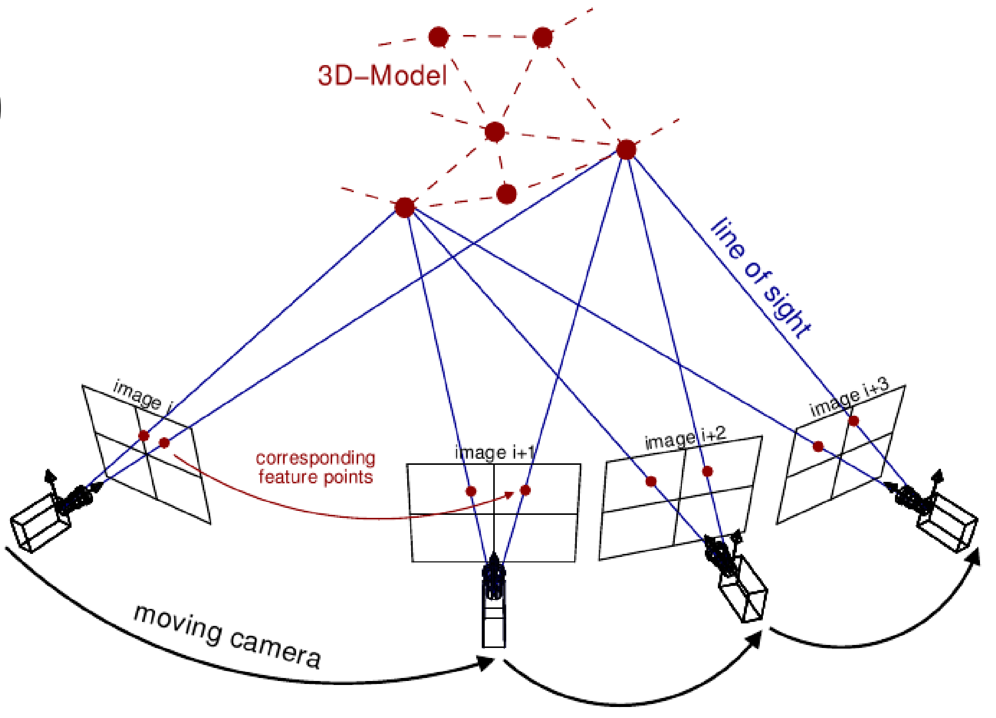
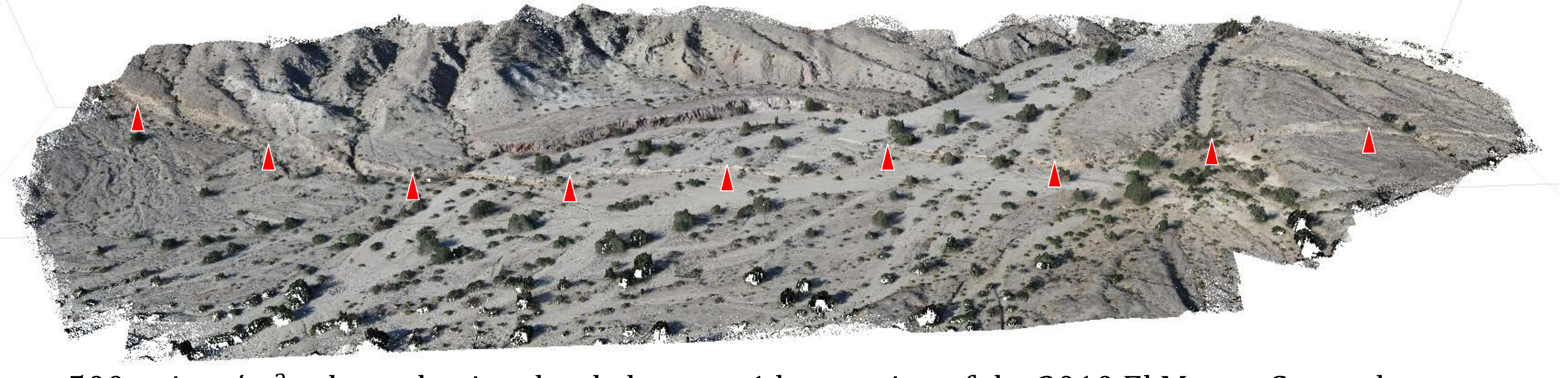
Structure-from-Motion

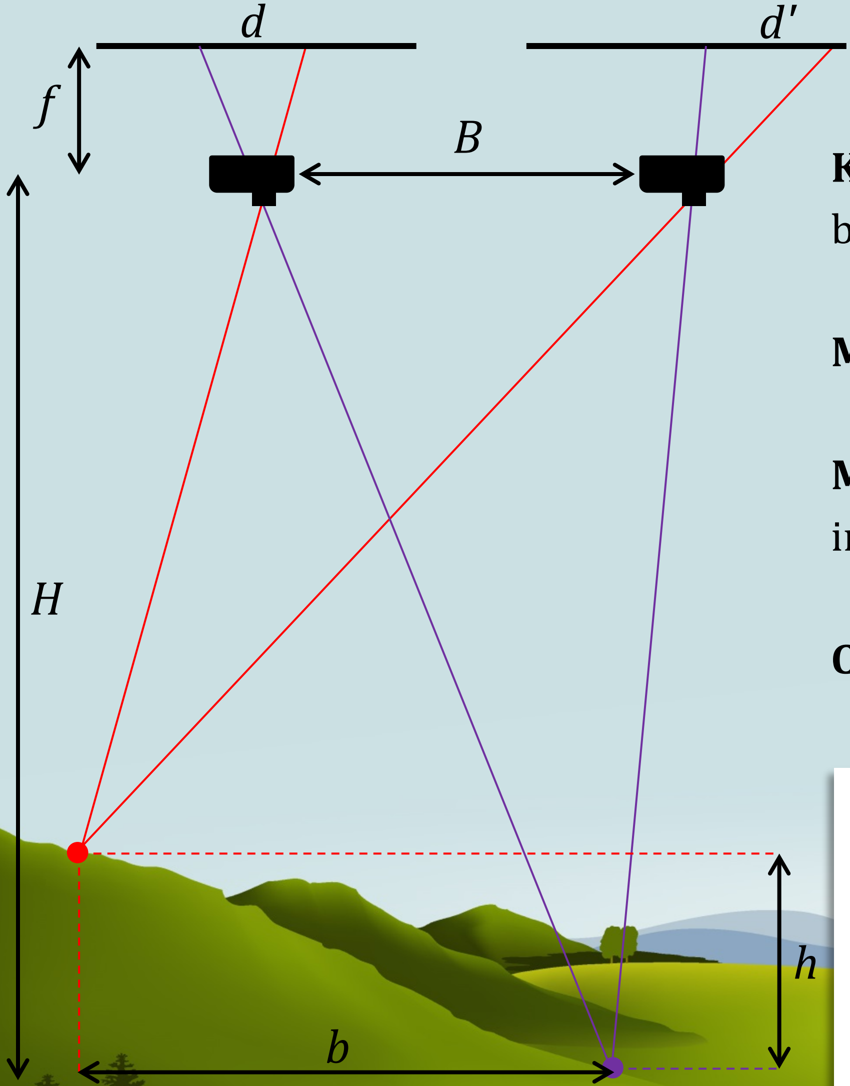
Edwin Nissen (Colorado School of Mines)



- **What is Structure-from-Motion?**
- **Examples of geoscience applications**
- **Mapping from UAVs and balloons**
- **Exercise**



~500 points/m^2 coloured point cloud along a ~1 km section of the 2010 El Mayor-Cucapah earthquake rupture generated from ~500 photographs captured in 2 hours from a helium blimp



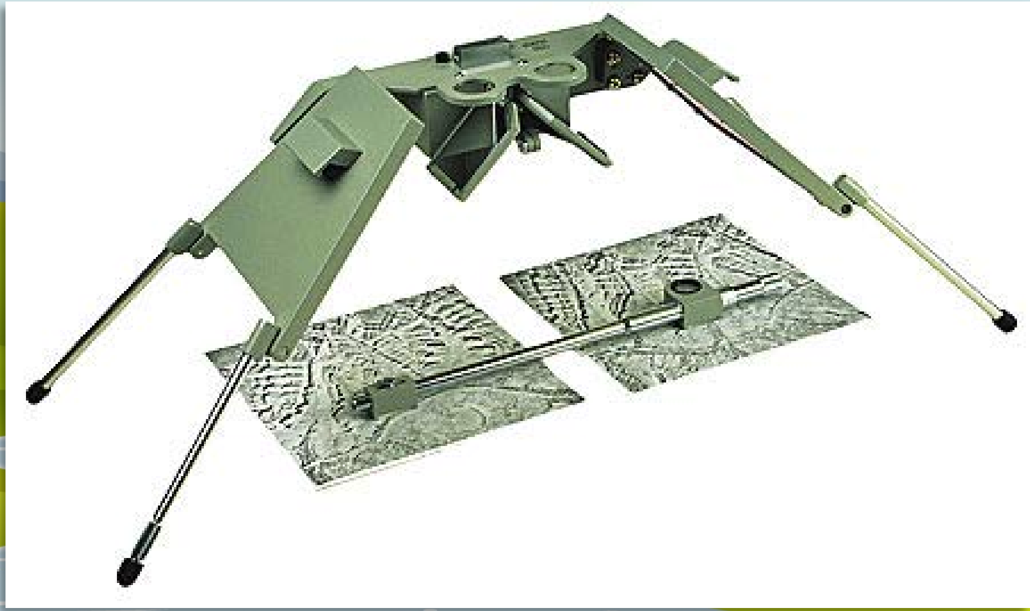
Traditional stereo-photogrammetry

Known camera height *H* and focal length *f*, and the baseline *B* between images

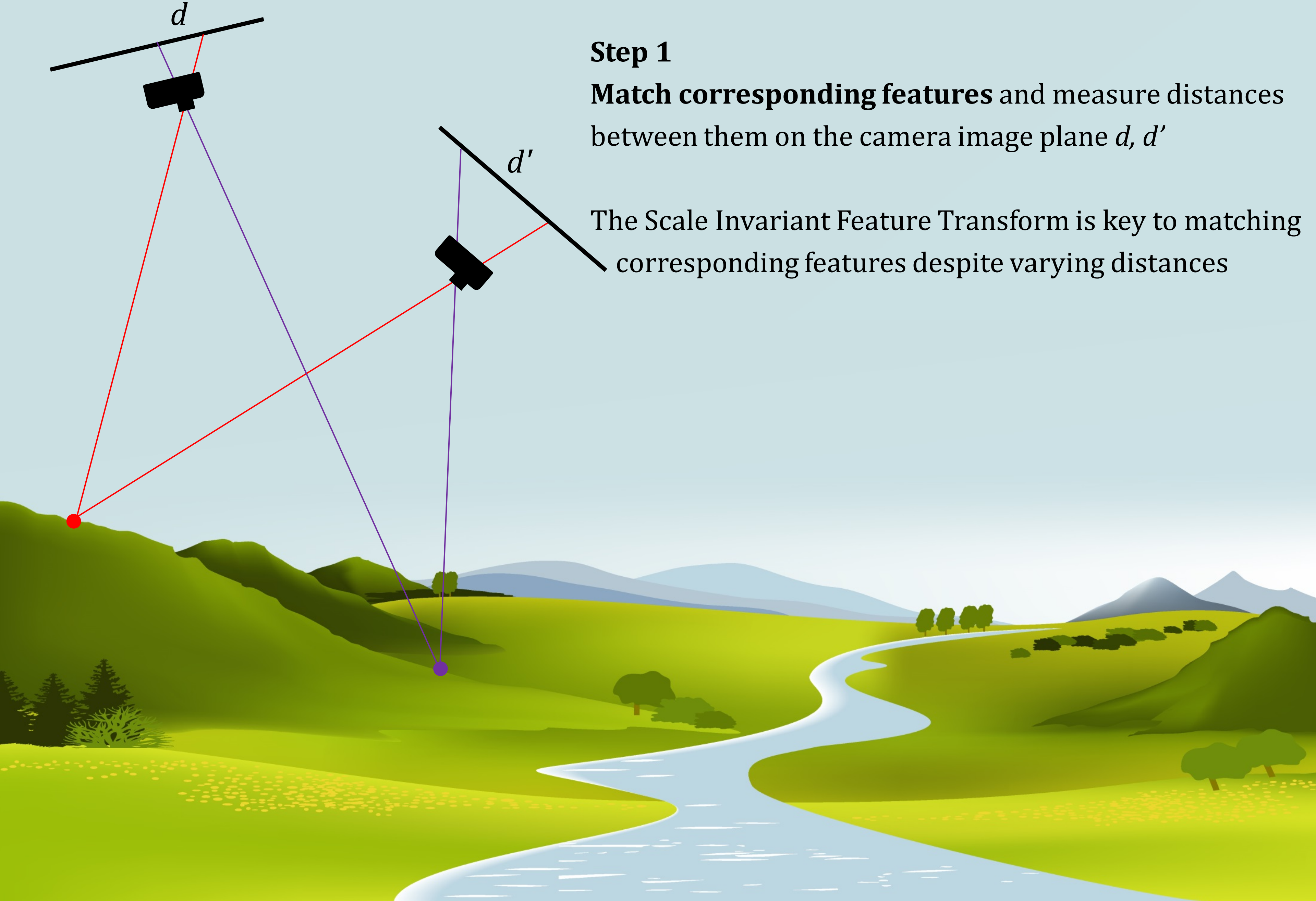
Match corresponding features

Measure distances between features on the camera image plane *d, d'*

Calculate relative positions of features *b, h*



Structure-from-Motion



Step 1

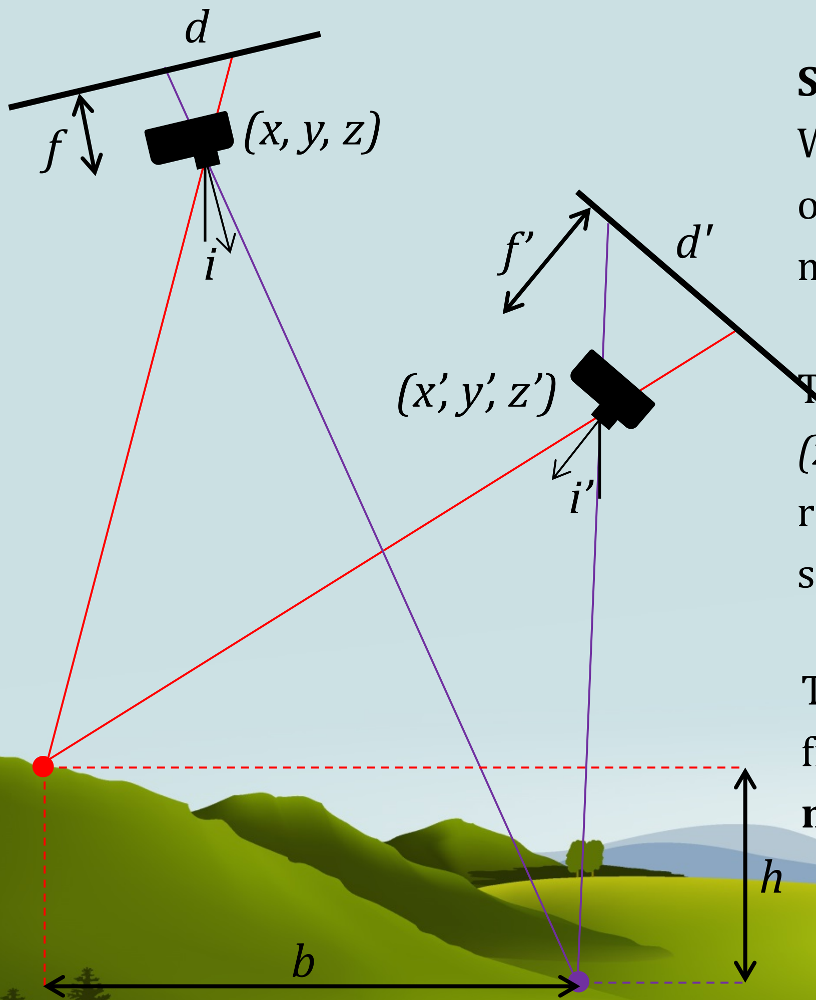
Match corresponding features and measure distances between them on the camera image plane *d, d'*

The Scale Invariant Feature Transform is key to matching corresponding features despite varying distances

Scale Invariant Feature Transform

• SIFT (Lowe, 1999) allows corresponding features to be matched even with large variations in scale and viewpoint and under conditions of partial occlusion and changing illumination

Structure-from-Motion



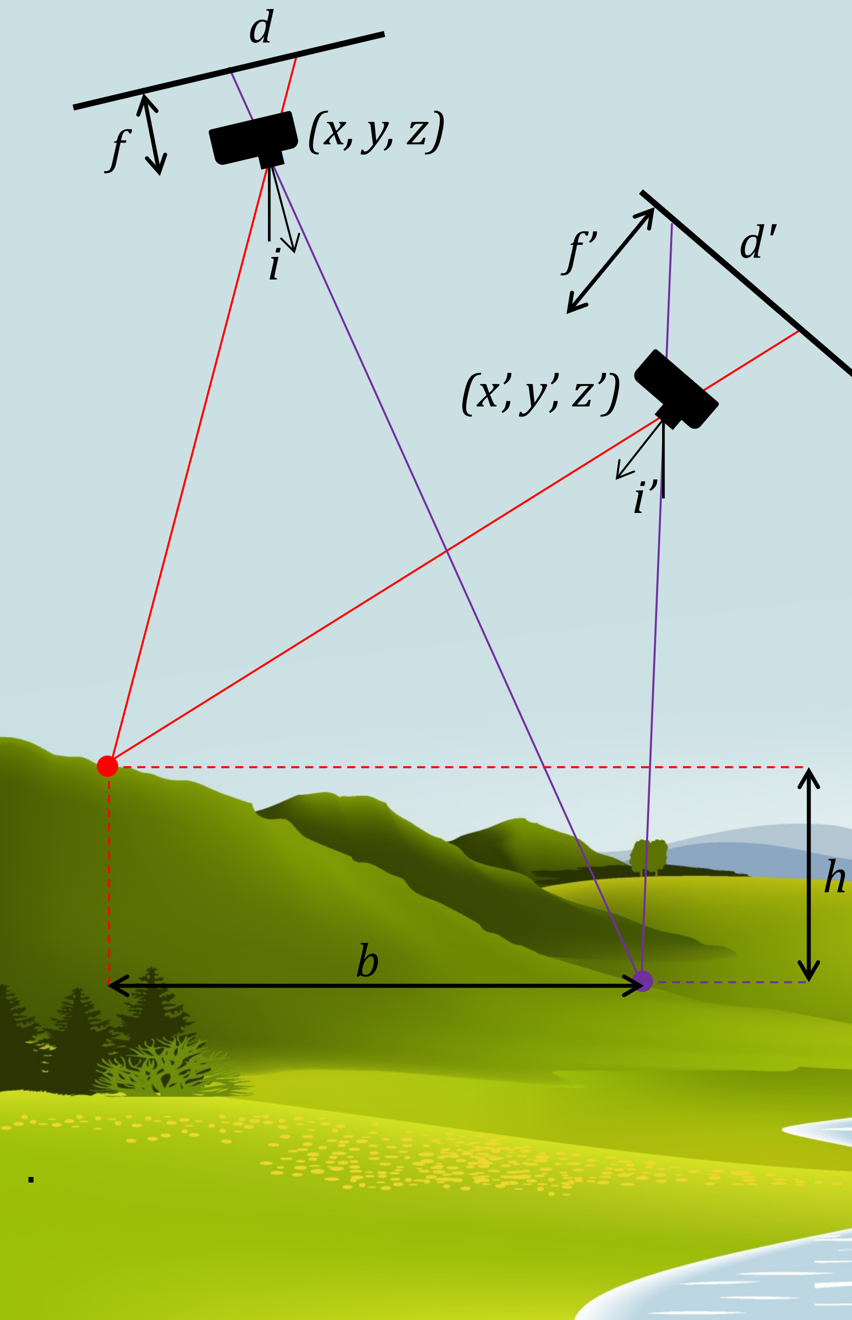
Step 2

When we have the matching locations of multiple points on two or more photos, there is usually just one mathematical solution for where the photos were taken.

Therefore, we can calculate individual camera positions *(x, y, z), (x', y', z')*, orientations *i*, *i'*, focal lengths *f*, *f'*, and relative positions of corresponding features *b, h,* in a single step known as **"bundle adjustment".**

This is where the term Structure from Motion comes from. Scene **structure** refers to all these parameters; **motion** refers to movement of the camera

Structure-from-Motion

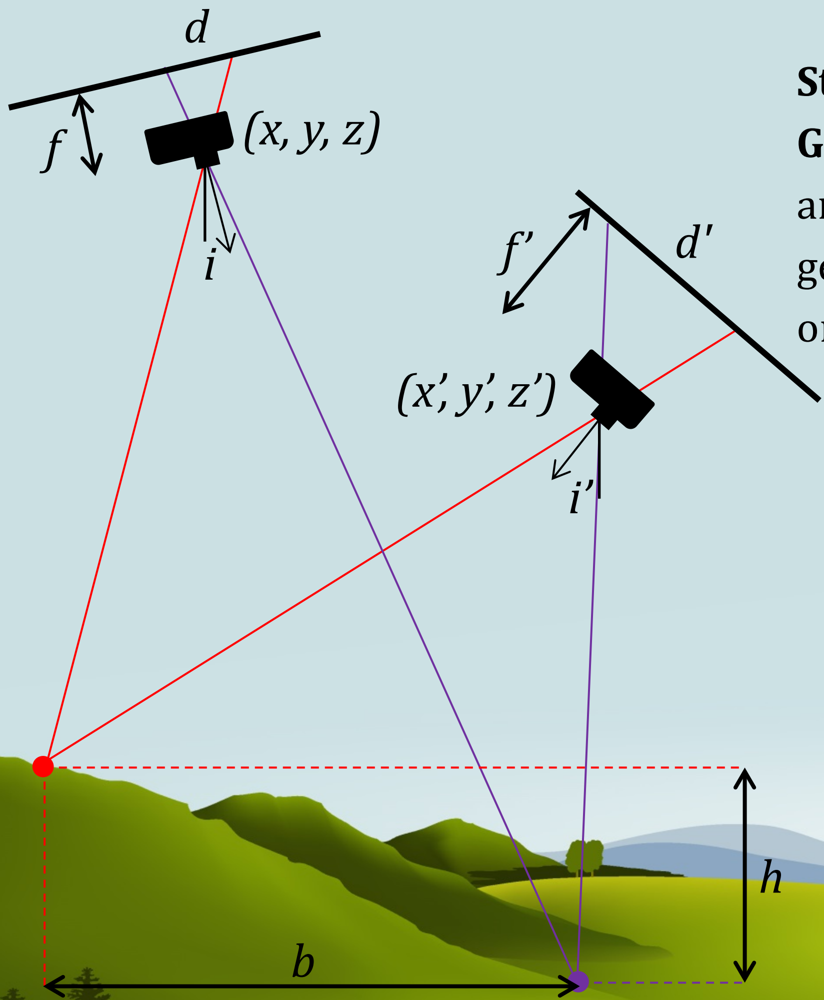


Step 3

Next, a dense point cloud and 3D surface is determined using the known camera parameters and using the SfM points as “ground control”.

All pixels in all images are used so the dense model is similar in resolution to the raw photographs (typically 100s – 1000s point/m^2). This step is called “**multiview stereo matching” (MVS)**

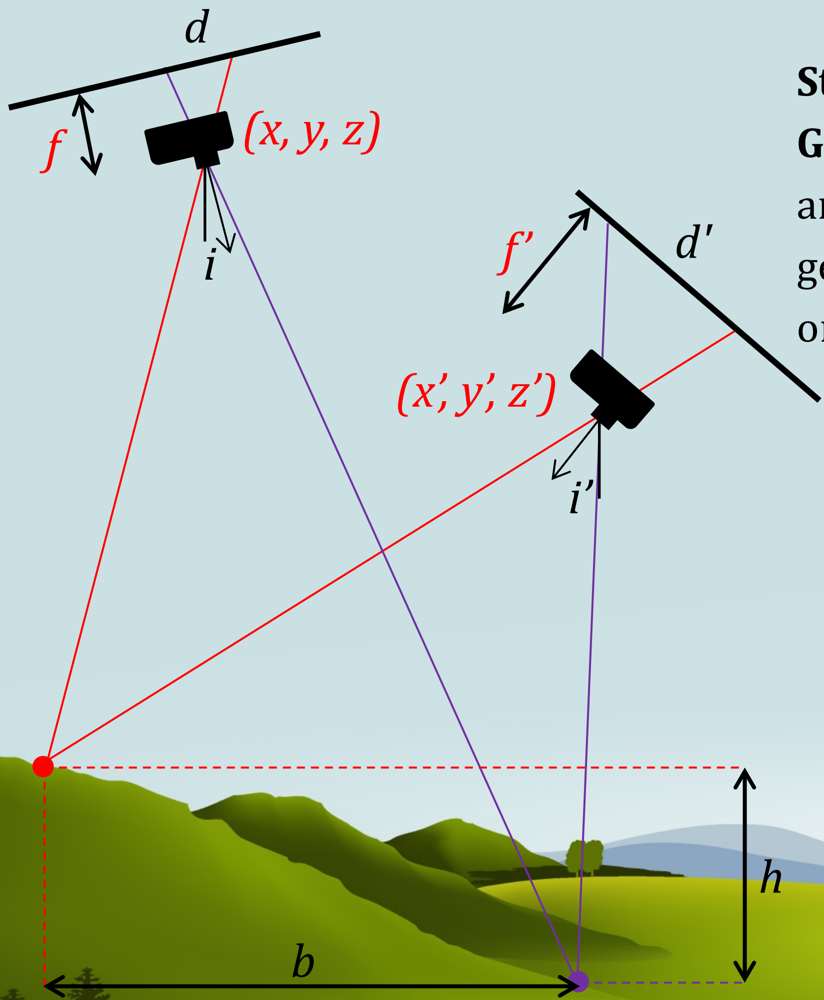
Structure-from-Motion



Step 4

Georectification means converting the point cloud from an internal, arbitrary coordinate system into a geographical coordinate system. This can be achieved in one of two ways:

Structure-from-Motion

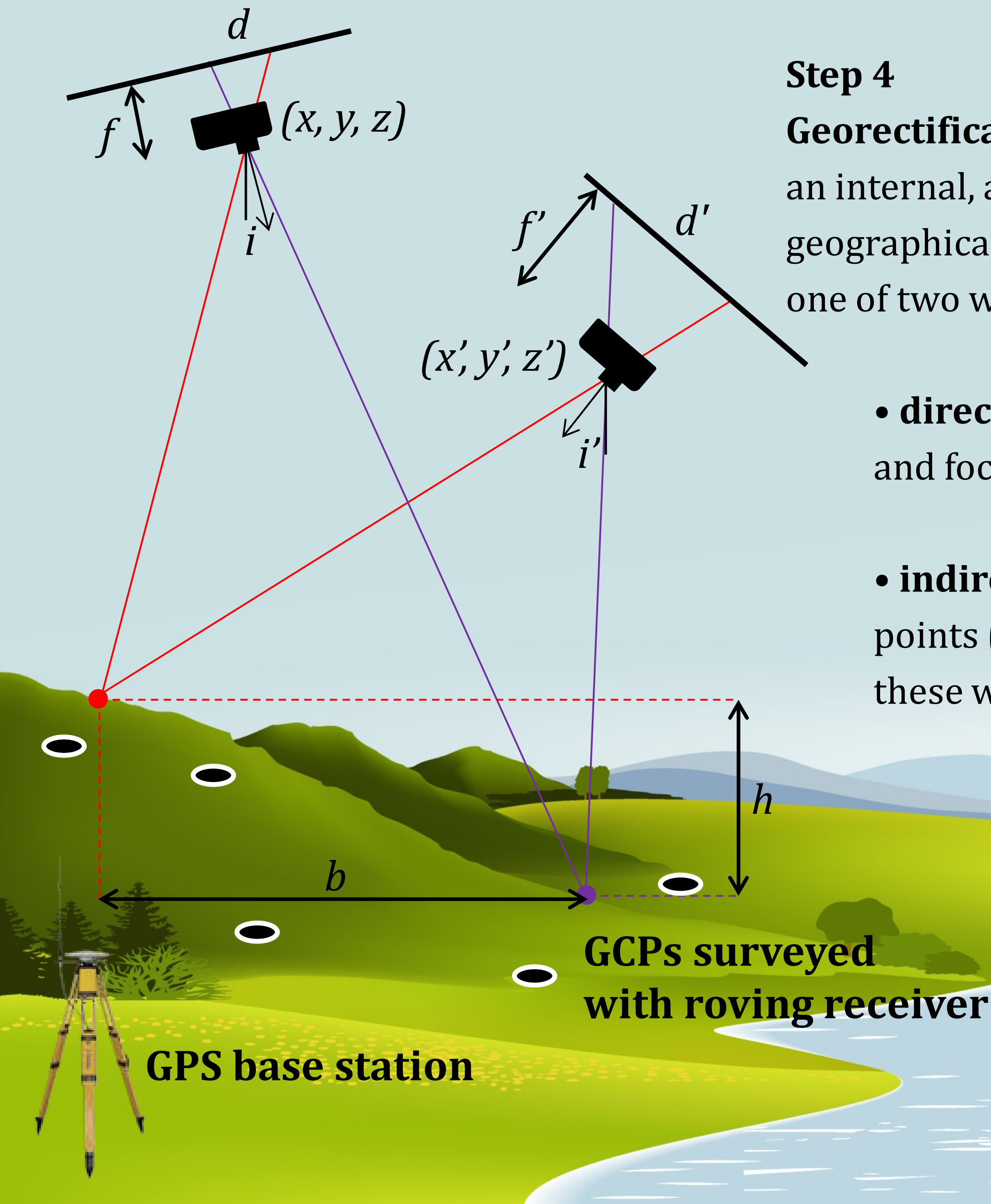


Step 4

Georectification means converting the point cloud from an internal, arbitrary coordinate system into a geographical coordinate system. This can be achieved in one of two ways:

- **directly,** with knowledge of the camera positions and focal lengths

Structure-from-Motion



Step 4

Georectification means converting the point cloud from an internal, arbitrary coordinate system into a geographical coordinate system. This can be achieved in one of two ways:

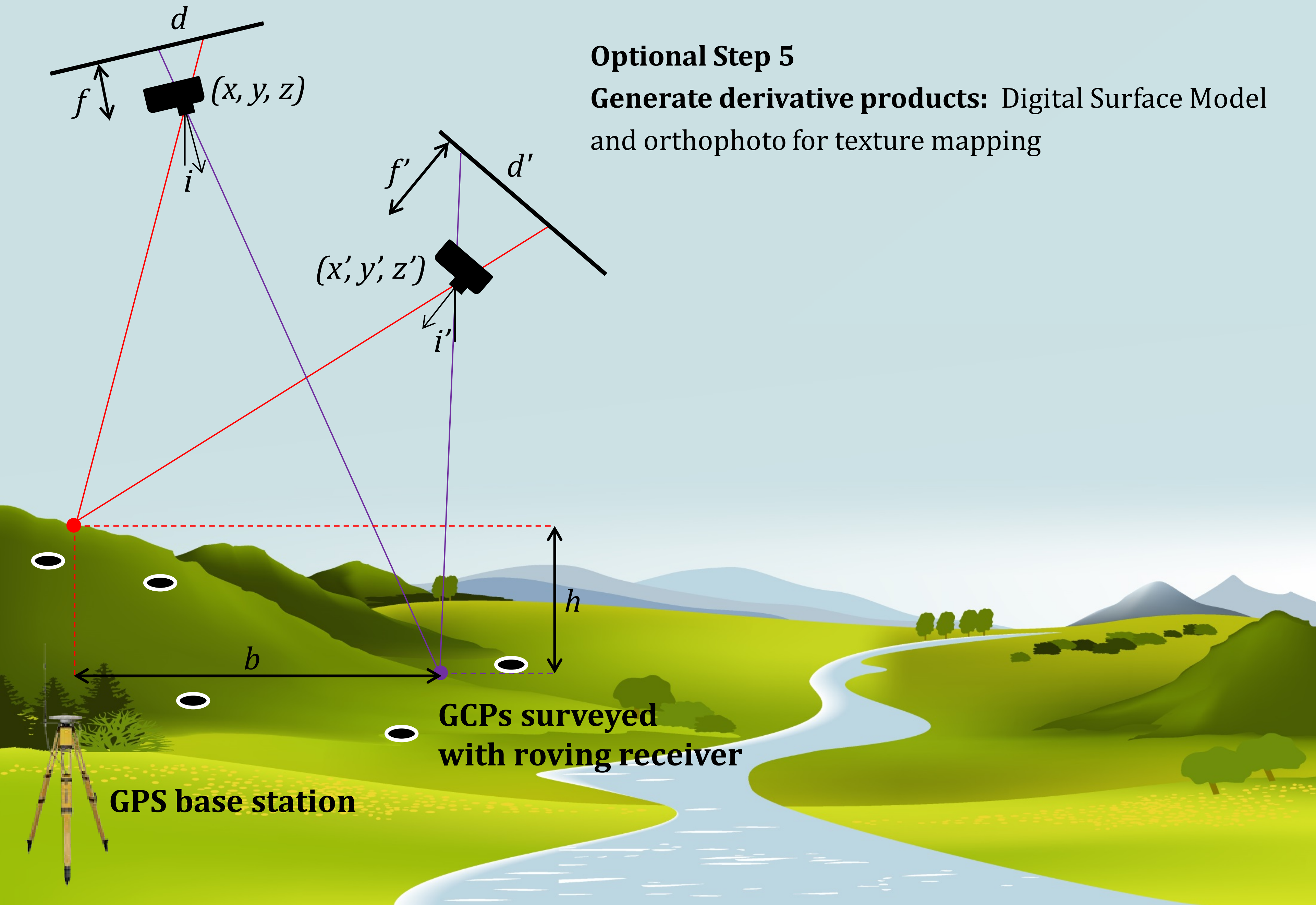
- **directly,** with knowledge of the camera positions and focal lengths

- **indirectly,** by incorporating a few ground control points (GCPs) with known coordinates. Typically these would be surveyed using differential GPS

Structure-from-Motion

Optional Step 5

Generate derivative products: Digital Surface Model and orthophoto for texture mapping



Camera lens distortions

f = focal length

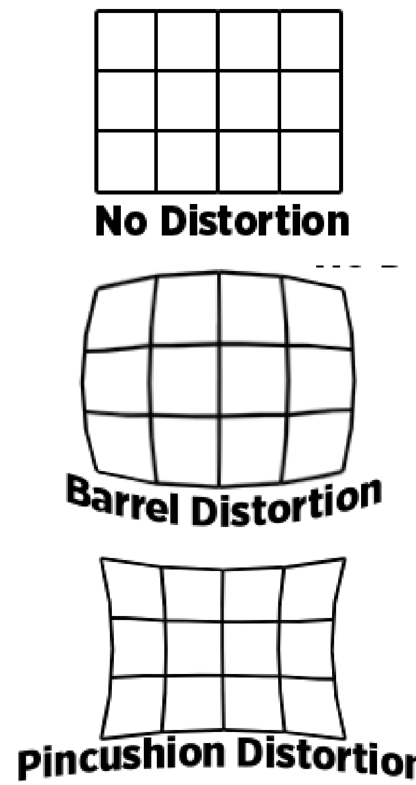
c_x = principal point x coordinate

c_y = principal point y coordinate

k_n = n^{th} radial distortion coefficient

p_n = n^{th} tangential distortion coefficient

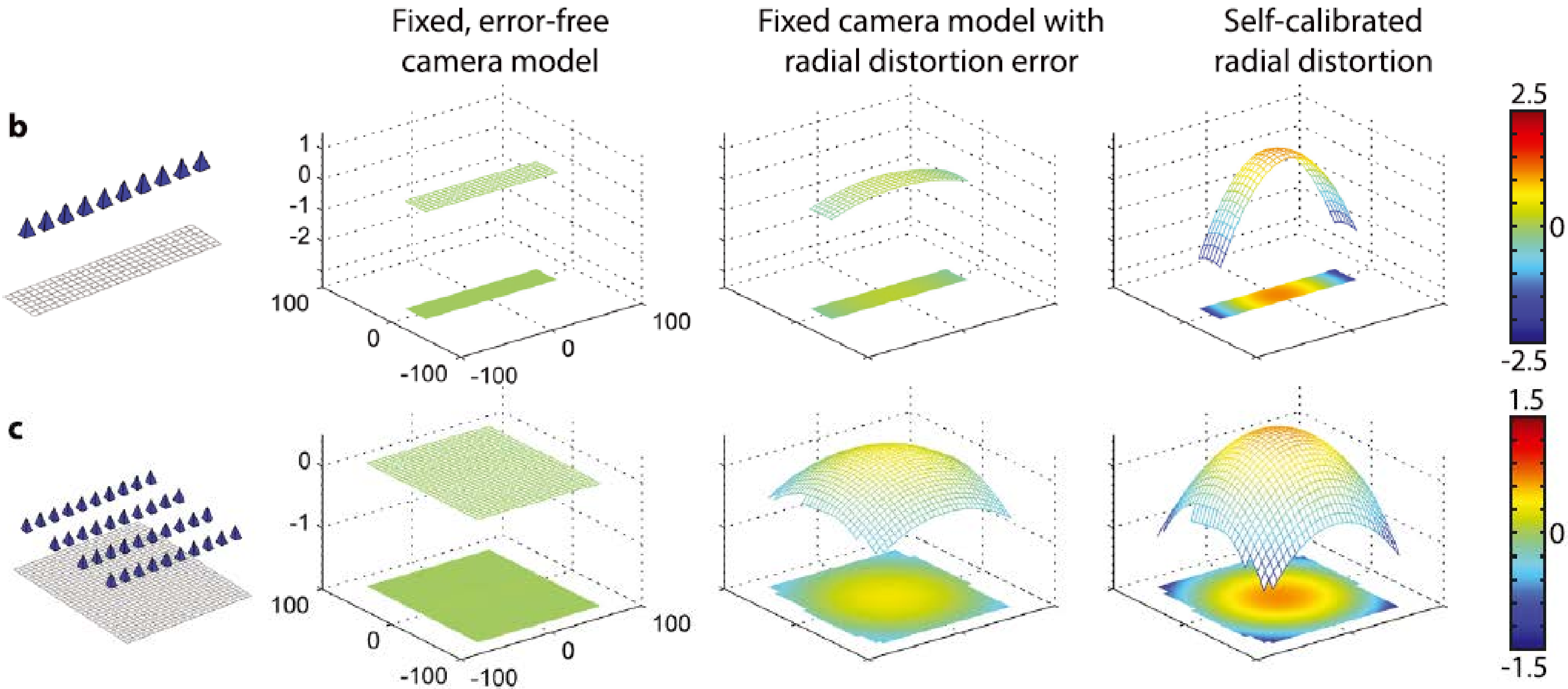
skew coefficient between the x and the y axis.



$k_1 < 1$

$k_1 > 1$

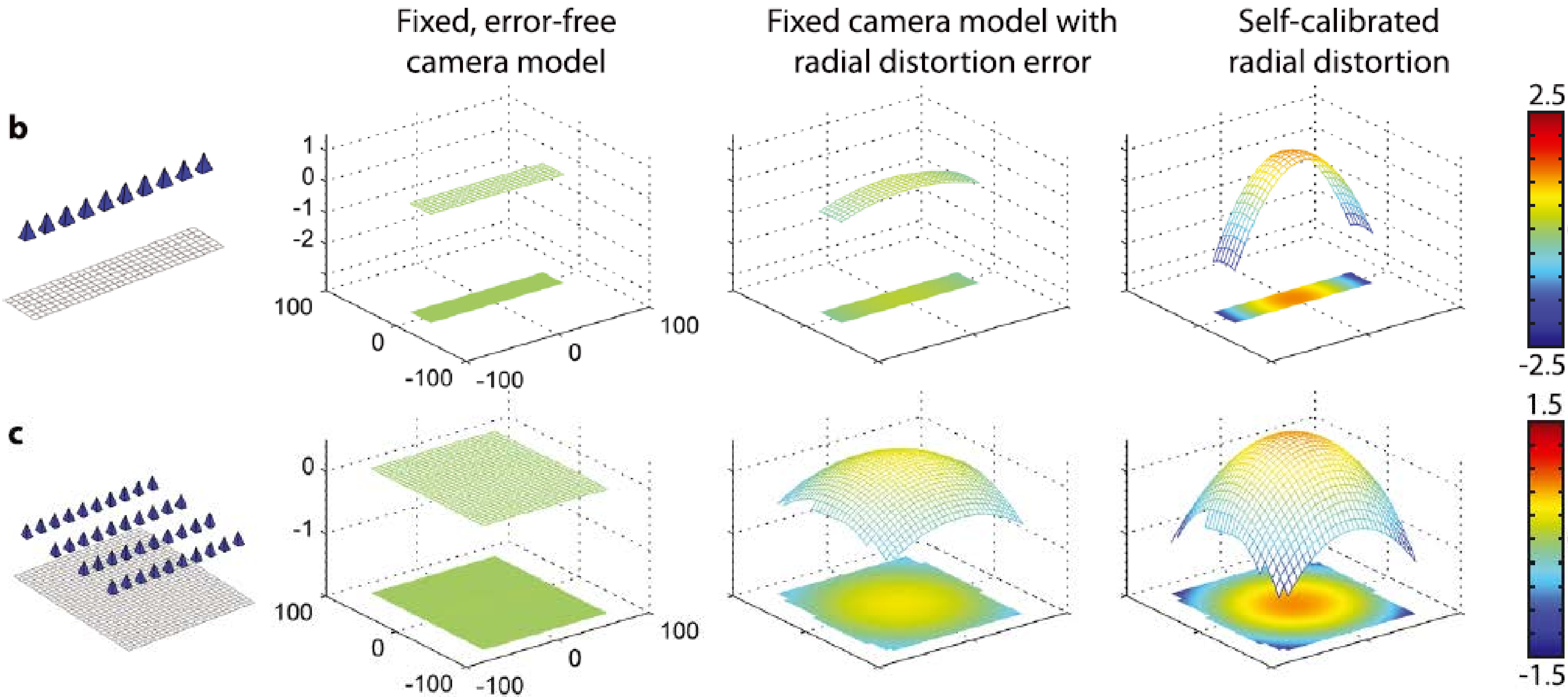
Camera lens distortions



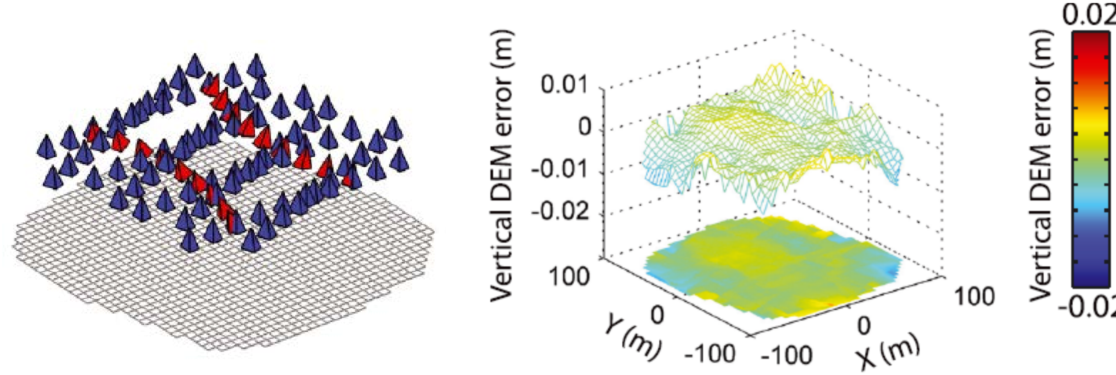
- Trade-off between lens radial distortion term and computed surface form can lead to "doming"

James & Robson (2014), Mitigating systematic error in topographic models derived from UAV and ground-based image networks, *Earth Surface Processes and Landforms*

Camera lens distortions



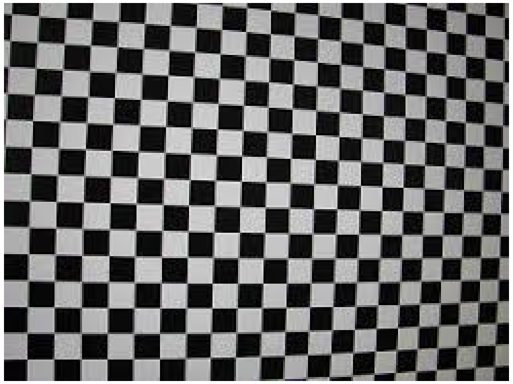
• Doming can be mitigated by incorporating a few oblique camera angles (in red)

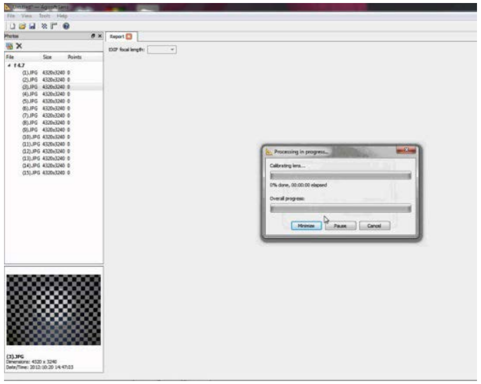


James & Robson (2014), Mitigating systematic error in topographic models derived from UAV and ground-based image networks, *Earth Surface Processes and Landforms*

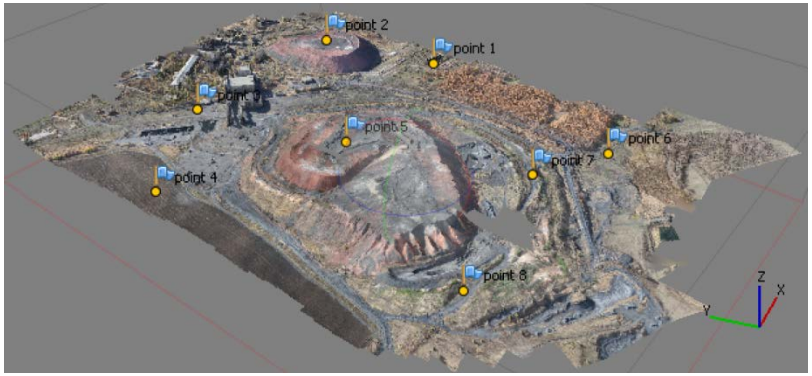
Camera lens distortions

• Doming can be mitigated by calibrating the camera parameters by photographing a calibration target

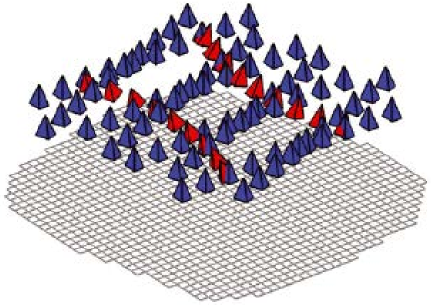


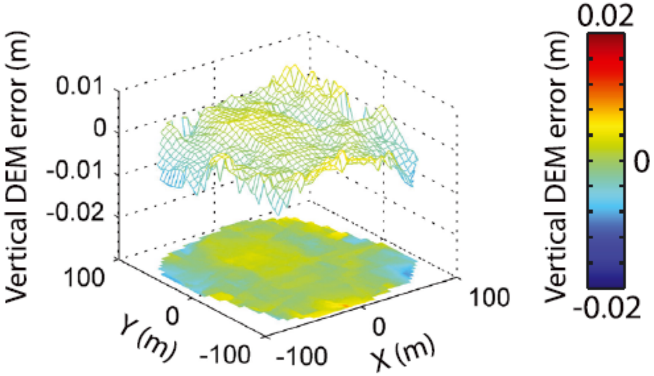


• Doming can be mitigated by georeferencing using ground control points



• Doming can be mitigated by incorporating a few oblique camera angles (in red)





Traditional stereo-photogrammetry

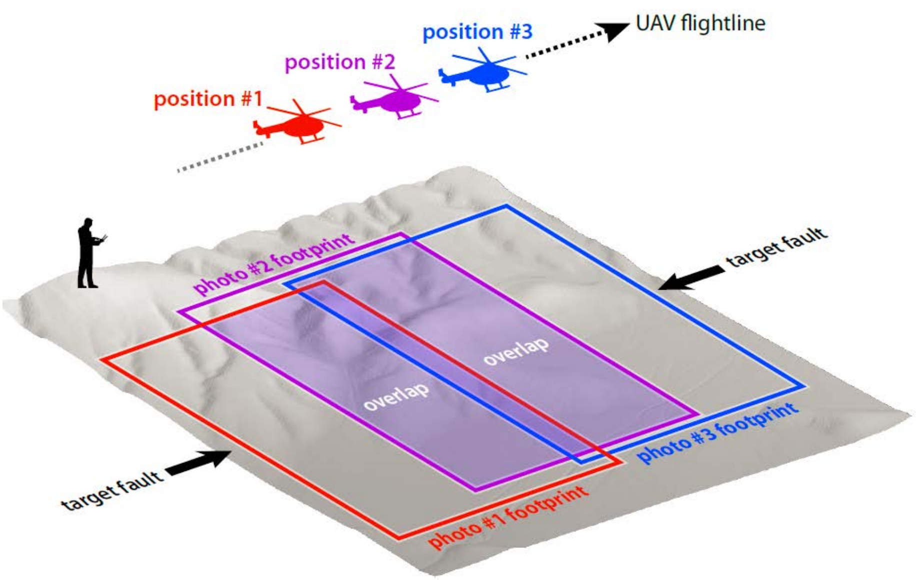
• Requires a stable platform such as a satellite or aeroplane at a fixed elevation

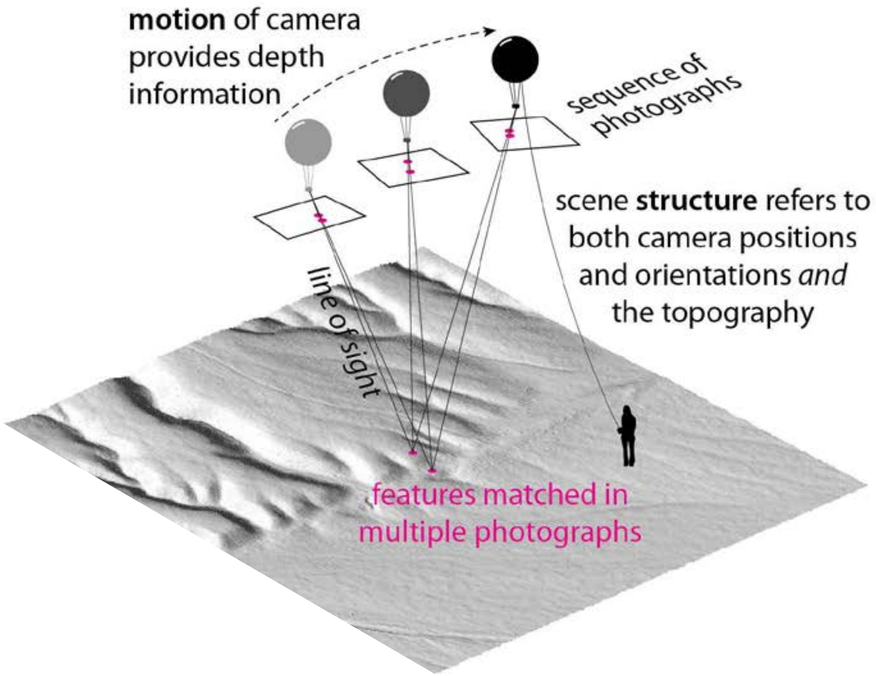
• Photographs collected at known positions with fixed orientations and incidence angles

Structure-from-Motion

• Photos from many angles and distances can be used, with no *a priori* knowledge of locations or pose

• Enables “unstructured” image acquisition from the ground, legacy air-photosets, or unmanned platforms



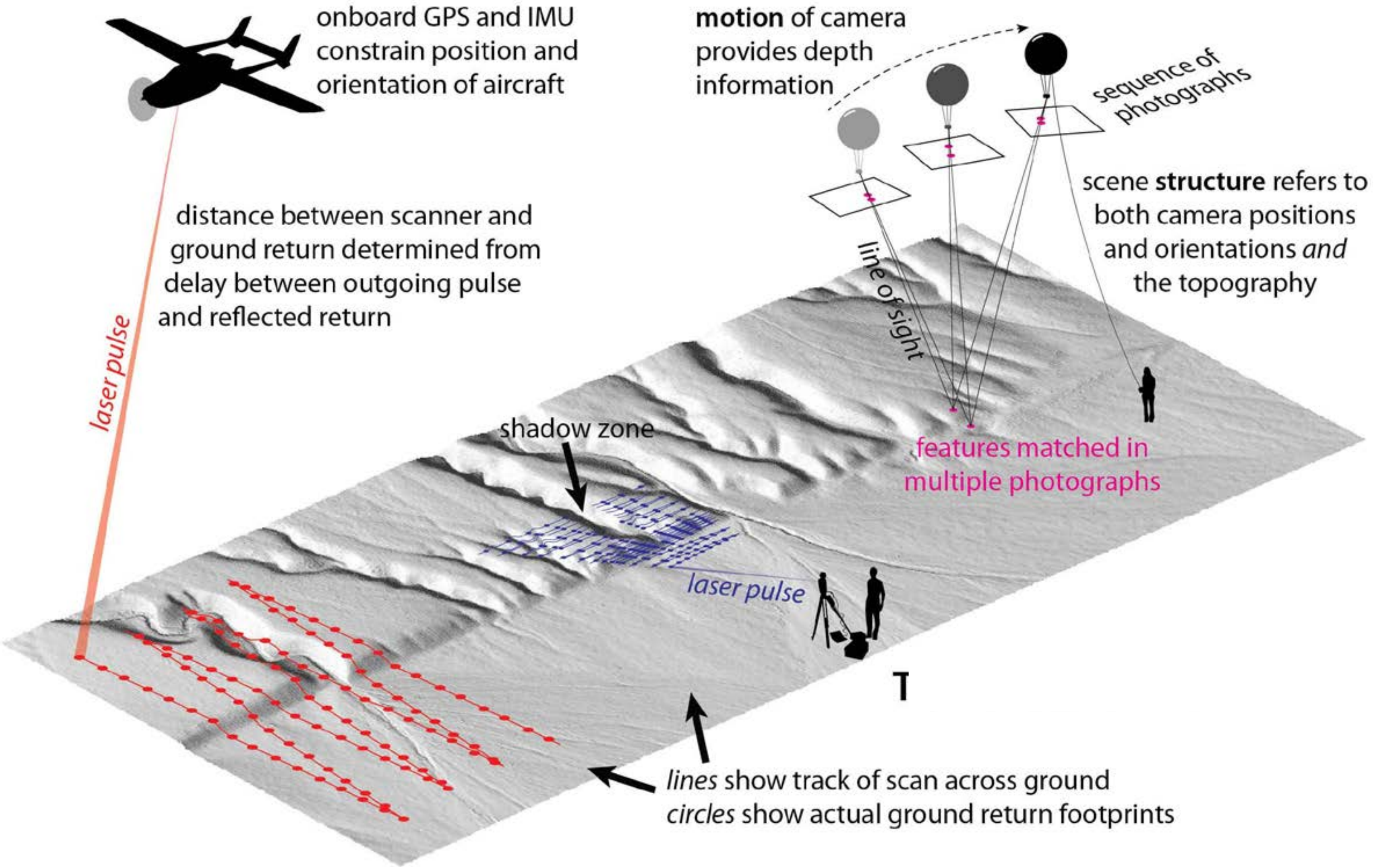


Lidar (ALS, TLS, MLS)

- Expensive laser equipment required
- Works in densely-vegetated landscapes
- Uses precise time-of-flight measurements but prone to artifacts from GPS and IMU

Structure-from-Motion

- Requires only a cheap camera
- Coloured points & orthophoto for texture mapping
- Back-solves for camera parameters; warping artifacts are a common problem but easily mitigated

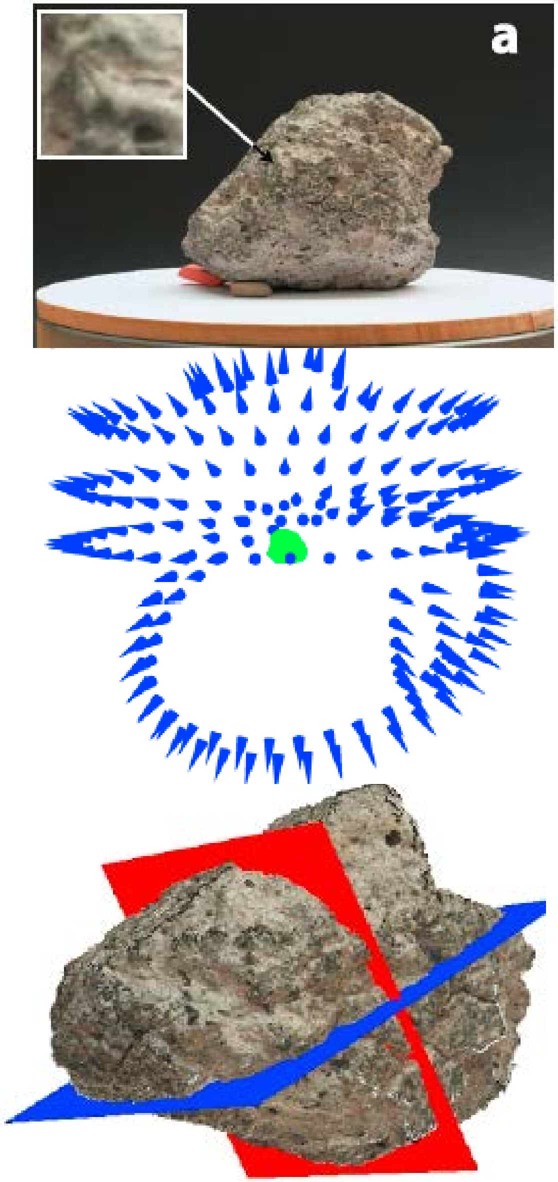


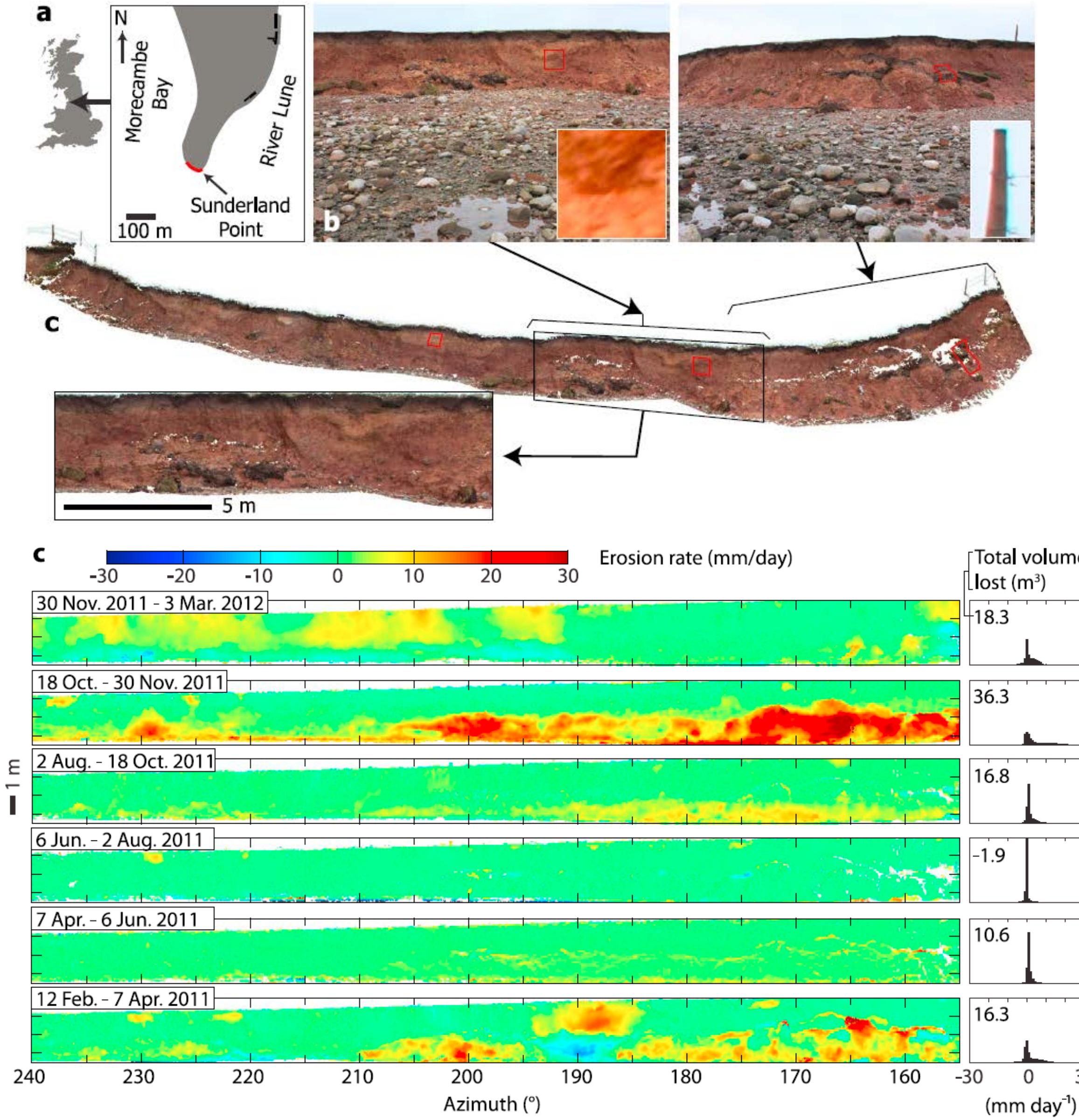
Where it all started…

Snavely *et al.* (2006). Photo Tourism: Exploring Photo Collections in 3D, *ACM Transactions on Graphics*

Snavely *et al.* (2007). Modeling the World from Internet Photo Collections, *International Journal of Computer Vision*

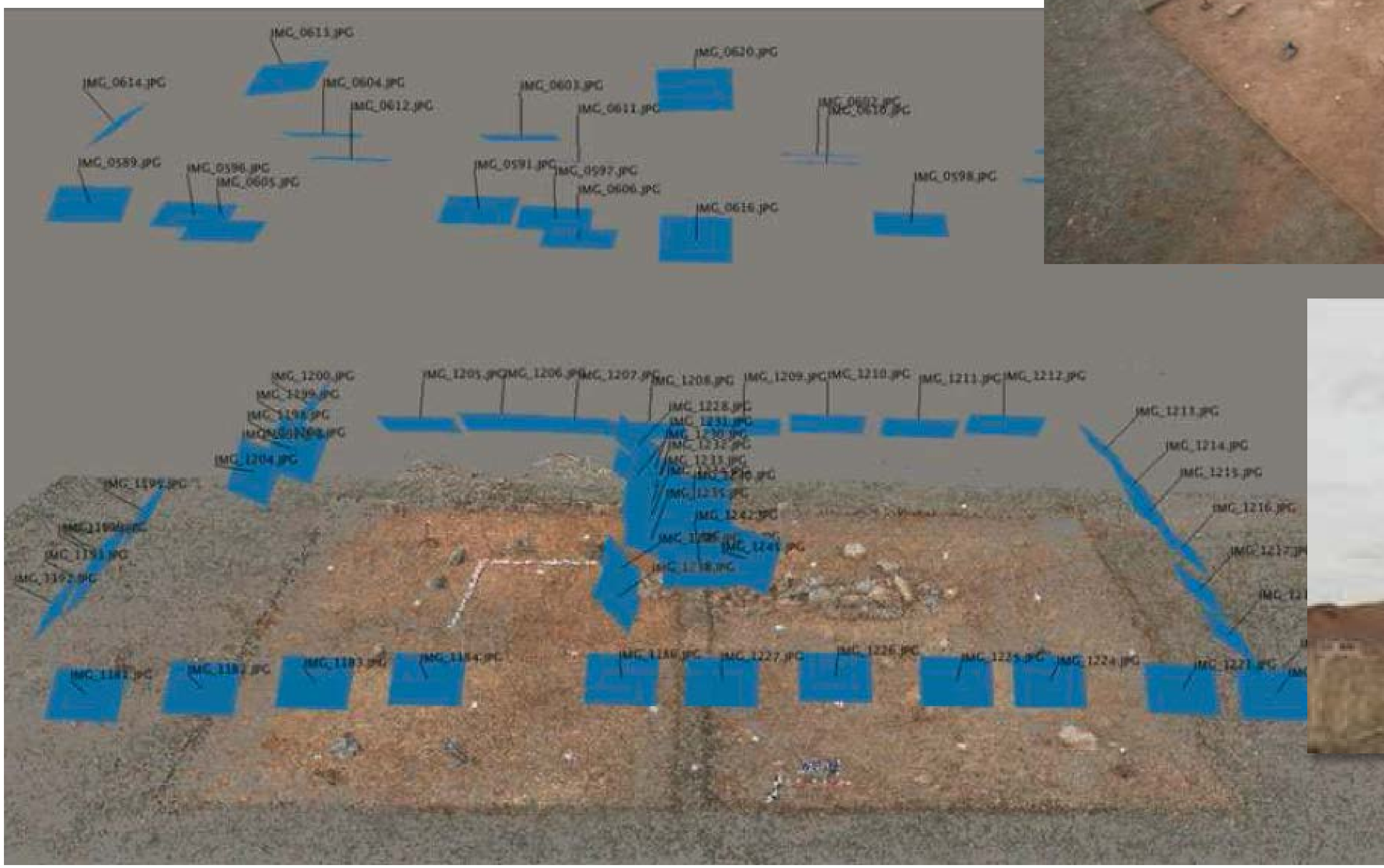
Ground-based SfM





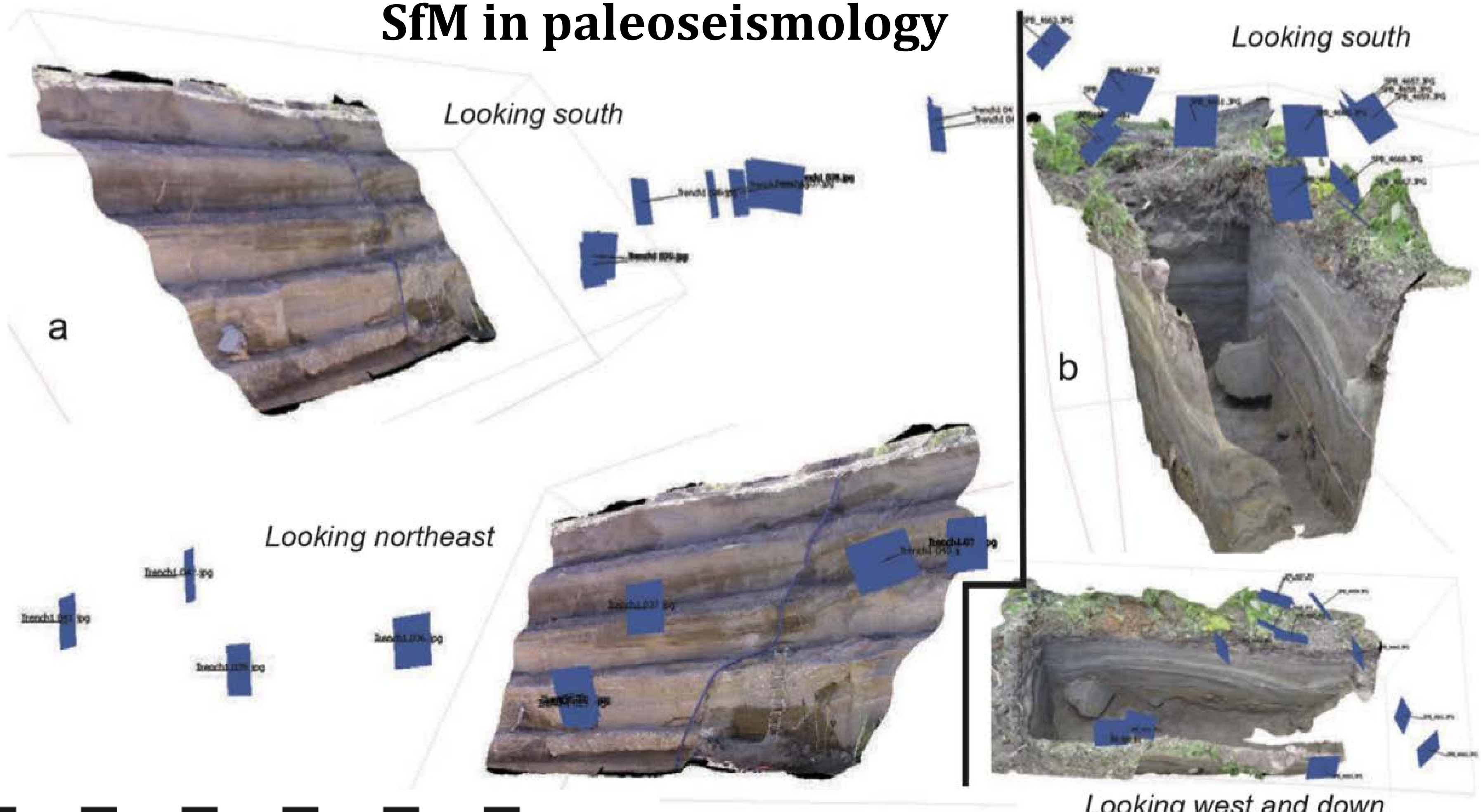
James & Robson (2012). Straightforward reconstruction of 3D surfaces and topography with a camera: Accuracy and geoscience application. *Journal of Geophysical Research*

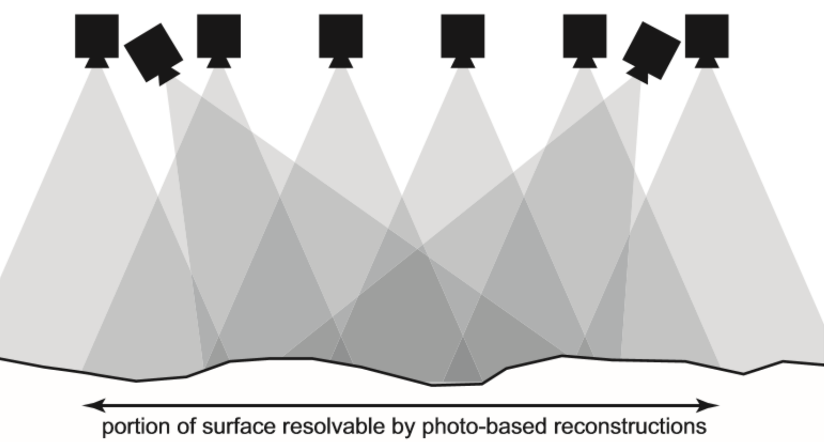
Ground-based SfM



Plets *et al.* (2012). Three-dimensional recording of archaeological remains in the Altai mountains, *Cambridge Univ. Press*

SfM in paleoseismology





Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

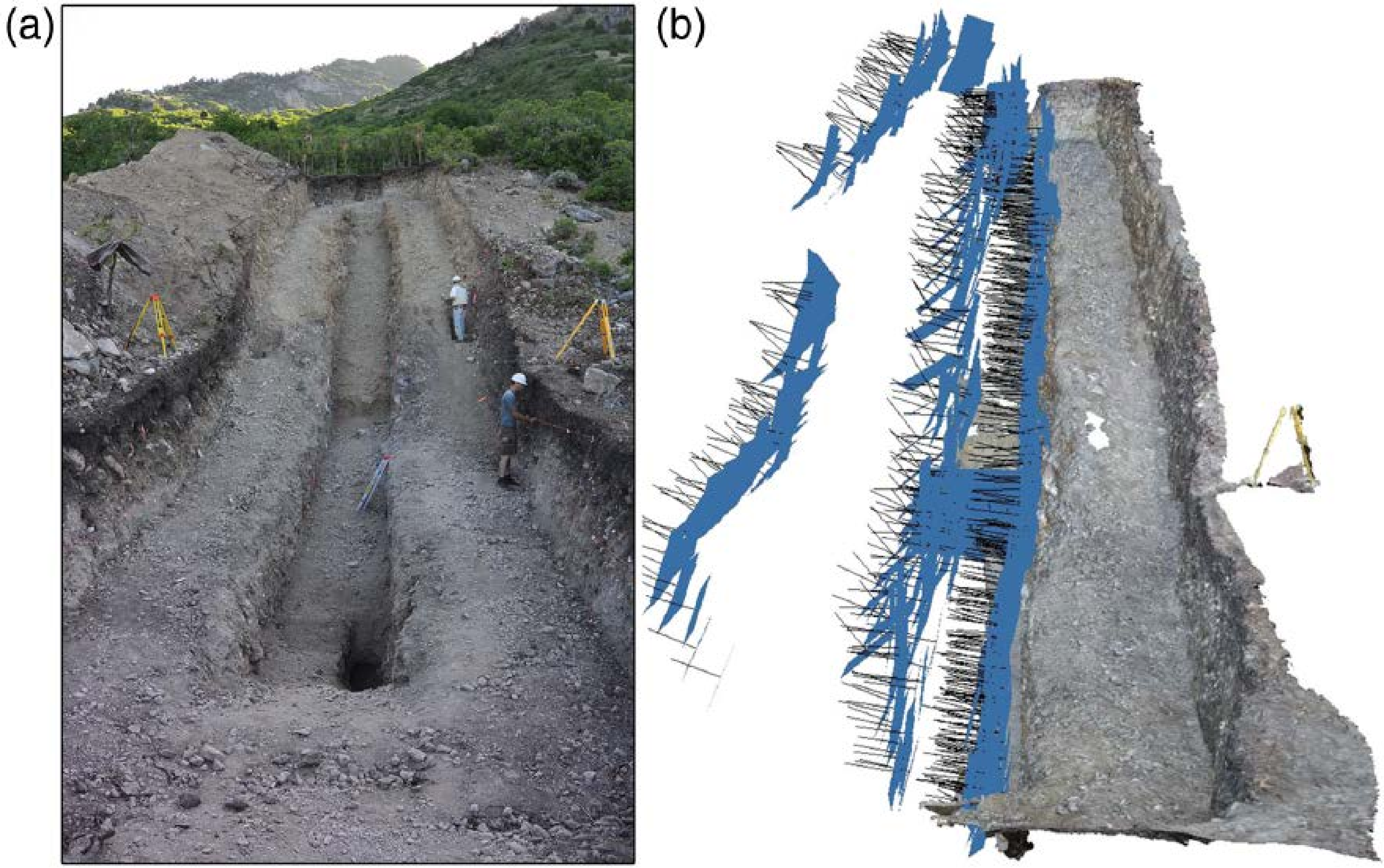
ELSEVIER

Review article

Ground-based and UAV-Based photogrammetry: A multi-scale, high-resolution mapping tool for structural geology and paleoseismology

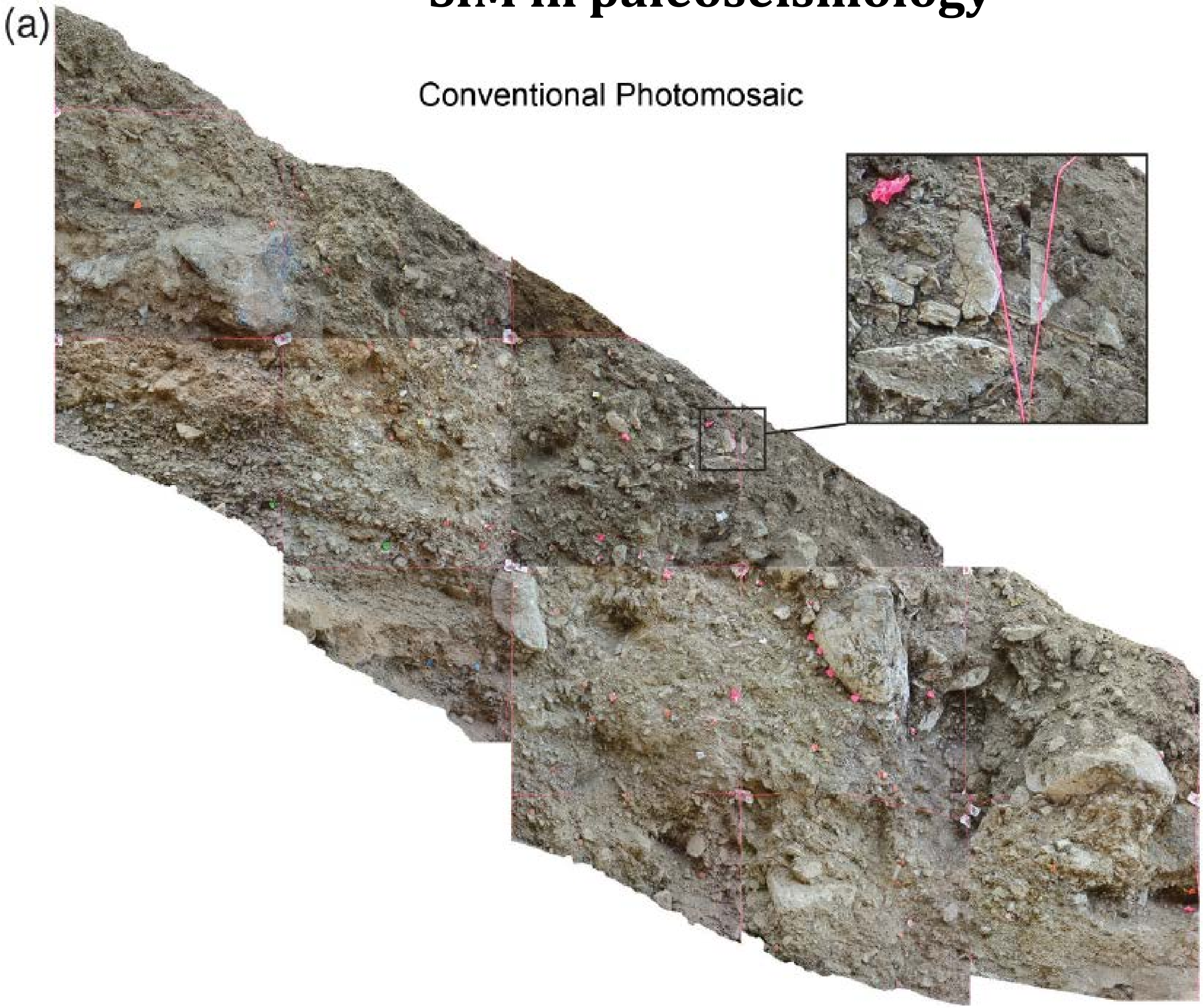
Sean P. Bemis [a, *], Steven Micklethwaite [b], Darren Turner [c], Mike R. James [d], Sinan Akciz [e], Sam T. Thiele [b], Hasnain Ali Bangash [b]

SfM in paleoseismology



Reitman *et al.* (2015), High-Resolution Trench Photomosaics from Image-Based Modeling: Workflow and Error Analysis, *Bulletin of the Seismological Society of America*

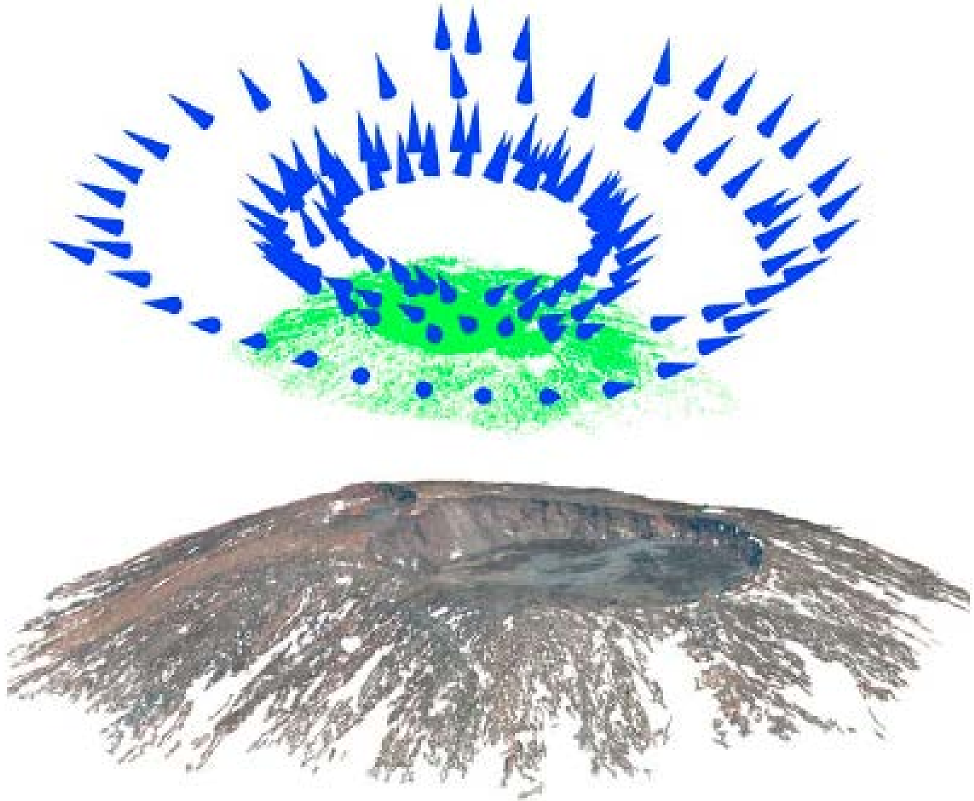
SfM in paleoseismology

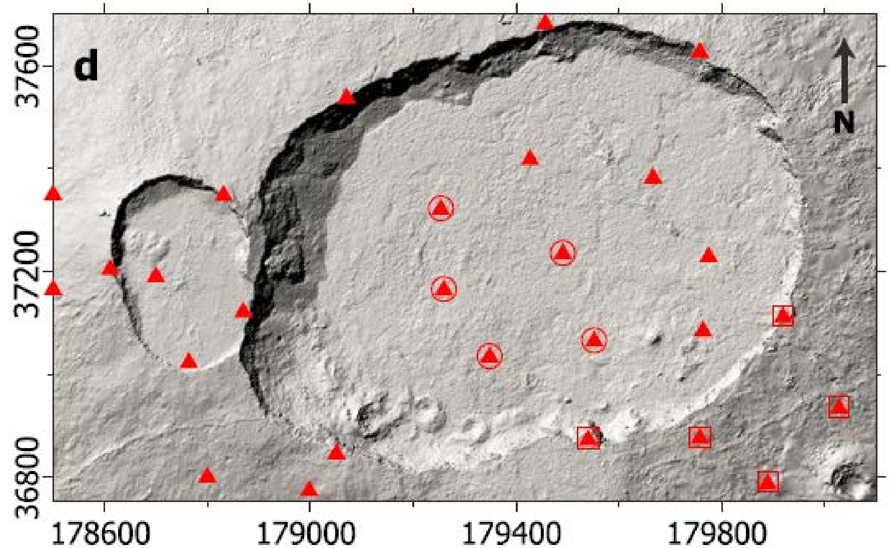


Reitman *et al.* (2015), High-Resolution Trench Photomosaics from Image-Based Modeling: Workflow and Error Analysis, *Bulletin of the Seismological Society of America*

Airborne SfM

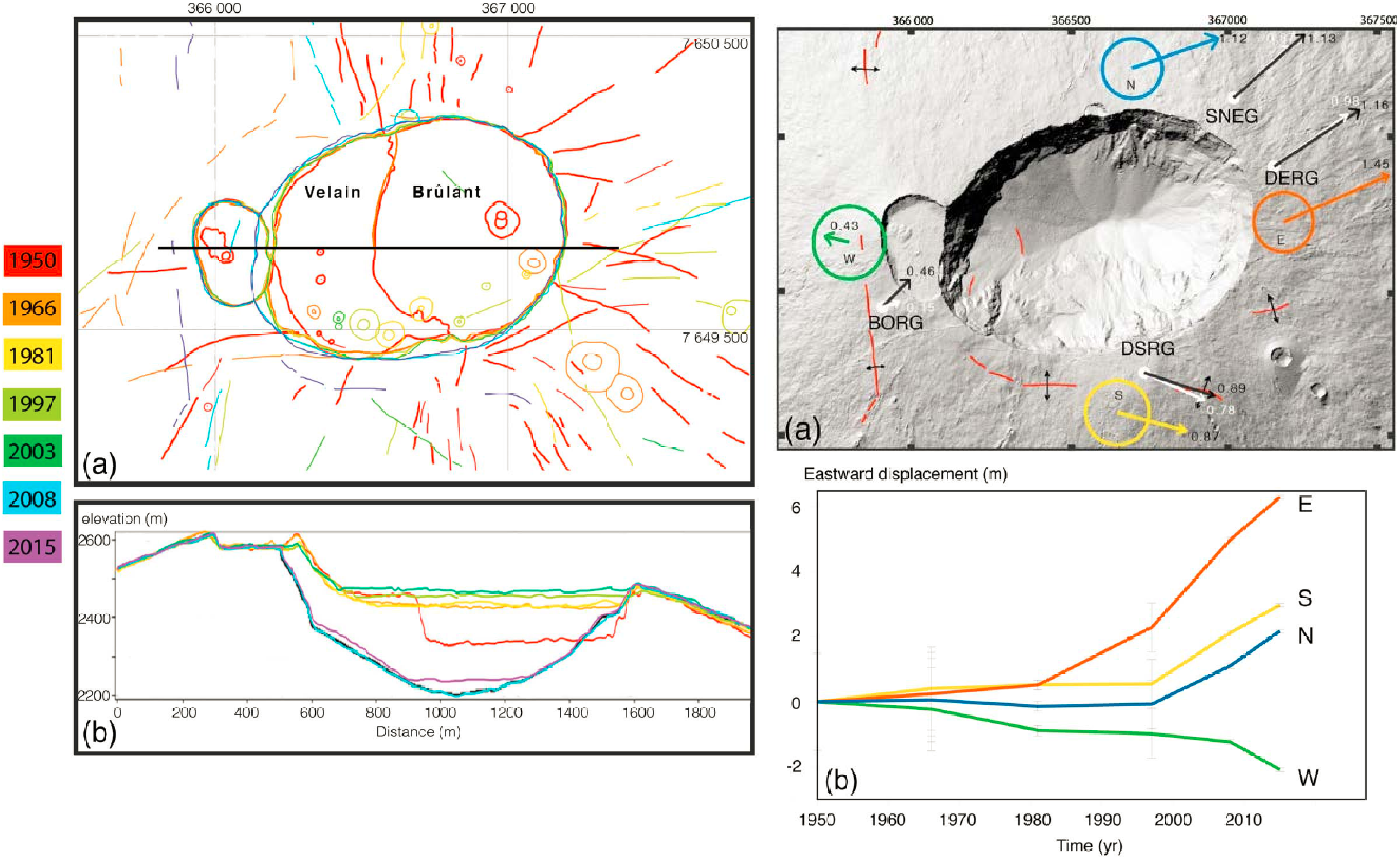
Summit crater, Piton de la Fournaise, La Réunion Island
~2 pts/m^2 point cloud using ~100 photos from a micro-light





James & Robson (2012). Straightforward reconstruction of 3D surfaces and topography with a camera: Accuracy and geoscience application. *Journal of Geophysical Research*

Airborne SfM



Derrien *et al.* (2015). Retrieving 65 years of volcano summit deformation from multitemporal structure from motion: The case of Piton de la Fournaise (La Réunion Island). *Geophys. Res. Lett.*

SfM from Unmanned Aerial Vehicles (UAV)

DJI Phantom 2 quadcopter (~$1k)

Custom built helicopter (~$15k)

Autokite (~$1k, discontinued)

Falcon Unmanned fixed wing (~$12k)

SfM from Unmanned Aerial Systems (UAS)

Allsopp helikite (~$2k)

Brooxes picavet (<$100)

Ramon's balloon (~$100s)

SfM from Unmanned Aerial Systems (UAS)

Pros Once in the air, can follow pre-set flight path. Robust in high wind and can take off and land anywhere. Can carry large SLR camera. Expensive.

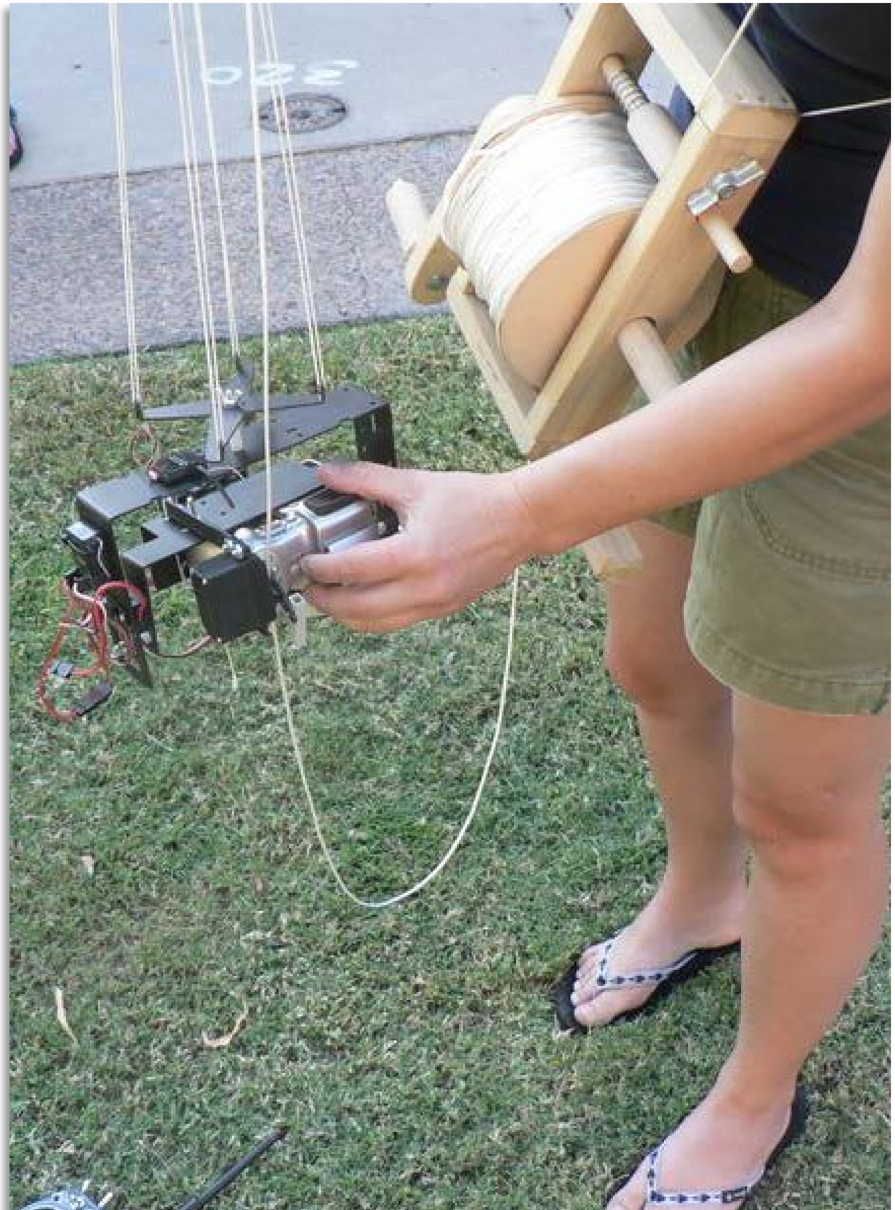
Cons Needs trained pilot to take-off and land and regular refuelling. Initial costs are high and requires careful maintenance. Regulations may need to be followed (FAA in the U.S.)

SfM from Unmanned Aerial Systems (UAS)

Pros Easy to self- launch and to pilot. Can cope in moderate winds. Very cheap!

Cons Can only carry small cameras and is susceptible to damage during landing. Batteries need frequent replacing/recharging.

SfM from Unmanned Aerial Systems (UAS)



Pros Easy to drag across target area. Once in the air can remain there. Can carry large SLR cameras. No FAA regulations!

Cons Requires helium, which can be expensive (>$100 per canister), and fiddly picavet. Cannot be automated. Difficult to deploy in windy conditions.

SfM from Unmanned Aerial Systems (UAS)

Pros Easy to drag across target area. Once in the air can remain there. Robust in high wind. No FAA regulations!

Cons Requires helium, which can be expensive (>$100 per canister). Cannot be automated. Carries small cameras.

SfM from Unmanned Aerial Systems (UAS)

The camera should have one essential feature and one preferable one:

Essential Time lapse setting – remotely takes photo every *x* seconds

Preferable Internal or external GPS tagging

Cheap, lightweight cameras can be used but lower-quality lenses can lead to large radial distortions in the photographs.

These can lead to warping of the topography unless they are dealt with.

SfM & MVS software

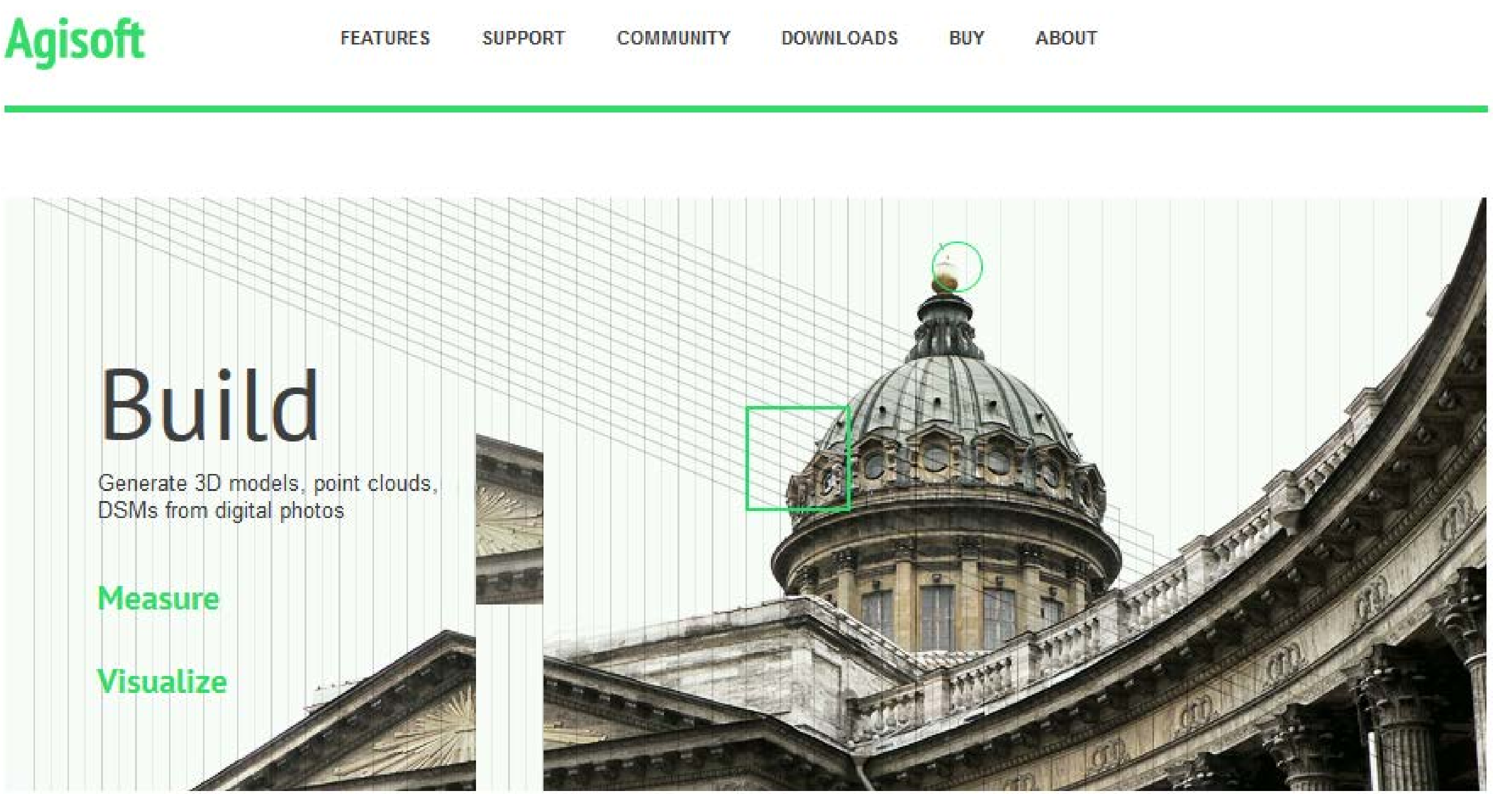
Table 1
Examples of open source and commercial software for photo-based 3d reconstruction.

Software	Url (valid on 17 May, 2014)	Notes
Freely available		
Bundler Photogrammetry Package[a,b]	http://blog.neonascent.net/archives/bundler-photogrammetry-package/	Used in James and Robson (2012). Script-based, no graphical user interface (GUI). Windows OS only.
SFMToolkit[a,b]	http://www.visual-experiments.com/demos/sfmtoolkit/	Similar software to above.
Python Photogrammetry Toolbox (PPT)[a,b]	http://code.google.com/p/osm-bundler/	Formerly OSM-bundler. Python-driven GUI and scripts, with a Linux distribution.
VisualSFM[b]	http://www.cs.washington.edu/homes/ccwu/vsfm/	Advanced GUI with Windows, Linux and Mac. OSX versions. Georeferencing options, but camera model is more restricted than that used in Bundler.
3DF Samantha	http://www.3dflow.net/technology/samantha-structure-from-motion/	SfM only, but with more advanced camera models than all above (Farenzena et al., 2009). Provides output compatible with several dense matching algorithms.
Web sites and services		
Photosynth	http://photosynth.net/	Evolved from Bundler. SfM only, no dense reconstruction. Can incorporate a very wide variety of images, but does so at the cost of reconstruction accuracy.
Arc3D	http://www.arc3d.be/	Vergauwen and Van Gool [2006]
CMP SfM Web service[a]	http://ptak.felk.cvut.cz/sfmservice/	
Autodesk 123D Catch	http://www.123dapp.com/catch/	
Pix4D	http://pix4d.com/	Also available as standalone software.
My3DScanner	http://www.my3dscanner.com/	
Commercial		
PhotoScan	http://www.agisoft.ru/products/photoscan/	Full SfM-MVS-based commercial package.
Acute3D	http://www.acute3d.com/	
PhotoModeler	http://www.photomodeler.com/	Software, originally based on close-range photogrammetry, now also implements SfM.
3DF Zephyr Pro	http://www.3dflow.net/	Underlying SfM engine is 3DF Samantha

Note: Table modified from http://www.lancaster.ac.uk/staff/jamesm/research/sfm.htm.
SfM = Structure from Motion; MVS = Multi-View Stereo.
[a] Uses Bundler (http://phototour.cs.washington.edu/bundler/) to compute structure from motion.
[b] Uses PMVS2 (http://grail.cs.washington.edu/software/pmvs/) as a dense multi-view matcher.

Bemis *et al.* (2014). Ground-based and UAV-Based photogrammetry: A multi-scale, high resolution mapping tool for structural geology and paleoseismology. *Journal of Structural Geology*

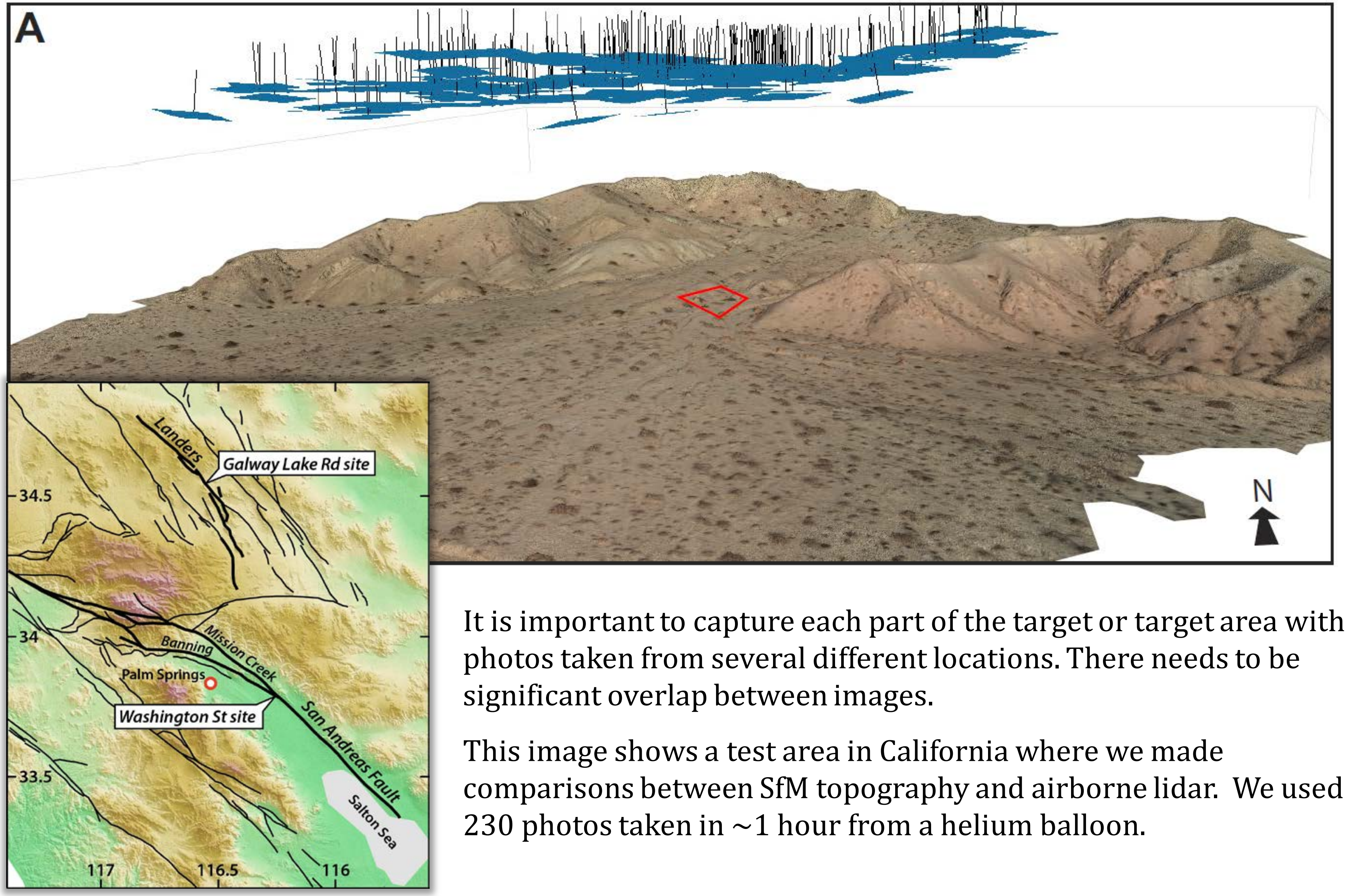
SfM & MVS software



Agisoft Photoscan Pro: $549 for an academic licence.

- Workflow includes *both* SfM *and* MVS, and builds DSM and orthophoto
- Intuitive graphical user interface (GUI)
- Data are georeferenced automatically if camera GPS stamps are available
- Camera calibration with Agisoft Lens
- Vertically-oriented orthophoto possible for trenching (see Reitman *et al.,* 2015, *BSSA*)

Resolution and precision of SfM topography



It is important to capture each part of the target or target area with photos taken from several different locations. There needs to be significant overlap between images.

This image shows a test area in California where we made comparisons between SfM topography and airborne lidar. We used 230 photos taken in ~1 hour from a helium balloon.

Johnson *et al.* (2014), Rapid mapping of ultrafine fault zone topography with structure from motion, *Geosphere*

Resolution and precision of SfM topography

Orthophoto

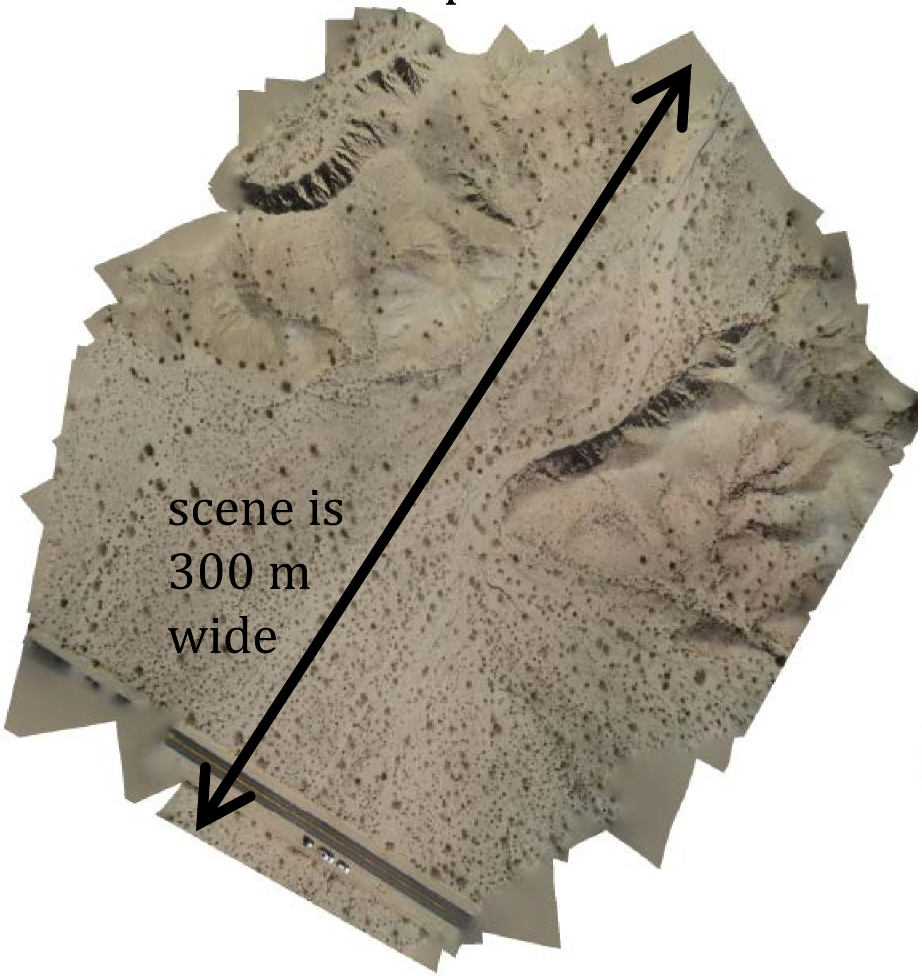


Photo coverage plot

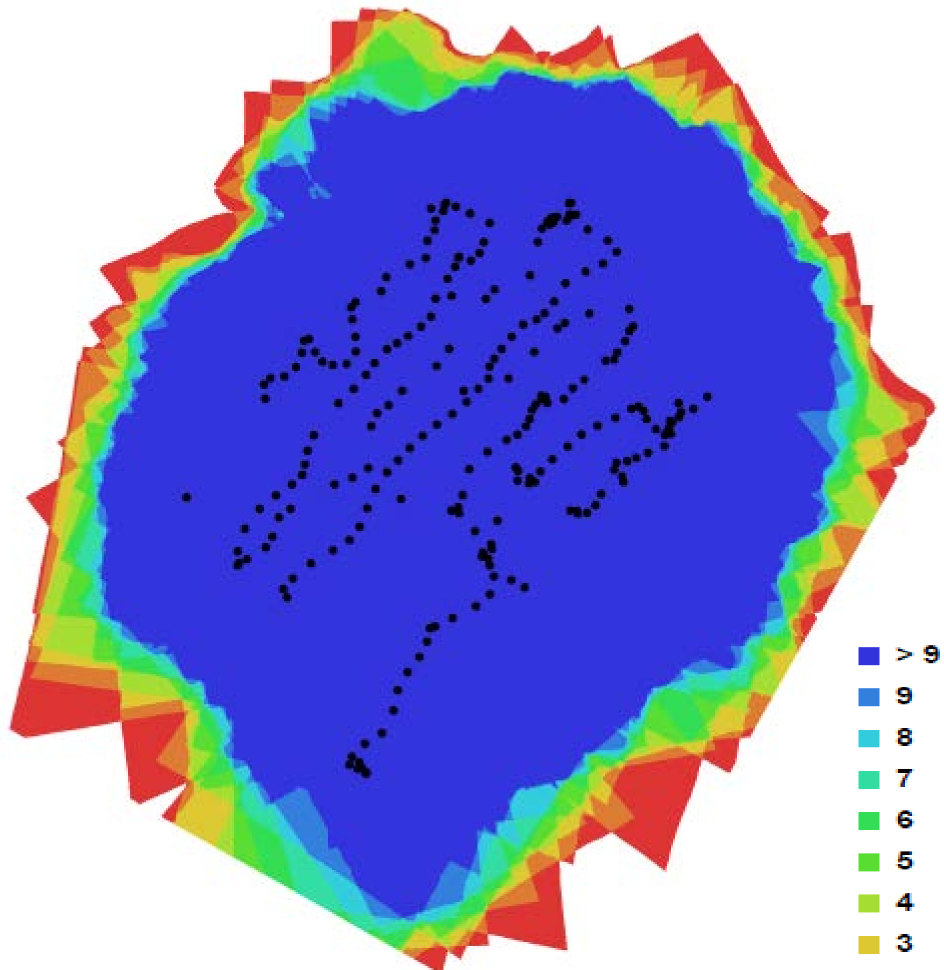
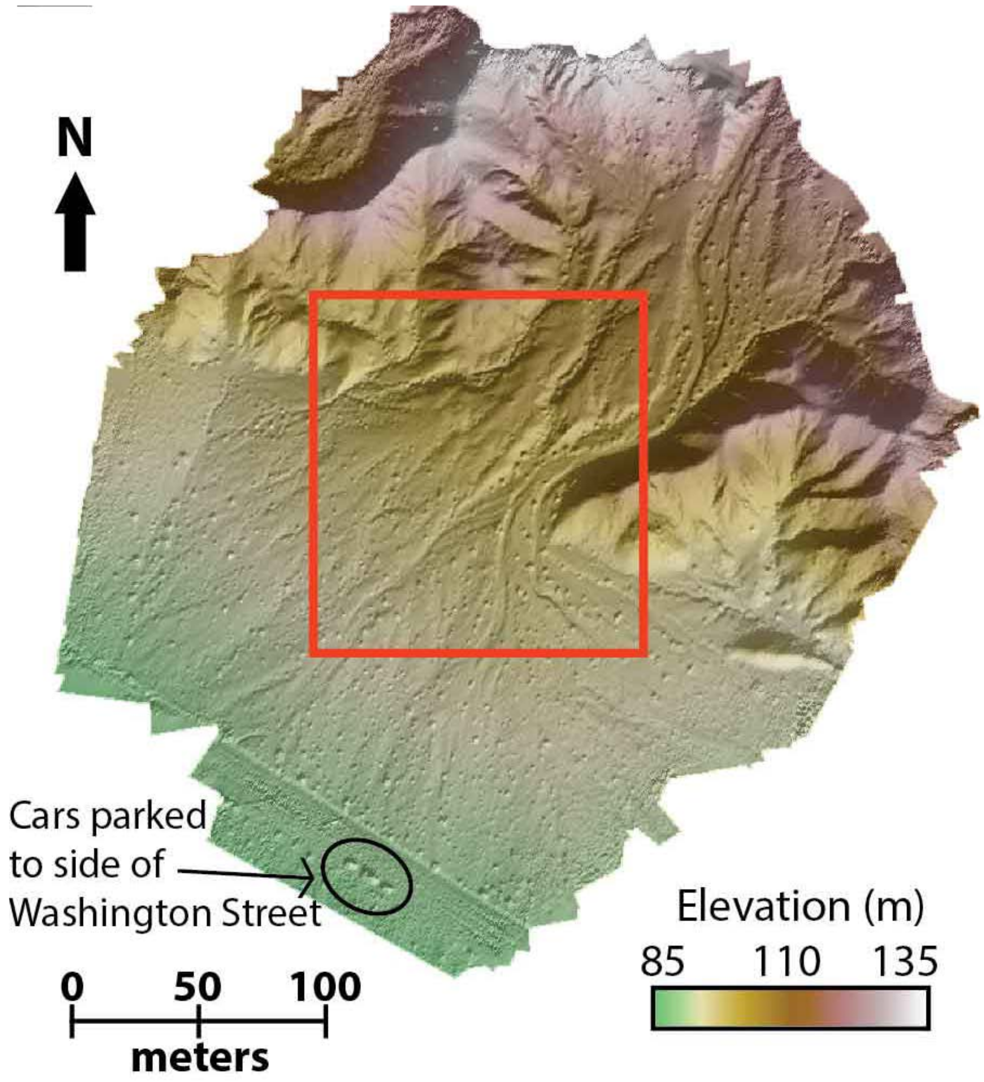
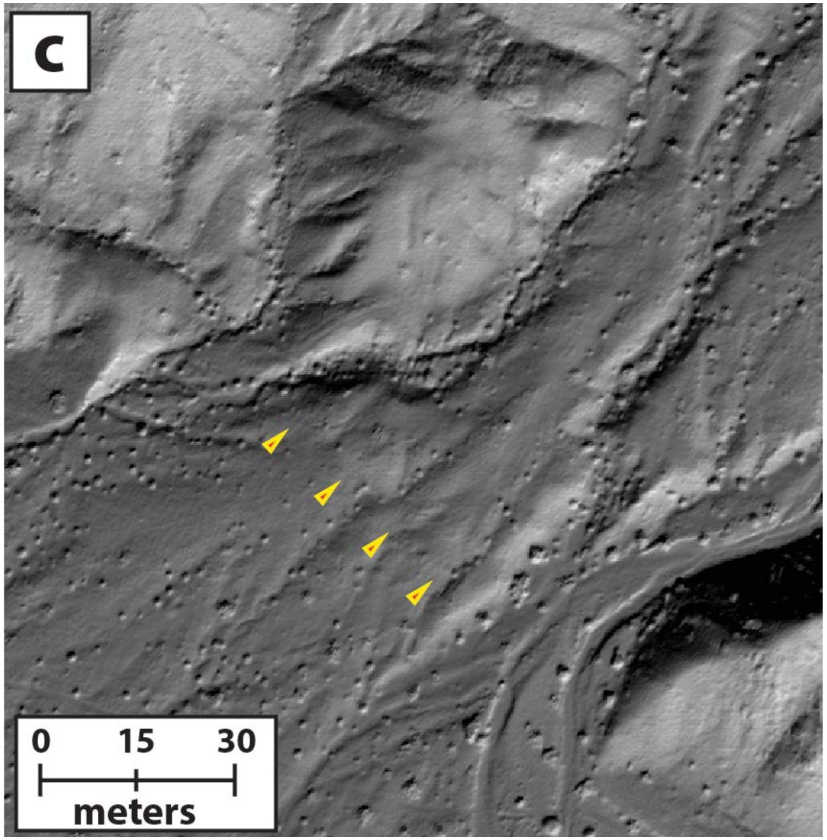


Fig. 1. Camera locations and image overlap.

Johnson *et al.* (2014), Rapid mapping of ultrafine fault zone topography with structure from motion, *Geosphere*

Resolution and precision of SfM topography



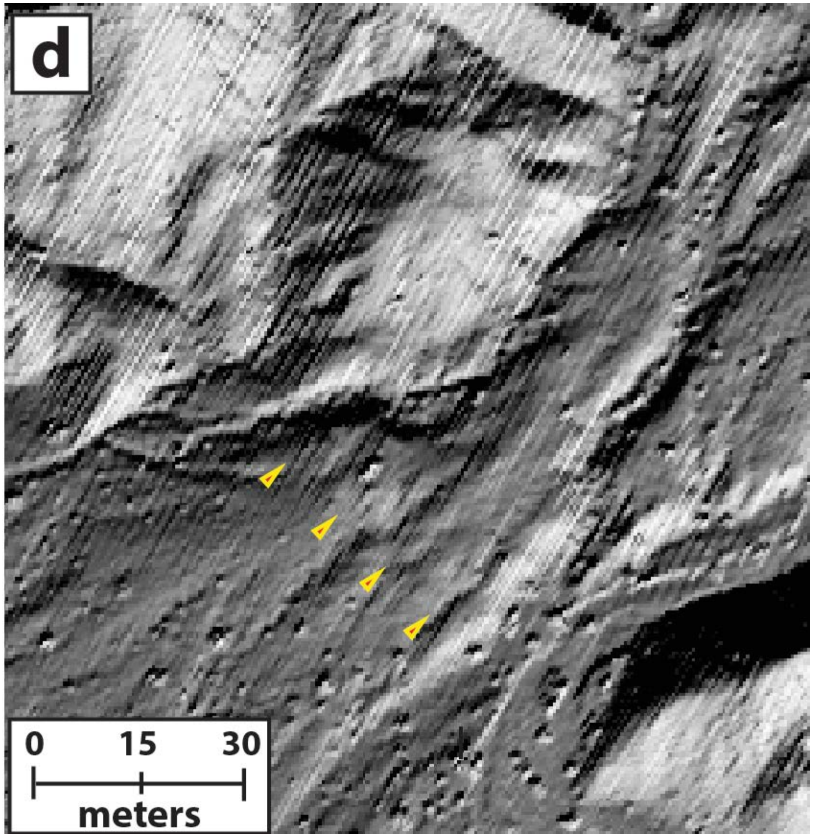


SfM ~700 pts/m^2

5 cm resolution DEM

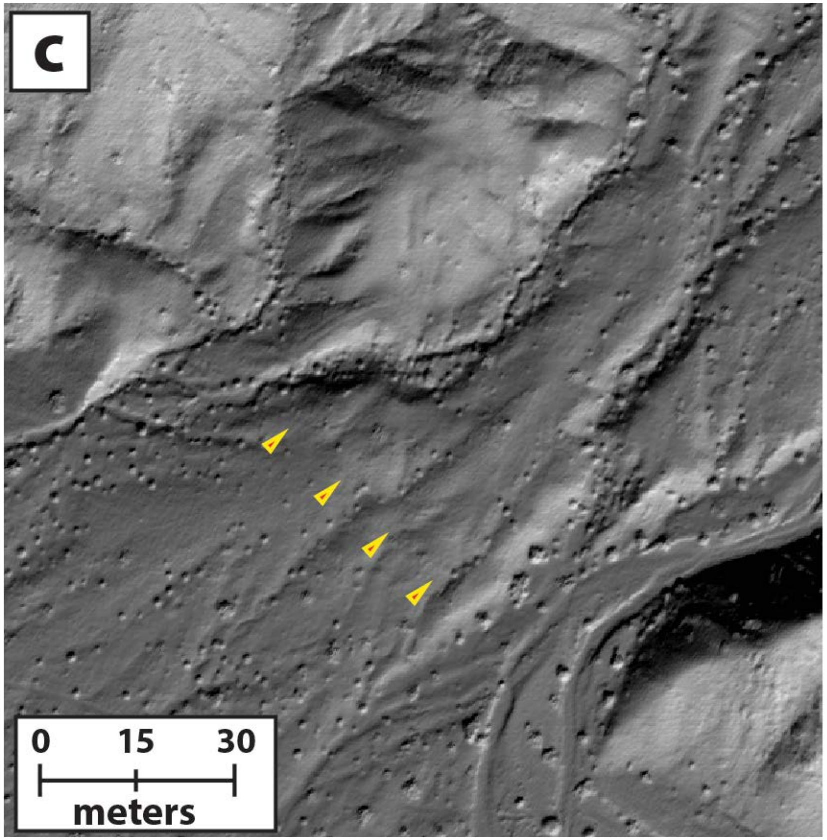
Johnson *et al.* (2014), Rapid mapping of ultrafine fault zone topography with structure from motion, *Geosphere*

Resolution and precision of SfM topography



B4 LiDAR ~4 pts/m^2

0.5 - 1 m resolution DEM

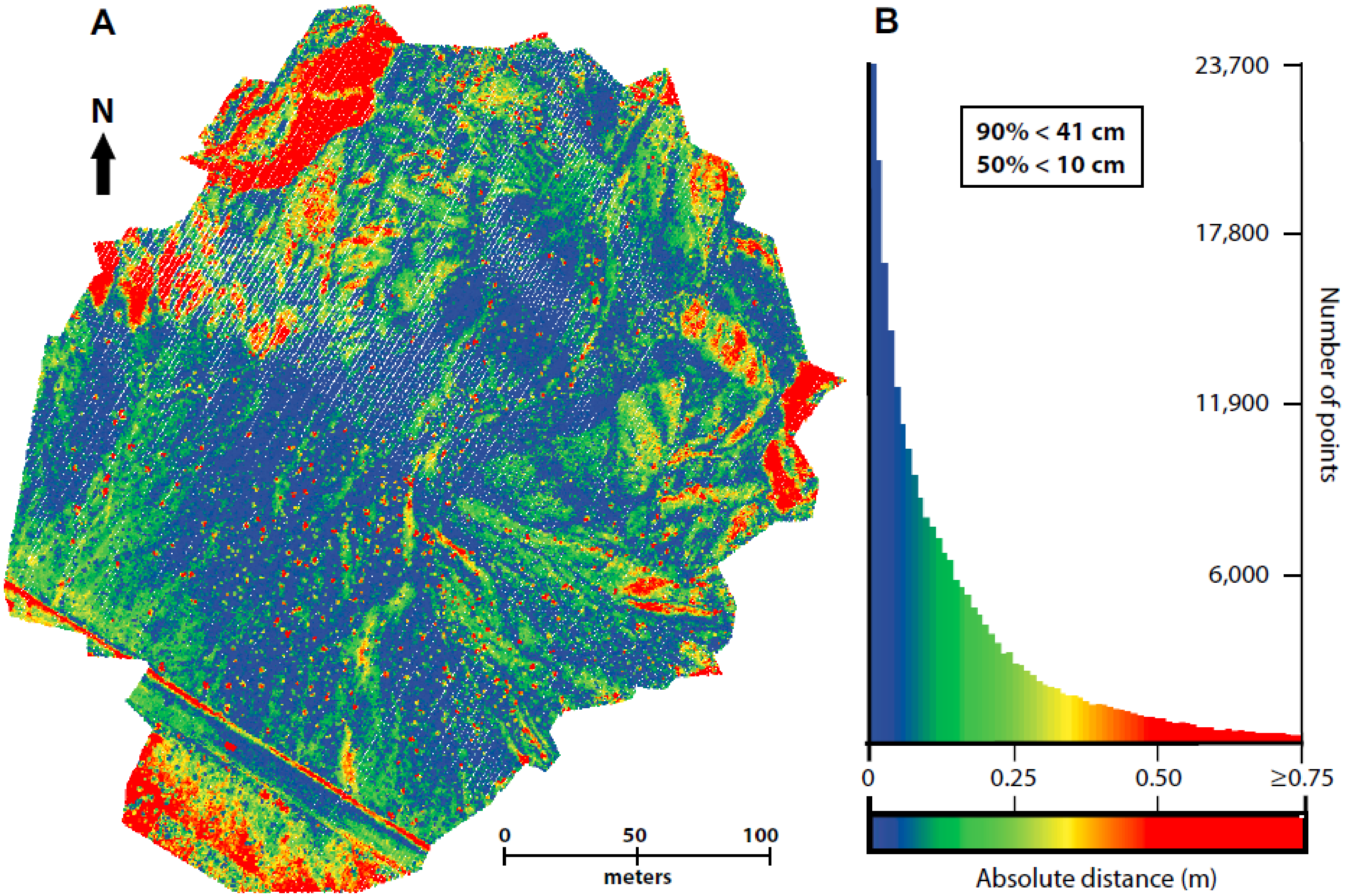


SfM ~700 pts/m^2

5 cm resolution DEM

Johnson *et al.* (2014), Rapid mapping of ultrafine fault zone topography with structure from motion, *Geosphere*

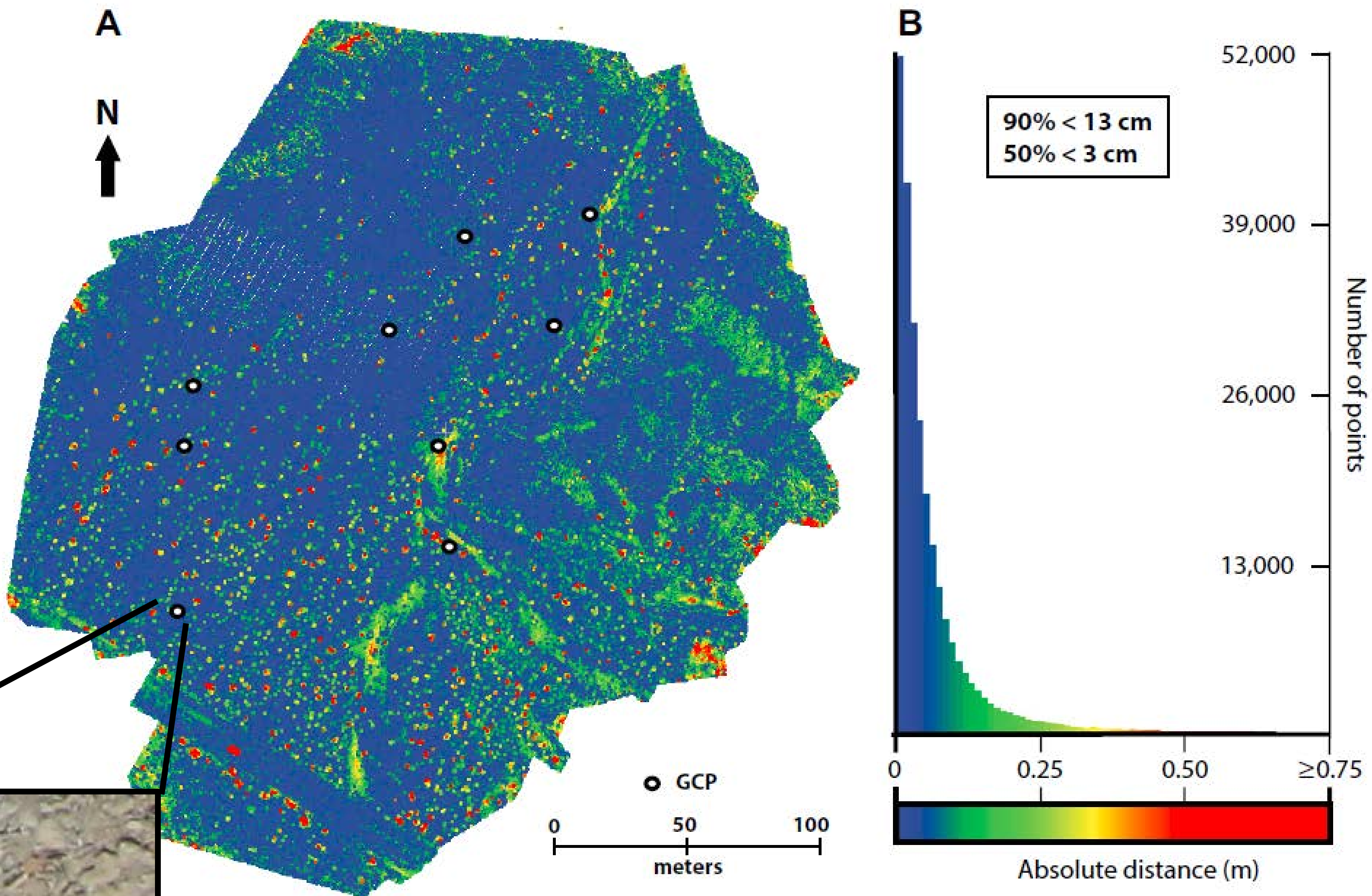
Resolution and precision of SfM topography



Note errors of >50 cm concentrated around edge of dataset. These probably reflect a trade-off in the bundle adjustment between estimates of the radial distortion of the camera lens and the topography

Johnson *et al.* (2014), Rapid mapping of ultrafine fault zone topography with structure from motion, *Geosphere*

Resolution and precision of SfM topography



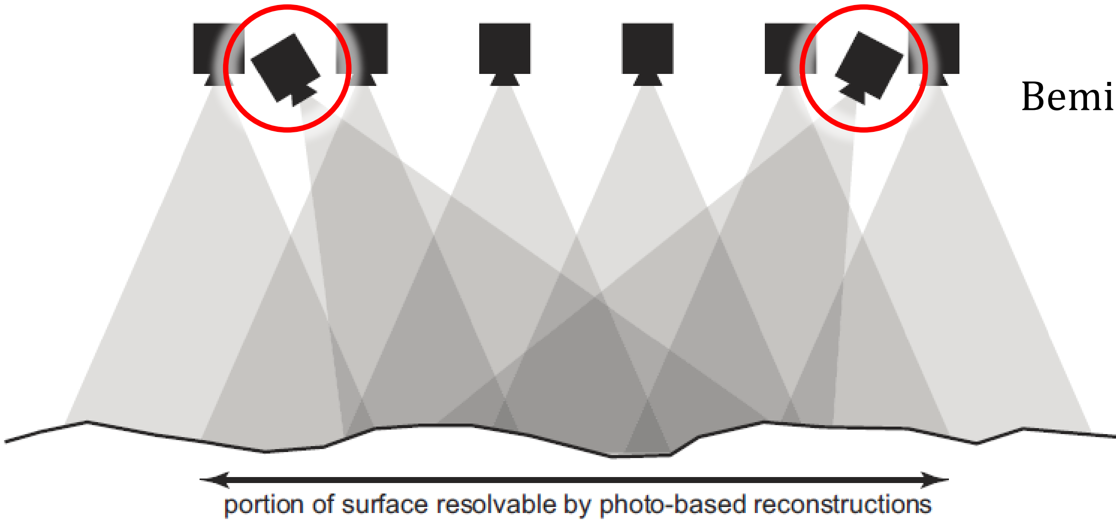
Distortion errors around the edge of dataset can be removed by deploying and surveying ground control points (using differential GPS), identifying these in the aerial photographs, and fixing the locations before the bundle adjustment.

Johnson *et al.* (2014), Rapid mapping of ultrafine fault zone topography with structure from motion, *Geosphere*

SfM exercise

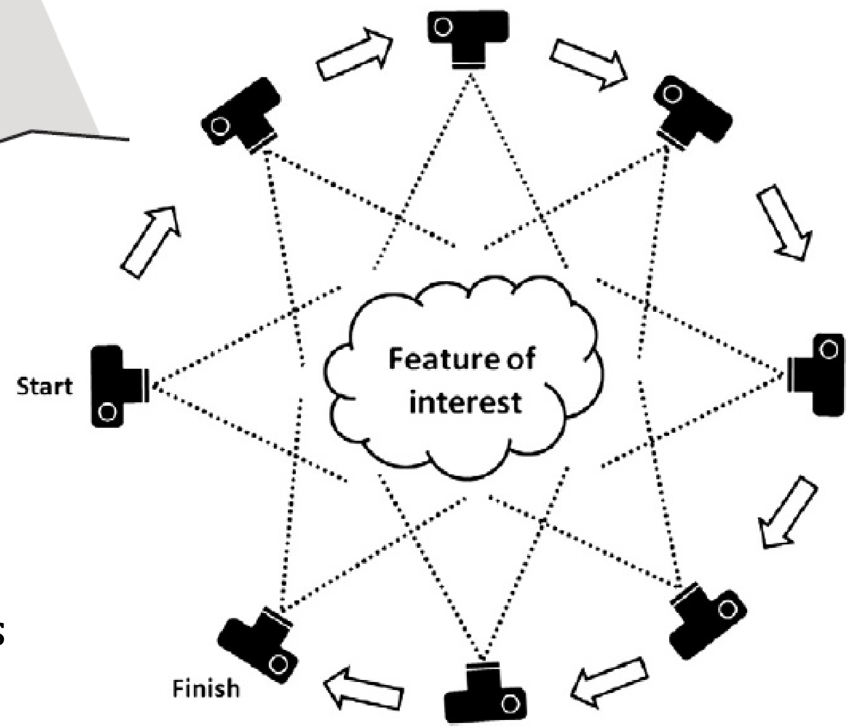
Option 1

Build your own model using your own photographs of a target on campus.
Make sure you have a way of transferring your photos onto the computer!



Bemis *et al.* (2014).

Westoby *et al.* (2012).



Tips

- Choose a target with some texture
- Ensure plenty of overlap between photos
- Capture the target from a variety of angles
- Try to capture the object in ~20 – 30 photos

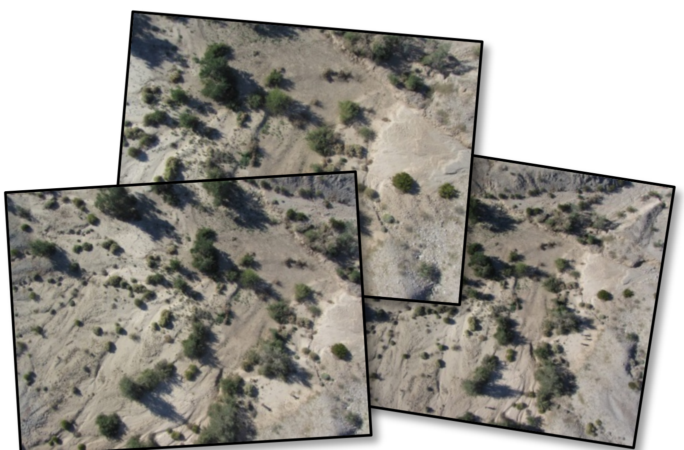
SfM exercise

Option 2

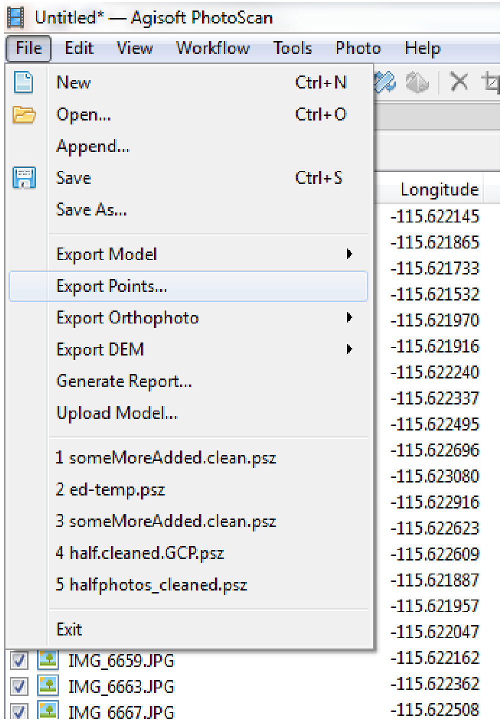
Build a model of the El Mayor-Cucapah rupture using 30 photos collected from a helium balloon

Tuesday, March 24, 2015

Time	Topic
8:30am	OpenTopography and other resources; open source tools and data discussion
9:30am	BCAL Lidar Tools
12:00pm	*Lunch*
1:00pm	**Structure from Motion (SfM)** • SfM Demo: El Mayor-Cucapah Earthquake Photos
3:30pm	**Lesson:** Topographic Change Detection, (e.g. iterative closest point (ICP) using CloudCompare)
5:00pm	Short course wrap up



SfM exercise



In the free trial version of Agisoft Photoscan, you are unable to save point clouds or gridded DEMs that you create.

However, if you *had* bought the license, you could then do the following:

File > Export Points

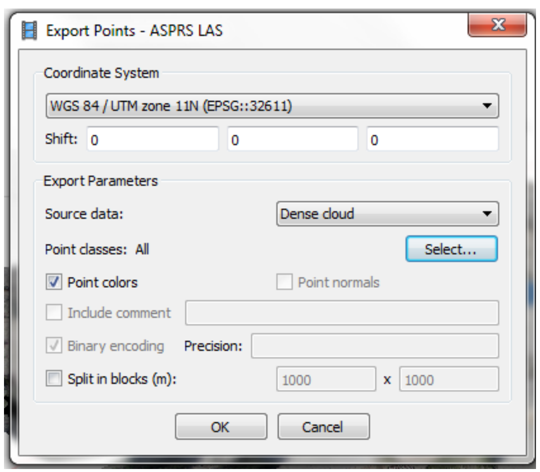
- save point cloud with attributes in a number of formats including .LAS and ASCII, and in a number of coordinate systems including UTM

File > Export DEM

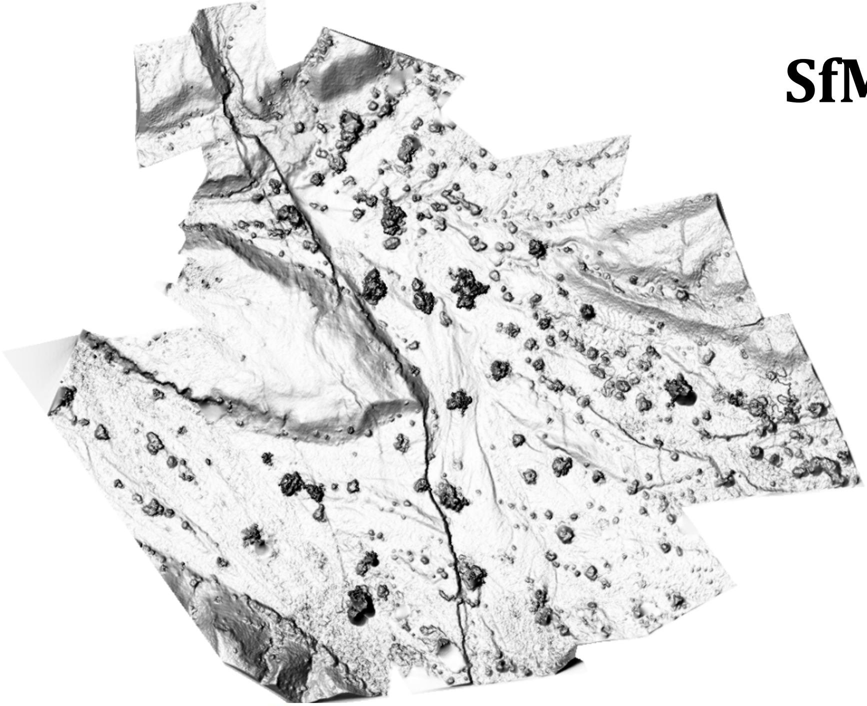
File > Export Orthophoto

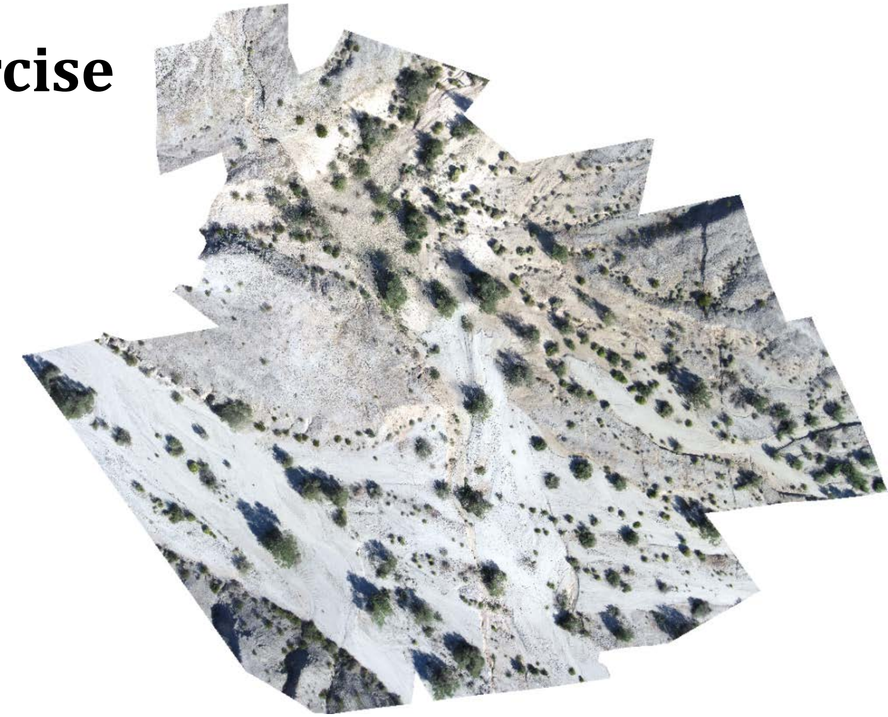
Generate Report

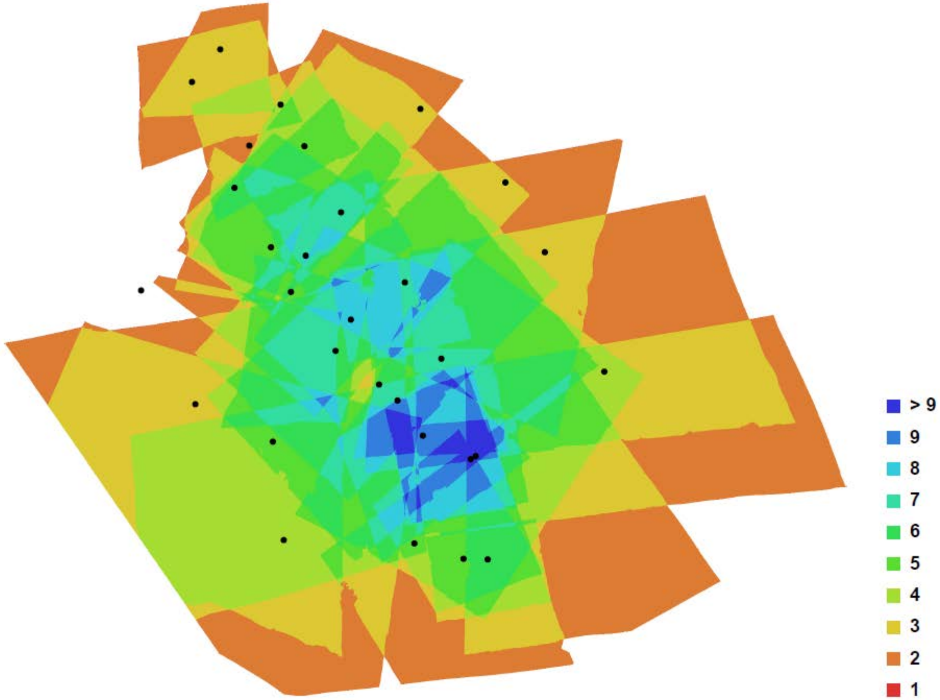
- the report contains a summary of the 3D model and data collection metrics



SfM exercise







Example products

Top left: artificially shaded DEM

Top right: orthophoto

Bottom left: camera locations (black dots) and image overlap (colours show #photos)