Observing Volcanic Eruptions with *Earth-Observing 1*: Smart Software, and the Volcano Sensor Web

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Volcano Monitoring and *EO-1*

- *EO-1* has been a superb platform for detecting and monitoring volcanic activity (inc. making exceptional use of nighttime data)

- Also for technology demonstrations:

- Autonomous Sciencecraft Experiment – ASE
  - New Millennium Program – Space Technology-6

- Orbital asset incorporated into Sensor webs – flood, fire, volcanoes
  - Volcano Sensor Web (VSW)
  - Template for HyspIRI

Autonomous Volcano Monitoring

JPL-ASE used advanced autonomy software to:

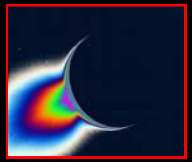
- Automate spacecraft retasking based on eruption detections using a globe-spanning Volcano Sensor Web (VSW)
- Streamline spacecraft operations
- Process data thus obtained
- Deliver products to end-users

The entire process is autonomous – for when speed is vital

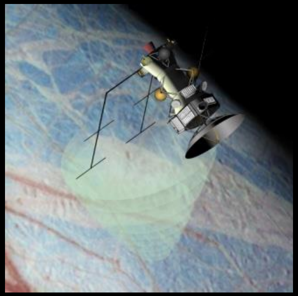
Planetary Applications

Volcanism across the Solar System

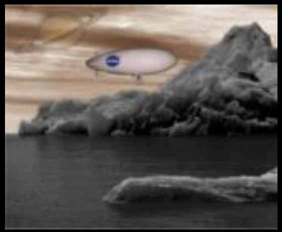
- Io, Enceladus, Triton = active
- Possibility of activity: Europa, Titan
- Possible future NASA missions:
  - Europa (NASA Flagship-class mission)
  - Io Volcano Observer (Discovery or NF class)
- Use of autonomy expedites event detection: allows retasking to observe dynamic events
  - Of greatest value during orbital reduction and mapping phases of potential Europa mission
  - Rapid processing of data identifies target process

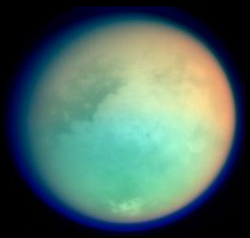


Enceladus Explorer concept

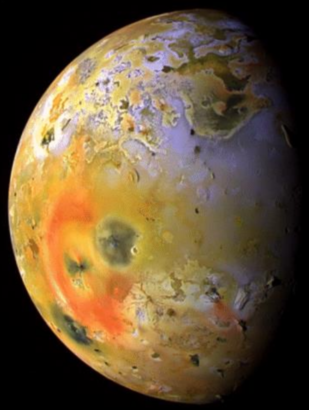


Europa mission concept



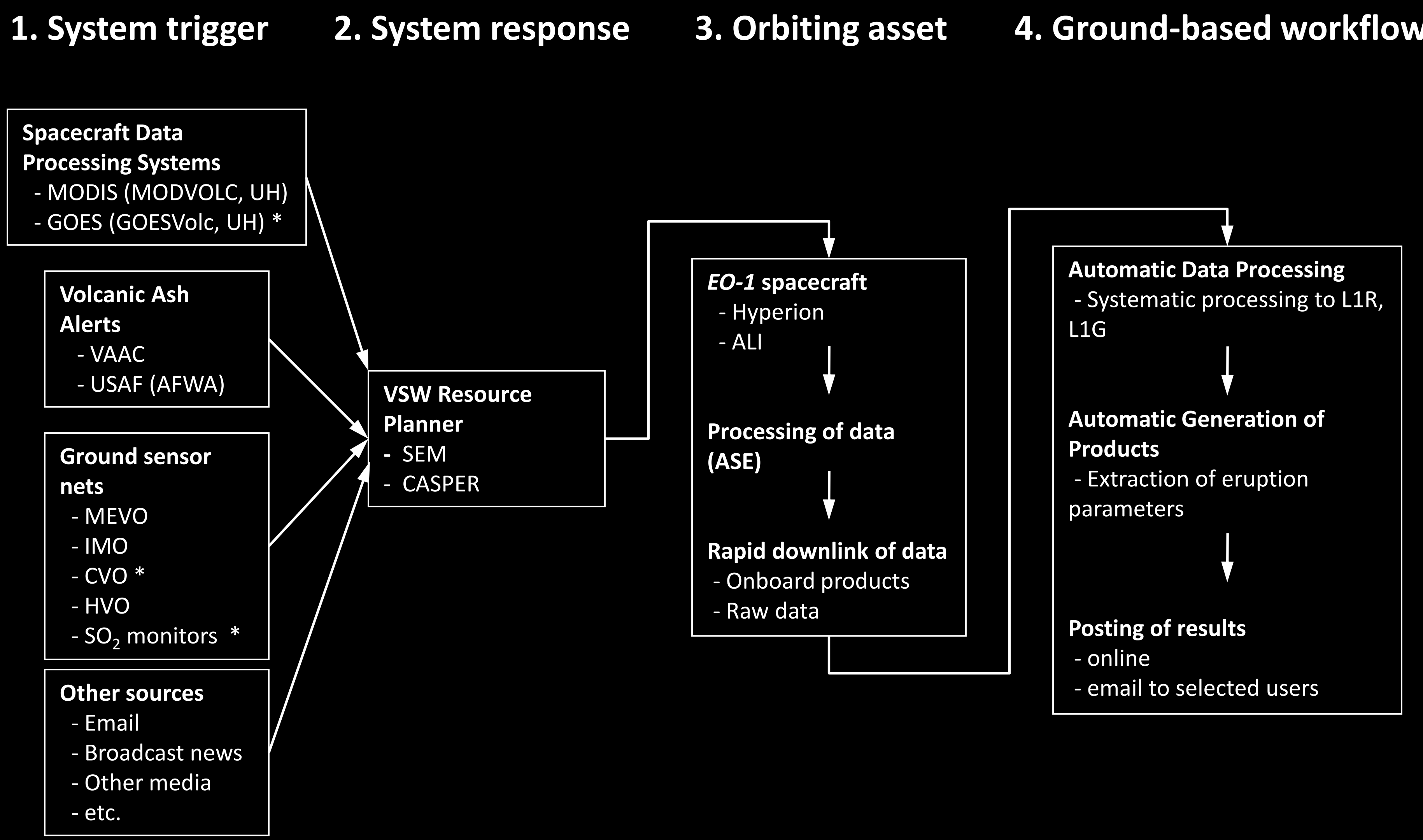


Titan Orbiter – Aerobot concept



Io Volcano Observer concept

VSW data flow



* Triggering from this source not currently active

Davies *et al.* (2013) JGR

EO-1 and volcanic activity

- *EO-1* launched - 21 Nov 2000 (NASA-GSFC)
- High-inclination orbit (89°)
- Nominal 16-day repeat time (day, nadir)
- Night = better for detection of thermal emission
- *EO-1* is pointable across-track E and W

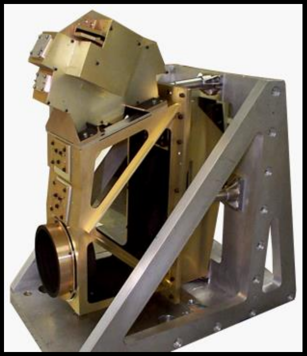
Yields 10 opportunities per 16 days (d, n) at mid-latitudes, more at high latitudes.

Hyperion

0.4-2.5 µm
220 bands, 30 m/pixel spatial resolution
7.7 km wide swath

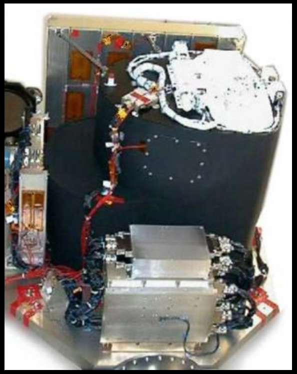
ALI - Advanced Land Imager

9 bands 0.4-2.5 µm, 30 m/pixel
PAN band, 10 m/pixel
~30 km wide swath

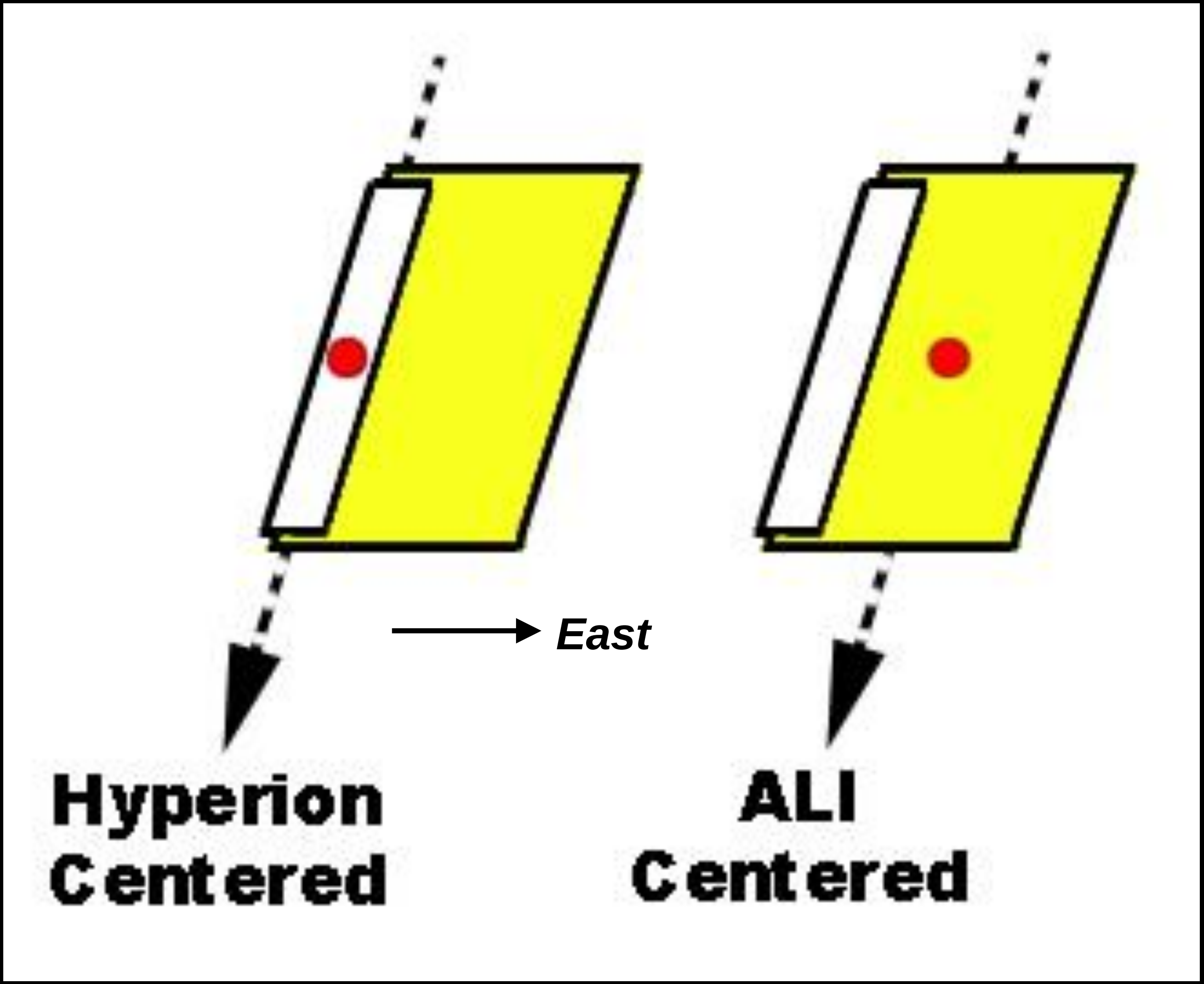


Hyperion

Advanced Land Imager



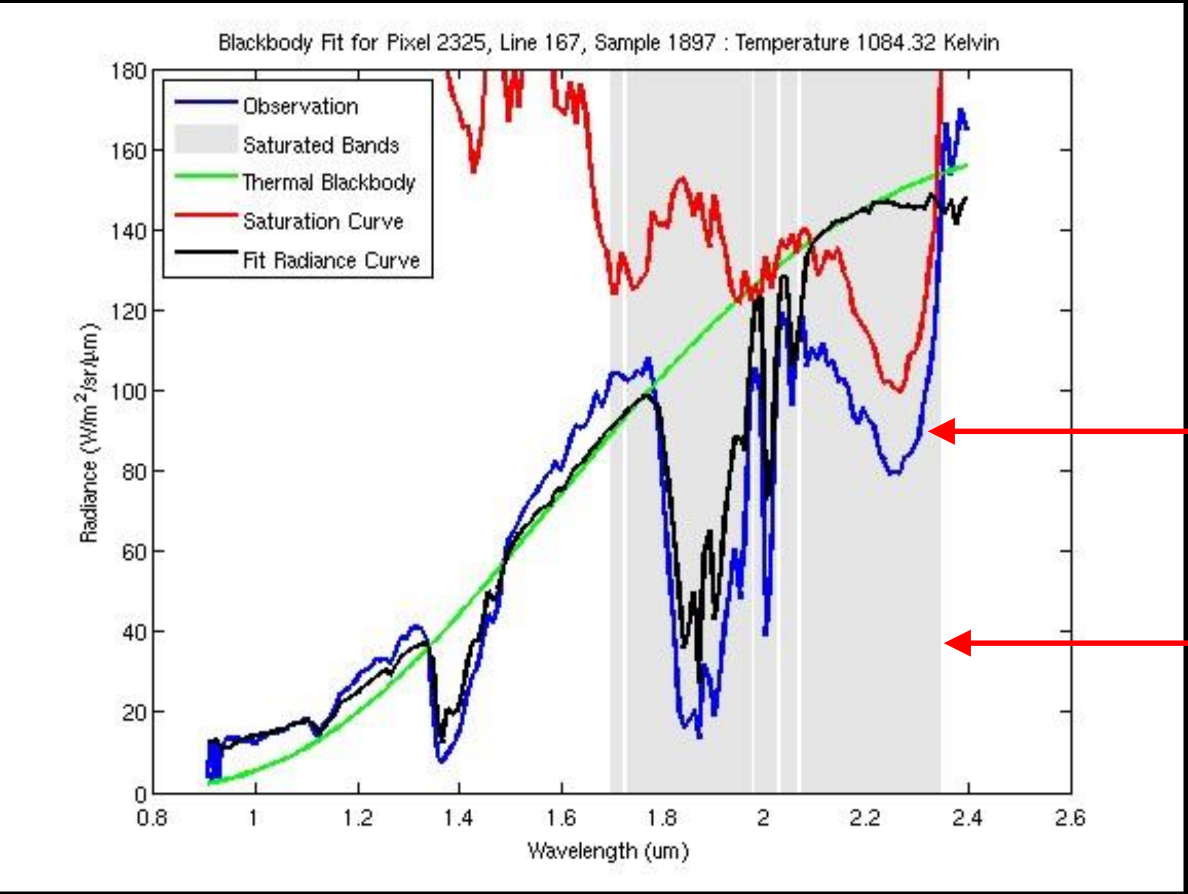
Hyperion and ALI footprints



This is daytime (descending): nighttime (ascending) is reversed left to right

EO-1 and volcanic activity

- Hyperion is *great for* imaging erupting volcanoes
- Wavelength range is sensitive to pixel brightness temps >450 K



"dip" = saturation feature

Grey area = saturated

If data saturated at longer wavelengths, shorter wavelengths usable for fitting black-body curves: see Wright *et al.*, Davies *et al.* pubs.

EO-1 and volcanic activity

- Identify thermal anomalies
- Locate vents (e.g., Nyamulagira, 2006 – in midst of crisis, *EO-1* only asset to do this close to eruption onset)
- Map thermal anomalies (also fires → JPL-Thailand Fire S/W)
- Quantify and map thermal emission
- Estimate discharge rate
- Chart eruption evolution

Autonomous Sciencecraft on *EO-1*

- ASE is *flight-proven technology*
  - NASA New Millennium Program ST-6 Project

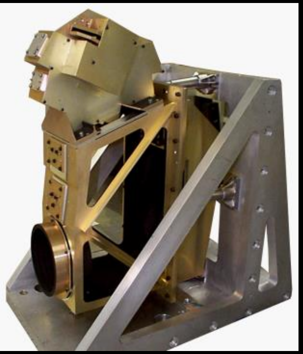
Onboard Science Data Processing

Autonomous Planning (CASPER)

Autonomous Execution Software (Spacecraft Command Language)

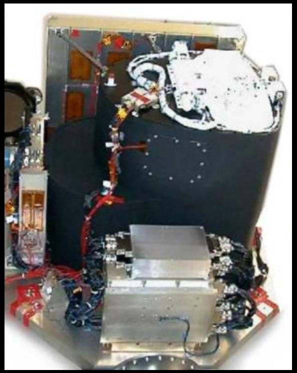
- Subsystem demonstration
- Funded to flight demonstrate autonomy software technology for future mission adoption
- Uses the Hyperion instrument (hyperspectral, 220 bands, 30 m resolution)

Also on *EO-1* – Advanced Land Imager (ALI)



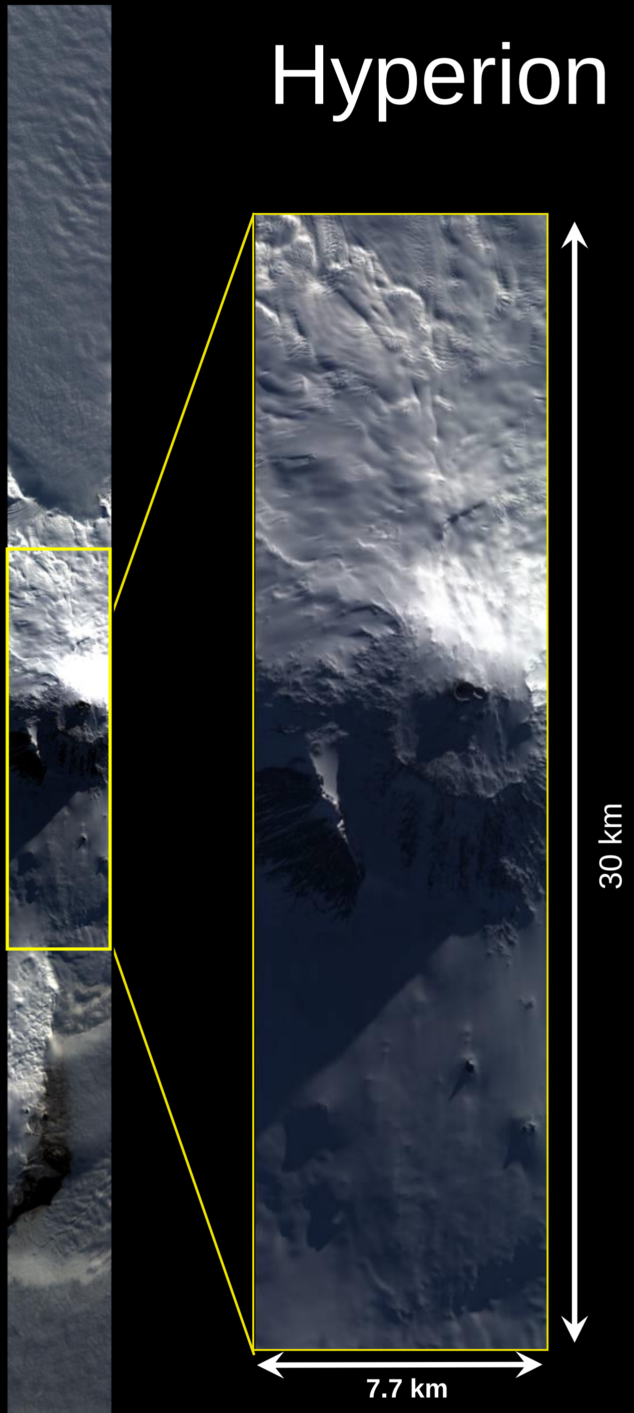
Hyperion

Advanced Land Imager



See Chien *et al.,* 2005; Davies *et al*., 2006, *RSE*; Doggett *et al.*, 2006, *RSE*

Hyperion and Science Classifiers



- *EO-1* Hyperion instrument
  - High spectral resolution imaging spectrometer
  - 220 bands from 0.4 to 2.4 µm (SWIR)
  - 30 m/pixel spatial resolution
- ASE Science Classifiers
  - THERMAL_CLASSIFIER (Davies *et al*. 2006, RSE) uses 4 bands
  - 7.7 km x ~30 km coverage area
- Thermal Summary Product
  - Extracts 12 wavelengths per pixel
  - Returns this information as very small file (~20 kB), with telemetry
  - If rest have to be discarded, the *science content is preserved*
  - Rapid alert of activity, plus data for quantitative analysis for hazard assessment: typically ~90 mins.

Erebus volcano, Antarctica, 13 Dec 2005

Eyjafjallajökull, 2010

JOURNAL OF GEOPHYSICAL RESEARCH: SOLID EARTH, VOL. 118, 1936–1956, doi:10.1002/jgrb.50141, 2013

Observing Iceland's Eyjafjallajökull 2010 eruptions with the autonomous NASA Volcano Sensor Web

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Iceland - 2010

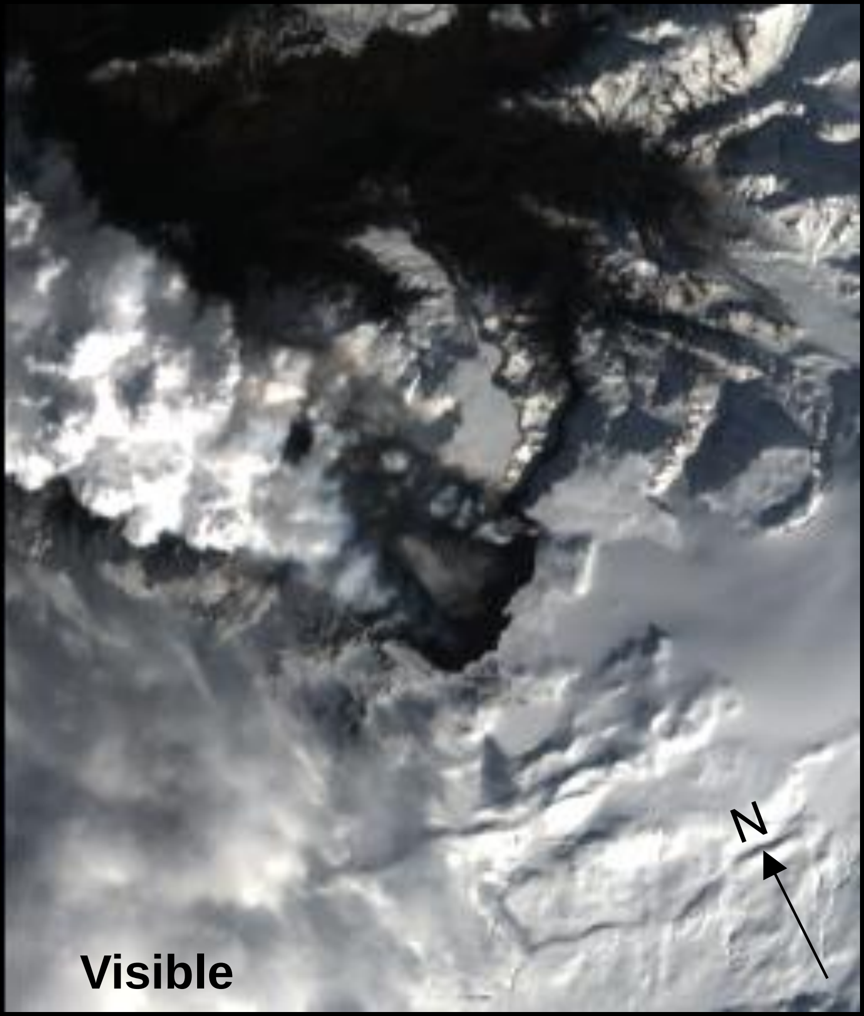
- We first became aware of Eyjafjallajökull (Fimmvorduhals) eruption on Saturday 20 March 2010 – ABC Evening News
- Updated operations planning software (a result of ASE) allowed fast, easy retasking of *EO-1*
- First data obtained and returned on 24 March 2010
- Between 24 March and 5 June, 50 observations pairs were obtained

Fimmvorduhals day	8
Fimmvorduhals night	7
Eyjafjallajökull day	18
Eyjafjallajökull night	17

- 50% of observations heavily impacted by clouds

24 March 2010

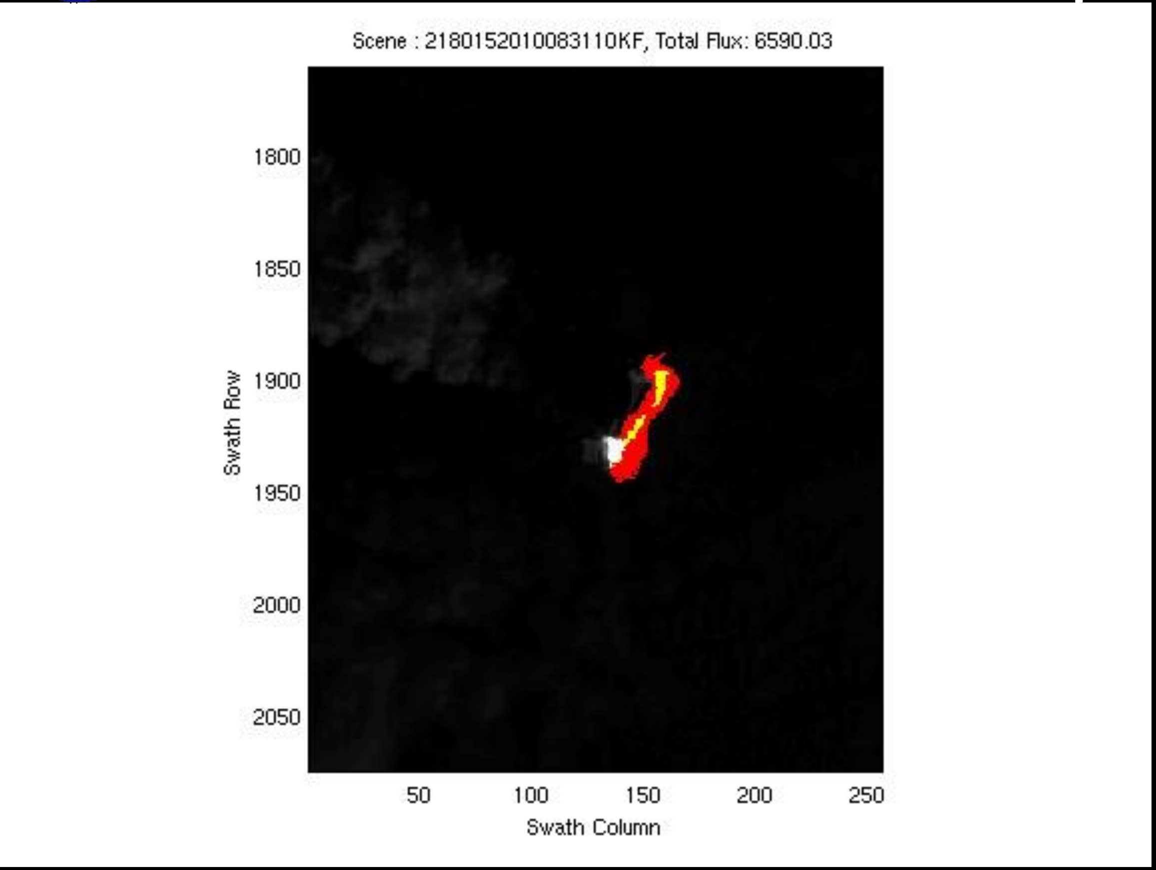
EO1H2180152010083110KF - Hyperion



7.7 km

Davies *et al.* (2013) JGR

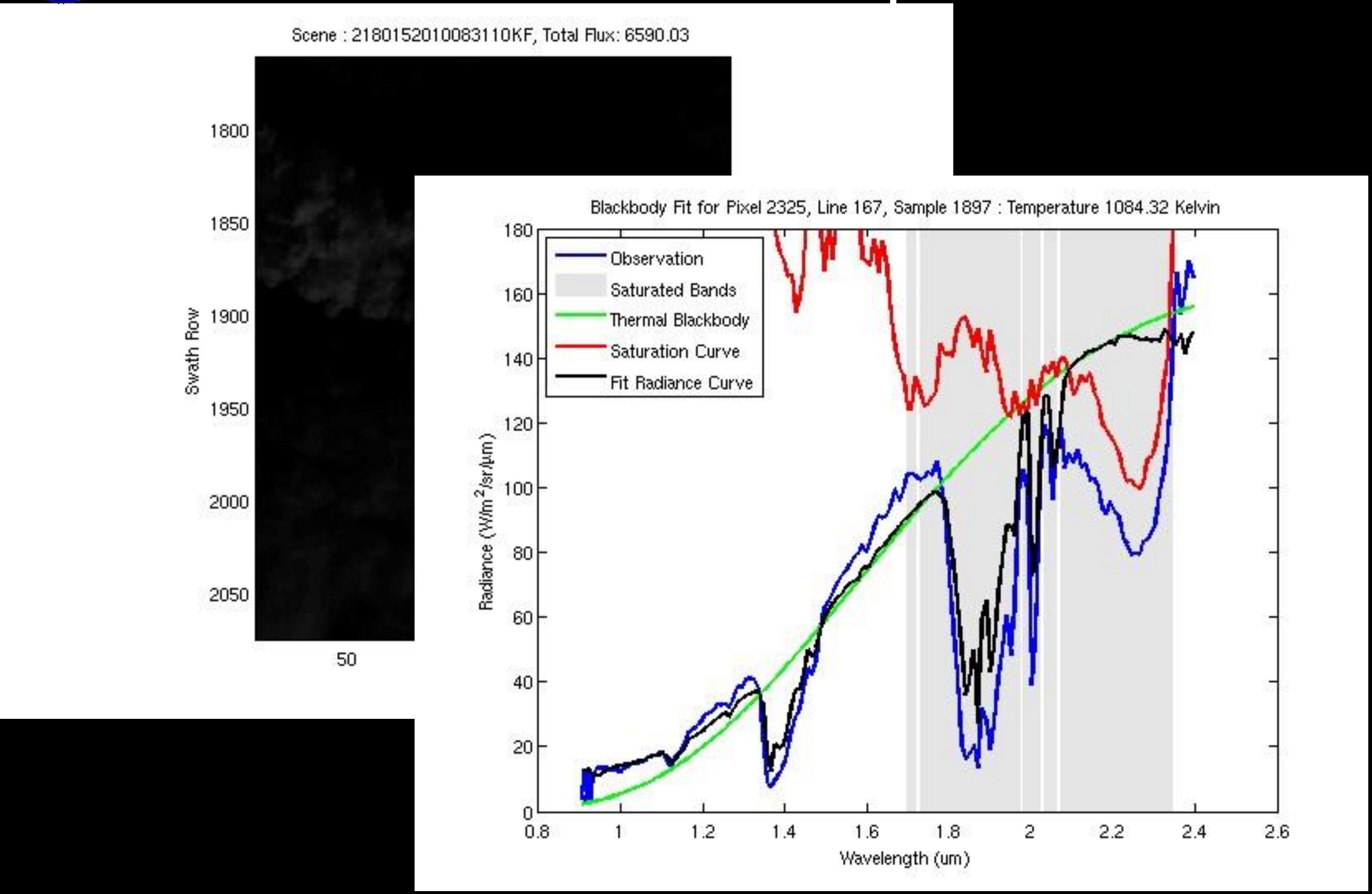
VSW automatic products



Map of hot pixels

Davies *et al.* (2013) JGR

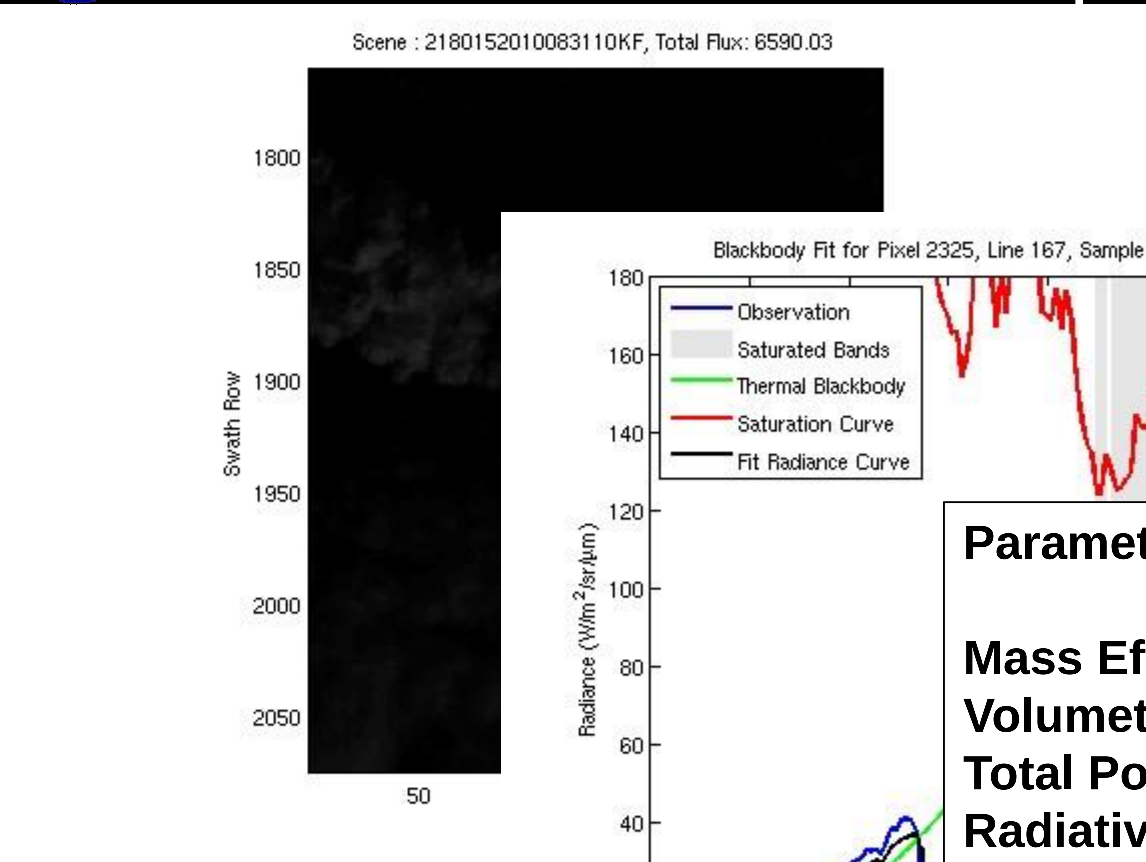
VSW automatic products

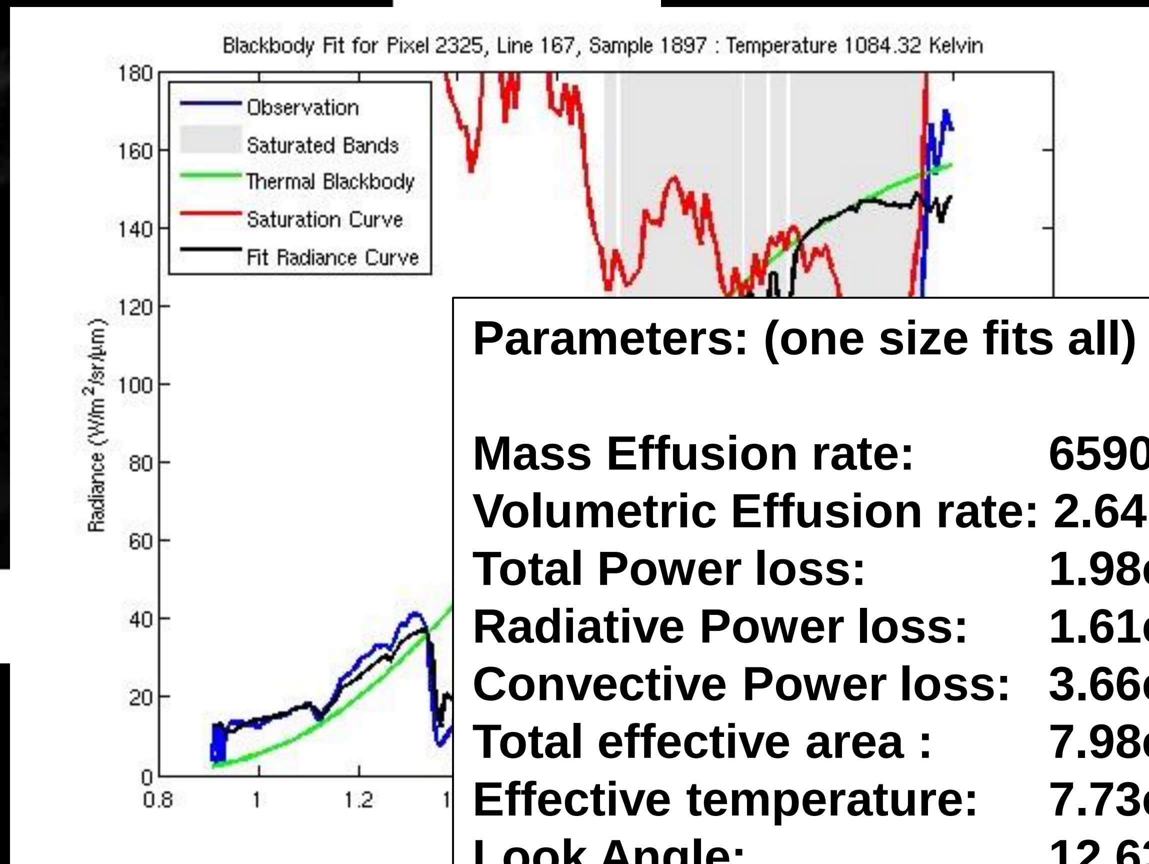


Fit to spectrum to quantify thermal emission

Davies *et al.* (2013) JGR

VSW automatic products





Parameters: (one size fits all)

Mass Effusion rate:	**6590.03 kg/s**
Volumetric Effusion rate:	**2.64 m^3/s**
Total Power loss:	**1.98e+09 W**
Radiative Power loss:	**1.61e+09 W**
Convective Power loss:	**3.66e+08 W**
Total effective area :	**7.98e+04 m^2**
Effective temperature:	**7.73e+02 K**
Look Angle:	**12.63 deg.**
Range to Ground:	**705.85 km**

Estimate of scene discharge rate, etc.

Davies *et al.* (2013) JGR

VSW data processing

1-T fit to unsaturated data of spectra identified as thermally anomalous

From these 1-T fits, area is found and total power calculated

This is converted into an effusion rate (min. value)

VSW data processing

Harris et al., 1999; Harris and Thornber, 1999

Q_F = effusion rate, such that

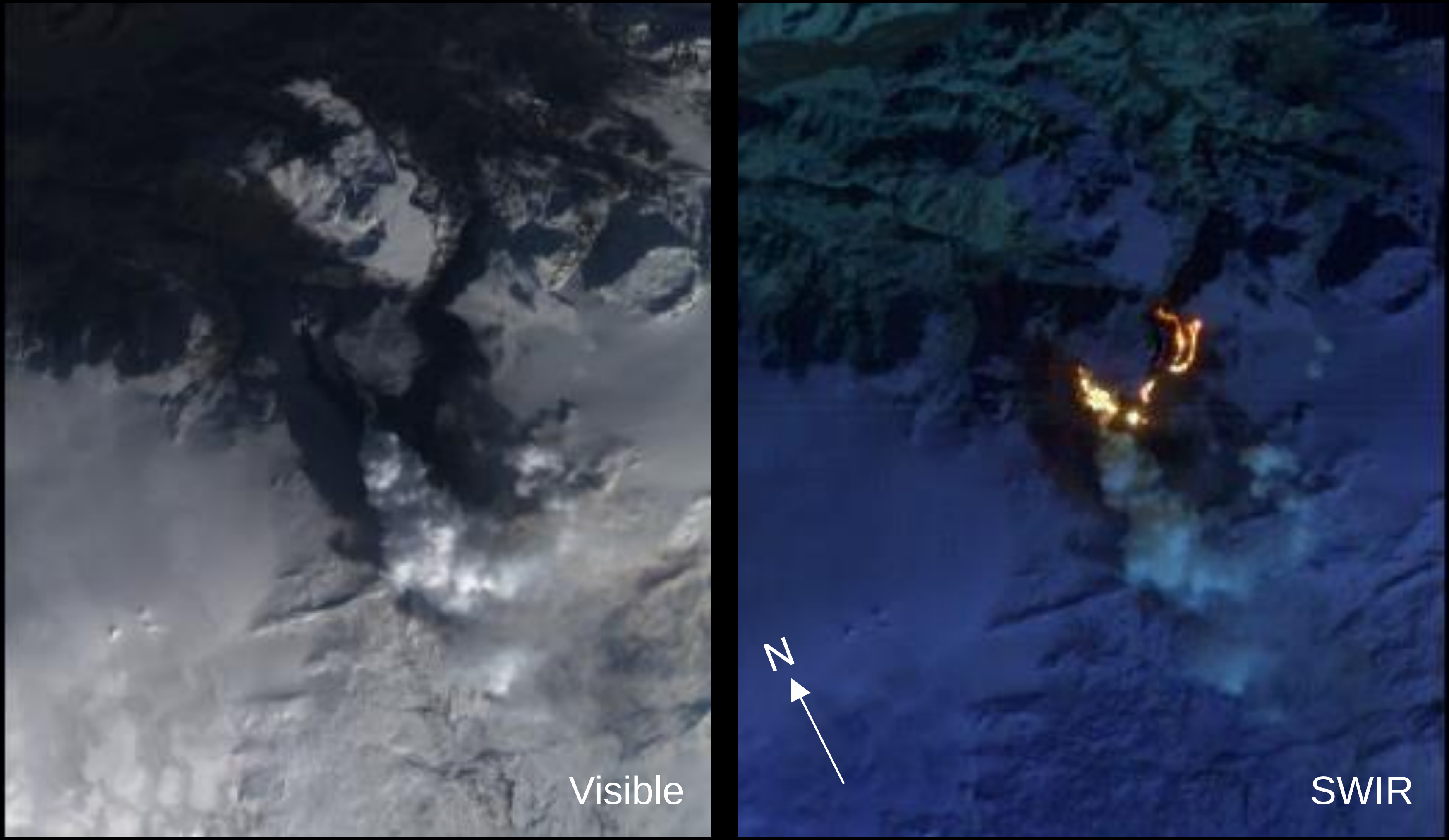
$$Q_F = \frac{Q_{TOT}}{\rho_{lava}\left(c_p\,\Delta T + L\,\Delta f\right)}$$

Q_{TOT} = total heat loss = $Q_{rad} + Q_{conv} + Q_{cond}$
ρ_{lava} = lava density (2600 kg/m^3
ΔT = temperature range through which the lava has cooled (200 K)
L = latent heat of fusion (3 x 10^5 J/kg)
c_p = lava specific heat capacity (1150 J/kg/K)
Δf = change in crystallization fraction over ΔT (0.45)

"One size fits all" – a trip wire, and for relative comparison from observation to observation

1 April 2010 - Fimmvorduhals

EO1H2180152010091110PF



7.7 km

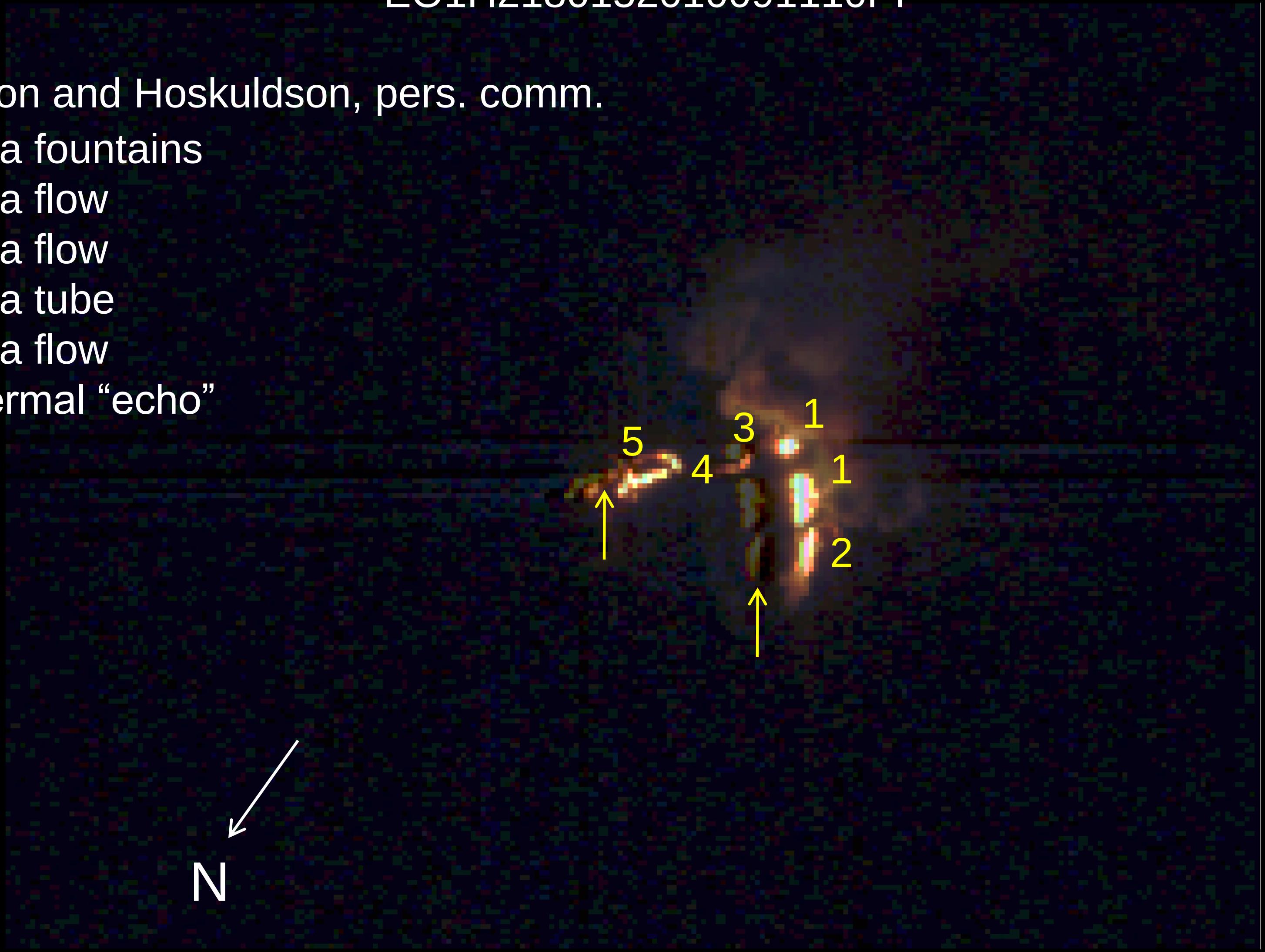
Davies *et al.* (2013) JGR

1 April 2010 - Fimmvorduhals

EO1H2180152010091110PF

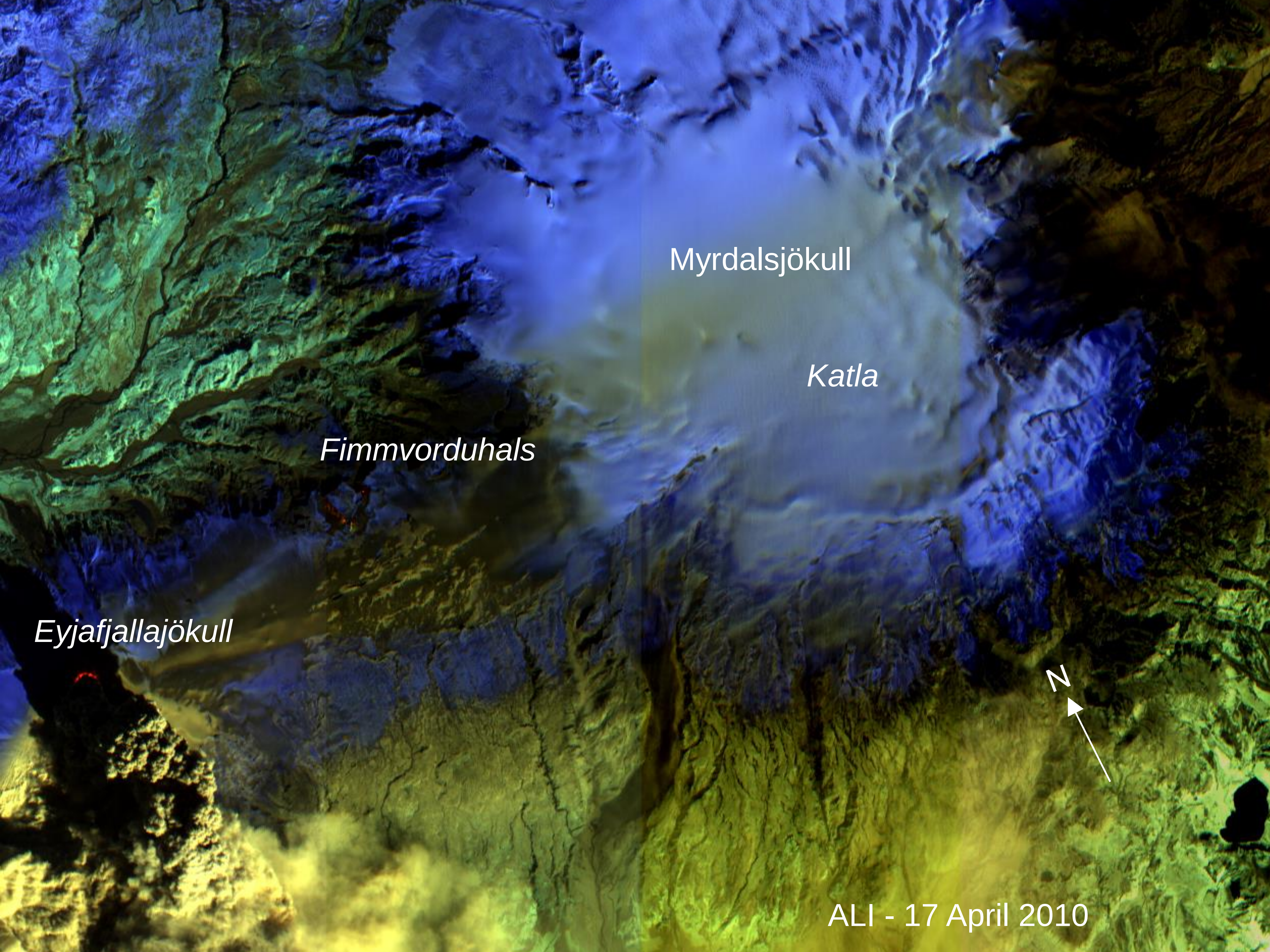
Thordarson and Hoskuldson, pers. comm.

1 Lava fountains
2 Lava flow
3 Lava flow
4 Lava tube
5 Lava flow
→ Thermal “echo”

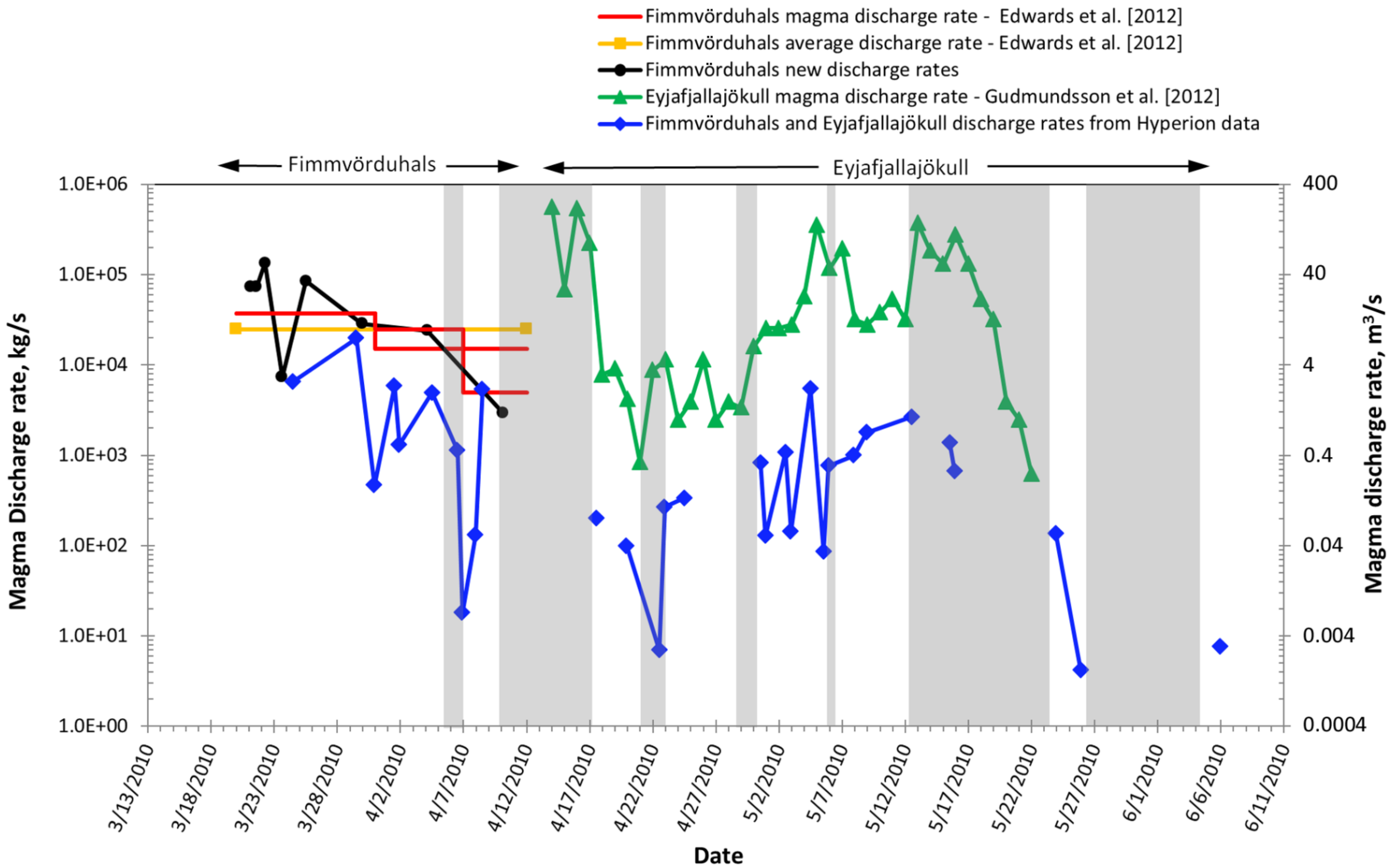


7.7 km

Davies *et al.* (2013) JGR


Myrdalsjökull
Katla
Fimmvorduhals
Eyjafjallajökull
N
ALI - 17 April 2010

Discharge rate comparisons



Davies *et al.* (2013) JGR

Lessons learned: 2004-2010

VSW and products are of most value where time is crucial and/or locations are remote/not accessible → Nyamulagira, 2006

The best “customer satisfaction” results from pre-determined agreements with individual end users, because in the middle of a volcanic crisis…

- local authorities work to the plan in place
- time commitment is already 100% - “what’s this?”
- it is not clear to whom products should be sent

Solution: make products available, and publicise availability

- working to make VSW products widely accessible beyond JPL
- triggering from updates to GVN
- talking endlessly about it → e.g., Pavlof, 16 Nov 2014

Payoff

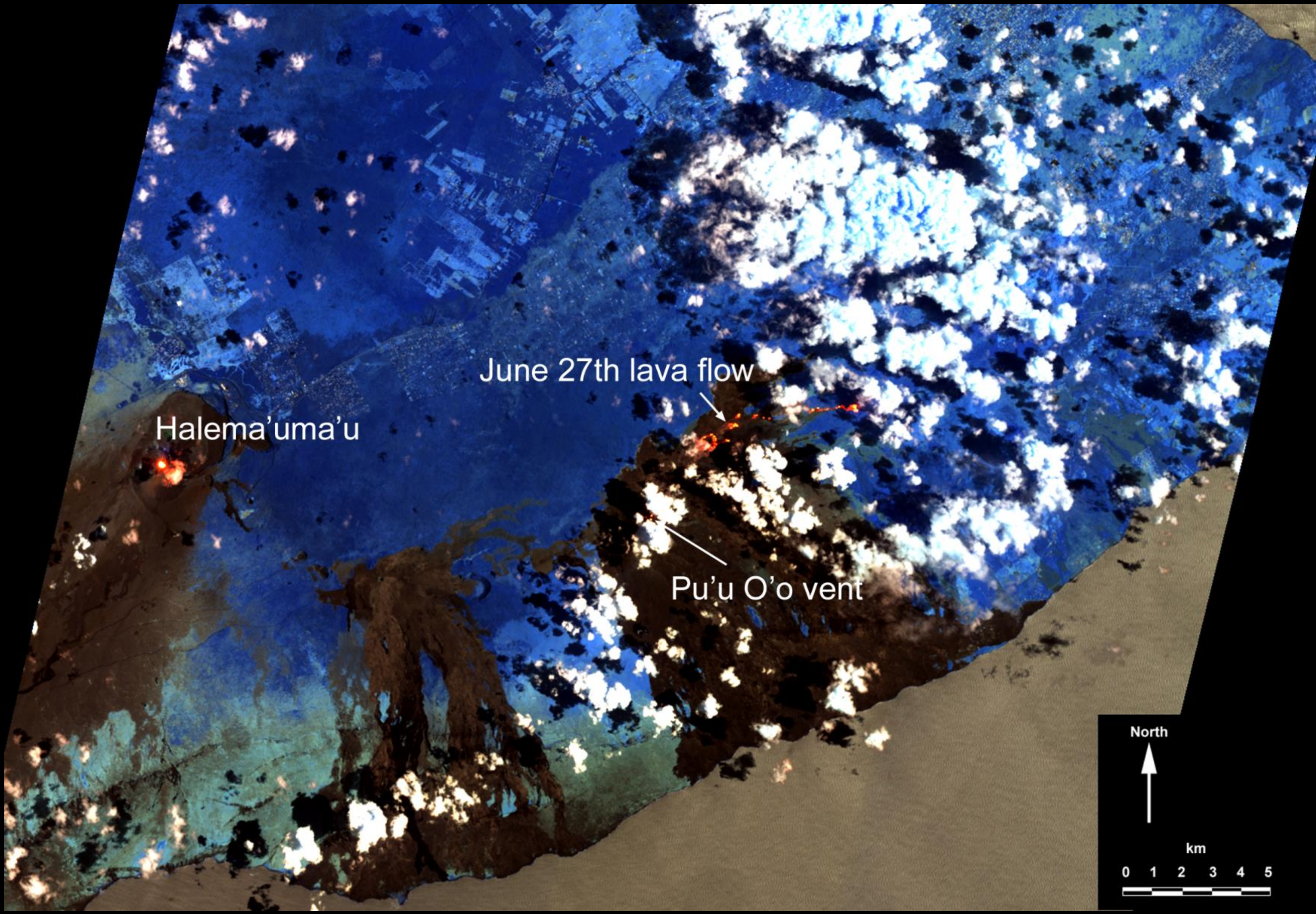
VSW provided data to HVO during “27 June” Pahoa crisis (Patrick *et al.*, 2015)

VSW worked like a charm during the 2014-2015 Nornahraun (Iceland) eruption

- Many EO-1 observations of Nornahraun
- Quick processing and delivery of data and products

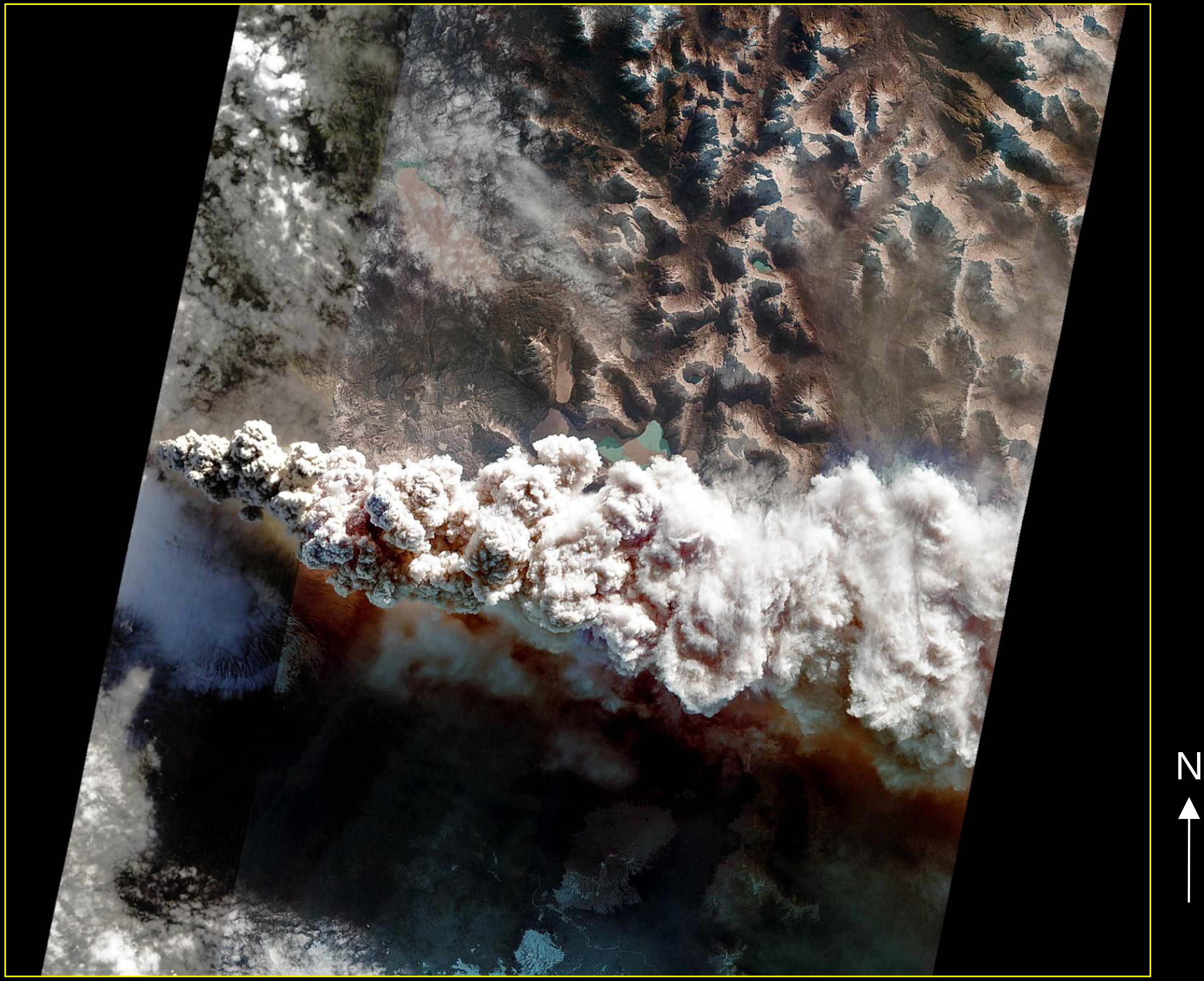
… A template for future HyspIRI operations and data processing and dissemination

Kilauea volcano, HI: Flows threatening Pahoa



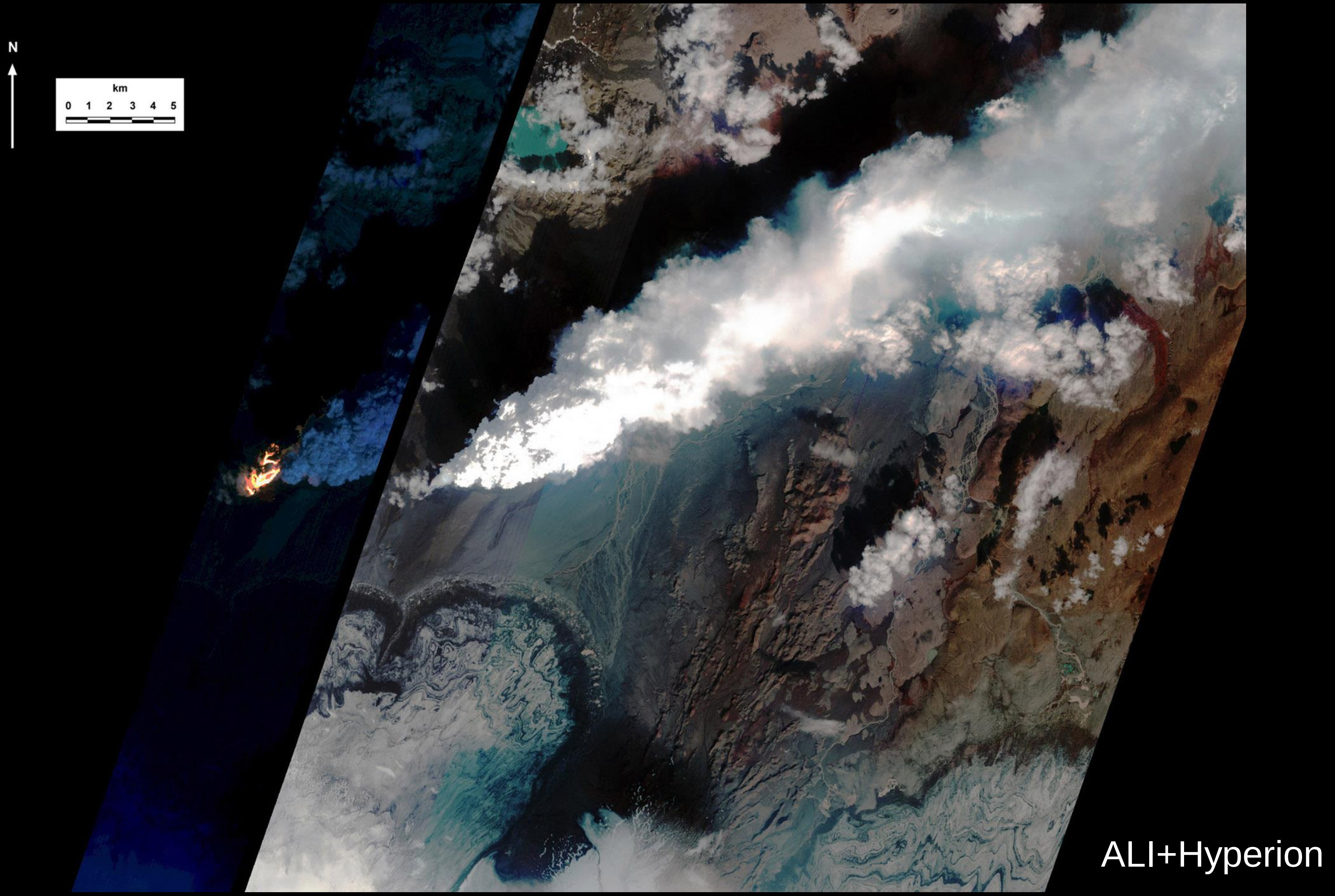
8 September 2014: ALI observation E01A0620462014251110KH

Puyehue, Chile – 14 June 2011



Combined Hyperion/ALI L1G product - NASA/JPL/*EO-1*/GSFC/Ashley Davies

Nornahraun- 3 Sept 2014

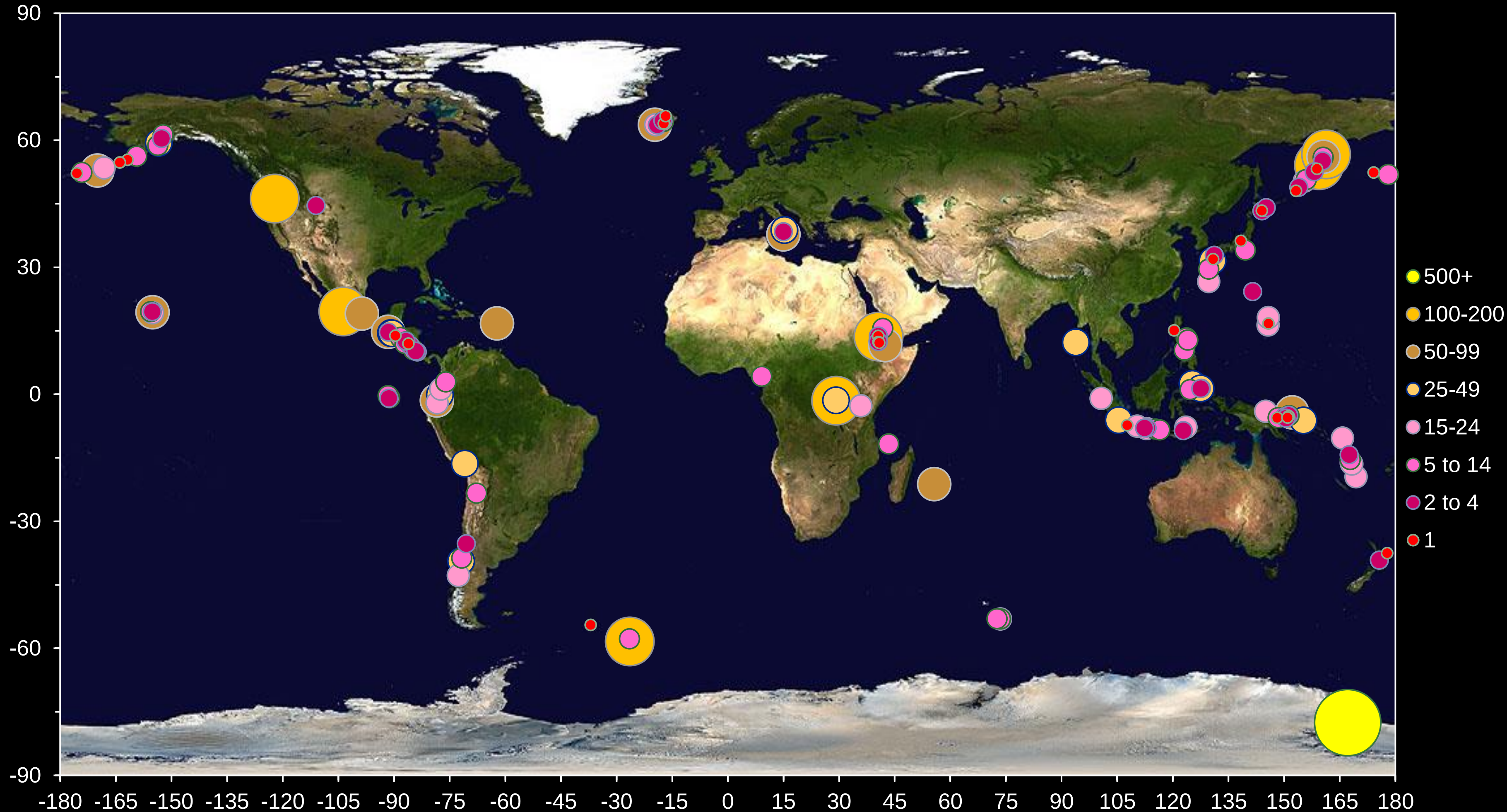


Tolbachik: 1 December 2012

EO-1 ALI: NASA Earth Observatory image by Jesse Allen

ASE and VSW volcano observations

May 2004 - Feb 2013



Total: 4956, including: 576 Erebus; 171 Mt St Helens; 89 Erta ‘Ale; 82 Etna

Acknowledgements

A large cast over the years!

Thanks to the *EO-1* MSO

GSFC, JPL

ASE Project

VSW Project

End

Backup slides

Figure 3. Davies et al., 2006, RSE.