Towards a Unified Theory for
Pre-Earthquake Signals

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Contents

I'll talk about:

- Stress-activated charge carriers in rocks
- Surface potentials
- Surface electric fields
- Massive air ionization
- "Thermal Infrared Anomalies"

I'll have little or no time to talk about:

- EM emission
- other pre-EQ indicators

The tools familiar to seismologists
are wonderful and powerful,
well suited to study seismic events

…but the tools familiar to seismologists
may not be appropriate to study
non-seismic, non-geodesic

pre-earthquake phenomena

Fundamental Solid State Defect

Oxygen anions in minerals
in igneous and high-grade metamorphic rocks
exist in the valence 1–
(instead of the usual 2–)

instead of $O_3Si\text{-}O\text{-}SiO_3$

there is $O_3Si\text{-}OO\text{-}SiO_3$

Quartz,
feldspars,
pyroxenes,
etc.

Peroxy

Peroxy is a diamagnetic point defect
about 100-1000 ppm

Peroxy is a dormant self-trapped positive hole pair

When stresses are applied, dislocations move

e^-

$$O_3Si/^{OO}\backslash SiO_3 + [SiO_4]^{4-} \rightarrow \{O_3Si/^{O\bullet}{}_{\bullet O}/SiO_3\} \rightarrow O_3Si/^{O\bullet}{}_{\bullet O}/SiO_3 + [SiO_4]^{3-}$$

peroxy link + O^{2-} matrix — broken peroxy link — broken peroxy link + $h^\bullet$

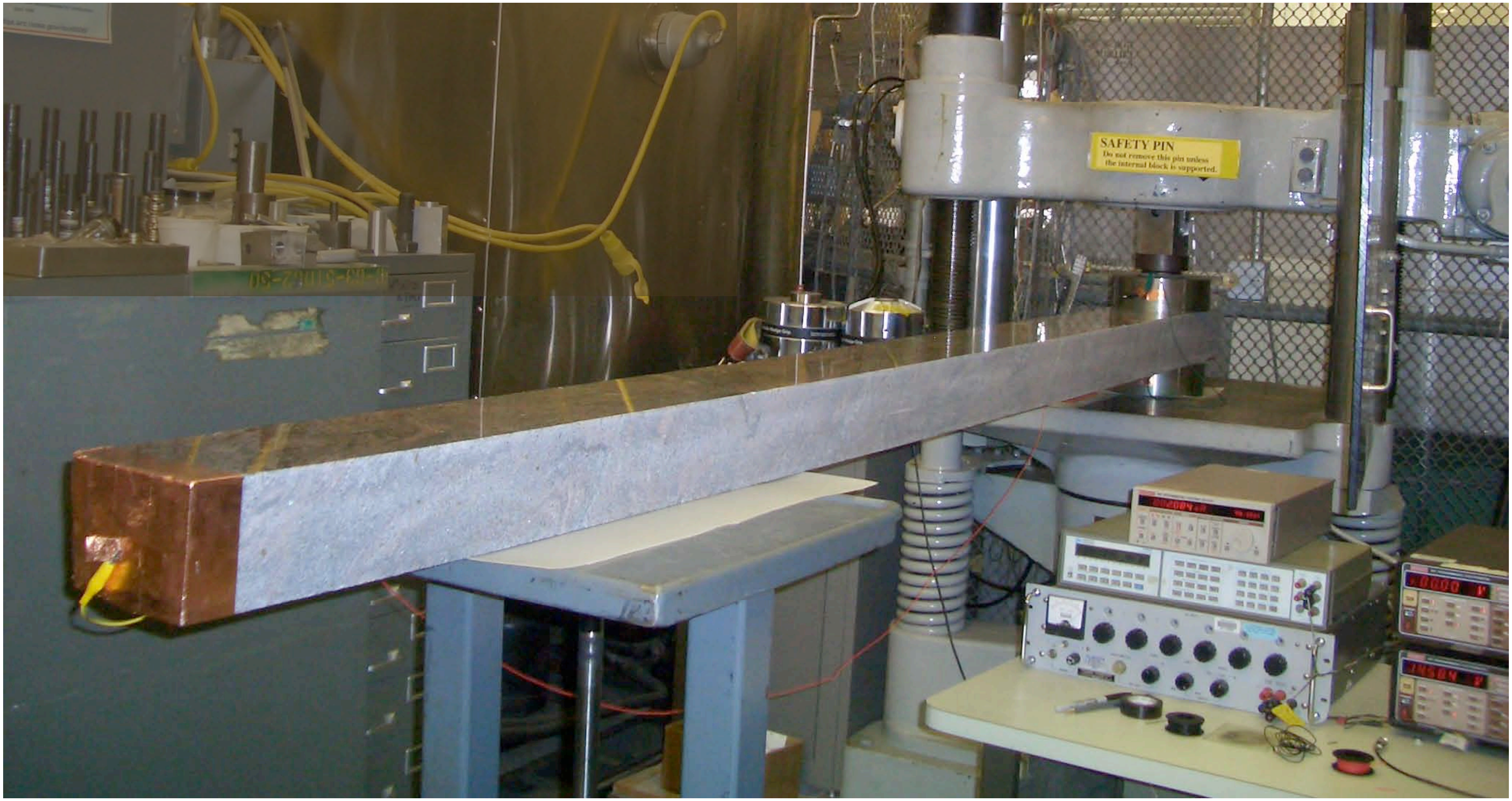
Dislocations cut through grains

Dislocations break peroxy links

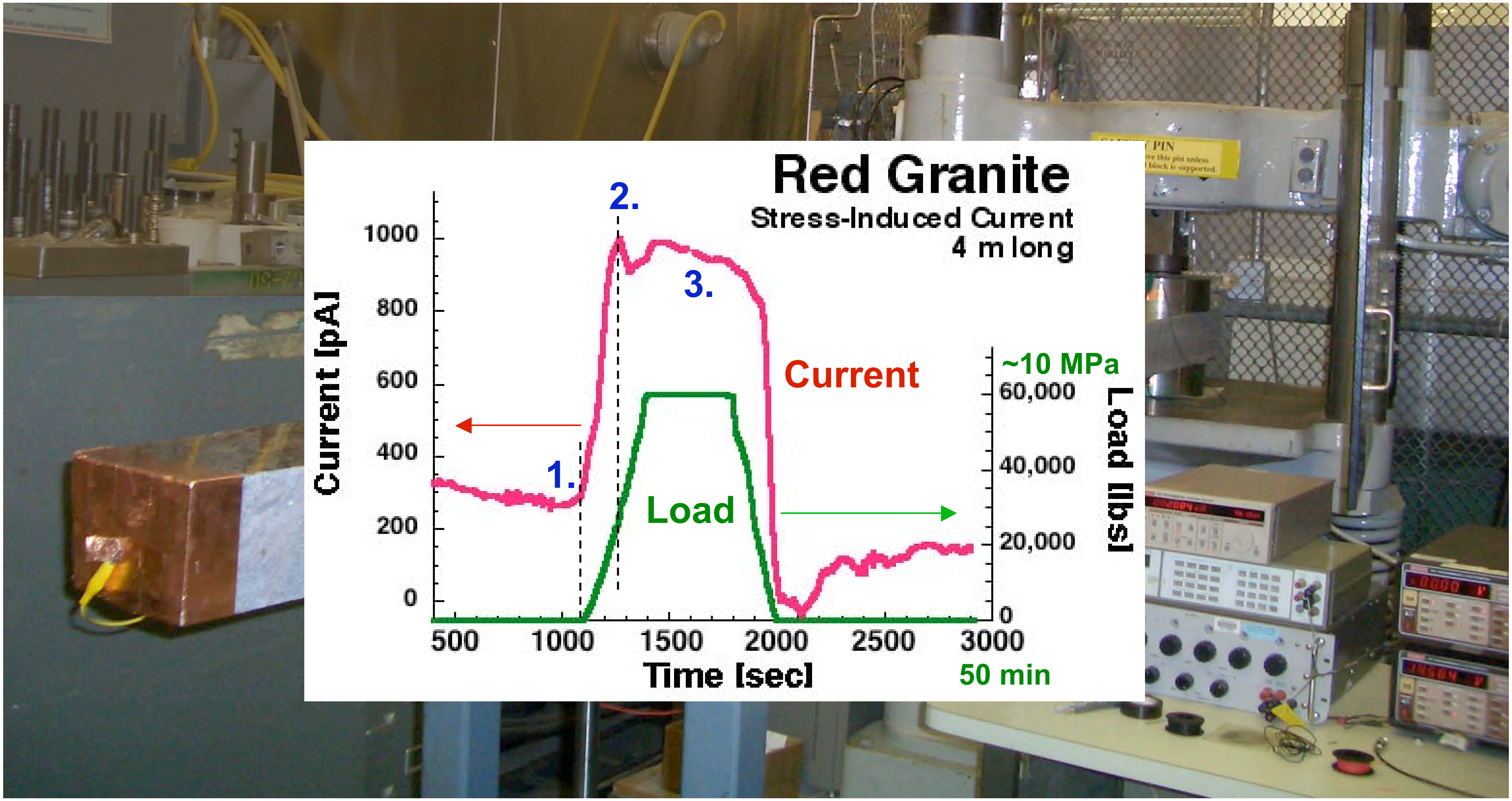
Electron transferred from neighboring O^{2-} generates an O^-

- O^- in a matrix of O^{2-} is a defect electron
- Positive hole or phole for short
- A phole is a positive charge carrier, $h^\bullet$

- $h^\bullet$ reside in the oxygen anion sublattice
- $h^\bullet$ reside in the valence band
- $h^\bullet$ propagate at ~200 m/sec (measured)
- $h^\bullet$ travel fast and far
  – meters in the lab, kilometers in the field

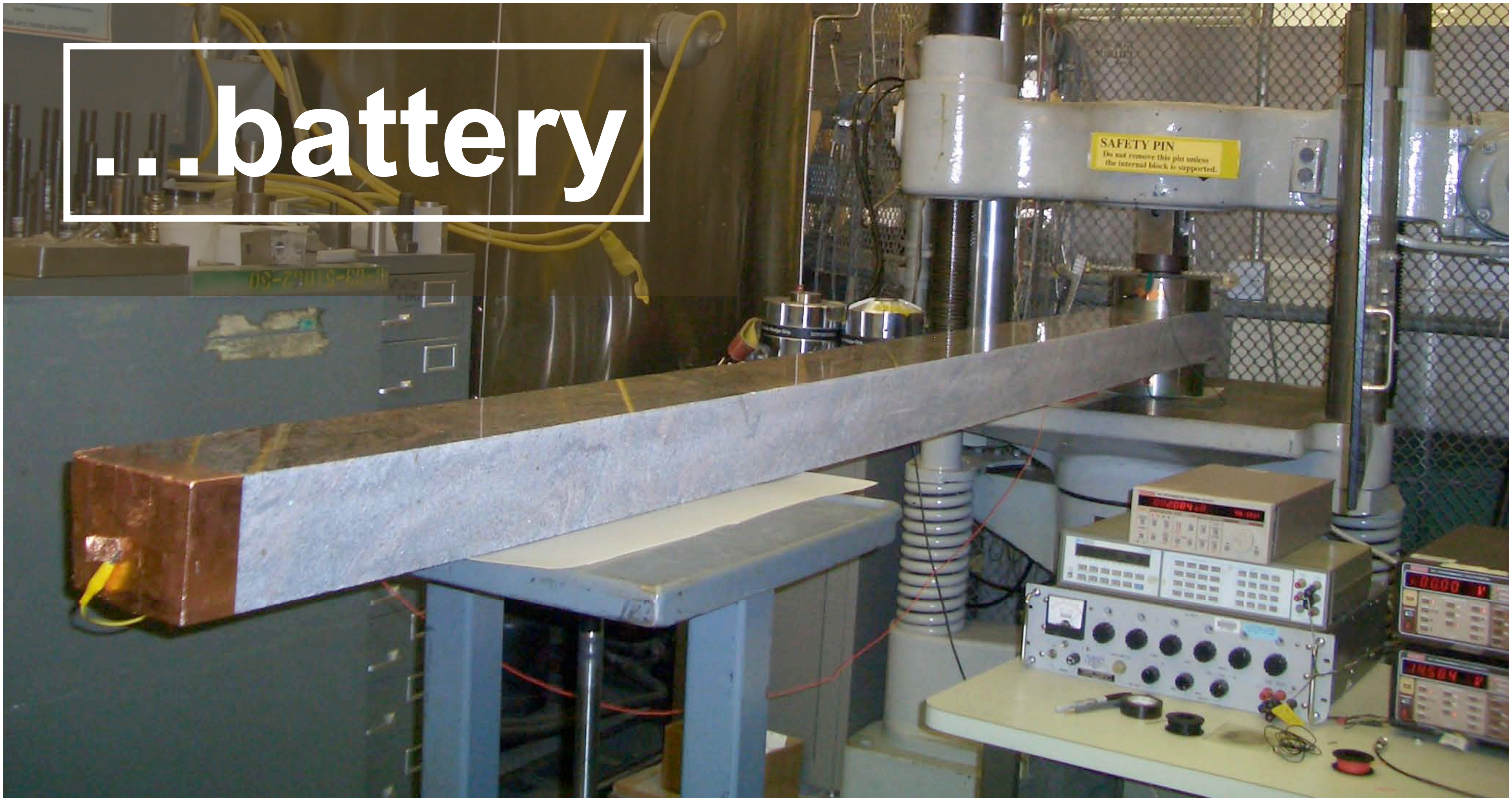


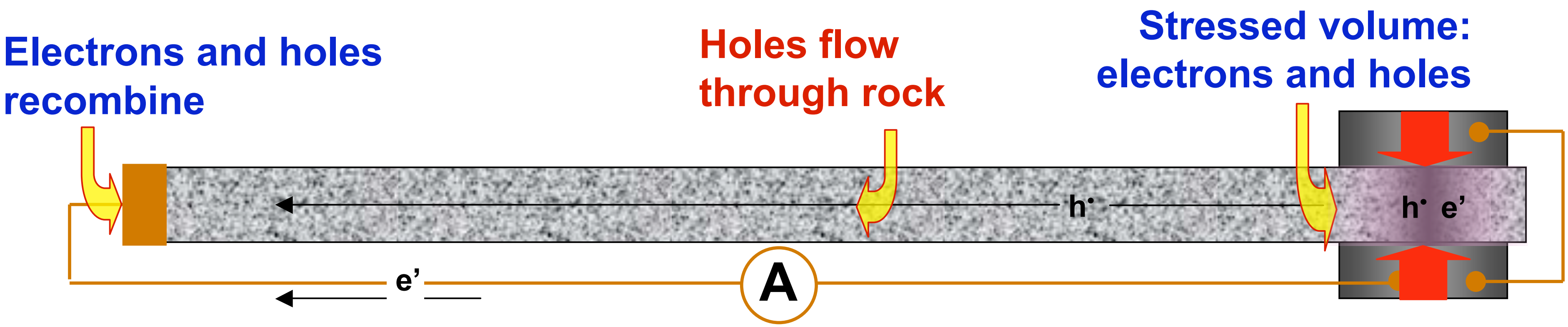
4 m long slab of granite to be squeezed at one end



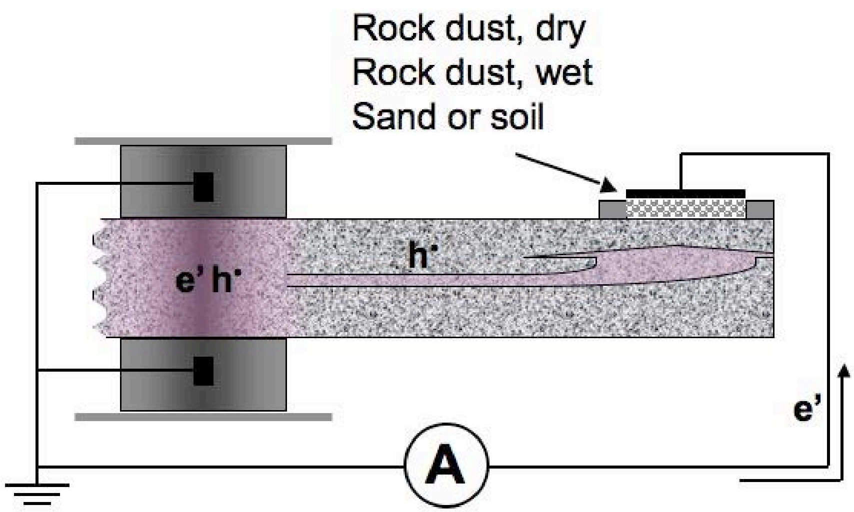
1. Current instantly starts to flow at very low stress levels
2. Current saturates
3. Current continues to flow at constant load

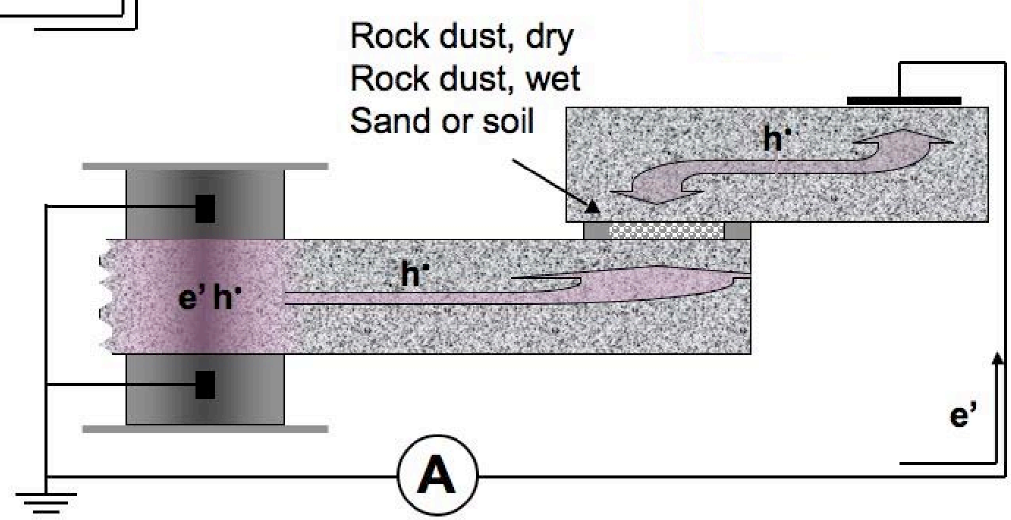
...battery


SAFETY PIN


Electrons and holes recombine
Holes flow through rock
Stressed volume: electrons and holes
h•
h• e’
e’
A

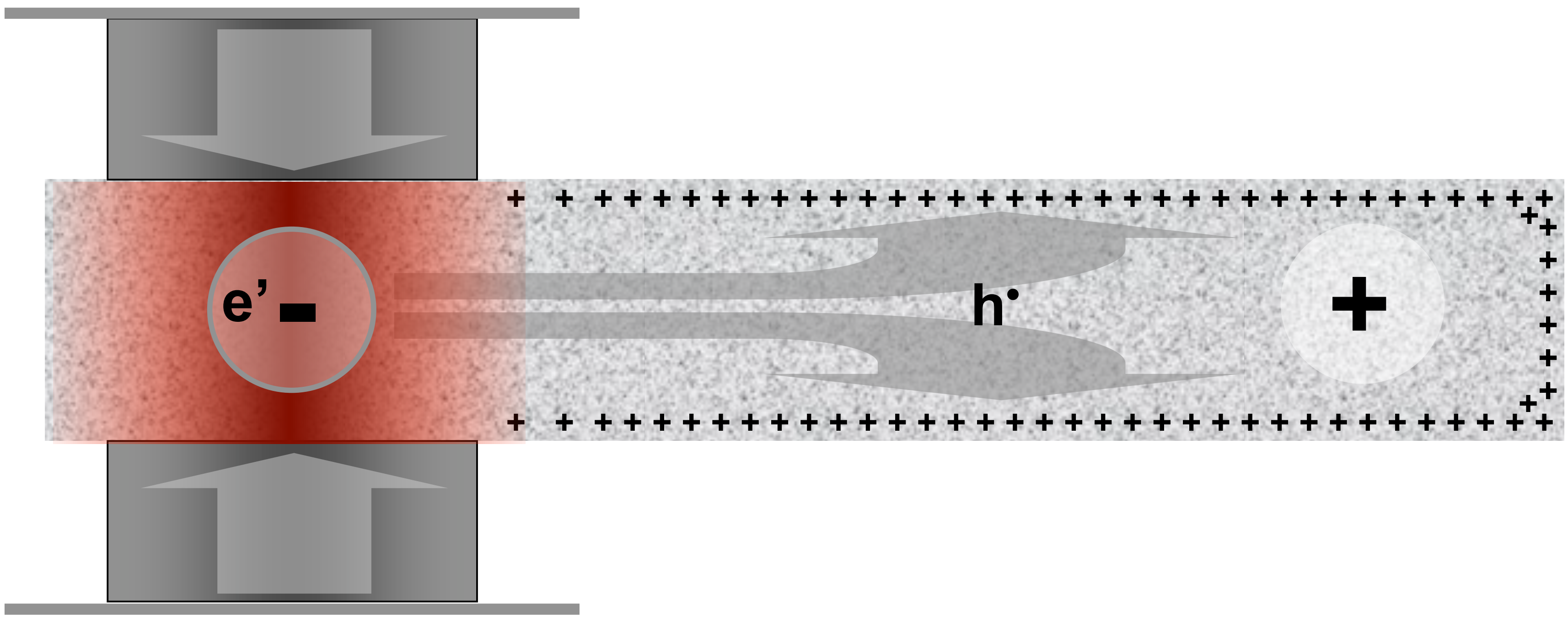
If $h^{\bullet}$ travel along valence band, they will pass across any grain-to-grain contact

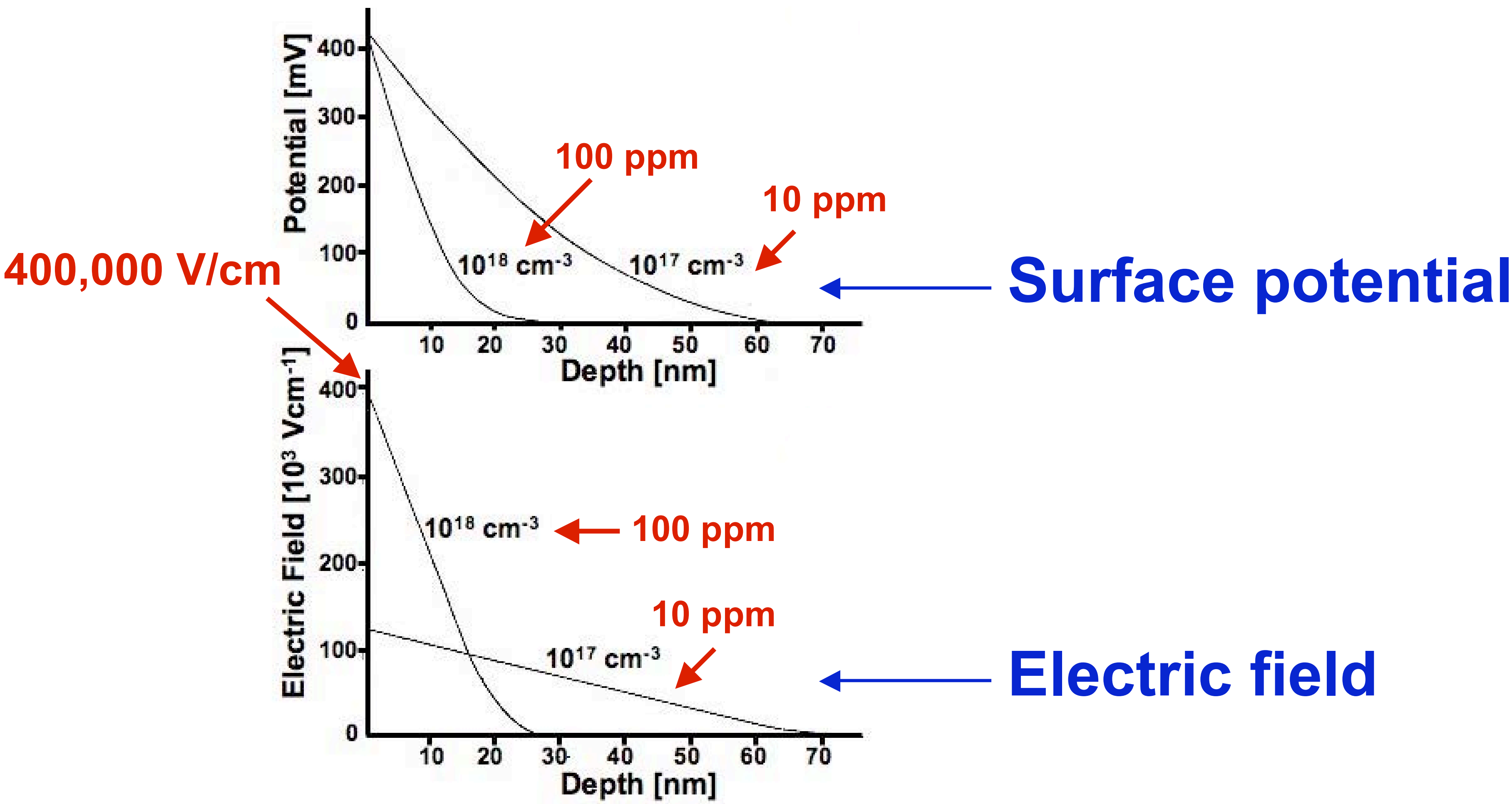




In addition,

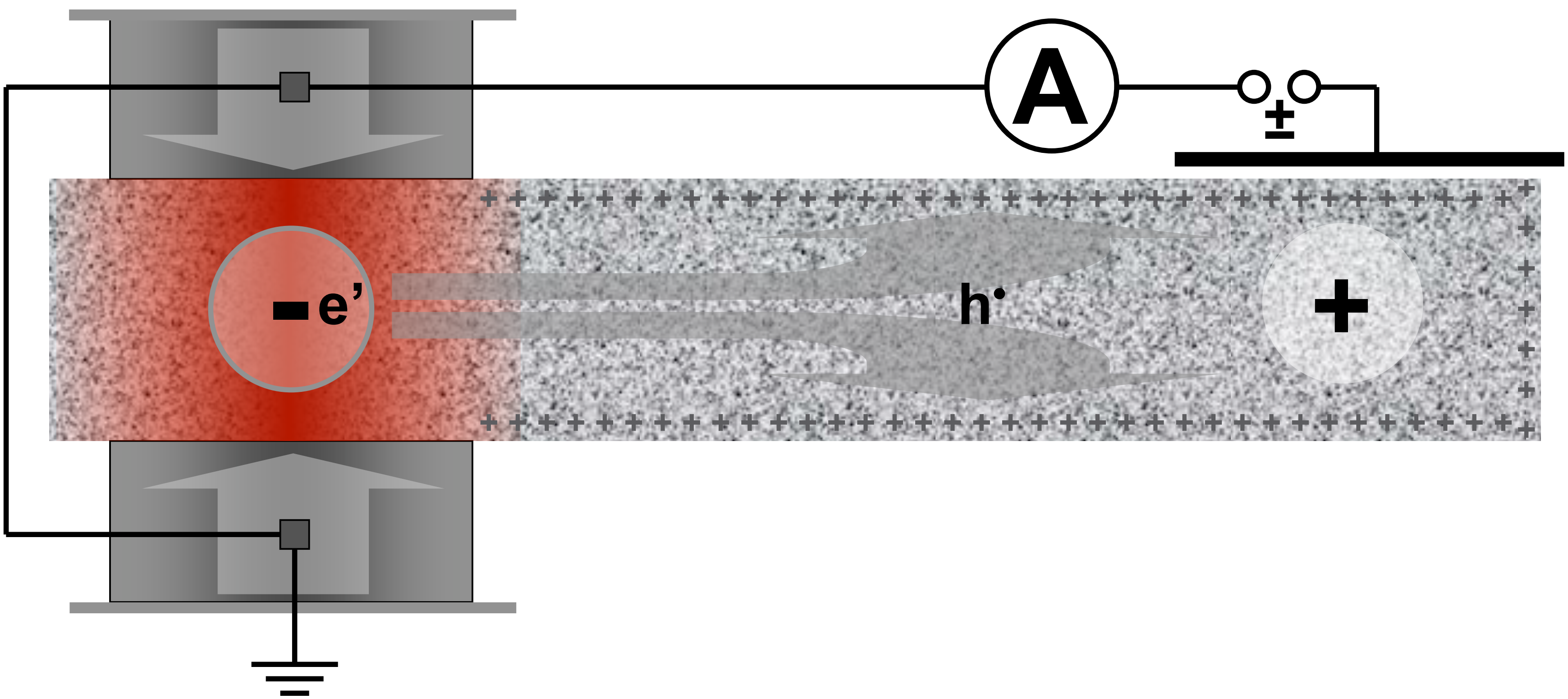
h• accumulate at the surface



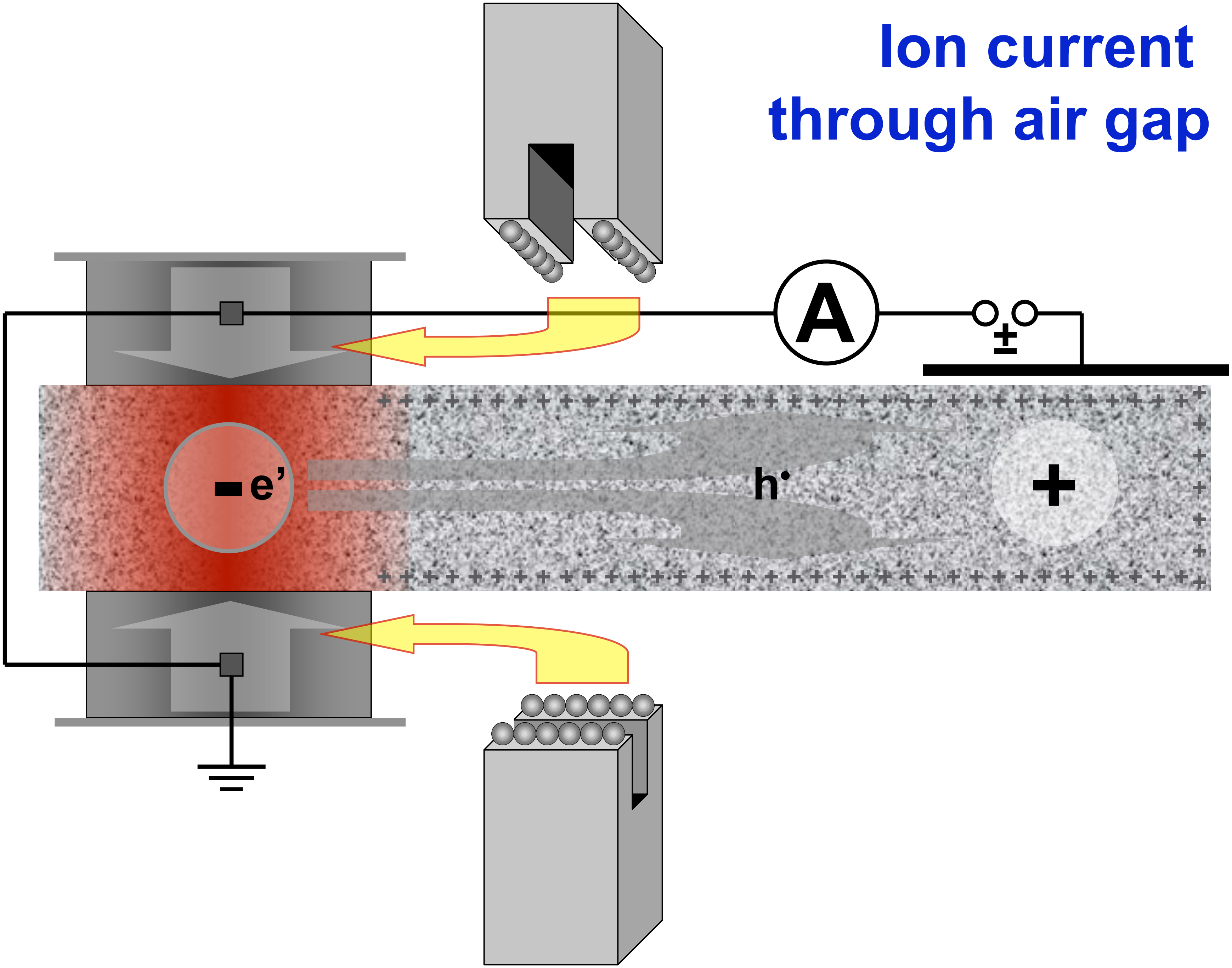


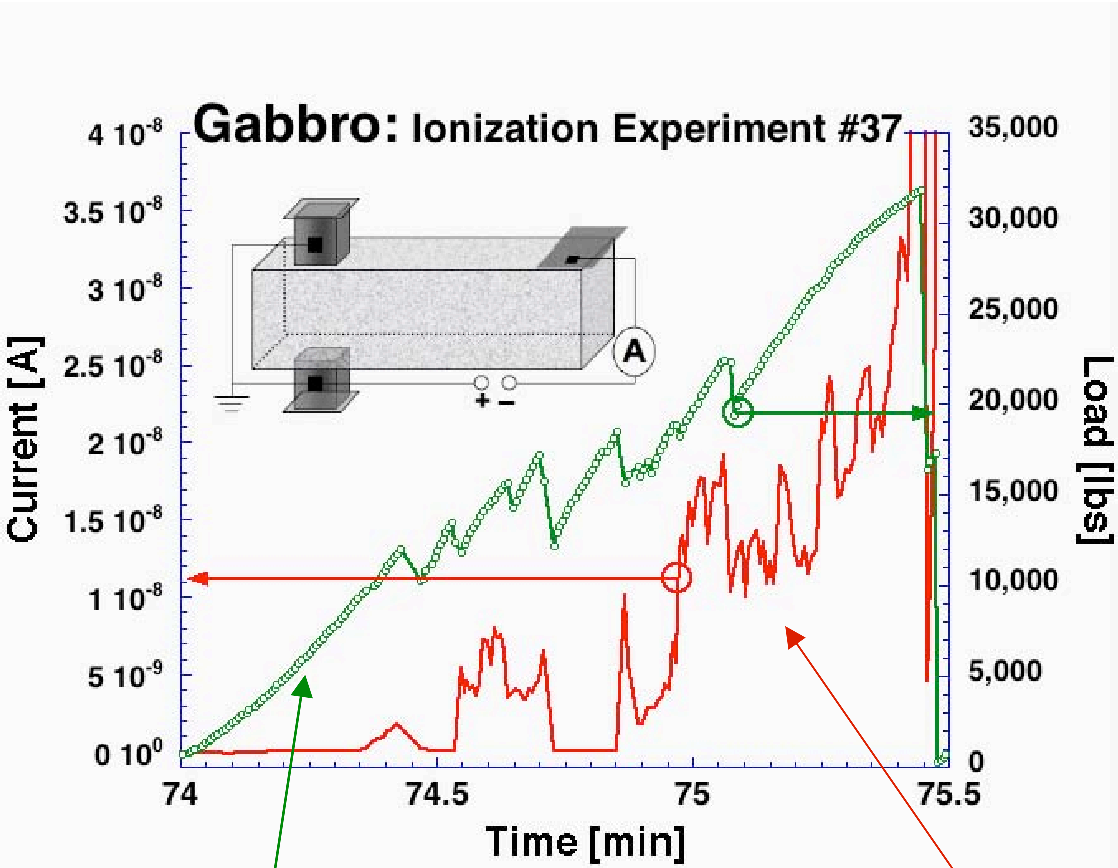
King and Freund, Phys. Rev. 1984

Ion current through air gap



Ion current through air gap





When rock is stressed at one end,

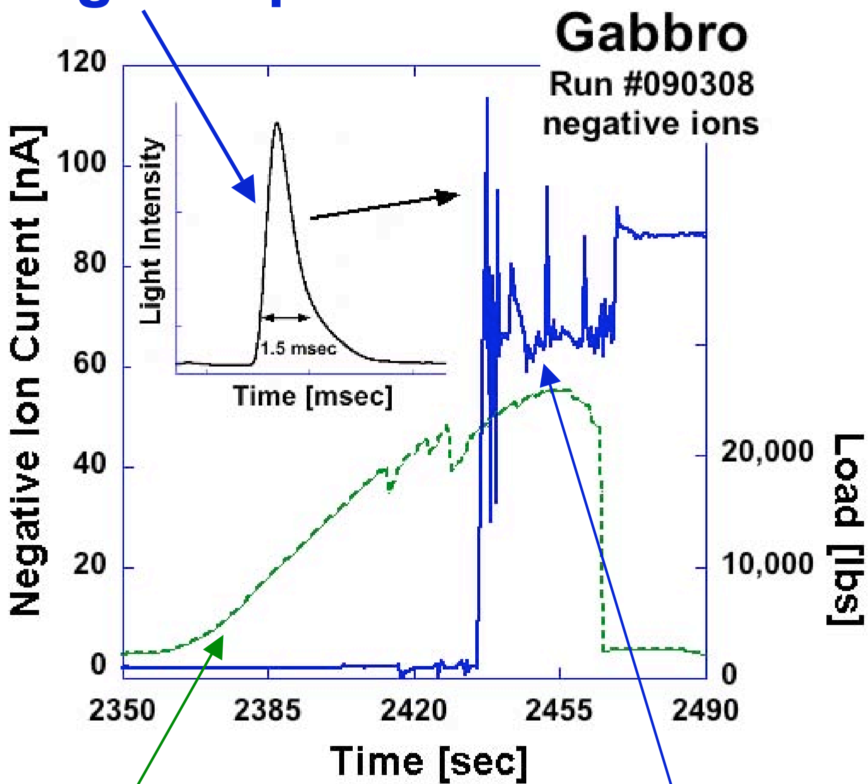
air molecules become field-ionized at the other end forming

positive ions

Load

~10^9 positive airborne ions cm^{-2} sec^{-1}

Visible Light blip



When rock is stressed at one end,

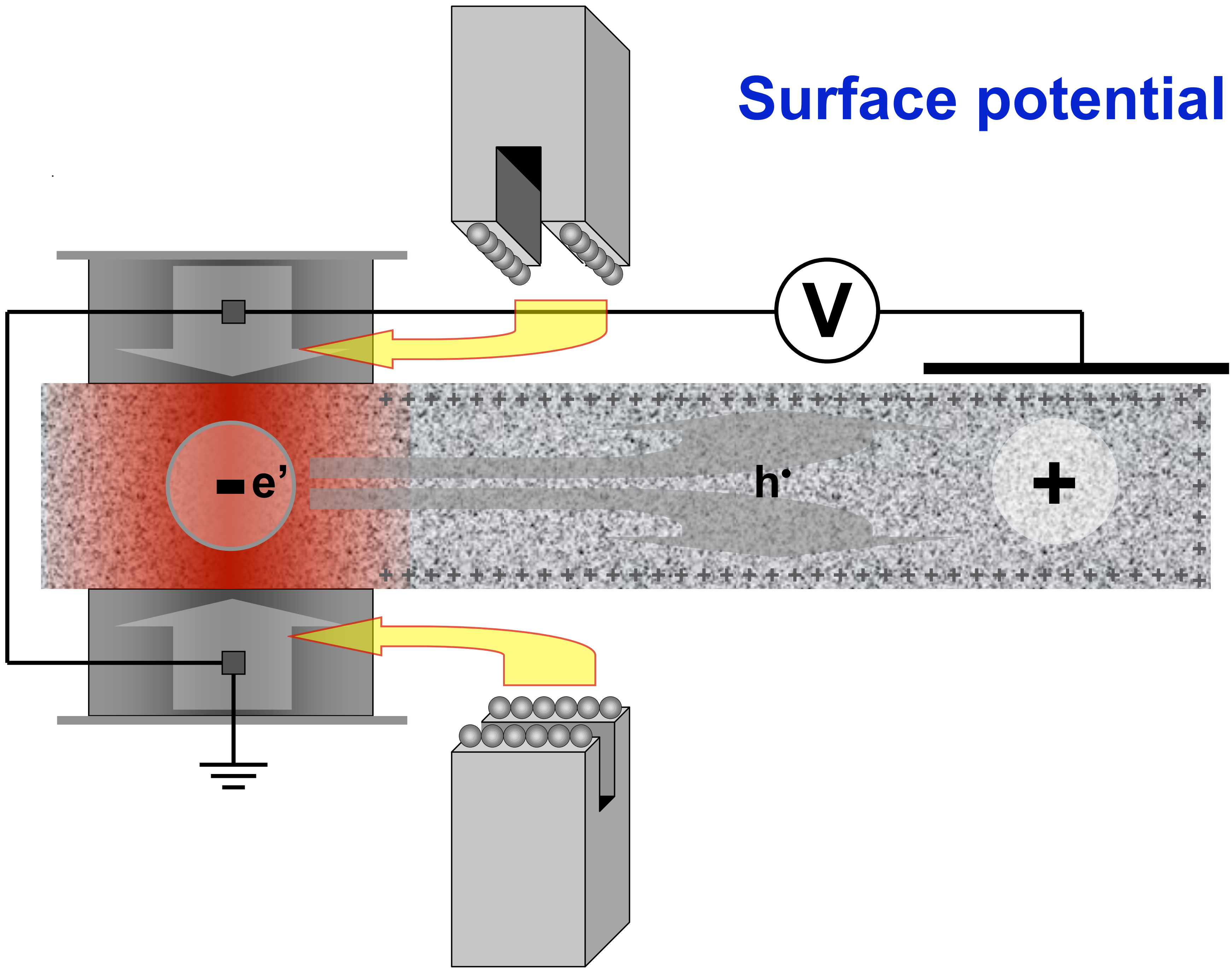
corona discharges occur at other end, forming free electrons and

negative ions

Load

~10^{10} negative charges cm^{-2} sec^{-1}

Surface potential



Surface potential

starts out positive

increases with load, reaching +3 V

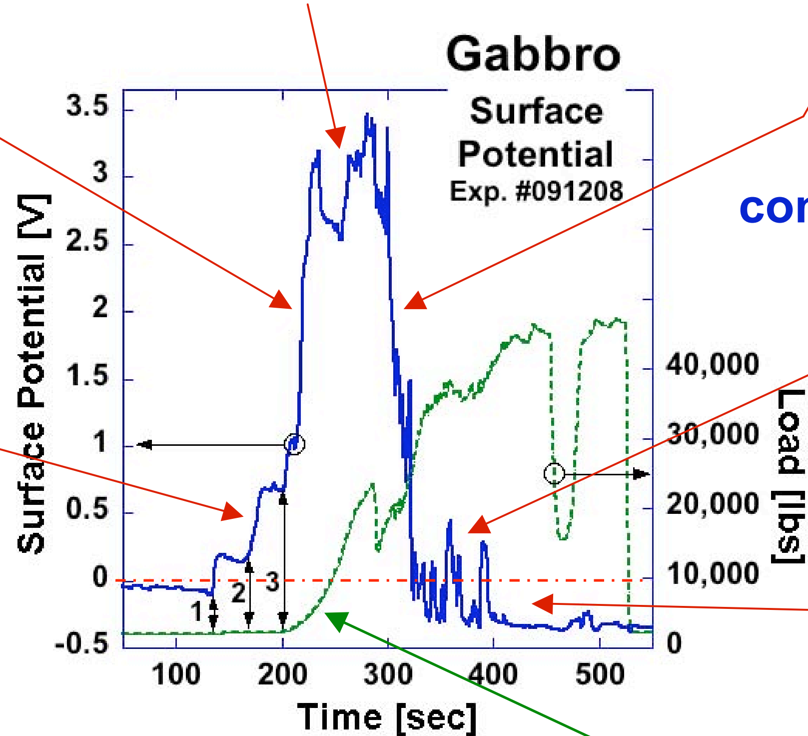
begins to fluctuate

collapses

continues to fluctuate

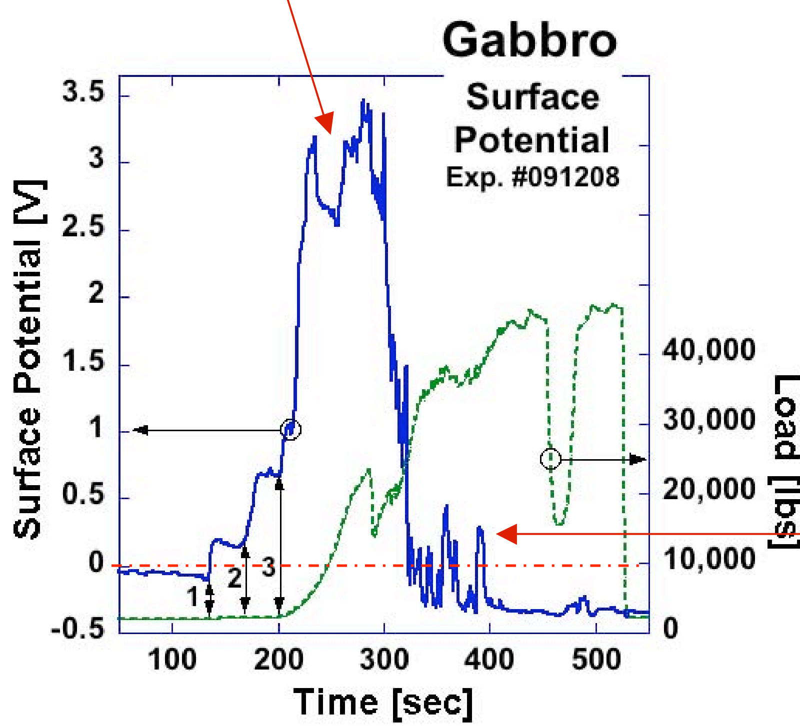
turns negative

Load



To build up 1 V surface potential requires ~10^{10} charges per cm^2

We measure ⊕ ions forming at rate of ~10^9 cm^{-2} sec^{-1}



Equivalent to ~1000 A km^{-2}

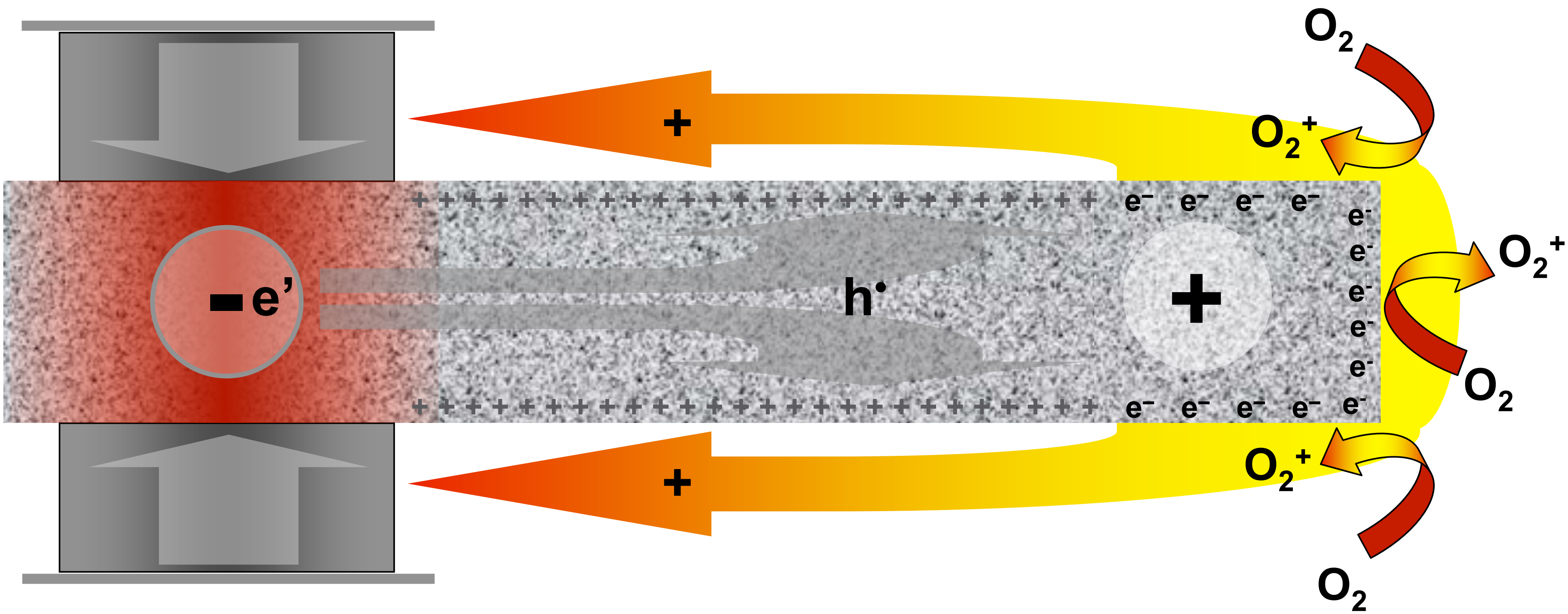
We measure ⊖ ions and electrons forming at rate ~10^{10} cm^{-2} sec^{-1}

Now we understand the surface potential changes

Step 1, a positive surface charge builds up: +3 V

Step 2, positive airborne ions form: ~10^9 cm^{-2} sec^{-1}

Step 3, corona discharges set in,
generating free electrons and negative airborne ions: ~10^{10} cm^{-2} sec^{-1}



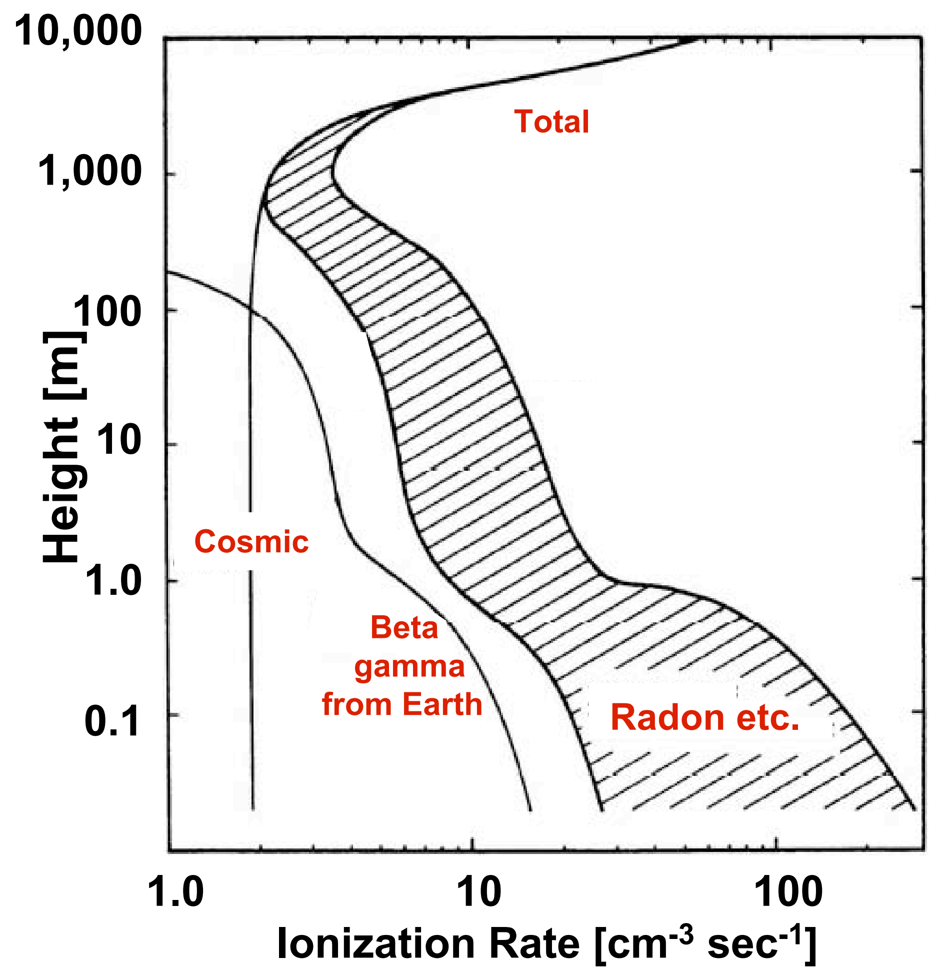
Applications

If $h^{\bullet}$ arrive at Earth surface and create high E fields, we expect to see:

Field ionization of air molecules

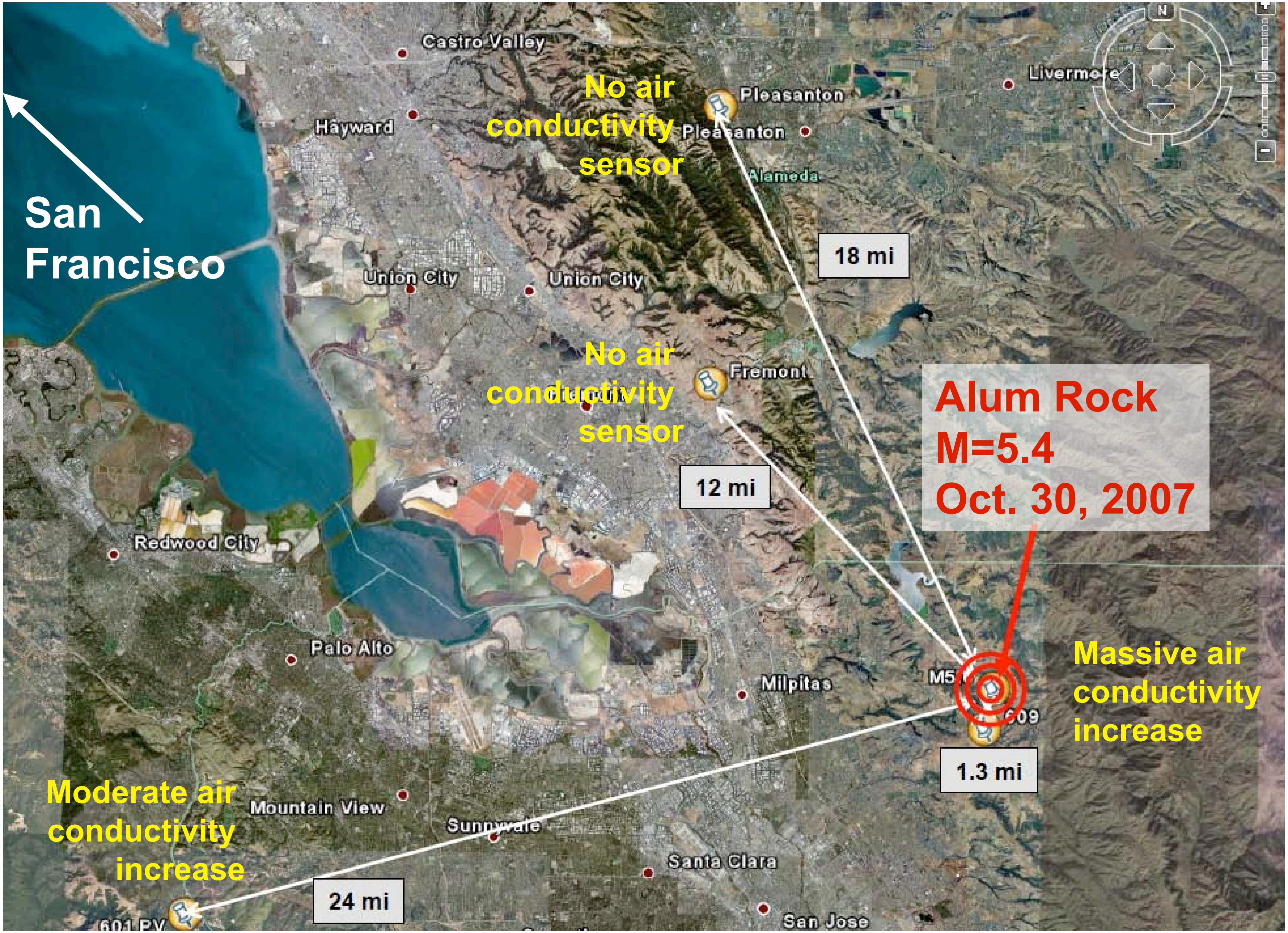
Sources of air ionization

- cosmic rays
- beta, gamma from Earth
- alpha from radon



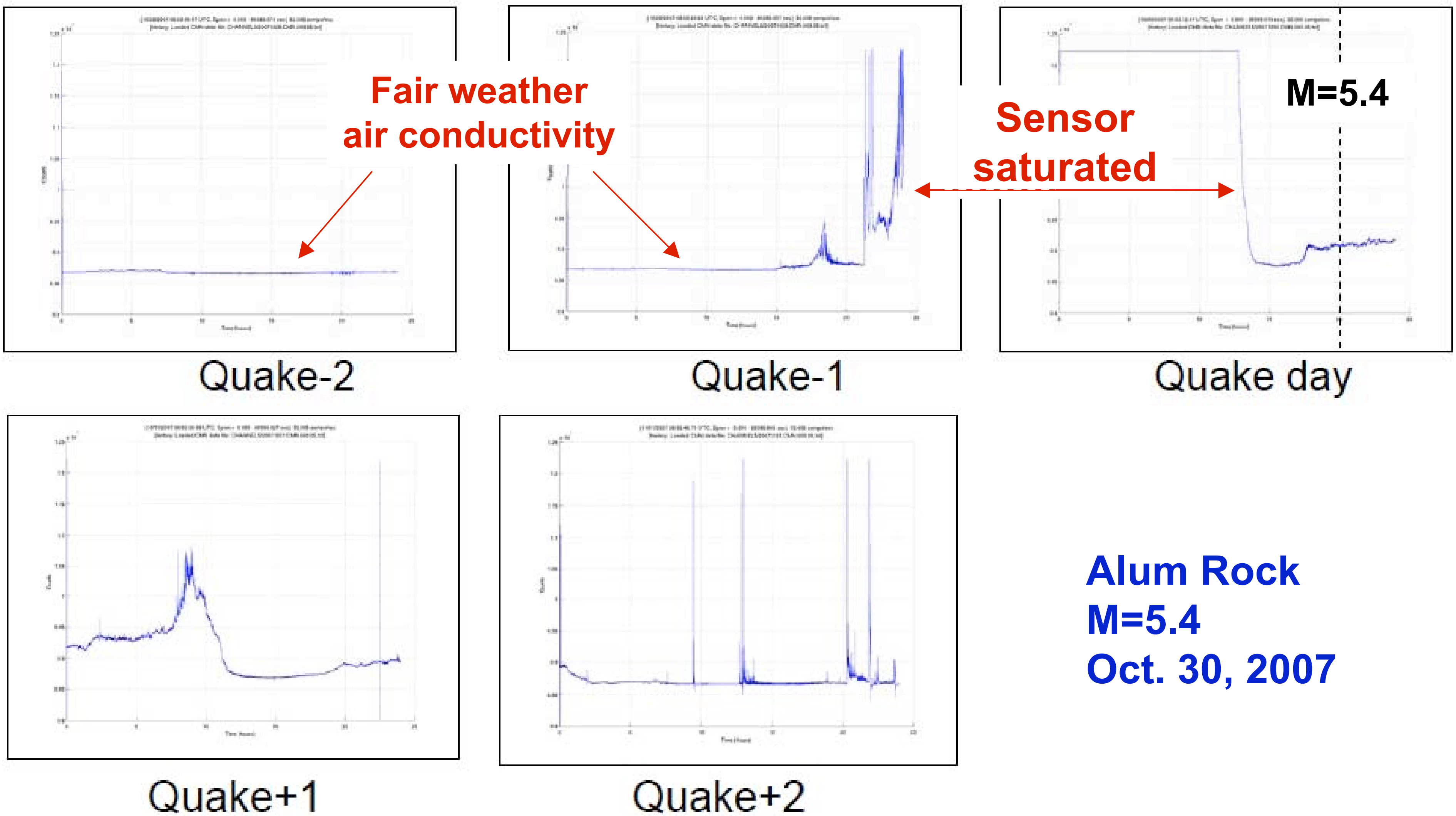
~20 ⟷ 200

fair weather range



San Francisco
No air conductivity sensor
No air conductivity sensor
18 mi
12 mi
Alum Rock
M=5.4
Oct. 30, 2007
Massive air conductivity increase
1.3 mi
Moderate air conductivity increase
24 mi
Castro Valley
Hayward
Pleasanton
Livermore
Union City
Fremont
Redwood City
Palo Alto
Milpitas
Mountain View
Sunnyvale
Santa Clara
San Jose

QuakeFinder Air Conductivity Sensor at Milpitas Site



Alum Rock
M=5.4
Oct. 30, 2007

Courtesy Tom Bleier, QuakeFinder

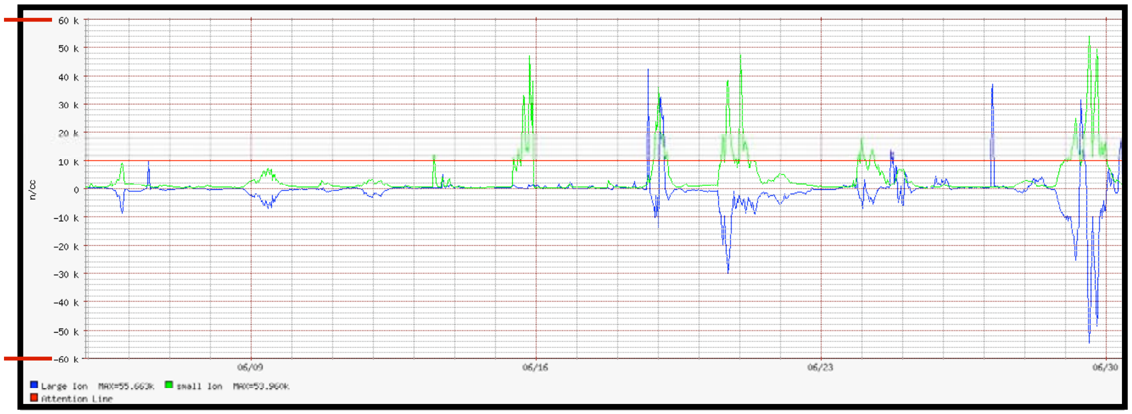
Air Ionization Field Measurements in Japan

50,000

⊕

⊖

50,000
cm^{-3}

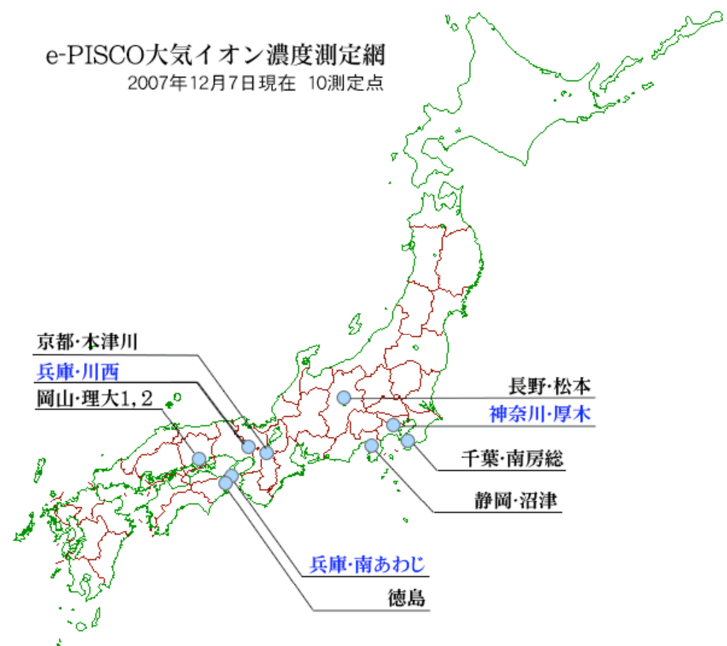


Kanagawa Station, June 2008

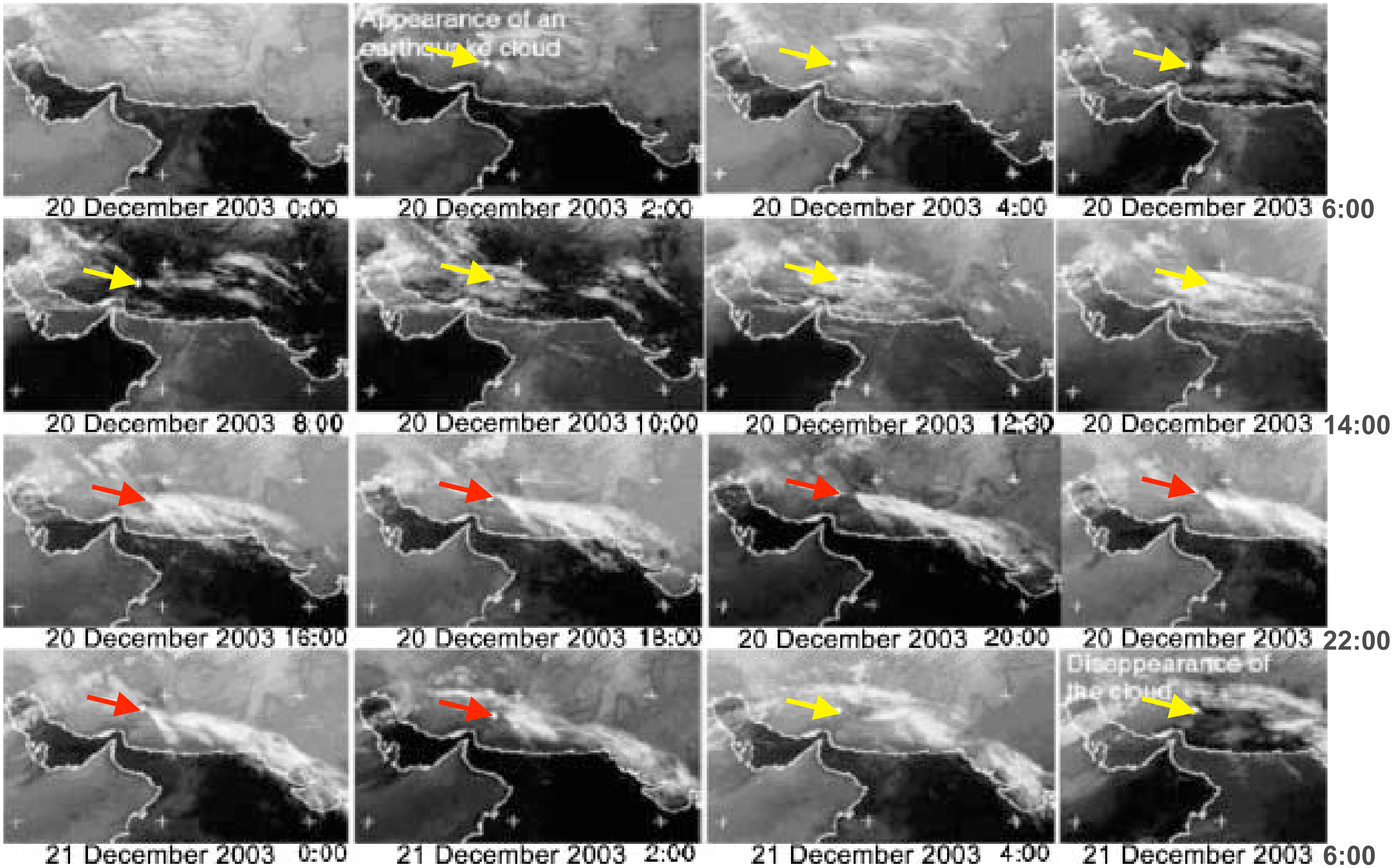
Positive ions
mostly small

Negative ions
mostly large

PISCO
9-station network



A cloud over Bam, Iran: MeteoSat



Courtesy Shou Zhonghao after Guangmeng Guo & Bin Wan 2008

Bam Earthquake M=6.8, Iran, Dec. 26, 2003

Pre-Earthquake Ionospheric Perturbations

Massive air ionization

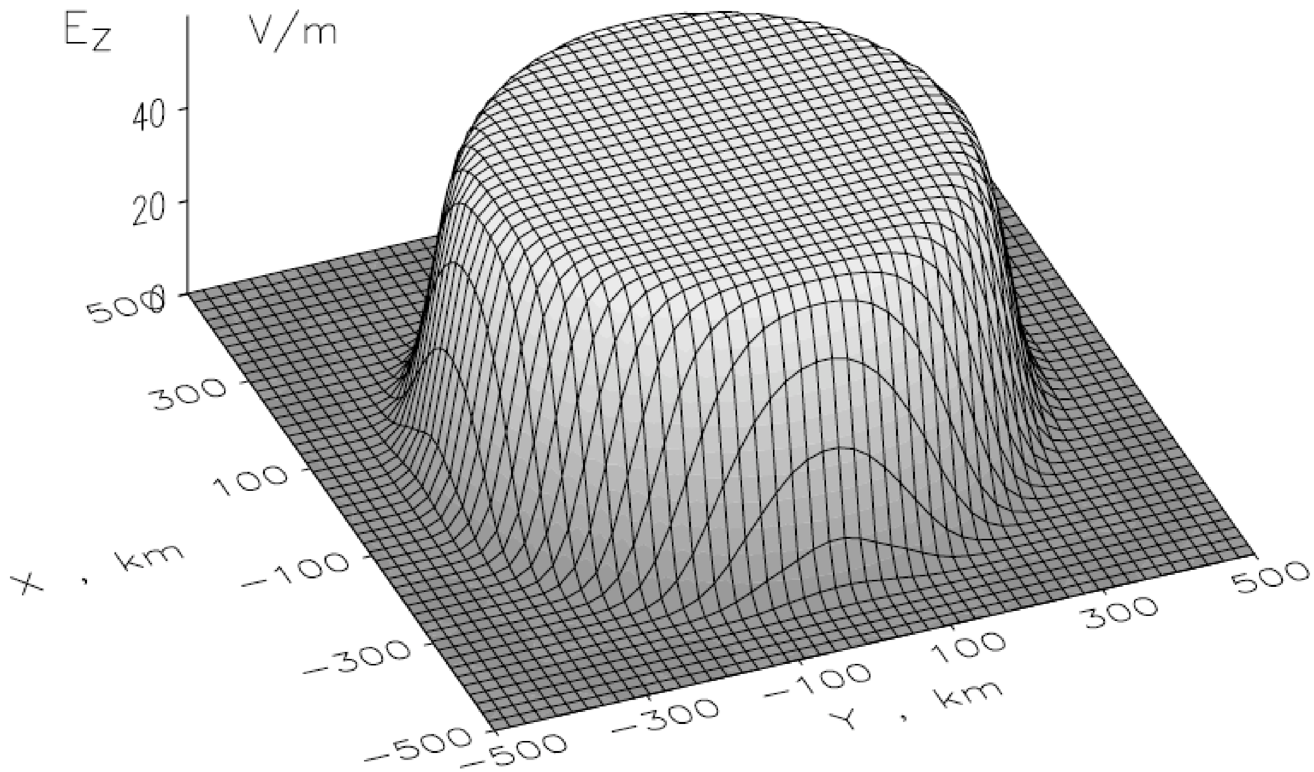
will change

vertical E field

Equivalent to ~1000 A km^{-2}

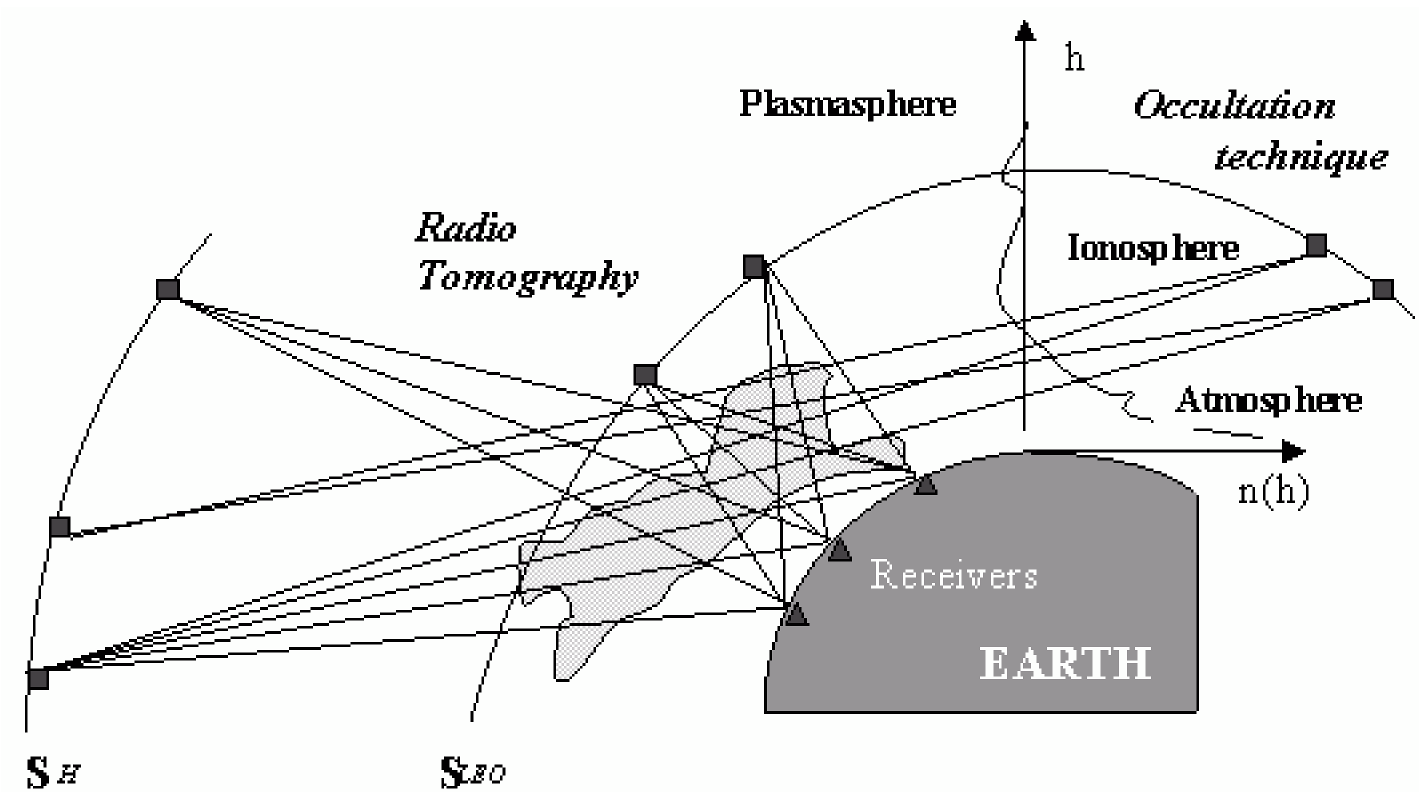
will affect

ionosphere



(Courtesy Valery Sorokin, 2008)

Radio-Tomography of the Ionosphere (RTI)

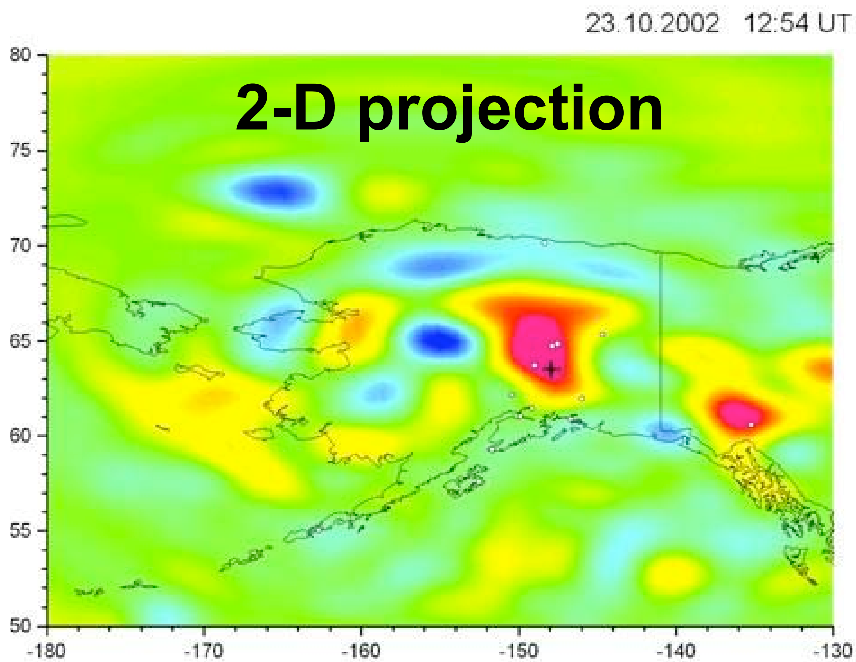


HORT
(High Orbital Radio
Tomography)

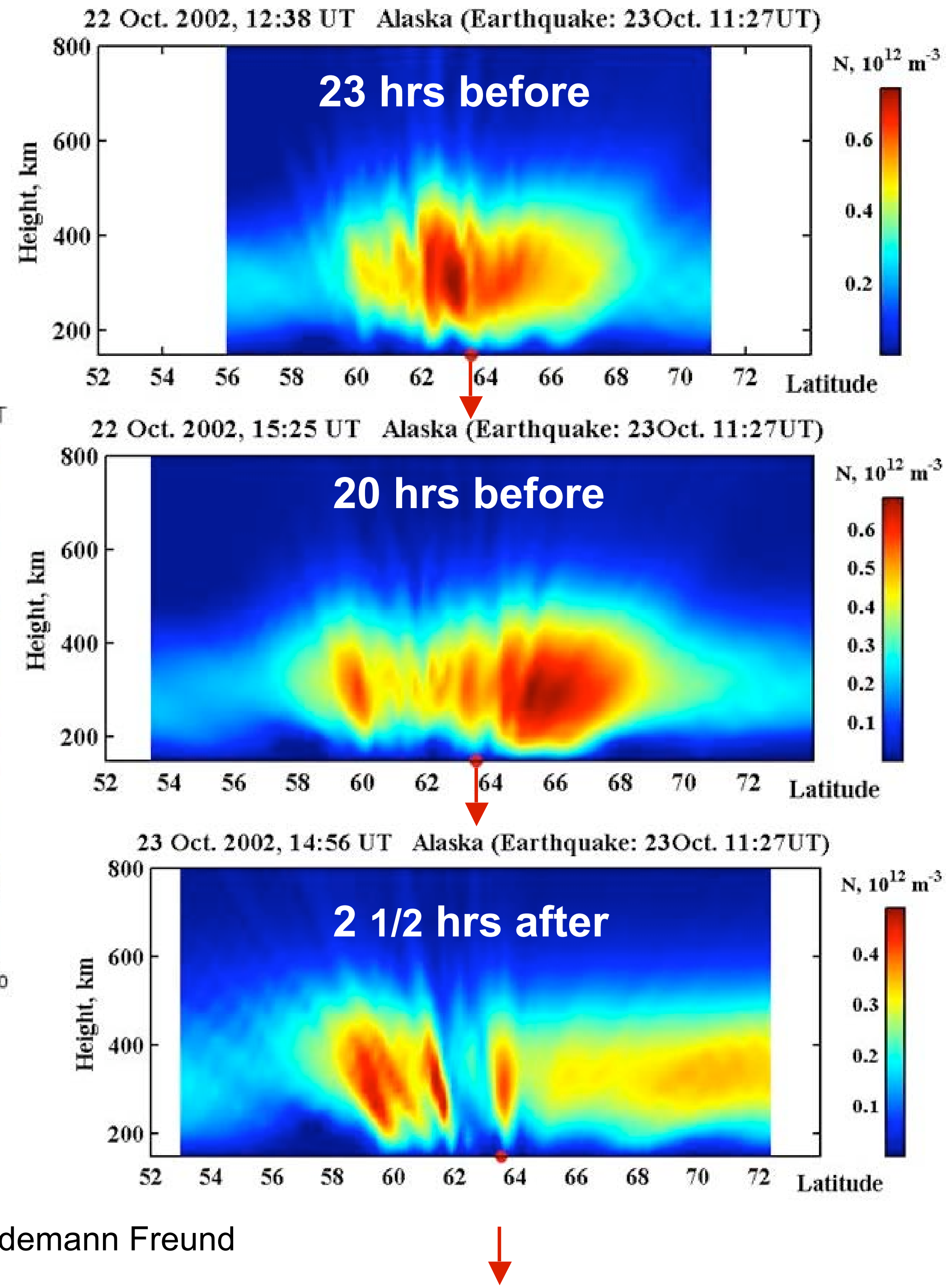
LORT
(Low Orbital Radio
Tomography)

Ionospheric Perturbation

M=6.4 EQ Alaska
23. Oct. 2002 at 11:27 UT



(courtesy Doug Rekenthaler 2008)



Summary so far

- When rocks are stressed, they turn into a battery
- Currents flow out of stressed rock volume
- Charge carriers are positive holes, $h^{\bullet}$
- $h^{\bullet}$ accumulate at the surface
- High electric fields
- Air ionization: Atmospheric effects √

  Ionospheric effects √

h• charge carriers recombine at surface

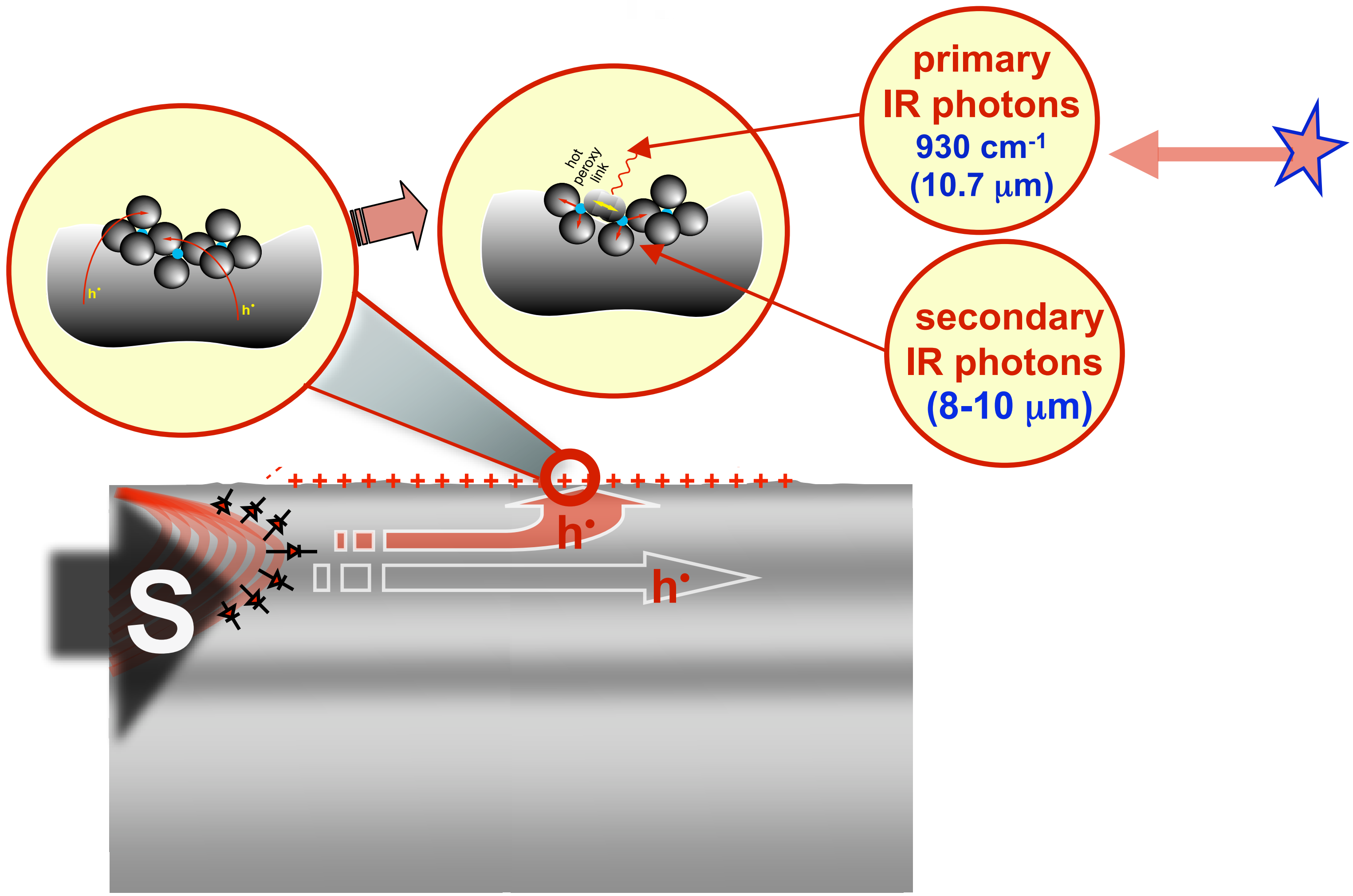
Energy released: ~ 2.4 eV

~ 2.4 eV deposited into new O–O bond

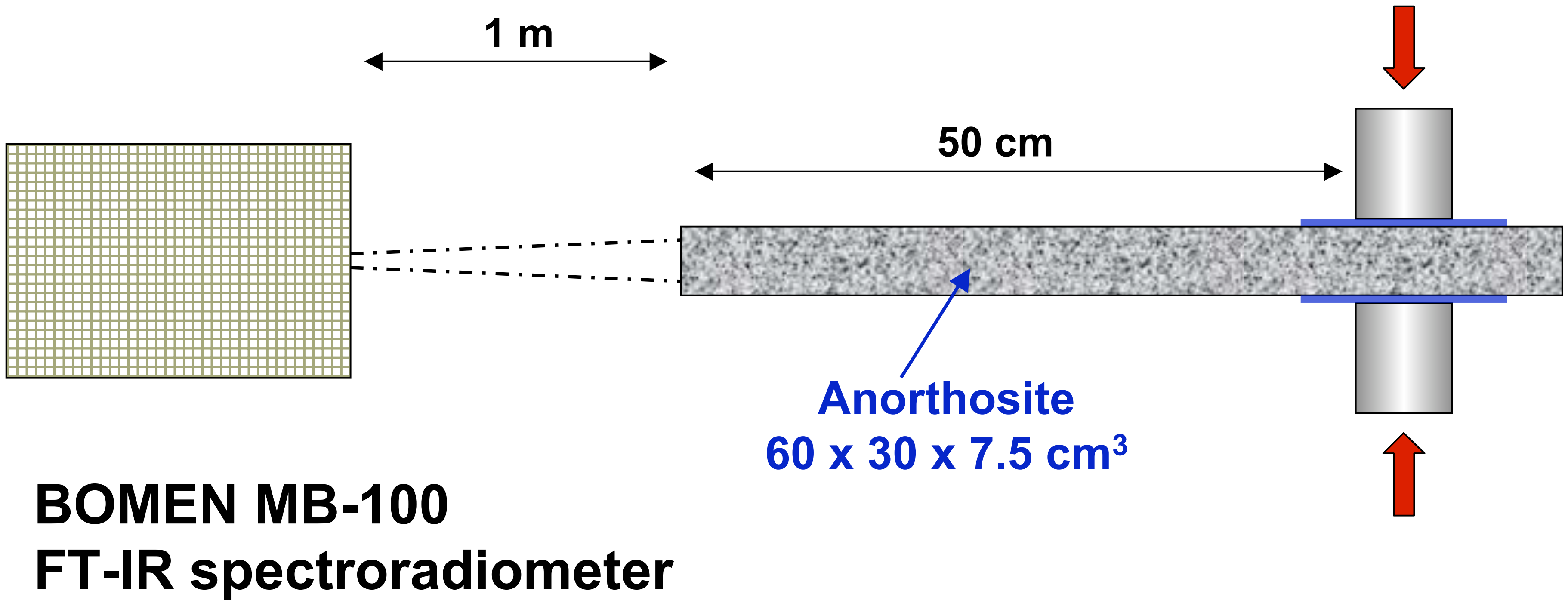
~ 2.4 eV equivalent to vibrational T of ~30,000 K

Very “hot” atoms

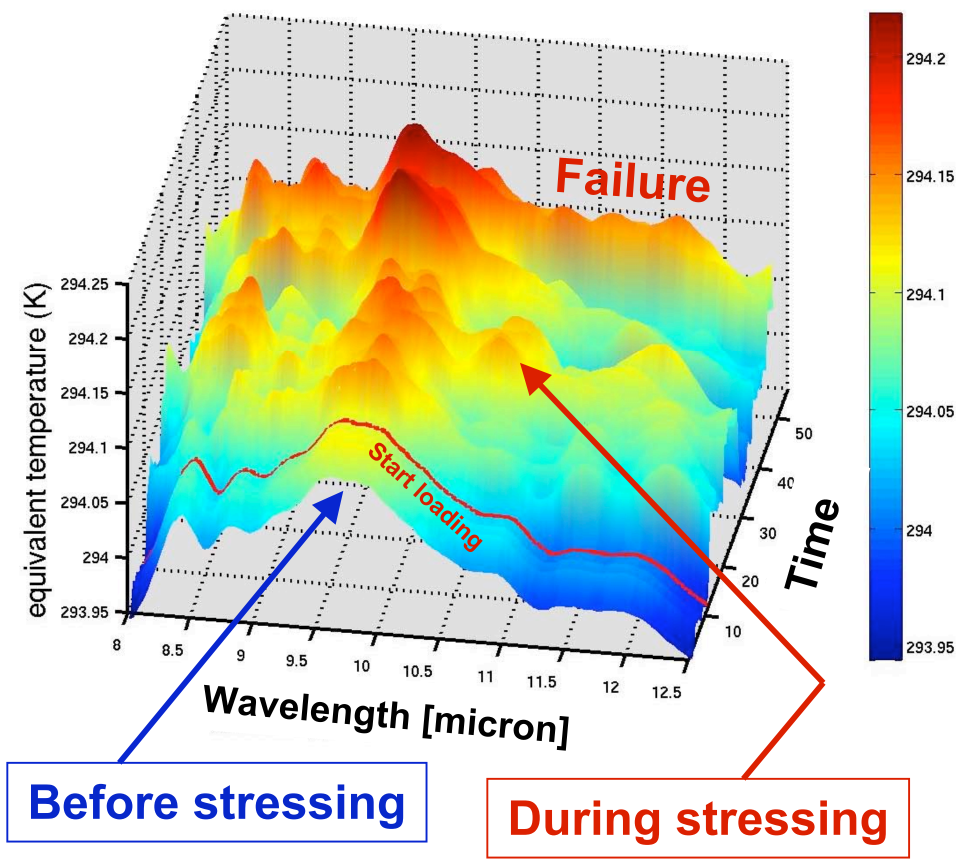
Emission of IR photons



Experiment

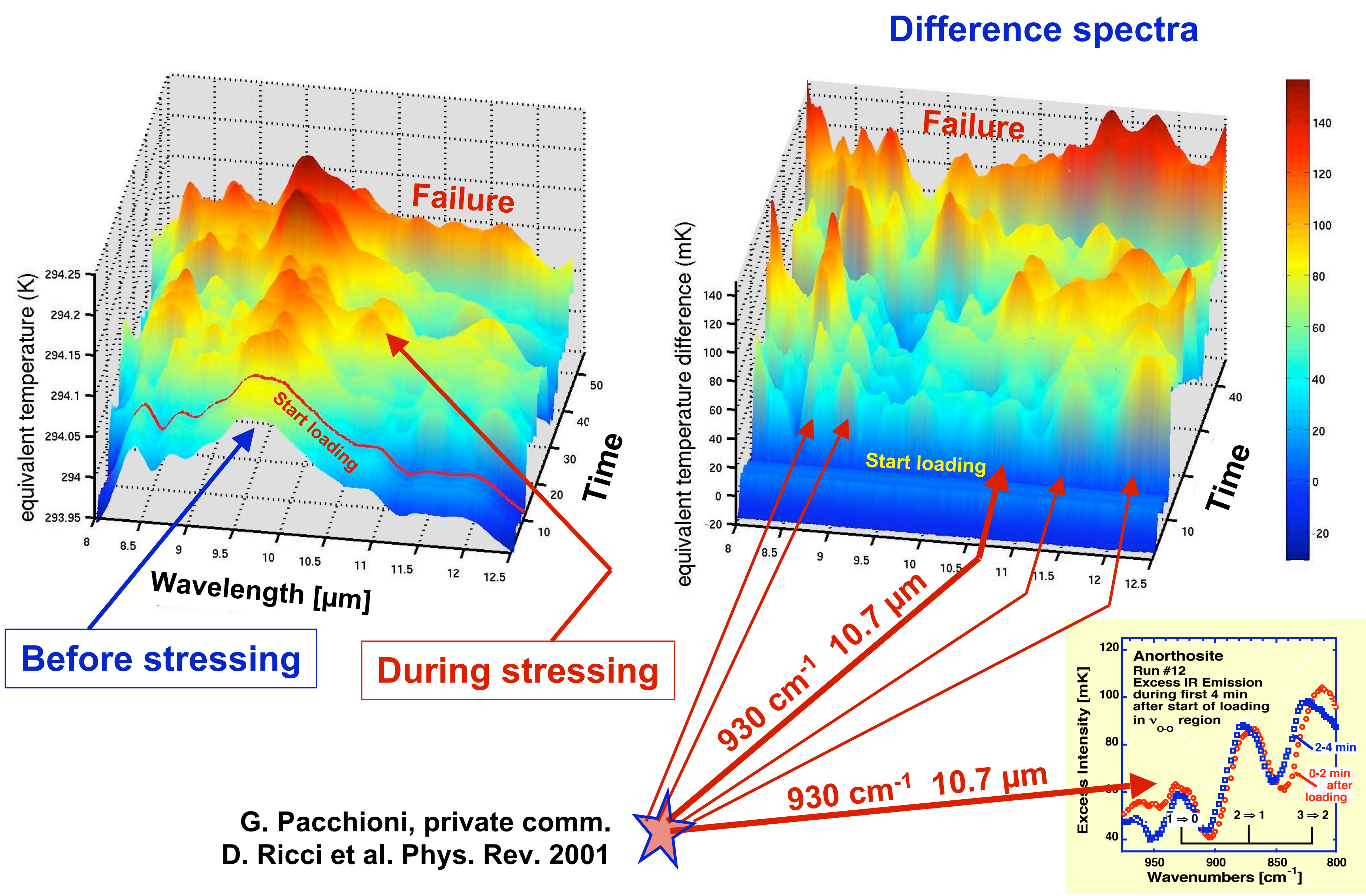

1 m
50 cm
Anorthosite
60 x 30 x 7.5 cm^3
BOMEN MB-100
FT-IR spectroradiometer

IR emission anorthosite



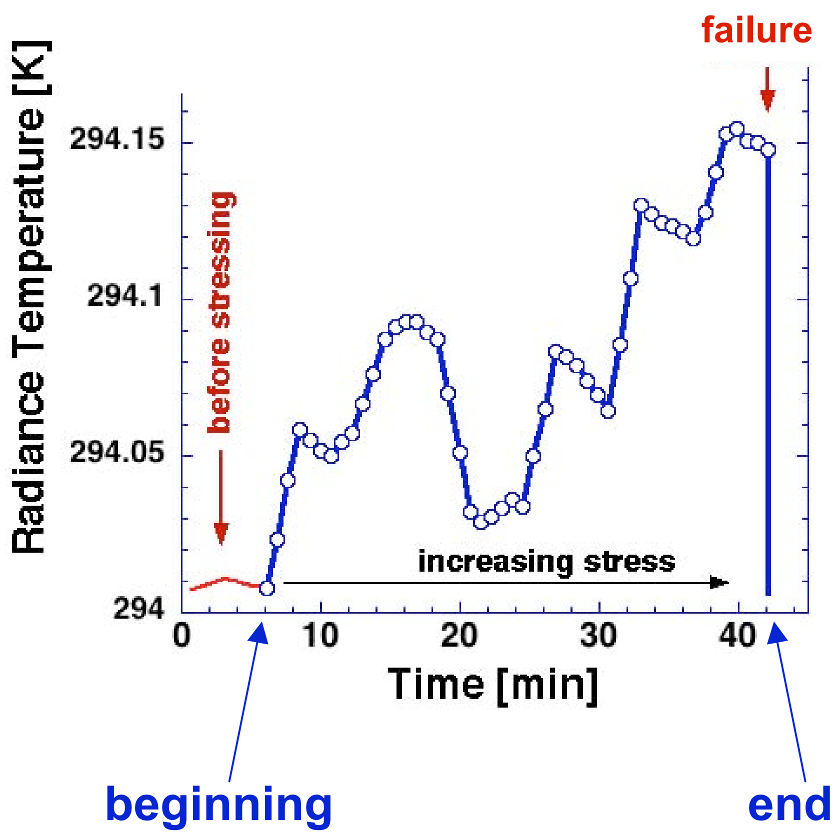
Anorthosite Run #12

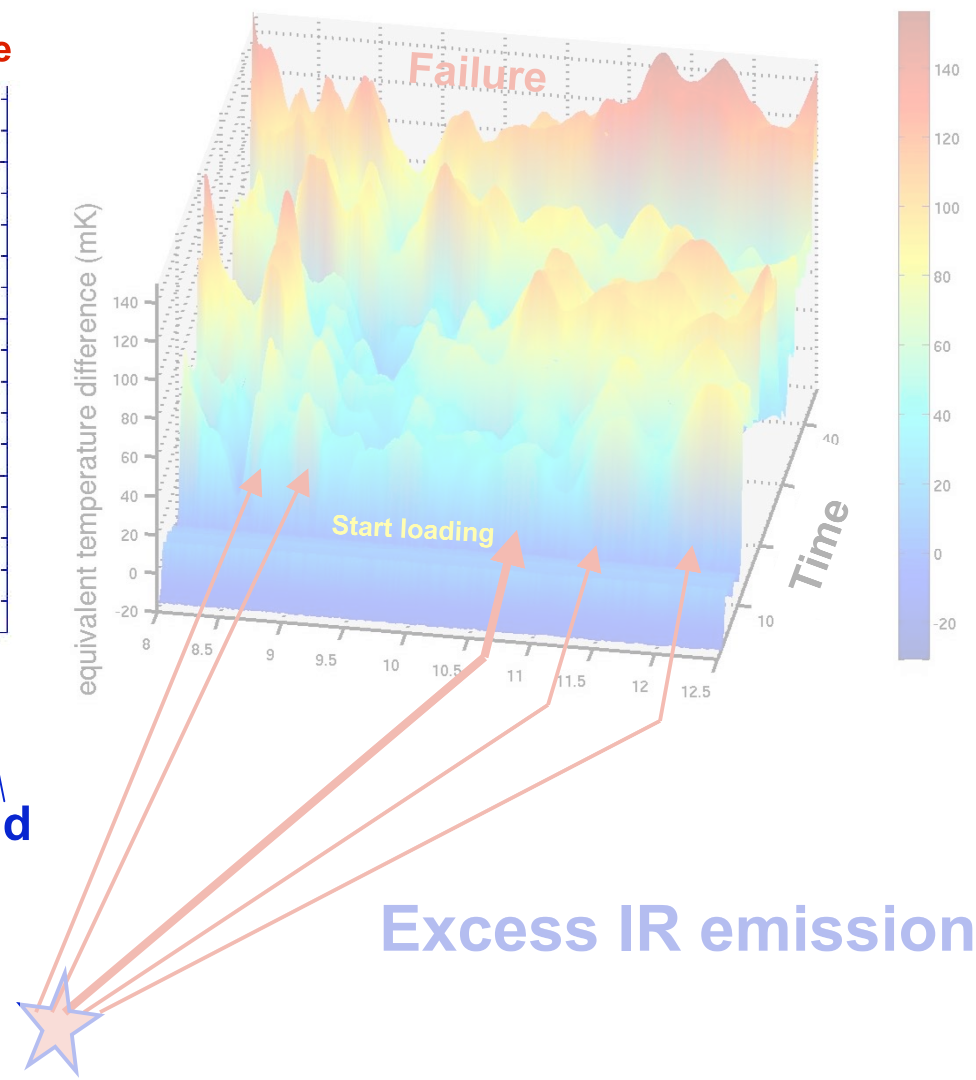
IR emission anorthosite



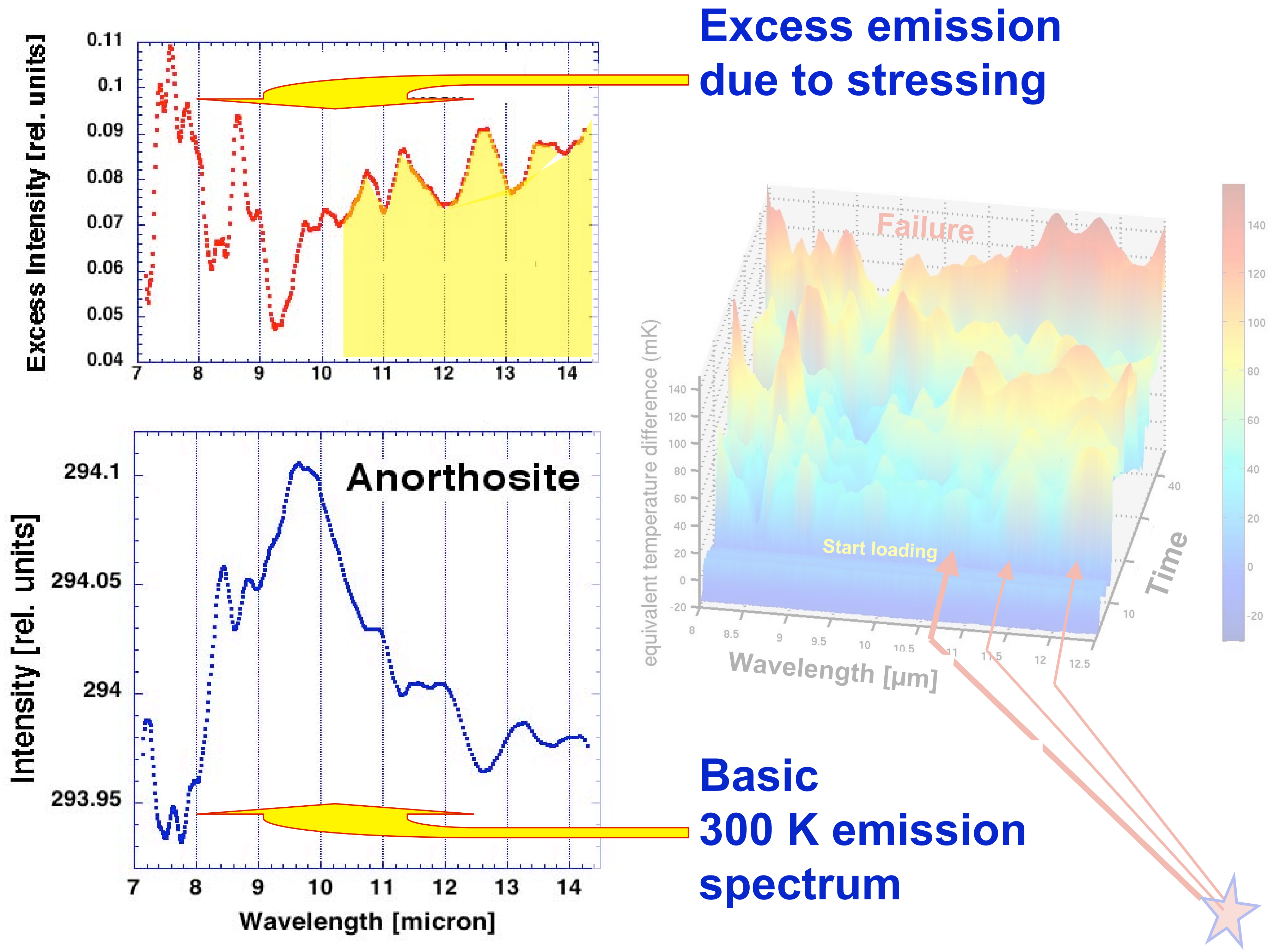
G. Pacchioni, private comm.
D. Ricci et al. Phys. Rev. 2001

Intensity fluctuations during stressing





Anorthosite Run #12



Excess emission due to stressing
Excess Intensity [rel. units]
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
7 8 9 10 11 12 13 14
Anorthosite
Intensity [rel. units]
294.1
294.05
294
293.95
7 8 9 10 11 12 13 14
Wavelength [micron]
Failure
Start loading
equivalent temperature difference (mK)
Wavelength [μm]
Time
Basic 300 K emission spectrum

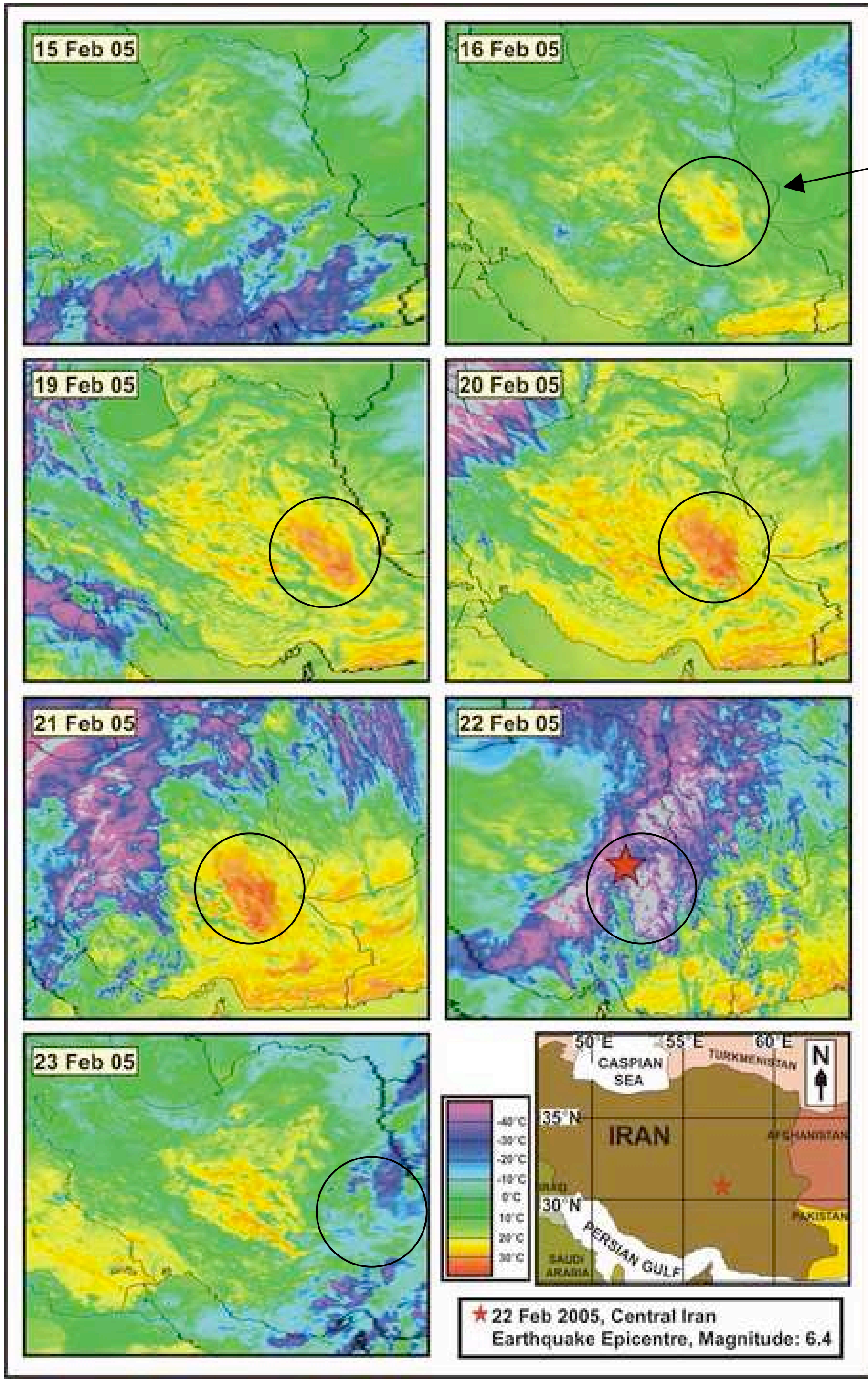
This is
not thermal IR radiation

- IR photons due to de-excitation
- Quantum-mechanically controlled
- Spectroscopically distinct

Applications

"Thermal Infrared Anomalies"

- **First reported in early 1990s**
- **Areas of enhanced IR emission**
  - **begin several days before major EQs**
  - **spread over large areas (up to 500 x 500 km^2)**
  - **end soon after seismic event and aftershocks**



~200 x 100 km²

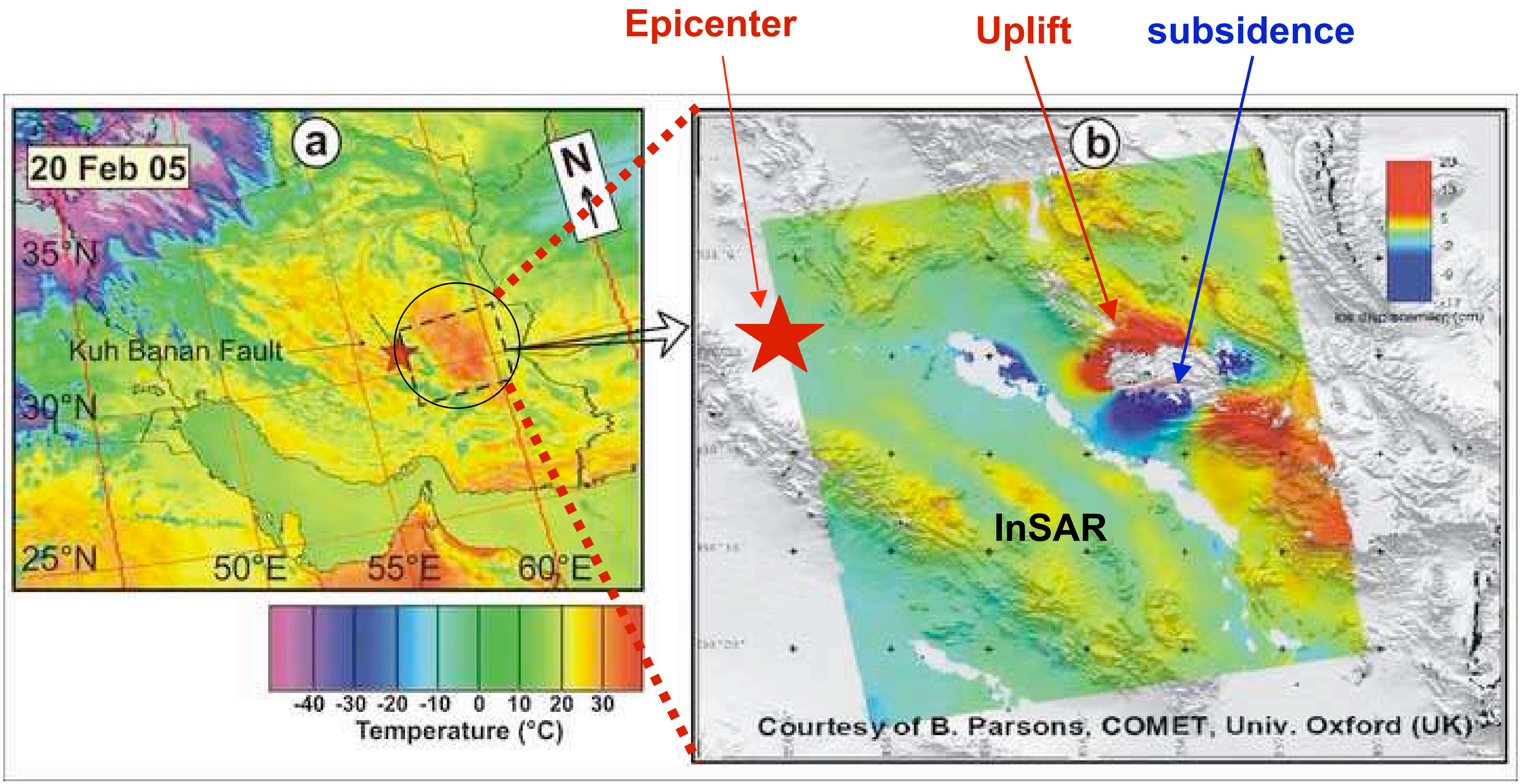
M = 6.4 event
in SE Iran

22 Feb. 2005

Desert environment
Ideal viewing conditions

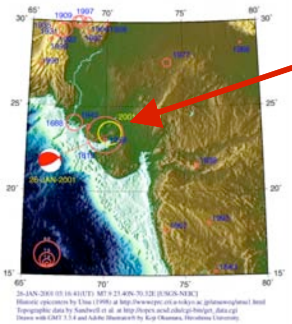
NOAA AVHRR satellite

(from: Arun Saraf et al.
Natural Hazards 2008)



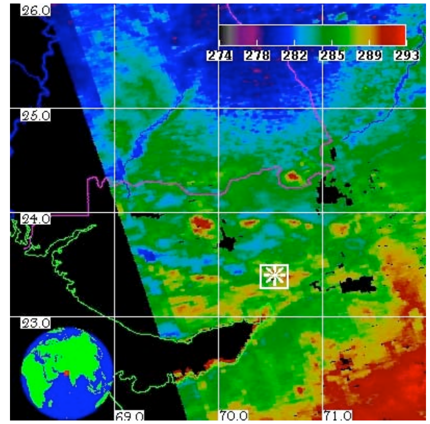
IR emission from region of maximum uplift/subsidence

(from: Arun Saraf
Natural Hazards 2008)

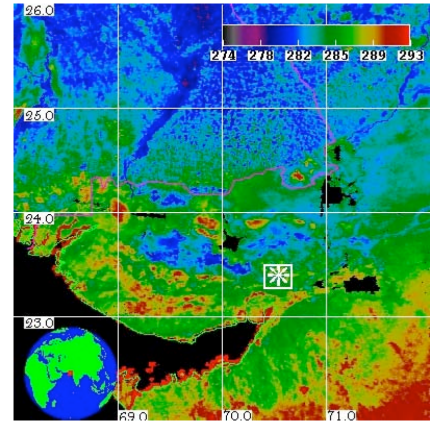


Gujarat EQ (India): Jan. 26, 2001 Depth 24 Km; M=7.6

Faults "light up" in the IR before earthquake

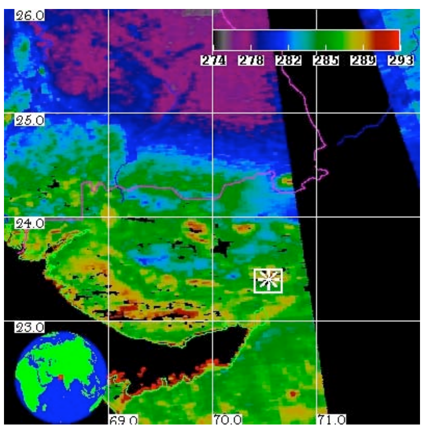


Jan 17: **-9 days**

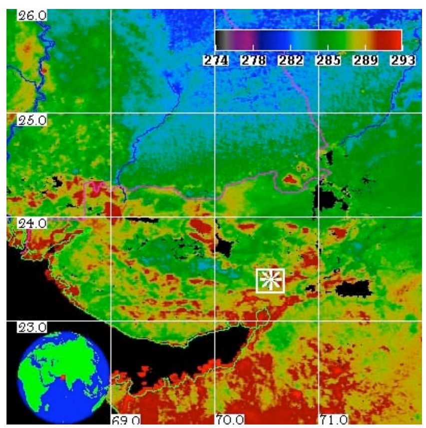


Jan 18: **-8 days**

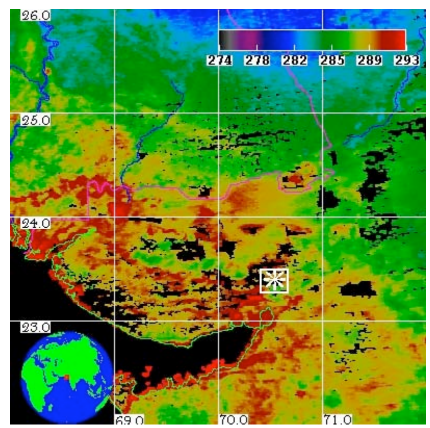
Jan 19: **-7 days**



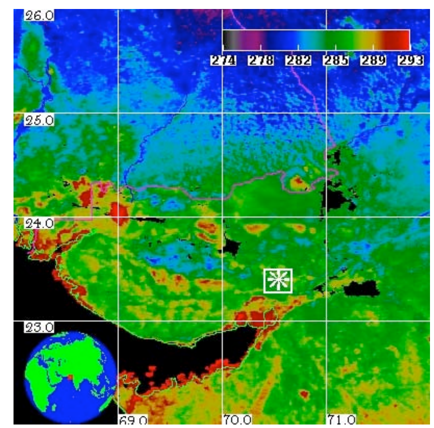
Jan 20: **-6 days**



Jan 21: **-5 days**



Jan 22: **-4 days**

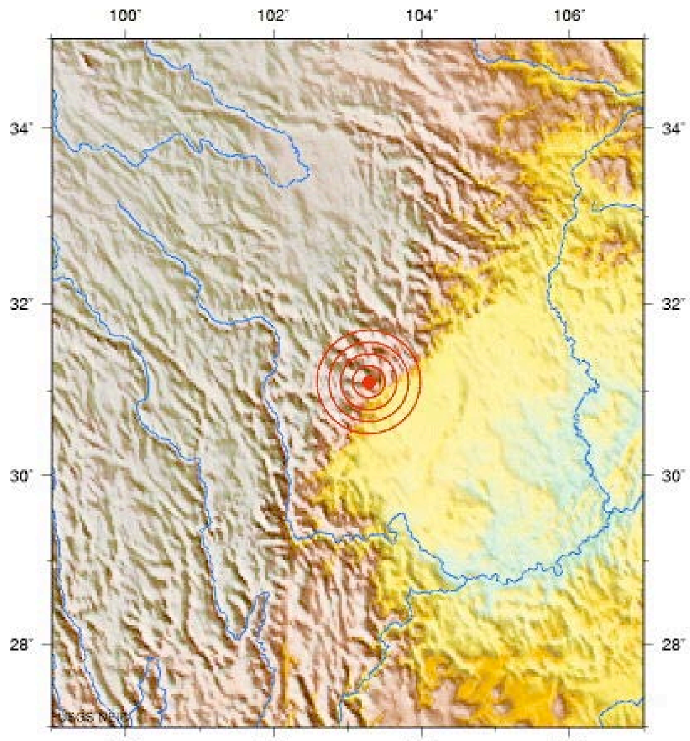


(After Ouzounov and Freund, Adv. Space Sci. 2004)

Wenchuan M~7.9

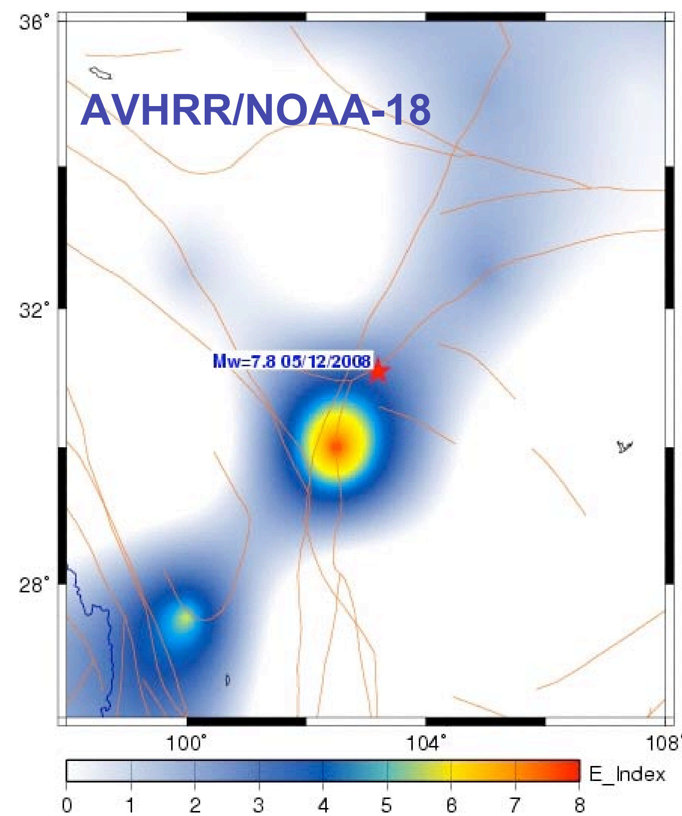
Sichuan, China, May 12, 2008

USGS location map



EASTERN SICHUAN, CHINA
2008 05 12 06:28:00 UTC 31.10N 103.28E Depth: 10.0 km, Magnitude: 7.9
Earthquake Location

TIR anomaly average March 2008



Courtesy Dimitar Ouzounov, NASA GSFC May 12, 2008

Non-seismic pre-EQ phenomena appear as

- Atmospheric effects √
- Ionospheric effects √
- IR emission √
- other ephemeral phenomena like EM emissions

…no time today

Conclusions

- **Non-seismic pre-EQ phenomena appear as**
  - **Atmospheric effects** √
  - **Ionospheric effects** √
  - **IR emission** √
  - **other ephemeral phenomena like EM emissions…**

- **We begin to understand the underlying physics**

- **Everything points to h• charge carriers, stress-activated in the rocks deep below**

- **The h• provide the basis for a unifying theory**

Collaborators

- **Ipek Kulahci**, Carl Sagan Center, SETI Institute, Mountain View.
- **Gary Cyr**, San Jose State University Foundation.
- **Minoru Freund, Jennifer Dungan, Vern Vanderbilt, Christine Hlavka, Buzz Slye**
  NASA Ames Research Center.

Summer Students

- Milton Bose, Julia Ling, Jeremy Tregloan-Reed, Matthew Winnick, Shicong Xi, James King

NASA Engineering Staff

- **Jerry Wang, Lynn Hofland, Frank Pichay, Ben Helvensteijn**