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High-resolution LiDAR and photogrammetric survey of the Fumanya dinosaur tracksites (Catalonia): implications for the conservation and interpretation of geological heritage sites

KARL T. BATES[1,2], FRANK RARITY[2], PHILLIP L. MANNING[2,3], DAVID HODGETTS[2], BERNAT VILA[4,5], ORIOL OMS[6], ÀNGEL GALOBART[4] & ROBERT L. GAWTHORPE[2]

[1]*Adaptive Organismal Biology Research Group, Faculty of Life Sciences, University of Manchester, Jackson's Mill, PO Box 88, Sackville Street, Manchester M60 1QD, UK (e-mail: karl.bates@postgrad.manchester.ac.uk)*

[2]*School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL, UK*

[3]*The Manchester Museum, University of Manchester, Oxford Road, Manchester M13 9PL, UK*

[4]*Institut de Paleontologia 'M. Crusafont', Carrer Escola Industrial, 23, 08201, Sabadell, Barcelona, Spain*

[5]*Former address: Consorci Ruta Minera, Carretera de Ribes, 20, 08698, Cercs, Barcelona, Spain*

[6]*Department de Geologia, Facultat de Ciencies, Universitat Autonoma de Barcelona, 08193, Bellaterra, Spain*

Abstract: Increasing political and social awareness of the importance of protecting the geological heritage is compelling geoscientists to consider new methods for reconciling conservation and exploration of their research sites. Terrestrial Light Detection And Range (LiDAR) imaging is an accurate method of collecting 3D spatial data that has so far been under-utilized in the geological sciences. This aim of this paper is to assess the value of integrated LiDAR and photogrammetric imaging as a tool for synchronizing scientific exploration with conservation of geological heritage sites.

Fumanya (Catalonia) is one of the most important Cretaceous tracksites in Europe, but the nature of exposure of the track-bearing surface has hindered quantitative documentation of the ichnites. Using integrated Light Detection And Range (LiDAR) imaging and photogrammetry it has been possible to construct high-resolution Digital Outcrop Models (DOM) of the tracksites. Photo-textured DOMs are a powerful visualization tool and function as fully 3D interactive databases that preserve information about the site that would otherwise be lost to erosion. LiDAR-derived DOMs have the potential to contribute profoundly to future geoconservation projects, particularly as a tool for documenting and monitoring heritage sites and promoting education and tourism. LiDAR scanning also provides sufficient resolution to perform robust quantitative analysis of dinosaur tracks.

The long-term conservation of high-quality geological heritage sites has been a problematic issue for decades (Gillette 1986; Agnew *et al*. 1989; Oms *et al*. 2002), and in recent years there has been collective effort to preserve elements of the Earth's geological history. This growing emphasis on geoconservation is reflected in the policies of national and international geological heritage organizations (e.g. UNESCO World Heritage, ProGEO, GEOSEE, GEOSITES, GeoPark), dedicated to establishing systematic frameworks for protecting and managing geosites for the purpose of education, tourism and research (Cleal *et al*. 1999; Page 1999; Garcia-Cortes *et al*. 2001; Rohling & Schmidt-Thomé 2004; Brilha 2005). Despite undoubted progress and numerous examples of successful conservation programmes (e.g. Agnew *et al*. 1989; Parkes & Morris 1999; Breithaupt *et al*. 2004; Falcon-Lang & Calder 2004), concerns about the deterioration of research sites persist (Barettino *et al*. 1999; Schulp & Brokx 1999; Clarkson 2001; Van Der Merwe 2003). Many key sites are susceptible to weathering, erosion and destruction by other means (quarrying, vandalism, etc.). The conservation and documentation of such sites requires new techniques to prevent the permanent loss of what is in many cases a finite natural resource.

LiDAR imaging is a highly accurate method of acquiring 3D spatial data and has been widely applied in other areas of heritage conservation (Weibring *et al*. 1997; Mason *et al*. 2000; Louden 2002; Barnes 2003; Bewley *et al*. 2005). To date LiDAR has been under-utilized in geology, both as an analytical and as a conservation tool. Breithaupt *et al*. (2004) used terrestrial LiDAR imaging and digital photogrammetry separately to record and map small sections of outcrop in Wyoming and Colorado (USA) containing abundant dinosaur tracks and skeletal remains. The potential to integrate LiDAR and photographic data and collect high-resolution quantitative data from sites through remote surveying suggests that the method may provide a means to merge conservation with scientific exploration of heritage sites.

To assess the value of integrated LiDAR imaging and digital photography as a geoconservation tool, a survey of the Maastrichtian dinosaur tracksites at Fumanya (SE Pyrenees, Catalonia) was undertaken using established ground-based procedures. The unique tracksites at Fumanya have undergone significant weathering since their exposure by open-air lignite mining in the 1980s (Schulp & Brokx 1999; Oms *et al*. 2002). The LiDAR survey has provided sufficient data to construct a variety of high-resolution 3D DOMs of the localities. The 3D geometry of individual tracks within the DOMs can be viewed and quantitatively analysed, providing the first comprehensive record of the tracksite in a 3D framework. The purpose of this paper is to report the methods involved in collecting field data and building high-resolution 3D DOMs, and to discuss the implications of the results for the conservation and interpretation of geological heritage sites.

Study area

Fumanya (SE Pyrenees, Catalonia)

The Fumanya sites are located between the Figols and Vallcebre villages, to the north of Berga (Barcelona province, Catalonia), by the western edge of the Llobregat river, in the foothills of Serra d'Ensija mountain in NE Spain (Fig. 1). The main locality is at Fumanya South, where more than 2000 tracks have been identified. Sites at Mina Esquirol, Fumanya North and Mina Tumí are linked by a mountain road that runs from Coll de Fumanya to Vallcebre village.

Geological setting

The Pyrenees fold-and-thrust belt formed at the boundary between the European and Iberian plates at the end of the Mesozoic and through the lower Tertiary. This belt is made up by Hercinian basement and a sedimentary cover that developed in foreland basins at both the northern and the southern edge of the orogen. The Vallcebre basin belongs to the latter and contains the studied sites.

The continental Late Cretaceous–Early Palaeocene sediments that filled the southern Pyrenean basins are known as the Tremp Formation or 'Garumnian' (see historical review by Rosell *et al*. 2001). The Tremp Formation was deposited following a marine regression that began near the Campanian–Maastrichtian boundary, accumulating sediments in an east–west foreland trough connected to the Atlantic Ocean. Above the Arén sandstone (and other related marine formations) the general stratigraphy of the Tremp Formation for the southern Pyrenees has the following units: unit a, a marine–continental transitional Grey Unit (marls, coals, limestones and sandstones); unit b, a fluvial Lower Red Unit (mudstones, sandstones, oncoliths and palaeosols); unit c, the lacustrine Vallcebre limestones and laterally equivalent strata; unit d, an Upper Red Unit (mudstones, sandstones, conglomerates and limestones). The age of these units is Maastrichtian (units a and b) and Palaeocene (units c and d). All these units can be recognized in the Vallcebre syncline, within the Pedraforca thrust sheet, which is one of the main structural units in the southwestern Pyrenees. Along this syncline dinosaur tracks are found throughout units a and b, with the Fumanya tracksites located at the very base of unit a. In this stratigraphic position a 5 m thick layer (the 'concrete level') contains the studied tracks, which are exposed in the footwall of the abandoned mining works. Palaeontological remains (ostracodes, gastropods, charophytes, vertebrate remains, etc.) and sedimentological observations suggest that the concrete layer represents an extensive carbonate mudflat deposited in a marine–continental transitional environment (Vila *et al*. 2005; Oms *et al*. 2007). The location of the tracks at the top of the concrete layer indicates that preservation occurred just before or as a result of a significant environmental change, specifically evolution to a more diversified environment, with coals, charophyte limestones, siltstones and fine-grained sandstones of limited lateral extent.

Palaeontology

The Tremp and Aren formations have yielded a diverse vertebrate fauna including fish, turtles, rays, lepidosaurs, crocodiles and dinosaurs, including theropods, titanosaurs, hadrosaurs and ankylosaurs (Vila *et al*. 2006). Since 2001 more than 60 localities with abundant vertebrate remains have been found, and the 14 sites excavated to date have produced over 500 bones (Galobart *et al*. 2003; Vila *et al*. 2006). The dinosaur track record consists of more than 15 localities, including sauropod trackways and hadrosaur tracks; dinosaur eggshells, eggs and clutches are also common (see **López-Martinez 2000; Bravo *et al*. 2005).

Much of this Late Cretaceous faunal diversity is present at the Fumanya sites (Schulp & Brokx 1999; Oms *et al*. 2007). The Fumanya sites, however, are unique in their preservation of *c*. 3500 dinosaur tracks and 40 recognizable trackways. The majority of tracks have been attributed to titanosaurid sauropods, alongside a likely theropod trackway at Fumanya South (Le Loeuff & Martínez 1997; Schulp & Brokx 1999; Vila *et al*. 2005).

Track preservation

The track-bearing surface at the Fumanya sites forms a steep dipslope, inclined at 60°, that runs north–south to form the western face of the quarries (Fig. 2). The majority of tracks have been interpreted as undertracks (Vila *et al*. 2005), although Schulp & Brokx (1999) mentioned the presence of well-preserved surface tracks (i.e. tracks formed at the foot–sediment interface; Romano & Whyte 2003) at the northern end of the Fumanya South site. In addition to tilting the track-bearing surface, Alpine tectonism has caused significant fracturing and veining, resulting in the displacement of a number of trackways. The track-bearing surface has also undergone significant physical weathering since its exposure in the 1980s (Oms *et al*. 2002). Schulp & Brokx (1999, p. 243) noted: 'Although the excavation of lignite ceased only a few years ago, even the prints that were only recently exposed are already being affected by erosion.' The tracks are preserved in soft, silty marl that is highly friable and has a fissile weathering texture. The altitude (over 1550 m) and

Fig. 1. Location of the Fumanya tracksites in the SE Pyrenees, near the town of the Berga (adapted from Vila *et al*. 2005).

Fig. 2. Photograph of the disused quarry at Fumanya South. The track-bearing surface forms a steep dip slope exposed by open-air lignite mining in the 1980s.

Pyrenean climate (high insulation indices, rain, ice, wind, etc.) mean that the site experiences extremes of temperature, and the steepness of the slope results in falling overburden further damaging the track-bearing surface. The distinct pattern of fractures on the track-bearing surface allows recognition of corresponding areas in photographs taken at discrete intervals since excavations ceased. These photographs clearly demonstrate the deterioration and loss of the ichnological record at Fumanya (Fig. 3).

Although the condition of many tracks has deteriorated, a significant number of tracks still clearly retain diagnostic features such as digit impressions and claw marks (Vila *et al*. 2005). The wealth of data available, and the rarity of Maastrichtian dinosaur tracksites (Lockley *et al*. 2002), makes Fumanya one of the most important Cretaceous dinosaur tracksites in Europe. However, a review of previous research illustrates the logistical difficulty in quantitatively studying and archiving the Fumanya tracksites.

Previous work

Since its first description by Viladrich (1986), the Fumanya South site has been the focus of a number of cartographic studies (Le Loeuff & Martínez-Rius 1997; Schulp & Brokx 1999; Vila *et al*. 2005). In these studies, the workers have experimented with a variety of novel approaches in an effort to overcome the fundamental difficulties of mapping the distribution and geometry of tracks on the largely inaccessible, steep quarry face. Schulp & Brokx (1999) produced the first general cartography of the Fumanya South site using a combination of climbing, surface grids, photogrammetry and simple visual surveying through binoculars. In 2002 some of the present authors used similar methods to produce a more detailed map of Fumanya South (B. Vila, pers. comm.). By using 5 m marked ropes it was possible to make a narrower surface grid than those used in previous cartographic studies. Having created a dense surface grid a series of high-resolution photographs of the track-bearing surface were taken, upon which track outlines and joints were marked as reference points. This allowed correction for perspective distortion to be achieved using photogrammetric software. At the northern extreme of the outcrop some of the authors were able to use climbing equipment to measure a number of trackways directly on the vertical surface. At Fumanya North, Mina Esquirol and Mina Tumi trackways were also mapped using climbing techniques and balloons.

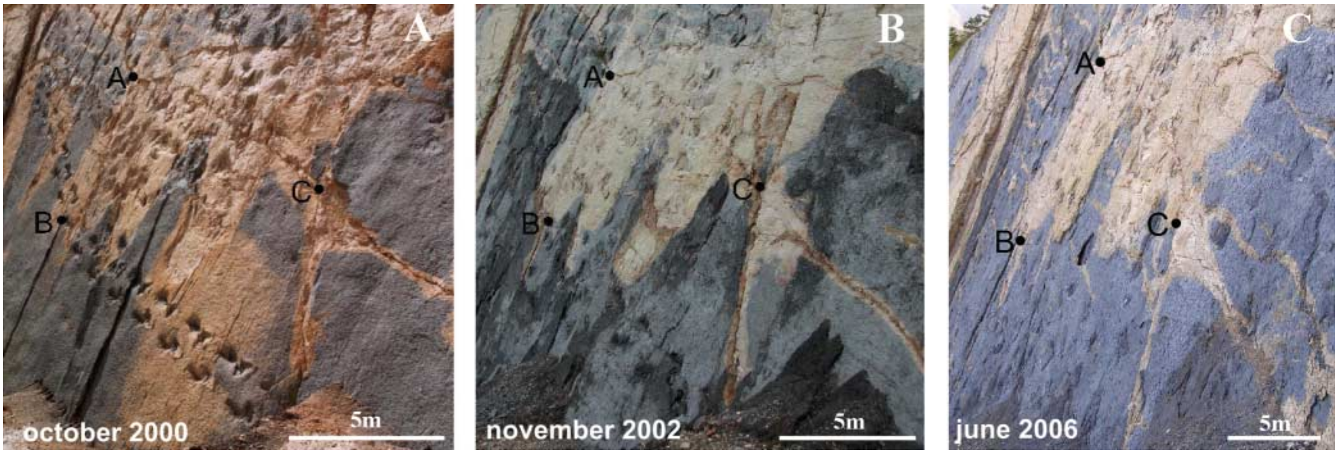

Fig. 3. Serial photographs of the same area of the track-bearing surface at Fumanya South illustrate the rapid weathering of the horizon and the loss of the ichnological record. Various features on the track-bearing surface (e.g. fractures, weathering patterns) allow recognition of common points (A, B and C) in the photographs.

The distribution of tracks on the surface at Fumanya South has been qualitatively constrained, but to comprehensively archive each of these valuable sites, a quantitative record of the distribution and 3D geometry of tracks is required. Integrated LiDAR imaging and digital photogrammetry, as a highly accurate remote method of collecting 3D spatial data, offers an ideal solution to the methodological difficulties that have so far prevented quantitative documentation of the tracksites.

Materials and methods

Fieldwork

Instrumentation. The fully portable RIEGL LMS-Z420i 3D laser scanner was chosen for its ability to rapidly acquire spatial data (12 000 *x*, *y*, *z* and intensity points per second) under demanding environmental conditions. The LiDAR scanner has a range of 800 m, 80° vertical and 360° horizontal fields of view and can be powered by a 24 V or 12 V car battery. The scanner uses a near-IR laser that is eye safe and requires no additional safety precautions. A Panasonic Windows tough-book with a Centrino Pentium 1.6 GHz CPU, 1 gigabyte of RAM and the software package RiSCAN PRO allows the operator to acquire, view and process 3D data in the field, thereby increasing the level of quality control on survey data. A digital camera (6.1 megapixel Nikon D100) was mounted on the scanner and, once calibrated, provided images that were used to extract an RGB colour channel and reflection intensity information for the point cloud; it was also used to texture map the final geoconservation model, to produce a photo-realistic representation of the outcrop. Precise global positioning was provided by the Trimble PRO-XR Differential Global Positioning System (DGPS), which utilizes a fixed base station to correct for the effects of systematic errors on the receiver (e.g. atmospheric propagation, satellite clock offset) to give sub-metre accuracy.

The scanner can be fitted with either a vertical mount or a tilt mount. A tilt mount was used in this survey and provided a full 180° rotation from the horizontal, giving a very wide field of view. The tilt-mounted scanner, digital camera and GPS were mounted on a heavy-duty surveyor's tripod (Fig. 4).

Fig. 4. The fully integrated scan unit (LiDAR, Nikon D100, laptop and DGPS) mounted on the tilt mount and surveyor's tripod.

Data acquisition. The LiDAR scanner emits a pulsed beam of light that is backscattered by the target object(s) and recaptured by the detector. The two-way travel time is divided in half and multiplied by the speed of light to derive a *z* value, whereas the *x* and *y* positions are calculated via laser deflecting mirrors within the detector (Bellian *et al*. 2005). The intensity of the return for each laser point is also recorded, and is determined by the reflective properties of the target surface. Laser intensity is therefore particularly sensitive to colour and moisture content of an exposure, as well as its distance from the scanner.

Full coverage of the track-bearing surface required a number of scan stations at each locality. Multiple scan stations provide more detailed 3D shape information by eliminating shadows (i.e. areas not visible to the laser) in the data caused by irregularities in the exposure surface. Both perpendicular and oblique scan perspectives were therefore necessary in this instance to prevent shadows occurring within the tracks themselves, which form features of negative relief (i.e. casts) on the scanned surface.

Prior to surveying it was uncertain precisely what scan resolution would be required to accurately capture the 3D geometry and particularly the depth (*z*) perspective of the tracks. Scan resolution describes the number of *x*, *y* and *z* points per unit area in the scan (i.e. the density of points within the resulting 3D point cloud). High-resolution scans are characterized by a small spacing between scan points, producing high-density 3D point clouds. Previous geological applications of LiDAR have focused almost exclusively on mapping large-scale features within exposures (e.g. bedding, fluvial channels, faults, etc.), relying on traditional methods (e.g. sedimentary logging) to incorporate sub-metre sedimentary structures into stratigraphic models (Bellian *et al*. 2005). Scan resolution is an important logistical constraint during fieldwork and data processing, as it determines the duration of the scan for a given area, and the size and manageability of the resulting dataset. The ability to view and process scans on a laptop in the field is crucial to finding appropriate scan resolutions for imaging 3D track geometry given constraints on field time and computer processing capability.

At each scan station a standard 360° panorama scan (1 998 000 points using the RIEGL LMS-Z420i) was used to acquire a single image of the entire exposure and its surrounding landscape. The panorama scan was coloured using photographic images acquired from the camera and wide-angle 14 mm lens (full 360° requires seven images). The operational software package (RiSCAN PRO) allows the panorama to be viewed on the laptop, and to serve as a template to select areas for higher resolution scans. The track-bearing surface was subsequently selected and scanned from each station at a variety of resolutions (0.01–0.08 m point spacings). At such fine resolutions, a single scan covering the entire track-bearing surface would have generated an unusable multi-gigabyte dataset. Instead, a series of smaller, overlapping scans were acquired to create more manageable files for later processing and interpretative work.

A series of high-resolution photographic images of the track-bearing surface were taken using 85 mm and 180 mm lenses on the Nikon D100. The height of the exposure required use of the tilt mount to capture the full vertical extent of the track-bearing face using both the 85 mm and 180 mm lenses. In both instances, the result was a high-resolution photographic mosaic of the exposure composed of horizontally and vertically overlapping images. The procedure was performed automatically in RiSCAN PRO by selecting the necessary tilt mount parameters and inputting the coordinates of the target area on the track-bearing face.

The field survey of the site was carried out in 6 days of good weather, during which time maximum priority was given to photographing the track-bearing face from each scan station at the time of optimum sun angle. As active scanners, LiDAR instruments generate the signal required to make measurements and are not reliant on natural lighting or environmental conditions (Habib *et al*. 2004; Bellian *et al*. 2005). LiDAR is affected only by extreme environmental conditions, which were not encountered during this survey.

Data processing and interpretation

Georeferencing scan stations. Georeferencing allows the spatial data collected from each scan station to be accurately located and linked within a single 'global reference framework' or Global Cartesian coordinate system; in this case the UTM coordinate systems was chosen with a WGS 84 Datum. The software used for scan alignment and georeferencing was PolyWorks, a commercially available package.

Point clouds from the 17 panorama scans (i.e. one from each scan station) were imported into PolyWorks to act as a representative matrix for its scan station. The '*n*-point pair alignment' function was used to manually pick three points that were easily identifiable in two overlapping scans. The distinctive geometry of the Fumanya outcrops and their internal features (e.g. large fractures and veins in the track-bearing surface) meant that selection of corresponding points could be made easily and an approximate manual alignment achieved in a matter of minutes. The point clouds were then automatically aligned using an automatic 'Best-fit function' tool that uses a least-squares algorithm to give the statistical best fit between two scans. The process was repeated until the 17 point clouds form a merged network of panorama scans, aligned to extremely high precision (standard deviation of less than 10^{-7}). The 17 scan positions were then locked together to maintain the accurate merging throughout the rest of the georeferencing process.

To georeference the aligned point clouds it was necessary to match the DGPS coordinates obtained in the field with the scanner's positions. Before post-processed DGPS coordinates were imported into PolyWorks, a reference point was assigned to the position of each scan station, in which the z value was offset to accommodate for the height of the DGPS receiver above the scanner (see Fig. 4). The PolyWorks 'auto-match' function was then used to automatically match the scanner reference points with the imported DGPS global coordinates, thus completing georeferencing. The merged point cloud is internally more accurate than the DGPS, therefore the auto-match process takes the GPS error into account and gives a best fit of the merged data to the DGPS points. The more scan stations there are, and the further apart they are, the more accurate the fit will be as the DGPS errors will be averaged out. The resulting aligned point cloud dataset was accurately (<1 m) positioned within a global reference framework. All other scans (i.e. high-resolution scans) were automatically georeferenced via the aligned and georeferenced panoramas.

Data manipulation and photo-texturing. Texturing the point clouds effectively merges scan information with undistorted digital photographs to produce a high-resolution 3D photo-textured model. Before photo-texturing scans must first be triangulated; that is, a surface must be created from the point cloud by connecting adjacent points with triangles. Once triangulated the scans consist of a series of points that have been connected to form a triangulated mesh. Each individual pixel within the photographic image is linked to its x, y, z coordinate within the correct triangular vertex by a texture coordinate recorded within the triangulated mesh (Bellian *et al*. 2005).

The accuracy and resolution of 3D surface geometry represented in the textured surface largely depends on the number of points within the scan data (i.e. the scan resolution). Photo-textured models are more likely to accurately depict 3D surface geometry when derived from dense high-resolution point clouds (Habib *et al*. 2004; Bellian *et al*. 2005). It is also desirable to use merged scans of the same exposure recorded from different perspectives (i.e. different scan stations) to reduce pixel-stretch effects. Irregularities in the scanned surface mean that point clouds recorded from a single perspective are inevitably $2\frac{1}{2}$D in nature (Bellian *et al*. 2005) and contain areas not represented by laser points (i.e. shadows). Integrating scans from different perspective helps to fill previously vacant 3D space, effectively eliminating shadows and the need for pixels to stretch to match adjacent scan points.

The triangulation process is performed automatically within the RiSCAN Pro software. The resulting mesh is then decimated in areas of the mesh with low topographic variation to reduce the number of points and triangles in the mesh without affecting the geometry. Automatic filtering functions are also available in RiSCAN PRO to reduce the density of point clouds (i.e. file size) to enhance the functionality of the scan and to remove erroneous or random points.

The IMMERGE tool within PolyWorks was also used to merge multiple scans into a single DOM. IMMERGE functions specifically as a fully automated tool for merging sets of 3D images or data into a unified triangulated mesh. An overlap reduction was performed prior to creating a unified mesh, to reduce memory usage and decrease processing time in IMMERGE. The PolyWorks overlap reduction automatically reduces the number of data points in overlapping regions by identifying and retaining only the most representative data points in these regions based on range and incident angle. Following overlap reduction the IMMERGE project was created by dragging the existing PolyWorks IMAlign project used to georeference the full set of panorama scans into an active IMMERGE interface. IMMERGE reads information from the IMAlign project and automatically calculates values for a number of parameters that control the quality of the merged polygonal mesh. PolyWorks allows the user to alter the values for all these parameters according to the desired quality of the final model. Only recommended values were used in this study.

Results

Digital Outcrop Models

Using data acquired in the field it was possible to construct a broad range of DOMs of the Fumanya dinosaur tracksites. The DOMs represent individual or a number of merged 3D point clouds coloured and/or photo-textured with undistorted digital photographs. The difference between the models reflects the number and resolution of merged scans and hence the robustness of the surface geometry represented by the scan data. The number and resolution of scans directly determines the size and manageability of the resulting dataset. A DOM can therefore be constructed based on a compromise between the resolution required for its application (e.g. high-resolution ichnological analysis, museum display, field trip planning) and the computer processing capability of the user. The ability to filter and integrate image data means that an infinite number of unique DOMs can be produced. A select number of model 'types' have been chosen for discussion in the following sections.

Octree DOMs. Octree DOMs (Fig. 5) consist of multiple panorama scans merged and filtered using an octree structure. The octree filter divides the total area of the scans into cubes with specified edge lengths and calculates a single representative point for each cube. The models shown in Figure 5 contain a panorama scan from each of the 17 scan stations, coloured using digital photographs. The model provides full coverage of the spatial extent of three adjacent tracksites and their intermediate landscape (Fig. 5a). Georeferencing using DGPS data allowed scans from Mina Tumi (not shown in Fig. 5a) to be accurately located within the model despite the absence of overlapping scans linking the exposure to the neighbouring sites. RiSCAN PRO allows the user to specify the resolution of the final model by stipulating the edge length of the cubes within the octree structure and hence the number of averaged points within the merged point cloud. The final model was filtered during the

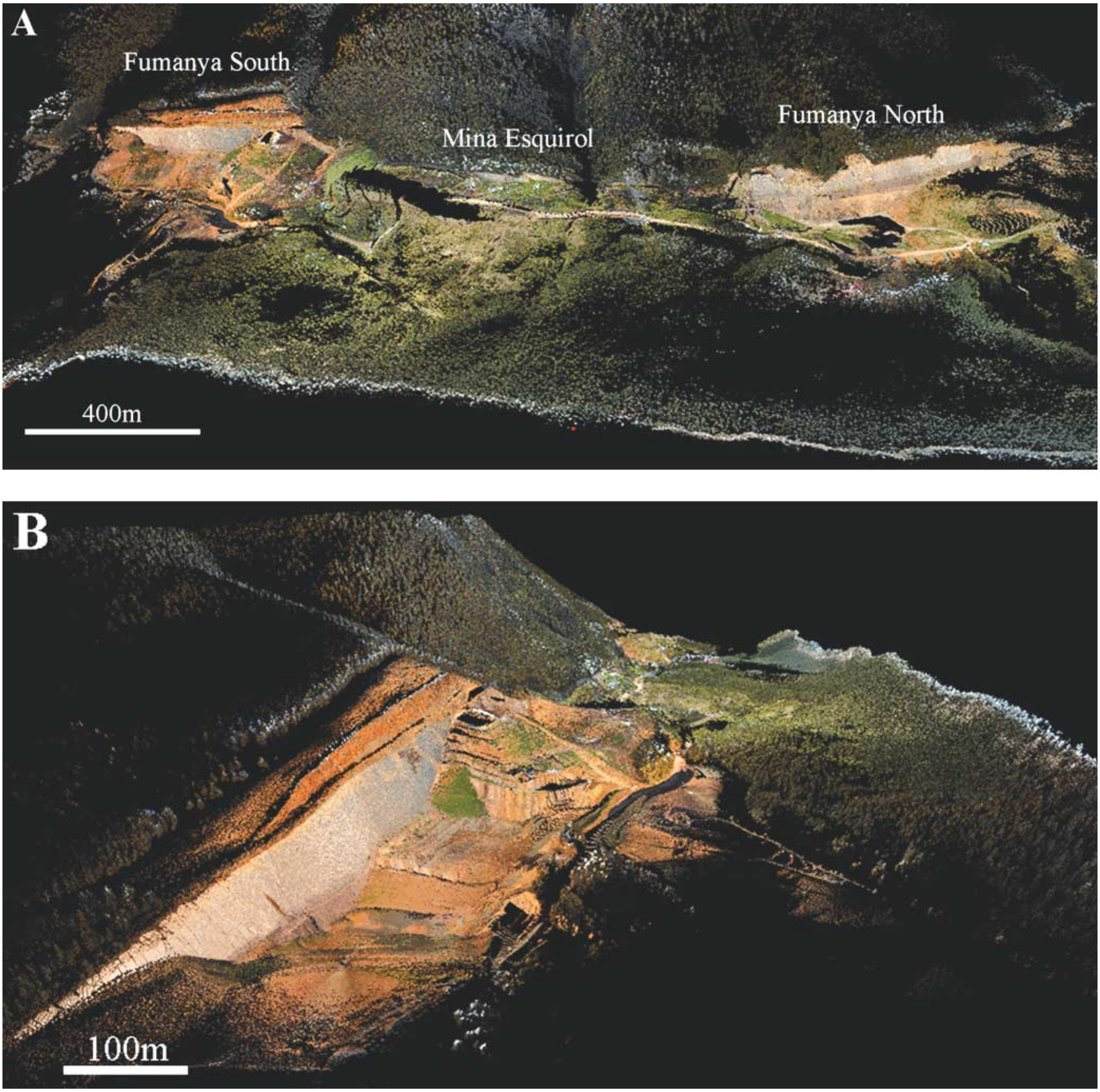

Fig. 5. (**a**) Aerial view of the octree DOM (0.15 m resolution) of the Fumanya South, Mina Esquirol and Fumanya North tracksites. (**b**) Aerial view of the octree model from the southern end of the Fumanya South site.

merging process to achieve a minimum point spacing of 0.15 m.

As medium-resolution models, octrees are easily manipulated and rotated to view the outcrops from any perspective. The resolution is sufficient to provide detailed representation of the geometry of the outcrops and certain geological features (e.g. large fractures) as well as the topography and many small-scale features in the surrounding landscape (e.g. roads, vegetation; see Fig. 5). However, the resolution is not sufficient to depict tracks and trackways, even when the track-bearing surface was viewed at close proximity (Fig. 5b).

PolyWorks IMMERGE model. A PolyWorks IMMERGE model of the Fumanya South tracksite was produced using five panorama scans acquired from different scan stations around the outcrop (Fig. 6). Unlike the octree model, the IMMERGE function creates a model in which the point clouds have been merged into a single triangulated mesh. In other words, discrete points with the point clouds have been joined by triangles to produce a continuous surface upon which digital photographs may be draped. Without the addition of digital photographs the model offers a very detailed representation of the landscape and

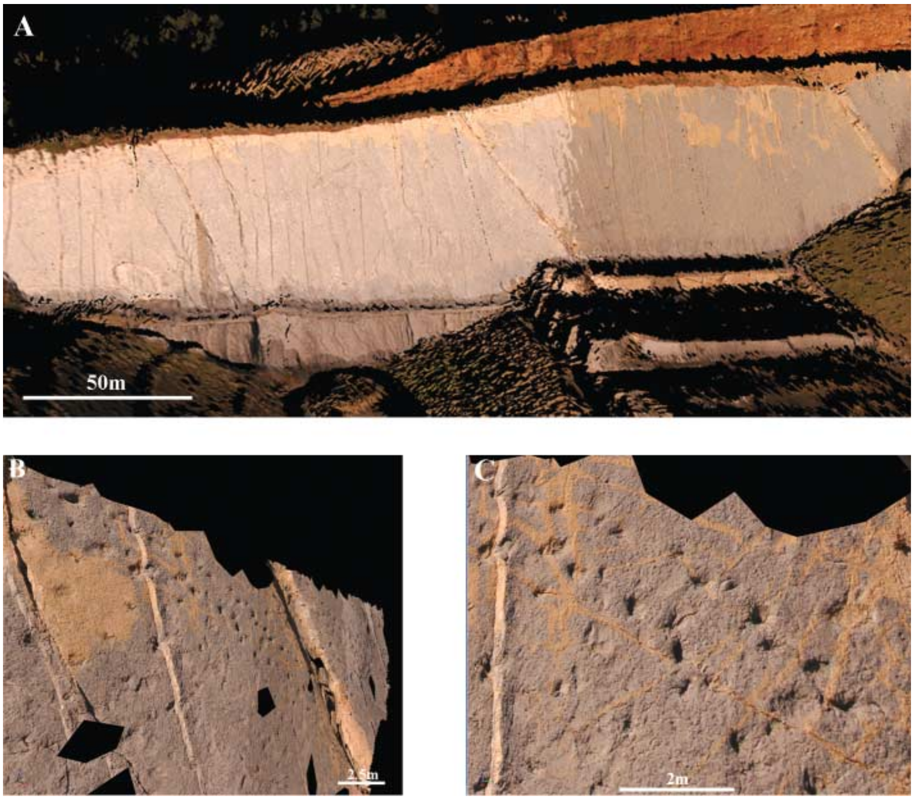

Fig. 6. (**a**) The IMMERGE model of the Fumanya South site photo-textured with images taken with the Nikon D100 with 14 mm lens. When textured with high-resolution photographs taken with the 180 mm lens the IMMERGE model offers a detailed representation of the track-bearing surface, as seen in (**b**) lateral and (**c**) front view.

the overall geometry of the track-bearing surface. Major fractures, veins and weathering features are clearly visible in the representation of the track-bearing surface (Fig. 6). Tracks and trackways, however, cannot be recognized.

Texturing the model with digital images from one or more of the five scan stations provides a 3D photo-realistic representation of the outcrop, in which the geometry of tracks and trackways is clearly visible (Fig. 6). The quality or detail in this representation is determined by the resolution of the photograph used. Photographs taken with the 14 mm lens provide some detail of the geometry of the track-bearing surface, and individual trackways are clearly recognizable (Fig. 6). However, in the majority of cases only the outline of a track may is seen, with little depth perspective present. Photo-texturing the model with images taken using the 85 mm and 180 mm lenses produces a much higher quality image in which the geometry of single tracks can be clearly seen (Fig. 6). However, the memory-intensive nature of photo-texturing means that whereas the complete panorama may be textured with 14 mm photographs only a limited area may be draped with 180 mm images before computer processing capability is exceeded.

High-resolution models. High-resolution scan data (<0.05 m point spacing) were collected primarily to facilitate ichnological analysis, but can also be used to produce highly detailed models of the track-bearing surface for conservation purposes. When textured with digital images the resulting models provide striking photo-realistic representation of tracks and trackways (Fig. 7). Filtering high-resolution scans prior to triangulation reduces the size of the dataset and allows larger areas to be photo-textured.

Integrating models. The ability to integrate DOMs of different resolutions offers a flexible solution to the limitations imposed by the size of the dataset. Integrating DOMs can be achieved by performing further merging functions or simply by viewing the models simultaneously in the same 3D window. This approach is particularly useful when the user wishes to view high-resolution models in the context of their wider landscape. In the present context, for example, the aim may be to place a high-resolution photo-realistic representation of a trackway within the context of the tracksite and its surrounding landscape. With currently available software and computer processing capabilities this aim is achievable only by placing relatively small, high-resolution scans within a medium-resolution representation of the surrounding landscape (e.g. an octree model). This approach is particularly effective when attempting to visualize and interpret the relative spatial location and geological context of widely separated palaeontological features (Fig. 8).

Animations of DOMs

Animations were created by integrating a coloured octree DOM (0.15 m resolution) of the Fumanya South, Mina Esquirol and Fumanya North sites and a number of high-resolution photo-textured scans of the track-bearing surface from each of these localities. The octree DOM itself is composed of 17 colour panorama scans and offers a medium-resolution (0.15 m point spacing) representation of each of the sites and their intermediate landscape. This medium-resolution framework serves as a visually effective spatial context for a number of well-preserved trackways depicted in the high-resolution photo-textured areas. Animations might be used as a short virtual fieldtrip to the three tracksites, and effectively portray the character of the landscape, the nature of geological exposures and the rich ichnological resource.

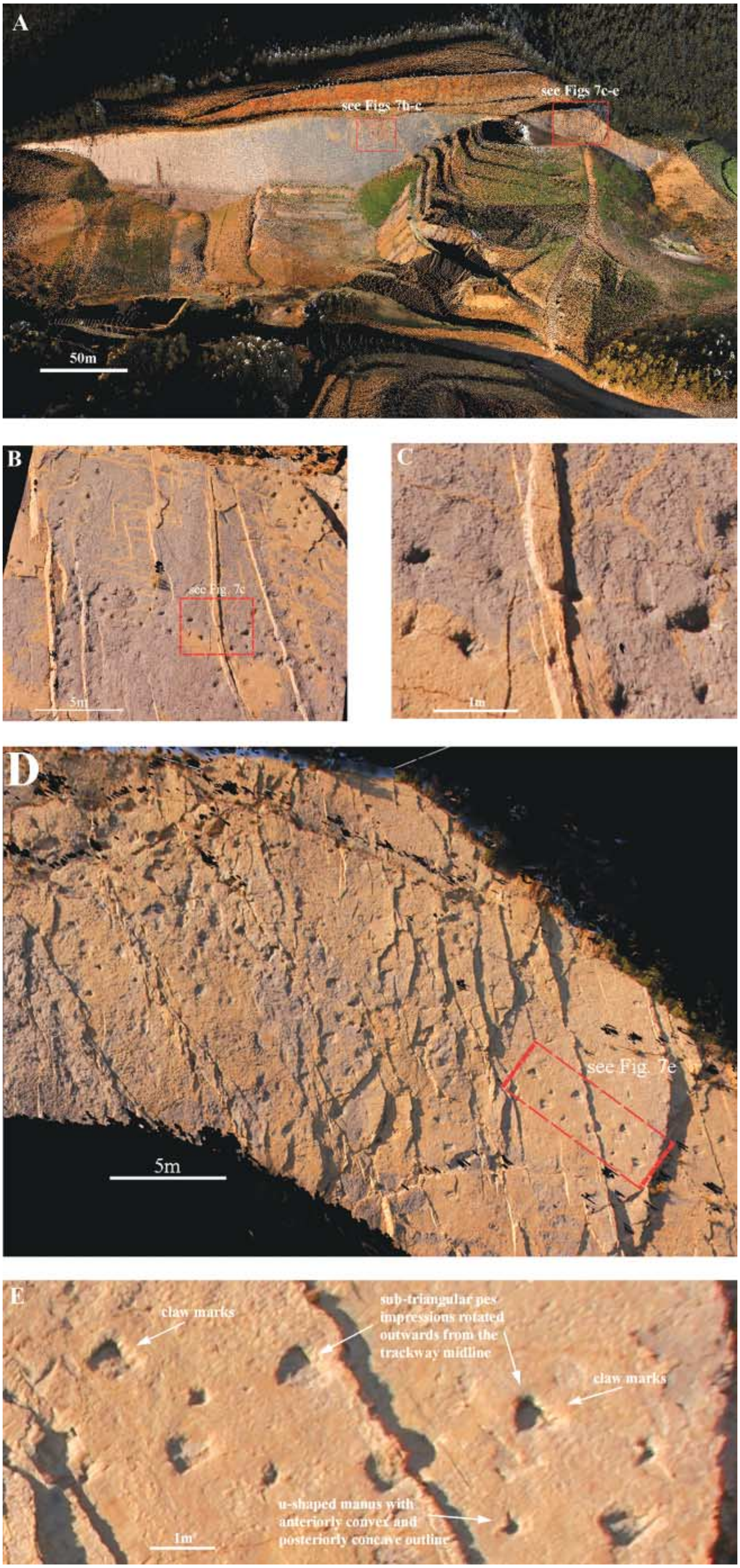

Fig. 7. (**a**) Aerial view of an integrated DOM of the Fumanya South site composed of an octree model (0.15 m resolution) and a number of small, high-resolution photo-textured scans (**b**–**e**). (**b**) High-resolution point cloud photo-texture with images taken using the Nikon D100 with 180 mm lens. (**c**) When viewed at such proximity the model retains its visual integrity and provides an extremely detailed view of the relief of the track-bearing surface, including a perspective on the depth of fossil tracks. (**d**) High-resolution scan photo-textured with images taken using the Nikon D100 with 14 mm lens. The model clearly depicts a well-preserved trackway at the northern extreme of Fumanya South as described by Schulp & Brokx (1999) and Vila *et al.* (2005). (**e**) The resolution of this model is sufficient to clearly depict a number of morphological features that have led previous workers to attribute these tracks to a titanosaurid sauropod dinosaur, including claw marks in sub-triangular pes tracks.

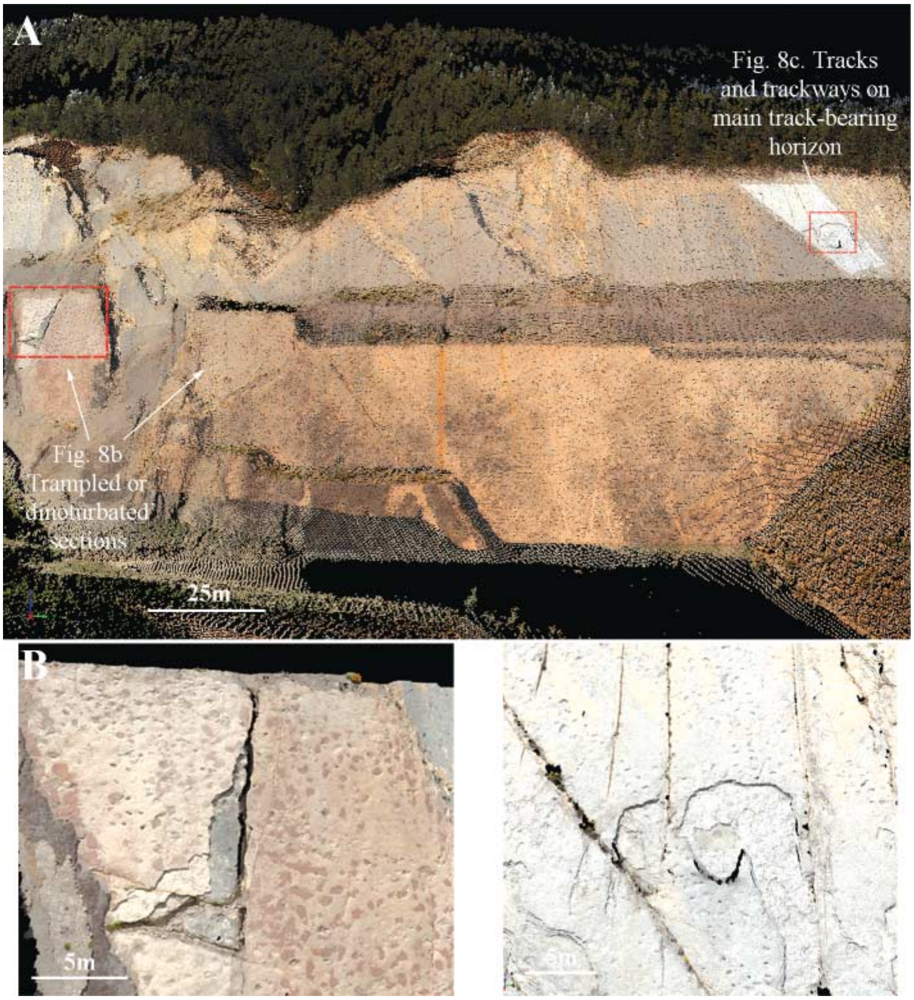

Fig. 8. (**a**) DOMs of the Fumanya North site composed of two high-resolution photo-textured scans inserted into a medium-resolution (0.15 m point spacing) octree point cloud. Small high-resolution models contain (**b**) a trampled or 'dinoturbated' section at the southern end of the site and (**c**) an area of the main track-bearing surface with a high density of tracks at the northern extreme of the site. Viewing high-resolution models within a larger, medium-resolution framework allows their features to be interpreted in their geological context; in this case, the trampled or dinoturbated section lies several metres above the main tracking-bearing horizon stratigraphically.

Discussion

DOMs and geoconservation of the Fumanya tracksites

Data acquisition and processing methods successfully facilitated the construction of a series of DOMs of the Fumanya tracksites in the context of their surrounding landscape. As site conservation archives these DOMs are superior to those created using traditional methods in term of accuracy, resolution and functionality. The quality of site visualization inherent in these models is extremely high and represents a major advance in the level of documentation achievable at geological and palaeontological heritage sites. Photo-realistic models provide a scaled 3D representation of tracks and trackways that includes a clear depth perspective, and includes even small-scale morphological features such as claw marks (e.g. Fig. 7d). Fossils retain their true spatial and geological context within the virtual 3D model of the exposure. Models are also fully interactive, allowing the user to explore and quantitatively interrogate the sites in the 3D realm, a facility that is lacking with traditional paper-based methods of documentation.

The Fumanya tracksites presented a real test of data collection and processing capabilities owing to their substantial spatial extent and the sub-metre scale of the abundant palaeontological resource (i.e. over 3000 fossil tracks of <1 m). Reconciling these two features and incorporating both into DOMs proved to be the major challenge in the model-building stage. Integrating small, high-resolution models within a larger, medium-resolution octree framework proved to be the most efficient and effective solution to the limits imposed by computer processing capabilities. Octree frameworks offer colour visualization of the tracksites in their surrounding landscape, and the density of points within the model (0.15 m point spacing) also provides a detailed representation of the geometry of the track-bearing surface at each site and many large-scale geological features (e.g. bedding, fractures, veins). Integrating high-resolution photo-textured scans into this framework was a simple procedure, and resulted in highly effective visual models of the tracksites.

Implications for geoconservation

Geoconservation organizations aim to develop systematic methods to identify, monitor and protect heritage sites, whilst encouraging sustainable exploitation of their unique resources for the benefit of future generations (Cleal *et al.* 1999; Bassett *et al.* 2001). The results outlined here indicate that integrated LiDAR imaging and digital photogrammetry has the potential to contribute profoundly to all of the objectives defined for geoconservation.

Integrated LiDAR and photographic imaging has clear advantages over traditional archival and documentation methods. The technique is non-invasive, fast and highly accurate, and crucially allows exposed fossils to fully retain their spatial context within an exposure, which can itself be viewed in its surrounding 3D landscape. This gives a sense of setting and flexibility of scale not possible through other methods of documentation and replication, such as manually illustrated cartographies, photography, and moulding and casting. Traditional methods are labour and skill intensive, and may be logistically difficult to perform because of the nature and size of a particular site, as has been the case at Fumanya, where climbing the quarry face is dangerous and impossible in many areas. However, data from such studies can be integrated with the LiDAR technique to provide an even more robust interpretation of the site. Integration of the DOMs with other georeferenced digital datasets can be performed rapidly and accurately using the alignment method described in this study (see above), and ensures that the distribution and orientations of exposed fossils are recorded within a global reference framework.

The derivation of a reusable digitized dataset from field surveys means that LiDAR data can be used to produce a number of different DOMs to suit a variety of conservation purposes. The first stage of a geoconservation programme typically involves identifying and prioritizing potential heritage sites. This is necessarily a comparative process, and may involve competition between sites separated by international boundaries and cultural divides. DOMs, particularly when viewed in 3D visualization suites, have the potential to play a crucial role in this decision-making process, principally by allowing governing bodies to preliminarily explore and compare sites before committing to expensive field excursions. The same advantage would be bestowed on researchers, who would have the ability to quantitatively interrogate sites and plan future field investigations within a virtual environment.

Where heritage sites have already been defined and prioritized, integrated LiDAR and photogrammetry may be used as a monitoring tool within a sustainable management strategy. For example, at ‘integrity sites’, defined as discrete localities where the fossil resource is finite and potentially short-lived (Weighell 2001), the technique may be applied to rapidly and relatively inexpensively archive valuable geological and palaeontological information before it is permanently lost. At longer-lived sites, which are generally awarded higher heritage status (Falcon-Lang & Calder 2004), continued integrated LiDAR and photogrammetric surveys would allow scientists and conservation agencies to monitor the deterioration of the site and evaluate potential protective measures. For example, high-resolution surveying might be performed annually to quantify and visually display the retreat of a cliff exposure or the erosion of fossil tracks on an exposed bedding surface. DOMs also provide a virtual 3D environment in which to plan the development of a heritage site and the installation of recreational and public facilities (e.g. roads, walkways, view points). LiDAR geological surveys can greatly improve our understanding of the spatial and palaeoenvironmental context of fossil sites within the 3D architecture of sedimentary facies. Sedimentological and stratigraphic information, apart from being valuable in itself, can assist palaeontologists in making informed decisions about the location of other fossiliferous sites within the 3D geological model, and in doing so allow land managers to construct high-resolution palaeontological sensitivity maps. These maps help categorize rock units on a scale of high to low cultural and scientific interest based on the type and distribution of fossils (Matthews *et al*. 2006). Sensitivity maps are now standard features of heritage and hazard management, and provide planners and land managers with valuable spatial information upon which to base decisions and communicate information to the public. The resolution of palaeontological sensitivity maps may be increased yet further by integrating surface LiDAR data with information from subsurface geophysical techniques such as ground penetrating radar (GPR) (Matthews *et al*. 2006). DOMs therefore not only document the geological and palaeontological resource of a heritage site, but may also contribute to the monitoring and progressive management of localities through time.

Arguably the most exciting prospect for DOMs is the interactive visualization medium they offer to education and geotourism. Working animations and interactive displays can be constructed for museums and websites, encouraging geotourism and promoting awareness of fossil resources and palaeontology. As an accurate digital method of data collection and storage, DOMs have the potential to significantly increase scientific access to key materials through the Internet and CD-ROMs. DOMs, displayed in computer laboratories or an immersive 3D environment, also constitute a valuable teaching tool, supplementing teaching collections and allowing students to inspect high-quality exposures from all over the world. In many instances, this may also relieve pressure on fossil collecting from heritage sites. Three-dimensional imaging may also be used for automated casting or ‘prototyping’ of fossils without damage to specimens (Chapman 1997). A scaled physical model of a site or specimen would provide an excellent teaching and research aid. DOMs housed in visitor centres may provide site-based information and unique interactive educational tools. For example, DOMs viewed in software packages such as Virtual Reality Geological Studio (VRGS) would allow the public to interact directly with the scientific resource and conduct their own virtual research (e.g. measuring track and trackway parameters). This level of interaction and visualization far exceeds existing on-site education tools.

Implications for vertebrate ichnology

The results of this study and its confirmation of the ability to accurately capture the precise 3D geometry of fossil tracks in the field using LiDAR imaging has profound implications for vertebrate ichnology. LiDAR scanning generates a quantitative 3D dataset that includes the entire outcrop and not just the outlines of tracks as subjectively defined by ichnologists. This provides a truly comprehensive 3D record of tracks and trackways in the context of their field exposure and sedimentary facies, from which more robust interpretations of track formation and preservation can be made.

Ichnological analysis is best performed on untextured point cloud data to limit file size and avoid potential inaccuracies associated with image distortion and pixel stretch effects. RiSCAN PRO contains neither the tools nor the visualization capabilities required to study the geometry of small-scale features such as dinosaur ichnites within raw point clouds. However, VRGS is ideal for the purpose of storing, processing and interrogating digital outcrop data (Hodgetts *et al*. 2007). VRGS can be used as an interface between RiSCAN PRO and other interpretive software by allowing dense point clouds to be edited and manipulated to the required format for importing into other packages, including Schlumberger’s reservoir modelling package Petrel. Petrel contains a number of algorithms that allow the user to automatically produce gridded surfaces over dense point cloud data. Model surfaces produced from dense LiDAR point clouds can be contoured according to the depth (*z*) value, and models of single tracks can clearly depict 3D surface geometry and changes in relief associated with variation in the distribution of pressure across the foot of the trackmaker during footfall (Fig. 9). Surfaces generated through high-resolution scans (i.e. 0.01–0.03 m point spacing) can be contoured at extremely fine intervals (up to 1 mm) to permit recognition of small-scale morphological features. Petrel contains measurement tools that allow the user to measure 2D and 3D distances between scan points or points on the model surface. Although the method still requires the user to define the limits of morphological features, the accuracy of the measurements themselves depends solely on the resolution of the scan data. The ability to view surfaces from any perspective and zoom in to high magnifications allows points to be located with extremely high precision. In addition to making fine-scale measurements, it is possible to section tracks in any orientation to produce a single 2D cross-section or a series of overlain sections that provide a unique perspective on changes in track relief. Outside the digital realm such analysis is not possible without physically dissecting and permanently destroying part of the subject study. LiDAR data therefore offer the potential of 3D archives of tracksites and infinitely reusable datasets that can be compared with other localities.

Conclusions

Fumanya represents an ‘integrity’ heritage site, and as such contains a valuable finite resource with a limited life expectancy. Prior to this study, difficulties associated with the nature of exposure had prevented the comprehensive documentation of the

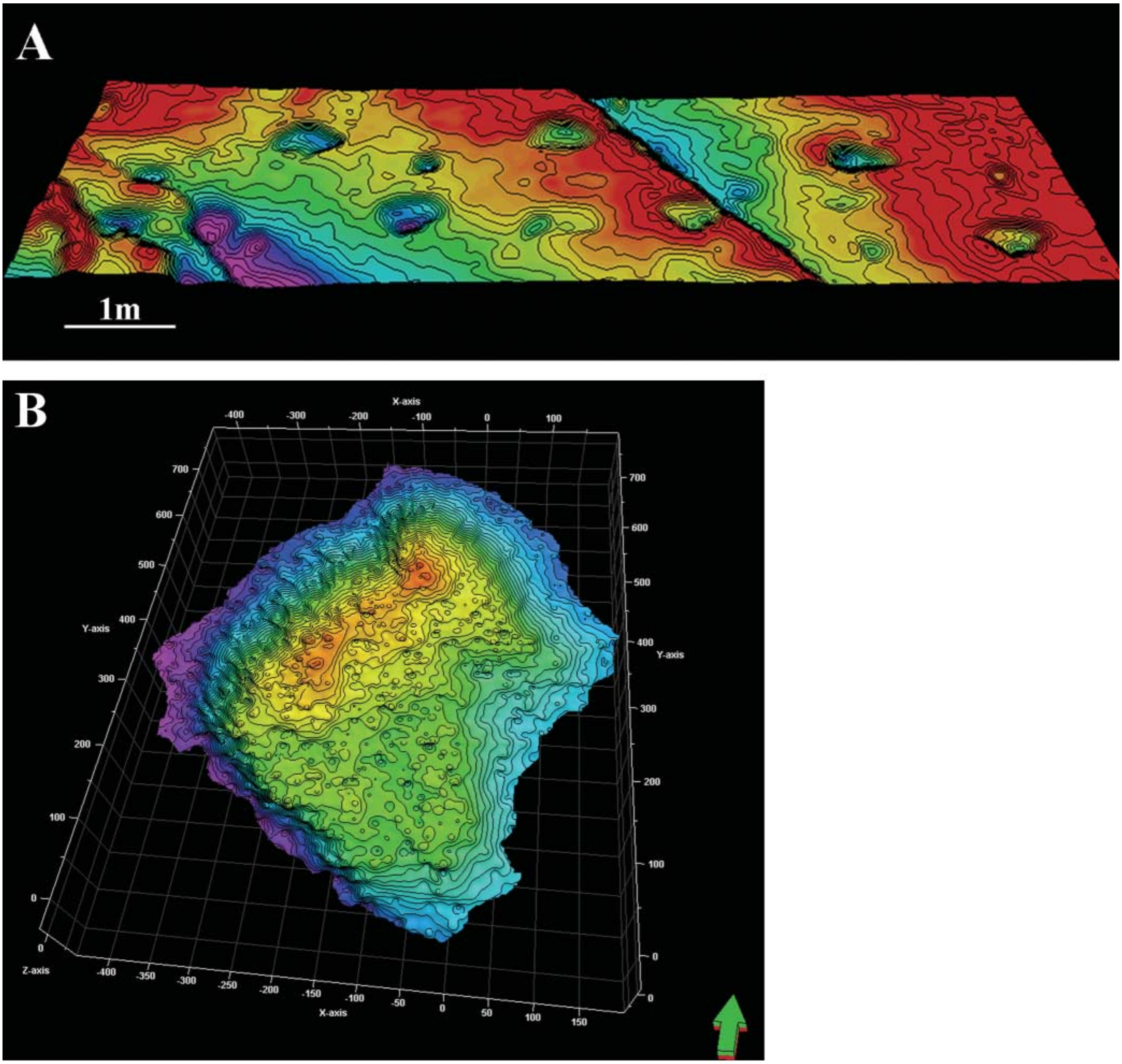

Fig. 9. Contoured and colour-coded surfaces produced from dense point cloud data collected by LiDAR scanning at the northern end of the Fumanya South site. (**a**) Section of trackway shown in Figure 7d and described by Schulp & Brokx (1999) and Vila *et al.* (2005); lateral view. (**b**) An individual track (left pes) showing detailed surface relief, highlighted by contours and colour coding (scales on axes are in millimetres).

tracksite and so had limited its impact within the scientific community. To address both these issues and evaluate the wider application of the technique, an integrated LiDAR and digital photographic survey of the site was undertaken. The method showed a number of advantages during data collection and processing, including the following: (1) data collection is rapid and efficient, with minimal supervision from the operator; (2) the long range of the scanner (<800 m) allows previously inaccessible areas to be surveyed at high resolutions from remote locations; (3) data can be displayed and processed in the field, increasing the level of quality control on the data; (4) field data can be backed up regularly.

The data collected in the course of this study were sufficient to build a range of photo-textured DOMs of varying resolutions that preserve the valuable geological resource at Fumanya. DOMs can be constructed to suit the purpose and computer capacity of the user. DOMs generated from integrated LiDAR and digital photographic data have clear advantages over traditional documentation techniques, including the following.

(1) Geological objects (e.g. fossils) retain their true orientations within an outcrop, which itself remains in the context of its surrounding 3D landscape.

(2) Integrated DGPS information places the models within a global reference framework. This additionally allows the model to be combined with other georeferenced digitized datasets.

(3) Photo-textured DOMs constitute a powerful visualization tool, particularly when viewed in an immersive 3D environment.

(4) DOMs can be used to plan and host virtual fieldtrips, allowing quantitative interrogation of remote sites from the desktop.

(5) It is possible to monitor fine-scale changes (e.g. as a result of weathering, erosion, vandalism, etc.) by repeat surveying of sites.

(6) DOMs provide a virtual 3D environment that can be used to construct sensitivity maps and to aid the decision of land managers.

(7) Data are communicable in the electronic medium, increasing the ease of scientific communication via the Internet and CD-ROMs.

By allowing workers to build high-resolution photo-realistic DOMs integrated LiDAR and digital photography may provide the means to produce a global inventory of geological heritage sites, with a unique level of accessibility. However, present limitations, notably its expense (total cost of surveying equipment and data processing software of the order of £100 000), are likely to mean that LiDAR is predominantly applied to sites of the highest scientific and economic importance. This study has shown conclusively that LiDAR can be used to map even small-scale geological structures, and that the technique will allow ichnologists to perform robust quantitative analysis of vertebrate track geometry in the field. It is, however, important to emphasize that LiDAR is not a stand-alone technique, and must be supported by direct field observations. Certain types of primary structural data (e.g. fault-plane displacement vectors) and sedimentological information (e.g. grain size, sorting, etc.) cannot yet be extracted from DOMs. LiDAR imaging is therefore most powerful when combined with more traditional geological field skills.

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