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THE TRANSJURANE HIGHWAY DINOSAUR TRACKSITES AND THEIR SIGNIFICANCE AND APPLICATION FOR ICHNOLOGICAL STUDIES OF DINOSAUR PALAEOBIOLOGY.

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INTRODUCTION

As has been unanimously commented upon in previous expert reports (Lockley, 2009; Bates, 2010; Hutchinson, 2010; Stevens, 2010), the dinosaur tracksites of the Transjurane Highway represent an incredible scientific and cultural resource. Having been fortunate enough to spend time visiting the tracksites during September 2010, in particular the Courtedoux—Béchat Bovais and Courtedoux—Sur Combe Ronde tracksites, we were able to see firsthand the extent to which this is overwhelmingly the case.

What makes the tracksites globally unique is twofold. Firstly, it is the fossils themselves, of which the sheer number alone is of great consequence, enabling statistical studies into track variation both between and within individual trackways. Even regardless of the abundance of tracks, their preservation is also of great interest to palaeontologists and sedimentologists. Secondly, it is not only the tracks themselves that warrant such praise, but also the methods of documentation that have been carried out as part of the ongoing Palaeontology A16 Project. The methodical collection of data combining traditional ichnological techniques with modern documentation technologies such as high resolution laser scanning and photogrammetry, as well as the collection of specimens and the production of casts has lead to an ichnological research resource that is internationally unparalleled in terms of volume of data and potential accessibility of that data.

However, as noted by Hutchinson (2010), documentation, scientific research, and subsequent publication must occur together, for data collection is nothing without published scientific findings, and as expressed by Stevens (2010), the monumental task of carrying out documentation and research simultaneously demands that such work be undertaken collaboratively in order to maximise efficiency. This report aims to present possible research projects that combine the extraordinary data collected by the Palaeontology A16 Project with recent advances in virtual ichnological methods with the hope of producing high impact publications that will become not only a part of global dinosaur track research, but integral to a wide range of palaeobiological studies concerning palaeo(bio)geography, biomechanics, palaeoenvironment and substrate mechanics. It is also important to make data and results accessible, not only to other researchers who can then advance the science further, but to the public as well, in order to educate and inspire future generations of scientists.

The remainder of this report is divided into three sections. The first of these sections will outline possible research projects including hypotheses, general methodologies, and the expected time taken to complete the research. The second part will look at how the data and research can be used to both engage with the public and be made more accessible to other researchers. Finally, the third section will discuss the challenges and technical aspects of working with such a volume of digital data as has been, and is currently being, collected by the Palaeontology A16 Project.

POTENTIAL SCIENTIFIC PROJECTS POSSIBLE WITH THE DATA FROM THE TRACKSITES

The digital documentation of the Transjurane highway dinosaur tracks has produced a wealth of data. The digitised tracksites can be used for carrying out basic research such as making accurate measurements of individual tracks and documenting the relationship between tracks and trackways, providing information directly applicable to answering questions regarding the size (Thulborn, 1990), speed (Alexander, 1976, 2006), gait (Day *et al.*, 2002; Day *et al.*, 2004), behaviour (Lockley, 1991), and palaeobiogeographical relationships (Lockley *et al.*, 1994) of the extinct track makers. Traditionally, such fundamental research has been limited to two dimensions, dealing only with length, width and other such measurements of tracks. Publication of such data has often been in the form of two dimensional diagrams and photos, making reproducible measurements difficult. The three dimensional laser scan data collected by the Palaeontology A16 team, particularly if made readily accessible (see section 2 below) represents the ideal accompaniment to publications of fundamental science such as descriptive work.

As noted by Hutchinson (2010) however, regardless of the high quality of such publications, descriptive work is nevertheless often restricted to specialist journals. Of utmost importance is to produce high impact research in collaboration with international scientists from multiple disciplines in order to bring the tracksites to the attention of the global community.

The Transjurane highway dinosaur tracksites are a fantastic resource for generating high impact research and subsequent publications with much wider applicability to palaeobiology as a whole. Much of the potential to conduct far reaching science lies in the quantity of tracks and completeness of trackways preserved at the sites in question. A track is the product of three factors: foot morphology, substrate, and limb dynamics (Padian and Olsen, 1989). The long trackways (over 100 m in length at the Courtedoux—Béchat Bovais tracksite) allow for a high sample size in which the animal's foot remains constant, and in which the substrate can be reasonably constrained. Knowing two of the three formational factors, one can begin to make informed interpretations of gait and limb motion. Alternatively, in areas where the trackway parameters remain relatively consistent (indicating consistency of gait), the tracks can be used to study local variations in substrate properties, which in turn can be mapped and applied to other trackways that may be varying due to substrate consistency.

Recent work at the University of Manchester by Falkingham (2009) and Falkingham *et al*. (2007; 2008; 2009; 2010a; 2010b; in review) has seen the development of computational techniques for simulating and studying track formation and resultant morphology. By using a technique known as Finite Element Analysis (FEA), in which a virtual substrate is divided into smaller, simpler components, the response of the substrate to a load (e.g. an animal walking over the substrate) can be modelled (Figure 1). By altering loading conditions and substrate properties, any number of tracks can be simulated and compared with real fossil tracks. Additionally, researchers at the University of Manchester have been collecting and maintaining laser scan data from tracksites around the world, which provides a strong data source for comparative work (Bates *et al.*, 2008a; Bates *et al.*, 2008b; Bates *et al.*, 2009a; Bates *et al.*, 2009b; Bates *et al.*, 2010).

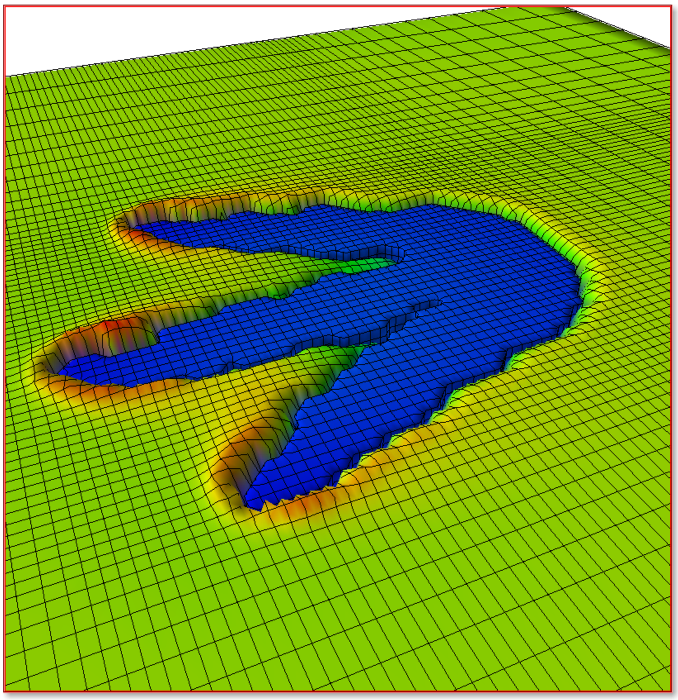

Figure 1 - A simulated theropod track using finite element analysis. Warmer colours indicate substrate displaced upwards, and cooler colours represent substrate displaced downwards. The elements into which the substrate (and foot) has been divided are shown. (From Falkingham, 2010)

Following are several potential research outlines for collaborative work between the University of Manchester and the Palaeontology A16 Project. These research outlines specifically aim to bring together the strengths of both teams, combining real three dimensional track data with computer simulations of track formation, and cover biomechanics, sedimentology, and taphonomy/preservation. Much of this research builds upon current and recent research carried out at the University of Manchester, and also employs equipment and techniques developed at said institution. Where the Palaeontoogy A16 Project provides data, the University of Manchester will reciprocate with comparative data, and computational facilities for carrying out modelling work. By combining the data from the Palaeontology A16 project and the techniques and expertise from the University of

Manchester Palaeontology Research Group, both groups will be able to be a produce collaborative research that will enhance the importance of their respective data stores and technical methods.

1. **[Biomechanics] Variations in limb dynamics between wide and narrow gauge sauropod trackways**

Some of the most striking trackways documented from the Transjurane Highway tracksites are those in which the ‘gauge’ changes from narrow to wide within the trackway (e.g. the two parallel trackways S18 and S19 on level 515 of the Courtedoux—Béchat Bovais tracksite). Traditionally, sauropod tracks have been described as either being wide gauge or narrow gauge (Farlow, 1992), that is, with the pedes near or crossing the midline of the trackway (narrow gauge) or set further apart (wide gauge) (Figure 2).

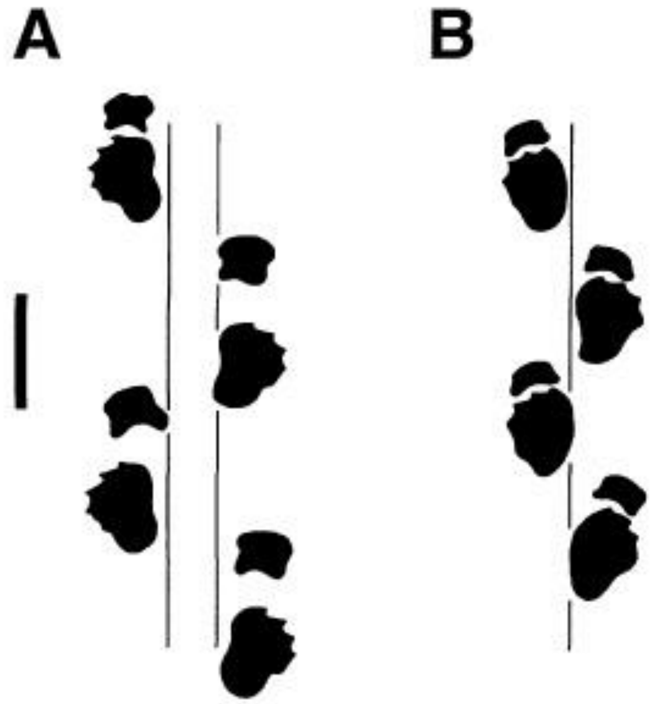

Figure 2 - Wide (A) and Narrow (B) gauge sauropod trackways. (from Wilson and Carrano, 1999)

Wilson and Carrano (1999) stated that the gauge of sauropod tracks was a consequence of skeletal morphology, and that it was unlikely a single sauropod could have produced both wide and narrow gauge trackways – obviously the trackway at Béchat Bovais contradicts this statement. More recent studies have proposed that trackway gauge may be a result of locomotor style or ontogeny (Wright, 2005; Henderson, 2006; Marty *et al.*, 2006; Carpenter, 2009), however a comprehensive study by Marty *et al.* (2010) suggested that gauge was independent of trackmaker size and speed.

The effects of skeletal morphology on track morphology can be tested using computer simulation. Given the skeletal reconstructions of predicted narrow and wide gauge trackmakers (Figure 3), a simplified ground reaction force can be reconstructed from the foot to the centre of mass (arrows, Figure 3). By applying the reverse of this force to virtual sauropod feet in the computer simulations, virtual tracks can be simulated to compare with the real tracks of the Transjurane Highway tracksites. In particular, it is the distribution of displacement rims (raised substrate) around the tracks that will be indicative of the loading conditions (Manning, 2004). A wider gauge stance would be expected to produce tracks in which the displacement rims are greater around the outside edge of the track owing to the direction of force. Comparisons can be made between the simulated 'wide gauge' and 'narrow gauge' trackways, and the Transjurane dinosaur trackways. Such a comparison can be made using quantitative methods owing to the digital nature of both the simulations and the laser scan data recorded from the Transjurane Highway trackways. The bipedal, tridactyl tracks may also be subject to a similar study, given that many of these trackways also display variations in gauge and configuration.

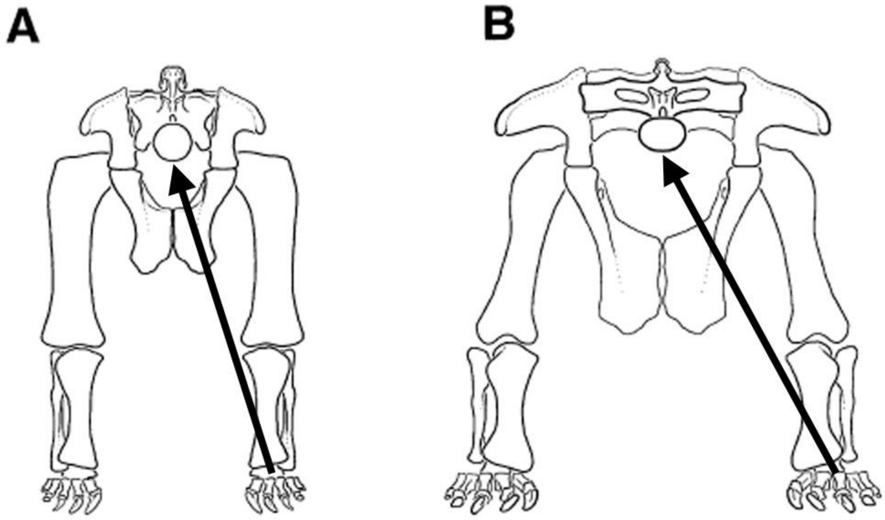

Figure 3 - Reconstructed pelvic girdles and hindlimbs of *Camarasaurus* (A) and *Opisthocoelicaudia* (B) in anterior view. Both figures are normalised to the same height. Black arrows represent reconstructed ground reaction force (the reactive force of the ground resisting the animal) from the foot to the centre of mass; note the more lateral direction of the force in B. (Adapted from Wilson and Carrano, 1999).

The above research takes advantage of simplifications in loading conditions, and builds upon pre-existing simulations of sauropod tracks produced by Falkingham *et al.* (2010a). As such, the study could be completed in approximately three months. However, the study could also be expanded upon by incorporating more complex and realistic loading conditions such as those produced by Stevens and Wills (2009). Finite element simulations could be generated using input data from gait reconstructions, and the resulting FEA tracks compared with those tracks scanned as part of the Palaeontology A16 Project in order to corroborate or disprove the locomotor reconstructions.

Additionally, comparisons could be made between the Transjurane Highway tracksites, FEA simulations, and other sauropod trackways from around the globe. By comparing simulated tracks with real fossil tracks from multiple sources, it may be possible to discern if the Swiss trackways in which gauge changes along their length are formed in the same way as trackways from elsewhere where trackway gauge remains consistent throughout trackway length. For this work, the University of Manchester already maintains digital collections of important sauropod tracksites from around the world (e.g. Paluxy River, USA, Liujiaxia

Geopark, China, and Fumanya, Spain) which could be used for direct comparison with both the digitised tracks of the Transjurane highway and the virtual FEA tracks. Given that these resources are currently owned by the University of Manchester, such comparative work could be undertaken at little or no cost to the Palaeontology A16 project, whilst greatly enhancing the scientific value of the project's data.

2. [Sedimentology] Predicting substrate conditions from tracks

The extent of the trackways present on many of the Transjurane dinosaur tracksites, particularly at Béchat Bovais, enables an observation of substrate properties over an area. Complimentary to the project outlined above, this project would aim to investigate the amount of variation attributable to sediment variation. The properties of a substrate at the time of track formation can be difficult to ascertain. Whilst grain size, shape, and composition can be reconstructed from thin-sections of the lithified sediment, factors such as water content – instrumental in determining the consistency and mechanical properties of the substrate – are lost when the substrate becomes a rock. Morphological variations within a trackway (ideally one where trackway parameters do not change along its length, indicating a consistent gait) can be compared with simulations in which the sediment properties are altered.

One of the primary advantages of computer modelling track formation over physical modelling is that parameters such as substrate properties can be controlled precisely and altered systematically independently of other variables such as loading and foot shape (Figure 4). With high performance computing (HPC), many hundreds of simulations can be run simultaneously, producing a range of results. By comparing the three dimensional track morphology of the fossil tracks (from the scan data) with the simulated virtual tracks, inferences can be made as to the mechanical properties of the track bearing substrate at the time of track formation (Falkingham *et al.*, 2009).

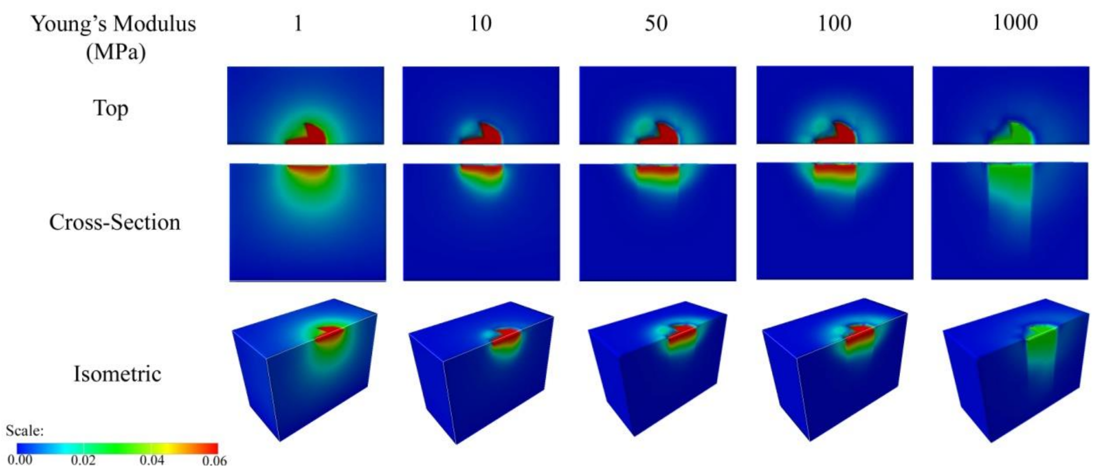

Figure 4 - Varying Young's modulus (the elasticity) of a soil, whilst maintaining other variables as constant. As substrate properties change, the track morphology (both surface and subsurface) alter. By directly comparing simulated tracks with digitised fossil tracks, inferences can be made about substrate mechanical properties at the time of track formation. (Image courtesy of P. L. Falkingham, University of Manchester)

By following long trackways and comparing individual tracks with those generated using FEA, a spatial map of substrate properties (i.e. softer to firmer substrate) can be produced. Such a map would have strong implications for palaeoenvironmental interpretations, as it could highlight a palaeo-water table, or indicate proximity to a body of water. The property map could be overlain onto the 3D scan data for visualisation purposes, and compared with changes in trackway parameters (inferred changes in gait). This may elucidate as to whether the change in gauge within sauropod trackways discussed above is related to substrate – e.g. the animal needing to adopt a different gait to deal with differing substrate.

This project would require detailed analysis of many individual tracks from the scan data, and the generation and execution of numerous computer simulations, both of which would then need to be compared with one another, before a spatial map of substrate properties could be produced and overlain on 3D scan data. As such, this project could be expected to take between 6 and 9 months.

3. [Preservation] Heterogeneity

The Courtedoux—Béchat Bovais tracksite is interesting in that it is clear that the original track bearing surface (level 515) was underlain by a firmer layer (level 510), as evidenced by subsurface layers containing desiccation cracks that are in most places only very slightly deformed by the tracks above. The inclusion of a firm layer some 5-10 cm beneath the current track bearing surface may have had considerable effects on the surface morphology of the tracks, preventing sediment from being displaced downwards, and instead forcing it upwards to create extensive displacement rims (Figure 5). It has also been reported that there was a microbial mat present on the surface of the track bearing substrate that aided in preserving the tracks by acting as a firmer, cohesive surface layer (Marty, 2008; Marty *et al.*, 2009). This too would have altered the mechanical properties of the overall substrate, potentially altering initial track geometry.

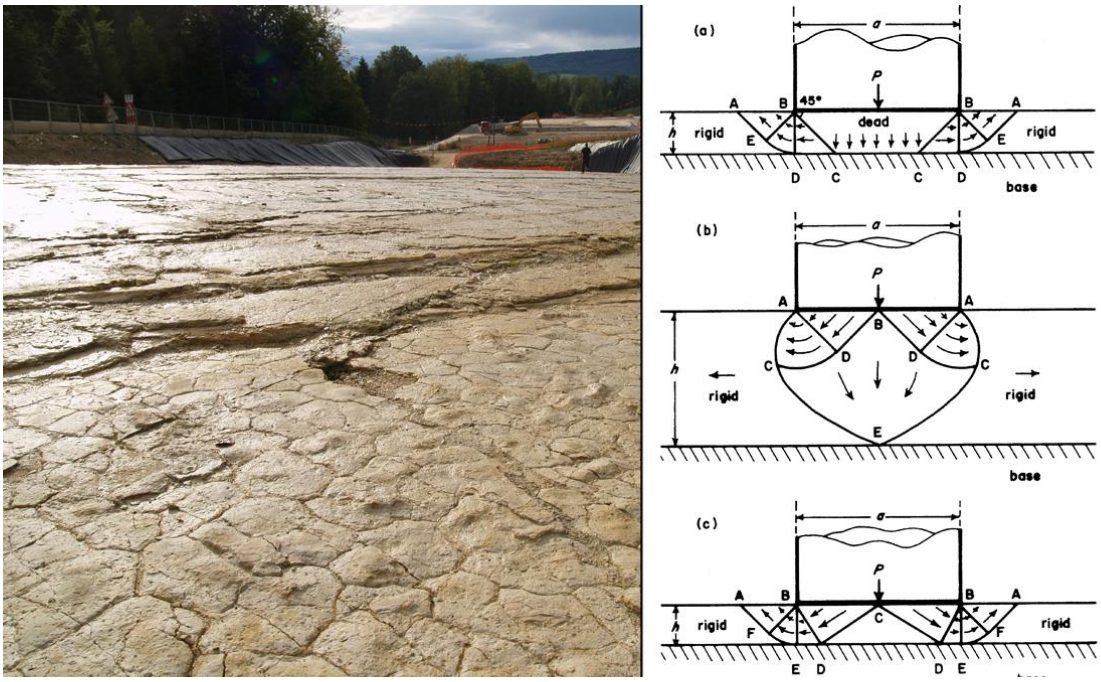

Figure 5 - Left; the Courtedoux—Béchat Bovais tracksite, showing the mud cracked subsurface level 510 exposed beneath the upper track bearing level 515 (Courtesy P. Falkingham). Right; different substrate failure mechanisms depending on the depth of a firmer subsurface layer (From Allen, 1997).

In order to draw comparisons between the tracks of the Transjurane Highway dinosaur tracksites and other tracksites world wide, and in order to make confident interpretations about the animals that made the tracks, it is important to understand the affect that the sedimentology has had upon the final track morphology. In a similar manner as that described above, simulations can be produced and run in which the presence of a microbial mat or subsurface firm layer can be added or removed, and the resulting differences in track morphology compared with the tracks from the Courtedoux—Béchat Bovais tracksite.

The Béchat Bovais tracksite itself currently hides a subsurface track bearing layer that can be seen in small exposed areas. This subsurface layer is much more resistant than the current, friable track surface. Excavation of the site and subsequent documentation including laser scanning and photogrammetry prior to the Highway being constructed is currently under way and financed by *paléojura* and this will moreover allow:

- Mapping of the second track bearing surface (i.e., the main track level 500) will include not only new data, but also potentially the undertracks of the current surface layer. This would provide great insight into sediment deformation through a heterogeneous substrate volume, and also provide data from a tracksite separated temporally from the current track bearing surface.
- A detailed sedimentological analysis throughout the depth of the current track bearing surface, which would provide initial parameters for simulating these tracks.
- Provide a more resistant surface for conservation purposes.

This research project is a more comprehensive undertaking than the previous two outlines, and would benefit from further excavation and documentation of the Courtedoux—Béchat

Bovais tracksite. As such, this project could be expected to take between nine and twelve months.

TECHNICAL ASPECTS

In his report, Stevens (2010) outlined the nascent nature of digital data collection in palaeontology. The importance and utility of maintaining a digital collection of dinosaur tracks and tracksites has been discussed both here and in previous reports of the area (Lockley, 2009; Bates, 2010; Hutchinson, 2010; Stevens, 2010), but cannot be overstated. It is an exciting time to work in vertebrate palaeoichnology, as the utilisation of laser scanning and photogrammetry become more widespread (Breithaupt and Matthews, 2001; Breithaupt *et al.*, 2001; Breithaupt *et al.*, 2004; Bates, 2006; Matthews *et al.*, 2006; Bates *et al.*, 2008a; Bates *et al.*, 2008b; Falkingham *et al.*, 2009; Bates *et al.*, 2010; Farlow *et al.*, 2010a; Farlow *et al.*, 2010b). Within the next decade, we can expect international collaboration and sharing of data to become far more common, resulting in a considerable advancement of our science thanks to the versatility of digital data, with colleagues able to send accurate three dimensional models of specimens via the internet.

At the University of Manchester, we have been collecting and maintaining a repository of laser scan data of both dinosaur tracksites and skeletons for over five years. Other institutions are also actively collecting and storing digital records of palaeontological specimens. However, at the moment this data is distributed among research groups and generally not distributed or made available to outside researchers. When it is, a lack of standardisation and distribution methods act as a hindrance to effective research.

The Palaeontology A16 Project is in a strong position to become the focus point for digitised fossil storage and distribution. Having collected vast quantities of photogrammetric and laser scan data of tracksites, and having subsequently catalogued and stored the data in a methodical, logical, and efficient manner, the Palaeontology A16 Project (or *Paléojura*) is ideally suited to forming the first international repository of laser scan data of dinosaur tracksites. The importance of creating the first repository for scan data must not be underestimated, as it would provide a platform for standardised formats and facilitate access to research data. As the situation currently stands, differing formats make sharing data difficult and time consuming as scientists spend time finding appropriate software with which to carry out analyses. We highly recommend that the Palaeontology A16 project be provided with the resources and long term support required for establishing such a data centre and encouraging standards among researchers, as has also been recommended by previous expert reports (Bates, 2010; Hutchinson, 2010; Stevens, 2010).

We would recommend that given the ubiquity of different software packages in use for visualising and analysing digital data, that an ASCII format is encouraged (containing X,Y,Z,R,G,B data), at least until commercial software and processes become more standardised, as this will provide the most compatibility with existing Point Cloud and CAD packages. Difficulties remain in setting up a digital repository centre, such as the rights and wishes of the researchers who collect and submit data to the repository. However, a system ensuring that those who use the data must reference both the owner of the data and the repository itself should provide an environment that encourages submission of data through the reward of citation. There are several existing examples of similar online databases such as the Palaeobiology Database (http://paleodb.org/cgi-bin/bridge.pl) and the Open Dinosaur Project (http://opendino.wordpress.com/) which although storing much smaller, simpler entries, could be used as examples for how to handle user submitted data and meet the needs of recognition of work and availability to a wide audience.

It would be a tragic loss to science if the large quantities of data collected by the Palaeontology A16 project were not professionally stored, curated, and made available to scientists, and perhaps also the public. Not only would the formation of a data centre place Switzerland and the project team firmly centre stage in global palaeontology, but such a centre would advance scientific progress across the world.

SCIENTIFIC EDUCATION OF THE PUBLIC USING THE TRANSJURANE HIGHWAY DINOSAUR TRACKSITES

The dinosaur tracksites of the Transjurane highway represent an exciting opportunity and resource with which to educate the public. Passing on the discoveries made by the scientific community is important, for it encourages members of the public to consider the natural world and their place in it. Relaying scientific discoveries to non-scientists, particularly children, may inspire the next generation of scientists, including not just future palaeontologists, but Doctors, Engineers, Biologists, and Physicists. Also, of course, much funding in palaeontology comes from the public, and making the effort to conduct outreach is one way of returning something for that funding.

Dinosaurs are one of the best subjects with which to educate the public about science, as they captivate the imagination in people of all ages. Dinosaur tracksites, such as those discussed here offer something quite different to the skeletons found in a museum. While mounted skeletons rarely fail to inspire awe in those who see them, tracksites maintain something deeper. That the tracks remain *in situ* infers a much more ethereal feeling, some deeper connection that truly brings the animals to life, as the observer appreciates that once these iconic beasts walked in this specific place.

We concur with the recommendations of Hutchinson (2010) that efforts be made to open at least one tracksite to the public so that they can see firsthand the important palaeontological sites. Such an attraction would be greatly complimented by using the laser scan data recorded from the Transjurane Highway dinosaur tracksites. The three dimensional scan data collected by the Palaeontology A16 Project is perfect for producing 'virtual field trips.' These can be as simple as animations providing a 'fly through' of the site(s), or as complicated as a fully interactive exhibit in which users can navigate their way around the virtual environment, and switch on or off layers of information such as bedding angles, directions of movement, or even reconstructions of walking dinosaurs (Stevens, 2010). Such digital accompaniments to the tracksites could be located on site, placing the tracksite in context with other sites further away, providing for instance a fly over of the general area before focusing on the tracksite in question. These virtual displays would allow visitors to visit the tracksite, and be able to view individual tracks close up and in great detail without the necessity of walking on the tracks themselves.

Alternatively, such digital tracksites could be exhibited in museums, or distributed via the internet to take the tracksites to the people (Bates *et al.*, 2009b). This has the advantage of further advertising the site itself and increasing the number of people who wish to visit the site and see the tracks for themselves.

CONCLUDING REMARKS

The Palaeontology A16 Project has, over the past ten years, made an outstanding effort to excavate, document, and study the dinosaur tracksites and other important palaeontological heritage on the future curse of the Transjurane Highway. In particular, the way that the digital data collection, including laser scanning and photogrammetry has been carried out and subsequently maintained is exemplary; as noted by Bates in his report (2010): "This is how science should be conducted."

The Palaeontology A16 project now finds itself in a position where it is poised to become a world leader and standard setter for modern palaeontology the world over.

We reiterate our recommendation that the Project be given the resources necessary to continue this work, such that Switzerland and the Project team become world leaders. This will generate benefits both on a local and global level. Locally, the tracksites can be used to engage with, and educate, the public, providing a major tourism boost for the area and fostering a greater interest in natural history and science in general among the populace. On a wider scale, becoming a leading authority on laser scan data, and being a central repository will facilitate collaborative research throughout the world, initiating a second ichnological renaissance. The project outlines provided here represent just a fraction of potential research that can be accomplished by utilising the data collected by the Project team, and cover several aspects of paleontological science. Further excavations such as at the Courtedoux—Béchat Bovais tracksite would provide both substantial future research benefits, and increase the success of conservation methods; a win-win scenario if resources can be provided to allow this.

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