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IMPLEMENTATION OF STRUCTURE FROM MOTION (SfM) TECHNOLOGY FOR EDCUATIONAL LESSONS

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Dedication

To my beautiful son, Emilio, this achievement is dedicated solely to you.

IMPLEMENTATION OF STRUCTURE FROM MOTION (SfM) TECHNOLOGY FOR EDCUATIONAL LESSONS

by

VALERIA VERONICA MARTINEZ, B.S., M.S.

DISSERTATION

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
in Partial Fulfillment
of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

The Department of Earth, Environmental Resource Sciences

THE UNIVERSITY OF TEXAS AT EL PASO
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Chapter 1: Introduction

Education is the most important obligation the humanity race has in order to evolve and thrive in the modern world. There are various applications for educators to teach valuable lessons to students, and not all deliveries will be the same for every lesson and for every student. Lesson being taught, the lesson delivery from educator to student often changes every time the lesson is implemented, depending on the learning ability of the students. Students have the ability to learn in different ways, such as the visual, auditory, kinesthetic, reading and writing learners (Oxford 2003). As educators aware of the four main learning abilities, we can develop lesson plans that contains a combination of all learning types so that we can serve the whole spectrum of learners. This educational combination has the objective for all students to understand, digest, and apply the lesson. In geoscience, many learning experiences are built around field trips to see and experience what was discussed in the classroom. However, students with disabilities are often at a disadvantage with respect to going to the field, and the educator often needs to modify their lessons to fulfill those students' needs while still achieving the learning objectives of the course (Stefan , et al. 2022). Often time, however, this leads to a lower quality learning experience for those students who need alternatives because educators have heavily depended on images or other alternate forms of presenting the information from the field. In recent years, Structure-from-Motion (SfM) models have emerged as a better choice to use for making alternatives to field trips and similar experiences (A., Zhao and Oprean 2020). SfM models provide a means of creating extremely high fidelity representations of the desired object or place, and therefore provide an opportunity for students to be virtually present where they might not be able to otherwise attend (A., Zhao and Oprean 2020).

As technology evolves, it is important that education evolves with it. In recent years, the education system has invested heavily in technology material for classrooms, such as laptops, tablets, etc. The investment objective is to deliver higher quality education with new and improved infrastructure and material for delivery of knowledge and content. This update has developed an opportunity for educators to have new material to enrich their lessons virtually in an innovative way. Many materials are available already online for educators to obtain and use in the classroom (Martinez V.V. and Serpa 2022).

Structure-from-Motion (SfM) models have been existing in recent years (Granshaw 2018) and their development keeps improving at the same rate as technology does (Granshaw 2018). SfM has been a beneficial visual tool for educators to help students, especially in geoscience to visualize and understand complex, three-dimensional concepts. SfM has been implemented in the whole education spectrum, from pre-Kindergarten to graduate level university courses (Hendajani, et al. 2019).

In this dissertation, I explore applications of SfM technology to the paleontological study of dinosaur footprints as well as to higher education and virtual field trips for persons with disabilities. The dissertation chapters are written as manuscripts, one published (Martinez V.V. and Serpa 2022) and the other to be submitted for publications in the professional literature. Chapter 2 is presents an example of how we would expect teachers to being to use the3D geological models in the classroom and Chapter 3 focuses on advanced topics that include the design, data collection, and processing of 3D models that is suitable for beginning non-majors in a university class and higher lever course for majors. Together these contributions show provide a starting point for educators to incorporate 3D models and the technology to build them into the classroom.

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Chapter 2: Introduction to Teaching Science with Three-Dimensional Images of Dinosaur Footprints from Cristo Rey, New Mexico

Abstract

In this paper we discuss the use of three-dimensional (3-D) imagery and virtual field trips to teach pre-university and non-major university geoscience courses. In particular, 3-D PDF (Portable Document Format) files can be used to either prepare students for or completely replace a field trip when logistical problems make the actual trip too difficult to be effective or when some students need an alternative accommodation. Three-dimensional images can replace or supplement classroom activities, such as the identification of rocks and minerals from hand samples or the identification of geologic structures from 2-D photographs and limited field observations. Students can also become involved in data collection and processing to further their understanding of photogrammetry and visualization. The use of 3-D imagery can make additional time available to instructors to cover more advanced topics and teach students more about the role of science in geologic research.

We use an example from Cristo Rey, New Mexico, where dinosaur footprints and tracks are present but difficult to see in many cases, and they are often in places that are hard to access for many people. At this site, approximately 10 000 photographs were collected and processed as 3-D images to show one approximately 72 m2 area of known footprints. However, we also conducted some very simple digital manipulations of the images that allowed us to identify new footprints and tracks that were not apparent when viewed in the field. The photographs and 3-D images have been donated to the Insights El Paso Science Center (denoted Insights Museum herein) that owns the fossil site, and they are now being used to develop educational materials and lessons for the nearby communities.

2.1 Introduction

The current pandemic has changed education in many ways, but few areas of science education have been impacted as much as the geological sciences where field observations and trips are a significant part of most geoscience curricula. During the pandemic, many universities replaced field trips and exercises with a variety of virtual field experiences (Rotzien, et al. 2021) some prior faculty reticence to the use of computer-based tools for field mapping classes and other field activities. In addition, prior to the pandemic there was a growing trend at many universities and schools in the USA to eliminate or restrict field activities because of administrative concerns about student liability, cost, and, in some cases, the lack of faculty able and/or willing to teach field-based classes on a regular basis. It is our opinion that the pandemic will be a major factor in a permanent decrease in the number of field-based geology activities in US universities. Furthermore, we expect that field observational geology will become virtual for nearly all pre- or early-college students who are not majoring in a geoscience.

One critical question regarding the changing emphasis on field experiences (Whitmeyer, Atchison and Collins 2020) in geoscience education is whether field-based activities are truly essential and where might they be most valuable. The authors of this paper are experienced geoscientists with considerable field experience, but we contend that there are some significant benefits to the use of technology in geoscience education. We argue that non-majors at universities and students in the pre-university system may learn more from virtual field activities than they might learn from actual field-based observations. In particular, we see that the use of three- and four-dimensional photogrammetry models and videos, as well as many other developing technologies like artificial intelligence and large-scale statistical methods (Whitmeyer, Atchison and Collins 2020), has an educational advantage over field work, because these methods of delivery are more relevant to many students. In addition, the incorporation of virtual activities and lessons in a modern textbook should provide more time for discussions of what geoscience researchers actually do and why that is important science. To test this concept, we are working with a local museum to develop educational materials on dinosaur footprints, and that effort is described below.

2.2 Study Area

Cristo Rey, New Mexico Figure 1is the site of numerous Cretaceous dinosaur footprints and trackways that are particularly difficult to recognize and map (Kappus and Cornell, A New Cretaceous Dinosaur Tracksite in Southern New Mexico 2003) (Kappus, Lucas and Langford 2011). Weathering patterns obscure or mimic many of the fossils and the locality experienced Tertiary uplift and tilting that deformed the site and made the terrain difficult to navigate. The fossil site is located adjacent to the US–Mexico border near the cities of Las Cruces, NM, and El Paso, TX, and this makes it a potentially valuable local education resource. The donation of the land to the Insights Museum in 2011 opened the site to educational groups and the development of exhibits, but that work is still in early development. In an effort to preserve as much information as possible on the dinosaur footprints and to provide students and teachers with a non-invasive way to study the fossils, (Martinez 2016) created a detailed high-resolution photographic record of a portion of the site and used that data to build 3-D images of the ground surface. Those images not only provide a record of the site but also led to the identification of several new footprints and fossils based on digital manipulation of the images.

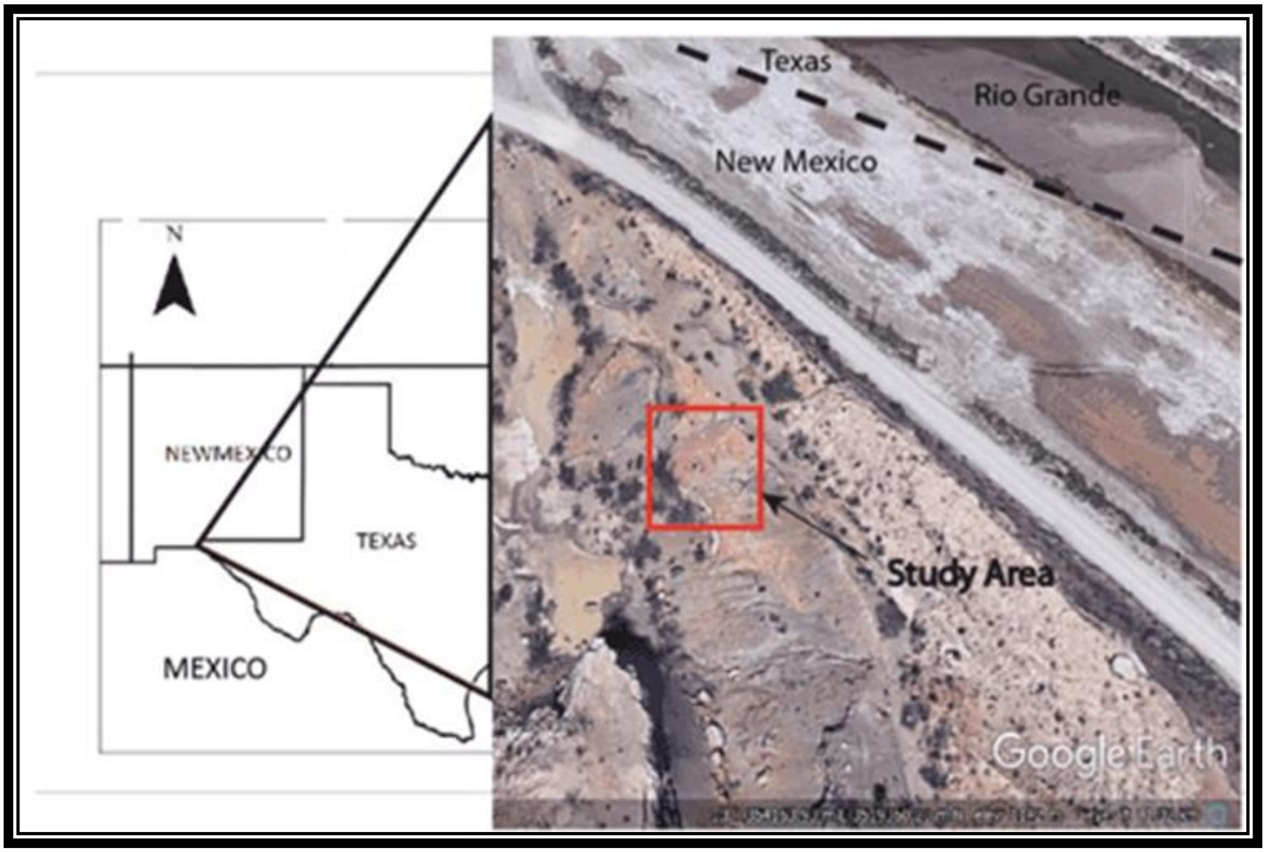

Figure 1 Map of the region modified from ©Google Earth (2021). The red box in the image shows the study area in Cristo Rey, New Mexico

The use of 3-D models to study fossils is a relatively recent technique (Djuricic, et al. 2016); (Bates, Manning and Hodgetts 2008); (Adams, et al. 2010); (Remondino, et al. 2010); (Tavani, Grannado, et al. 2014) that has advantages over methods such as paper mapping, plaster casts or collecting samples as it is non-destructive and can be easily shared with a wide audience. Our preliminary study of the images we collected (Martinez 2016) shows numerous Cretaceous Theropoda, *Iguanodon*, and *Ankylosaurus* footprints Figure 2 previously identified by (E. Kappus, S. Lucas, et al. 2010) and (Kappus and Cornell 2003) as well as new footprints and trails of those dinosaurs that were not previously recognized. These images were donated to the Insights Museum and we are helping to develop educational resources for the local community to encourage studies of the fossils.

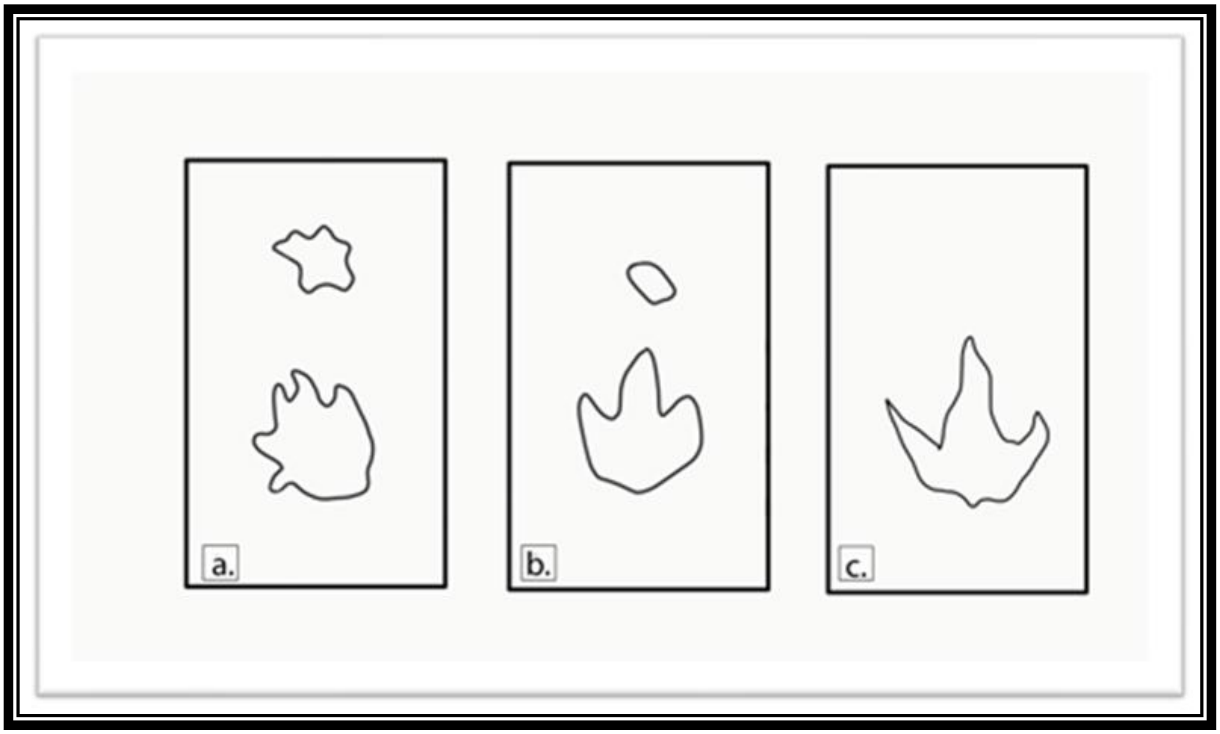

Figure 2 The general shapes of the three types of Cretaceous dinosaur footprints identified (Kappus and Cornell, 2003; Kappus et al., 2011; Martinez, 2016) at Cristo Rey. Panel **(a)** is an ankylosaur, panel **(b)** is an iguanodon, and panel **(c)** is a theropod (outlines modified from Kappus (Kappus, Lucas and Langford 2011).

Our educational activities focus on both methodology and fossil identification for several age groups. In the USA, geology is often taught in middle schools for 11- to 13-year-old students. It is also a popular choice for university students who do not want to use mathematics but are required to take at least one science course. We are focusing on the use of 3-D images that can be easily used in the classroom and manipulated by students with minimal expense or expertise. Our intent is to use this approach to increase interest in the study of geology amongst these groups of students, so we can increase the rigor of our courses over time. Initially the fossil identification activities will follow traditional lessons plans that include the identification of dinosaurs based on their footprints, estimating the size and speed of a dinosaur based on the measured stride (Thulborn 1990), and looking at dinosaur activities in relationship to their environmental setting (Lockley, New Mexico Museum of Natural History and Science 2011) (Lockley, The Paleobiological and Paleoenviromental Importance of Dinosaur Footprints 1986). We anticipate that the Insights Museum will expand on our preliminary work, but we will work closely with them to develop some initial lessons based on our own experience of discovery at the site.

2.3 Geologic Background

The first fossil footprints, identified as Cretaceous theropod footprints, were discovered by Kappus and Cornell (Kappus and Cornell 2003). The footprints are in Cretaceous sedimentary deposits that were intruded by a Tertiary trachyandesite dome (Lovejoy 1976). The dinosaur tracks are located primarily in the upper sandstone of the Anapra formation, which is a massive cross-bedded arkosic sandstone varying in thickness from 1–2 m and interbedded with grey and purple shale (Lockley, The Paleobiological and Paleoenviromental Importance of Dinosaur Footprints 1986). These sedimentary layers indicate that the Cretaceous environment in this area was a shallow sea (Kappus, Lucas and Langford 2011).

2.4 Methods

Most of the initial research on the Cristo Rey tracks consisted of field notes, photos, and drawings (Kappus and Cornell 2003), (Kappus, Lucas and Langford 2011). More recently, technology has become available to create 3-D visualizations of geologic units (Carrivick, Smith and Quincey 2016), and this is changing the way fossils are studied (Remondino, et al. 2010). Eric Kappus, Jose Hurtado, and Raed AlDouri (personal communication, 2016) used lidar to record the Cristo Rey footprints to produce the first 3-D images of the site. The resulting anaglyph 3-D images require anaglyph glasses to see and cannot be easily manipulated on a computer, but they provide the inspiration for continued work in this area.

2.4.1 Data Collection

The original goal of this project was to create a digital record that could be used in educational programs and research that did not require field visits in all cases. The materials needed for this project can be easily obtained and used with teachers and their students (Fleming and Pavlis 2018). However, we did use materials in this project that may not be readily available to most teachers. For example, we used a Nikon camera series D3100 digital single-lens reflex (DSLR) camera for our photography and Agisoft Photoscan Pro™ and ENVI™ software for processing and data analysis, which may not be affordable for most teachers. However, a cell phone camera

Figure 3 Grid layout used to take photographs. The grid spacing is 1 m, and photos were taken from each grid intersection with a camera aimed into the target grid space. The shaded area shows the area we processed for this study, and the heavy dashed line outlines the map area from (Kappus, Lucas and Langford 2011)

and several inexpensive and free software packages can be used if the data set is kept small (Fleming and Pavlis 2018).

Figure 4- The grid system used in this study was based on two metric tape measures laid out perpendicular to each other to establish the locations for photographs. The positions of the individual grid intersections at 1 m spacing were marked as shown in Figure 2.5.

We collected approximately 10 000 photographs and reduced the number to 7600 photographs using a grid system that was approximately 9 m across in the *x* direction and 8 m across in the *y* direction Figure 3. Four people were needed for the data collection with one located at position (0,0) to establish the origin position, one person measuring the *x* coordinates with a measuring tape, another measuring the *y* coordinates with a second measuring tape Figure 4and one using a meter stick to precisely mark grid points on the outcrop using temporary adhesive stickers labeled with the point's coordinate number Figure 5. The lead author, Martinez, developed the grid system, supervised the grid measuring process, and took all the photographs. At each grid intersection, a suite of photographs was taken at a distance of ∼ 1 m from the surface with the camera directed into the adjacent grid areas. This was done at each grid position until all four corners had been occupied for photography. The total number of pictures taken at each grid position depended on the surface texture and variations in the surface of the target. For example, if there were a lot of variations in the target surface, then more pictures were taken in order to capture sufficient details for subsequent modeling.

Figure 5 This photo shows the circular mark used to indicate the intersection of two 1 m spaced grid lines in the survey area.

2.4.2 Data Processing

The images were processed using the structure from motion (SfM) photogrammetry technique (Westoby, et al. 2012). The photogrammetric processing was done using Agisoft Photoscan Pro software to create a 3-D model from the photos. Each set of photos for a single grid section was processed individually to form a 1 m × 1 m “chunk” (Agisoft Metashape 2021), because the data set was too large to process the entire set as a single unit. Once all the chunks were created, they were arranged to form larger chunks, starting with grid positions (0,0) and (0,1). In this fashion, the chunks were iteratively aligned and merged to make progressively bigger chunks.

In 2015–2016 we were limited by available computing power and did not have sufficient RAM and CPU power to create a single model for the entire outcrop. For that reason, we chose to work on a subset of our data in an area where Kappus et al. (Kappus, Lucas and Langford 2011) found the most dinosaur footprints. In early 2021 we used Pix4D software to reprocess some of the data for this paper and have had some success, but we have not yet been able to produce a single model of the entire area. There is insufficient overlap of photos between some of the grid areas to use the SfM software to completely merge all of the images into a single model (Wenzel, Rothermel and Fritsch 2013). The method we used to collect data focused on coverage within each grid area but not on the connectivity between grid areas.

Besides the problems with the lack of overlap between grid sections in many of our photos, the camera was also too close to the surface to accurately capture all of the topographic relief in the region (James, Robson and Smith 2017). We also did not have position information for the individual photos, so it was not possible to georeference the data (Brush, et al. 2019). This was our first effort to collect photogrammetry data, and we recognize our mistakes. We subsequently collected small unmanned aerial vehicle (sUAV, i.e., drone) and lidar data which we will compare to our hand-held photography in the near future. Despite the problems with the initial work, we have high-quality photos of the entire fossil site and can produce 3-D images of the individual gridded sections independently or in small groups. This provides us with an excellent educational data set that students and teachers can access freely and learn more about fossils and photogrammetry techniques.

2.5 Education Application

As noted above, our photos were not georeferenced and lacked sufficient overlap to produce a continuous 3-D model of the area. When we collected the data in 2015, we had no previous experience with photogrammetry and only knew that a lot of photos from a range of orientations were needed to produce a model. This experience is one of several early efforts (Brush, et al. 2019) (Pavlis and Mason 2017) (Fleming and Pavlis 2018) among a group of faculty and students in our department to explore photogrammetry as a potential tool for geoscience research and education. We have subsequently learned a great deal more about photogrammetry, and we recognize the need to pre-plan a project with careful consideration of goals and methodology (Brush, et al. 2019); (Carrivick, Smith and Quincey 2016); (James, Robson and Smith 2017); (Bemis, et al. 2014); (Wenzel, Rothermel and Fritsch 2013).

The photographs described in this paper make up our initial donation to the Insights Museum to provide a permanent record of the fossil site. In addition, we will provide 3-D images made with the SfM software (cloud data) that can be distributed in a variety of formats. The basic format for the cloud data as seen in Figure 7 and Figure 6 is LAS (LASer), a format commonly used for lidar point cloud data, which can be manipulated using software like Cloud Compare™, which is freeware and has the ability to make depth measurements and comparisons with other data sources and many other relevant applications. In addition, we can post images on the web and produce 3-D PDF files (see the Supplement) that can be opened using software from Adobe™ on most standard laptop computers and tablets. For this project, we are focusing on the 3-D PDF images, because most schools and universities have access to these files and the Adobe Acrobat software necessary to interact with them. In many US schools, students are not allowed to access

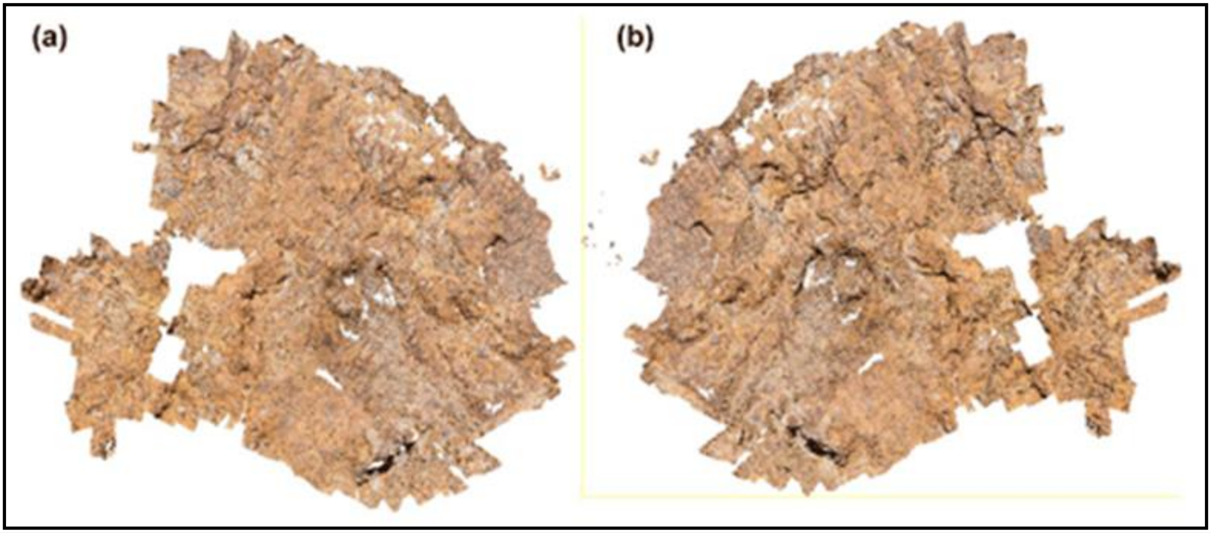

Figure 7- Front and back view of Cristo Rey 3-D PDF image from grid sections (3, 4) to (3, 5) and (4, 4) to (4, 6). Each image occupies an area of approximately 2 m by 2 m. Panel **(a)** shows what a field observer would see in the fossil locality, and panel **(b)** shows the same image as panel **(a)** but reversed to show the back side of the fossil image which a field observer would not see.

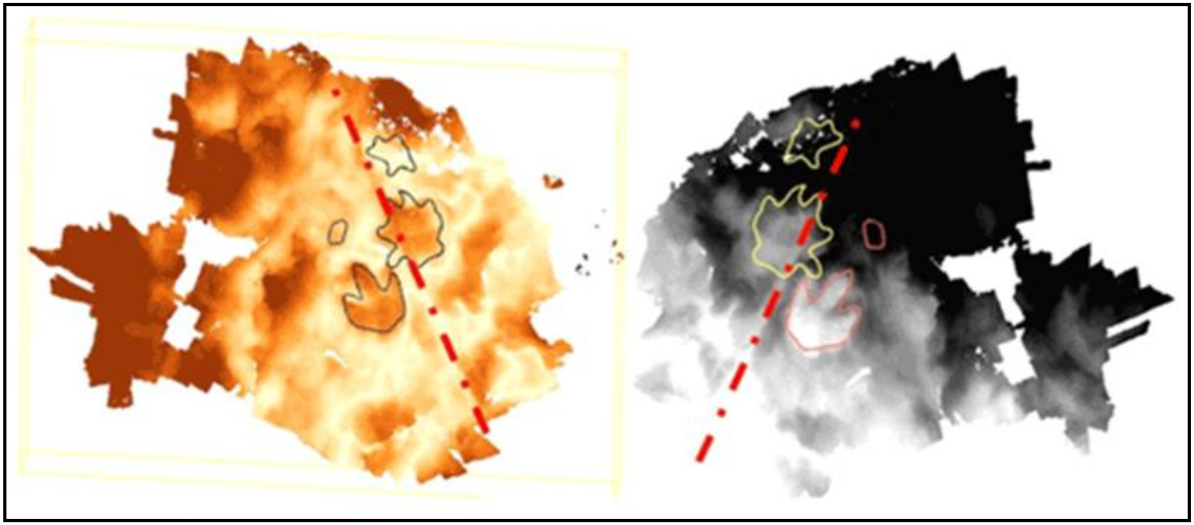

Figure 6- The same images shown in Figure 7 but the natural color of the images has been replaced by colors that vary with depth. The dashed red line shows the location of a fracture in the rocks, and the footprints are outlined in this image.

some websites, and in particular, Sketchfab is usually not considered appropriate for pre-college-age students although it is an excellent site for pos options for manipulating the 3-D PDF files to help students recognize fossils and they can be accessed without a direct connection to the internet.

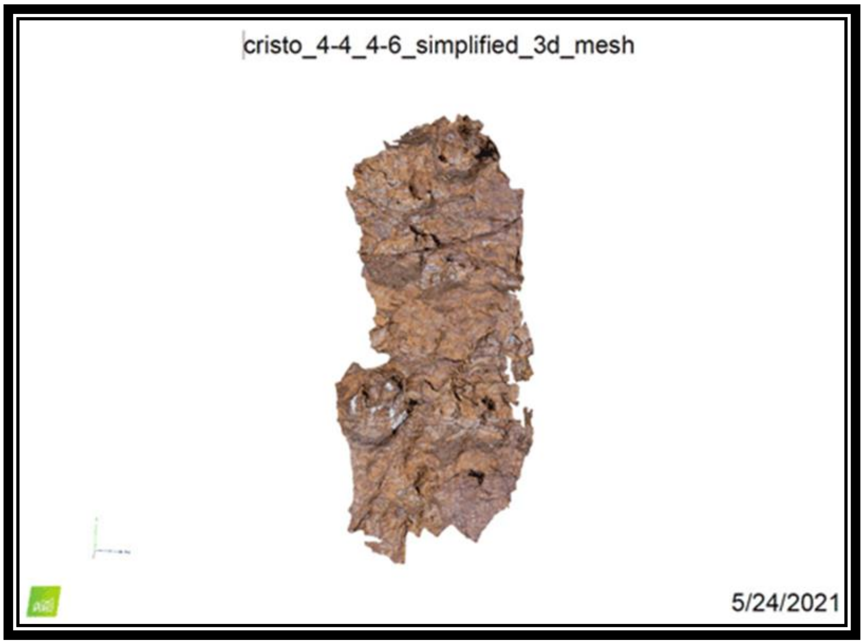

Figure 8-This figure is a 2-D image of the 3-D PDF of Cristo Rey sections 4–5 and 4–6 included in the online supplement to this published version of this chapter (https://doi.org/10.5194/gc-5-1-2022).

The original fossils identified by Martinez, (Martinez 2016), were from a small set of photos where she removed the color from a 3-D PDF image and found that the weathering patterns in the rocks obscured the footprints and distracted from recognition of the fossil relief. This was first observed by simply turning the 3-D PDF over and looking at the back side which had no color at that time and showed the footprint as a high area rising above the background rock. Subsequent mapping of depth variations at a small scale combined with color removal made more footprints and tracks apparent in the site as shown in Figs.6 and 7.

2.5.1 Fossil identification

Our experience suggests that most students first learn about fossils by seeing a few examples, usually photographs in a textbook, and learning to recognize some basic characteristics of a fossil that can be used to identify the source. For students living near a fossil locality, this may also involve a field trip to collect fossils. However, some fossil localities are rapidly disappearing as the fossils have all been collected. Cristo Rey fossils have been heavily collected and most remaining fossils are in hard to access areas that may not be safe to visit for young people with little or no field experience. We also hope that the remaining fossils will not be collected so that scientific studies of the footprints can be conducted well into the future.

Figure 7 and Figure 6 show images from a part of the area that includes two footprints and are photographs of the actual 3-D dense cloud models. A 3-D PDF of that area is included in the Supplement, and a 2-D image of the figure is shown in Figure 8 The supplemental 3-D PDF file should be manipulatable with Adobe Acrobat Pro with 3-D enabled but may take a few minutes to open. Readers and students can change the orientation and tilt of the 3-D image to bring out varying views of the depth and highlight the mud ridges around the footprint. The image on the left side of Figure 7 shows a view of what would be seen in the field if the lighting were good. However, because the students will have a 3-D image **Error! Reference source not found.** to look at, they w ill be able to manipulate it with a computer, tablet, or smart phone in ways that are not available to the field observer. One of the first things we did with the images when we started this project was to turn the 3-D PDF image over and look at the back side where footprints that are depressed in the top side pop out as raised impressions on the back side of the image as shown on the right side of Figure 7

The footprints may be difficult for students to find initially because there is a lot of color variations in the rocks. However, we can change the colors in the computer image also; Figure 7 shows the same images as shown in Figure 7 but the true colors are replaced by two tone color variations that change intensity with depth. In this format, the most visible footprint is easily seen as a depressed area that is darker brown than the surrounding, yellow high areas in the right-hand image and as a light area in the backside of the image where we used grey tones. Students can experiment with their image colors, orientation or scale to find a representation that helps them to visualize the footprints and learn something about how visualization works in the process.

Once students learn to find the footprints in the image, they can compare them to published information (Thulborn 1990) to identify the dinosaurs that made the prints. Students can also measure the prints and if there are sufficient prints, they can measure the stride of the dinosaurs to make an estimate of the sizes of the dinosaurs. Some additional lessons that can be included might be to look at how mud was apparently pushed away from the footprint and compare that to how a human footprint changes when a person runs compared to a walking person's footprint in mud. In some cases, students might consider how a footprint would look if the dinosaur were pushing along in shallow mud while swimming. This would provide additional information about the environment and lifestyle of the dinosaurs (Boggs Jr. 2012).

This data can also give teachers a chance to develop their students' critical thinking skills. Cristo Rey is located in a desert region, but the dinosaurs clearly lived in a shallow water environment in our area which could open a discussion on climate change (Dalla Vecchia 2008), for example. Comparing how the students might displace mud in a wet environment and observing similar features in the dinosaur footprints could create a better understanding of how science works and builds understanding of the processes we study. The mud ridges around the footprints also provide evidence the dinosaurs were walking on a sloping surface which was subsequently tilted in the opposite direction during uplift of the area. In addition, some footprints overlap other footprints which opens discussions of the time relationships and whether one of the types of dinosaurs found in our area could have lived there at a much earlier time than another. These observations would make an excellent exercise for the students to explore with the entire data set.

2.5.2 Photogrammetry

In addition to learning about fossils, students can learn more about the process of visualization and making 3-D images from the more than 7000 photos available from the Insights Museum. There are inexpensive or free software packages available to work with smartphone images to build 3-D models (Fleming and Pavlis 2018). This gives students an excellent opportunity to learn more about how humans perceive depth and dimensionality, for example. Where more sophisticated software is available, students can work on building a geologically accurate representation of the Cristo Rey fossil sites. This should also give students a good understanding and the necessary skills to look at rocks and minerals, for example, or any number of subjects in 3-D which is likely to be common in their future regardless of the career they choose.

The methods used in this project are not intended for rigorous research projects where accurate measurements are critical. Rather, we are focusing on the visualization aspect of photogrammetry and making it easily accessible to teachers and students in a wide range of applications. For more advanced courses and research applications, it will be critical to train students in the details of properly planning a project (James, Robson and Smith 2017) (Wenzel, Rothermel and Fritsch 2013) (Brush, et al. 2019) (Fleming and Pavlis 2018) to ensure they get the intended information from their photos. We also hope that properly collected research data will become available for education applications. However, more casual application of photogrammetry in educational settings is an effective method to build interest in a topic and, more importantly, to expand the level of information available in a classroom or textbook from 2-D images to 3- and even 4-D images.

2.6 Conclusions

At many US universities, introductory geology is taught using a small set of rock and mineral samples in a lab often combined with field excursions that may be taught by graduate students with little training in the broad range of topics covered in the lab. Introductory physical geology textbooks and lab manuals typically devote 4 to 5 chapters to rock and mineral identification and a chapter on, for example, structural geology that uses photographs or sketches where a student is expected to memorize the names of the features in the image. One reason for this is that geoscience is often not taught at the high school level (ages 14 to 18 typically) and there are relatively few geoscience majors entering the universities as freshmen. As a result, departments try to recruit majors from the students who choose to take a geology course to meet a science elective or because their major requires it. Those students are often not well prepared for a more rigorous science course and departments may focus on making their course interesting, informative, and relevant but usually not as difficult as, for example, an introductory physics or chemistry course. We compare this to students taking an introductory university biology class that is based almost entirely on pictures, dissecting animals, and field trips to collect plants and insects. Many students might enjoy such a class, but it is not likely to inspire many of them to become research scientists when this method is used at the university level.

We are not suggesting that field experiences or working in a lab with samples is not valuable, particularly in more advanced classes, but many universities train teachers who only take one introductory geology class before they teach a class in the pre-college system. As a result, few students learn much about what makes geology a science or arrive at universities with the intent of becoming a geologist. We believe the increasing availability of 3-D images that can show a wide range of scales and include videos on a tablet or cell phone frees up an instructor and textbook to explain the processes behind the images and how a geologist studies the Earth using sophisticated equipment in greater detail than is possible with a 2-D image. We also have the flexibility of linking specific images and lessons from Microsoft Word documents to PowerPoint lessons to aid students in viewing the lesson digitally.

The use of 3D PDF files in a classroom or textbook is just the first of many possible uses of digital data and software to give students a sample of the tools that many researchers use regularly. The tools that we used to generate the 3-D PDF files from the photographs can easily be accessed and manipulated on a smartphone or tablet. The same methods can be applied to rocks and minerals, outcrops, and large-scale geologic features. Rotzien, (Rotzien, et al. 2021) used 3-D

Google Earth images to prepare students for field mapping. Google Earth is often used in labs and introductory classes and textbooks so this is not a new idea. However, Google Earth is not usually of high enough resolution to see the detailed outcrop images or identify rock types or fossils. It cannot be manipulated with other software, so it is not the ideal tool for the lessons we think students should have. We believe the primary outcome of using higher-level technology in introductory classes is that students will see geoscience more as a rigorous science than as something that should be left to pre-university level courses with teachers who may not see the subject as a "real" or quantitative science.

We would like to see a change in how introductory university geoscience is taught with more emphasis on understanding the nature and process of science and its applications through the use of a broad range of high-resolution digital imagery. Exercises could involve looking at a variety of characteristics from one area or seeing the same geologic feature in different places and varying stages of development, for example. Every university could develop virtual field trip activities using digital data from their local area, so students can learn about why geology is relevant to their lives. Software, such as *StraboSpot* (https://Strabospot.org, last access: April 2018; (Walker, et al. 2019), is becoming more available and could provide the tools for rewriting our non-majors' textbooks, so students get a more realistic idea of how the Earth works and what a geoscientist does. The possibilities for developing virtual class materials are growing rapidly, and we think now is the time to bring it into the classroom.

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Chapter 3: Developing Digital Resource Base Using Photogrammetry to Develop Class Materials for Educational Purposes

Abstract

We had an opportunity to collect a variety of photographic and LiDAR data from a single site in Cristo Rey, New Mexico. The data included 1 set collected using a high-quality handheld camera, 2 sets using drones flying low over the site, and 2 LiDAR data sets—one professional set and one iPhone set, in an area where dinosaur footprints have been mapped. The data were processed using Agisoft Metashape software to produce 3D dense cloud models of the site. We compared the various models and found they all provided approximately centimeter resolution of the footprints and some, the handheld camera and LiDAR models, were well within the millimeter resolution range. We used the professional LiDAR model as a reference to compare the quality of all of the other models and found small variations in the data quality but all of the models showed the footprints accurately. We propose using any of these data collection systems to teach geoscience in an introductory classroom, lab, or field setting.

3.1 Introduction

The global dependence on rapidly changing technology is growing and, for that reason, our education system must prepare students to do more than just use current technology. We must give students the necessary skills to contribute, anticipate and adapt to future changes in technology. In many cases, however, the STEM skills and thought processes needed for current and future technology applications are not taught in our schools and universities. We believe that this is due, in part, to instructors and administrators lacking up-to-date technical knowledge. It is not practical to require all educators to take extensive additional training to fill this need but, we must find a way to include more technical instruction in the classroom, ideally while using resources that fit an existing instructional plan and require minimal training.

One particular area of technology that we are focused on is the use of photogrammetry to teach geoscience (Martinez V.V. and Serpa 2022). It is our opinion that the use of 3-dimensional (3D) photogrammetry models in geoscience education will become as essential as PowerPoint software became several decades ago for presentations of visual concepts in a geoscience classroom. At this time, we also believe that one of the most effective educational uses of photogrammetry would be for instructors and students to collect image data and build 3D models of geologic features in their community to emphasize the combination of field observations and technology with a relevant activity. To achieve our goals, we first need to determine which photogrammetry techniques would be most useful and effective in a geoscience classroom. For that reason, we compare data collected using a handheld camera, Light Detection and Ranging (LiDAR), Iphone12 ProMax LiDAR, and drone images of dinosaur footprints near El Paso, Texas Figure 9. The relatively small size (centimeters to a few meters) of the footprints makes the use of aircraft and satellite data unrealistic in this case. In this paper, we examine various photogrammetry data collection techniques to determine what might work best for geoscience education and projects.

For education purposes we felt the particular characteristics of the various collection methods that were most important included: 1) ease of use, 2) how long the collection took, 3) accuracy, 4) resolution, 5) skill level required, 6) cost and 7) access. There are also variations in the software used to processes the data and variations in display or interpretational applications but these are characteristics that appear to be evolving rapidly and all of the data we looked at could be displayed and analyzed using a variety of common software packages. We did not compare processing aspects of photogrammetry in this paper.

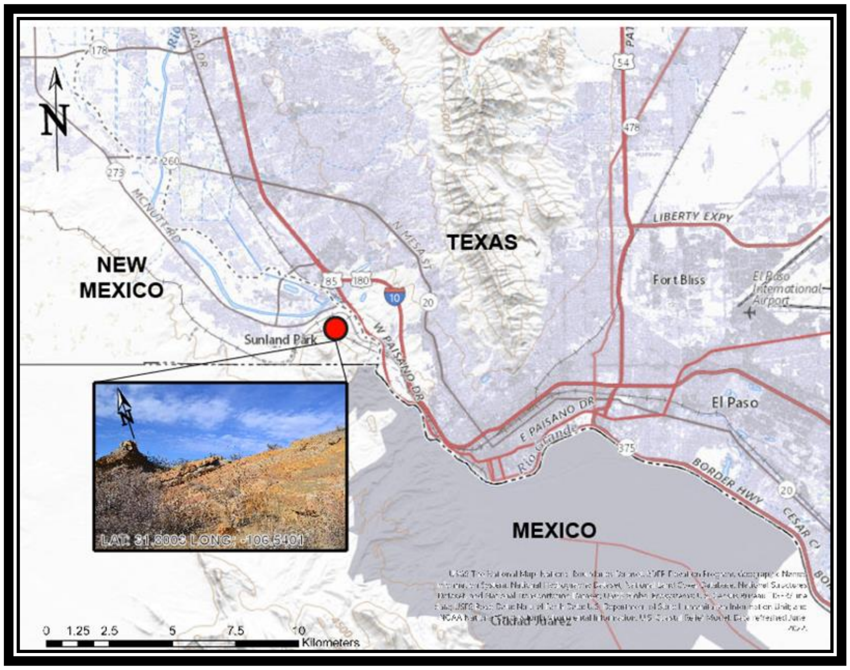

Figure 9- Location of the 72 m^2 study area in Cristo Rey, New Mexico (31.8003° N and -106.5401° W).

The results of this study suggest that each method of data collection has unique strengths and weaknesses that should be considered when designing any particular research or educational project. Education and reconnaissance research applications may require less rigor than a research project that involves careful measurements but preplanning is essential for all applications and students should learn to plan their experiments and evaluate the resulting data quality as part of their education. That said, however, most of the data described in this paper were not collected based on a carefully designed plan; rather they are the product of preliminary equipment tests, training exercises and/or unanticipated access to equipment. In many ways this may more closely mimic what happens when a class is assigned to collect data or an instructor is demonstrating data collection to a number of students. This provides an excellent opportunity to learn from mistakes and to recognize what is most important for data collection; so, our study is, in our opinion, a good model for introductory geoscience education applications.

3.2 Background

The study area is located in the Mt. Cristo Rey region of Sunland Park, NM Figure 9. The first fossil footprints, identified as Cretaceous therapod footprints, were discovered by (Kappus and Cornell, A New Cretaceous Dinosaur Tracksite in Southern New Mexico 2003). The footprints are in Cretaceous sedimentary deposits that were subsequently intruded by a Tertiary trachyandesite dome, (Lovejoy 1976). Kappus, (Kappus and Cornell, A New Cretaceous Dinosaur Tracksite in Southern New Mexico 2003), (E. Kappus, S. Lucas, et al. 2010), (Kappus, Lucas and Langford 2011), (Kappus and Cornell, A New Cretaceous Dinosaur Tracksite in Southern New Mexico 2003), used traditional field-mapping methods which include careful visual observations in the field that are then recorded on paper maps Figure 10. Compass and ground-based distance measurements were used to locate and orient the various fossils. Martinez, (Martinez 2016), subsequently collected high resolution photographs of a part of the site to preserve a record of the footprints. The photos were taken on a premeasured grid but the individual camera orientations were not well located within that grid. As a result, the absolute locations and orientations of the footprints were not constrained in the initial models so drone data were also collected at the site. Martinez (Martinez 2016), used that data to build 3D photogrammetry models of the ground surface Figure 10 b that not only provided a record of the site at the time the photos were collected but also led to the identification of several new footprints and trackways based on digital manipulation of the models.

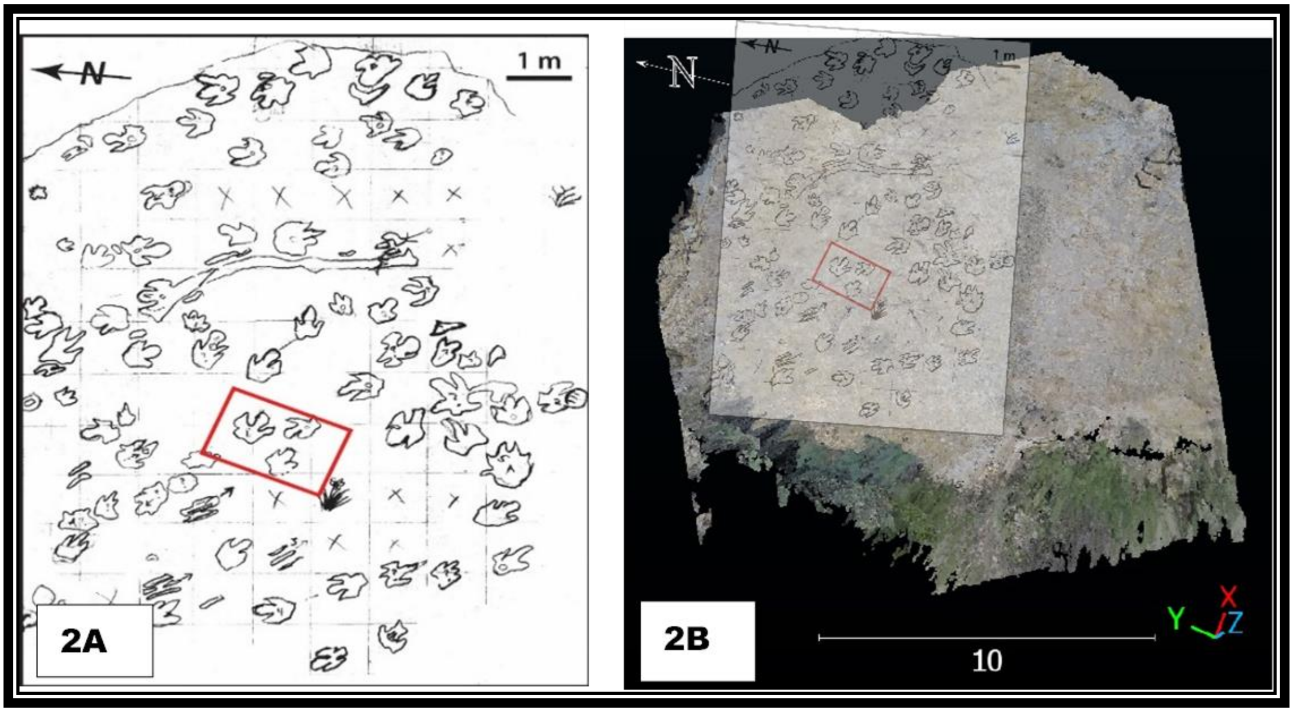

Figure 10- Kappus map (Kappus, 2011) and B. Kappus map superimposed on the drone model map from (Martinez, 2016) with the interpreted locations of footprints and trackways shown for each individual representation of the area. The red rectangular boxes show the position of a particular easy footprint to identify in the area with a few more obscure footprints nearby. This box will be the focus of subsequent evaluation of the data.

One important result of Martinez (Martinez 2016),was that it was the first of a group of studies using photogrammetry to study geologic problems at the university. Those early studies generated great student interest and led to student-directed efforts to learn more about photogrammetry and incorporate it into their research (Brush, et al. 2019), (Fleming and Pavlis 2018), (Horowitz S.S. and Schultz 2014). This is the type of (Martinez V.V. and Serpa 2022) experience we would like to see happen in an introductory geoscience classroom where students participate and learn about geoscience using exciting new technology which they can directly interact with and control.

3.3 Data Collection

The images used to create 3D digital models of geologic features are typically collected with a handheld camera, a camera mounted on an aerial device capable of moving about the feature while taking pictures, or a LiDAR system which also may move about and include a camera. The camera provides color images from a wide variety of angles around the geologic feature, much like moving a mirror can provide images of different parts of an object. If those images are stitched together appropriately (i.e. using photogrammetry techniques), they would make a 3D model of the object showing relative positions. In order to get the approximately correct positions of objects in the various images, the photos would need to be georeferenced by measuring the 3D position of the camera or placing several markers on the ground with known 3D locations.

LiDAR is different in that it transmits pulses of light energy from a laser that are reflected off the object and returned to the LiDAR device (Petrie and Toth 2009). The travel time for the light energy is recorded and the location and orientations of the source and receivers and the speed of light are known so the travel times can be converted to distance and direction from the LiDAR device with great precision (NOAA n.d.). However, the resulting LiDAR 3D model would only give distances and not color variations unless a camera is also recording pictures that can be overlain on the model. The distances measured by the LiDAR device are considered to be highly accurate because the speed of light is very well known. LiDAR has been used and modified since the late 1960 to gather topological data sets. LiDAR sets can be gathered via aircraft (plane or UAV) and/or terrestrial stations (NOAA n.d.)

Critical information about the camera data collection includes the quality of the camera, its distance from the object and the amount of overlap between images. All of the data collection methods including LiDAR require the location and orientation of the camera or LiDAR recorder be known for all of the recordings if accurate measurements are needed for the model. Most photogrammetry software can, however, produce a 3D model from photos that are not located if there is sufficient overlap between photos to allow the individual photos to be aligned relative to each other based on the identification of common features from one photo to the next. The resulting 3D model may be an accurate visual representation of the object photographed but it will not have any reliable scale information unless ground control (i.e. targets with known locations) are used throughout the area being photographed or the images are georeferenced using some other source to locate the camera or images.

Because the Cristo Rey site is close to the UTEP campus it is frequently used for class exercises and experiments by the Earth, Environmental, and Research Department at UTEP. In particular, the area where (Martinez 2016) collected her dinosaur footprint data was used subsequently to test a variety of methods for collecting photogrammetry data. We have 2 sets of both LiDAR and sUAV (drone) data from the study area in addition to the initial high-resolution handheld camera data. All of our data were processed using Agisoft Metashape software to build a 3D model.

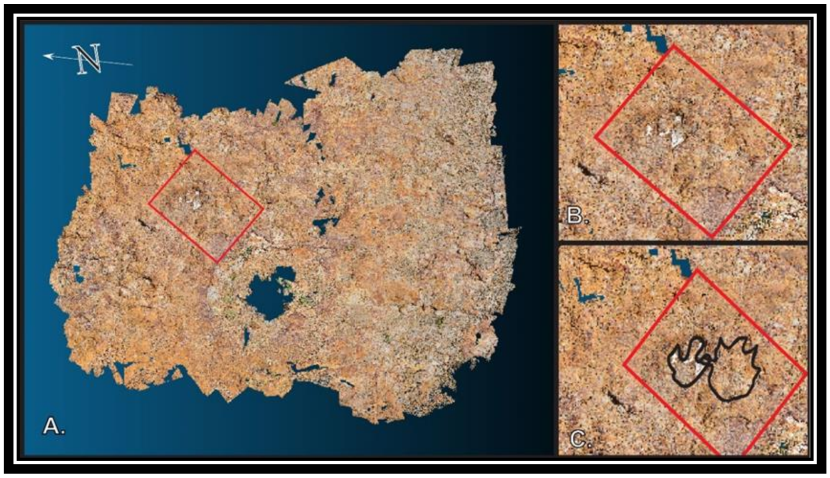

Figure 11- Dense point cloud model, HH_VM_Mega, based on the handheld camera data (Martinez, 2016). A. shows the entire surveyed area, B. is a closeup of one particularly prominent footprint with traces of plaster embedded, and C. shows an outline of the prominent footprint and an adjacent footprint that was identified from the model. The red box outlines the area of the 2 footprints and shown in figures throughout the paper.

3.3.1 Hand-held Camera

Using a handheld camera to collect data would appear to be the simplest method of data collection because it requires only a camera or smart phone, little if any training, and some method to orient and locate (S. Tavani 2020) (Tavani, Billi, et al. 2022) the images. Martinez, (Martinez 2016), used a Nikon D3100 digital single-lens reflex (DSLR) camera. The handheld images were collected within a 9m by 8m grid system marked on the ground surface of the study area (Martinez 2016). Each grid section was marked by a circular sticker labeled with its number and the markers were spaced approximately 0.3 m (1 ft) apart throughout the area. The grid numbering system (X,Y) ranged from (0,0) to (8,9), where each point represented a station for taking pictures of the area. The number of pictures depended on the texture of the bed rock, where highly variable textures were photographed more than low variable textured areas. The camera was held within 2m of the object. It took two days to collect the complete data set with similar lighting for all of the collection time. Approximately 10,000 images were collected and subsequently reduced to about 7500 images in the area of primary interest.

A high-quality camera was used, the photographs were taken close to the objective, and Martinez (Martinez 2016), took great care to photograph each grid section completely but did not pay as much attention to the overlap of photos between grid sections and the camera position and orientation during the data collection. Although markers were used to locate where the photographs were taken, those markers were not located on any global system (i.e. UTM or latitude and longitude). The height of the camera was known approximately because we know Martinez' height but no record was made of whether she bent over to take some pictures or did something else to change the camera height or orientation. Because this was our first attempt to collect photogrammetry data, we did not know these were serious mistakes and we could not georeferenced our data. As a result, the data had to be processed without any scale information (Martinez 2016) and could not be converted to a single 3D model because there was insufficient overlap between photos from adjacent grid sections. The excessive number of photographs also was too much for our computer system at that time and the model had to be separated into ‘chunks’ (Agisoft PhotoScan User Manual: Professional Edition, Version 1.2 2016)with a separate chunk for each grid area. In many cases chunks could not be merged with adjacent chunks, so a single model was not produced. We did, however, generate a number of small models containing approximately 3 adjacent chunks throughout the entire area. Despite those limitations, the footprints were well-defined in individual models and the photogrammetry experience was an invaluable lesson on data collection. New footprints and trackways were discovered that would not have been discovered using traditional mapping techniques despite the location issues with the data (Martinez 2016). We subsequently georeferenced the handheld camera data using the LiDAR and drone data to produce a relatively continuous model sUAV mounted camera (Figure 3.3).

3.3.2 Drone Data

We collected 2 drone data sets at Cristo Rey. The first (Martinez 2016) was collected as part of the fossil imaging project because we wanted to know whether a drone could provide photographs that were sufficiently clear to image the fossil footprints. A 3DR Solo with a mounted Hero 4 Black GoPro camera 12 megapixel was used in an automated georeferenced mode to collect images and videos. A flight plan was programed so the sUAV would fly autonomously over the site. The flight plan was developed by using a grid system, where each of the points in the grid system the sUAV would stop and take pictures. This grid system is different from the handheld system in that it had fewer grid points and took a consistent number of pictures across the region regardless of the variations in roughness of the surface. This model is shown in Figure 12.

In 2021, Dr. Laura Serpa collected drone data from Cristo Rey using a DJI Mini 2 flying manually fairly close (1m-5m) to the ground in an effort to duplicate the original handheld camera experiment. The DJI mini has a lens that is a 24mm equivalent of a 35mm camera with an image size of 4000 x 3000 pixels and each image is georeferenced. The UAV flew manually because the DJI Mini 2 does not have an autonomous flight option, but we did set the photo timing to be automatic with one picture every 2 seconds. Because this was not done autonomously, we could maintain a low altitude across the survey area and fly at a very slow speed. However, because the flight was human controlled, there were unpredictable variations in the height of the camera, the number of photos in a specific area, and the speed of the drone. The entire area was covered in less than 20 minutes. The weather (rainy) and lighting conditions (overcast) did not match the original handheld camera or the first drone surveys and approximately 5 years had passed since

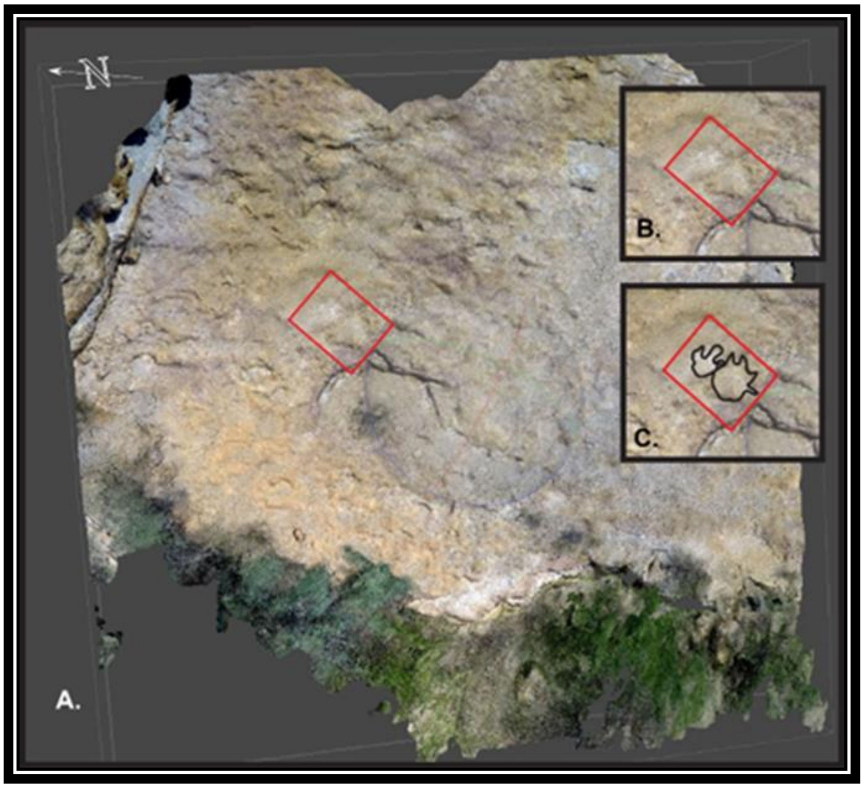

Figure 12- Drone image produced from data collect with a sUAV flying autonomously (Martinez, 2016). A. shows the entire survey with the Red box defining the area of footprints that is a focus for the work. B. is a close up of the red box area and C. shows the red box and C. shows the red box area with the inferred footprints outlined in black.

(Martinez 2016) collected her data. After we processed the newer drone data (Figure 3.5) it was apparent that there were some changes at the site due to weathering and erosion but the data appeared visually to match the handheld camera data and the earlier drone data fairly well. The DJI Mini 2 is relatively inexpensive, has a good camera and gps system and is very easy to fly. The manual mode of flying the small drone requires the operator to be responsible for ensuring there is adequate overlap between photos and a constant altitude of the drone is difficult to maintain. In some ways the handheld and the DJI mini drone data are similar in that there is less uniformity in the data they collect. Some areas will have better coverage, more photos, or be nearer to the objective than other areas.

Figure 13- Drone model, LF_sUAV, sUAV data collected by Serpa in 2021.

3.3.3 LiDAR Data

Both the drone and the handheld camera methods provide photographic data which can be used to create very realistic 3D models of an area (Niculita, Ciprian and Tarolli 2020). Our LiDAR data does not include photographic data so it has to be colored artificially using some criteria such as depth variations or sun-angle information. The position of the LiDAR equipment is important, and data can be collected from either a ground-based instrument or from an aircraft. Most LiDAR equipment requires several minutes for setup and data collection and some expertise with the equipment is usually required also. A professional quality LiDAR system can be quite expensive but the recent addition of a LiDAR system to some iPhone's (Tavani, Billi, et al. 2022) has provided a much simpler way to collect data by hand without the need for additional equipment or extensive training. We collected data using both a professional system and an iPhone for comparison.

3.3.3.a Professional LiDAR Data

Professional (i.e. tripod mounted terrestrial lidar scanning system; TLS) LiDAR data were collected using a Riegl VZ-400 laser scanner at 1540 nm (Whelley, et al. 2017). To capture the dinosaur footprints in a point cloud, the LiDAR scanner was mounted on a ~1.5-m-high tripod for three scans both upslope and down slope of the target outcrop to maximize coverage. Each scan was taken with 0.04° angular spacing, which achieves 7 cm point spacing 100 m from the scanner. The scanner's vertical field of view is 100° and extends 40° below horizontal and 60° above. A rotating stage enables data collection from all directions. A Trimble R8 Global Navigation Satellite System (GNSS) Differential GPS receiver was used to place the scanner and image data in a geographic reference frame. Each scan took ~5 minutes, however set up of the whole system takes an additional 10 minutes for each scan, and initial (once daily) setup of the DGPS base station, which takes an additional half hour. Once collected, individual TLS scans were combined into a single point cloud and exported in Laser format (.LAS) using scanner specific software, Riscan

Pro. A Digital Elevation Map (DEM), is a demonstration of bare surface topography of earth (USGS). The DEM Figure 14 was collected via LiDAR by Dr. Patrick Whelley from NASA Goddard Space Flight Center. This DEM is displayed with ArcGIS 10.6.1 using stretch map display. Stretch map display in ArcGIS 10.6.1 is a display of the raster data by stretching its properties such as brightness, contrast, and gamma (ArcGIS). Having the DEM set up in stretch layer map, dinosaur footprints and tracts are noticeable as shaded depth features where the darker the area represents a deeper surface area.

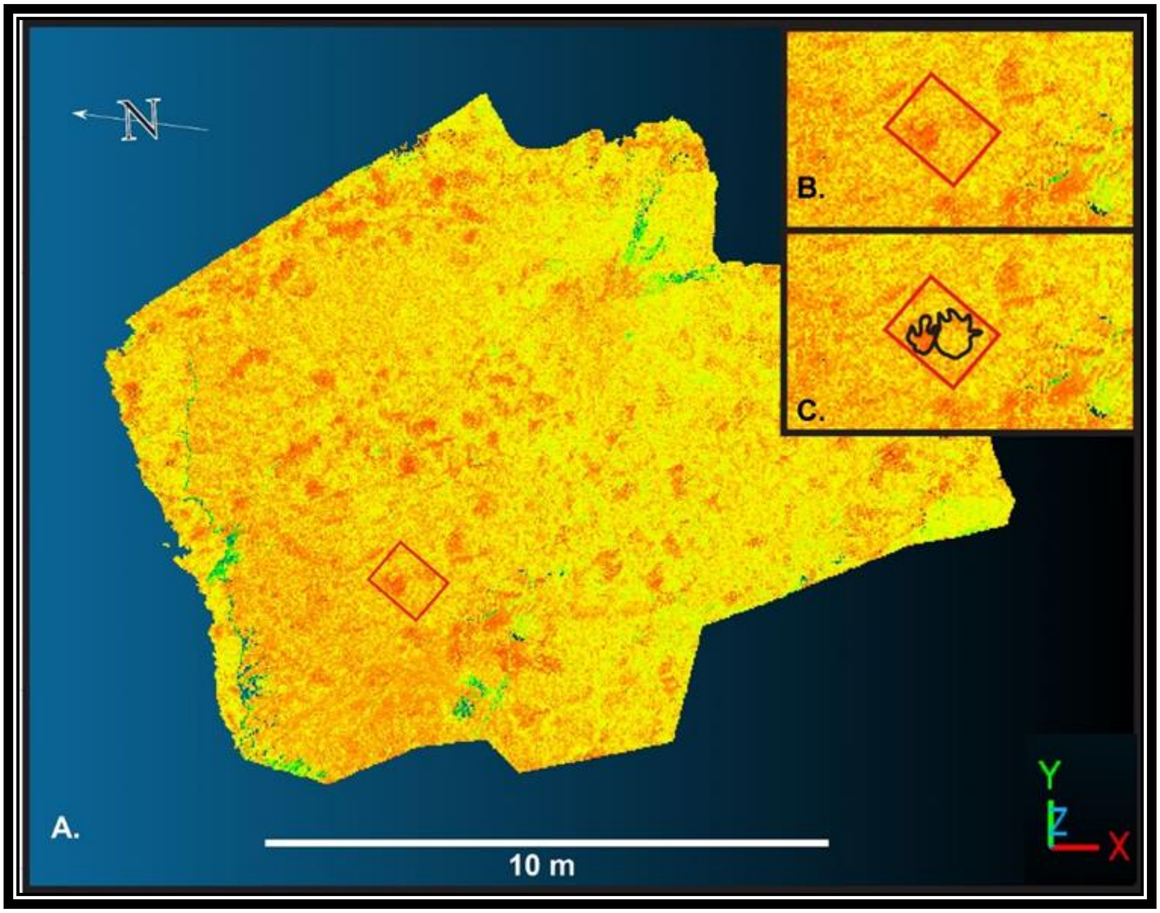

Figure 14- The .las file, PW_LiDAR, displays in DEM Amplitude form built from the LiDAR data at Cristo Rey. The red box indicates the area of footprints to be compared between data sets. The colors represent variations in depth of the model surface with darker showing greater depth.

3.3.3.b iPhone LiDAR Data

In addition to the tripod LiDAR data, we used an iPhone 12 Max Pro™ to collect LiDAR data Figure 15 as part of this study. Apple recently released the iPhone 12 Max Pro with an integrated LiDAR data collection system. The phone has three lenses located in the back of the device, one is a camera for long shots, the second is a close-up camera and the third is the LiDAR system. We used this device to collect data at Cristo Rey and processed the data with 3D Scanner App on the phone. To scan an object, the mobile device must be moved around the object of interest manually.

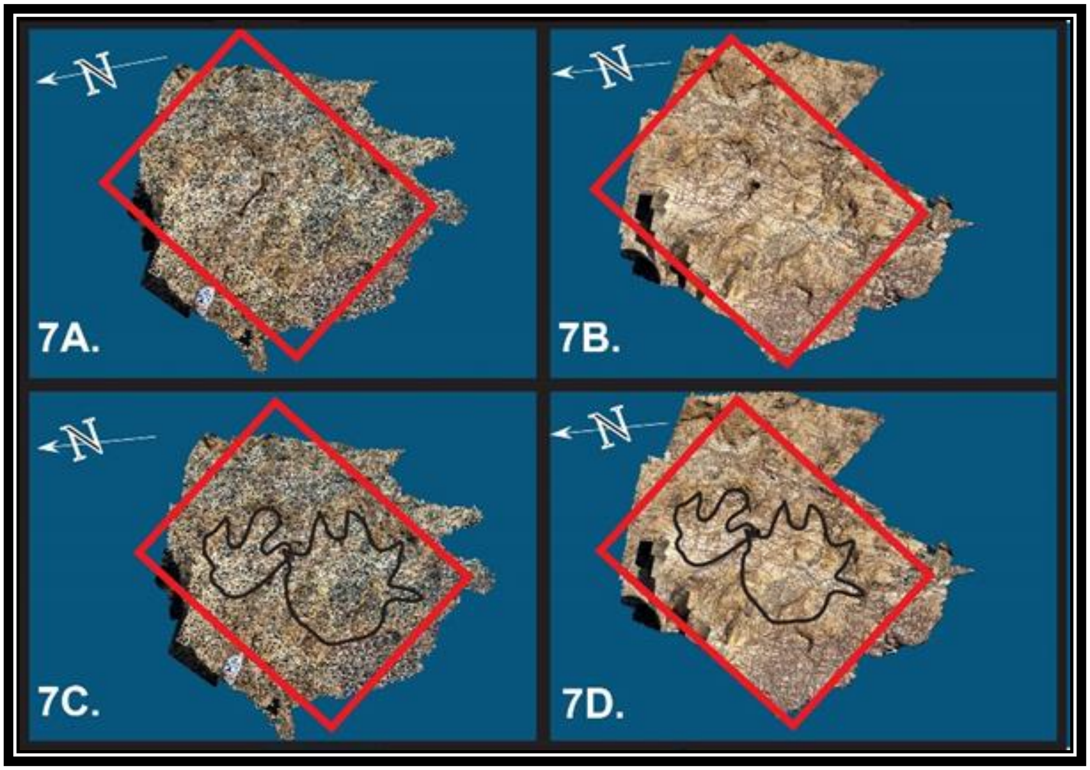

Figure 15- LiDAR images collected via iPhone. Model 7A was produced using Apple software and model 7B was processed using Metashape Agisoft software. 7C. and 7D. displays the outline of the footprints previously found in the area. The three-toe footprint on the right side belongs to an Anklyosaurus. The red boxes correspond to the areas shown in Figure 3.6

On April 2022, Martinez went to the study area to collect LiDAR data using the mobile device. In a period of thirty minutes, five models were collected and processed. Five of the models were small areas, consisting of 20 to 38 images for each model. The small areas were approximately 2 to 3 square meters. The other five models were larger areas including one that encompassed the entire the study area, approximately 72 square meters, covered by the handheld camera experiment. The data were processed using software provided with the iPhone and transferred to a computer for processing using Metashape Agisoftware to compare digital data sets Figure 15.

3.4 Processing Data Sets

One critical lesson for students who are just beginning to learn how to build 3D models on the computer is to develop an organization for their data that is consistent and makes sense to the user. The data sets include a large number of photos in *.jpg format or raw camera formats that have to be converted to jpg format. The processing stream Figure 16 can generate numerous files and users may also want to process the images before building the models or process the models later using other software. All of this leads to a highly complex collection of data that can easily become impossible to manage. For that reason, we developed the consistent system of data management described below and students should be encouraged to develop some system that works for them also.

The camera data were collected from the handheld camera, sUAV's, and IPhone_ in *.jpg format and were processed to "dense point cloud" 3D models using Metashape Agisoft with similar processing parameters. The professional LiDAR data were processed separately at NASA but the same standard processing as we used in the other data sets can be used for that data also. The processing followed the same sequential steps with each data set organized in a folder with a name that contained the date that the data were collected, and the type of camera system used.

Because the handheld camera system has substantially more images than any of the other data sets, we created a parent folder that contained subfolders that were labelled for each grid section containing images taken from the separate grid areas. The parent folder also contained the Metashape Agisoft™ files and project for each system. Once the folders and images were organized, a Metashape Agisoft™ project was created for each individual system or grid. The project files contain data stored by Metashape during processing and include information on the alignment of the photos and the software determined position of each "point" or photo bit that is correlated and located in the model from one or more photos. When displayed together, the points merge into single image (point cloud) at some viewing distances and will pixelate into individual points if viewed too closely. Once the dense point cloud models were completed, we exported each model Figure 11 thru Figure 15 in a *.las format file to allow comparison of the 3D models in other software packages.

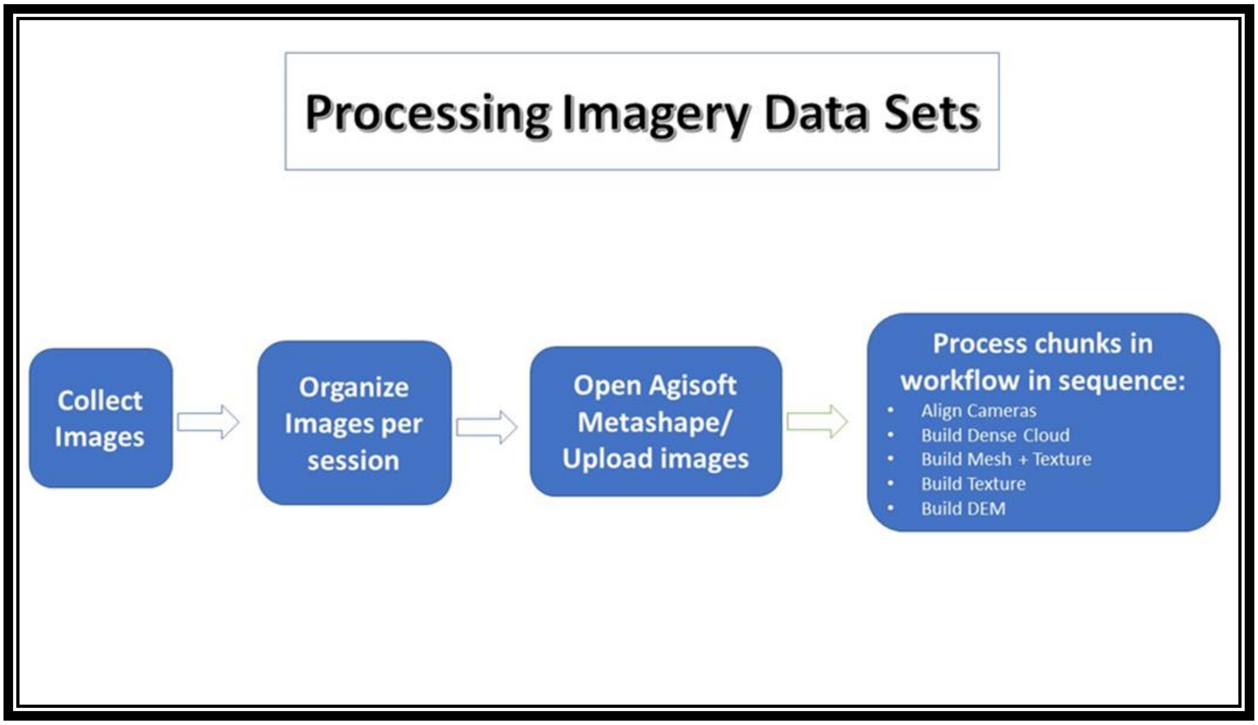

Figure 16- Workflow diagram of processing imagery datasets.

3.5 Comparison of 3D Models

In order to create a relatively rigorous basis for comparing our various data collection methods, we used CloudCompare Software to compare the 3D models made from the different data sets. CloudCompare is freeware that can be downloaded easily. It is designed to display and manipulate 3D models in a variety of ways based on the location and properties of the individual points within the model(s). CloudCompare has a somewhat steep learning curve and we recommend focusing, initially, on a few simple functions. In particular, it is a good choice for displaying the 3D models and that is a very simple function to use. We also used a variety of options in Cloud Compare™ to compare our various data sets which required a bit more skill but we feel it is nothing a beginning high school or college student could not manage.

To compare our data sets, we exported all of our 3D models from Agisoft Metashape as dense point clouds in .las format and imported those into a common display in CloudCompare. Because all of our 3D models covered the area defined by the red box in Figure 11 thru Figure 15 we expected that area to overlap fairly closely in CloudCompare when we opened all of the files

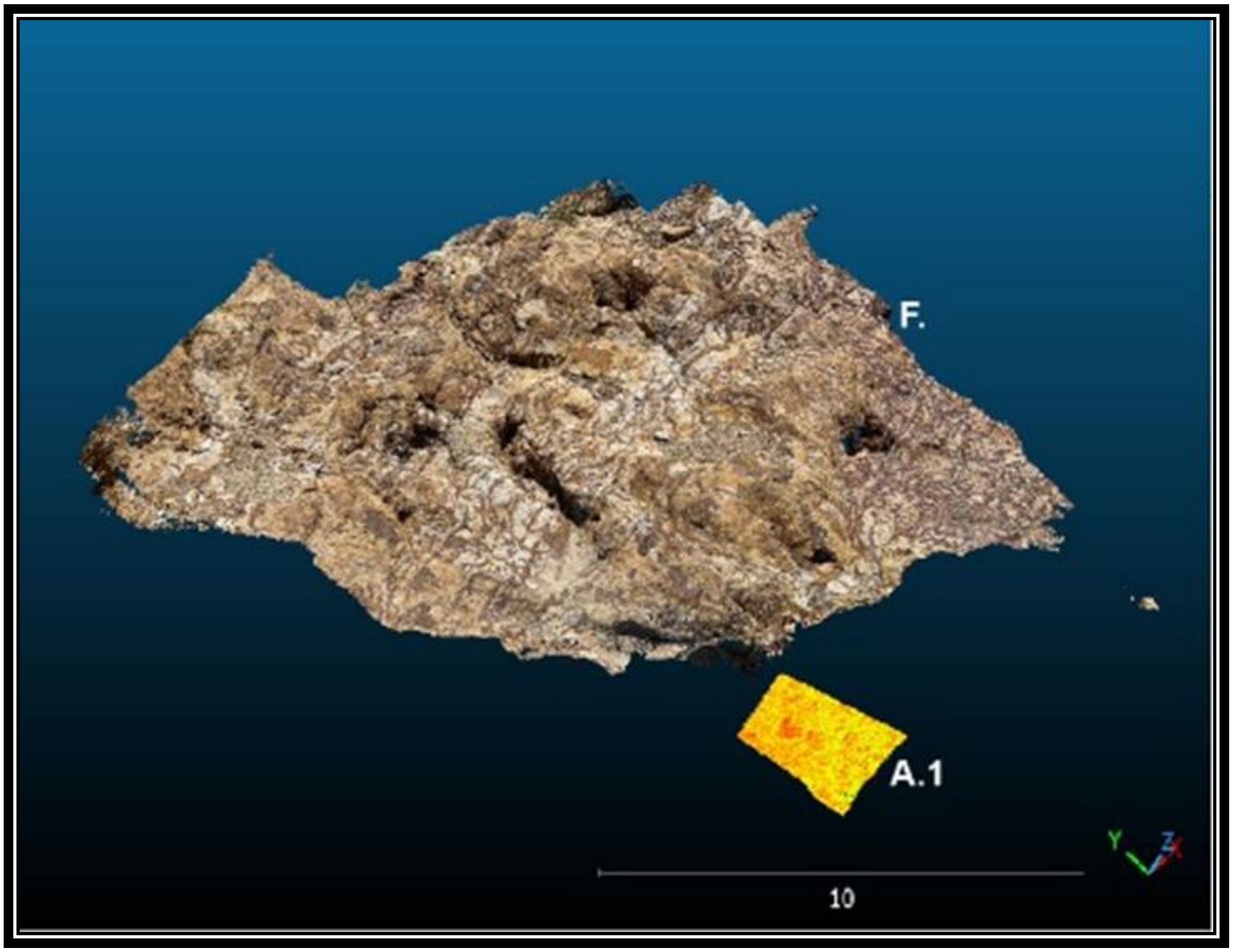

Figure 17- perspective view of the iPhone lidar data (F) and the professional lidar data (A.1) opened in CloudCompare. The differences in scale appear to be due to different georeferencing schemes used by different data collection devices.

together. The first thing we observed, however, was that some models did not appear at all and others filled the entire page. See Figure 8 for an example. Thus, our first problem was to solve what caused this mismatch when all of our models focused on the exact same footprints in our area. We determined that the problem came from differences in the projections or scaling used for the different models. In particular, the handheld camera data were not georeferenced so Metashape had defaulted to what it considered to be a typical size for the photographs that was much larger than the real data. The 2021 drone data were referenced in latitude and longitude, the 2016 drone data and the professional LiDAR data were in UTM coordinates and we are not sure what the georeferencing was for the iPhone LiDAR data.

To resolve this problem without reprocessing all our models, which would have taken significant time, we chose to make the professional LiDAR model our "standard reference" because it was assumed to be the most accurate data we had. We then used the alignment option in CloudCompare to line up the footprints in the red boxes on all the modelsFigure 11 thru Figure 15 and scale them to match as well as possible. We ran the CloudCompare distance measure between the standard LiDAR model and each of the other models individually to determine how well the models aligned after we rescaled them.

Following the alignment, we used CloudCompare software to measure the surface density of the aligned points to give us an estimate of the resolution of the various methods. There are many other operations that can be done in CloudCompare to help visualize and interpret the data but a discussion of those options is beyond the scope of this work.

We started our analysis by focusing our alignment on the small area of the data, identified by a red box in Figure 11 thru Figure 15 where one footprint is particularly prominent, and another is identifiable only in the digital data (Martinez 2016). That appears to have created a reasonable alignment for all of the data but we recognize some features may be slightly distorted because of the limited alignment area. The following is a brief description of the alignment process in CloudCompare.

3.5.1 Process 1: Cloud Alignment

We began by uploading the professional LiDAR data set and then the second data set we were aligning to the LiDAR data. The files are selected, then we open the "Align 2 Clouds" icon located on the top of the tab menu and select the professional LiDAR file as the reference file. We then select four or more points on one of the models (points on the dinosaur footprints in the red box that we can see in both models) and then match them to what appears to be identical points on the other model. The software then aligns those points by shifting the unaligned model's points to match those on the professional LiDAR model. This included changing the scale and orientation of the unaligned model as needed to make the match. Additional points on the two models are then selected and the process is repeated until the errors in the alignment are minimized as well as possible. We then save the previously unaligned model as an aligned model with approximately the same scale and location of the footprints as found in the professional LiDAR data set. One measure of the quality of the alignment is given by the distance between points on the professional LiDAR and the newly aligned data set, so that is the second process we ran on CloudCompare.

3.5.2 Process 2: Distance Computation

The distance computation is run from a tool located on the top menu of CloudCompare. We select the "Approximate Distance" tab to get a statistical report on the distances between points on the 2 models. Similar to the alignment step, we select the professional LiDAR point cloud as the reference and compared each of the aligned models to that reference as a measure of how well the aligned model match the reference. For a perfect alignment, all of the distances between the two models would be zero. This could be affected by the differing numbers of points in the two models but that should give a very small measure of the differences if the fit was otherwise well matched. We can display where the models are most closely aligned and where the greatest differences are located so that we could go in and adjust the model alignments if it appeared useful. Table 1 lists the average distances between the various data sets.

3.5.3 Process 3: Alignment and Distance

We initially measured the distance between the unaligned Professional LiDAR and the 2016 drone models in CloudCompare because they had the same UTM georeferenced system while the other models were based on a variety of other systems. The models matched fairly well with an average distance of 0.596 m separating the two models (Table 1). A visual inspection of the distribution of the distances Figure 17 showed that the largest differences were near the perimeter of the overlapping models. We attribute the differences to the GoPro camera on the drone which had a wide-angle lens and was not as high quality as the other cameras. This may have produced a slight distortion in the model. We also recognize that fewer photos or less overlap between images along the edges of the models may have reduced the quality of the alignment also.

We then aligned the other models to the professional LiDAR model using the CloudCompare alignment. One problem we encountered was the lack of photos for the professional LiDAR model which did not allow us to line up points visually. For that reason, we first aligned the models with the 2016 drone model and then used the "fine registration" option located in the CloudCompare tool tab to improve the alignment with the professional LiDAR model. This was necessary because the 2016 drone model and the professional LiDAR were not a perfect match. The 2016 drone model differed from the professional LiDAR by more than 0.5m (Table 1) after applying the fine registration. In view of the fact that the footprints we are interested in studying are typically between 0.5 and 1.0 m long, the discrepancy between the LiDAR and the 2016 drone data could produce significant measurement uncertainties for some applications.

We also recognized that the distance results varied by who was aligning the models and how much attention they paid to small variations and/or the initial manual alignment. Both of these factors affected the quality of the fine alignment so that we saw considerable variations in the matches. The data shown in Figure 17 were all prepared by one of us and we took care to get the alignment as close as possible so that the variations are expected to reflect differences in the size and/or distribution of points between the professional LiDAR and the individual models. The distribution of the distance variations is also informative in that we can assess whether the area we are particularly interested in is well matched to our designated reference model.

The distance measurement for the 2016 drone data has the largest misfit with an average difference of approximately 0.6 m. The handheld camera and the 2021 drone data had very similar fits and generally matched the professional Lidar within 4-5 cm. As noted previously, this was somewhat expected because the data collection parameters had some notable similarities. We infer that the variations in the map distribution of distances for those 2 models are more a reflection of inconsistencies in the manual data collection than differences in the data collection devices used. Finally, the iPhone LiDAR did surprisingly well with a fit near 1 cm with significantly fewer photos. The iPhone LiDAR model was focused specifically on the target footprints that were used in the alignment and that may have contributed to the high quality of the fit also.

3.5.4 Process 4: Surface Density

After the alignment we measured the surface density of the models using CloudCompare. This option is located in the tool menu under “Geometric Features” and then “other”. This tool computes the .las files “surface density” in points per square meter using an algorithm based on edge detection (Canny 1986) where the higher the point density in a given model the more likely the models will detect increasingly sharp or rapid changes in the topography (i.e. high frequency variations).

3.6 Results

3.6.1 Alignment and Distance

When we opened the various models in Cloud compare, the professional LiDAR and the 2016 drone data lined up fairly well but aligning the other models proved to be difficult in some cases. In particular, the lack of photos for the professional LiDAR model did not allow us to line up points visually. For that reason, we lined up the models with the 2016 drone data first and then used the “fine registration” option in CloudCompare to improve the alignment with the professional LiDAR model. This was necessary because the 2016 drone model and the professional LiDAR were not an ideal match. The 2016 drone model differed from the professional LiDAR by more than 0.5m (Table 1) after applying the fine registration. In view of the fact that the footprints we are interested in studying are typically between 0.5 and 1.0 m long, the discrepancy between the LiDAR and the 2016 drone data could produce significant measurement uncertainties for some applications.

We also recognized that the distance results varied by who was aligning the models and how much attention they paid to small variations and/or the initial manual alignment. Both of these factors affected the quality of the fine alignment so that we saw considerable variations in the matches. The data shown in Figure 9 were all prepared by one of use and we took care to get the alignment as close as possible so that the variations are expected to reflect differences in the size and/or distribution of points between the professional LiDAR and the individual models. The distribution of the distance variations is also informative in that we can assess whether the area we are particularly interested in is well matched to our designated reference model.

The distance measurement for the 2016 drone data has the largest misfit with an average difference of approximately 0.6 m. We attribute this large difference to the GoPro camera on the drone which had a wide-angle lens and was not as high quality as the other cameras. This may have produced a slight distortion in the model. We also observed that the worst fit is along the edges of the model where fewer photos or less overlap between images may have reduced the quality of the models also. The handheld camera and the 2021 drone data had very similar fits and generally matched the professional Lidar within 4-5 cm. As noted previously, this was somewhat expected because the data collection parameters had some notable similarities. We infer that the variations in the map distribution of distances for those 2 models is more a reflection of inconsistencies in the manual data collection than differences in the data collection devices used. Finally, the iphone LiDAR did surprisingly well with a fit near 1 cm with significantly fewer photos. The iphone LiDAR model was focused specifically on the target footprints that were used in the alignment and that may have contributed to the high quality of the fit also.

Table 1

Table 1. Comparison of model parameters

Name	Number of cameras	Point Count	Ave point distance from Prof LiDAR	Peak Surface point density in pts/mm
Professional LiDAR	NA	40,945,707	NA	0.231
2016 drone		13,260,317	0.596 m	0.500
2021 drone	790	117,935,430	0.043 m	0.170
Handheld camera	750,000	418,640,273	0.048 m	4.774
Iphone LiDAR	33	3,746,217	0.014 m	1.321

3.6.2 Surface Density and Resolution

The surface density, measured in the number of points per square millimeter gives us a measure of how small of a detail we can observe and measure in our models. The more points per square millimeter, the more detail we should be able to observe in our model. Figure 18 shows the surface densities measured for our various models and their distribution and peak values are listed in Table 1.

The handheld camera has the highest densities and this is inferred to be due to the high number of images taken for this project. The highest distribution of high-resolution images is focused in the area of maximum “roughness” where more photos were taken. It is not clear based on this information that there is anything we need to see at sub-millimeter scale in this model but it might be interesting to conduct more studies to look for very small fossils or other objects to determine whether this resolution is needed.

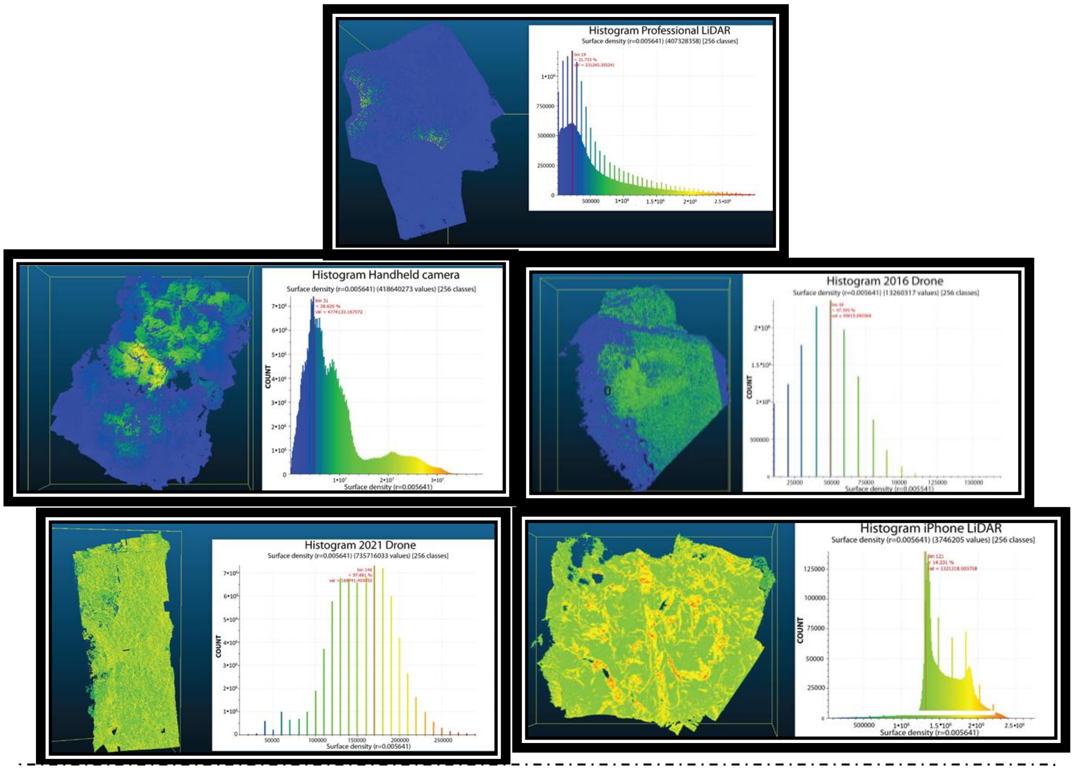

Figure 18- Distance measurements between individual models and the Professional Lidar model data. Each distance calculation includes a distribution map on the left and a histogram on the right showing the distribution of the fit.

The iPhone LiDAR also has a high surface density with slightly more than 1 point per millimeter captured with only a few images. The drone data and professional LiDAR all showed less than one point per millimeter with the lowest densities reported for the 2021 Drone data and the professional LiDAR. The footprints outlined in the red boxes in Figure 11 thru Figure 15 are clearly visible in all of the models. In fact, some additional processing of the professional LiDAR suggests there are many more footprints visible in that data than have been seen elsewhere. More processing of the various data sets in the future may confirm that observation.

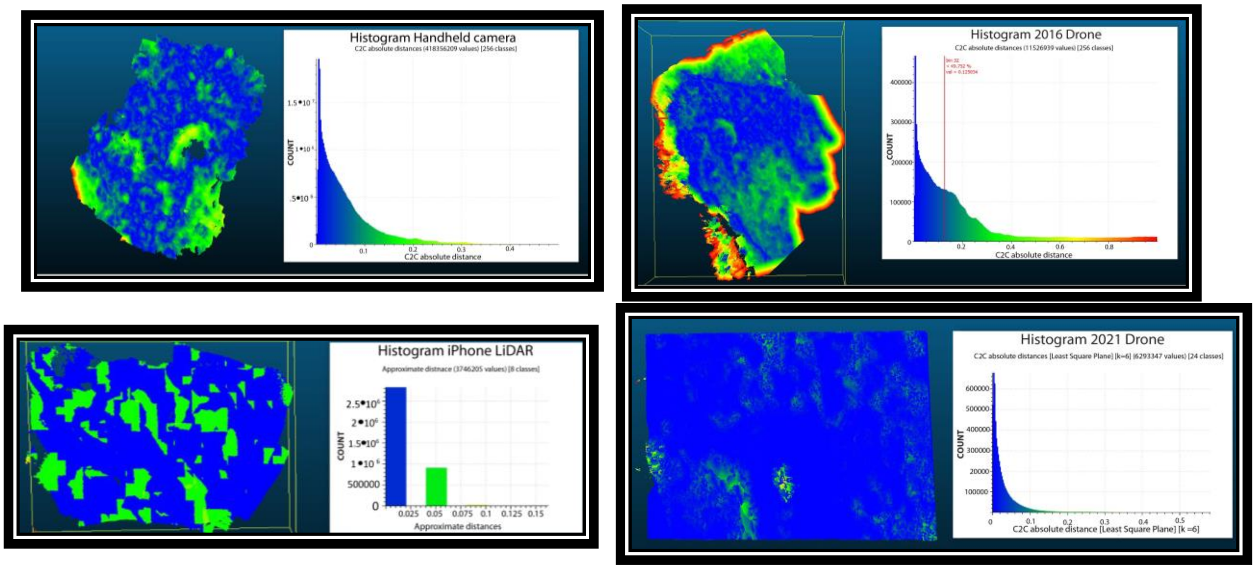

Figure 19- Maps and histograms of the distribution of the various model surface densities in points/mm.

3.7 Discussion

Our working hypothesis is that students will learn geology better if they have realistic 3D models to manipulate in the classroom and, more importantly, can go outdoors in their community and photograph and build their own 3D models to show features that they think fit the concepts presented in their classroom or textbook. This may be the way many large introductory classes get field experience. More important are the lessons they will learn about what a scientist does and how they do it. Learning to interpret observations and identify sources of error or uncertainty is a critical part of our science and students should learn that early in their coursework even if they are not planning to become a scientist.

In this paper we have described some of the steps we used to learn to collect and process images of geologic features to produce realistic 3D models that can be used in education and, in some cases, research. Because the handheld camera data were our first data collection and processing effort, we made a number of mistakes but were able to identify and map new dinosaur footprints in the area nonetheless (Martinez 2016). So, one of the first lessons we learned was that data collection does not have to go perfectly to get useable results. That said however, it would have been easier and the models would have been more useful if we had planned our project more carefully. We see this as a valuable lesson for a classroom exercise. Students will make mistakes but they can learn from those mistakes and continue to improve the quality and useability of their models based on those lessons. Being able to produce and manipulate a 3D model for the first time is exciting for all students.

In addition to the lessons on data collection and processing, we think that students should learn to analyze the quality of their data. The CloudCompare software is free and easy to download but the data sets may be too large for some computers. Similar projects can be created that require only a few photos that students could collect using a smart phone or iPhone LiDAR camera. One lab exercise might involve students producing images of a feature on campus, for example, and then comparing all of their results to identify what worked best and where students had problems. Once started using a software package like CloudCompare, students can explore the analytical tools on their own if they have an interest in that.

University and college instructors can learn to do what we did with this data on smaller scale with relative ease. We think the level of the activities is well within the reach of young students from a wide variety of backgrounds so instructors should also be able to learn enough to teach this approach to some of their lessons. The use of photogrammetry in an introductory classroom that may include mostly non-majors might improve the general understanding of science. It would certainly teach a more valid view of what scientist do and why they do not always agree that looking a series of 2D pictures in a textbook or on screen and memorizing the names of the items shown.

3.7.1 Fieldtrip Applications

From an educational perspective, we believe that new materials and approaches to visualizations during a lecture will improve the ability of students to learn and digest new information. Viewing and working with three dimensional and LiDAR data sets in class before going to the field will prepare students to understand what they will be looking for in the field. Also using a 3D realistically shaded model of a basic structure during class and bringing in different variations of the structures, as well as possible local examples of features that might not be easy to identify during a field trip will also prepares students to collect point cloud materials and be able to process them and convert them into their own models and files. Having this ability to generate and display such data gives the students an opportunity to present and display their knowledge and their computational skills in order to facilitate to prove their objective.

3.8 Conclusions

The availability of a wide variety of photogrammetry data sets from a single location gives us a unique opportunity to compare the models produced from these images to determine how we can best bring photogrammetry into an introductory geoscience classroom. All of the models show dinosaur footprints and, thus, would provide 3D visualizations to the classroom and allow more advanced manipulations of the data. Students would be able to experiment with ways to improve the visualizations using ArcGIS Pro, Microsoft Word, PowerPoint, and CloudCompare.

In order to bring photogrammetry into the classroom, students and schools need some fairly simple equipment. The Professional LiDAR system that we used may not be ideal to bring to the classroom because it is expensive and requires some skill to operate. All of our data compared well with the Professional LiDAR data so we are enthusiastic about recommending any of the data collection techniques for a classroom setting. The pros and cons of the various methods include:

<u>Ease of Use and skill level:</u> All of the methods were easy to use but the drone and iPhone LiDAR were a bit easier because they provided GPS information directly with the images. The handheld phone required external markers to locate the images properly but many cameras and smart phones now provide location information.

<u>Collection time:</u> The fasted data collection was achieved using the iPhone LiDAR but all of the instruments were relatively fast. The handheld camera took the longest to collect the data but that was also the largest data set. The surface density measurements clearly indicated we had collected far too many images for the goal of documenting the visible dinosaur footprints. But additional processing and analysis could indicate the large data set has more to show us.

<u>Accuracy and resolution:</u> These quantities are not fully documented in this study but the preliminary measurements of distance from the Professional LiDAR model and surface density suggests that all of the equipment has done a good job of resolving features within a few centimeters or better.

<u>Cost and Access:</u> Most students today own a smart phone or can borrow one if needed to take pictures of a geologic feature so that might be the most cost-effective choice to start a classroom photogrammetry project. The drone option may be more fun to use and the DJI mini 2

drone we used for the 2021 drone model is about the same cost or slightly more expensive than a standard smart phone with a good camera. The iPhone 12 with LiDAR is more expensive but about the same as a more advanced drone system. The problem with drones is that they are not legal to fly everywhere and there is a possibility of someone being injured by a drone. The advantage of the drone, however, is that they can be flown to photograph things that may not be accessible otherwise, like a cliff face or area that requires more mobility than some students have.

One of the most important observations we can make from this study is that we have become more enthusiastic about building and manipulating 3D models as we explore them. We have not seen any students who did not want to build 3D models or manipulate them. We have seldom seen this type of enthusiasm from students who are looking at pictures in a textbook or standing in a group outdoors while a professor tells them what they are looking at. The collection and processing of 3D models is an ideal learning tool that can be used to cover geoscience and many statistical, mathematical, and computer science concepts in a single activity.

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Chapter 4: Summary

Structure from Motion (SfM) is a tool that has a wide range of uses in education and research. It is easy to produce accurate and highly detailed educational materials using techniques like SfM so students can also be involved in producing SfM 3D models. Using 3D models in a class not only enhances the lectures and assignments, but it also exposes to students to a new approach that may more nearly demonstrate how and why a scientist makes field observations. It builds student understanding of science and technology.

Understanding what SfM is, how it is developed, and how to display their models, exposes the students and educators to new technology developments and teaches how technology can impact research. SfM generates a new visualization of the objects that is a major improvement over photographs and videos. Because students are able to manipulate the colors, textures, and sizes of the object in a SfM 3D model, they will learn that they can bring out new details in data that they may not have observed visually without applying new processes to data. The students and educators will have a unique opportunity to use a tool that will feed their scientific curiosity.

The material presented in this dissertation is particularly important because it is part of a newly developing awareness of how 3D models, SfM, and photogrammetry can change the way we teach observational science. Our focus has been on geologic application primarily and what we envision is a complete change in how geology is taught in some cases. In particular, majors and non-majors in an introductory geoscience class can make observations that are often not introduced until the junior or senior year of a geology major curriculum. This includes concepts like creating a geologic map based on field observations, measuring strike and dip, bed thickness, clast size, distribution, and sources.

In both education and research applications, 3D models will preserve outcrop information in a more useful format than is available from photos and maps. The ability to evaluate the level of accuracy will enchance geology studies that previously were limited by access and the need to carry what tools could be used while hiking or climbing in what can be difficult terranes. It is possible to revisit a digital site often and as technology advances, new tools can be applied to existing 3D models. One area that may become very important in future year will be the ability to revisit sites and build new models that can

The data for this dissertation have been donated to the Insights museum educational program, where the data will be used for their educational models. The data will also be uploaded to V3Geo.com and Opentopography.org to provide free access for the public.

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Vita

Valeria Veronica Martinez is an alumnus from the University of Texas at El Paso. She completed her Bachelors in 2014 and her Masters in 2016, both in Geological Sciences. During her Ph.D., she has presented several potential projects to different agencies, including at the federal level. She enjoyed her time during her graduate school teaching other students as well as being a mentor.

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