Io: Volcanic Advection and Heat Flow

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Io’s hot spots

Observations

Modes of volcanic activity

Quantifying thermal emission

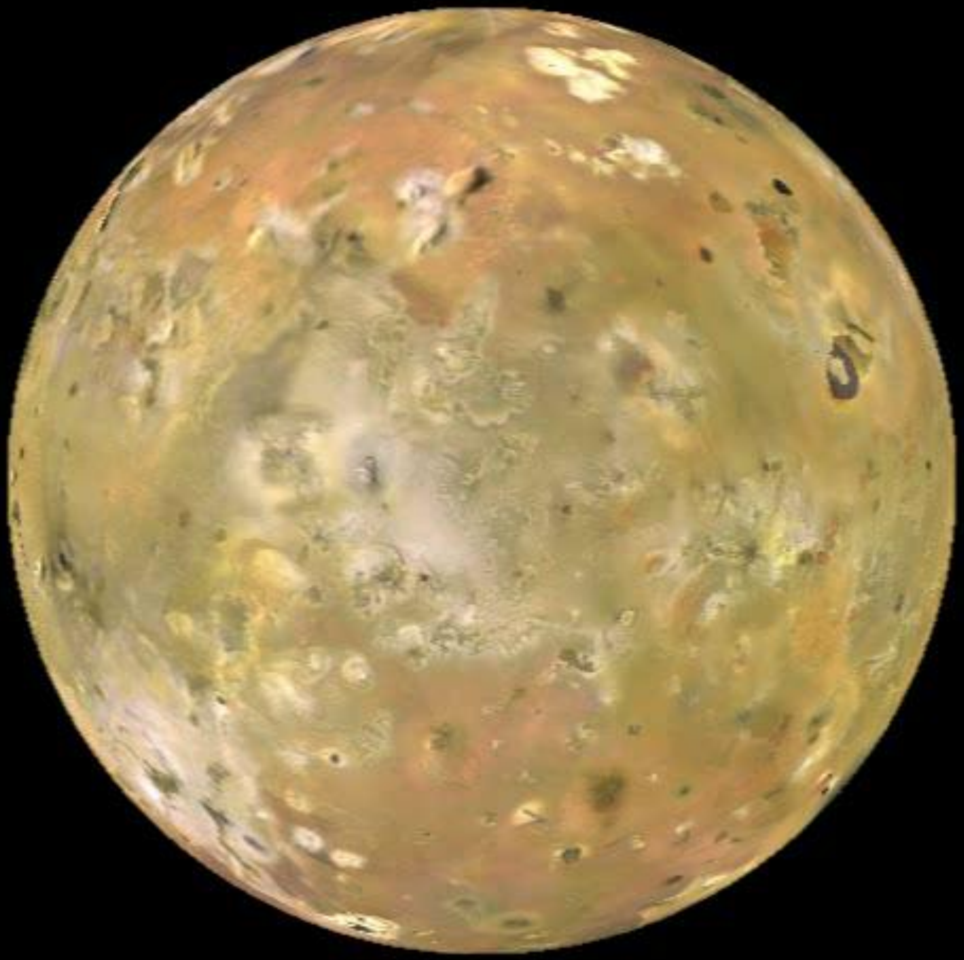
Derivation of erupted volumes

Heat flow analysis

Questions

Volcanism on Io

- The most extreme example of tidal heating in the Solar System
- Powerful, highly voluminous eruptions
- Resurfacing has erased all impact craters
- Lithosphere is *cold*
- Heat pipe volcanism (Moore, 2014)
- Faults can be exploited (e.g., Leone et al., 2009)



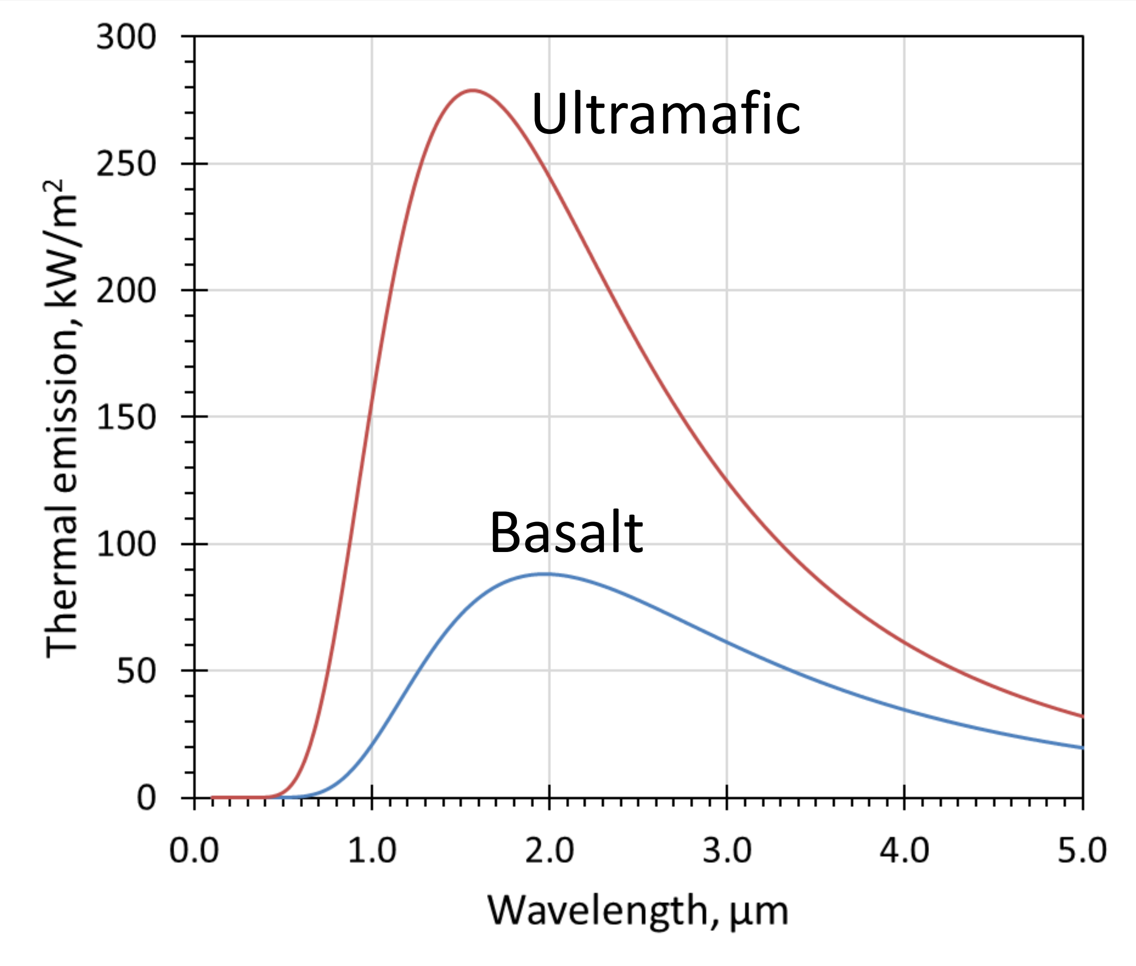
What is the composition of silicate lavas on Io?

Io’s volcanism is dominated by low-viscosity, quite fluid lavas

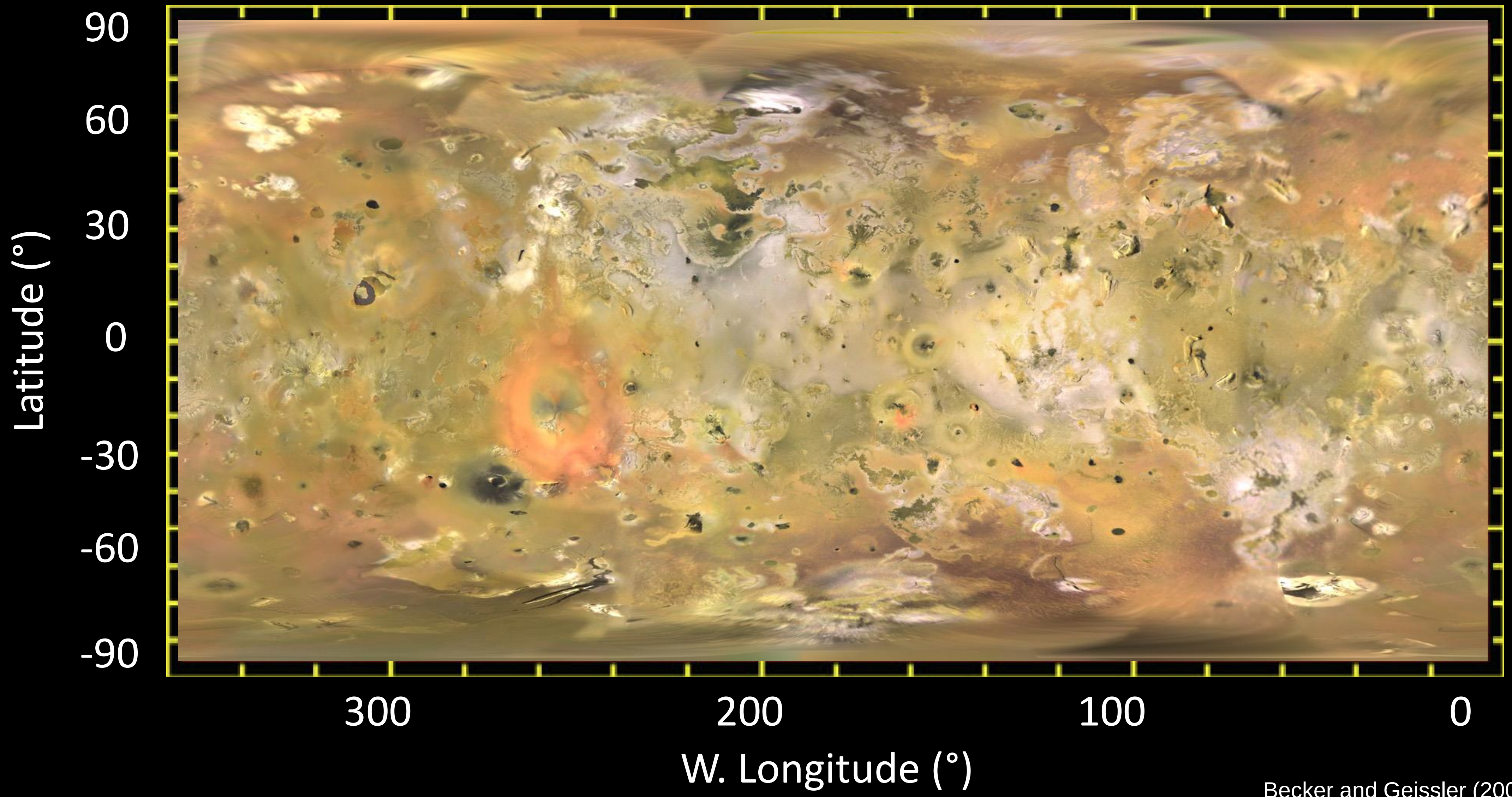
Basalt erupts at ~1150 °C (~1440 K)

Komatiite erupts at ~1577 °C (~1850 K)

The hotter the lava → more interior heating → a more liquid source area

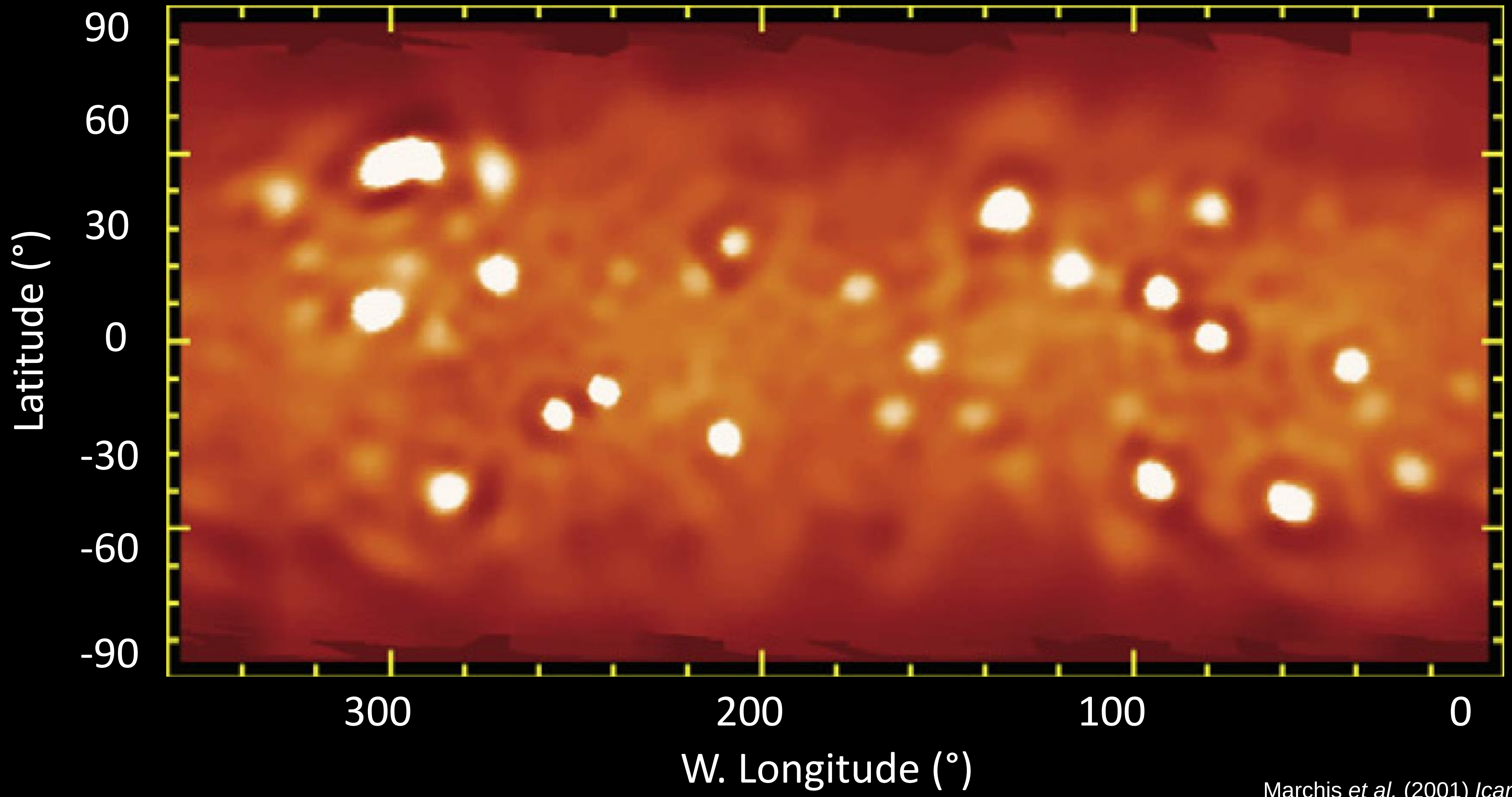


Voyager and *Galileo* data



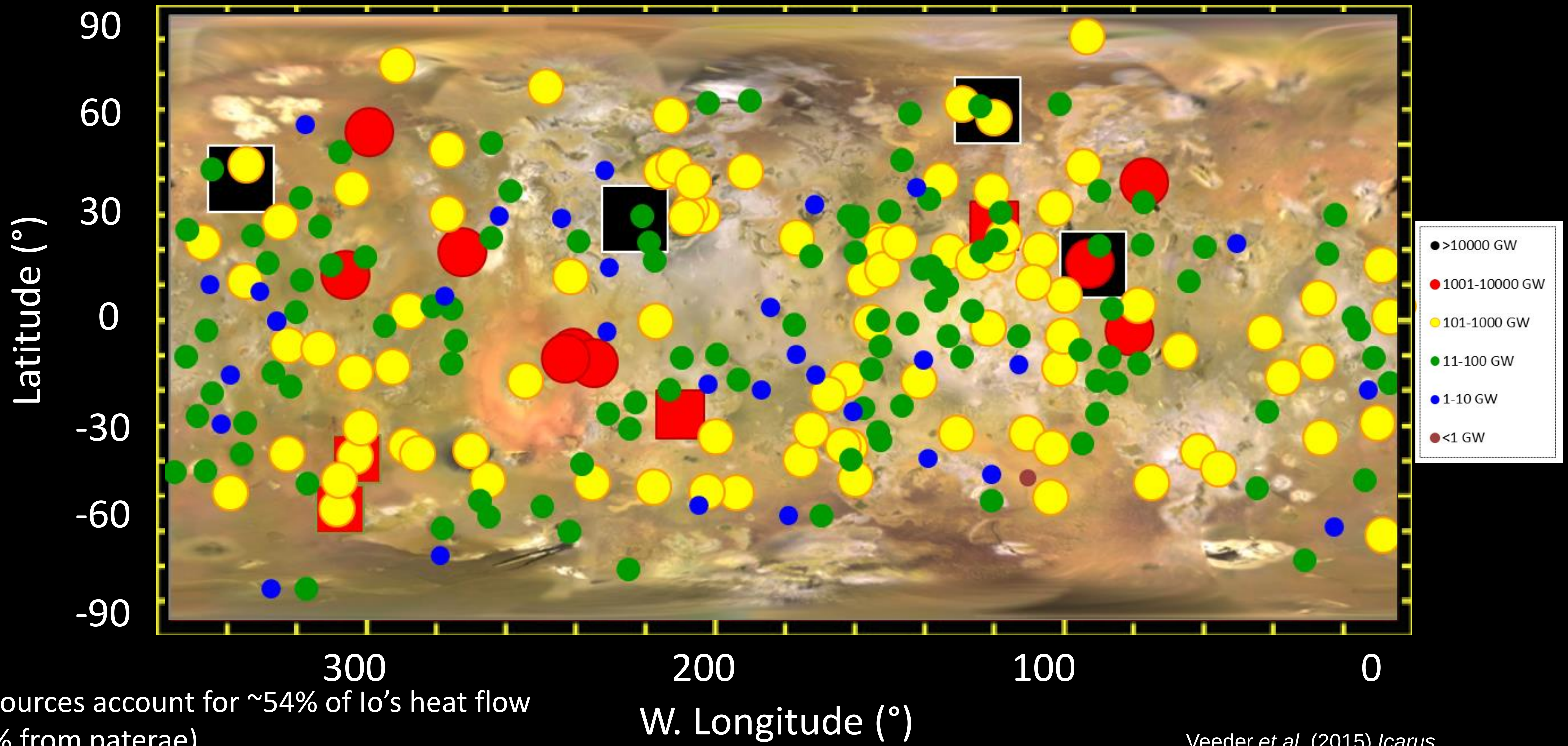
Becker and Geissler (2005)

Io from Earth: Keck AO data (4.7 µm)



Marchis *et al.* (2001) *Icarus*

Io volcanoes ranked by thermal emission



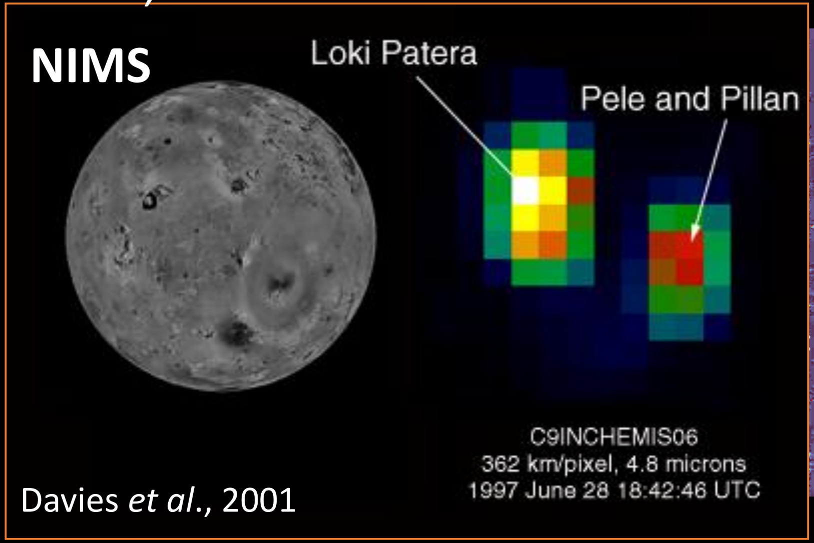
242 sources account for ~54% of Io's heat flow (~70% from paterae)

With outbursts = ~57% of Io's heat flow

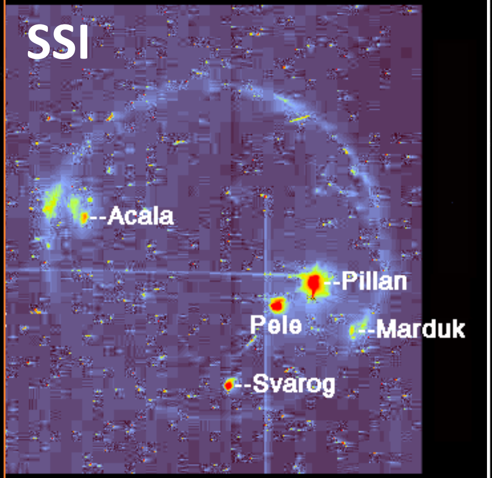
Veeder *et al.* (2015) *Icarus*

Galileo NIMS and SSI observe volcanism on Io

Pillan, 1997

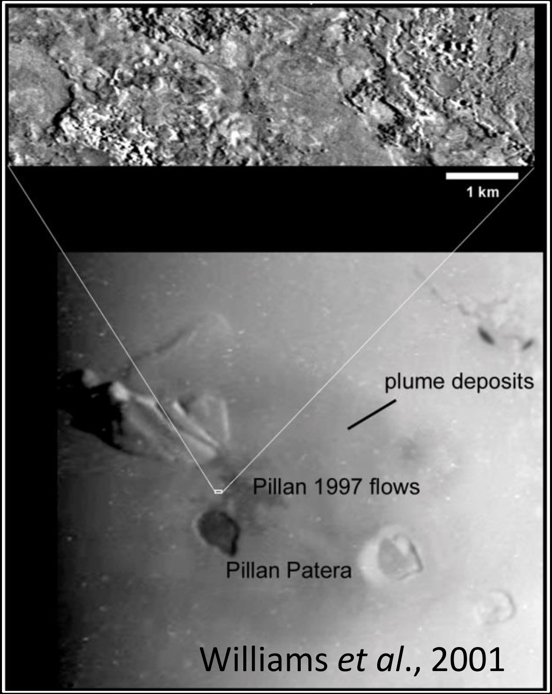


Davies *et al.*, 2001



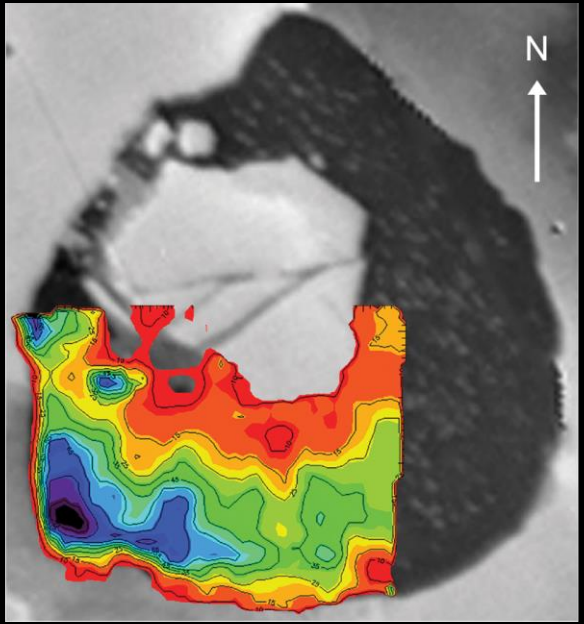
Keszthelyi *et al.*, 2001

Pillan flows at 9 m/pixel



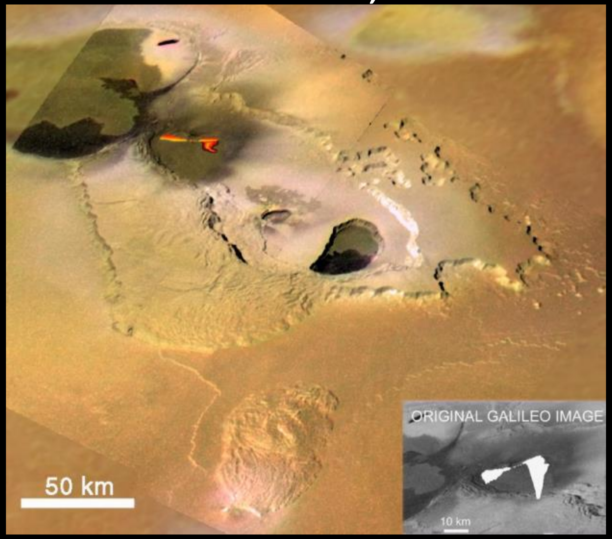
Williams *et al.*, 2001

Loki Patera surface temperature map from NIMS data

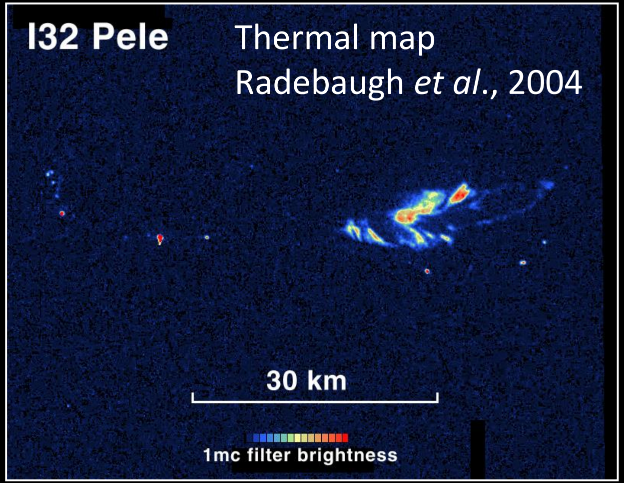


Davies (2003) *GRL, 30,* 2133-2136.

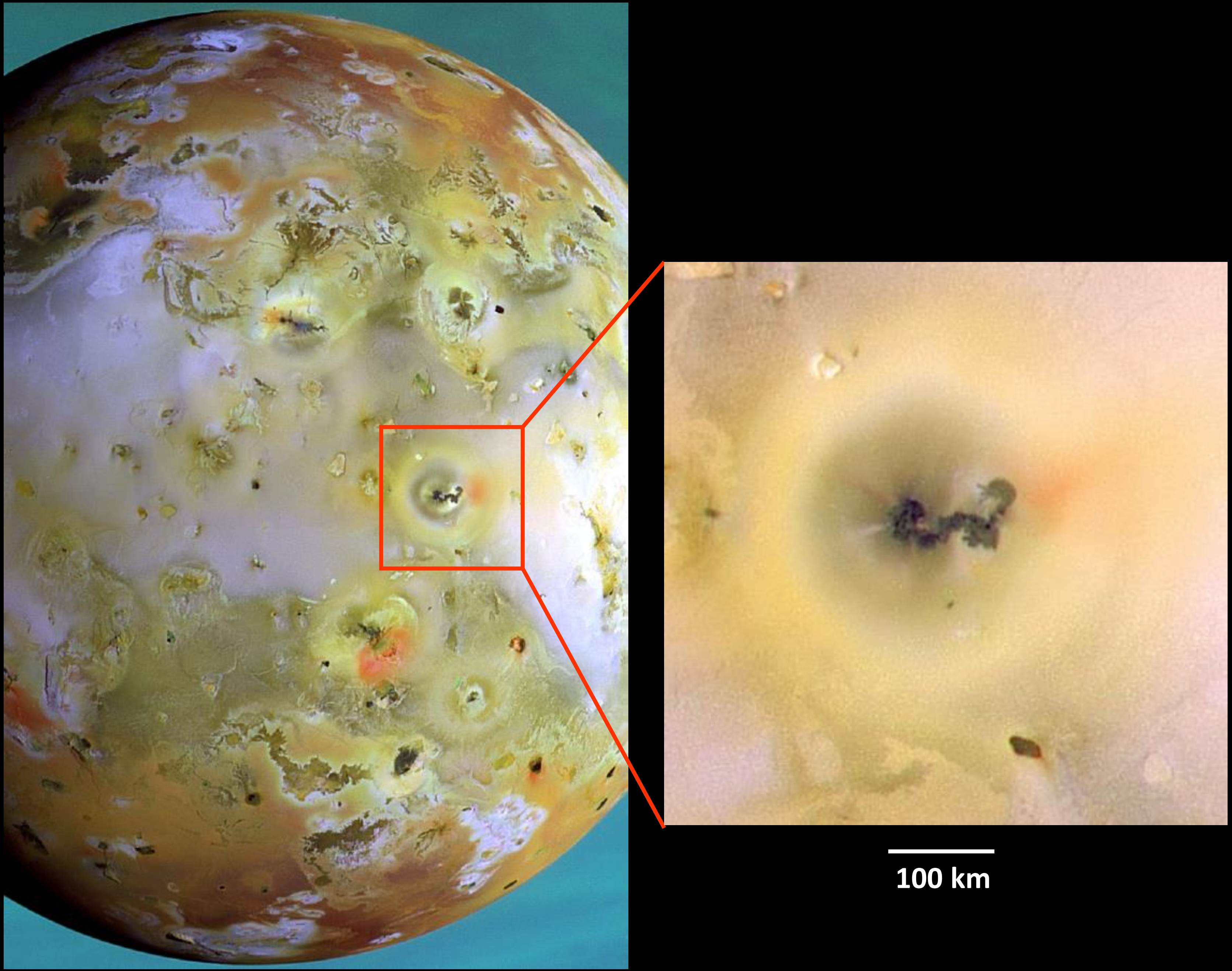
Tvashtar Paterae, Feb 2000

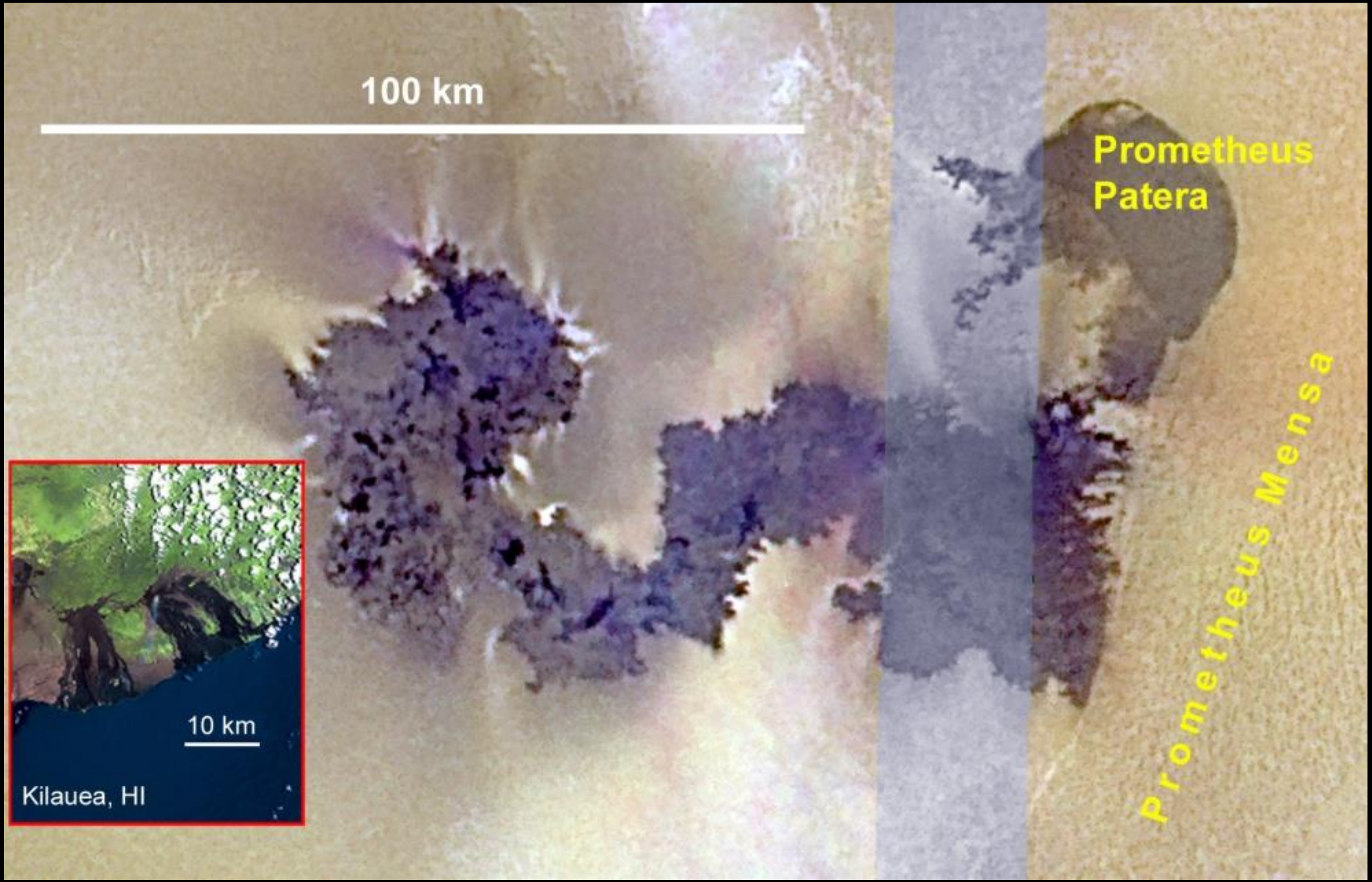


Keszthelyi *et al.*, 2001

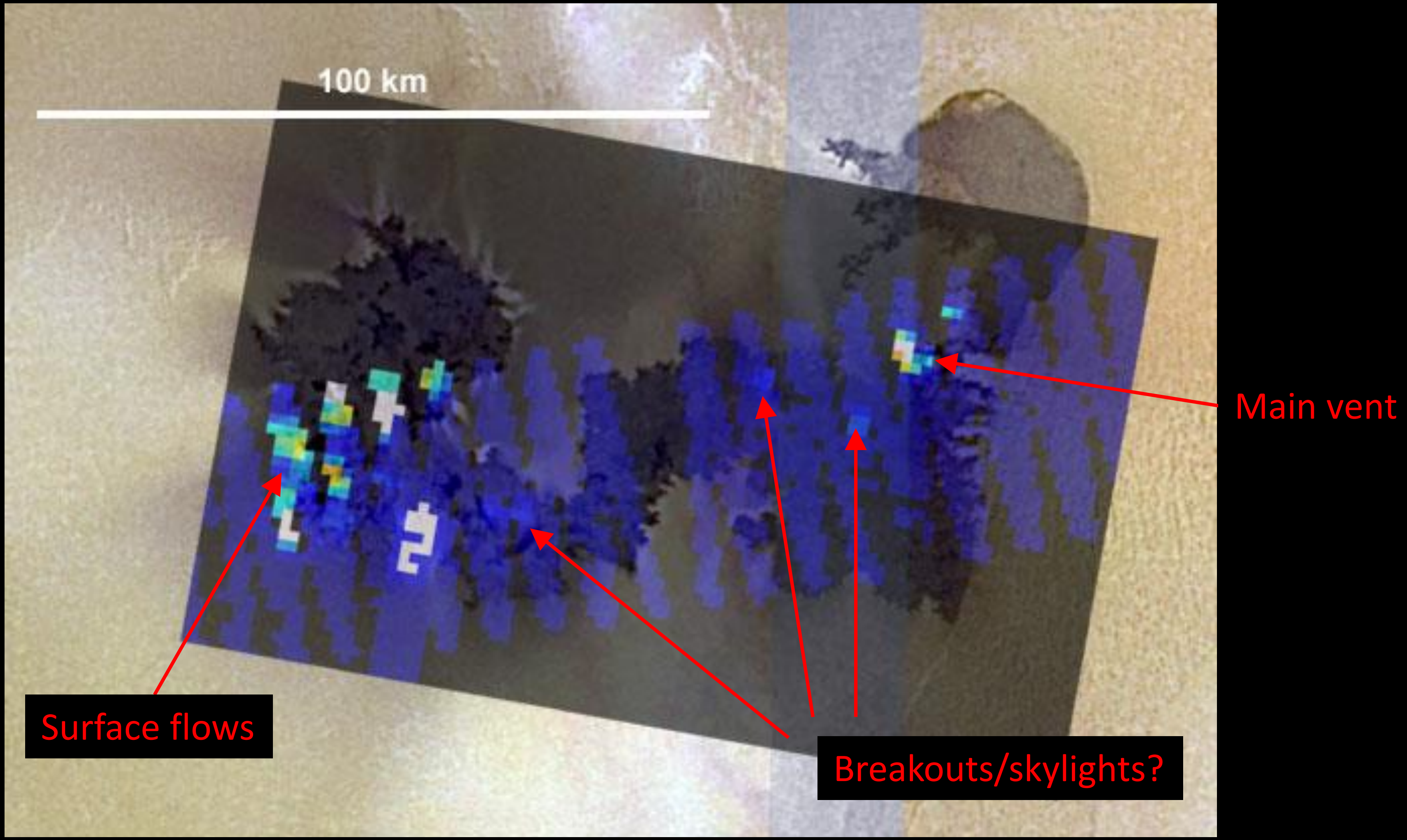


Thermal map
Radebaugh *et al.*, 2004


100 km


100 km
Prometheus
Patera
Prometheus Mensa
10 km
Kilauea, HI

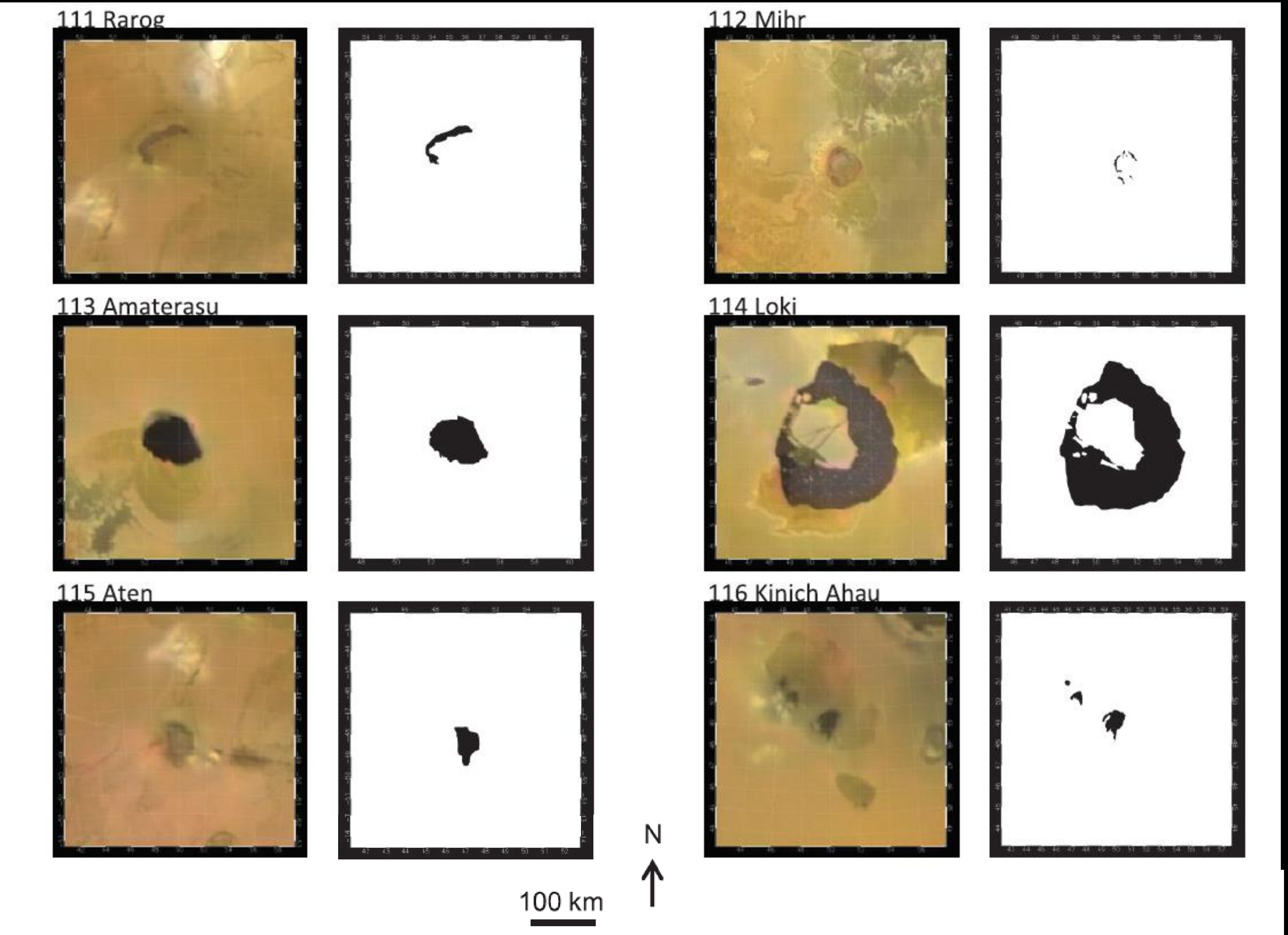
Prometheus – tube-fed lava flows



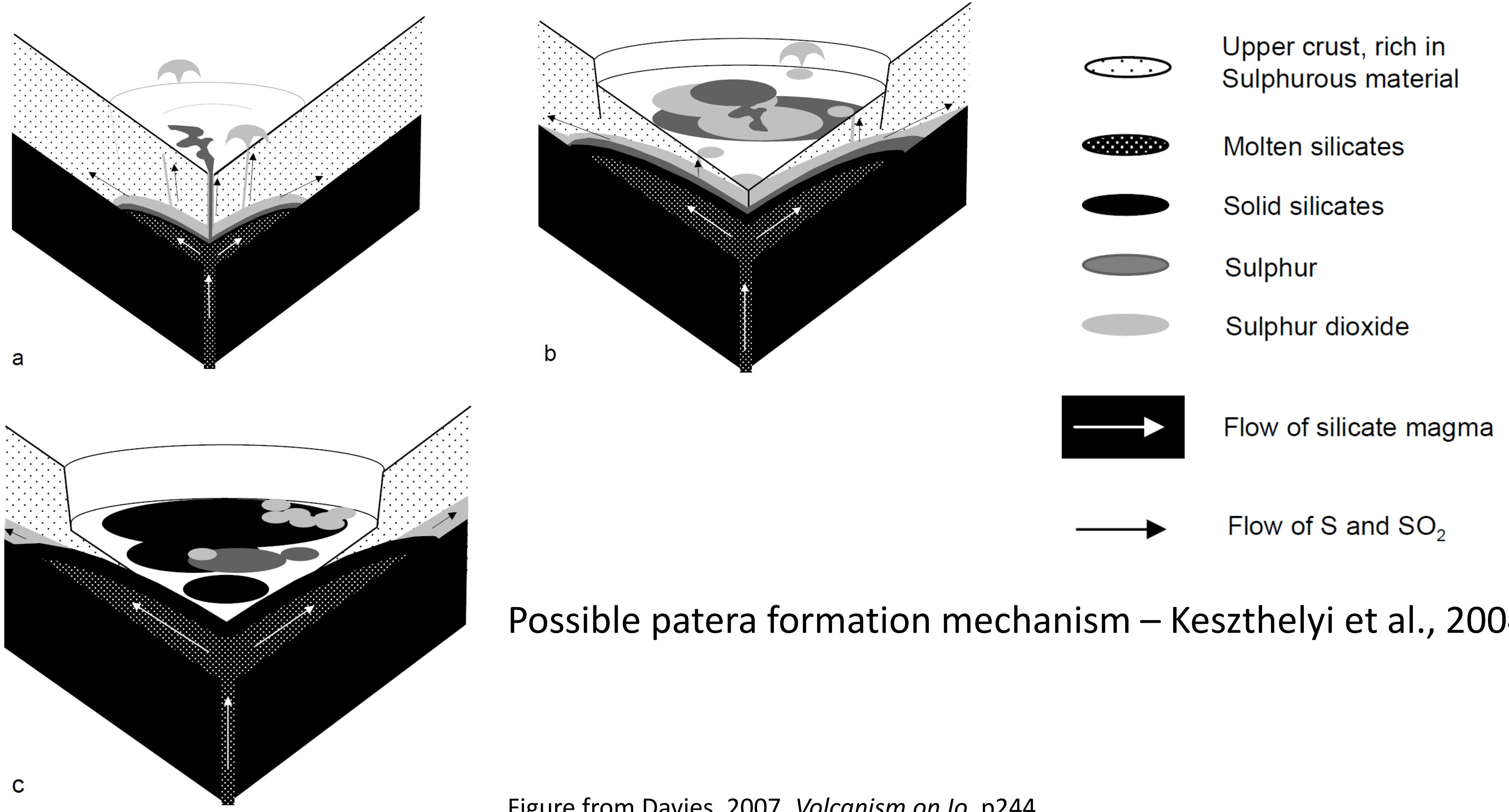
NIMS: 24INPROMTH91A 11 Oct 1999
Average spatial resolution: 1.4 km/pixel

Leone et al. (2009) *Icarus*

Paterae – ubiquitous on Io – source of most endogenic heat – catalogued by Radebaugh et al., 2001



Veeder *et al.* (2011)

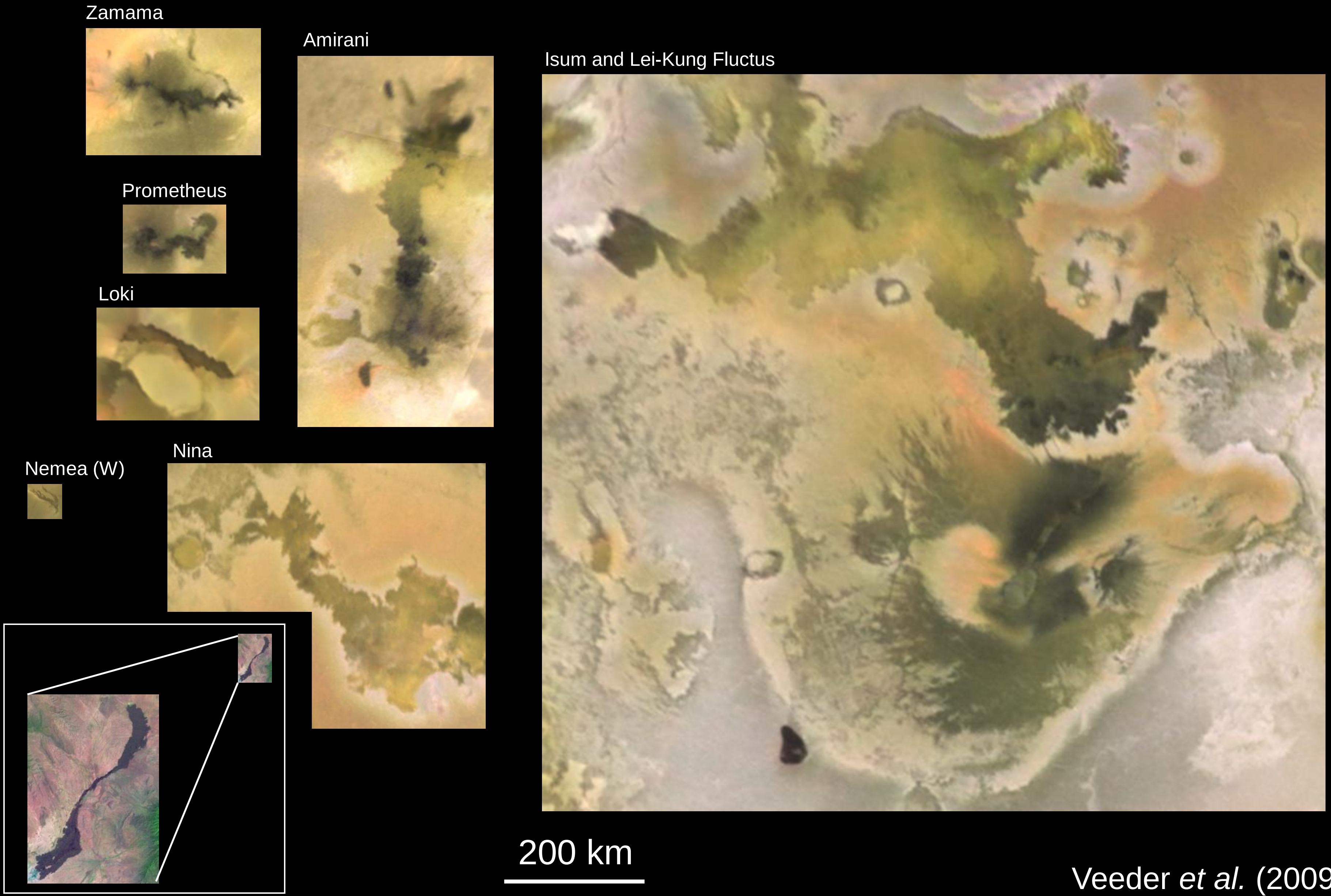


Possible patera formation mechanism – Keszthelyi et al., 2004

Figure from Davies, 2007, *Volcanism on Io*, p244.

Flow fields on Io

range in size from ~600 km^2 to >2.5×10^5 km^2



Veeder *et al.* (2009)

Styles of volcanic activity on Io (1)

- Volcanism is dominated by high-temperature, low viscosity silicates

- Activity also driven by interactions with exsolving primary volatiles and with lithospheric volatiles during ascent (S, SO_2) and on the surface

- Many active paterae (e.g., Radebaugh et al., 2002; Lopes et al., 2004)

- Extensive lava flow fields (e.g., see Veeder et al., 2009)

- Active, overturning lava lakes (Janus Patera, Pele – e.g., Davies et al., 2001)

and....

Styles of volcanic activity on Io (cont'd)

- At least one quiescently overturning lava lake (or lava "sea") – Loki Patera (e.g., Rathbun et al., 2002; Davies, 2003; Matson et al., 2006; Rathbun and Spencer, 2006; de Kleer et al., 2017).

- Powerful, dike-fed lava fountain episodes feeding voluminous flows (likely cause of "outbursts") (See Davies, 1996)

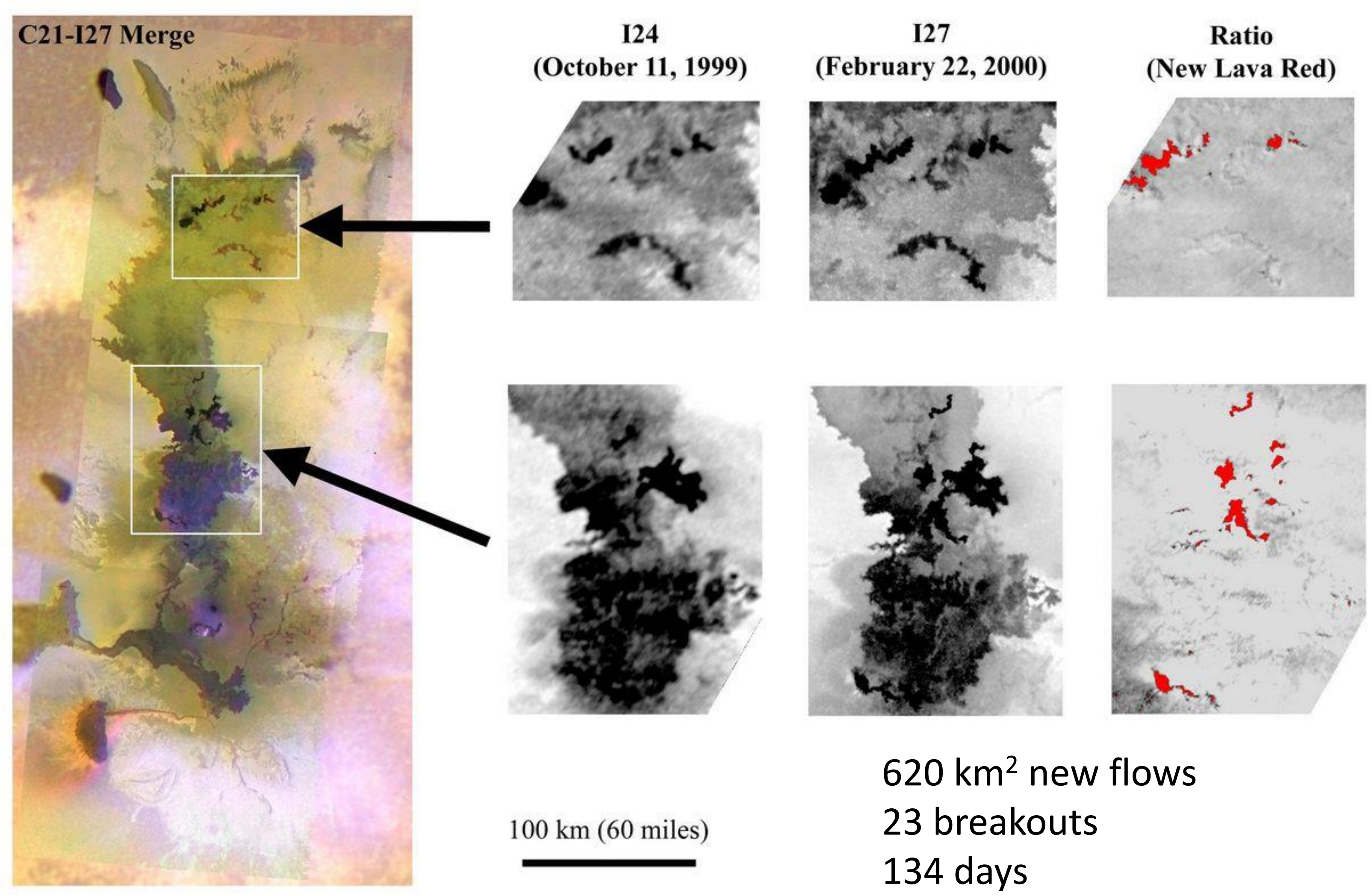
- Smaller and more frequent fountain events (de Kleer and de Pater, 2016a,b)

- Secondary S, SO_2 volcanism (see Prometheus plume papers: e.g., Kieffer et al., 2000)

- Transient explosive activity (Davies et al., 2018, *GRL*)

Calculation of effusion rate (1)

Amirani eruption rate (TADR) estimation

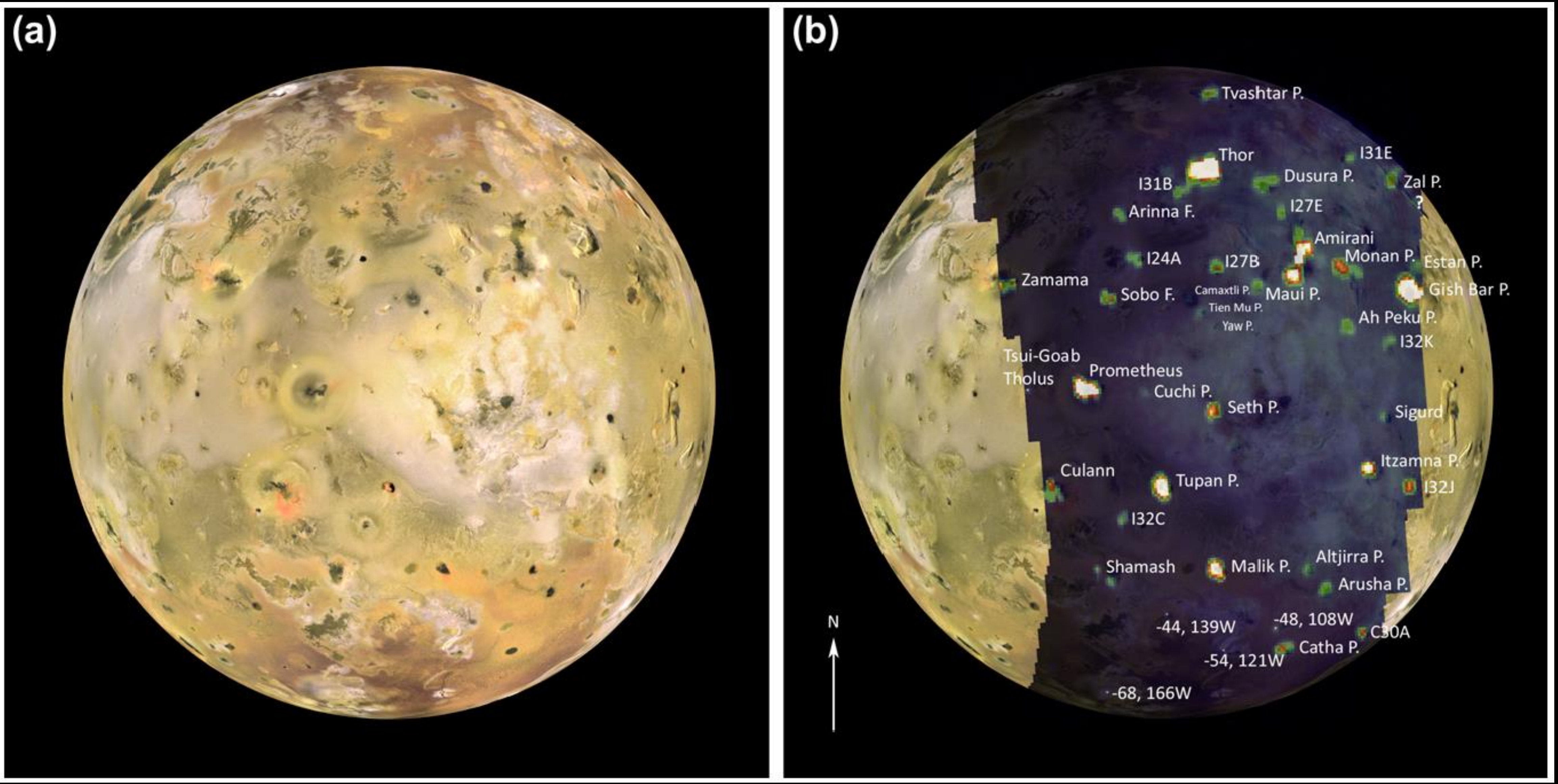


620 km^2 new flows
23 breakouts
134 days
TADR = 60-600 m^3/s
Keszthelyi *et al.,* 2001

Flow thickness in this case is not known

Williams et al. (2001) measured post-eruption flow thickness at Pillan = ~10 m

Davies et al. (2000) and Davies (2003) used NIMS data to estimate eruption volumetric rates



Veeder et al. (2012)

Calculation of effusion rate (2)

- From thermal emission: best with multi-wavelength infrared data
  - *Galileo* NIMS data (0.7 to 5.2 μm)
  - AO data (~2 to ~5 μm)

- NIMS sensitive down to surfaces at ~200 K

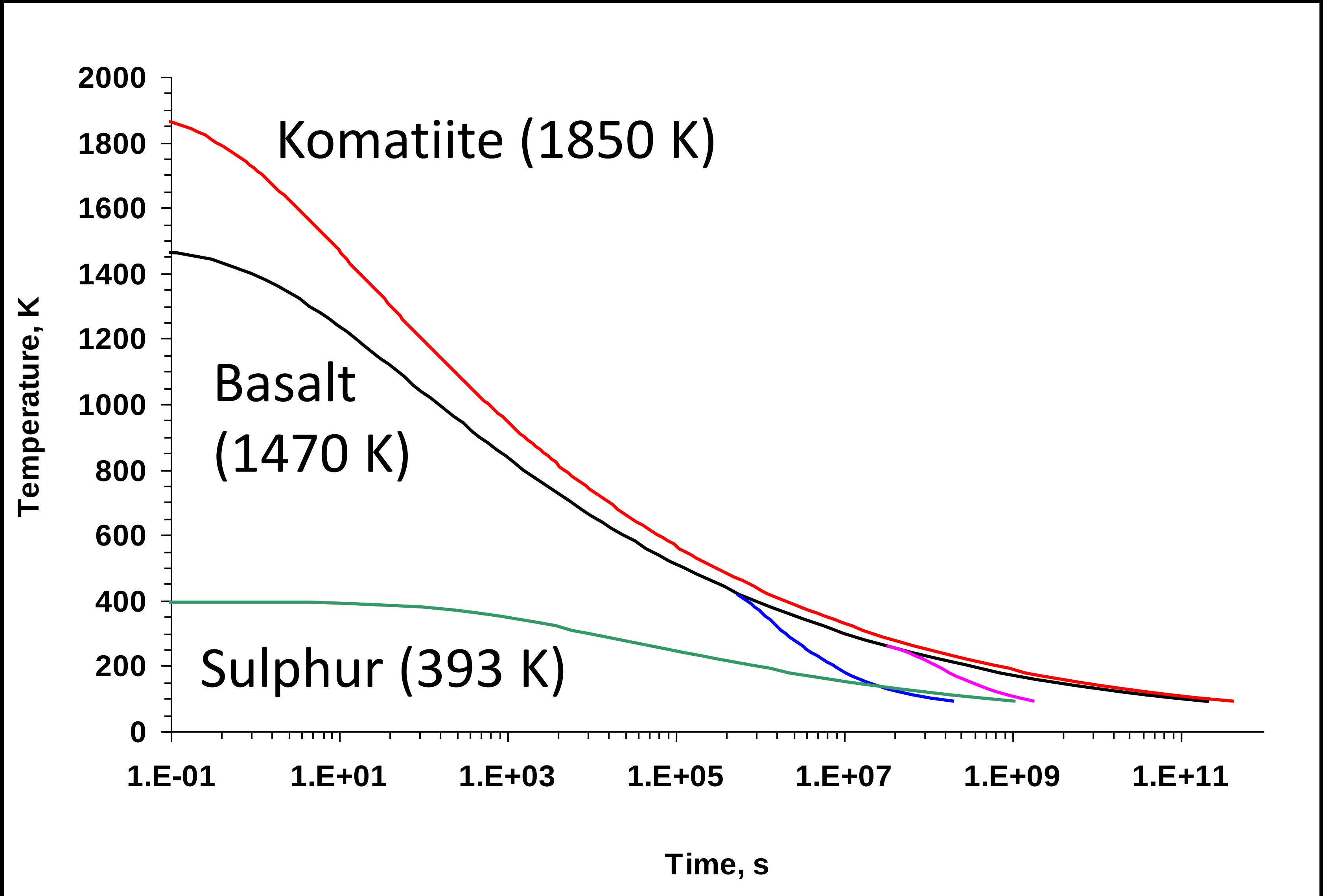
- Models of thermal emission – fit combination of black body curves to the data

  1T, 2T fits (Davies *et al*., 1997, 2001, etc, etc.)

Multiple temperature component models (Carr, 1986; Davies, 1996; Howell, 1997)

Davies, 1996 - Derives areal coverage rate – variants utilise variable effusion rate, lava crust crack fraction, separate vent and flow units

Cooling curves for lavas on Io



Davies *et al.,* 2005

Calculation of effusion rate ($Q_{F(NIMS)}$, m^3/s)

- Using NIMS data - Davies et al. (2000)
- Calculate F_{rad}
- Determine eruption style (flows, lake, other)
- If flows, calculate F_{cond} (= 20% F_{rad} ; Johnson et al., 1995; Davies, 2003); $F_{rad\,=}\,F_{rad}$

$$Q_{F(NIMS)} = \frac{F_{tot}}{\rho_{lava}(L + \ c_p \left[T_{erupt} - T_{NIMS}\right])}$$

ρ_{lava} = lava density

L = latent heat of solidification

C_p = specific heat capacity

T_{erupt} = lava eruption temperature

T_{NIMS} = minimum NIMS detection threshold (filled pixel = 180 K)

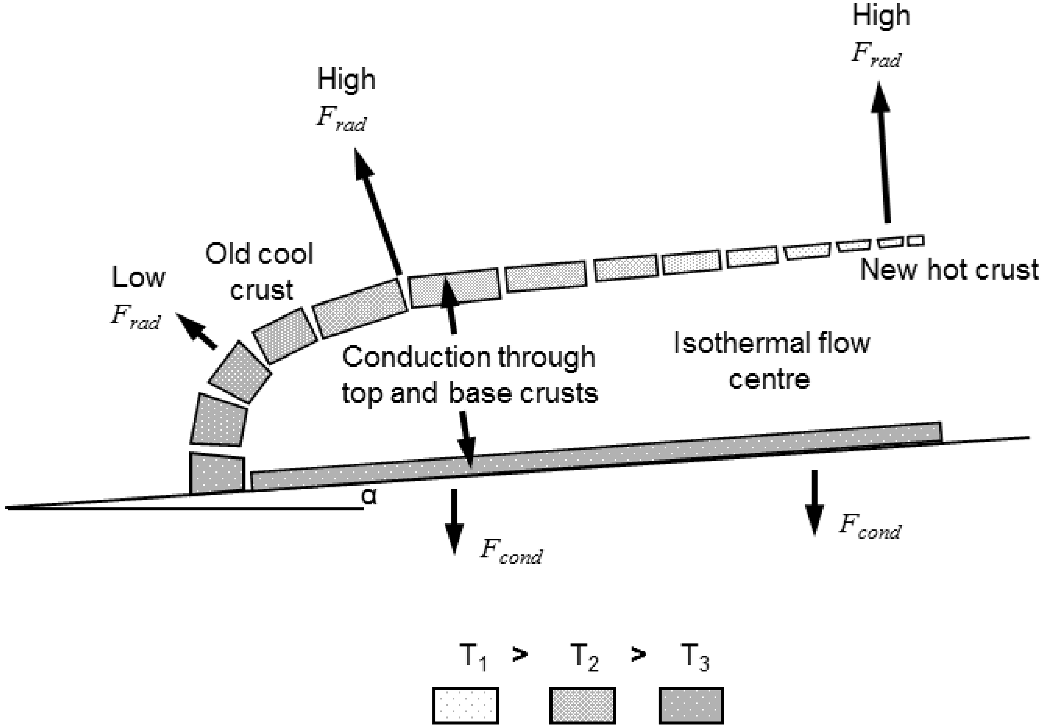
IFM – generation of integrated thermal emission spectrum

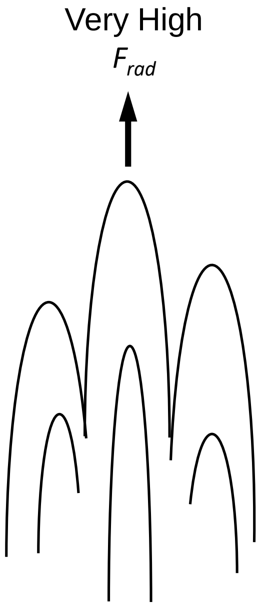
Active flow **+** **Active vent**

$$Q_{rad\,(\lambda),i} = \sum_{i=1}^{i=n} \frac{c_1 \varepsilon}{\lambda^5} \left((1-f) \frac{A_i}{\left(e^{c_2/\lambda T_{crust}} - 1\right)} \right) + \left(f \frac{A_{i,crack}}{\left(e^{c_2/\lambda T_{eruption}} - 1\right)} \right) + Q_{rad\,(\lambda),i2} = \sum_{i2=1}^{i2=n} \frac{c_1 \varepsilon}{\lambda^5} \left(\frac{A_{i2}}{\left(e^{c_2/\lambda T_{crust}} - 1\right)} \right)$$

Cool crust

Crack fraction



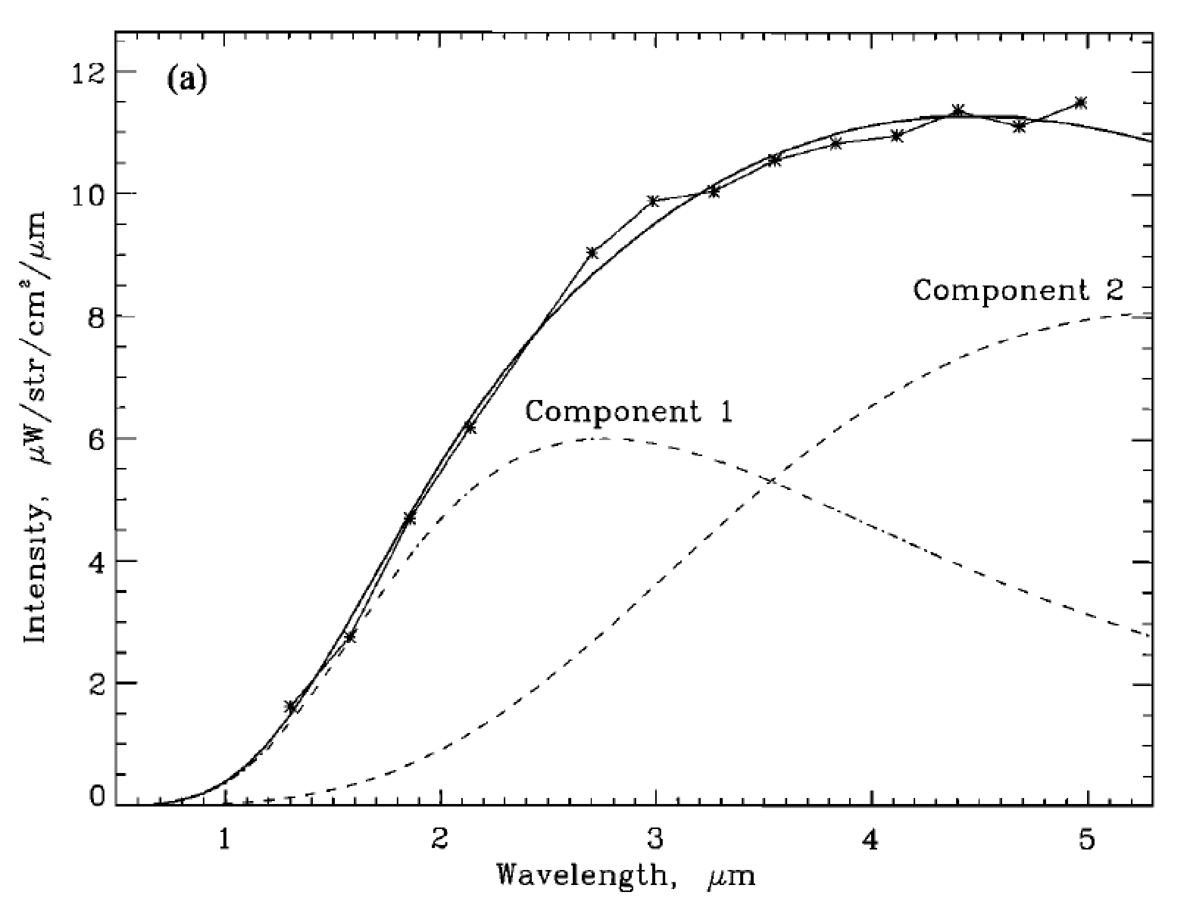


Lava fountains;
Roiling “cauldron”

After Davies (1996, 2007)

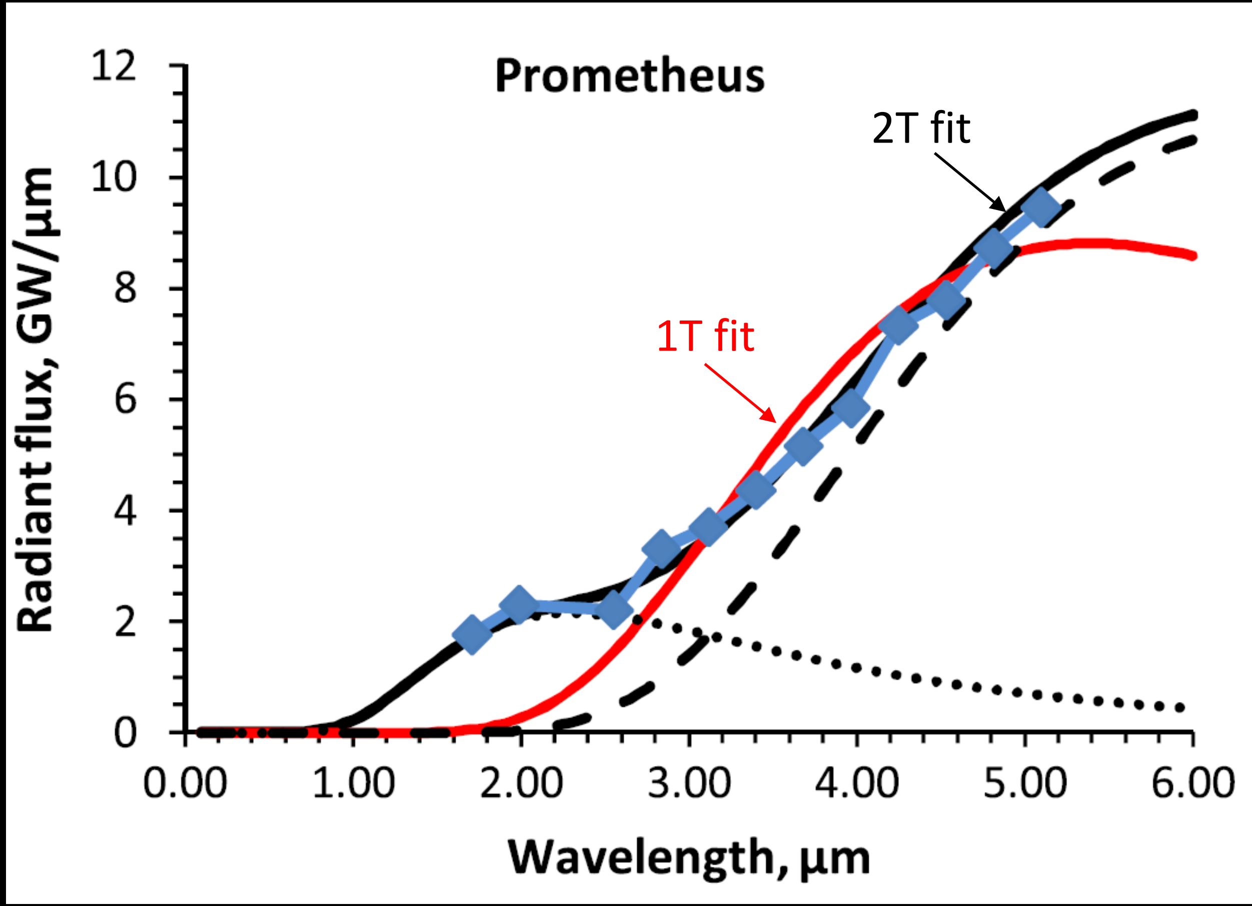
Temp/area model fits to NIMS data

IFM dual-component fit to **Pillan** outburst
Davies et al., 2001, *JGR*



Interpretation – lava fountains feeding expanding flows

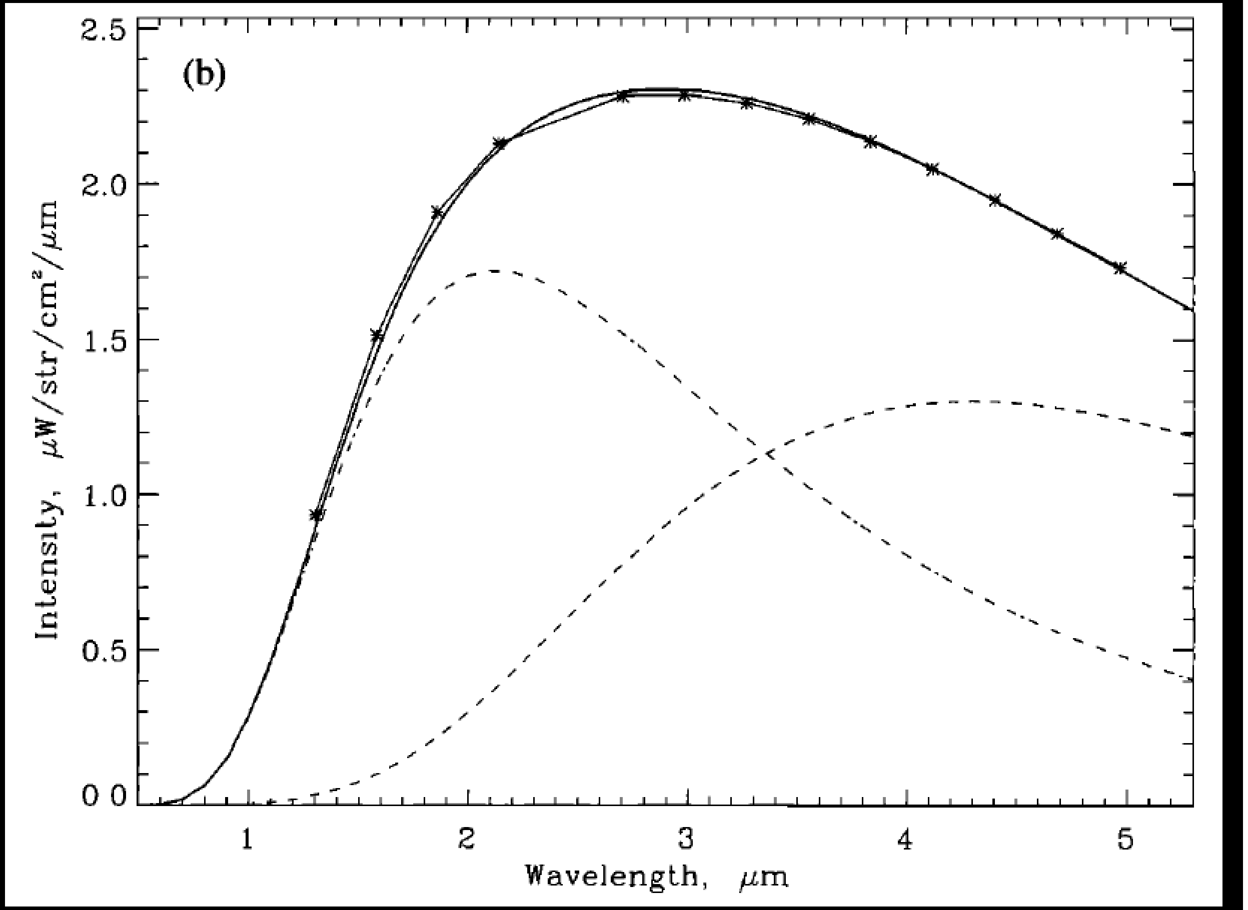
2-T, 2-A fit to **Prometheus** data, G1, June 1996
Davies and Ennis, 2011, *Icarus*



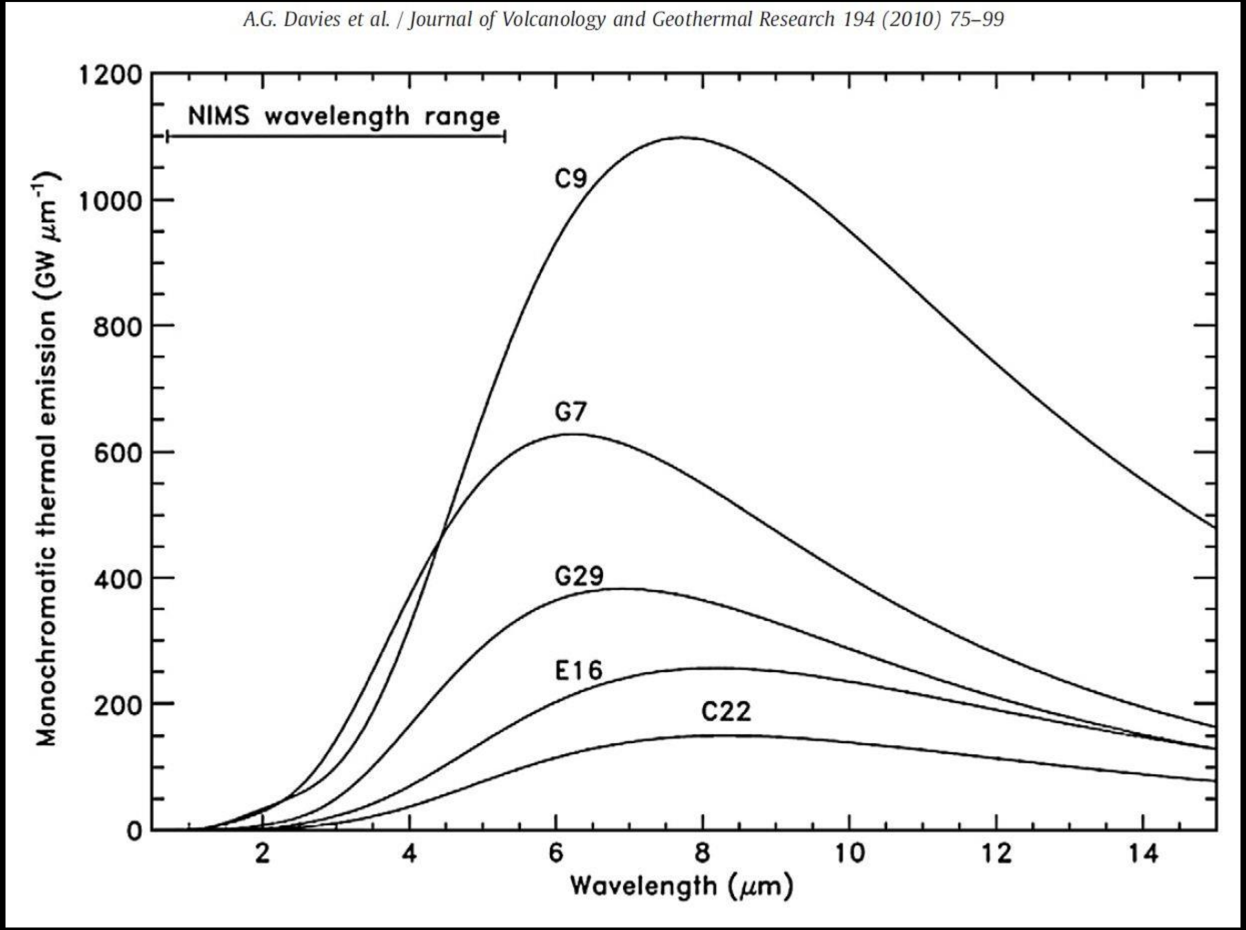
Interpretation – active flows with insulated crusts

Temp/area model fits to NIMS data

IFM dual-component fit to **Pele** NIMS data, 1998
Davies et al., 2001, *JGR*



Variable spectra of **Loki Patera** in NIMS data – 2T fits
Matson et al., 2006, *JGR;* Davies et al., 2010, *JVGR*

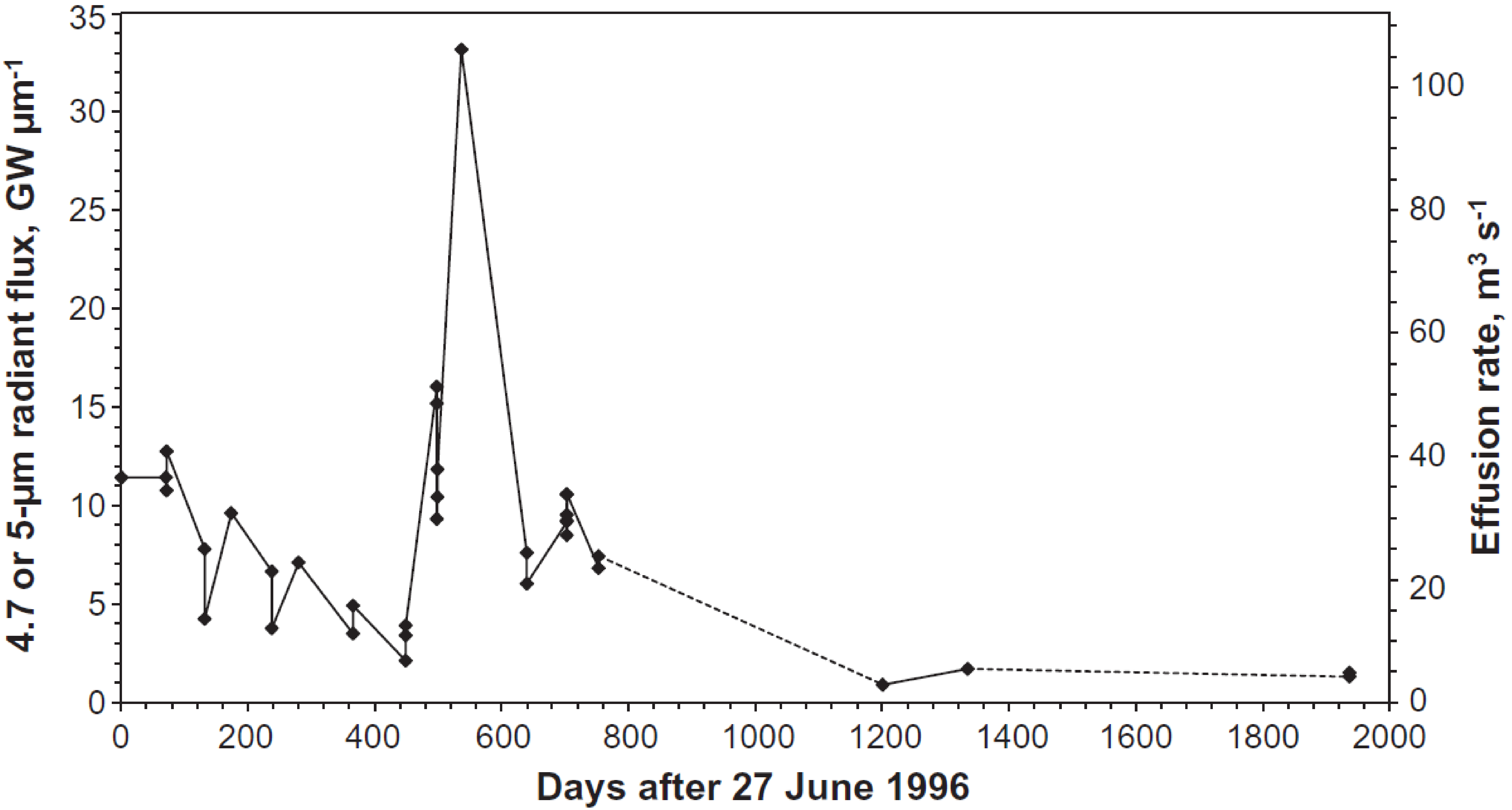


Interpretation – active, overturning lava lake –
Spectral signature similar to terrestrial lava lakes

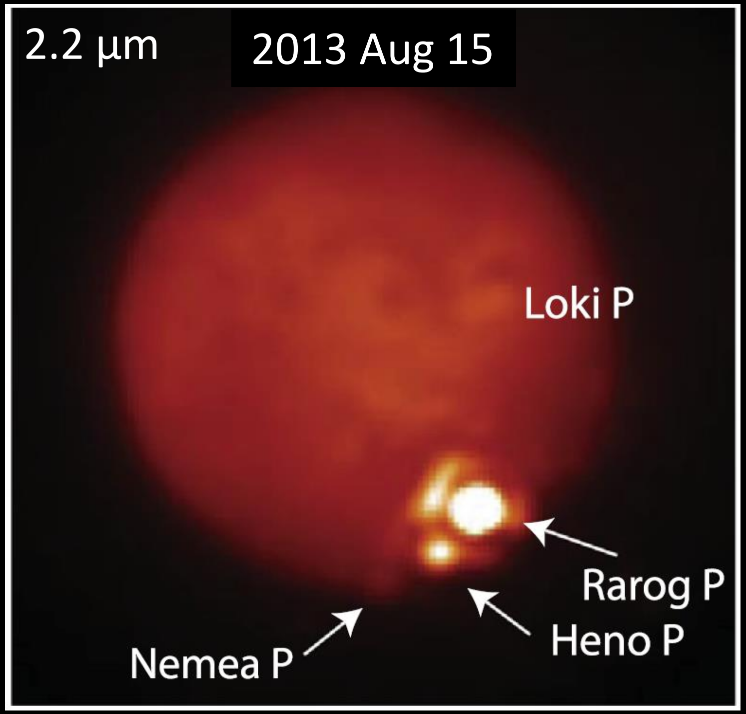
Interpretation – periodic, quiescently overturning lava lake
e.g., Rathbun et al., 2002; Davies, 2003; de Kleer et al., 2017

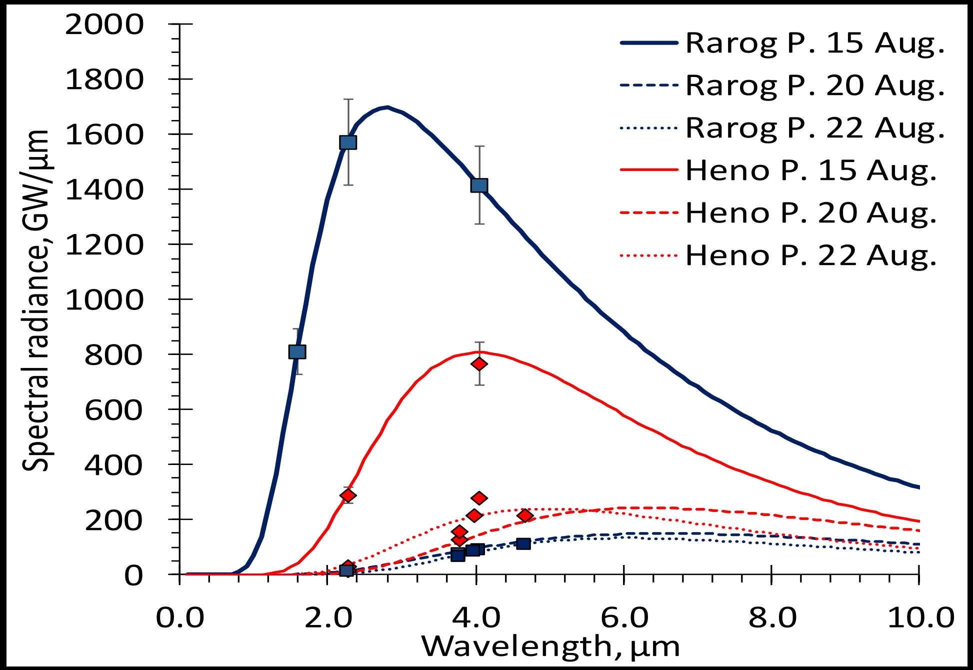
A.G. Davies, M.E. Ennis / Icarus 215 (2011) 401–416

Zamama – *Galileo* NIMS data



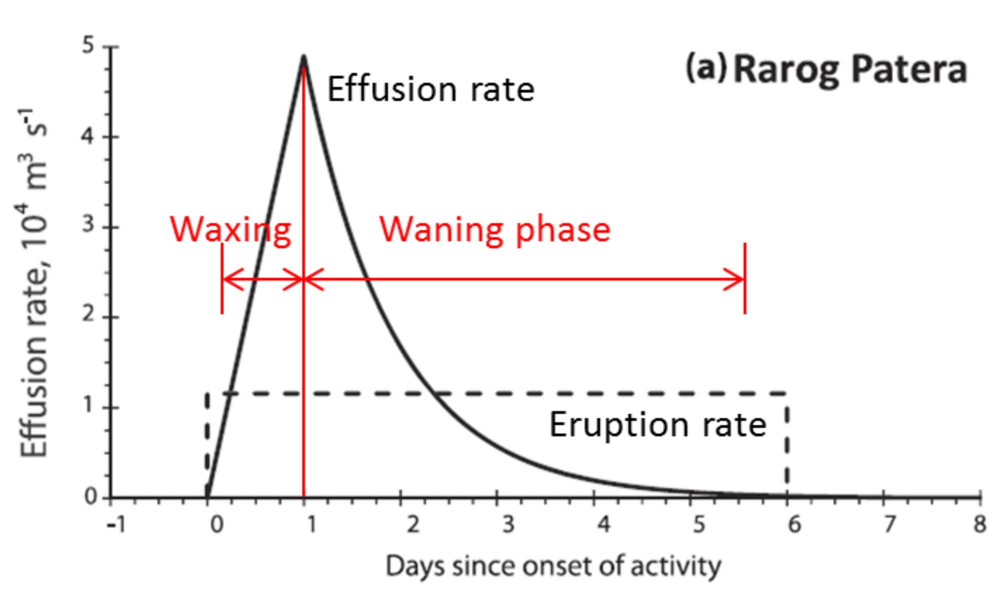
AO-detected outbursts – Rarog and Heno Paterae

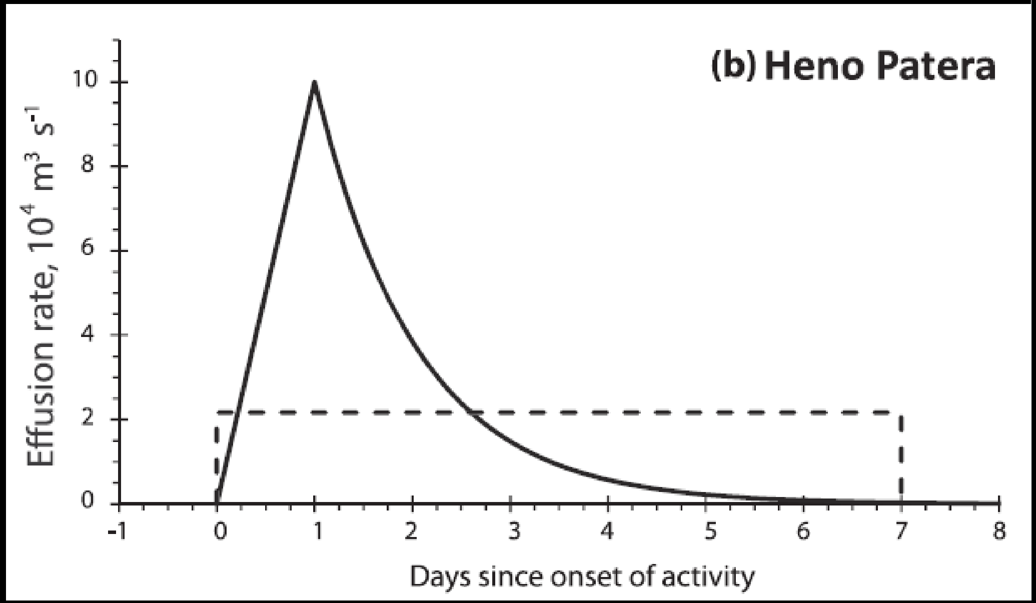




de Pater *et al.* (2014a) *Icarus*

AO-detected outbursts – Rarog and Heno Paterae





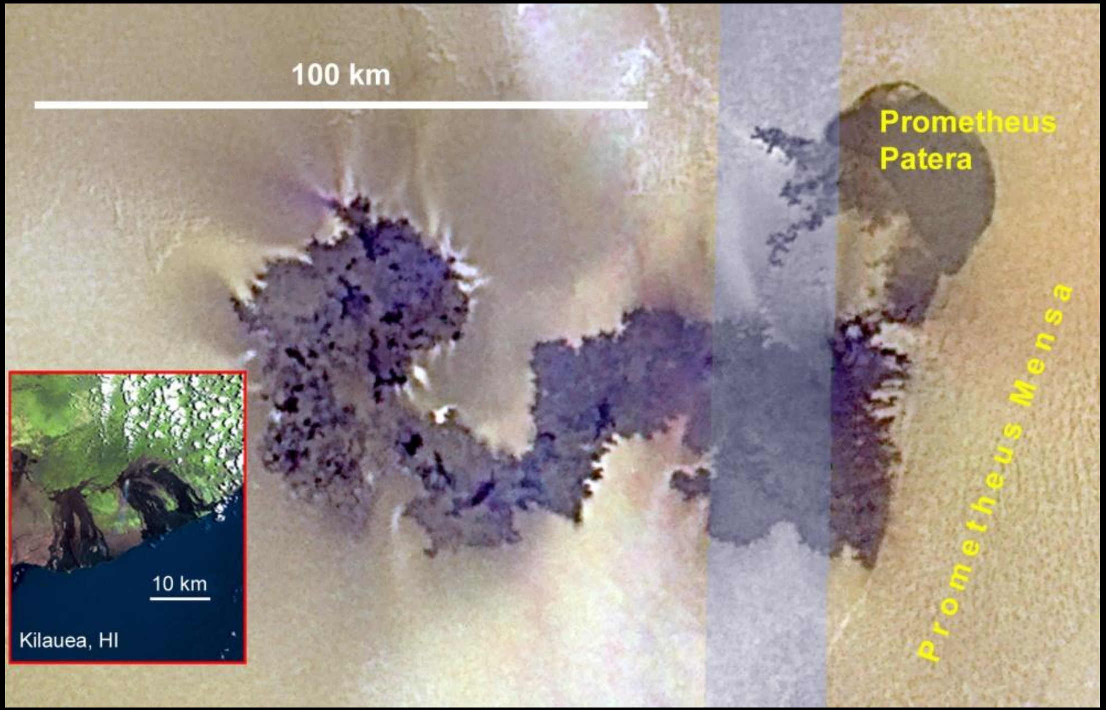
de Pater *et al.* (2014a)

	Duration (days)	Area covered (km^2)	Volume erupted* (km^2)	Peak Q_f (m^2)	Q_e (m^2)
Heno Patera	7	1300	13	10^5	2×10^4
Rarog Patera	6	540	5	5×10^4	10^4

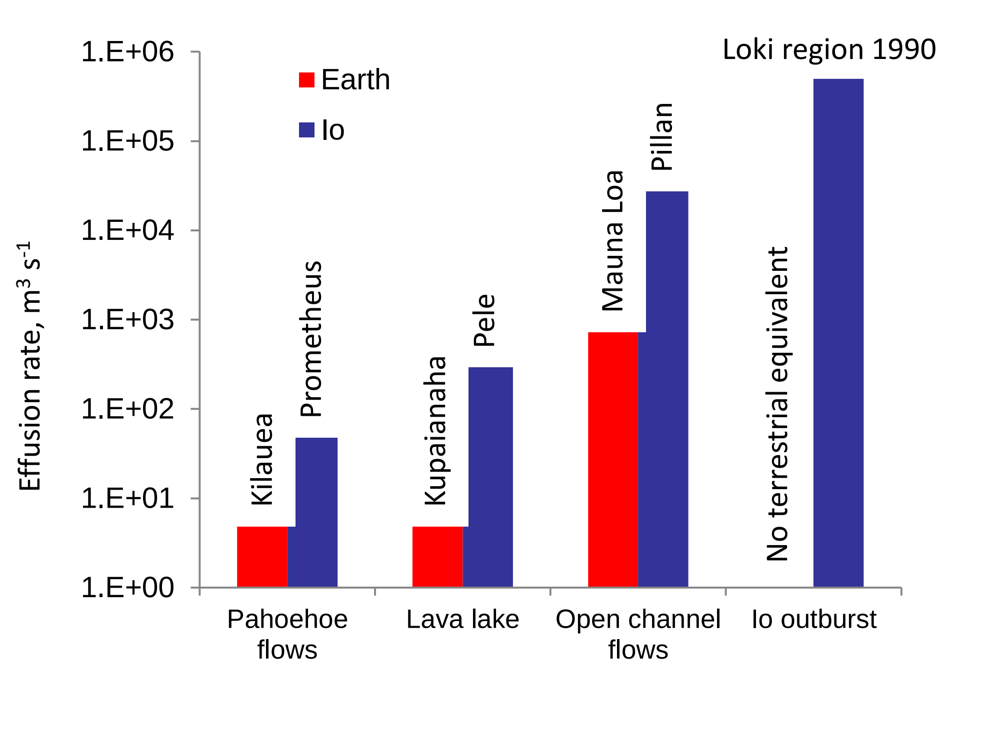
*assuming Pillan-like 10-m thick flows

Io's eruptions take place on scales that dwarf contemporary eruptions on Earth.

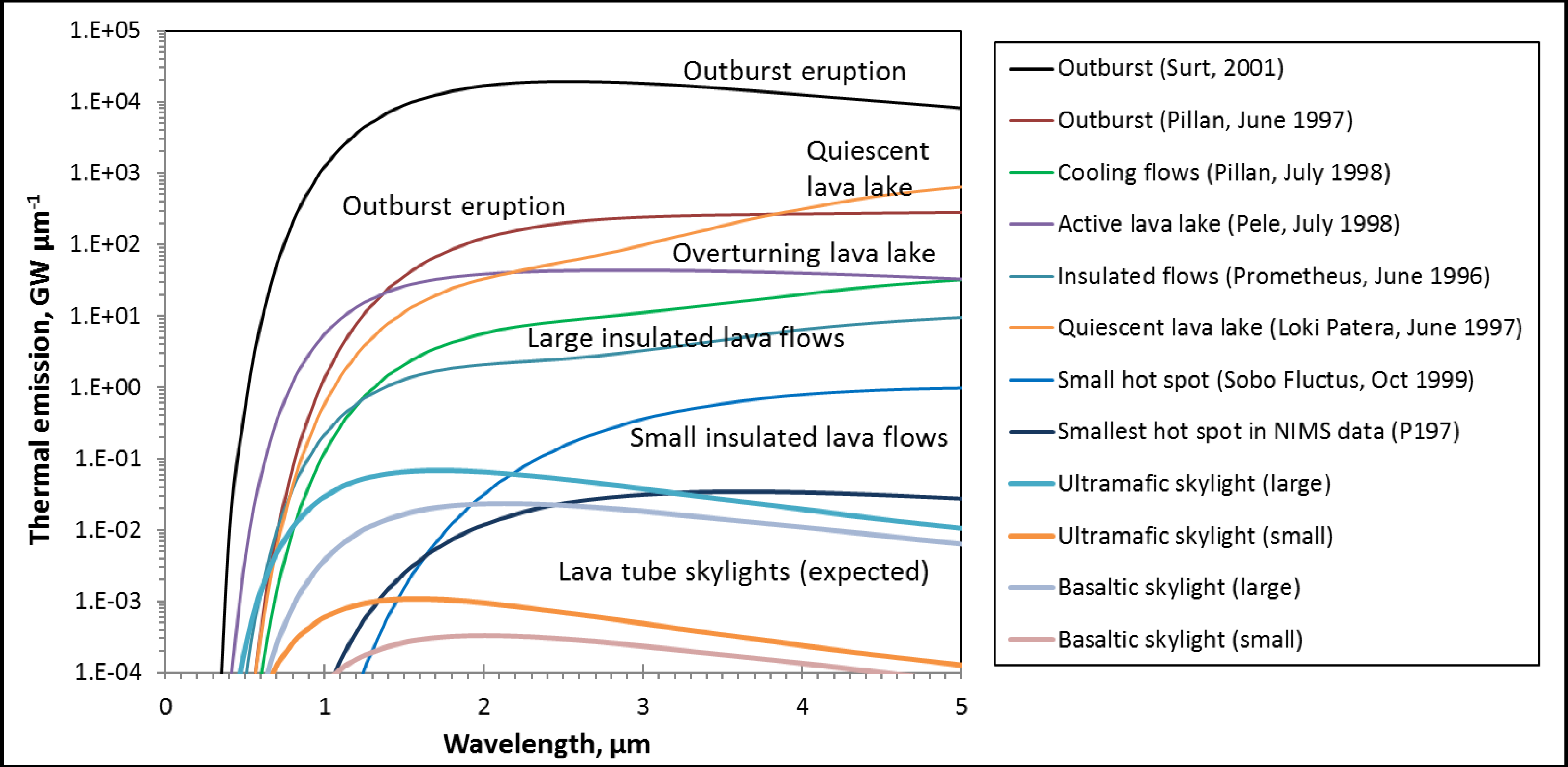
20 years of activity at Prometheus and Kilauea



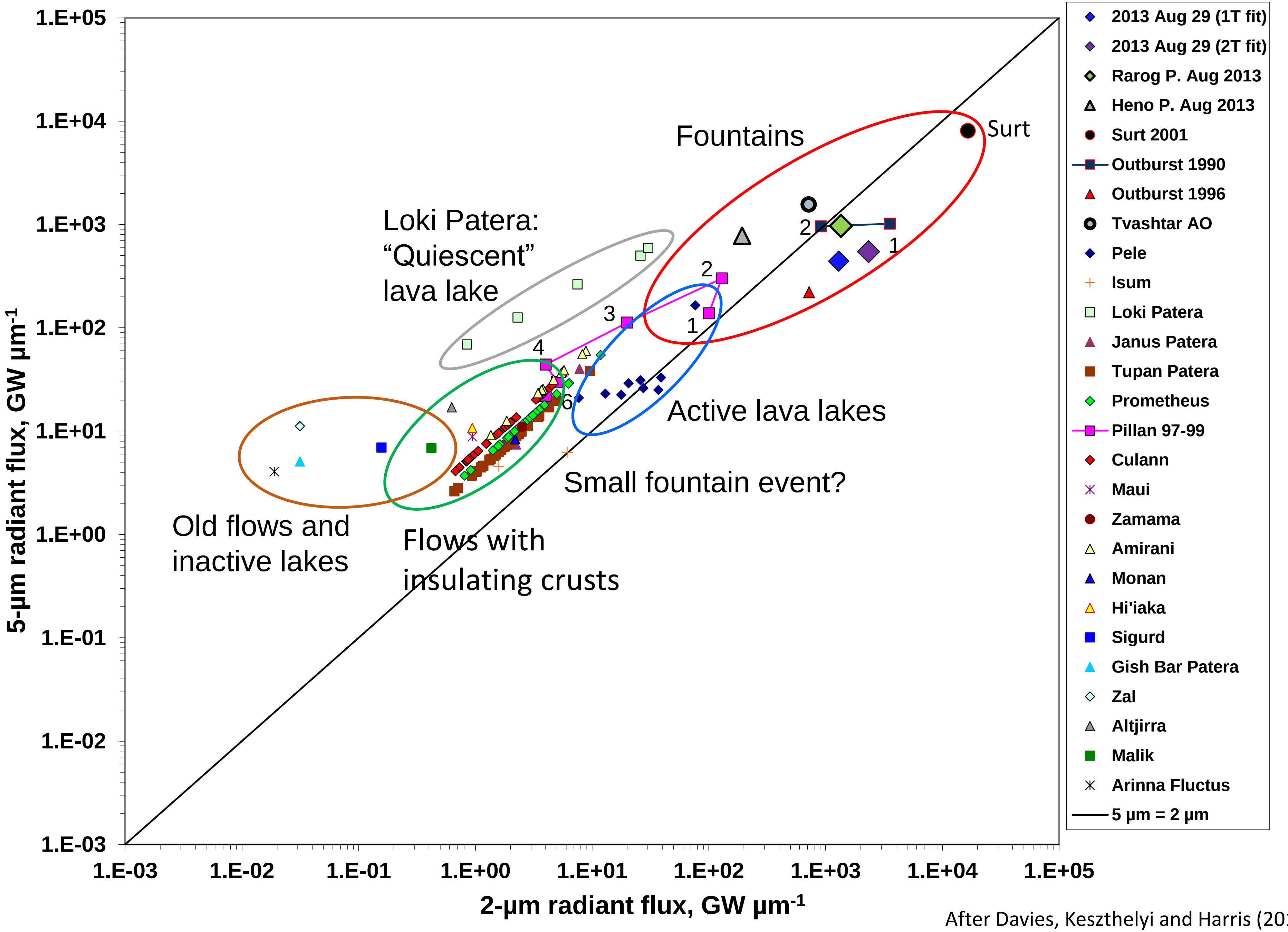
Effusion rate comparisons – contemporary eruptions



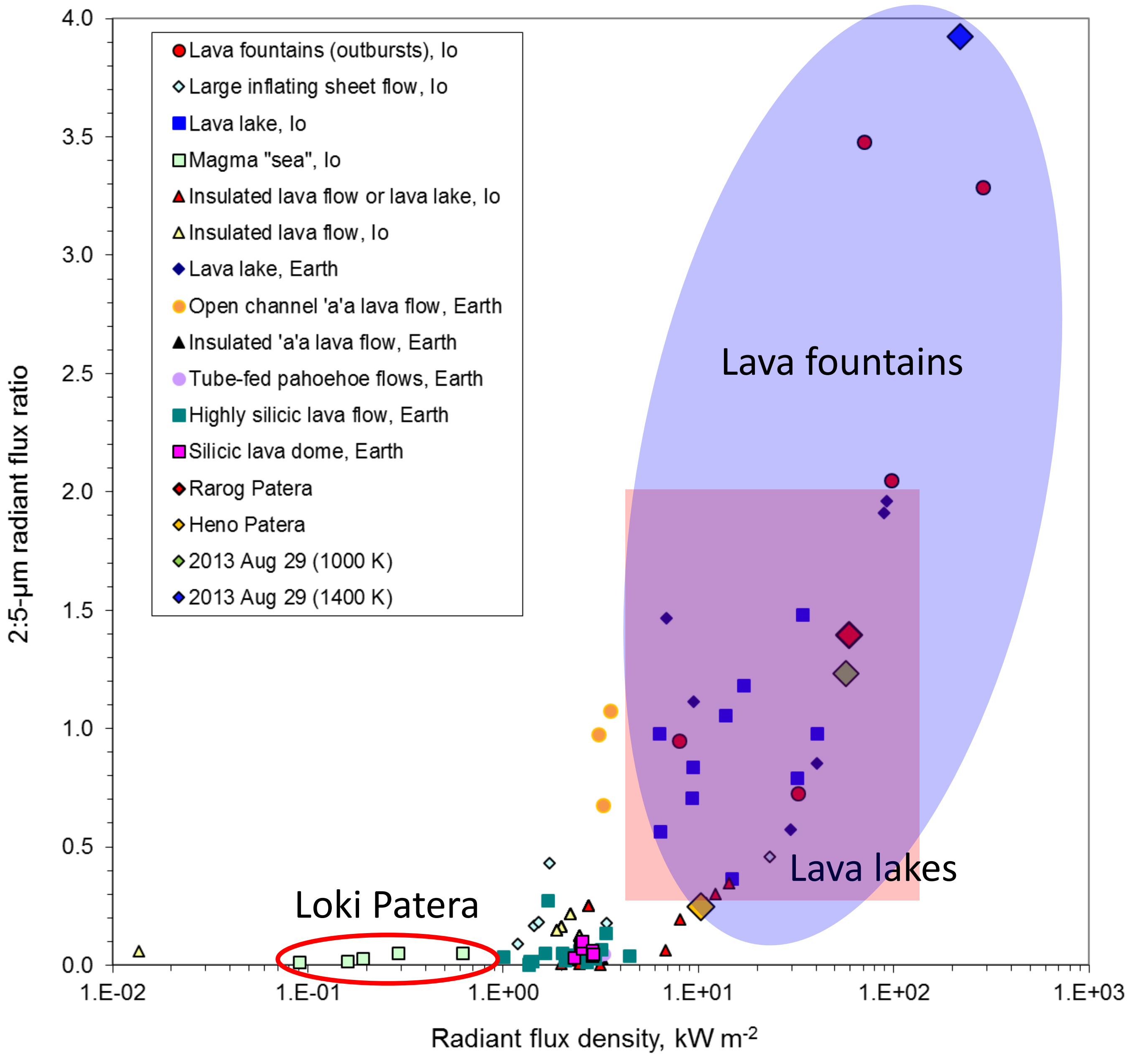
Io: volcanic IR thermal emission



Davies et al. (2017) *JVGR*



After Davies, Keszthelyi and Harris (2010)



After Davies, Keszthelyi and Harris (2010) *JVGR*

Style of volcanic activity and derivation of T_{erupt}

Credit: Katia Kraft

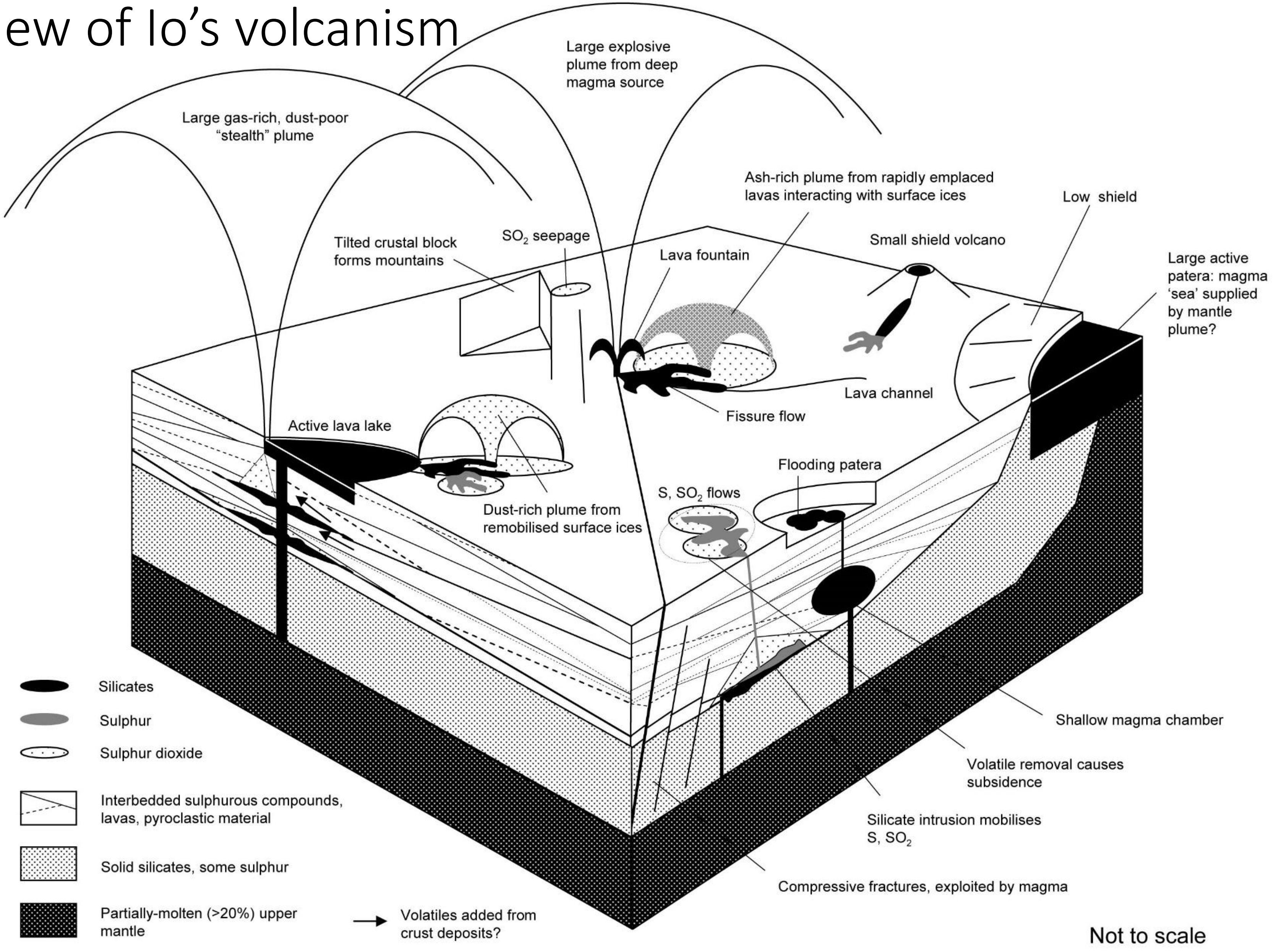
Credit: USGS

Credit: Olivier Grunewald/Boston.com

Davies et al. (2018) *GRL*

Credit: Robert Citron (Smithsonian Institution)

Post-*Galileo* view of Io's volcanism

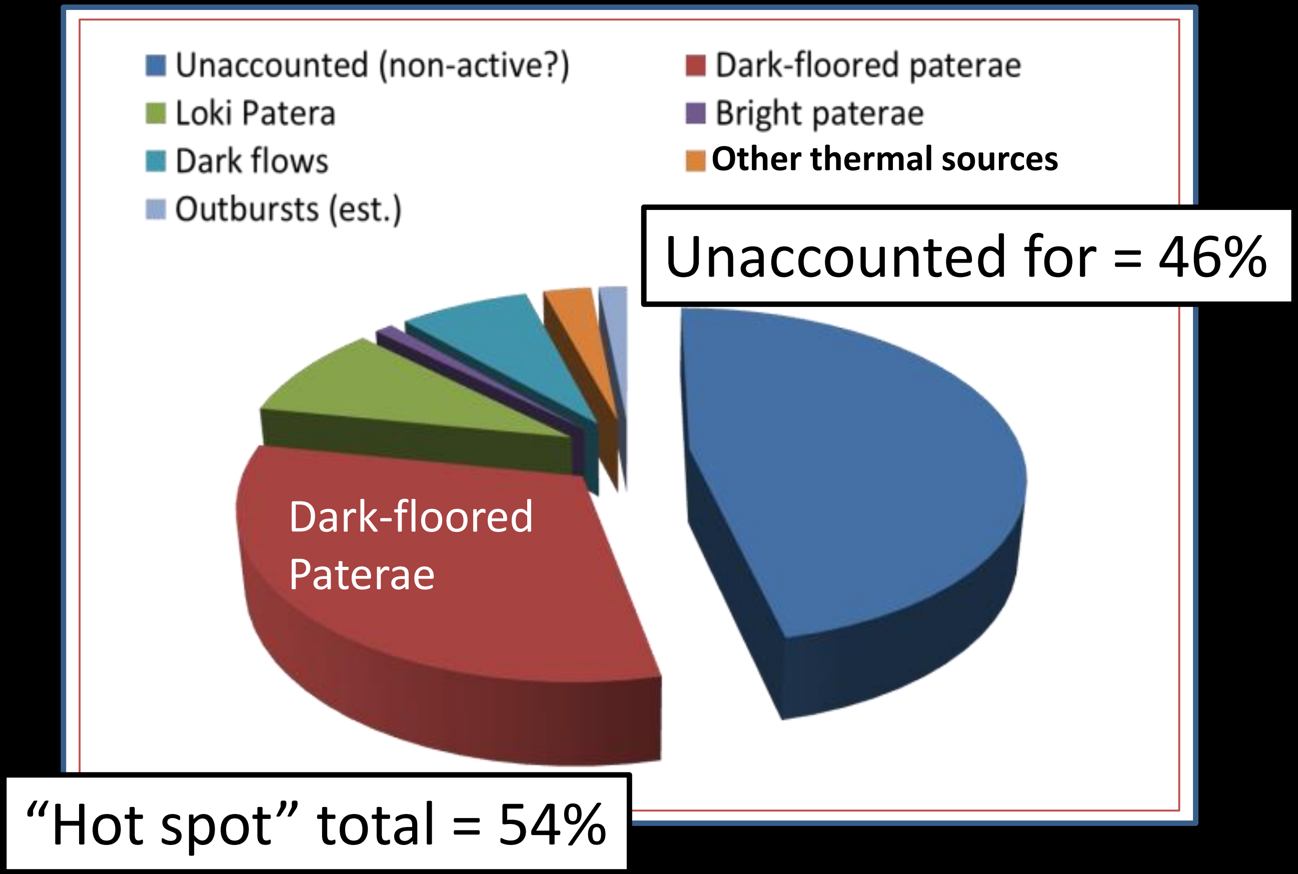


Davies (2007) *Volcanism on Io,* p289

Heat Flow – follow-up

Heat flow from Io’s volcanoes: 250 sources

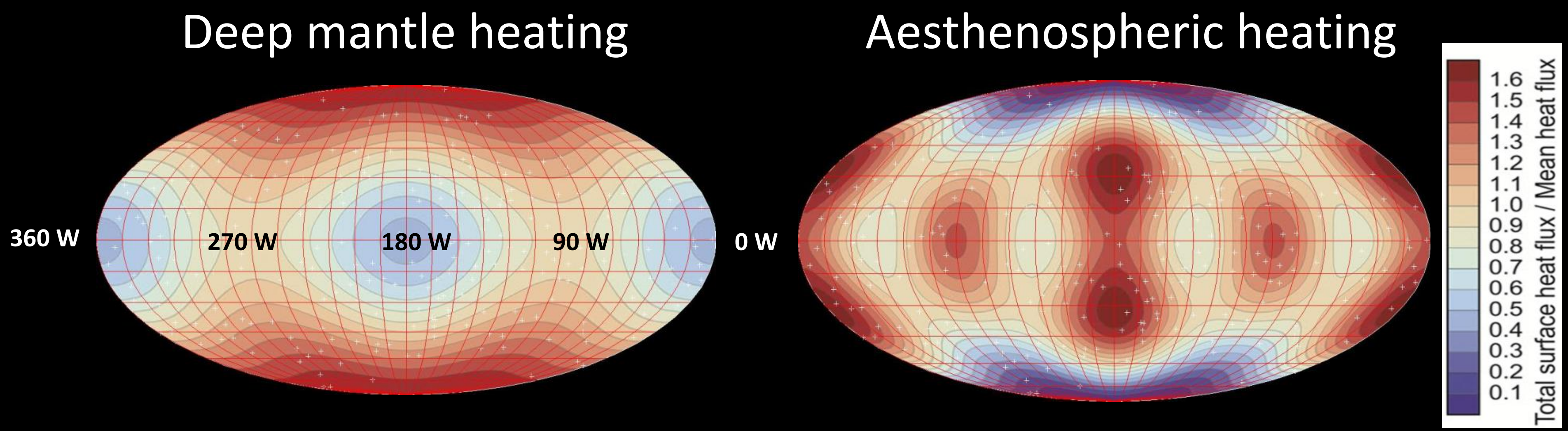
Io’s global heat flow: $1.05 \pm 0.1 \times 10^{14}$ W (Veeder *et al.*, 1994, 2012)



Data from Veeder *et al.* (2015)

Tidal heating and surface heat flow

End member cases (Segatz *et al*., 1988; Ross *et al.,* 1990)

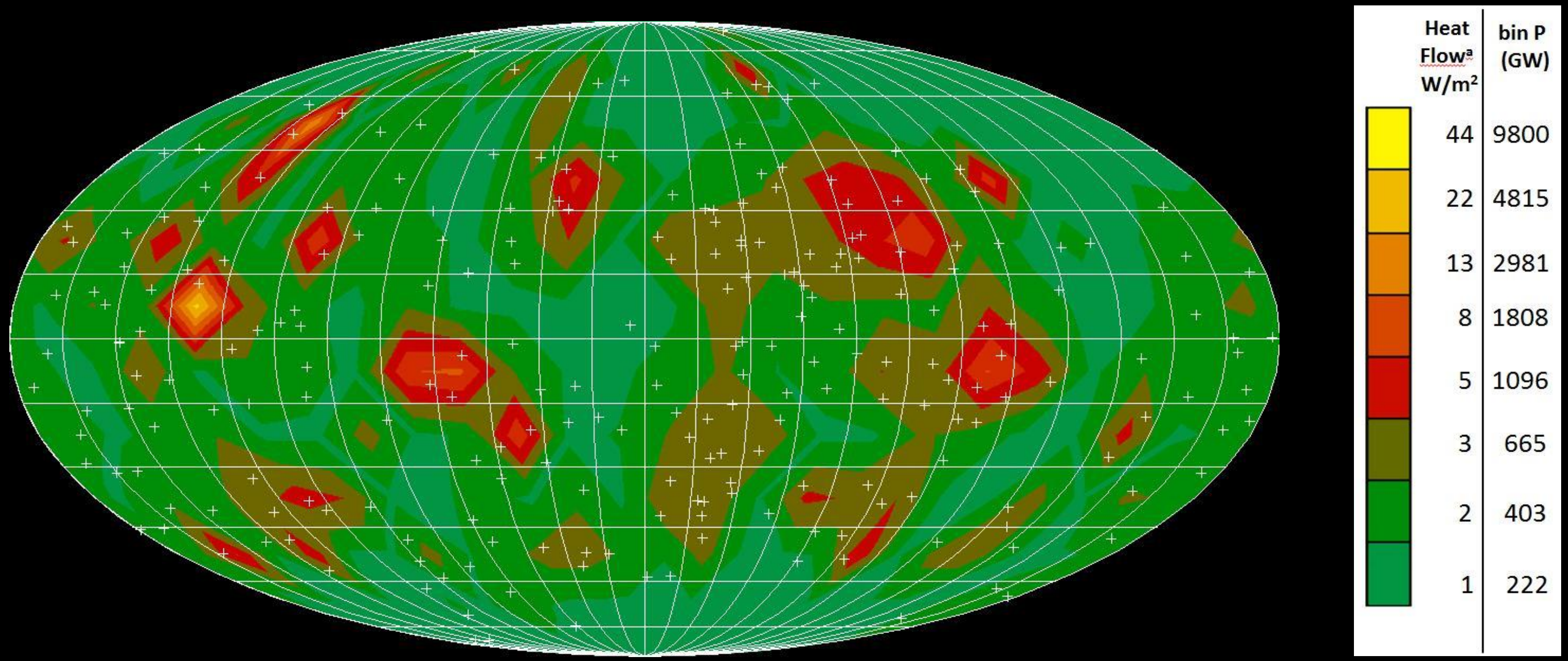


After Hamilton *et al.* (2013)

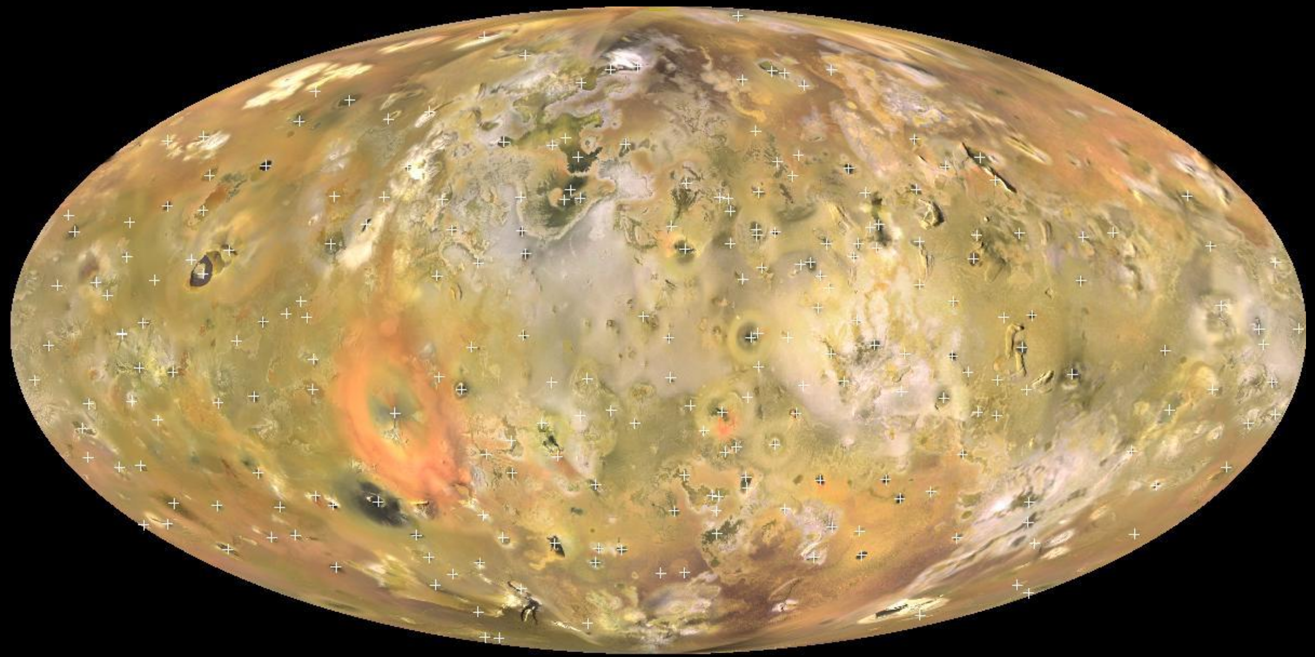
Realistically, a mixture of deep and shallow heating is probably required

e.g., Tackley *et al.,* 2001; see Hamilton *et al.* (2013) for 1/3 deep. 2/3 shallow case

Heat flow map (centre lon. 180° W)



15° bins



Io’s average heat flow

Average active area volcanic heat flow (2% of Io) ≈ 68 W/m^2

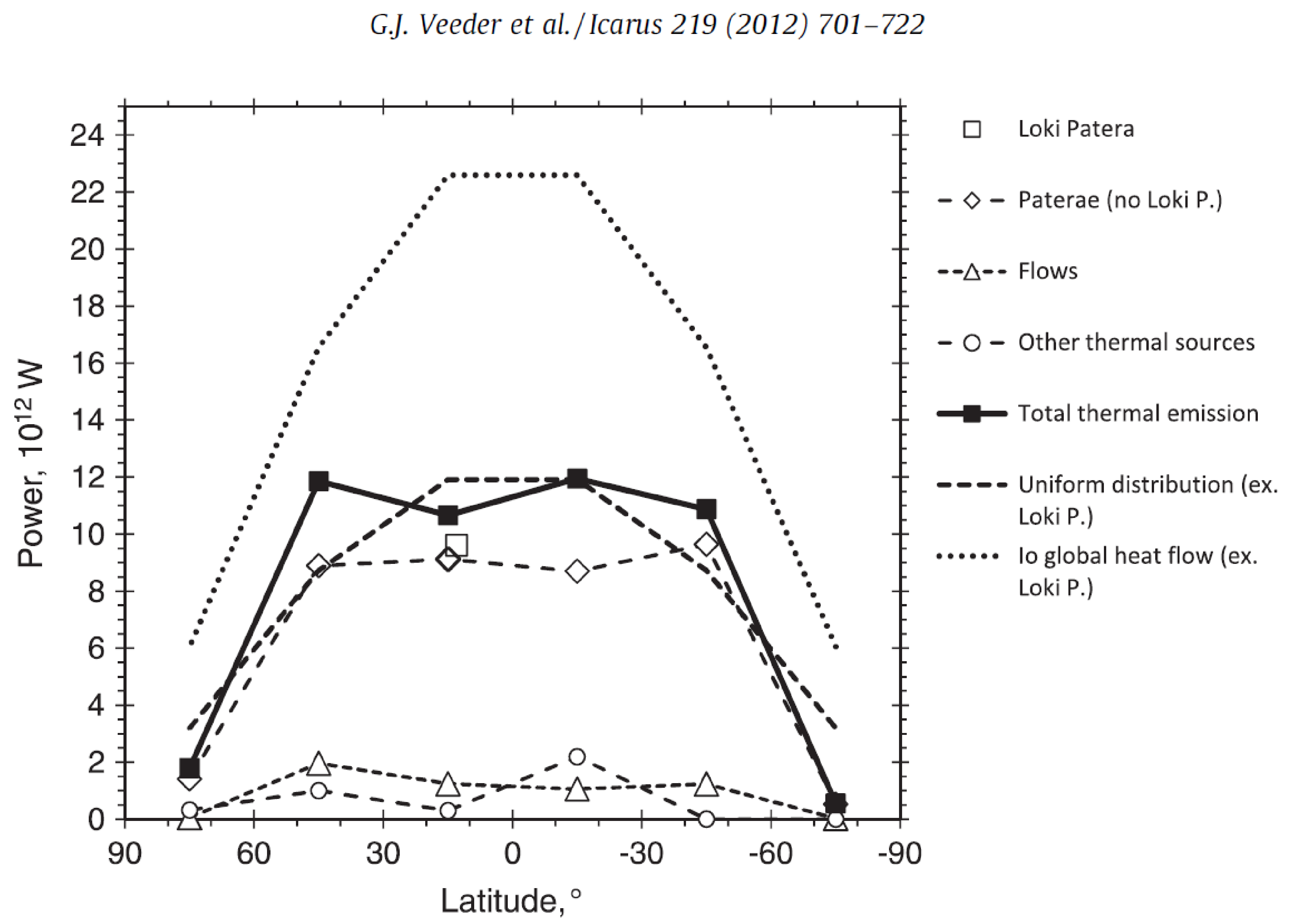
What of the 46% “unaccounted” heat flow?

Spread evenly across Io, this equals 0.98 ± 0.05 W/m^2

- Earth = 0.07 W/m^2
- Moon = 0.03 W/m^2

This value of 0.98 W/m^2 is used to set the base heat flow for the heat flow map

Veeder et al. (2012, 2015) Io volcanic heat flow distribution



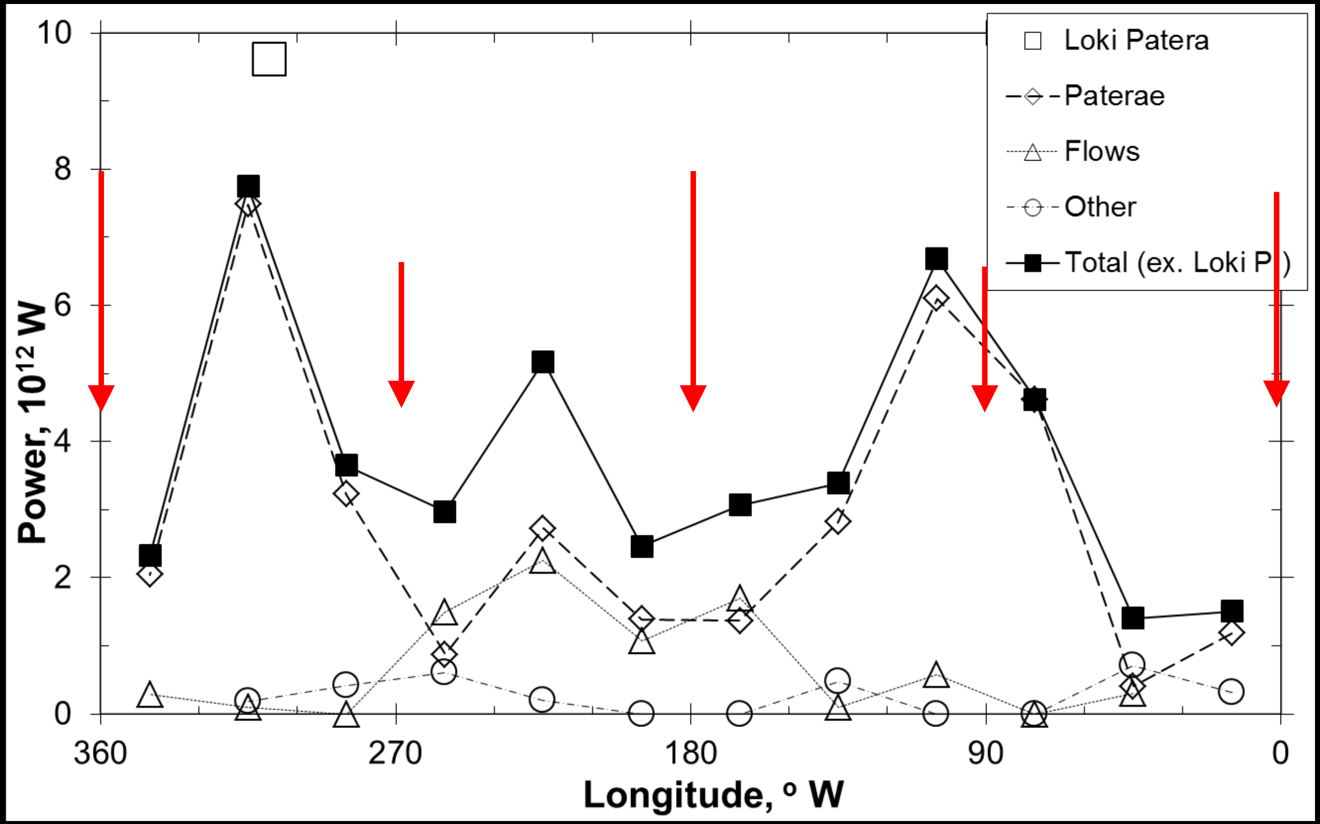
Preponderance of thermal emission towards lower latitudes

Slightly more thermal emission in N hemisphere (not including Loki Patera)

Favours aesthenospheric tidal heating

Distribution of volcanic thermal emission

as measured by Veeder et al., 2012, 2015.



Base image: Veeder *et al.* (2015)

Thermal emission from large lava fields – single peak at ~220° W.

Dark paterae in a bimodal distribution dominate thermal emission

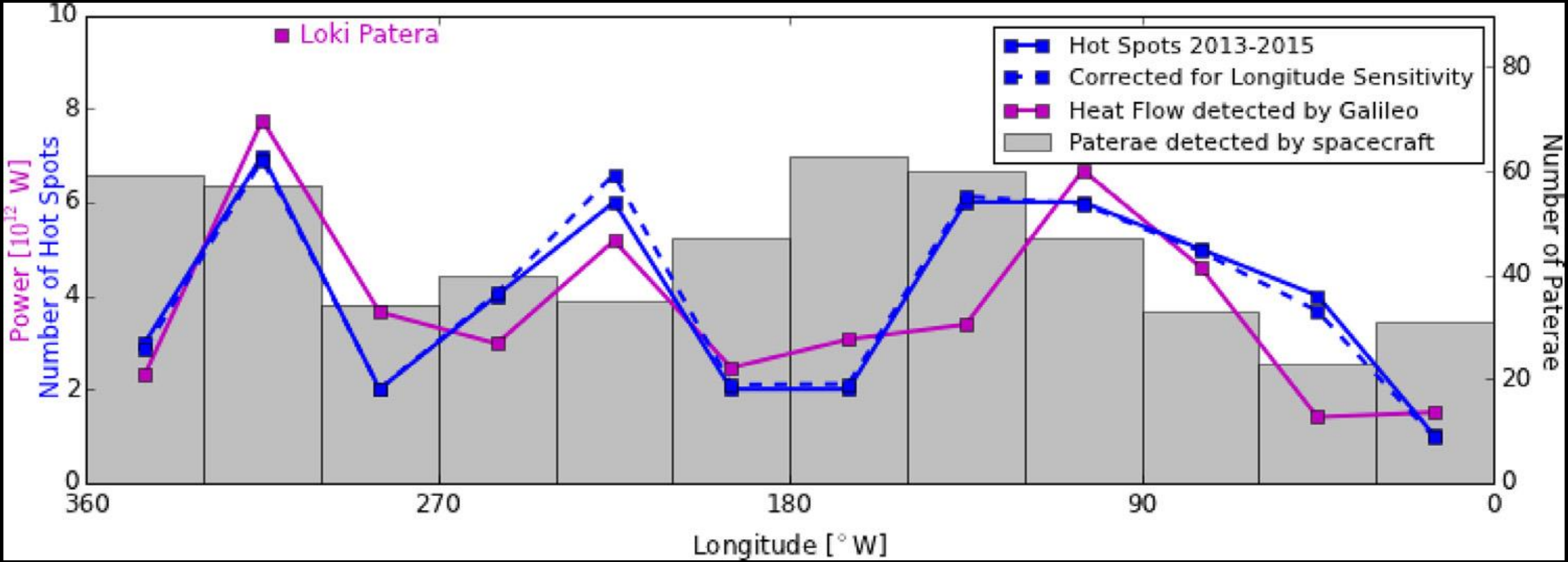
Total thermal emission peaks at ~315° W and ~105° W.

This is a shift eastwards from that expected from aesthenospheric heating

Hamilton et al. (2013) found the same shift from studying volcanic features; partly mitigated by lateral movement of melt (Tyler et al., 2015)

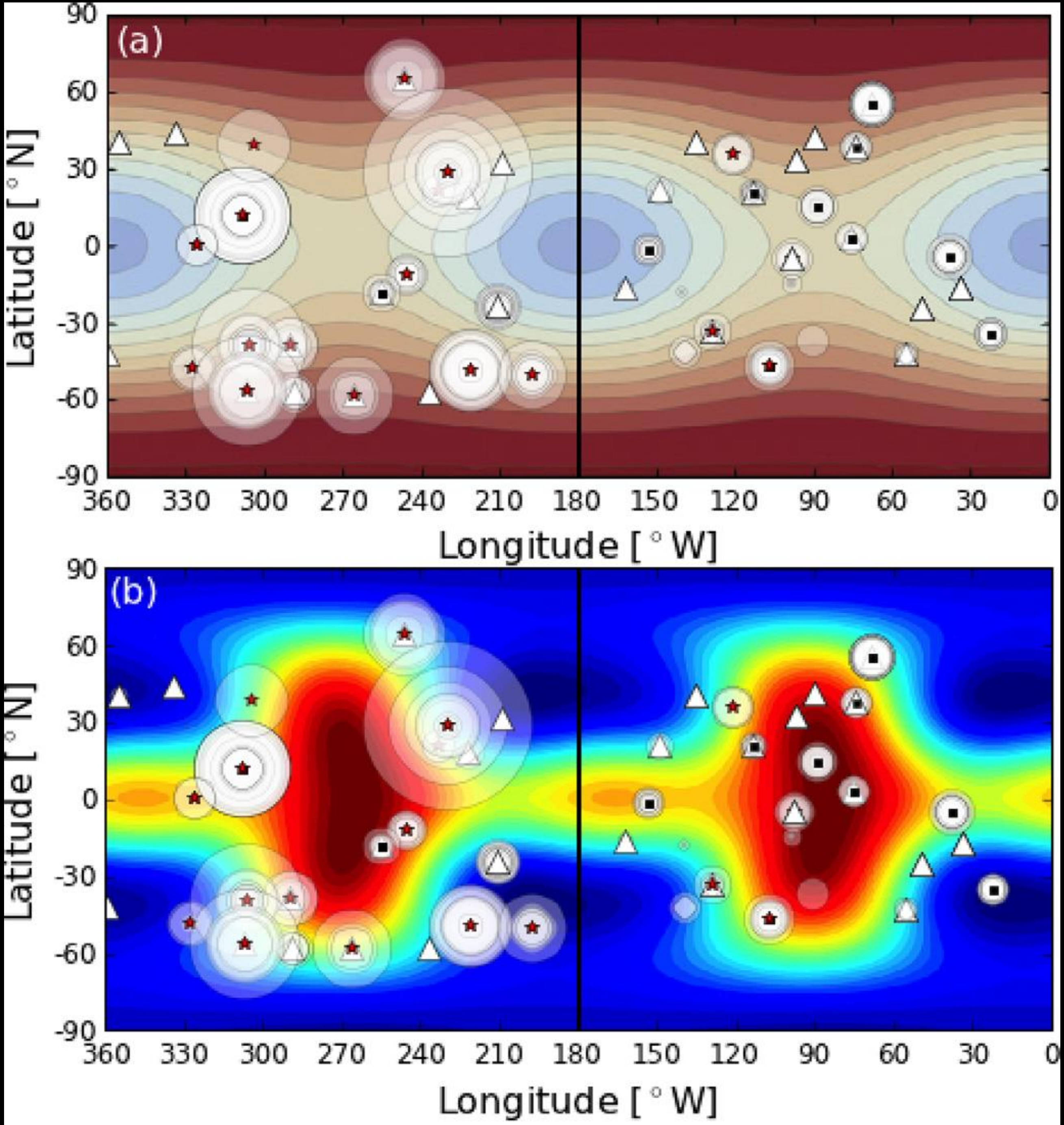
Minimum at ~200° W is real – area is well imaged

Minimum at 345° W to 45° may be real as imaging is low resolution



Blue lines = Ground-based telescope-derived volcanic thermal emission; de Kleer and de Pater (2016);
Purple lines = *Galileo*-derived heat flow; Veeder et al. (2012)
Histogram = Paterae; Hamilton et al. (2013)

"The mismatch between the 2013–2015 hot spot numbers and the *Galileo* power measurements (blue and purple lines) from 120 °to 150 °W may be due to the particularly high concentration of low-intensity hot spots in this region.
de Kleer and de Pater (2016) Icarus, 260, 405-414."



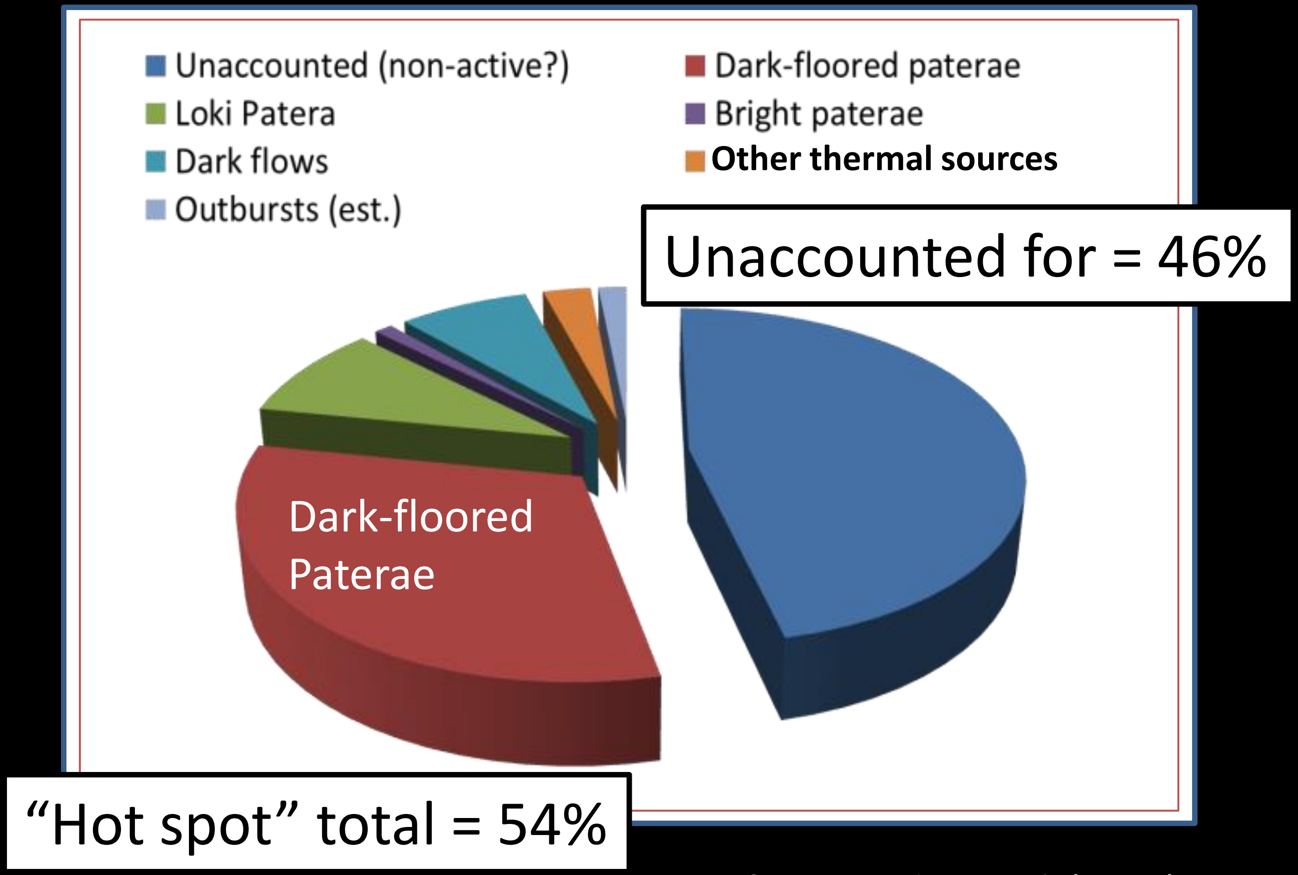
Ground-based detections of medium to large volcano thermal emission plotted on the deep-mantle tidal heating model.

Shallow tidal heating model with a partially-fluid interior, base image from Tyler et al. (2015).

de Kleer and de Pater (2016) Icarus, 260, 405-414.

Heat flow from Io's volcanoes: 250 sources

Io's global heat flow: 1.05 ± 0.1 x 10^{14} W (Veeder *et al.*, 1994, 2012)



Data from Veeder *et al.* (2015)

"Unaccounted" possibilities - (Veeder et al., 2012)

Old, cool flows not imaged by PPR

"Layer cake" lava flow stacks

Shallow intrusions, releasing heat slowly at the surface

Low-temperature surface activity (S, SO_2)

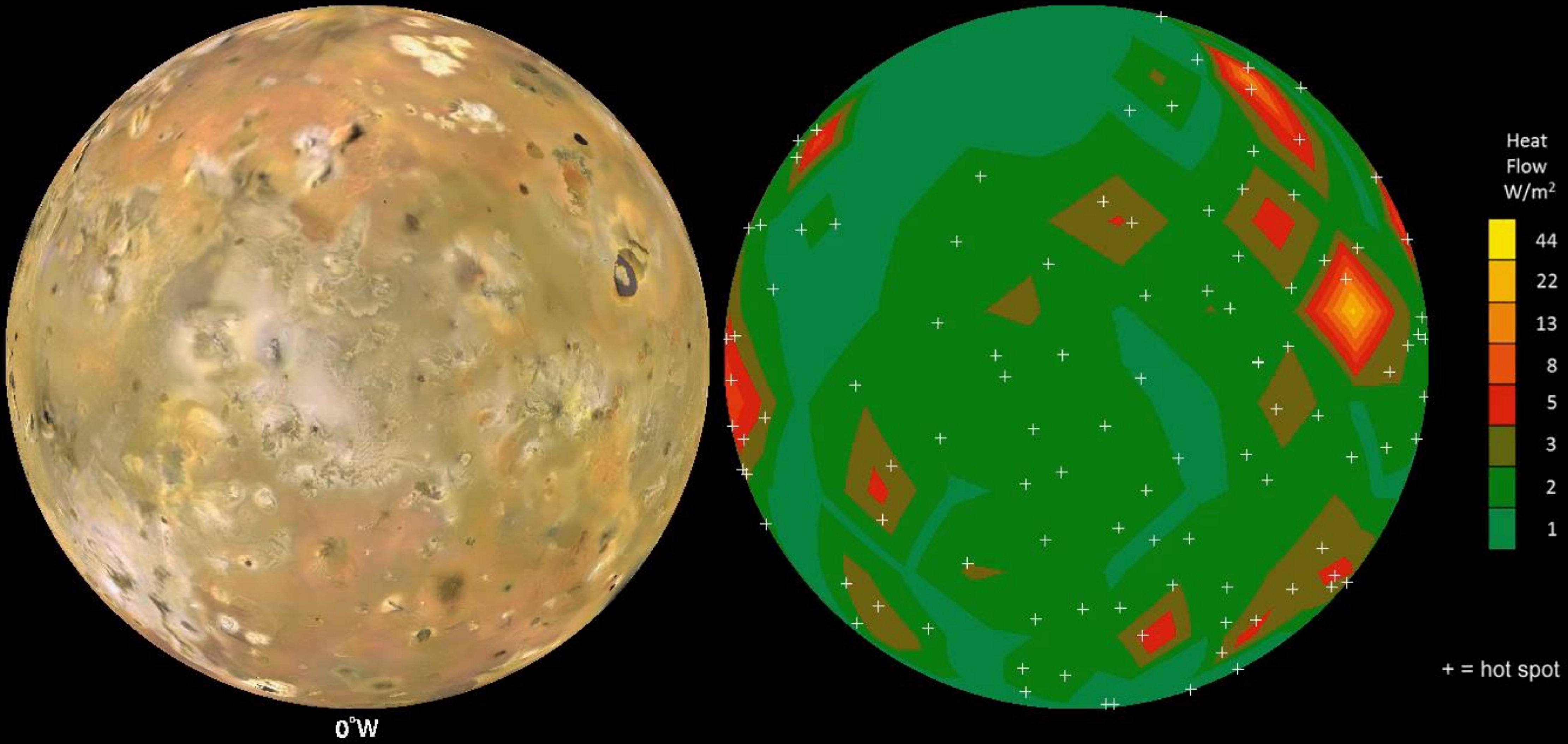
Very small thermal sources

Low T volatile movement (e.g., "stealth" plumes)

Poorly imaged polar heat flow (see Matson et al., 2004)

Questions

- Can we be sure that the observed distribution of volcanism reflects the distribution and magnitude of tidal heating?
- What is the dominant composition of Io’s lavas, and does this change with location?
- Is volcanic activity tidally controlled at a local or regional level?
- What constraints on interior modelling can be met through remote sensing, both from the ground and from spacecraft?
- What of the “unaccounted for” heat flow? (e.g., low temperature S, SO_2 volcanism, not observed by *Galileo* – see Veeder *et al.,* 2012, 2015)
- What causes the offset in heat flow?
  - no mix of deep and shallow heating can account for the offset
  - lateral melt movement is only partial solution



Data: Veeder et al. (2015) *Icarus* – Excel spreadsheet available in Supplementary Material
Movie: Davies et al. (2015) *Icarus* – available in Supplementary Material