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UAV-BASED PHOTOGRAMMETRIC PROFILING OF LESSOR'S QUARRY IN

SOUTH HERO, VERMONT

Erin L. Dundas

Honors Thesis

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ABSTRACT

Structure from Motion (SfM) Photogrammetry has been increasingly utilized as an

effective tool for research in the geosciences. This study applies SfM photogrammetry to

concepts of structural geology and uses it to illustrate the three-dimensional geometry of

geologic structures at Lessor's Quarry in South Hero, VT. This field site is important because it

is widely used for teaching the three-dimensional visualization of geological features in Geology

field classes. Three-dimensional visualization is a critical skill for success as a geologist, but

typically is very difficult for students to learn. The goal of this project was to create interactive

three-dimensional models of Lessor's Quarry with illustrated projections of geologic features

that can be used by students to observe the features from different viewpoints. I utilized an

Unmanned Arial Vehicle (UAV) to obtain images of the quarry and used Agisoft™ Metashape

photogrammetry software to produce the three-dimensional models of the quarry. I added

illustrations of the projected geological structures using freely available 3D modeling software

including Autodesk SketchUp and Autodesk Maya to explore how they relate across the walls.

These 3D models will help students develop three-dimensional visualization skills that can be

applied to common geological problems. They illustrate concepts such as apparent dip and show

how features project into the subsurface. Understanding these concepts is necessary in order to

visualize the trigonometric calculations needed to determine where geological resources can be

efficiently explored or extracted. This technology is an important resource that can be applied to

a wide range of studies.

INTRODUCTION

Lessor's Quarry in South Hero, Vermont is situated in Middle Ordovician aged Glens

Falls Limestone (Figure 1) and preserves three-dimensional geological features, such as faults

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and folded bedding planes, that can be projected across the quarry. Lessor's Quarry is a popular site for UVM geology field trips because it is uniquely positioned within the bedrock in a way that reveals the three-dimensionality of geological features. Despite its heavy use for educational purposes, no formal research has been conducted or articles published on its geology, and the geological features preserved in the quarry walls have never been recorded visually. There is no better place in the area to observe geological features in three-dimensions; it is a perfect model for illustrating the concepts of apparent dip and subsurface projection because you can see features from multiple orientations. These concepts are important because efficient extraction of crucial natural resources, such as water and oil, depend on a thorough understanding of the three-dimensionality of geological features. The only research done in this location has been conducted by students taking GEOL 001, 005, 101, and 361. Students enrolled in GEOL 101, Introduction to Field Geology, visit Lessor's Quarry near the end of the semester to apply everything they have learned up to that point. At this location, they must learn how to visualize geological structures such as faults and bedding planes in three dimensions as they would look if they were projected across the quarry. Since classes are limited in how much time they can spend in the field and we cannot project physical planes across the quarry to help with visualization, having three-dimensional models that can be used in the classroom to supplement their field experience would be extremely valuable for students to more thoroughly grasp these concepts.

The main goals of this research are 1) to develop a model that illustrates the three-dimensional architecture of Lessors Quarry, including its geological features and 2) to use the model to illustrate some basic concepts of field geology, including the concept of apparent dip and subsurface projection techniques. I used SfM Photogrammetry (e.g. Bemis et al., 2014; Gomez & Kennedy, 2017; Westoby et al., 2012) to create the three-dimensional models to

illustrate these concepts and the three-dimensional geometry of the quarry, showing how the structures relate across the quarry walls. SfM is a technique of digital photogrammetry used to create three-dimensional models of structures and objects from overlapping images. This project demonstrates an application of photogrammetry and how it can be used to illustrate these three-dimensional structural problems so they can be easily visualized and understood. The final products of this study are three-dimensional models of the quarry exemplifying the results of a geometric analysis of dipping geological structures, including faults and bedding planes, in a format that can be used to help students in future geology classes learn how to visualize projections of geological structures in three dimensions. An underlying goal of this project was to create a starting point for other students and faculty to incorporate drones into their own teaching and research by outlining a guide for drone operation and regulations.

BACKGROUND

SfM Photogrammetry has been increasingly used as an effective tool for research in the geosciences. Applications of SfM include mapping of geologic structures (Vasuki et al., 2014), creating high resolution digital elevation models that are compatible with Geographic Information System (Westoby et al., 2012), and the quantification of landscape change from river channel erosion (Lane, 2000), among others. Based off the distribution of published articles for different disciplines of geology, SfM is most commonly used in applications of geomorphology (the study of Earth's surface and processes that change it) to monitor sediment transport rates and changes in topographic features, but its popularity as a resource in other geological studies is continually spreading because of its affordability, ability to collect high resolution data, and diverse range of applications (Westoby et al., 2012). A more recent application of SfM involved the use of an unmanned aerial vehicle (UAV) to capture images of a

volcanic ash plume from different angles to construct a three-dimensional model of the plume (Gomez & Kennedy, 2017). This provided insight to gas emission and eruptive dynamics and made it possible to accurately calculate the volume of the ash-plume.

Three-dimensional thinking is such an important skill for geology that articles have been published on methods for teaching it and on research into mental processes associated with three-dimensional visualization abilities (Kuiper, 2008). Shepard and Metzler (1971) conducted their famous rotation experiments to investigate how the human brain processes two-dimensional drawings of three-dimensional objects and how it imagines rotation around the object's axes. These experiments were able to compare the amount of time it took to mentally rotate objects by different amounts. Shepard & Metzler (1971) concluded that the amount of time required to mentally rotate a three-dimensional object increases linearly with the number of degrees of rotation and that mental rotation in depth takes the same amount of time as mental rotation in the picture plane. These studies justify the need for visual tools to help students develop the ability to imagine the projection of features where they cannot be observed.

The concepts I am applying this technology to as a method of illustration include apparent dip, fold geometry, and three-dimensional projection techniques. Apparent dip is the concept that a dipping plane appears to have different slopes depending on the reference frame it is viewed from (Figure 2). When viewed from a reference frame normal to its strike (strike direction is in the direction of a horizontal line on the plane), the maximum dip of the plane can be seen; this is known as the true dip. When viewed from any other reference frame, the dip of the plane will appear to be less than the true dip; this is known as an apparent dip. This concept is difficult to understand when the observer is not able to visualize the three-dimensional projection of the plane. Fold geometry is also difficult for students to visualize since it deals with

imaginary planes that are used to describe fold orientation. This imaginary plane is known as the

axial plane and is defined by the fold axis and a line connecting hinge points in different layers

of the fold (Figure 3). Being able to visualize the projection of three-dimensional features into

the subsurface offers insight into the location of natural resources and where to extract them.

These are all important learning goals in GEOL 101 (Introduction to Field Geology).

METHODS

The majority of the data I collected were aerial photographs of the quarry walls and floor

taken from different angles. I followed methods of data collection and processing for obtaining

accurate, high quality results as outlined in Bemis et al. (2014). As a general rule for

reconstructing three-dimensional images, each section to be reconstructed must be covered by at

least two images captured from different positions (Figure 4). Additional images of each section

from different positions increase the accuracy of the reconstruction to a certain point; angular

differences between photographs of the same section should be limited to 10-20° to avoid

inaccurate reconstruction, and all images should be taken under similar lighting conditions to

avoid images from the same section appearing different (Bemis et al., 2014).

The first step in creating the model was clearing all of the plants obstructing the quarry

walls. I took photographs of the walls using a DJI Phantom 3 SE UAV and Android tablet that

were purchased for the UVM Geology Department with funding from a Hawley Mudge research

grant that I was awarded. I calibrated the drone's compass before flying and flew in Positioning-

GPS mode when collecting data because it allows the drone to hover in place based off a

combination of GPS signal, pressure altitude, and visual positioning, making the hover more

stable and the recorded position of the drone more accurate. I activated the grid overlay on the

camera screen to help estimate overlap amount between images. I developed a manual outlining

rules for legally operating a UAV for educational purposes; it also outlines relevant features that are important to have a thorough understanding of in order to collect useful data (Appendix A). This manual is intended as a quick guide for future students and faculty to get started with the information they need to fly legally and be able to adjust the UAV settings to meet the needs of their specific projects. I hold a private pilot certificate and completed the additional requirements to add a drone certificate to my aeronautical ratings; this step is not necessary for students to use a drone for research, but is more convenient as it reduces the number of regulations that must be complied with in order to operate the UAV legally. Professors and faculty are not legally able to operate a UAV for research without a drone certificate. A guide for becoming certified is outlined in Appendix B.

When obtaining images for the model, I took pictures early in the morning before the sun was high enough for the walls to cast shadows on each other. I went at the same time of day each time to keep lighting consistent throughout the photographs in order to avoid processing errors. I captured images along two horizontal transects across each wall at different elevations, with intervals allowing approximately one-third overlap between images. I vertically aligned the camera locations between the top and bottom transects to ensure there were at least two images of the same location from different angles. I captured additional images from different angles anywhere that the wall geometry was complex and difficult to capture from the regular transects. Geotagging was not used because it is time consuming and such a high level of precision was not necessary for the goal of this project.

I selected a subset of images from each wall to eliminate any duplicate or blurry images, as well as images where the lighting was inconsistent. At the expense of model resolution, I had to minimize the number of pictures to keep the processing load manageable for the computer. I

processed these images and generated a three-dimensional model using Agisoft^{TM} Metashape photogrammetry software (www.agisoft.com), purchased through another Hawley Mudge grant. I used this program on a computer with 16GB of RAM, an intel 6-core i7-8700k Processor at 3.70GHZ, NVIDA GEFORCE GTX 1070ti Graphics Processor, 500GB M.2 Samsung 870 EVO Solid State Drive, and a 1TB Seagate FireCuda Solid State Hybrid Drive. I created models of the quarry at different stages starting with the North Wall, then adding the East and South Walls subsequently. I processed these all as separate models; a potentially more efficient way to do this would have been to add each wall as a "chunk" within the same Agisoft^{TM} project, processing each wall individually then stitching them together. I cut the dataset down to 92 images for the full model of the North, East, and South walls, which took over seven hours to process. In addition to the three models showing the North Wall (Figure 5a), North and East Walls (Figure 5b), and North, East, and South Walls (Figure 5c), I created models of specific sections of the walls to illustrate geological concepts; these models are discussed in detail in the Results section.

In order to make the models, I first organized the images into folders by wall. I loaded the images into an Agisoft^{TM} project using the "Add Folder" function under "Workflow" on the toolbar (Figure 6). It is important not to add or remove any images from the folders or change file or folder names at this point; doing so can make it impossible for the program to find the images again later in processing, particularly when building a texture. To create a point cloud, I used the "Align Photos" function under "Workflow" on the toolbar (Figure 6). I disabled all preselection when aligning the images because I did not use geotagging, and I left the advanced settings at default (Figure 7a). If photo alignment failed without preselection, I reran the alignment selecting "Generic Preselection" and "Reset current alignment" (Figure 7b). I built a dense cloud using the "Build dense cloud" function under "Workflow" (Figure 6) at high quality

with mild depth filtering and allowed calculation of point colors (Figure 8), then built a mesh

using the dense cloud as the source data with the surface type set at "Arbitrary (3D)", face count

set at high, interpolation enabled, and calculation of vertex colors allowed (Figure 9). I decreased

the face count as needed for the models I exported as COLLADA files for 3D manipulation to

keep file sizes small enough to use with modeling software. At this point, the model looks

complete when viewed in Agisoft™, but a texture must still be built. I used the "Build Texture"

function under "Workflow" (Figure 6) and selected "Adaptive orthophoto" for the mapping

mode and "Mosaic (default)" for the blending mode, and enabled hole filling and ghosting filter

(Figure 10). I exported the models under File >> Export >> Export Model (Figure 11) as 3D

PDFs for viewing purposes. Under "Export Mode", I chose a local coordinate system in meters

and I exported the texture as a JPEG and exported vertex colors (Figure 12a). I also exported the

models as COLLADA files for manipulation with 3D modeling software; under "Export Mode" I

exported cameras and vertex colors, and exported the texture as a JPEG (Figure 12b). Batch

processing can speed up this procedure because it allows you to preset the workflow so that it

runs without interruption from start to finish (Figure 13); complications can arise with this

method if one of the steps fails to process correctly. I imported the COLLADA files into

SketchUp and Maya, and used the drawing tools to create planes to fit the planar features visible

on the quarry walls. These programs cannot export models as 3d-PDFs, which are the most

convenient and user-friendly formats for viewing, but animations can be created showing the

three-dimensionality of the structures; they can also be exported in other three-dimensional

formats and converted to 3d-PDFs with the proper software.

I produced multiple three-dimensional models to illustrate different geological concepts including apparent dip, fold geometry, and subsurface projections. My first model uses the NE corner of the quarry to illustrate the concept of apparent dip by fitting a plane to a fault that is visible on both the North and East Walls (Figure 14). When viewed from the North Wall only, the fault appears to be a horizontal line across the wall (Figure 15); when viewed from the East wall, it appears to be a diagonal line across the wall (Figure 16). When the fault is viewed from both the North and East Walls together, it becomes evident that it is a non-horizontal planar feature that appears to dip different amounts depending on the direction it is cross-cut from, as previously shown in Figure 2. This is seen more easily in a three-dimensional model with a plane projected between the walls that can be viewed from different perspectives. My next model shows the three-dimensional geometry of folds by projecting a synclinal fault between the North and South Walls and illustrating its axial plane (Figure 17 a and b). It is very difficult to visualize the three-dimensional projection of a fold from a flat wall, such as the North Wall at Lessor's Quarry, because the fold axis cannot be seen (Figure 3). The intersection of the axial plane with the wall can easily be determined by connecting the hinge points on the layers of the fold, but the angle that it projects into the wall cannot be determined without determining the orientation of the fold axis, as described in Figure 17a. My last model illustrates the projection of geologic features from the South Wall underneath the North Wall using the geometry of the East Wall as a guide (Figure 18). This is useful for visualizing the spatial relationship between planar features and the ground surface, which helps make geometrical calculations more intuitive.

APPLICATIONS TO TEACHING GEOLOGICAL CONCEPTS

Since three-dimensional visualization is such a difficult concept to teach, especially when dealing with imaginary reference planes, it is valuable to have interactive three-dimensional models of geological structures with projections illustrating these concepts. Faults, bedding, and other planar features appear to strike perpendicular to the surface they are viewed from and dip parallel to it. This concept is known as "apparent dip" and is difficult for students to understand until they are able to visualize the three-dimensional projection of the plane into the wall. Figure 2 illustrates how one plane can appear to have different orientations depending on the reference frame it is viewed from. A three-dimensional model with projections can make this concept very easy to grasp by showing the plane that otherwise must be imagined (Figure 14). Fold geometry is another concept that is very difficult for students to grasp since it deals with the projection of imaginary planes. Axial planes are imaginary planes that are defined by the fold axis and the line that passes through the hinge points in all the layers of the fold; the orientation of this plane is used to describe the fold geometry. In a flat wall, the orientation of the fold axis is unknown (Figure 3) so the three-dimensional projection of the fold between two walls must be able to be visualized in order to determine the orientation of the fold axis, and therefore the axial plane. These imaginary planes can be physically represented by the three-dimensional models, which make the concept significantly easier for students to grasp (Figure 17 a and b). The subsurface projection of geological structures (Figure 18) is one of the most important concepts for students to understand since it determines where natural resources can be found and whether or not they can be efficiently explored or extracted. Once this concept can be visualized three-dimensionally, the trigonometric calculations required to determine locations and depth are intuitive.

<u>CONCLUSIONS</u>

This study explored the three-dimensional geometry of geological structures in Lessor's Quarry and how they relate across the walls. SfM photogrammetry is an effective tool for the construction of models to illustrate the three-dimensional structure of geological features. The unmodified models can easily be viewed in 3d-PDF format with Adobe Reader, which is convenient for classroom use to supplement field observation. Since photogrammetry files are so large, models intended for concept illustration must be created at low resolution in order to be manageable for the three-dimensional modeling software. I created three-dimensional models that illustrate concepts of apparent dip, fold geometry, and subsurface projection by using the geometry of features visible on each wall and knowledge of how they relate structurally. These models cannot be directly saved as 3d-PDFs, but animations showing their three-dimensionality can be created or they can be exported as other three-dimensional files and converted to 3d-PDFs with the proper software. These models are useful to help effectively teach difficult concepts relating to three-dimensional visualization. Future work could involve building georeferenced three-dimensional models with high enough accuracy that quantitative data can be recorded by them, rather than strictly using the models for conceptual exploration. Higher quality three-dimensional illustrations could also be made with additional time and more user-friendly modeling software.

FIGURES

Figure 1

Location map of Lessor's Quarry in South Hero, VT

Sources: Esri, HERE, Garmin, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, © OpenStreetMap contributors, and the GIS User Community
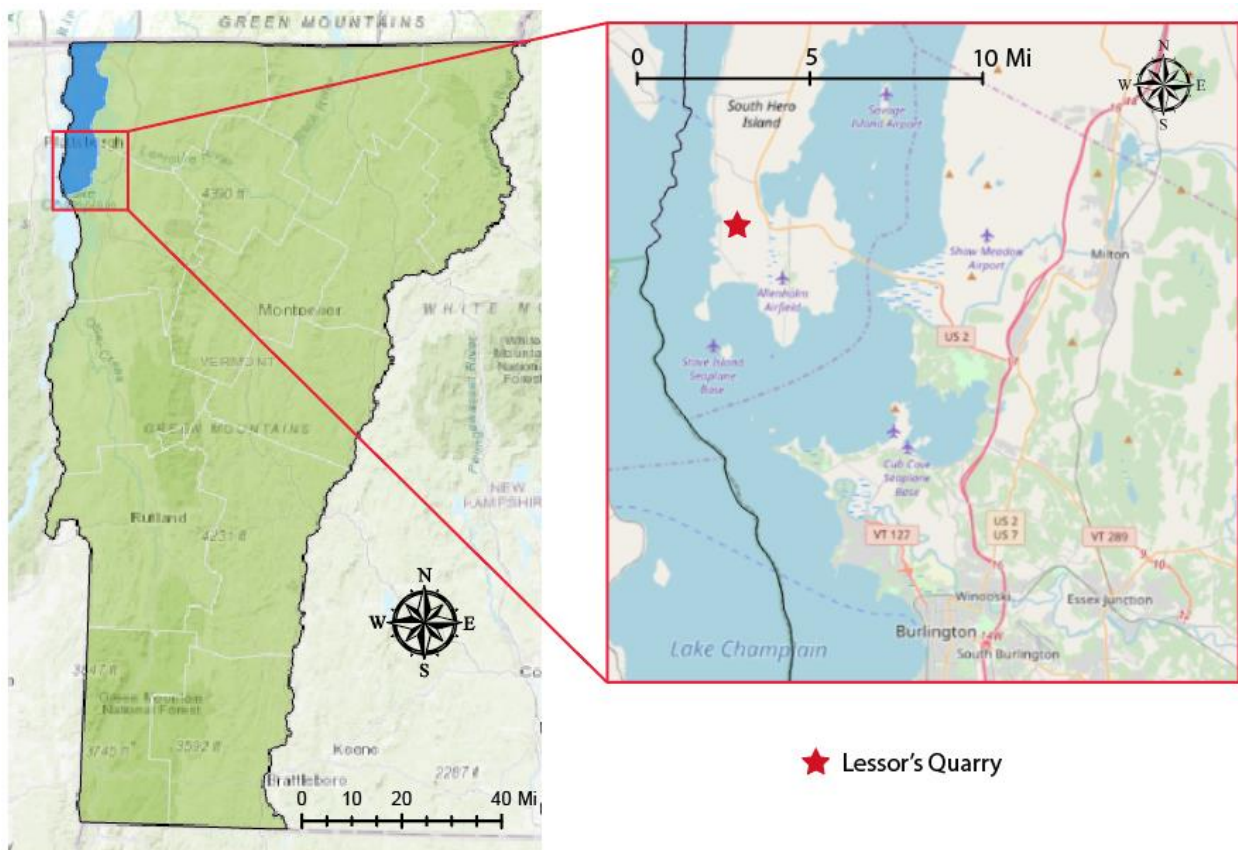
Figure 2

Faults viewed from the North and East Walls at Lessor's Quarry: faults viewed from the North Wall appear to be approximately horizontal (an apparent dip), while the same faults viewed from the East Wall are dipping shallowly (the true dip).
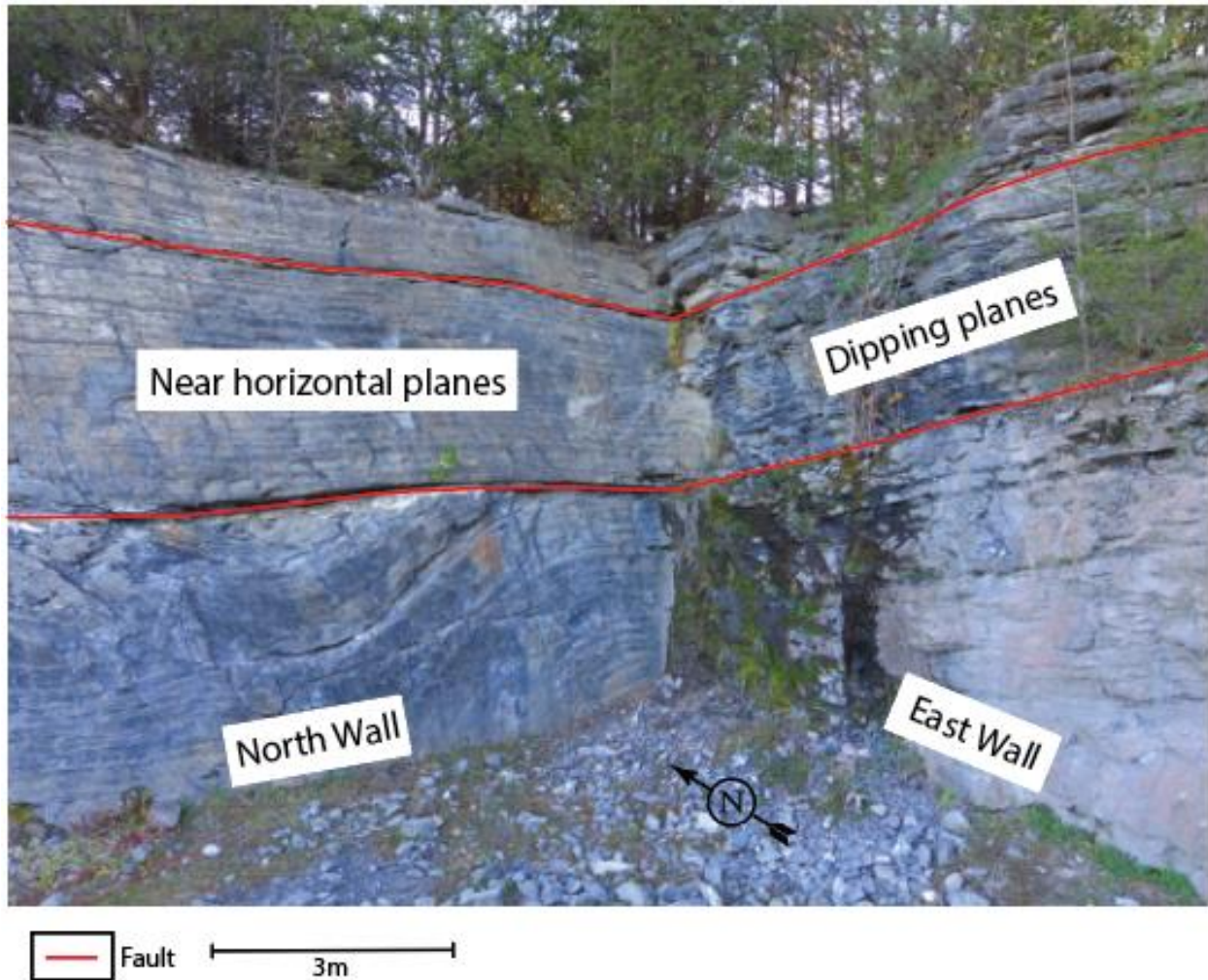
Figure 3

Synclinal fault with the hinge point and the intersection of the axial plane with the wall indicated.
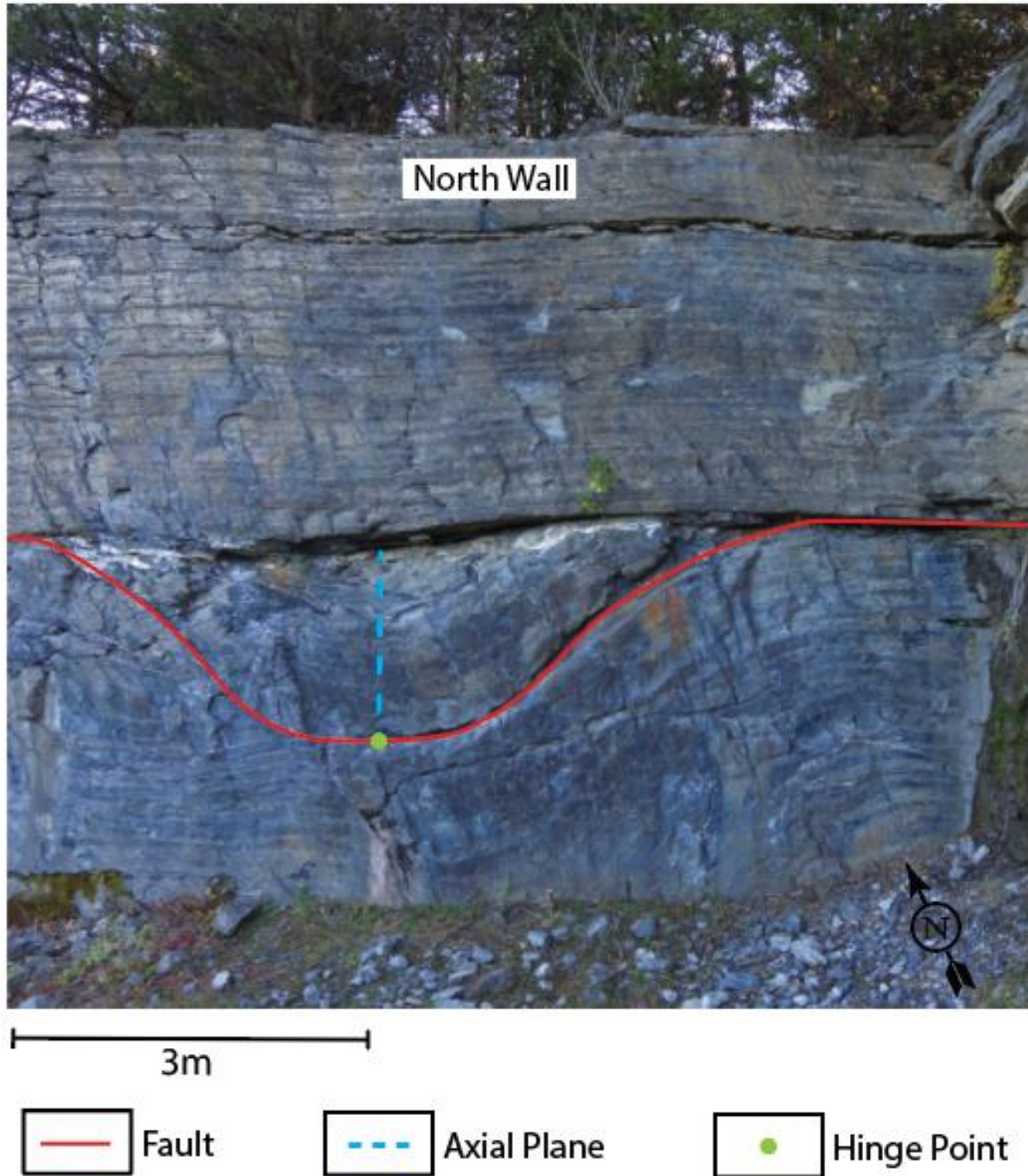
Figure 4

Example of camera positioning to three-dimensionally reconstruct the indicated portion of a surface (figure taken from Bemis et al., 2014).

portion of surface resolvable by photo-based reconstructions
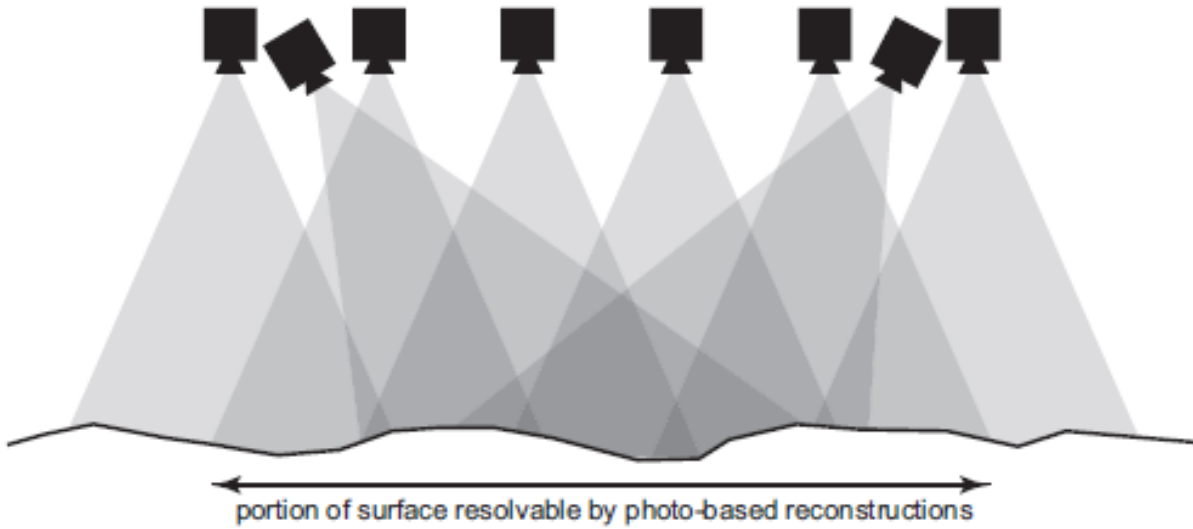
Figure 5

(a) Snapshot of a three-dimensional Agisoft™ model of the North Wall of Lessor's Quarry
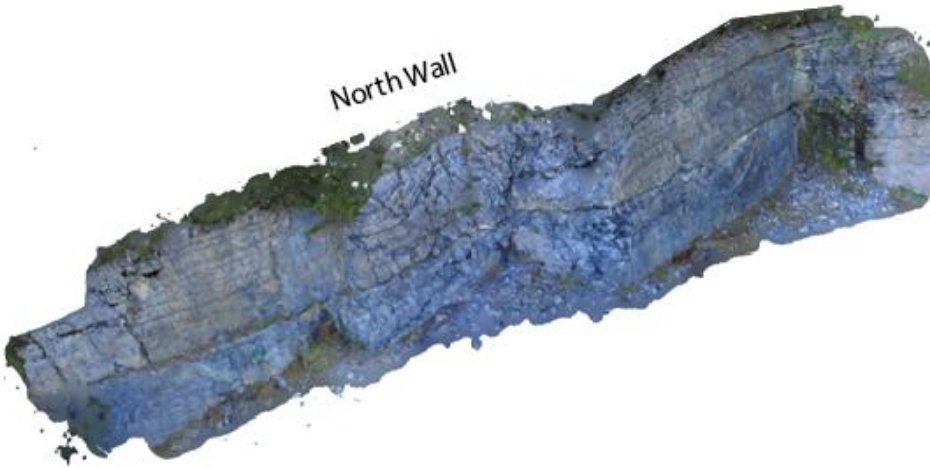
(b) Snapshot of a three-dimensional Agisoft™ model of the North and East Walls of Lessor's Quarry

(c) Snapshot of a three-dimensional Agisoft™ model of the North, East, and South Walls of Lessor's Quarry
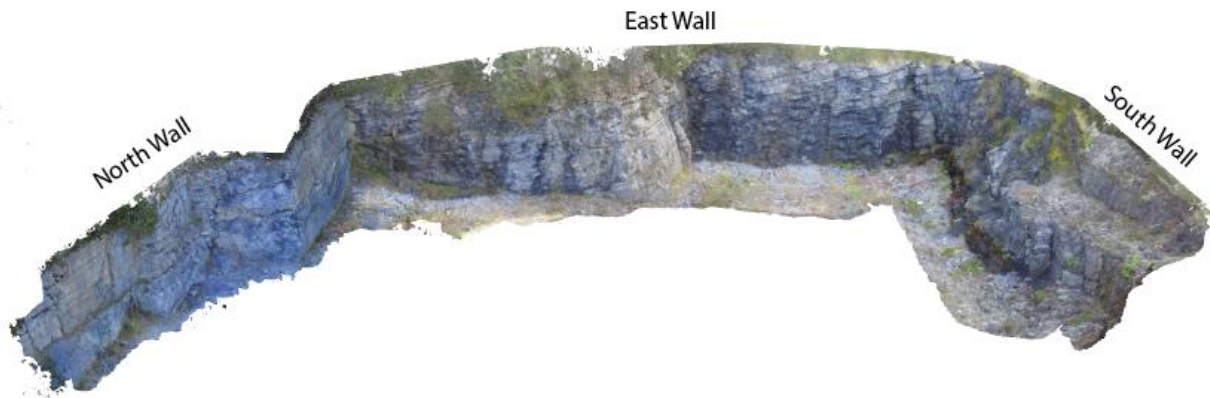
Figure 6

Agisoft™ processing options are found under "Workflow" on the toolbar
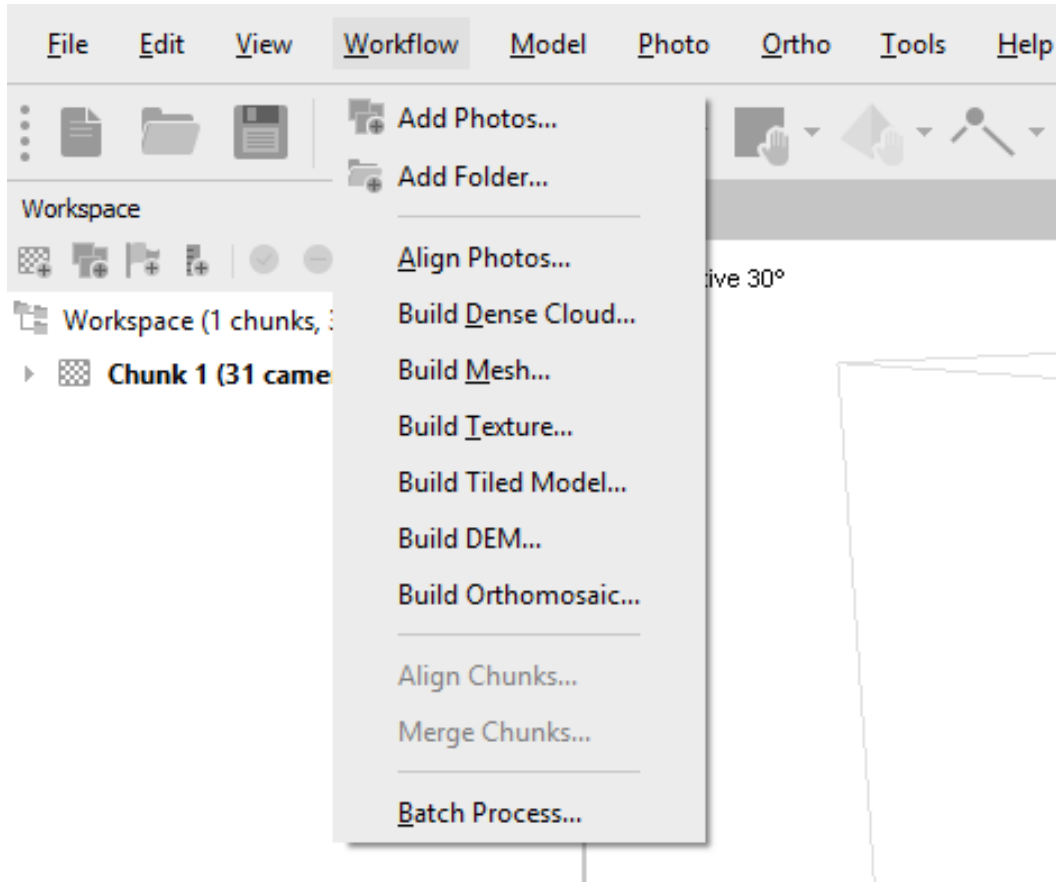
Figure 7

(a) settings used to create a point cloud in Agisoft[TM]
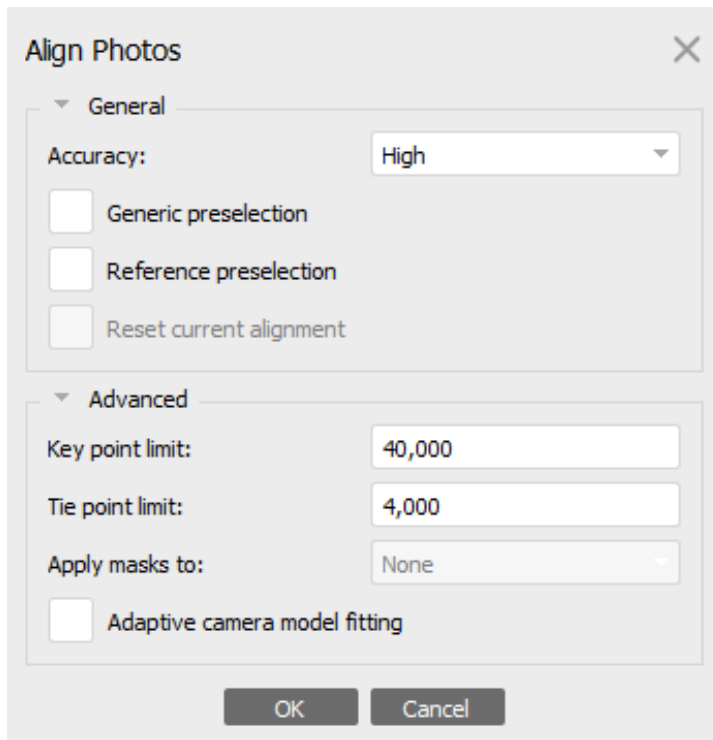
(b) Settings used to create a point cloud in Agisoft[TM] if first alignment without preselection fails
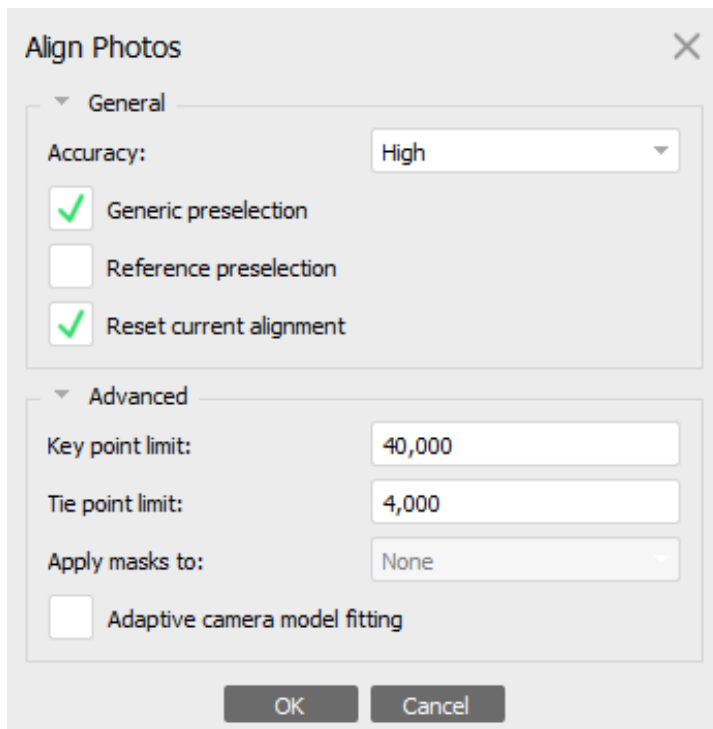
Figure 8

Settings used to build a dense cloud in Agisoft™
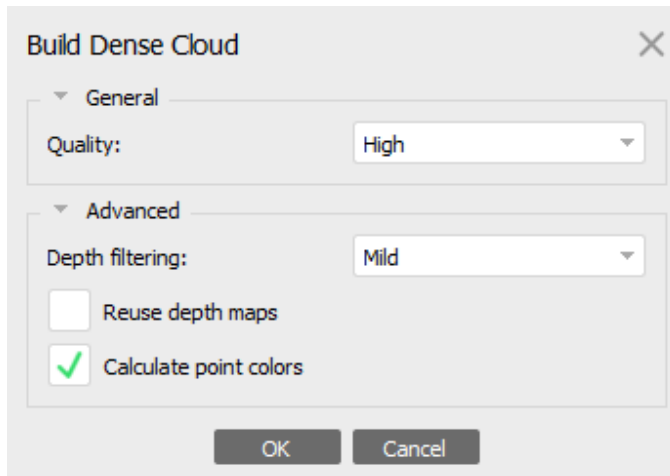
Figure 9

Settings used to build a mesh in Agisoft™ for demonstration models. The face count must be decreased for models used with 3D modeling software so that exported models will not be too large to import in the program.
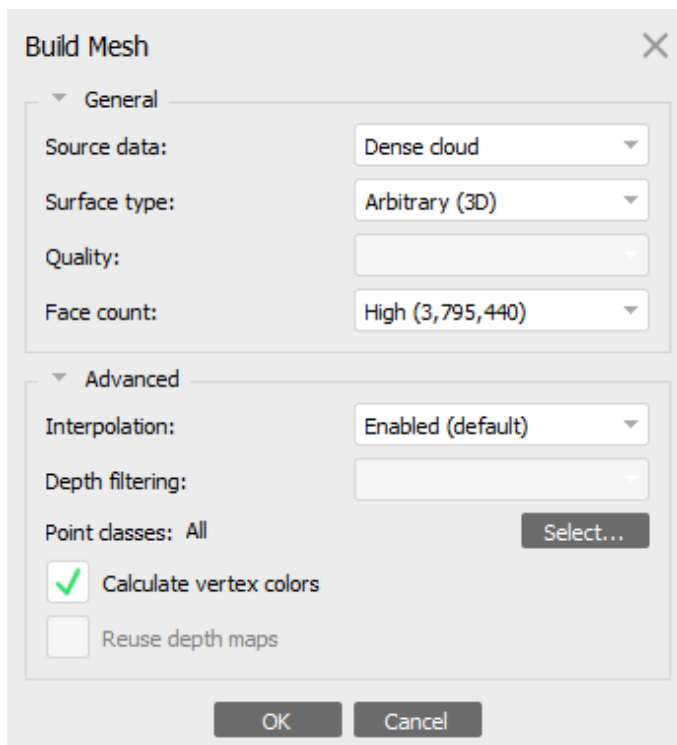
Figure 10

Settings used to build a texture in Agisoft^{TM}
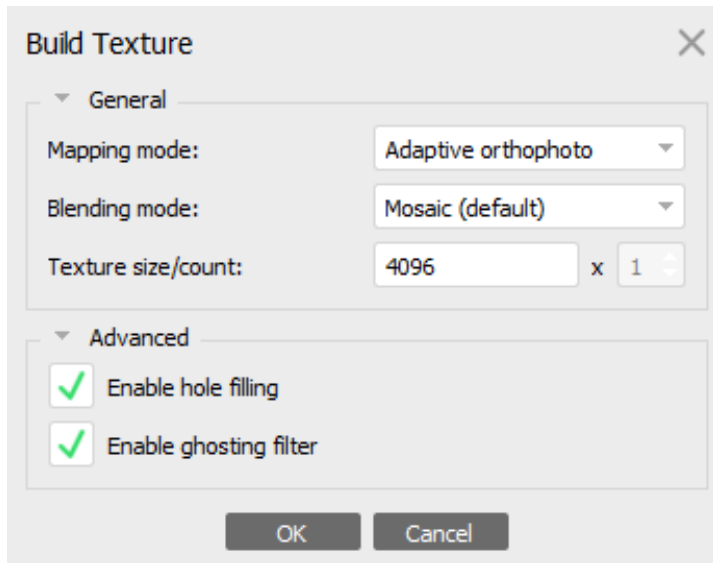
Figure 11

Agisoft^{TM} export options are found under File on the toolbar
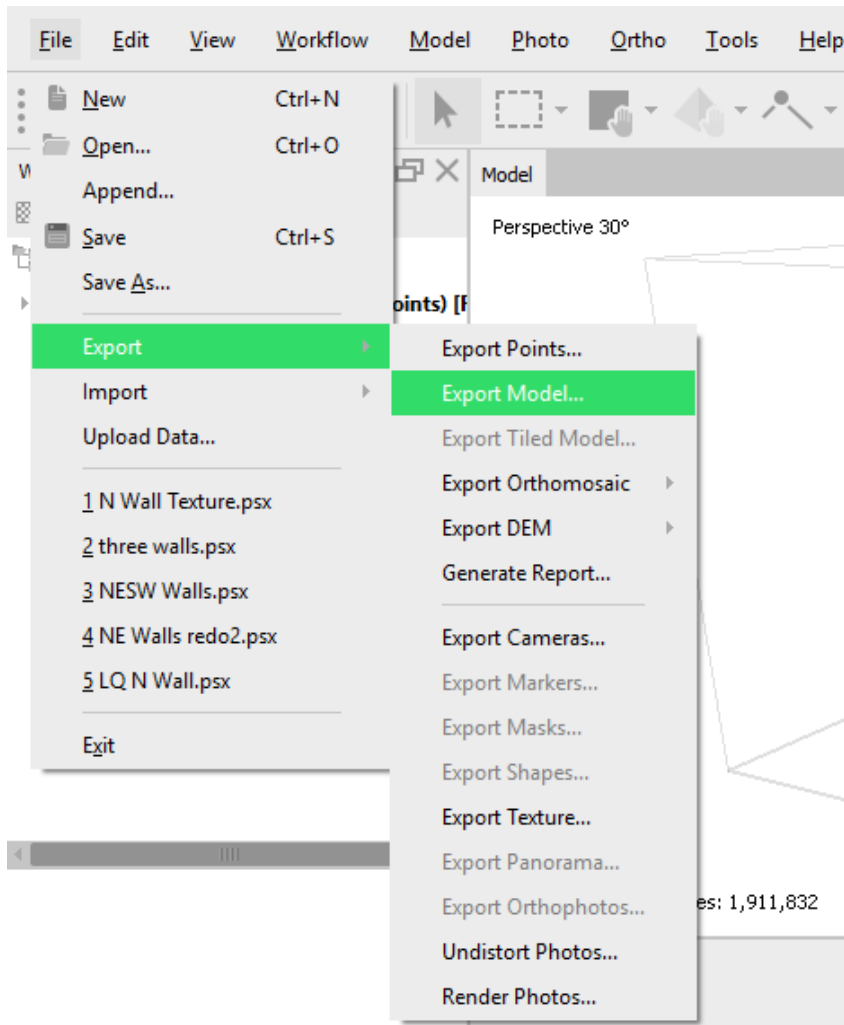
Figure 12

(a) Settings used to export models in Agisoft[TM] as a 3d-PDF for viewing
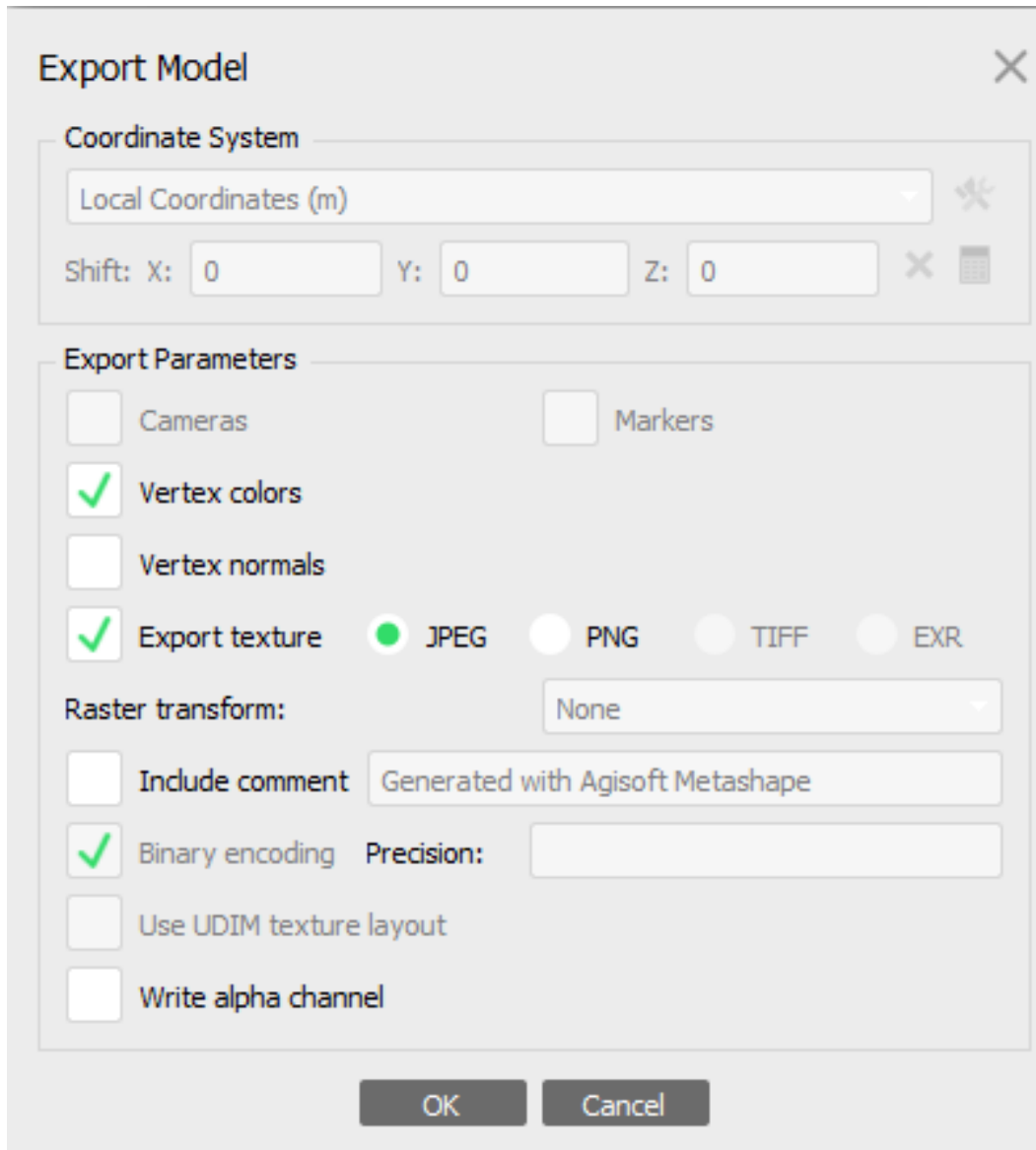
(b) Settings used to export models in Agisoft^{TM} as a COLLADA file for 3D modeling
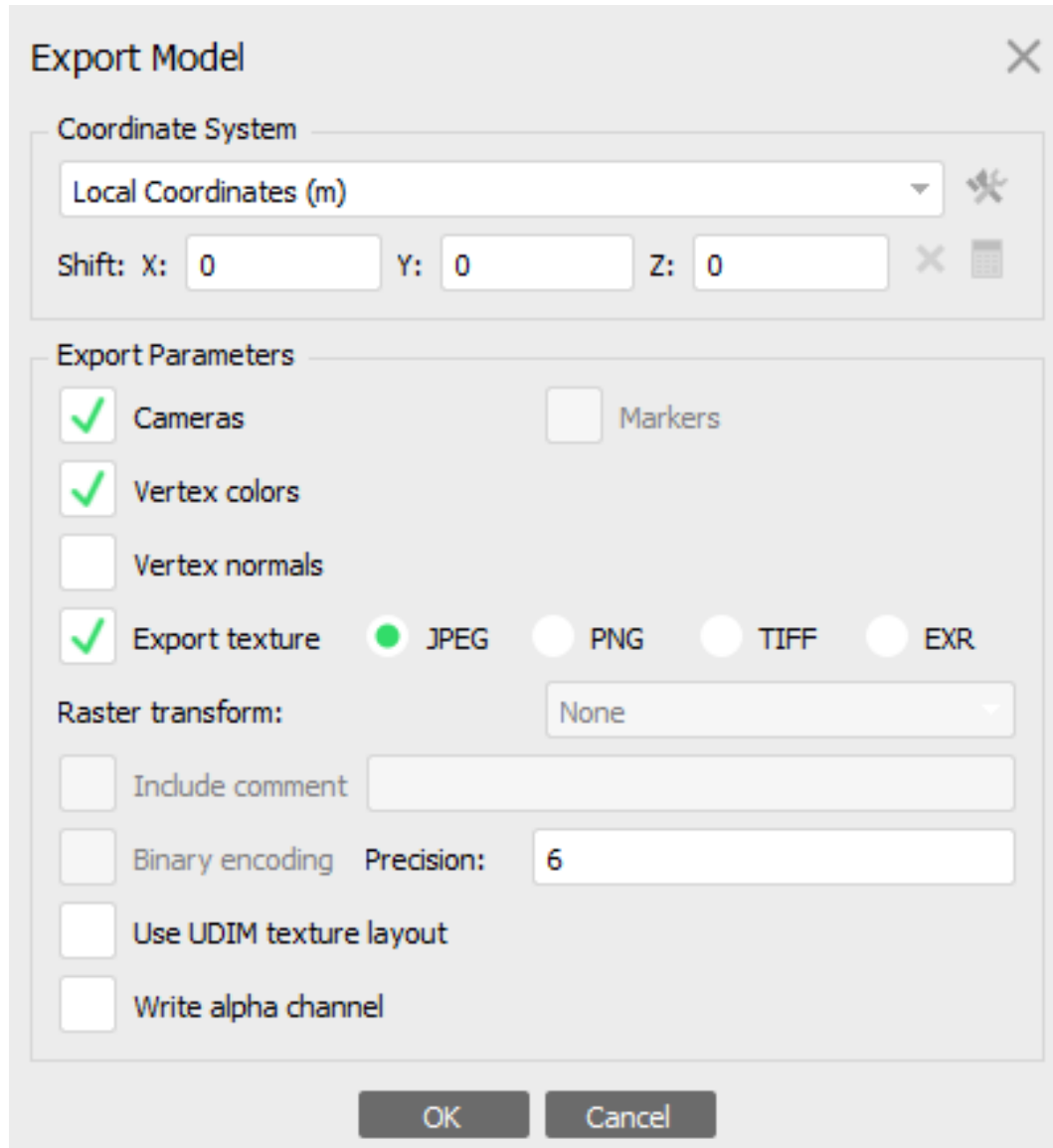
Figure 13

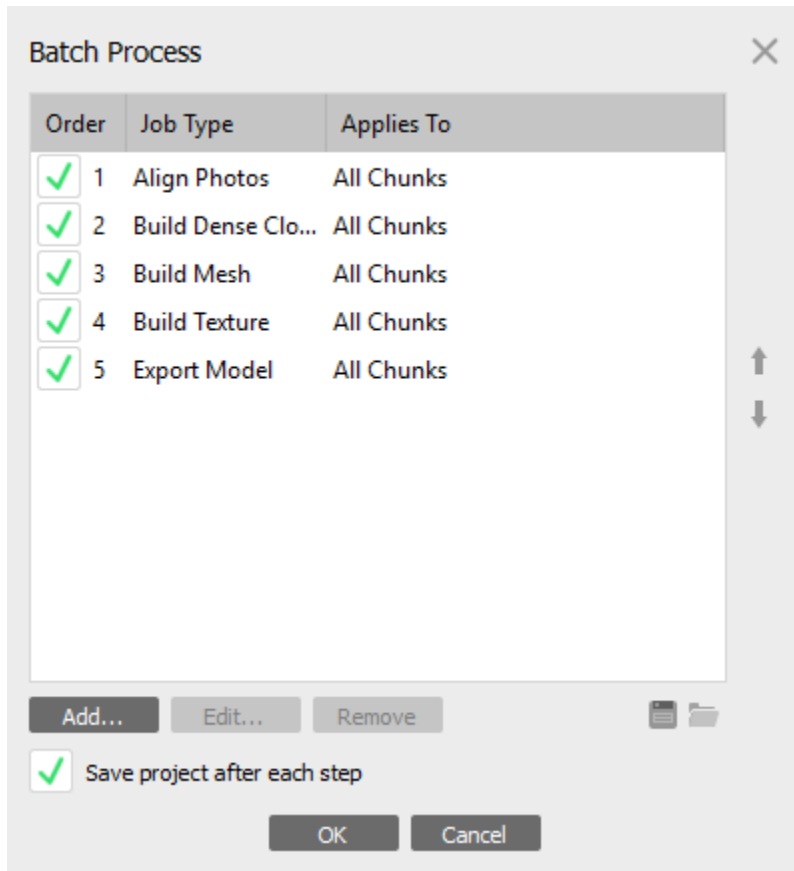Agisoft^{TM} batch processing

Figure 14

Snapshot of a three-dimensional model of the NE corner of Lessor's Quarry with a plane fit to a fault to help illustrate the concept of apparent dip and show how a plane's orientation can be determined when its cross section is observed from two or more perspectives.
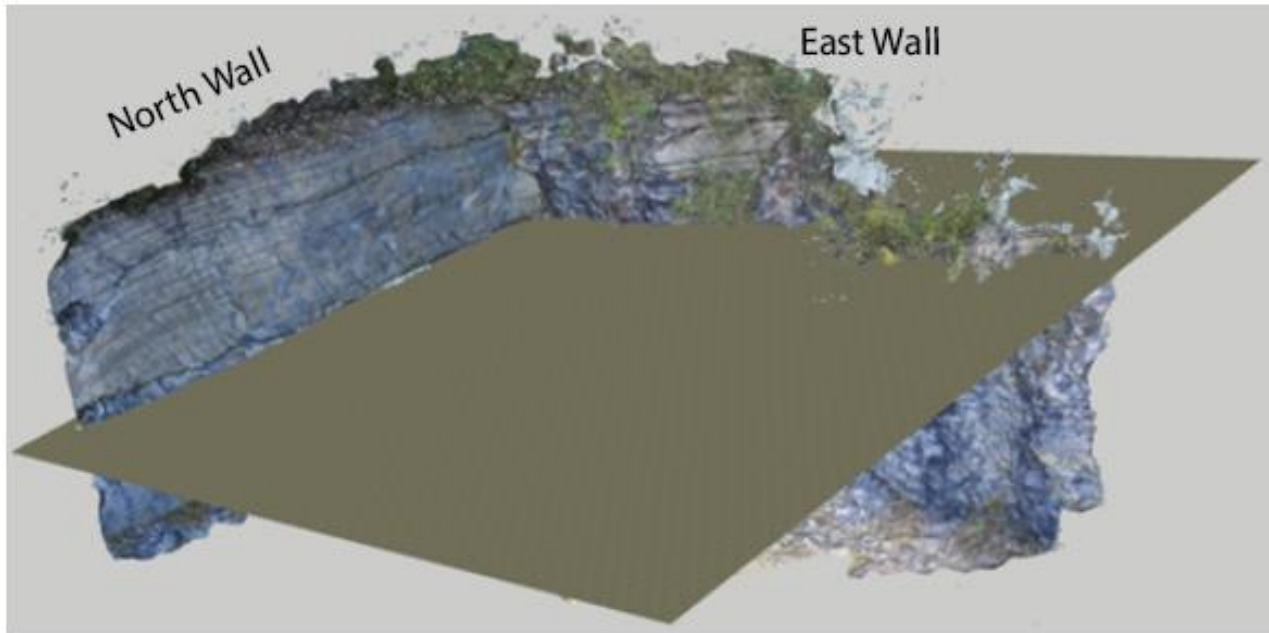
Figure 15

Faults and bedding planes on the top of the North Wall appear as approximately horizontal linear features when viewed in isolation.
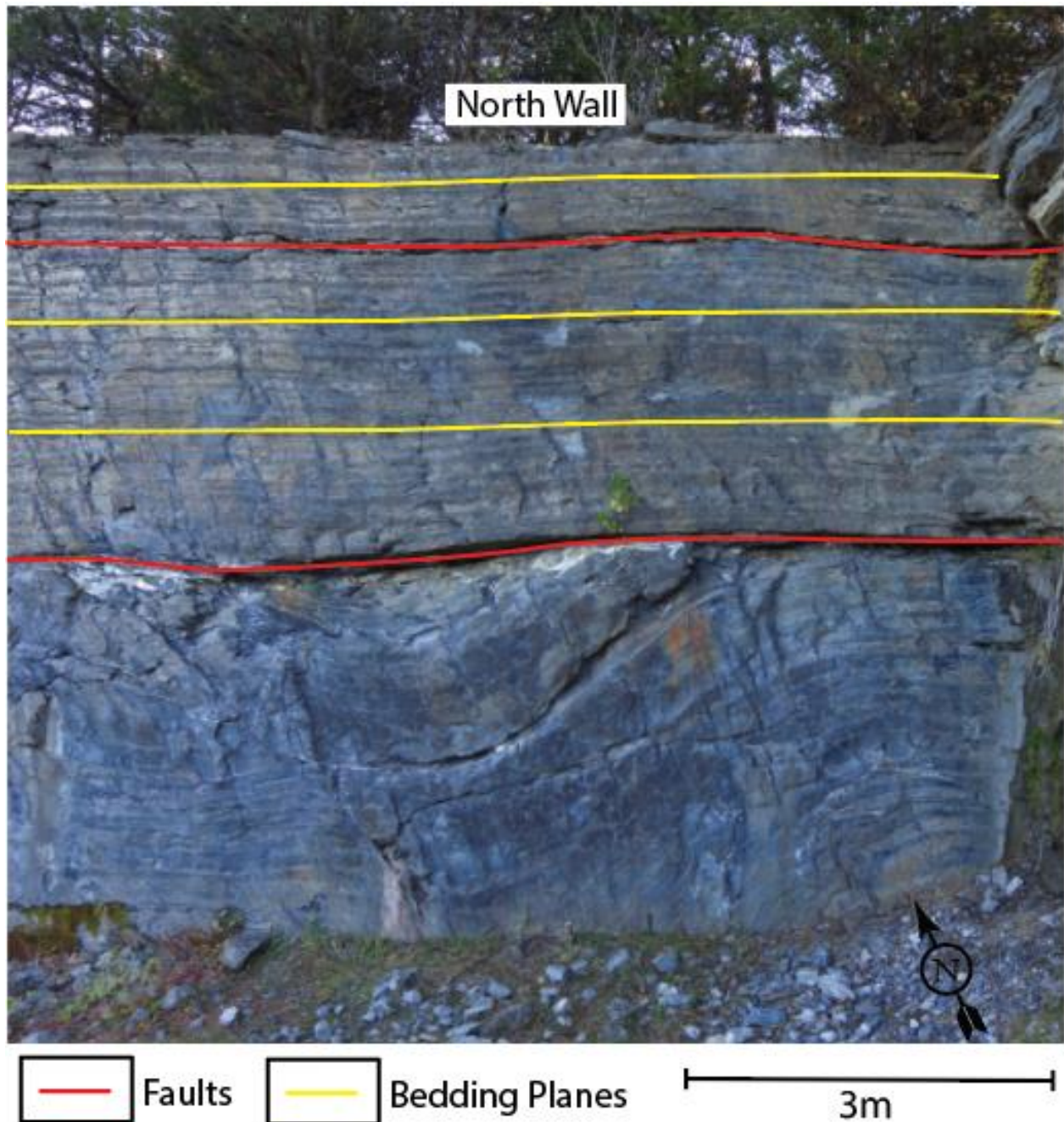
Figure 16

Faults and bedding planes viewed from the East Wall at Lessor's Quarry appear as diagonal linear features.
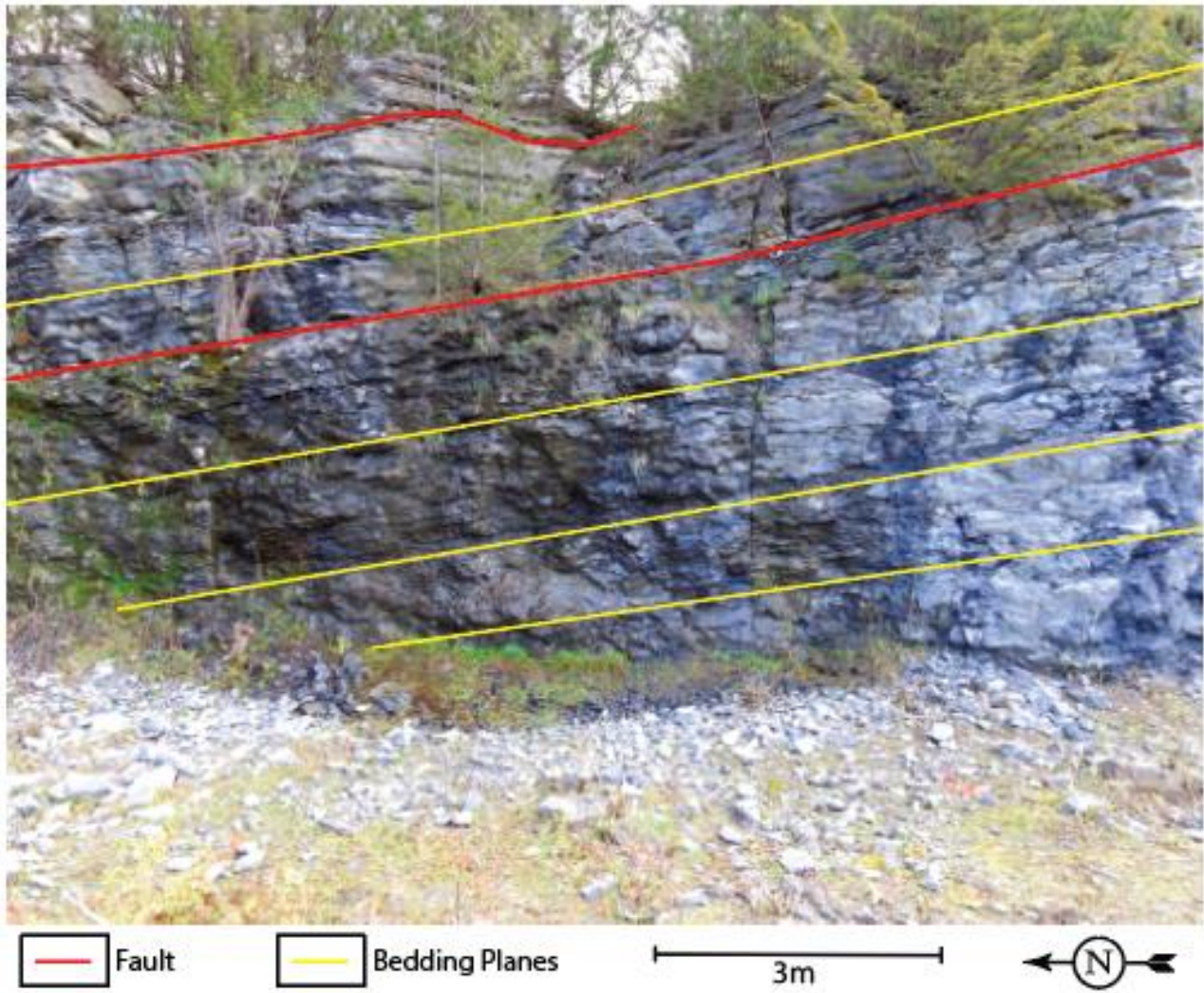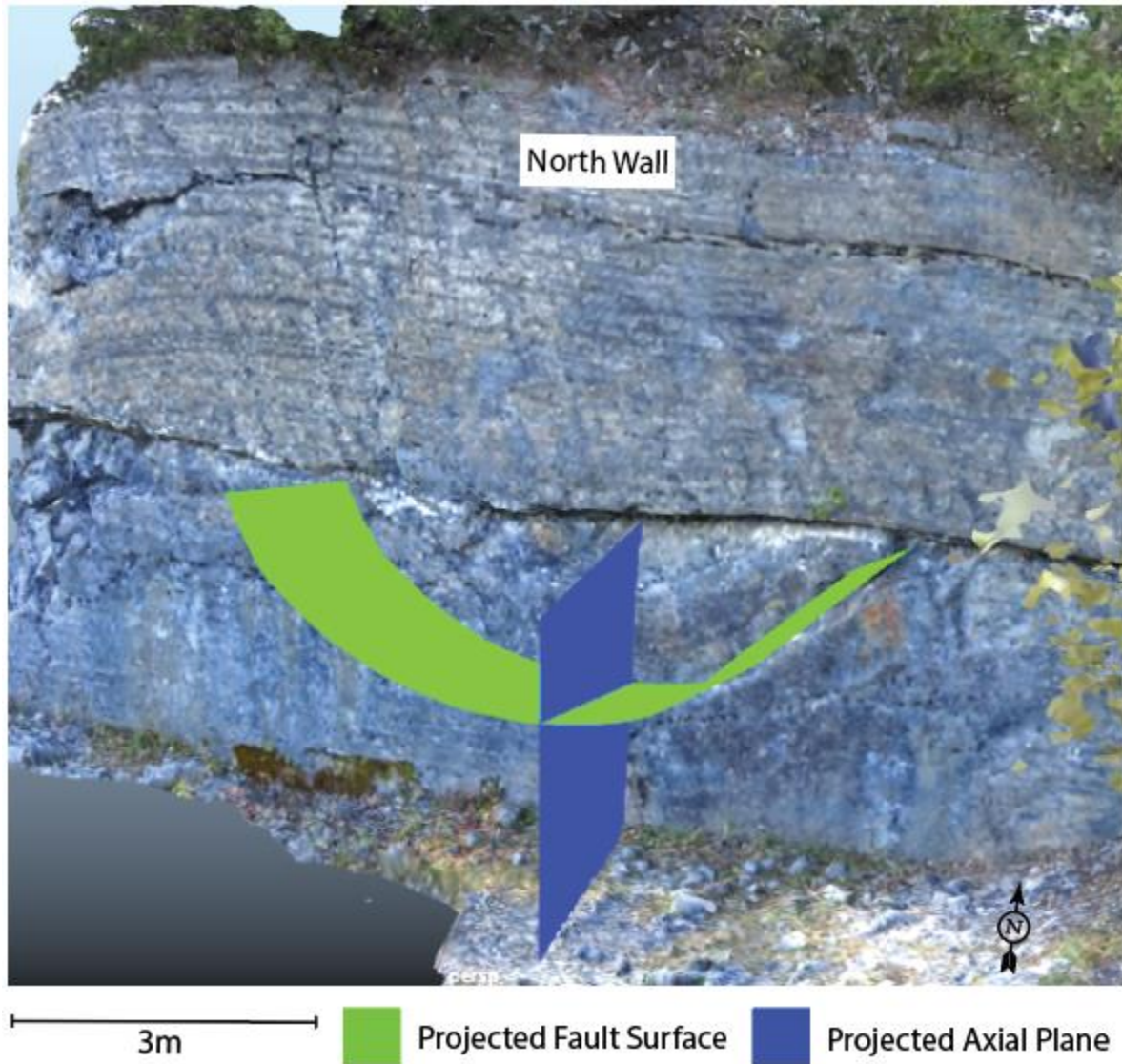
Figure 17

Three-dimensional geometry of a synclinal fault with projected axial plane:

(a) The axial plane is projected from the trace of the hinge points visible on the North Wall toward the trace of the hinge points visible on the South Wall (could not be pictured with two-dimensional snapshots).

(b) The plunge of the fold axis follows the dip of the faults and bedding planes visible on the east wall
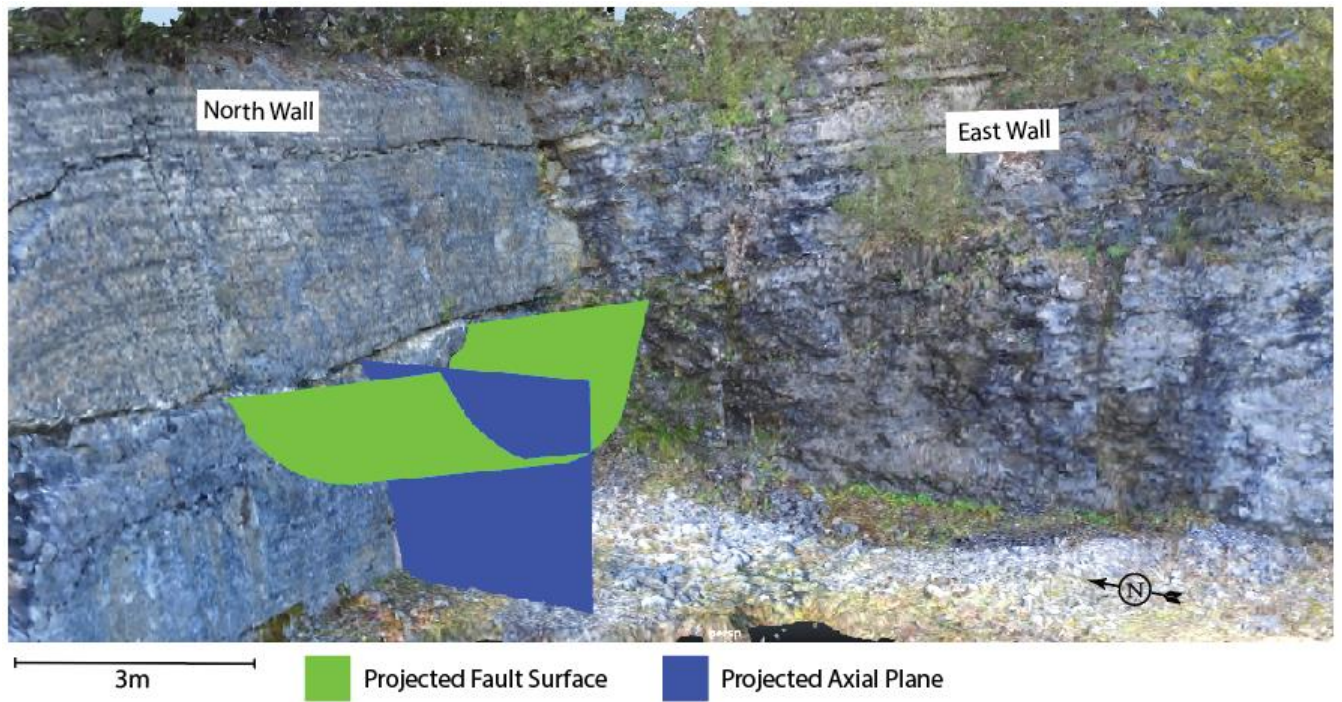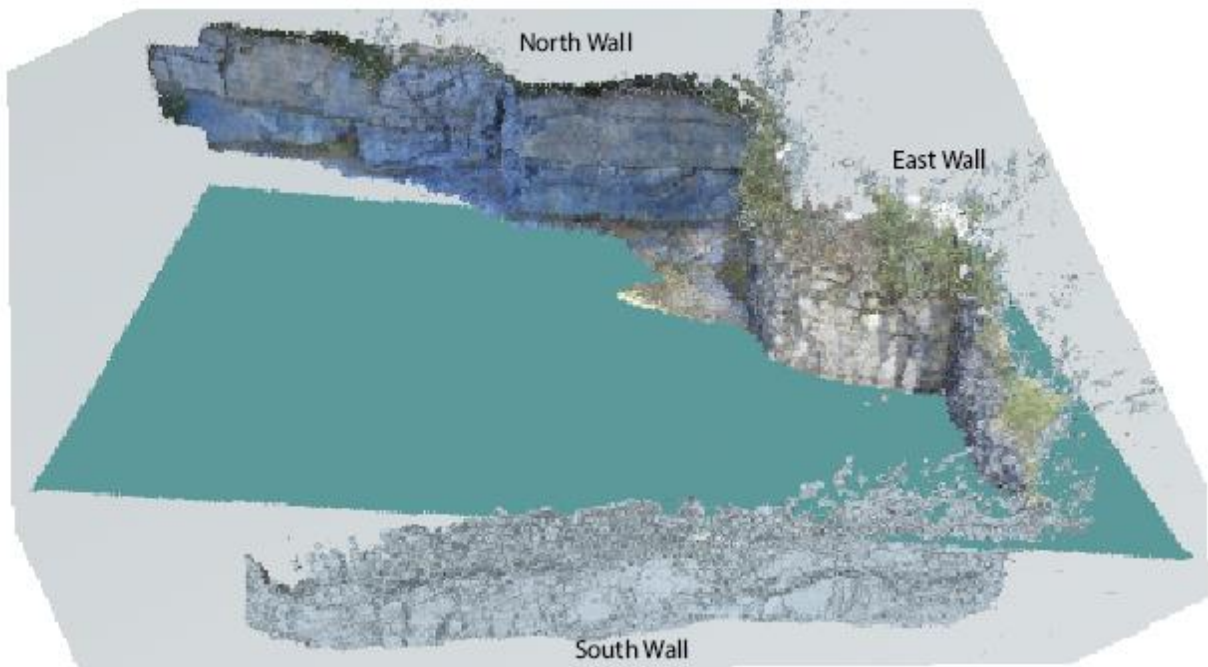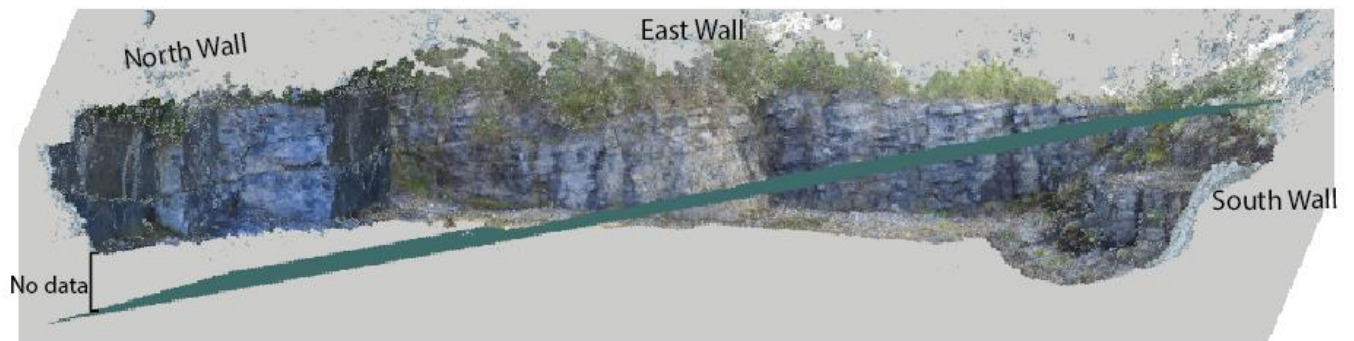
Figure 18

(a) Projection of the ground surface from the top of the South Wall underneath the North Wall.

(b) Projection of the ground surface from the top of the South Wall underneath the North Wall, showing the gap where data is not observable from the North or South Walls, but can be seen on the East Wall

DJI Phantom 3SE Manual

NOTE: Return to home feature is disabled to avoid hitting overhanging trees when using drone at outcrops. Closely monitor battery levels and heed low and critical battery level warnings to avoid crashes. This can be re-enabled in MC Advanced Settings. Beginner Mode can be enabled in MC Settings and should be used for first flights.

It is the responsibility of the drone operator to ensure they are familiar with current Federal Aviation Administration (FAA) regulations prior to flying.

Batteries:

- Press button once to check charge level

- Press once then press and hold to turn drone on or off

- Charging: lights will stop flashing when charge is full

Controller:

- Left Stick

  o Forward/backward

  o Left/right turn

- Right stick

  o Up/down

  o Left/right

- Wheel (on left)

- o Adjusts camera angle

- S1 switch (right)

  - o Controls flight modes (see below)

- S2 switch (Left)

- Charging: Light changes from red to green when charge is full

Flight Modes:

- When "multiple flight modes" is **not** enabled (from DJI GO app MC settings), the aircraft is locked in P (positioning) mode.

  - o P-GPS, P-OPTI, and P-ATTI are automatically selected based off satellite coverage

- When "multiple flight modes" **is** enabled, us the S1 switch to change modes

  - o Positioning Mode

    - ▪ Needs strong GPS to be effective

    - ▪ Hovers based off GPS signal (when available), pressure altitude, and visual positioning

  - o Attitude Mode

    - ▪ No GPS or vision positioning available for stabilization or hovering

  - o Function Mode

    - ▪ Intelligent Flight Mode is activated

Camera:

- Adjust camera/video display settings from camera MENU >>> settings icon

    o Turn on grid to help gauge photo position and overlap

- Adjust camera settings from camera MENU >>> camera icon

    o Photo: Choose single shot, HDR, burst, AEB, or interval depending on project

    o Image format: Choose to shoot in RAW, JPG, or RAW&JPG (RAW keeps all

      photo data)

    o White balance: Adjust for environmental conditions

    o Style: Landscape for outcrops

- Adjust ISO, Shutter, and EV from settings below the photo/video button

Important Tips:

- NEVER fly above 400ft AGL (FAA violation)

- Aircraft will not hover in attitude mode

- Fly in P mode when using video (just keep Multiple Flight Modes disabled and it will

  select a P mode based off satellite coverage). P-GPS is best (most stable and accurate

  hovering)

- Shoot in RAW&JPG mode (RAW keeps all the photo information)

- Activate grid function and keep 1/3 image overlap to construct profiles

- Only remove or insert the micro SD card when the drone is turned off

Setup:

- Attach propeller guards to drone

- Screw propellers on to motors following black and gray color coding (follow arrows on propellers to screw them in the right direction). Do not over tighten, use the propeller wrench to remove them if they are too tight.

Flying:

- Carefully remove camera lens cover and stabilizer

- Make sure micro SD card is inserted

- Turn on controller, drone, and tablet

- Mount tablet on controller and straighten antenna

- Open DJI GO app and select phantom 3SE

- Tap Camera button

- Adjust settings as desired from app (see previous sections for guidance)

- Calibrate compass: Tap status bar at top center of screen >>> tap Calibrate (next to Compass)

- Check the status of all equipment from the status bar (check battery charge and temperature) and check for updates

- **Taking off:**

  - Push both sticks to the bottom inside corners simultaneously to start propellers

  - Push right stick forward to takeoff

- o OR tap the takeoff button on the left side of the screen (check for low hanging
   objects)

- **Landing:**
  - o Lower the drone slowly until it is on the ground then pull the right stick all the
     way back to stop the propellers and prevent it from automatically taking off again
  - o OR tap the landing button on the left side of the screen when in a safe landing
     area free of debris

__Drone Certification Guide__

(The FAA also has a step by step guide: https://www.faa.gov/uas/commercial_operators/. I recommend reading through it and following the links for each section to familiarize yourself with the website.)

1. Study and register for the unmanned aircraft knowledge test

    a. http://candidate.catstest.com/locations/burlington-technical-center/

    b. The test code is UAG (Unmanned Aircraft General – Small)

2. Make an IACRA account and complete the application for the remote pilot certificate

    a. https://iacra.faa.gov/IACRA/Default.aspx

    b. Under applicant options >> Start New Application

    c. Application Type: Pilot

    d. Certifications: Remote Pilot – Initial

    e. Certificate Category/Class: Small Unmanned Aircraft System

    f. Start application, fill out personal information and supplementary data

    g. Under "Basis of Issuance", you will be doing option A by registering for the knowledge test with the link provided at the top of this page. You can take the training course mentioned in option B as practice for the knowledge test, but it will only cover the material specific to drones, it will not cover any of the airport/sectional chart information. It is designed for pilots who are also getting a drone certificate, so it assumes you already know all the other required material (it

3. View Privacy Act, Review Application, and Submit Application

4. You will need to meet with a Recommending Instructor or Certifying Officer to complete the application. You will need to know your FTN, Application ID, and knowledge test ID. Your FTN can be found under User Information when you log into IACRA and your Application ID will be shown to the left of your application in the console. Your knowledge test ID should be on your knowledge test certificate.

5. Print out your temporary certificate if you are going to fly before your permanent certificate is mailed to you. You must have your signed certificate on you while you are flying.

You will need to take a recurrent knowledge test every two years to keep your certificate. The test code is UAR (Unmanned Aircraft General – Recurrent).

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