Dynamic Science from Repeat, High-res Stereo Imagery: Ice Sheets to Volcanoes

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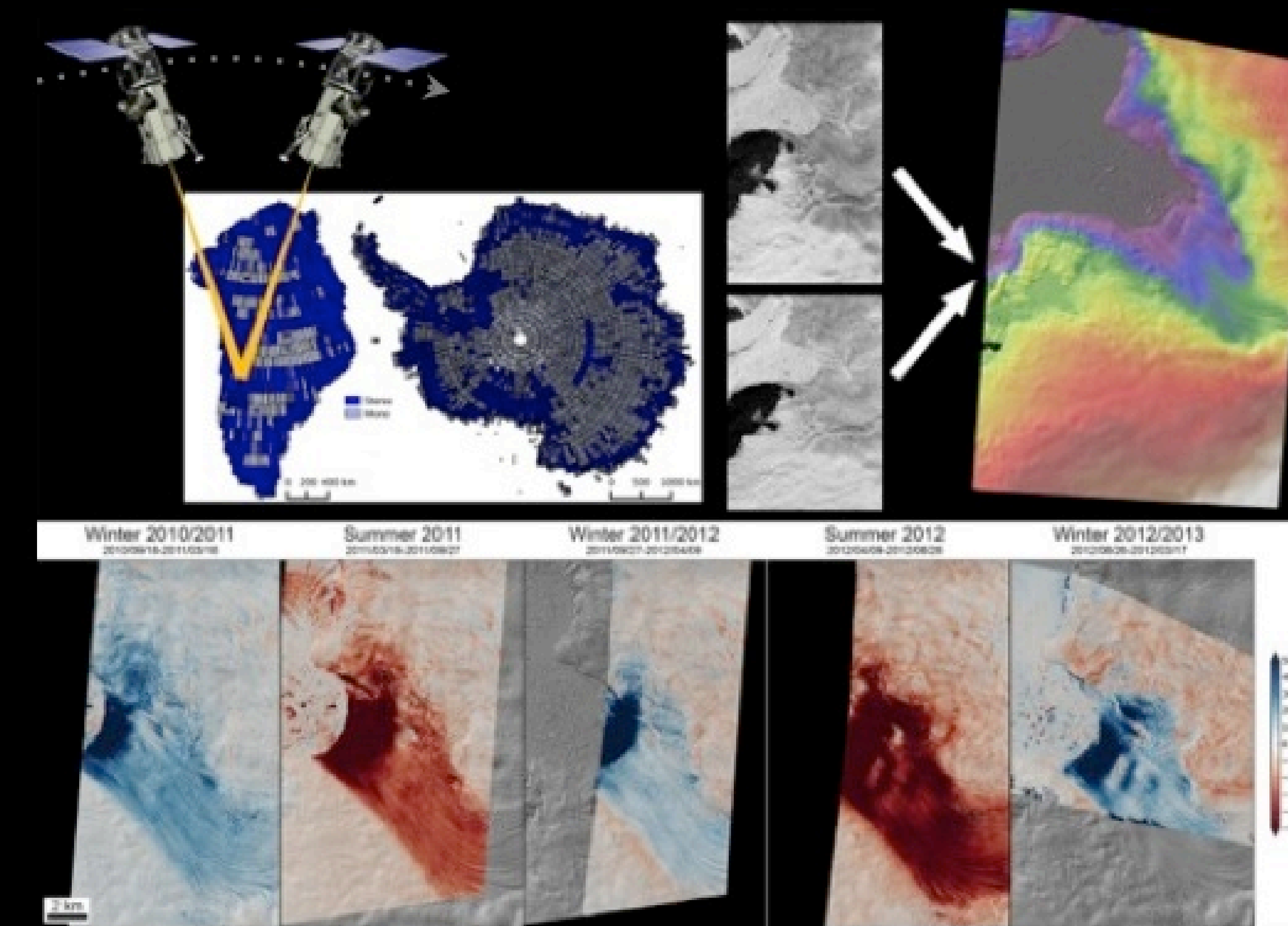
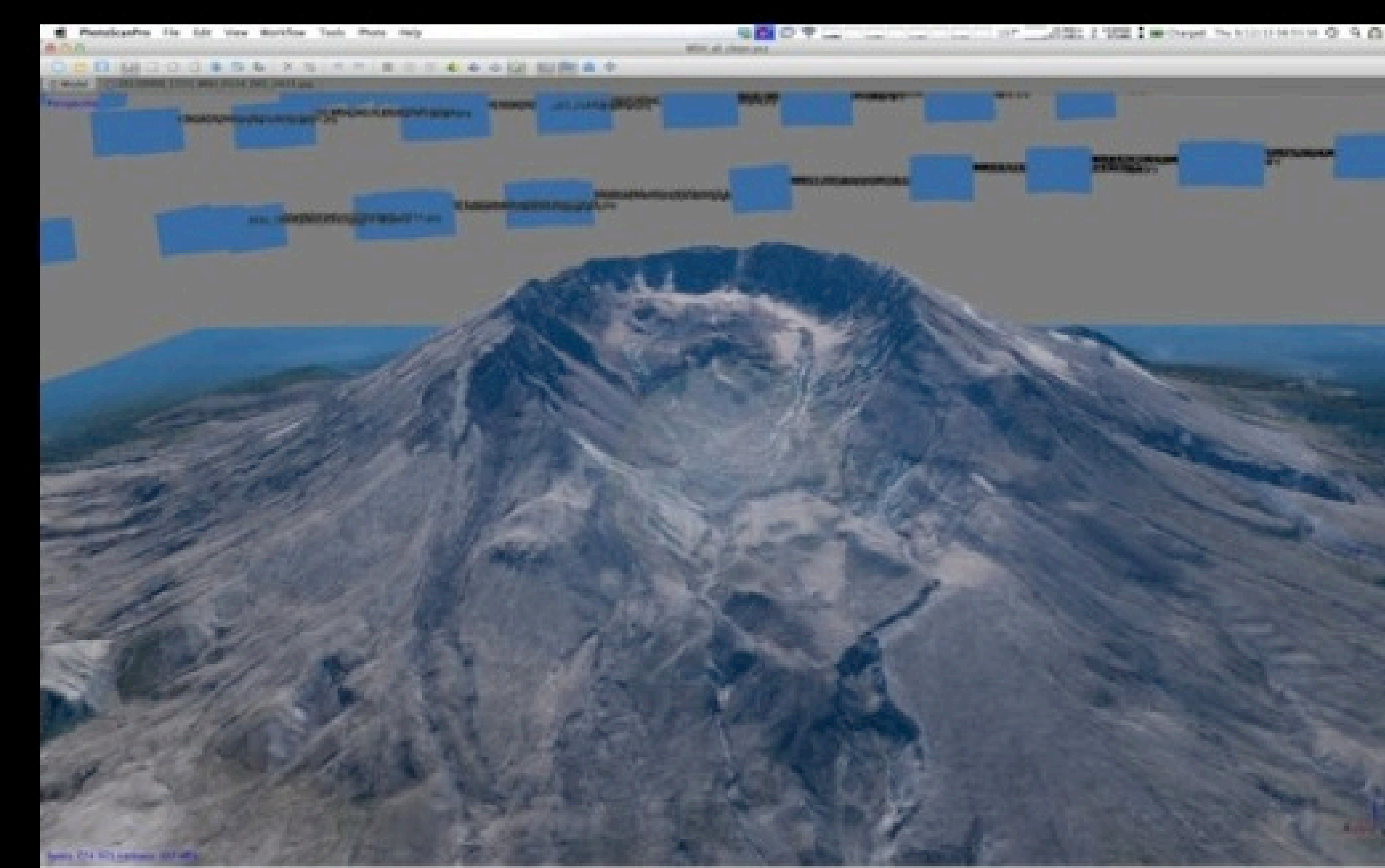
EARTH & SPACE SCIENCES
UNIVERSITY of WASHINGTON
College of the Environment

Outline

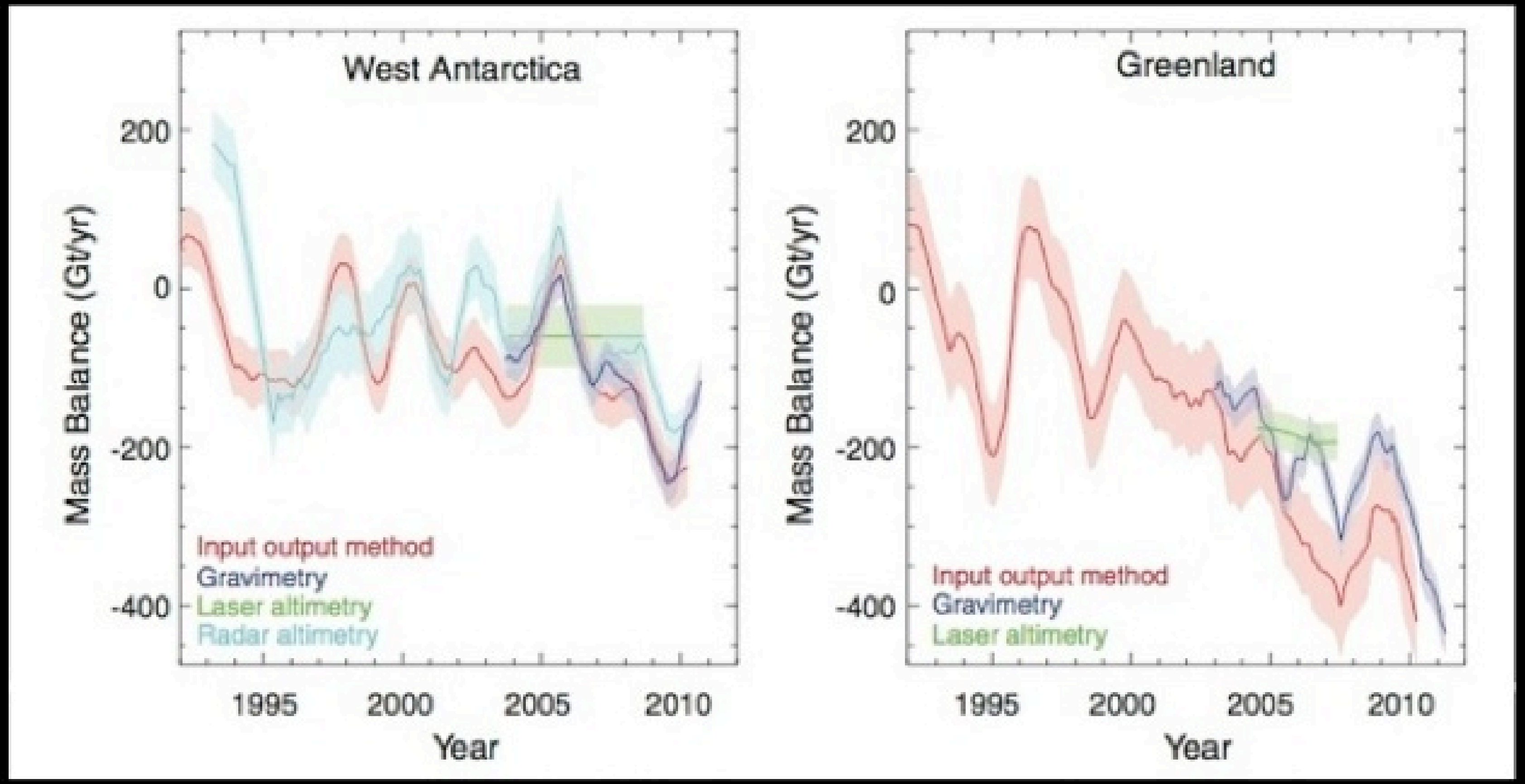
- Background & Motivation
- Commercial High-res Satellite Stereo
- Oblique Aerial DSLR SfM surveys
- Summary
- Discussion Topics/Questions

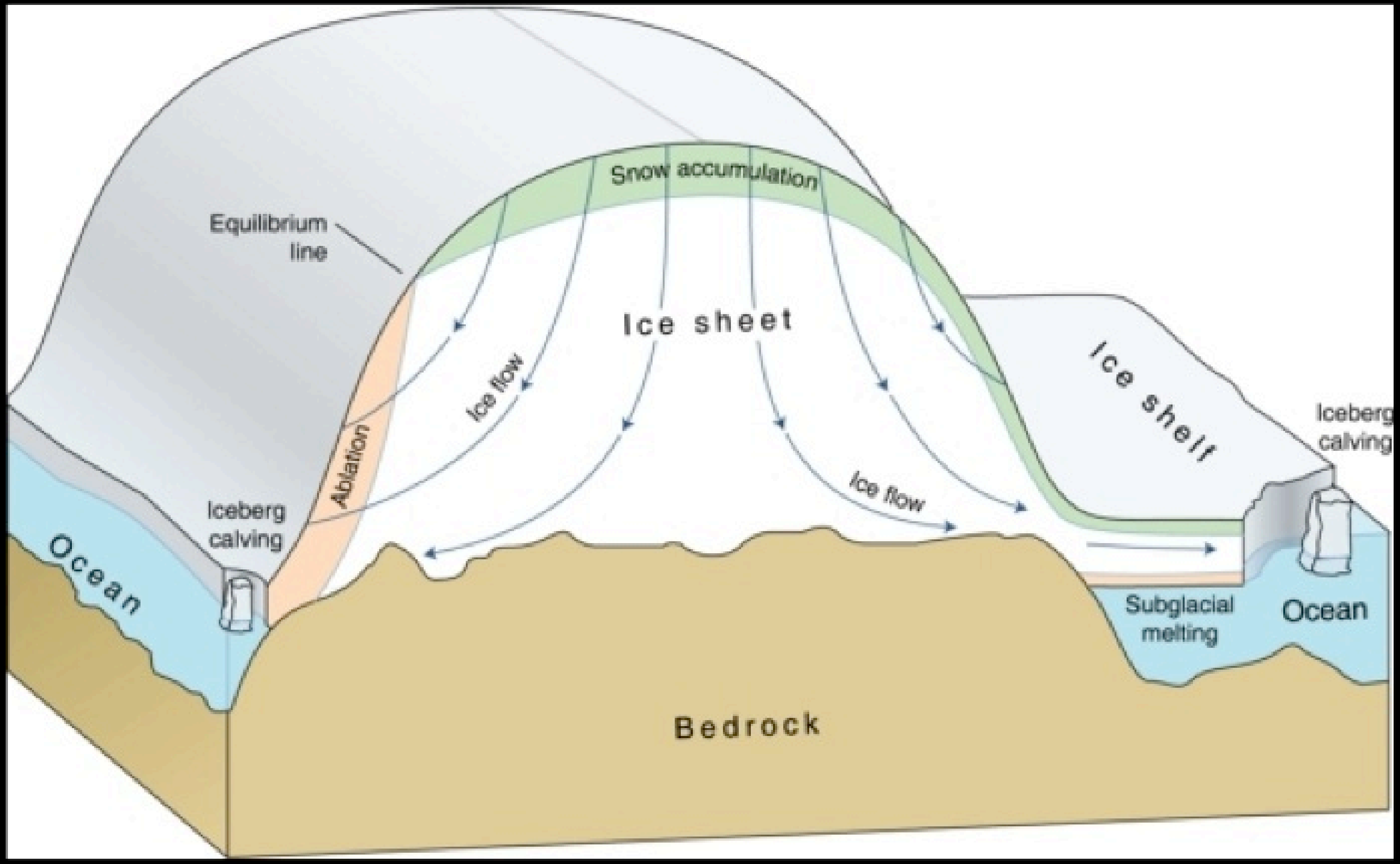


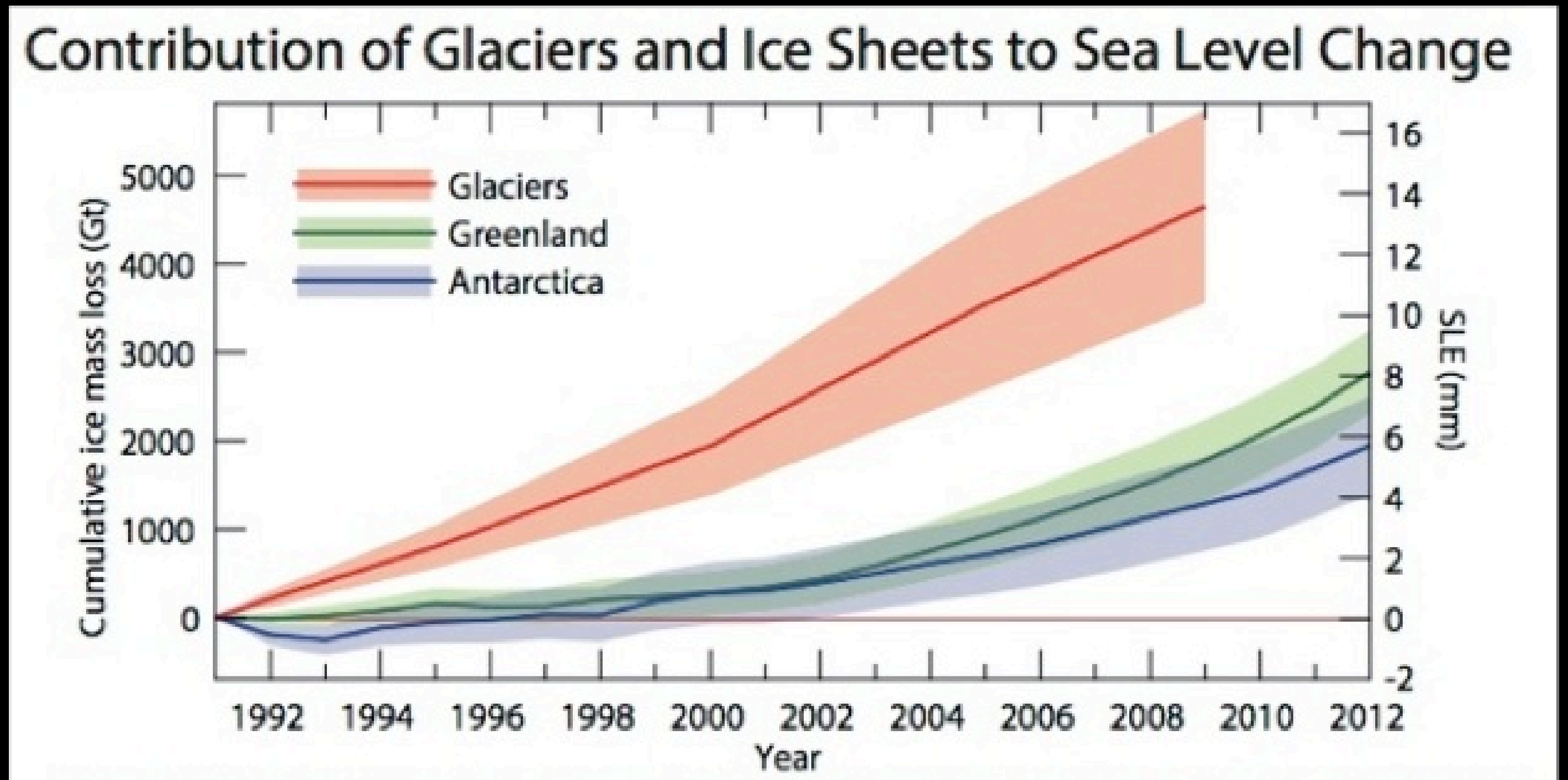


Ice Sheet Mass Balance

- Two components:
  - Input: precipitation
  - Output: melting, discharge (calving)
- Increasing mass loss from 1992-present
- Implications for 21st Century sea level rise







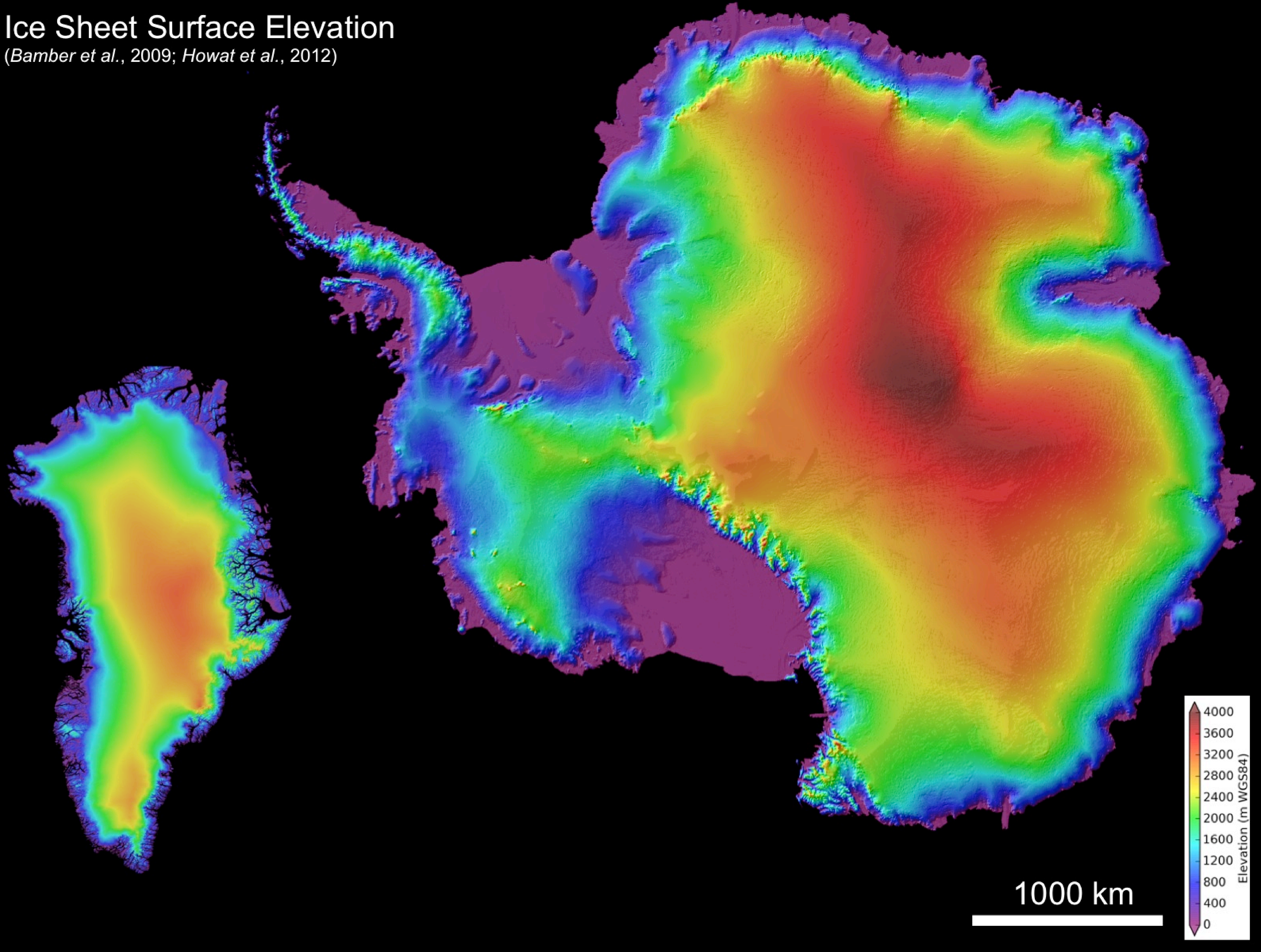
Cumulative ice mass loss from glacier and ice sheets (in sea level equivalent) is 1.0 to 1.4 mm yr^{-1} for 1993-2009 and 1.2 to 2.2 mm yr^{-1} for 2005-2009.

http://www.solcomhouse.com/icecap.htm

Shepherd et al. (2012); IPCC AR5 (2014)

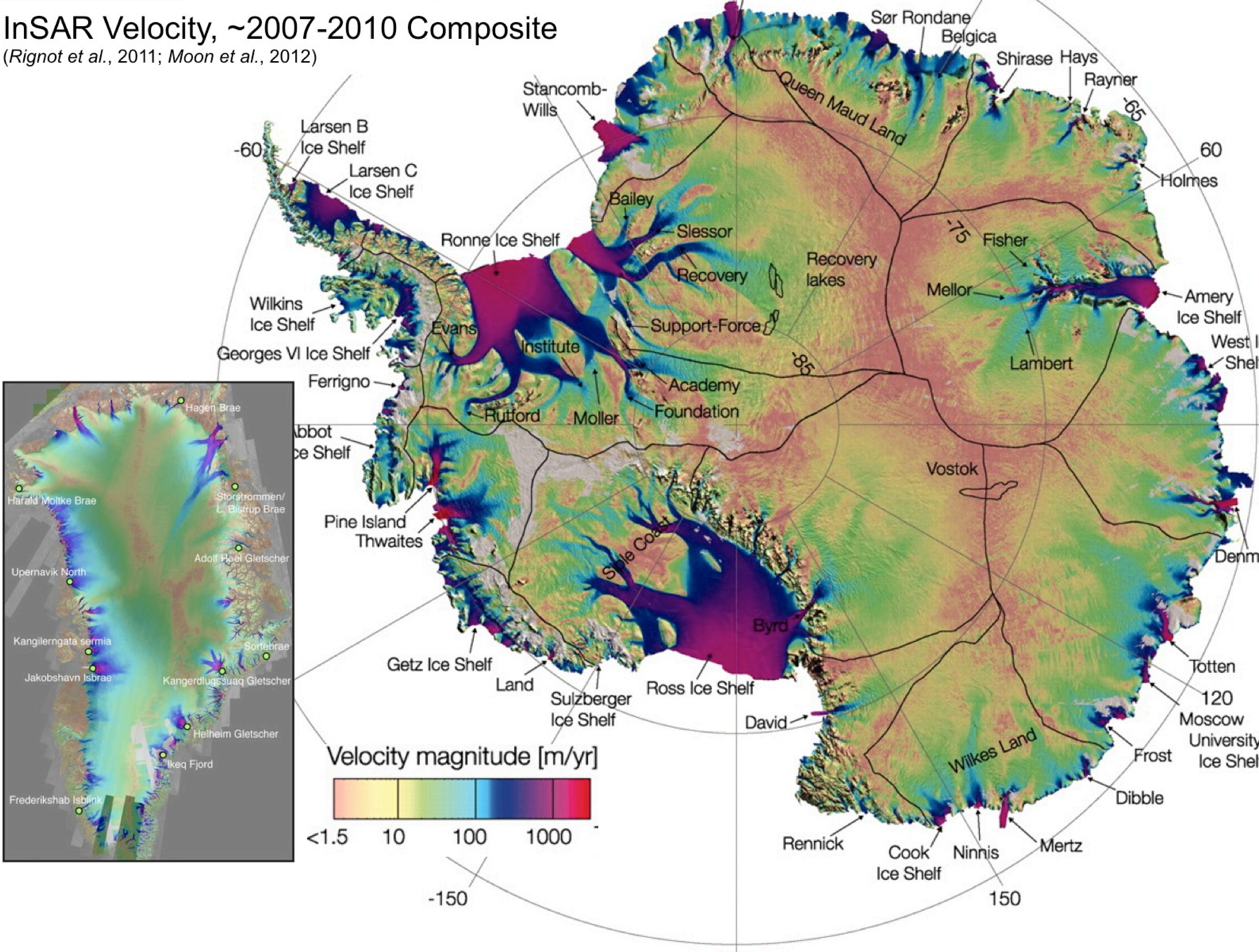
Ice Sheet Surface Elevation

(*Bamber et al.*, 2009; *Howat et al.*, 2012)



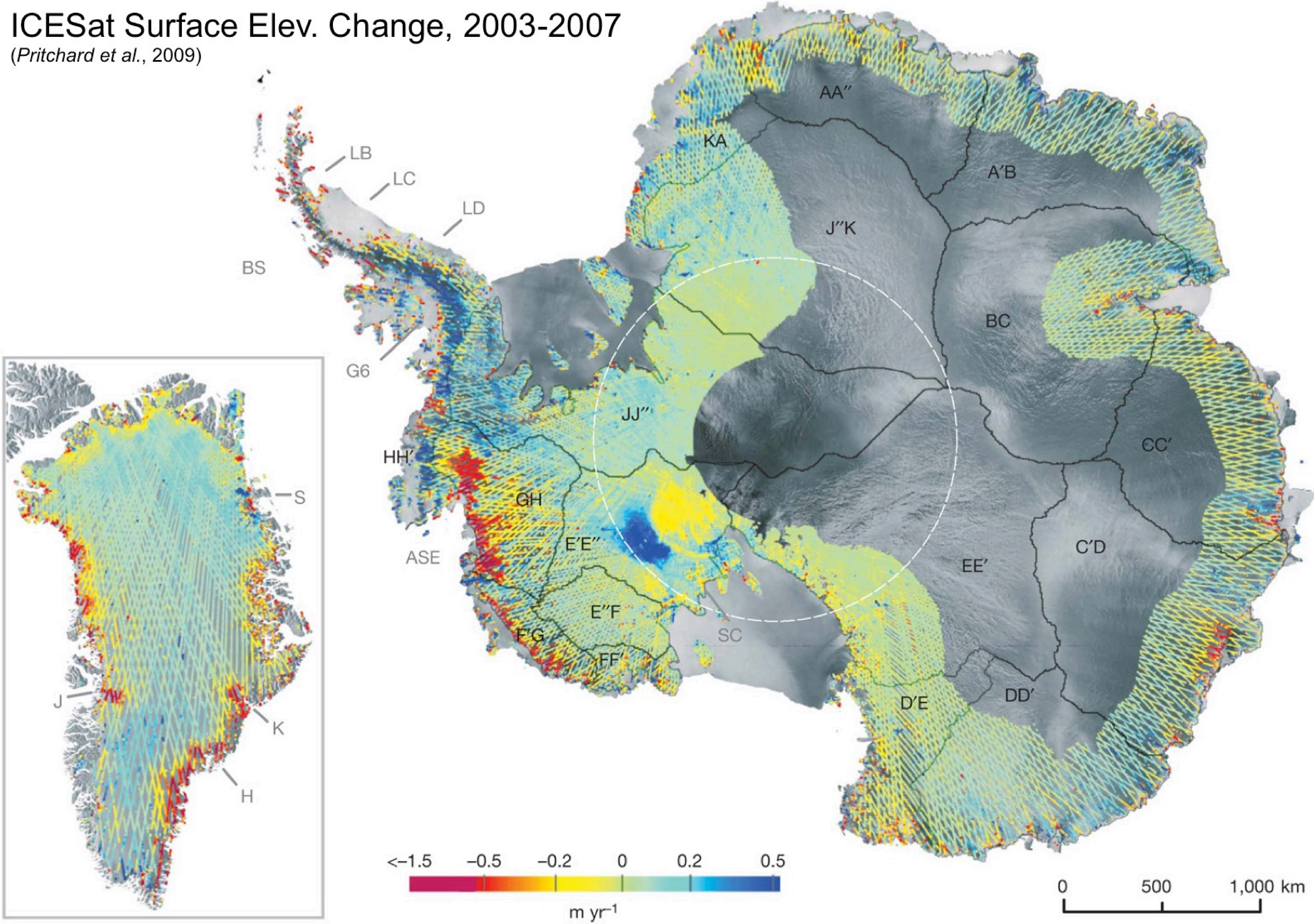
InSAR Velocity, ~2007-2010 Composite

(*Rignot et al.*, 2011; *Moon et al.*, 2012)

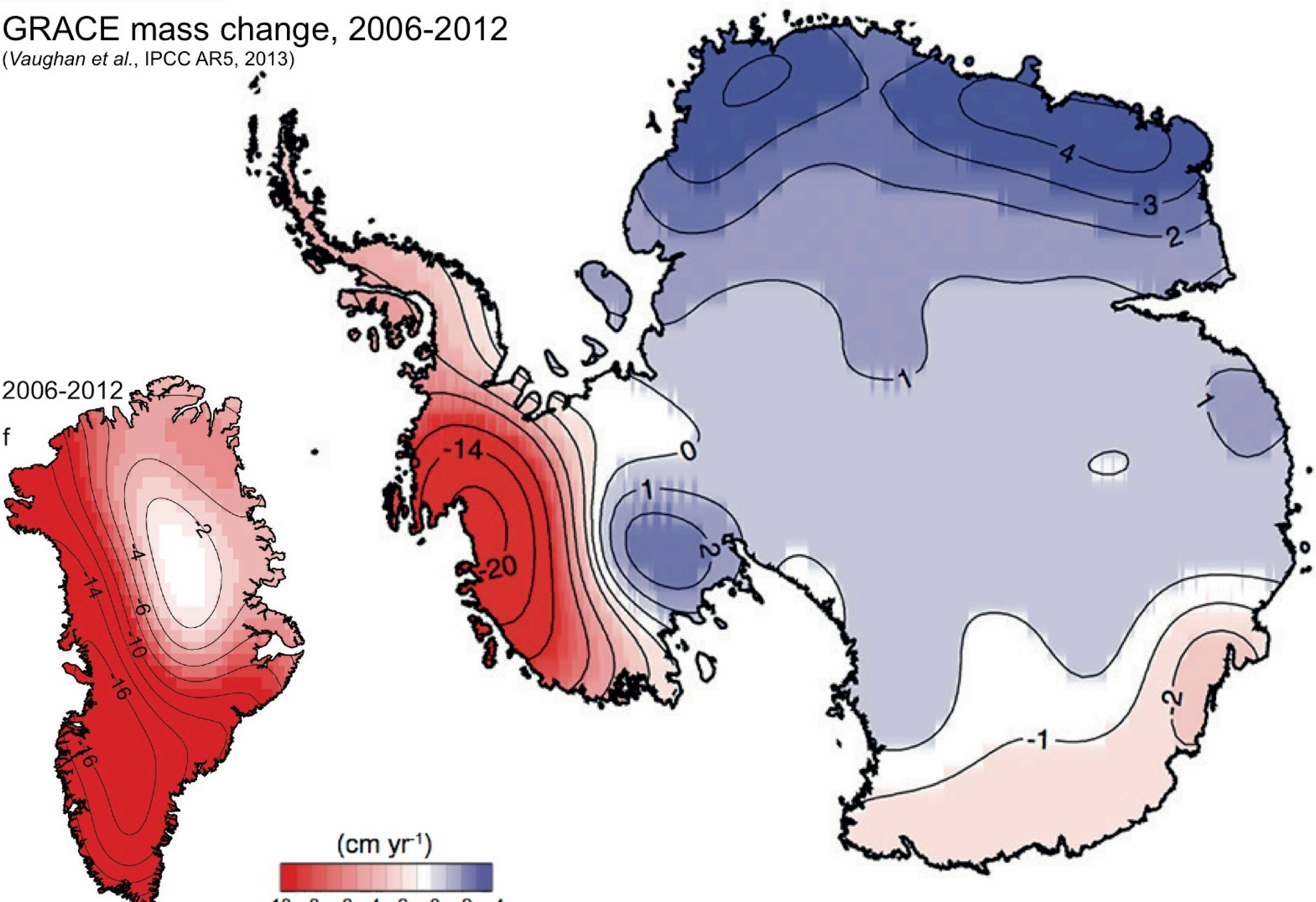


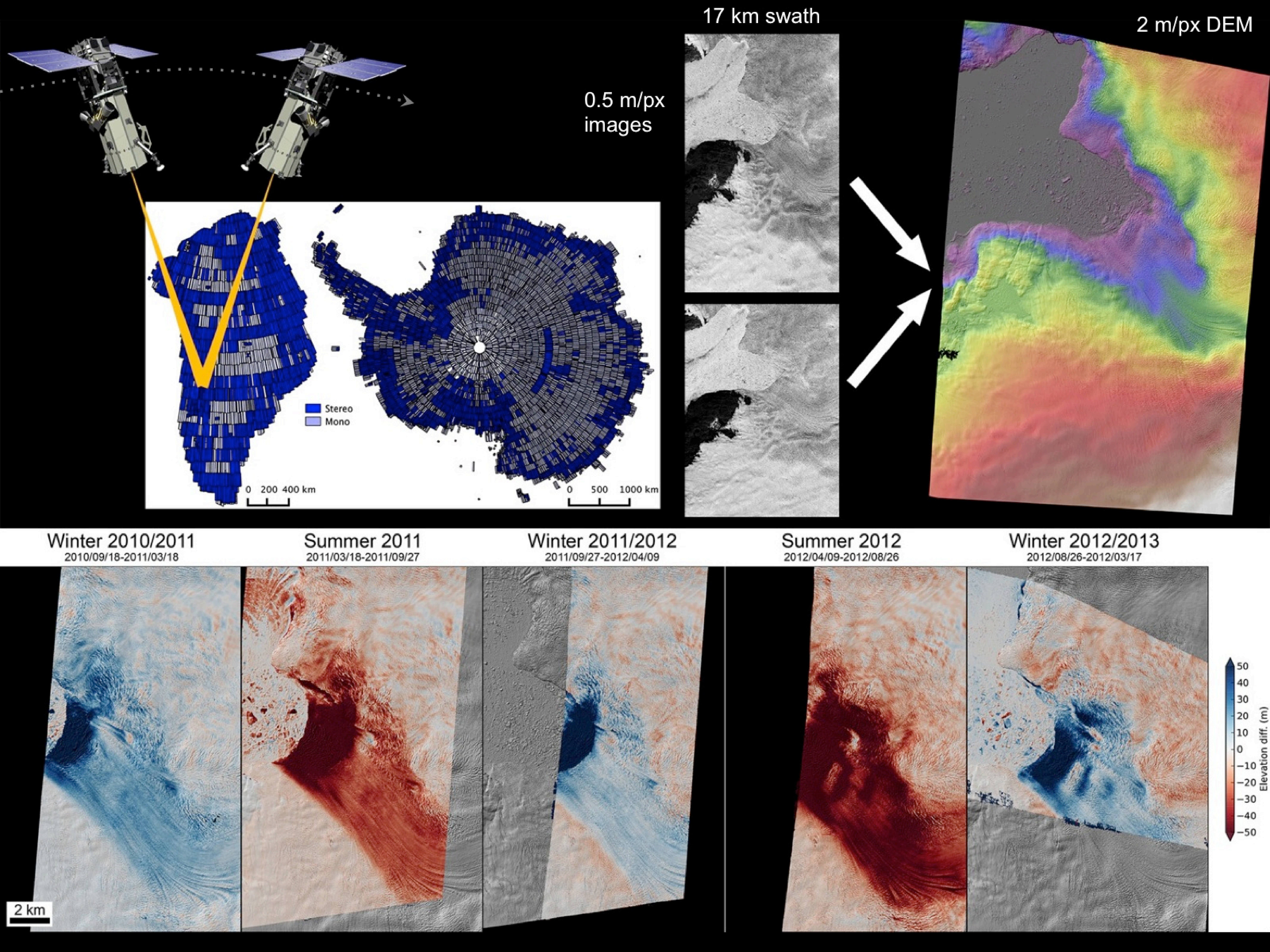
ICESat Surface Elev. Change, 2003-2007

(*Pritchard et al.*, 2009)



GRACE mass change, 2006-2012
(*Vaughan et al.*, IPCC AR5, 2013)




17 km swath
2 m/px DEM
0.5 m/px images
Stereo
Mono
0 200 400 km
0 500 1000 km
Winter 2010/2011
2010/09/18-2011/03/18
Summer 2011
2011/03/18-2011/09/27
Winter 2011/2012
2011/09/27-2012/04/09
Summer 2012
2012/04/09-2012/08/26
Winter 2012/2013
2012/08/26-2012/03/17
2 km
Elevation diff. (m)
50
40
30
20
10
0
−10
−20
−30
−40
−50

Motivation

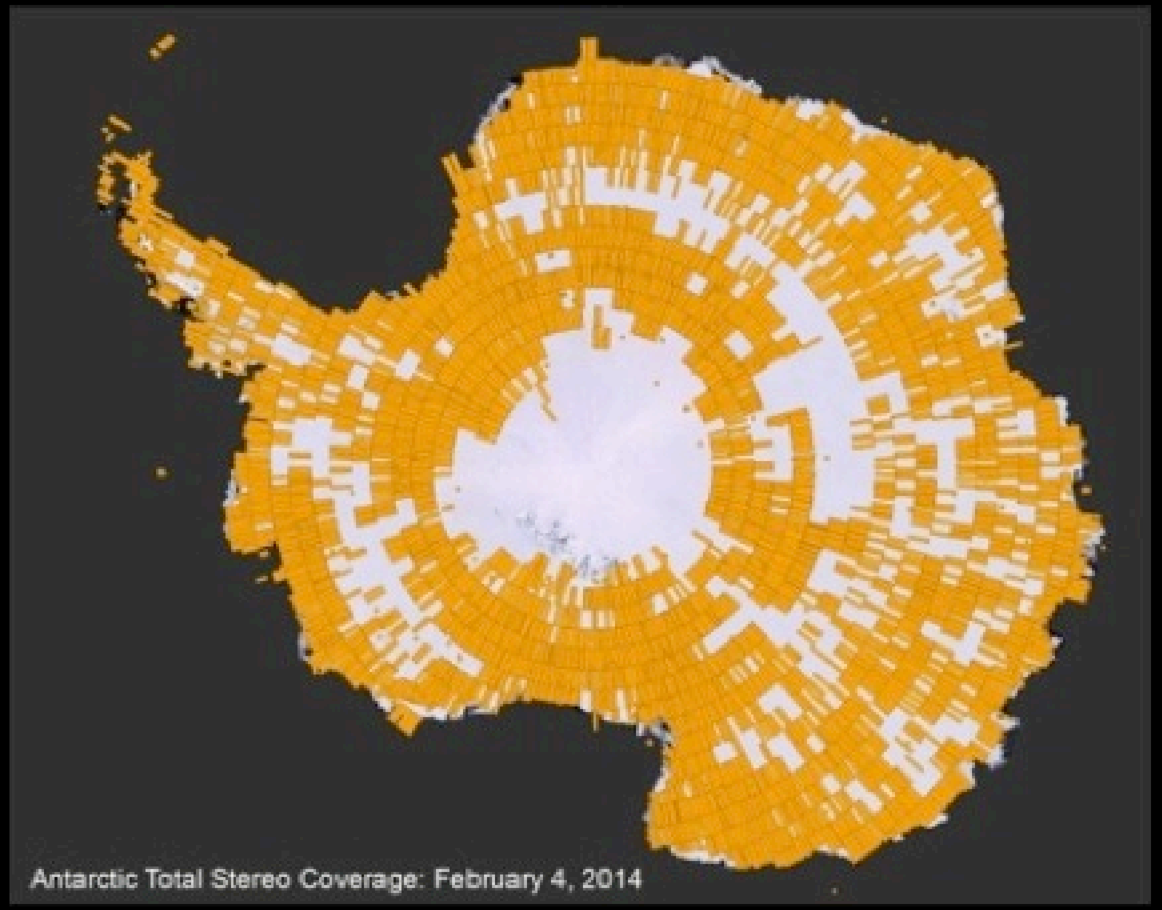
Repeat measurements of surface topography capture ice dynamics/variability, mass loss, and characterize the processes driving observed change.

- Ice sheets – sea level rise
- Mountain glaciers – regional climate change, outburst floods
- Seasonal snowpack – water resources, avalanche hazards

The NGA Commercial Stereo Imagery Opportunity

- ~5 billion km^2 of archive imagery at no cost
- 5 satellite constellation (+WorldView-3 in July)
- “On-demand” mono/stereo imaging, <1-2 day repeat
- ~0.3-1.0 m/px panchromatic, ~17 km swath
- Current PGC stereo tasking:
  - Both poles from 60-84°
  - All glaciers and volcanoes on Earth
  - Himalayas, Alps, Andes
- ~80-90% of Arctic/Antarctic in stereo each year.
- Restricted raw/orthorectified imagery but derived products (e.g. DEMs, velocity maps) can be distributed

Ikonos QuickBird GeoEye-1 WorldView-1 WorldView-2

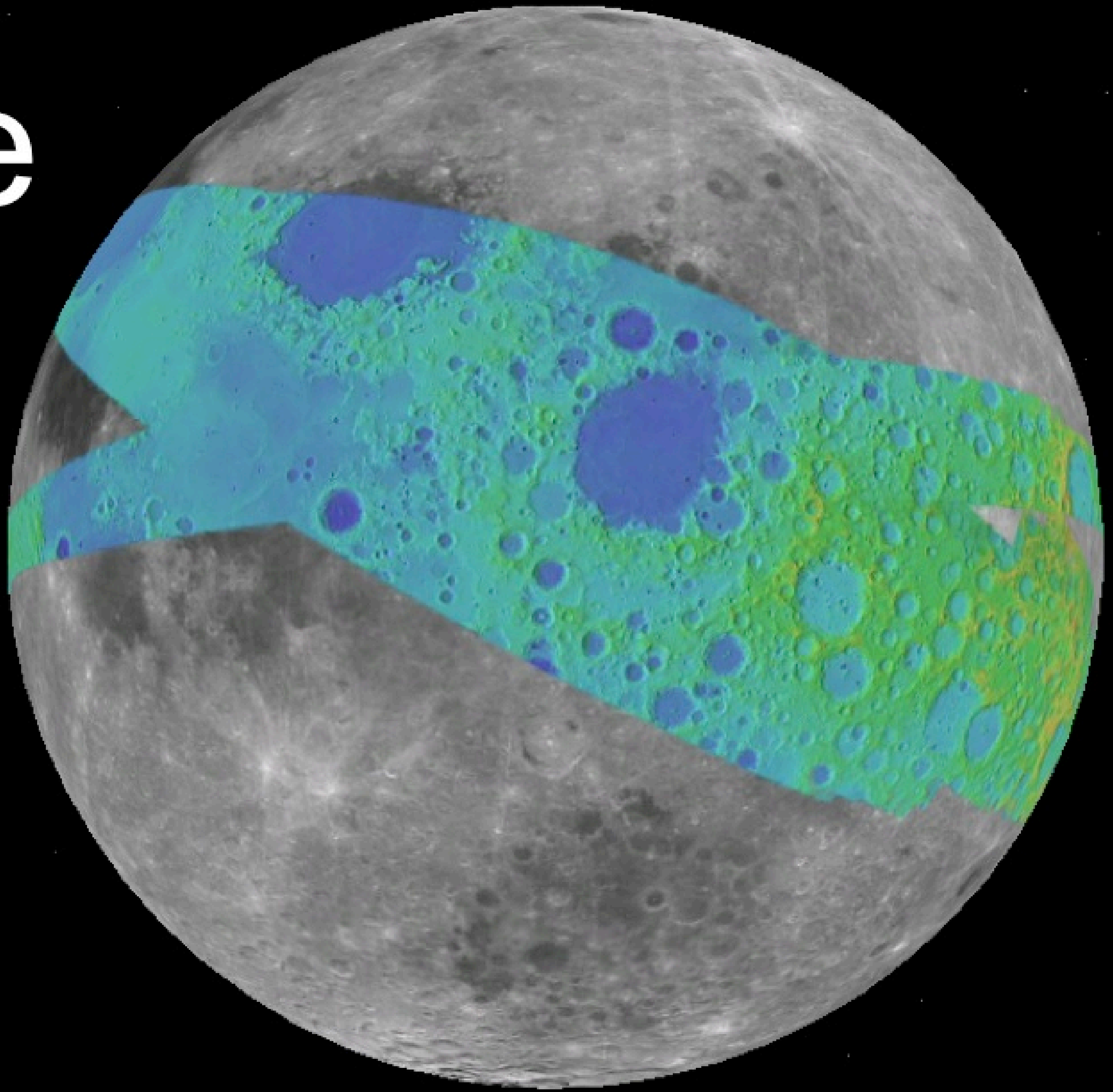


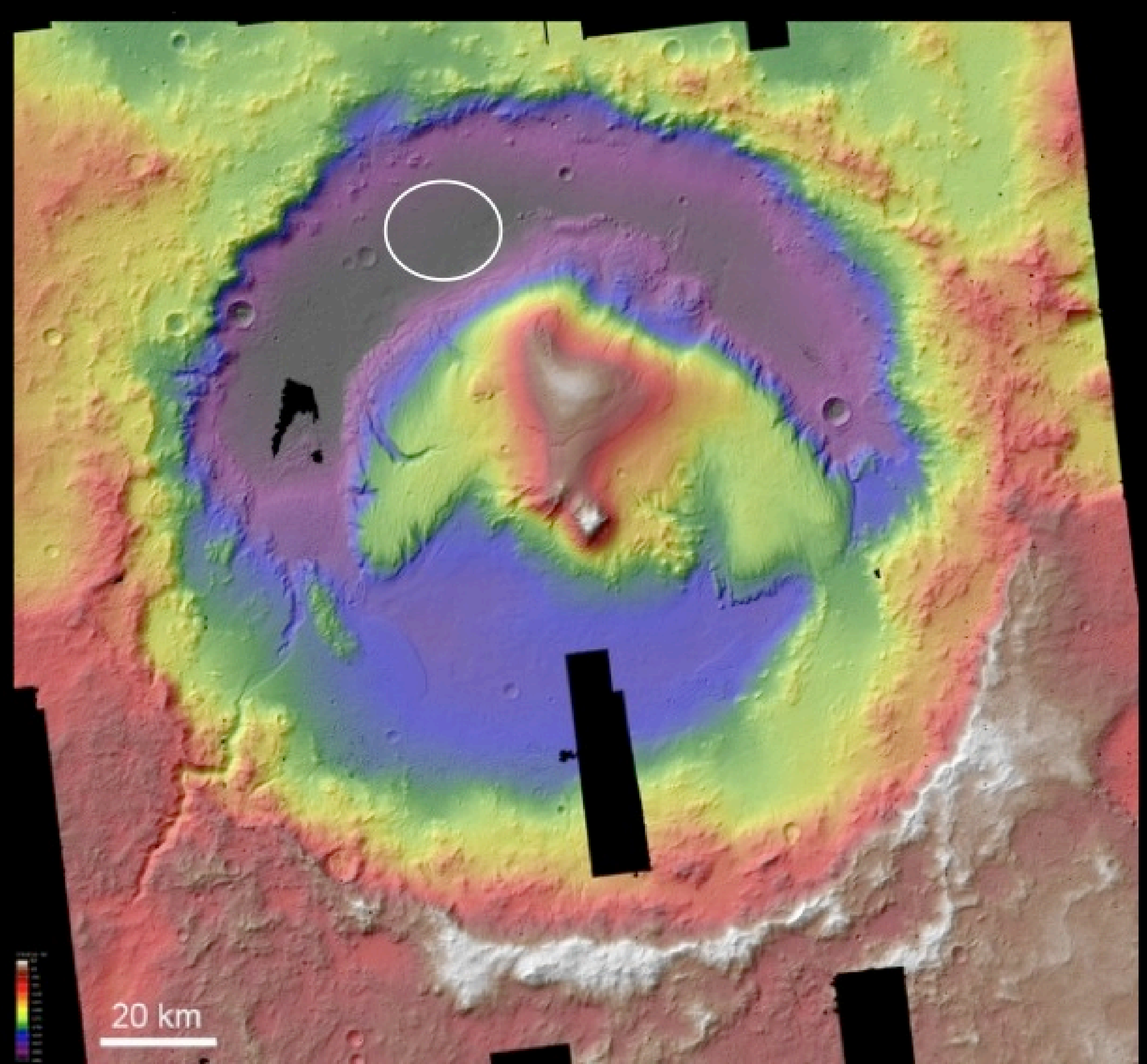
Paul Morin, Polar Geospatial Center, University of Minnesota

DigitalGlobe Stereo Archive - 6/1/2014

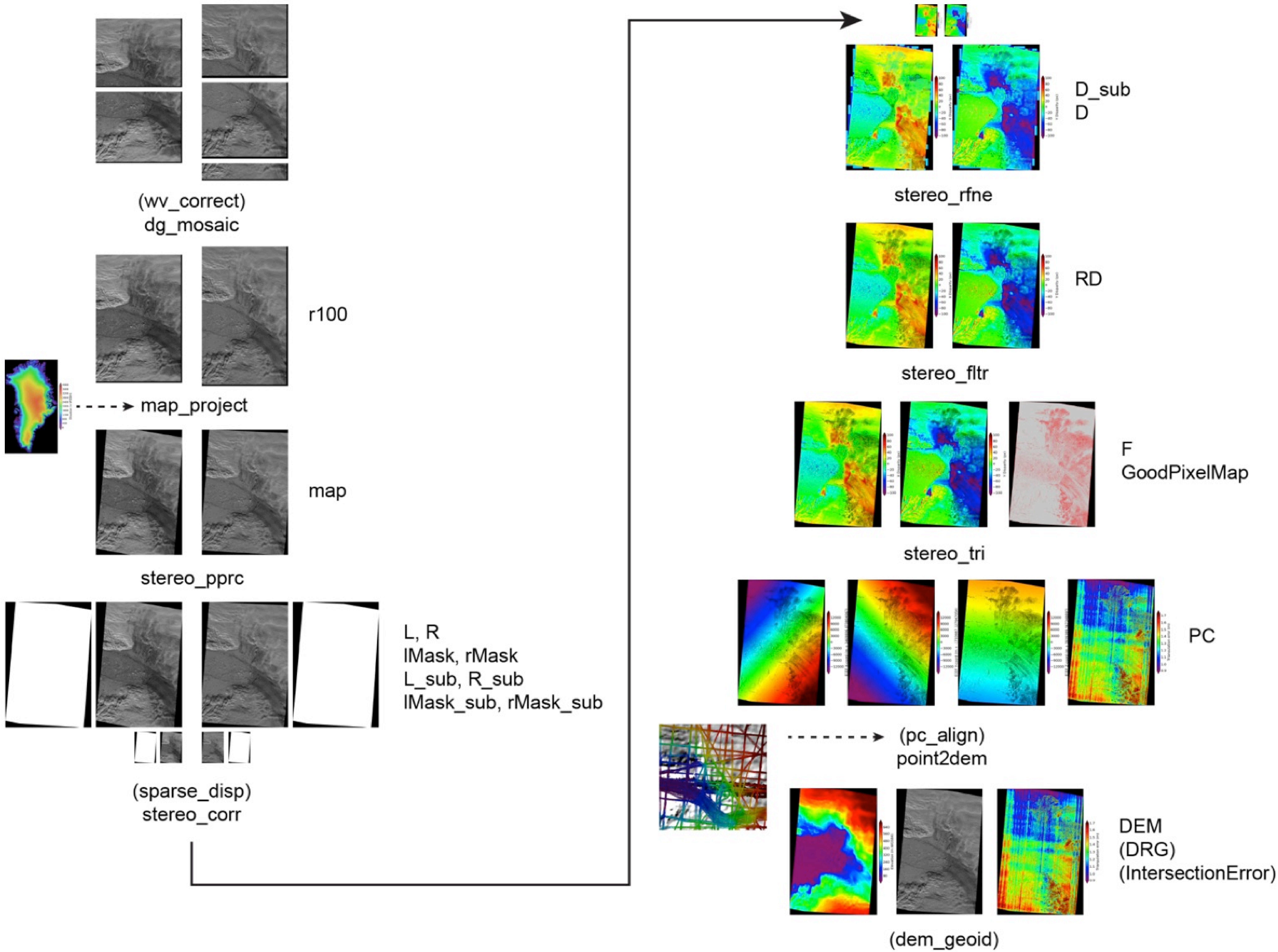
Ames Stereo Pipeline

- Automated, open-source, command-line tools
- Mars Pathfinder (1997)
- NASA planetary orbiters (2008)
- Commercial stereo (2012)
- C++/Python, multithreaded, memory-efficient, scalable
- Pleiades Supercomputer
- Binaries for Linux/OSX
- Source available on github



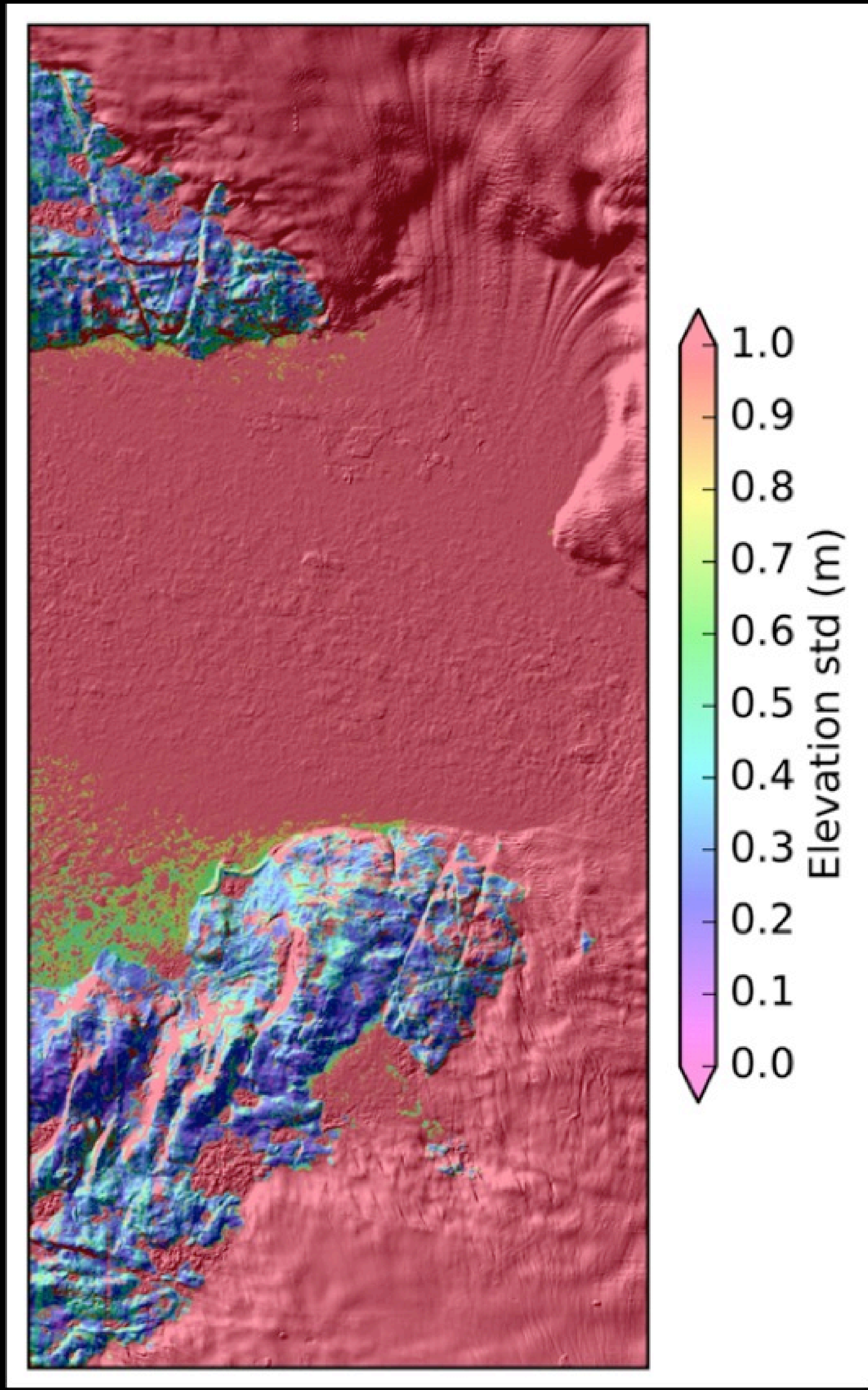


Top: Apollo Metric Camera DEM mosaic
Bottom: Gale Crater, Mars, MRO CTX DEM Mosaic

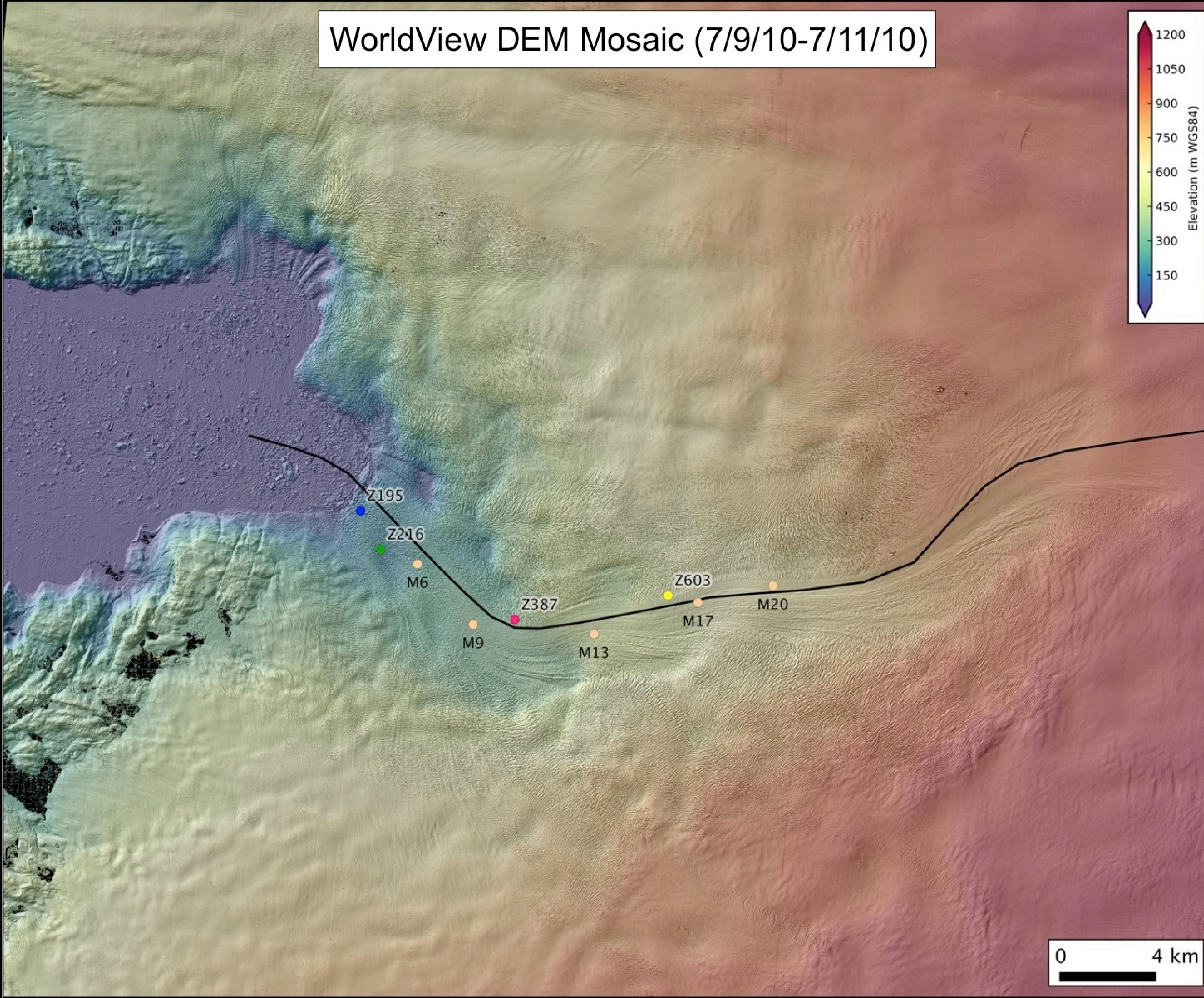

(wv_correct)
dg_mosaic
r100
map_project
map
stereo_pprc
L, R
lMask, rMask
L_sub, R_sub
lMask_sub, rMask_sub
(sparse_disp)
stereo_corr
D_sub
D
stereo_rfne
RD
stereo_fltr
F
GoodPixelMap
stereo_tri
PC
(pc_align)
point2dem
DEM
(DRG)
(IntersectionError)
(dem_geoid)

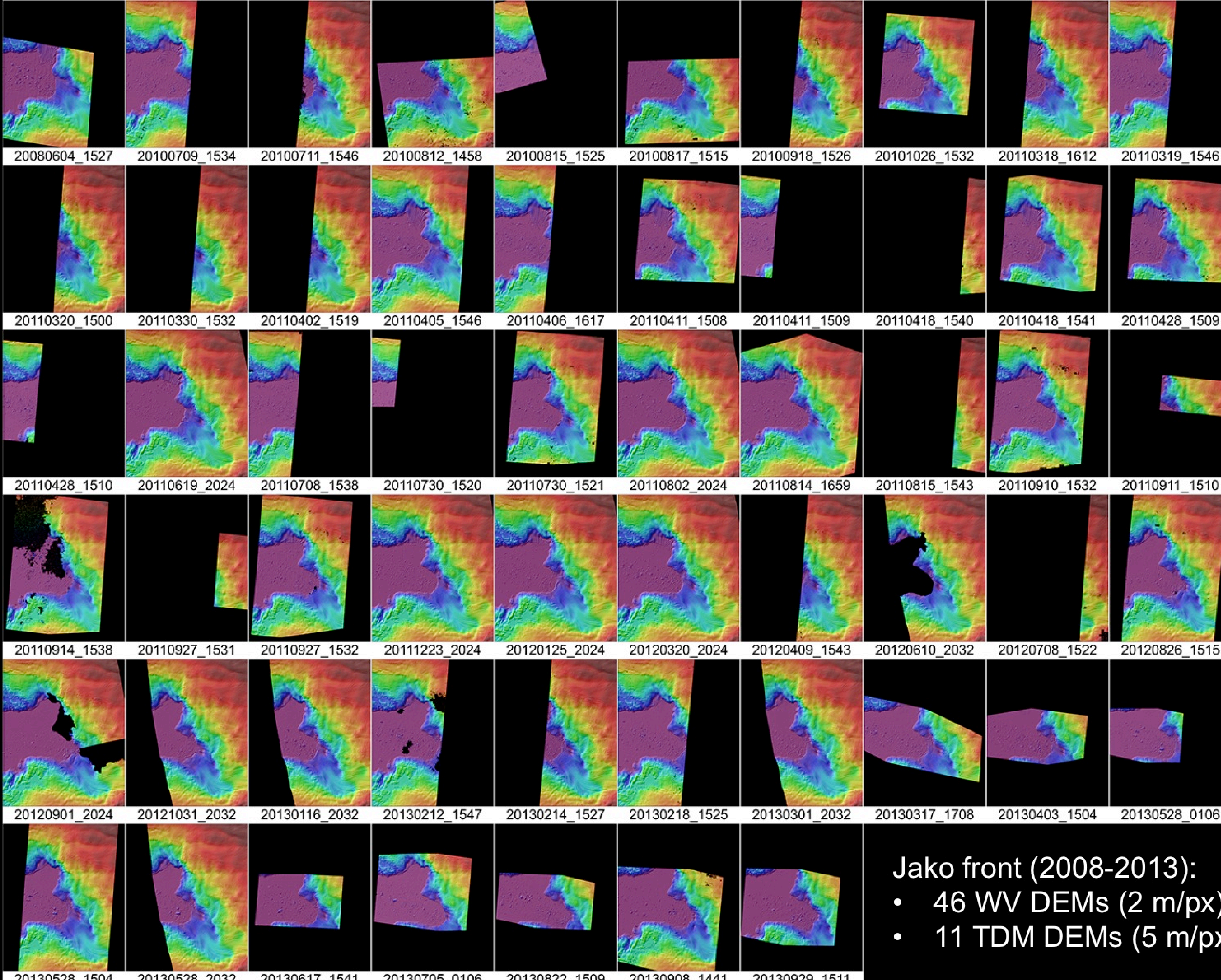
ASP + WorldView FAQ

- Processing time:
  - ~0.5-24 hr on 8-core workstation
- DEM posting: ~2 m/px
- Accuracy:
  - Uncorrected vert/horiz accuracy: ~5 m
  - Corrected/relative accuracy: <1 m



~20-40 cm standard deviation over bedrock for 31 co-registered DEMs

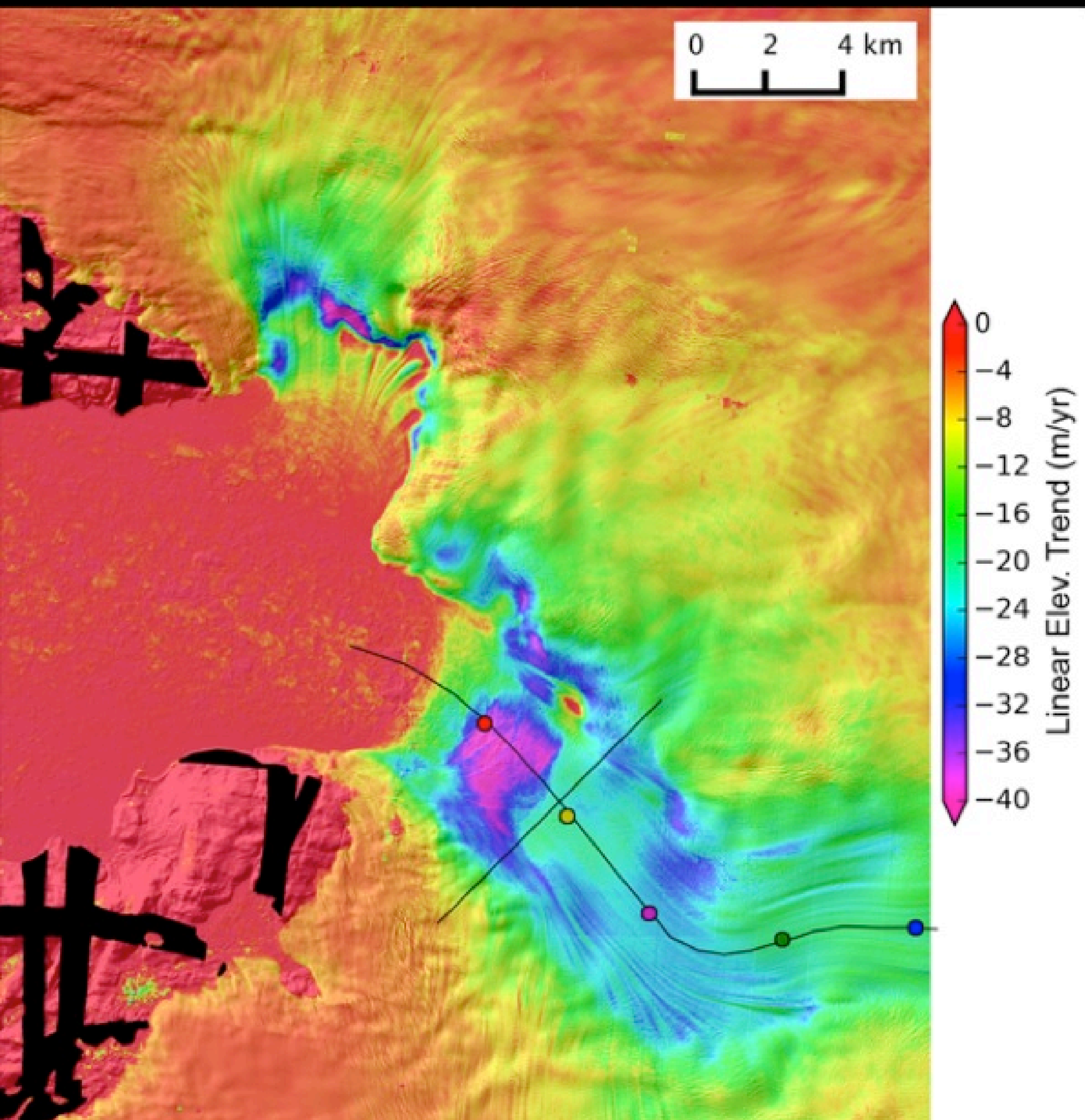

WorldView DEM Mosaic (7/9/10-7/11/10)
1200
1050
900
750
600
450
300
150
Elevation (m WGS84)
Z195
Z216
M6
Z387
M9
M13
Z603
M17
M20
0
4 km

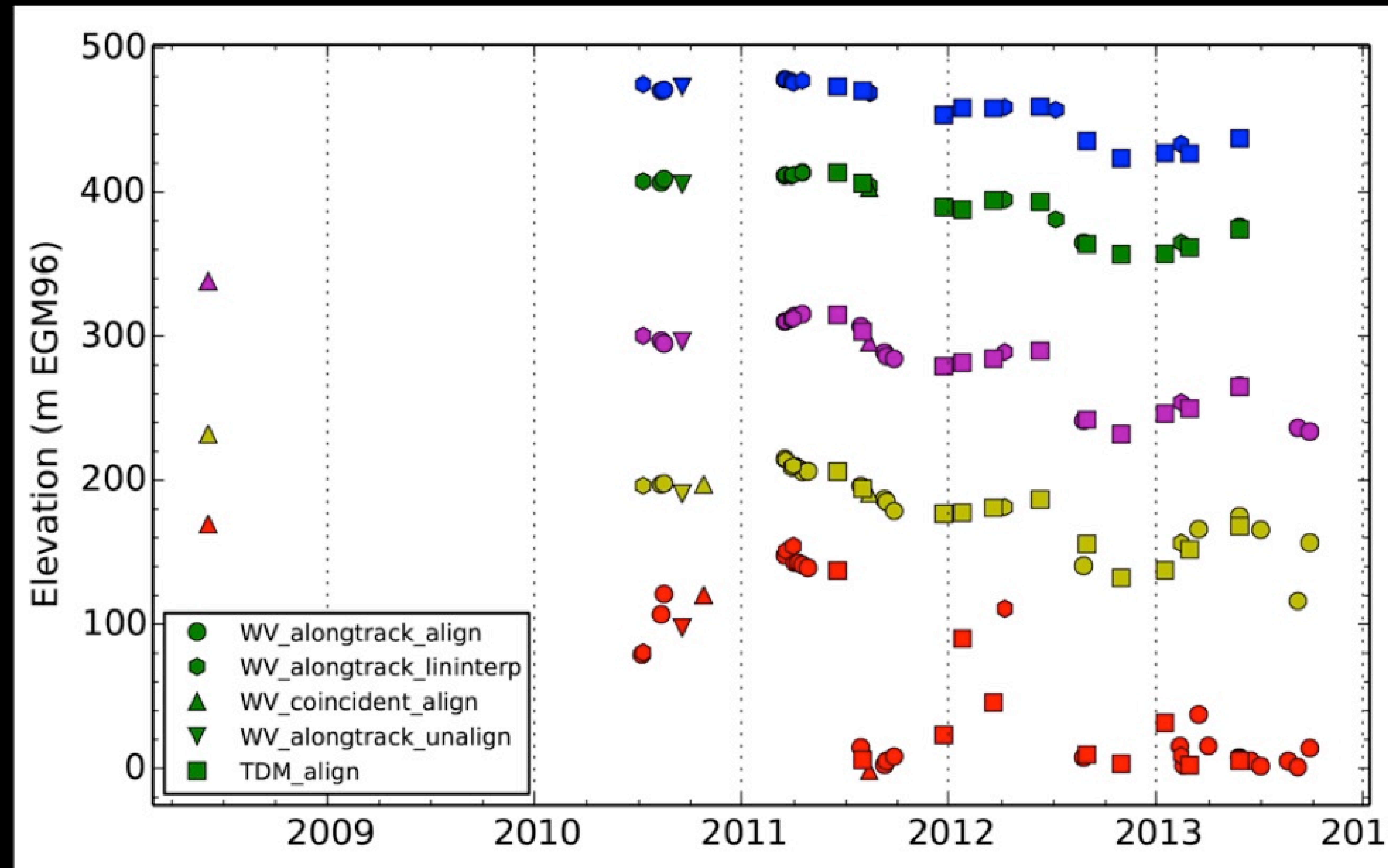


Jako front (2008-2013):

- 46 WV DEMs (2 m/px)
- 11 TDM DEMs (5 m/px)

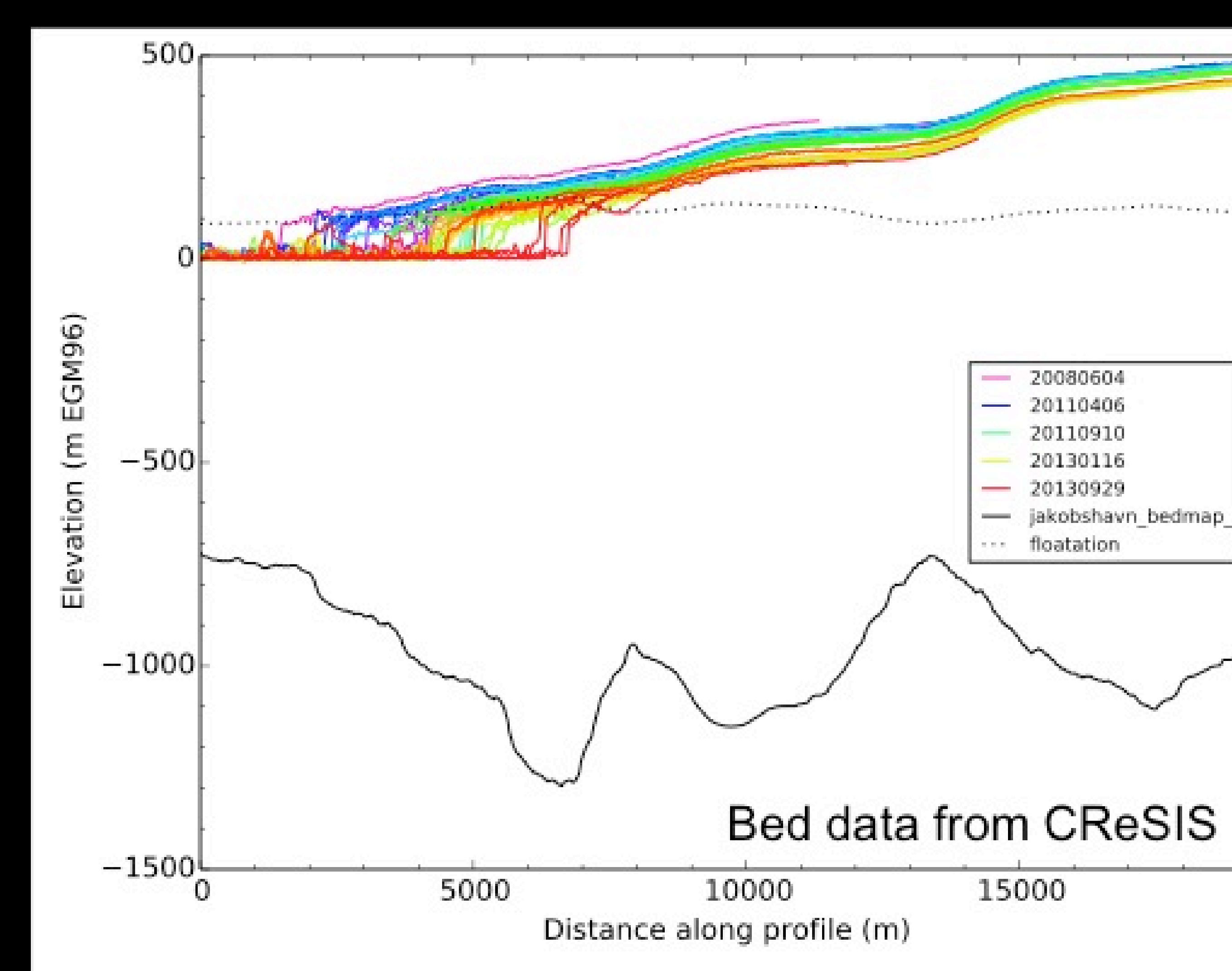
Interannual/Seasonal Variability

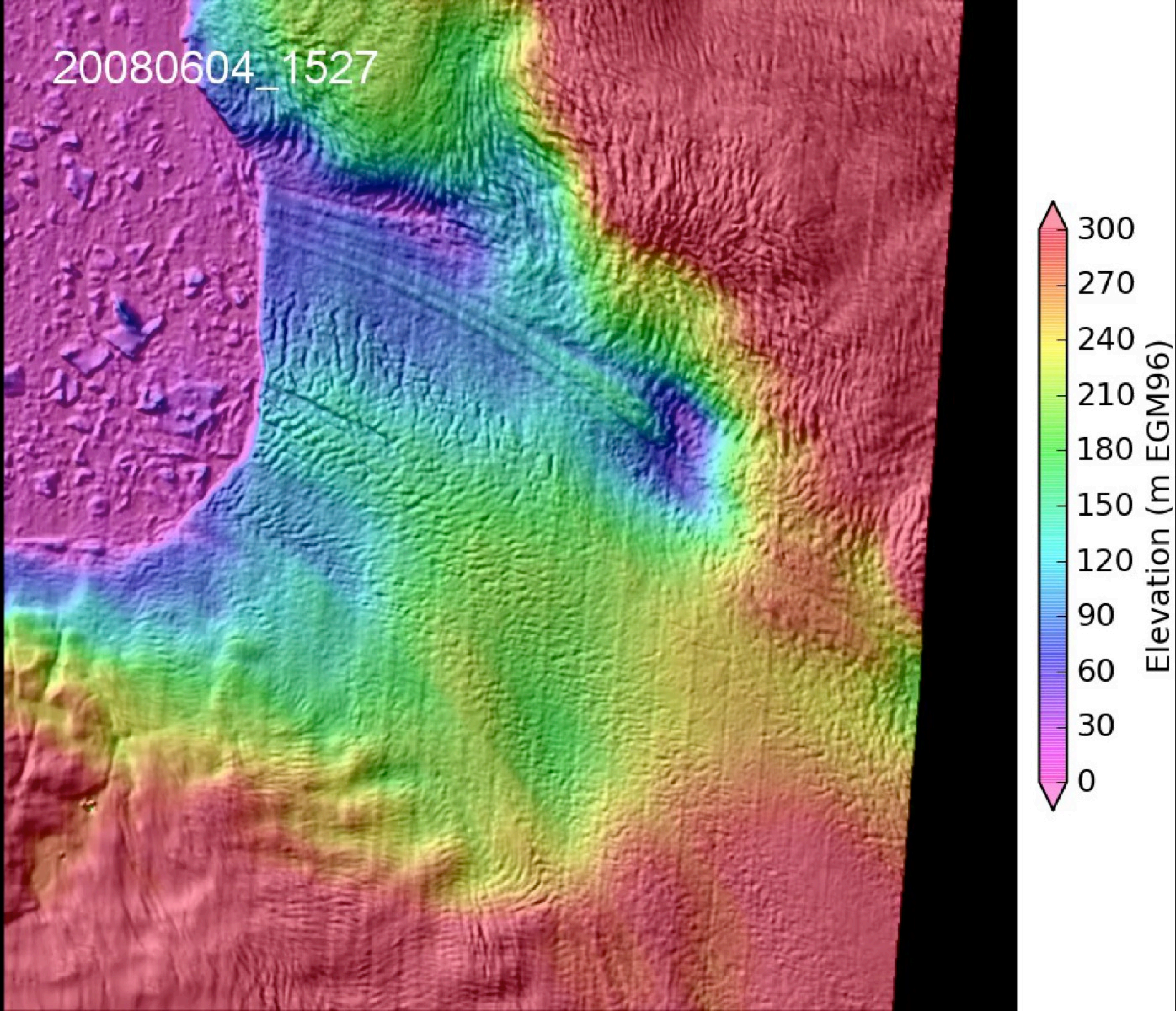




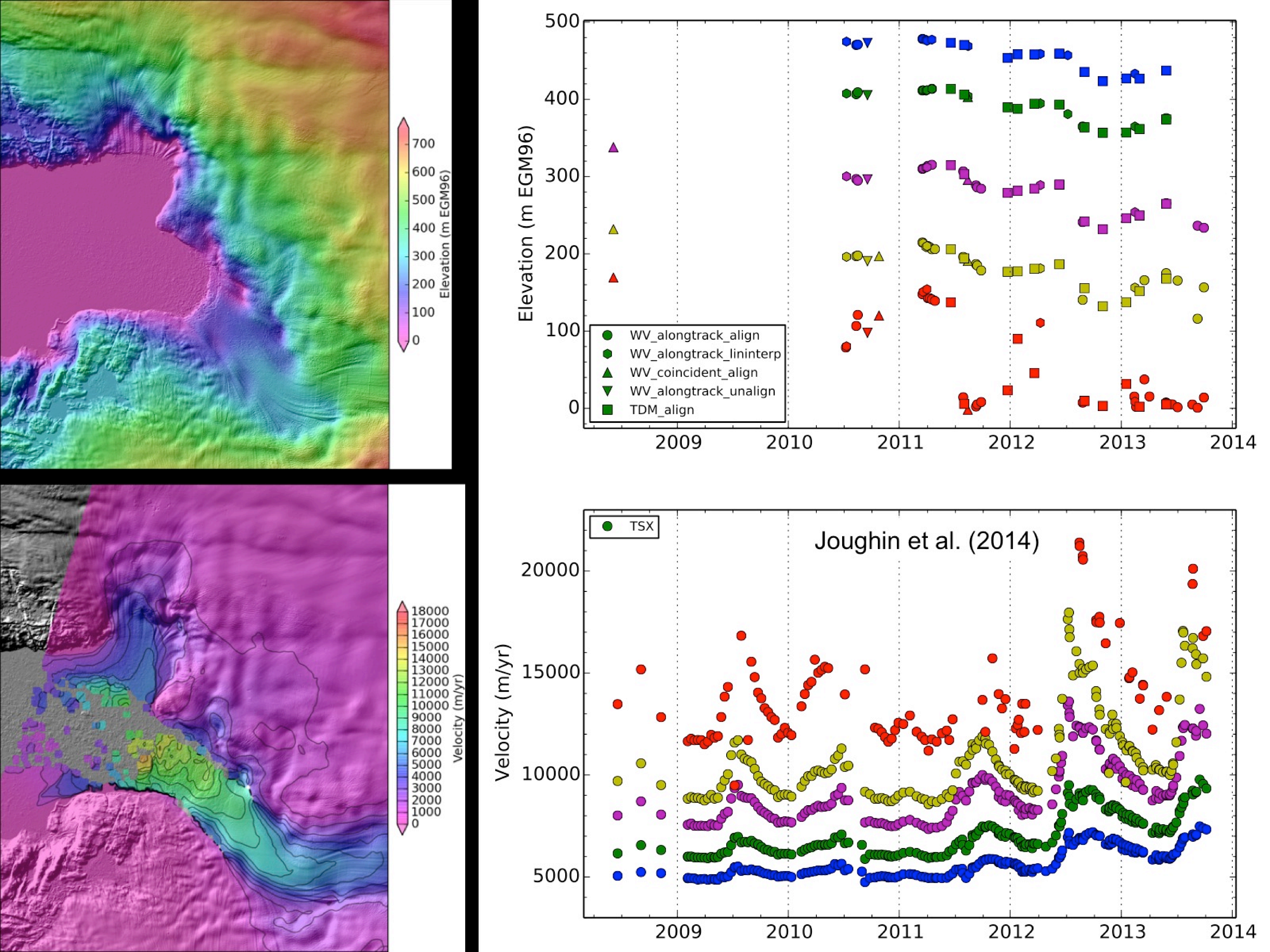
2008-2013: 57 high-res DEMs

- Interannual trends
  - Thinning over trunk of -15 to -40 m/yr
  - Thinning over grounded ice -2 to -4 m/yr (SMB)
- Seasonal cycle
  - Summer thinning of -30 to -50 m/yr
  - Winter thickening of +10 to +15 m/yr

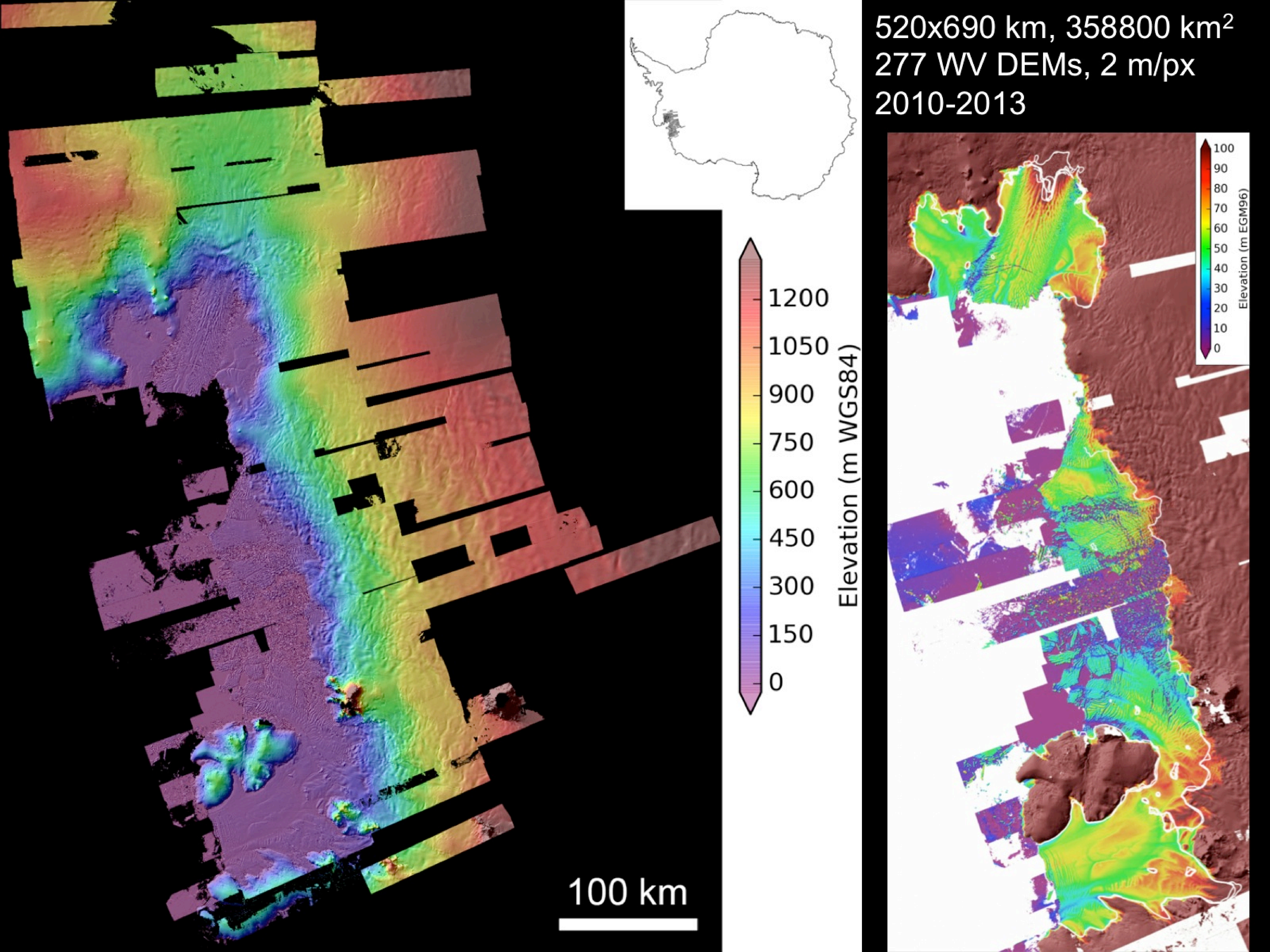


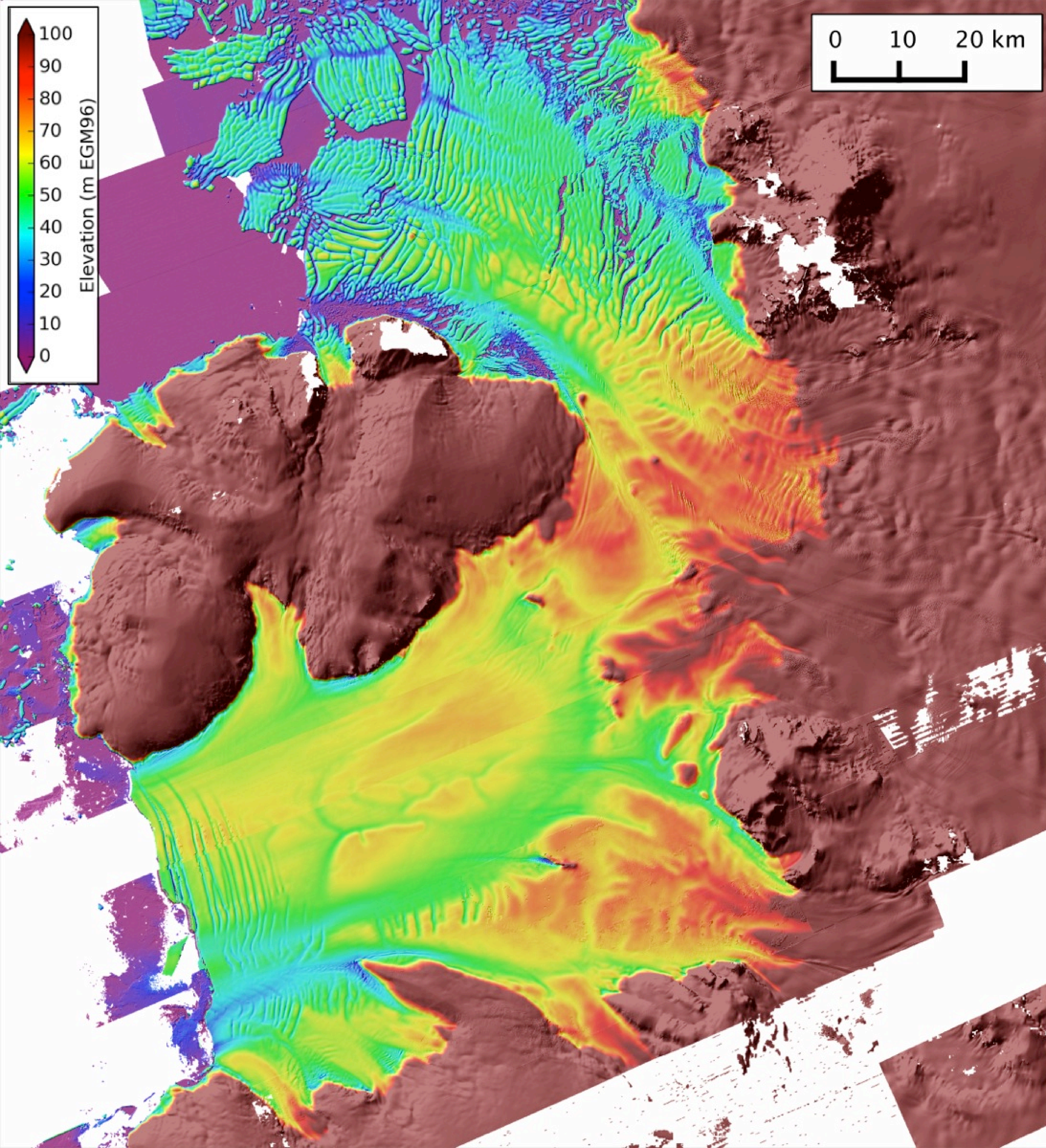


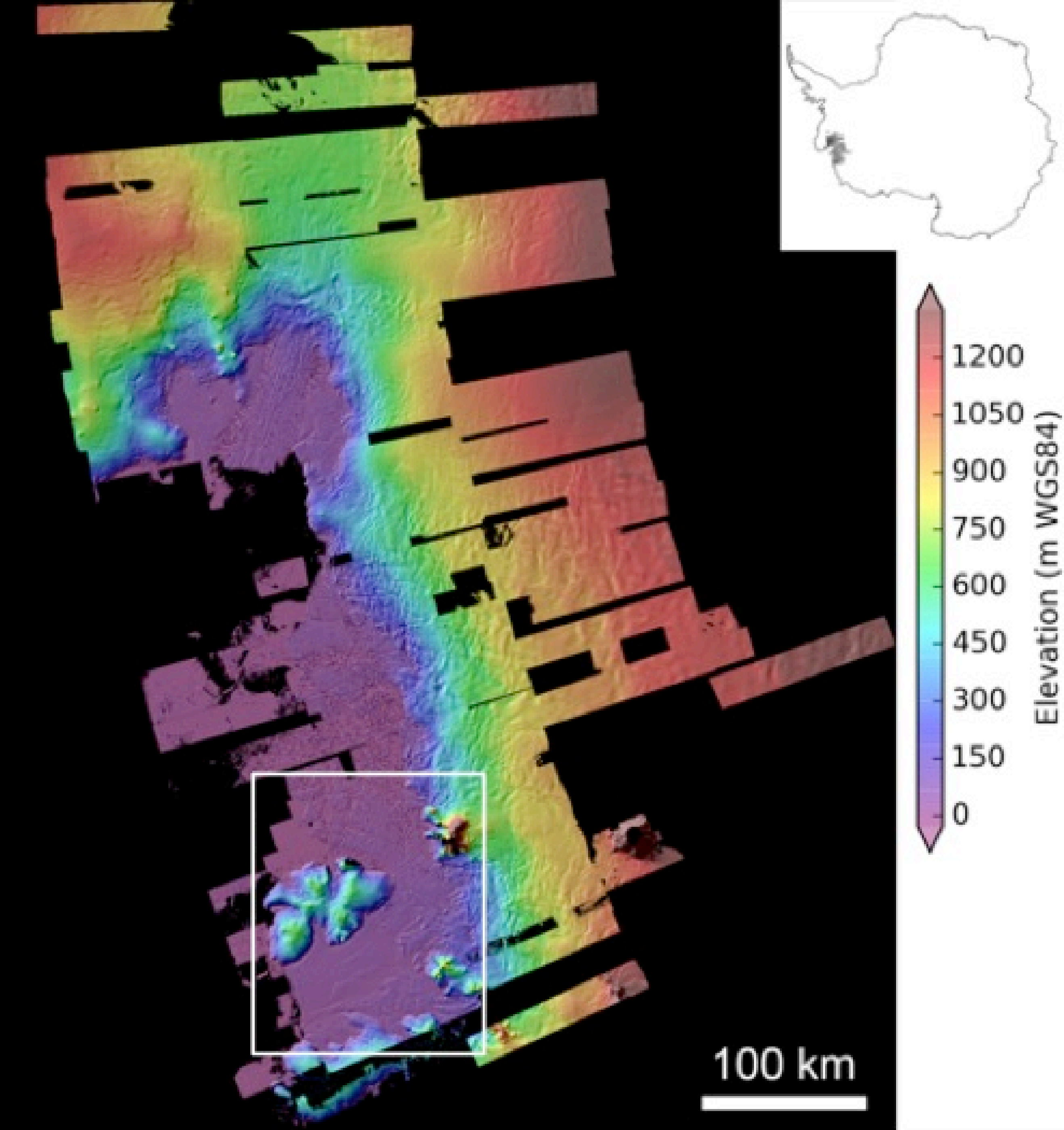
20080604_1527
300
270
240
210
180
150
120
90
60
30
0
Elevation (m EGM96)

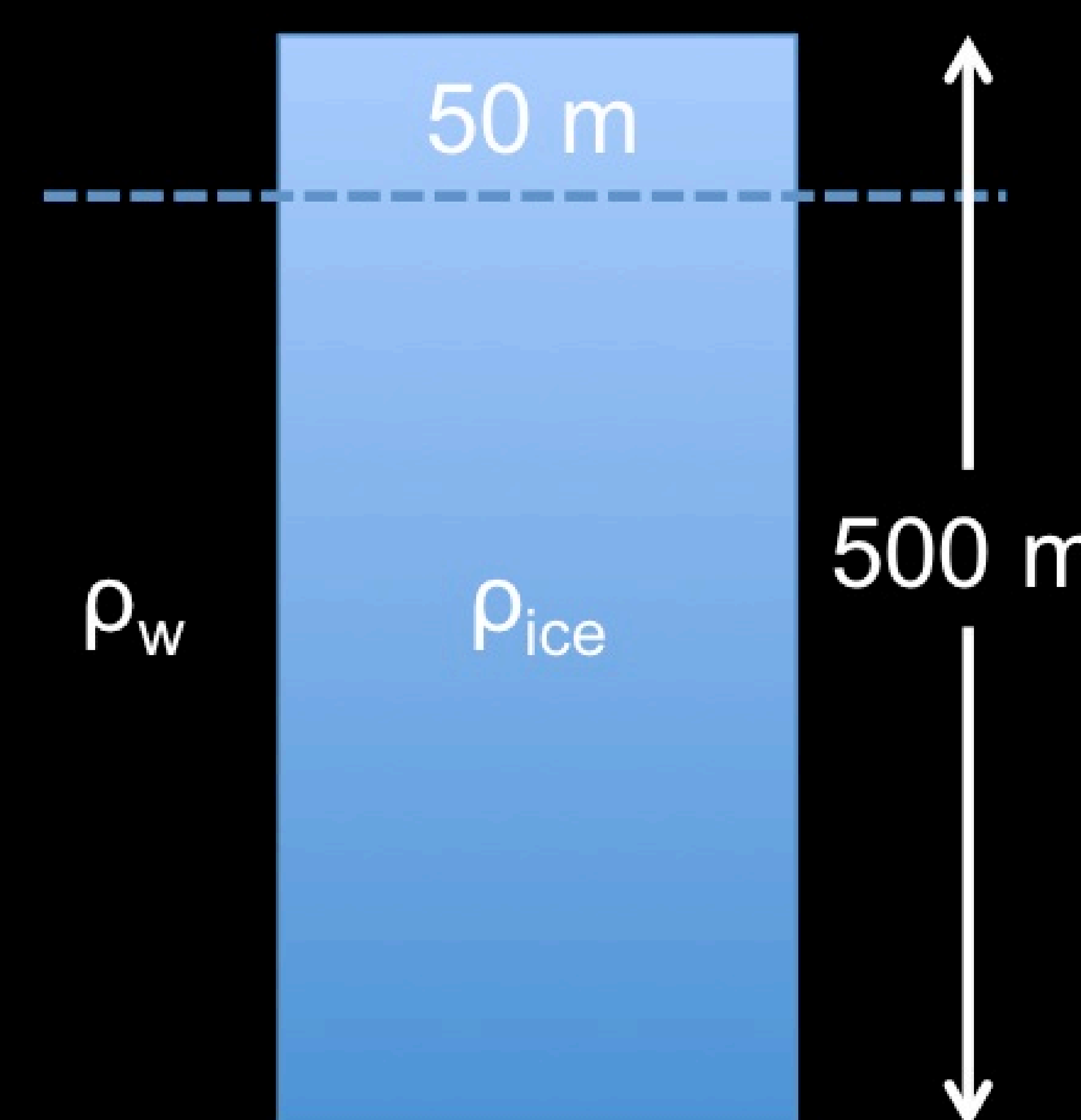


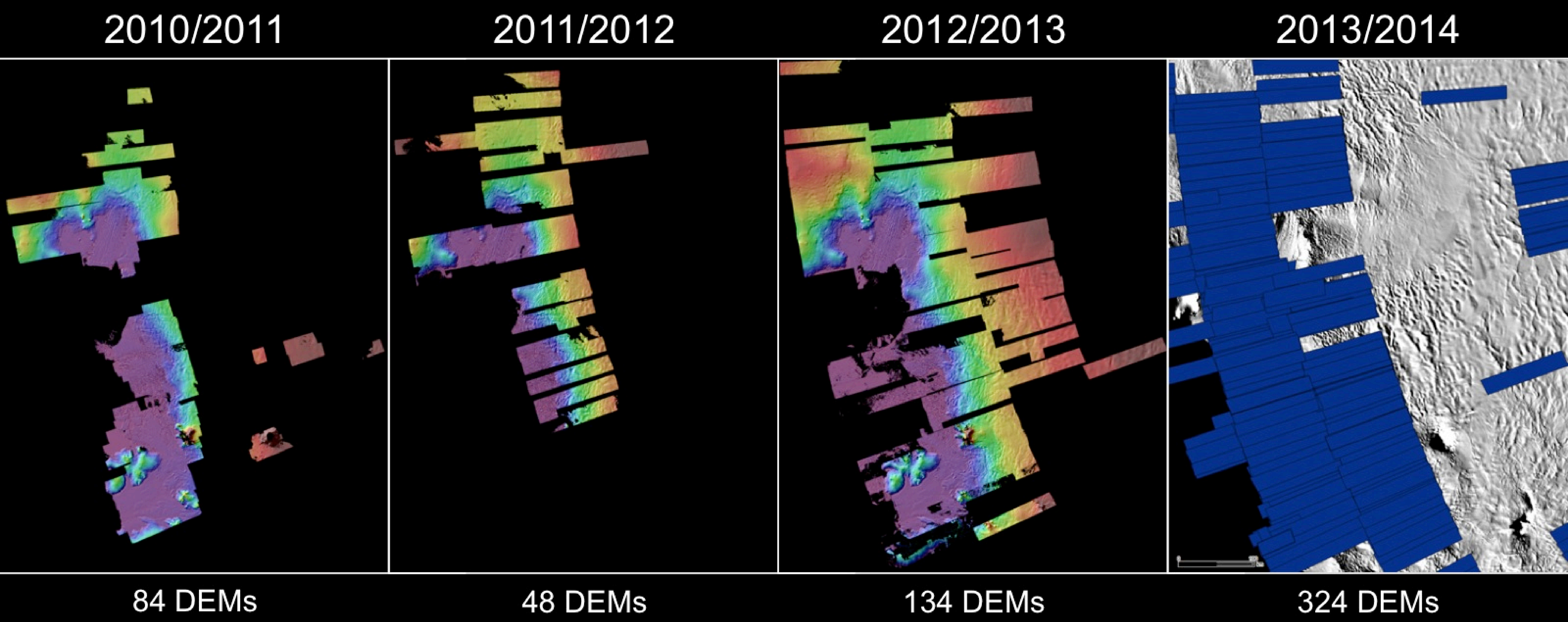
Elevation (m EGM96)
700
600
500
400
300
200
100
0
Velocity (m/yr)
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Elevation (m EGM96)
500
400
300
200
100
0
2009
2010
2011
2012
2013
2014
WV_alongtrack_align
WV_alongtrack_lininterp
WV_coincident_align
WV_alongtrack_unalign
TDM_align
TSX
Joughin et al. (2014)
Velocity (m/yr)
20000
15000
10000
5000
2009
2010
2011
2012
2013
2014


520x690 km, 358800 km^2
277 WV DEMs, 2 m/px
2010-2013
1200
1050
900
750
600
450
300
150
0
Elevation (m WGS84)
100 km
100
90
80
70
60
50
40
30
20
10
0
Elevation (m EGM96)

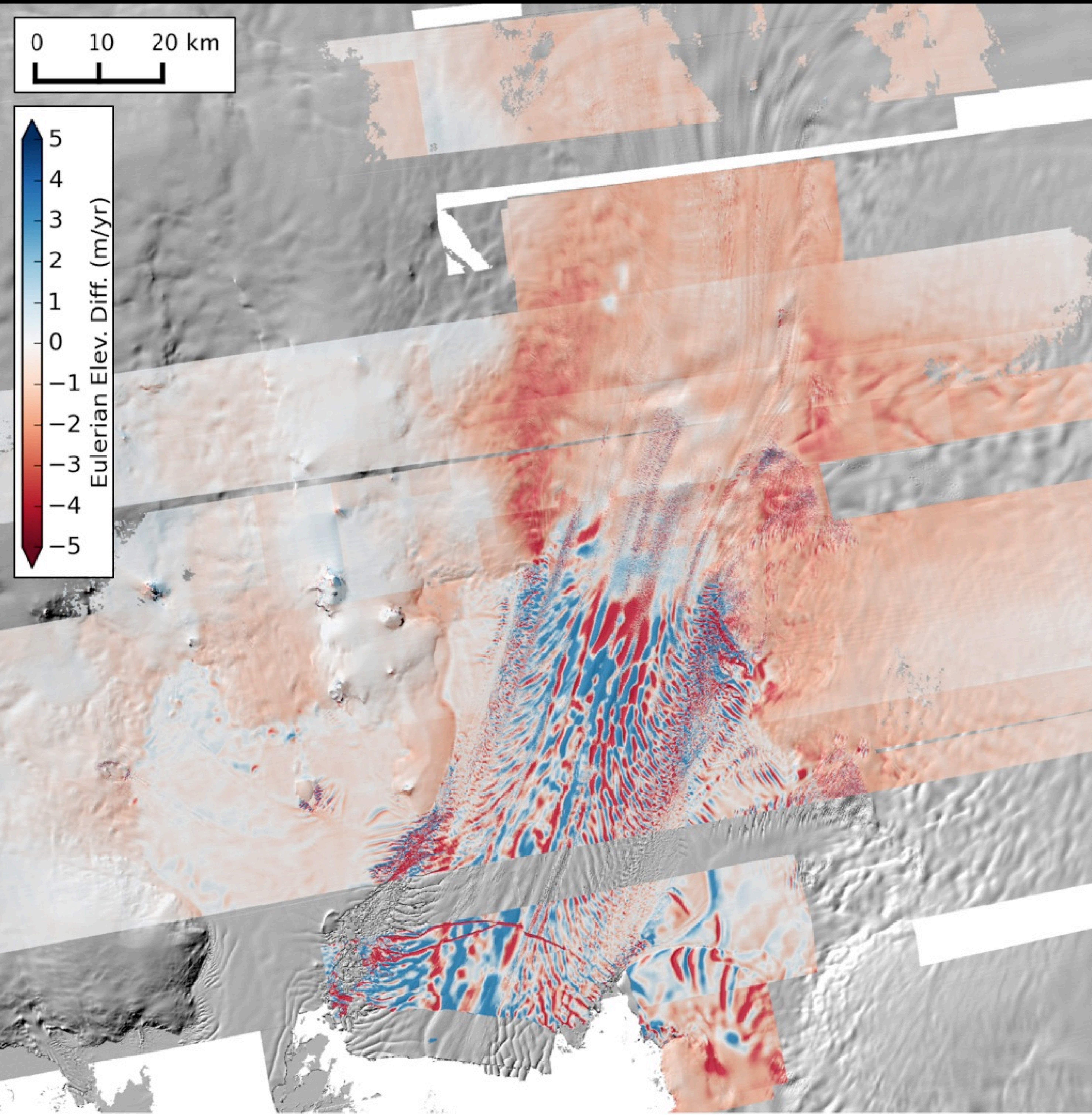

100
90
80
70
60
50
40
30
20
10
0
Elevation (m EGM96)
0 10 20 km

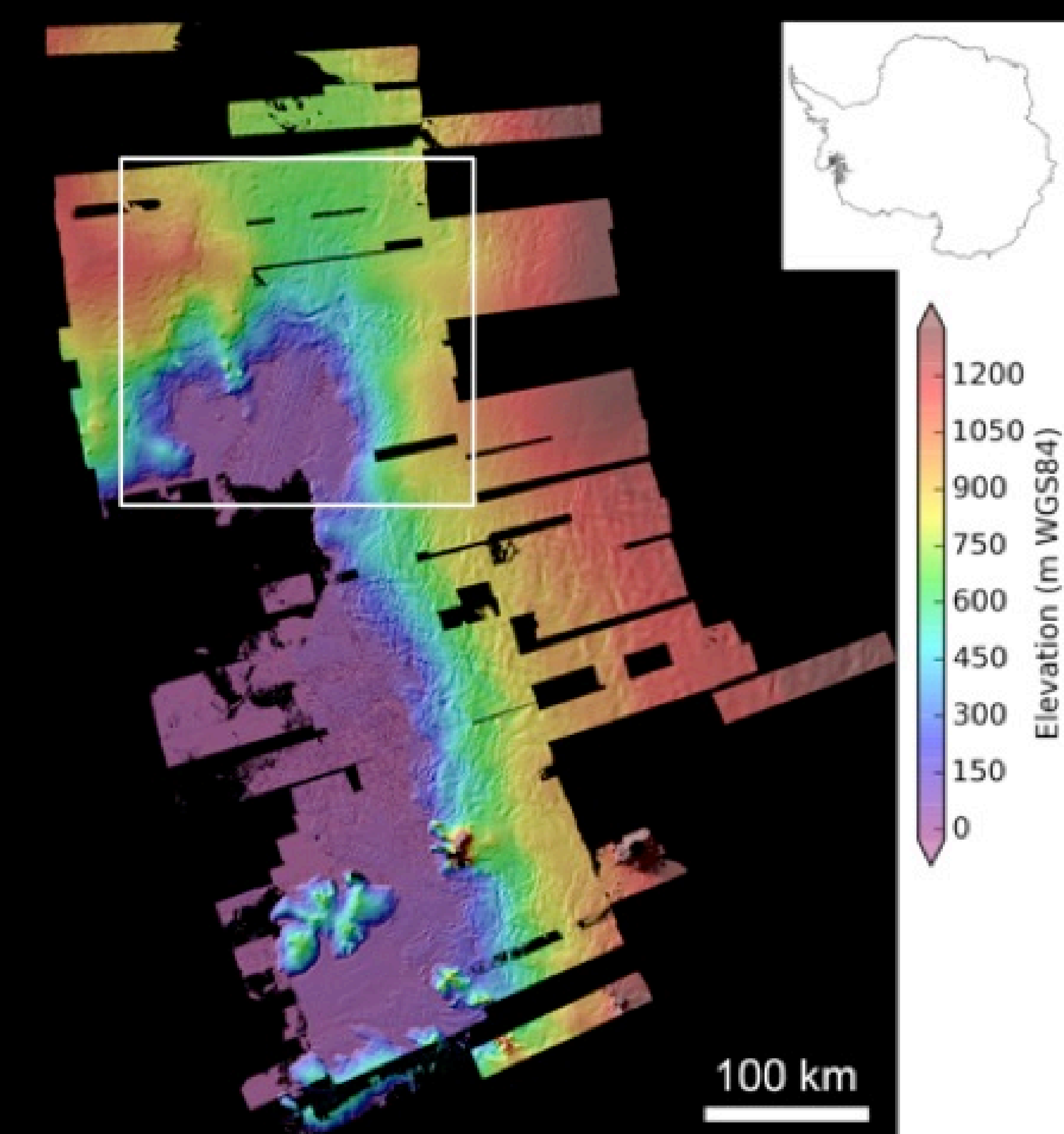

1200
1050
900
750
600
450
300
150
0
Elevation (m WGS84)
100 km

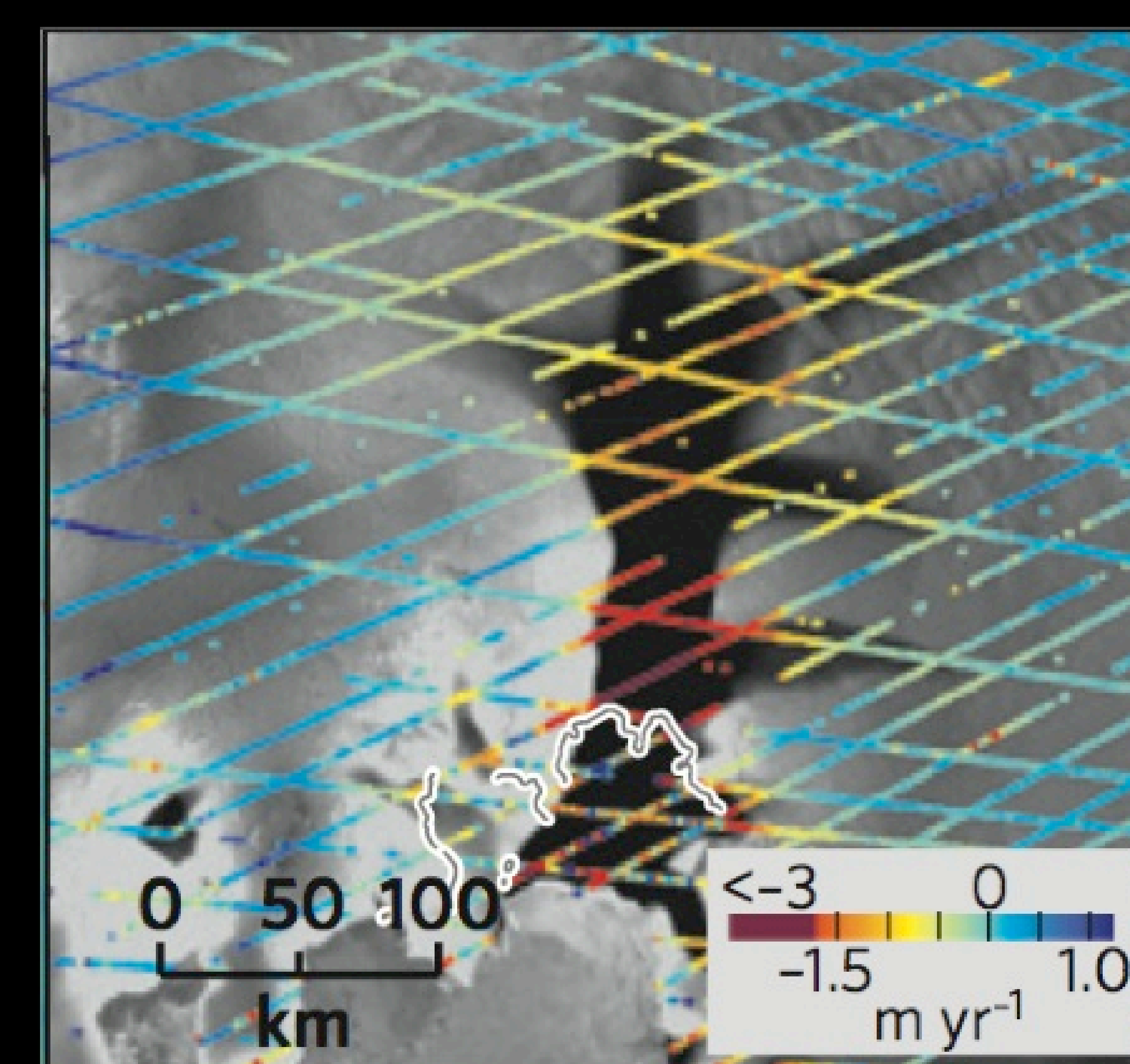

50 m
ρ_w
ρ_{ice}
500 m


2010/2011
2011/2012
2012/2013
2013/2014
84 DEMs
48 DEMs
134 DEMs
324 DEMs

Pine Island Glacier
2010/2011 - 2012/2013
Eulerian dh/dt

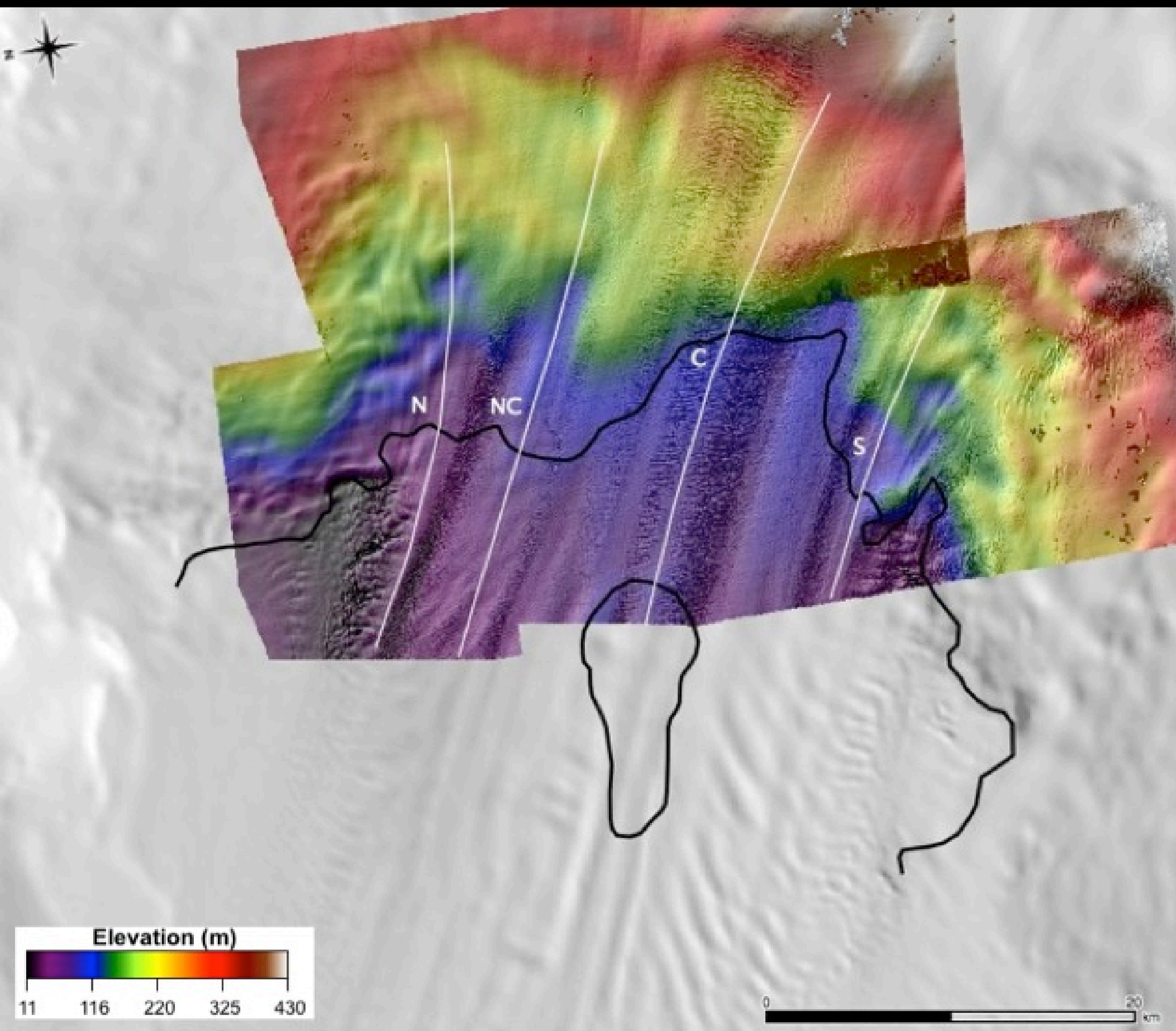




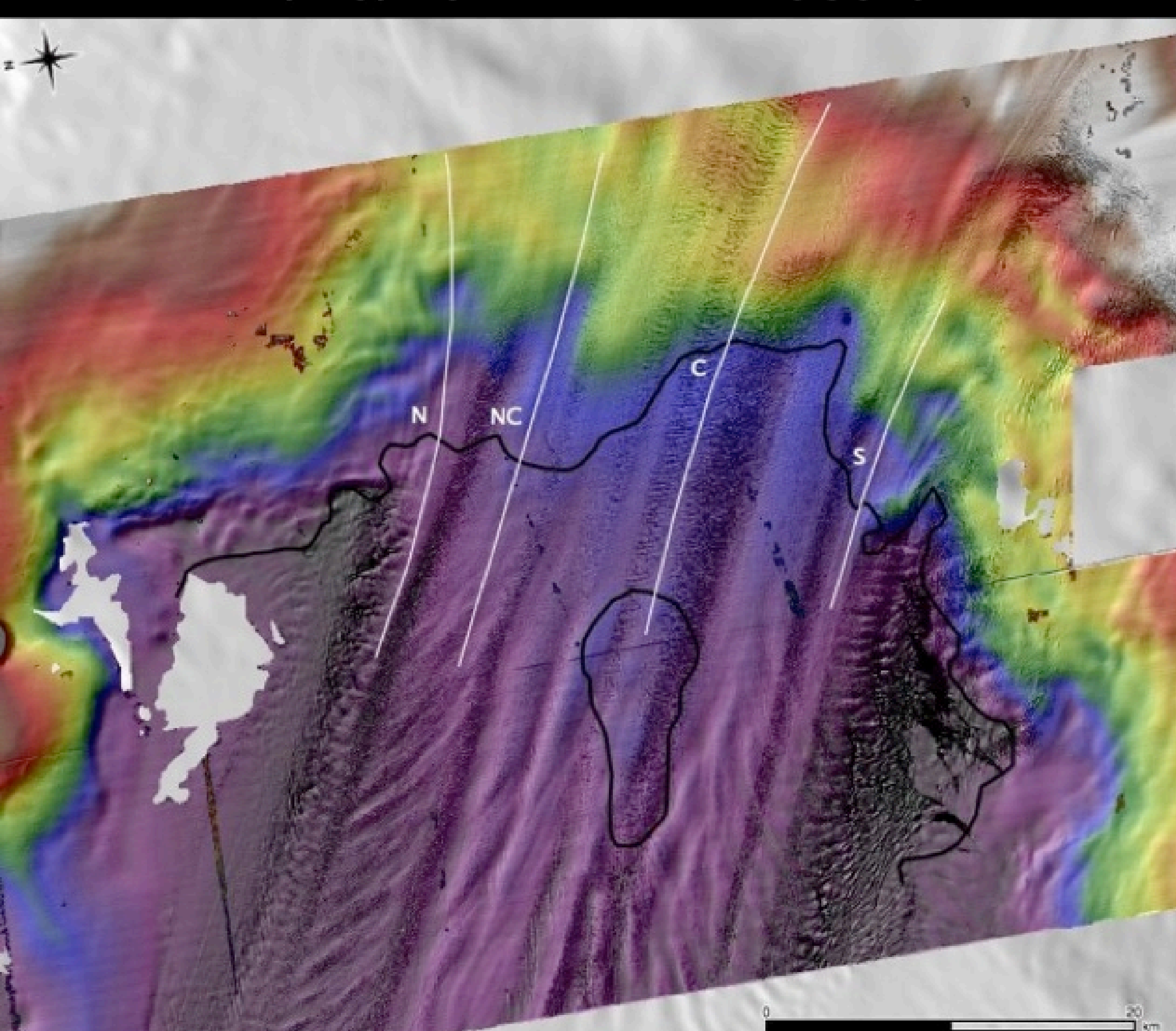


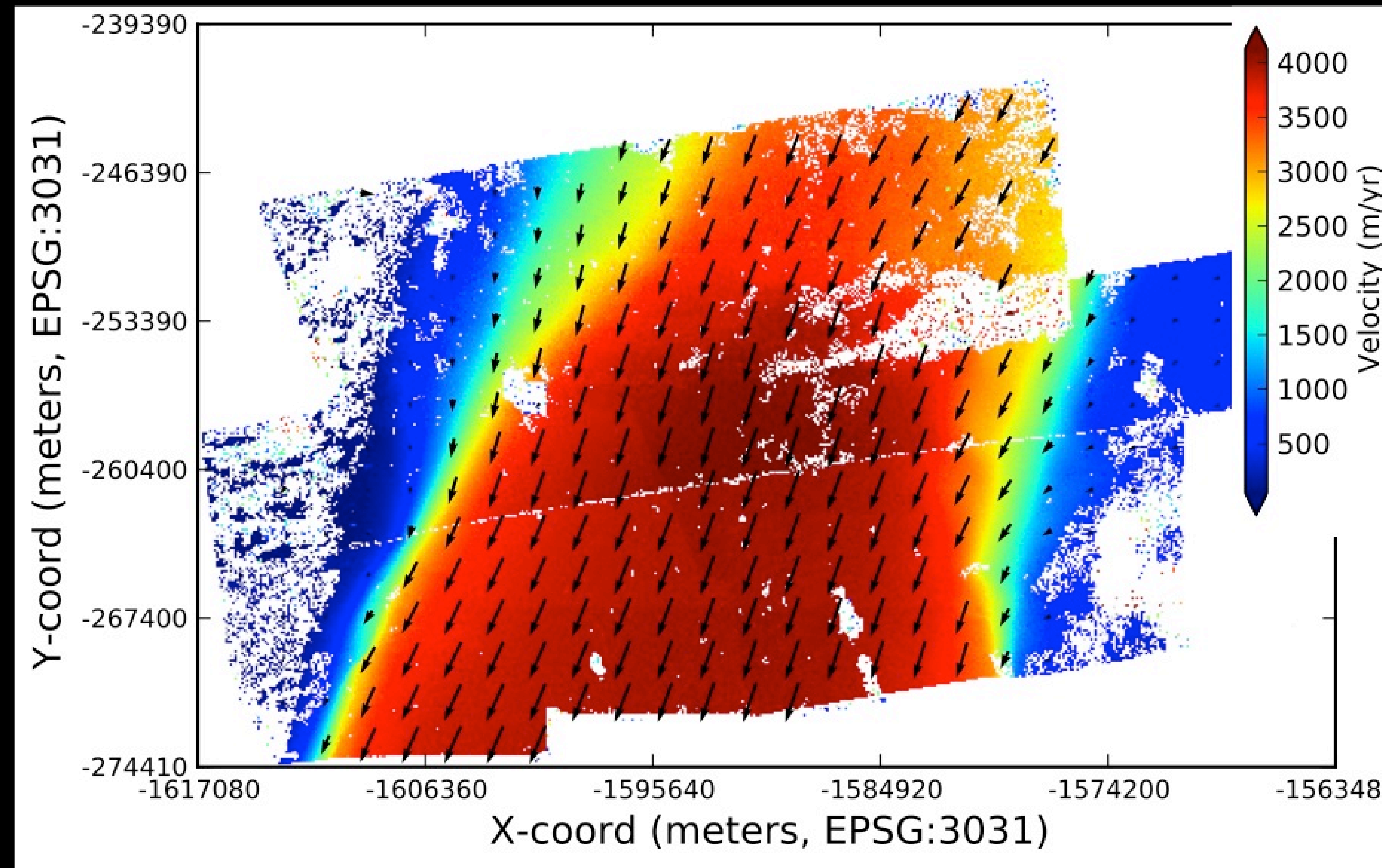
Velocity Map from DEM correlation
Pine Island Glacier, West Antarctica

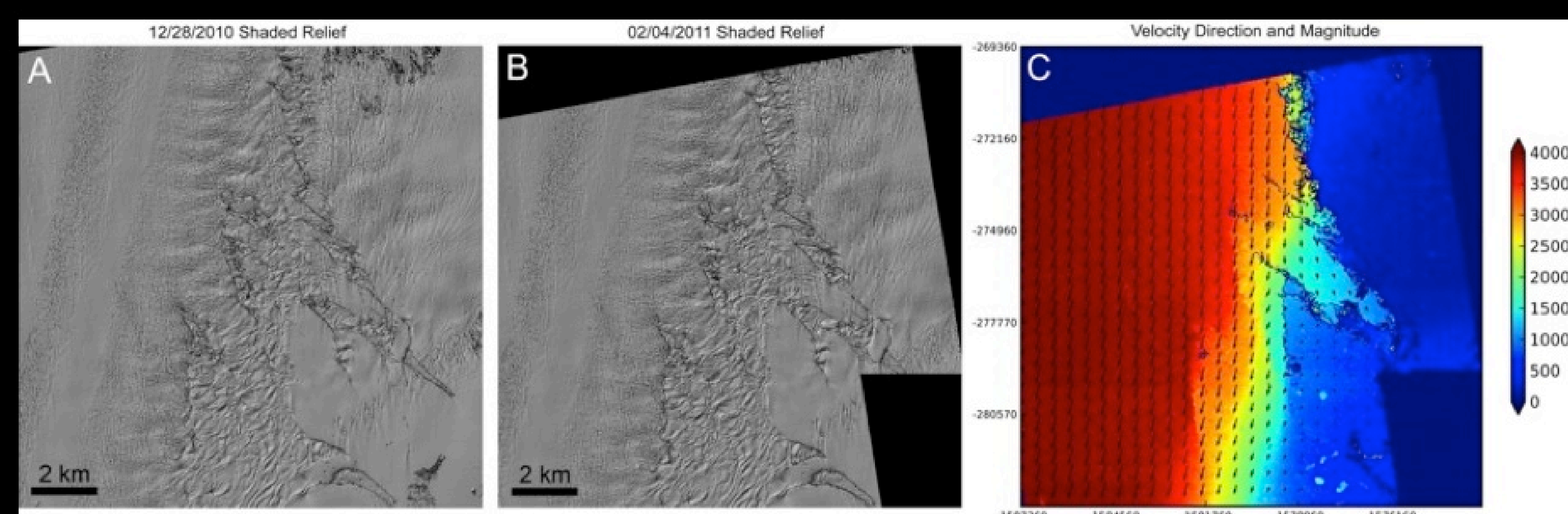
1/13/2011 DEM Mosaic



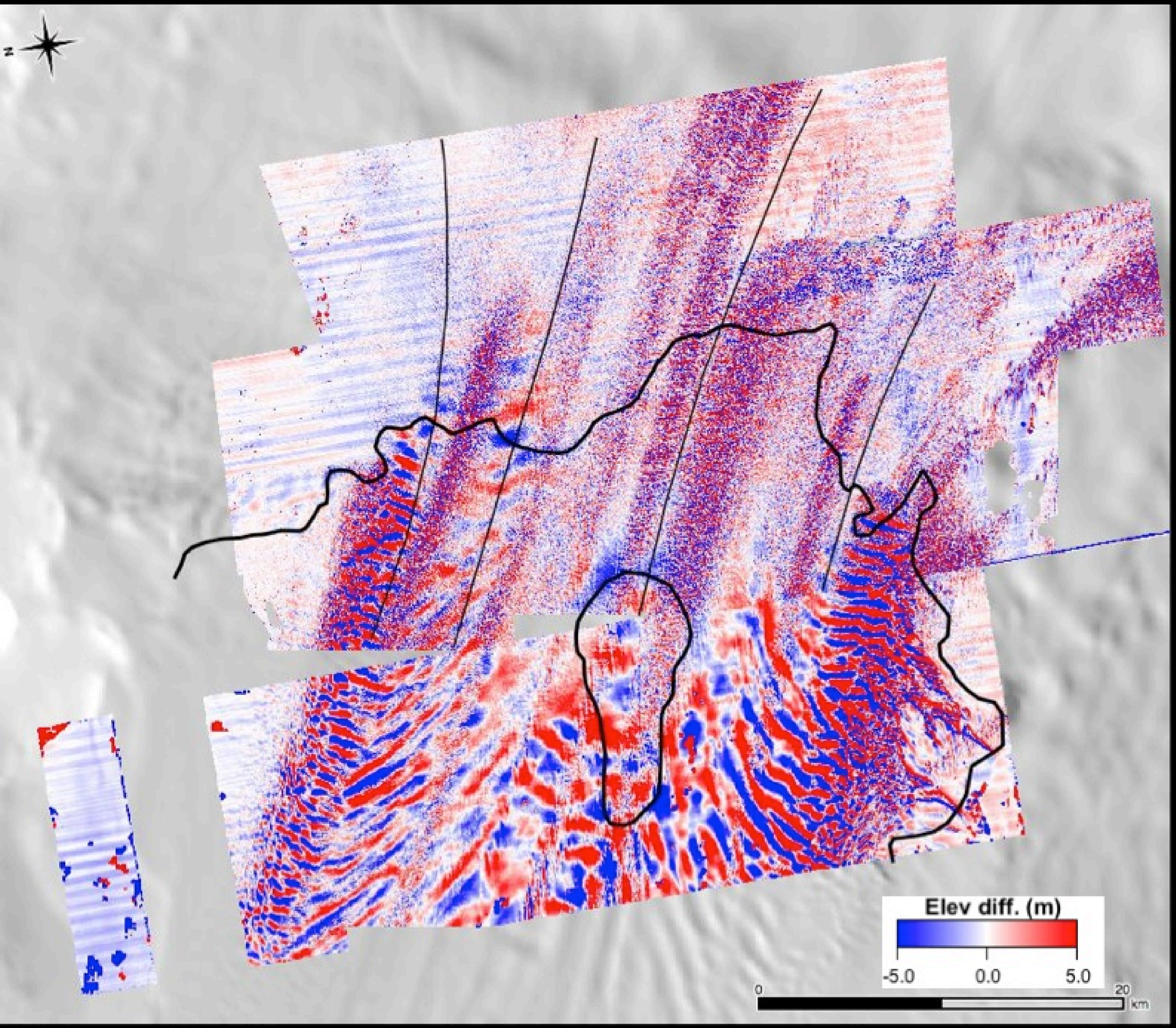
2/23/2011 DEM Mosaic



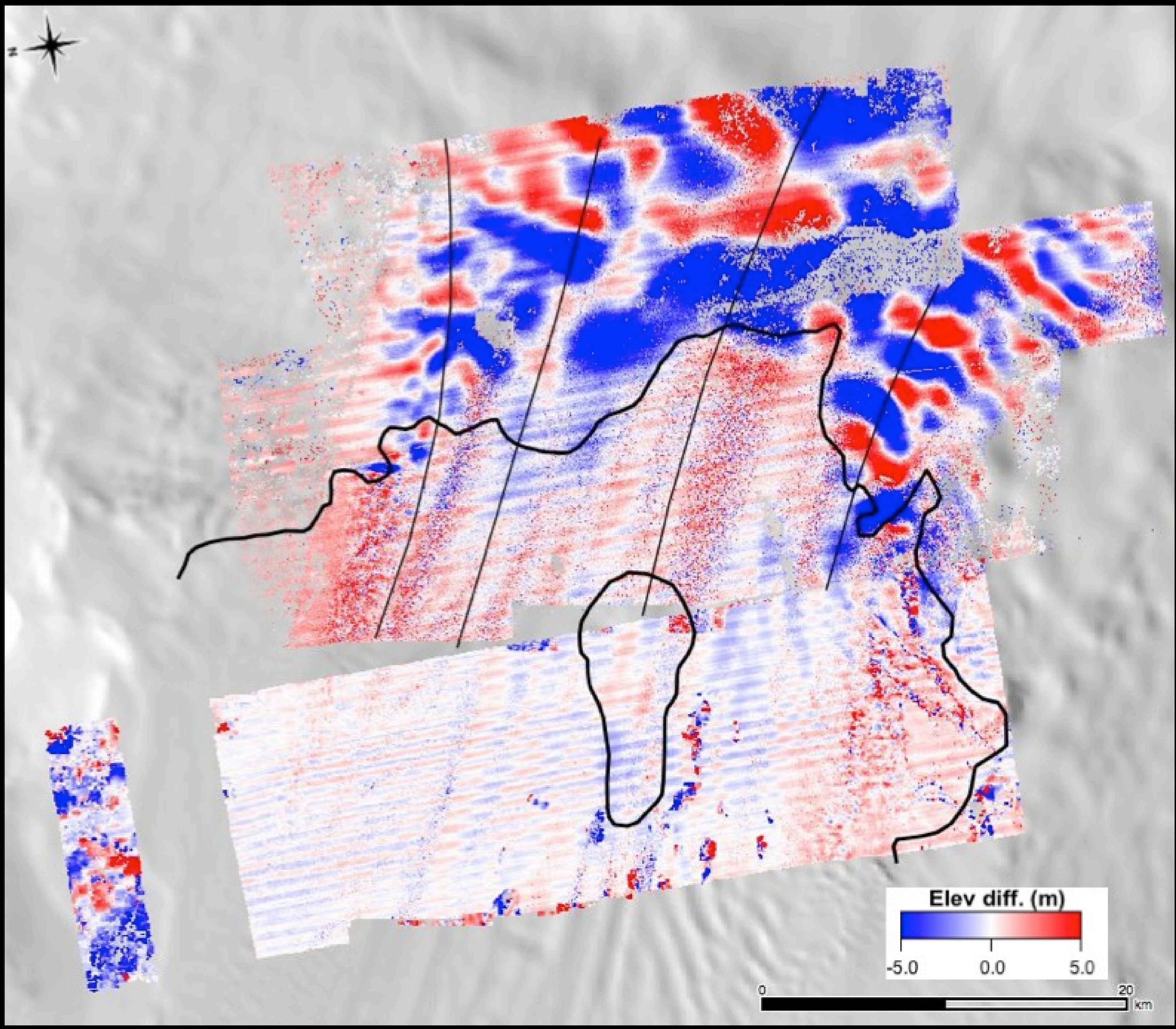




Eulerian Elevation Difference

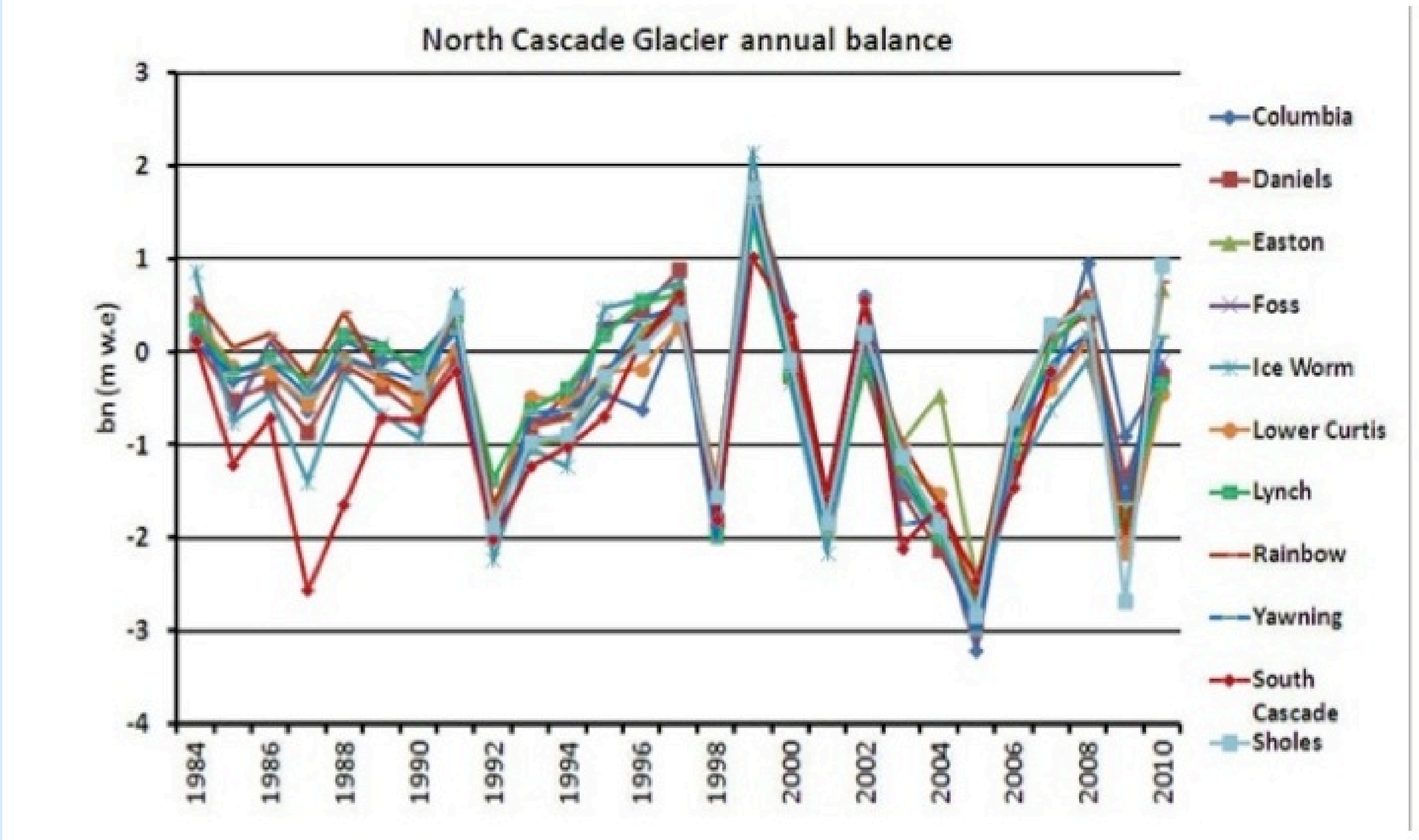


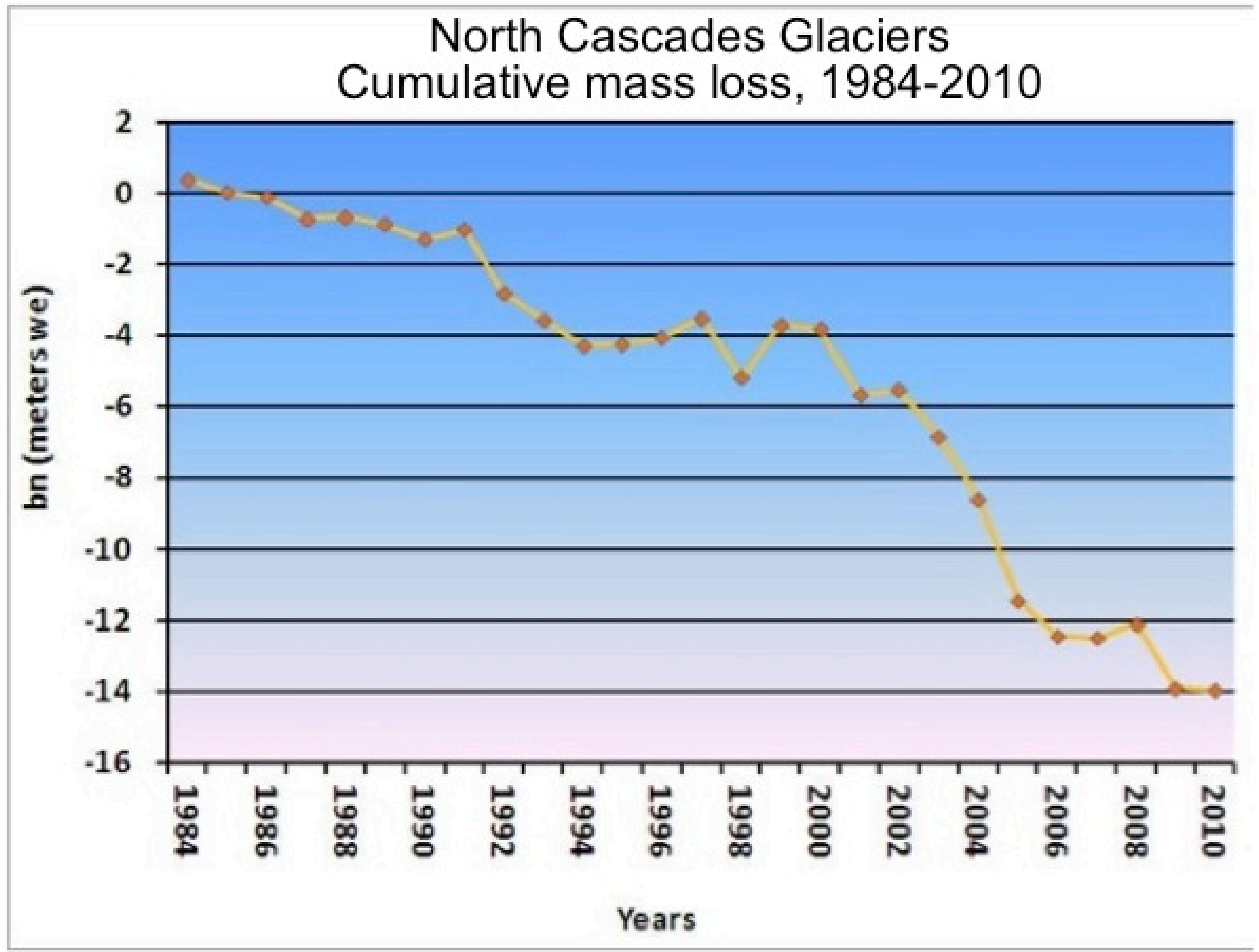
Lagrangian Elevation Difference



Motivation

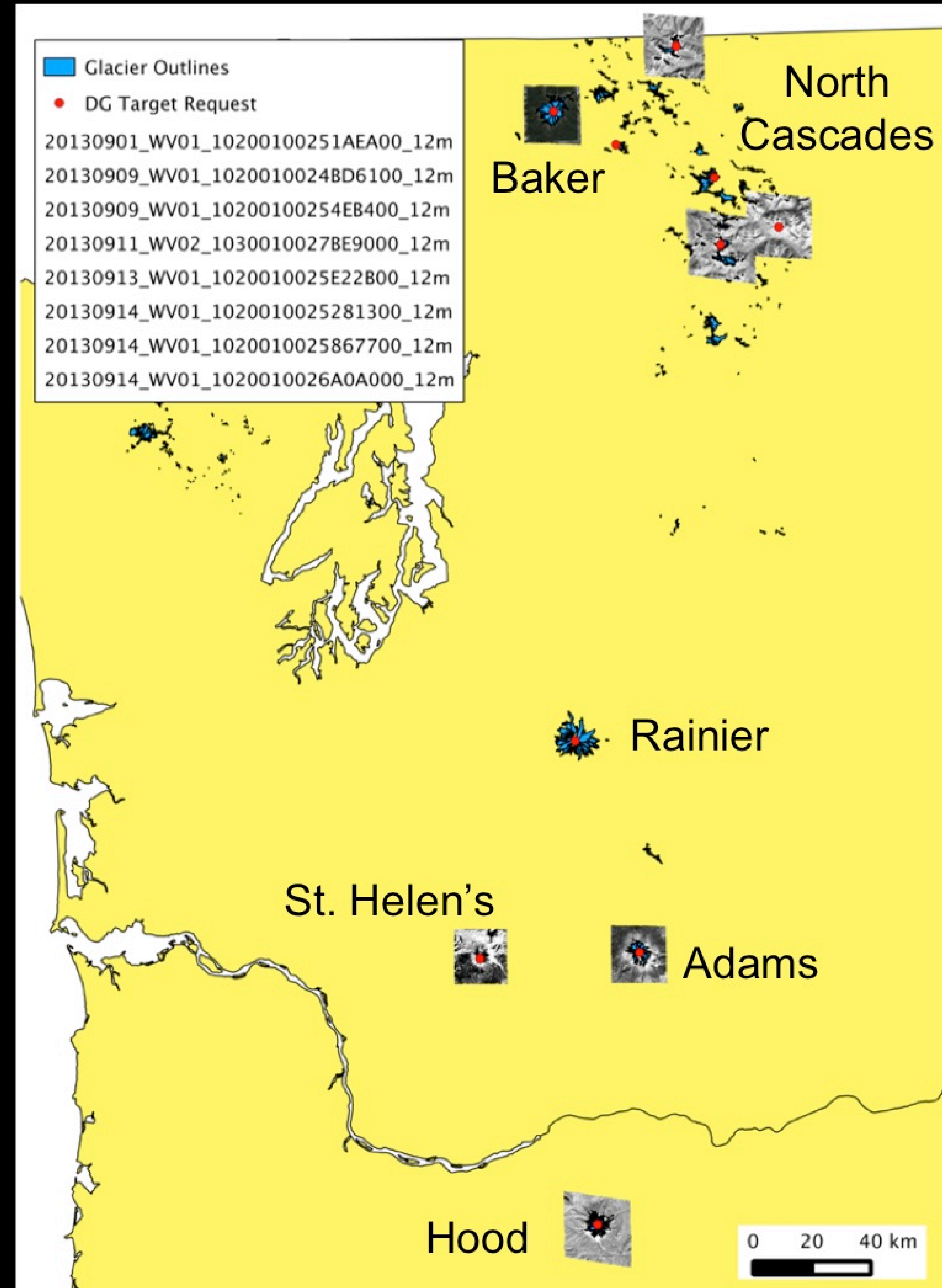
- Mountain glaciers are natural laboratories for studying fundamental glacial processes (e.g. subglacial drainage system evolution)
- Mt. St. Helen's – unique opportunity to study the birth and evolution of a glacier
- Long-term mass balance measurements provide valuable regional climate data
- Cascade glaciers currently in a state of disequilibrium
- Hazards – outburst floods, lahars, etc.



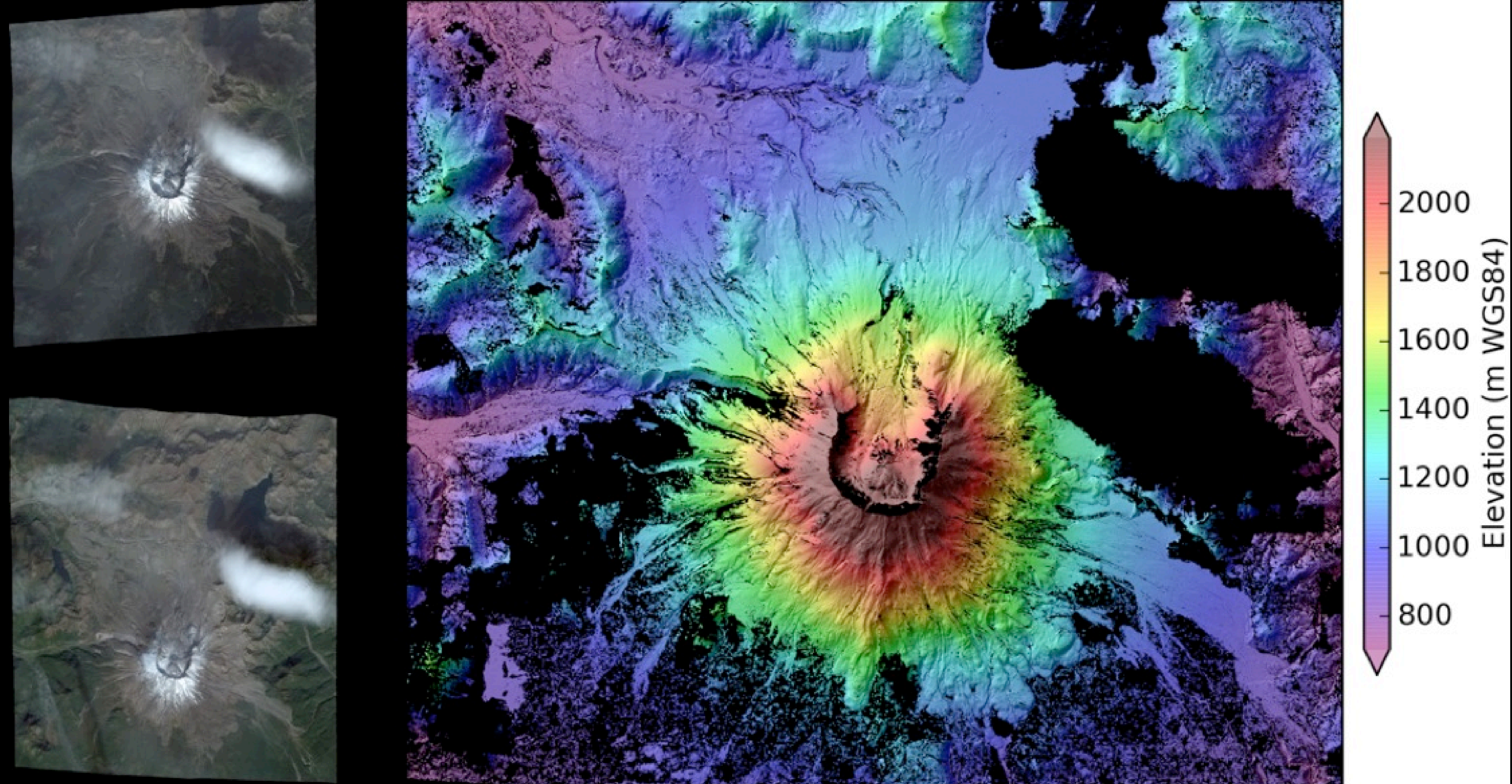


NORTH CASCADE GLACIER CLIMATE PROJECT
http://www.nichols.edu/departments/glacier/

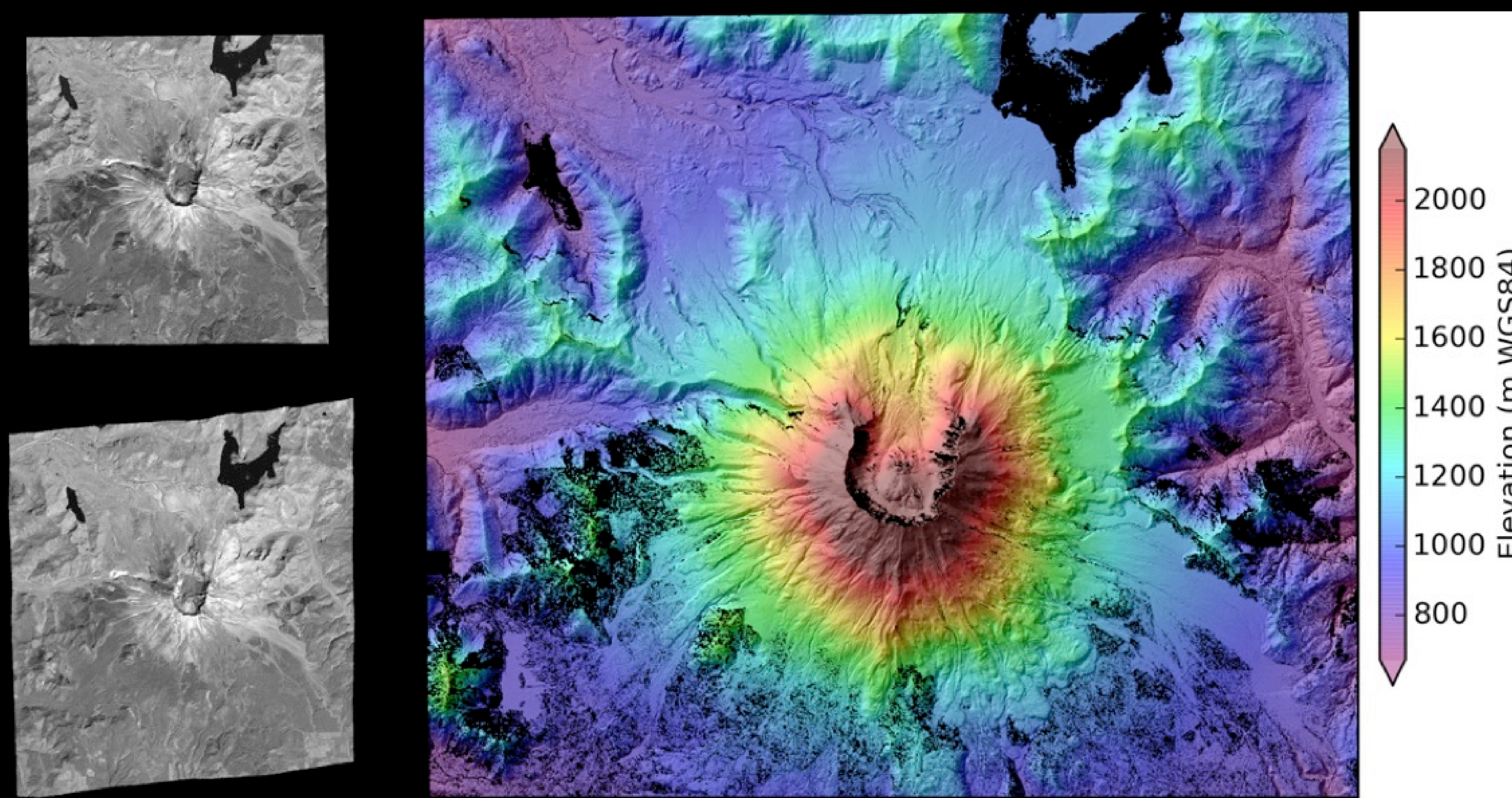
2012/2013 Cascades Stereo Acquisitions



2012-10-18

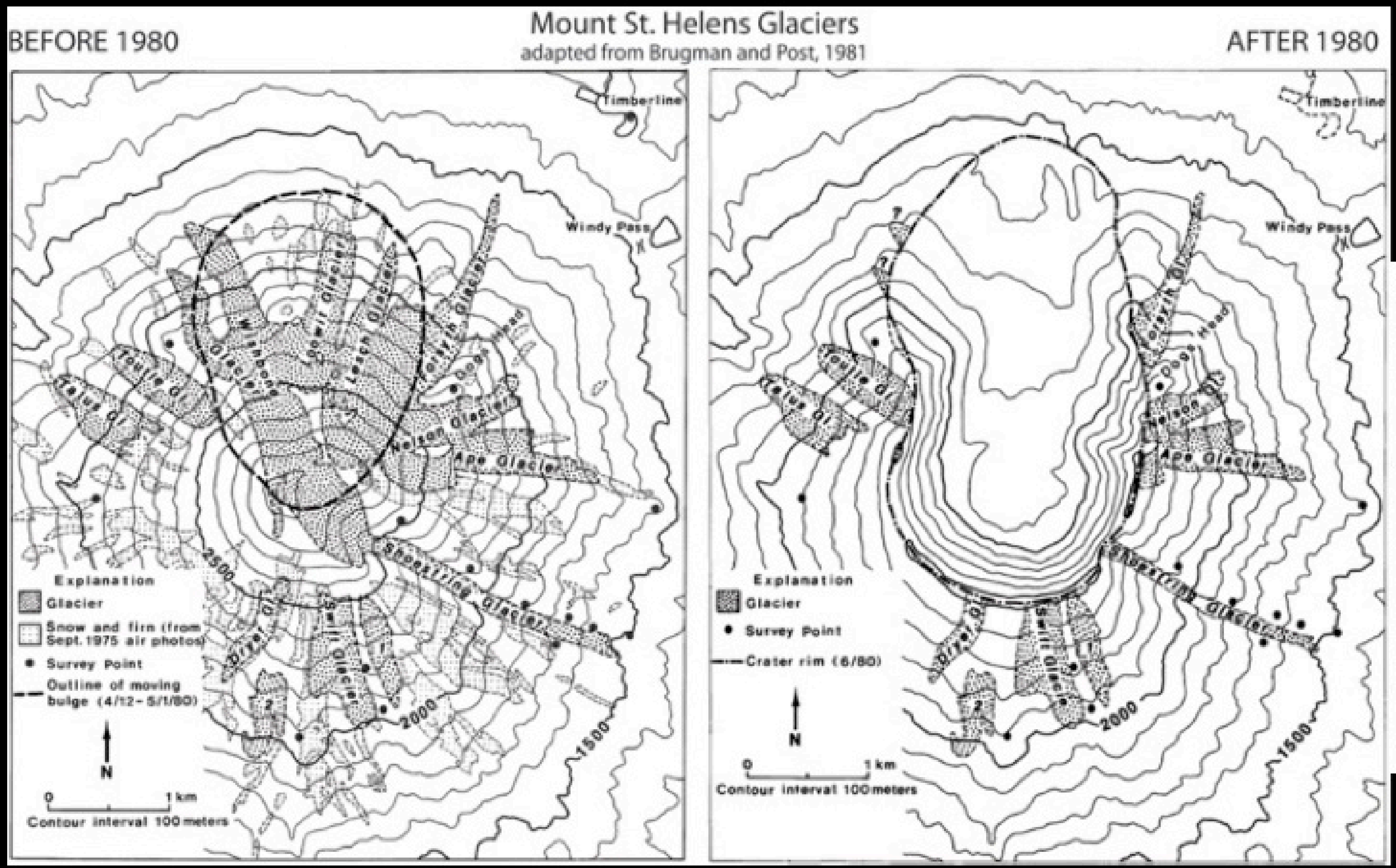


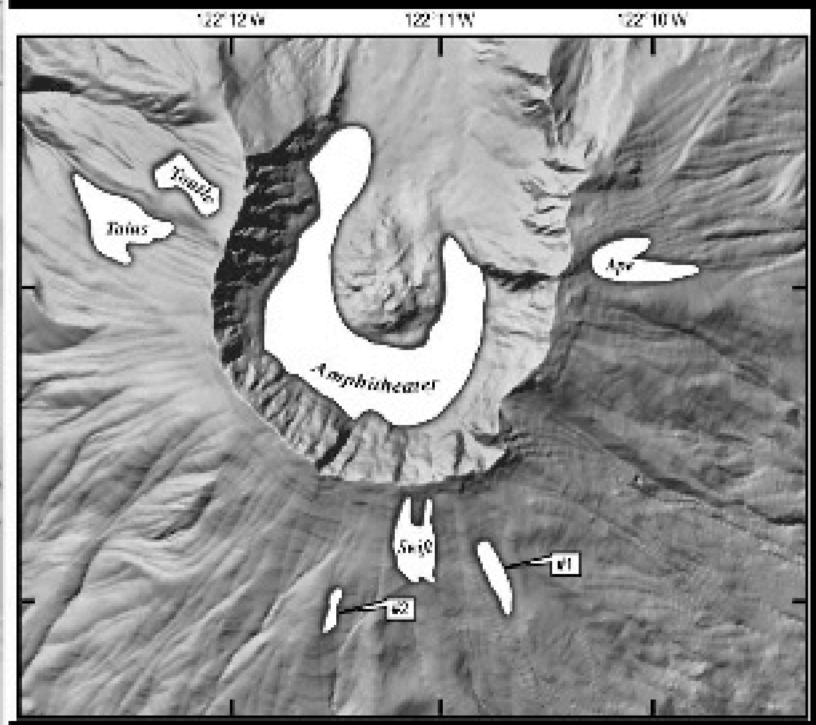
2013-09-09



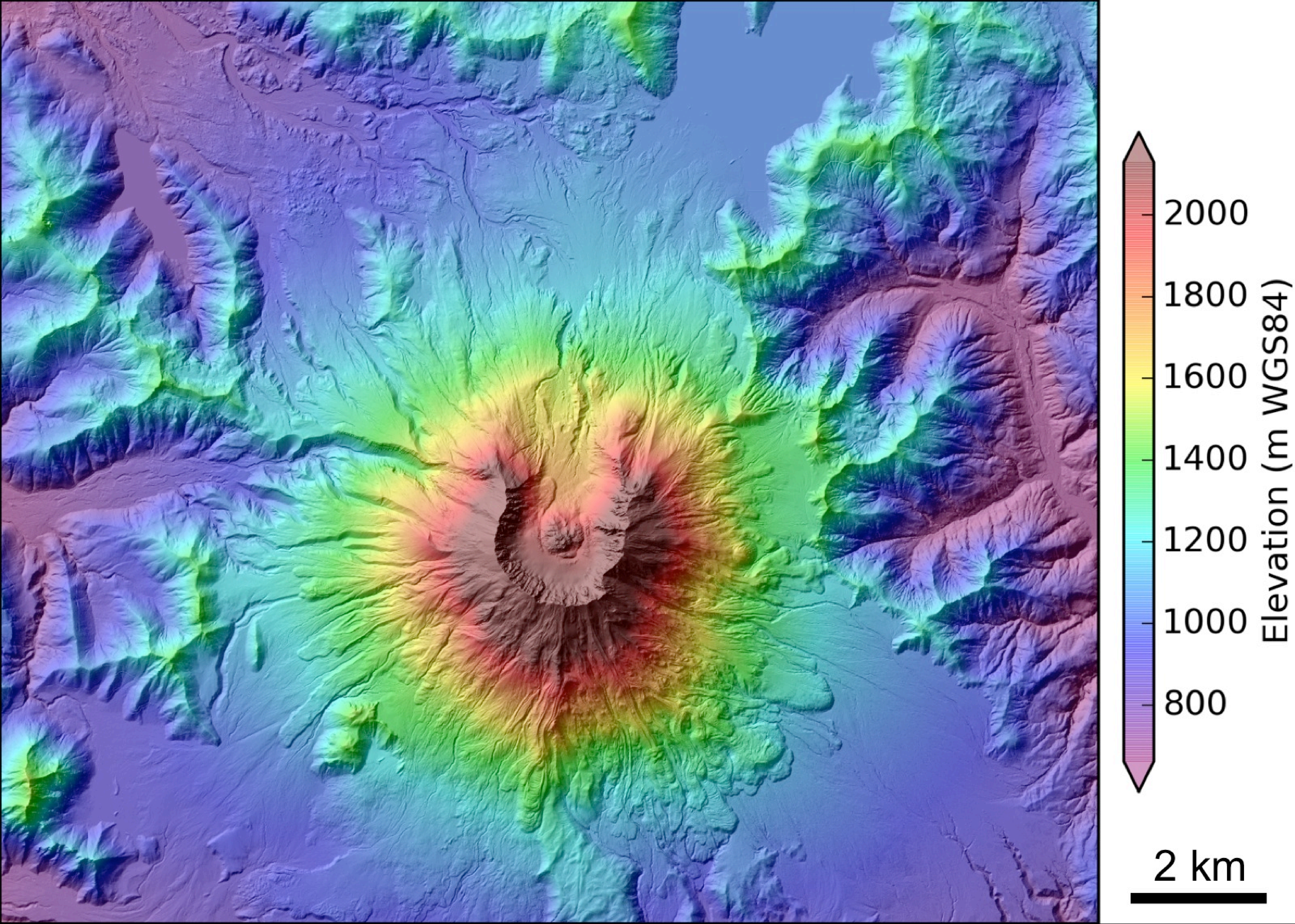
Ampitheater (Crater) Glacier

- 70% of MSH ice lost in 1980 eruption
- Largest glacier, including pre-eruption
- Accumulation via snow/rock avalanches
  - Mass balance difficult to constrain (~1/3 rock debris)
- Debris cover hinders ablation (<2 cm/yr)
- Walder et al (2008):
  - No diurnal/seasonal velocity variations
  - Minimal basal sliding (limited subglacial hydrological system)

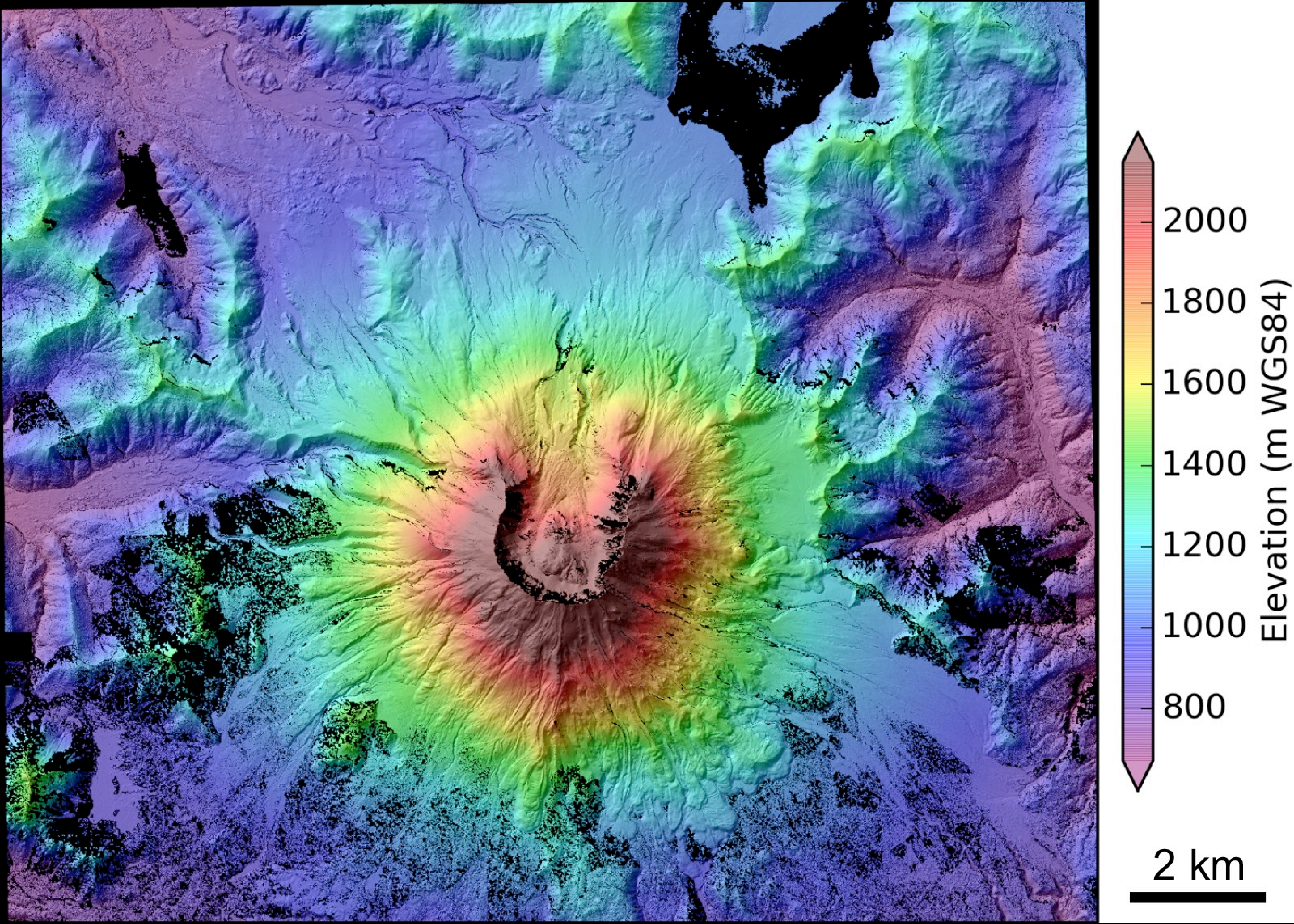




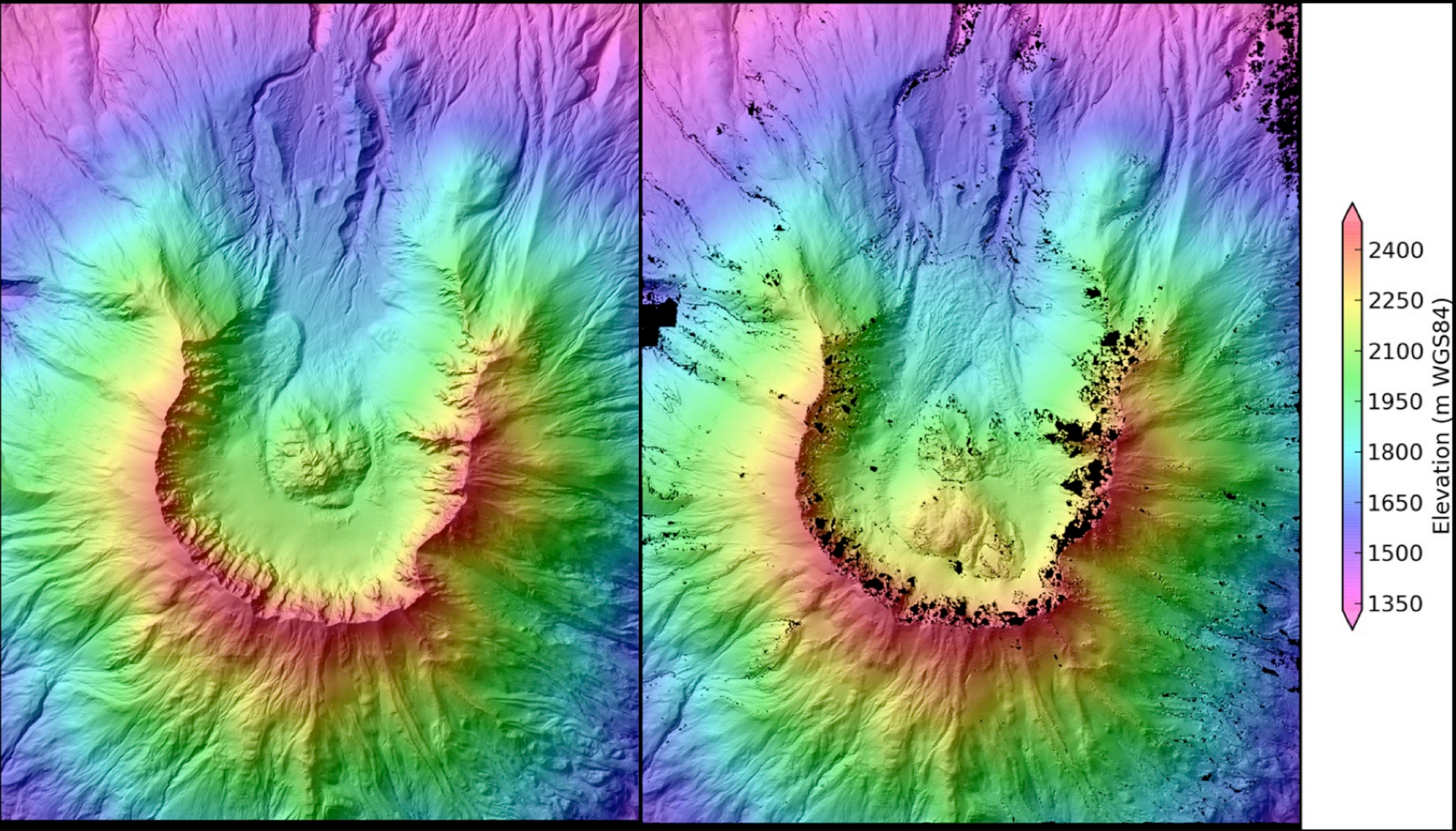
Schilling et al. (2004)



Bare Earth LiDAR, 9/20/2003

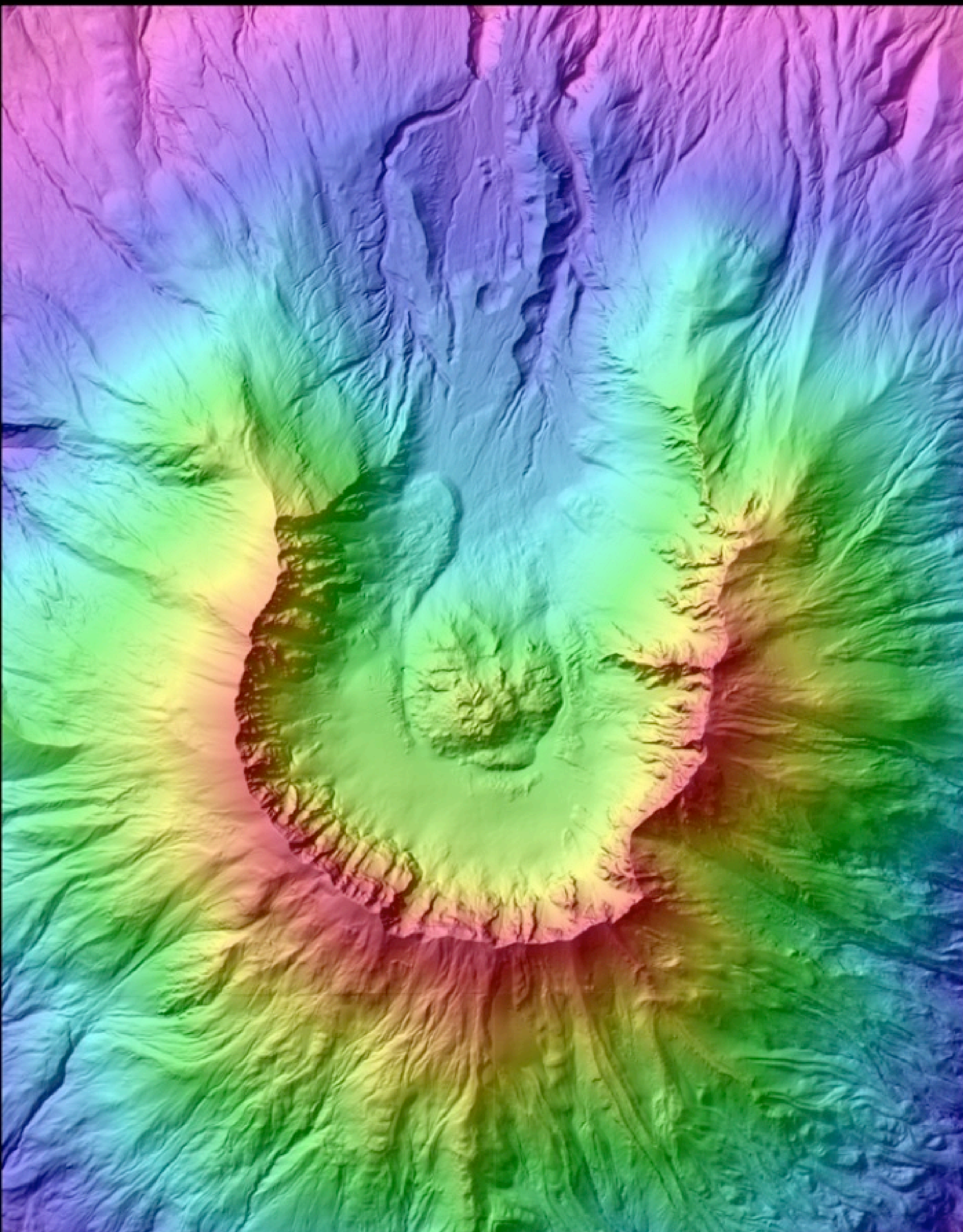


WV Stereo DEM, 9/9/2013

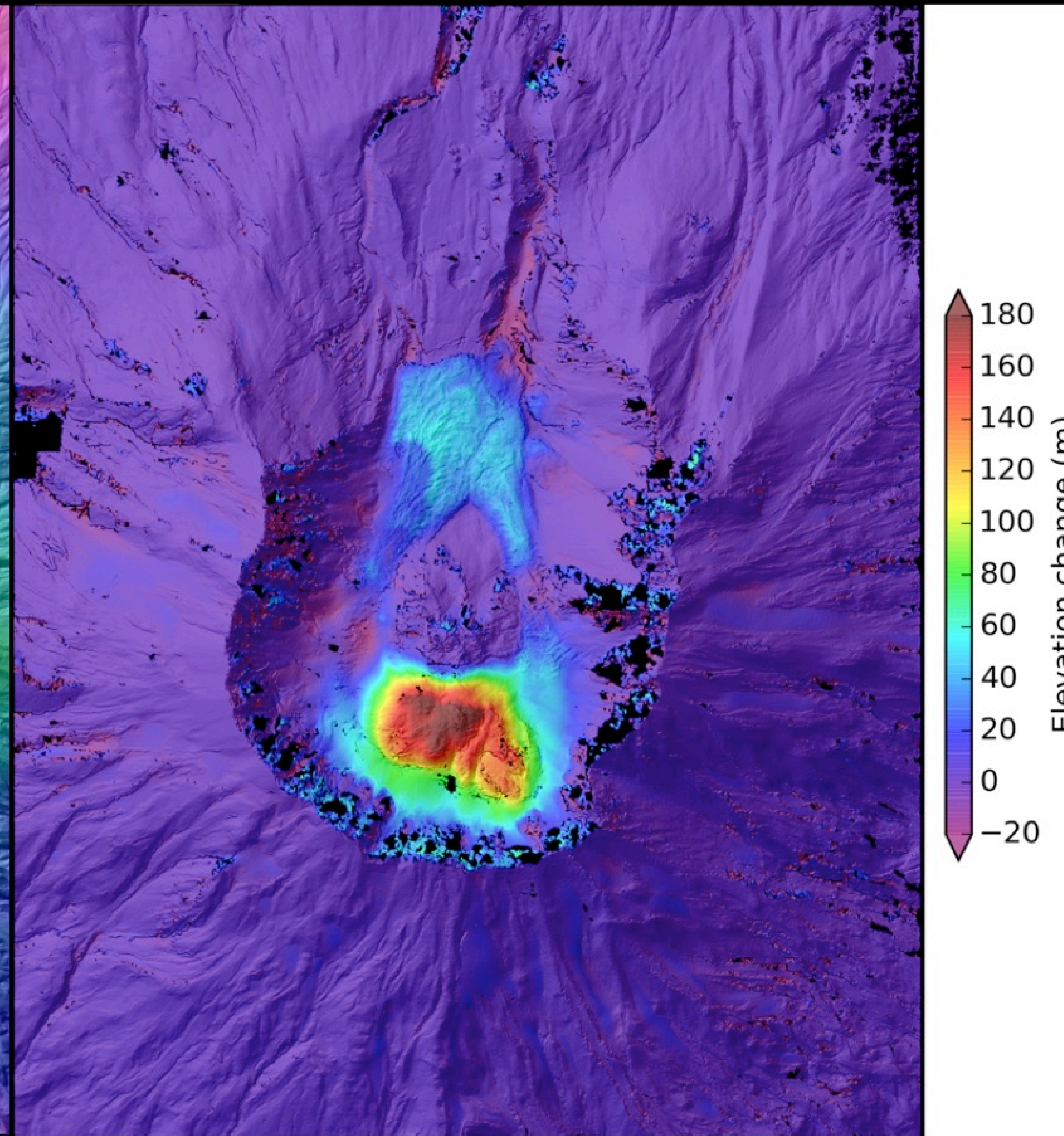


2003-09-20 LiDAR

2012-10-18 WV Stereo

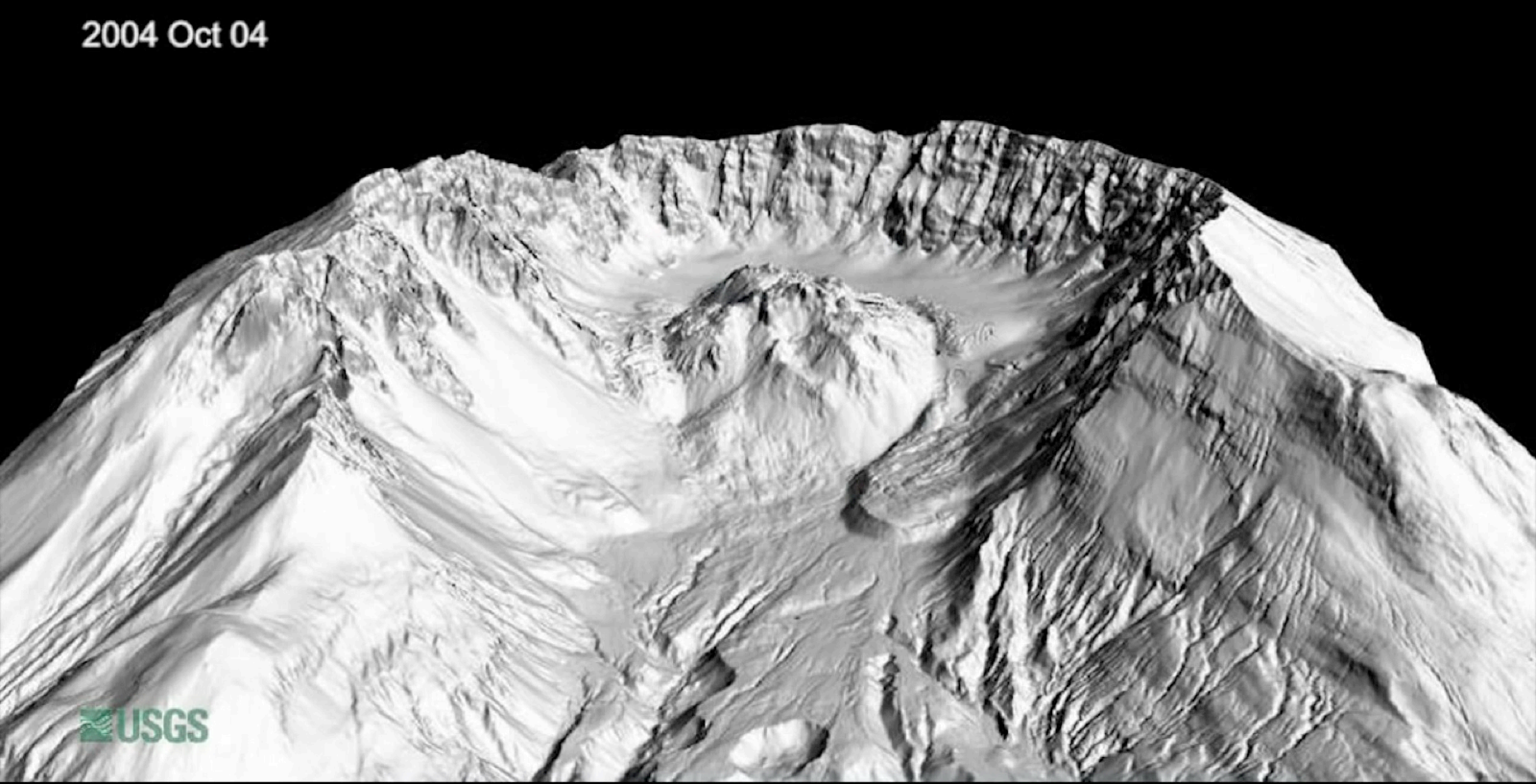


2003-09-20 LiDAR



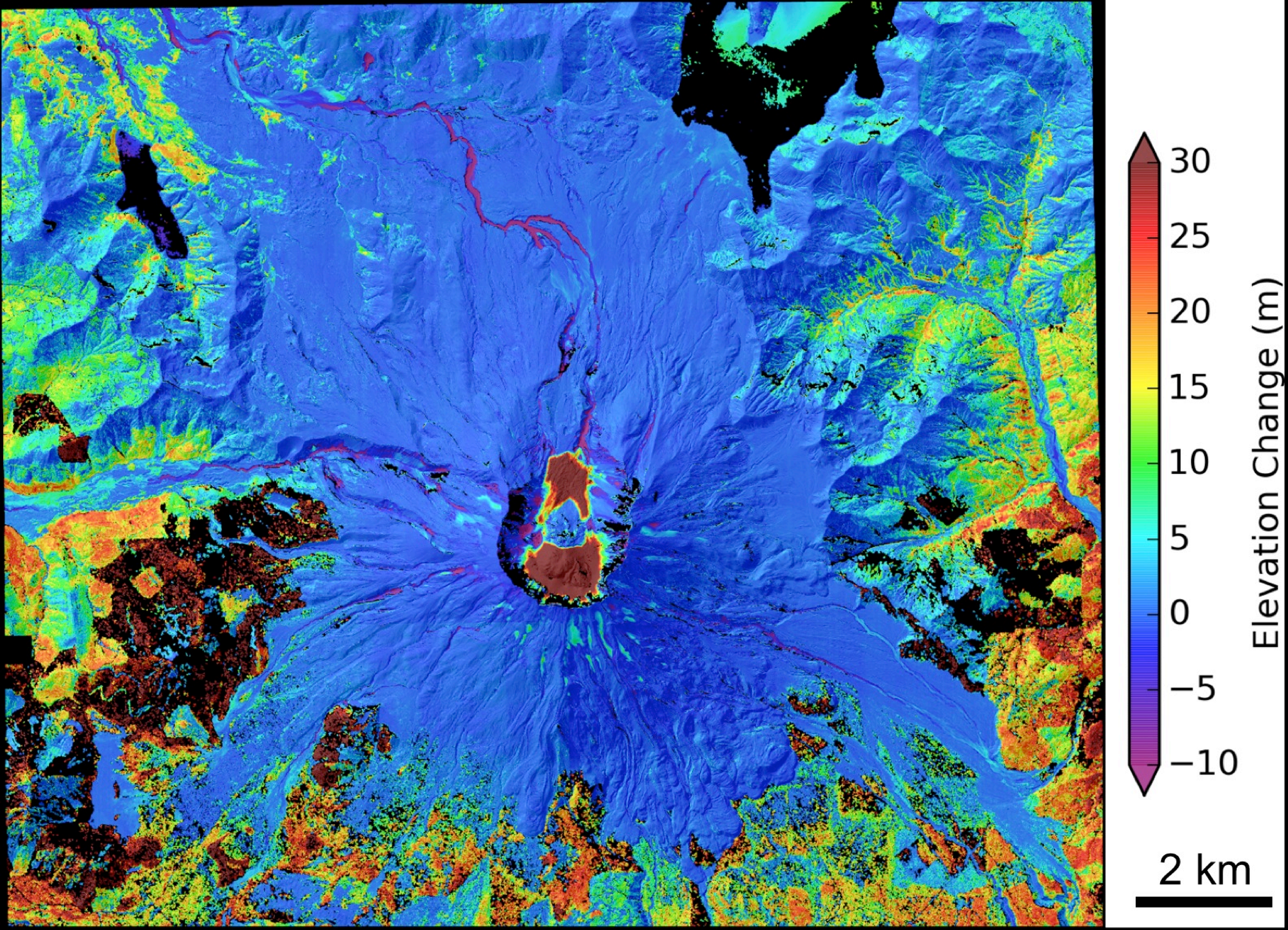
2012-10-18 – 2003-09-20

Time-series of dome and glacier growth at Mount St. Helens, Washington, 2004-2012

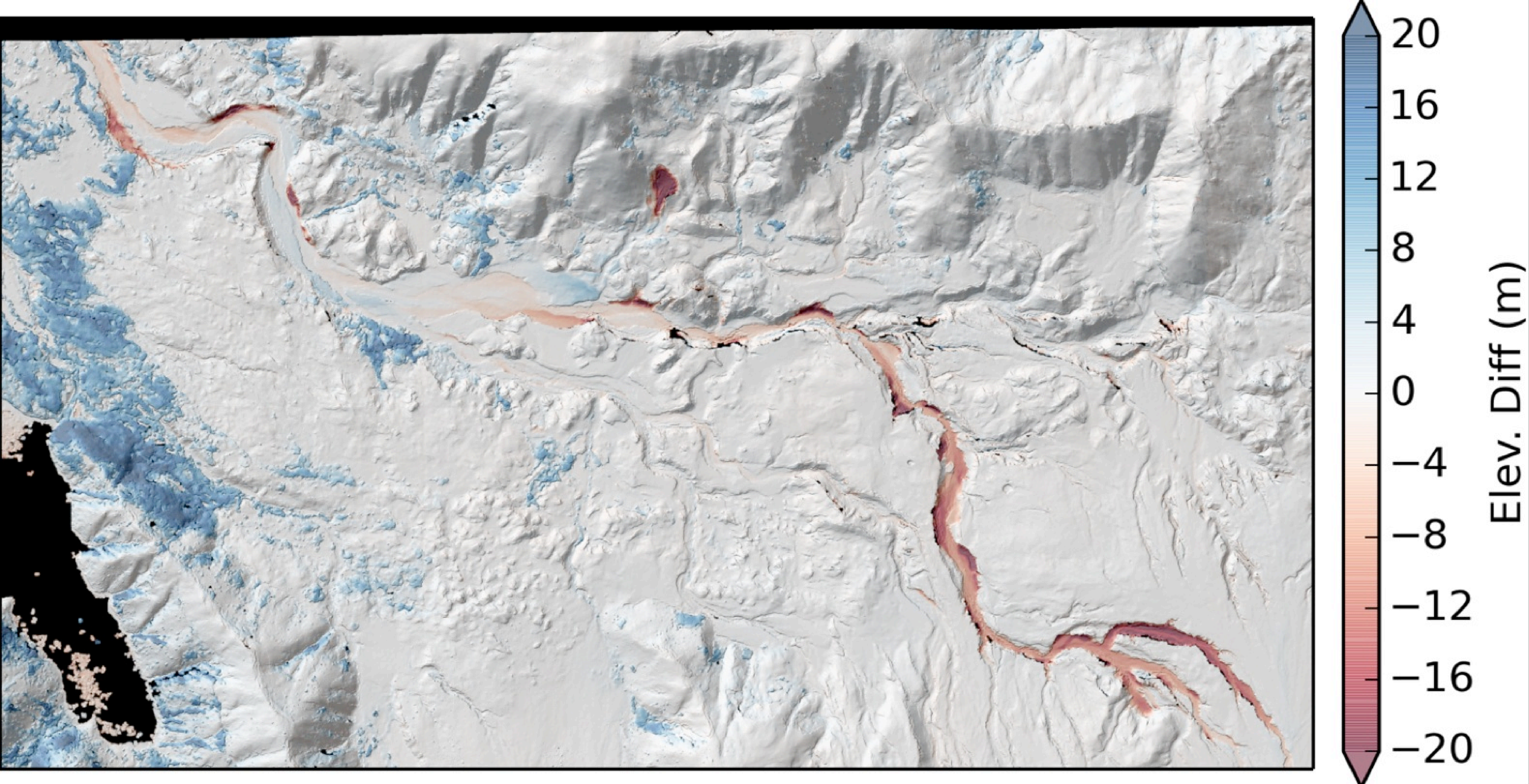


Steve Schilling, Angie Diefenback, James Messerich
USGS Cascades Volcano Observatory

U.S. Geological Survey, 1/1/2012
http://gallery.usgs.gov/videos/627

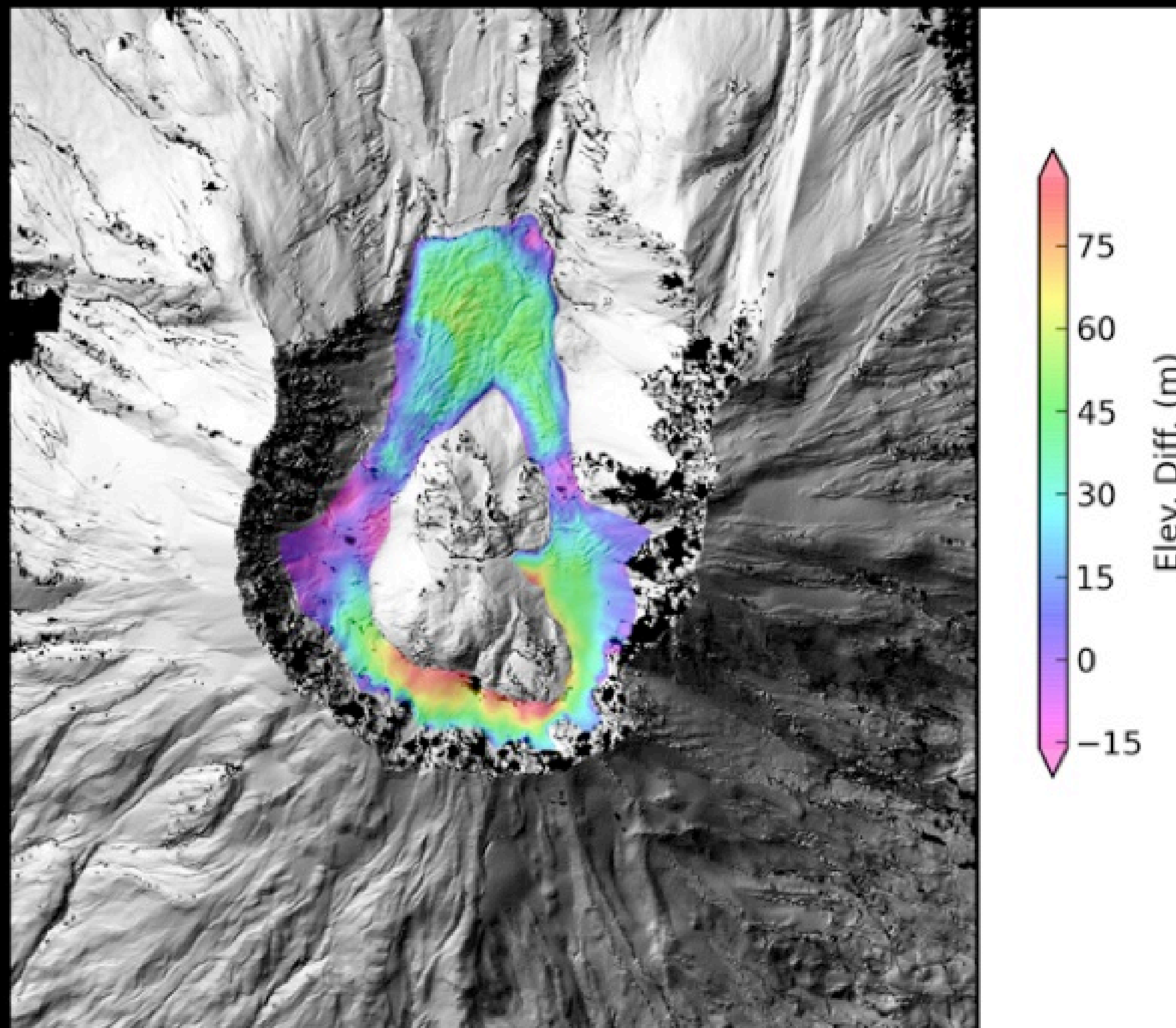


~10 year elevation change (9/20/2003 bare earth LiDAR to 9/9/2013 WV DEM)

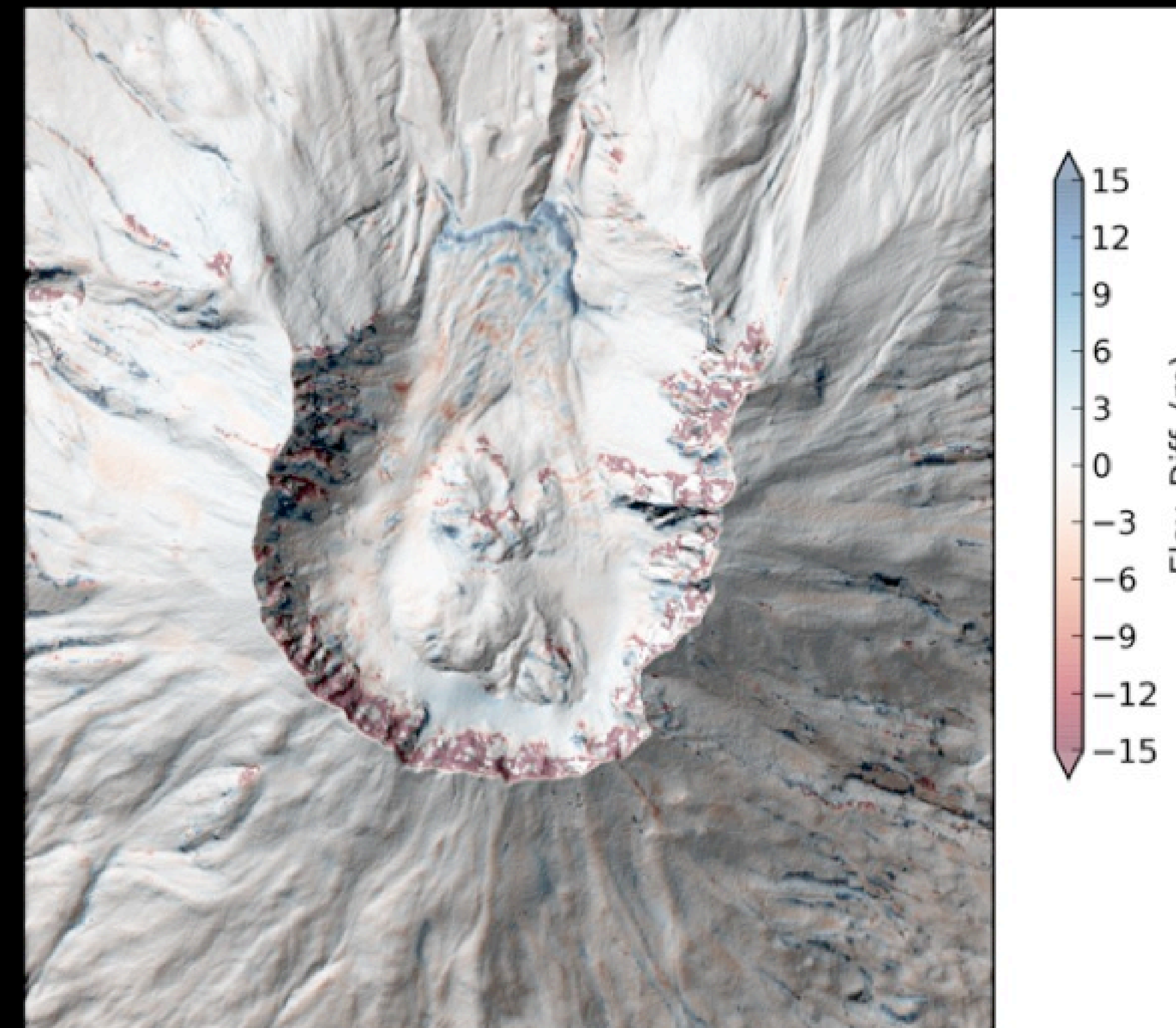


~10 year elevation change (9/20/2003 bare earth LiDAR to 9/9/2013 WV DEM)

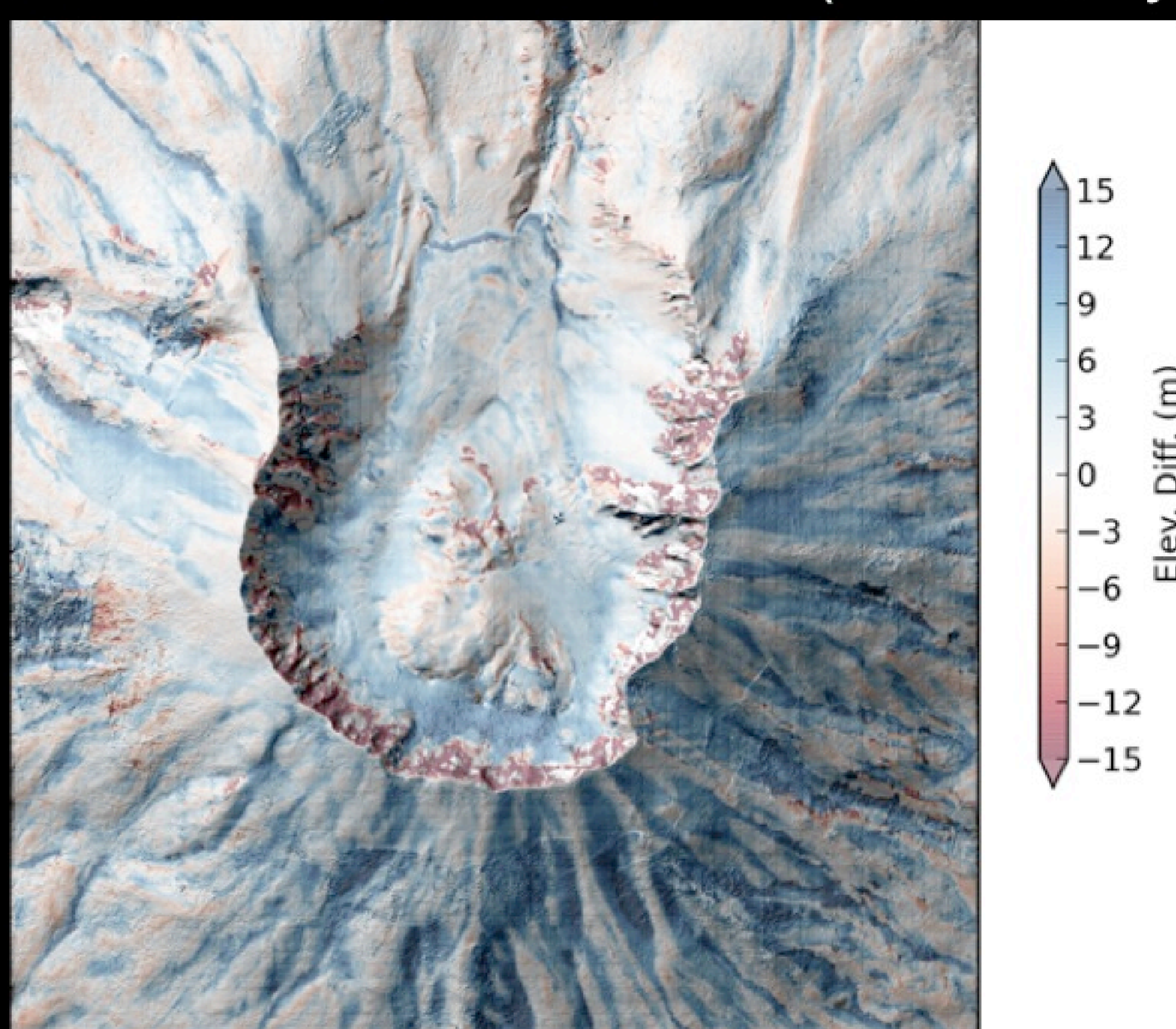
10 year glacier volume: +4.1x10^7 m^3



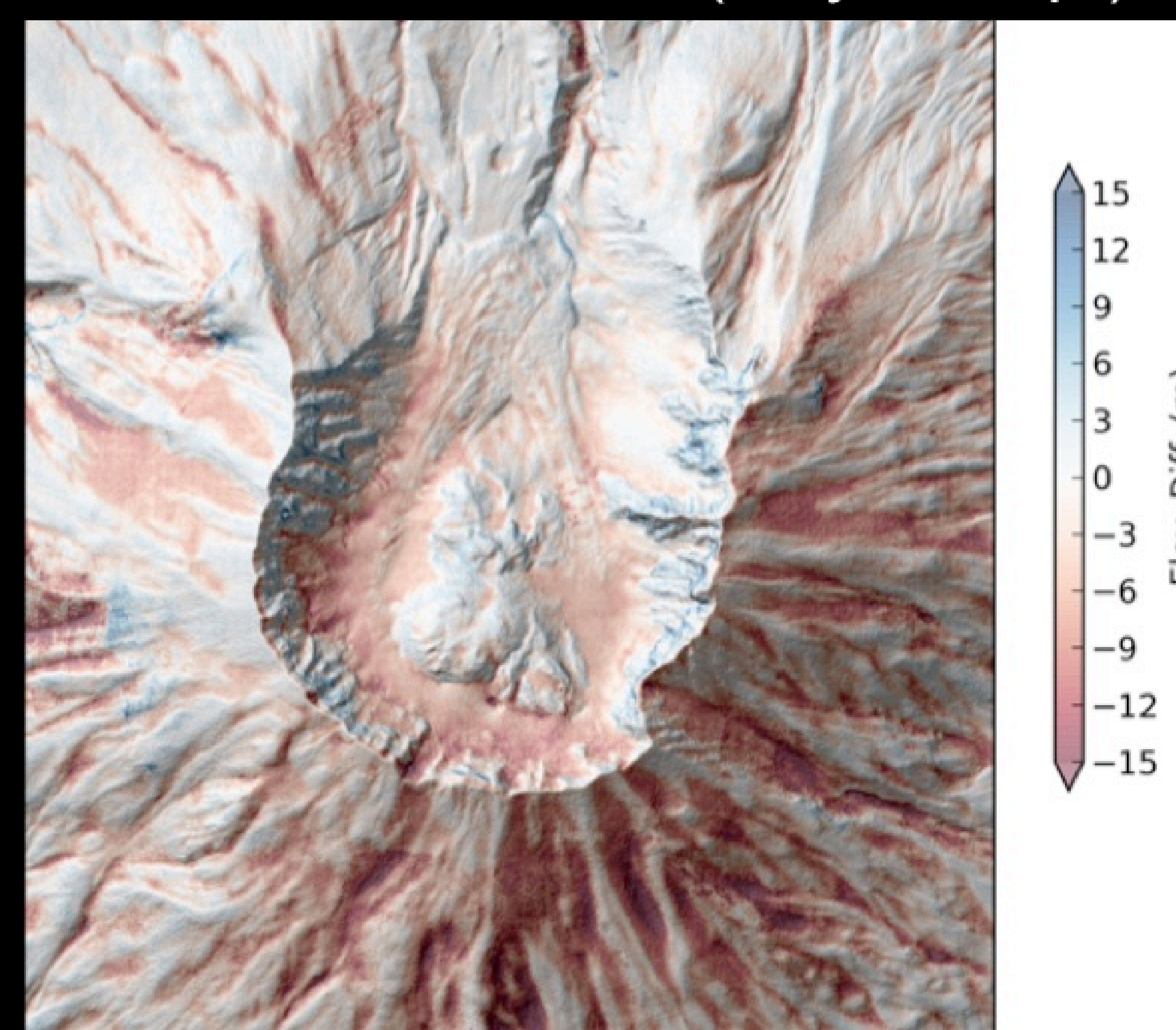
1-year glacier advance: ~40-70 m/yr



Winter snow accumulation (Oct to May)

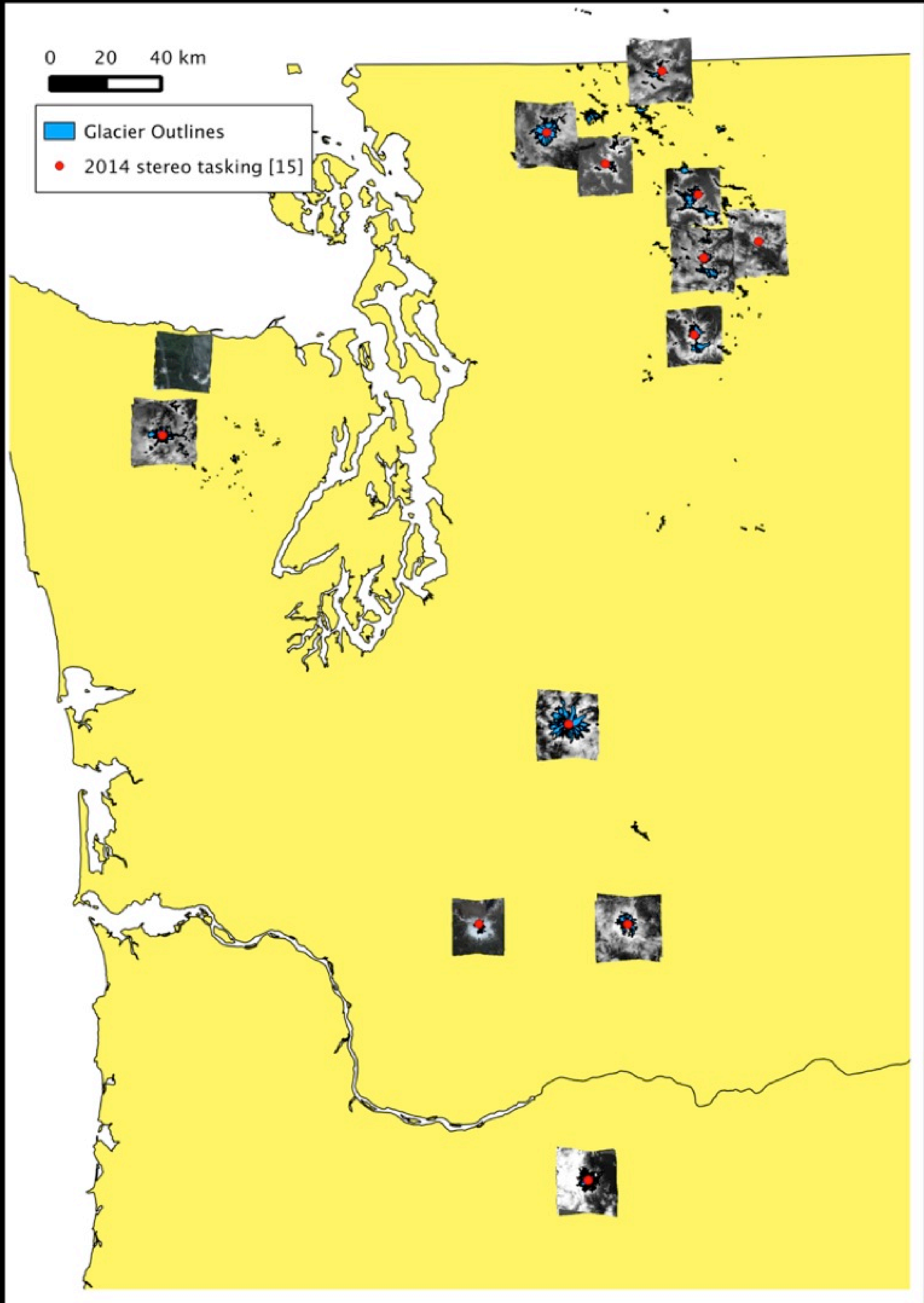


Summer snow melt (May to Sept)



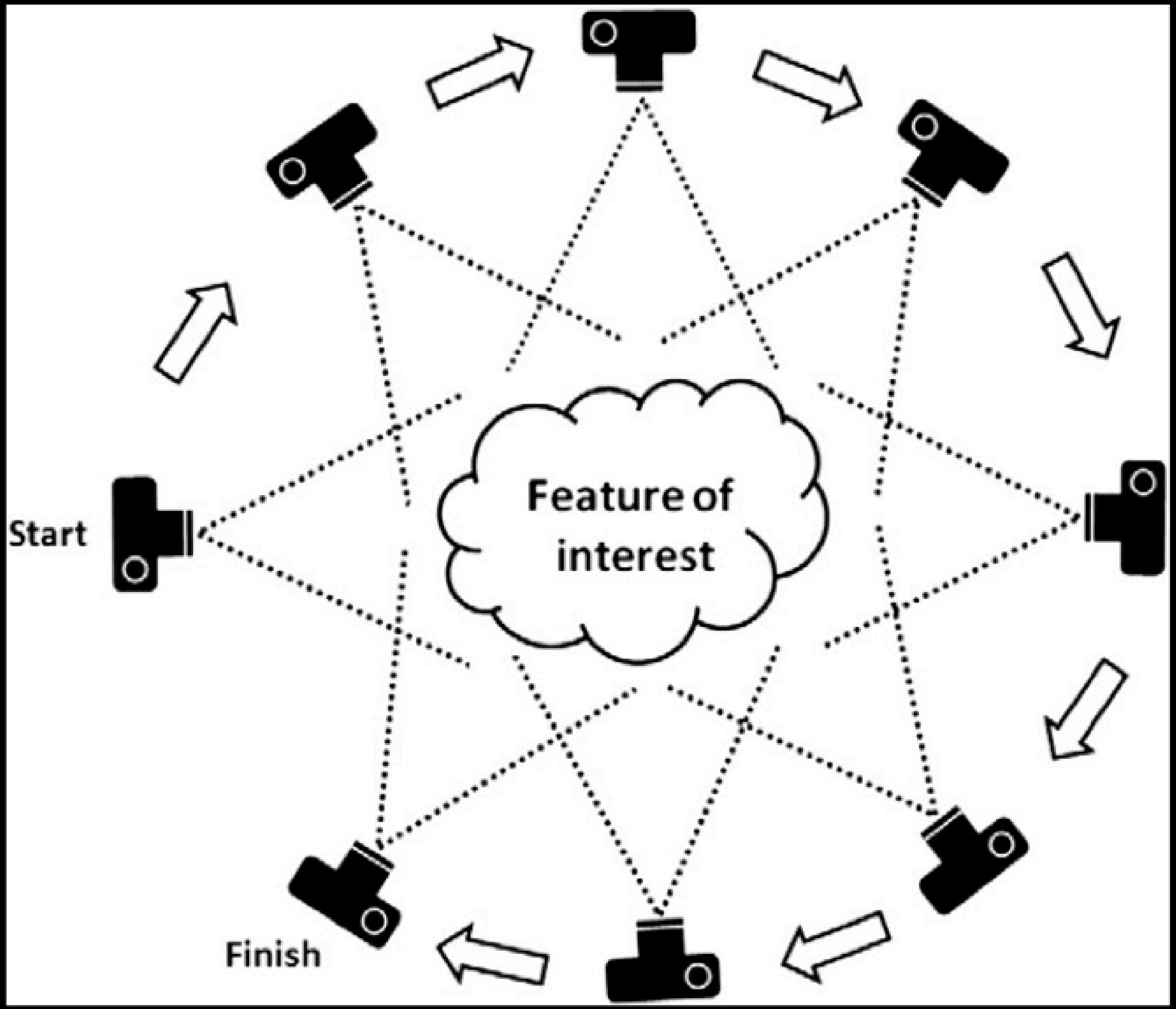
Spring 2014 WV Stereo Acquisitions

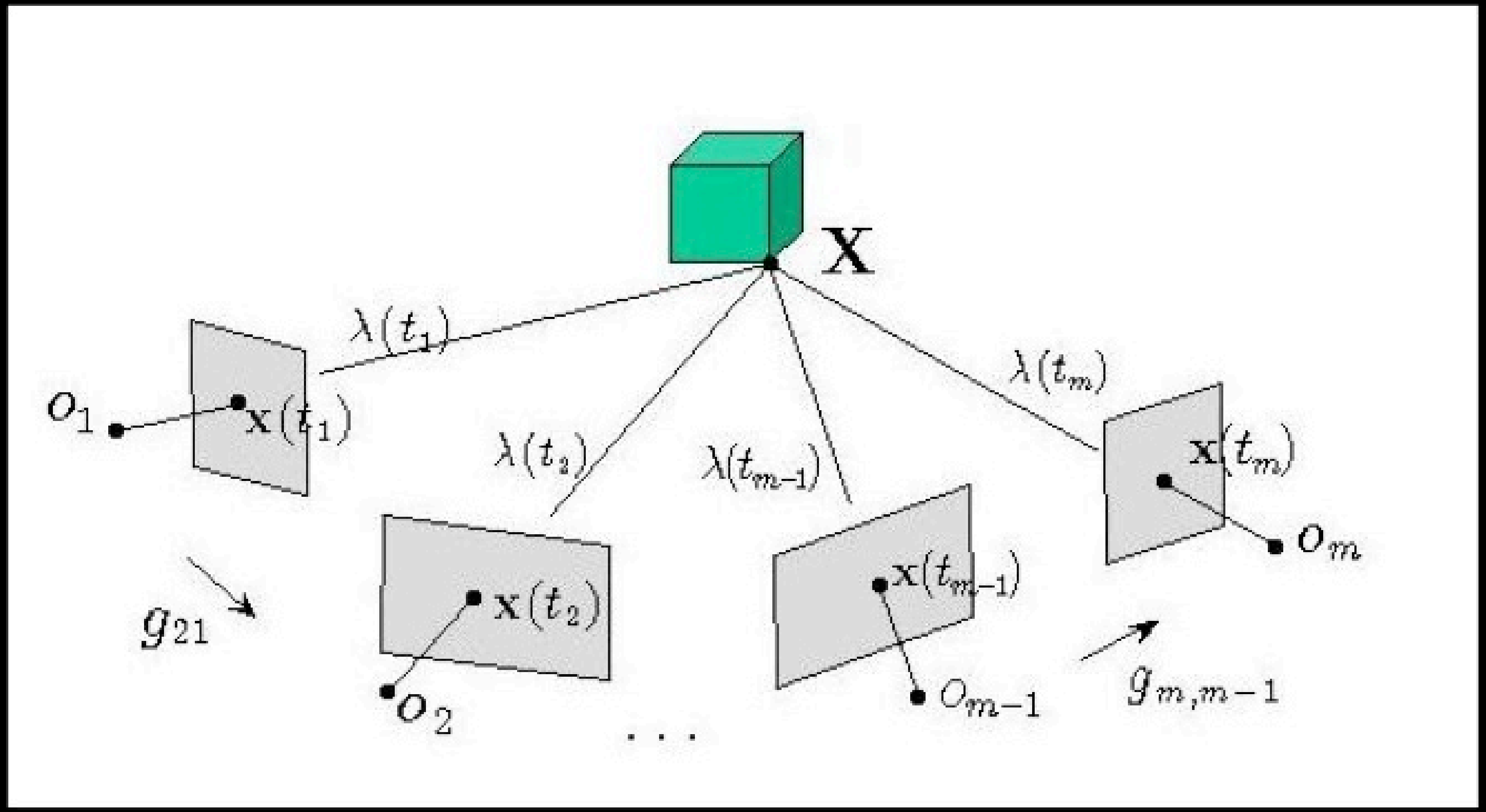
- 15 targets
- April/May (max snow) and Sept/Oct (min snow)
- 4/14/14 to 5/19/14:
  - 30 acquisitions
  - Most targets >2x
  - Some ~30-50% cloudy
- Rainier
  - Monthly stereo



Structure from Motion (SfM)

- 3D info ("structure") from multiple viewpoints ("motion")
- Minimize occlusion
- Consumer cameras
- Automated software, minimal training required
- Scale/orientation from known camera positions (GPS) or ground control





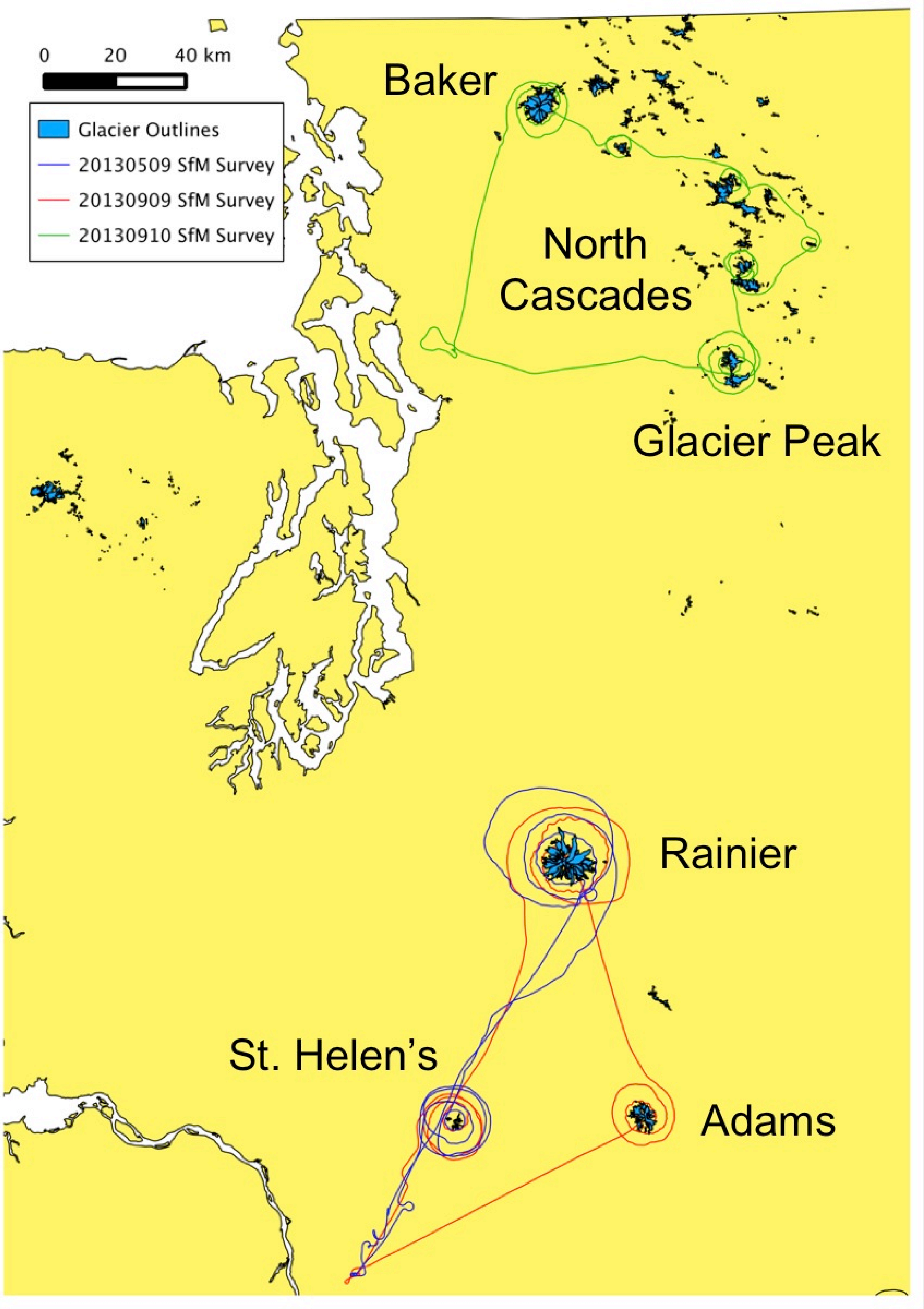
UW ESS STF Equipment

- Nikon D800 DSLR (36.3 MP, 7360 x 4912 px)
  - Four professional lenses
  - GP-1 GPS unit (~5 m accuracy)
- Trimble GeoXH GPS + Hurricane antenna
  - 1 Hz logging
  - ~10-15 cm accuracy
- 12-core processing workstation (QRC lab)
  - Agisoft PhotoScanPro
  - ERDAS Imagine + Leica Photogrammetry Suite
  - Open Source Tools (VisualSFM, QGIS, etc.)


MENTAL

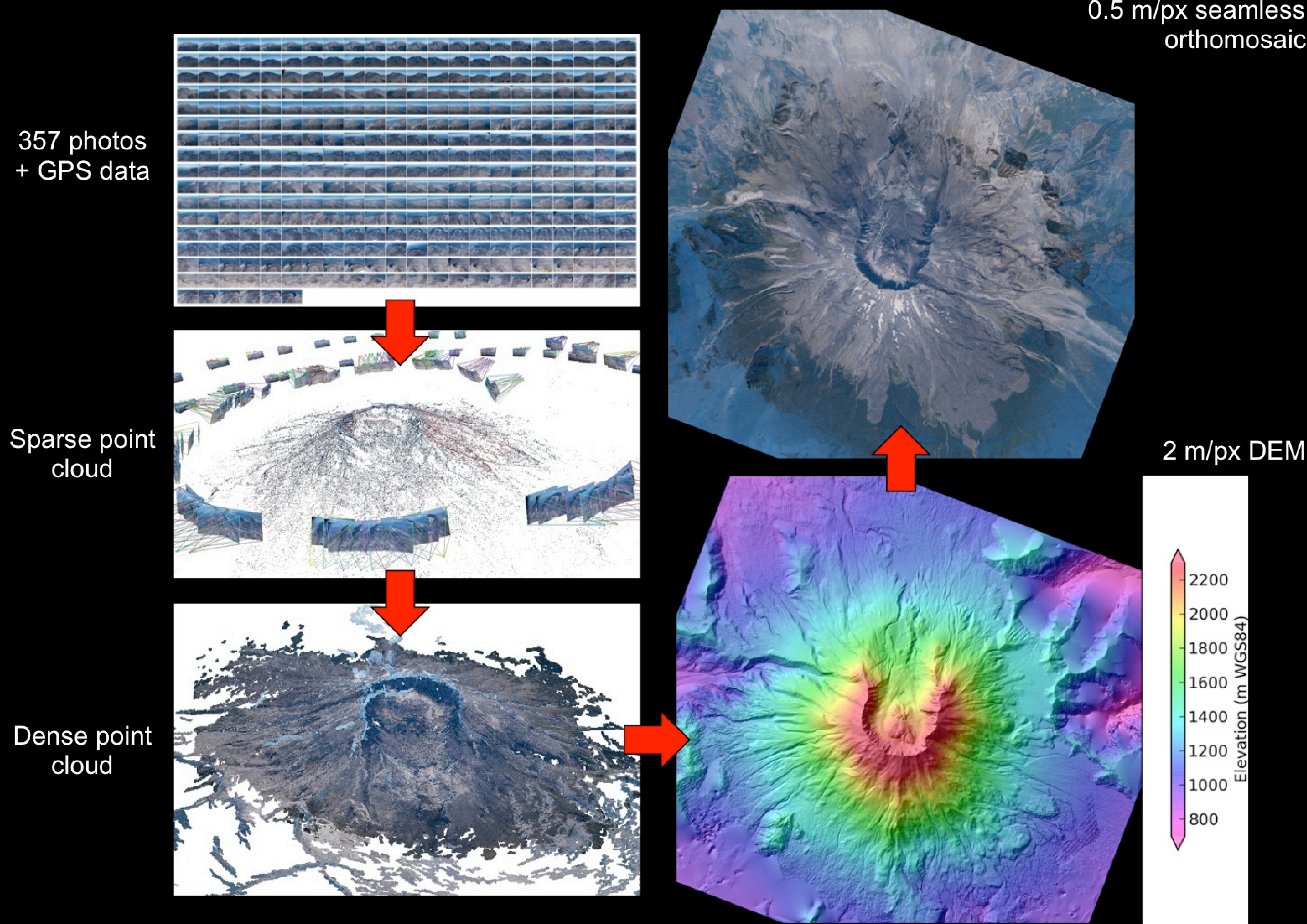
2013 Oblique Aerial Surveys

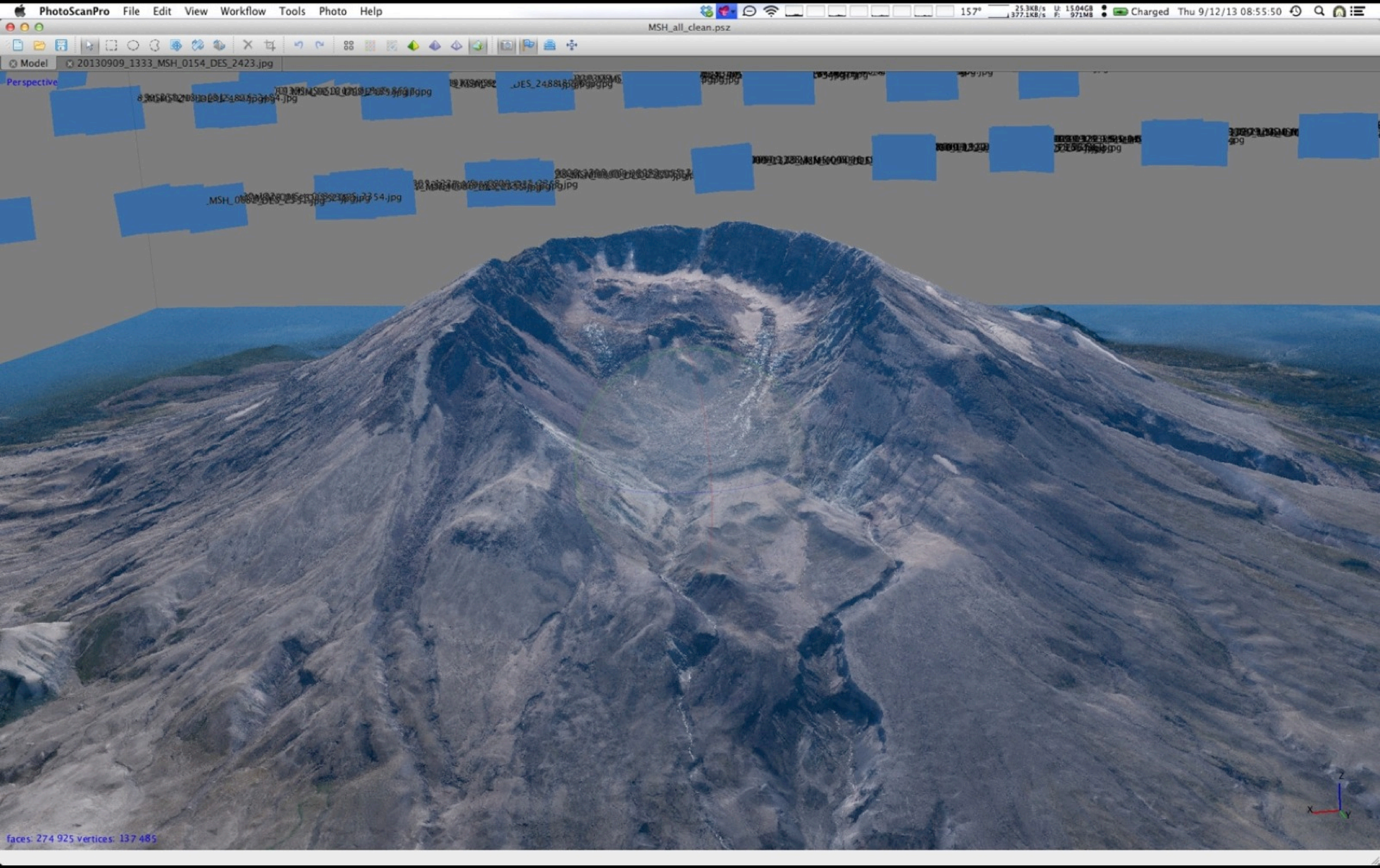
- 3 flights, 2.5 hr each
- $50/hr shared costs
- 2-3 passes
- 5000-15500’ altitude

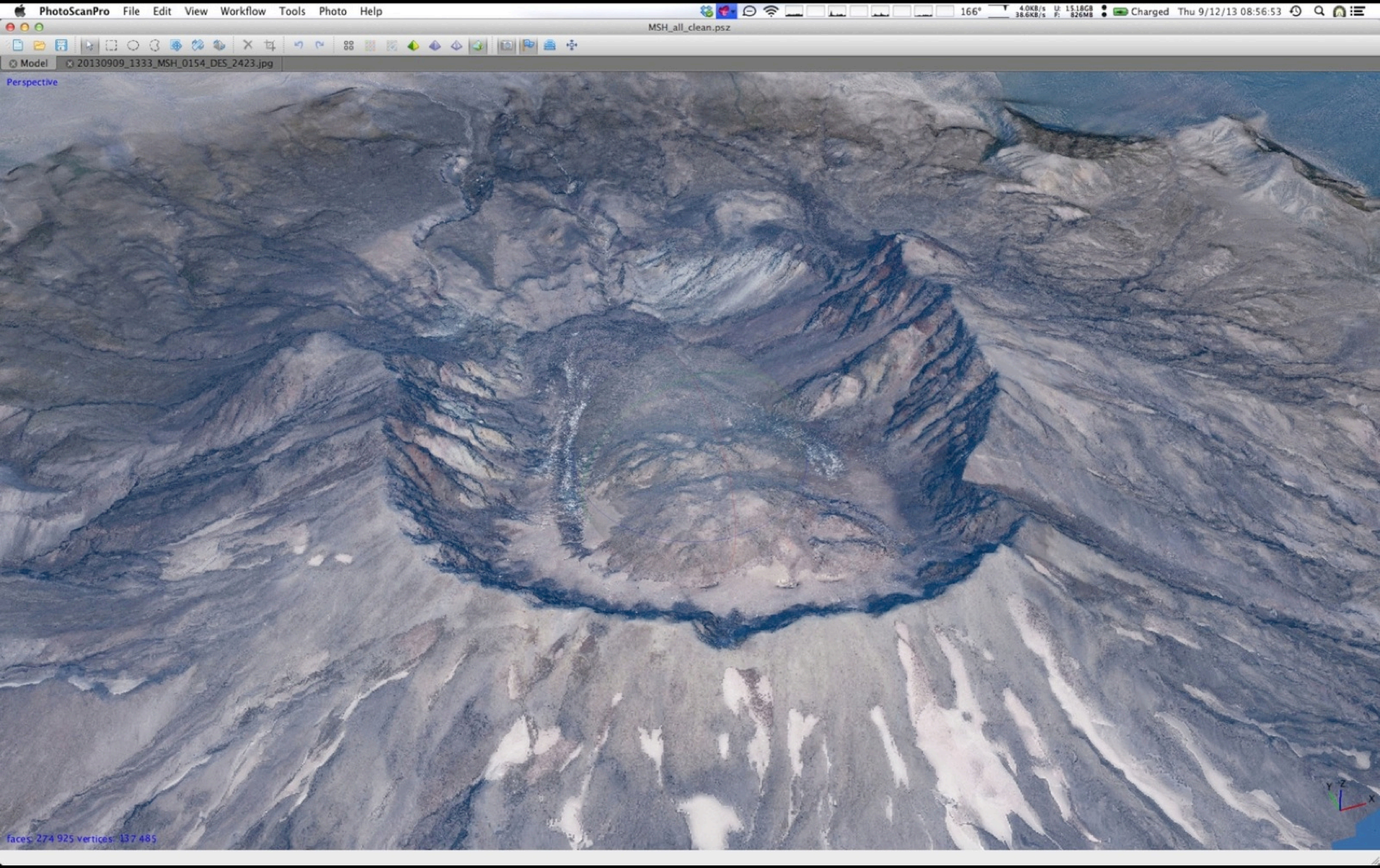


Mt. St. Helen’s, 9/9/13
D800 (36 MP, 50 mm lens,7360x4912 px)

Structure from Motion Workflow




PhotoScanPro File Edit View Workflow Tools Photo Help
Charged Thu 9/12/13 08:55:50
MSH_all_clean.psz
Model
20130909_1333_MSH_0154_DES_2423.jpg
Perspective
faces: 274 925 vertices: 137 485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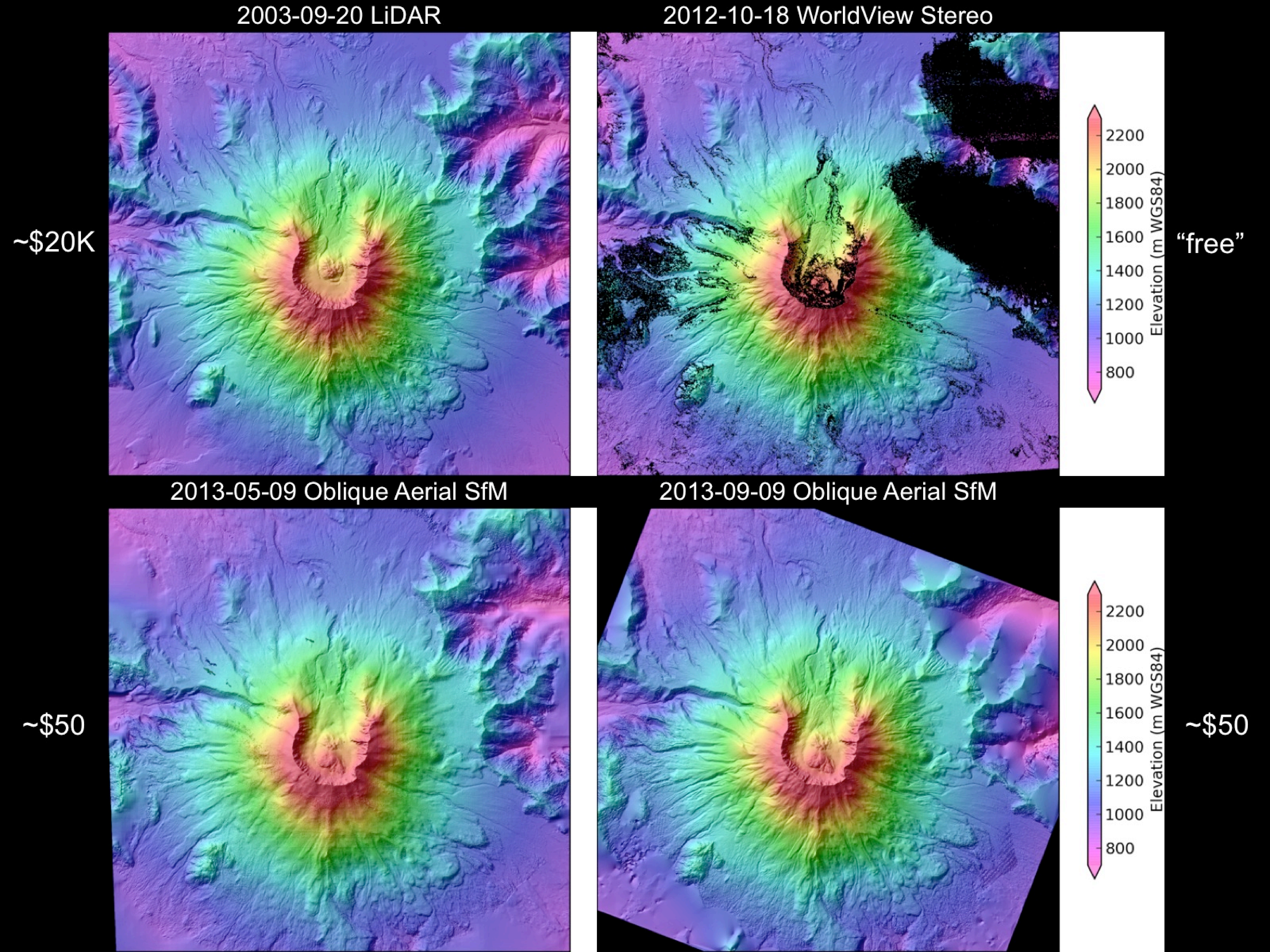
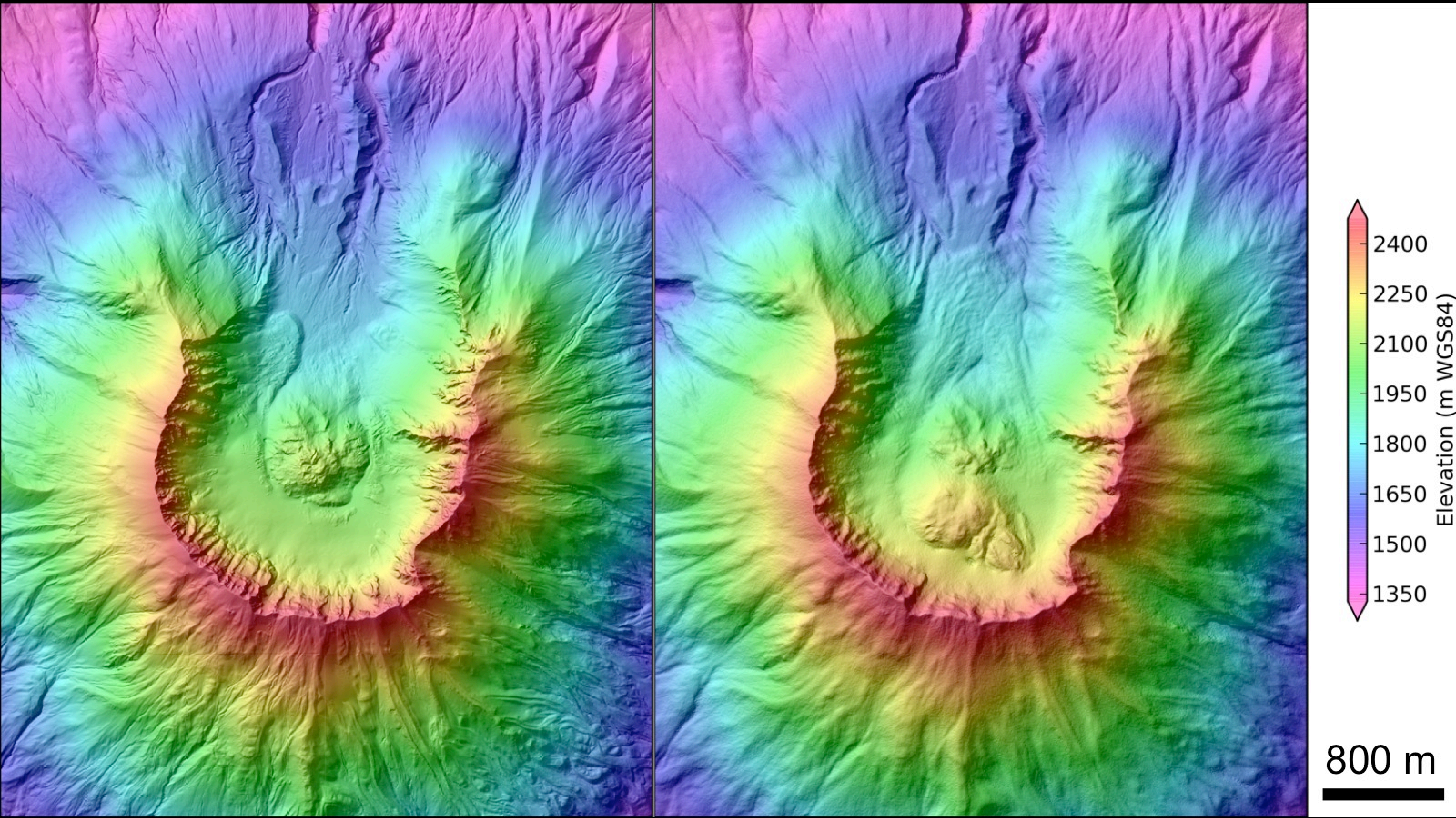
Perspective
faces: 274 925 vertices: 137 485

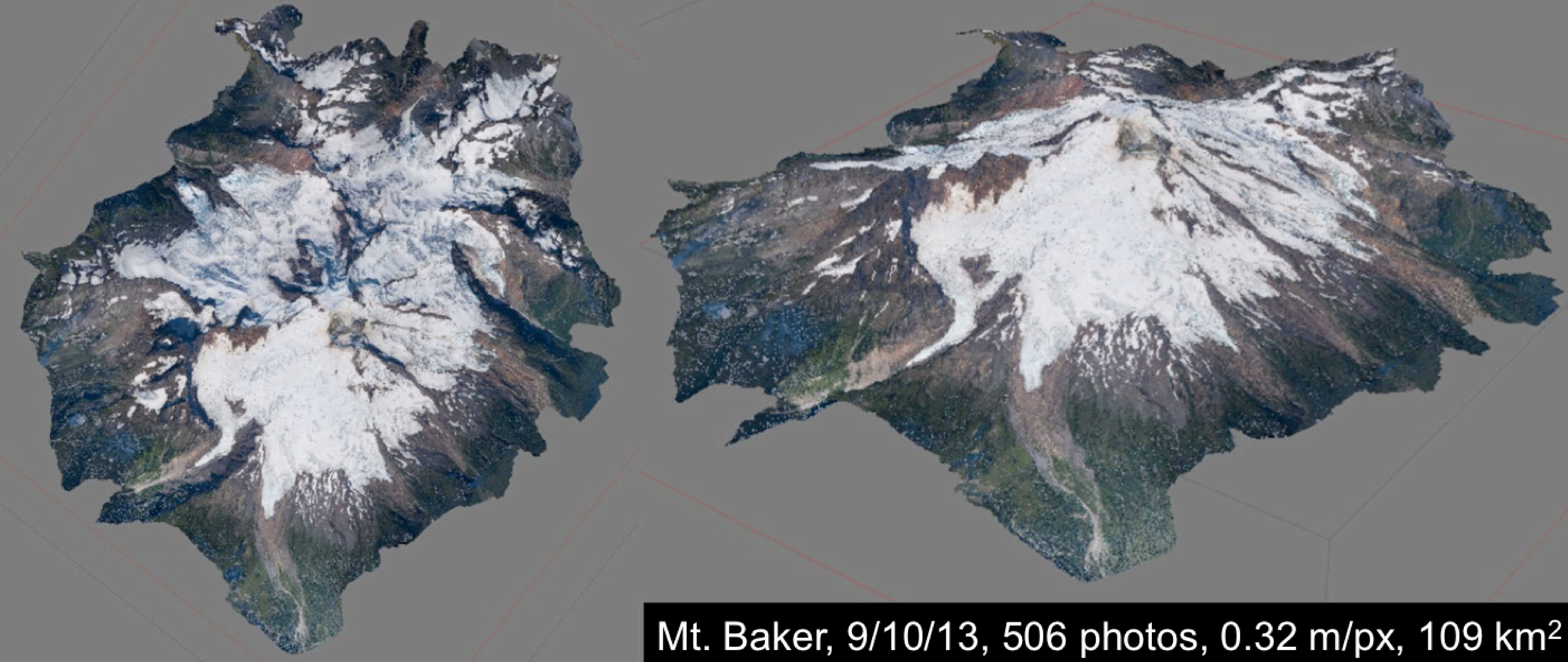

2003-09-20 LiDAR
2012-10-18 WorldView Stereo
2013-05-09 Oblique Aerial SfM
2013-09-09 Oblique Aerial SfM
~$20K
"free"
~$50
~$50
Elevation (m WGS84)
2200
2000
1800
1600
1400
1200
1000
800

2003-09-20 LiDAR

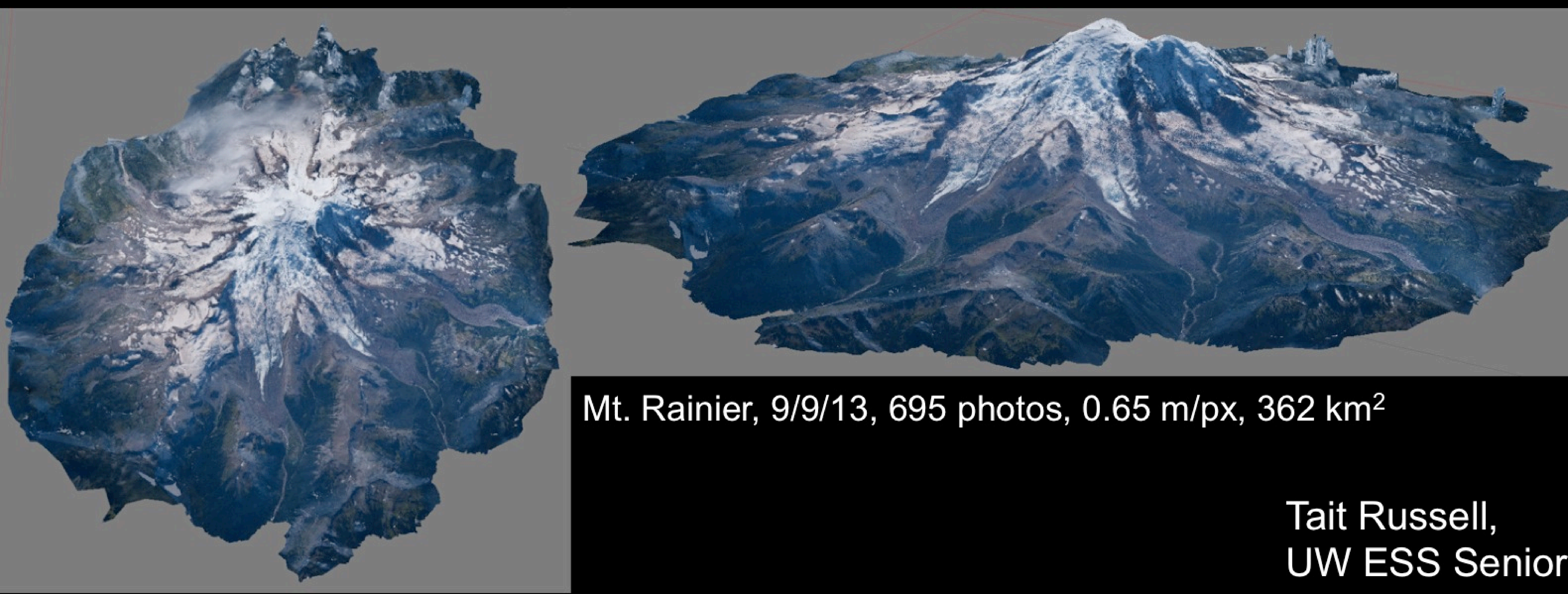
2013-09-09 Oblique Aerial SfM



("medium" quality)



Mt. Baker, 9/10/13, 506 photos, 0.32 m/px, 109 km^2



Mt. Rainier, 9/9/13, 695 photos, 0.65 m/px, 362 km^2

Tait Russell,
UW ESS Senior

Progress in Physical Geography
1–20

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DOI: 10.1177/0309133313515293
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SAGE

Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photography

Arko Lucieer
University of Tasmania, Australia

Steven M. de Jong
Utrecht University, The Netherlands

Darren Turner
University of Tasmania, Australia

Figure 3. The remote controlled UAV OktoKopter equipped with digital camera and GPS.

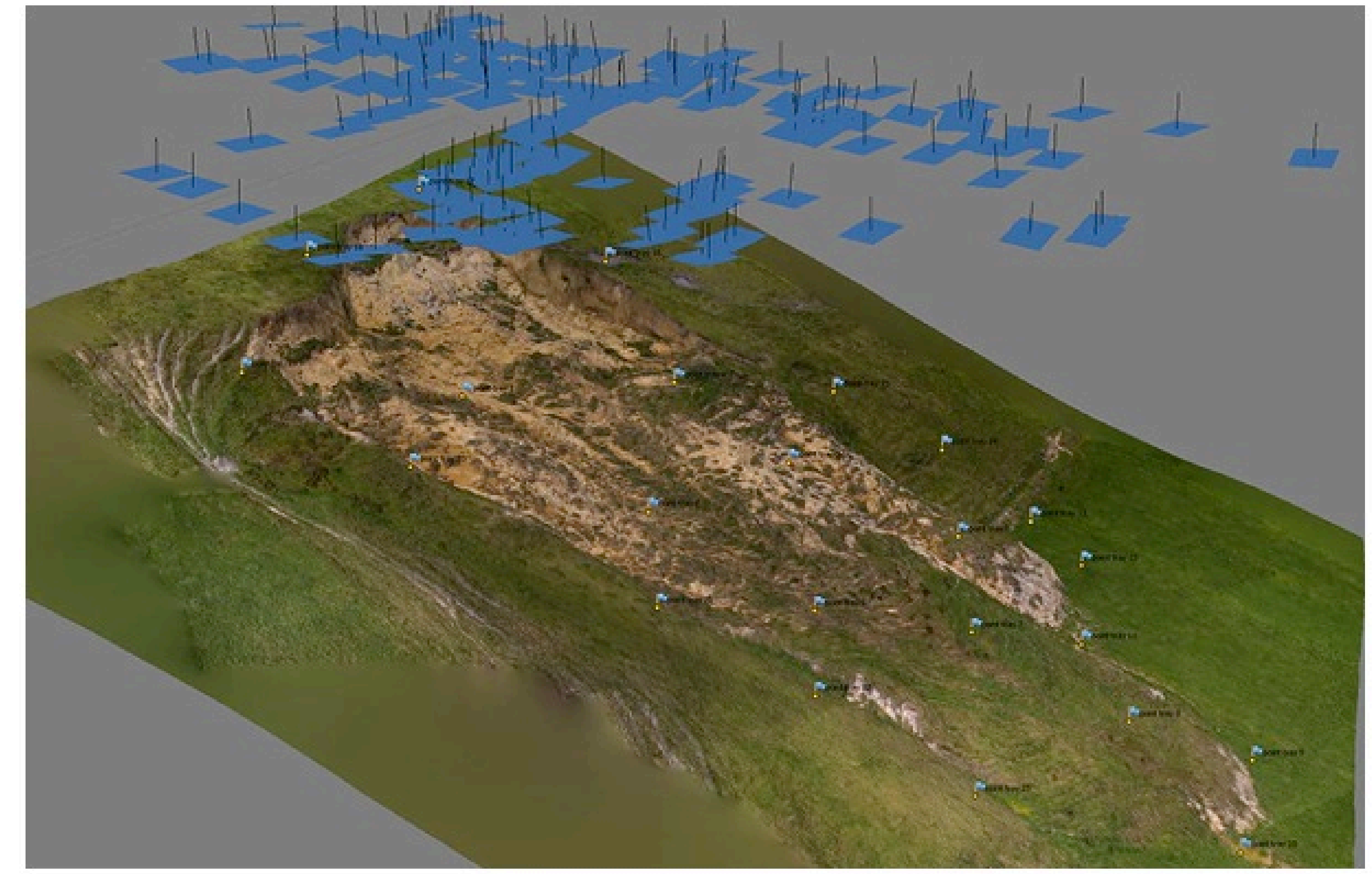

Figure 4. Perspective view of the texture-mapped 3D surface acquired on 10 November 2011. The blue squares over the landslide show the camera positions and orientations during image acquisition by the UAV. The numbered flags on the landslide show the positions of the ground control points used for the bundle adjustment.

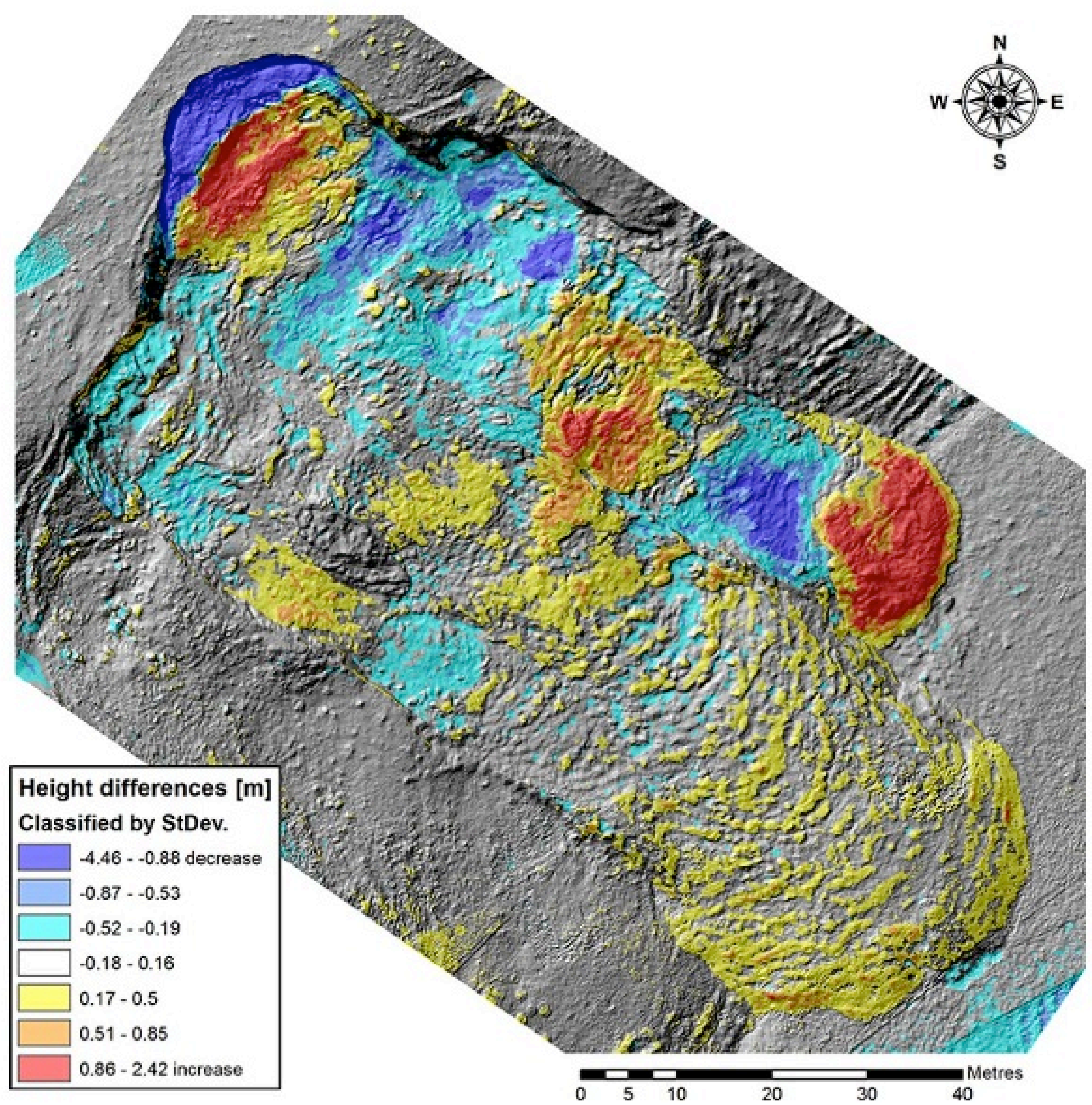

Figure 6. Difference between the 1 cm DEMs of 19 July 2011 and 10 November 2011 illustrating the surface changes and as such the dynamics of the landslide. Note the significant retreat of the main scarp and the expansion of the toes.

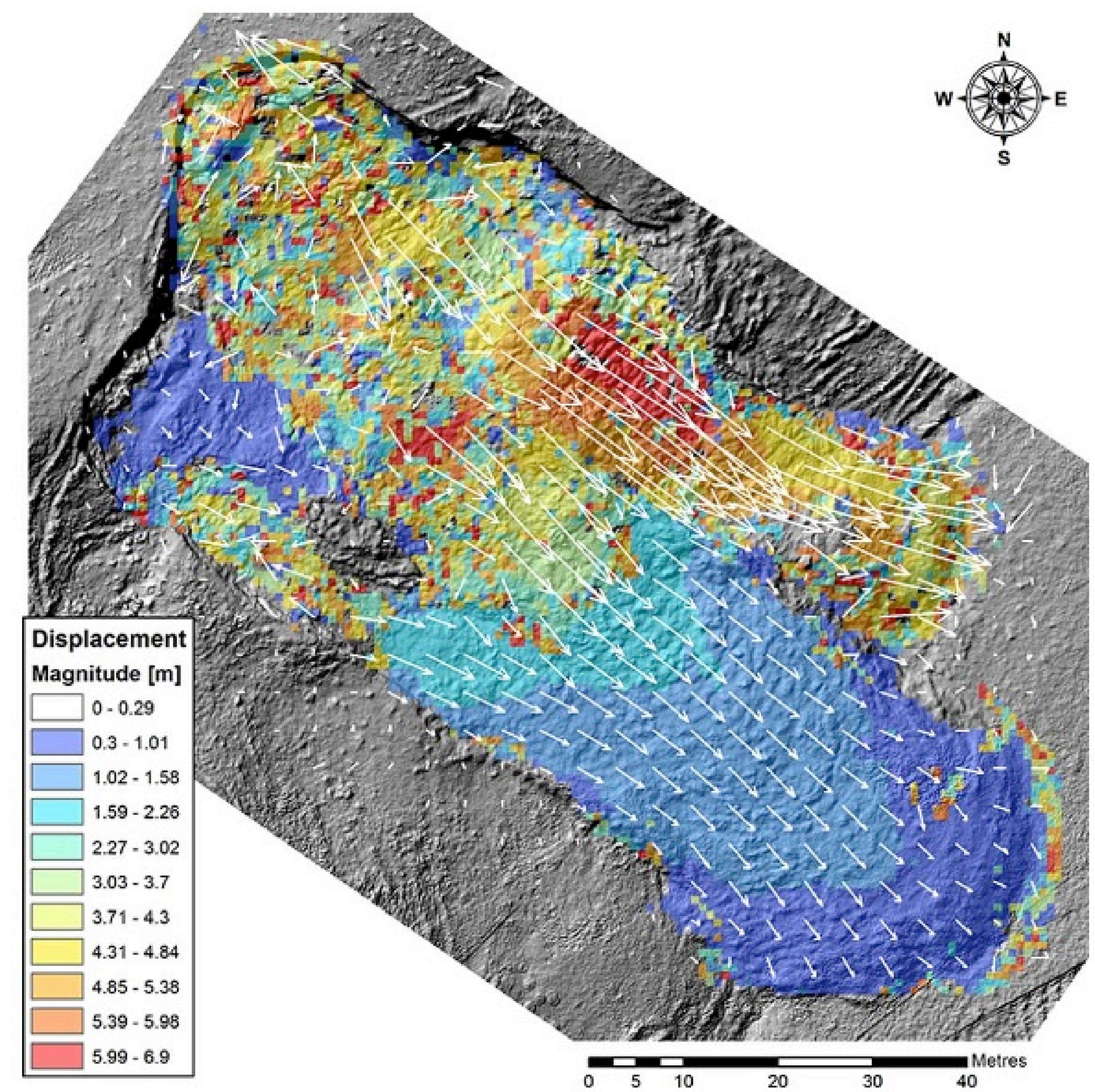

Figure 7. Displacement of the Home Hill landslide between 19 July 2011 and 10 November 2011 using the COSI-Corr algorithm. The white vectors indicate displacement directions and the coloured layer illustrate the combined magnitude of displacements in the N–S and E–W directions.

Remote Sensing of Environment 150 (2014) 93–103

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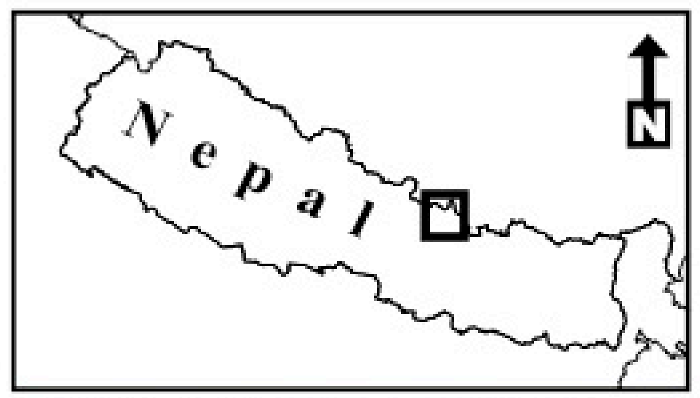
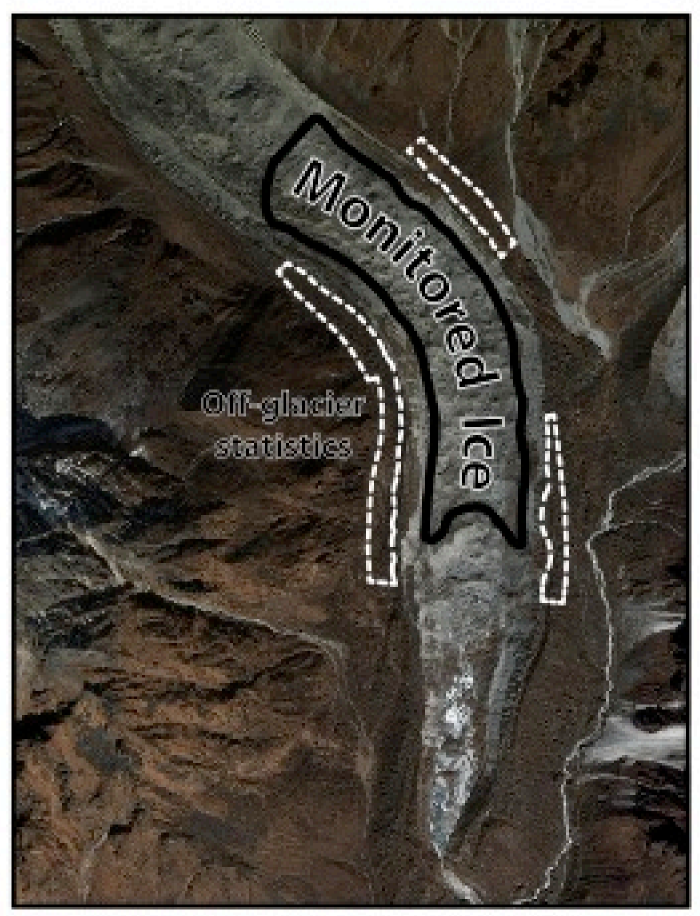
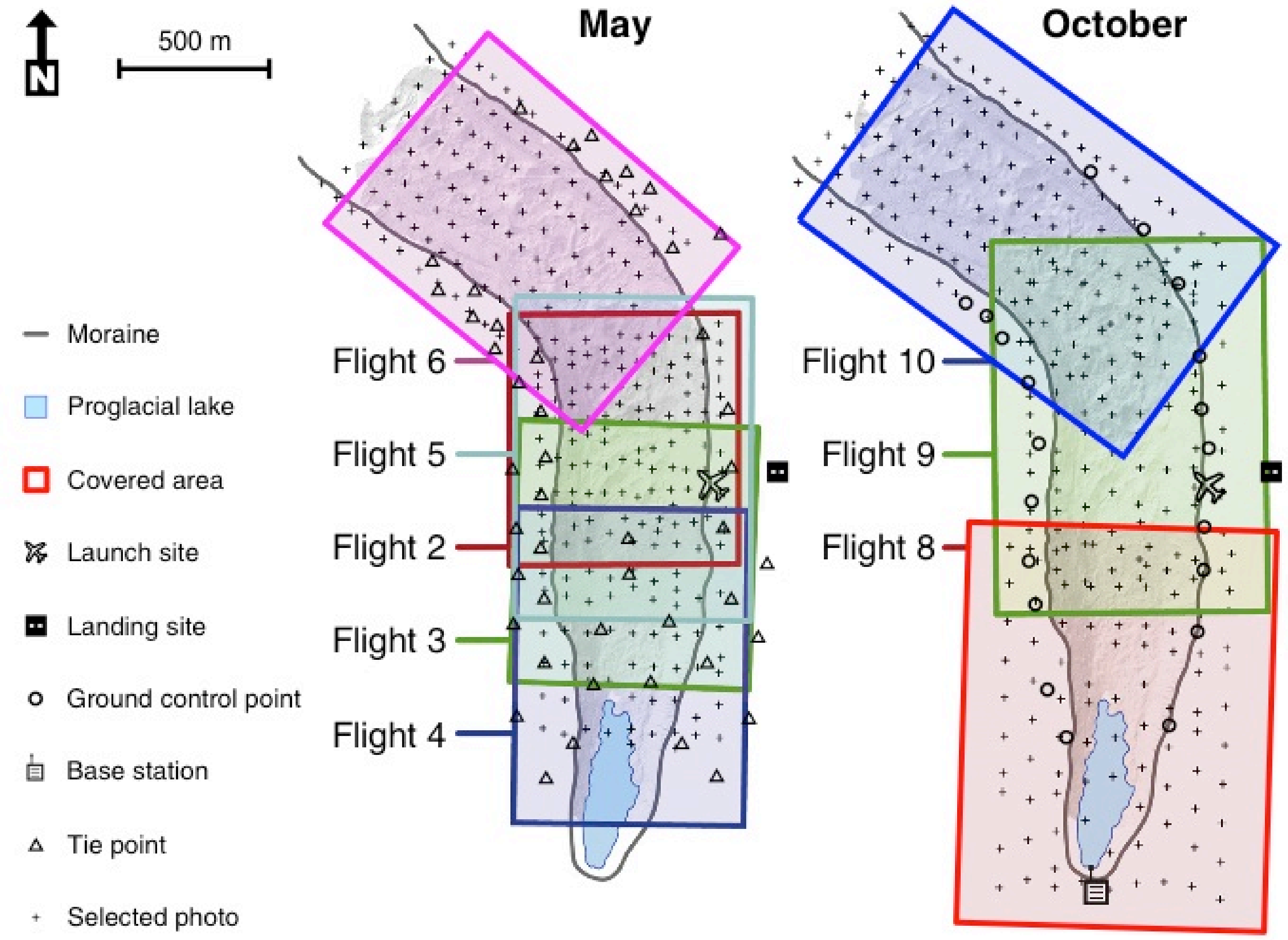
journal homepage: www.elsevier.com/locate/rse

High-resolution monitoring of Himalayan glacier dynamics using unmanned aerial vehicles

W.W. Immerzeel [a,b,c,*], P.D.A. Kraaijenbrink [a], J.M. Shea [b], A.B. Shrestha [b], F. Pellicciotti [b,c], M.F.P. Bierkens [a], S.M. de Jong [a]







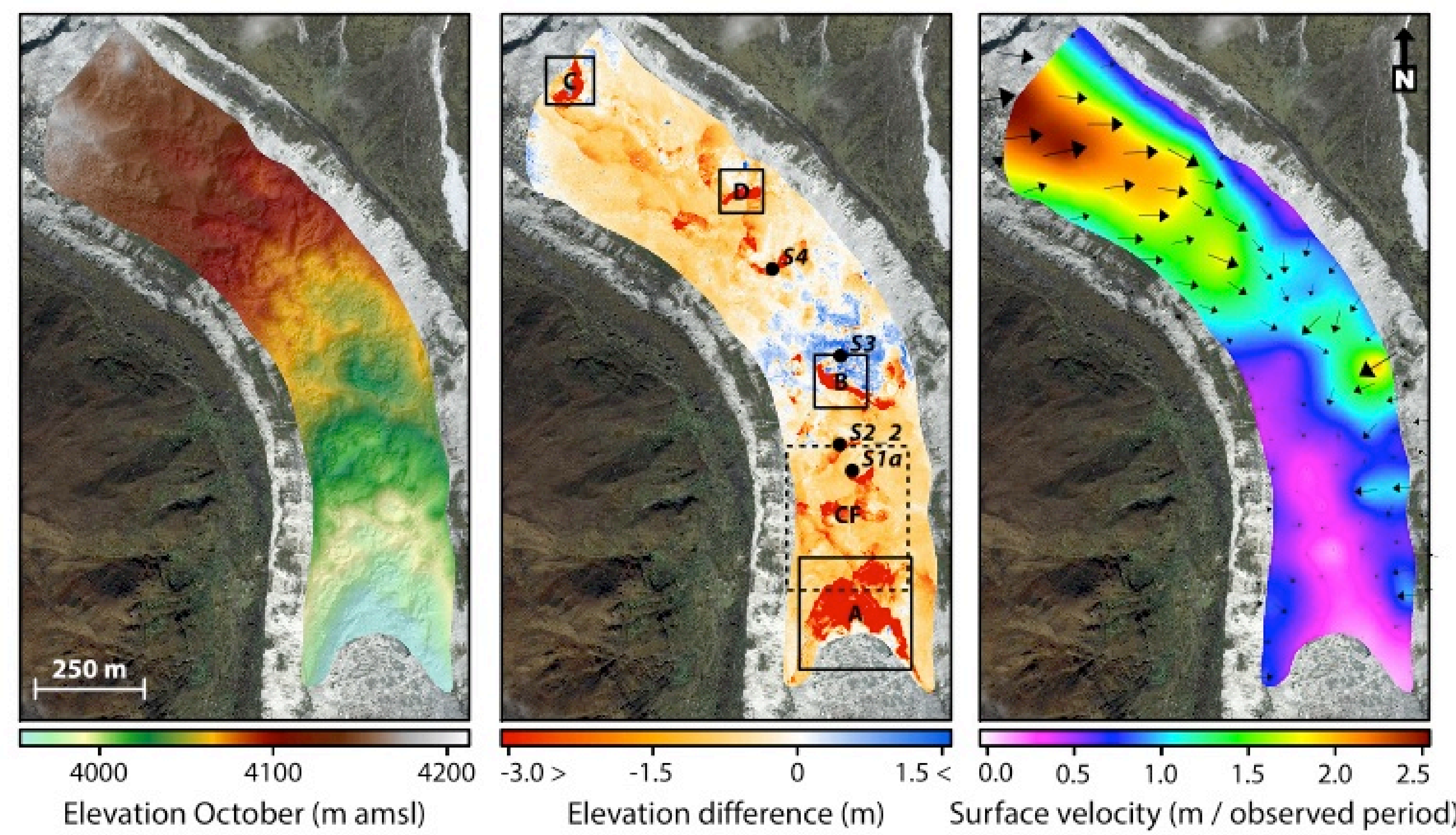


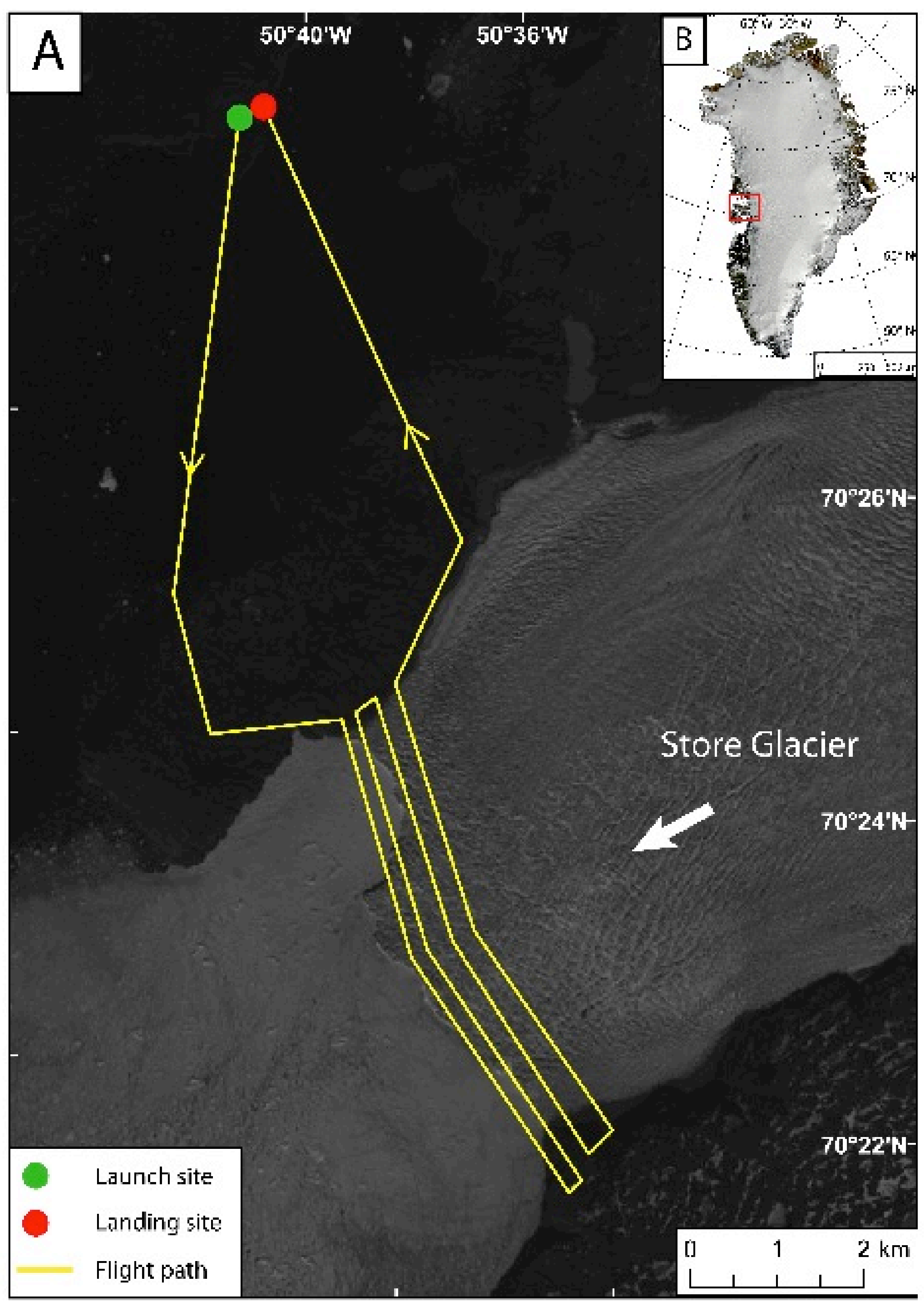
Fig. 5. Digital elevation model in October 2013 (left panel), changes in elevation between May and October 2013 (middle panel), and the derived surface velocity and direction of flow (right panel). The middle panel shows the locations of the ablation stakes and the extents of the panels of Fig. 7 (solid boxes) as well as the extent in Fig. 8 (dashed box).

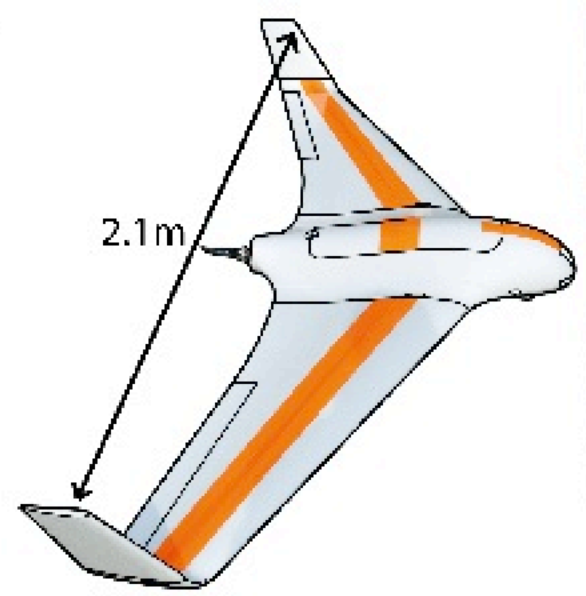
The Cryosphere Discuss., 8, 2243–2275, 2014
www.the-cryosphere-discuss.net/8/2243/2014/
doi:10.5194/tcd-8-2243-2014

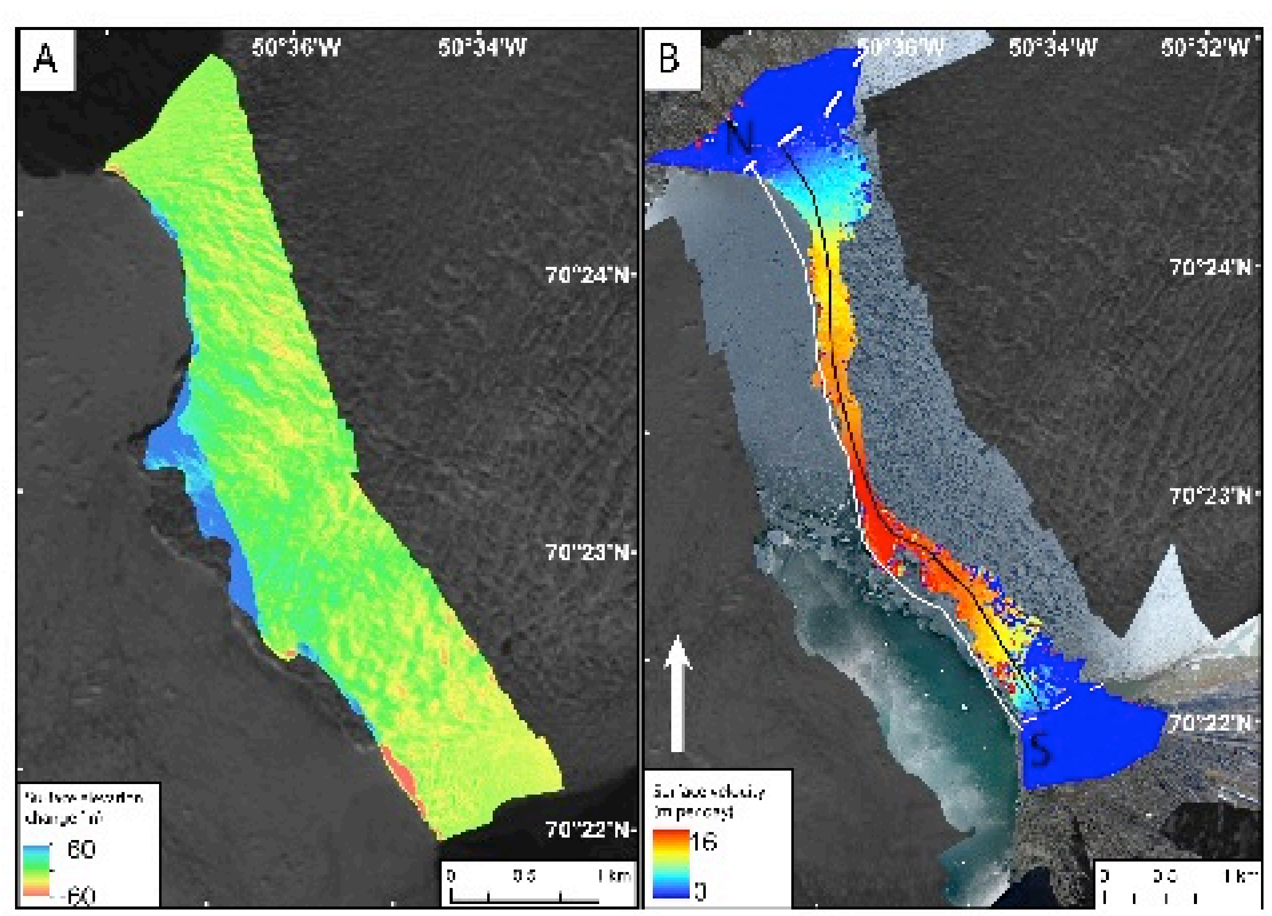
The Cryosphere
Discussions
Open Access

Repeat UAV photogrammetry to assess calving front dynamics at a large outlet glacier draining the Greenland Ice Sheet

J. C. Ryan[1], A. L. Hubbard[1], J. Todd[2], J. R. Carr[1], J. E. Box[3], P. Christoffersen[2], T. O. Holt[1], and N. Snooke[4]







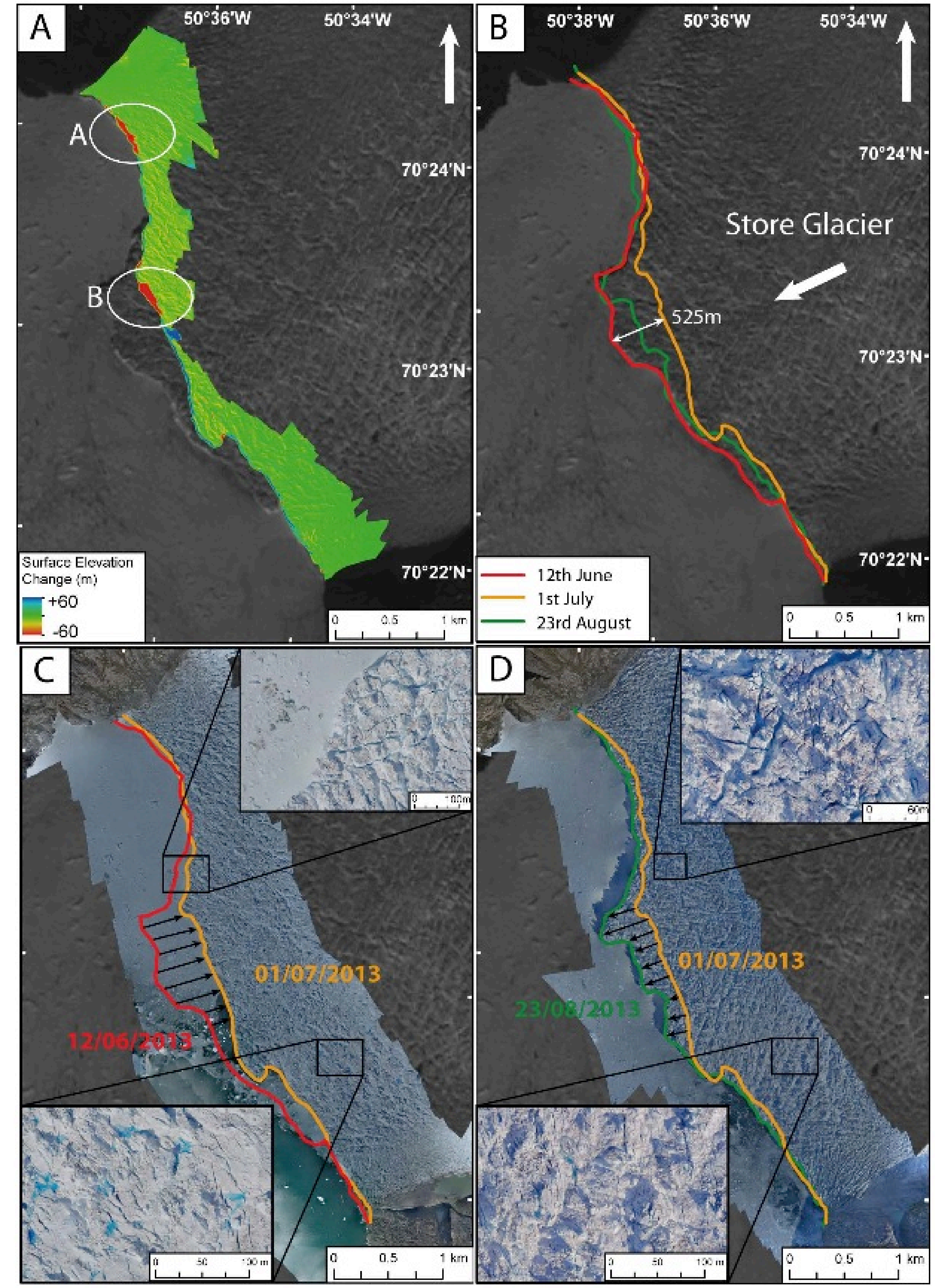


Fig. 3. (A) Surface elevation difference between two DEMs collected on the 1 July and 2 July. Red areas show elevation loss whilst blue areas show elevation gain. White circles highlight the calving events that occurred between the two UAV surveys. **(B)** The position of the calving front of Store Glacier during the summer of 2013. **(C)** Calving front retreat observed between 12 June and 1 July. Inset is an orthorectified image of the water-filled crevasses observed on 1 July with a pixel resolution of 30 cm. **(D)** Calving front advance observed between 1 July and 23 August. Inset is an orthorectified image showing water-filled crevasses observed on 23 August. The coverage and size of water-filled crevasses is smaller.

DIY UAVs

Hobby airframe ($100)

+

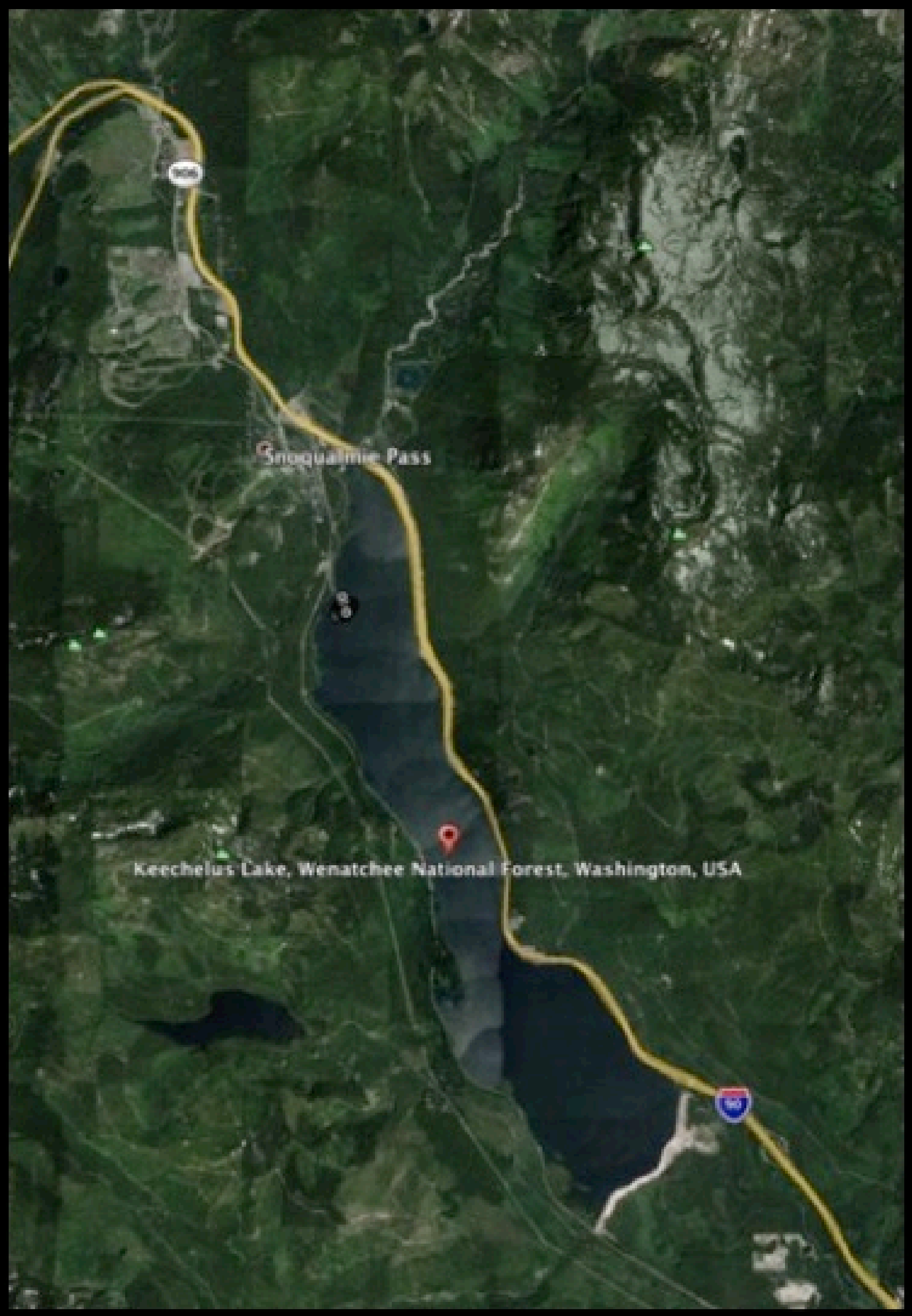
Autopilot + GPS ($280)

+

Sensors ($200)

- Cheap: ~$500-1000 total
- On-demand, repeat surveys in minutes
- Low altitude (<400') = high-resolution (cm/px)
- ~5-100 km range, ~0.2-2.0 hr flight time

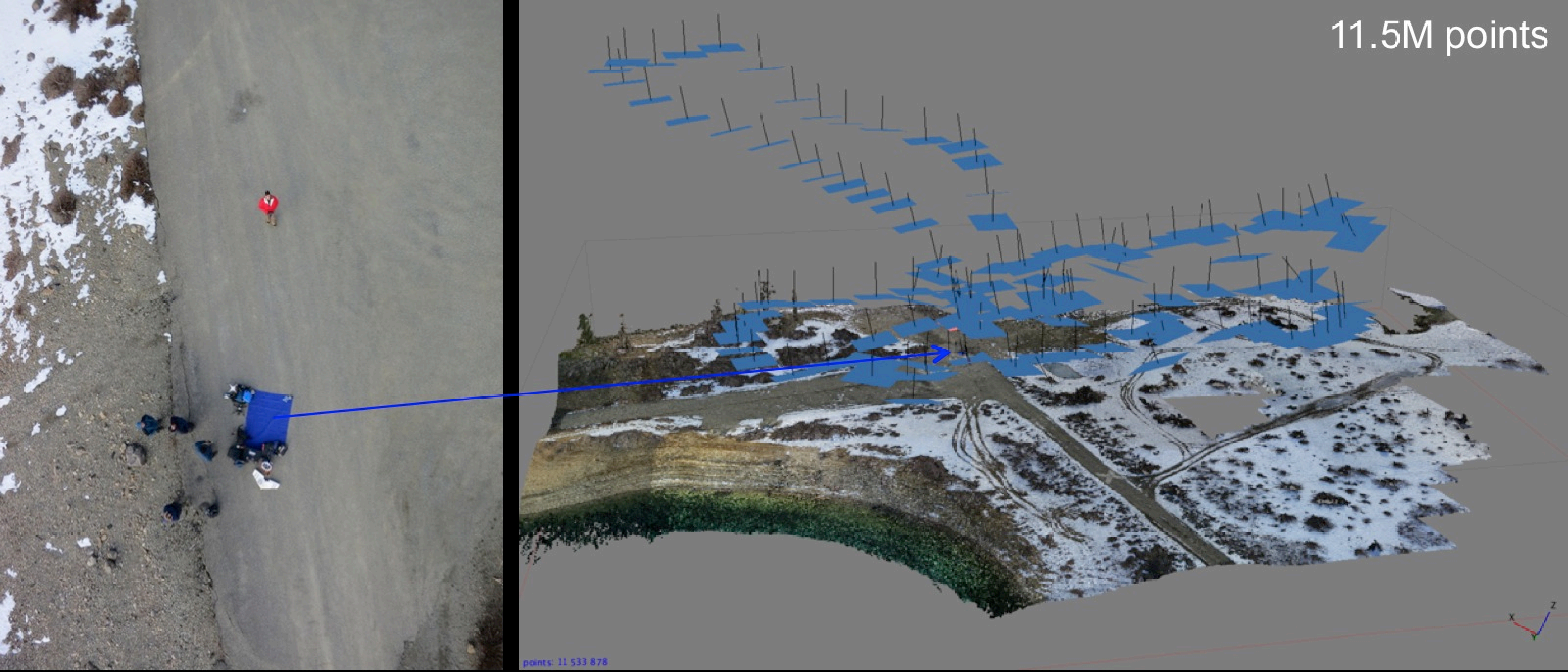
Keechelas Lake Pilot Study



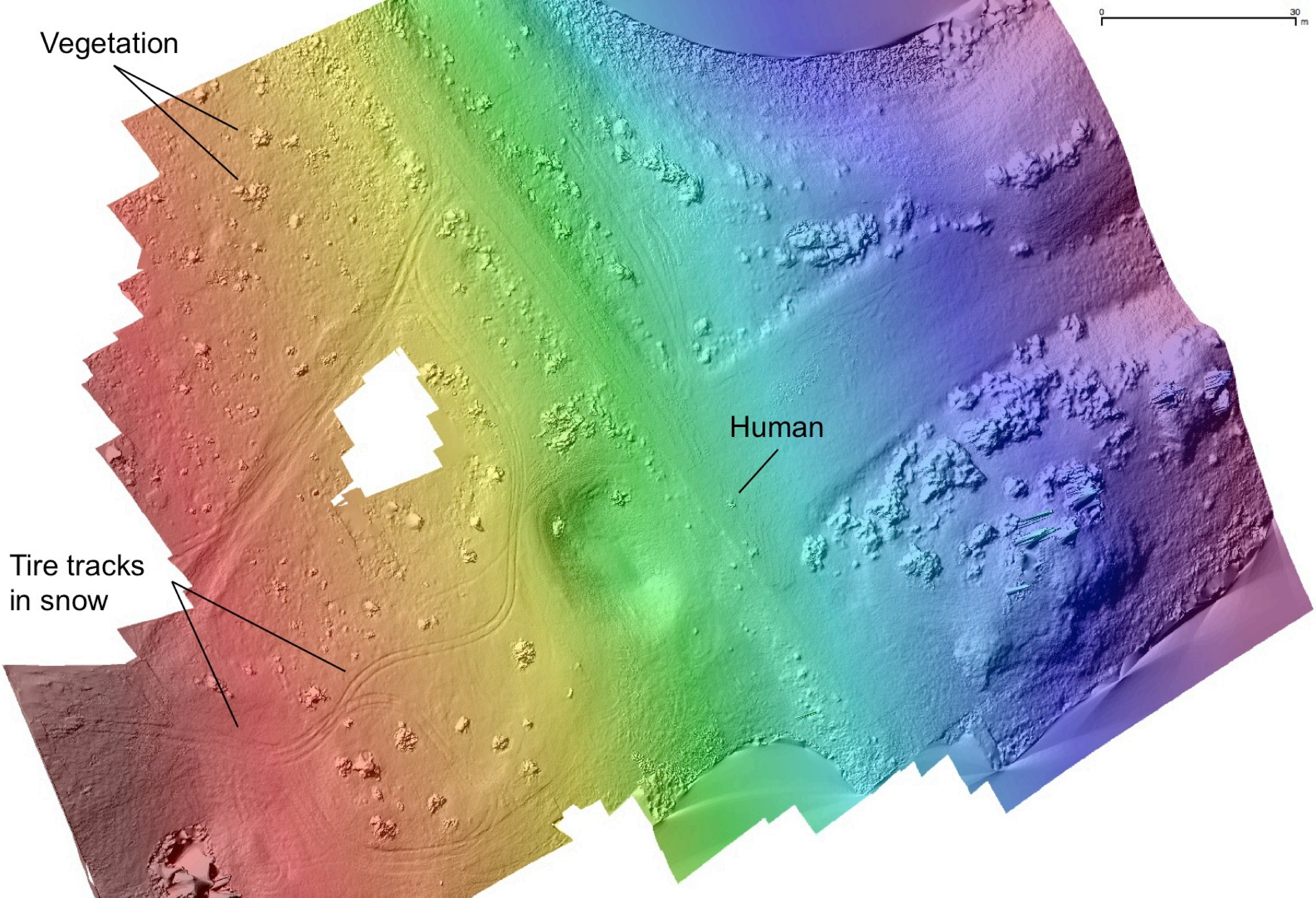
Blade 350 QX Quadcopter

+

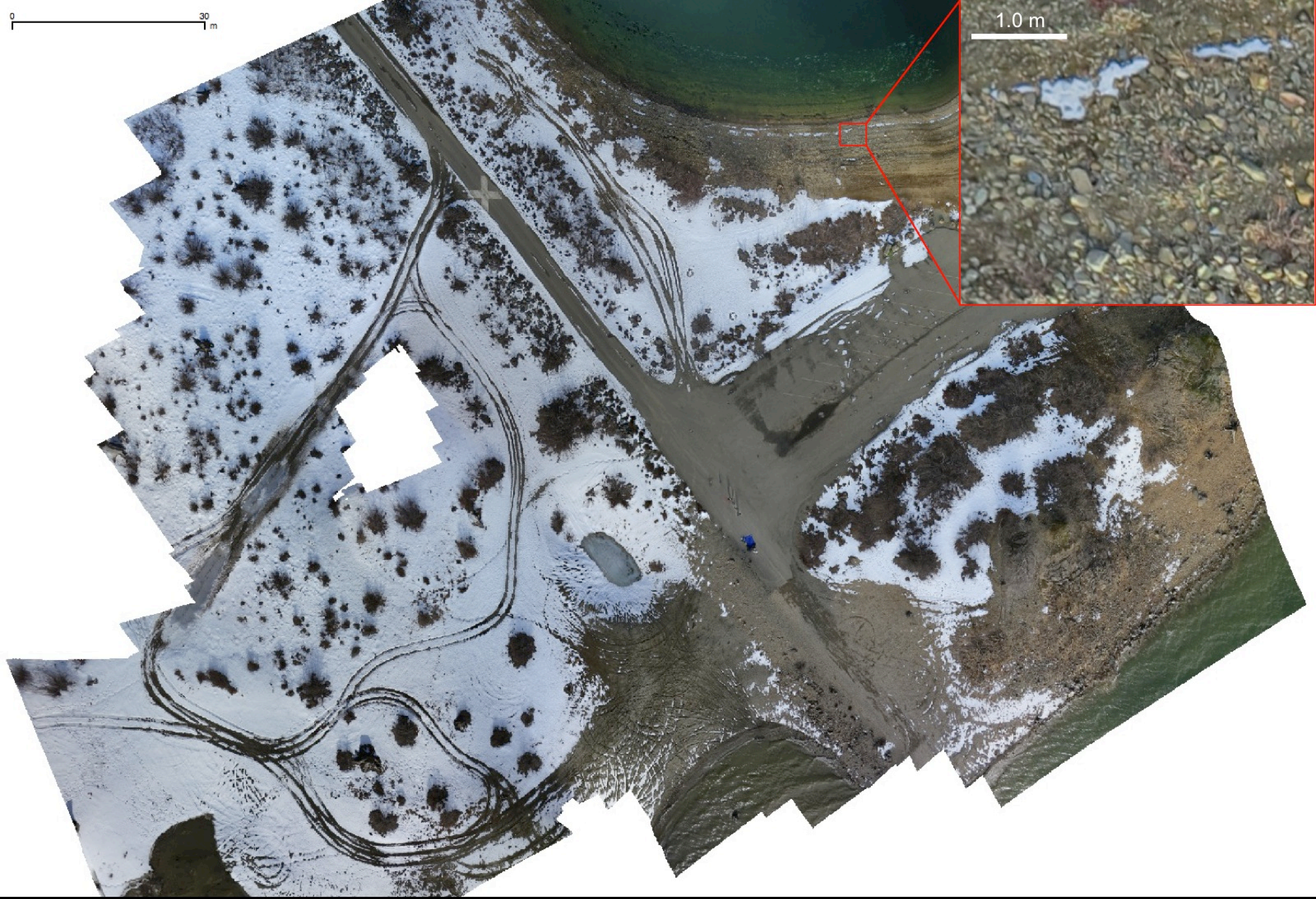
12.1 MP Canon S100



- ~5 minute manual flight
- ~120 images

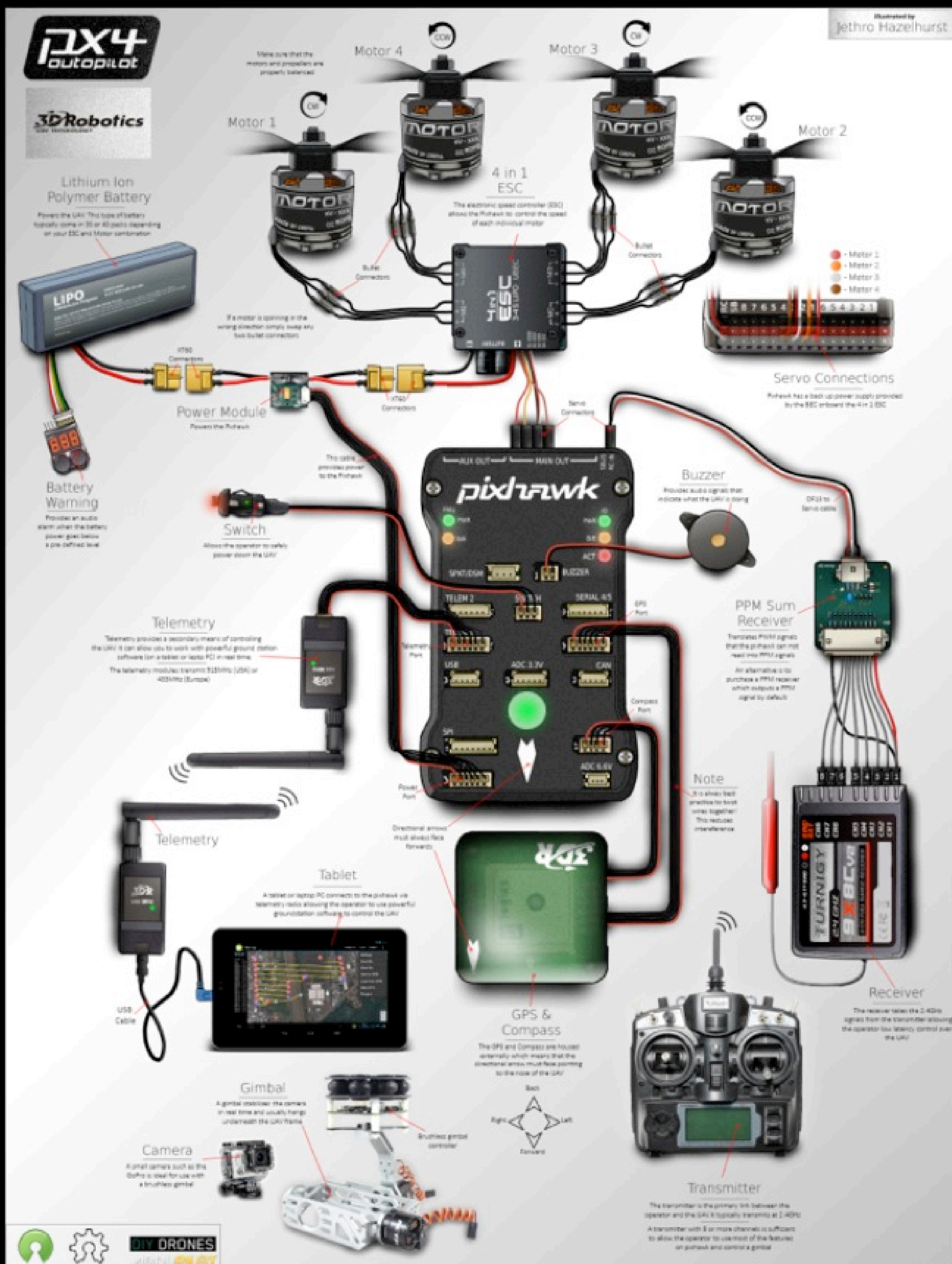


~200x200 m, ~5 cm/px topography

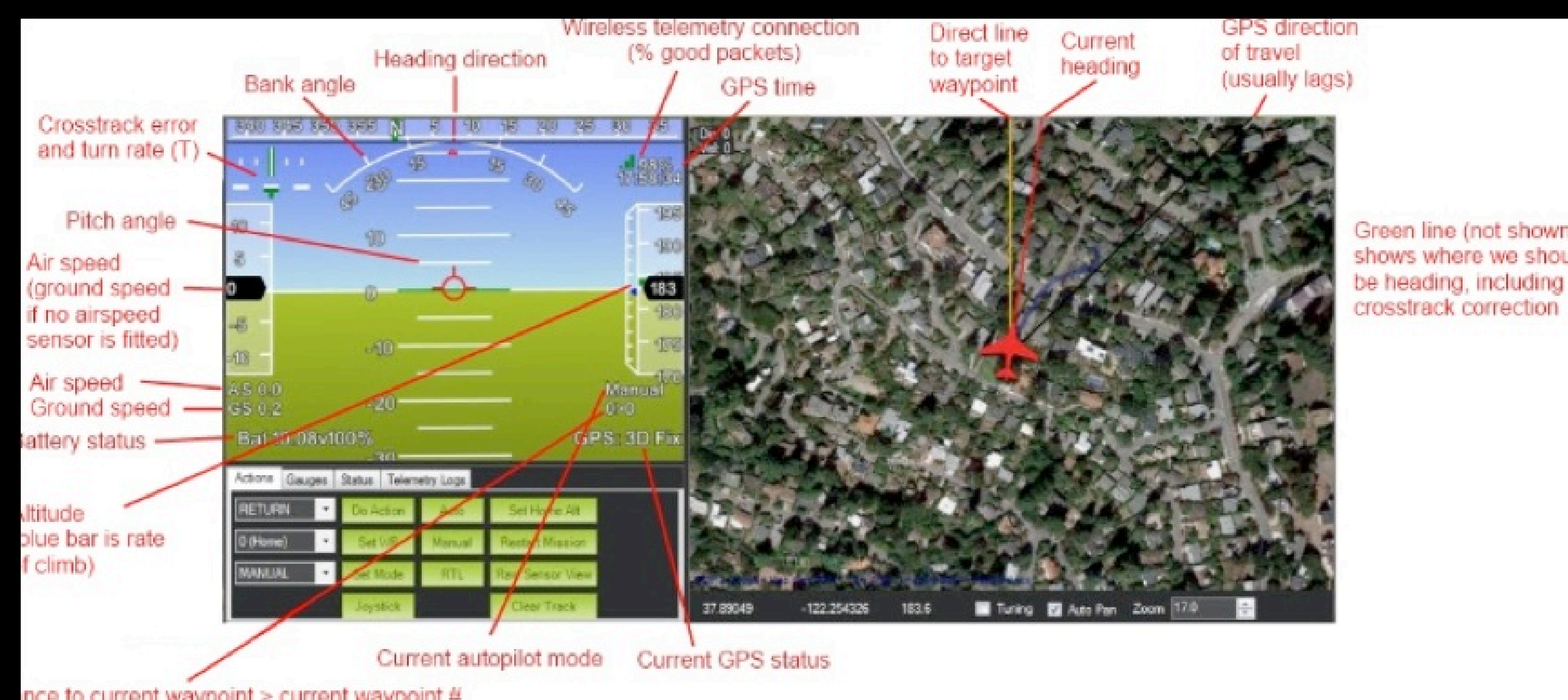


~200x200 m, ~1 cm/px image mosaic

Open Source Autopilot Systems (~$100-200)



http://3drobotics.com/



GPS waypoint navigation & camera triggering

2014 Ice Mapping 'Bots

$700 hexacopter

$200 quadcopter prototype

$150 airplane

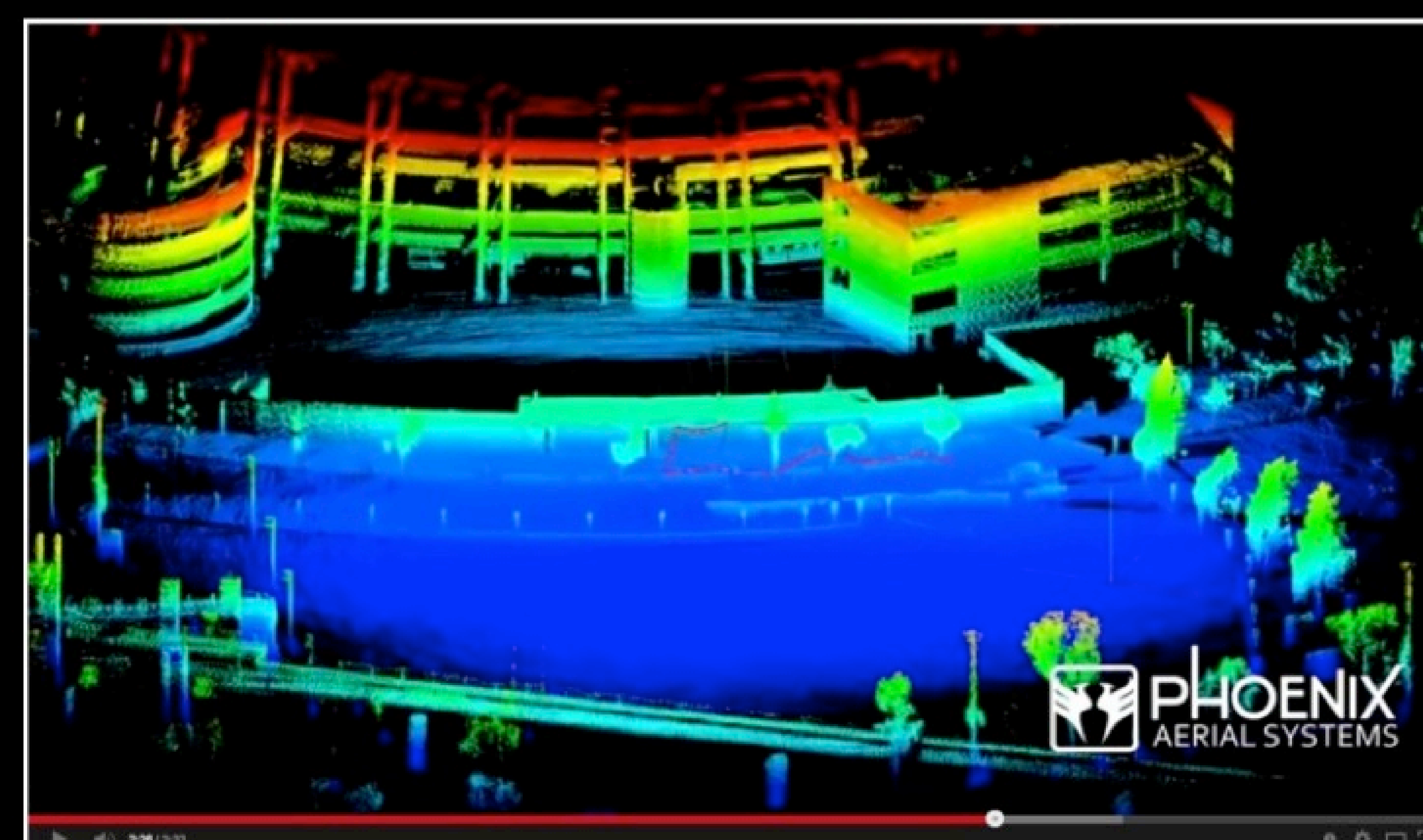
$150 flying wing

Cool toys. Now what?

- Near Term Goals
  - August 2014: Easton Glacier, Mt. Baker
  - August 2014: Block Mountain, MT
- Long Term Goals
  - Antarctic ice shelf surveys, melt rates
  - Greenland outlet glacier calving dynamics

The Future

http://quadcopters.co.uk



http://www.phoenix-aerial.com/

A modern photogrammetry toolbox

- Inexpensive or “free” data acquisition with cm to meter-scale DEM products
- Repeat surveys in minutes-months
- Automated, open source processing tools

Platform	Image Resolution (m/px)	DEM Resolution (m/px)	Coverage (km^2)	Repeat Interval	Equipment Cost	Survey Cost
Commercial Stereo	~0.5-1.0	~2.0	10-10^6	Days-years	“free”	“free”
Oblique aerial SfM	~0.1-1.0	~1.0-2.0	10-1000	Hours-days	$1-3K	$50-500/hr
UAV SfM	~0.01	~0.01-0.1	1-100	Minutes-hours	$1K	“free”

Summary

- Automated pipeline for commercial stereo:
  - ~2 m/px DEMs
  - ~5 m uncorrected accuracy, <1 m corrected/relative
- Repeat DEMs offer unprecedented spatial/ temporal resolution for dynamic science
  - Each DEM is like an airborne LiDAR survey
  - Dense DEM timeseries are like continuous GPS measurements, everywhere
- Software, instrumentation continues to improve
- Baselines are established, the real science will come from continued observations…

Bonus Slides

Stereo Satellite Imagery

- Products
  - High-res point clouds, DEMs, orthoimages
  - 2D/3D displacement (velocity) maps
- Measurements
  - Volume (mass) change
  - Surface velocities
  - Calving front position/height
  - Ice shelf, iceberg thickness
- Specific applications:
  - Ice stream and outlet glacier dynamics
    - Real-time, 10 min, Jakobshavn ~30 cm displacement
  - Ice shelf thickness
  - Subglacial lake evolution
  - Alpine glacier mass balance
  - Regional snowpack evolution (need density)
  - Real-time: glacier surging, calving events

Commercial Stereo

- Pros
  - High-resolution (30-46 cm/px), multispectral
  - Along-track stereo acquisition
  - Regional Coverage
  - Repeat interval of ~1-2 days
  - Derived products freely distributable
  - 11-bit products offer high dynamic range
- Cons
  - Competition
  - Limited tasking control
  - Restricted, no “raw” data access
  - Proprietary instruments
  - Occlusions for binocular stereo
  - Passive observation – no polar nighttime observations, clouds

What can a new, gazing instrument do that can’t be done with existing DigitalGlobe, Astrium, TanDEM-X, SkySat-1, or Planet Labs resources?

Gazing Instrument + Platform Wishlist

- >11-bit HDR image data (shadows, rock/snow)
- Advanced attitude control, vibration isolation
- High angle (>40°) off-nadir targeting
  - Ability to capture overhangs
- Short repeat interval, ~1 day
- High orbital inclination – polar observations (>70°)
- High resolution, <1 m GSD
- Footprint ~5x5 km
- Low-res context imager?
- ICESat-2, or simple laser altimeter onboard?
- Camera model development?

Other applications

- Sea ice displacements
- Volcanic deformation
- Fluvial erosion/deposition
- 3D cloud structure
- Avalanches, landslides
- Vegetation height, biomass
- Wildlife observations
  - Population
  - Heading, velocity, surfacing rate (e.g. marine mammals)
- Wildfire observations – multi-look
  - Thermal IR?
- Gazing at the Moon?
  - Planetary Resources
- Bathymmetry (clear water, color)
- Reservoir volumes – flood hazards, water resources
- Plantary analogs – gully evolution
- Fault displacements – 2D/3D
- Structural mapping – exposed and beneath thin ice
- Landsat science objectives?
- Astronaut photo archives
- Wave heights
- Geysers

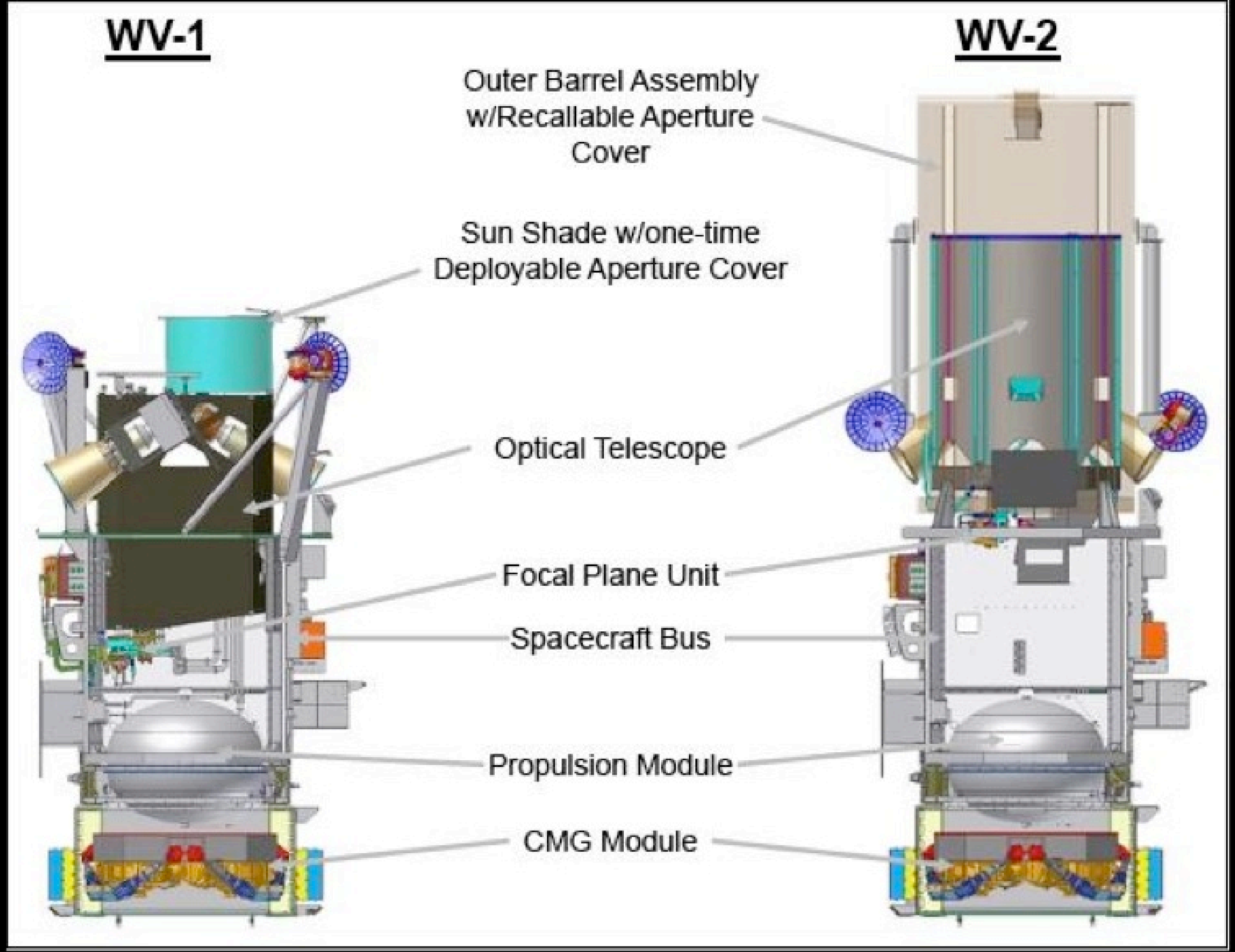
WorldView-2

Spacecraft:

- 770 km altitude, 7.5 km/s velocity
- <500 m instantaneous geolocation accuracy
- State of the art attitude control sys
- Off-nadir angles of <40°

Instrument:

- ~13.3 m focal length, ~1.1 m primary mirror, 1.28° FOV
- Panchromatic (0.46 m/px)
  - ~35420 samples (50 CCDs)
  - ~30K–462K lines
  - 16 Gigapixel camera (11 bit)
- 8-band multispectral (1.8 m/px)
  - 400-1040 nm



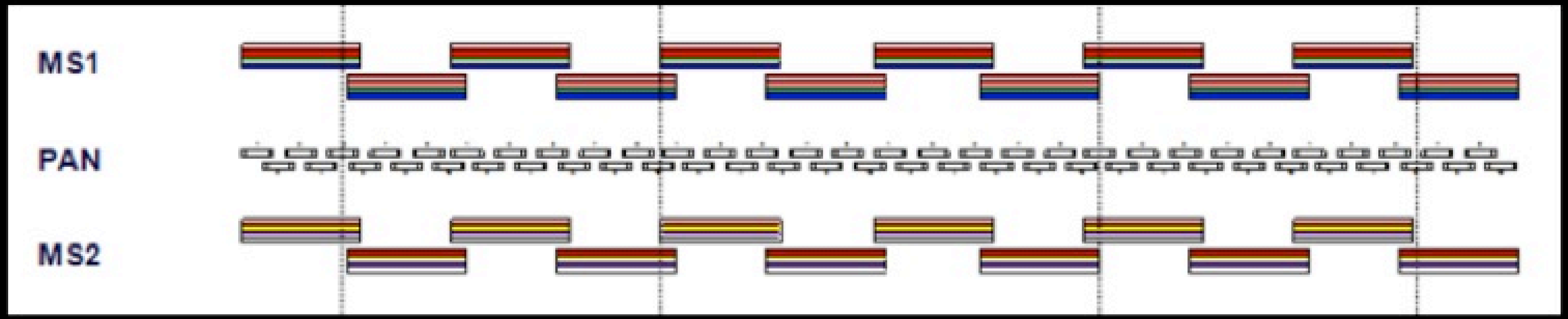
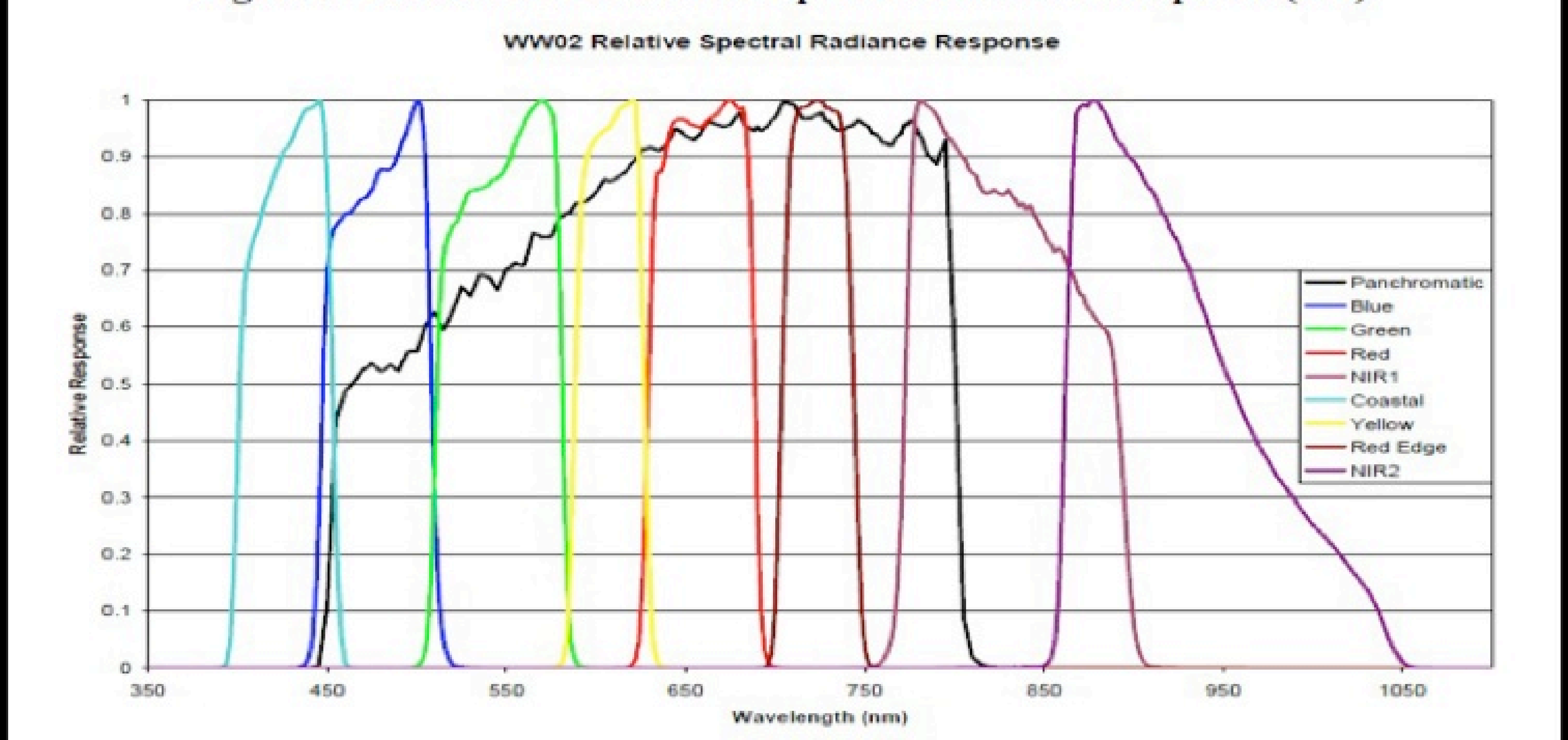


Figure 2: WorldView-2 Relative Spectral Radiance Response (nm)

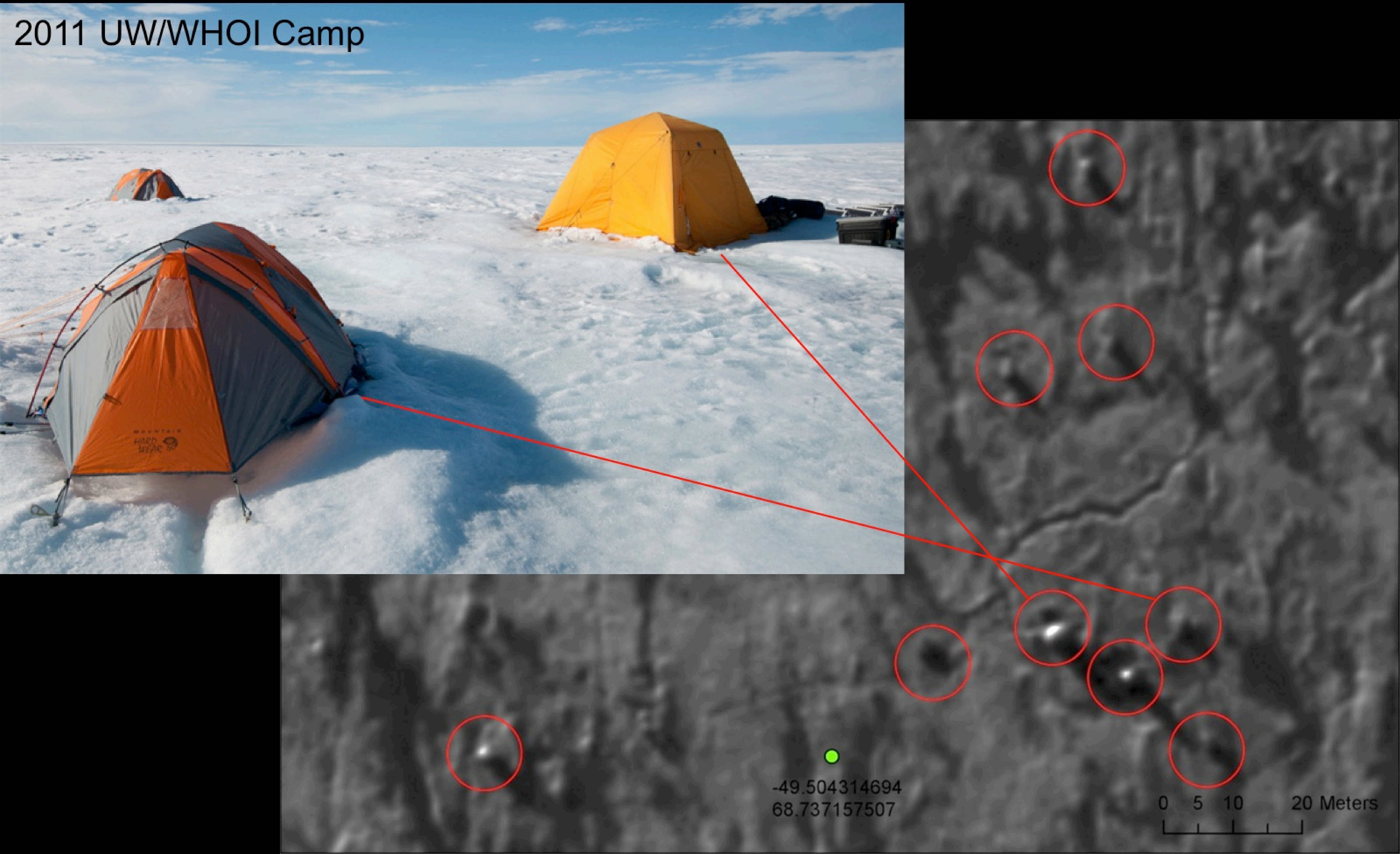


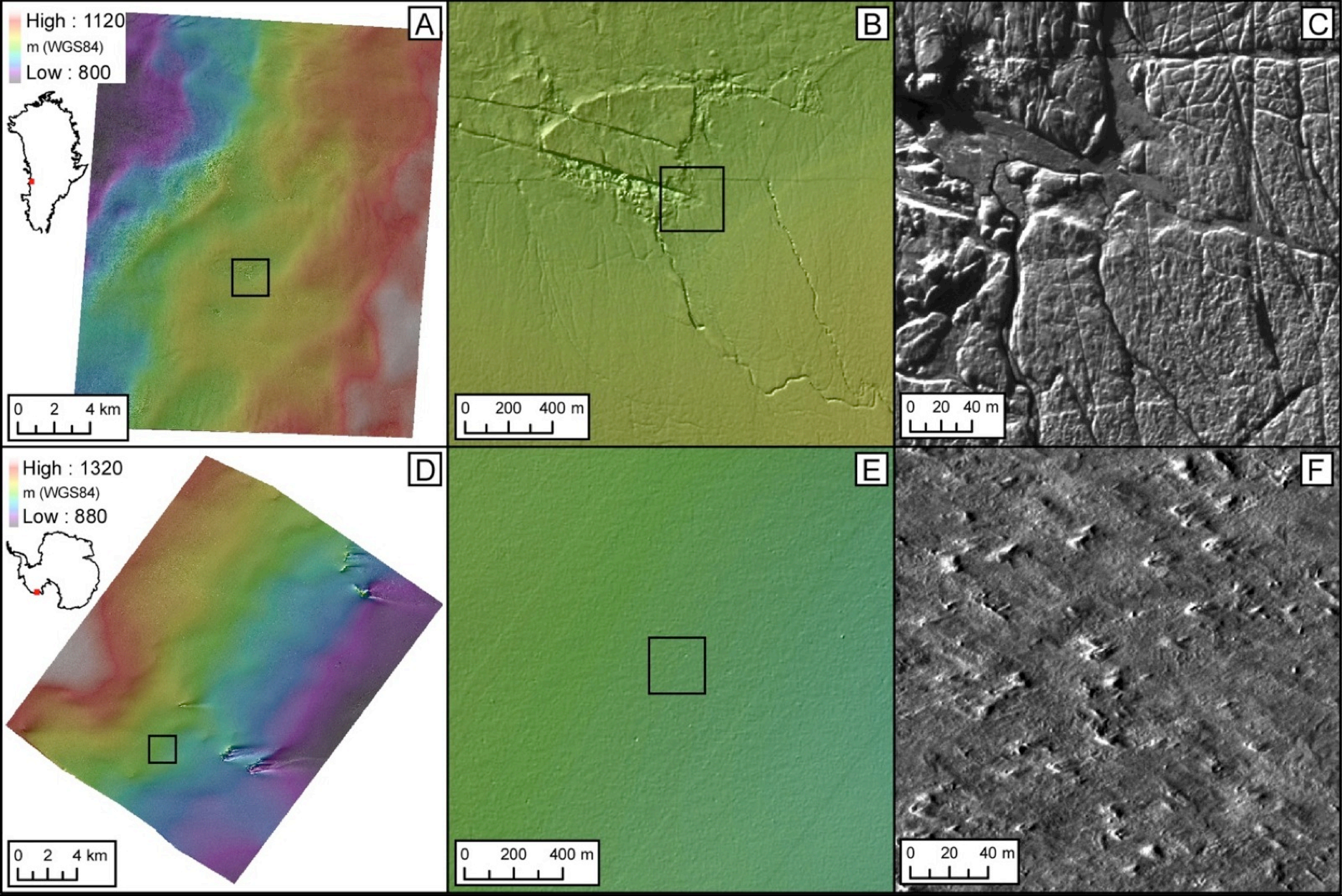
DigitalGlobe L1B Sensor Models

- Rigorous Linear (Synthetic 1D)
  - Relates image row to timestamp in spacecraft ephemeris/attitude tables
  - Earth-Centered, Earth-Fixed coord sys
  - Optical distortion, geometric, radiometric correction
- Rational Polynomial Coefficients (RPC)
  - Ratio of 3rd-order polynomials relating image row,col to exterior lat,lon,z

$$r_n = \frac{\sum_{i=1}^{20} LINE\_NUM\_COEF_i \cdot \rho_i(P,L,H)}{\sum_{i=1}^{20} LINE\_DEN\_COEF_i \cdot \rho_i(P,L,H)} \text{ and } c_n = \frac{\sum_{i=1}^{20} SAMP\_NUM\_COEF_i \cdot \rho_i(P,L,H)}{\sum_{i=1}^{20} SAMP\_DEN\_COEF_i \cdot \rho_i(P,L,H)}$$

WorldView-2 Sample
West Greenland lakes





A
High : 1120
m (WGS84)
Low : 800
0 2 4 km
B
0 200 400 m
C
0 20 40 m
D
High : 1320
m (WGS84)
Low : 880
0 2 4 km
E
0 200 400 m
F
0 20 40 m

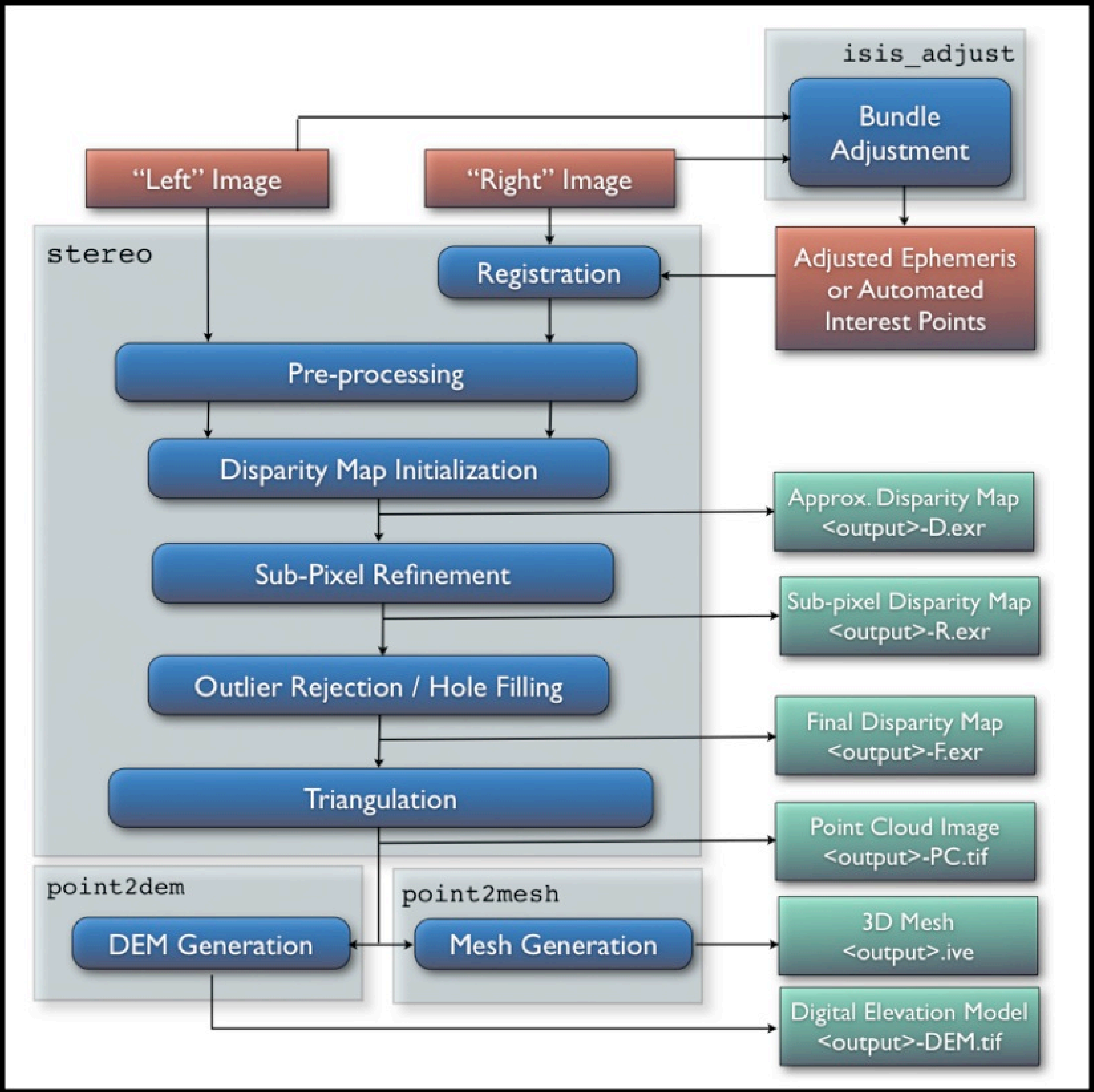
ASP Workflow

Can be simple:

```
stereo img1.tif img2.tif out
point2dem –tr 4.0 –t_srs ‘proj4 str’ [--orthoimage img1.tif] out-PC.tif
```

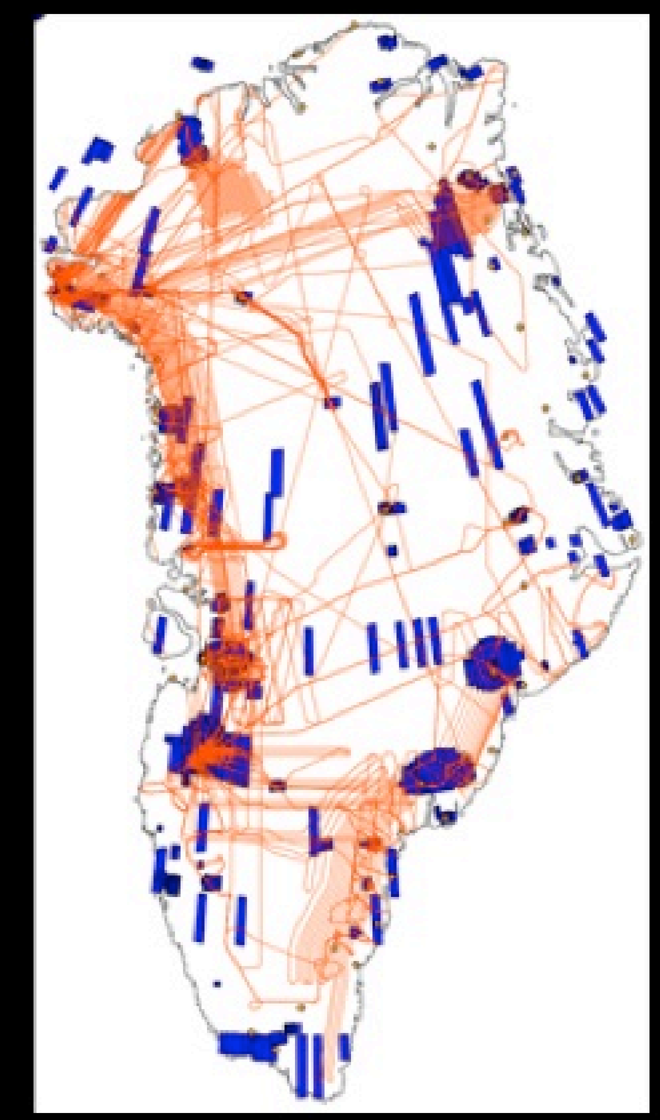
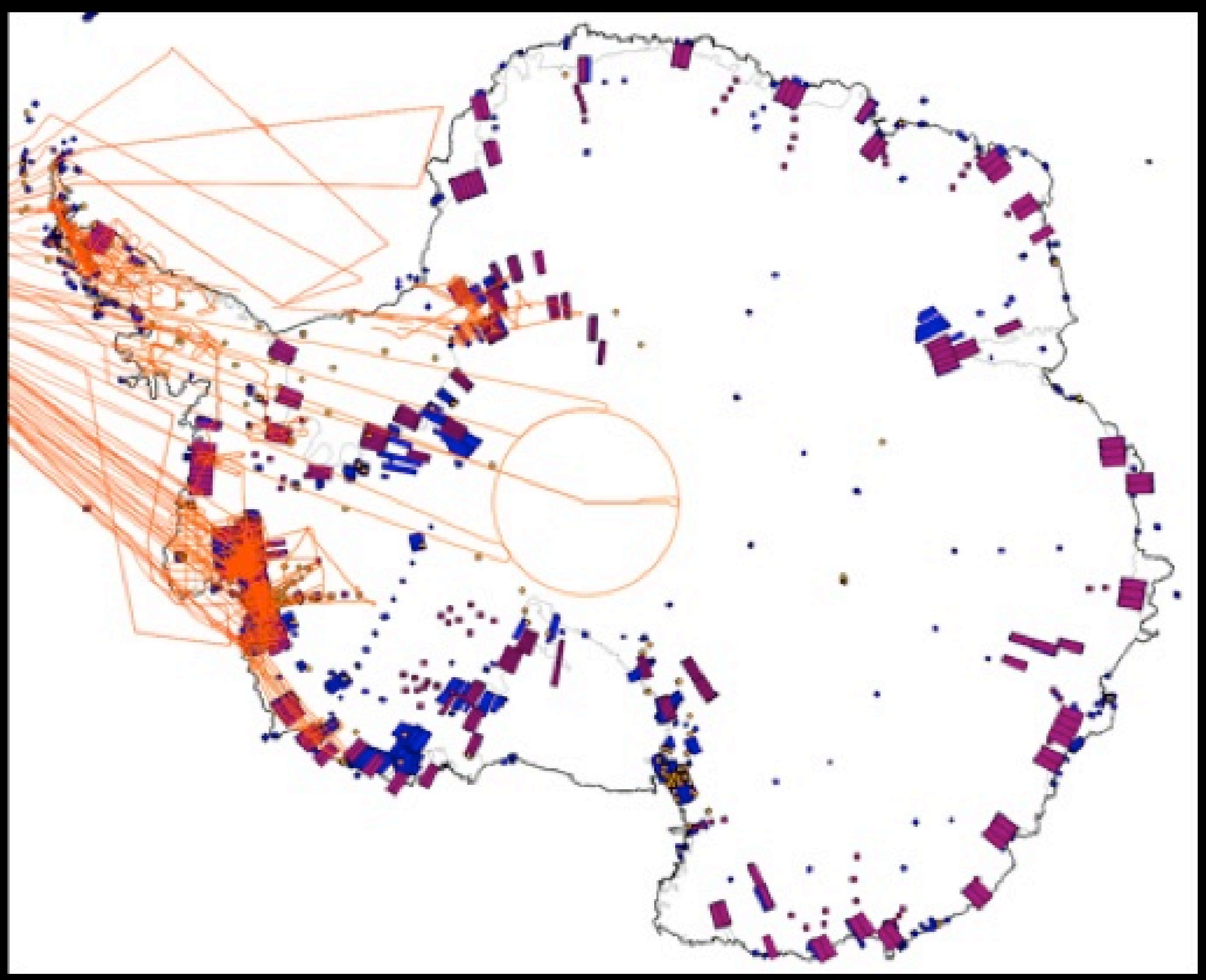
Or…

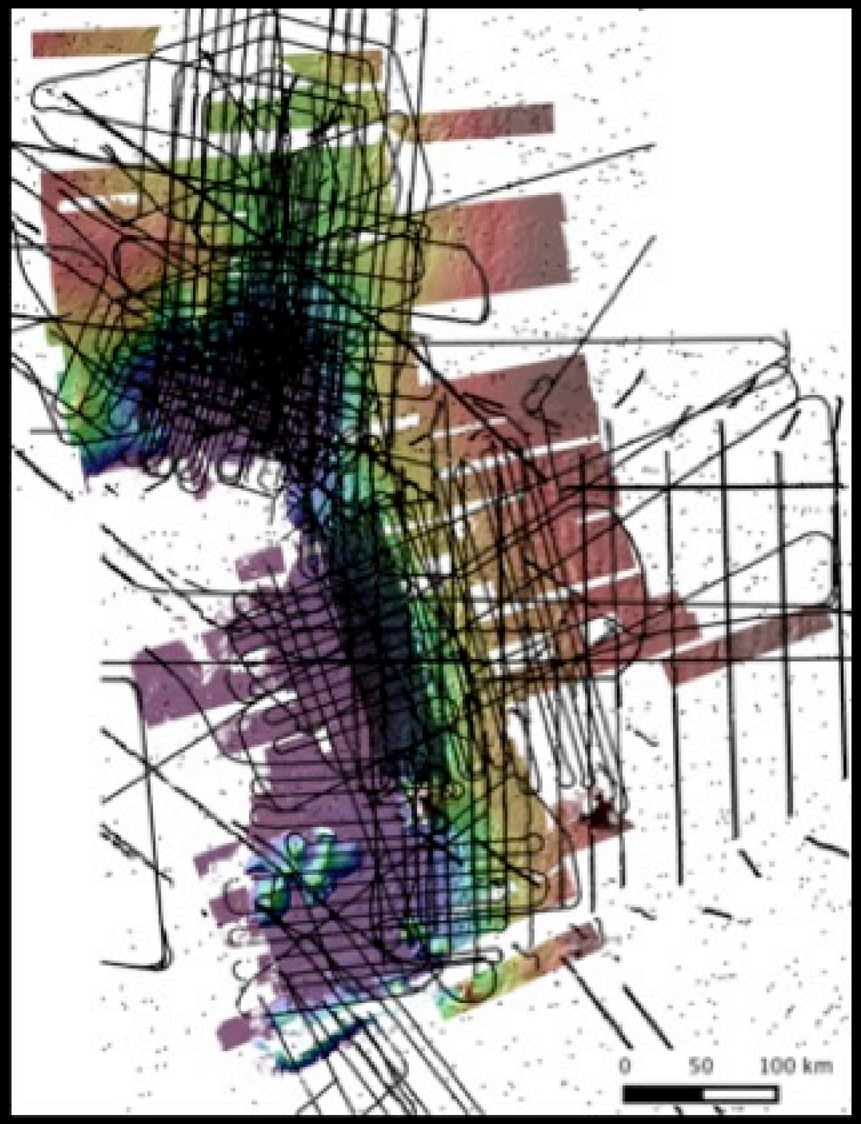
```
stereo_pprc
    -t [ --session-type ] arg             Select the stereo session type to use
    --left-image-crop-win arg (=xoff yoff xsize ysize)
    --alignment-method arg                Rough alignment for input images.
    --force-use-entire-range              Normalize images based on the global
    --individually-normalize              Individually normalize the input images
    --nodata-value arg                    Pixels with values less than or equal
    --nodata-pixel-percentage arg         The percentage of (low-value) pixels
    --nodata-optimal-threshold-factor arg Pixels with values less than this
    --threads arg (=0)        Select the number of processors (threads) to use.
    --no-bigtiff              Tell GDAL to not create bigtiffs.
    --tif-compress arg (=LZW) TIFF Compression method. [None, LZW, Deflate,

stereo_corr
    --prefilter-kernel-width arg (=1.5)   Sigma value for Gaussian kernel used in
    --prefilter-mode arg (=2)             Preprocessing filter mode. [0 None, 1
    --corr-seed-mode arg (=1)             Correlation seed strategy. [0 None, 1
    --corr-sub-seed-percent arg (=0.25)   Percent fudge factor for disparity
    --cost-mode arg (=2)                  Correlation cost metric. [0 Absolute, 1
    --xcorr-threshold arg (=2)            L-R vs R-L agreement threshold in
    --corr-kernel arg (=21 21)            Kernel size used for integer
    --corr-search arg (=auto)             Disparity search range. Specify in
    --corr-max-levels arg (=5)            Max pyramid levels to process when
    --compute-low-res-disparity-only      Compute only the low-resolution
    --disparity-estimation-dem arg        DEM to use in estimating the
    --disparity-estimation-dem-accuracy arg

stereo_rfne
    --subpixel-mode arg (=2)           Subpixel algorithm. [0 None, 1 Parabola, 2
    --subpixel-kernel arg (=35 35)     Kernel size used for subpixel method.
    --disable-h-subpixel               Disable calculation of subpixel in
    --disable-v-subpixel               Disable calculation of subpixel in
    --subpixel-max-levels arg (=2)     Max pyramid levels to process when using
    --subpixel-em-iter arg (=15)       Maximum number of EM iterations for
    --subpixel-affine-iter arg (=5)    Maximum number of affine optimization
    --subpixel-pyramid-levels arg (=3) Number of pyramid levels for

stereo_fltr
    --rm-half-kernel arg (=5 5)          Low confidence pixel removal kernel (half
    --rm-min-matches arg (=60)           Minimum number of pixels to be matched to
    --rm-threshold arg (=3)              Maximum distance between samples to be
    --rm-cleanup-passes arg (=1)         Number of passes for cleanup during the
    --erode-max-size arg (=1000)         Max size of islands that should be
    --disable-fill-holes                 Disable filling of holes using an
    --fill-holes-max-size arg (=100000) Max size in pixels of holes that can be
    --mask-flatfield                     Mask dust found on the sensor or film.

stereo_tri
    --universe-center arg (=None)   Center for radius measurement thresholding.
    --near-universe-radius arg (=0) Radius of inner boundary of universe in
    --far-universe-radius arg (=0)  Radius of outer boundary of universe in
    --use-least-squares             Use rigorous least squares triangulation
    --compute-error-vector          Compute the triangulation error vector, not

point2dem
    --nodata-value arg                   Nodata value to use on output. This is
    --use-alpha                          Create images that have an alpha channel
    -n [ --normalized ]                  Also write a normalized version of the
    --orthoimage arg                     Write an orthoimage based on the texture
    --errorimage                         Write a triangulation intersection error
    --fsaa [=arg(=3)]                    Oversampling amount to perform
```



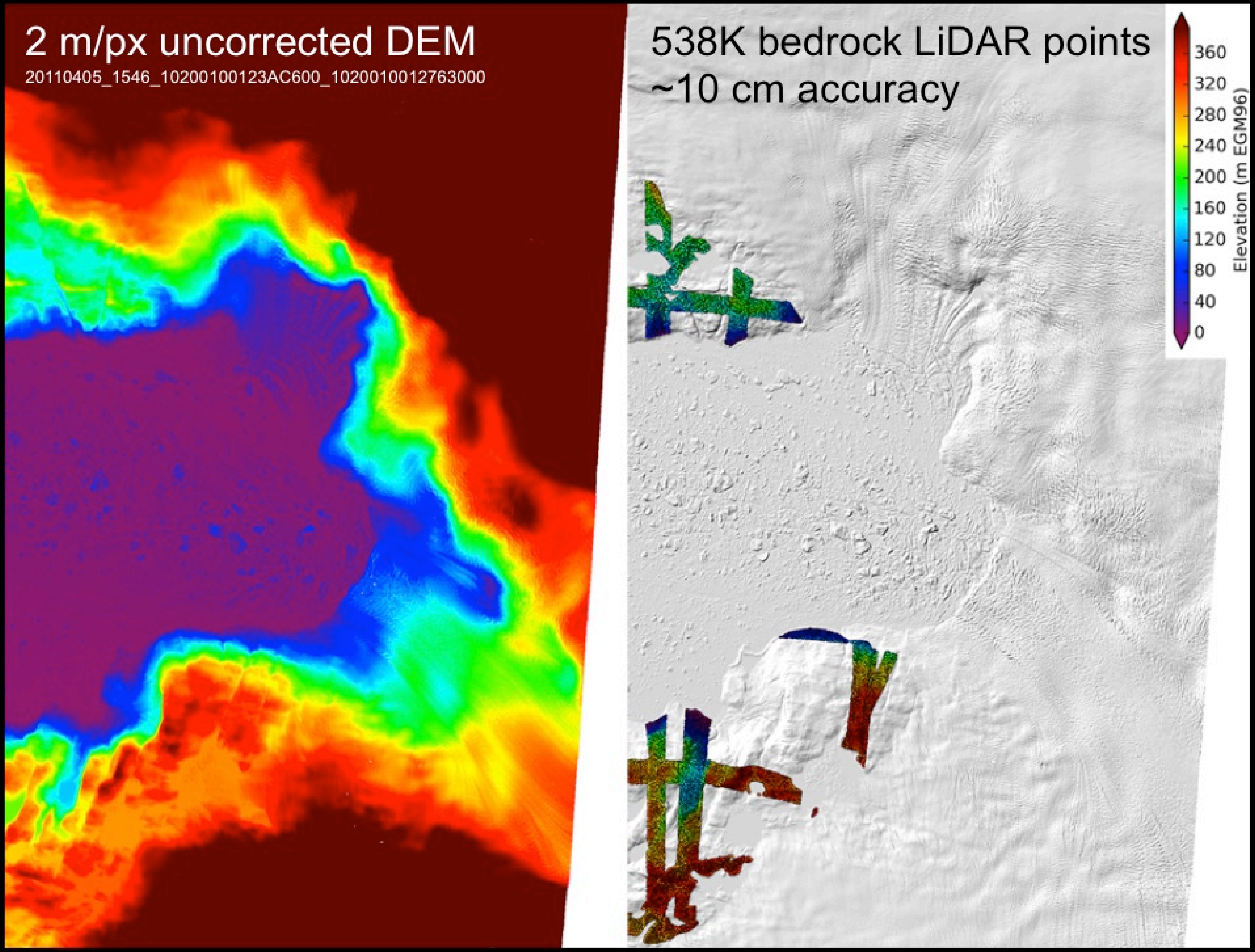
Control Data

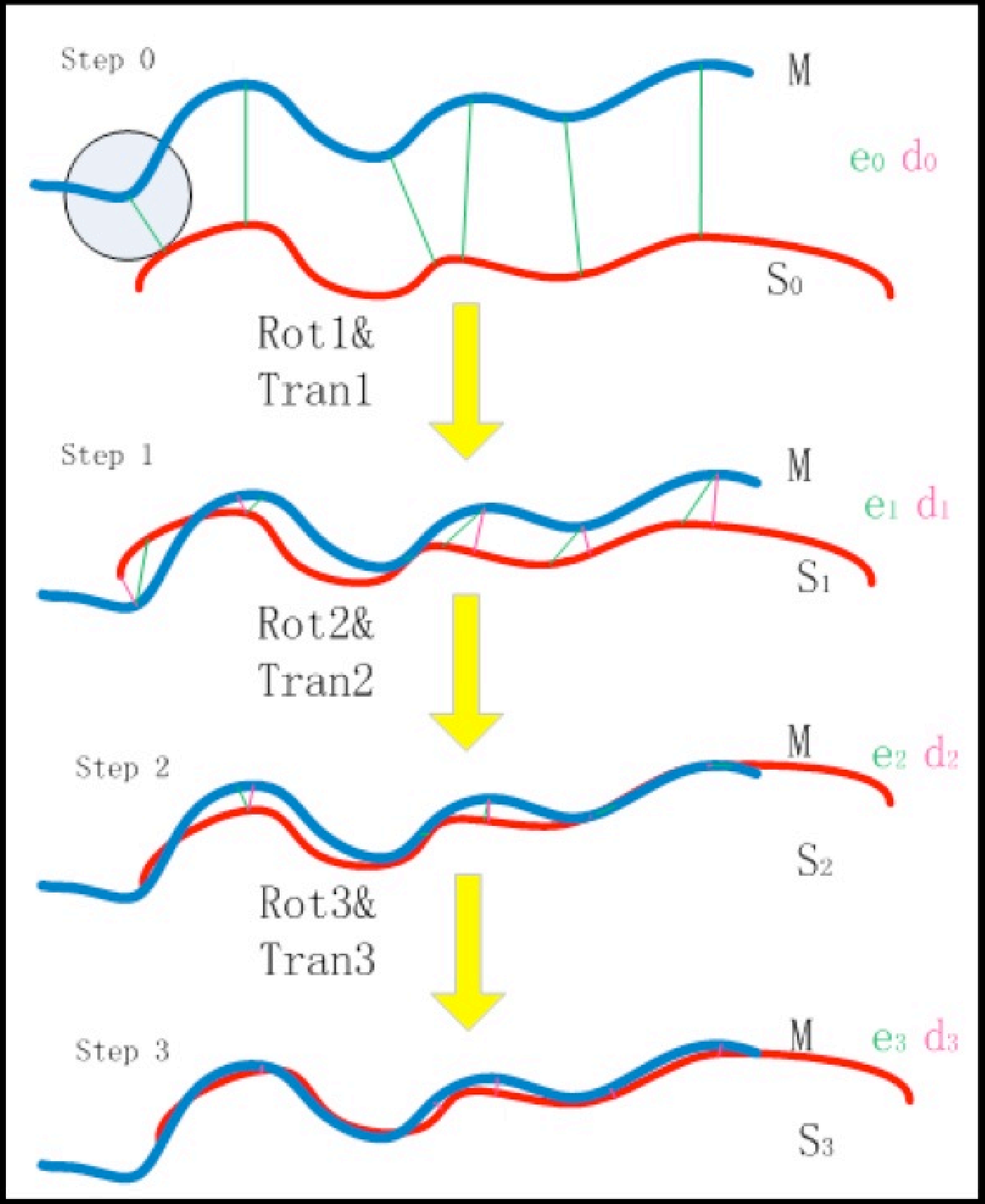
- NASA Operation IceBridge
  - ATM, LVIS airborne LiDAR
  - 2009-present
  - ~0.1-0.2 m vertical accuracy
- NASA ICESat-1
  - Satellite laser altimeter
  - 2003-2009
  - ~170 m along-track spacing
  - ~0.1 m vertical accuracy
- Continuous GPS
  - ~mm/cm accuracy



ICP DEM Co-registration





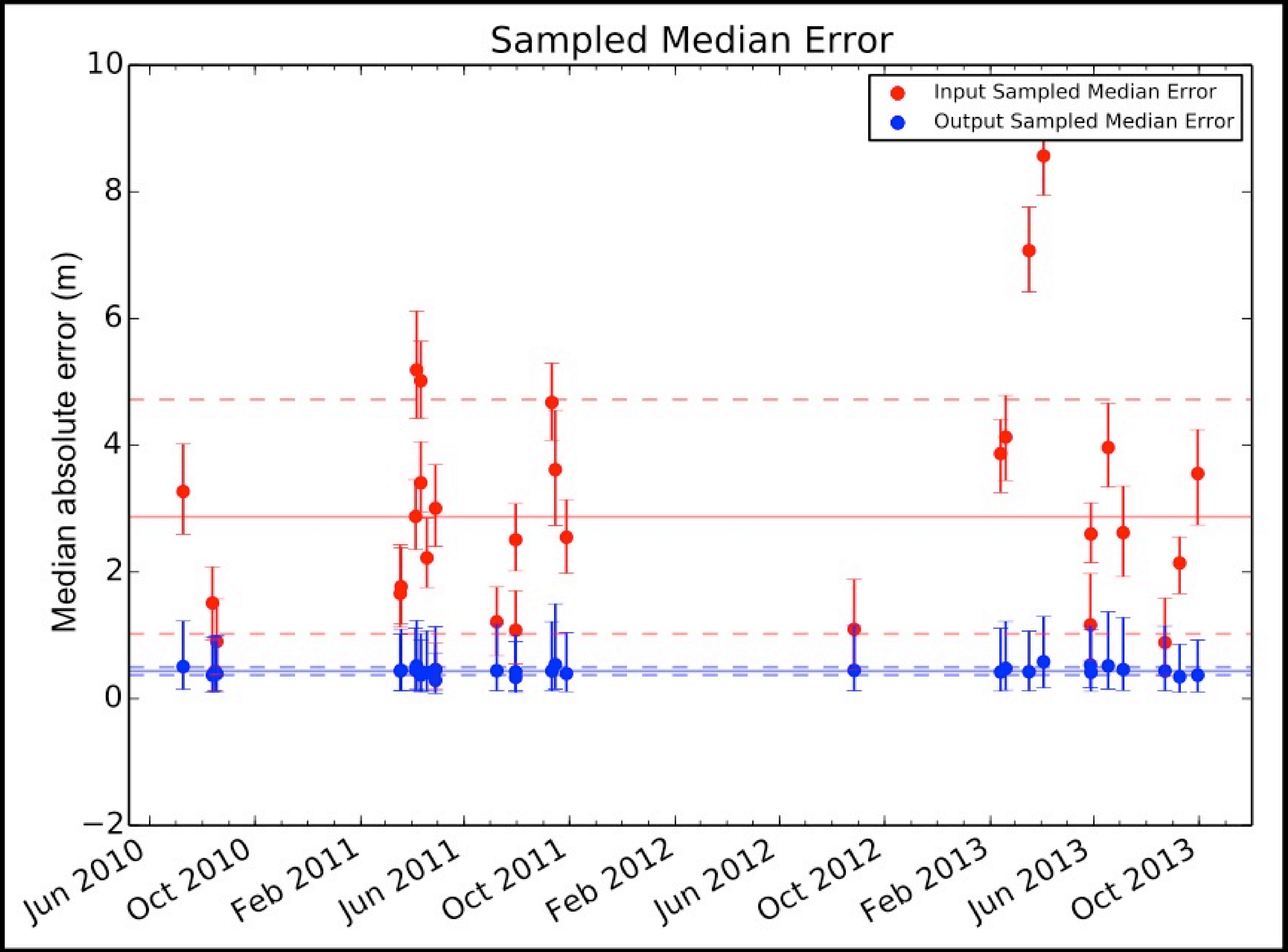
Input Median Error: 2.88 m

Libpointmatcher (point-to-plane) - 23 iterations, 14 s

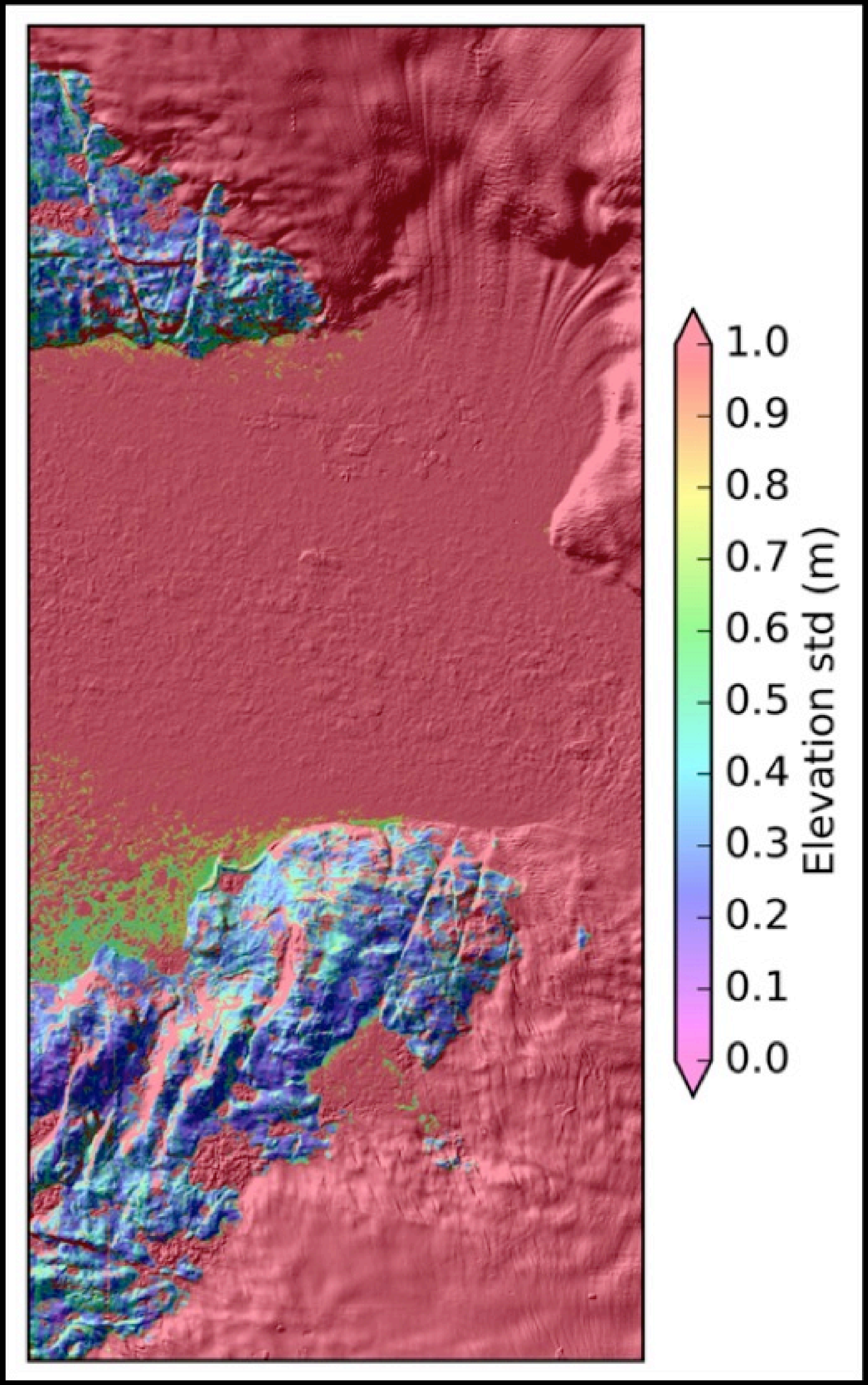
ECEF translation vector (m): (-0.066, 0.9756, 3.334), 3.47 m

Output Median Error: 0.45 m

Absolute Vertical Accuracy

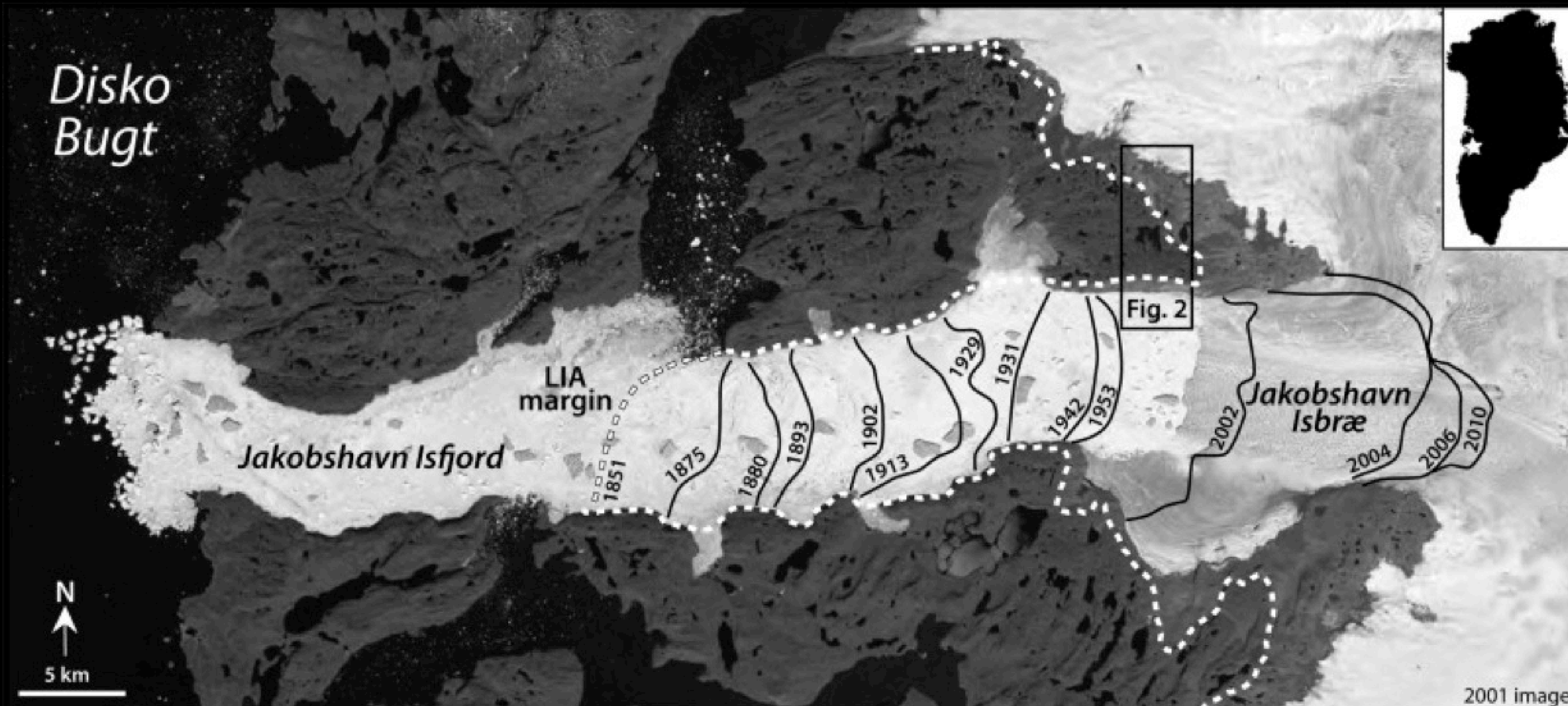


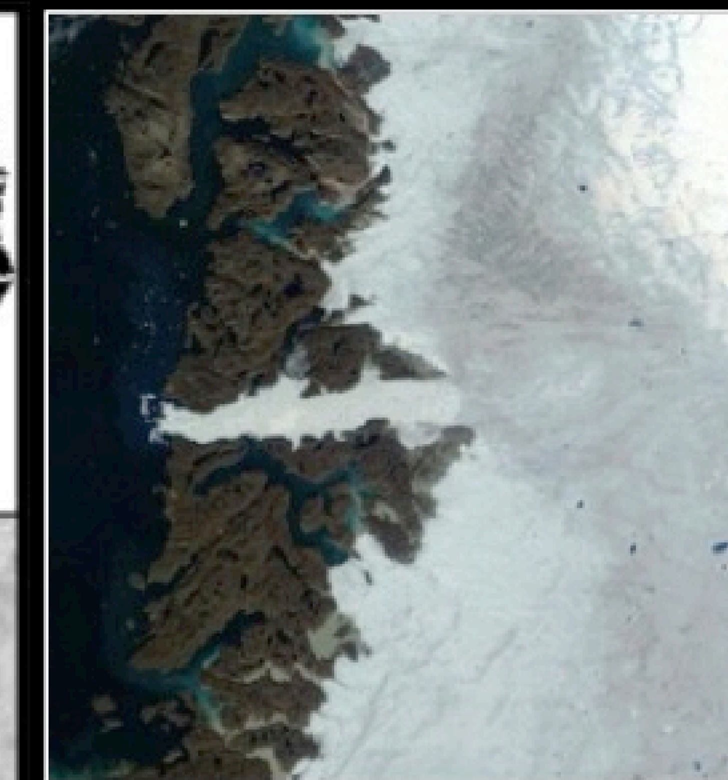
- Median error (WV DEM – LiDAR) for ~100K points over rock, before (red) and after (blue) ICP co-registration
- Red/blue pair for each DEM (31 total)

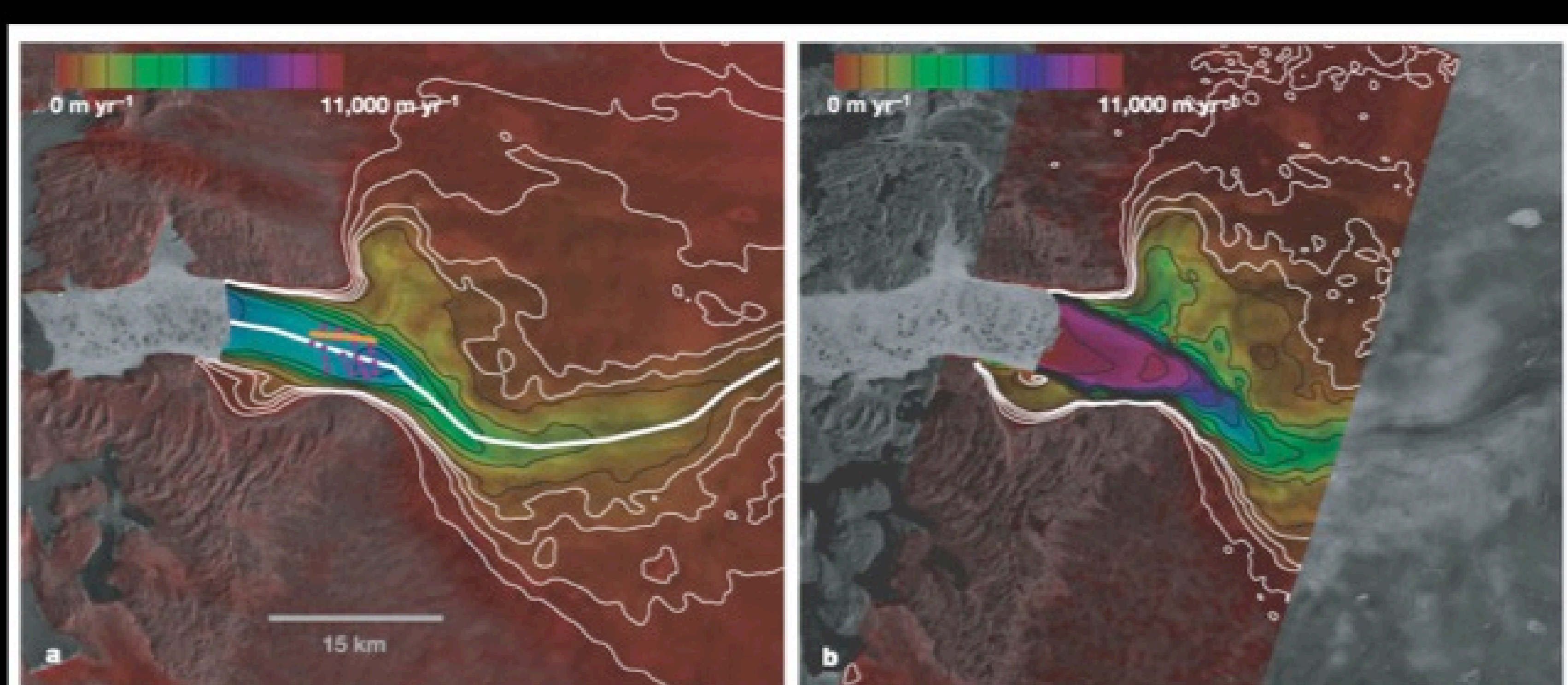


~20-40 cm standard deviation over bedrock for 31 co-registered DEMs

Jakobshavn Isbrae, Greenland

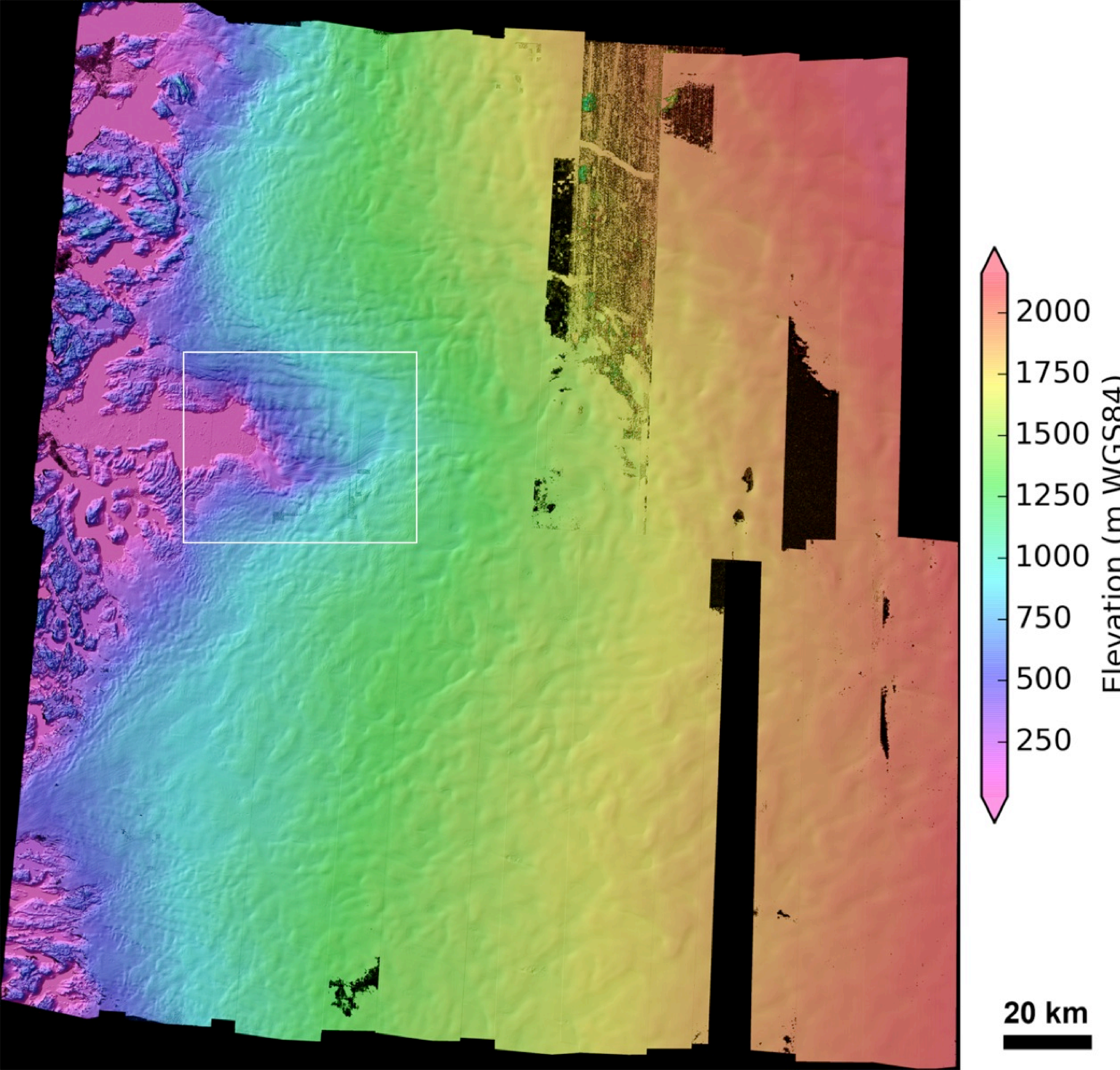






Jakobshavn ~2x vel. increase, 1992-2000
(*Joughin et al.*, 2004)

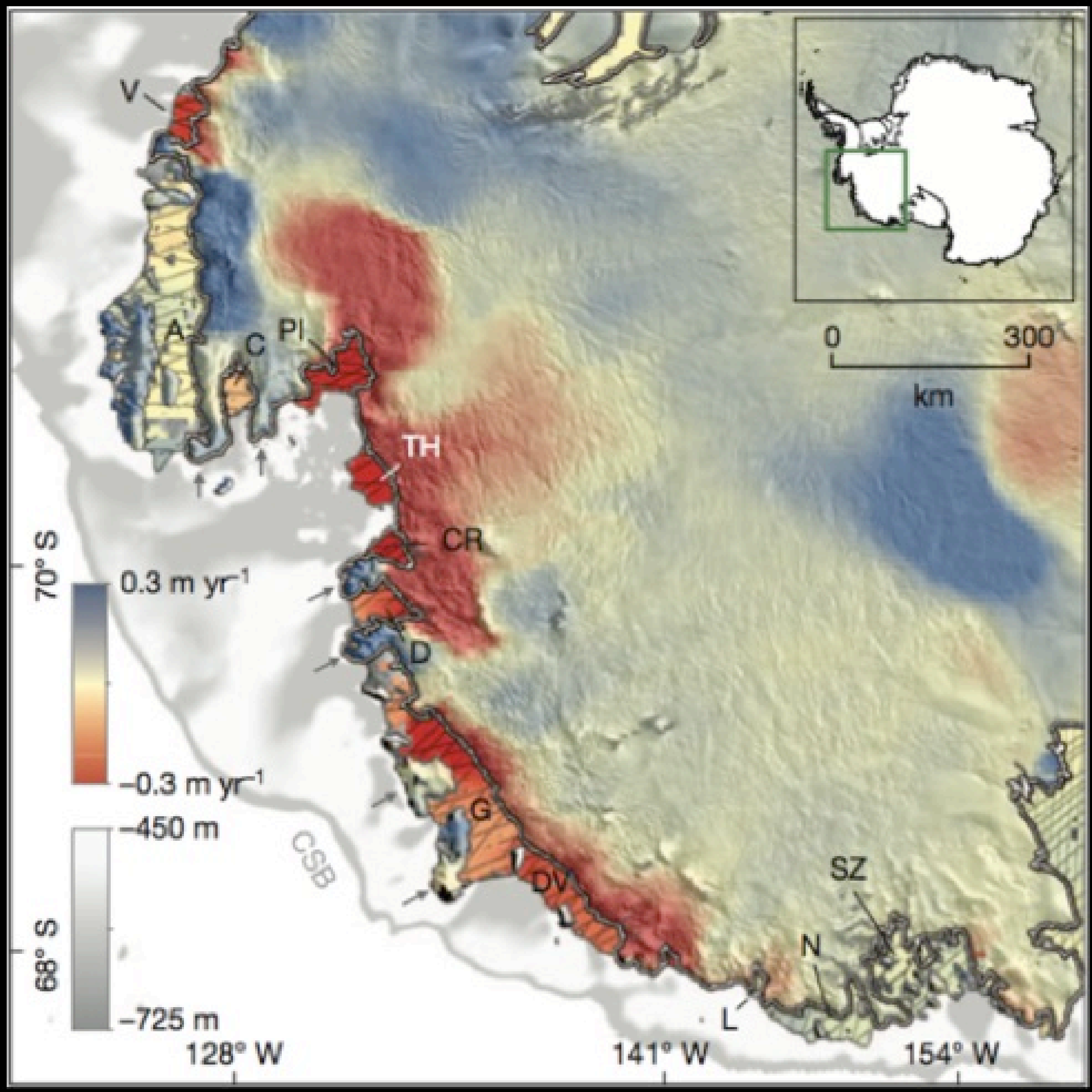
- Drains ~6.5% of Greenland ice sheet (~42 Gt/yr)
- Fastest glacier on Earth: ~8-18 km/yr, 20-50 m/day
- ~40 km of terminus retreat since ~1850
- 3-4x speedup since early 1990s

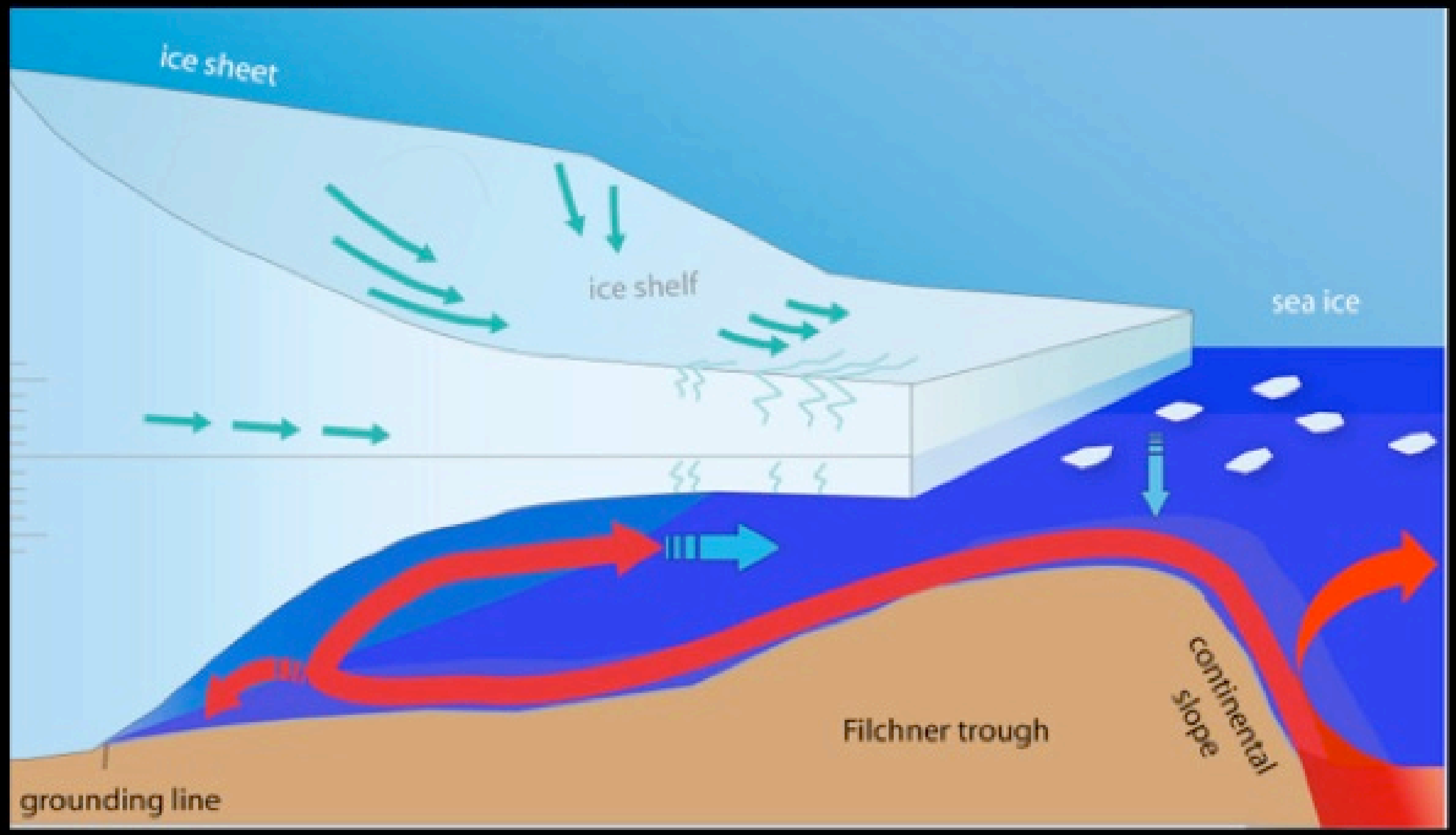


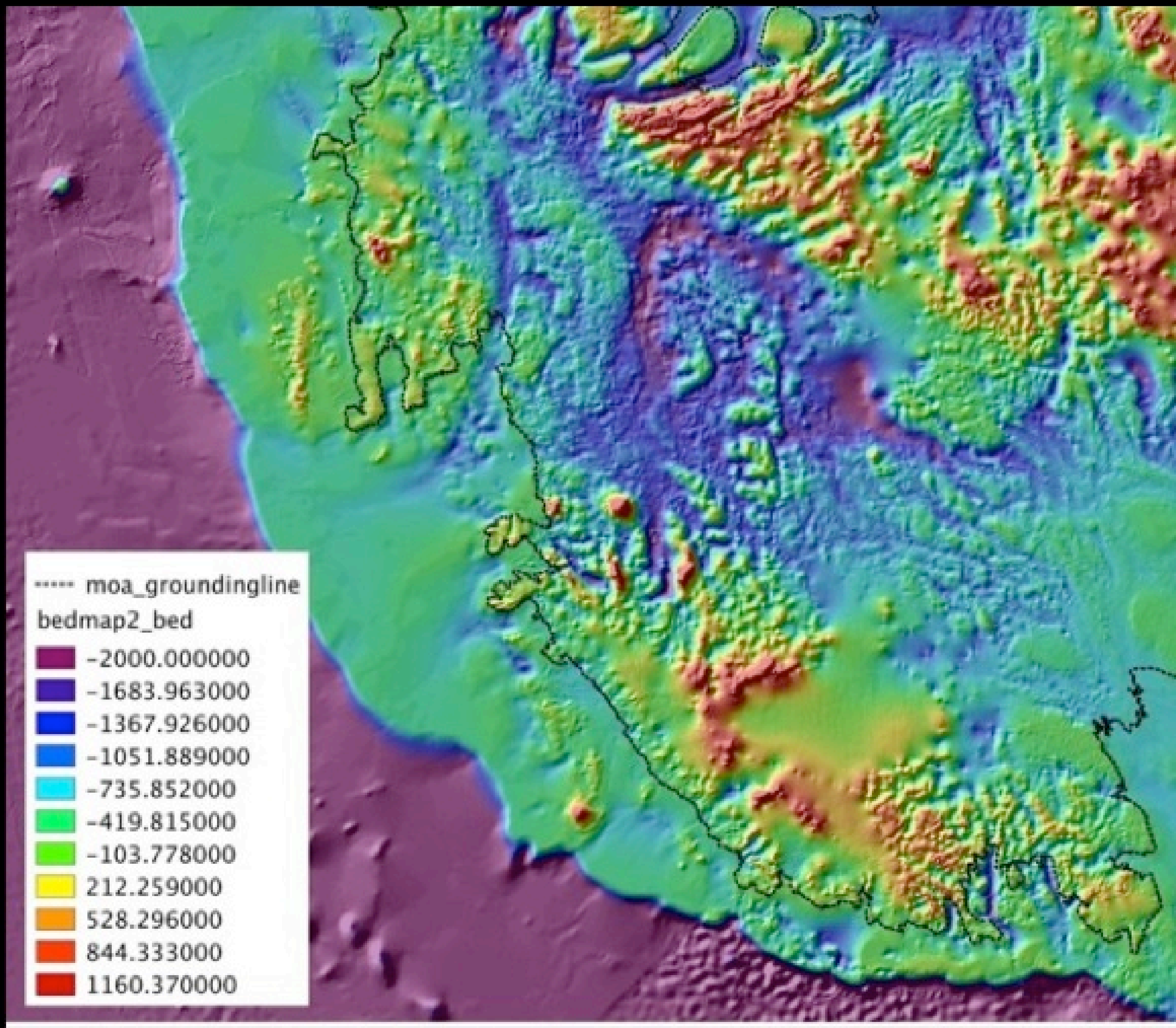
- 220x240 km
- 50000 km^2
- 142 WV DEMs
- 2009-2013
- Gaps: clouds & saturated img

Amundsen Coast, West Antarctica

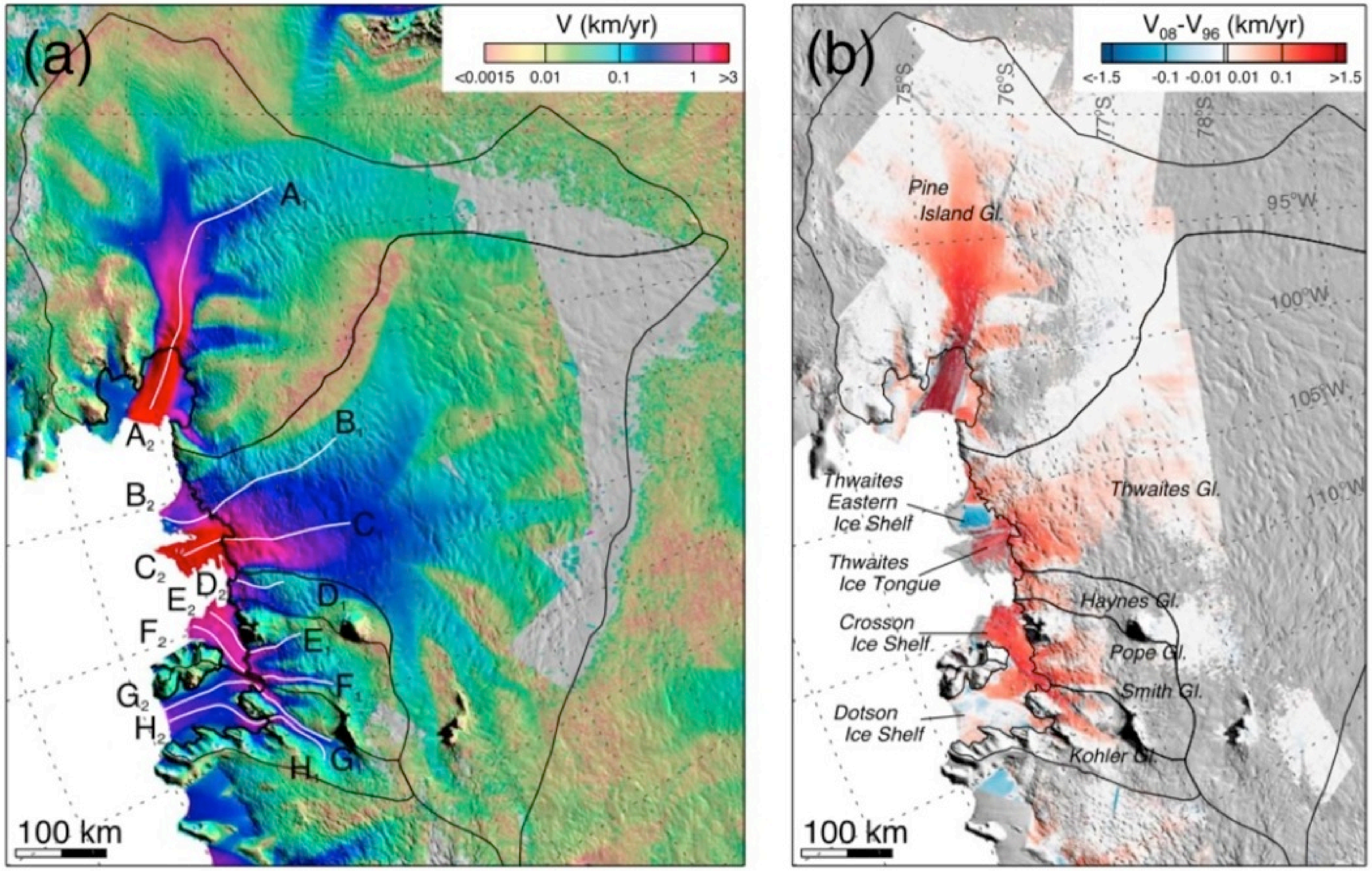
- Warm ocean water, ice shelf melt at grounding line (GL)
- GL retreat, velocity increase, thinning
- Irreversible retreat - “Weak underbelly”
- ~3-4 m total SLR in WAIS
- Fundamental observations:
  - Ice shelf melt: Where? When? How much?
  - Inland response

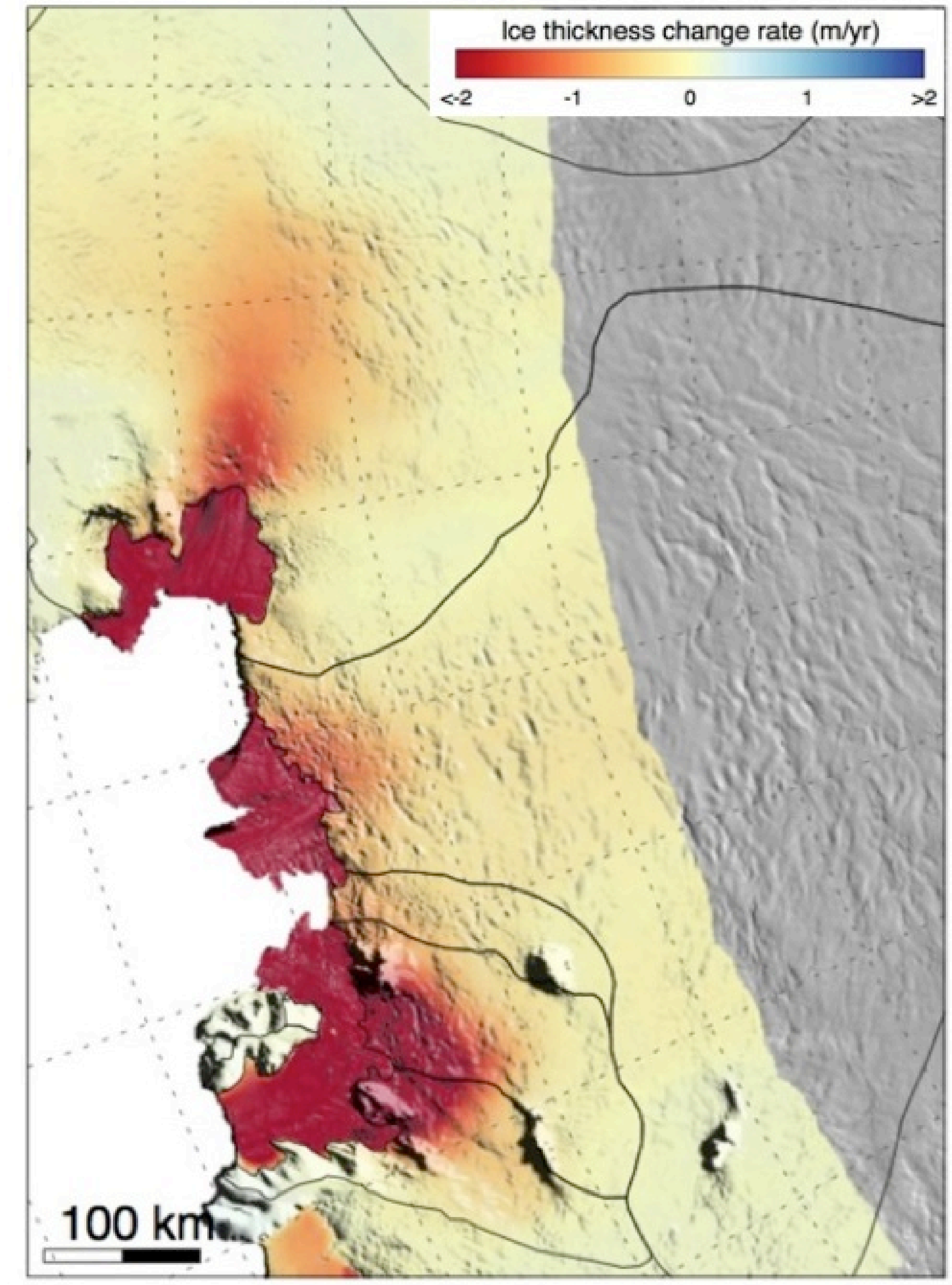






Pritchard et al. (2012)
BEDMAP-2 data from Fretwell et al. (2013)

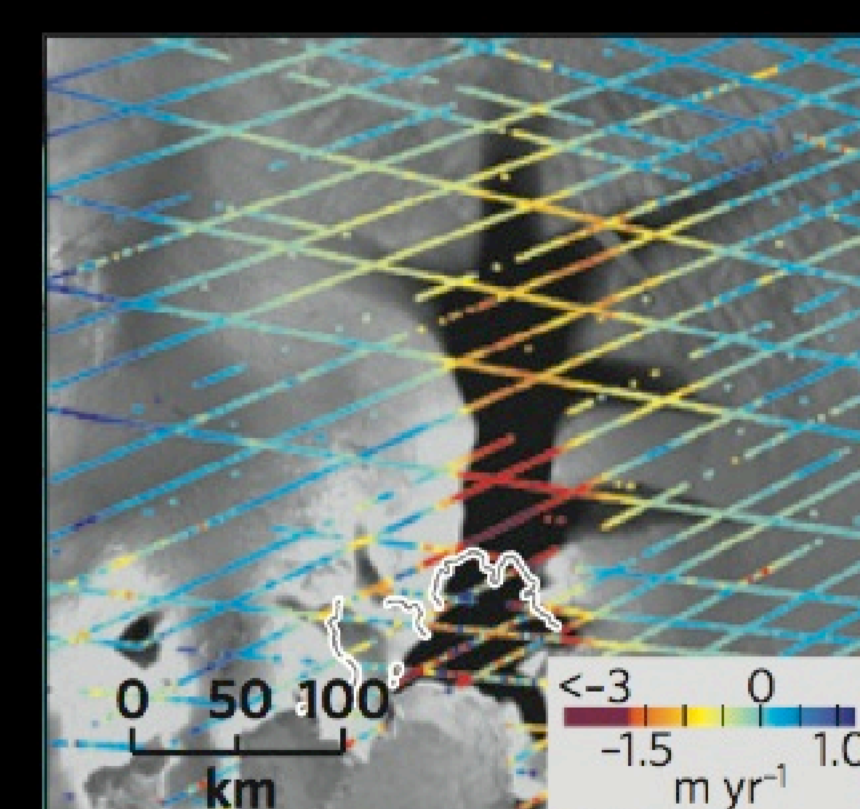




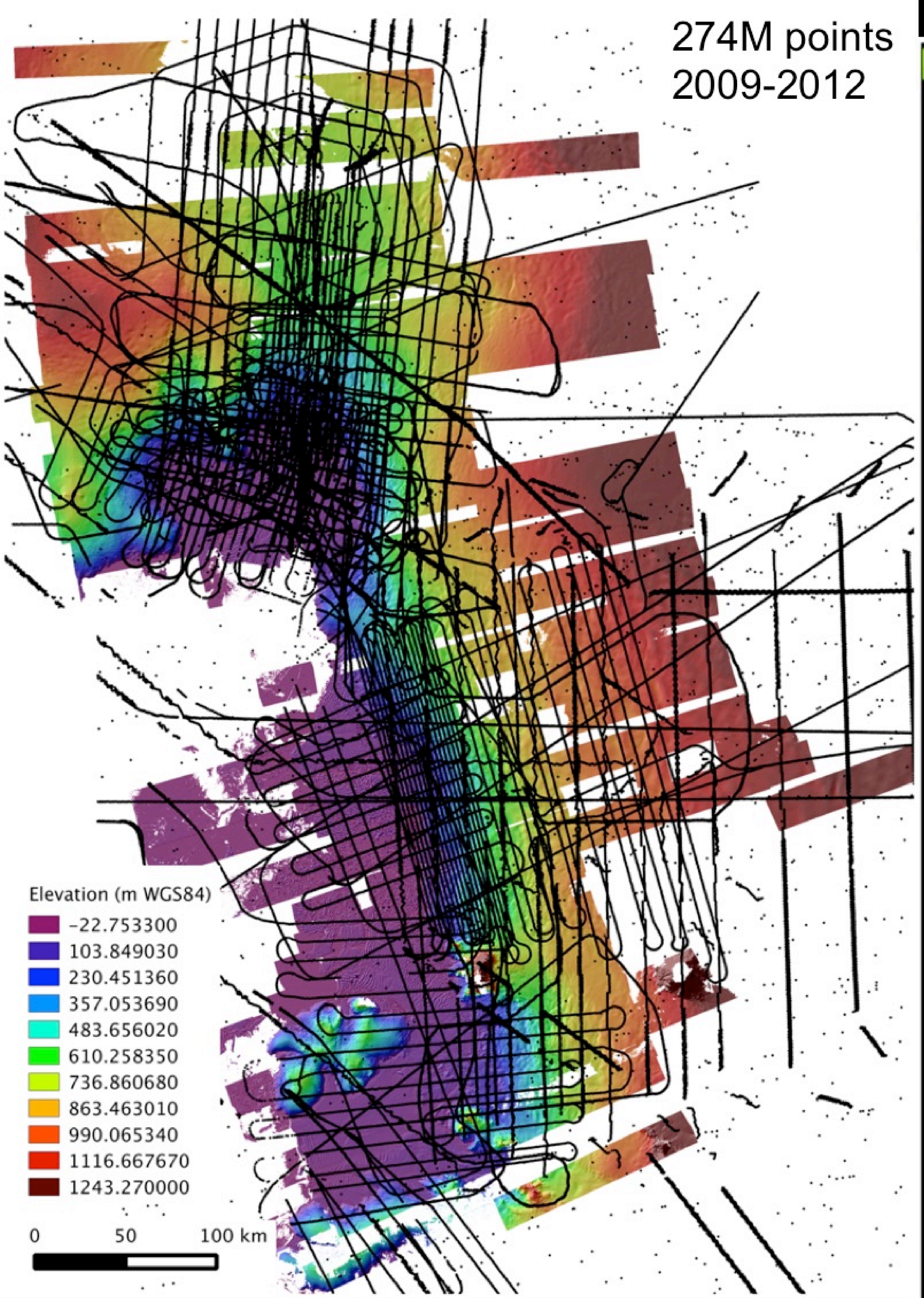
2008 Velocity
PIG/Thwaites: ~4 km/yr

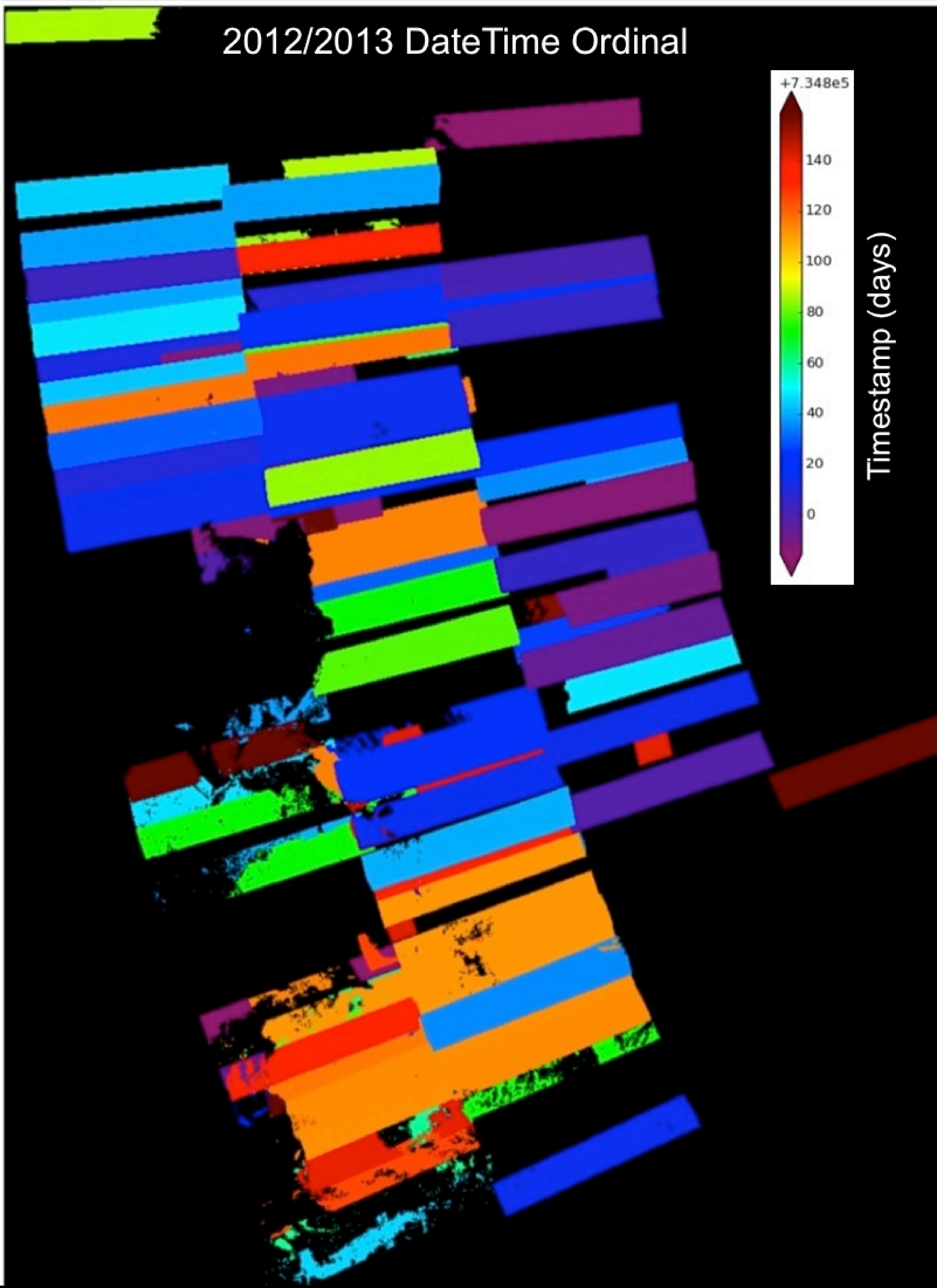
1996-2008
~1.5-2x velocity increase

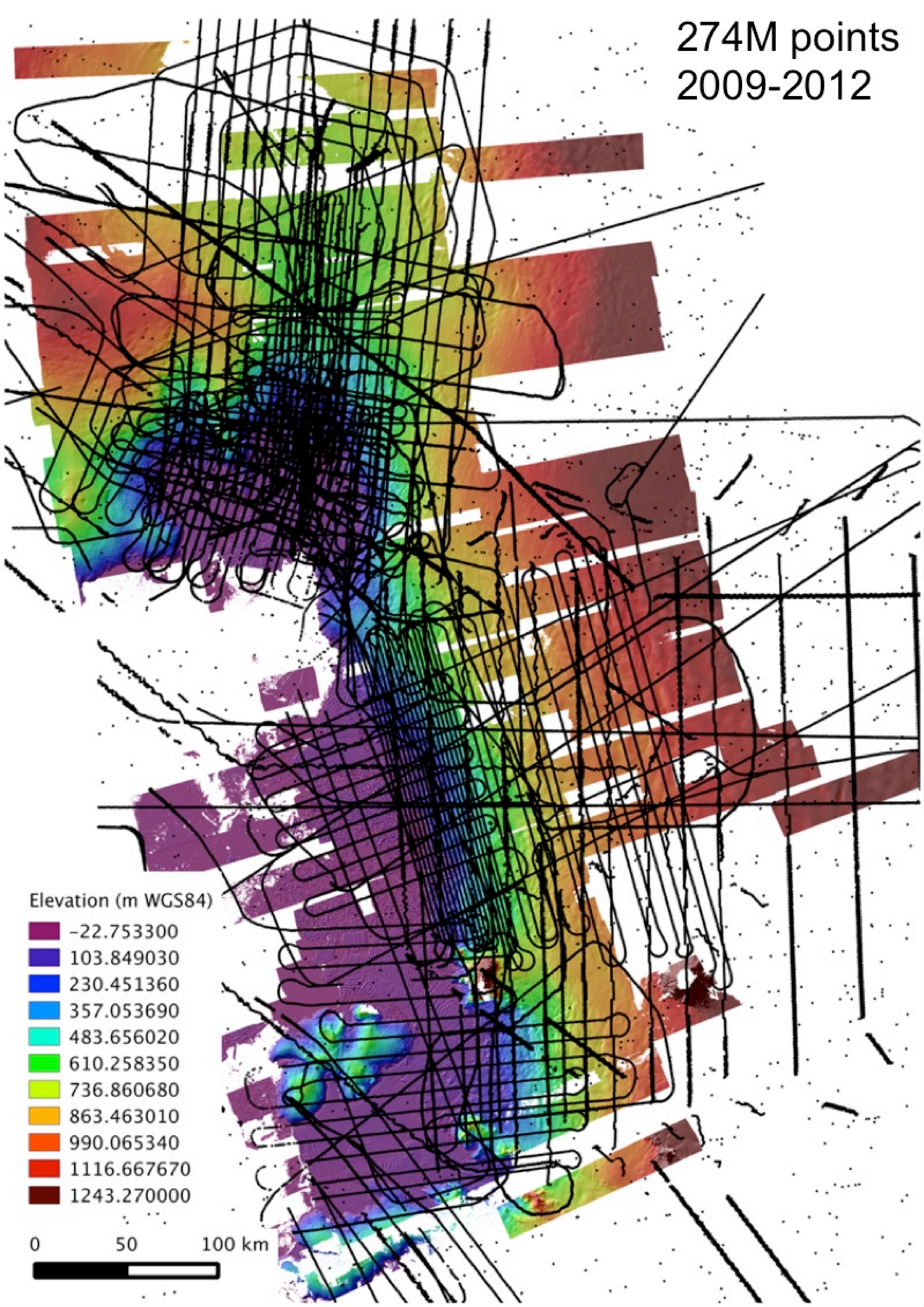
2003-2009
~4-8 m/yr thinning

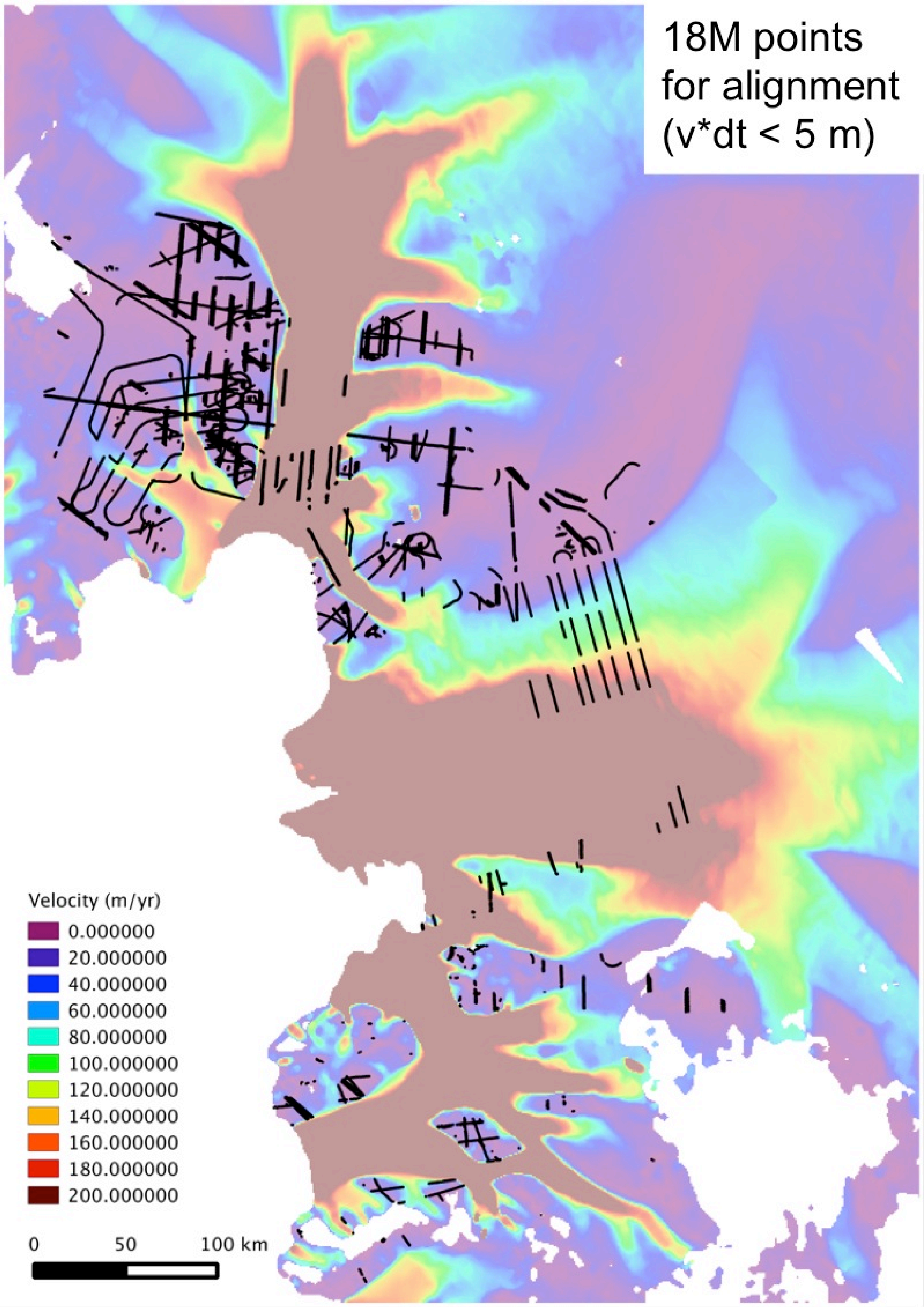


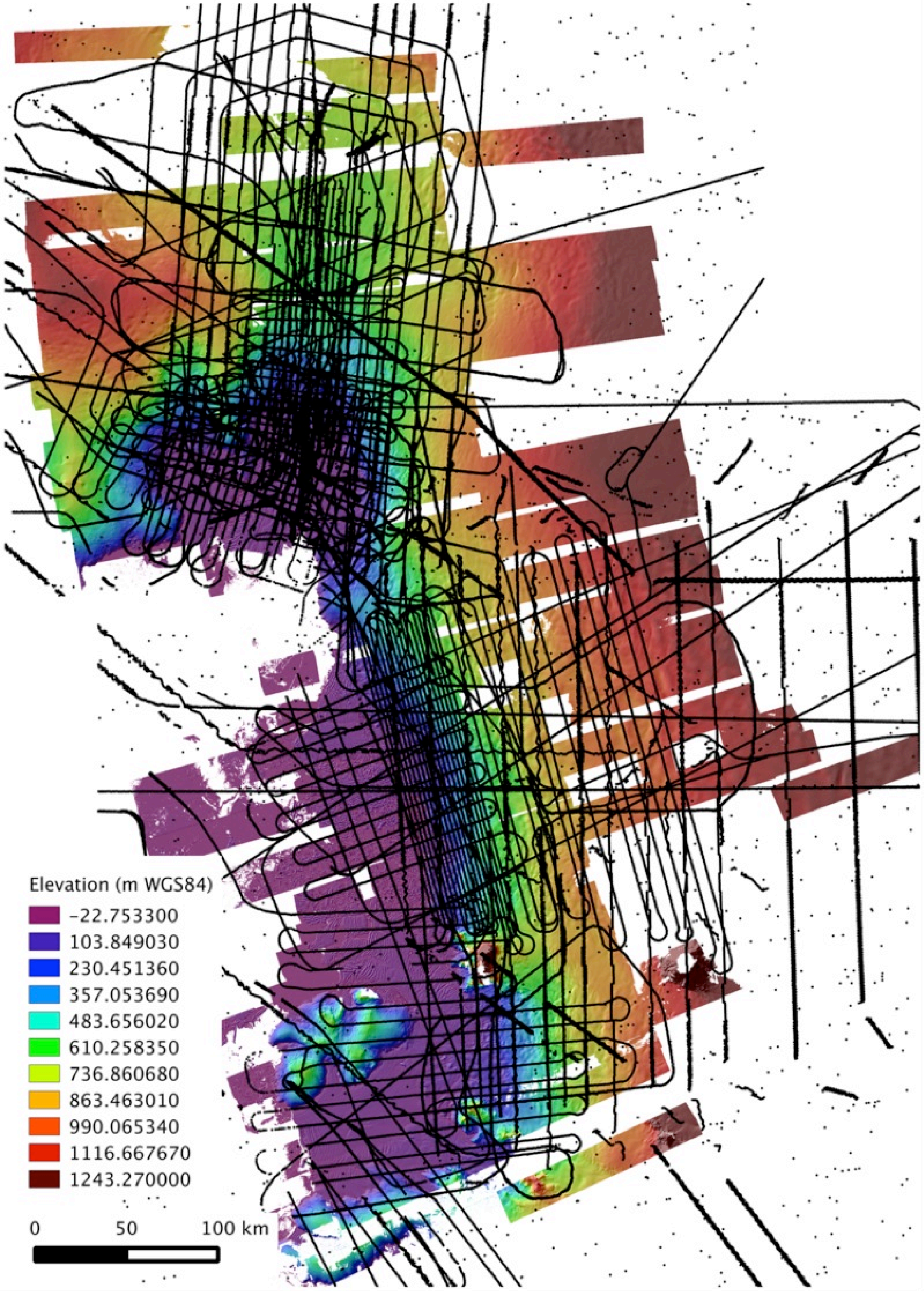
Mouginot et al. (2014), Pritchard et al. (2012), Joughin and Alley (2011)

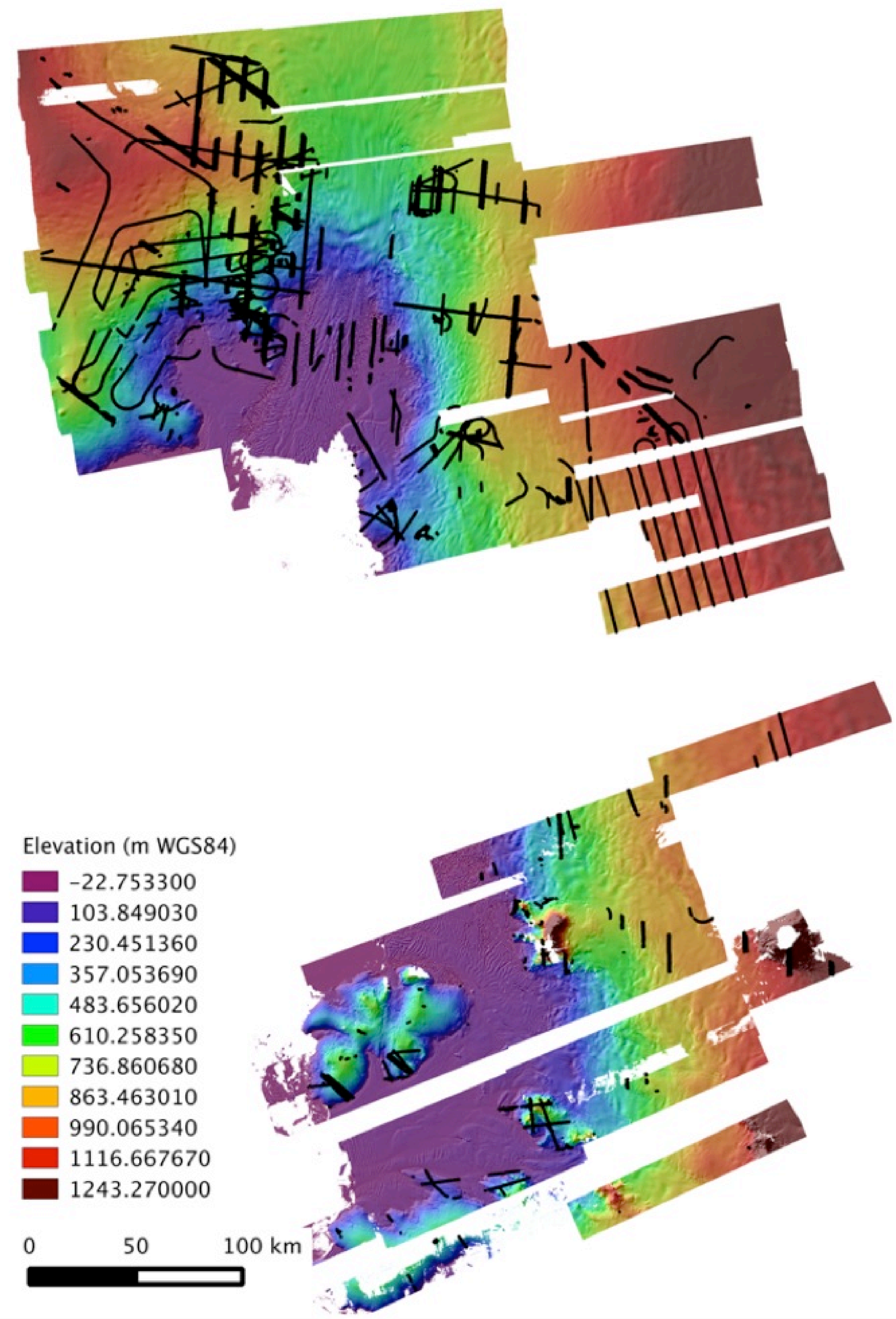

274M points
2009-2012
Elevation (m WGS84)
-22.753300
103.849030
230.451360
357.053690
483.656020
610.258350
736.860680
863.463010
990.065340
1116.667670
1243.270000
0
50
100 km


2012/2013 DateTime Ordinal
+7.348e5
140
120
100
80
60
40
20
0
Timestamp (days)


274M points
2009-2012
Elevation (m WGS84)
-22.753300
103.849030
230.451360
357.053690
483.656020
610.258350
736.860680
863.463010
990.065340
1116.667670
1243.270000
0
50
100 km

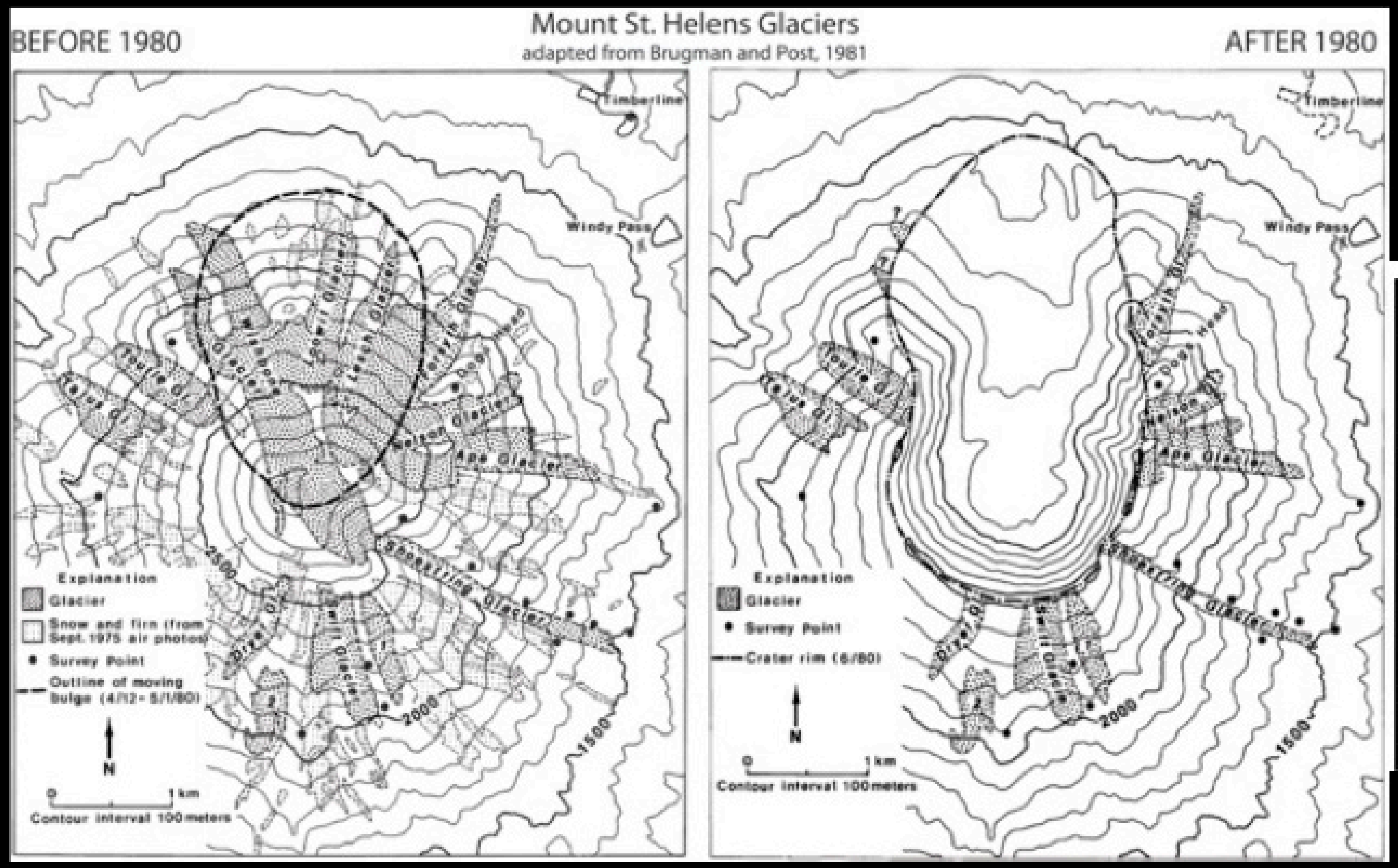

18M points
for alignment
(v*dt < 5 m)
Velocity (m/yr)
0.000000
20.000000
40.000000
60.000000
80.000000
100.000000
120.000000
140.000000
160.000000
180.000000
200.000000
0
50
100 km

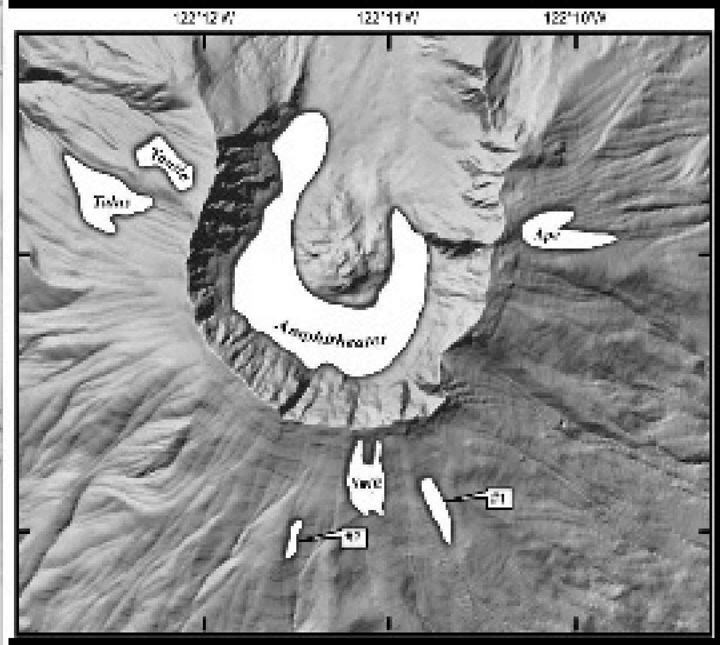

Elevation (m WGS84)
-22.753300
103.849030
230.451360
357.053690
483.656020
610.258350
736.860680
863.463010
990.065340
1116.667670
1243.270000
0
50
100 km


Elevation (m WGS84)
-22.753300
103.849030
230.451360
357.053690
483.656020
610.258350
736.860680
863.463010
990.065340
1116.667670
1243.270000
0
50
100 km

Mt. St. Helen's

- 1980 eruption and debris avalanche
- 70% of ice lost
- 1980-1986 dome
- 2004-2008 dome
- Birth and evolution of Crater glacier





Schilling et al. (2004)