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The condition, use and future of the UK's largest accessible dinosaur tracksite at Spyway Quarry, Dorset

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Numerical datasets related to this article can be found in the Supplementary information of this paper. The raw images used to create the 2021 3D model and the 3D model files are available on Figshare (doi:https://doi.org/10.6084/m9.figshare.21256107), an open online database repository hosted by Digital Science, a subsidiary of Nature Springer.

ABSTRACT

Spyway Quarry in Dorset contains >100 tracks made by large sauropod dinosaurs walking across what was a shelly beach in the Early Cretaceous. It is the largest *in situ* easily accessible UK dinosaur tracksite, a unique location for the public to directly engage with dinosaurs. Following consultation on how best to open and manage the site considering its 'value', longevity, and resources available, it was left unstaffed with the track surface directly accessible. The site has been open to the elements since 2013 and to the public since 2016. We created a new photogrammetric model of the site in 2021, for comparison with an existing 2014 model to identify any changes in the trackway surface and to assess the sustainability of direct public access and weathering to the surface. To understand public use of the site, we installed a visitor counter, compiled social media reviews, and analysed photographs of visitor's movement on the quarry surface. We provide quantitative evidence for exfoliation of the track surface and reduction in the prominence of individual tracks over time primarily due to natural processes. Visitor data suggest ~10,000 people visit annually, and feedback suggests potential improvements to visitor directions and information. We do not recommend substantial changes to the site management plan given resource constraints. Our work highlights the importance of using 3D imaging techniques to document sites upon discovery and thereafter and making these data openly available to all for conservation monitoring, communication and to preserve sites' legacies.

1. Introduction

Dinosaur tracksites are relatively common globally, with many hundreds of sites known spanning the majority of the Mesozoic Era, from the Late Triassic through to the end of the Cretaceous (*e.g.*, Lockley, 1991; Falkingham et al., 2016). Within the UK, isolated dinosaur tracks from the Jurassic and Cretaceous are common discoveries in several areas, but *in situ* tracksites (comprising multiple tracks and/or trackways on a single exposed bedding plane) are relatively rare. Examples have been discovered in South Wales (*e.g.,* Lockley et al., 1996), the Isle of Wight (Pond et al., 2014), Dorset (Ensom, 1995; Ensom, 2006), Sussex (Shillito and Davies, 2019), Oxfordshire (Day et al., 2004), Yorkshire (Romano and Whyte, 2003) and Scotland (Brusatte et al., 2016; dePolo et al., 2020), but in some cases are no longer accessible (having been quarried away, collected by museums, or buried) or are situated on rapidly eroding coastal sections that are often relatively remote or difficult to find and/or access, *e.g.*, due to steep slopes or steps and tides. As a result, there are few easily accessible tracksites that can be visited by the public and that include interpretative material.

In January 1997, dinosaur tracks were identified near Acton, East Dorset, during quarrying of the Purbeck Limestone Group (latest Jurassic–Early Cretaceous) by Keates Quarries Ltd (Fig. 1). The tracks were initially found by quarry worker Kevin Keates, forming a series of large shallow depressions on the top surface of a ~200 m^2 exposure of the Lower Freestone, within the Stair Hole Member of the Durlston Formation (previously the Intermarine Member of Clements, 1993). These were subsequently identified by Kevin Keates, together with another local quarry worker, Treleven Haysom, as potential dinosaur tracks. The typically bowl-shaped tracks present at the quarry were produced by sauropods, a group of mostly very large herbivorous dinosaurs that were diverse and abundant globally during the Jurassic and

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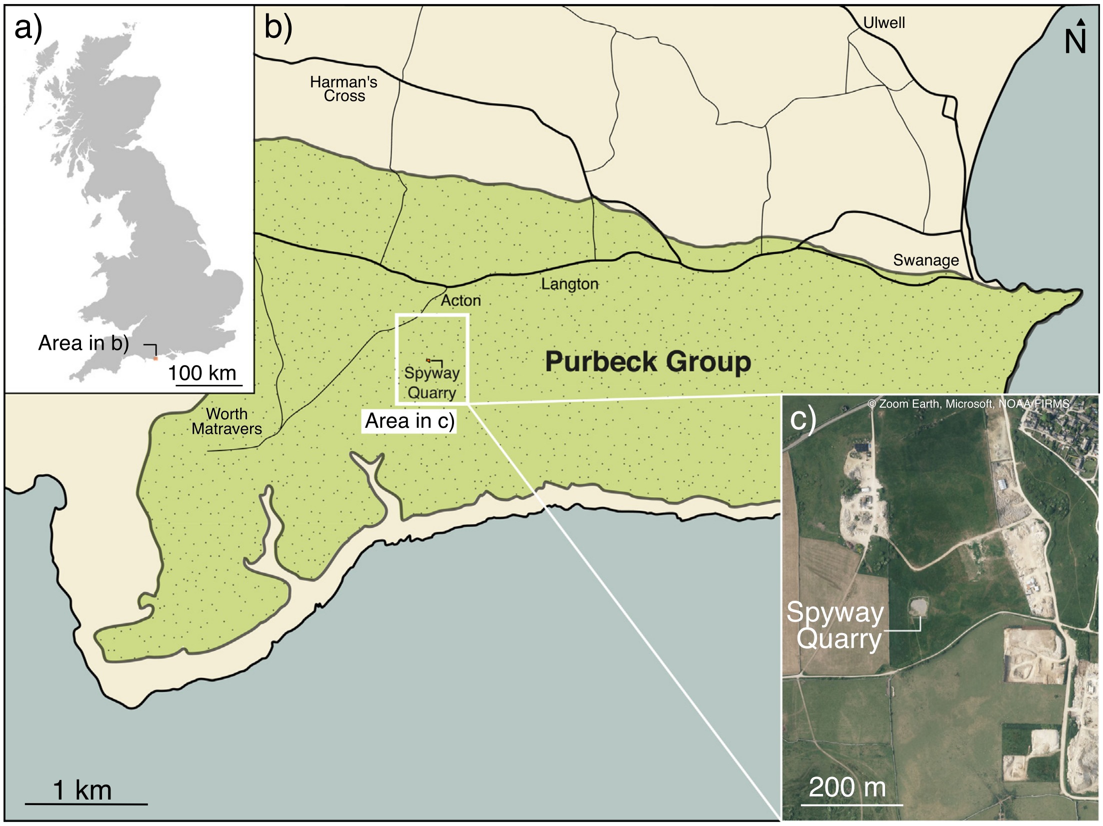

Fig. 1. Maps showing (a) the general location of Spyway Quarry along the Dorset coast, southern UK; (b) the area surrounding Spyway Quarry and the local extent of the Purbeck Group (stippled area); (c) a satellite image of Spyway Quarry (50.60216 N; 2.02020 W) and the surrounding active Keates and Lewis Quarries (image taken from Zoom Earth).

Cretaceous, and the site, with >100 individual tracks, is arguably the largest exposed dinosaur tracksite in the UK that is constantly accessible, *e.g.*, not tidal, no steps required, and with easy to locate tracks. The tracksite was known for many years as Keates Quarry, but recently the name was changed to Spyway Quarry to minimise confusion with the name of the quarry company.

Following the initial discovery, the landowner of Spyway, the National Trust, employed a palaeontologist, Joanna Wright, to map the site and conduct a scientific survey. Her unpublished internal report (Wright et al., 1998; see also Wright, 1998) provided a description and interpretation of the site, trackmakers and its significance, as well as outlining a series of conservation recommendations, which included opening the site to the public. Wright et al. (1998) proposed the erection of a permanent fence around the site, waterproofing of the track surface, re-covering of a portion of the site, and a public pathway, viewing platform and information boards, but they considered that public access to the track surface should be restricted given the potential for damage and erosion. Following this work, the site was covered so that quarrying of the surrounding land could continue. Spyway Quarry was registered as a Regionally Important Geological Site (RIGS; RIGS ID SY97/15) based on its value to Earth Science (educational, scientific, historical and/or aesthetic) in Dorset in 1997 and is one of ~60 sites in the county (Dorset's Important Geological Sites Group, 2012). It is protected from development by Dorset County Council but does not have the same statutory protections as a nationally designated Site of Special Scientific Interest.

In 2013, following completion of quarrying in the immediate area, the tracks were uncovered, and the National Trust and the Jurassic Coast Trust developed a long-term management plan for the site. The decision was made to fully open the site to the public, allowing direct access to the trackway surface. A deliberate decision was made to keep the site relatively low key, with minimal publicity and subtle signposting, to control visitor numbers and to fit with the 'Journey of Discovery' ethos at the heart of the Jurassic Coast visitor experience (Scriven, 2021). The site was therefore opened in 2016 to the public on an unstaffed basis and although the boundary of the quarry is fenced, visitors can enter at any time *via* a gate. The site is not covered with a protective structure, which would have been prohibitively expensive, and no varnish or sealer was applied to the surface as the local quarry workers advised that this would potentially exacerbate rather than minimise damage to the surface. An information panel was erected within the quarry boundary to help visitors interpret the site. Annual maintenance of the site conducted by the National Trust includes spraying with herbicide to minimise growth of vegetation in the numerous major joints and cracks that cross the quarry surface.

The decision to allow direct access to the track surface was based in part on an assessment of the scientific value of the site (Scriven, 2021). Wright et al. (1998) considered the tracks to represent primary prints (*i.e.*, formed on the actual surface on which the dinosaurs were walking) based on the presence and detail in the raised displacement rims around many tracks and the truncation of infilling sediment laminations with the sidewall of at least one track. This was based on the interpretation that transmitted tracks (*i.e.*, an impression of the track formed under the surface that the animal walked on: Lockley, 1991), would be overlain by broadly parallel laminations. However, later re-investigation by the Jurassic Coast Trust considered them much more likely to be transmitted in nature based on the poor preservation of morphological details, and critically, the impression of several tracks in overlying sedimentary layers (Ensom, P. and Manning, P. *pers. comm.*, 2013/14). Moreover, although the total number of individual tracks is large (>100), they do not form clear trackways and preserve relatively limited morphological information (Wright et al., 1998). The scientific and educational value of the site was therefore deemed to be low, although a full scientific description has yet to be published and is

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currently in preparation. To support future monitoring and conservation of the site, as well as public engagement activity, a photogrammetric model of the site was produced in April 2014, as a permanent, detailed and scaled record of the tracks (Ferraby and Powlesland, 2019). This model is publicly available on the Sketchfab website. The online presence of the site also includes pages on the Jurassic Coast Trust and National Trust websites, and some attempts have been made to use augmented reality at the site (*e.g.*, Bennett et al., 2022).

After more than five years of public access, there is now a need to document the current state of the site and the impact of previous management decisions. Here, we use a new photogrammetric model, and visitor counter and review data to assess the impact of opening the site to the elements and the public. We explore how the site is used by visitors and discuss the implications for its future conservation and management.

2. Methods

2.1. Making and analysing the photogrammetric 3D models

To document changes in the track surface since 2014, we generated a new photogrammetric model of the quarry in August 2021 for comparison to the existing model generated in April 2014 by the Landscape Research Centre when the site was re-exposed and prior to opening to the public (see Ferraby and Powlesland, 2019). Our methods largely follow those of Ferraby and Powlesland (2019). First, the quarry surface was largely cleared of large (>2 cm) pieces of debris (including large blocks around the edge of the quarry that had fallen onto the surface from the vertical quarry face) and individual tracks were gently brushed clean to remove loose materials and dust. To ensure sufficient overlap of images for model compilation and that the whole surface (~24 m × 34 m) was covered, images were taken in transects spaced at 1 m intervals across the surface. Photos were taken on a Nikon D750 digital SLR camera with an 18–55 mm f/3.5–5.6G lens mounted on an extendable pole (*c.*, 3.2 m elevation) to create a wide field of view at an angle of ~20° from vertical (Fig. 2). The camera was controlled remotely using the free iOS app *Cascable* installed on an iPad. Each photo was checked to ensure ~50–60% overlap with the previous photo and for quality (*e.g.*, no blurring, shadows, or people in the frame). The visitor notice board was used as the scale to calibrate the model.

After the fieldwork, all photos were uploaded to a high-performance workstation at the University of Birmingham and a final quality check was conducted to remove any unsuitable photos. A total of 1378 photos were subsequently imported to the software *Agisoft Metashape Professional* (version 1.7.4) to create a 3D photogrammetric model. The photos were aligned automatically (accuracy setting - high) based on matching points and used to generate a dense 3D point cloud (quality setting - high, depth filtering - mild). A 3D mesh (face count - high) was created from this dense cloud and a texture derived from the photographs (mapping mode - generic, blending mode - mosaic) was then mapped onto the mesh to create a photorealistic 3D model. The resulting model was then cropped, and any background noise removed to isolate the quarry surface for analysis.

To facilitate comparison of the track surface between the 2014 and 2021 3D models and the original line map (generated using a total station surveying tool) from Wright et al. (1998), line maps highlighting the position of tracks and other key features on the quarry surface were made. Screenshots of the quarry surface from each 3D model were taken and individually imported into *Inkscape* (note that the quarry surface was not flattened for this comparison). A new layer was created, and then individual tracks were drawn freehand into this layer. The 2014 and 2021 track layers were then overlaid on each other and compared to the original line map from Wright et al. (1998) to synchronise the numbering scheme for individual tracks with that of Wright et al. (1998) and to check for consistency in the placement and shape of tracks and the exposed surface through time.

A more quantitative comparison of the difference between the 2014 and 2021 models was generated by importing photogrammetric models of the 2014 and 2021 quarry surface into the software package CloudCompare (version 2.12). The models were finely registered, aligning the two meshes by the manual picking of point pairs (at easily matchable locations like the corners of prominent tracks). The distances between the two surfaces were then calculated using the 'Cloud-to-Mesh Distance' tool. A diverging red and blue colour scale (see online version) representing this was applied to the 2014 model surface indicating where material has been lost (red) or gained (blue) away from a minimum level of sensitivity (approximately 2 cm). Additionally, a case study using the same method was applied to photogrammetric models of track 41 (as a model existed for this track from 2014).

2.2. Fracture analysis of quarry surface

A high-resolution image of the textured photogrammetric model of the 2014 quarry surface was imported into software package *ImageJ* (version 1.53). The image was converted from RGB colour to 8-bit greyscale (based on the sum of the RGB values) and its contrast was enhanced. The image was then thresholded to isolate just the surface cracks from the background as best as possible. A 'remove outliers' operation was used to remove speckles/noise not representing fractures. The image was then exported into Adobe Photoshop (version 23.2)

Fig. 2. Demonstration of the image capture system in action, used to take photos of the quarry surface for the 3D model by undergraduate researchers Harry Jones and Lewis Haller in August 2021 at Spyway Quarry. Photograph taken on a GoPro HERO3+ Silver Edition camera positioned above an exposed vertical quarry face in the east of the quarry.

and final non-crack features (*e.g.*, noise, track edges) erroneously still present were manually erased. The image was then put back into ImageJ and skeletonised, creating a 1-pixel wide network of the crack systems, which was then dilated to be uniformly 3 pixels thick. The image was then exported back into Photoshop and this raster image of the network of fractures was automatically converted to vector lines (with only minimal loss of information). An SVG file of the vector fracture lines was then exported for use in the MatLab package *FracPaQ* (Healy et al., 2017). *FracPaQ* was used to quantify the density, distribution, and direction of fractures across the quarry surface. A version assessing fractures on the 2021 quarry surface was not made for comparison because fewer clear fractures could be automatically isolated from the photogrammetric model's texture, using the above method, and would thus not be directly comparable or reveal useful information about areas that had increased in fracture density. Indeed, it is likely that no new fractures large enough to be picked up by this method occurred within the study interval and smaller cracks and fractures that developed tended to occur in already highly fractured areas and thus, were difficult to isolate.

2.3. Determining visitor movements on the quarry surface

To assess the most visited areas of the quarry surface we used still images taken from a tripod mounted GoPro HERO3 + Silver Edition camera positioned above an exposed vertical quarry face in the east of the quarry. This camera took photographs of the quarry surface every 30 s for approximately 1 h each day from 12th to 17th August 2021. We specifically only use images from intervals when the research team was not working in the quarry to avoid biasing the movements of visitors, who tended to gravitate towards researchers to find out more about their work. In total, we analysed 335 photographs containing instances of people on the quarry surface. The photographs were imported into Adobe Lightroom v 5.2 and lens distortion was removed using lens profile settings for the camera model. Corrected images were imported into Blender alongside a photogrammetric model of the Spyway Quarry surface in top-down orthographic view. The positions of prominent cracks and tracks on the quarry surfaces were located in the photographs and on the photogrammetric model and used to fit a grid of approximately 3 m^2 squares over the photogrammetric model (a lattice object) and the photos (multiple Bezier curves edited to the correct perspective positions). The positions of people within the photographs could then be marked within the grid over the photogrammetric model (by small cubes). This was done for every photograph before the final count of people within each grid square was totaled. See Supplementary Figure 1 for an example of this set-up in Blender and the x- and y-coordinates of the grid. These data were mapped as a heatmap in R Studio and overlaid onto a greyscale image of the photogrammetric model of Spyway Quarry from 2021. Note that some areas of the quarry were out of the view of the camera (see Supp. Fig. 1) and therefore visitor use of these surfaces was not documented.

2.4. Collection of visitor data to Spyway Quarry

To determine the total numbers and relative timing (through the day, month, and year) of visitors to Spyway Quarry, we collected hourly data using a SensMax DE bi-directional counter with horizontal infra-red beam sensor set mounted at the main access gate to the site from the Priest's Way footpath (Supp. Fig. 2). The sensor set is mounted ~80 cm above the path between the gatepost and records every time the beam between the two sensors is broken, *i.e.*, visitors either entering or leaving the site. The counter was installed on 12th August 2021 with recorded data used from 13th August 2021. Data were read from the counter on 26th November 2021, 8th February and 1st April 2022. Unfortunately, the counter initially became unstuck from the weather casing and slipped down (such that the beam was no longer aligned) at some point in late October to November 2021. The mechanism used to realign the sensors in February 2022 failed and hence, the data from November 2021 to March 2022 are considered incomplete and used with caution. Values recorded by the counter were divided by two because visitors generally enter and leave the site *via* the same gate.

Google visit data was also collected to provide a secondary source of relative changes in visitor numbers to Spyway Quarry through time as well as an estimate of the amount of time that visitors spent at the site. Google visit data collates anonymised data from users who opt into the Google Location History (Google Business, 2022). Popular times are shown as relative histograms by day and by hour and are based on averages over the previous few months. The data itself is not downloadable so screenshots of the online graphs were taken on 5th July, 5th August, 28th September and 30th November 2021, and the 1st January, 3rd February, 2nd March, and 21st June 2022 from the Google page for Spyway Quarry by the National Trust. Visit duration data is based on the average time spent at the site over the previous few weeks.

2.5. Assessing the visitor experience

In light of COVID-19 concerns about conducting in-person interviews during the main 2021 study interval, we sought to understand visitors' experiences of Spyway Quarry (including issues such as accessibility and learning outcomes) using online review aggregators (TripAdvisor - 37 reviews; Google reviews - 113 reviews) accessed in June 2022. Posts were organised into common themes based on if they were perceived as a strength or weakness of the site.

3. Results

3.1. Changes to the tracksite over time

3.1.1. Size of the track surface

The number of recognised tracks has changed through time with numbers increasing based on newly exposed areas and/or closer inspection and decreasing as tracks become more indistinct (Figs. 3 and 4). 111 tracks were initially identified by Wright et al. (1998) on the quarry surface with a further three marked as indeterminate (numbered here as tracks 1–114 in Fig. 4). However, we note that Track 44 is missing from the originally figured line drawn map in Wright et al. (1998). We have not amended the numbering system to avoid confusion between different iterations. Based on the 2014 and 2021 photogrammetric models and field observations in 2021, a further 24 tracks were identified giving a total of 138 tracks at the site (tracks 115–138 in Fig. 4). These are predominantly located around the edges in the northern, northwestern, and eastern areas of the quarry where in 2014 there was a larger surface exposed than today or in 1998. Not all were still fully exposed in 2021 due to encroachment on the surface by vegetation and the embankments, *e.g.*, tracks 90, 102, 120–123, and 133 (see Figs. 4 and 5). Also, a number of tracks that were identified in 1998 are no longer readily discernible on the surface in 2021 including tracks 55, 64, 67, 83, 93 and 94 with several others appearing very faint, *e.g.*, tracks 7 and 8.

3.1.2. Quantitative difference map

Comparison of the 2014 and 2021 3D photogrammetric models (Fig. 6) indicates changes of ± ~20 mm are present across many areas of the surface. Loss of material (highlighted in red; Fig. 6) occurs primarily along fractures and within or along the rims of individual tracks, particularly at points where fractures and tracks intersect. This loss of material represents in some cases breakage/exfoliation of the surface - in other cases (such as the rims) it may represent more gradual weathering over time. These changes are pronounced given that tracks have an average depth of ~10–45 mm with the rim having a maximum depth of ~25 mm (Wright et al., 1998). Gain of material (highlighted in

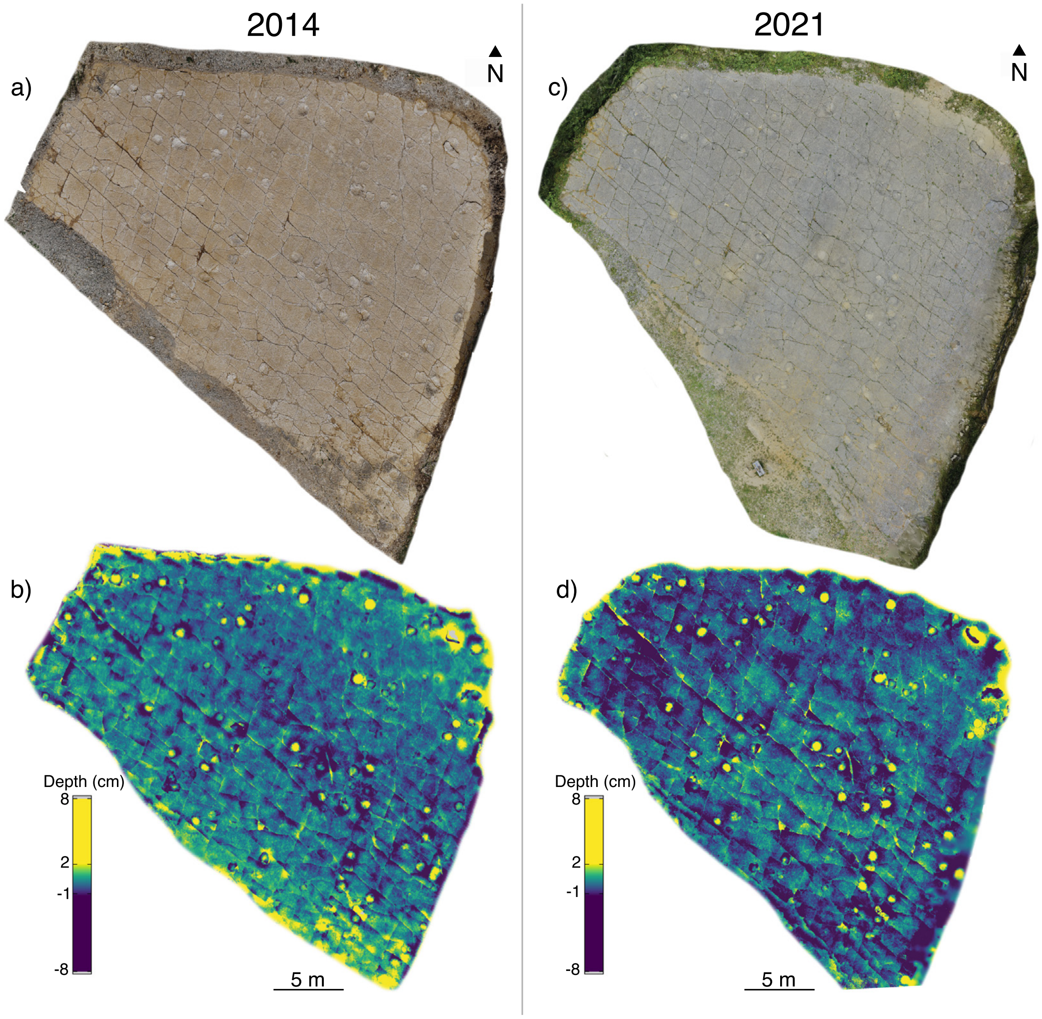

Fig. 3. Textured photogrammetric models of Spyway Quarry surface from 2014 (a) and 2021 (c). Height maps of flattened photogrammetric models of the Spyway Quarry surface from (b) 2014 and (d) 2021, detailing prominent tracks, cracks, and other reliefs. Minor colour differences generally reflect slight differences in flattening or photogrammetric model accuracy, rather than a change over time. Some detail around quarry edges has been lost during flattening. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

blue; Fig. 6) generally represents the accumulation of loose material on the surface or within fractures. The edges of the quarry surface generally show additions or loss of material between the two models but these are disregarded here due to these areas being more likely to contain artefacts in the photogrammetric models and the generally higher and more variable levels of foliage and debris, including loose material cleared from the tracks prior to imaging as detailed in Methods.

3.1.3. Qualitative observations

Quantitative results were ground-truthed by examining a number of individual tracks on the quarry surface. Areas where material has been lost can easily be recognised because of the different colours of newly exposed and less weathered surfaces (Figs. 3 and 7) and closely match the damage map in Figure 6.

3.2. Fracture map of the quarry surface

The quarry surface is extensively fractured with >3 fractures/m^2 across the majority of the quarry surface (Fig. 8). The most intense fracturing is in the southernmost part of the quarry reaching >20 fractures/m^2 within two grid cells (see darker colours in Fig. 8). There are two dominant fracture directions nearly perpendicular to one another running ~NNE–SSW and SE–NW, with smaller and less extensive fractures distributed relatively consistently across the surface in all directions. Fractures are commonly infilled with small loose pieces of rock that have broken away from the surface elsewhere and/or vegetation. Most individual tracks are intersected by one or more fractures.

3.3. Visitor use and experience of the site

3.3.1. Visitor use of the surface

We recorded 1703 non-unique visitor occurrences on the visible areas of the quarry surface across the sample interval, *i.e.*, each visitor may be counted multiple times if they appear in multiple photographs (Supp. Table 1). The most highly visited single spot in the quarry was the information board with 393 recorded occurrences (Fig. 9). Other occurrence 'hotspots' are present on the quarry surface in the area along the southwest edge of the quarry surface, near the visitor information board, and then associated with two clusters of distinctive tracks immediately in front of the visitor information board (reaching the highest number of occurrences at Track 57, adjacent to a long groove on the surface that has been interpreted as a foot drag mark: Wright et al., 1998) and then another cluster towards the northern edge of the quarry, again associated with a relatively obvious cluster of tracks. Note that the far western and eastern edges of the quarry are not included in our analysis because they were not visible in the photo dataset, although qualitative observation of visitors suggests that they commonly spend time immediately next to the quarry wall on the eastern edge of the site.

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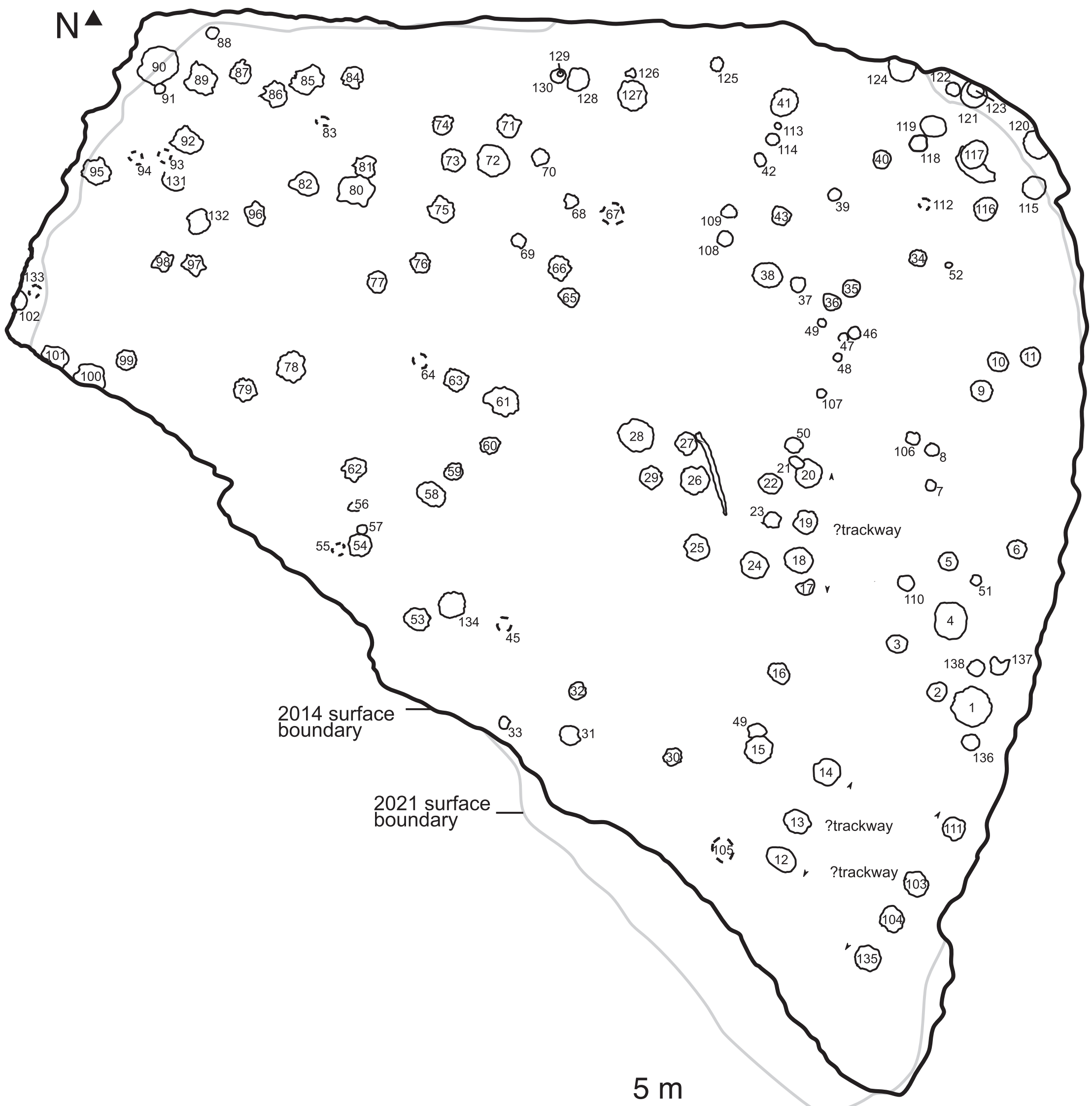

Fig. 4. Line map of identified tracks through time at Spyway Quarry (1998–2021). Track numbering follows Wright et al. (1998) for tracks 1–111; extended with newly identified tracks from photogrammetry and in the field in 2021 (tracks 115–138). Tracks that are poorly preserved or otherwise very indistinct/no longer visible are outlined with a dotted line. Changes to the extent of the quarry surface from 2014 to 2021 are shown by a fainter outline (the 2021 limit) in the NW, NE and S of the quarry outline. Three groups of tracks potentially representing trackways are identified between arrows on the map. Track 15a of Wright et al. (1998) is labelled as 49.

3.3.2. Visitor numbers

Visitor numbers as recorded by the counter were highest in August 2021, with 1802 visitors recorded over the 19 days from first installation of the counter, then declined through September and October (Fig. 10a; Supp. Table 2). As noted above, absolute values for data from November to March are considered incomplete due to the sensor having been dislodged. August therefore saw the highest number of weekly visitors, exceeding 600 per week during the final two weeks of the month. Visitor numbers were typically around 250–300 per week in September and October, although with some weeks dropping below 200 visitors. Maximum visitors on any single day were around 120 in August 2022. Visiting hours unsurprisingly correlate with daylight hours, with first visitors tending to arrive within a couple of hours after sunrise and the last visitors within 1–2 h after sunset, meaning visiting hours extended for longest during the summer months and declined into the autumn and winter (Fig. 10b). The daily visitor numbers show some signs of positive skew, with relatively few visitors early in the day, a peak around late morning to midday, and then a gradual reduction in visitor numbers through the afternoon and early evening. In some months a second, or even higher, peak is present in the mid-afternoon. There is no consistent pattern in the data of weekends being busier than weekdays for visitors between months (Fig. 10c). However, in terms of total visitors per day over the course of the study interval, Spyway Quarry receives the most visitors on Saturdays and Sundays.

The average visit duration to Spyway Quarry based on Google analytics data from July to November 2021 was ~20–25 min (Supp. Fig. 3). This appears to partially conflict with suggestions from online reviews of dwell times of ~10 min. Absolute numbers of visitors cannot be assessed from the Google data but the pattern of use of the site through the day was generally congruent with our own visitor counter. During the winter months, visitor numbers were too low for Google analytics to display daily histograms.

3.3.3. Visitor experience

The site appears to be overall well-liked by visitors, with average review scores of 4.5 out of 5 (Tripadvisor) and 4.1 out of 5 (Google Reviews), although with a broad range of scores from very negative to very positive. Common positive comments (Table 1) were framed

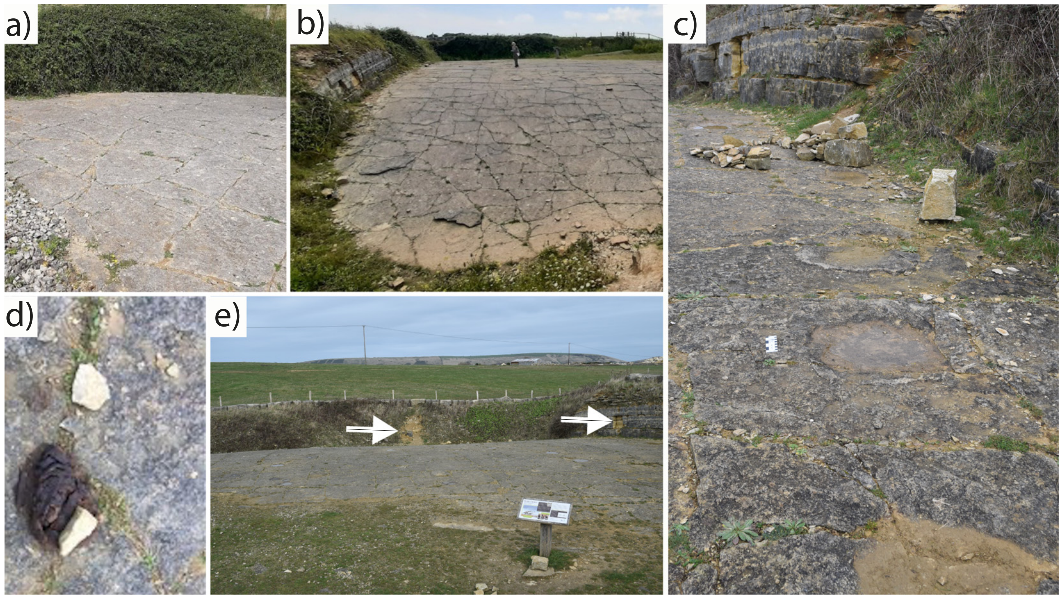

Fig. 5. Summary images showing a variety of hazards impacting the quarry surface. (a) and (b) Encroachment onto the quarry surface at the edges and loose blocks/gravel on the surface. (c) Tracks infilled with rainwater in the foreground, quarry fractures infilled with mud and vegetation, and in the background piles of large, jointed blocks that have come down from the edge of the quarry, *i.e.*, the layers above the surface are evident. Scale bar in (c) is 13 cm. (d) Cowpat on surface from when the gate to the quarry is left open and livestock can enter the site. (e) Arrow at northern quarry edge shows unstable margins and bank collapse on to the surface and in the east, a pronounced hole exposing a fresh surface where material has been weathered out.

around the sense of awe at being able to walk within the tracks of dinosaurs, and the persistence of these tracks over 145 million years of geological time, as well as the setting within the wider landscape. The interpretative panel, although small, was highlighted by several reviews as informative. Very common negative comments (Table 1) were primarily around difficulties in finding the site, insufficient signposting, and distance from car parks. Visitors also commonly considered the tracks difficult to interpret and underwhelming. Interestingly for the current context, several visitors highlighted concerns about the future of the tracks, noting that they were likely to erode away with one specifically flagging the heavily cracked nature of the surface.

4. Discussion

4.1. Causes of the changes in the track surface

Since the opening of Spyway Quarry in 2014 there have been significant changes in the extent of the track surface and the quality of preservation of individual tracks (*e.g.*, Figs. 3, 4, 6 and 7). Encroachment at the edges of the quarry by vegetation and mass wasting of the surrounding slopes (Figs. 4 and 5) has reduced the number of exposed tracks by ~4%, and individual tracks have suffered damage through defoliation and erosion of the surface (Figs. 6 and 7). Quantitative comparison of the 2014 and 2021 models demonstrates that much of the damage is associated with the numerous major natural fractures that cross the surface, although erosion is also concentrated around the rims of individual tracks. The impact of these changes is that many of the tracks have become less pronounced over time, exacerbated by their typically shallow depths (~10–45 mm; Wright et al., 1998), with some (which were probably already very indistinct in 2014) now being difficult or even impossible to identify. This is exacerbated by changes in the colour of the surface as it has weathered over time. Thin displacement rims also show significant damage in a number of places.

Damage occurs to tracks across the entire surface (Fig. 6), not just in those areas that are most frequently visited by the public (Fig. 9) and not just in the areas of highest fracture intensity. Whilst our data and observations suggest that the former may be a contributing factor, we consider the primary cause of deterioration of the surface from natural weathering processes due to the combination of intense natural fracturing, exposure to the elements, and growth of vegetation along fractures in the surface.

4.2. Implementation of original conservation recommendations of Wright et al. (1998)

Wright et al. (1998) identified three main considerations in the development of a conservation plan for Spyway Quarry (Table 2): (1) protecting the tracks from vandals, illegal collection and/or visitor erosion; (2) protecting the tracks from the elements, and (3) displaying the site for visitors' enjoyment and understanding.

First, the tracks were considered relatively safe from illegal collection as the Lower Freestone Bed in which they occur is thick and well cemented (Wright et al., 1998). To date, no tracks have been removed, and there is no evidence that this has been attempted (*e.g.*, hammer marks, saw scars) or evidence of malicious vandalism of the site. The only recorded damage to the site from collection was noted in Wright et al. (1998) when the original protective fence around the site was scaled and an attempt was made to extract a piece of unidentified bone embedded in the surface that resulted in its partial destruction. Note that no evidence of the bone is now evident on the surface and the whereabouts of the remaining parts of this element are unclear. The large size of the individual tracks, relatively poor preservation of features and lower aesthetic appeal (when compared to classic tridactyl dinosaur tracks) likely further reduce their desirability despite their relative rarity in the UK for this time interval. More significant is the visitor (and occasionally livestock when the gate to the site is left open by the public) erosion from walking over and touching the tracks, which was thought would lead to rapid deterioration particularly around the fragile edges of the tracks (Wright et al., 1998). Our observations and data show that there is evidence for this style of damage but weathering processes probably also play a significant role.

Second, weathering is a continuous process but is most destructive in the winter when freeze–thaw processes operate with multiple cycles of rain entering cracks only to freeze and expand the cracks fracturing the surface. Swelling and expansion of mud within the cracks can also

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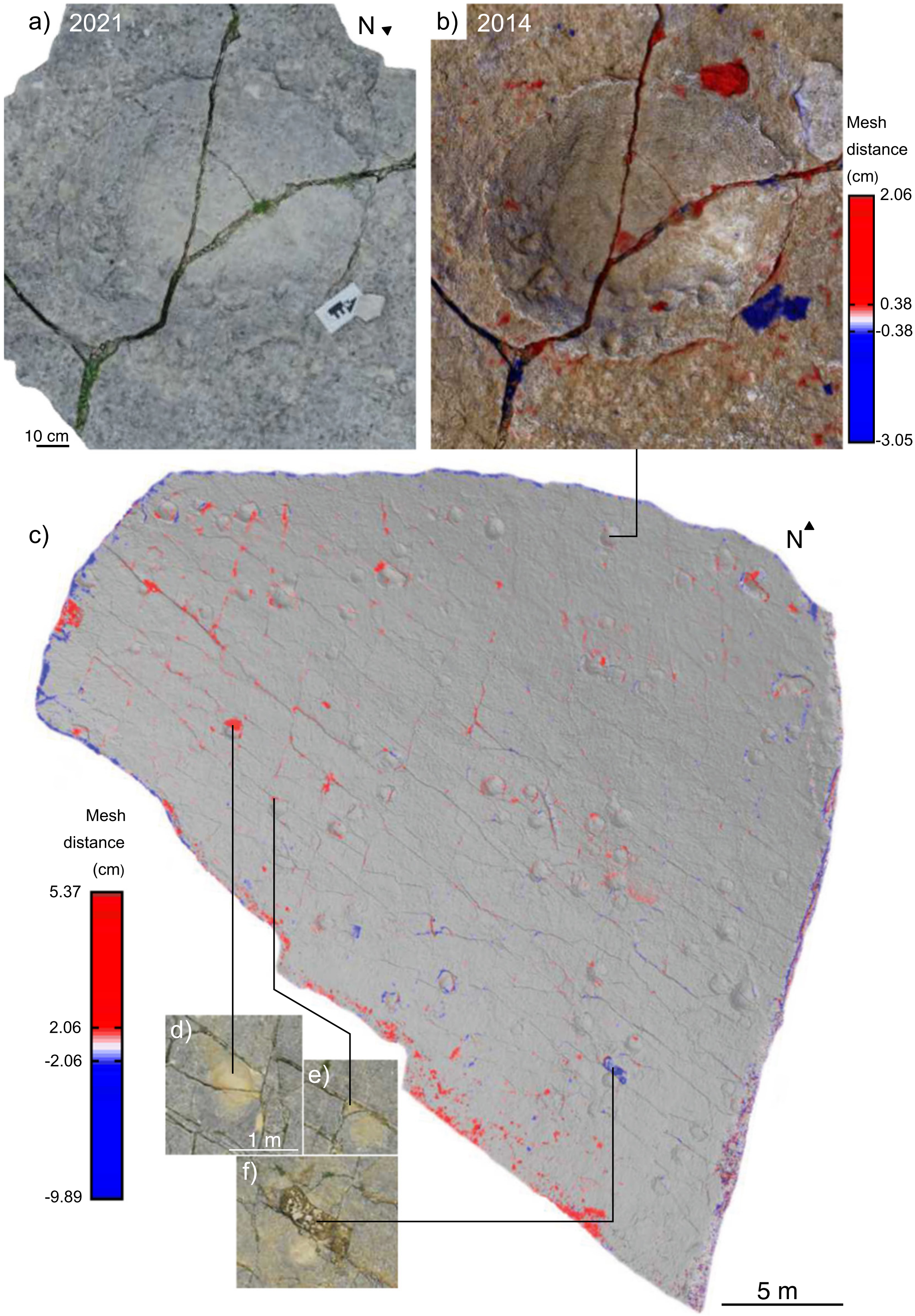

Fig. 6. Comparison maps showing damage and loss of material at Spyway Quarry based on the mesh distance between photogrammetric models of Spyway Quarry from 2014 and 2021. (a) and (b) show photogrammetric models of Track 41 from 2021 (a) and 2014 (b); the 2014 model (b) has red colouration highlighting areas now missing in 2021 (a), blue colouration indicates areas where material has been added (*i.e.*, scale bar, loose material, plant growth). A photogrammetric model from 2014 of the whole quarry surface is shown in (c); red coloured areas indicate material has been lost 2014–2021, primarily due to fracturing and these fragments being lost/moved; blue indicates material gained 2014–2021, primarily due to loose material being repositioned and plant growth. The location of Track 41 is detailed on the quarry surface in (c). (d) Track 78 showing loss of half of the track surface. (e) Track 62 showing damage around the edge of the track. (f) Large surface depression above Track 13 filled with mud and loose material from quarry surface and margins. To best see the differences in the surface please see the colour version of this article online. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cause material to flake away along with daily temperature fluctuations leading to expansion and contraction of the rock (*e.g.*, García-Ortiz et al., 2014). This process of fracturing the surface is exacerbated by rainwater, which is naturally slightly acidic (pH ~5–5.5) causing carbonate to dissolve over time and resulting in a loss of definition of features (so-called 'rounding'). Standing water can collect particularly in the

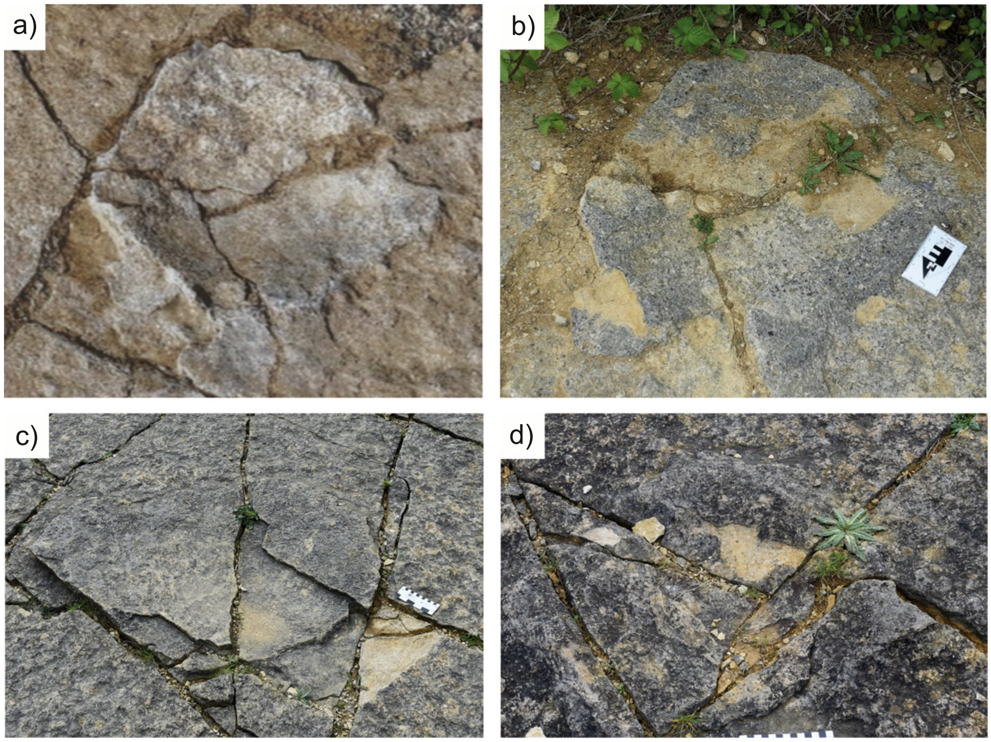

Fig. 7. Summary photos showing different kinds of preservation and damage in Spyway Quarry. (a) and (b) show Track 95 in 2021 and 2014, respectively. Note the widening of the fractures, loss of definition from the track edge and missing material shown by exposed yellow/brown fresh rock surface. (c) In 2021, a large section lifted at intersection of two large fractures and (d) Track 98 in 2021 with material coming from the track surface itself originating from the fracture. Scale bar in (c) and (d) is 13 cm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

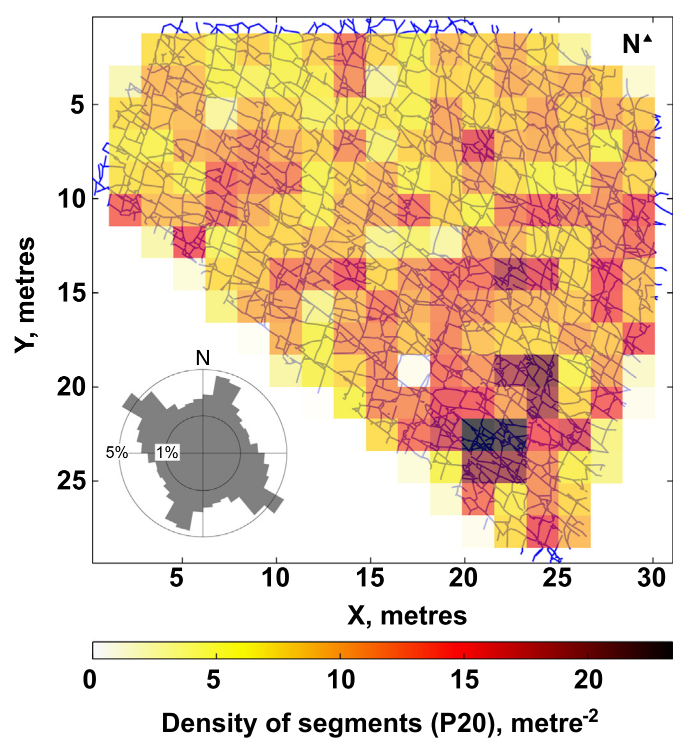

Fig. 8. Heat map showing relative density and distribution of fractures (units of length^{-2}) on the surface of Spyway Quarry. The vector lines representing identified fractures from the 2014 photogrammetric model underlay the density heat map. Bottom left-hand corner is a rose diagram plotted using area-weighting, presenting the distribution of fracture orientations in relation to North. Mapped traces (n = 2232), segments (n = 5405) and nodes (n = 7637). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

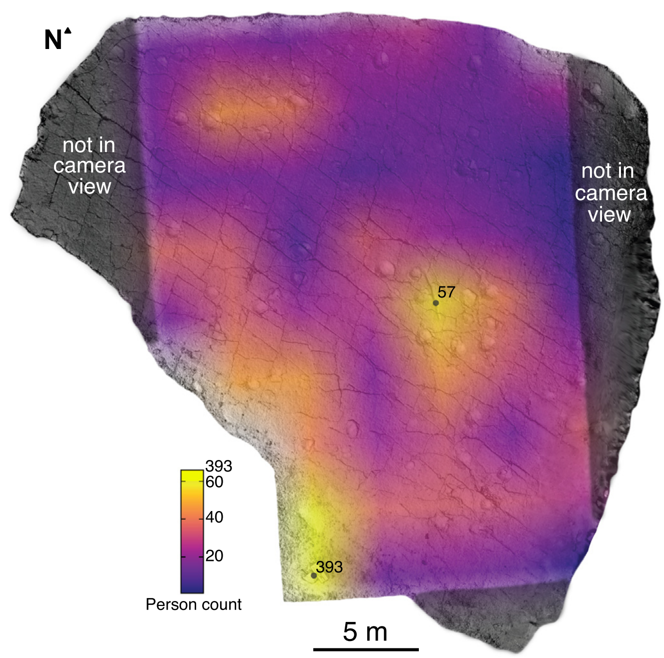

Fig. 9. Colour gradient map detailing areas (binned into approximately 3 m^2 grid squares) of the quarry surface most frequently occupied by people in periodically taken photographs. Warmer colours (lighter grey–white in print version) indicate areas more frequently visited/where people stay for longer. The location of the highest recorded people count on the quarry surface and overall highest value are marked on the map (57 on the quarry; 393 at information board). Colour scale linear from 0 to 60, then identical from 60 to 393. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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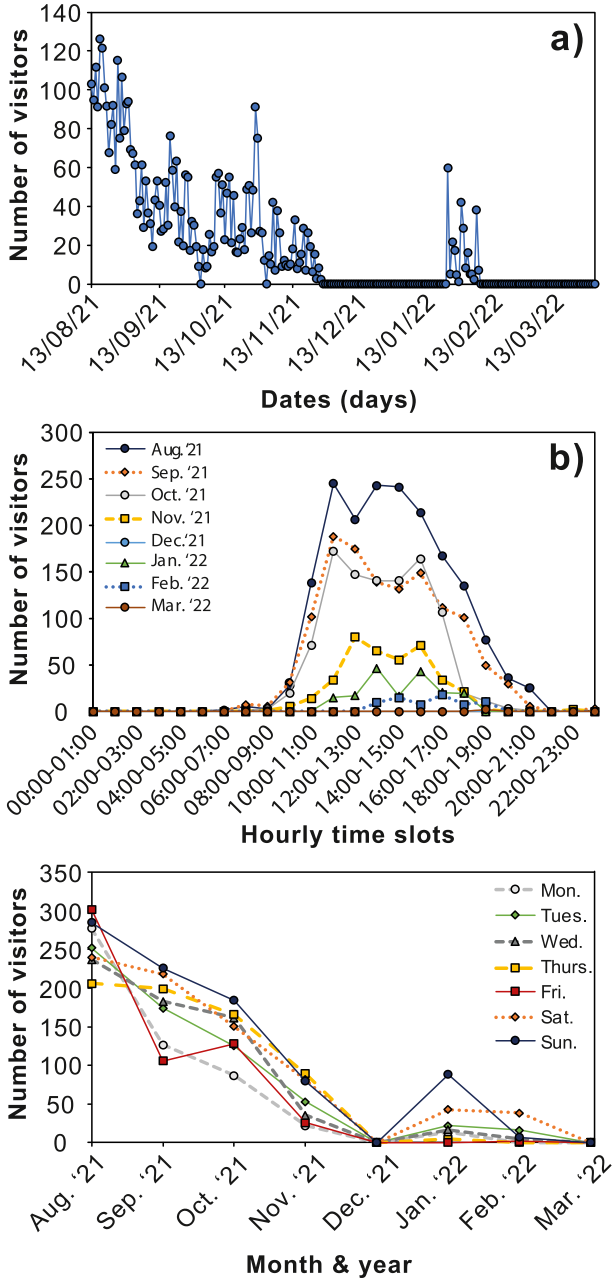

Fig. 10. Summary of visitor data from 13th August 2021 to 31st March 2022 based on the counter installed at Spyway Quarry. a) Number of visitors across the entire study interval. b) Total number of visitors in each one-hour time window for each month. c) Total number of visitors per day in each month. Note that data from 26th November to 31st March is considered suspect because of sensor misalignment.

Table 1
Summarised key themes in positive and negative visitor comments for Spyway Quarry, drawn from Tripadvisor and Google reviews.

Positive visitor comments	Negative visitor comments
Sense of awe at the geological age of the tracks and their persistence to the present day	Distance of walk to quarry from car parks, insufficient signposting/directions, difficult to find
Experience of being able to stand directly in a dinosaur track/on the track surface	Difficulty in identifying/interpreting the tracks, some felt underwhelmed
Setting of the site in the wider landscape	Not enough for visitors to stay at site for more than short period of time (10–15 min typically mentioned)
Uniqueness of the tracks within the UK	Concerns that not enough done to protect the site and that tracks will disappear over time
Interpretive board is informative	

deeper tracks, and the strongly sloped quarry surface encourages running water over the surface during heavy rain further enhancing mechanical (*e.g.*, *via* abrasion) and chemical weathering. To a lesser extent, erosion from wind and dust were also identified by Wright et al. (1998) as a potential problem. As identified in Section 3.2, the network of surficial fractures is one of the main areas where damage is located. This highlights the importance of weathering to the deterioration of the surface over time. Indeed, weathering is the biggest challenge to all outdoor sites with 'cleaned' surfaces such as this quarry surface most at risk (*e.g.*, Marty et al., 2004; García-Ortiz et al., 2014). Multiple options are available to protect the surface each with pros and cons but the limitation remains the cost and time required to directly protect the surface from the elements, *e.g.*, sealants to waterproof the surface, sheltered building and/or a climate-controlled walled (and staffed) building (see example of Lark Quarry below).

A number of additional factors were also noted that were not mentioned by Wright et al. (1998). First, the preferential growth of plant

Table 2
Summary of conservation recommendations by Wright et al. (1998) and their implementation.

Suggestion	Implemented	Comment
Waterproof quarry surface	No	Concerns from experienced local quarry workers that this process may exacerbate rather than minimise weathering.
Erect a permanent fence around the site	Partially	An outer wooden fence is present to keep out livestock and for health and safety reasons but not to keep visitors off the surface as originally envisioned.
Retain an elevated viewing platform	No	When visitor access was restricted to the perimeter of the quarry this allowed visitors to look over the quarry more easily but was not necessary when access to the surface was directly permitted. It is still possible to walk fully around the rim of the quarry allowing an elevated view of the site.
Retain the exposed vertical section so the overlying rocks can be seen	Yes	The overlying beds are exposed. These mainly serve an aesthetic purpose that illustrates that this was part of a quarry, no wider stratigraphic context or educational materials are provided (see Fig. 6). Note that the nature of the rock units which fracture into large blocks may create a hazard for visitors.
Re-cover part of the site to reduce erosion	No	The entire known surface is currently open to the public and the elements, although the entire site was covered from 1998–2013 whilst quarrying was underway in the immediate environs.
Provide information boards for visitors explaining the site	Yes	One interpretative panel is provided at the top of the quarry (Fig. 12).
Make a path around the site with perhaps sacrificial tracks that the public can touch	No	Visitors are not encouraged to walk around the rim of the quarry although this is possible (see above). No tracks have been lifted as visitors have direct access to the quarry.
Unstaffed site with pedestrian access only	Yes	The site is open 24 h per day all year round. The area is fenced, and access is by foot only.

material along fractures in the surface, which is likely to exacerbate weathering processes (*e.g.*, Fig. 6). This is currently managed by the National Trust *via* annual spraying of the surface with herbicide. Second, the potential access of livestock to the site if visitors leave the gate open (Supp. Fig. 2). It is unclear how frequently this may occur. The gate does have a spring to help it close but the latch requires the gate to be firmly pulled shut on entry/exit to be engaged properly. Finally, by leaving the overlying layers exposed above the track surface (~2 m high), the heavy fracturing of the beds means that large blocks can fall out (*e.g.*, pile of blocks at quarry edge in Fig. 5c). This could damage the surface with blocks impacting and then being moved around the surface and could be a hazard for visitors themselves who frequently sit underneath the quarry wall.

Third, Wright et al. (1998) ultimately concluded that visitors should not be allowed direct access to the quarry surface but instead walk around the edges of the site, viewing it from above with tracks and information panels (including a site map and palaeo-reconstruction of the site) made accessible around the edges to help visitors understand what they are looking at. We note that visitors have direct access to the surface and visitor erosion does likely contribute to the continued erosion of the site particularly as the number of loose pieces increases and these are removed and or moved around the site. A staffed site was considered unfeasible given the potential cost to the visitor and the set-up and maintenance to the operators.

An excellent example of a site where a variety of conservation approaches have been trialled, with varying degrees of success, is Lark Quarry (now Dinosaur Stampede National Monument), Australia. Lark Quarry contains > 3000 tracks exposed over a small area (~210 m^2), is scientifically valuable and was initially interpreted as unique evidence of a dinosaur stampede (Thulborn and Wade, 1979) or more recently as the product of time-averaged activity in a riverine setting (Romilio et al., 2013). The site was discovered in the late 1970s (Thulborn and Wade, 1979) and set up as a major tourist attraction but left unstaffed (Agnew and Demas, 2014). The track surface was sealed, taking one individual five months to seal a surface roughly half the size of Spyway Quarry and a sheltering roof built over the site (Wright et al., 1998; Agnew et al., 2014). However, deterioration of the surface was significant over the following decades due to factors such as temperature extremes, water damage, animal excrement and carcass decomposition, theft, vandalism, and direct visitor contact with the surface (Romilio et al., 2013; Agnew and Demas, 2014). Hence, in 2002, the site was enclosed in a state-of-the-art temperature-controlled conservation building and fully developed into a staffed tourist attraction to prevent its loss. Whilst an extreme case, experiences at Lark Quarry do highlight that regular monitoring is key to ensuring site integrity and timely interventions and that the only 'fool-proof' way to truly preserve sites is construction of a fully enclosed, climate-controlled building and removing direct visitor access to the surface. This is a notably rare approach and conservation plans are highly variable between sites globally because of the wide range of considerations involved from number of sites, scientific, historical and or cultural value of the site, economic impacts, and resource availability. As a result, it is most common to leave tracks exposed, occasionally with some interpretative aids.

4.3. The future of the site

Spyway Quarry is a unique visitor attraction and provides firsthand evidence of the presence of sauropods in Dorset in the Early Cretaceous informing the make-up of vertebrate communities for a time and location where the UK body fossil record is very poor (*e.g.*, Benson, 2009; Barrett et al., 2010; Barrett and Maidment, 2011; Lomax and Tamura, 2014). With no new further protections provided for the site, the surface will continue to deteriorate and the tracks become progressively more indistinct and difficult to recognise within the coming decades. The question becomes what can or should be done to ensure that this part of the Jurassic Coast experience and legacy is not lost.

The size of the individual tracks and the site overall, makes it impractical to lift the surface for relocation to a more secure and protected location. Museums rarely have the space to store or display large trackway surfaces. This highlights the critical importance of accurately recording sites upon discovery to ensure that a record for both the public and scientific study is available long-term as well as to provide a time stamp against which to monitor changes and, if necessary, put in place interventions. Photogrammetric models are increasingly quick and easy to generate requiring only a device that can take photos as input to computer software packages (*e.g.*, *AliceVision Meshroom* or *COLMAP*, see Falkingham, 2021 for a review of free and commercial software packages) or phone applications, many of which are freely available. Many of the latest generation of smart phones and iPads now also, as standard, incorporate 3D laser scanning capabilities (LIDAR) with applications that can automatically generate downloadable 3D models. Depending on the nature of the site or feature being recorded, it may also be necessary to utilise an extendable pole (as here) or drone to ensure sufficient field of view in images. However, increasingly no formal technical training is required to generate a high-quality 3D model and thus, this approach is widely accessible to all. This approach should therefore be a standard part of monitoring and recording protocols and will be especially valuable at sites which are difficult to access physically (*e.g.*, remote location) to improve their accessibility digitally. Whilst models can be qualitatively evaluated and/or utilised for outreach or record keeping, quantitative model analysis (*e.g.*, comparison of two models as in Fig. 6) does require a more specialist expertise, as these approaches are not yet so easily automated. Models and raw data of key sites and/or features should as routine be stored publicly in permanent (and free) scientific online repositories such as Figshare (https://figshare.com) or Zenodo (https://zenodo.org/) (see recommendations of Falkingham et al., 2018). A link to these data from any published outputs (*e.g.*, journal articles, reports, or online resources, where they are available) should also be provided (and *vice versa*) to ensure maximum traceability. Subsequently, 3D models can also be uploaded to Sketchfab, an outreach focused site, with links included to the main scientific repository.

The conservation and communication measures proposed in 1998 by Wright et al. (1998) still stand as the best options to preserve the site if maintaining the long-term integrity is a priority and indeed are standard recommendations for the preservation of many *in situ* tracksites (*e.g.*, García-Ortiz et al., 2014). However, the difficulties, expenses, and rationale for not implementing these at the time remain unchanged and are not unique to the Jurassic Coast but play out globally (*e.g.*, Agnew and Demas, 2014). Furthermore, erosion is a natural part of the Jurassic Coast that has shaped the coastline and inland areas and will continue to do so and is an accepted part of the Jurassic Coast ideology. Thus, active efforts are underway to understand and record the legacy but not to retain every aspect as it currently exists.

Quarrying of the Portland Limestone continues on the Isle of Purbeck and will do so for the foreseeable future raising the possibility of further discoveries that may supersede Spyway Quarry. Tracks are known from throughout the Early Cretaceous sediments, including the Cherty Freshwater, Intermarine (now the Stair Hole Member) and Corbula members of the Purbeck Group, but these are predominantly tridactyl in nature (which may reflect the fact that these are easier to recognise) with few sauropod tracks known (Ensom, 1995, 2006; Wright et al., 1998). Tracks are most commonly found as isolated occurrences (not part of trackways), largely because of the nature of the quarrying process and/or of coastal exposures that reveal them. Some Purbeck quarries sell discrete tracks identified during quarrying for decorative landscaping. A second smaller sauropod tracksite was found in 2018 during quarrying by staff at Lewis Quarry, not far from Spyway Quarry and likely from the same stratigraphic horizon (Bournemouth University, 2018). The track surface was imaged, and a number of tracks lifted for storage/display following development of a conservation plan drawn up in collaboration with the quarry operators and landowners the

National Trust so that the surface could subsequently be quarried (Bournemouth University, 2018). As a result, this tracksite no longer exists. This highlights tensions between the commercial value of the stone being quarried and the scientific or cultural value of trackway sites and helps to explain why not all sites are conserved.

4.4. Public value of site and potential improvements

Although our visitor count data are incomplete, they do demonstrate intensive use of the site, with likely > 2000 visitors/month in the busiest summer months (*e.g.*, August), lower numbers in the autumn (and likely also the spring) and low numbers of visitors throughout the winter. Conservatively, we estimate at least 10,000 visitors to the site annually. Whilst a number of visitors may happen upon the tracks whilst traversing the coast path, social media reviews indicate that a number do come specifically for the tracks themselves, and the Jurassic Coast Trust runs guided walks throughout the summer months each year together highlighting the high value of the site for local tourism. Although not captured by our data, the site is also used by a number of educational groups (*e.g.*, undergraduate students at the University of Birmingham and University College London). Whilst visitor feedback was overall positive, there were a number of areas of negative comments which could be considered for future site management. In particular, these include the difficulties of finding the site from the two main access car parks (Fig. 11). These difficulties perhaps contribute to a relatively frequently expressed view of visitors of feeling underwhelmed when they arrived at the site. Consideration could be given to better signposting from car parks and perhaps more information in car parks and/or online on what to expect at the site to manage visitor expectations and enhance their experience. Notably these interventions could strike a balance by not increasing the advertising and driving further footfall to the site to minimise conflict with the 'journey of discovery' ethos.

The current level of information provided at the site is relatively modest (one information panel: Fig. 12), although covering most of the key points. This could be expanded, perhaps through the incorporation of QR codes linking to further information or augmented reality to show reconstructions of the potential trackmakers (*e.g.*, Bennett et al., 2022) or additional information boards provided at the site itself. Once scientifically described, University and other formal education groups, particularly local school groups, might benefit from basic resources (*e.g.*, quarry map, interpretative images of individual tracks or classroom activities) that could be hosted online.

5. Conclusions

Spyway Quarry is the largest easily accessible *in situ* dinosaur tracksite in the UK. It provides direct evidence for the presence of sauropod dinosaurs in Dorset in the Early Cretaceous and the public with the opportunity to engage directly with dinosaurs. Here we used a range of photogrammetric models, images, and visitor analytics to assess how the site has changed between 2014, when it was first opened to the public and the elements, and 2021 when our study took place in order to evaluate the site's current conservation plan. Our work shows that the site has changed through time with deterioration and loss of material evident across the entire surface although focused primarily along fractures that cross the surface, and on track margins as a function of primarily weathering processes and to a lesser extent visitor erosion. We show that the site is popular with ~10k visitors per year including educational and tour groups highlighting the wide appeal of the site and value to local tourism. Whilst the deterioration and eventual loss of the site is disappointing based on its current trajectory, letting erosion play out is part of the natural cycle and ethos of management for the Jurassic Coast and meaningful interventions have high cost and significant logistical considerations. Retaining access to the surface for visitors is considered a priority by the managing bodies and indeed appreciated by visitors. Thus, at present, we recommend only minimal changes to the current management plan for Spyway Quarry to maximise the value to visitors and the heritage sector more broadly. Our recommendations are as follows:

[1] In the wider context of Earth Science sites, Spyway Quarry is not an immediately high-risk site and will be viable for the coming decades. Thus, we recommend site monitoring every ~3–5 years, a timescale over which we might expect to see a quantifiable change in the surface and consistent with the frequency of ~3 to a maximum of 6 years recommended by Wignall (2019) for "robust" Earth Science sites. This should include generation of a new 3D site model for the public record, and for quantitative comparison with those from 2014 and 2021. This should be complimented by a qualitative evaluation of any damage against

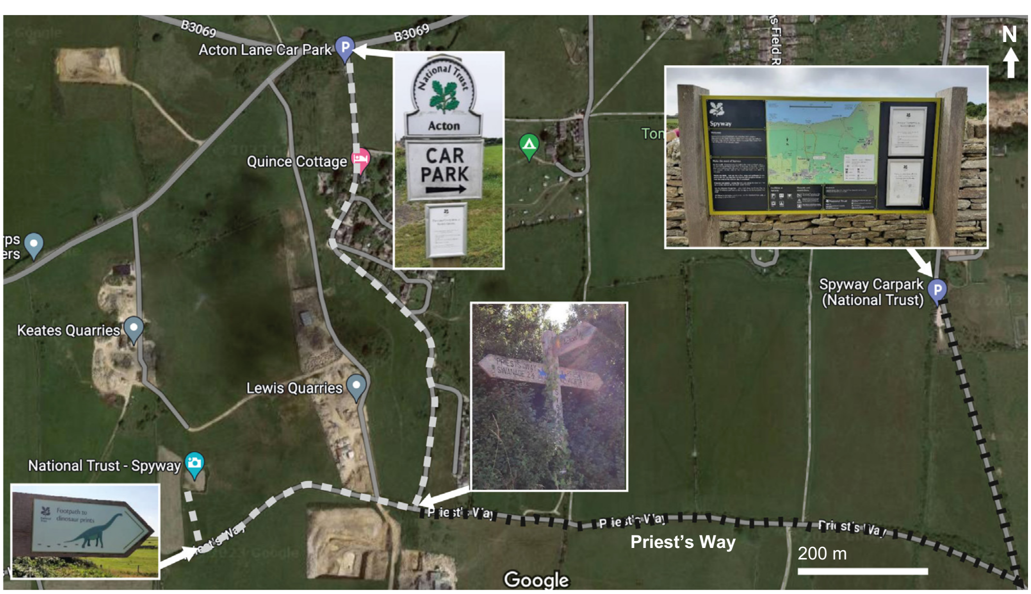

Fig. 11. Map showing the main access car parks (Acton and Spyway), walking routes (dashed lines) and signage to Spyway Quarry. Acton car park has a small A4 sheet of directions to Spyway Quarry underneath the car park sign. Spyway car park included a map of the local area with Spyway Quarry marked on. The tri-sign at the intersection of the routes from the Acton and Spyway car parks does not signpost Spyway Quarry only Priest's Way. Background map is from Google Maps.

Fig. 12. The interpretative panel at Spyway (previously Keates) Quarry created by the Jurassic Coast Trust.

an image of the 2021 3D model, to both validate any large changes detected in the site surface in the model as well as very small changes below the sensitivity of our technique (±2 cm). This dual approach would allow interested parties to understand how the site is changing and at what rate to understand the longevity of the site (and other similar sites).

[2] Expansion of the information available at the site for visitors to aid interpretation.
[3] Free online resources for educational groups and visitors.
[4] Continued removal of plant life from the surface.
[5] Encourage visitors to walk around the quarry to get a clearer overview of the surface.
[6] Add a 'please make sure the gate is closed behind you' notice to the main quarry gate to reduce livestock access.
[7] Evaluate current signposting provision from car parks to site.
[8] Increase the information available on the site in car parks to better manage visitor expectations.

Here we present a valuable case study using a novel array of digital tools to assess how anthropogenic and natural processes can be used to monitor changes in geosite condition and use through time. The approaches and lessons learned here are widely applicable to geosites globally. Most importantly our work emphasises the wider need for 3D models and detailed photographs of sites to be made upon discovery and at regular intervals (determined based on the risk to the site) and made openly accessible to the public. This will provide a key resource for site monitoring, improve the accessibility and value of sites to a global audience, and ensure that a record of our palaeontological heritage is preserved for posterity. Thus, generation and open access to such image data online should form an integral part of any site management plan.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pgeola.2023.01.001.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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