Precursory TEC enhancement immediately before the 2011 Tohoku-Oki earthquake

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020919 GPS antenna standing against the tsunami debris (photo by GSI)

GPS is versatile

Original

Spin-off

Precipitable Water Vapor

Crustal movement

POD

Navigation

Earth rotation

Seismometer

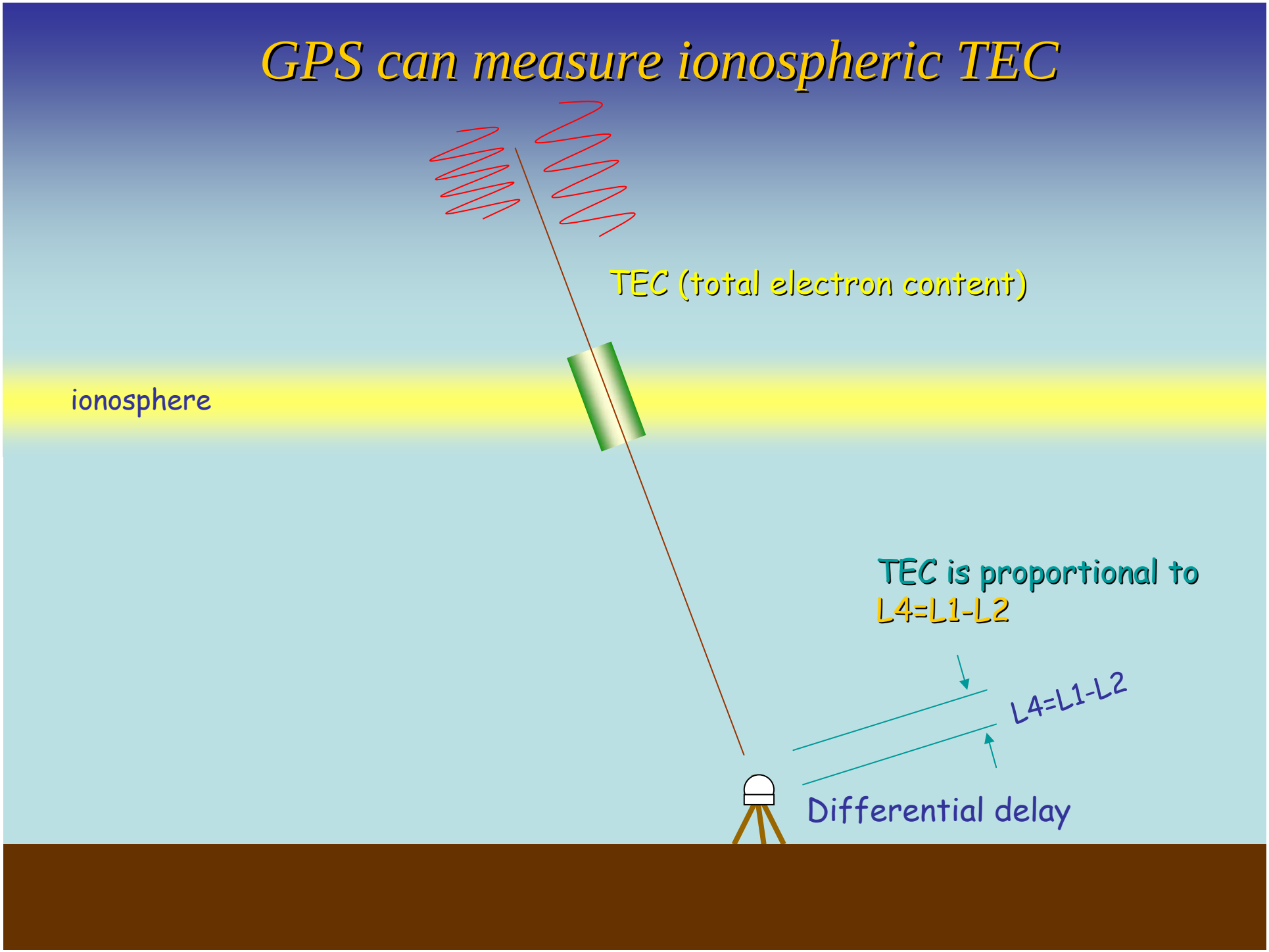
Time transfer

Total Electron Content

Soil moisture

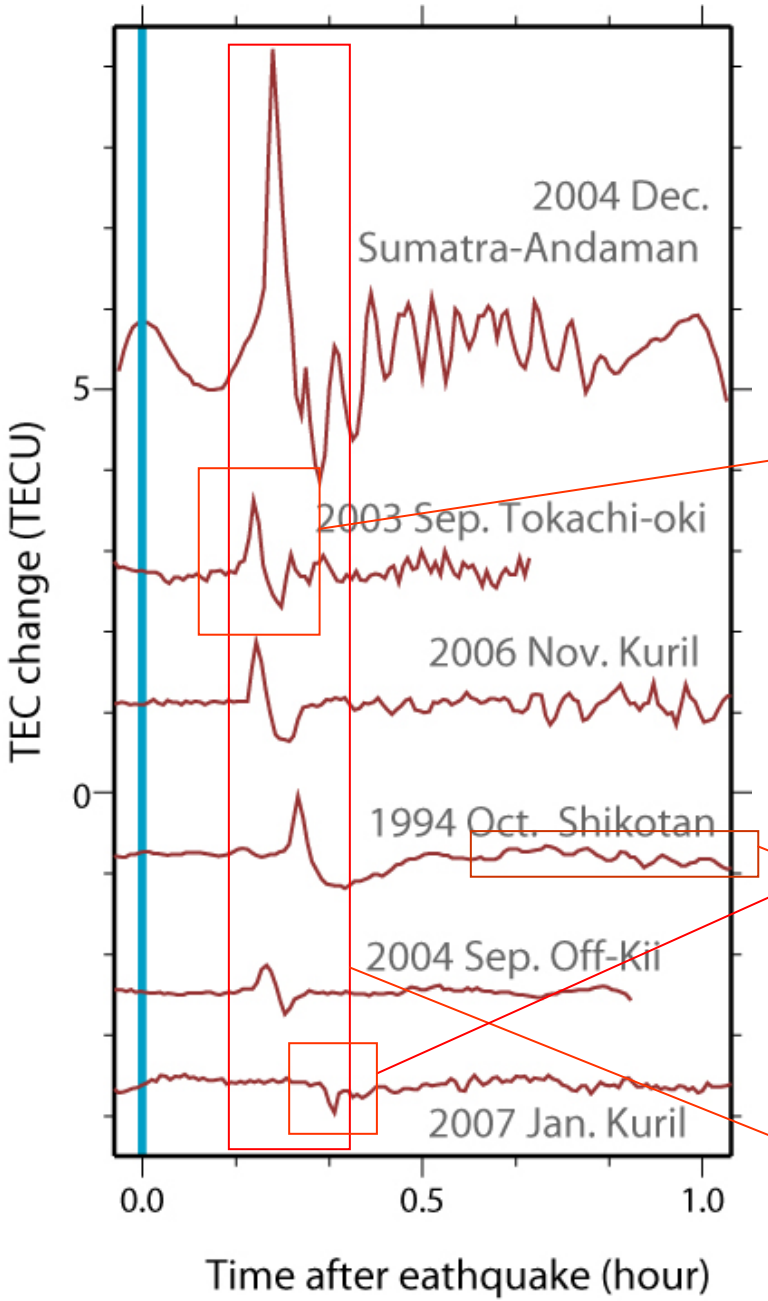
Snow depth

GPS can measure ionospheric TEC

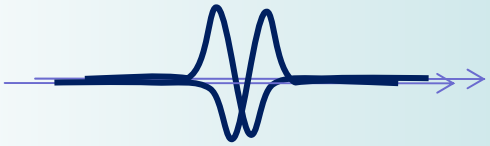


Coseismic Ionospheric Disturbance

Past examples



2. Positive initial motion, period ~4.5 min.
amplitudes a few 0.1~1 TECU

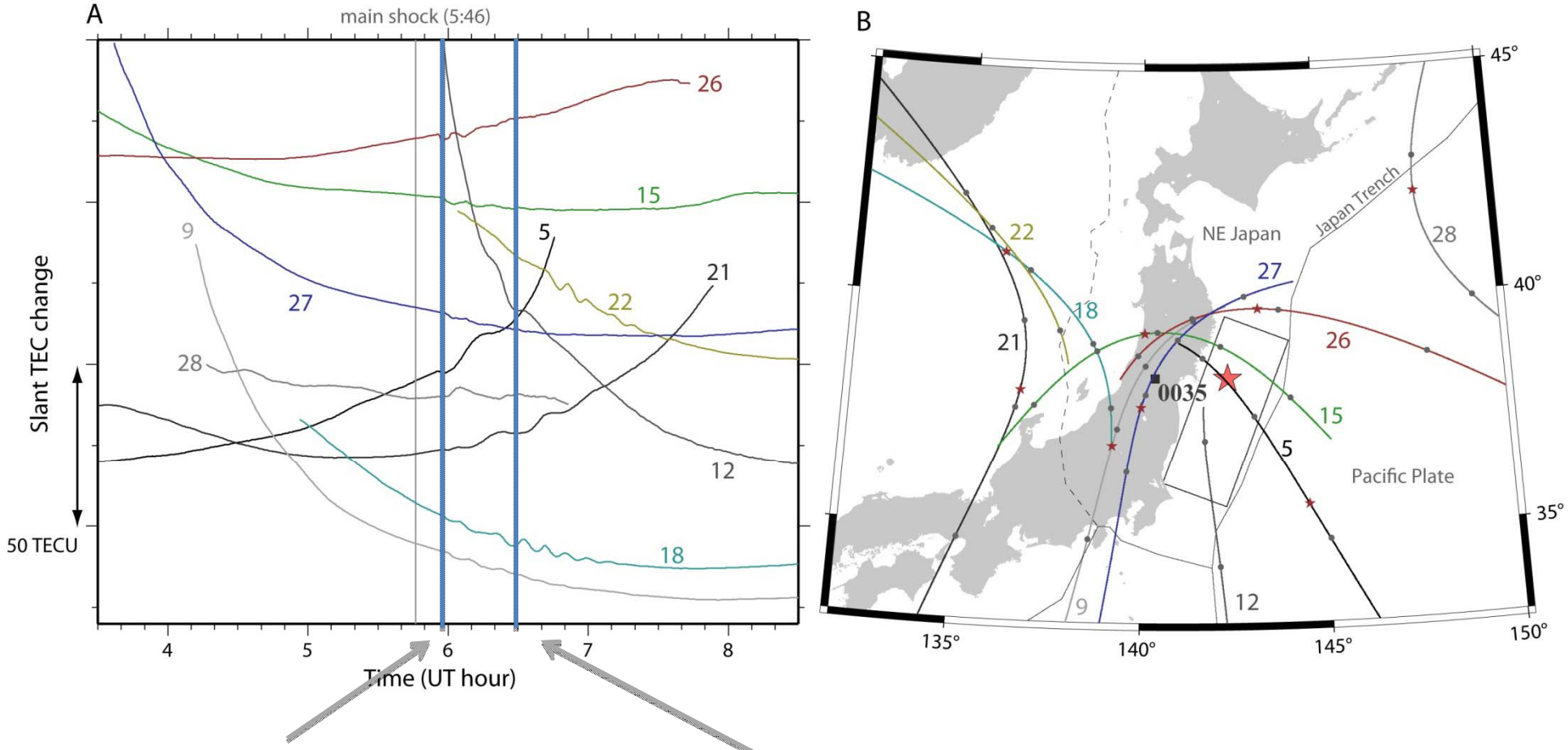


"N-shape"

3. Resonant oscillation continues

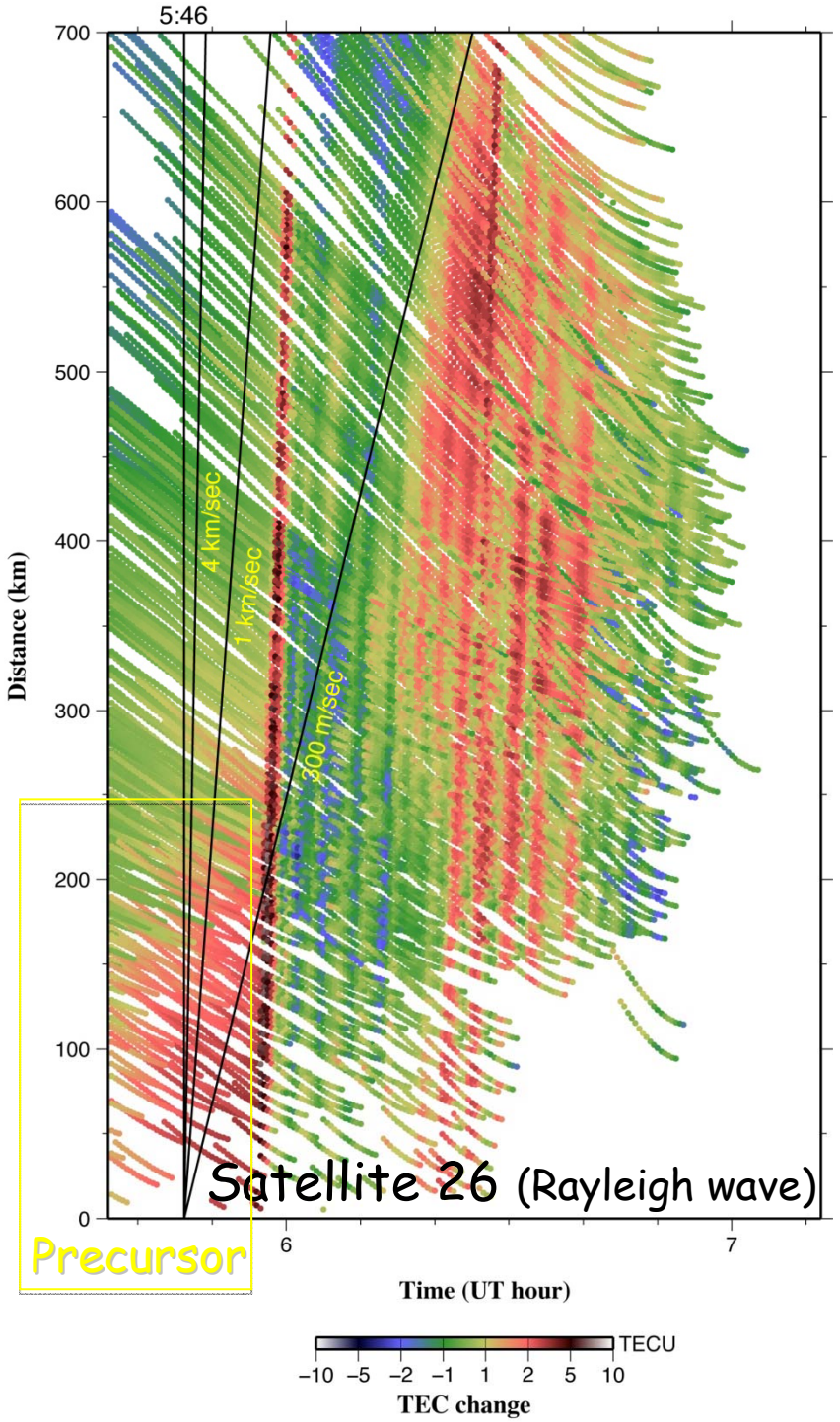
1. Appear ~10 min. after eq.

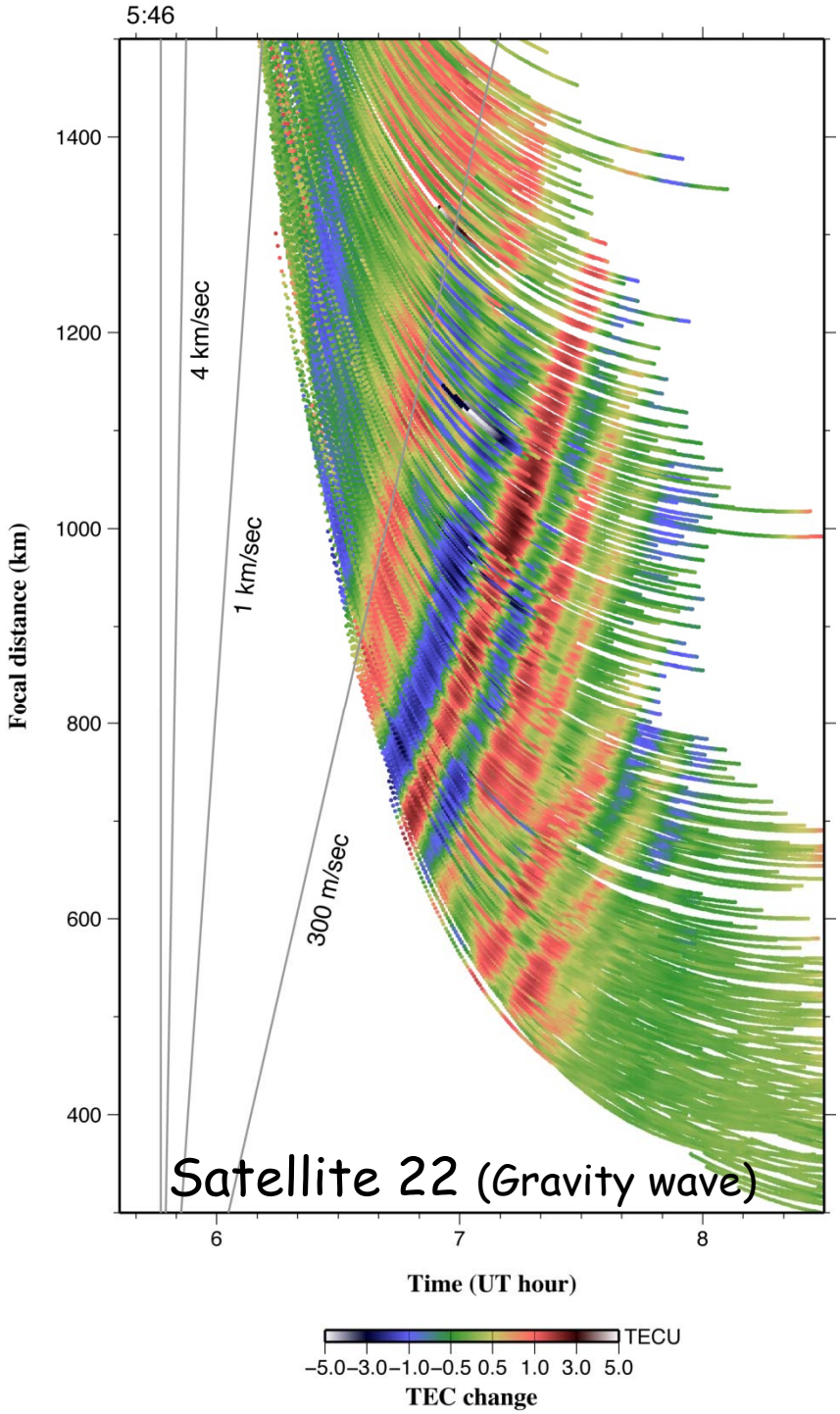
Raw TEC and Sub-ionospheric point (SIP) trajectory 3.5-8.5 UT



10 min.
(arrival of acoustic wave)

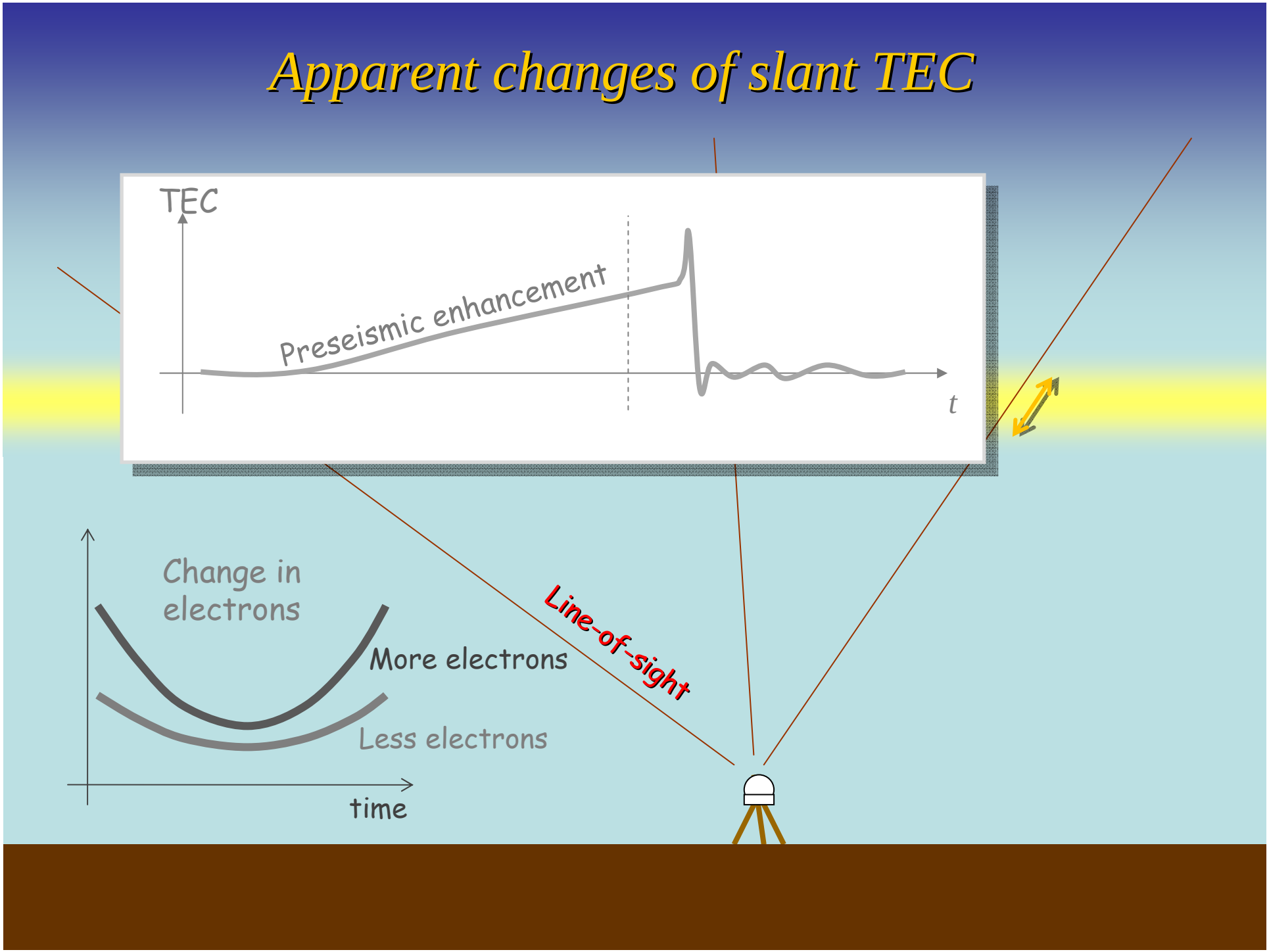
40-60 min.
(arrival of gravity wave)


5:46
Distance (km)
4 km/sec
1 km/sec
300 m/sec
Precursor
Satellite 26 (Rayleigh wave)
Time (UT hour)
TECU
−10 −5 −2 −1 1 2 5 10
TEC change

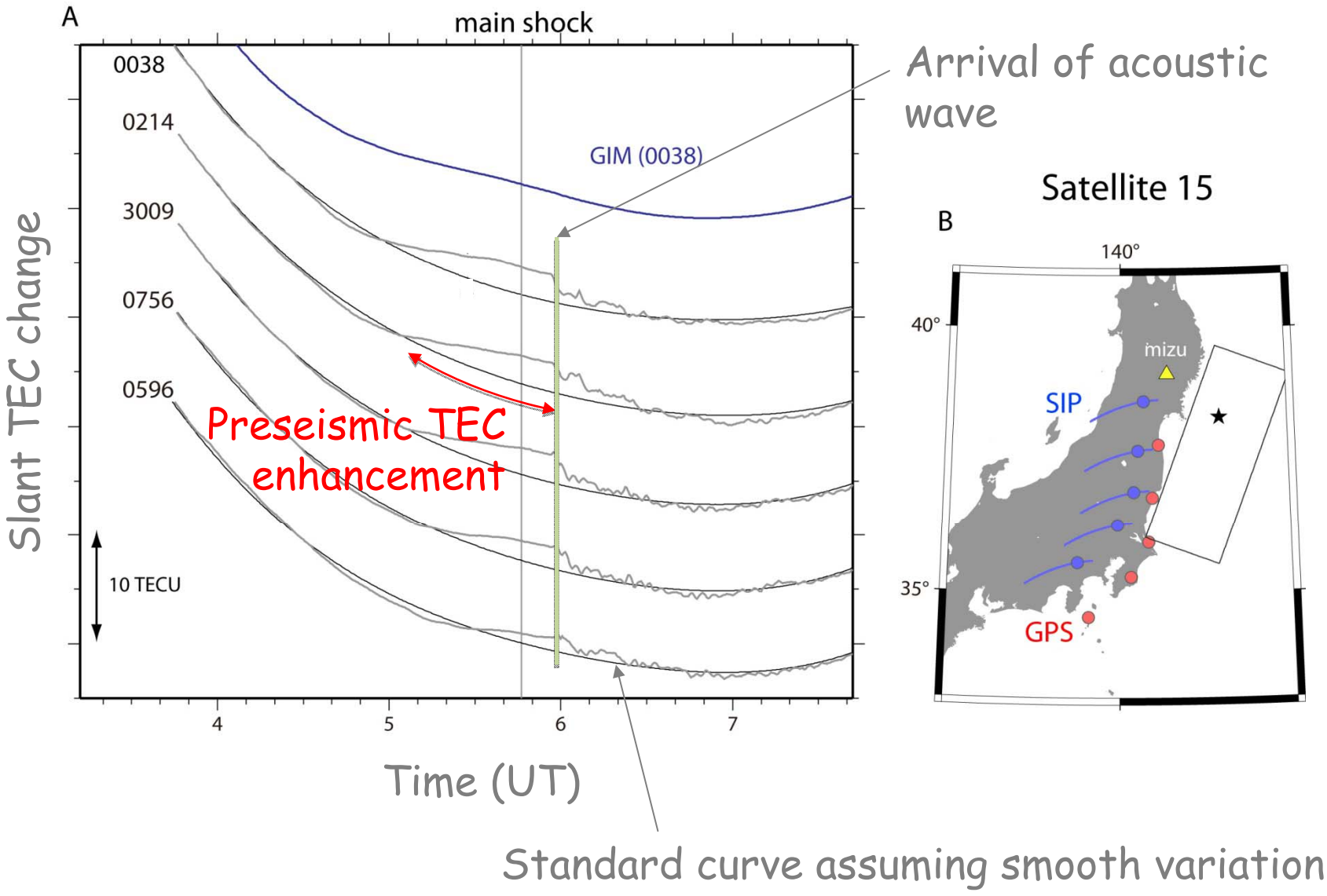

5:46
Focal distance (km)
4 km/sec
1 km/sec
300 m/sec
Satellite 22 (Gravity wave)
Time (UT hour)
TECU
−5.0 −3.0 −1.0 −0.5 0.5 1.0 3.0 5.0
TEC change

Slant TEC time series
Satellites 15/26

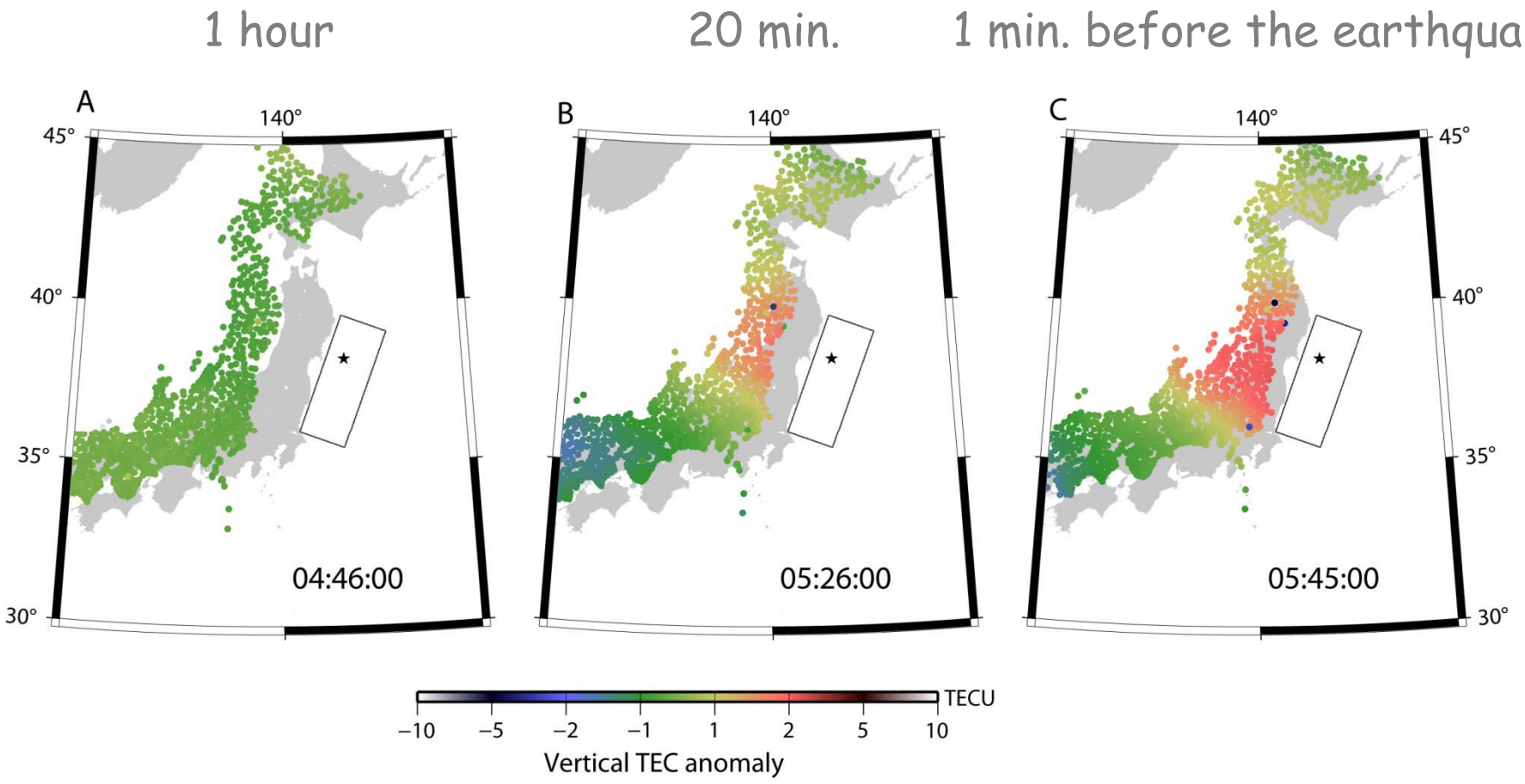
Apparent changes of slant TEC



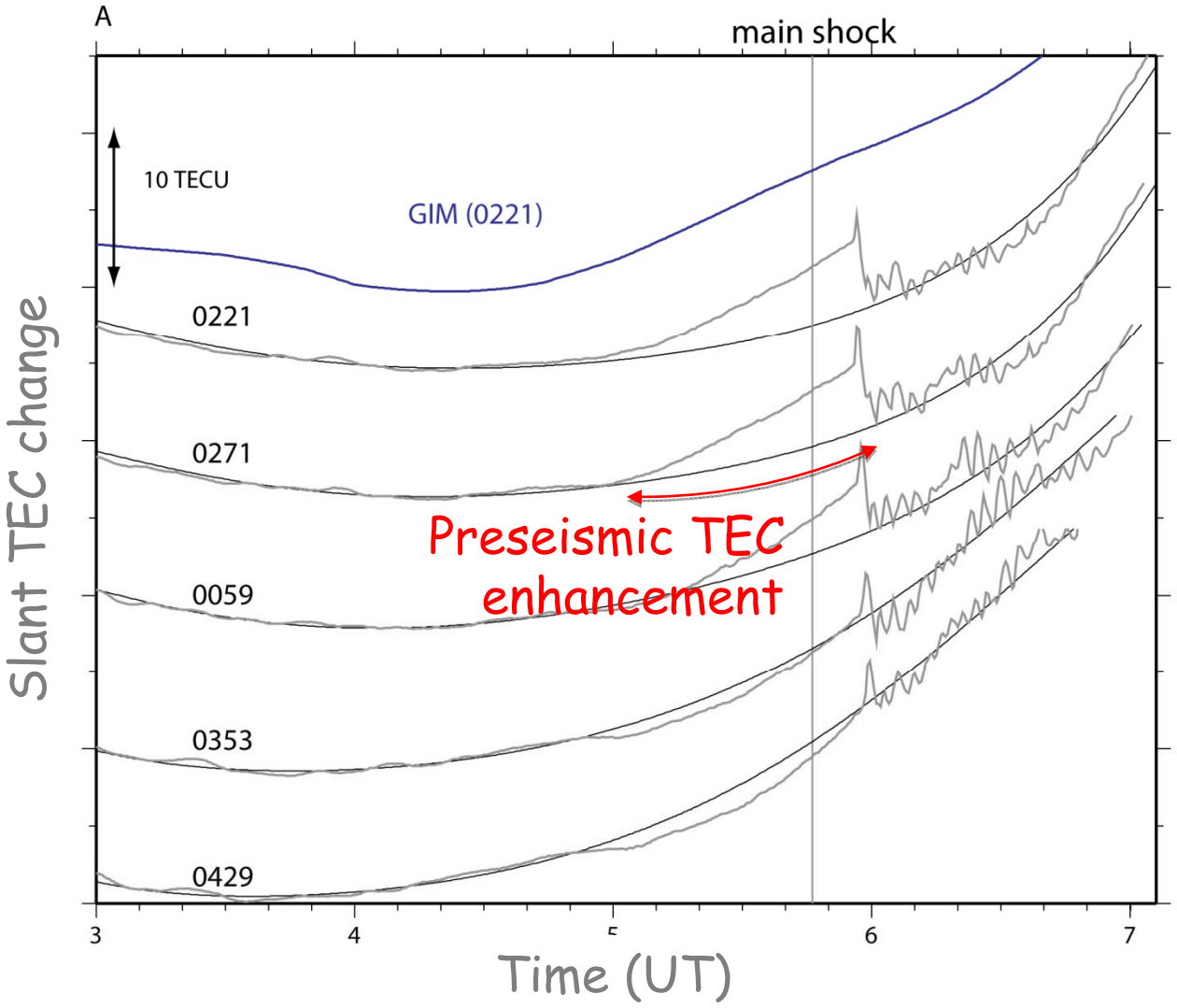
Slant TEC with satellite 15 near zenith

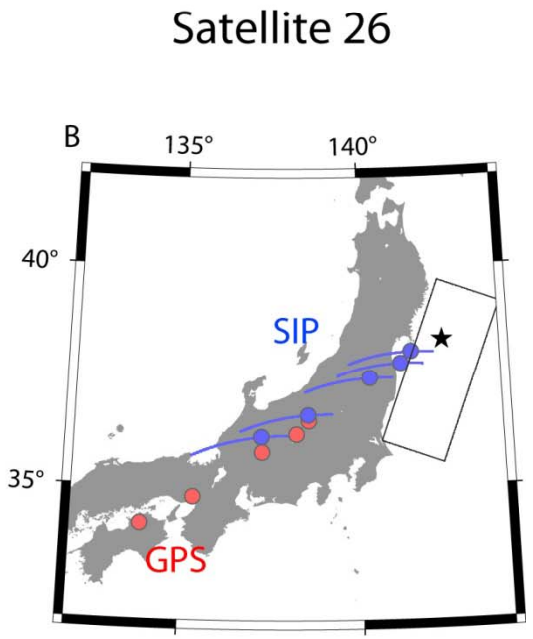


Preseismic TEC enhancement : Satellite 15

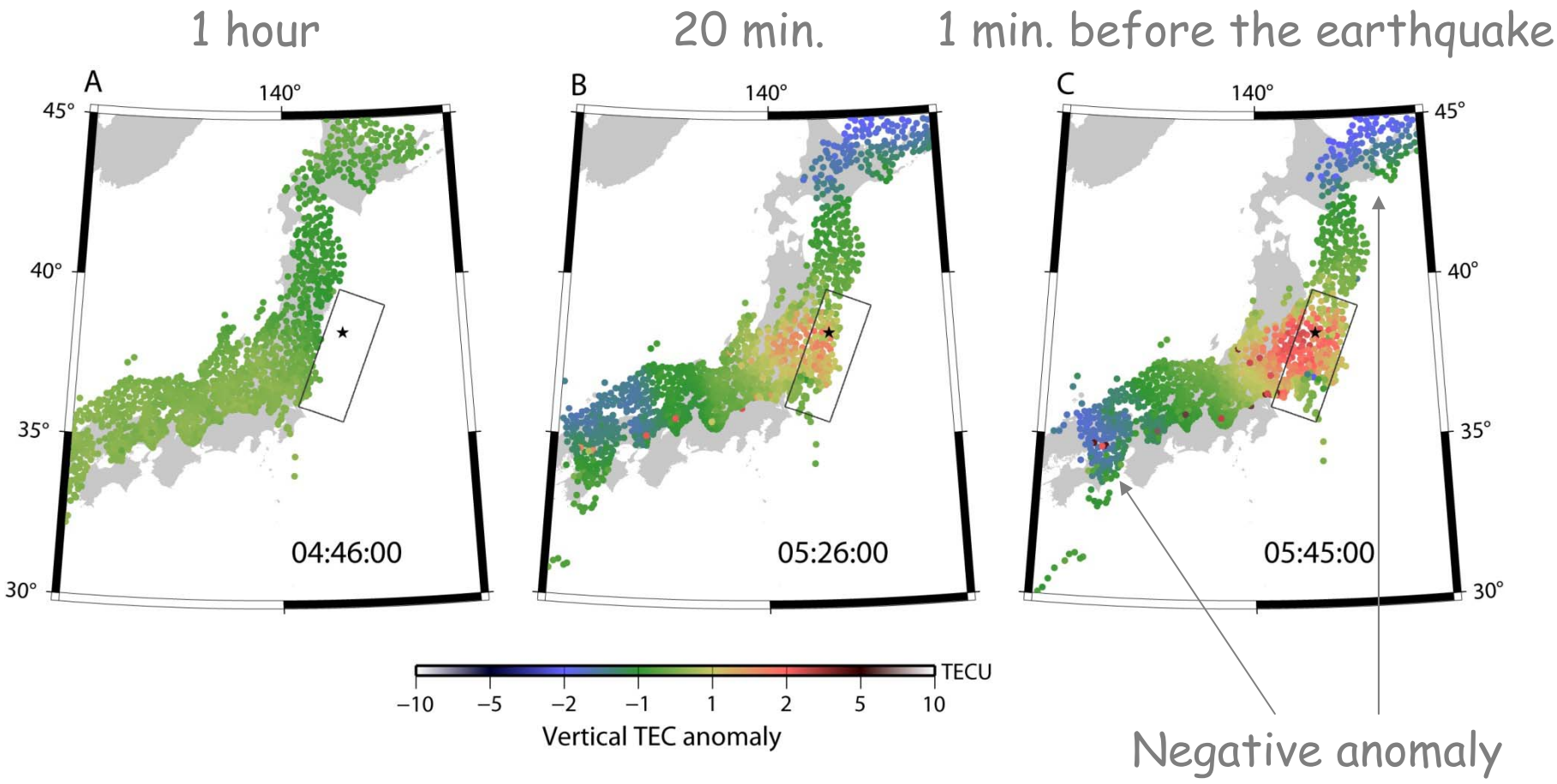


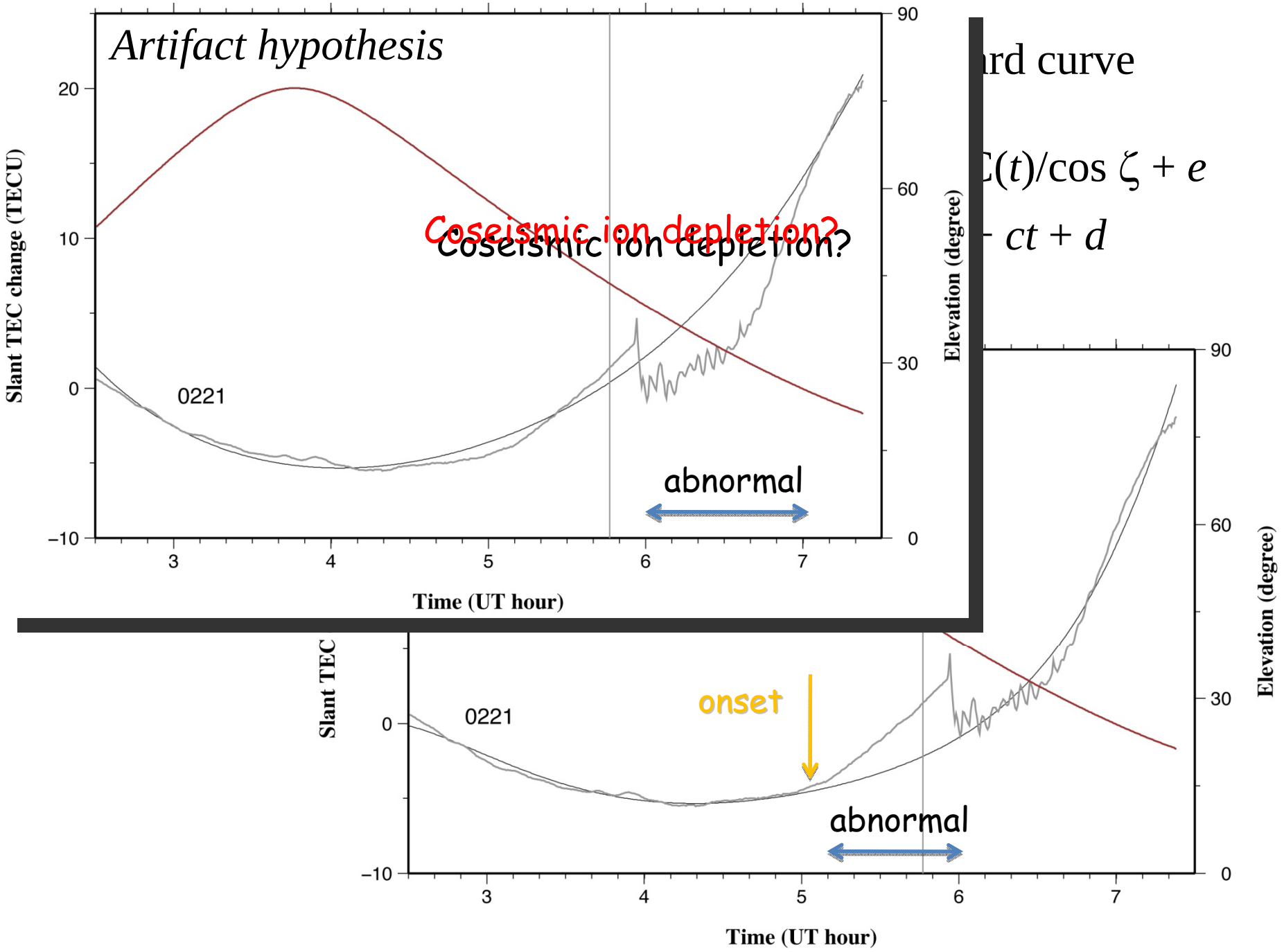
Slant TEC with satellite 26 in the eastern sky





Preseismic TEC enhancement : Satellite 26



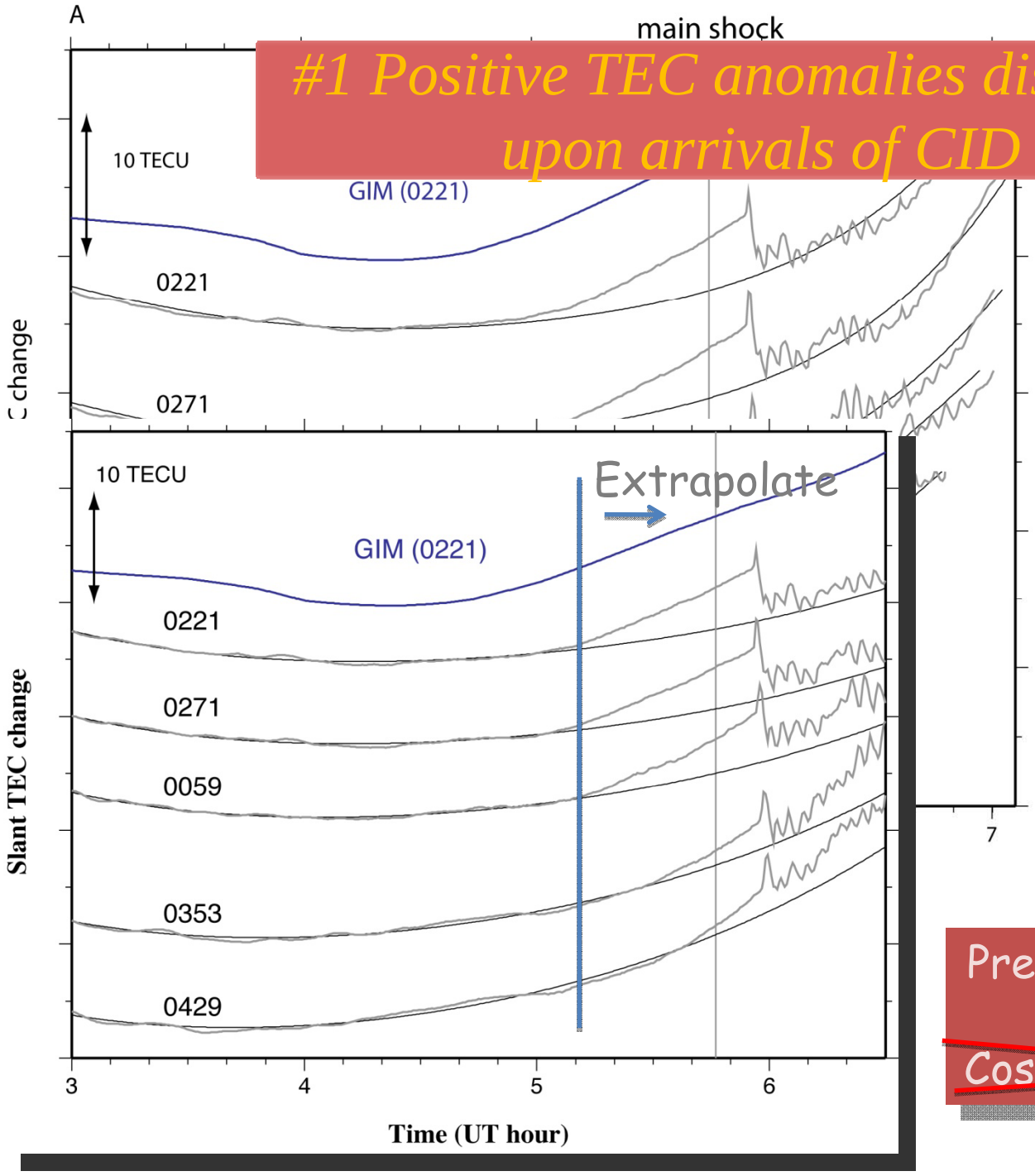

Artifact hypothesis
Coseismic ion depletion?
Coseismic ion depletion?
0221
abnormal
Slant TEC change (TECU)
Elevation (degree)
Time (UT hour)
rd curve
C(t)/cos ζ + e
- ct + d
Slant TEC
onset
0221
abnormal
Slant TEC
Elevation (degree)
Time (UT hour)

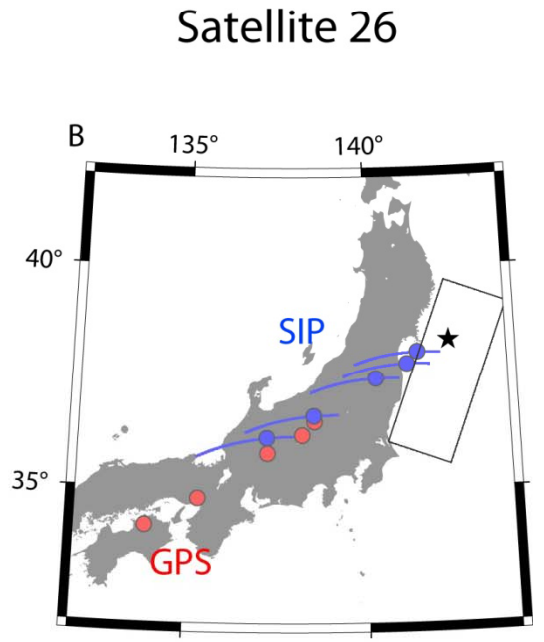
Four objections to the Artifact hypothesis

1. *Extrapolation*
2. *d*TEC/*dt*
3. *Satellite #9*
4. *Numerical identification of onset*

Please see my GRL paper [*Heki*, 2011] for detail

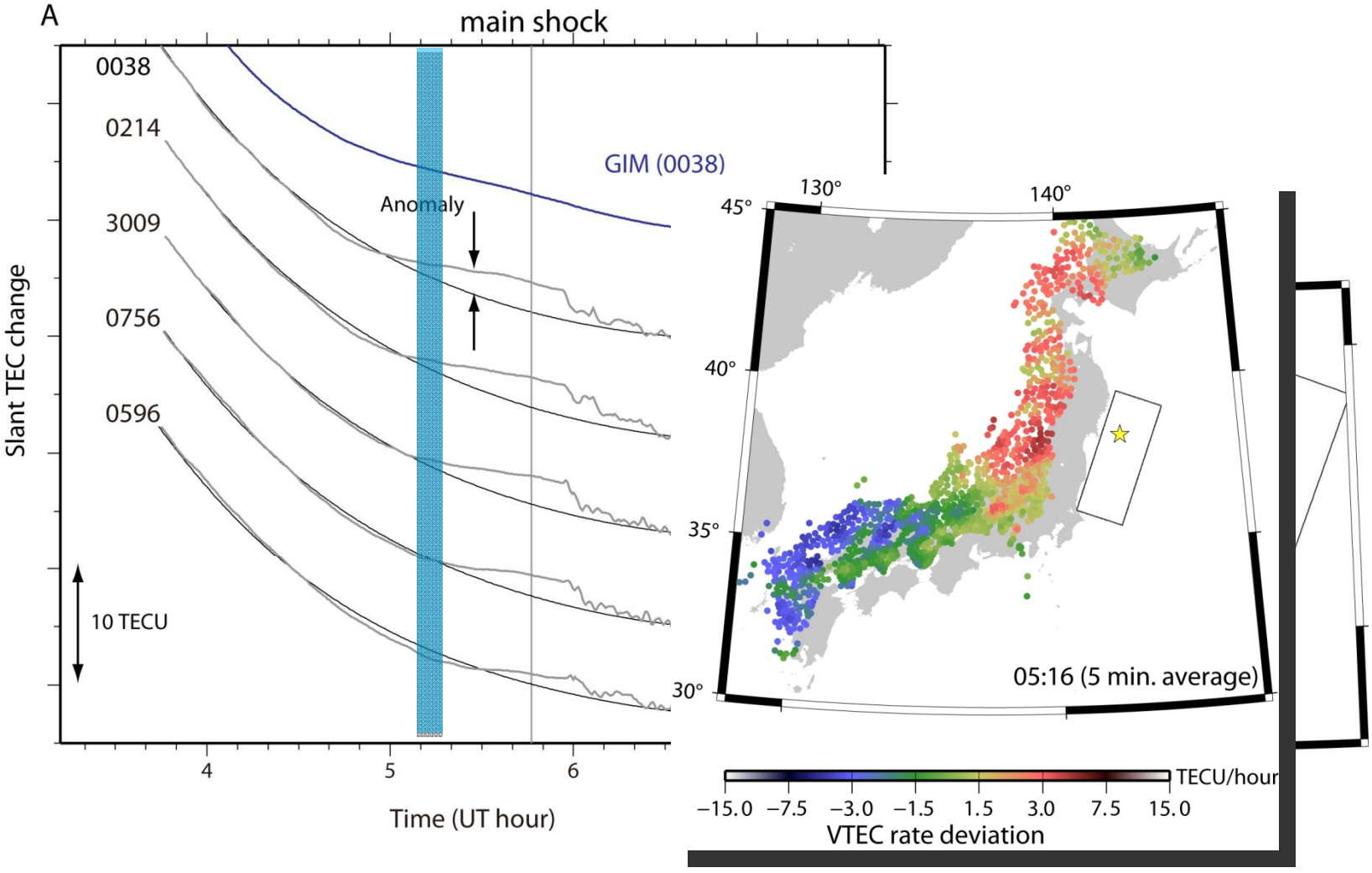
#1 Positive TEC anomalies disappear upon arrivals of CID

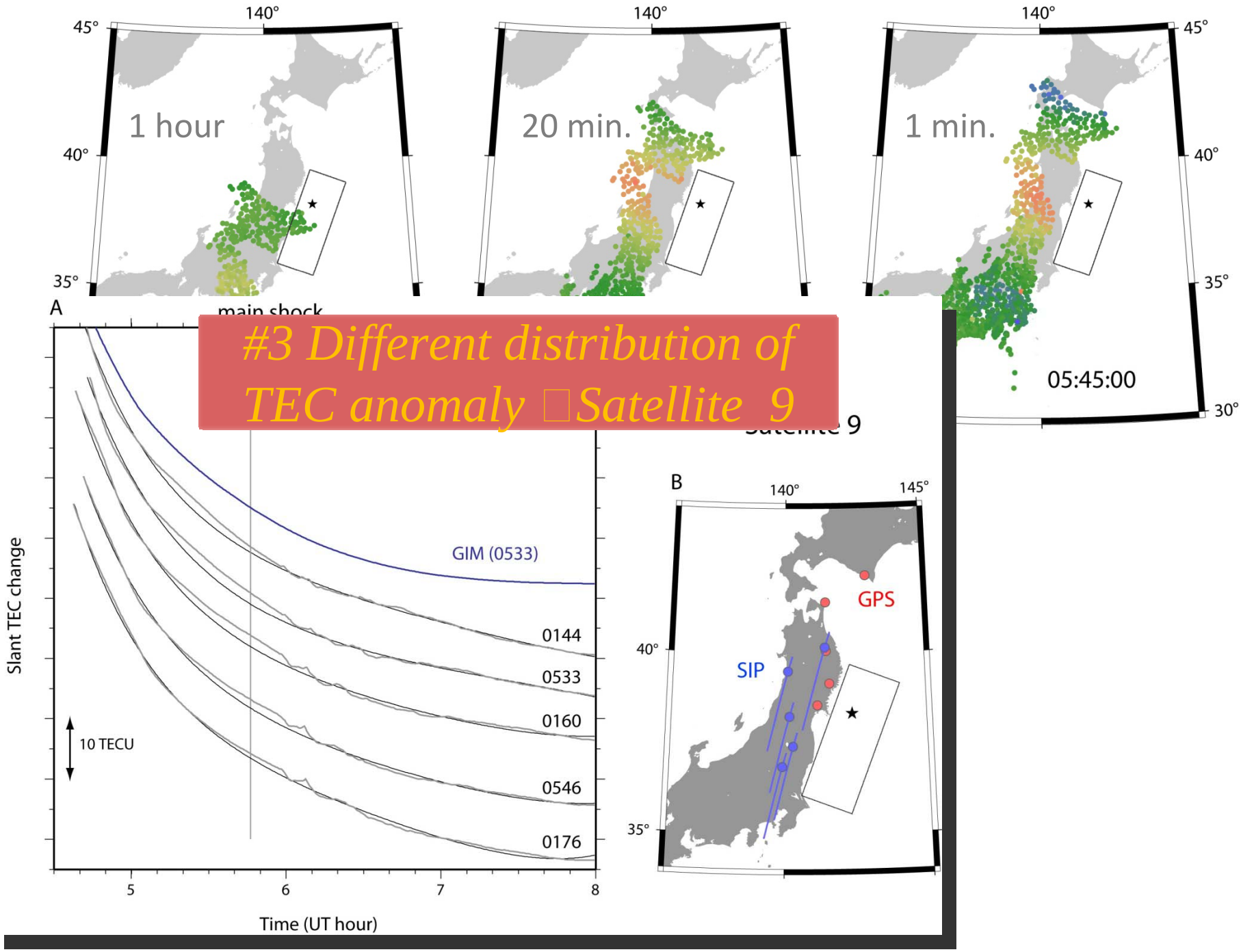




Preseismic TEC increase
or
~~Coseismic TEC decrease?~~

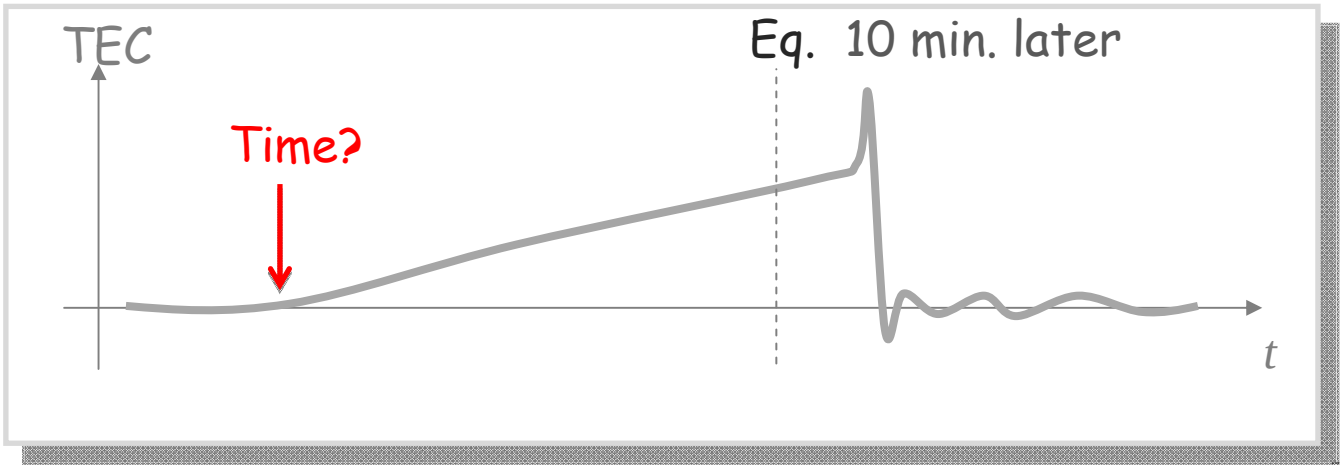
#2 dTEC/dt 30 minutes before earthquake





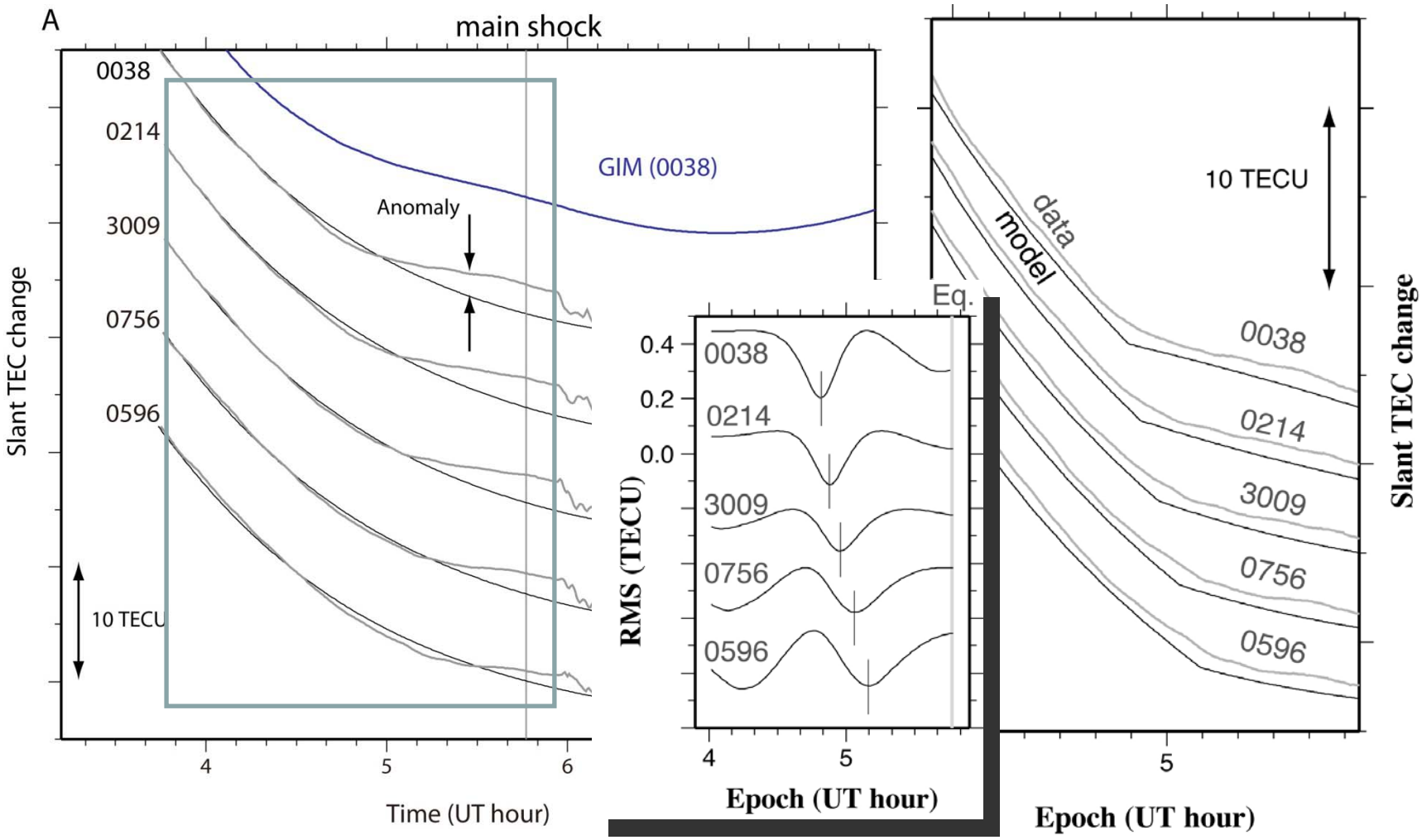
#3 Different distribution of TEC anomaly □Satellite 9

What time did the anomaly start?



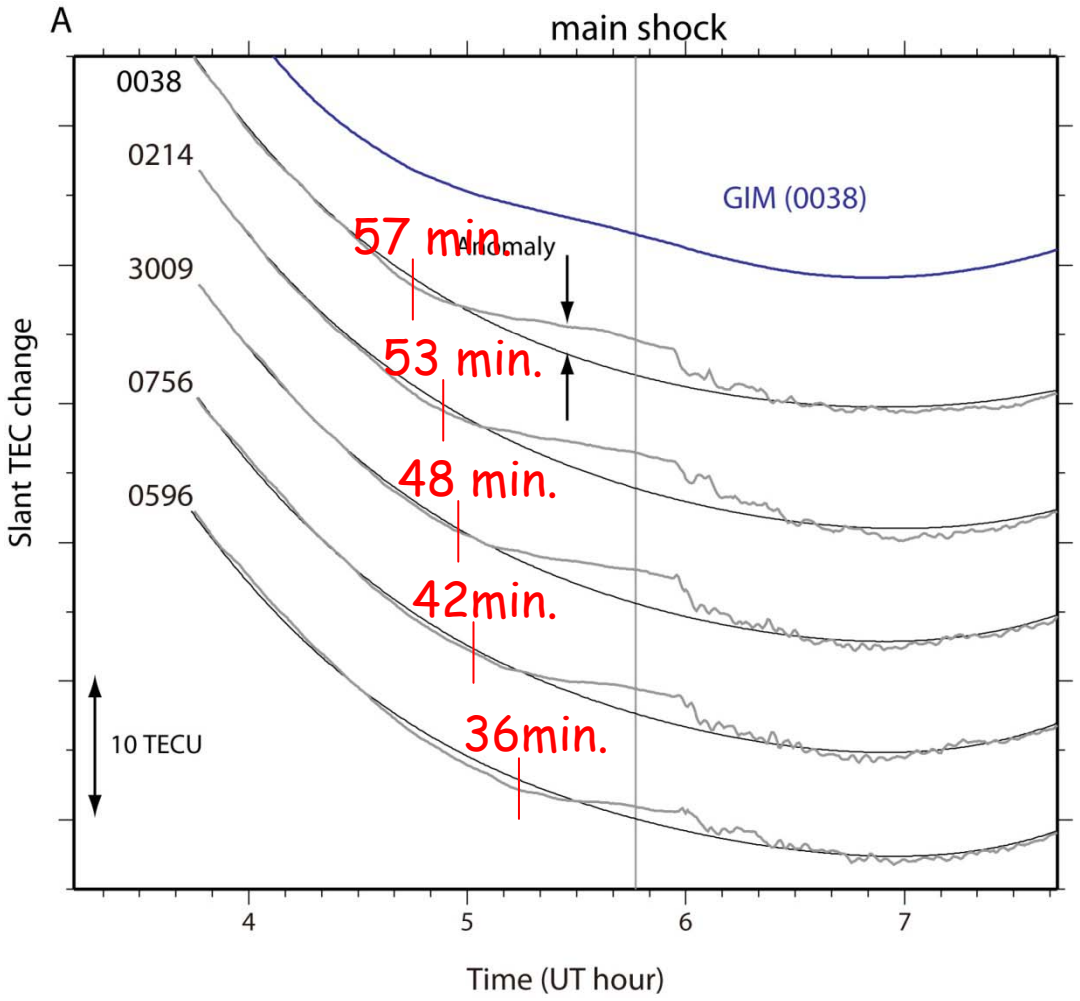
Objective inference of preseismic TEC breaks

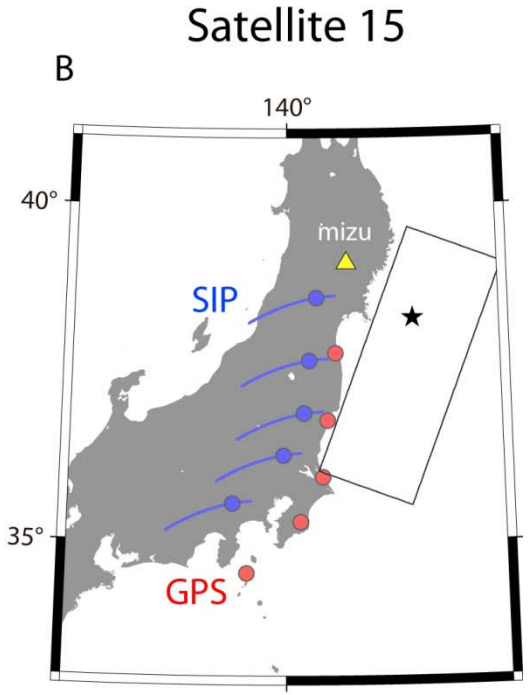
Modeling preseismic changes with
two lines connected to each other



Objective inference of break points

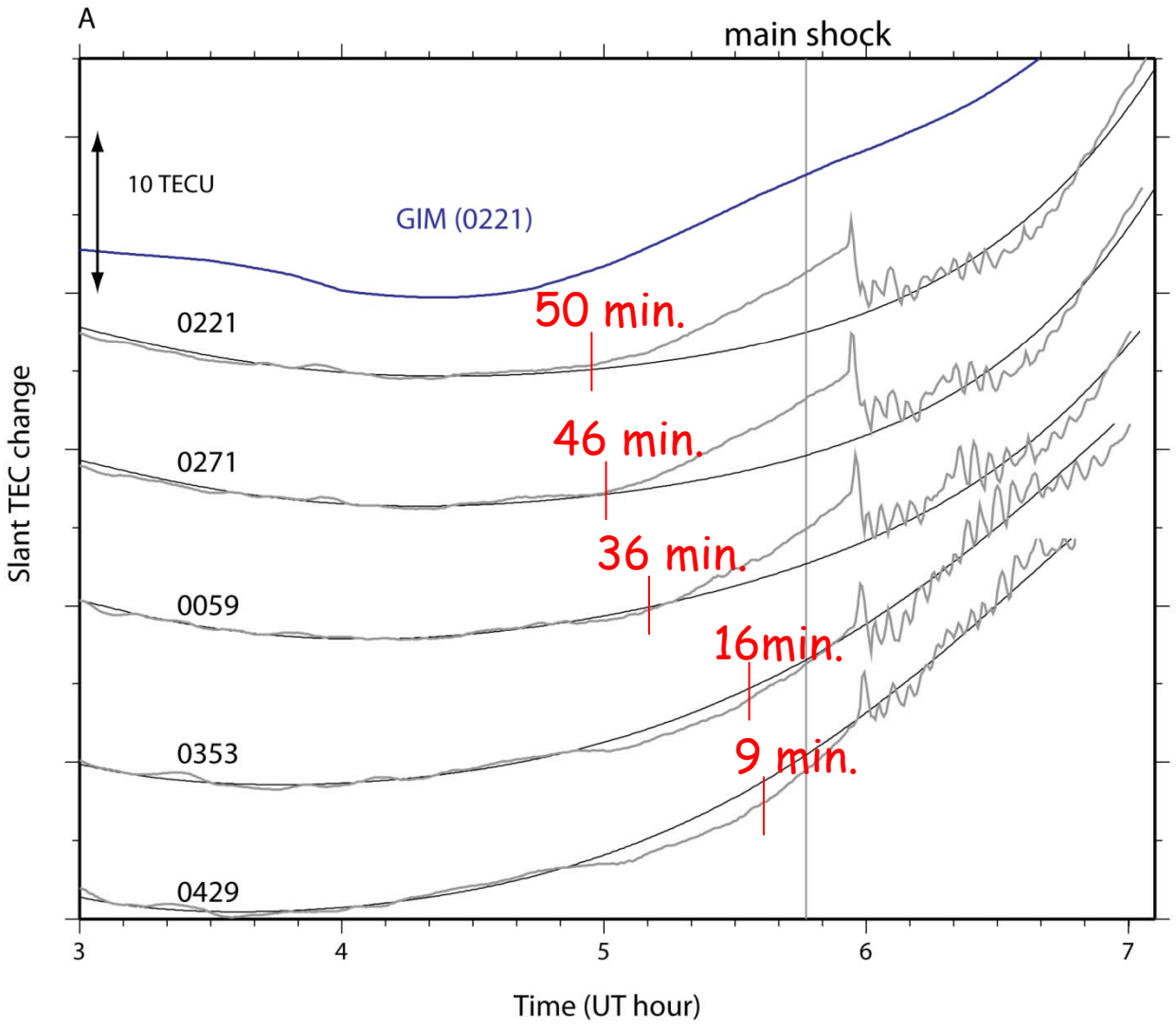
(Satellite 15, search window: 4.0-5.8 UT)

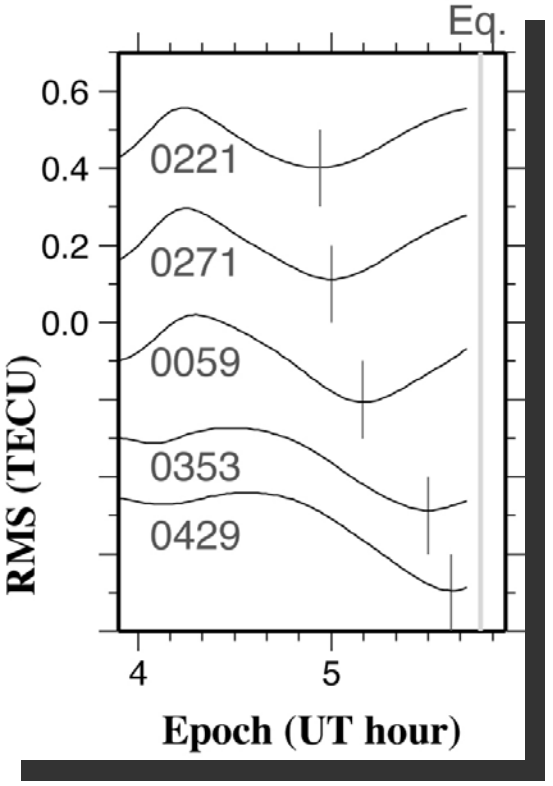




Objective inference of break points

(Satellite 26, search window: 3.0-5.8 UT)





What happened in the ionosphere?

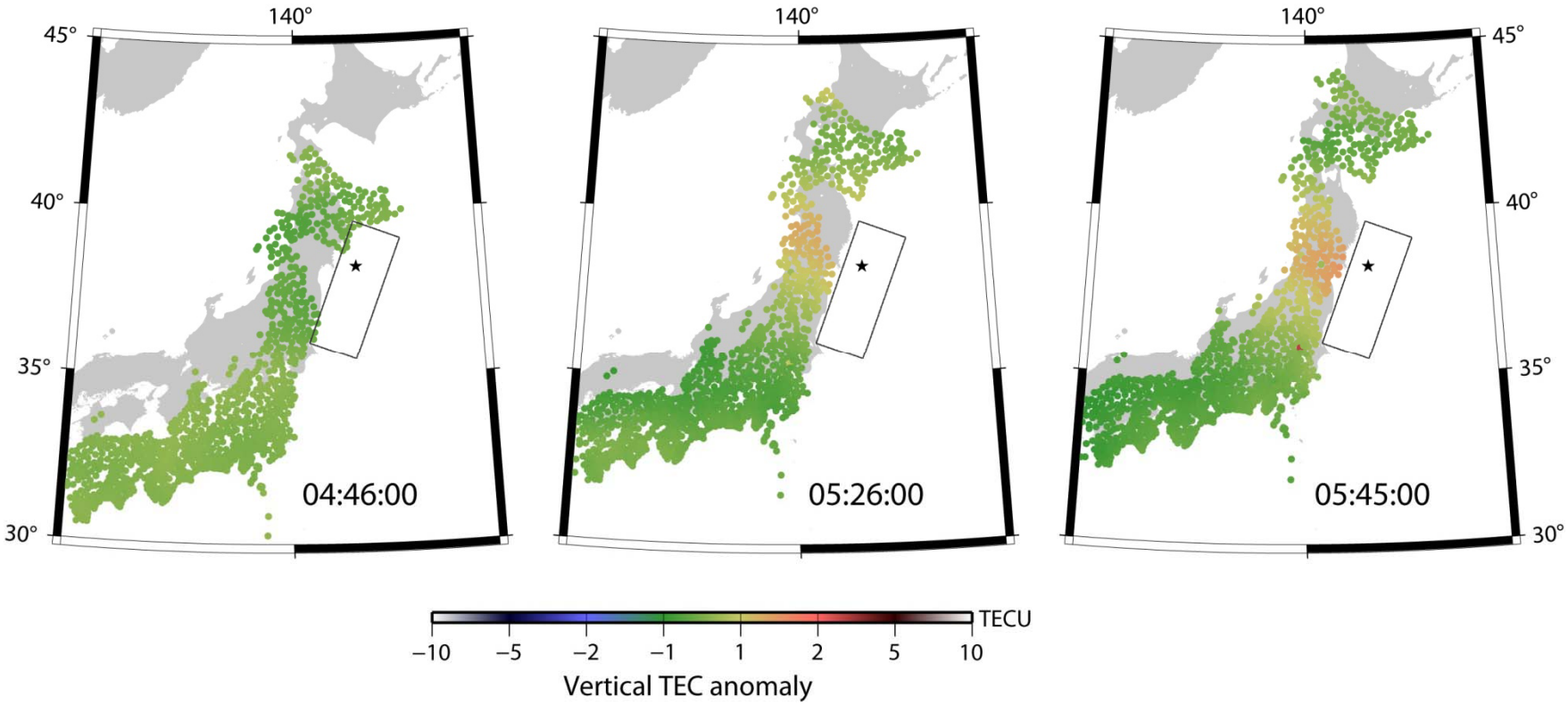
3-D structure of the TEC anomaly

Satellites 15,26 : strong anomaly

Satellites 9,27 : weak anomaly

One more satellite: satellite #27 in southern sky

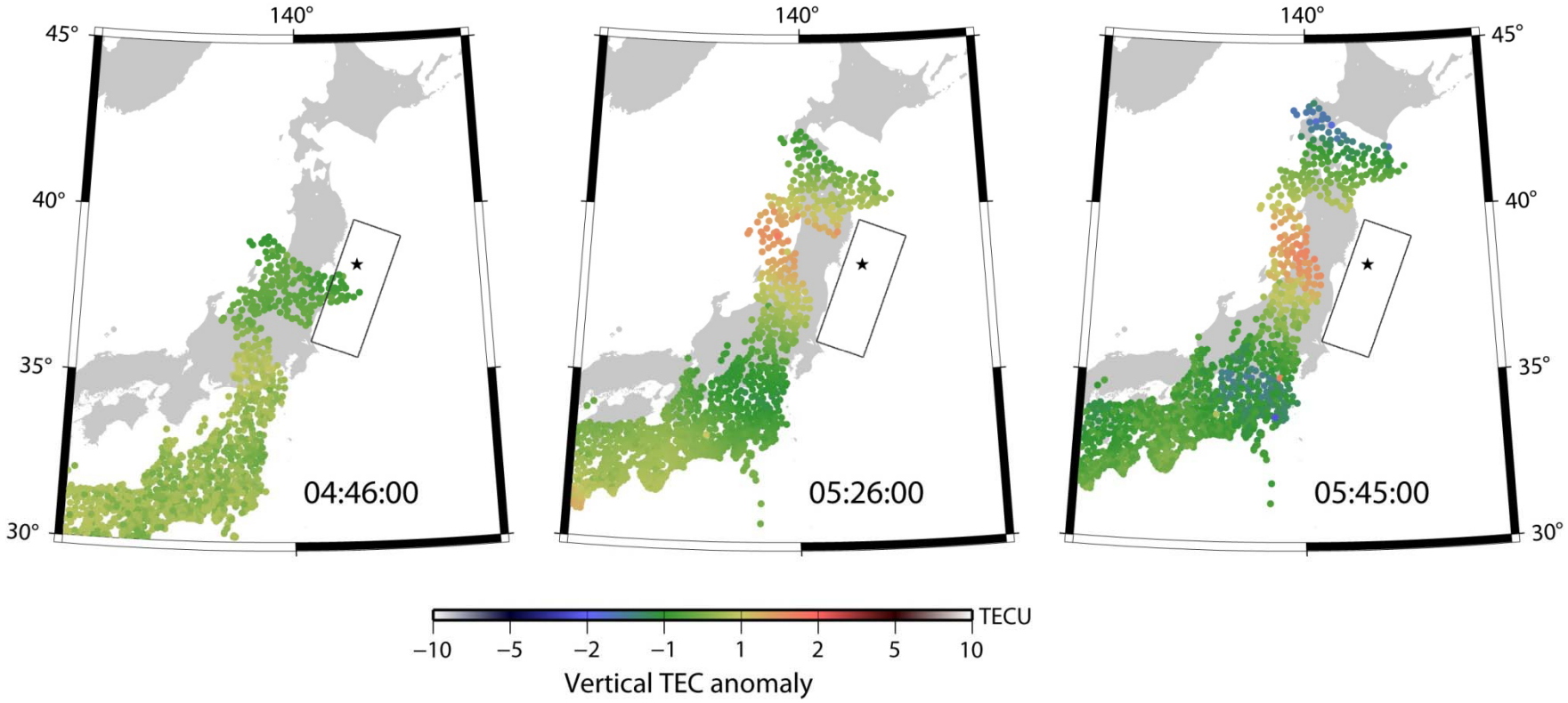
1 hour | 20 min. | 1 min. before the earthquake



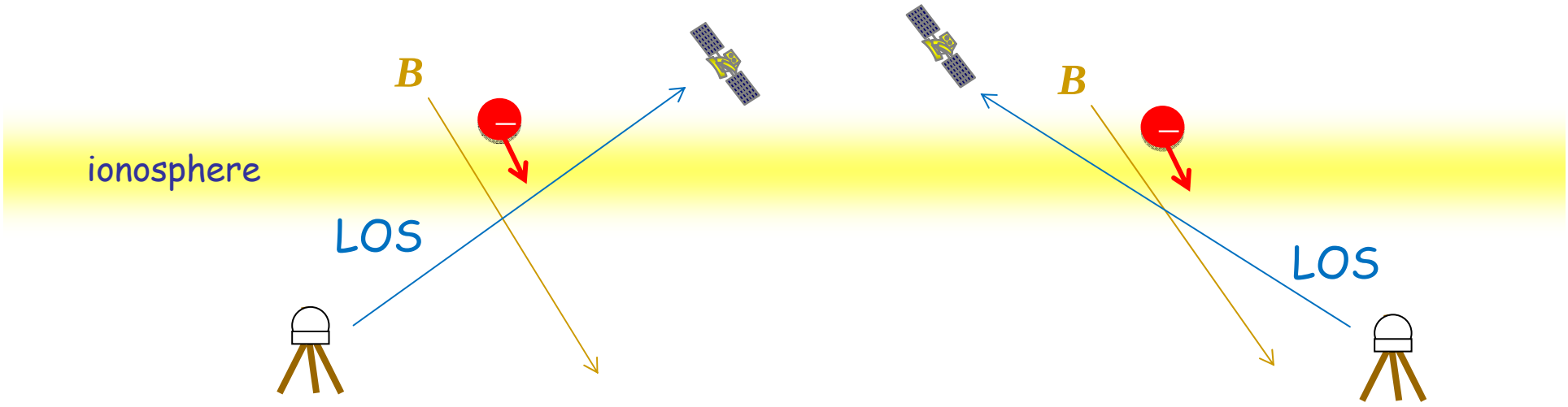
Satellite with strong anomaly (15,26)
Satellite with weak anomaly (9,27)

One more satellite: satellite #9 in the southern sky

1 hour | 20 min. | 1 min. before the earthquake



Satellite with strong anomaly (15,26)
Satellite with weak anomaly (9,27)

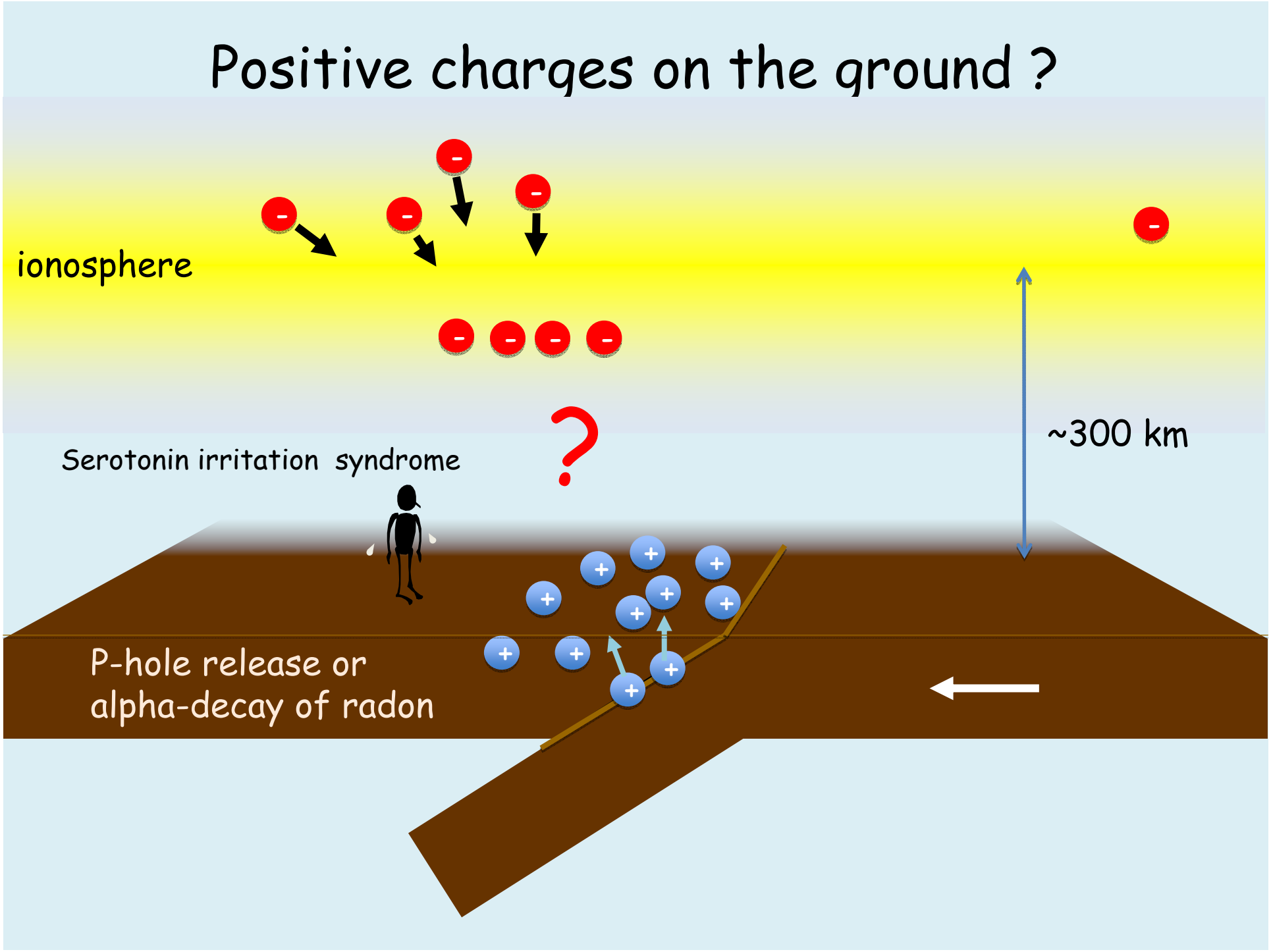


strong anomaly

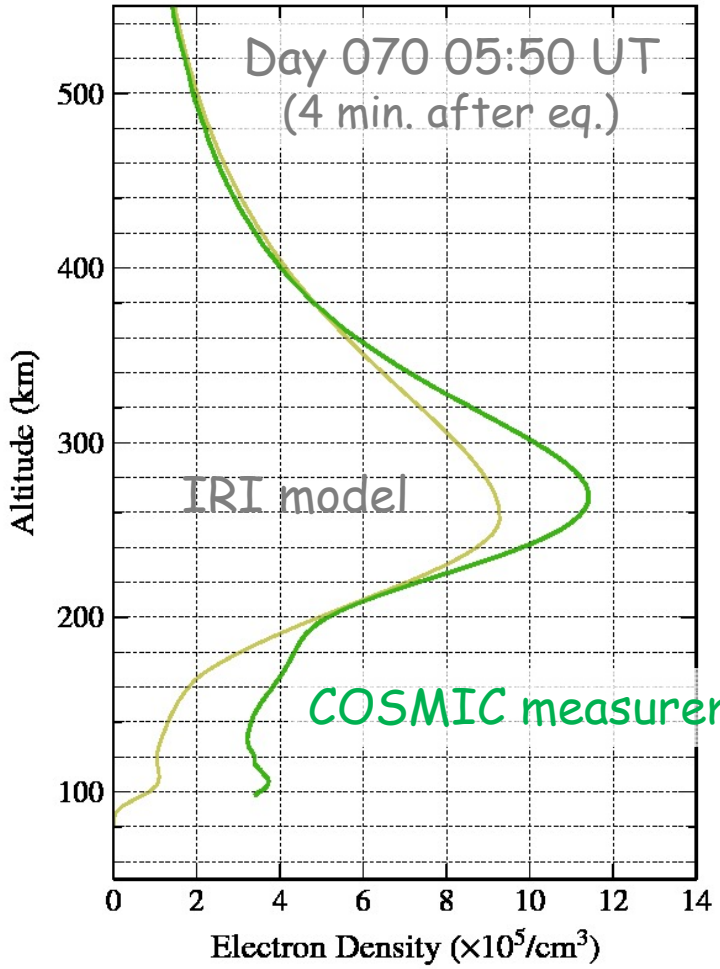
weak anomaly

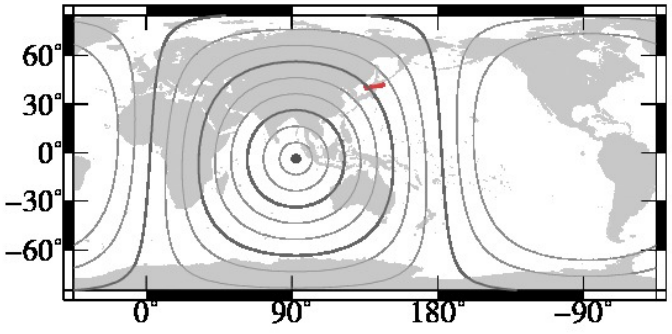
Downward displacement of electrons along ***B*** *?*

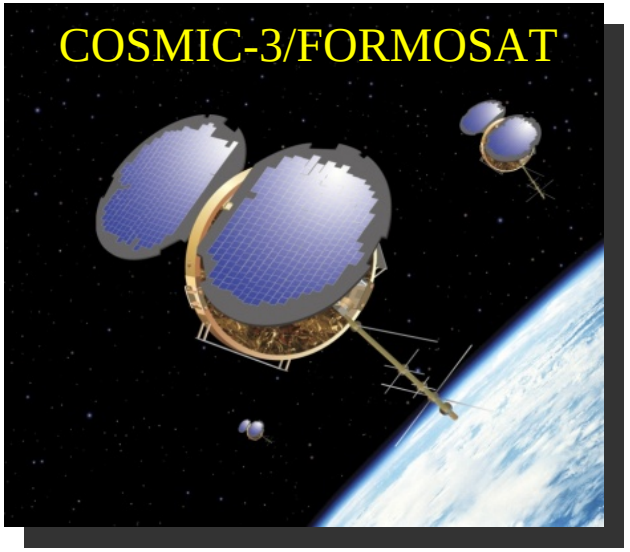
Positive charges on the ground ?



Electron density profile with GPS Radio Occultation





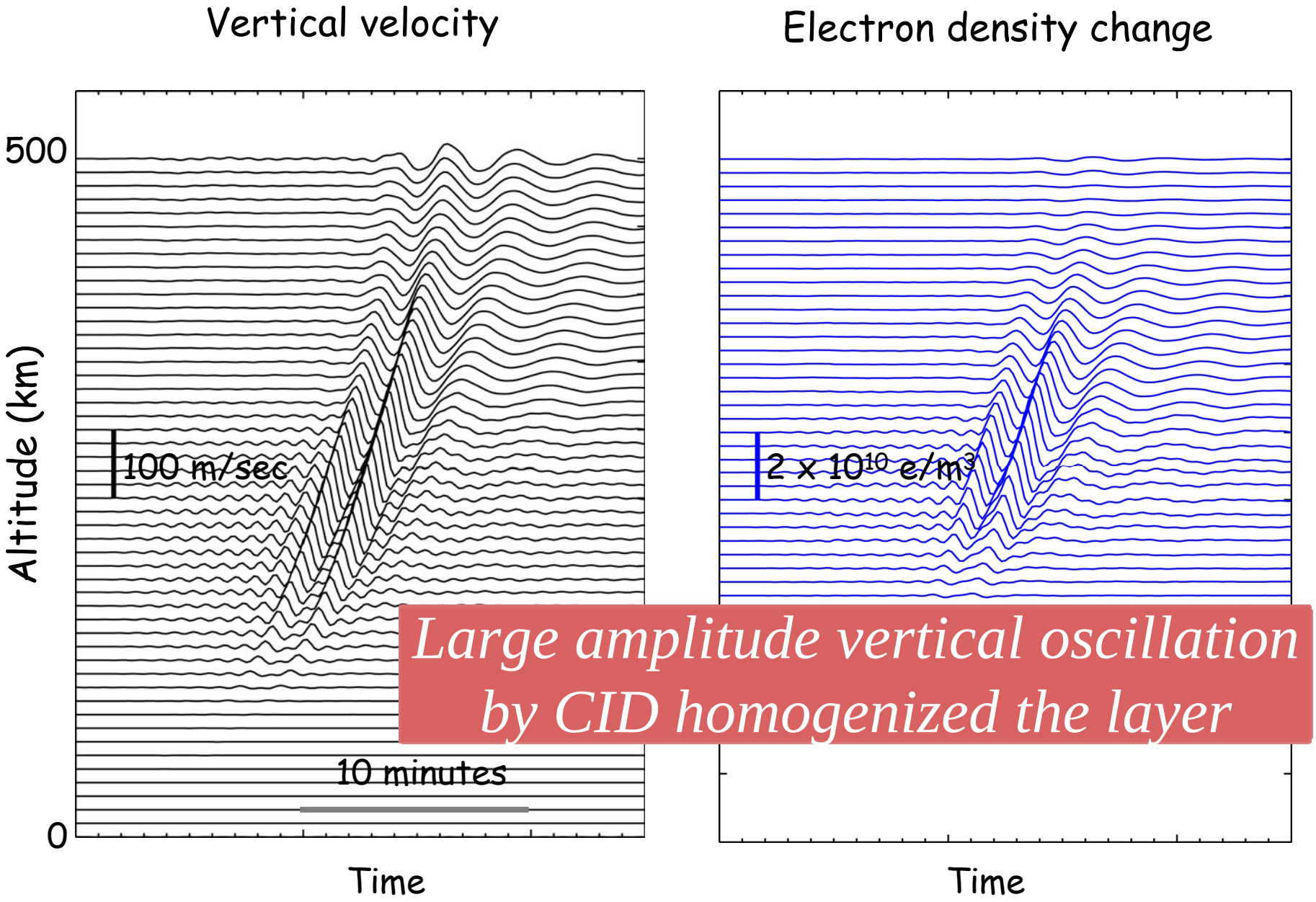


More electrons in lower thermosphere?

Why did anomaly disappear ?

Acoustic wave arrival

Rolland, Lognonné and Munekane (JGR, 2011)

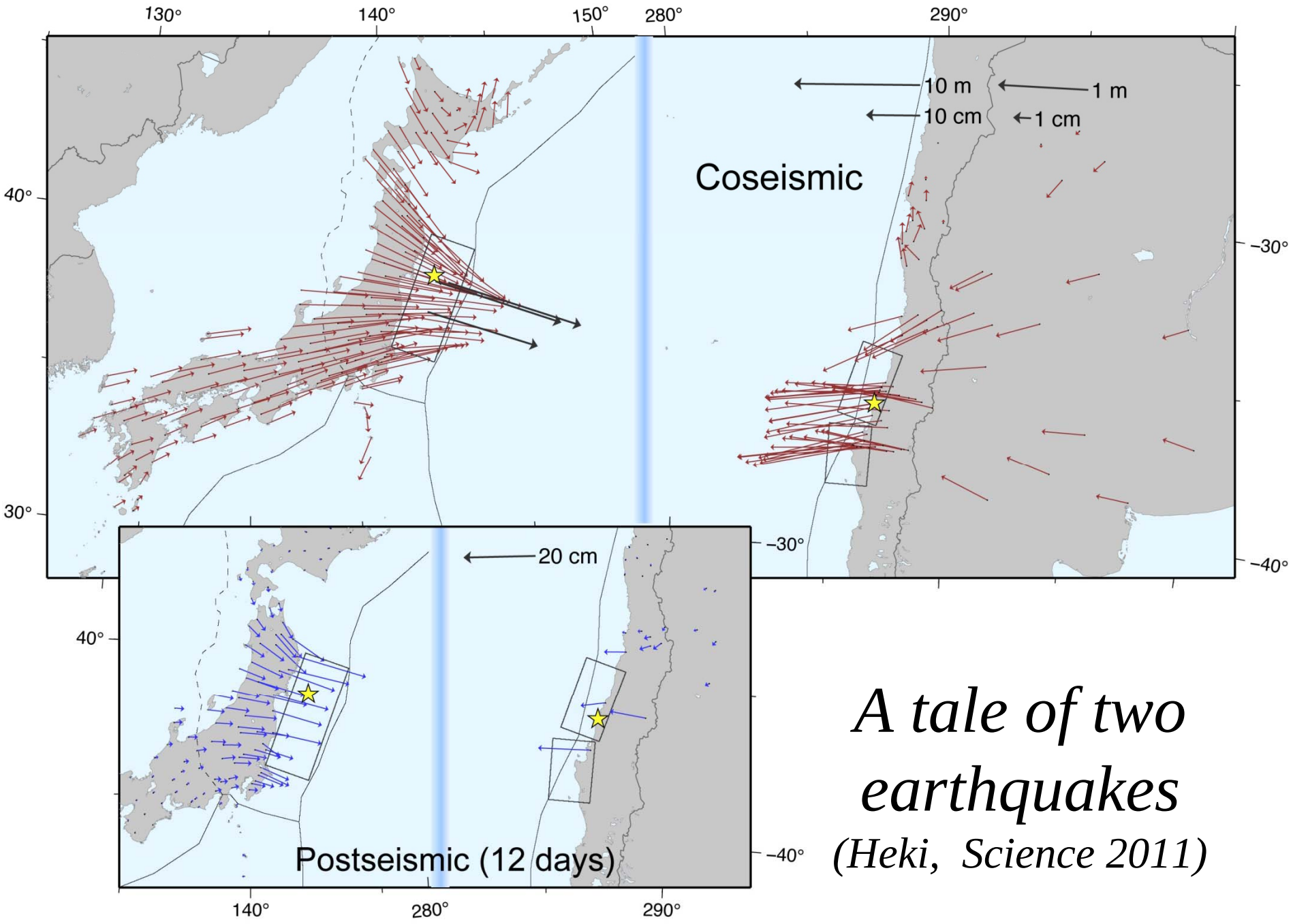


Large amplitude vertical oscillation by CID homogenized the layer

Other large earthquakes ?

2010 Chile M_W8.8,

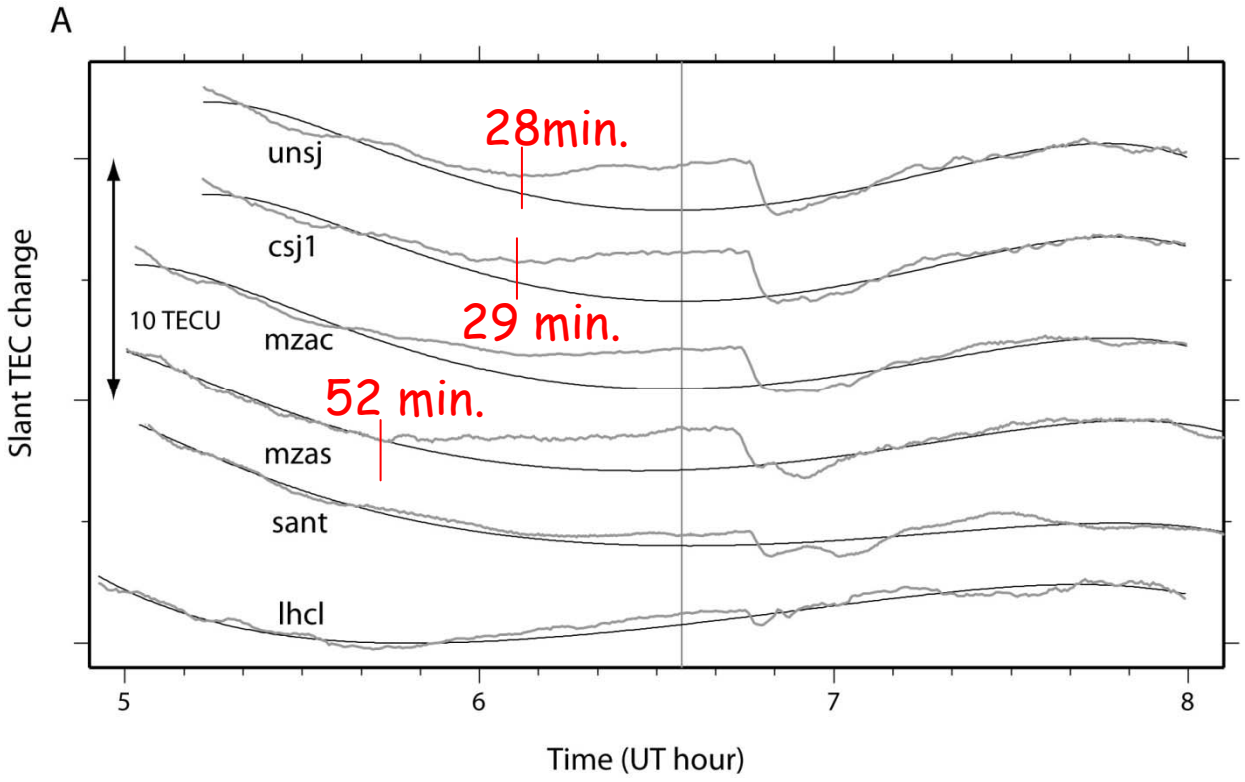
2004 Sumatra-Andaman M_W9.2

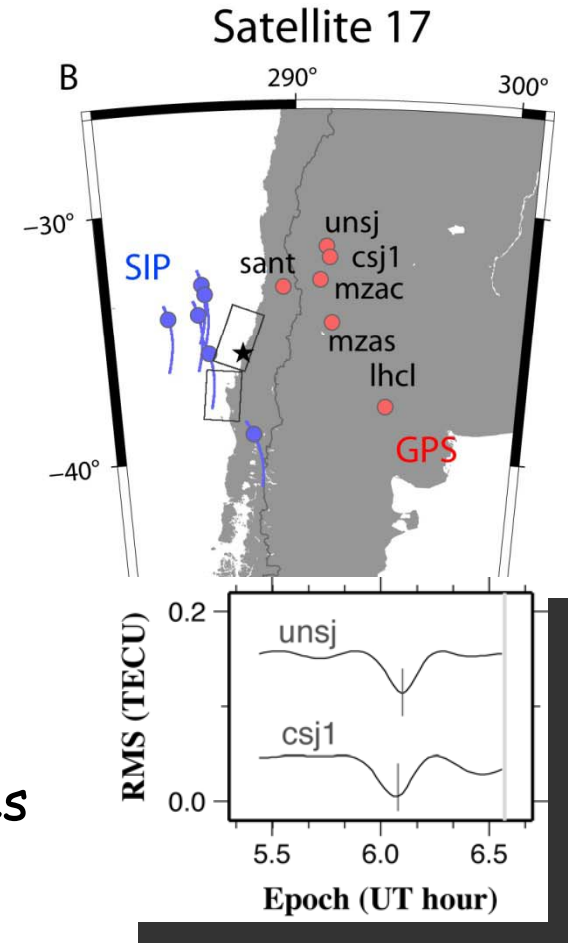


A tale of two earthquakes

(Heki, Science 2011)

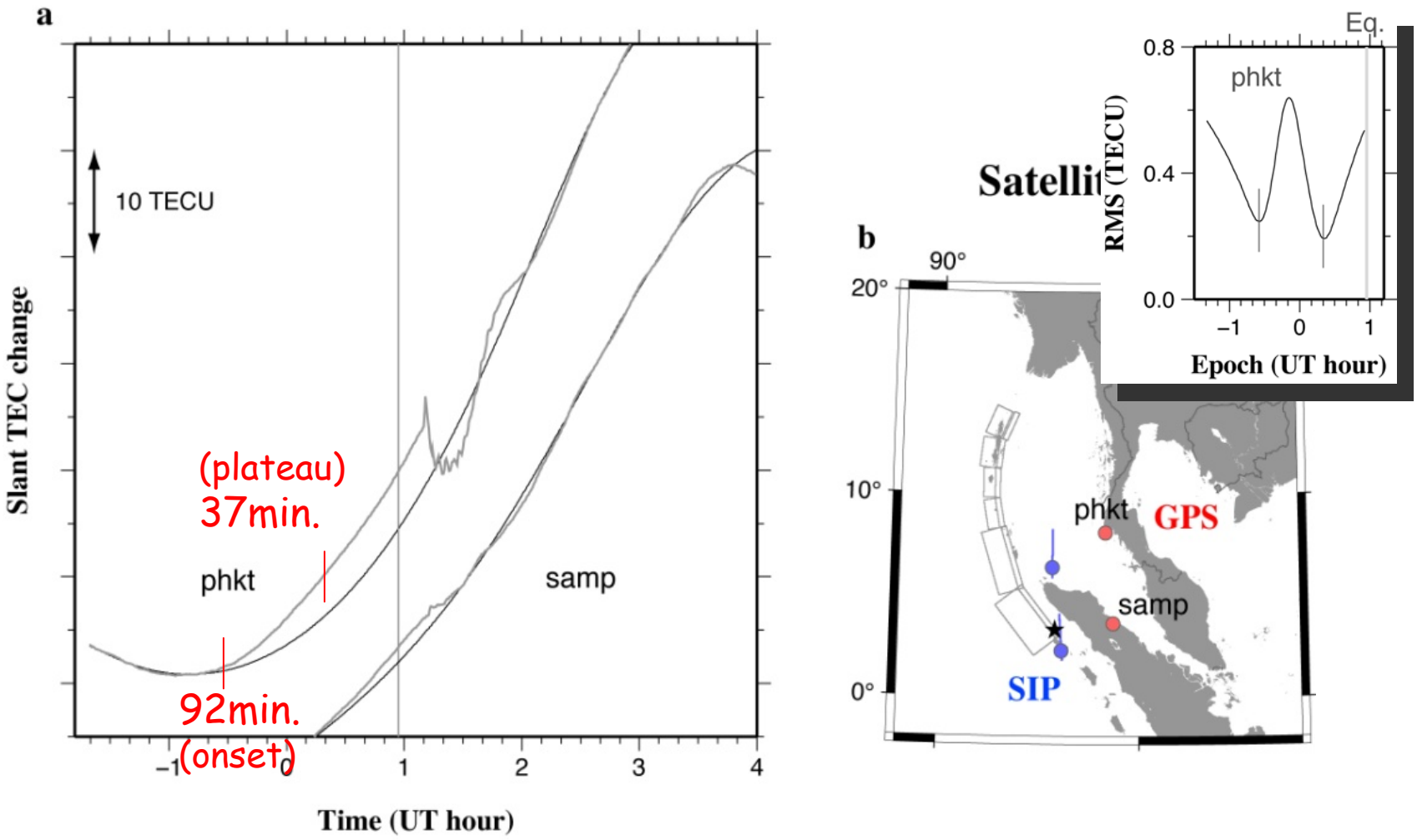
2010 February Chile (Maule) Earthquake





Similar signature in TEC changes

2004 December Sumatra-Andaman Earthquake



Larger and longer preseismic TEC change signatures

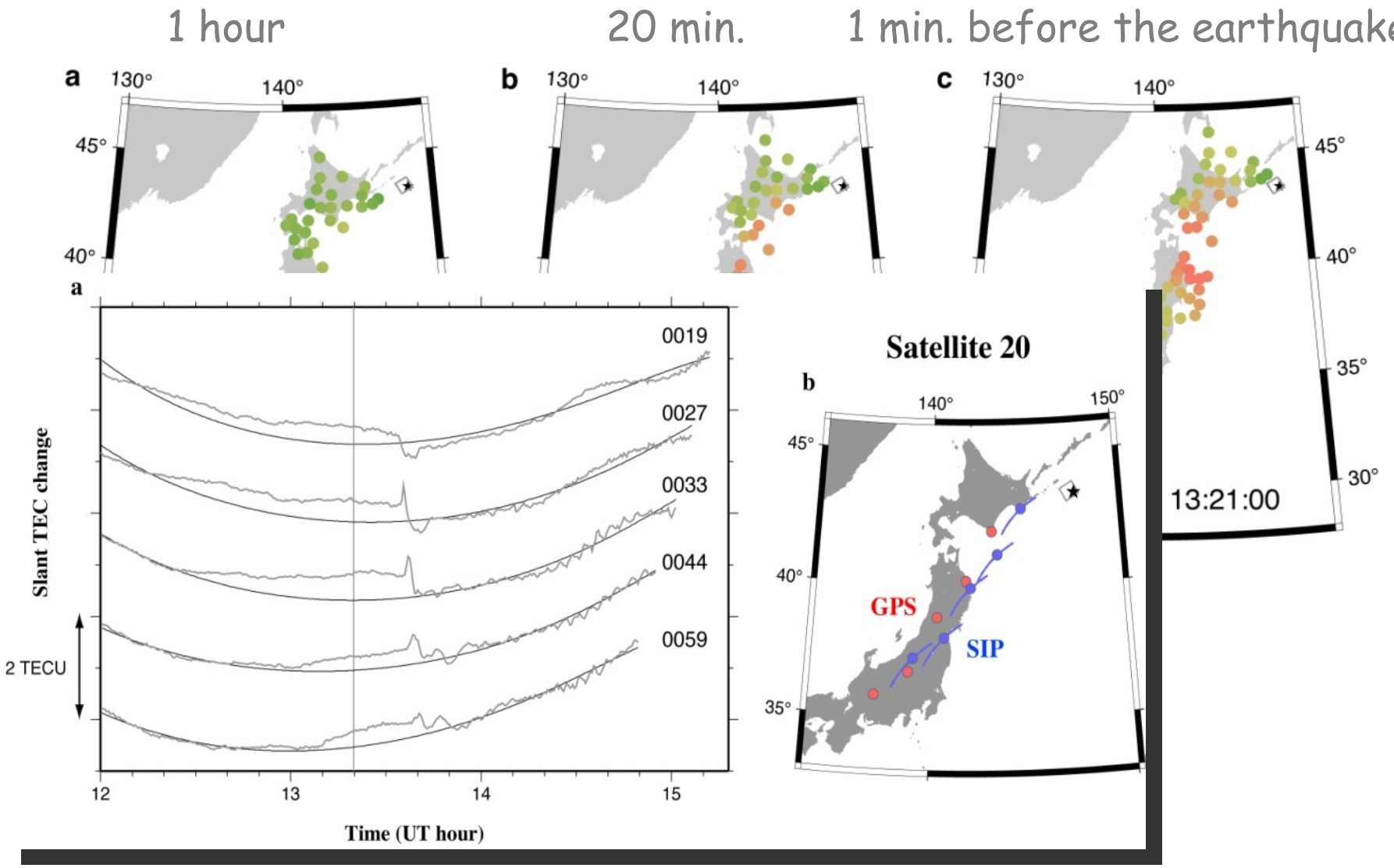
M8 class earthquakes?

1994 Hokkaido-Toho-Oki (Shikotan)M_W8.3,

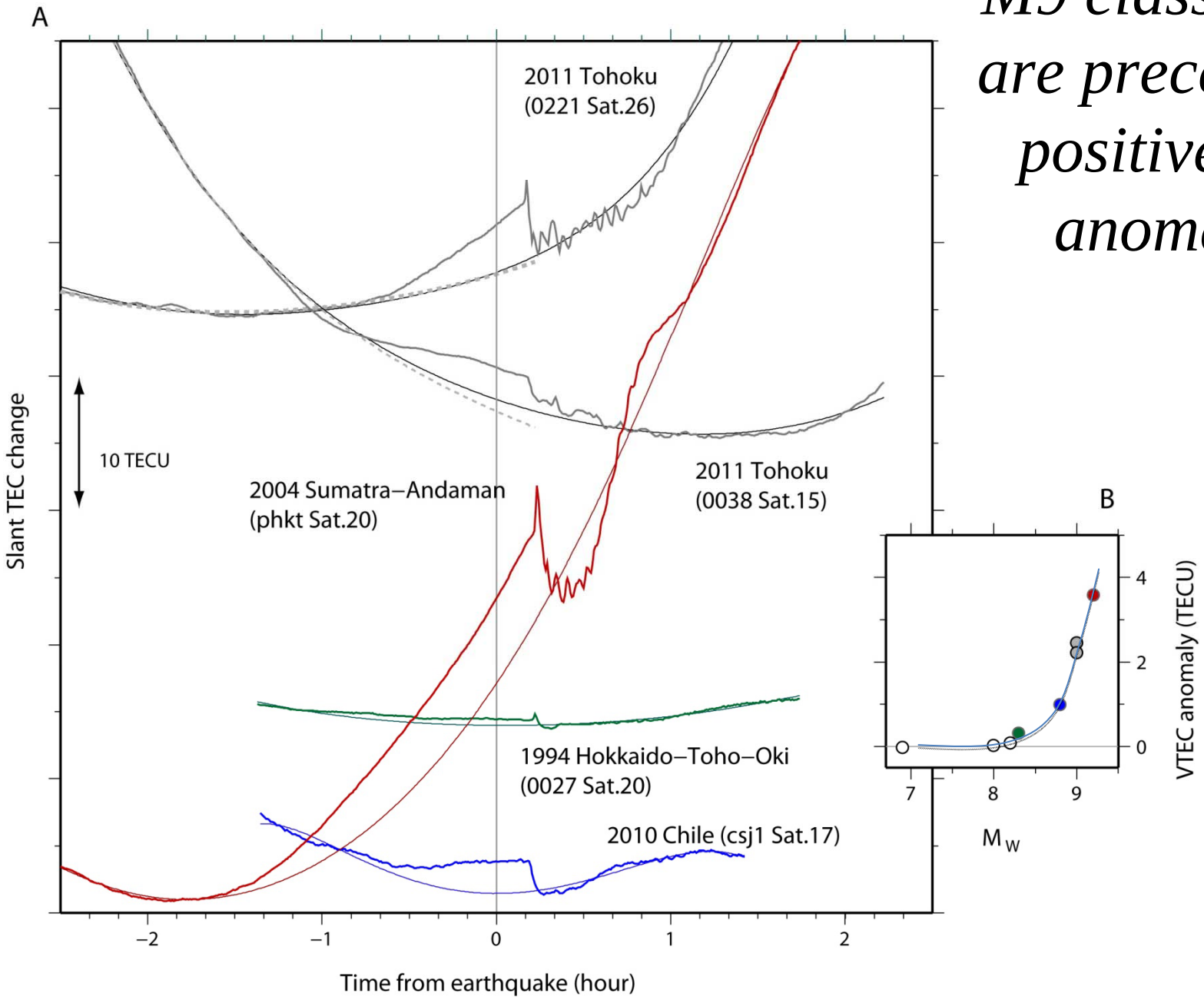
2003 Tokachi-Oki M_W8.0

2006 Kuril Islands M_W8.2

1994 Hokkaido-Toho-Oki (Shikotan) eq. (M8.3)

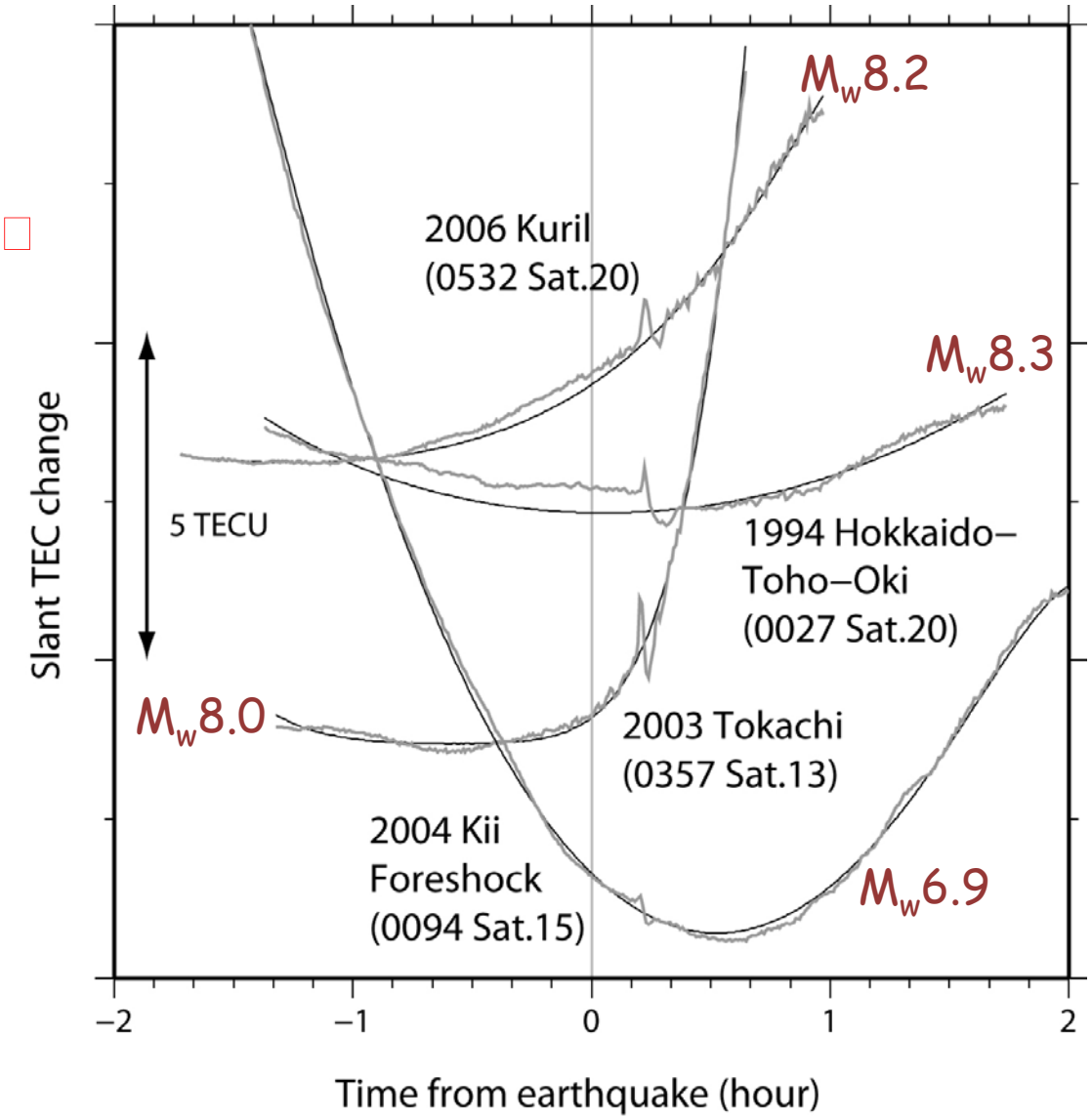


M9 class events are preceded by positive TEC anomalies



M7-8 class events show little preseismic TEC anomalies

(Small signals for the M_w8.2 and M_w8.3 events



Earthquake Prediction

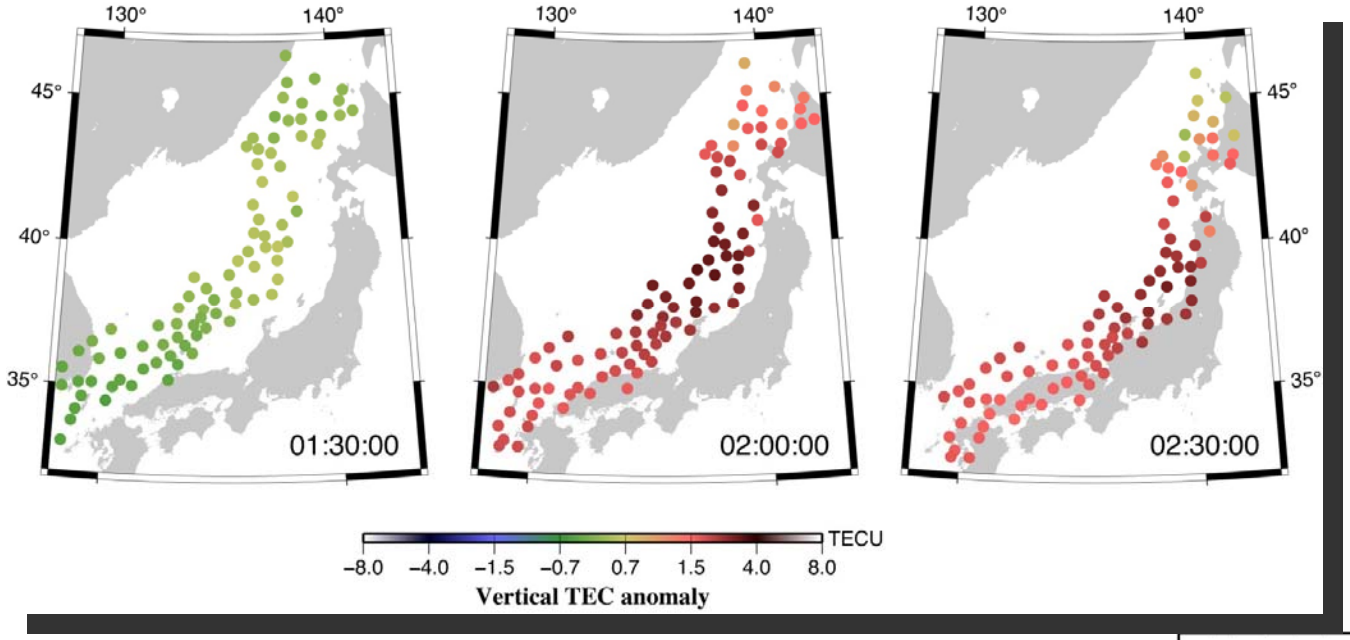
1. When positive TEC anomaly started, an earthquake will occur in 1 hour or so (When?)

2. Rupture will occur beneath the anomaly (Where?)

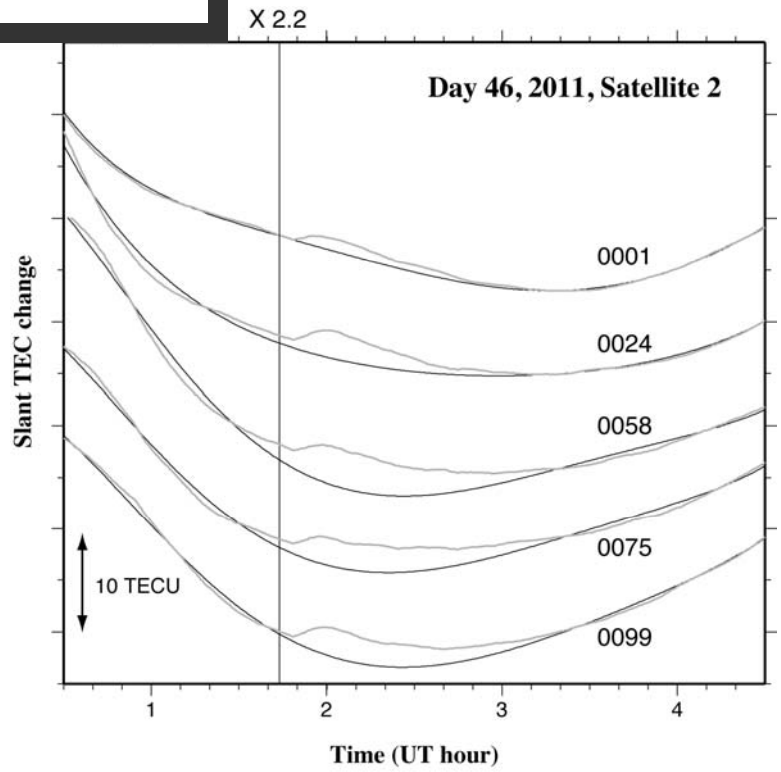
3. Anomaly depends on magnitude, and visible only for M9 class events (How large?)

(Three "musts" of Earthquake Prediction)

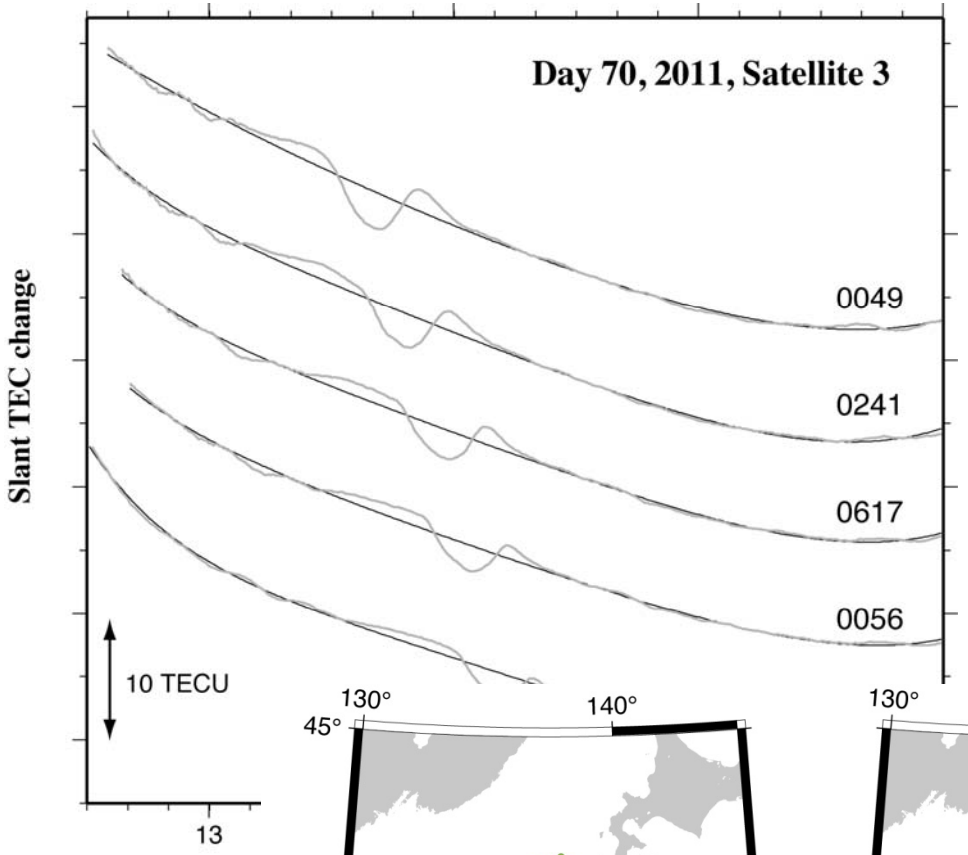
Similar TEC anomalies irrelevant to earthquakes?

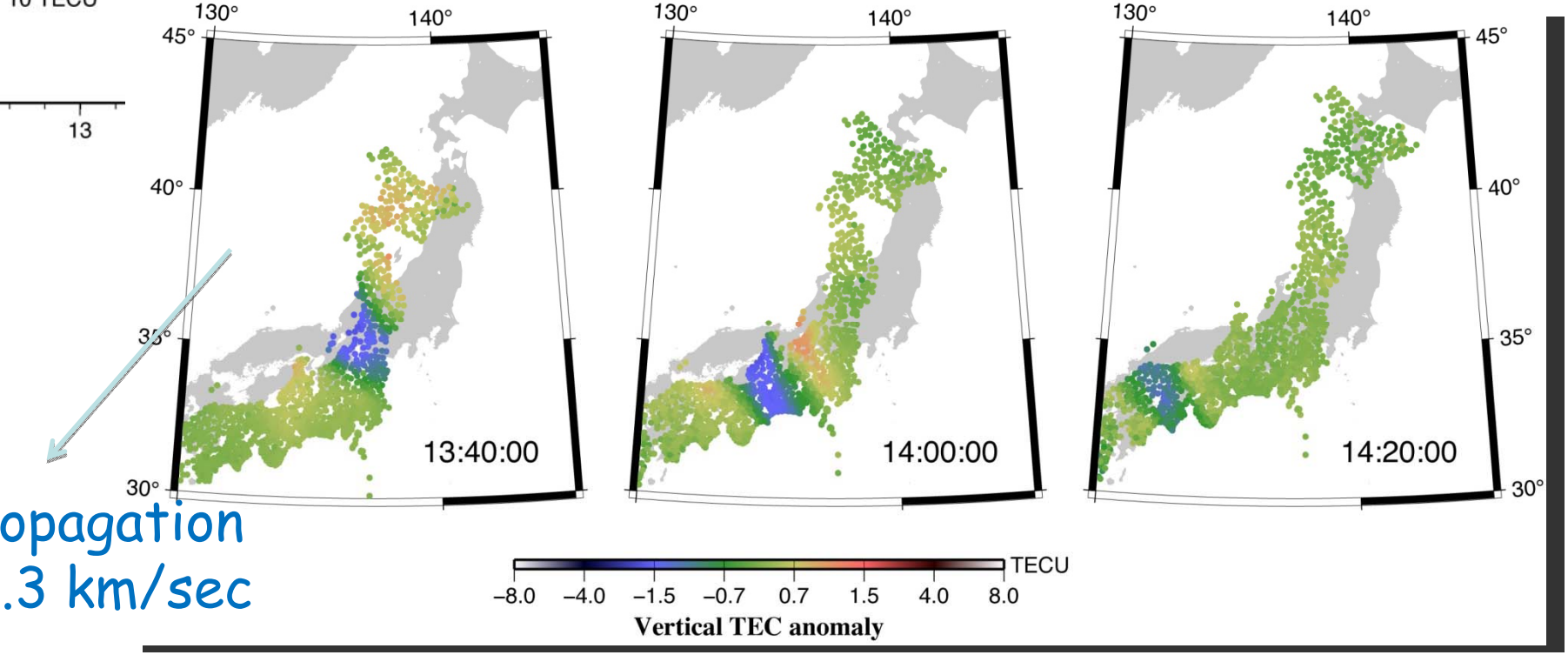


Sudden Increase of TEC (SITEC) by a solar flare



Medium-scale traveling ionospheric disturbance (MSTID)





Propagation
~0.3 km/sec

4 months of TEC

(3009, Satellite 15)

3 events exceeding 1.5 TECU in VTEC

Day 061

Day 070

Day 094

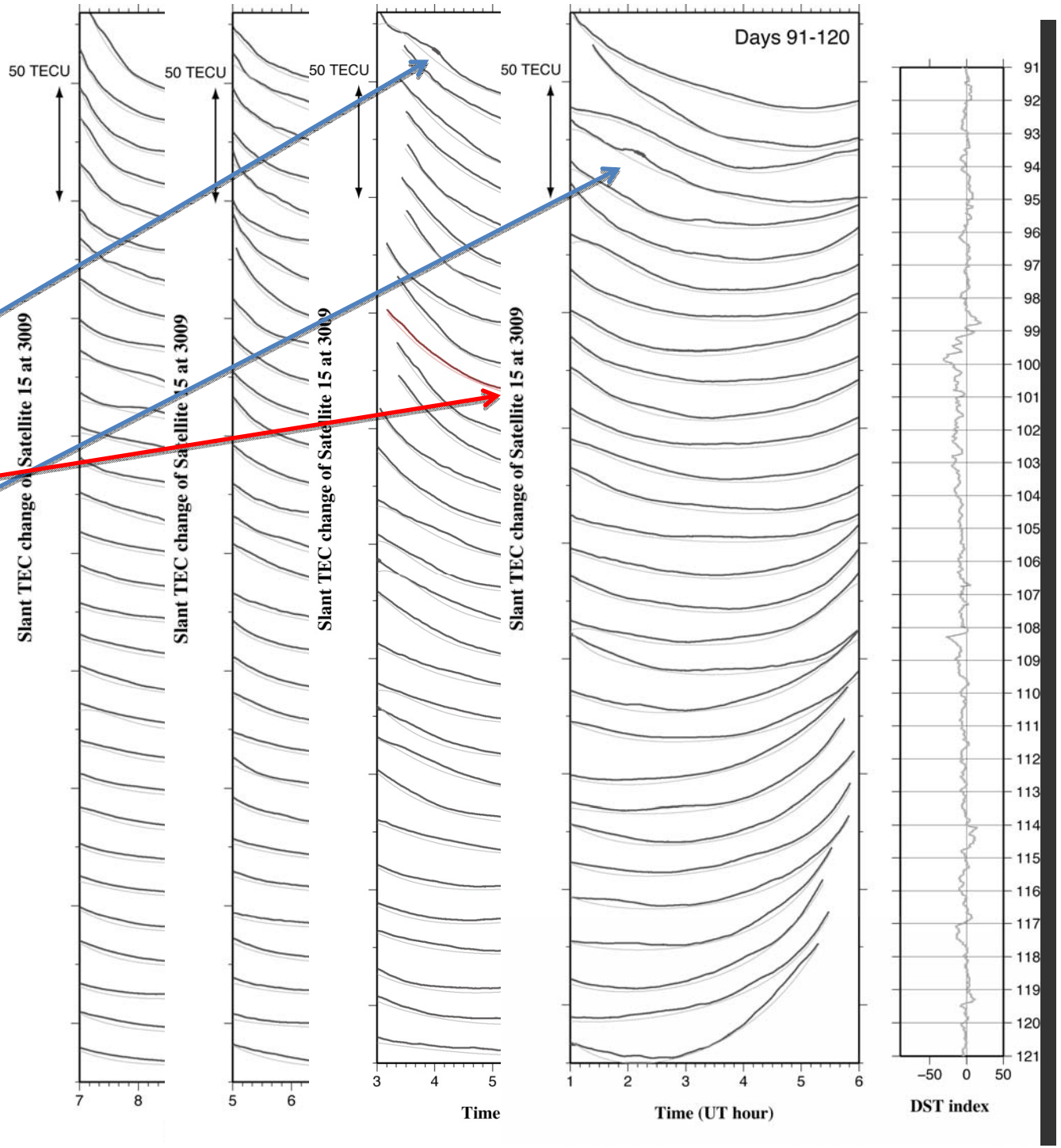
Standard deviation

Jan. : 0.34 TECU

Feb. : 0.37 TECU

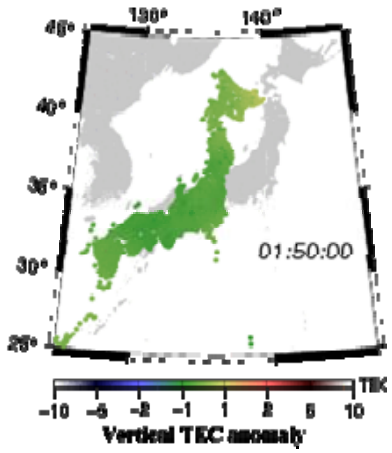
Mar. : 0.56 TECU

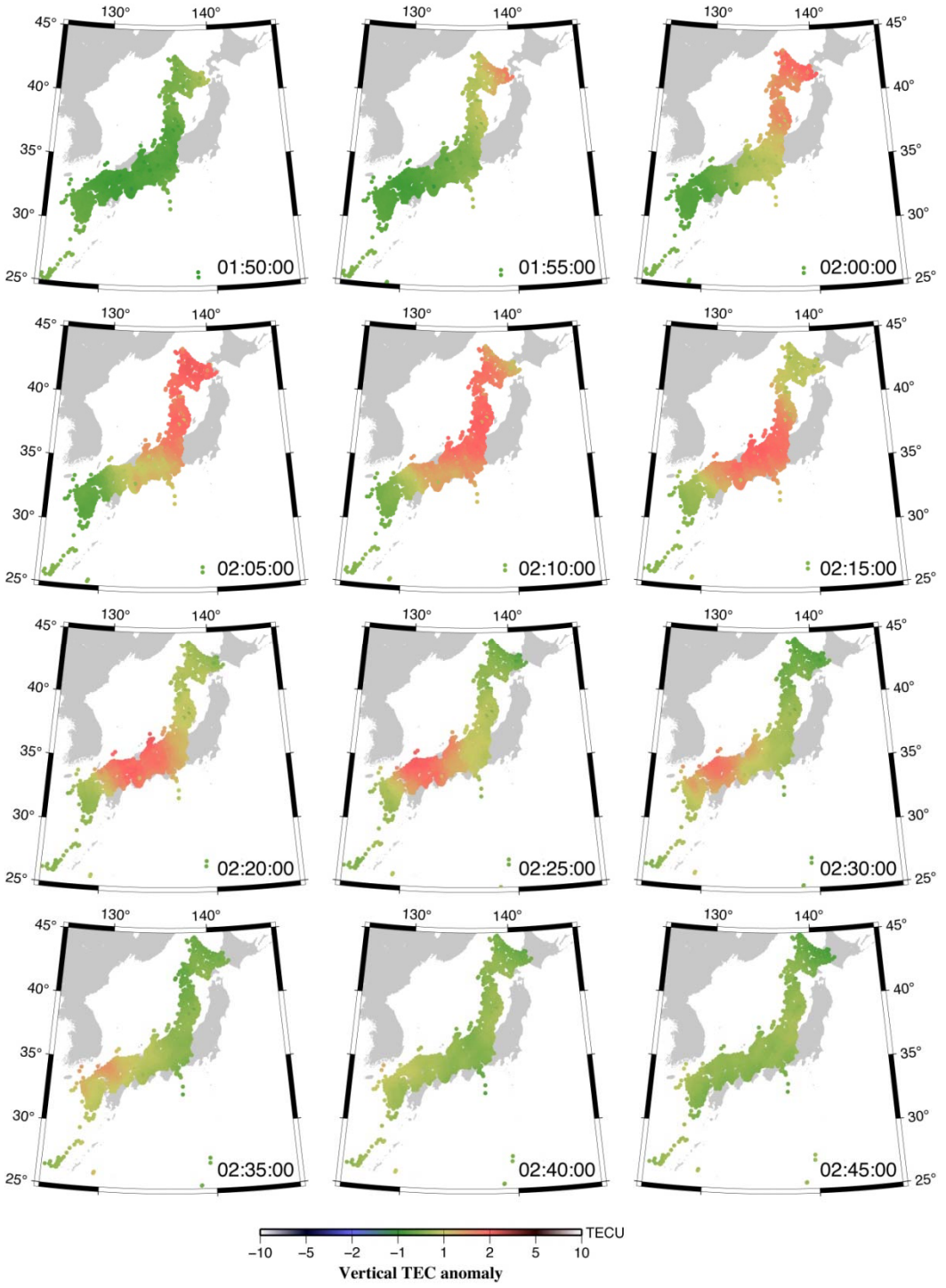
Apr. : 0.52 TECU



Day 094
Passage of LSTID

Propagation
~0.3 km/sec



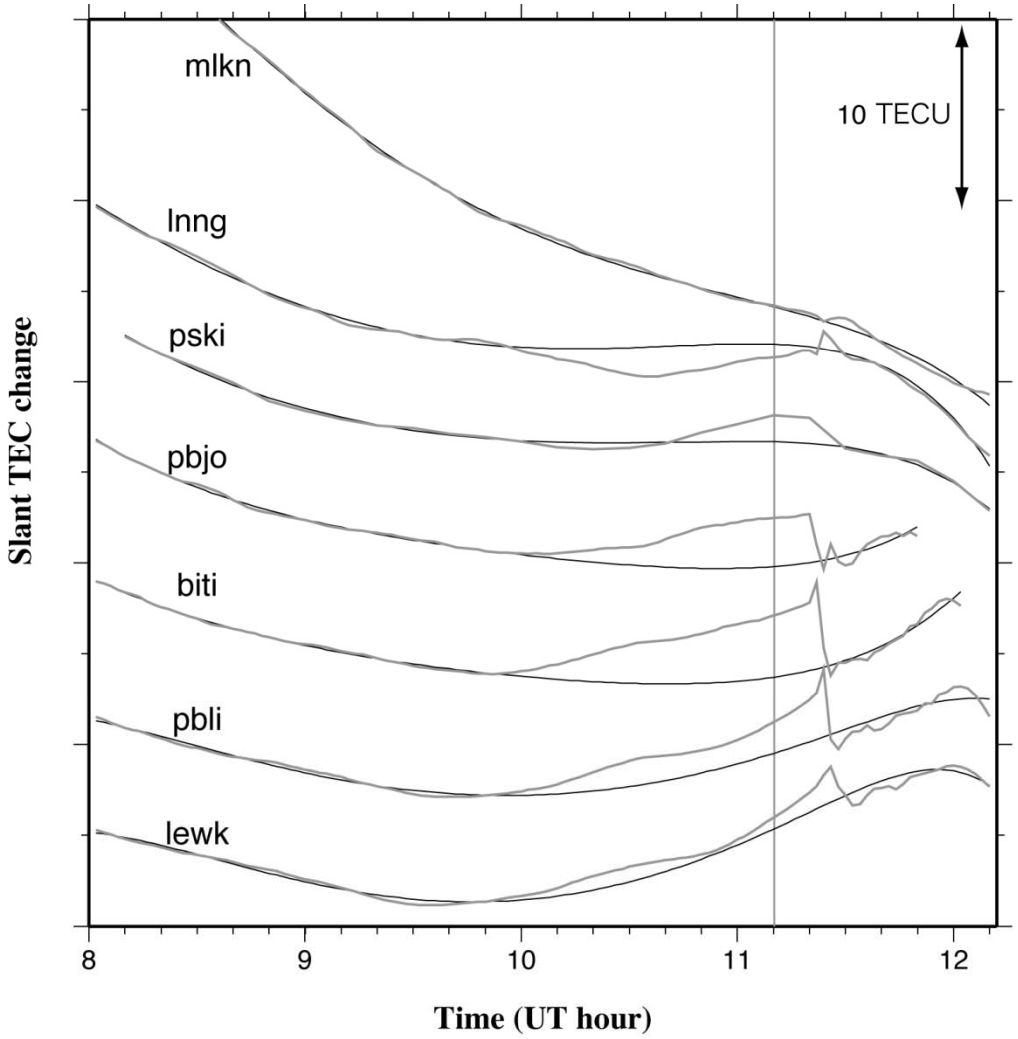


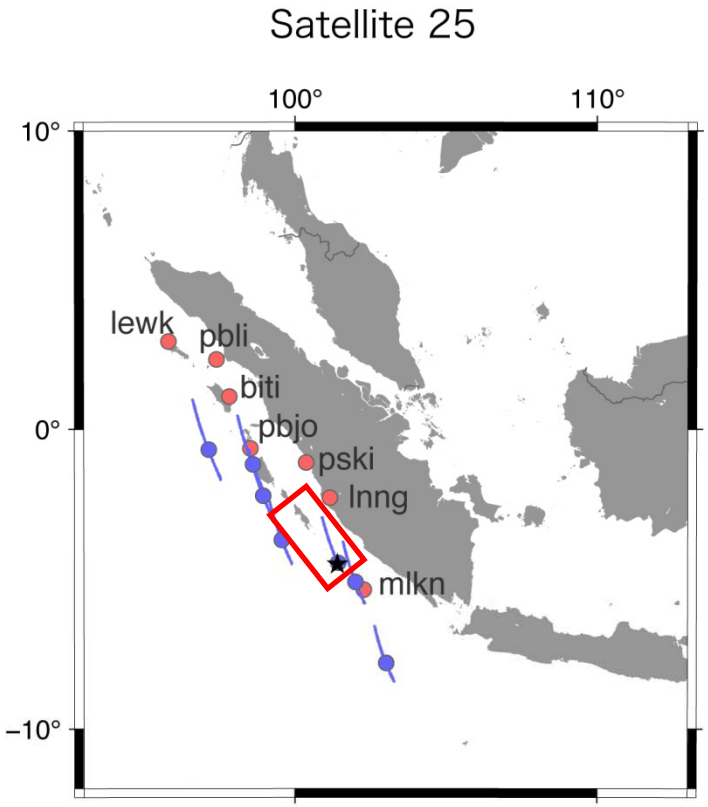
One more large earthquake analyzed last month

Similar TEC anomalies relevant to earthquakes?

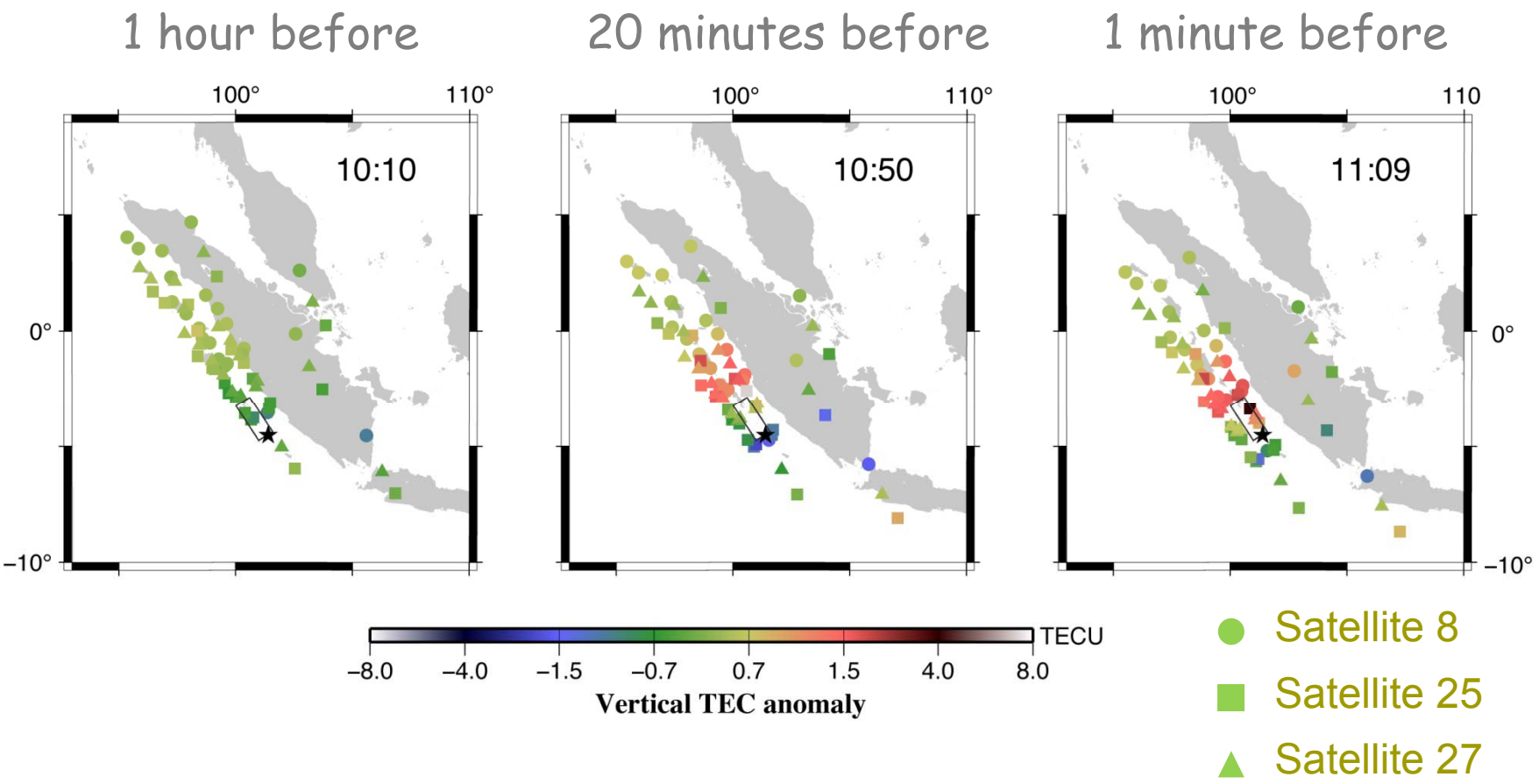
2007 September, Bengkulu Earthquake, Sumatra (M_w8.6)

GPS data from SUGAR network (2 min. sampling)





TEC anomaly before 2007 Bengkulu Eq.



Thank you for your attention

Hokkaido University
SPACE GEODES