Automated 3D model reconstruction from photographs

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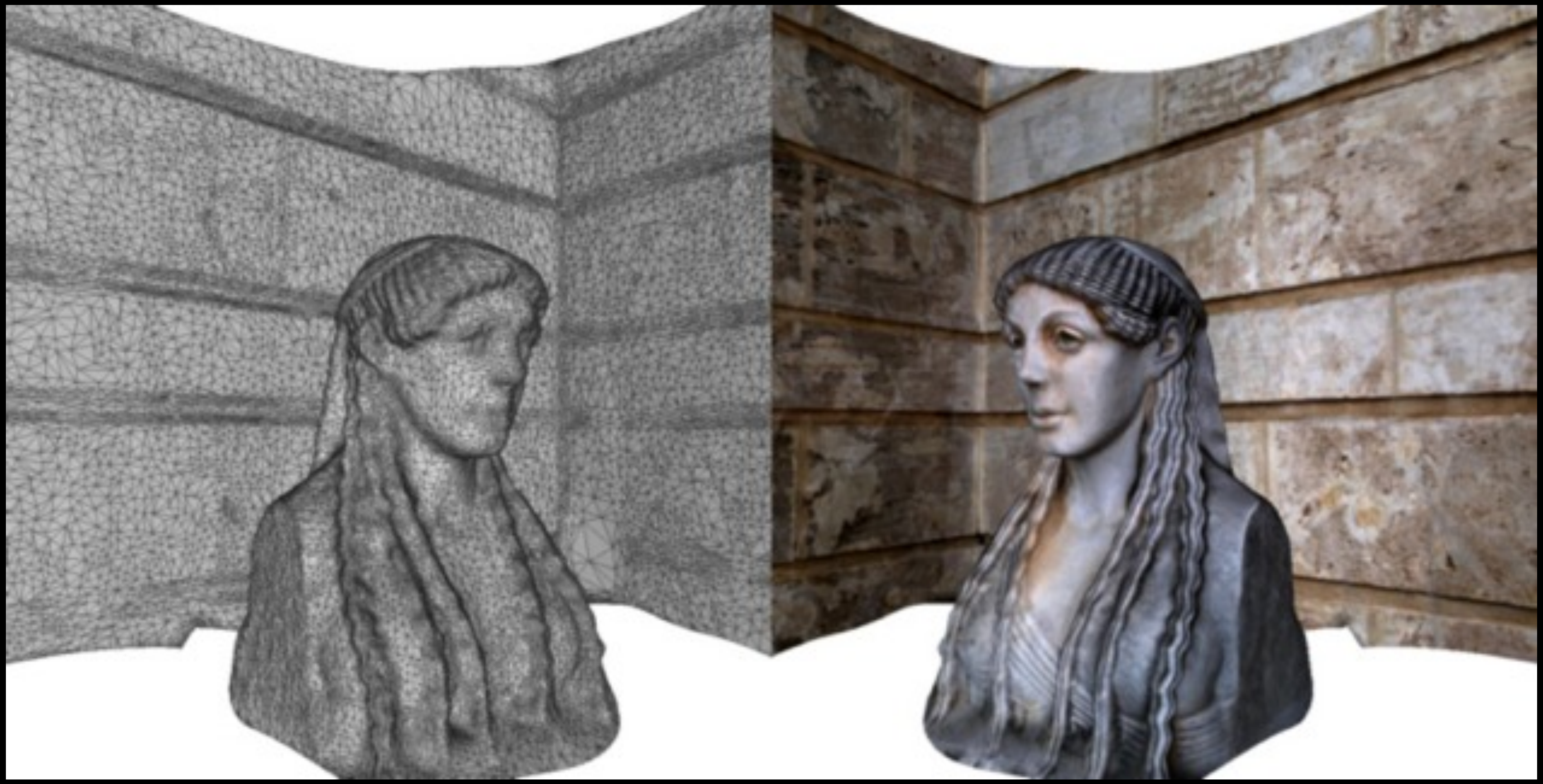


Outline

- Introduction, Outcomes, Motivation
- Software
- Photography
- Case study 1: 2.5D
- Geometry processing
- Case study 2: 3D
- Other topics
- Limitations
- Case study 3: Indigenous rock art
- Additional applications
- Further reading, references, and discussion

These slides will be made available online so no need to take notes.

Workshop outcomes

- Familiarity with the state of the technology.
- Knowing what questions to ask, the terminology.
- Familiarity with the software and tools.
- Some expectations of the limitations.
- Knowledge of a range of applications/research the technology is being applied to.

Introduction

- iVEC: A joint venture between the 5 main research organisations in Western Australia.
  - The University of Western Australia
  - Curtin University
  - Murdoch University
  - Edith Cowan University
  - CSIRO

- Runs the following programs
  - Supercomputing technology and uptake
  - Education and training
  - Industry and government uptake
  - eResearch
  - Visualisation

- Provides researchers with
  - supercomputing resources
  - storage
  - visualisation infrastructure
  - high speed networks
  - expertise

Pawsey building

Visualisation @ UWA

Visualisation

- Definition in the context of science/data visualisation

> Visualisation is the process of applying advanced computing techniques to data in order to provide insight into the underlying structures, relationships and processes.

- Key word is "insight".
- "Turning data into images and animations".
- Finds application across a wide range of disciplines.
- Often employs novel capture methodologies, display technologies and user interfaces.
- Frequently requires high performance computing and sophisticated algorithms.
- Outcomes
  - Revealing something new within datasets.
  - Finding errors within datasets.
  - Communicating to peers.
  - Communicating to the general public.

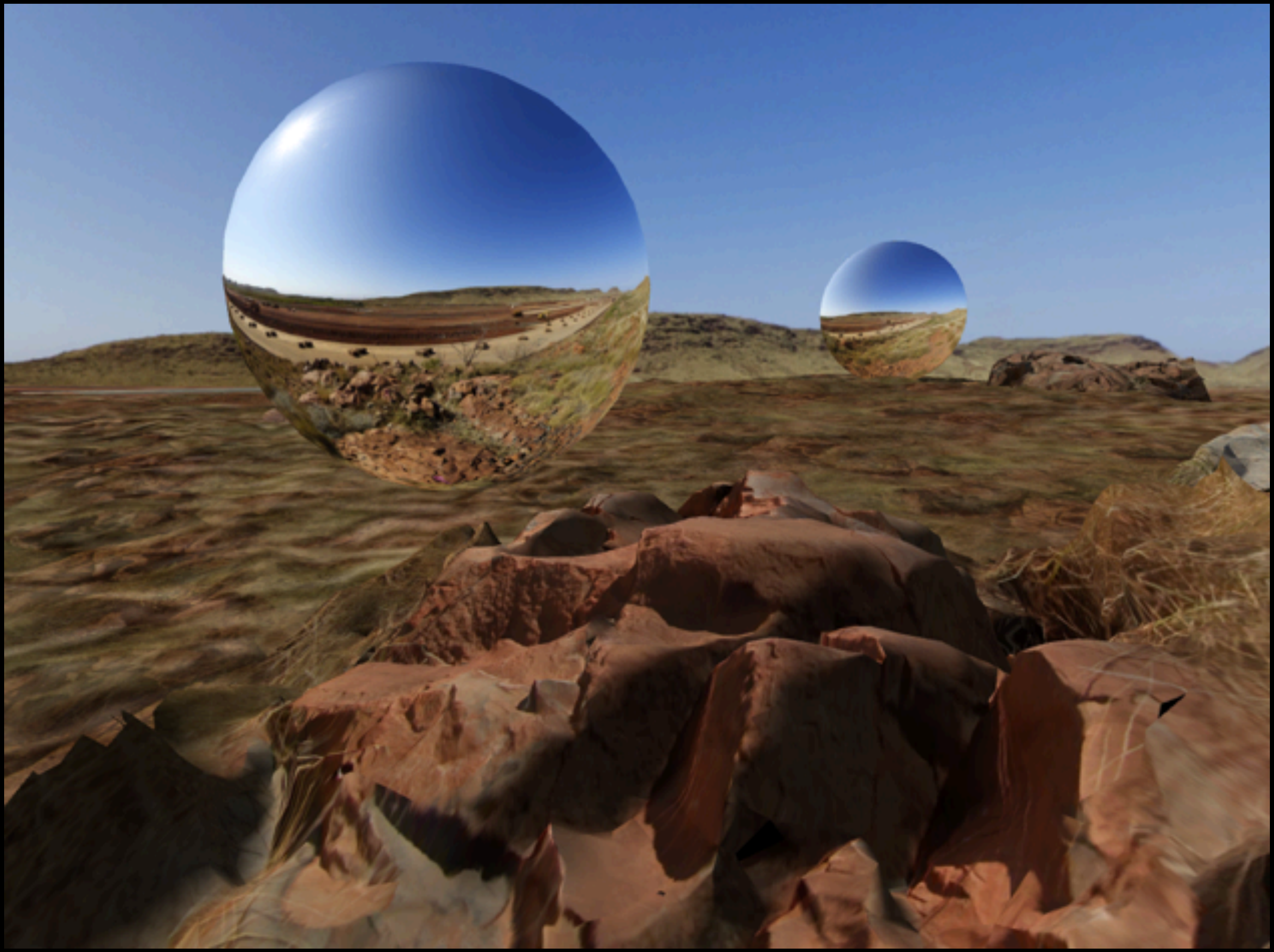
3D reconstruction from (ad hoc) photographs

- Goal: Automatically construct 3D geometry and texture based solely upon a number of photographs.

- Similar to traditional photogrammetry but employs different algorithms.
- Creating richer objects (compared to photographs) for recordings in archaeology and heritage.
- Wish to avoid any in-scene markers required by some solutions.
  Often impractical (access) or not allowed (heritage).
- Want to target automated approaches as much as possible.
  [Current site surveys recorded 100's of objects].

Motivation :Virtual worlds, Serious gaming

- Creating 3D assets for virtual environments, serious games.
- Removes the need for time consuming 3D modelling.
- Removes the interpretation that can occur if one models real objects with organic forms.

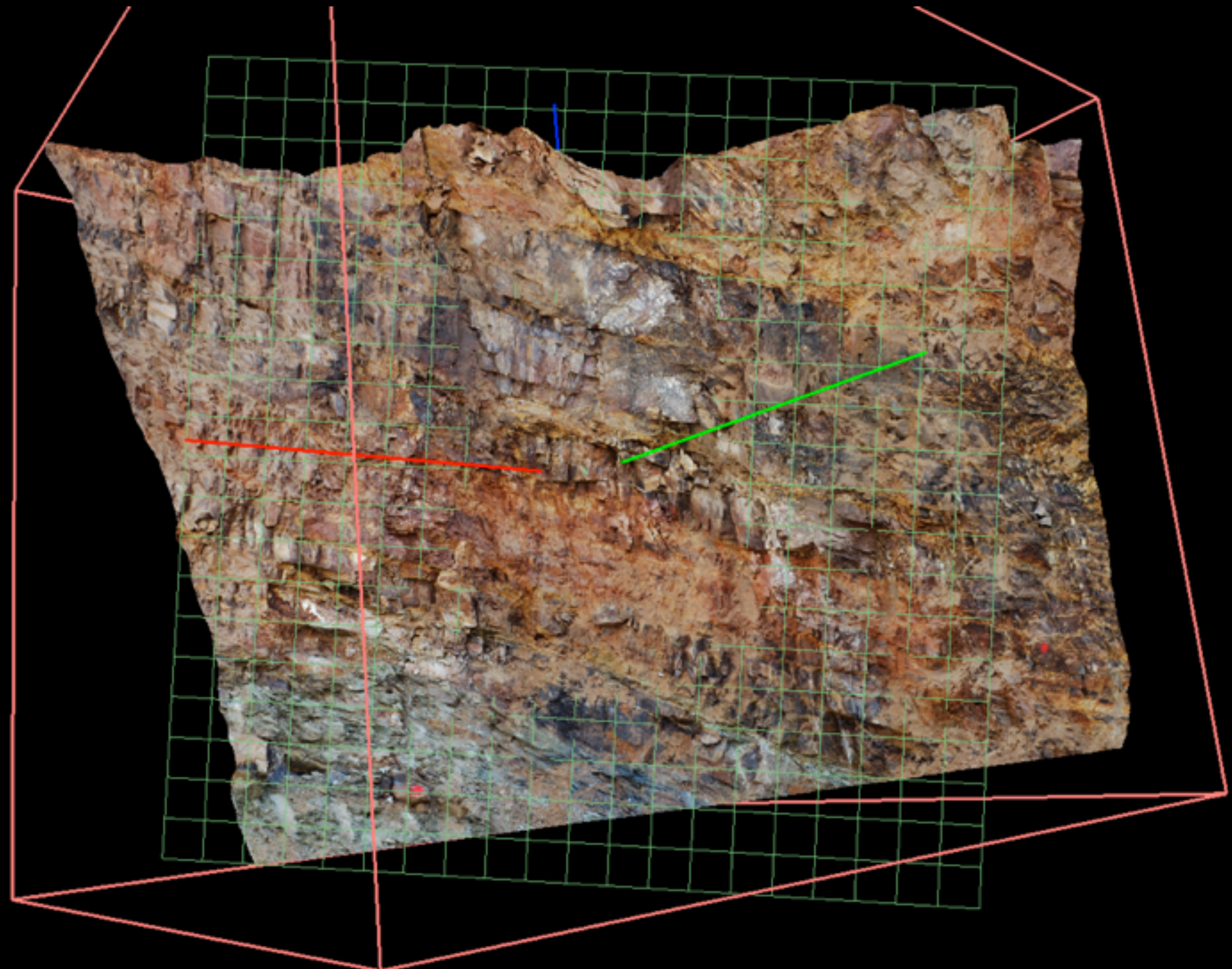


Motivation : Research

- Medical applications
  - engaged in a current project to measure breast volume in breast feeding mothers.
- Non intrusive capture can have advantages.
- Capture of 3D objects for forensic analysis
  - engaged in a current project to identify lineage of head bust molds and detect fakes.

Motivation : Geoscience

- Capturing geological structures for analysis.
- Often in difficult terrain.



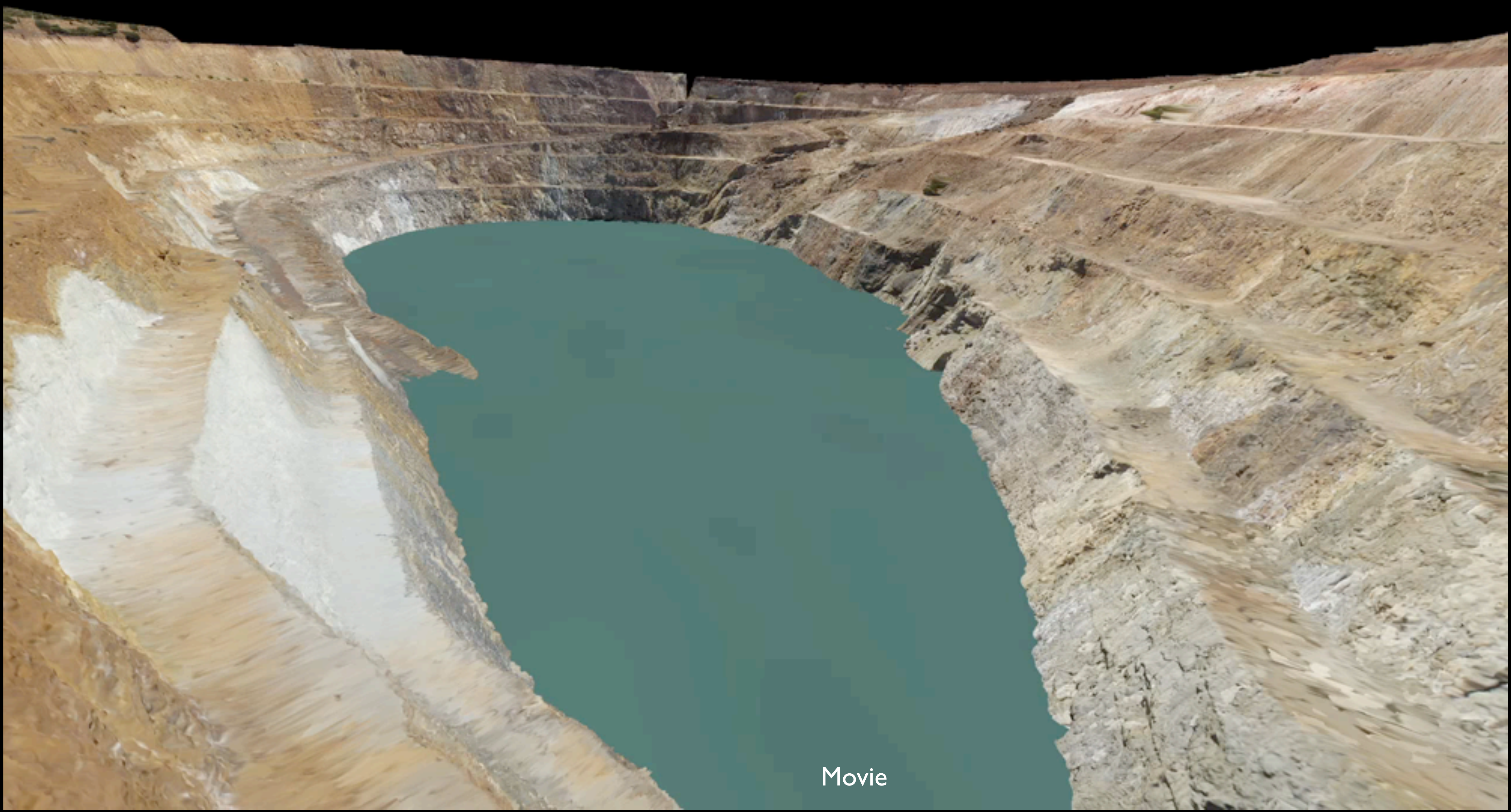
Motivation : Geoscience

- Aim to apply analysis techniques to the surface.
- Fault line detection, bulk properties, etc.

Movie

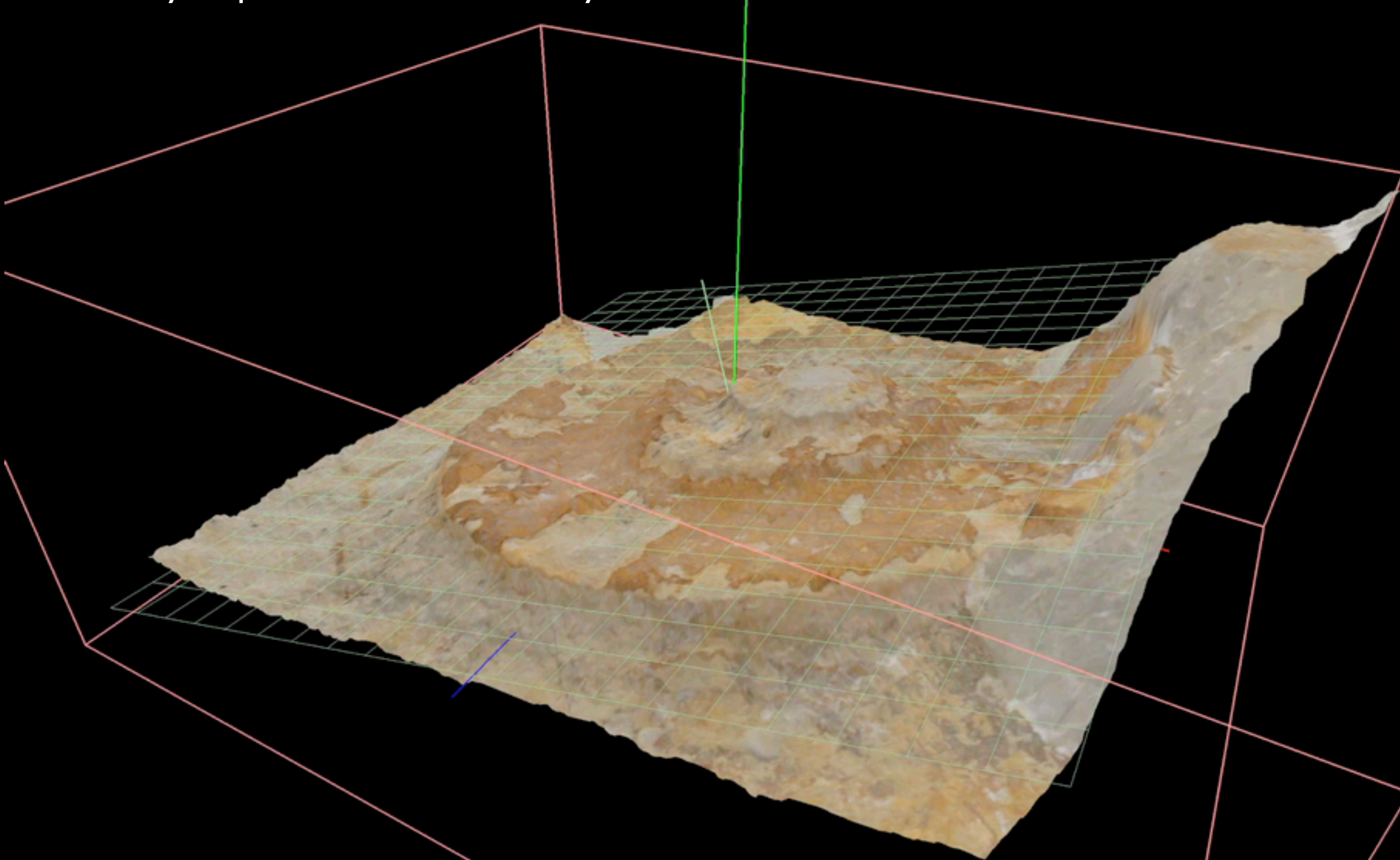
Motivation : Mining

- Capture rock volume removed in mining operations.
- Advantages from a safety perspective, don't have to close down operations to allow surveyors on site.



Motivation : Fossil

- Non-destructive capture.
- Ability to perform structural analysis, derive metrics.



Movie

History

- Photogrammetry is the general term for deriving geometric knowledge from a series of images.
- Initially largely used for aerial surveys, deriving landscape models.
  Generally stereoscopic, that is, just two photographs.
- More recently the domain of machine vision, for example: deriving a 3D model of a robots environment.
- Big step forward was the development of SfM algorithms: structure from motion.
  This generally solves the camera parameters and generation of a 3D point cloud.
- Most common implementation is called Bundler: "bundle adjustment algorithm allows the reconstruction of the 3D geometry of the scene by optimizing the 3D location of key points, the location/orientation of the camera, and its intrinsic parameters".

Other technologies

- In some areas it is starting to replace technologies such as laser scanning. LIDAR - light detection and ranging.
  - particularly so for capture of object in difficult locations
  - only requires modest investment
- Another technology are so called depth cameras
  - Primesense (eg: Kinect)
  - Structured light techniques (eg: Artec Scanner)
- The above do have some advantages
  - LIDAR generally gives better accuracy
  - Structured light can cope with (limited) motion
- Future: Light field cameras (plenoptic camera).

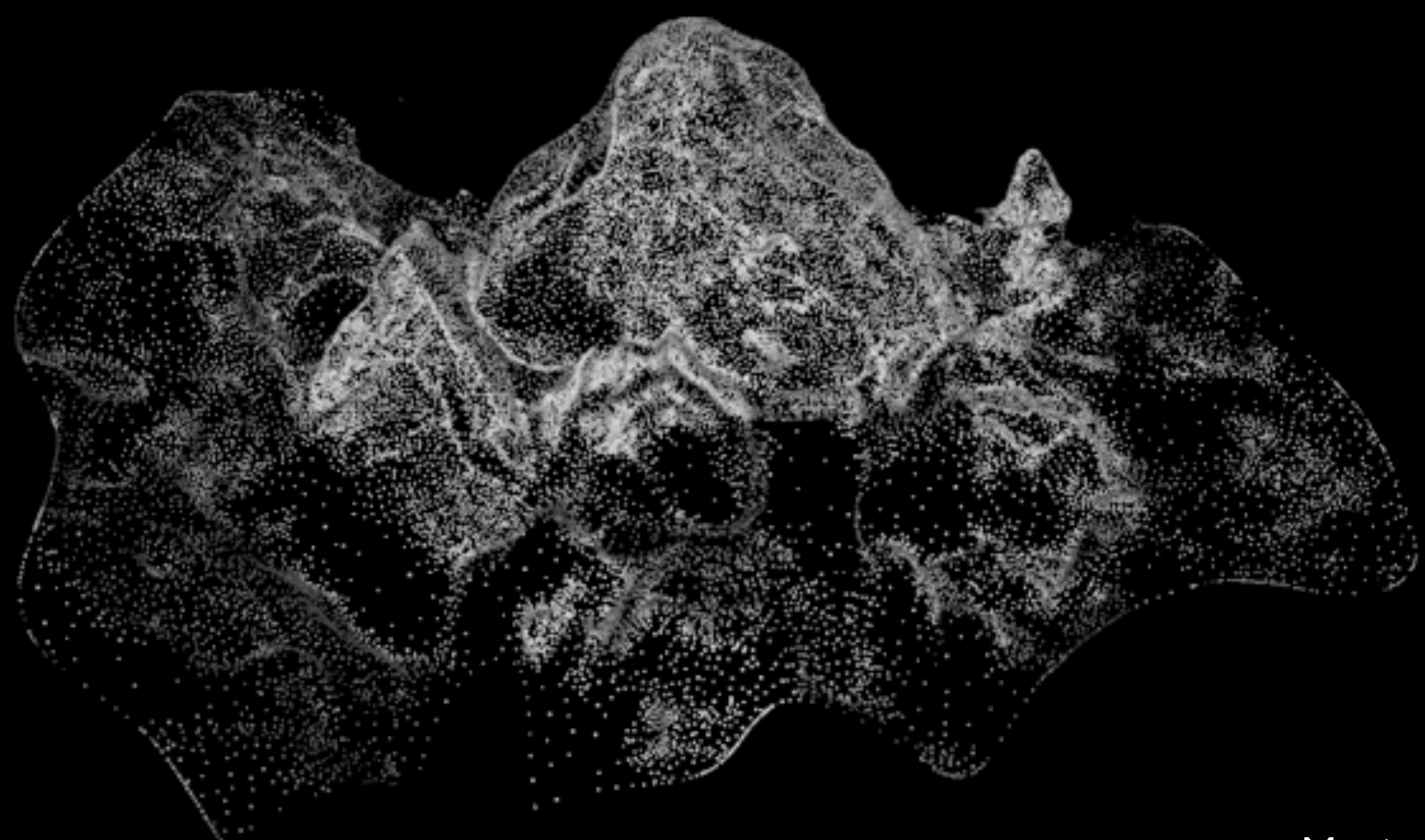
LIDAR

Structured light

Software

- Processing pipeline
- SiroVision
- PhotoScan
- PhotoSynth
- PhotoModeller / Scanner
- 123D Catch
- Visual SfM (Structure from Motion)
- Apero (not yet evaluated)

- Considerations



Movie

Software : Pipeline components

- Perform lens calibration (only done once, optional)
- Read images, correct for lens, and compute feature points between them
(eg: SIFT - scale invariant feature transform)
- Compute camera positions and other intrinsic camera parameters
(eg: Bundler, SfM - Structure from Motion, http://phototour.cs.washington.edu/bundler/)
- Create sparse 3D point cloud, called "bundle adjustment"
(eg: PMVS - Patch-based Multi-view Stereo, http://www.di.ens.fr/pmvs/)
- Create dense point cloud
(eg: CMVS - Clustering Views for Multi-view Stereo, http://www.di.ens.fr/cmvs/)
- Form mesh from dense point cloud
(eg: ball pivoting, Poisson Surface Reconstruction, Marching Cubes)
- Reproject images from camera positions to derive texture segments
- Optionally simplify mesh (eg: quadratic edge collapse decimation) and fill holes
- Export in some suitable format (eg: OBJ files with textures)

Software : Typical pipeline

SIFT for key point extraction between images

↓

SfM software package Bundler to generate a sparse 3D point cloud

↓

PMVS2 (Patch-based Multiview Stereo softwarw) to reconstruct the model of the imaged scene as dense point cloud

↓

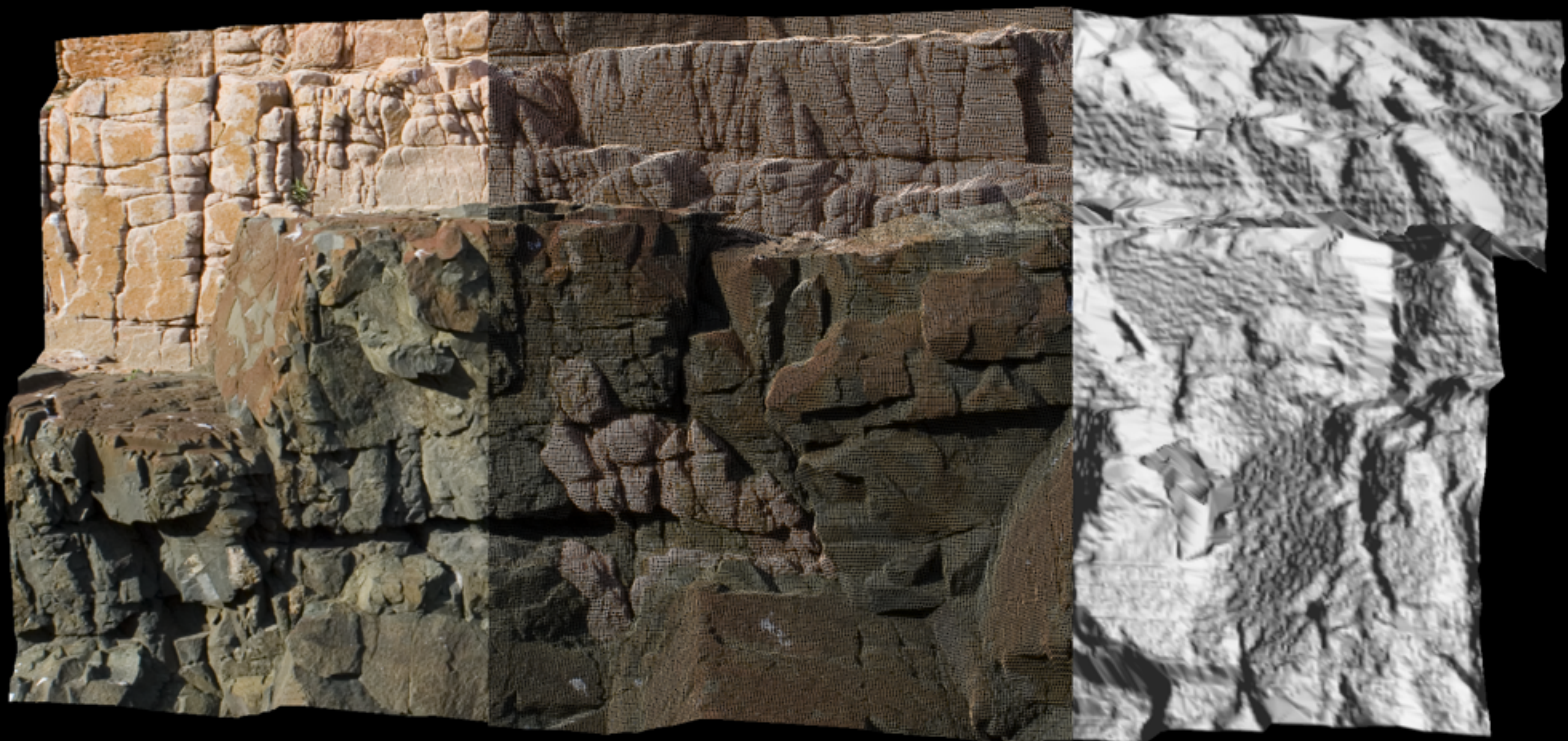
Convert point cloud to mesh

↓

Re-project textures

Software : Sirovision

- Captured from 2 images only, stereo pairs but with wide base line separation.
- With in-scene markers and calibrated lens claims 3 to 5cm accuracy at 100m distance.
- Targeted mining industry, developed by CSIRO.

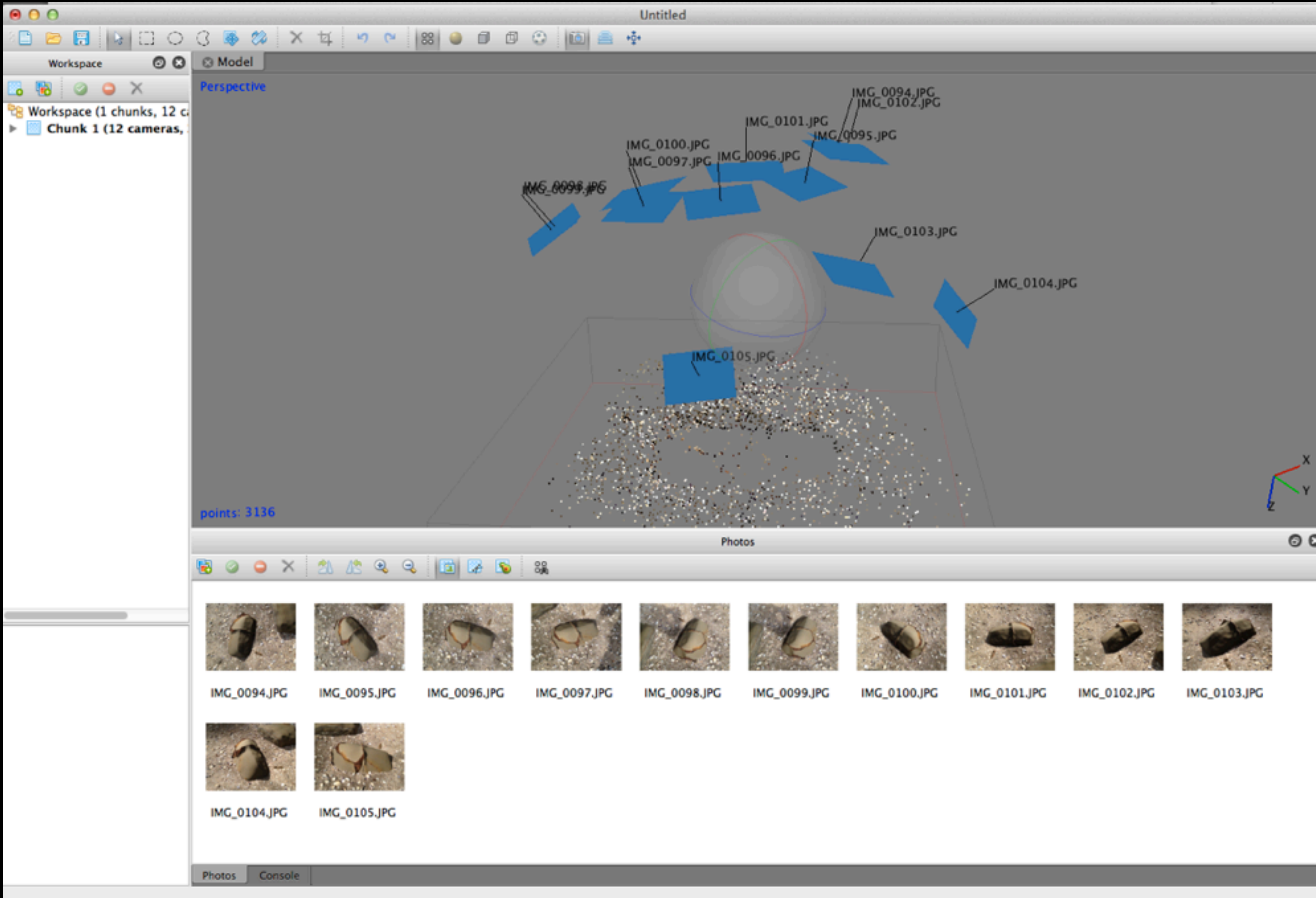


Textured　　Mesh　　Surface

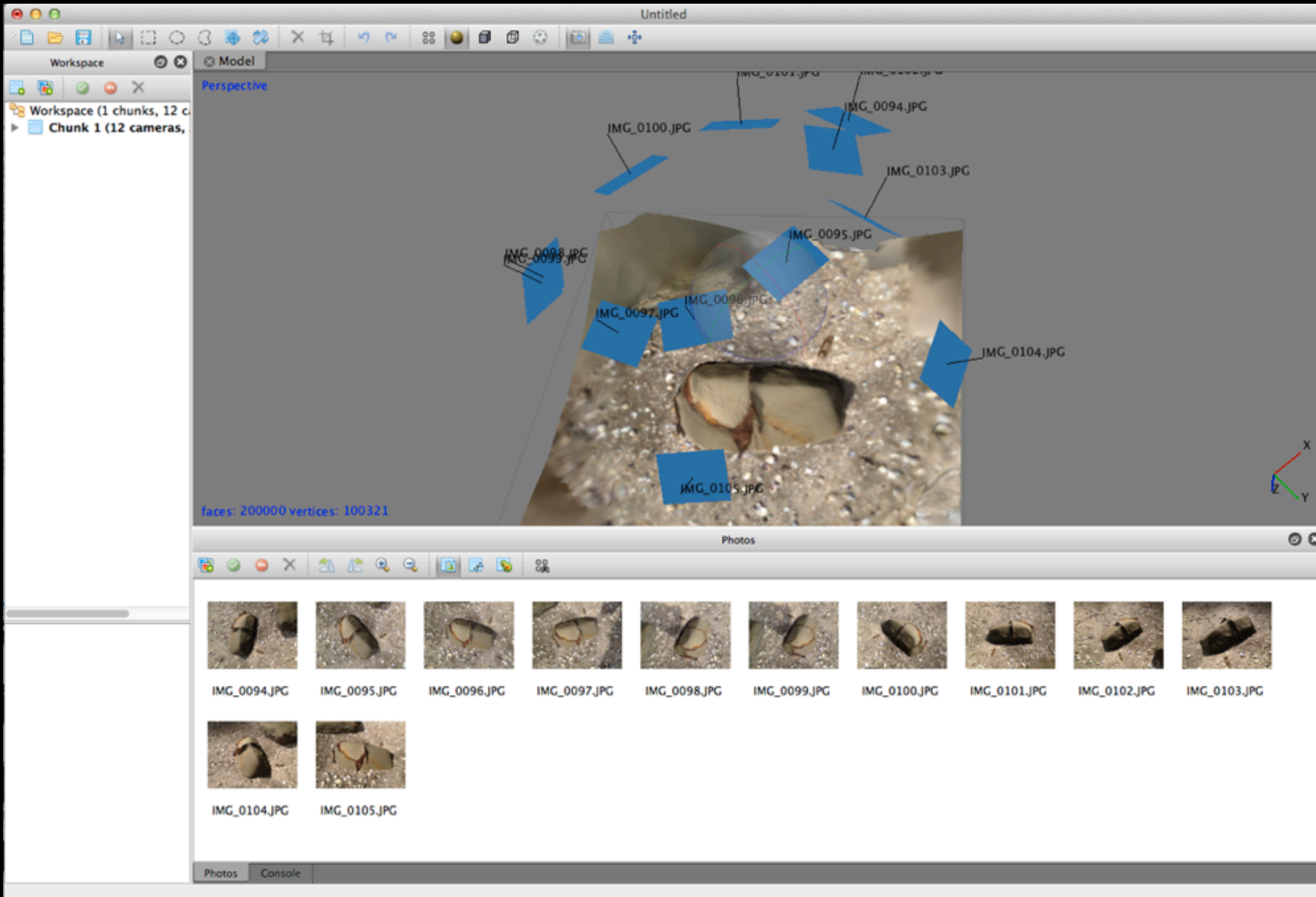
Software : PhotoScan

- A series of individual steps (pipeline) one follows
- From AgiSoft
- Good mixture between low level control and automation
  Generally “just works” but can tuned for problematic cases
- Seems to be the slower of all the packages explored
- Available for Mac and MSWindows
- http://www.agisoft.ru/products/photoscan

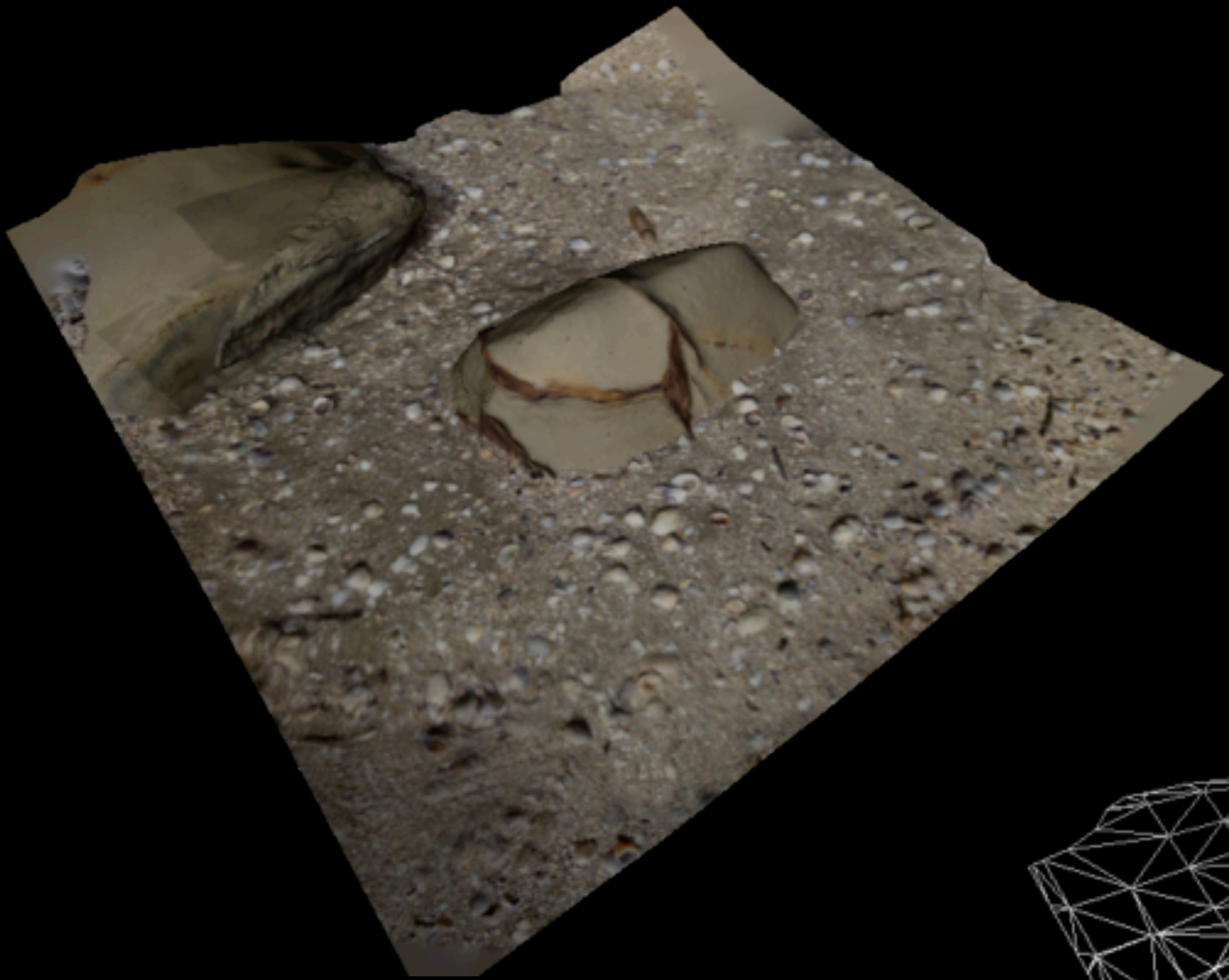
Software : PhotoScan

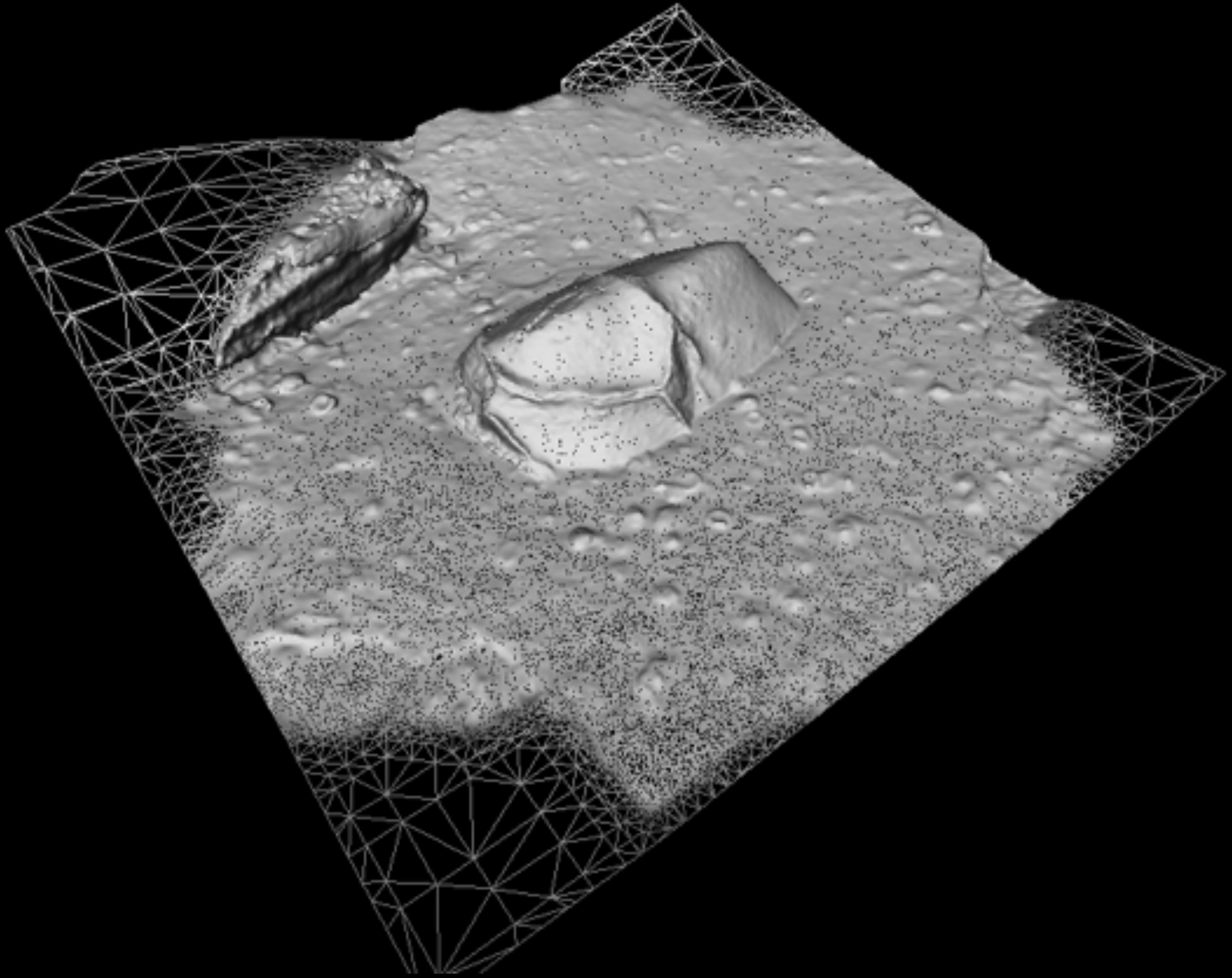


Software : PhotoScan



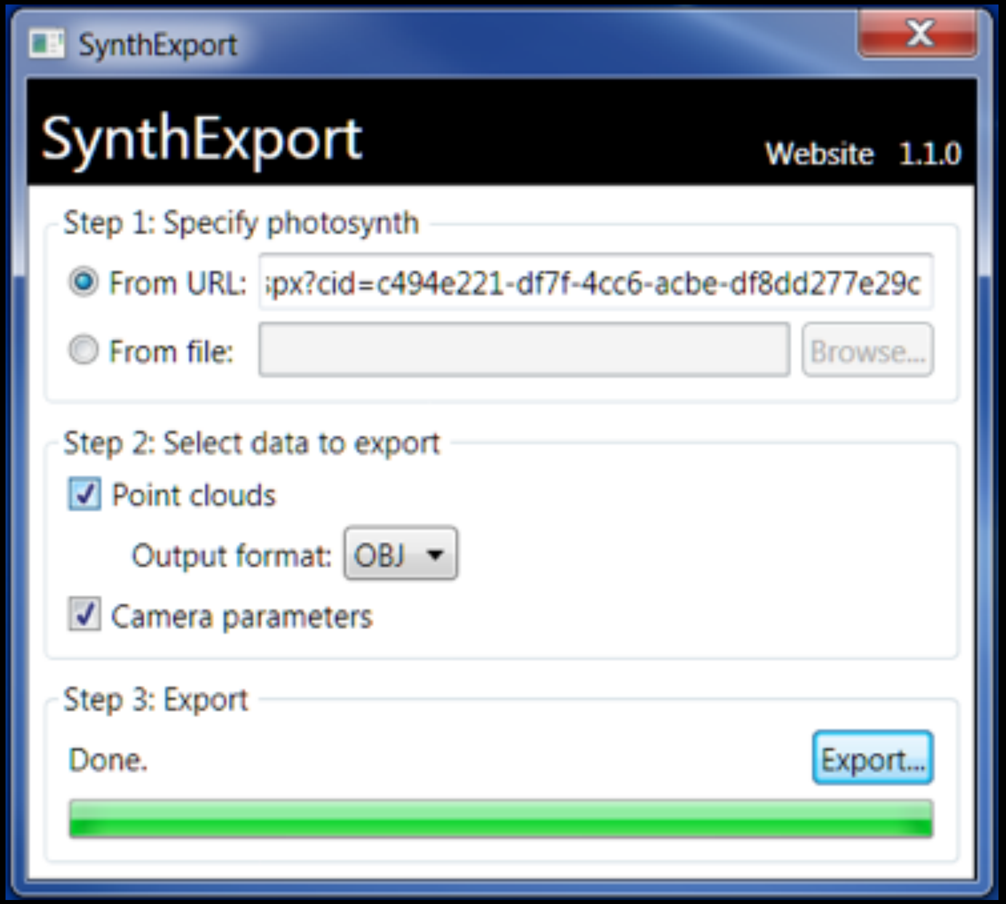
Software : PhotoScan



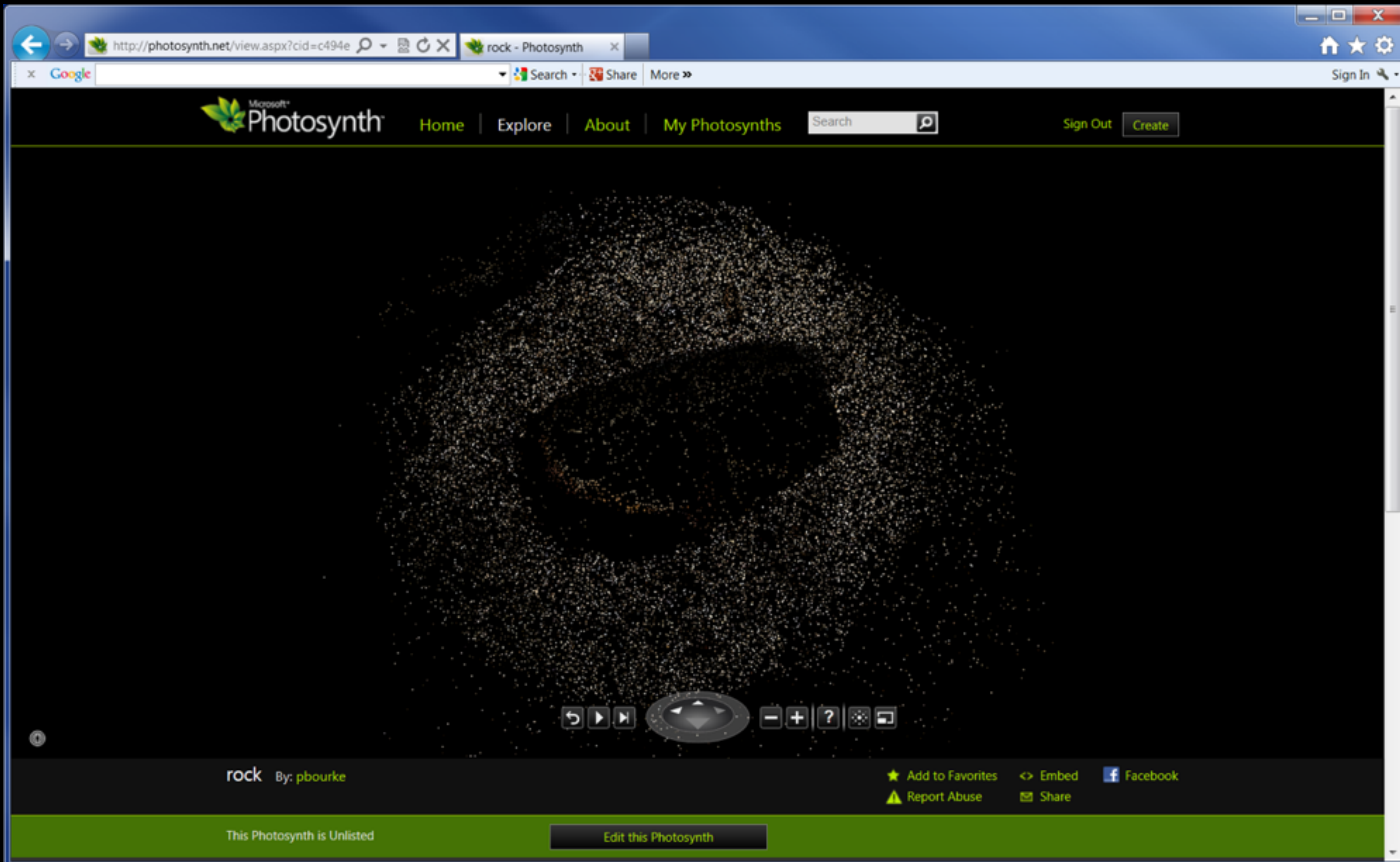


Software : PhotoSynth

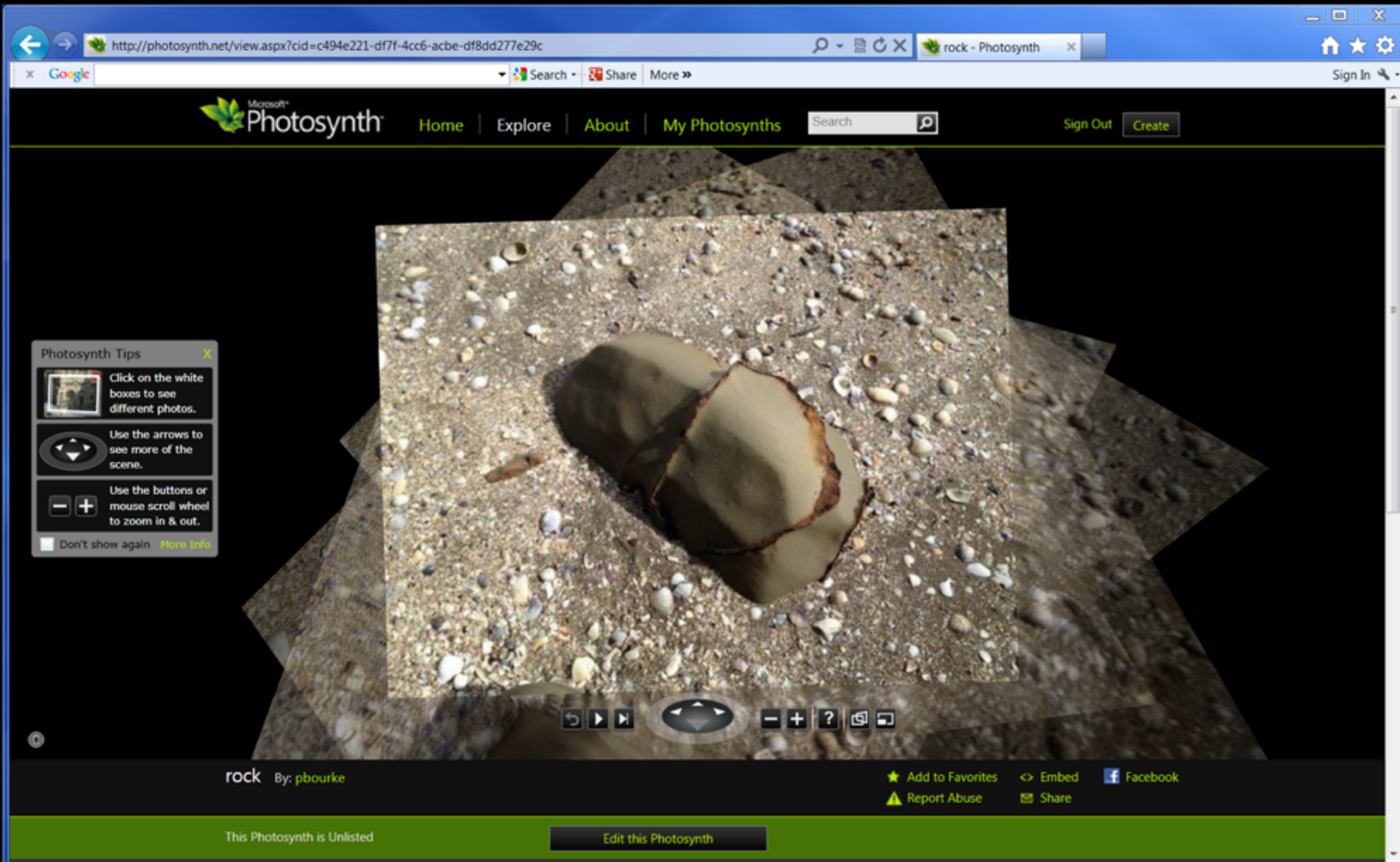
- Microsoft, MSWindows only (obviously)
  http://photosynth.net
- Based upon Bundler. GUI front end, computed remotely.
- Provides a "image effect" based upon reconstructed surface
- Excellent for identifying image sets for other pipelines
- Not possible to extract the mesh/texture data from within the online software itself
- Synth Export - http://synthexport.codeplex.com/
  Provides point cloud and camera parameter export
  Would need to reconstruct mesh by other means.



Software : PhotoSynth



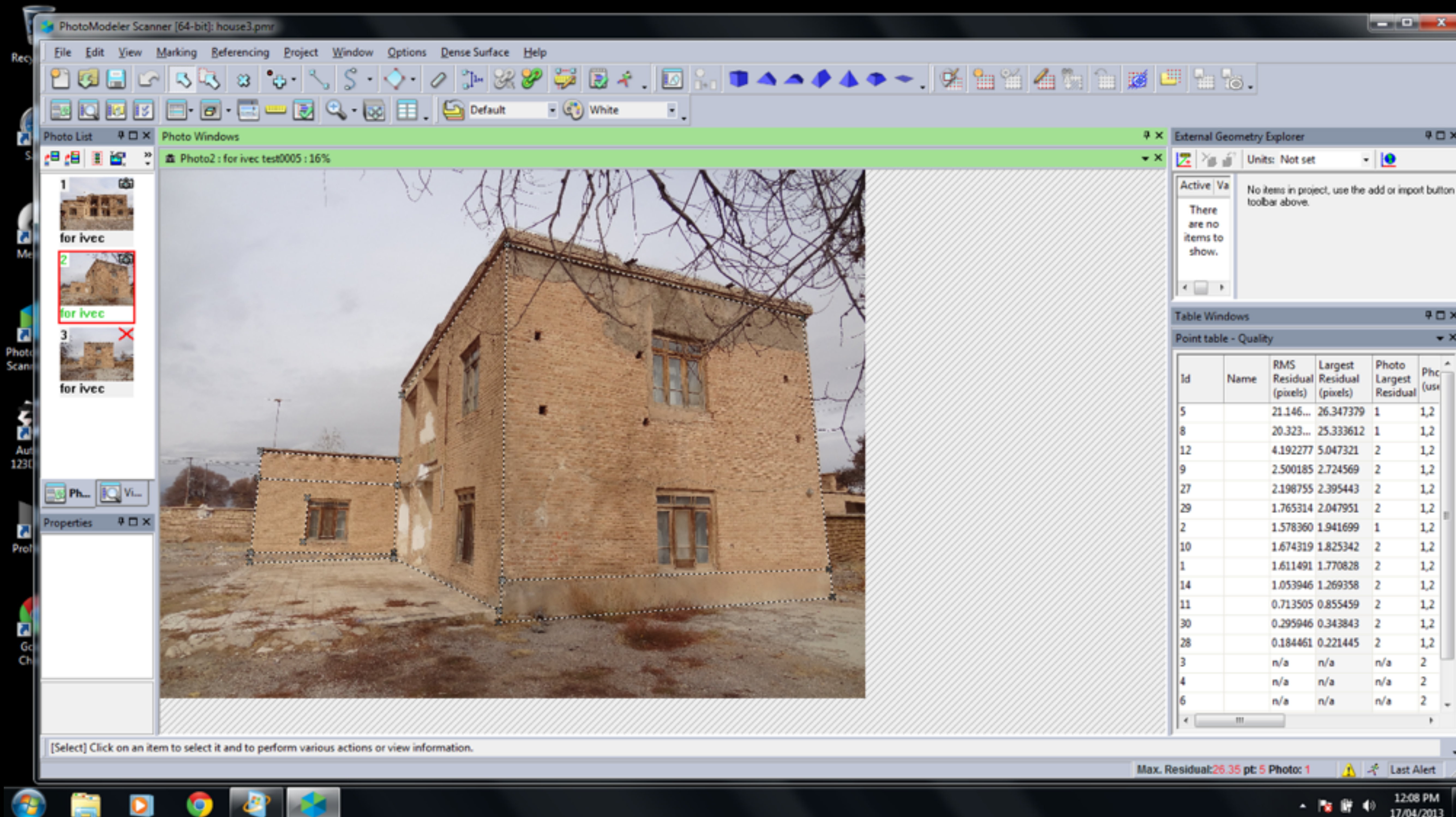
Software : PhotoSynth



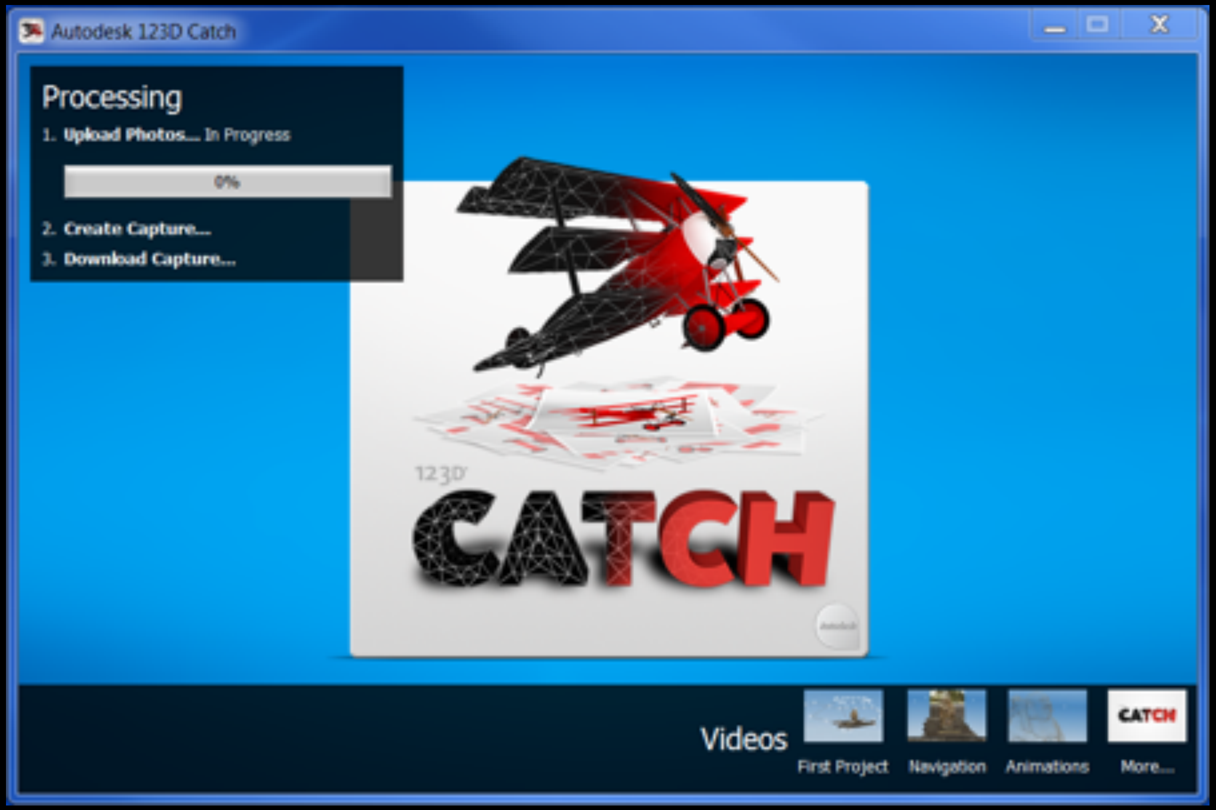
Software : PhotoModeller

- From EOS systems
- http://www.photomodeler.com/
- Comes in two flavours, the standard package is for human driven extraction of rectangular objects such as building facades
- PhotoModeller Scanner is for more organic shapes
- Claims to be capable of very accurate results (perhaps)
- Requires a lot of manual interaction
- MSWindows only

Software : Photomodeller

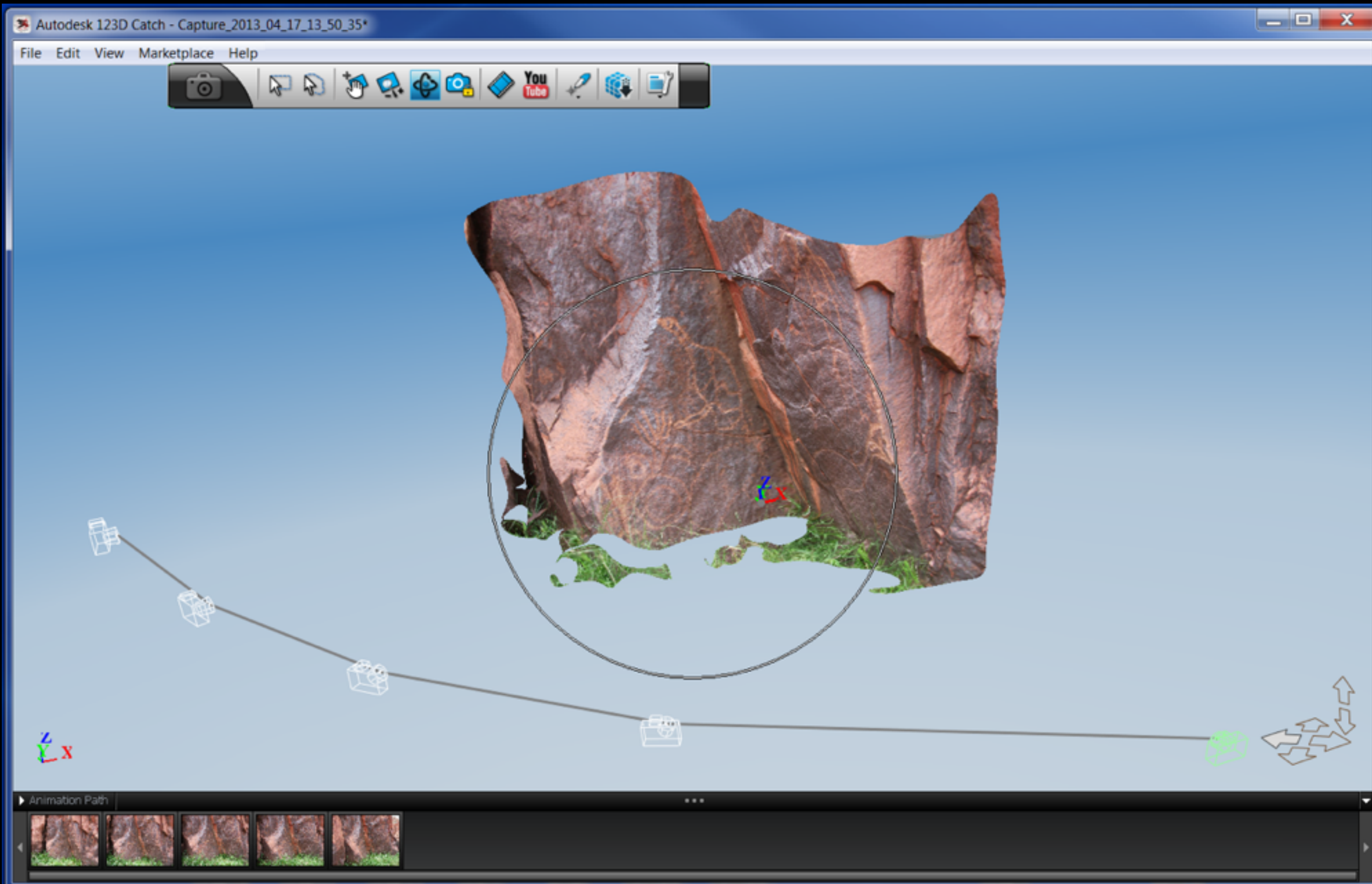


Software : 123D Catch

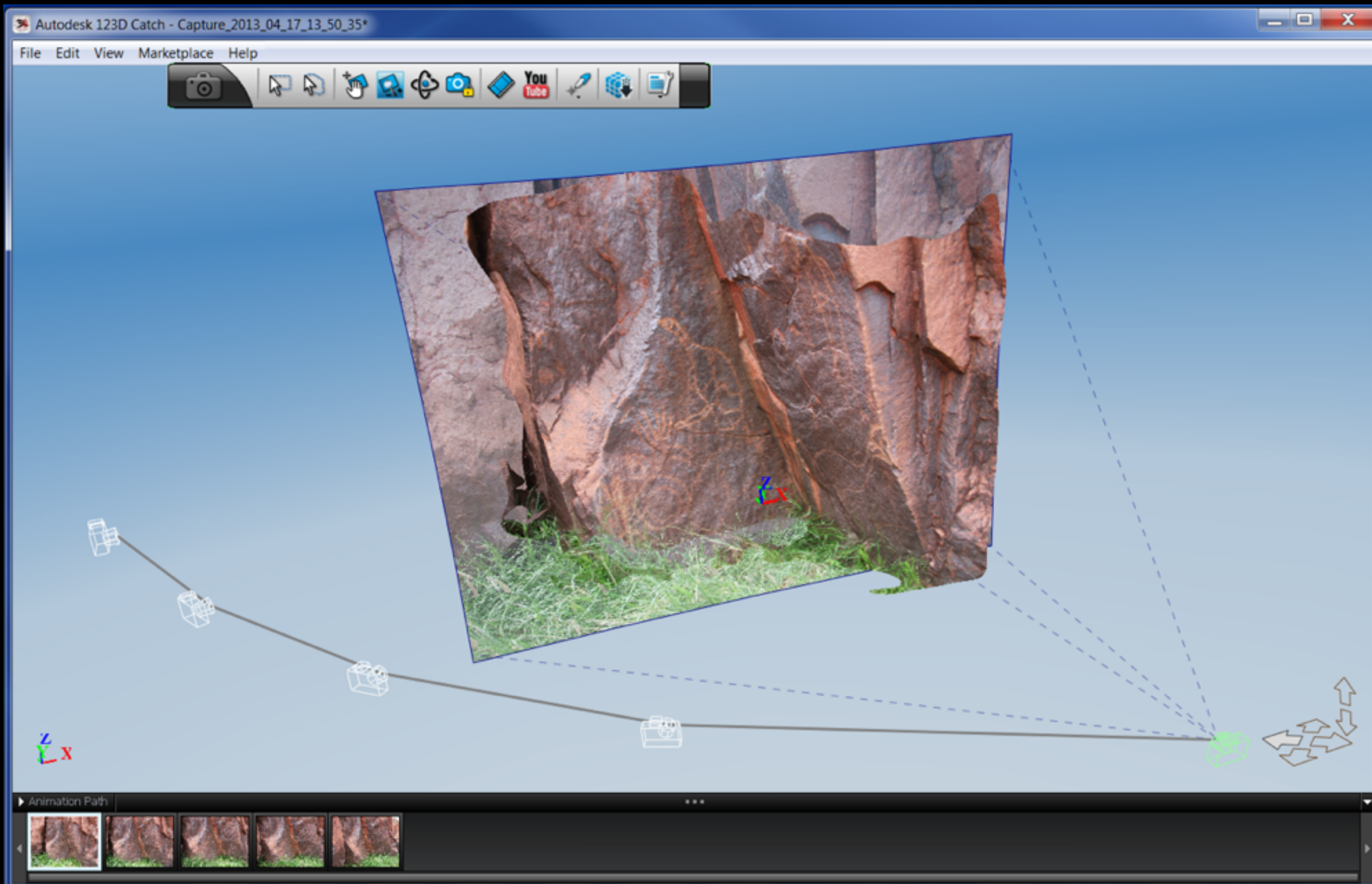


- From AutoDesk
- Free (so far)
- Cloud based so requires an internet connection
- High rate of success but no option to change algorithm parameters if things don't work
- Does not provide access to intermediate data, such as the point cloud
- No option for camera calibration
- MSWindows only GUI
- Easily the best option when starting in this field
  Personal strategy: if 123D Catch doesn't work then try more manual processes

Software : 123D Catch



Software : 123D Catch



Software :Visual SfM - Bundler

- From the University of Washington
- An open source distribution of Bundler (MSWindows, Mac, Linux)
- Includes a GPU accelerated implementation
- Matches images, derives camera attributes, and computes a point cloud
- Dense point cloud and mesh generation needs to be performed elsewhere
- http://www.cs.washington.edu/homes/ccwu/vsfm/

- Bundler on Mac OS X called easyBundler
- http://openendedgroup.com/field/ReconstructionDistribution

Software : Apero

- Open Source
- From the Matis of the French I.G.N (Institut Géographique National)

Software : Distinguishing features

- Degree of human guidedness and interaction required
  Our goal is for largely automated processes
- Requirement or opportunity for camera calibration
  Should result in higher accuracy vs simply a model
- Sensitivity to the order the photographs are presented
- The number of photographs required
- Degree to which one needs to become an "expert", learning the tricks to get good results
  There are a potentially a large number of variables
  Trade off between simplicity and control
  123D Catch is at one end of the scale, PhotoModeller Scanner at the other end

Photography : lens

- Fixed focal length lens, also referred to as a "prime lens"
- Generally have some minimum focus distance and small aperture
- Otherwise focus to infinity
- EXIF: generally software is reading EXIF data from images to determine focal length
- Most "point and click" cameras have a fixed focal lenses because they require no moving parts, don't require electronics (not drawing extra power)
- So ... low cost cameras often work better.
- We use Canon 5D MK11 and 111 with fixed focal lenses, and point-and-click cameras.

Sigma 28mm, Canon mount

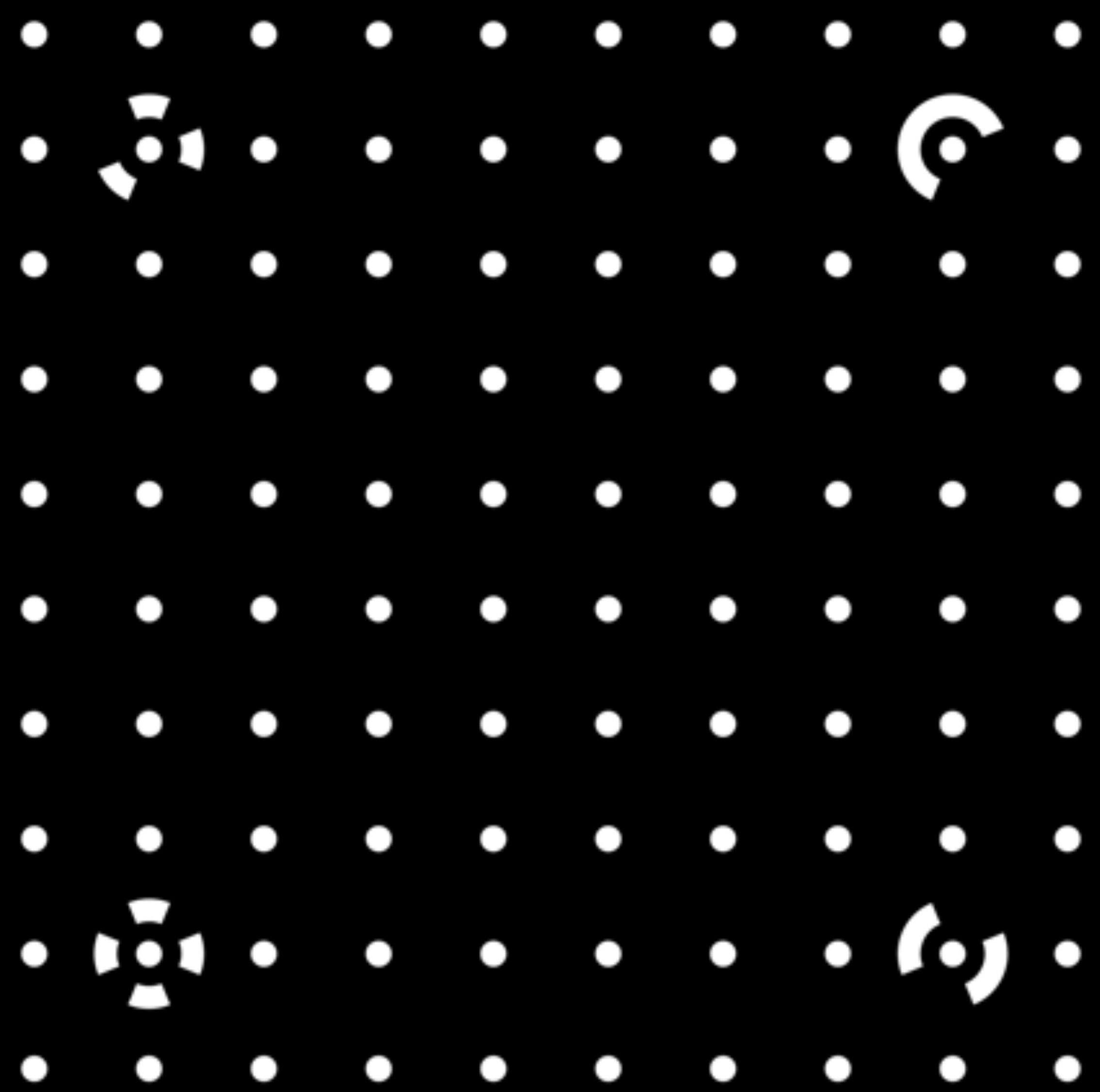
Sigma 50mm, Canon mount

Photography : shooting guide

- Obviously one cannot reconstruct what one does not capture
- Aim for plenty of overlap between photographs (Can always remove images)
- For 2.5D surfaces as few as 2 shots are required, more generally 6
- For 3D objects typically 20 or more
- Generally works better for the images to be captured in order moving around the object
- Generally no point capturing multiple images from the same position!
  The opposite of panoramic photography for example
- Camera orientation typically doesn’t matter, this is solved for when computing camera parameters in the Bundle processing
- Calibration: Most of the packages that include accuracy metrics will assume a camera calibration

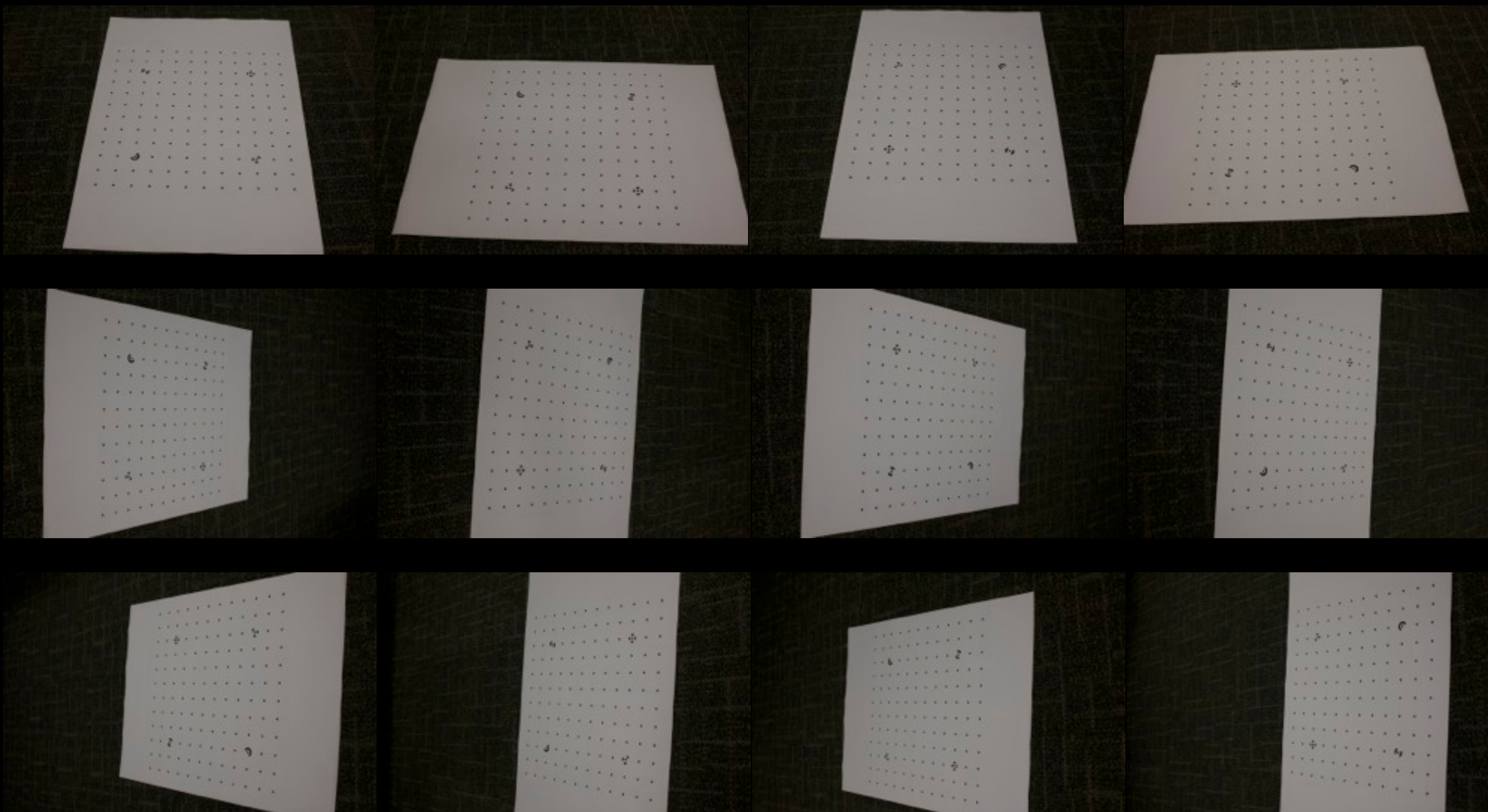
Photography : Camera calibration

- Camera/lens characteristics derived from Bundle process.
  Can perform on idealised patterns beforehand
- Different procedures depending on the software
- Calibration pattern used by PhotoModeller shown here



Photography : Camera calibration

- 4 photographs captured (one from each direction)
- Repeated with the camera in three orientations (rotated 90, 0, -90)



Photography : 2.5D example






Photography : 3D example

Photography : 360 degree

Case study 1 : Motifs, Indian Temple

- A relatively low number of photographs are required for 2.5D surfaces
- Degree of concavity determines the number of photographs required
  Can't reconstruct what cannot be seen
- Facades and engravings typically require between 3 and 6 images
- Photographs can be orientated at any angle
- Each object takes perhaps 15 sec to capture
  10 minutes (on average) to process

Case study 1 : Motifs, Indian Temple





Case study 1 : Motifs, Indian Temple

1000 pillar temple

Movie

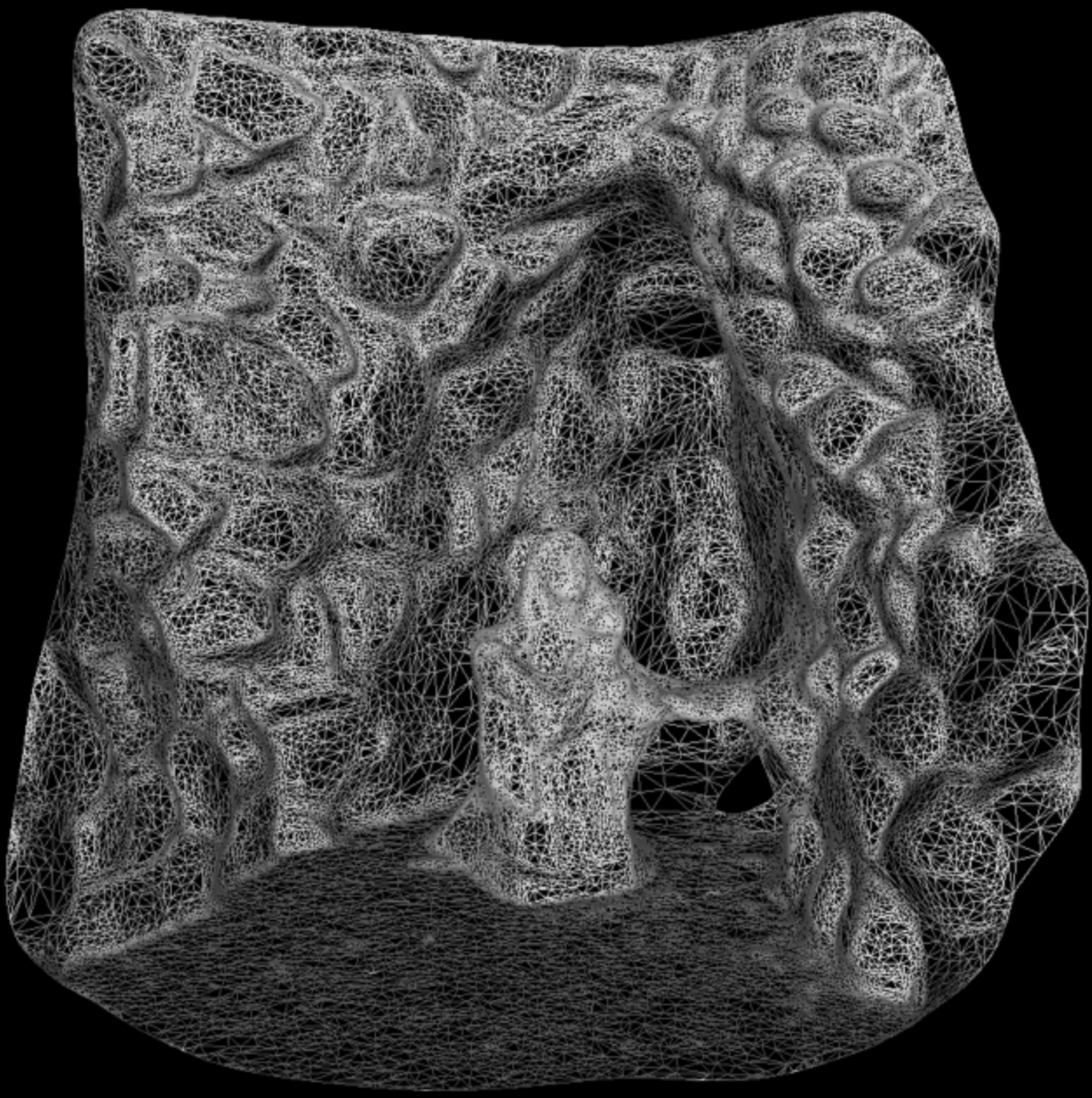
Geometry processing

- Generally dealing with unstructured meshes

- Mesh simplification
- Mesh thickening
- Hole closing
- Cleaning shrapnel
- Per vertex editing

- Meshlab
- Blender

- File formats

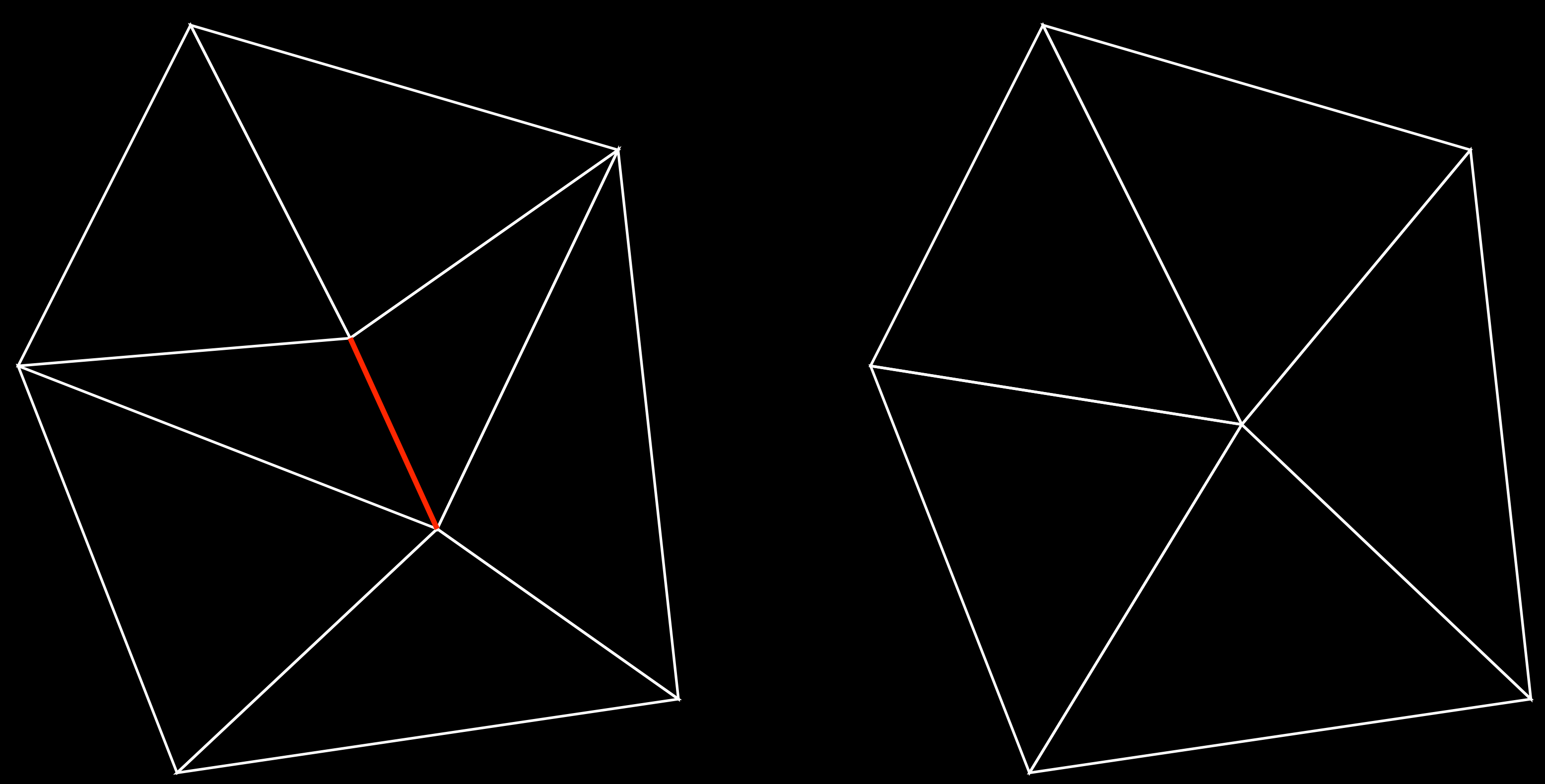


Geometry processing : Mesh simplification

- Meshes directly from the reconstruction (generated from the dense point cloud) are generally inefficient. Often need to reduce them for realtime applications and/or web based delivery
- Also used to create multiple levels of details (LOD) for gaming and other realtime applications
- The goal is easy to understand: remove mesh density where it will make minimal impact on the mesh appearance. For example, don't need high mesh density in regions of low curvature
- Most common class of algorithm is referred to as "edge collapse", replace an edge with a vertex
- A texture and geometry approximation ... need to estimate new texture coordinate at new vertices
- Need to preserve the boundary
- This has been a common topic in computer graphics research and is still a huge topic in computer graphics, see Siggraph over the last few years

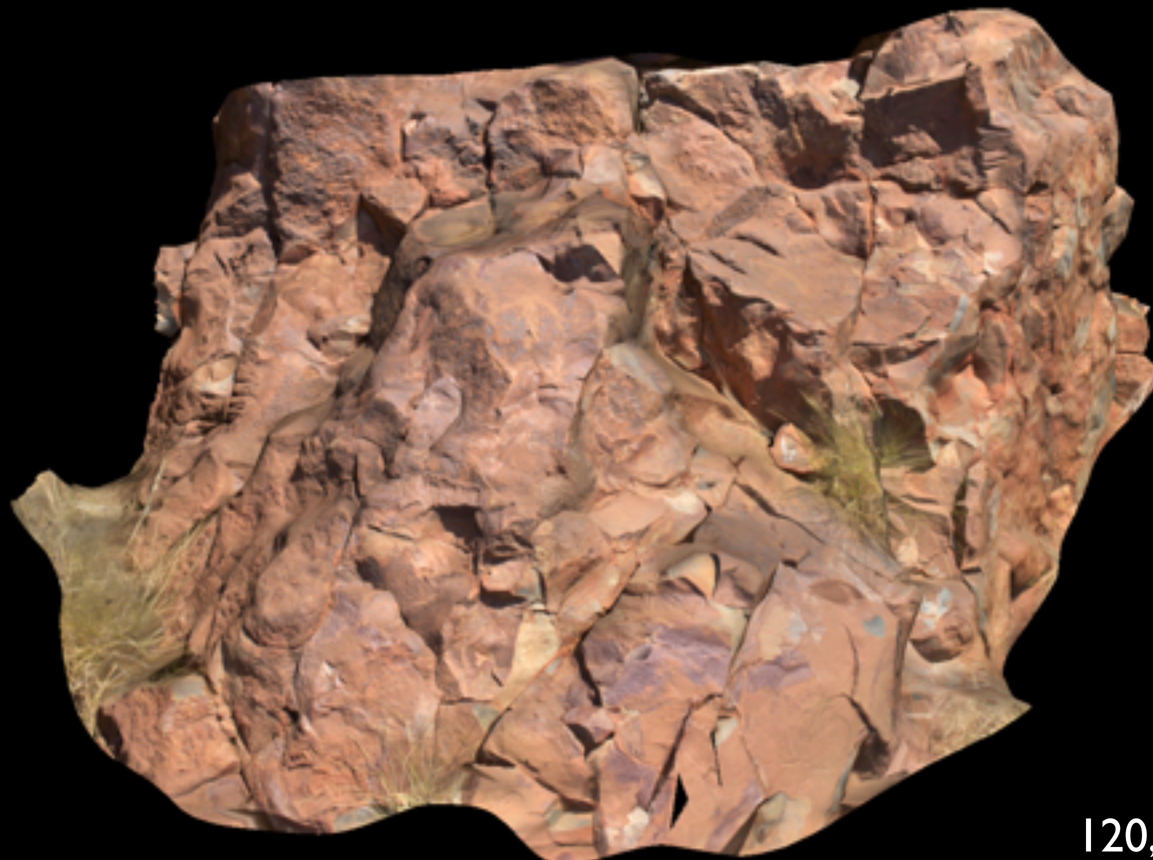
Geometry processing : Mesh simplification

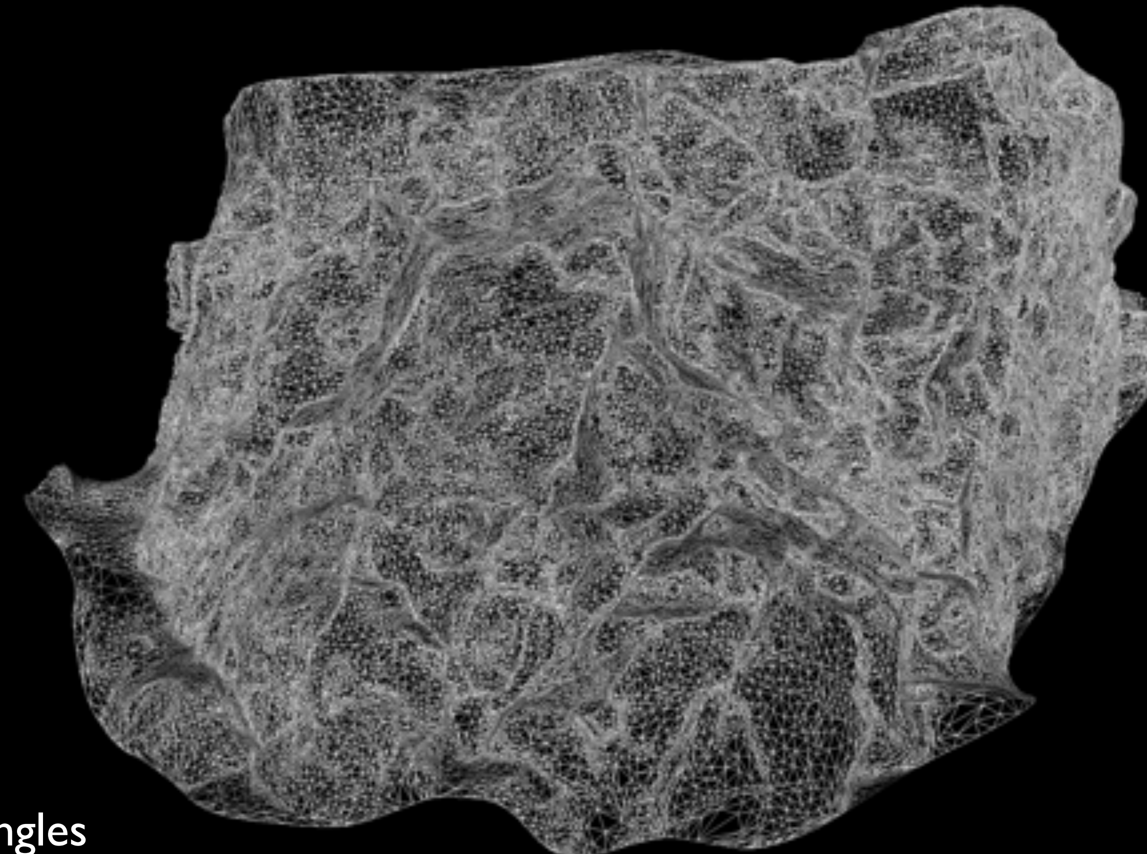
- Most edge collapse algorithms involve replacing an edge with a vertex
  - How to choose the edges to remove
  - Where to locate the new vertex so as to minimise the effect on the surface
  - How to estimate the new texture coordinate
- Number of triangles reduces by 2 on each iteration
- Can calculate the deviation of the surface for any particular edge collapse
  Choose edges with smallest deviations



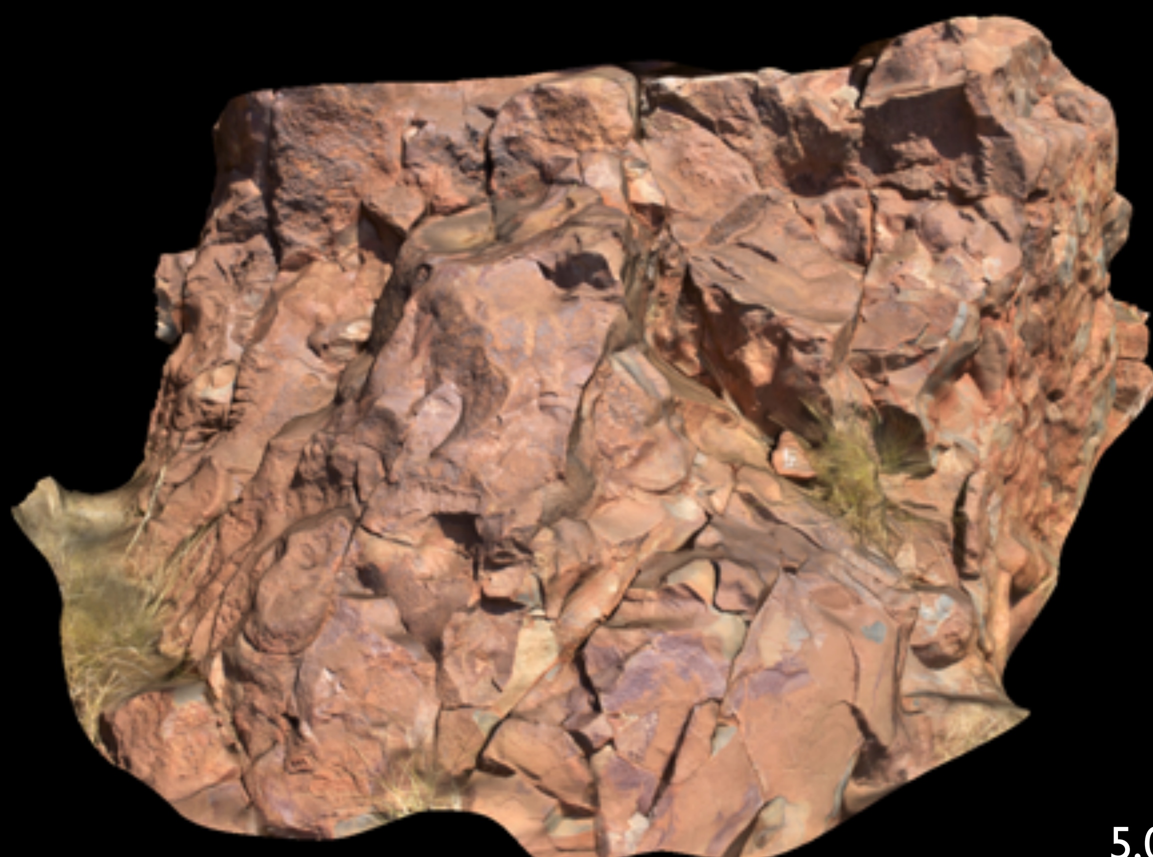
Red edge removed, results in two fewer triangles

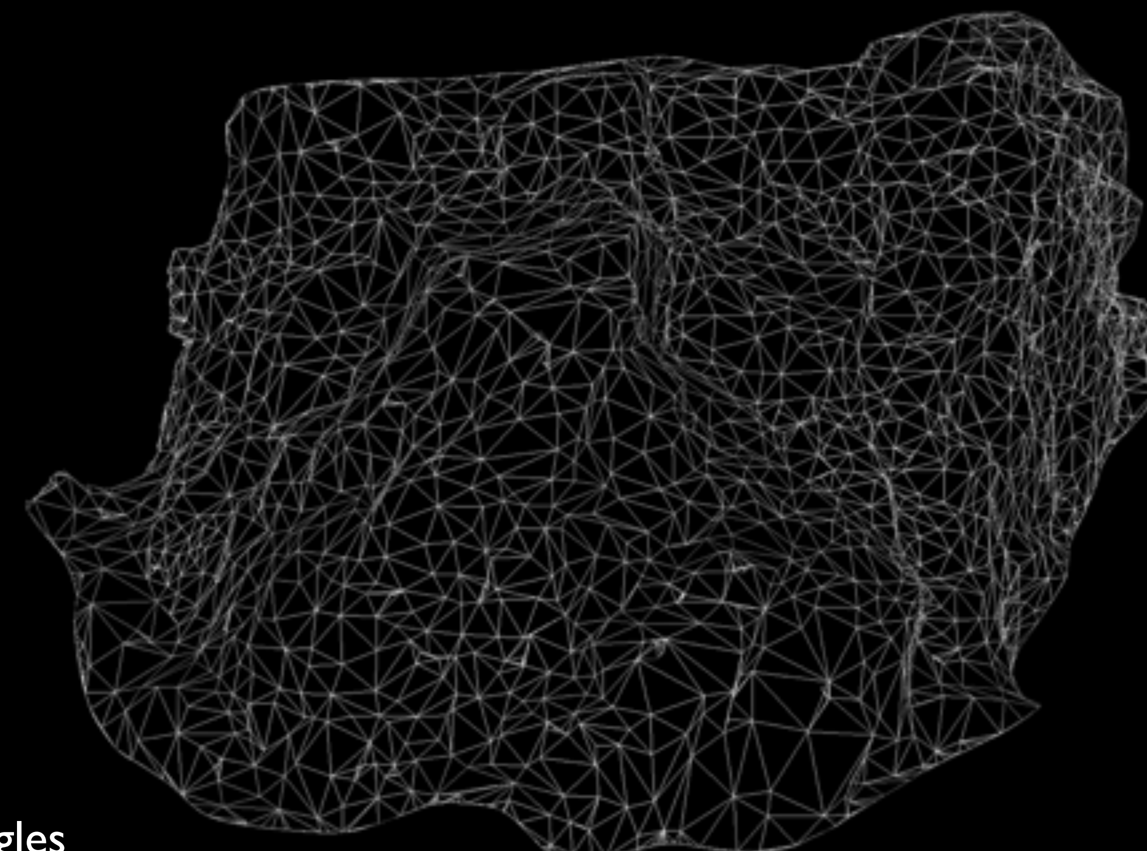
Geometry processing : Mesh simplification





120,000 triangles



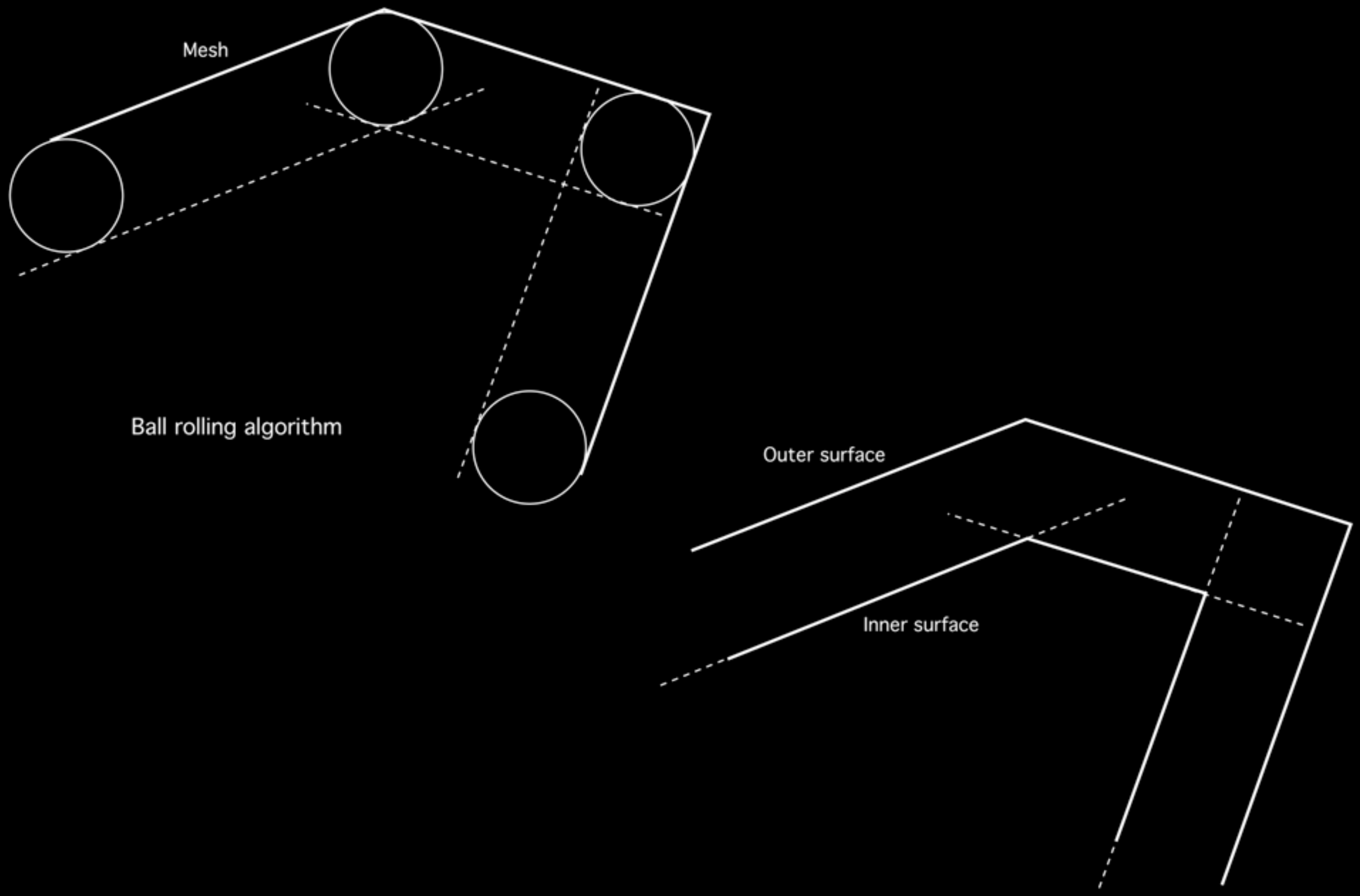


5,000 triangles

Geometry processing : Mesh thickening

- Cases exist where one does not want idealised surfaces, "infinitely thin" surfaces
- Double sided rendering in realtime APIs not quite the same visual effect as physical thickness
- Required to create physical models, see rapid prototyping later
- Perhaps the most common algorithm is known as "rolling ball"

Geometry processing : Mesh thickening



Geometry processing : Mesh thickening

Movie

Geometry processing : Removing shrapnel and hole closing

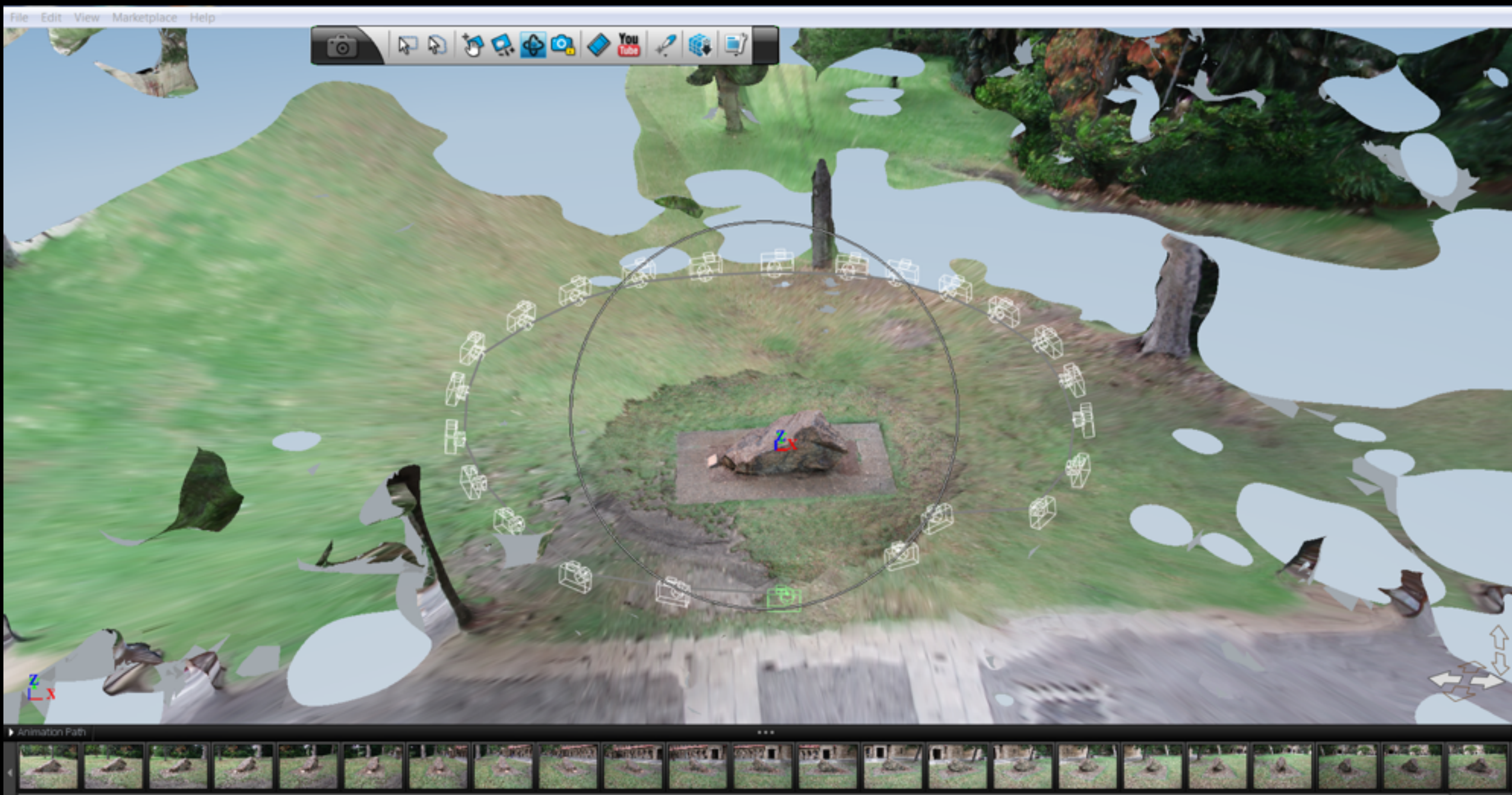
- Very common for there to be extraneous geometry
- Reconstructing parts of the scene that are not of interest

- Not uncommon for meshes to contain small holes, although also performed automatically by some packages

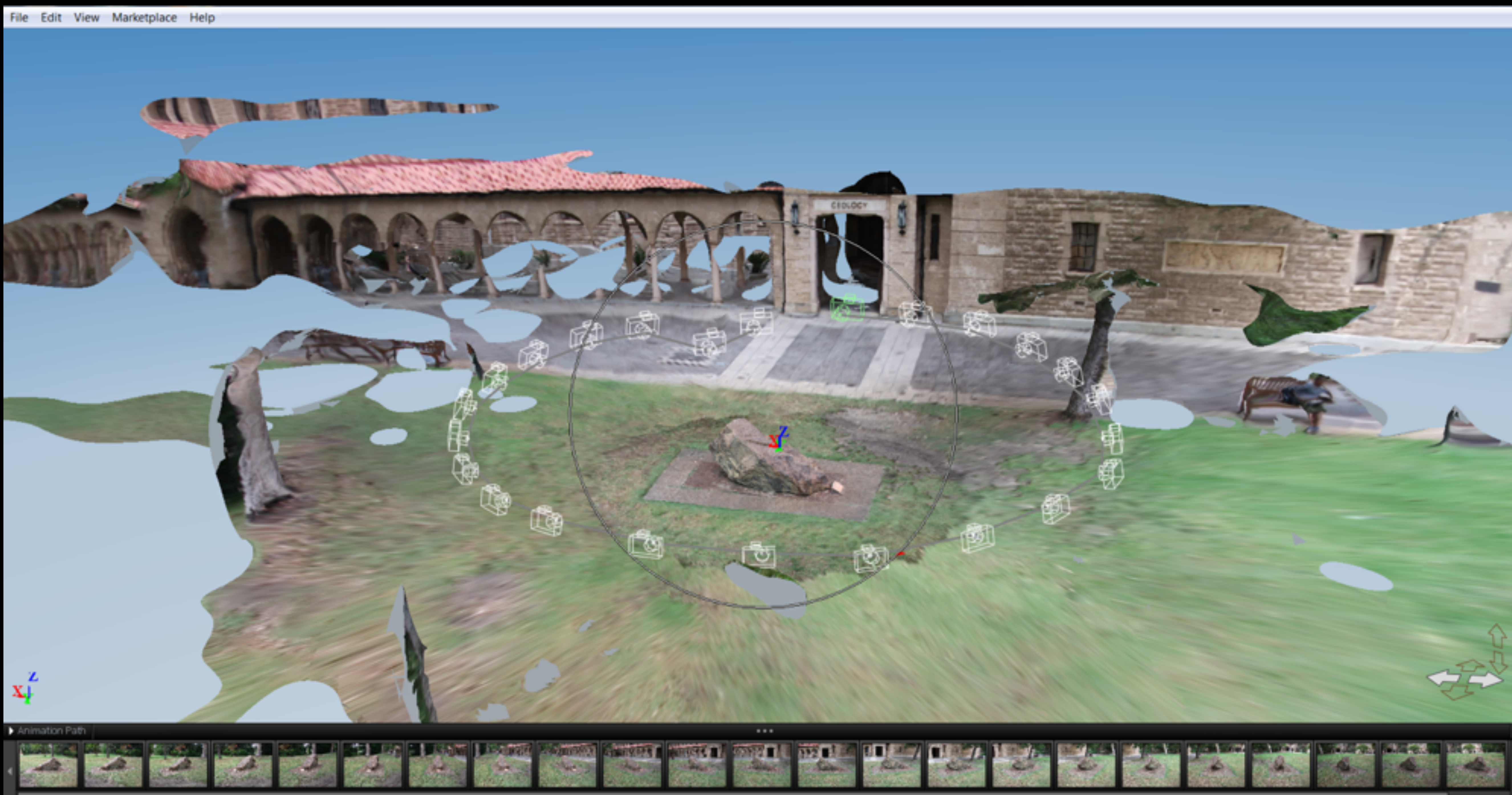
- Typically use MeshLab for hole closing

Geometry processing : Removing shrapnel and hole closing

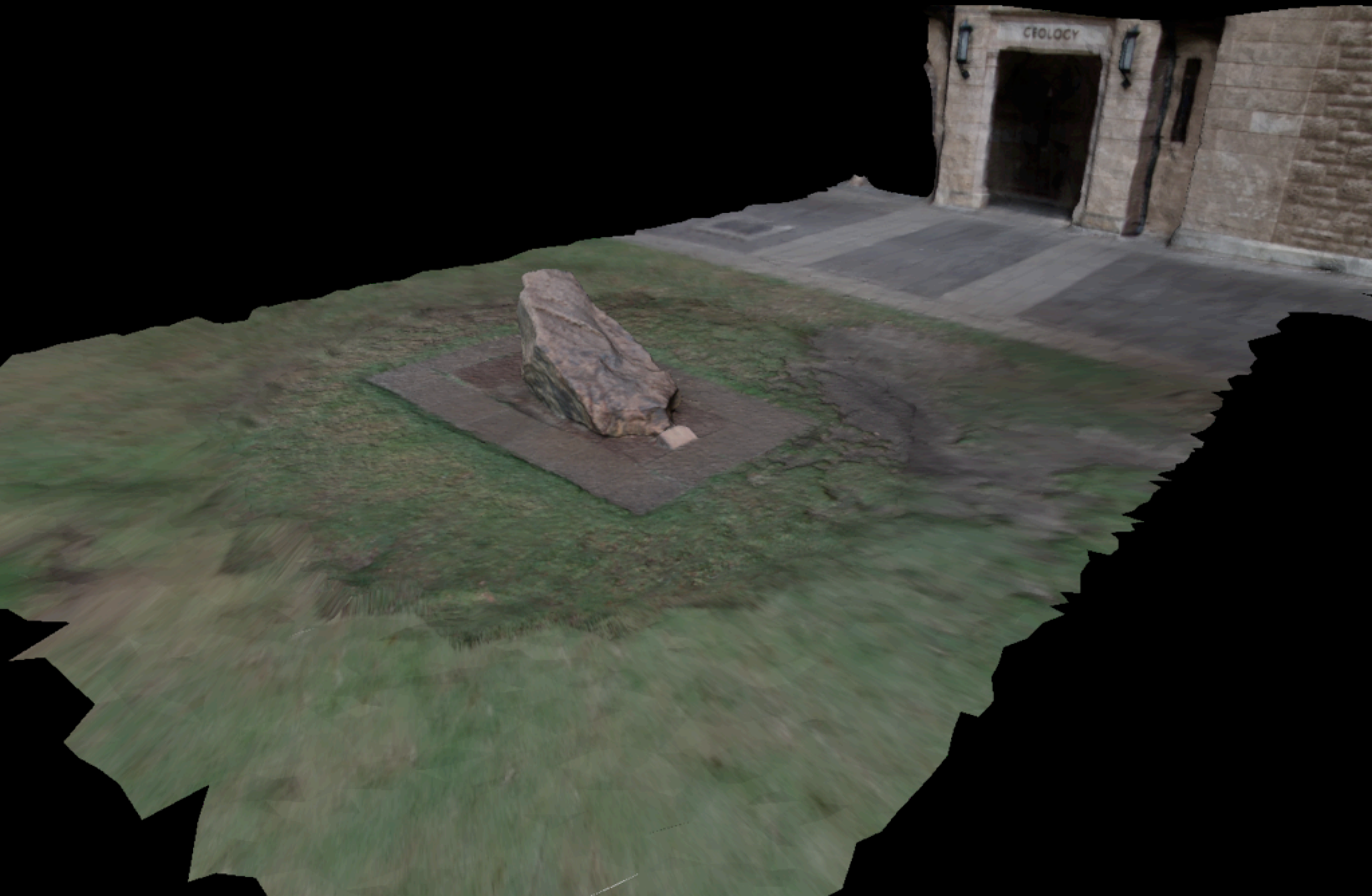
Geometry processing : Removing shrapnel and hole closing



Geometry processing : Removing shrapnel and hole closing



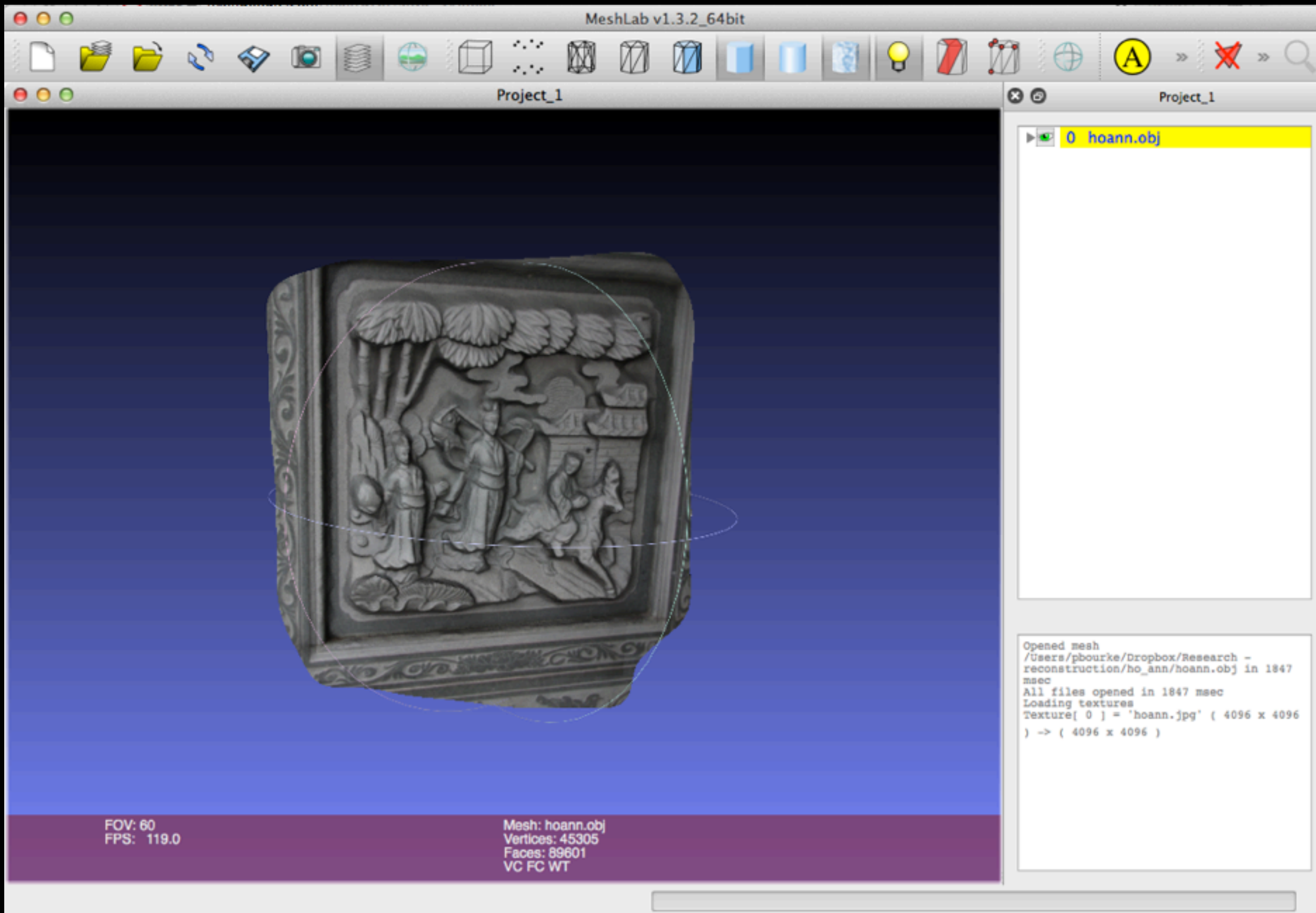
Geometry processing : Removing shrapnel and hole closing



Geometry processing : MeshLab

- There are a number of packages that can be used to manipulate the resulting textured mesh files
- Meshlab is the free packages of choice
- It is cross platform with a high degree of compatibility
- Very general tool for dealing with general meshes
- Has a large collection of algorithms and is extensible
- Unfortunately not all algorithms are "reliable"
- In cases where raw Bundler is used to create a point cloud, Meshlab can be used to construct the mesh using one of a number of algorithms
  - Ball pivot (my general choice)
  - Marching Cubes
  - Poisson surface reconstruction

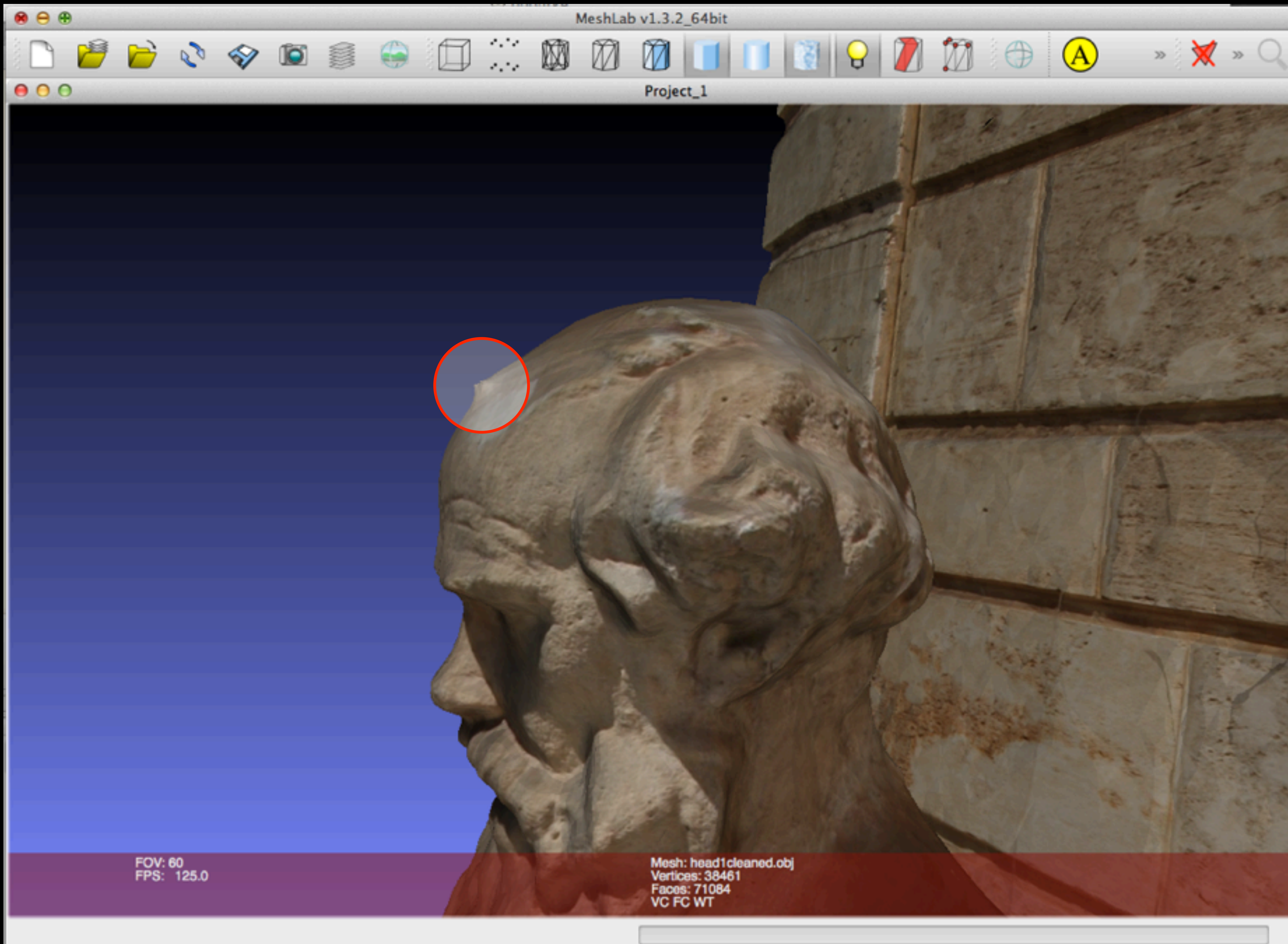
Geometry processing : MeshLab



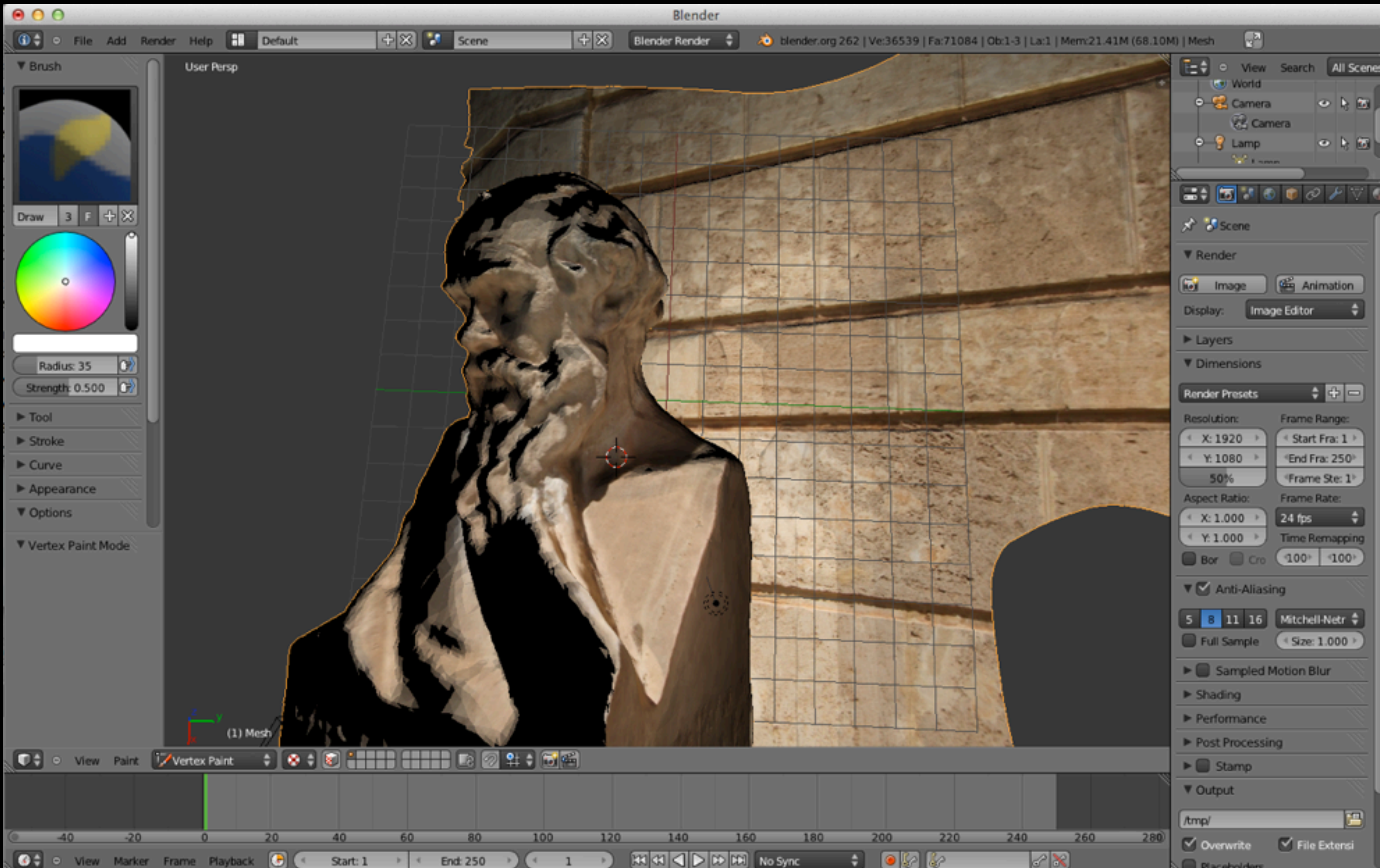
Geometry processing : Blender

- Largely used for per vertex editing
- “Big hammer to crack a small nut”, takes some time to learn the interface
- For example, not uncommon to get “spikes”
- Contains it’s own mesh simplification and thickening algorithms
- Also used to export in a myriad of additional formats
  For example fbx for Unity3D, not available in MeshLab

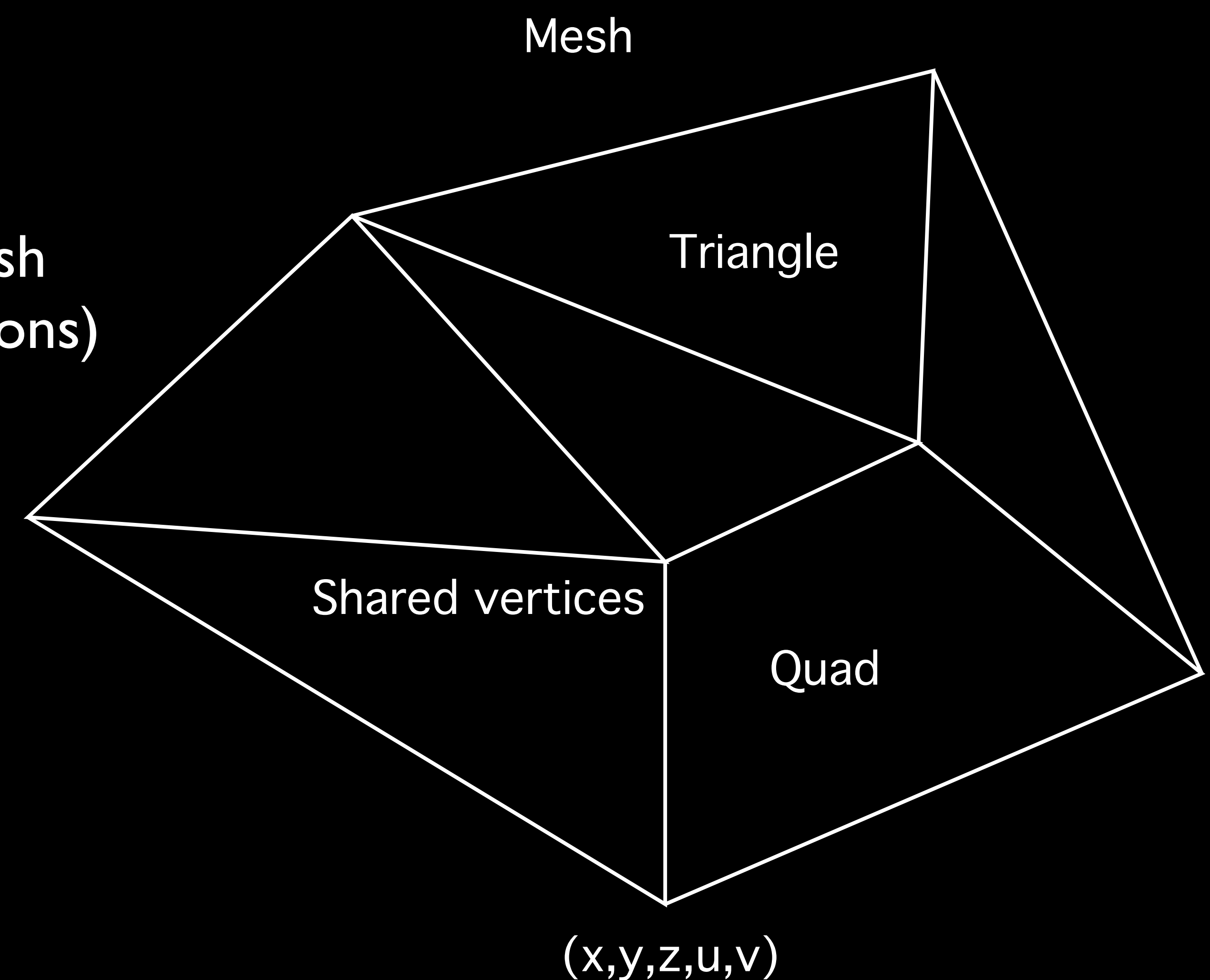
Geometry processing : Blender



Geometry processing : Blender



Geometry processing : File formats



- Requirements: unstructured triangular mesh
  - mesh (vertices - edges - triangles - polygons)
  - texture coordinates
  - image based textures

- Common options
  - 3ds (3DStudioMax)
  - vrml, x3d
  - obj (Wavefront)
  - dae (collada)

- Pretty much standardised on obj, desirable characteristics
  - text only so human readable
  - relatively easy to parse by software for post processing or custom utilities
  - well supported by commercial 3D applications (import/export)
  - shared vertices so no chance of numerical holes
  - supports multiple texture materials and images

Geometry processing : File formats

- Anatomy of an OBJ file. Consists of 3 parts
  - vertex, face, normals, texture coordinates
  - materials file
  - texture image files

```
mtllib ./stone.obj.mtl

v 7.980470 5.627900 3.764240
v 8.476580 2.132000 3.392570
v 8.514860 2.182000 3.396990
   :
   :
vn -0.502475 -1.595313 -2.429116
vn 1.770880 -2.076491 -5.336680
vn -0.718451 -4.758880 -3.222428
   :
   :
vt 0.214445 0.283779
vt 0.213670 0.287044
vt 0.211291 0.287318
   :
   :
usemtl material_0
f 5439/4403/5439 5416/4380/5416 7144/6002/7144
f 5048/4013/5048 6581/5437/6581 5436/4400/5436
f 5435/4399/5435 5049/4014/5049 5436/4400/5436
   :
   :
```

vertices

normals

texture coordinates

triangles

vertex index

normal index

texture coordinate index

filename

material name

```
newmtl material_0
Ka 0.2 0.2 0.2
Kd 0.752941 0.752941 0.752941
Ks 1.000000 1.000000 1.000000
Tr 1.000000
illum 2
Ns 0.000000
map_Kd stone_tex_0.jpg
```

Case study 2 : Aphrodite (UWA)

- Require significantly more images ... a 360 objects
- 16 images in this case, a relatively low number for a full 3D object
- Some algorithms perform better if the images are captured in sequence with the best matches at the start of the bundle adjustment
- Depends on whether the software does a compare between all images
- Diffuse lighting conditions so no strong shadows, see later on limitations
- "Bald" spot because no photographs from above, see later on limitations on access

Case study 2 : Aphrodite (UWA)

Case study 2 : Aphrodite (UWA)

Movie

Aphrodite (Lady of Cythera)
16 images

Other topics

- Resolution: real vs apparent
- Relighting
- Rendering
- Texture editing
- Annotation

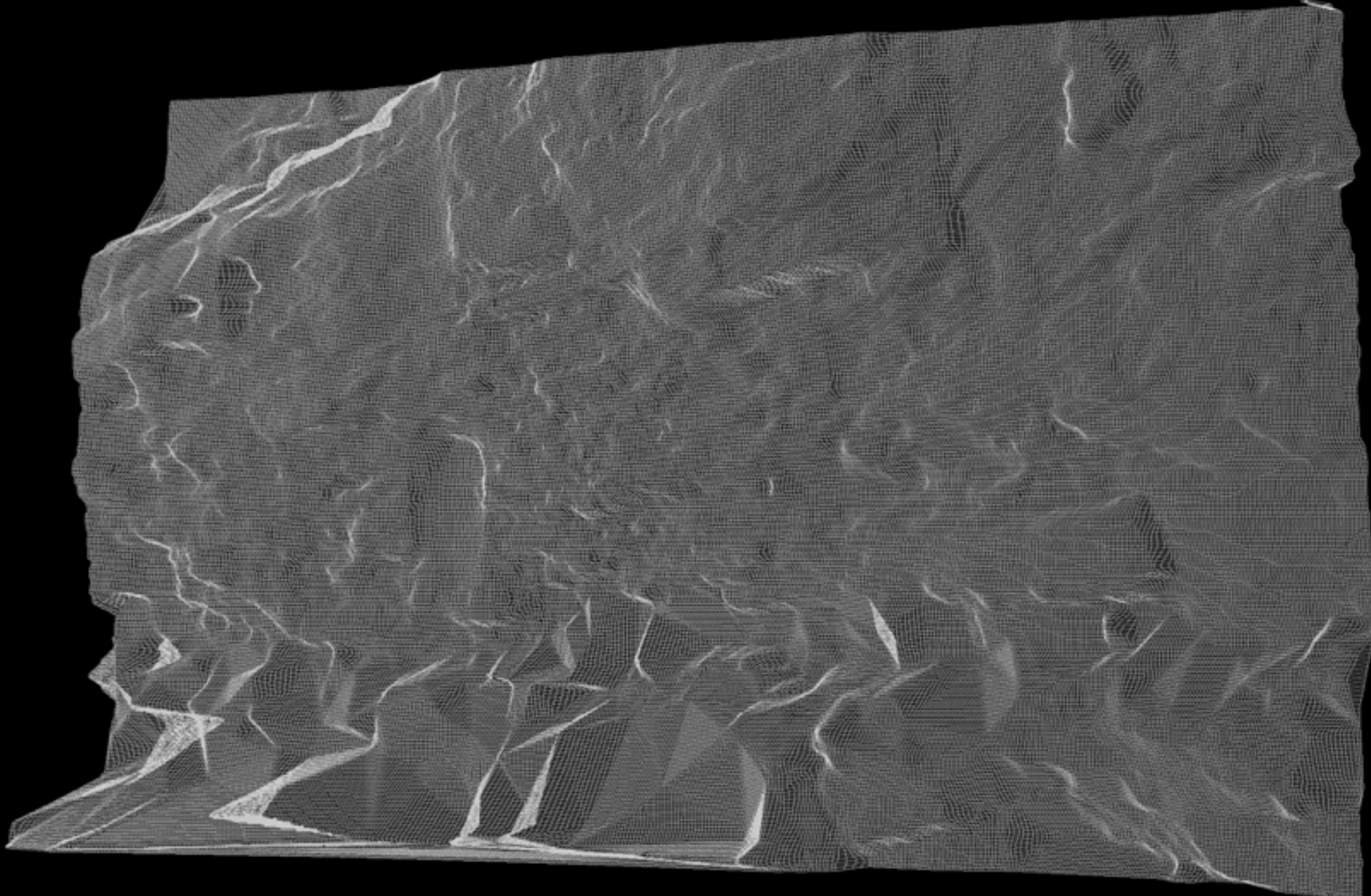
Other topics : resolution

- Actual mesh resolution vs apparent mesh resolution
- Texture resolution rather than geometric resolution
- Requirements vary depending on the end application

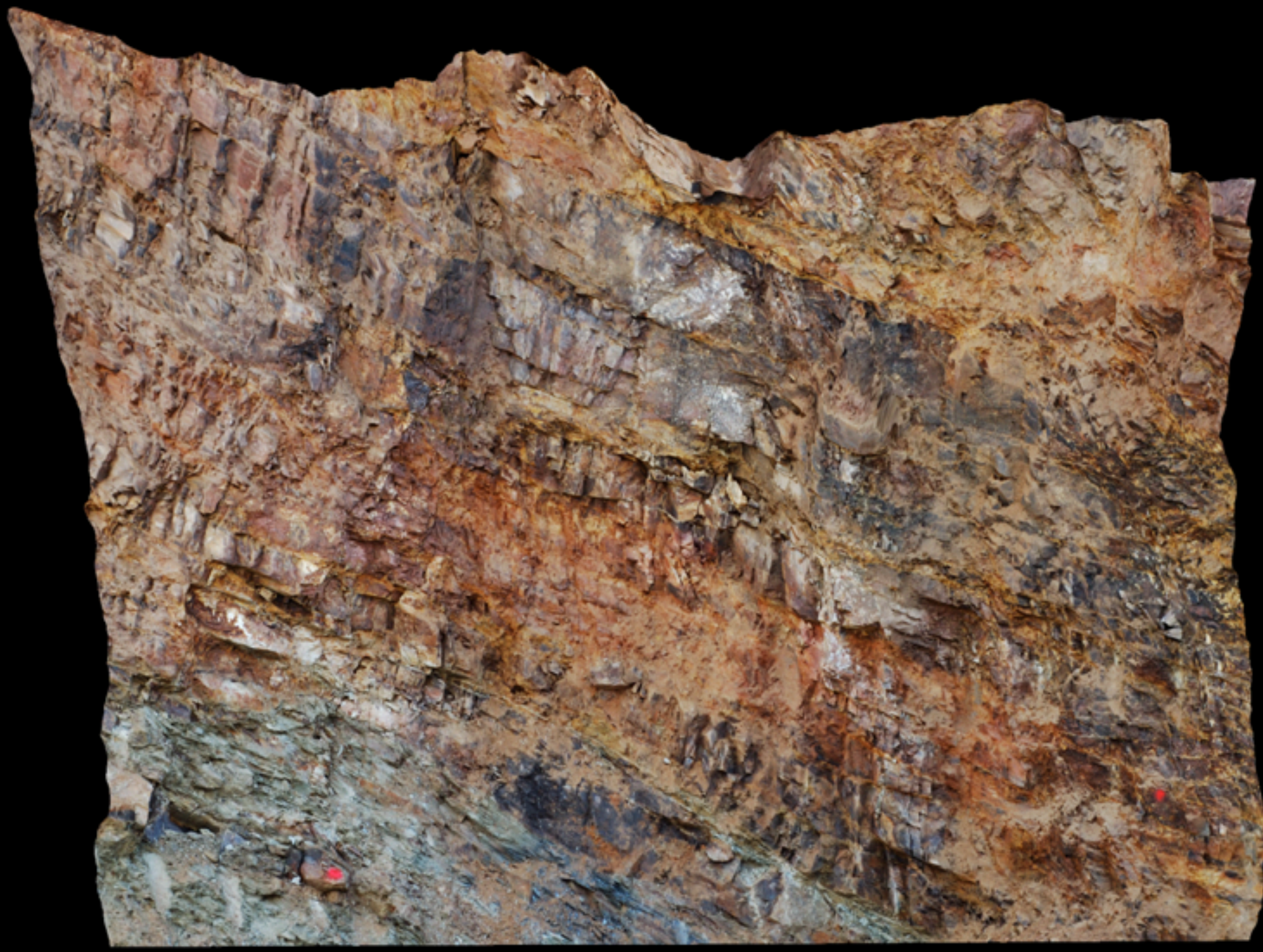
	Geometric resolution	Texture resolution
Gaming	Low	High
Analysis	High	Don't care
Education	Medium	High
Archive/heritage	High	High
Online	Low/Average	Low/average

Other topics : resolution

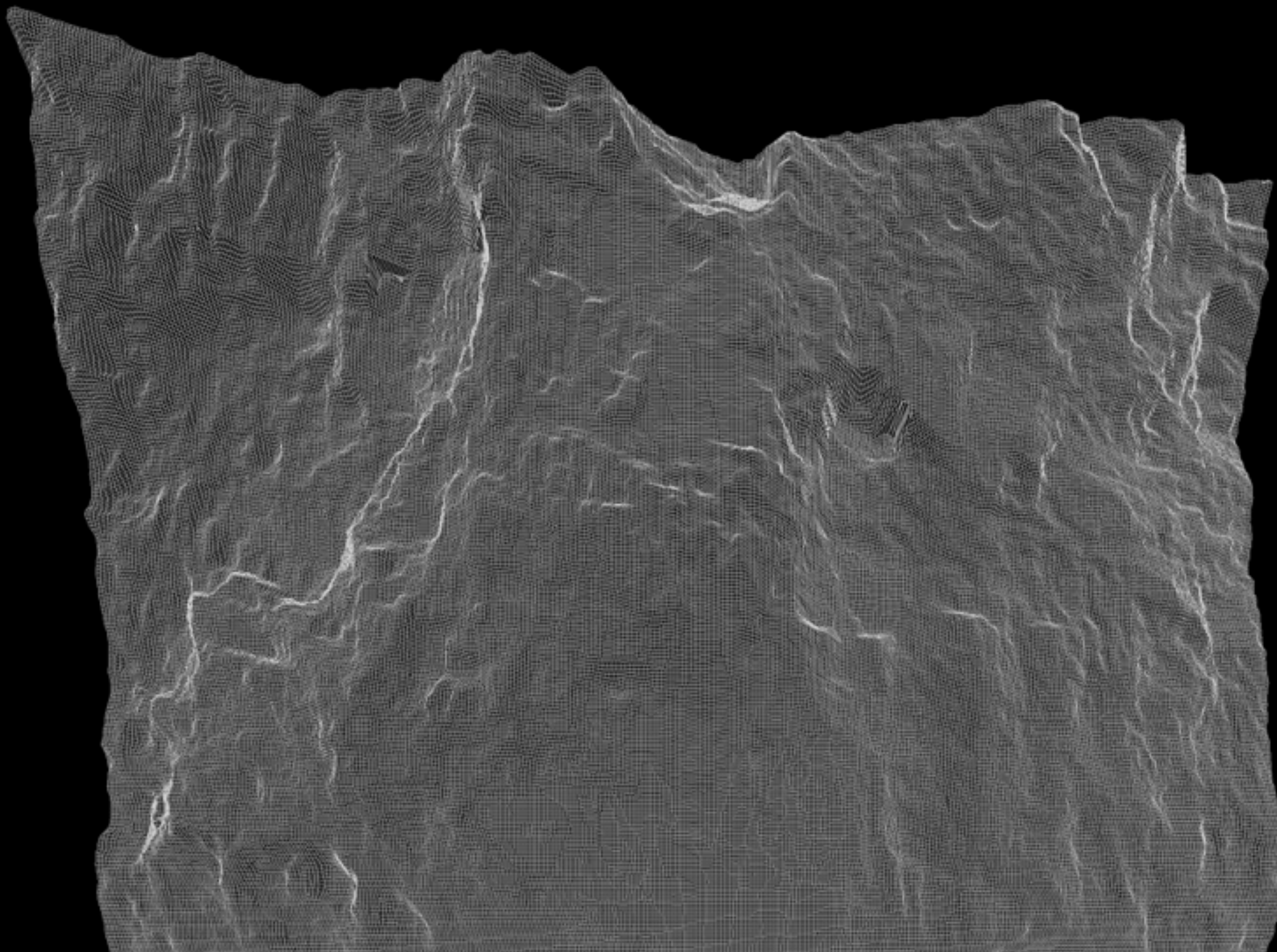
Other topics : resolution



Other topics : resolution



Other topics : resolution



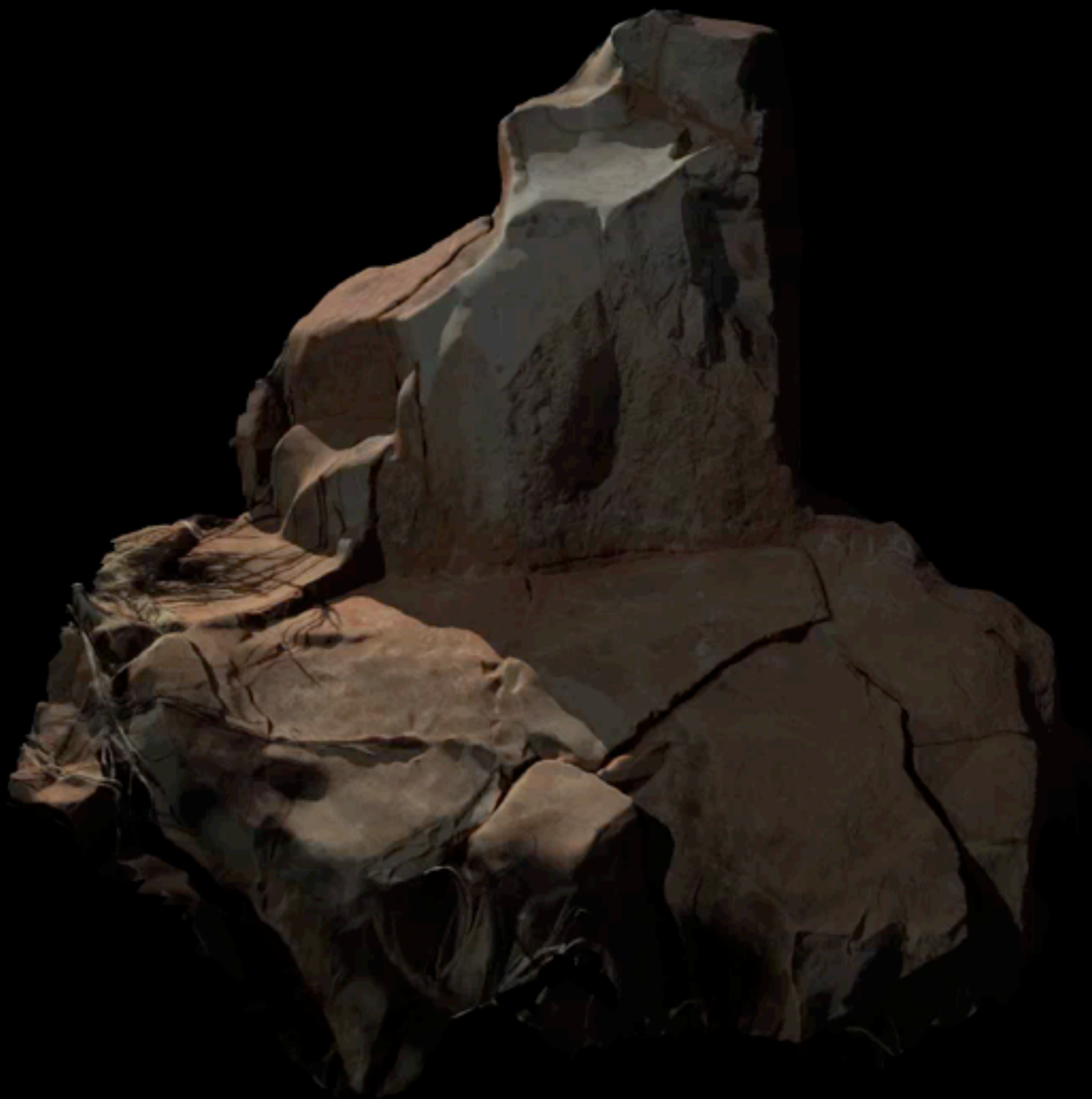
Other topics : resolution

Other topics : Relighting

- We have a 3D model, can "relight" it
  For example: cast shadows, adjust diffuse/specular shading
- Obviously works best with diffuse lit models
- See later for baked on texture limitations
- Interesting in the archaeology context since it is well known that some features are "revealed" in different lighting conditions
- Cannot replicate effects of dyes but can replicate effects due to shading/shadowing of fine details

Other topics : Relighting

Other topics : Relighting



Other topics : Relighting

Other topics : Rendering

Movie

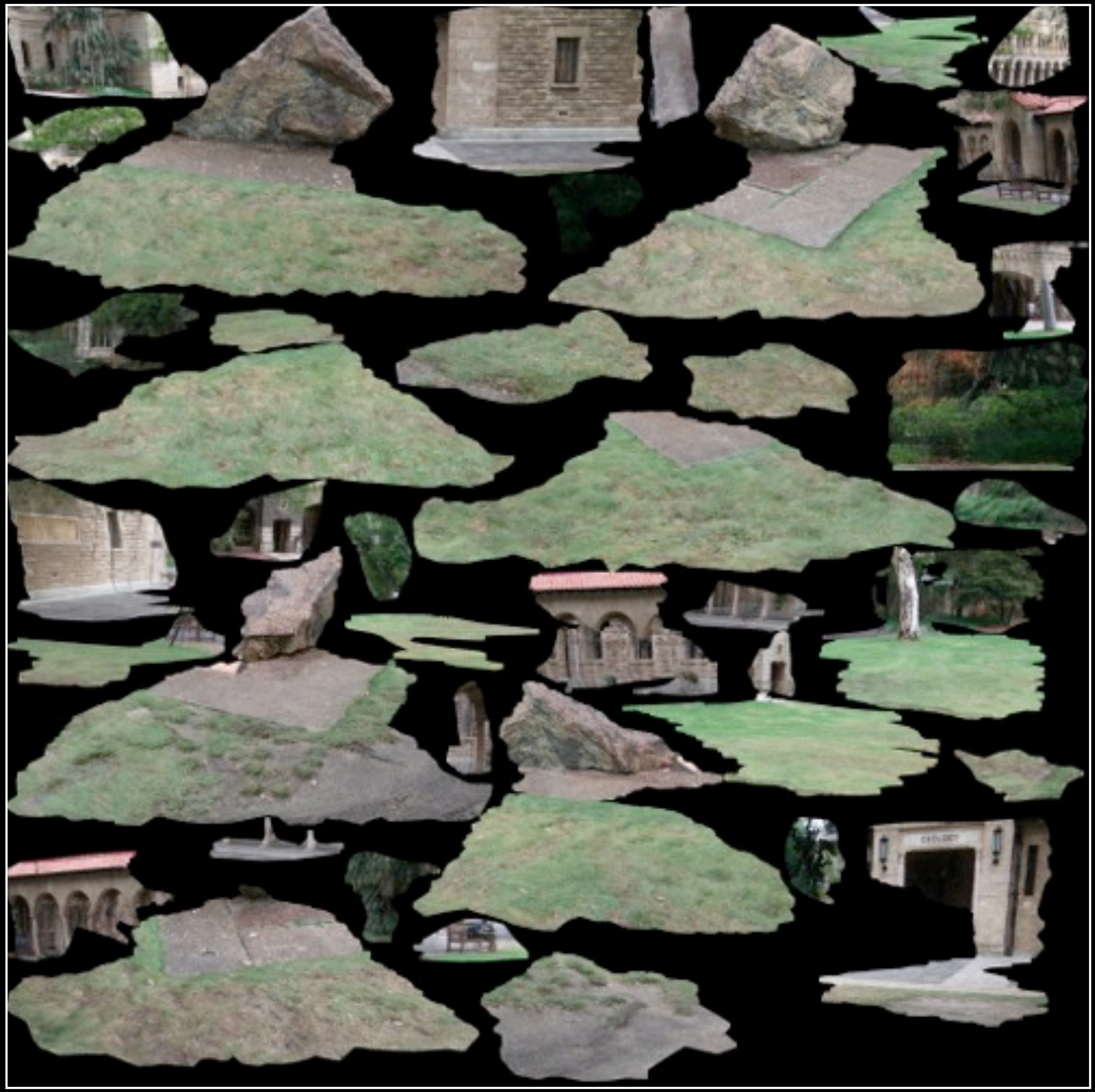
Other topics : Analysis

Movie

Other topics : Annotating

- Textures from the reconstruction algorithms are often "interesting"
- Exact form of the texture depends to some extent on the software being used
  Can often identify the software based upon the appearance of the texture maps
- They are derived from re-projection of the image from the derived camera position onto the reconstructed mesh, hence potentially very high quality (perceived resolution)
- Can generally still be drawn on, treated as an image for image processing in PhotoShop, etc.

Other topics : Annotating



Texture map 1

Texture map 2

Other topics : Annotating

Textured mesh

Other topics : Annotating

Other topics : Annotating

Movie

Limitations

- Occluders - Problematic
- Movement in the scene
- Thin structures
- Baked on shadows
- Lighting changes during capture
- Access to ideal vantage points

Limitations : Occluders

- Algorithms seem to be generally poor at handling foreground occluders
- For example: columns in front of a building
- Capturing the backdrop behind an object
  - Often better, assuming possible, to capture them separately

Limitations : Occluders

Limitations : Movement

- Objects to be reconstructed obviously need to be stationary across photographs
- Grass moving in the wind is a common problem for our field work

Movie

Limitations : Thin structures

- Difficult to reconstruct objects approaching a few pixels in the images (sampling theory)
- Again, example of grasses in the rock art examples presented so far

Limitations : Thin structures

Limitations : Baked on shadows

- Shadows obviously become part of the texture maps
- Can be alleviated somewhat by photographing in diffuse light
- For outside objects can sometimes choose times when object is not directly lit
- Can sometimes choose diffuse lit days, cloudy

Limitations : Baked on shadows

HMAS Sydney Cairn,
near Canarvon

Limitations : Lighting changes and access

- For field work access to preferred positions for photographs may be problematic
- Similarly capturing photographs from above the object, elevated positions
- When capturing 30+ photographs for 3D objects the lighting conditions may change eg: clouds passing overhead
- Shadows of the photographer

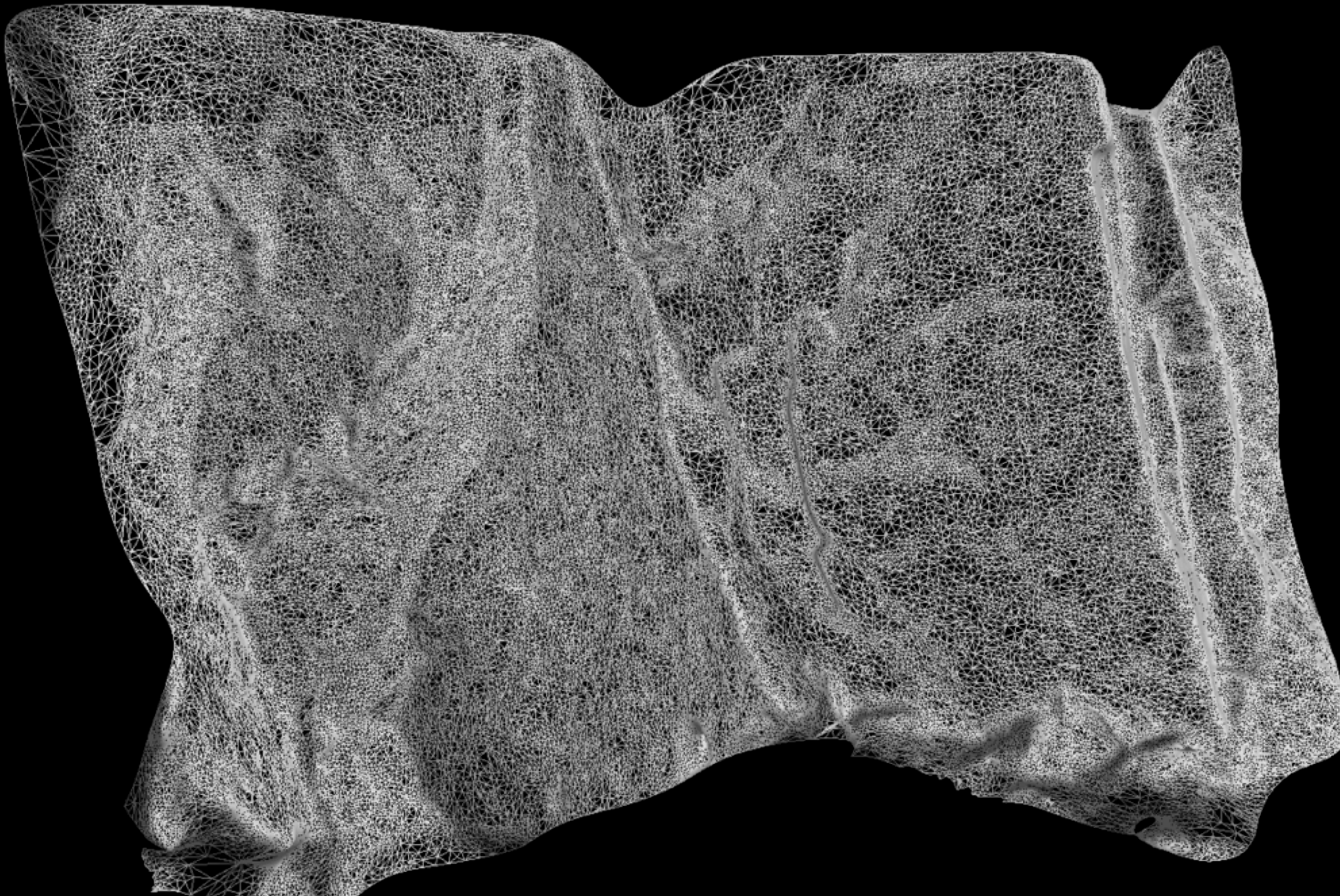
Case study 3: Indigenous archaeology

- Wanmanna
- Automated processes critical, 250 pieces of rock art

Populating virtual worlds

3D reconstruction

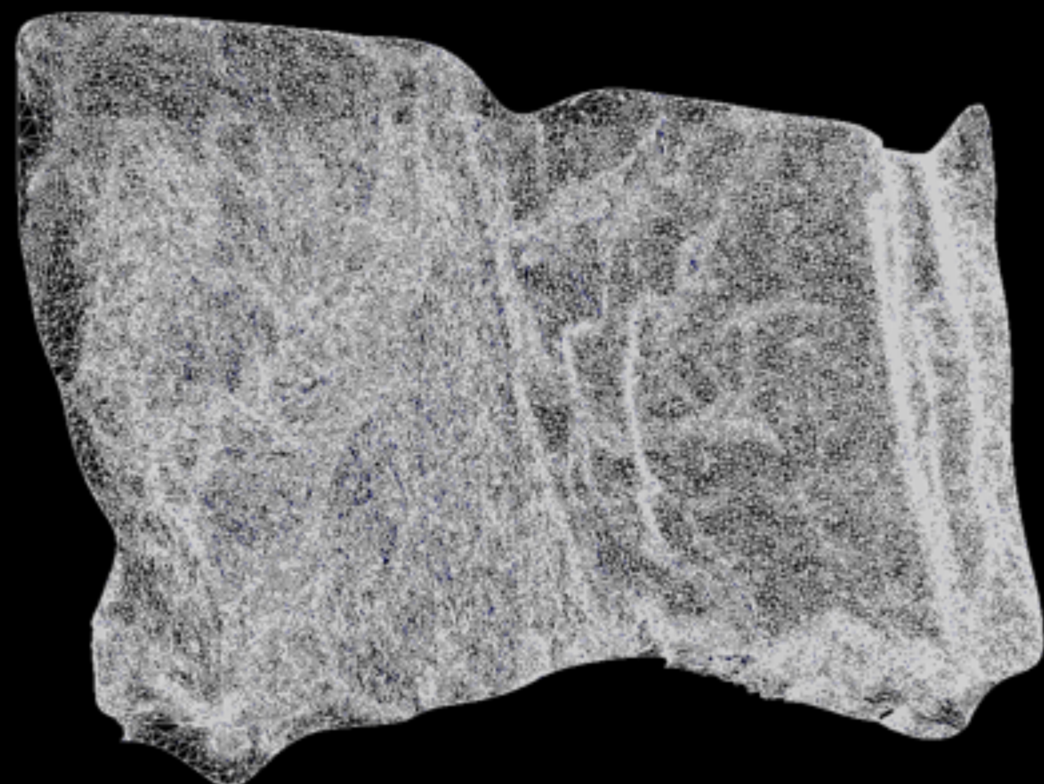
Reconstructed mesh



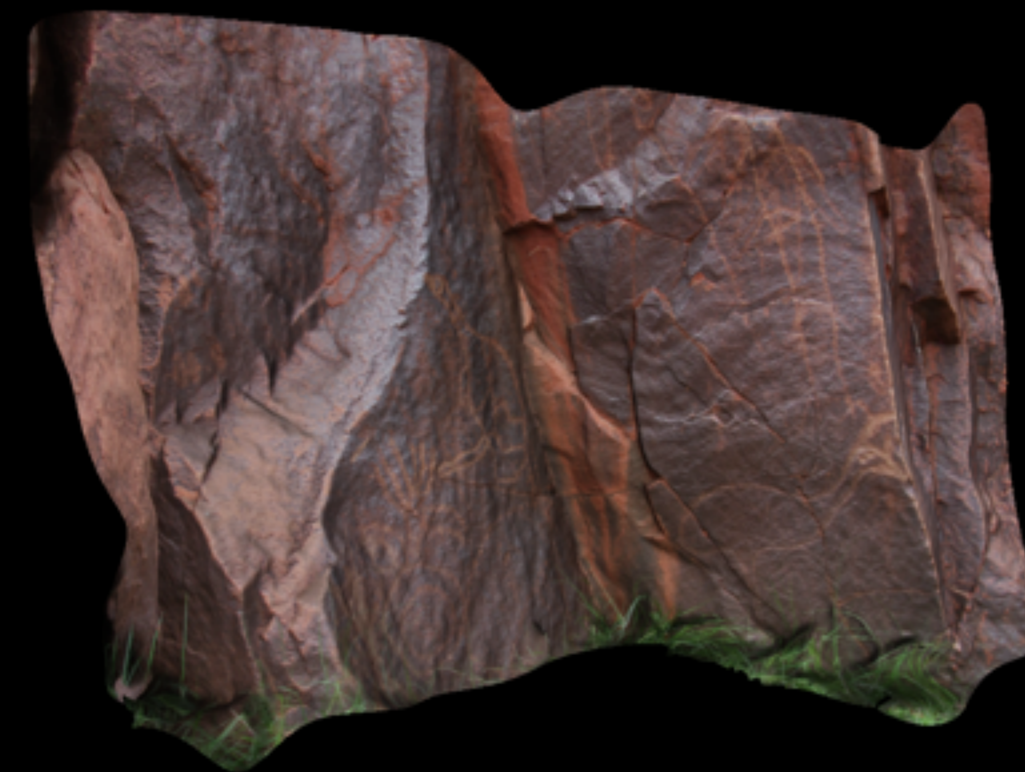
Textured 3D model

Movie

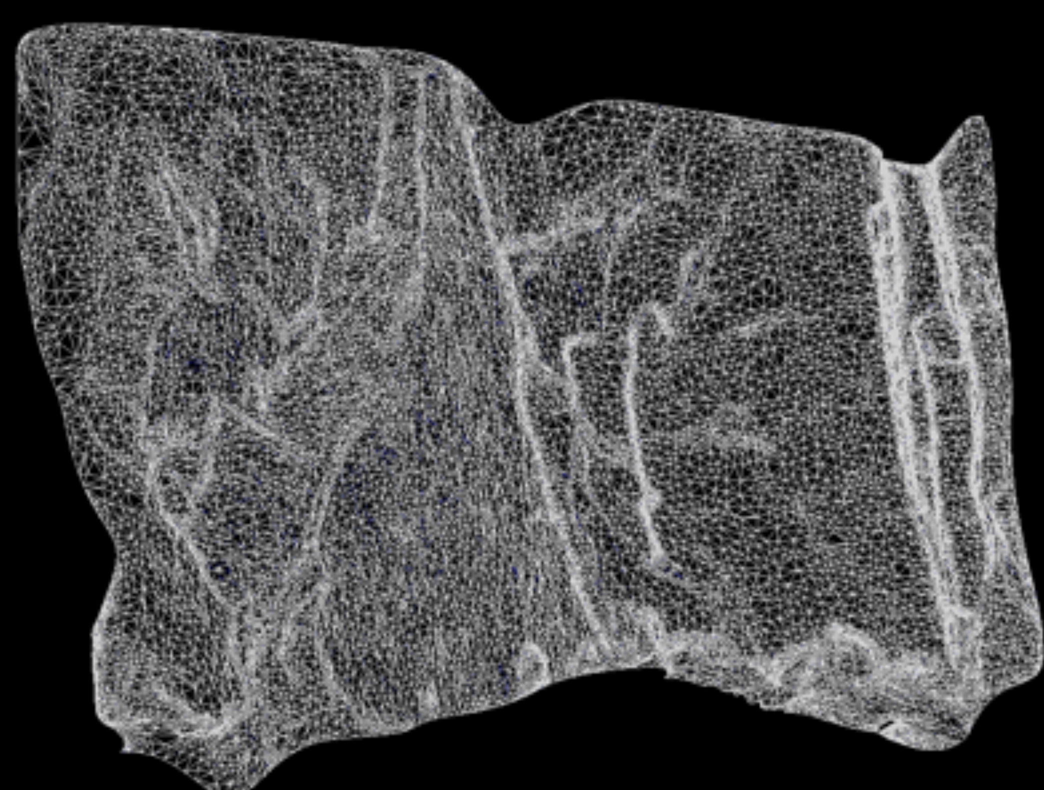
Mesh decimation: Online and populating virtual worlds



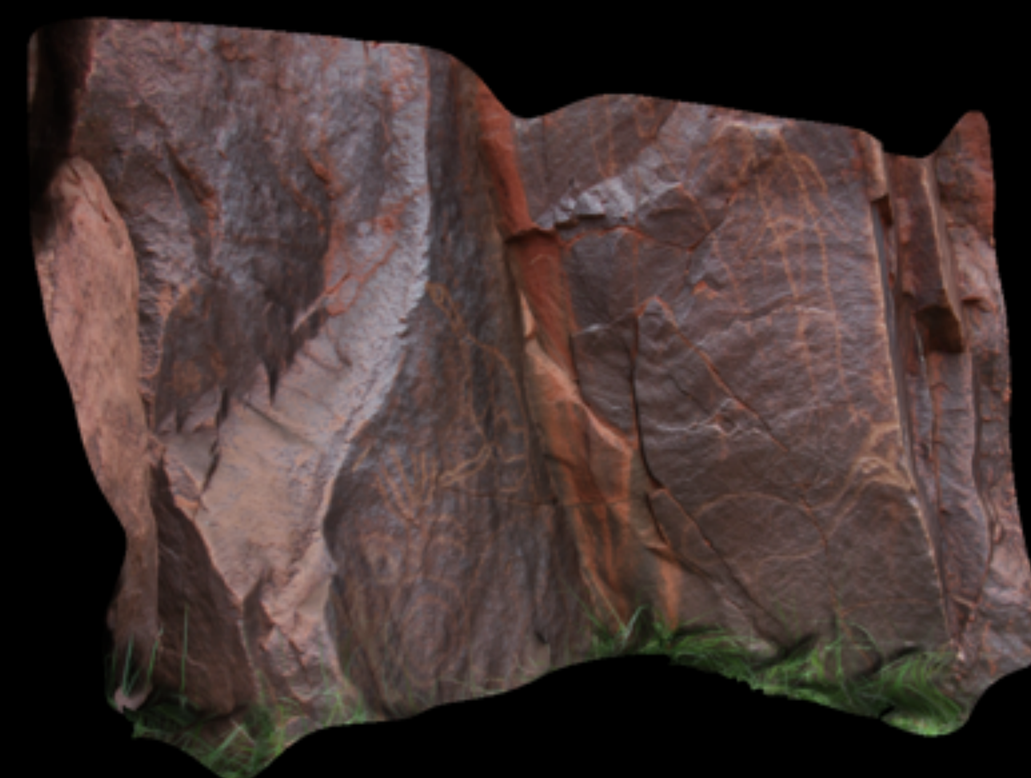
120,000 triangles



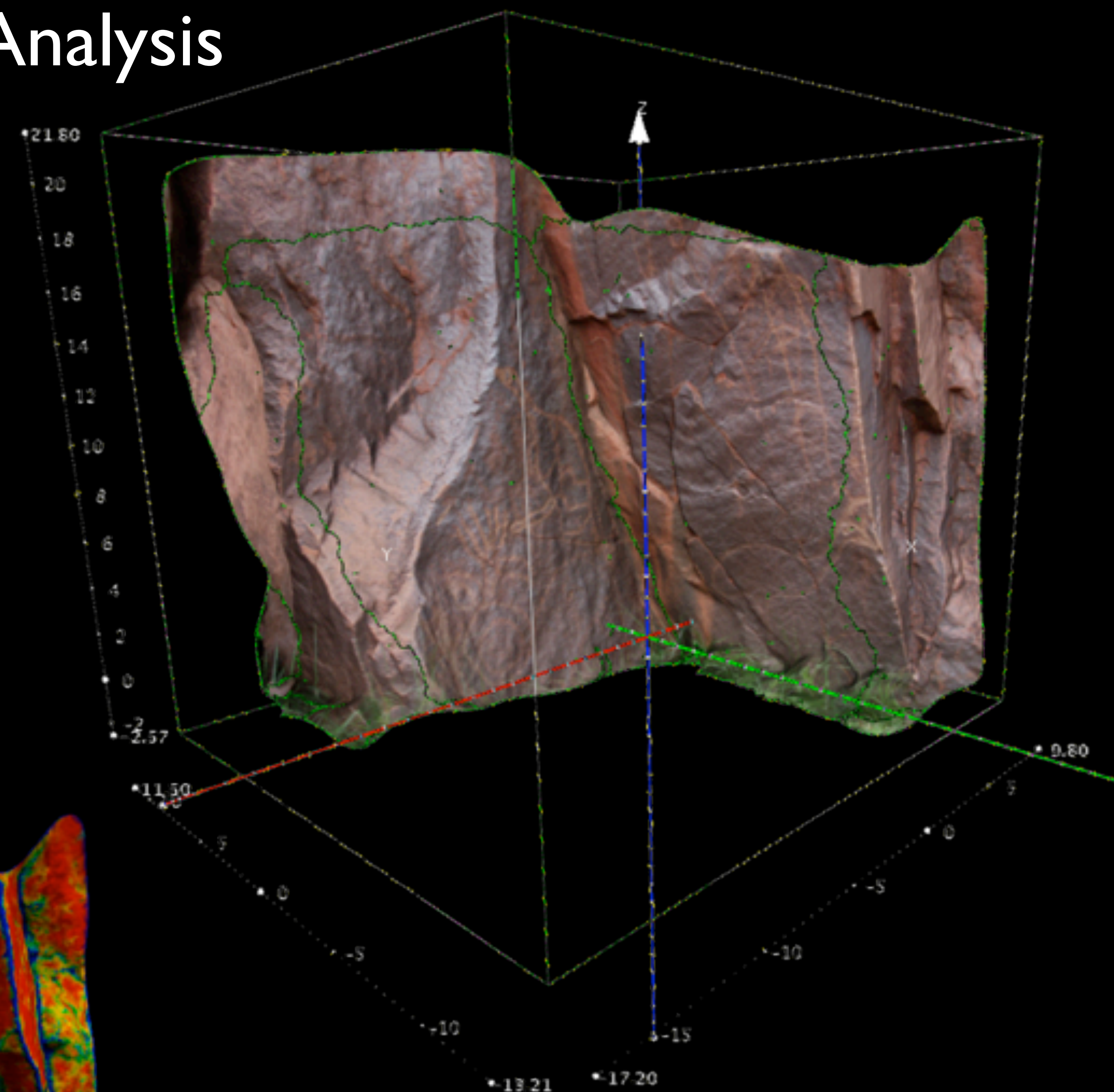
Quadratic mesh decimation



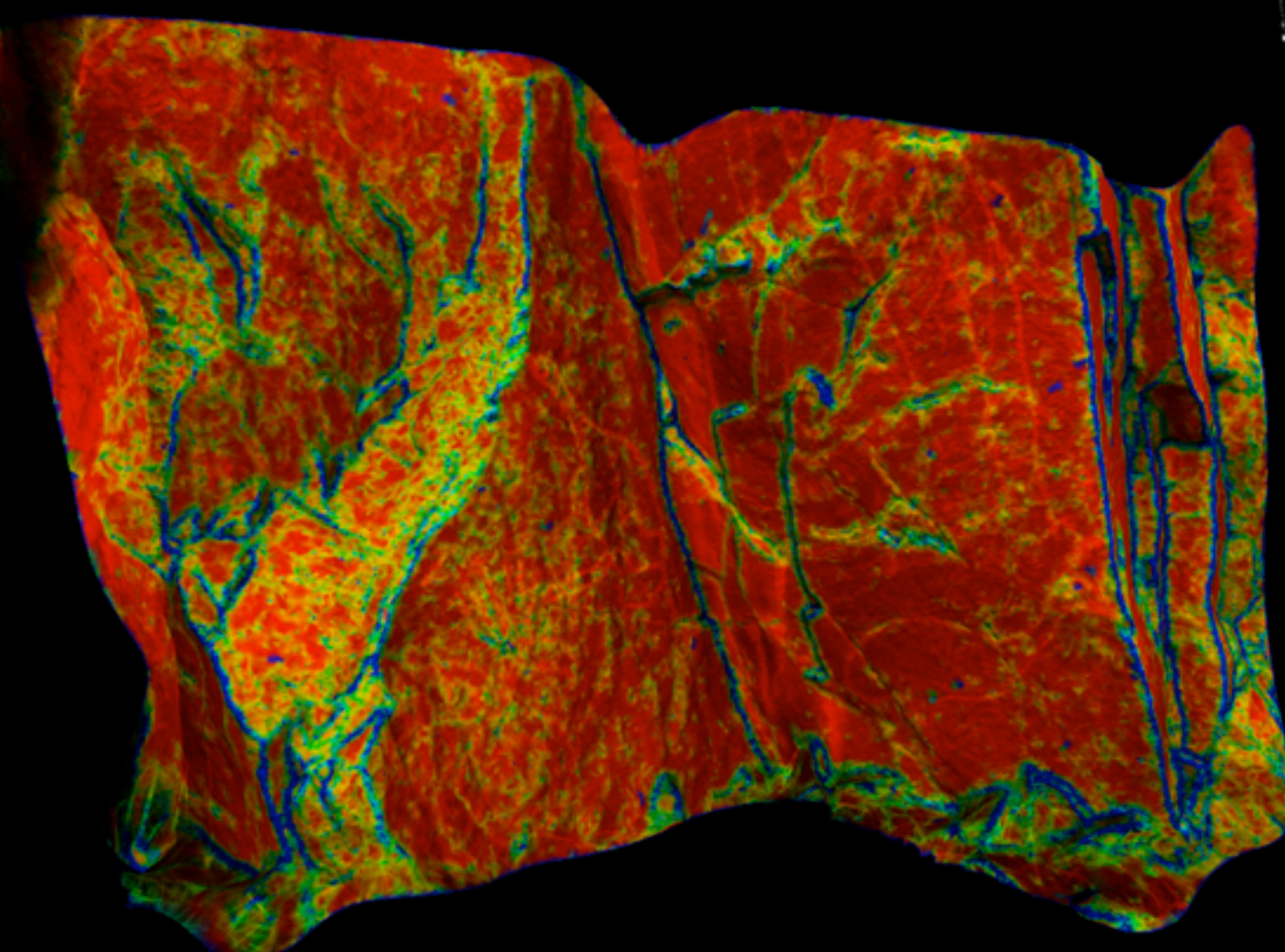
40,000 triangles



3D Analysis



Discrete curvature



Relighting

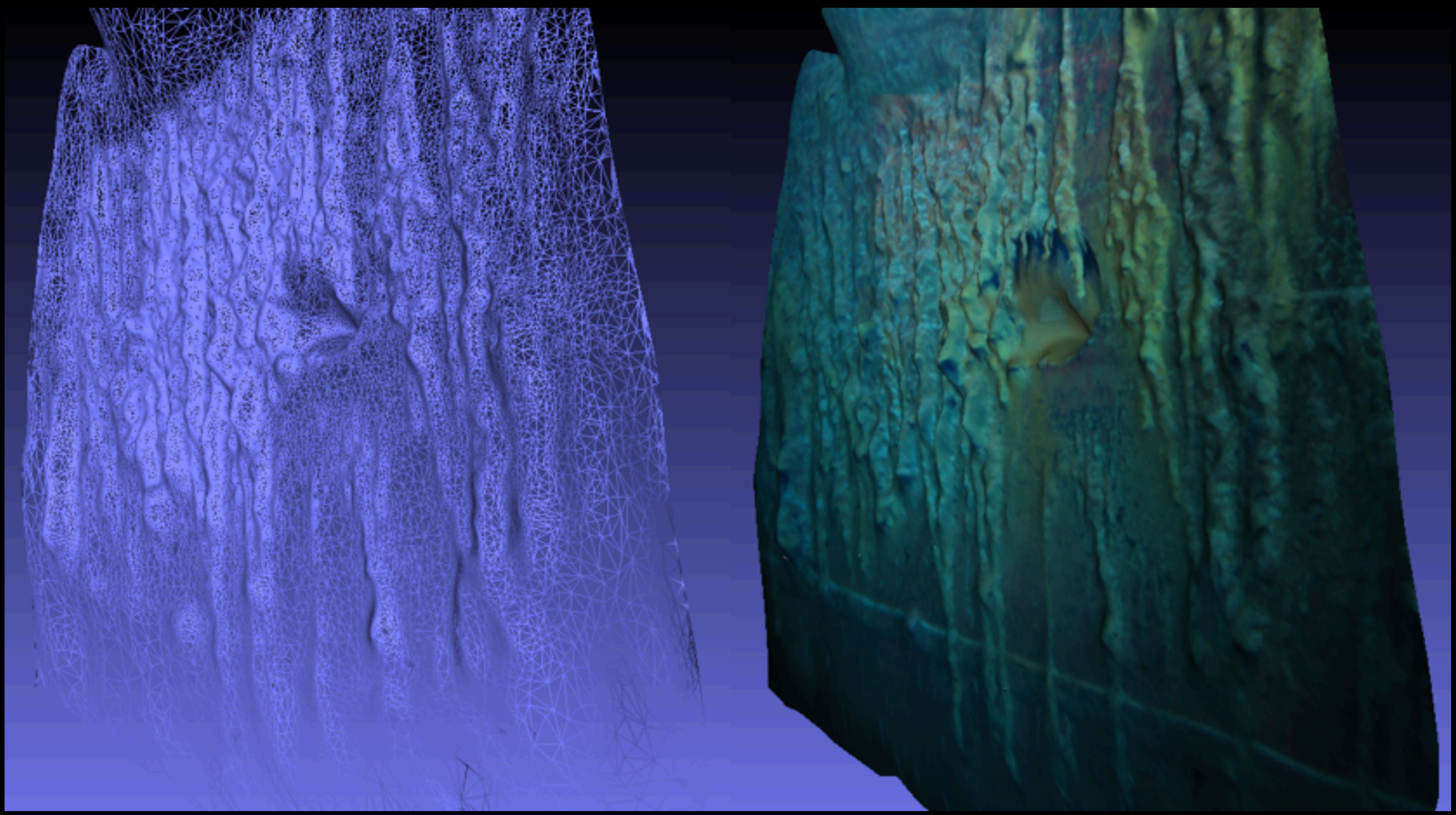
Movie

Image processing and annotating

Movie

Additional applications

- Underwater
- Aerial photography
- Rapid Prototypes



Kormoran

Additional applications : Underwater

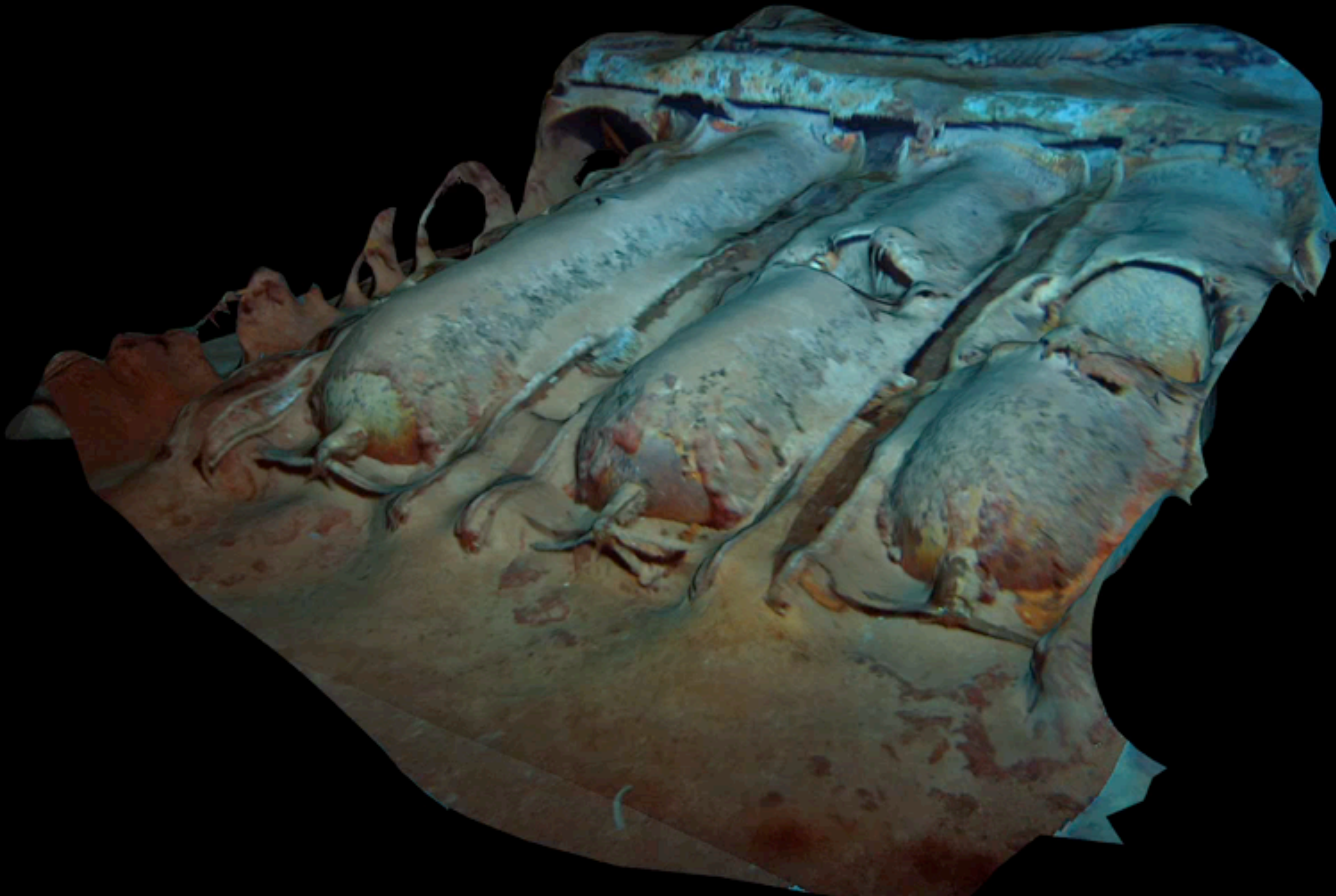
- Capture of underwater object more challenging.
- How to compensate for the light absorption through a column of water.
- Example: HMAS Sydney in 2.5KM of water.





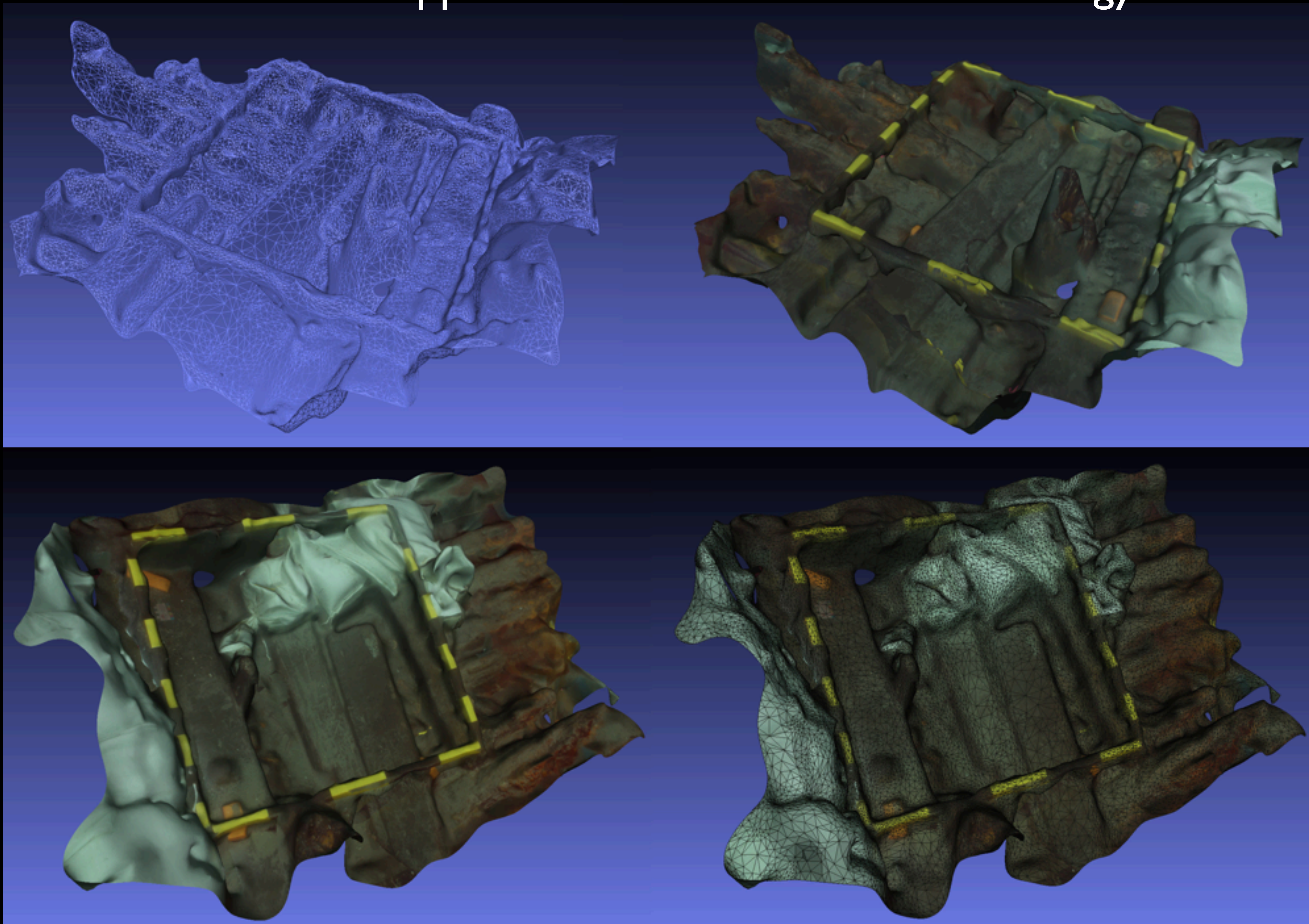
HMAS Sydney

Additional applications : Underwater



Movie

Additional applications : Underwater Archaeology



Additional applications : Aerial photography

- Capturing inaccessible geological formations
- Also building structures out of reach
- Vibration and rolling shutter issues

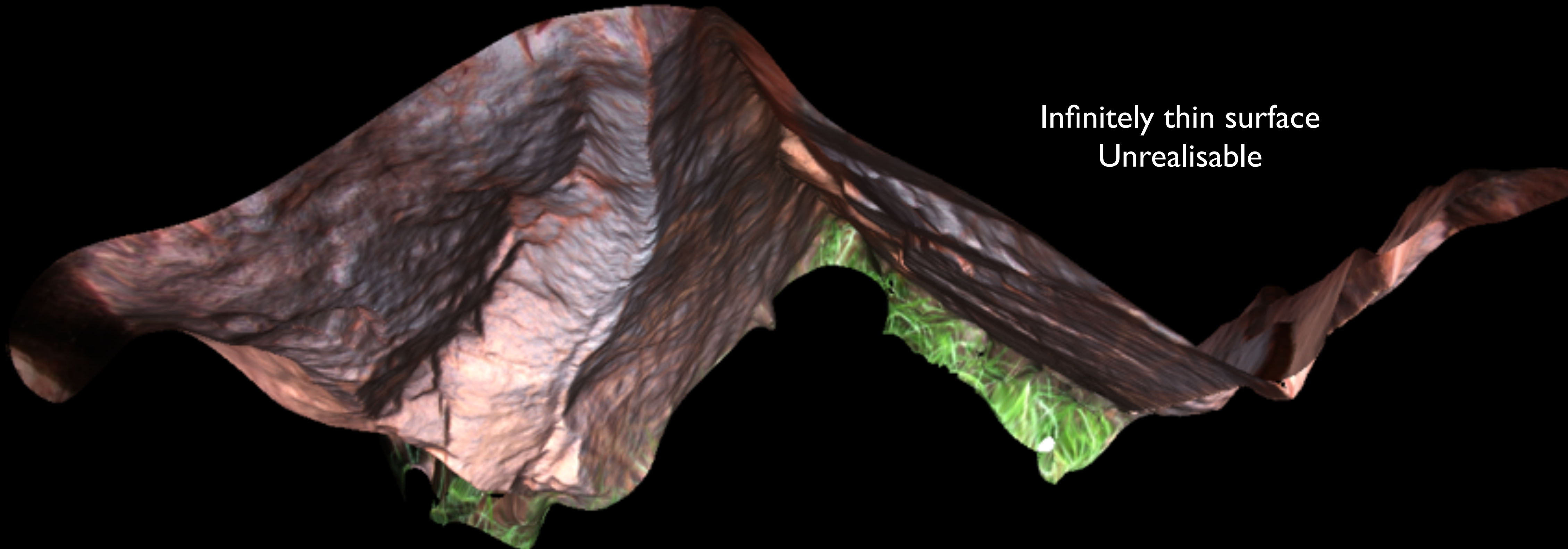
Additional applications : Aerial photography

Movie

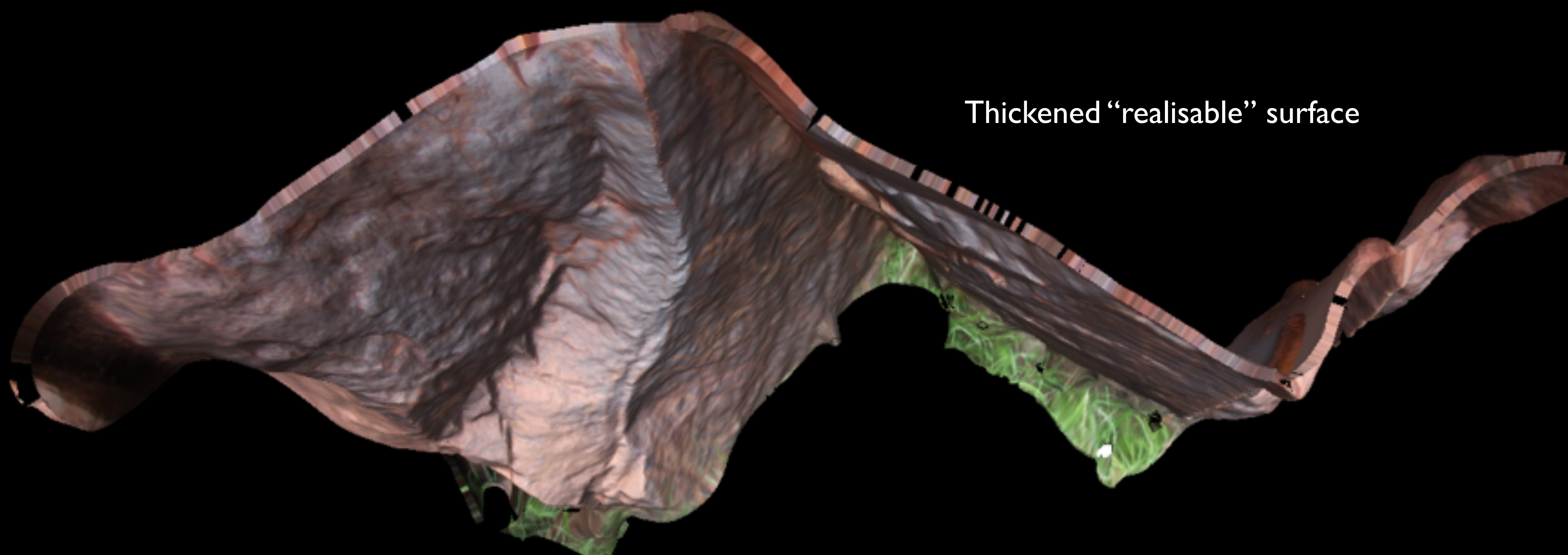
Additional applications : Rapid prototypes

- Can complete the loop:
  capture a real object photographically - reconstruct it - generate a real object.
- Requires a solid object (thickened), with enough structural integrity.
- Models need to be "watertight", hence hole closing algorithms.
- Main printer for colour prints is the ZCorp.
- http://www.zcorp.com/
- Recommend using online services such as Shapeways.
  http://www.shapeways.com

Additional applications : Rapid prototypes

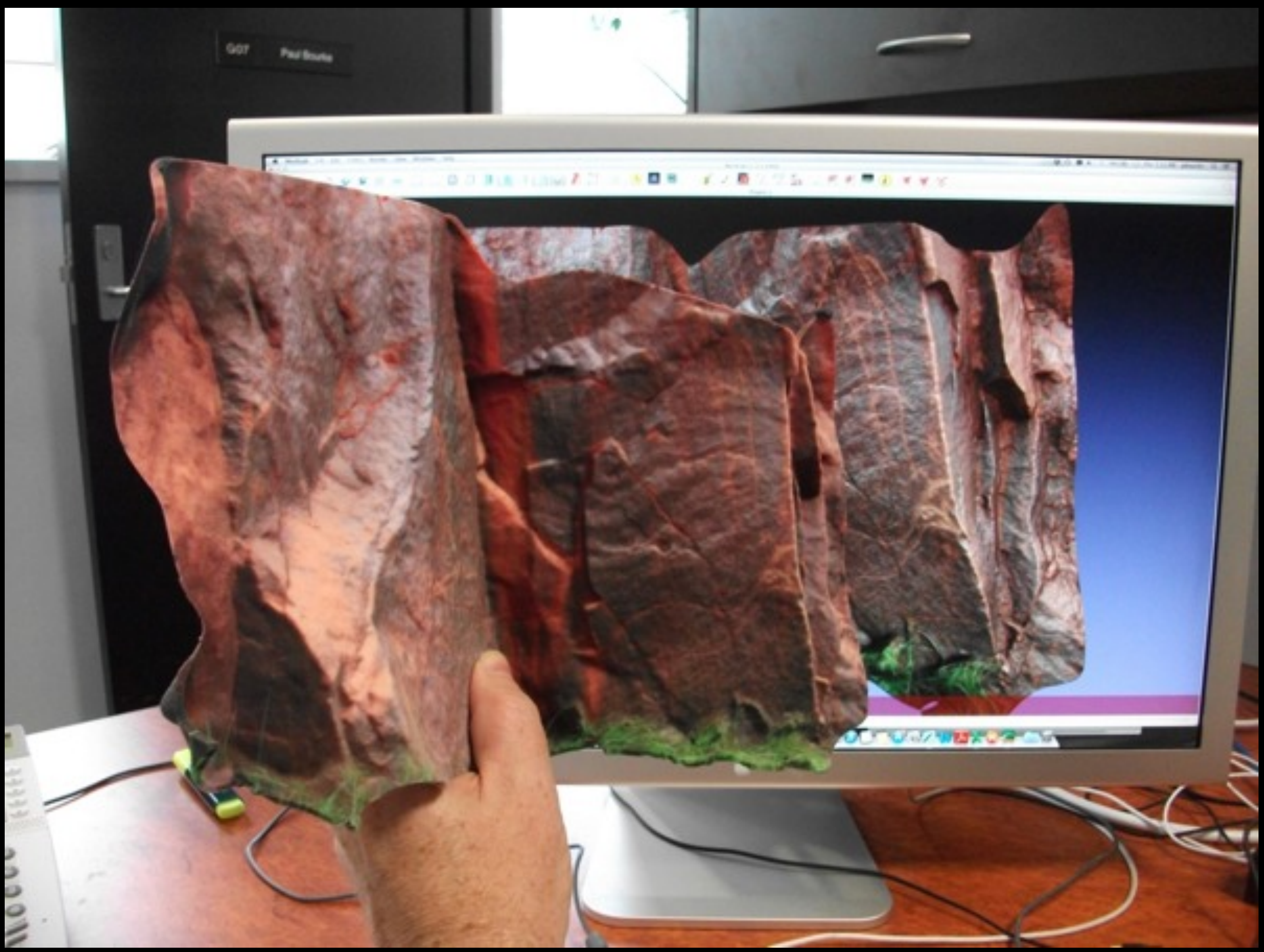


Infinitely thin surface
Unrealisable



Thickened “realisable” surface

Additional applications : Rapid prototypes



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Questions / discussion