDAR, (b) only in the field walking, and (c) in both within the archaeological picture of each area of the landscape not only provides a more complete understanding of the character of the remains themselves, but can inform on site formation processes at work after the active life of the features in question. Features more deeply buried or completely collapsed (in the case of structural remains) will typically be less visible during fieldwork assessments.

In the context of the present study on Montserrat, the overwhelming likelihood is that the majority of landscape features belong to the historic era and were stone-built. Thus, the absence of stone at a feature in the field could indicate some type of more unusual earthwork, while the irregular presence of small amounts of stone might indicate post-abandonment soil or ash accumulation, leading in turn to the expectation that other features farther downslope might be equally hidden or that stones were removed for use elsewhere. This point may be obvious enough, but we mention it here because it is representative of the observational process carried out in reading and interpreting the evidence presented by the combination of a desktop and in-field visual assessment of the LiDAR, and the features identified in the landscape itself. This close reading practice allows us to extract more comprehensive information from the LiDAR data than simply documenting the presence of an individual feature and its likely function.

The archaeology of Montserrat is unusual because it requires a different approach than that used for regions where earthworks and buried features are most common. While working solely with the terrain model is generally accepted as sufficient for identifying and interpreting earthworks and buried features using LiDAR-based DTMs, the standing stone-built

remains require us to engage directly with the point cloud in making identifications and interpretations. The situation is further exacerbated by a land-cover situation that likewise requires special treatment. The frequent presence of large boulders and fallen trees, often partially supported by neighboring vegetation, creates a circumstance in which there are many non-archaeological features that are similar in morphology (as captured in the LiDAR point cloud) to the archaeological features of interest. Moreover, all the zones surveyed in 2014 have ground surfaces covered with ash deposits. At Locust Valley, the young forest growth and relatively good visibility conditions may have permitted LiDAR to detect features buried by ash, yet invisible to the naked eye; conversely, at Lower Waterworks the combination of dense scrub vegetation and deep ash deposits may have obscured many archaeological features from both the LiDAR analysis and survey archaeologists on the ground. The extent to which Montserrat's ash deposits interfere with LiDAR classifications will be further explored in an upcoming field season.

It is worth considering, finally, how utterly unimaginable the type of research reported here would have been at the time of *JFA*'s launch 40 years ago. This is not merely because the archaeological application of airborne laser scanning is a development of the past dozen years or so (*JFA* has begun to publish papers with "LiDAR" in their titles only in the last several years), but also because of all the other technological advances that make its integration into a field project possible. In 1974, the internet and email did not yet exist; the in-field use of personal computers was still a decade away; neither handheld GPS appliances nor Geographical Information Systems had yet been invented; devices allowing the storage and computational analysis of big data measured in terabytes were merely a dream. To reflect on the impact of so much progress in technology on archaeological practice, both in the field and in the lab, is also to realize that it is next to impossible to predict the shape of field archaeology 40 years from now. But it can be safely predicted that technological progress will continue apace, and archaeologists should expect in the future to be blindsided from unexpected quarters. Even a chapter on the future of regional survey written only a dozen years ago (Cherry 2003) now seems dated. What seems important to emphasize, and what this article has tried to exemplify, is that archaeologists should use emergent technologies not simply because they exist and are available (and often impressive), but as additions to an increasingly sophisticated toolkit that can make field archaeology more effective and powerful and can contribute meaningfully to the

solution of archaeological research questions—in our case, the identification of historic-era sites and modified landscapes in the challenging setting of neotropical forest impacted by volcanic disaster.

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