Kumamoto M 6.0 and 7.0 Earthquakes of April 14, 16 2016

Electric Power
John Eidinger
G&E Enginering Systems Inc.
September 15 2016

Acknowledgements

- Kyushu Electric
- Kubota: More than 90 man-days effort to collect information
- Professors Murayama, Shoji, Nojima, and their students
- JSCE
- JWWA
- Kumamoto Water Department
- Kumamoto Prefecture Public Works (levees, roads)
- NTT (phones, cells)
- MILT (expressways)
- Seibu (gas)
- Alex Tang, Prof. Kaz Konegai

(1) Human damages (as of Jun 30, 2016)

	persons
dead	69
Missing	1
Seriously injured	364
Slightly injured	1, 456
TOTAL	1, 890

(2) House damages (as of Jun 30, 2016)

	Number of houses
Total collapse	8, 044
Partially destroyed	24, 274
Some damages	118, 222
TOTAL	150, 540

Lifelines

- Electric Power: Moderate, locally severe damage
- Water: Moderate damage + regulatory shutdown
- Highways: Severe damage
- Railroads: Moderate damage, locally severe
- Natural gas: Moderate damage
- Levees: Severe damage
- Total Repair Cost (for lifelines): ~$ 2 Billion US.
  Economic impact: much, much larger

Hazards

- Shaking: PGA > 0.5g for ~ 420 km^2 (28 km long by 15 km wide). Most of this is in rural areas, but Mashita town heavily hit. Main population area in Kumamoto City < 0.25g. Fukuoka City < 0.05g. Farmland covers 40% of strongest shaking areas. Forested hills cover 50% of strengest shaking areas.

- Liquefaction: settlements > 0.5 meters in main water well area; in Mashita; sporadic 5 - 10 cm elsewhere.

- Landslide: extensive deep-seated slides where PGA > 0.4g and slope > 30 degrees. Total failure of many bridges. Failure of some transmission towers.

- Fault offset. About 20 km of surface faulting, commonly 0.3 to 1 meter, some places 2 meters. A few lifeline crossings, including roads, tunnels, electric power poles, a few pipes. Some severly tilted distribution poles.

- No tsunami issues


Sendai
Niigata
Kobe
Tokyo
Fukuoka
Kumamoto
Kyushu


Fukuoka
Kumamoto
Mount Aso

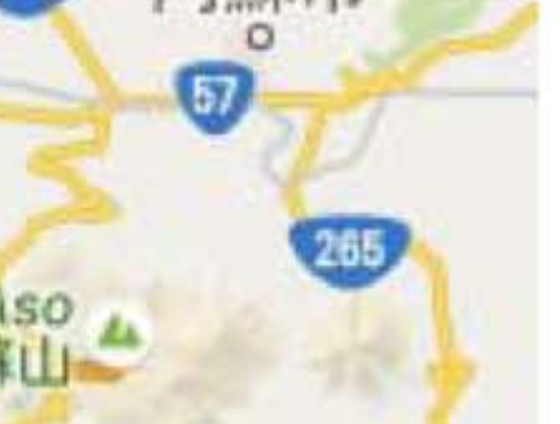
Nankan
南関町
Omuta
大牟田市
Arao
荒尾市
Yamaga
山鹿市
325
Kikuchi
菊池市
Nagomi
和水町
Tamana
玉名市
Nagasu
長洲町
387
325
Gyokuto
玉東町
501
3
Koshi
合志市
Ozu
大津町
Kikuyo
菊陽町
Kumamoto
熊本市
Mashiki
益城町
Mw 7.0
Mw 6.0
Mifune
御船町
445
Uto
宇土市
Misumi Line
443
57
218
Kosa
甲佐町
266
Uki
宇城市
Hikawa
氷川町
KUMAMOTO
Yamato
山都町
Gokase
五ヶ瀬町
265
Bay
amakusa
天草市
442
Ubuya
産山
212
Aso
阿蘇市
57
265
Mount Aso
阿蘇山
Minamiaso
南阿蘇村
Takamori
高森町
325

Ground Motions

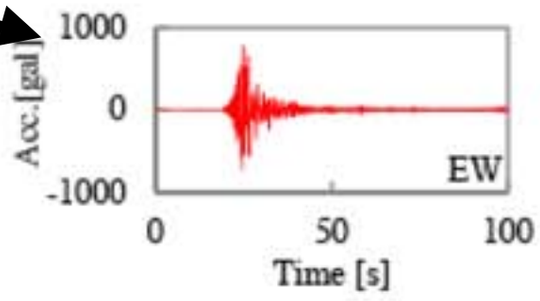
1975
Aso
1723
1848
1889
1625
Mashiki
F
1895
Mw 7.0
Kumamoto
1898
Mw 6.1
H
1619
F = Futagawa Fault
H = Hinagu fault

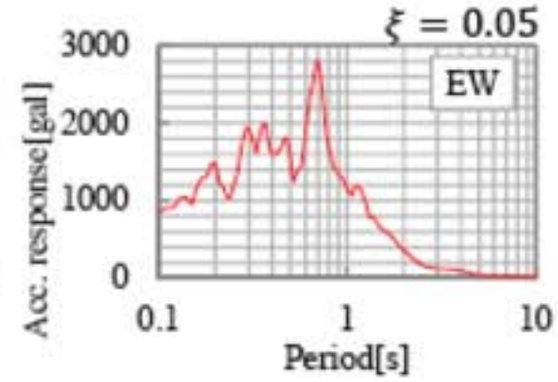
Tamana
玉名市
Gyokuto
玉東町
Koshi
合志市
Ozu
大津町
Aso-ohashi
Mount Aso
阿蘇山
阿蘇市
Okirihata-ohashi
Kikuyo
菊陽町
Minamiaso
南阿蘇村
Takamori
高森町
Kumamoto
熊本市
KMM006
Mashiki
益城町
Shinkansen derailment
Liquefaction areas
in Minami-ku
Severely affected area
along Akitsukawa in Mashiki
Kyushu
expressway
infra-
damage
Minami
御船町
Misumi Line
Uto
宇土市
KMM008
Prefectural
road bridge
damage
Shinkansen infra-damage
Matsubase, Uki
Uki
宇城市
Kosa
甲佐町
KUMAMOTO
Hikawa

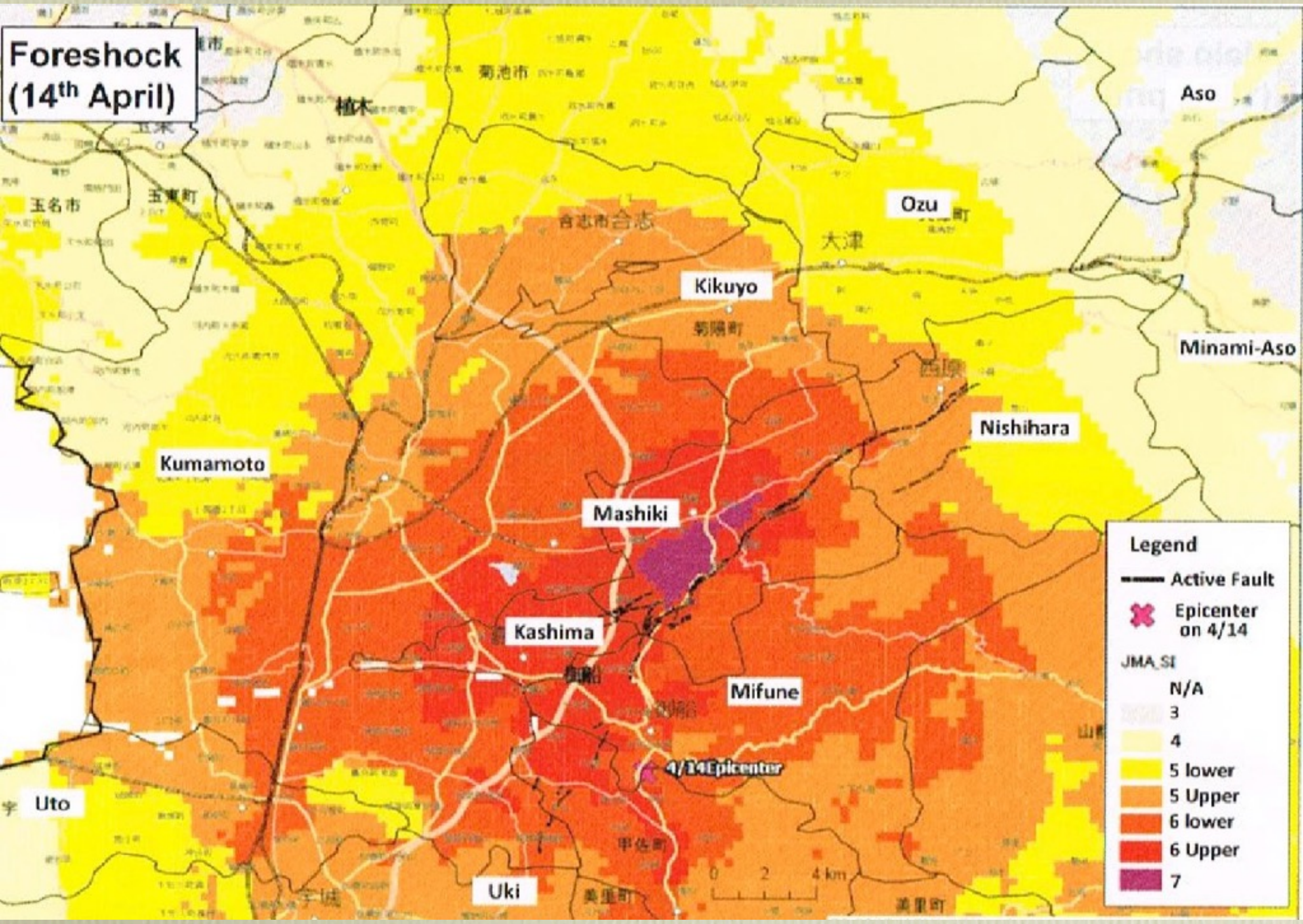
K-NET KMM006: Kumamoto

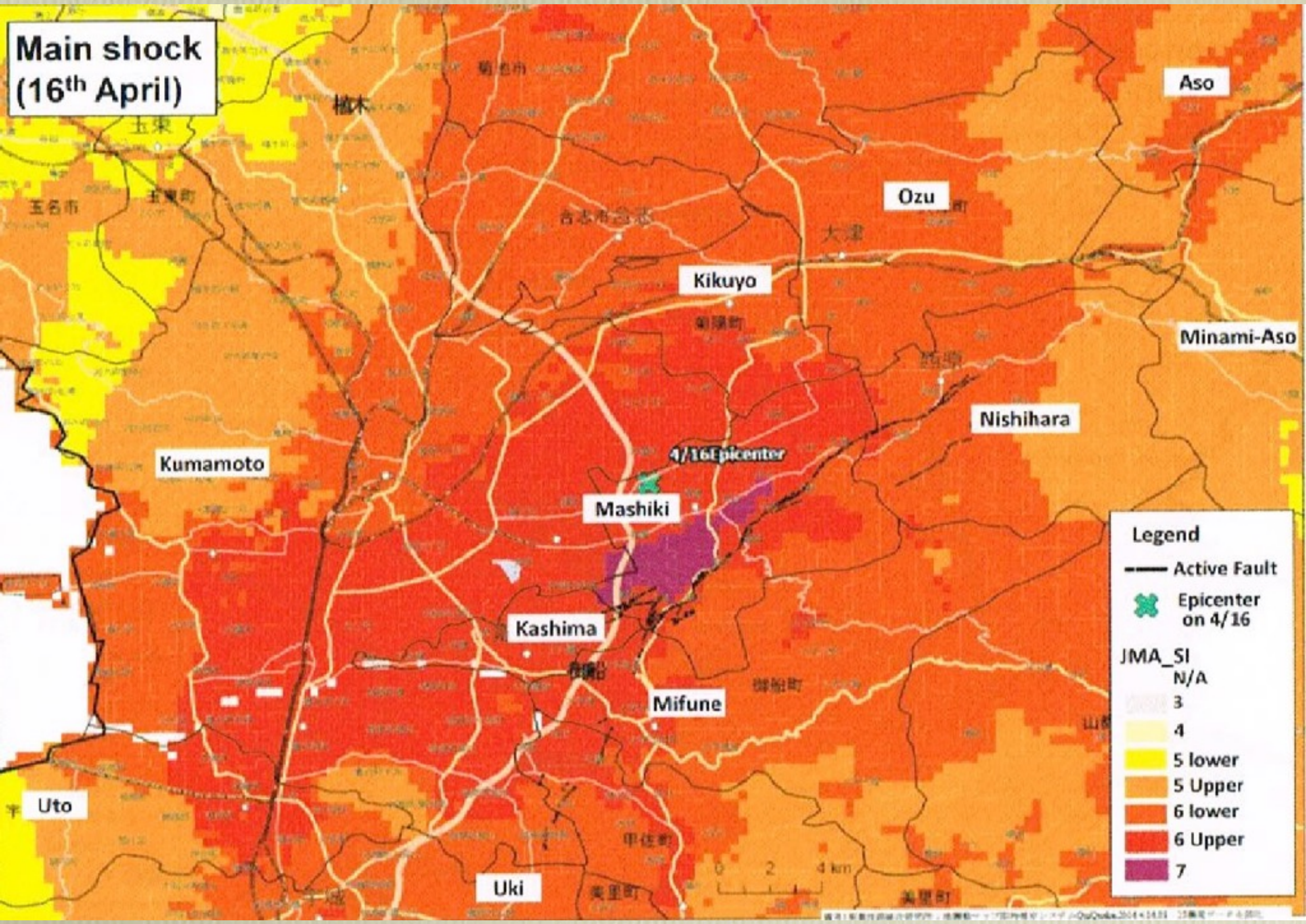


K-NET KMM008:Uto






Foreshock
(14th April)
菊池市
植木
玉名市
玉東町
合志市合志
大津
Ozu
Aso
Kikuyo
菊陽町
Minami-Aso
西原
Nishihara
Kumamoto
Mashiki
Kashima
Mifune
4/14Epicenter
Uto
Uki
美里町
0 2 4 km
Legend
Active Fault
Epicenter on 4/14
JMA_SI
N/A
3
4
5 lower
5 Upper
6 lower
6 Upper
7


Main shock
(16th April)
Aso
Ozu
Kikuyo
Minami-Aso
Nishihara
4/16Epicenter
Kumamoto
Mashiki
Kashima
Mifune
Uto
Uki
Legend
Active Fault
Epicenter on 4/16
JMA_SI
N/A
3
4
5 lower
5 Upper
6 lower
6 Upper
7
0 2 4 km

Futagawa Fault

- April 16 2016 Mw 7.0
- ~3 events in 26,000 years, including 2016
- Right Lateral, south side “up”
- Rupture length ~ 30 km. Dip 60-84° WNW
- Rupture direction to ENE
- Maximum offset observations = 2.0 meters horizontal, 0.5 meters vertical up (south side) typical, 0.2 meters up (north side) in some places

Hinagu Fault

- April 14 2016 Mw 6.1 (various as Mw 6.0)
- Right Lateral
- Rupture length ~ 15 km. Dip 60-80°
- No surface fault offset observation

April 16 M 7.0

35°

30°

130°

135°

140°

PGA [gal]

PGA (g)

2000.0

1000.0 1.0

500.0 0.5

200.0 0.2

100.0 0.1

50.0 0.05

20.0

10.0

5.0

2.0 0.002

1.0

0.5

0.2

April 16 M 7.0

35°

30°

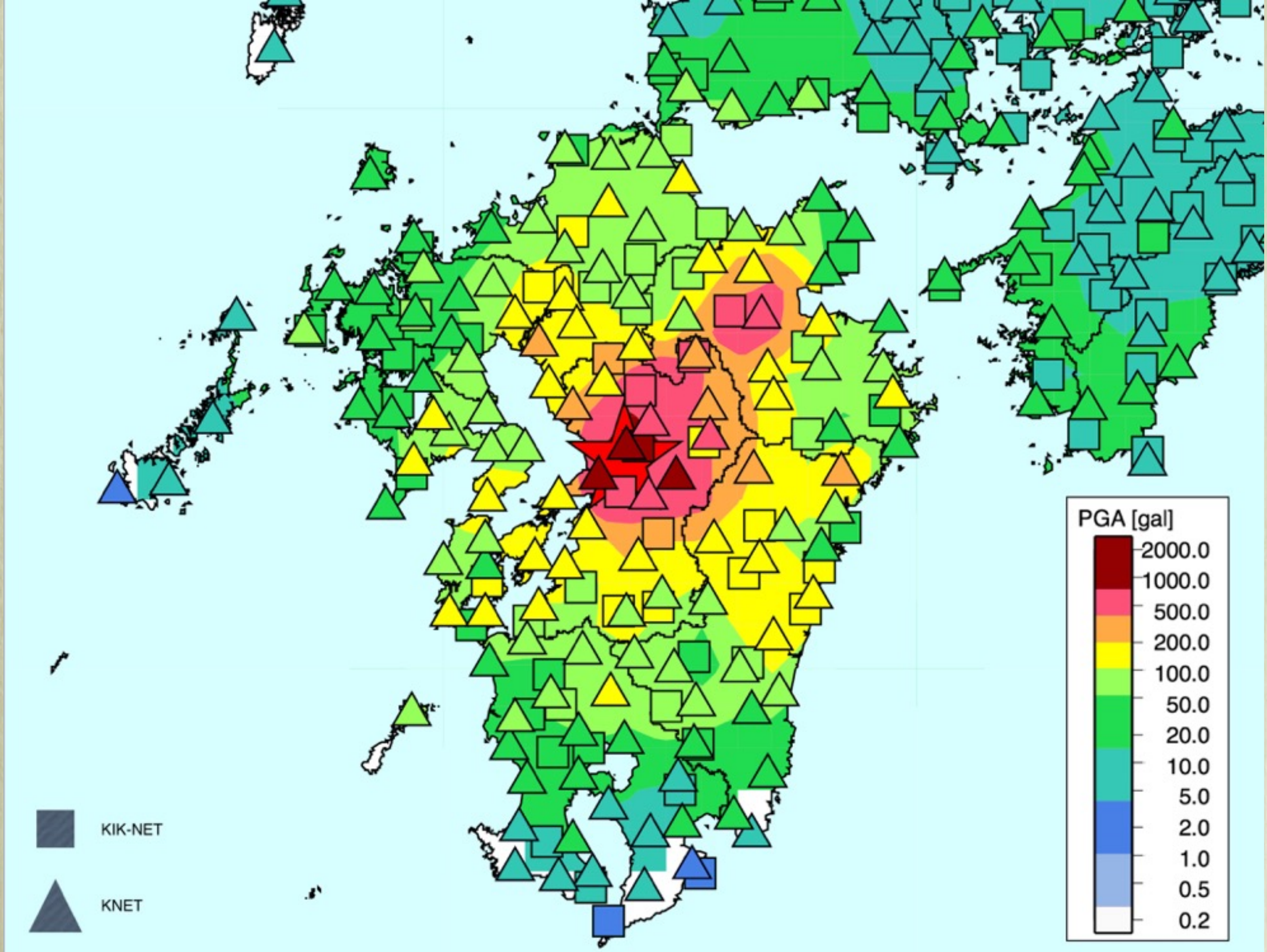
130°

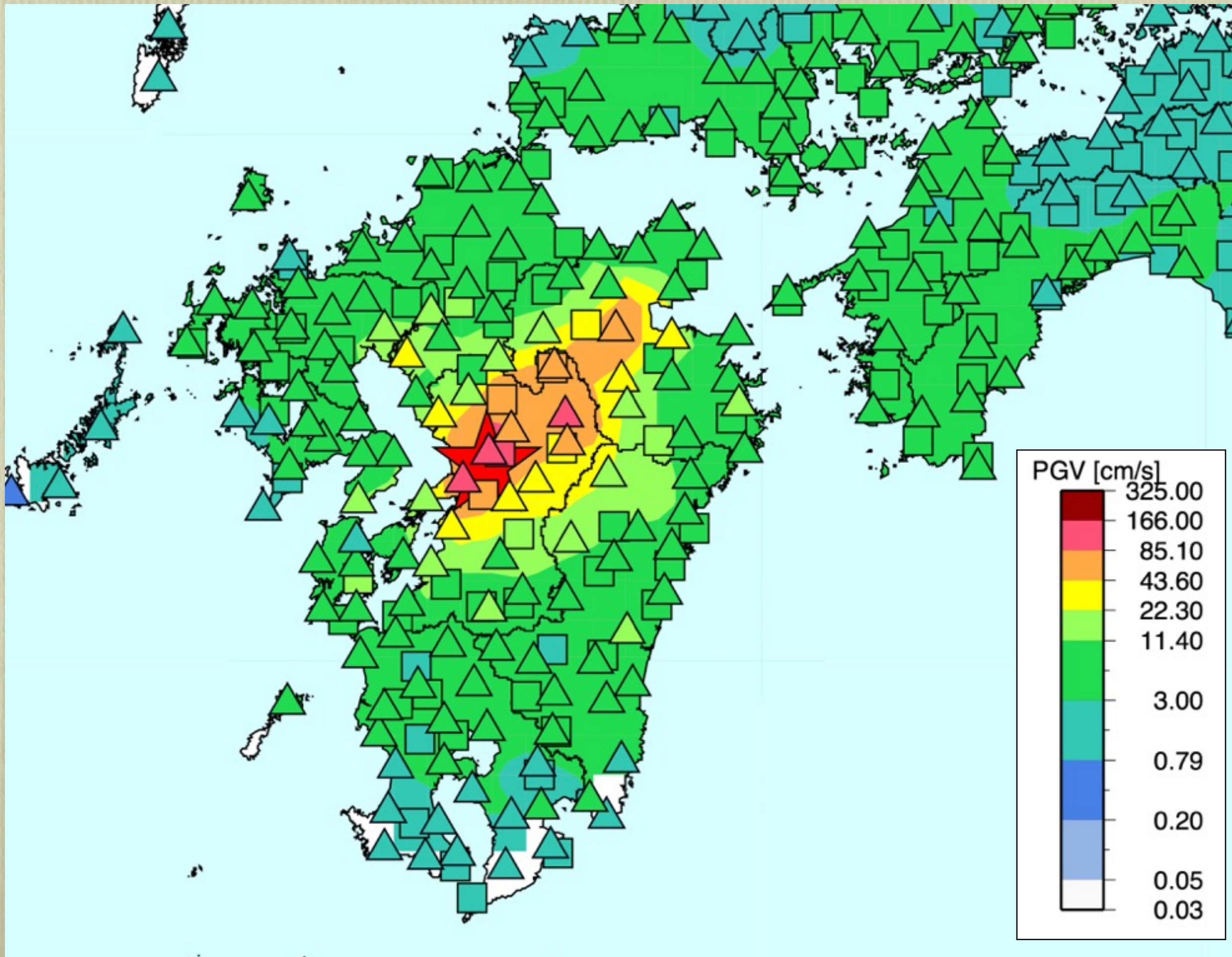
135°

140°

PGV [cm/s]

325.00
166.00
85.10
43.60
22.30
11.40
3.00
0.79
0.20
0.05
0.03


PGA [gal]
2000.0
1000.0
500.0
200.0
100.0
50.0
20.0
10.0
5.0
2.0
1.0
0.5
0.2
KIK-NET
KNET


PGV [cm/s]
325.00
166.00
85.10
43.60
22.30
11.40
3.00
0.79
0.20
0.05
0.03

PGA [cm/s/s]

1000
100
10
1
0.1

1
10
100
1000

Epicentral Distance [km]

K–NET
KiK–net

KIK-NET
KNET

PGV [cm/s]

100
10
1
0.1
0.01

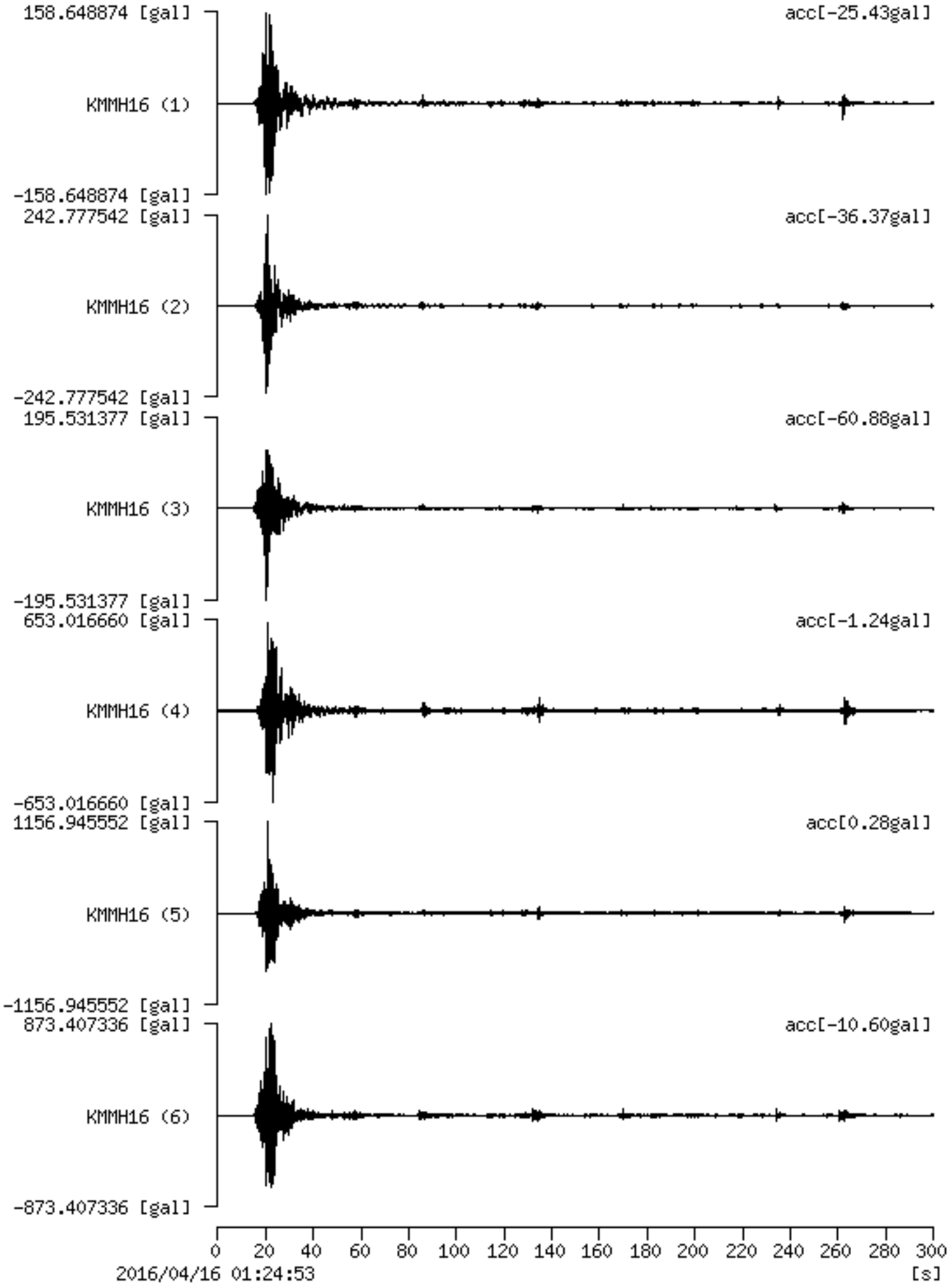
1
10
100
1000

Epicentral Distance [km]

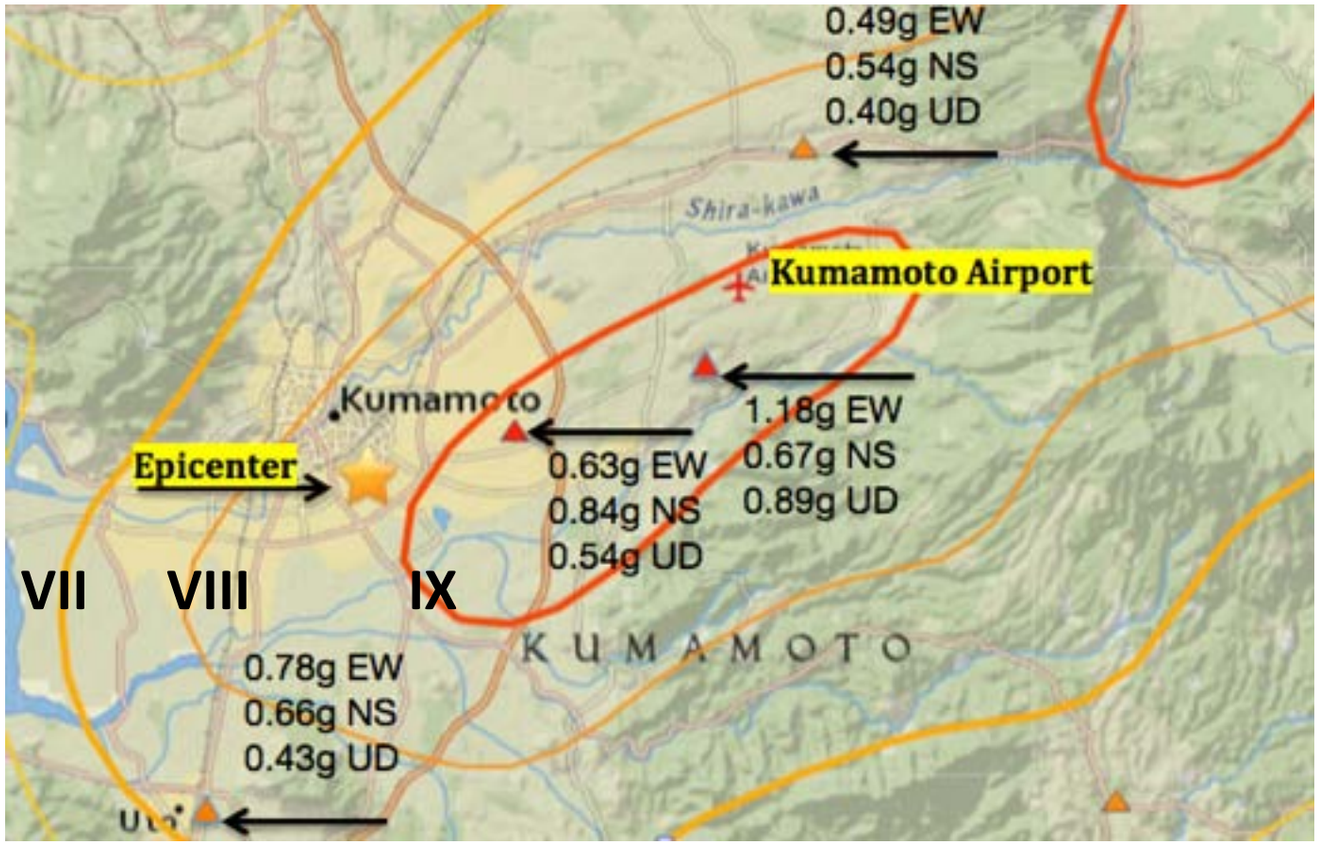
K–NET
KiK–net

KNET
KIK-NET

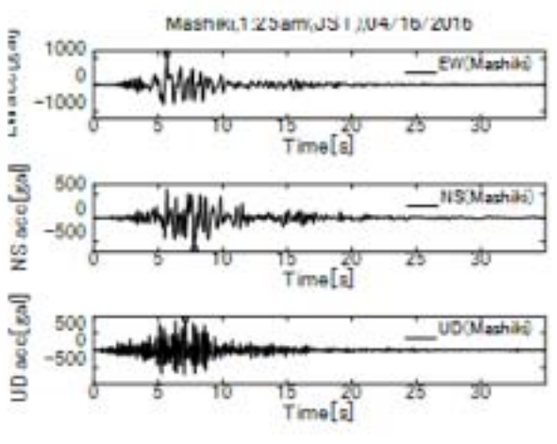
2016/04/16-01:25 32.753N 130.762E 12km M7.3(KMMH16)

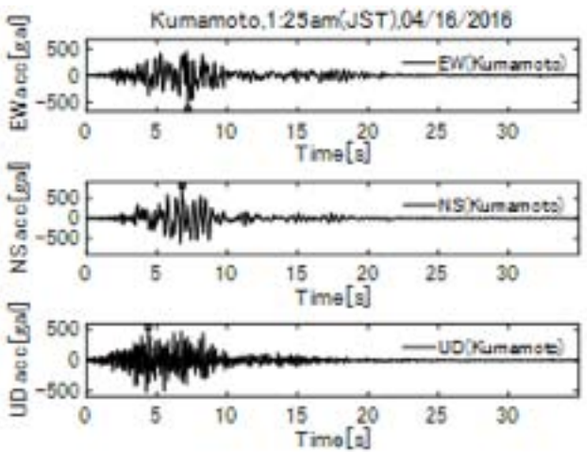


Kumamoto Airport



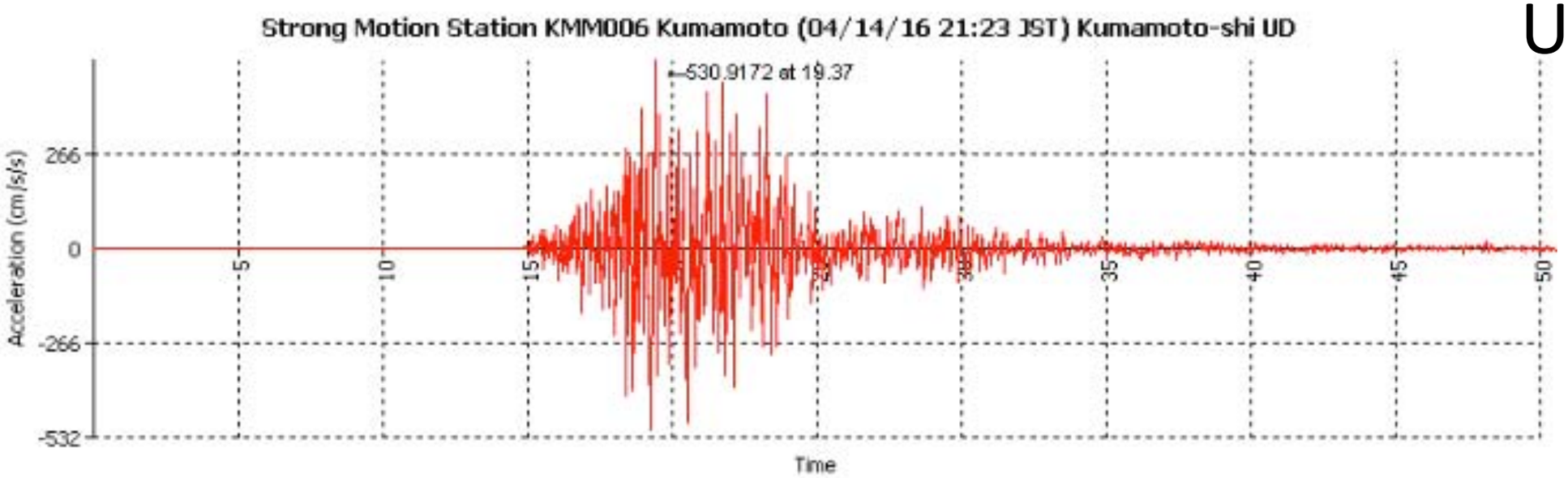
Summary of the ground motions recorded nearest to the Kumamoto Airport. The PGAs for the three components of each record are shown. The map also shows the intensities of the earthquake estimated by the USGS using PGA+PGV conversion to MMI.

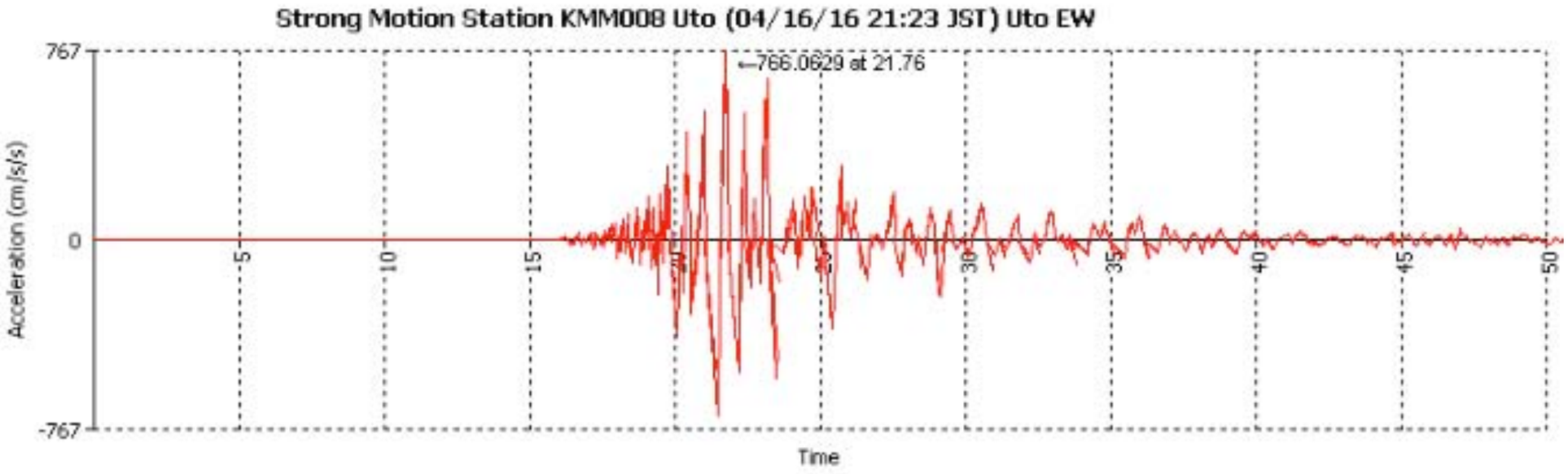


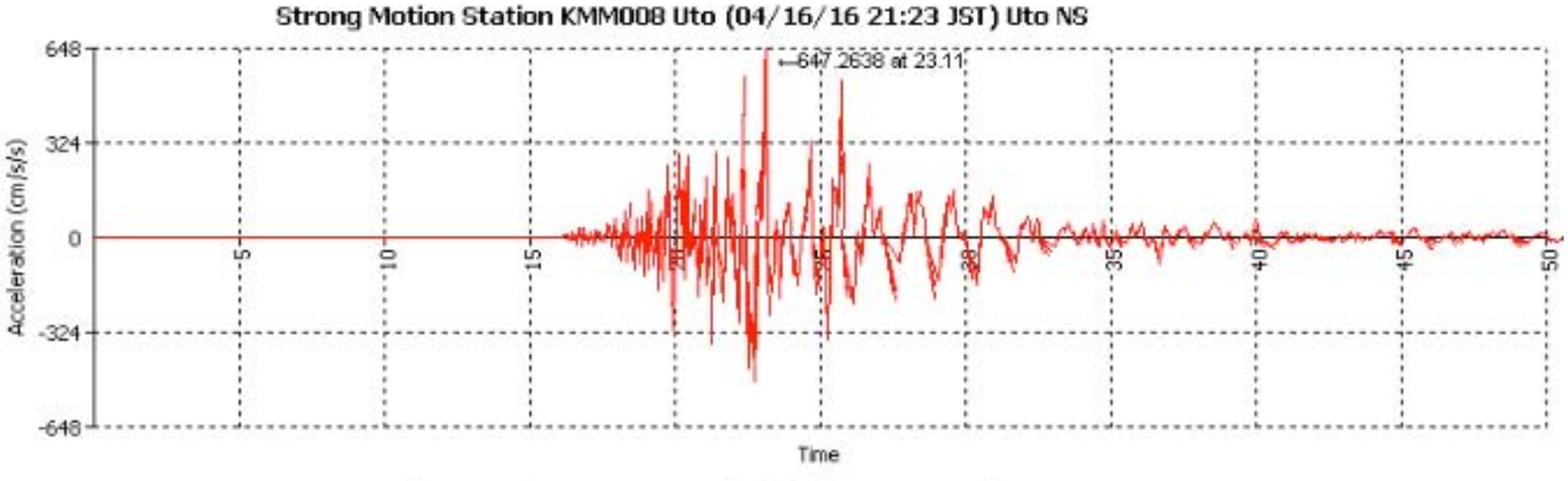


The recorded time histories at Mashiki, left, and Kumamoto, right. Courtesy Peter Yanev.

Uto City Hall







Strong Motion Station KMM008 Uto (04/16/16 21:23 JST) Uto UD

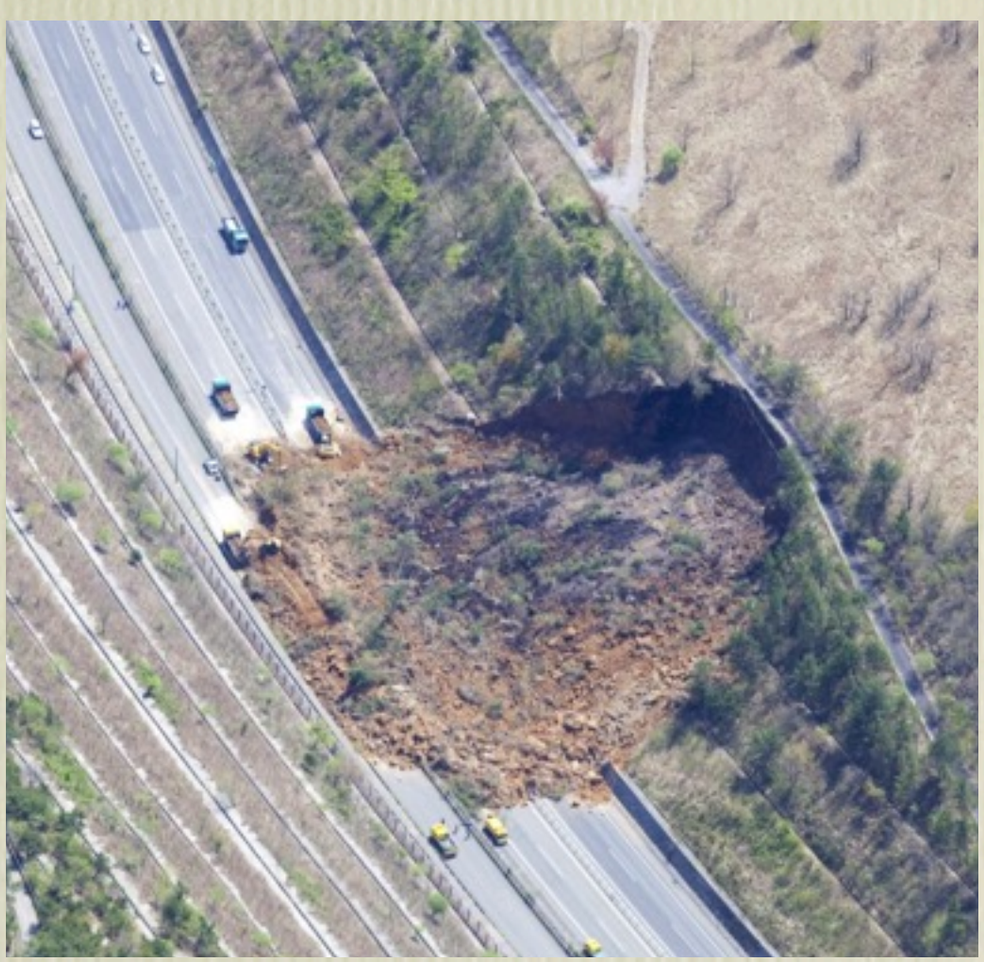
Landslides

PGA ~0.4g+. Slope > 35°. Percent Massive Slide = 10%

PGA ~0.4g+. Slope > 35°. Percent Massive Slide = 20%

Foreground: Bridge Collapsed due to landslides at abutments
Background. Massive landslide fails 4 lane expressway and railroad tracks


熊本
Kumamoto
大分
Oita
57
57
200m
water flume
4 lane expressway (route 57)
JR railway
bridge




九州地整はるかぜ
【ヘリ位置】熊本県上益城郡益城町
【撮影位置】熊本県上益城郡益城町


九州地整はるか
【ヘリ位置】熊本県上益城郡御船町
【撮影位置】熊本県上益城郡御船町

PGA ~0.7g+. Embankment failure


Original Embedment

Electric Power

Kyushu Electric

- FY 2015. Sales 79,210 million kWh (down from 85,352 million kWh in FY 2011)
- Revenue about $8 Billion / year

Kyushu Electric

- On Thursday April 14, at 21:26 JST, Mashiki Town in Kumamoto was hit by a foreshock of seismic intensity 7 on the Japanese scale, which led to outages affecting as many as 16,700 households.

- We responded by setting up the disaster control headquarters as we put all available resources into recovery, and by 23:00 JST the next day, Friday the15th, we got power transmission through HV distribution lines fully restored.

- However, immediately afterwards at 1:25 JST on Saturday the 16th, a main shock of intensity 7 struck Mashiki Town and Nishihara Village, causing as many as 476,600 households to lose power, the greatest outage due to earthquake we have ever experienced in Kyushu.

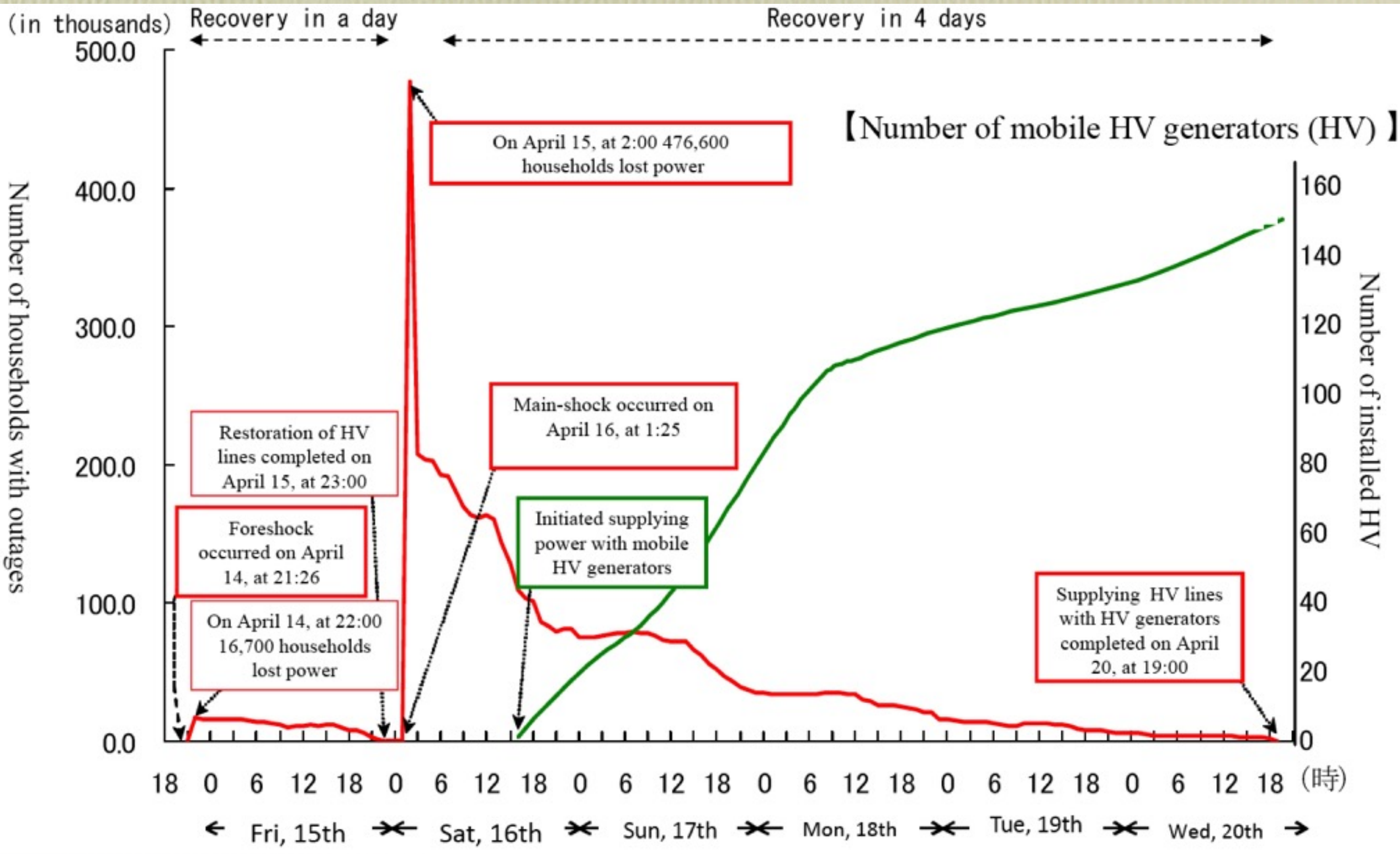
Kyushu Electric

- The restoration effort involved more than 4,000 personnel – 2,185 from Kyushu Electric Power, 1,423 from contractors, and 629 from the other electric utilities. The work proved to be extremely challenging due to factors such as landslides and damaged roads, and we deeply appreciate each and every one of these people for their sense of mission and their efforts towards restoration of electricity.

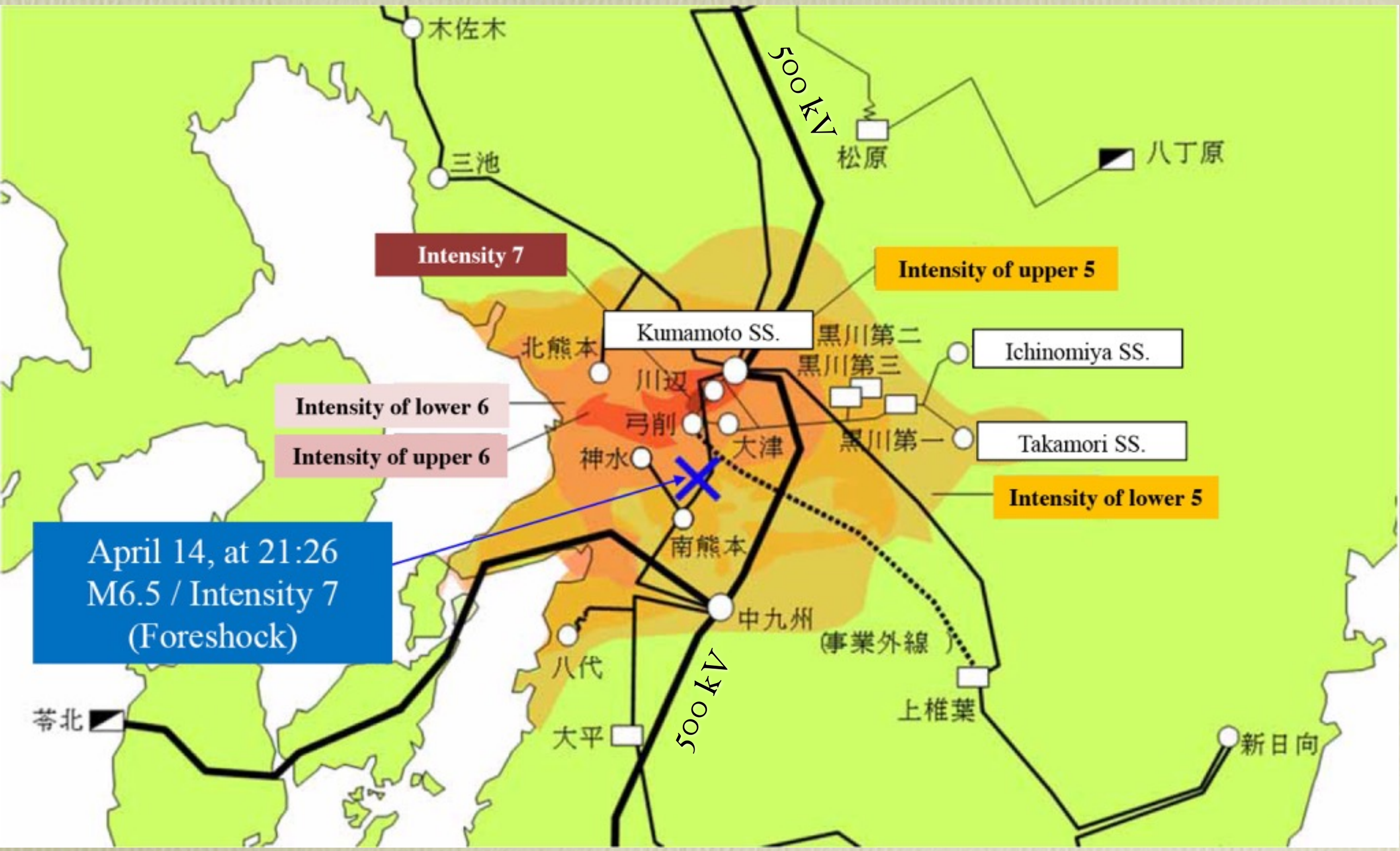
- We got down to restoring power using a total of 169 mobile HV generators – 59 from Kyushu Electric Power and 110 from the other electric utilities. It was just after 19:00 JST on Tuesday the 20th when we got the power from the generators to all HV distribution lines, except those that proved to be too difficult to restore.

- We continued our restoration work to have two temporary transmission towers and 15 poles installed in the Ichinomiya/Takamori area and achieved temporary recovery by 22:00 JST on Tuesday the 27th.

Kyushu Electric

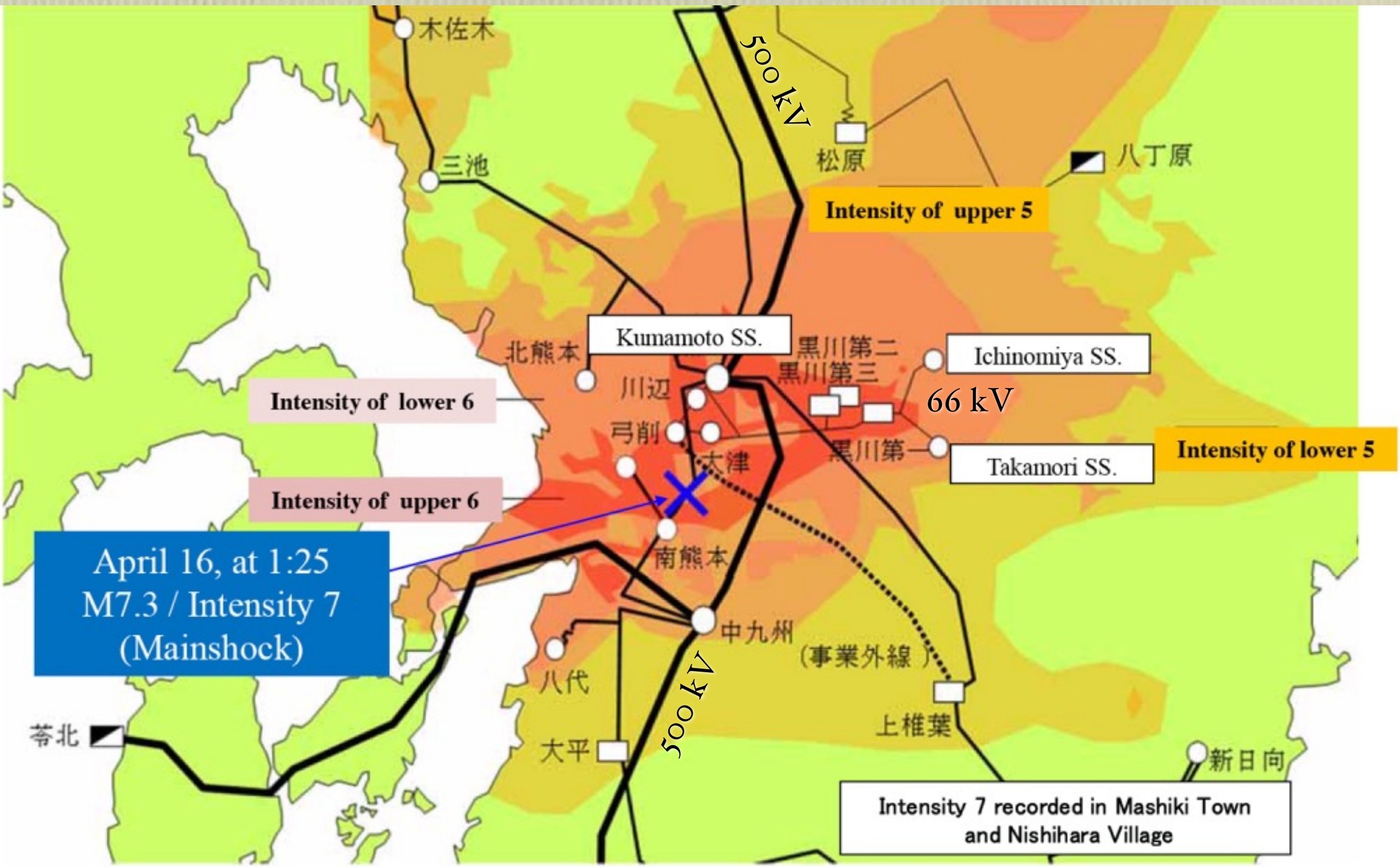


Kyushu Electric. Fore Shock, April 14 at 21:26



Kyushu Electric. Main Shock, April 16 at 1:25

Genkai

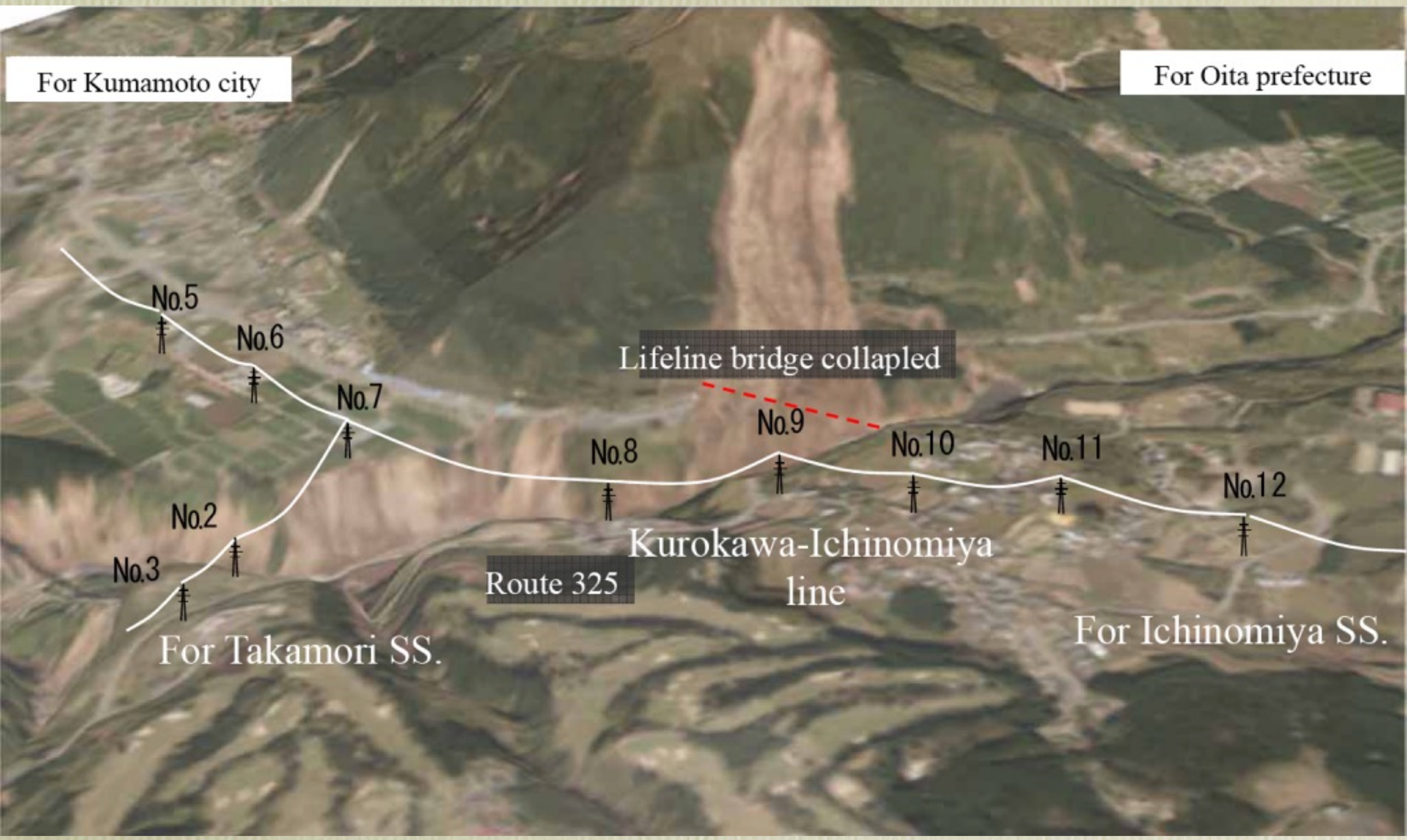


Sendai

Kyushu Electric. Damaged Facilities

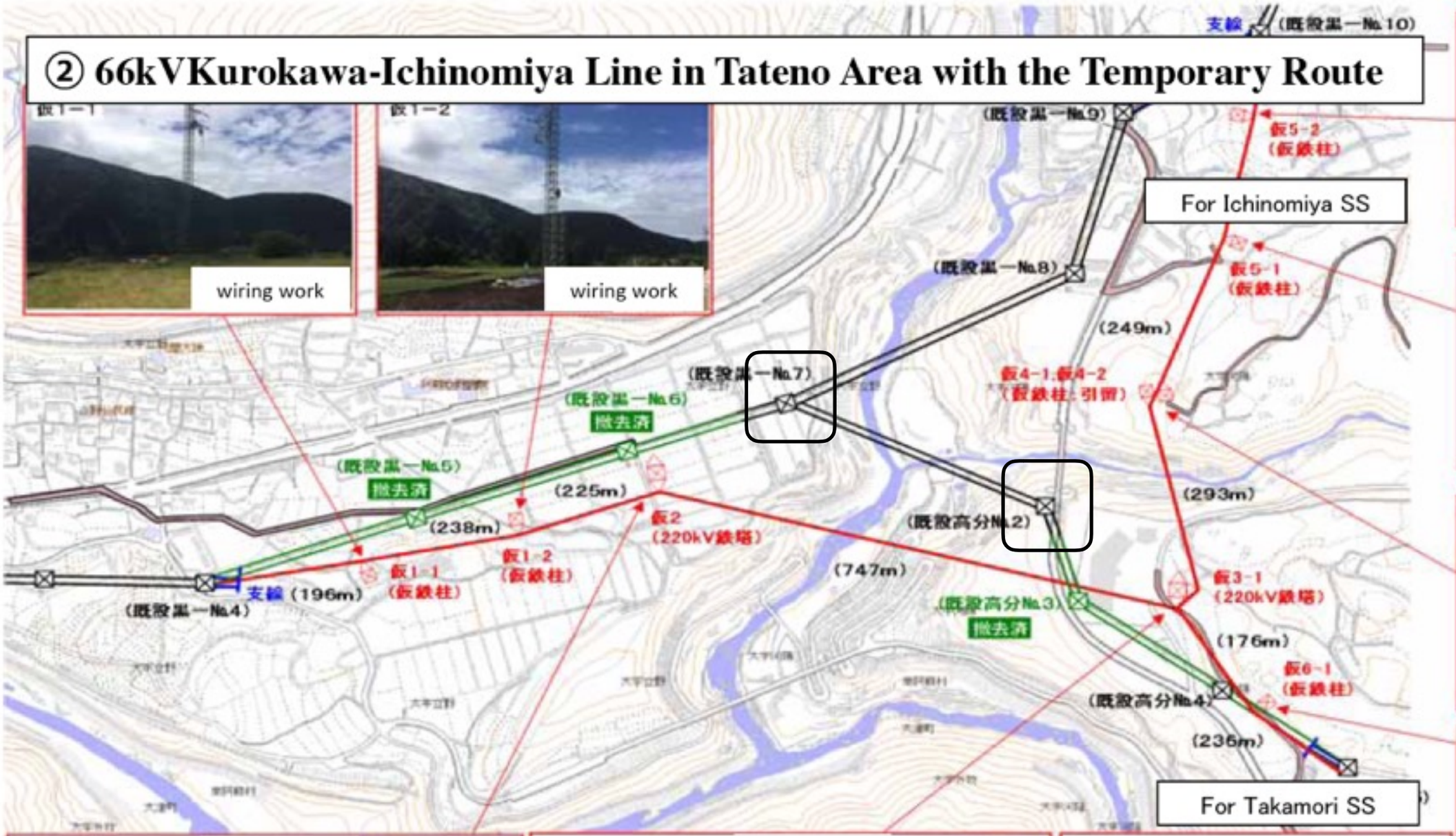
Facilities	Damage	Notes
Hydro power	9 Power plants	・Damage to headrace channels caused by landslides and etc.
Transmission	27 Lines	・Large-scale landslides around steel towers ・Damaged insulators and etc.
Transformation	10 Substations	・Transformer oil leakage, insulator damage and etc.
Distribution	259 Lines interrupted	・Damaged, collapsed, sloped power poles ・Breakage or crossing of electric wires, and etc.

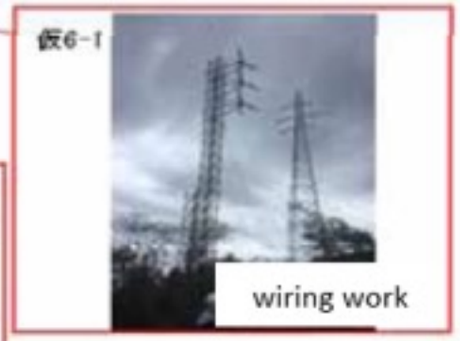
Kyushu Electric. Transmission Line Issues



Kyushu Electric. Transmission Line Issues

② 66kVKurokawa-Ichinomiya Line in Tateno Area with the Temporary Route



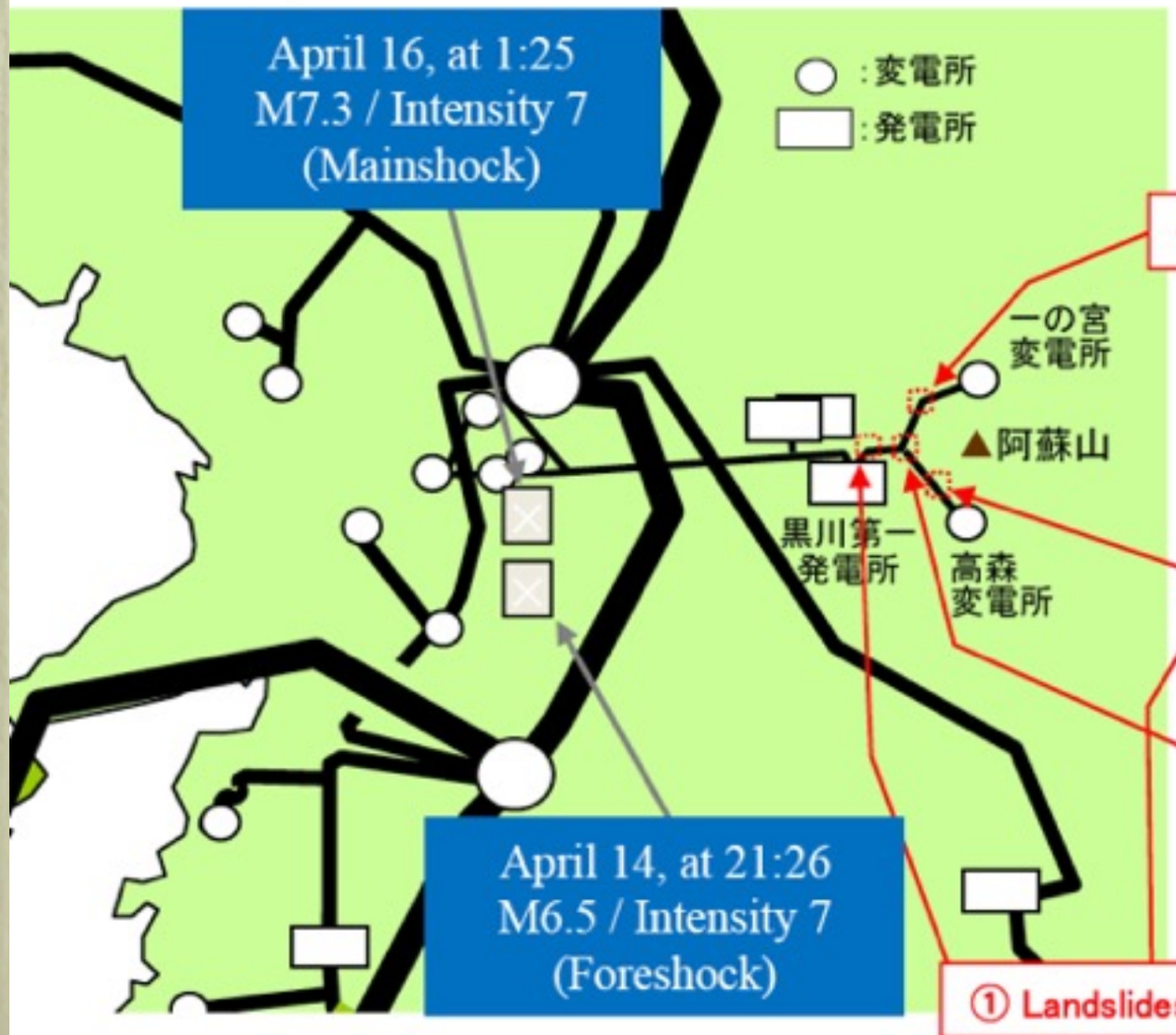


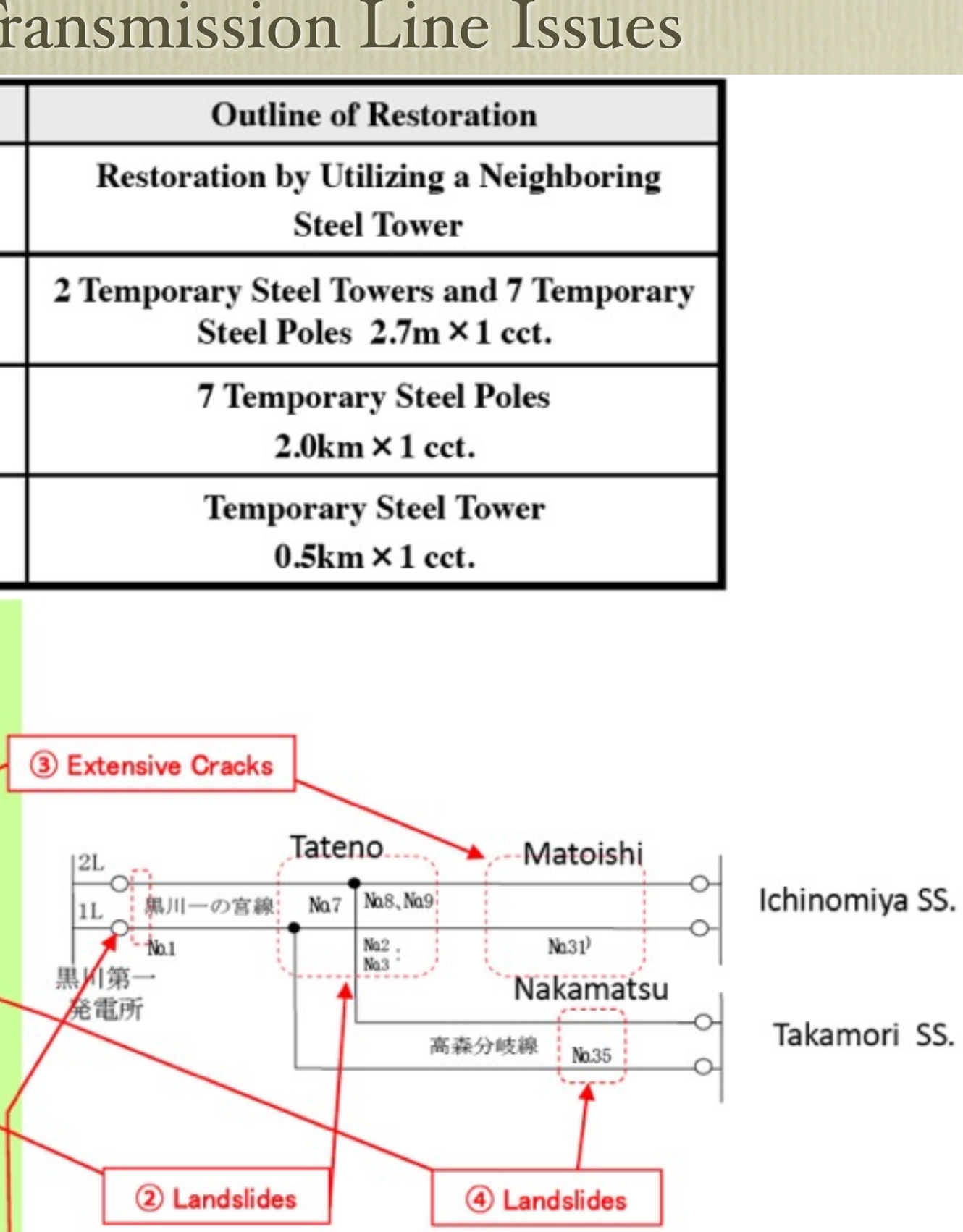
※ 写真は復旧工事の様子を掲載


Steel Tower
Minor Damage
(buckled brace)
10
Steel Pole
No Damage
9
8
Steel Tower
Major Damage
(2 foot PGD)
7
Steel Tower
Major Damage
(3 foot PGD)

Kyushu Electric. Transmission Line Issues

Damaged Sites	Outline of Restoration
① Kurokawa-Ichinomiya Line around No.1 site	Restoration by Utilizing a Neighboring Steel Tower
② Around Kurokawa-Ichinomiya Line in Tateno area around No.7	2 Temporary Steel Towers and 7 Temporary Steel Poles 2.7m × 1 cct.
③ Around Kurokawa-Ichinomiya Line in Matoishi area around No.31	7 Temporary Steel Poles 2.0km × 1 cct.
④Around Takamori branch Line in Nakamatsu area around No.35	Temporary Steel Tower 0.5km × 1 cct.

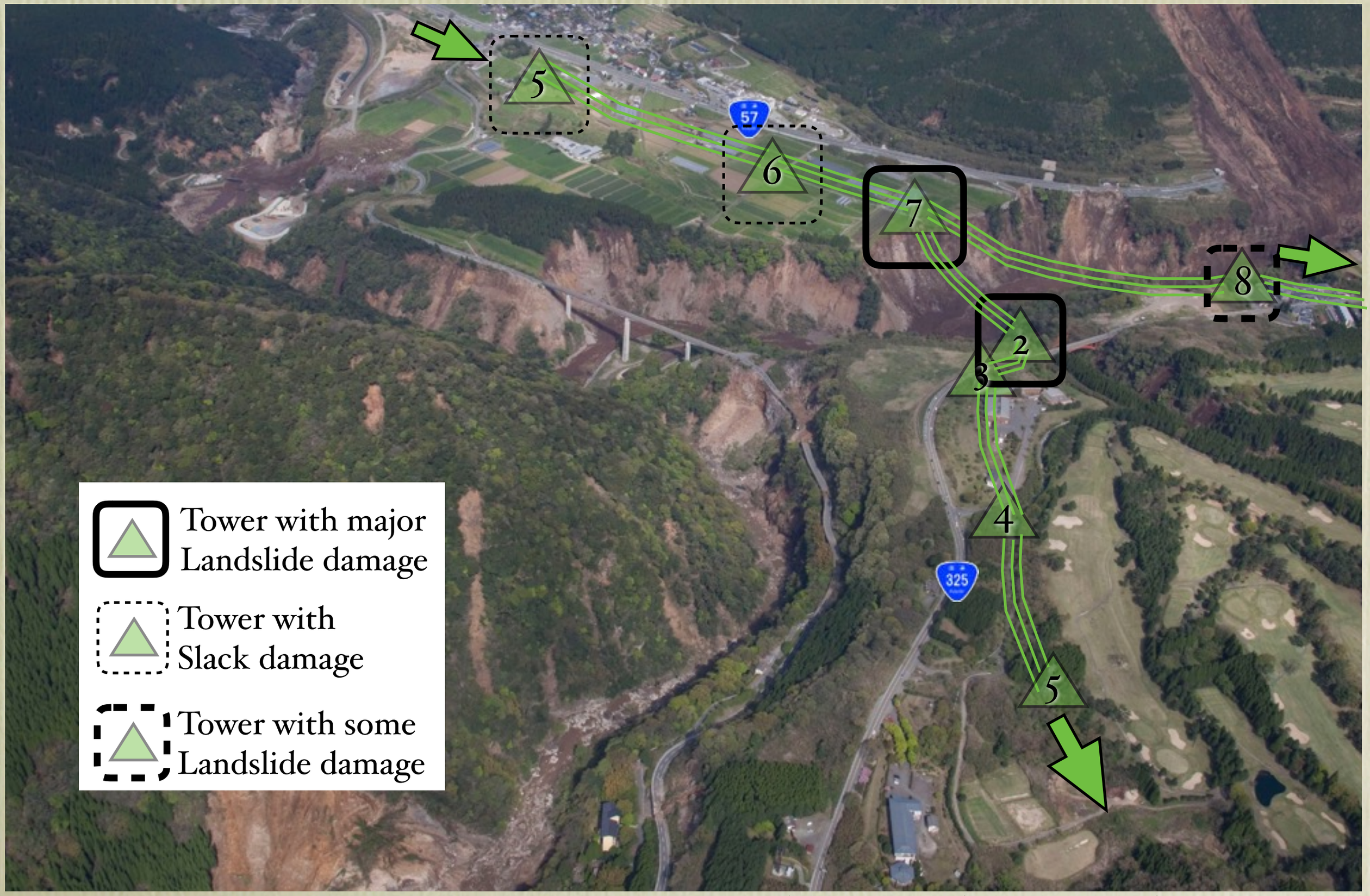




Numbers in the table and the diagram show transmission towers that require restoration.

From Kurakowa Substation
2 lines, 66 kV

To Ichinomiya
Substation, 2 lines, 66 kV



To Takamori Substation, 2 lines, 66 kV


New
Tower
New
Pole
New
Pole
Orig
Tower
7


8


あぶない
さくの中に
関係者
立


2

Direction of Landslide


Direction of Landslide

T

C

C

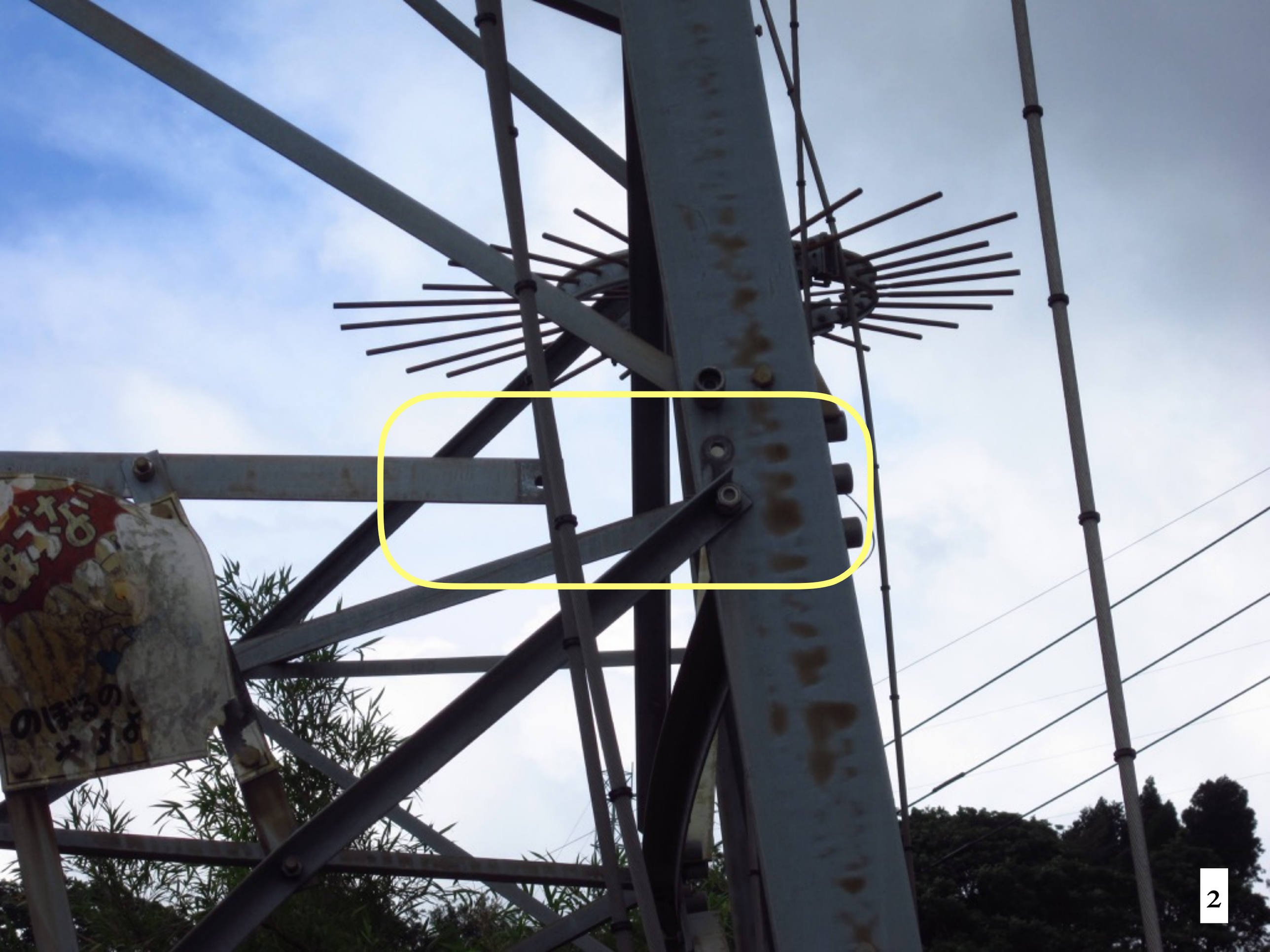
T

Buckled

Disconnected

PGD

PGD


のぼるの
やめて

PGD

2

Steel Pole 9
No apparent yielding

Steel Pole 9
No apparent yielding

Steel Tower 10
Buckled Brace

Kyushu Electric. Transmission Line Issues

③ 66kVKurokawa-Ichinomiya Line in Matoishi Area Affected by Extensive Cracks

66kVKurokawa-Ichinomiya Line No.30

66kVKurokawa-Ichinomiya Line No.31

Damaged Foundation of the Tower No.32

Which Failure Mechanism?

Strong Inertial Shaking Causes the Porcelain Insulators to vibrate against each other, damaging sheds. Or, Cable dynamics allow the strings to compress, allowing shed-to-shed and string-to-string impacts. No faults occurred due to this damage mode

?

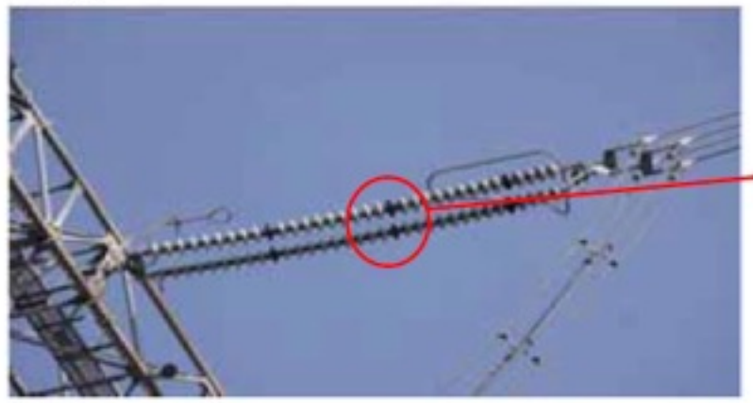
?

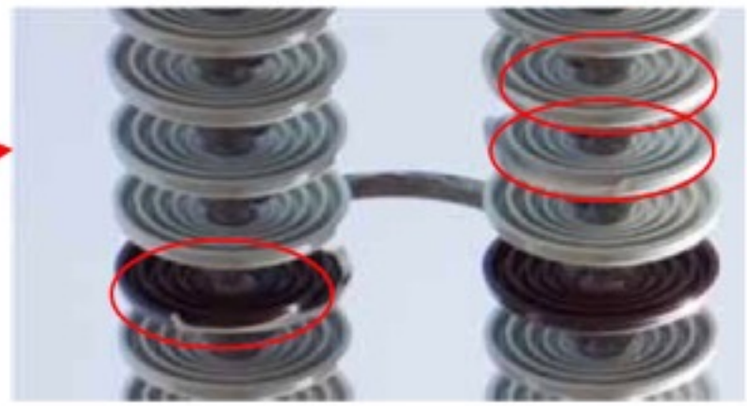
Typical 500 kV Strain Tower Jumper Configuration

Kyushu Electric. Transmission Line Issues

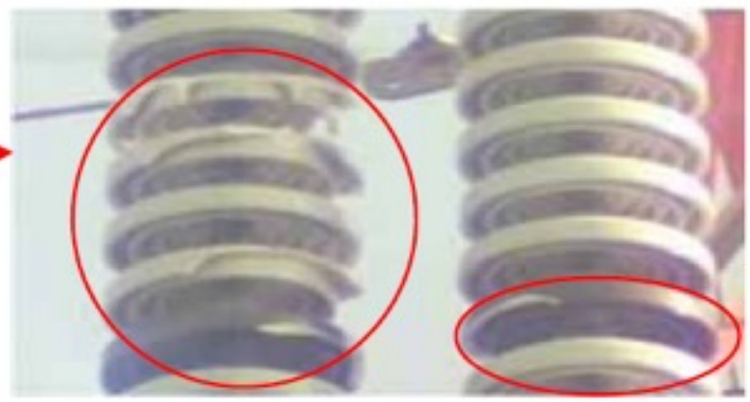
500kV Insulators Damaged

500kV Kumamoto
trunk line
№217-219

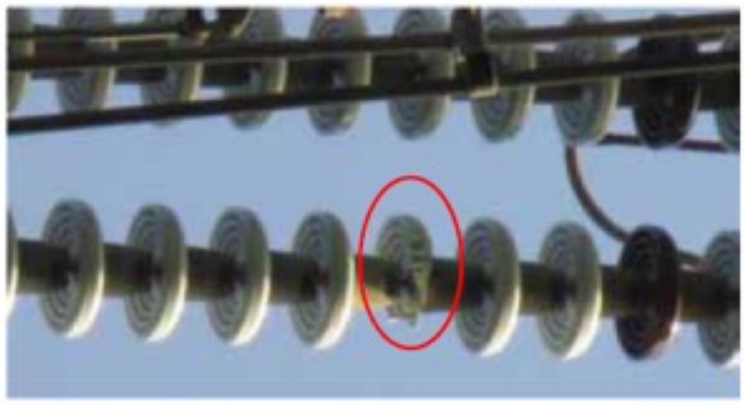




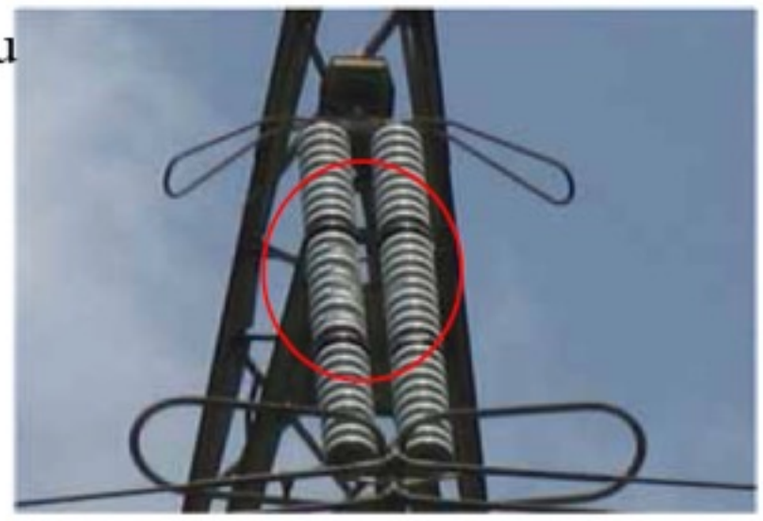
500kV Reihoku
thermal power line
№191



500kV Naka Kyushu
trunk line
№23

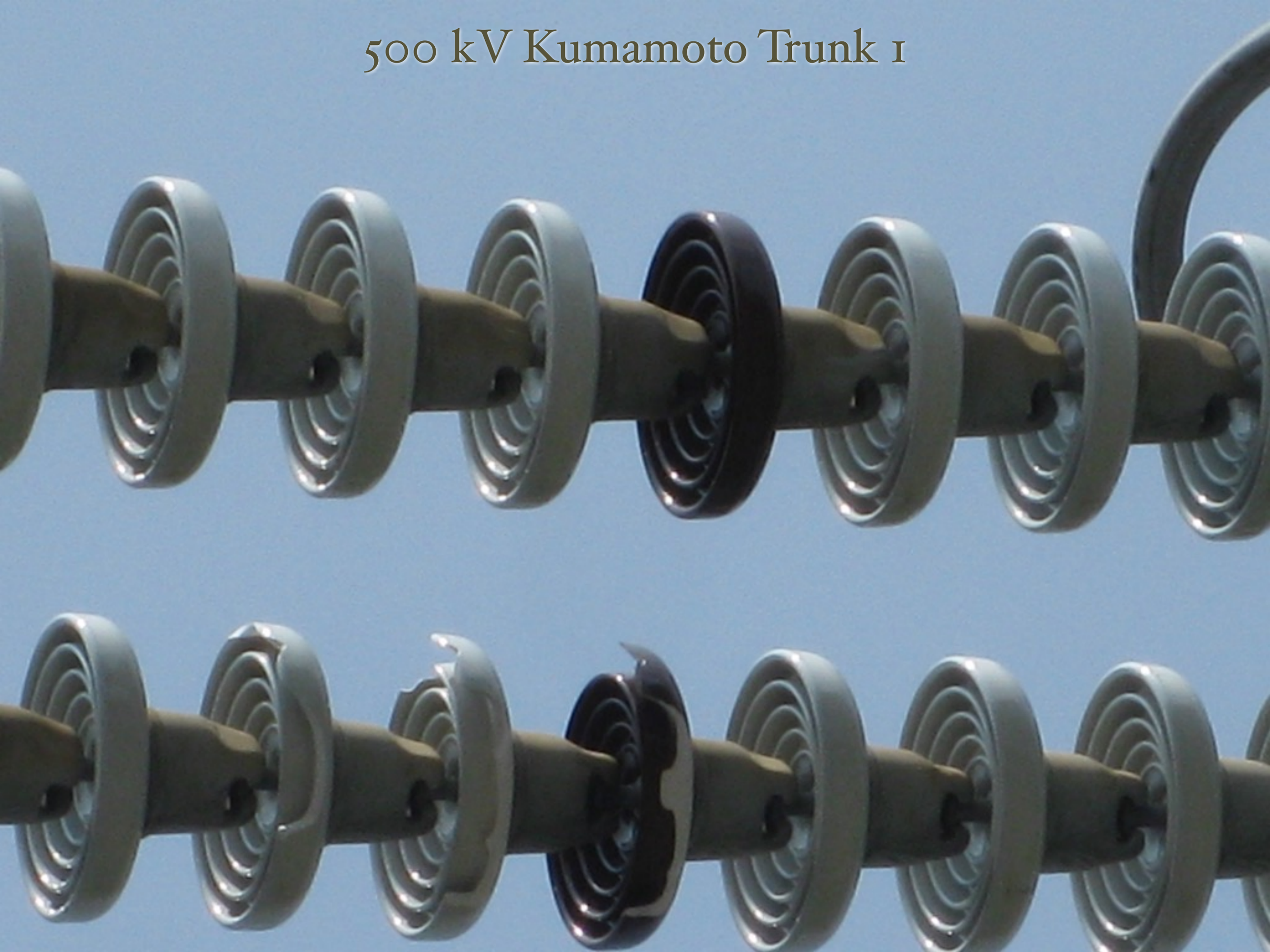


500kV Naka Kyushu
trunk line
№30

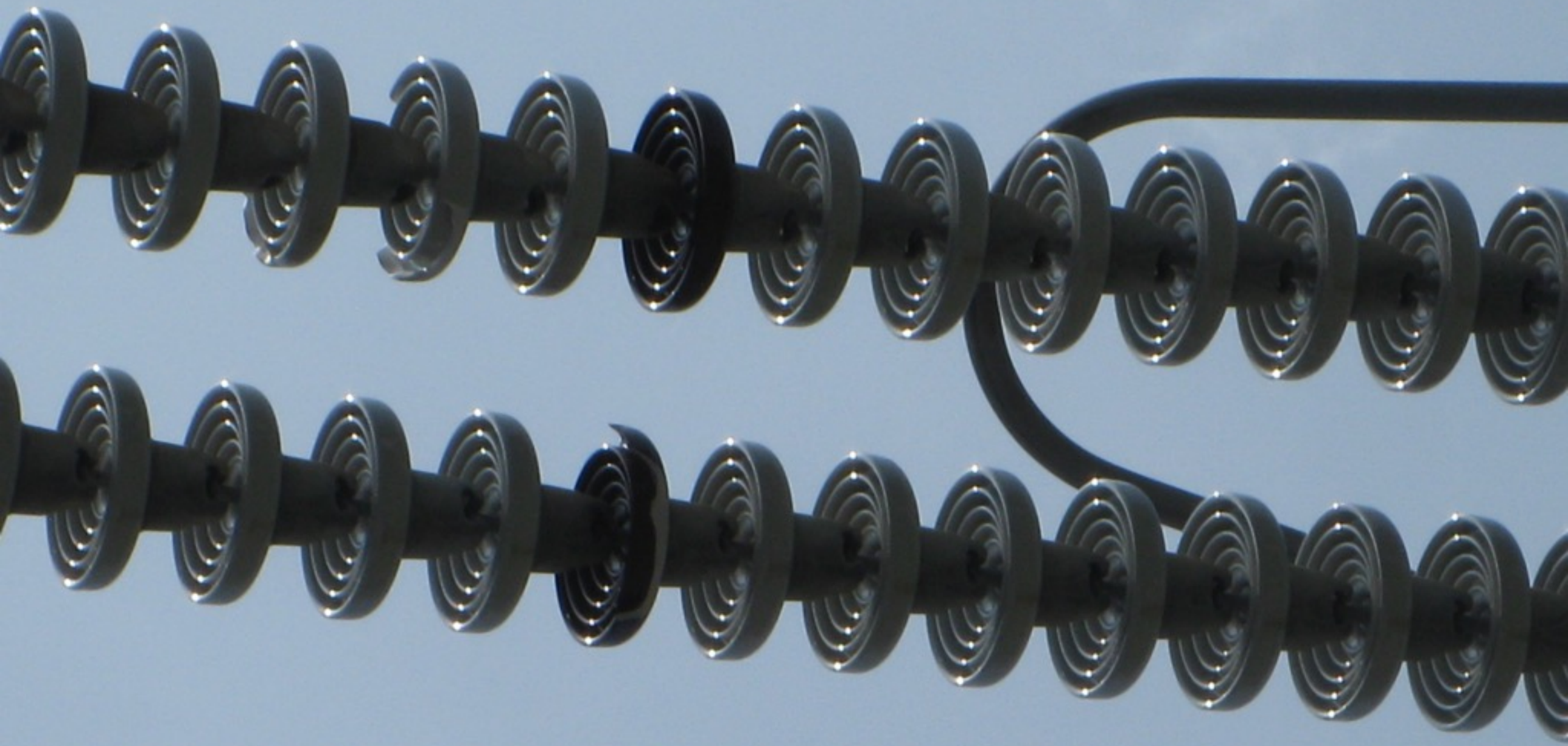


Solution: add spacers. Cause: vertical motions?
This damgae did not cause faults

500 kV Kumamoto Trunk 1



500 kV Kumamoto Trunk 2



500 kV Reihoku Trunk

500 kV Reihoku Trunk

500 kV Reihoku Trunk

66 kV Kurakawa - Ichinomiya No. 5

66 kV Kurakawa - Ichinomiya No. 5

66 kV Kurakawa - Ichinomiya
No. 7
April 16 821 am

66 kV Kurakawa - Ichinomiya No. 7

66 kV Kurakawa - Ichinomiya
No. 8
April 16 8:35 am

66 kV Kurakawa - Ichinomiya No. 8
April 16 8:28 am

66 kV Kurakawa - Ichinomiya No. 8
April 16 8:28 am

66 kV Kurakawa - Ichinomiya
No. 31
April 16 9:29 am

66 kV Kurakawa - Ichinomiya
No. 31
April 16 9:29 am

66 kV Kurakawa - Ichinomiya
No. 30
April 16 9:29 am

66 kV Kurakawa - Takamori No. 2 April 16 8:28 am

66 kV Kurakawa - Takamori No. 2 April 16 8:21 am

66 kV Kurakawa - Takamori
No. 2
April 17 8:52 am

66 kV Kurakawa - Takamori
No. 2
April 17 8:52 am

Kumamoto Substation 2004. First Built - 1975

1-3ø 500 - 220 kV TR

1-3ø 220 - 66 kV TR

1-3ø 66 kV RE

66 kV

500 kV Yard GIS 4 Lines

220 kV Yard 10 Lines

161 m

Imagery Date: 2/11/2004 lat 32.909470° lon 130.902137° elev 247 m eye alt 908 m

2015

Southeast part of Yard, 500 kV, 500 - 220 kV TR, pre-earthquake

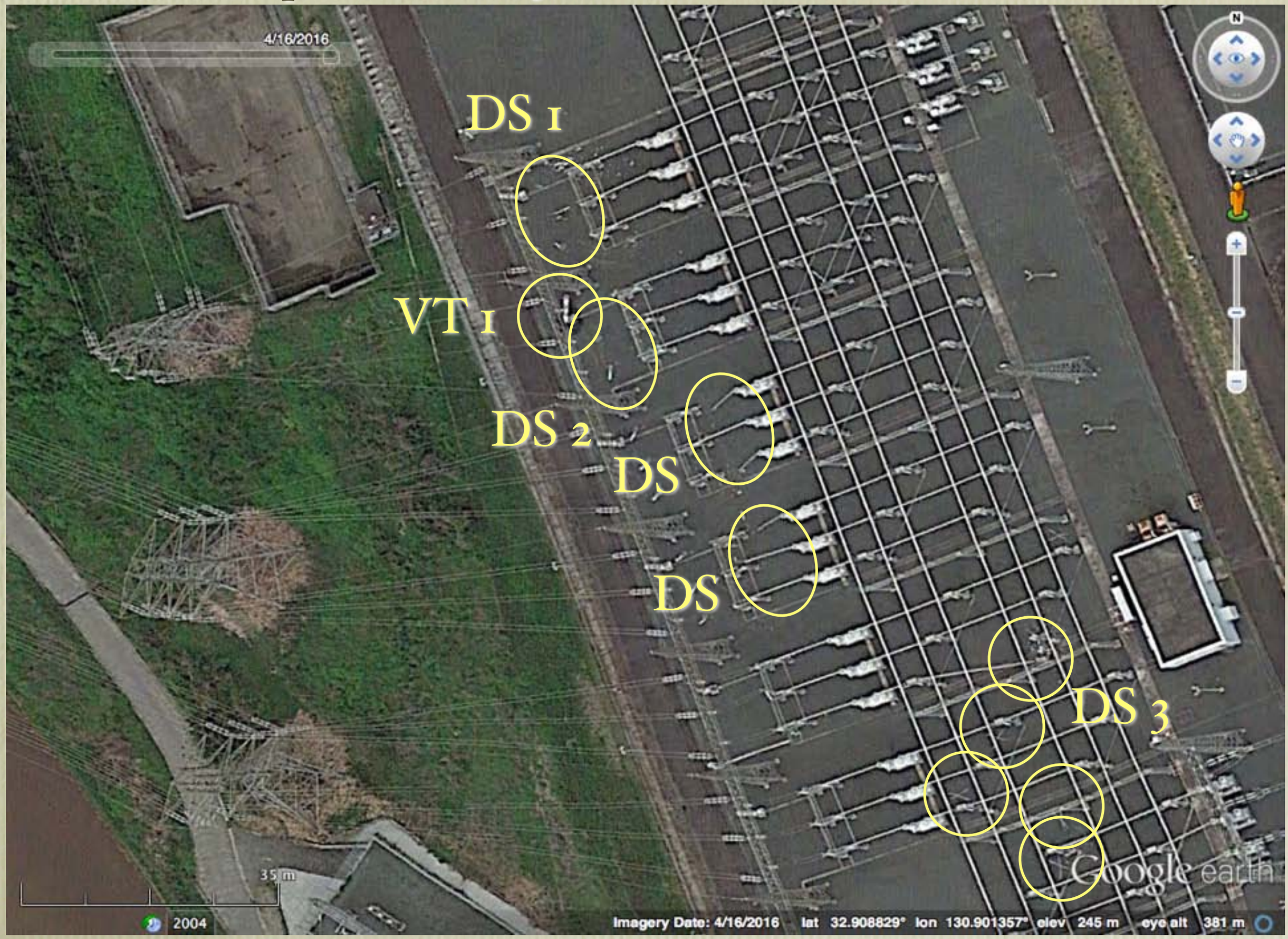
66 kV Bushing

GIS

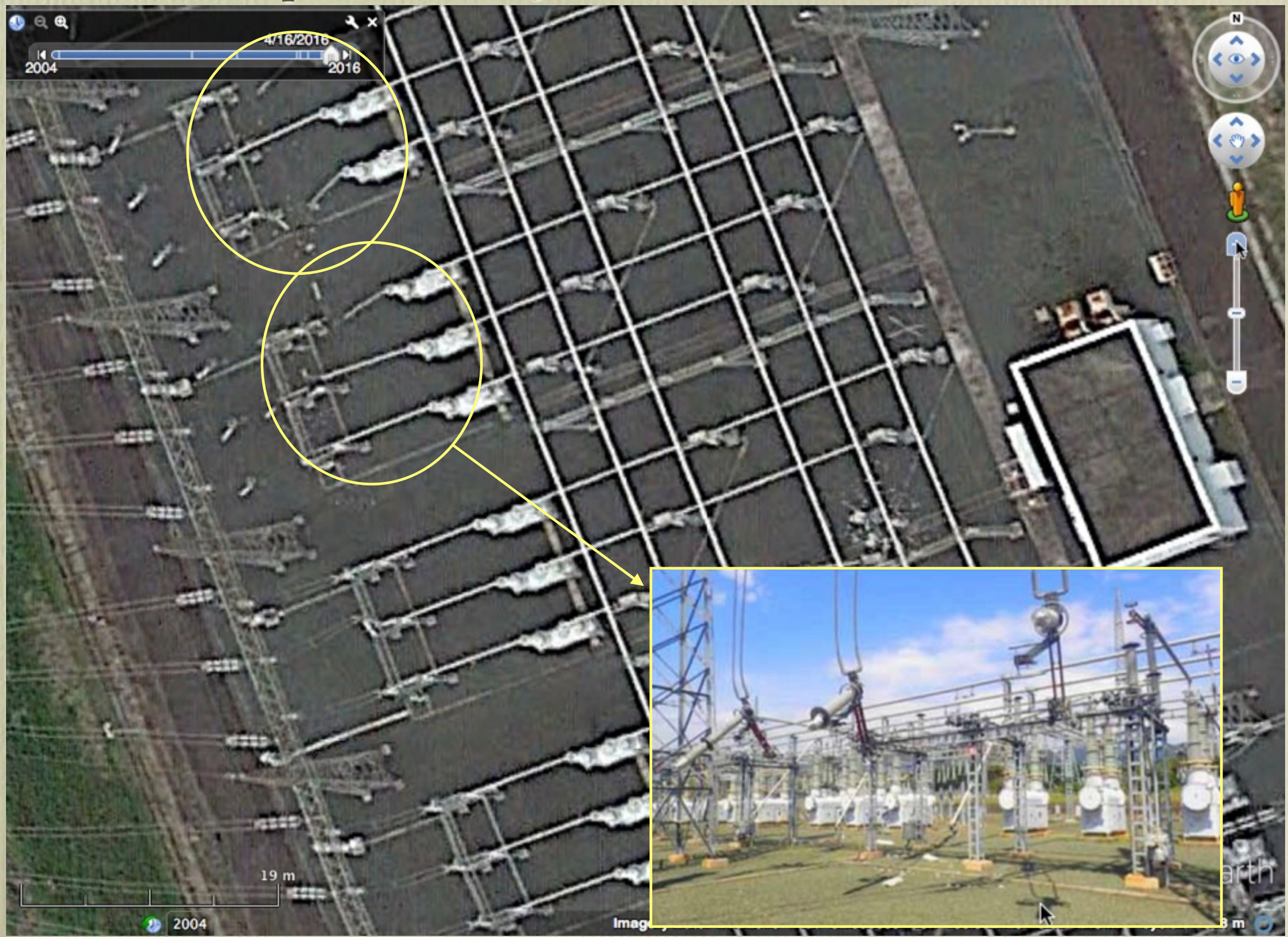
66 kV Slipped Bushing and oil leakage

66 kV Neutral Bushing

April 16 2016 JST After Main Shock



April 16 2016 JST After Main Shock



April 16 2016 JST After Main Shock

DS 1

DS 2

VT. Older design. No seismic qualification
Similar device broke at Sendai 2011 Tohoku EQ

April 16 2016 JST After Main Shock

VT. Older design. No seismic qualification

April 16 2016 JST After Main Shock

VT. Older design. No seismic qualification

April 16 2016 JST After Main Shock

DS 2

April 16 2016 JST After Main Shock

DS 2

April 16 2016 JST After Main Shock

April 16 2016 JST After Main Shock DS 3 (Pantograph)

DS 3 (Pantograph)

April 16 2016 JST After Main Shock

DS 1 220 kV

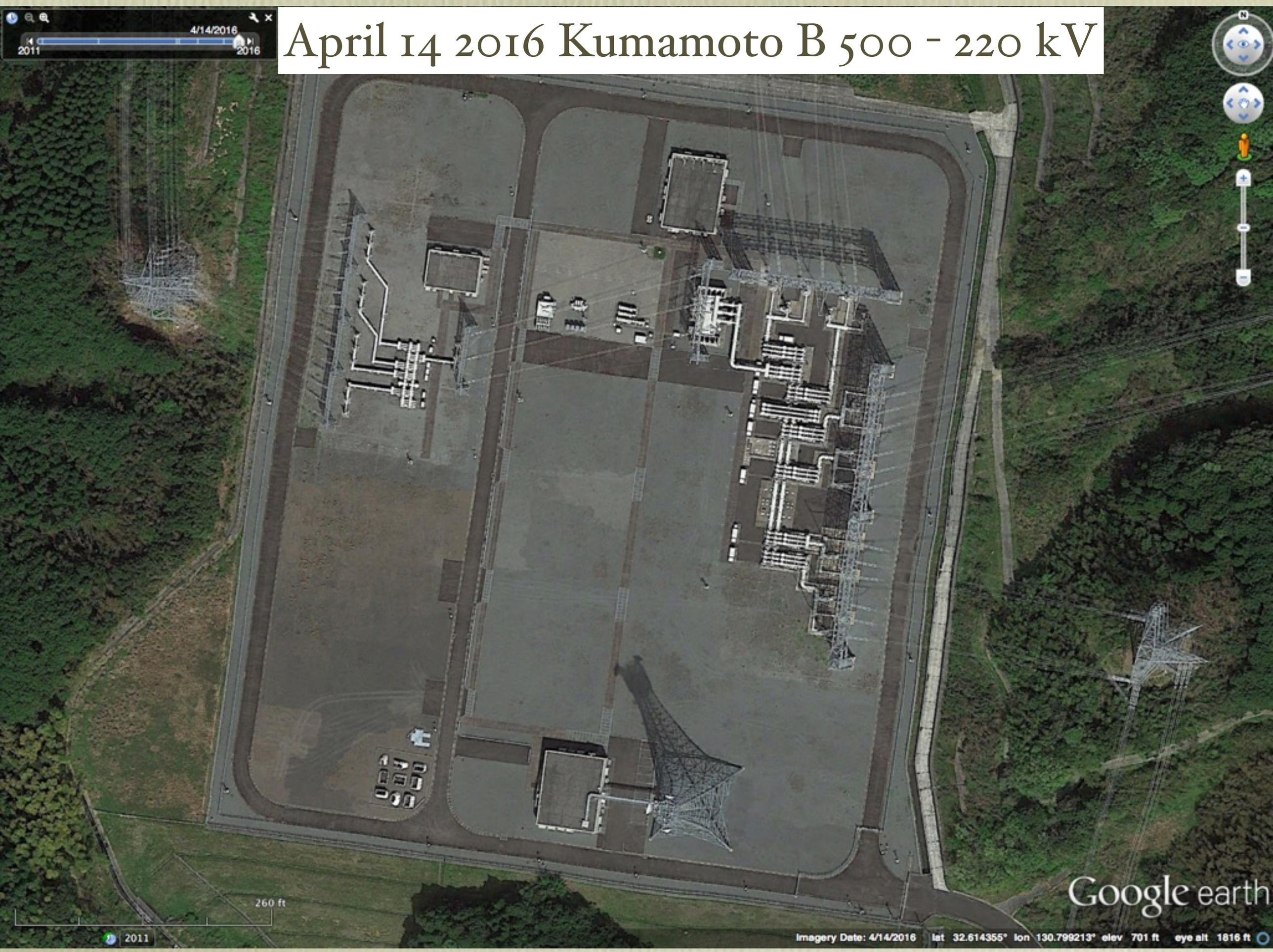
DS 3 220 kV

DS 220 kV

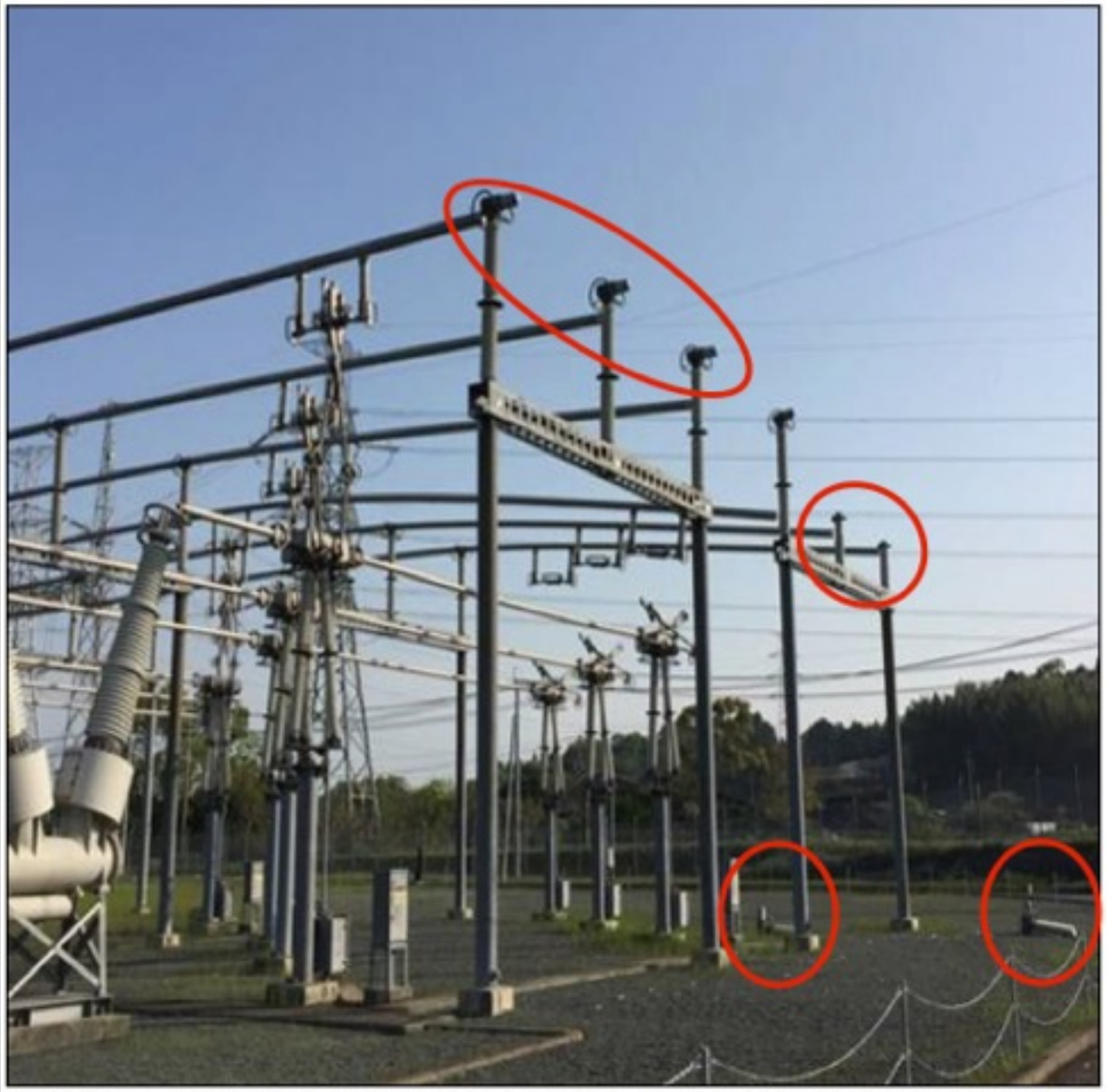
DS 220 kV

CB 220 kV

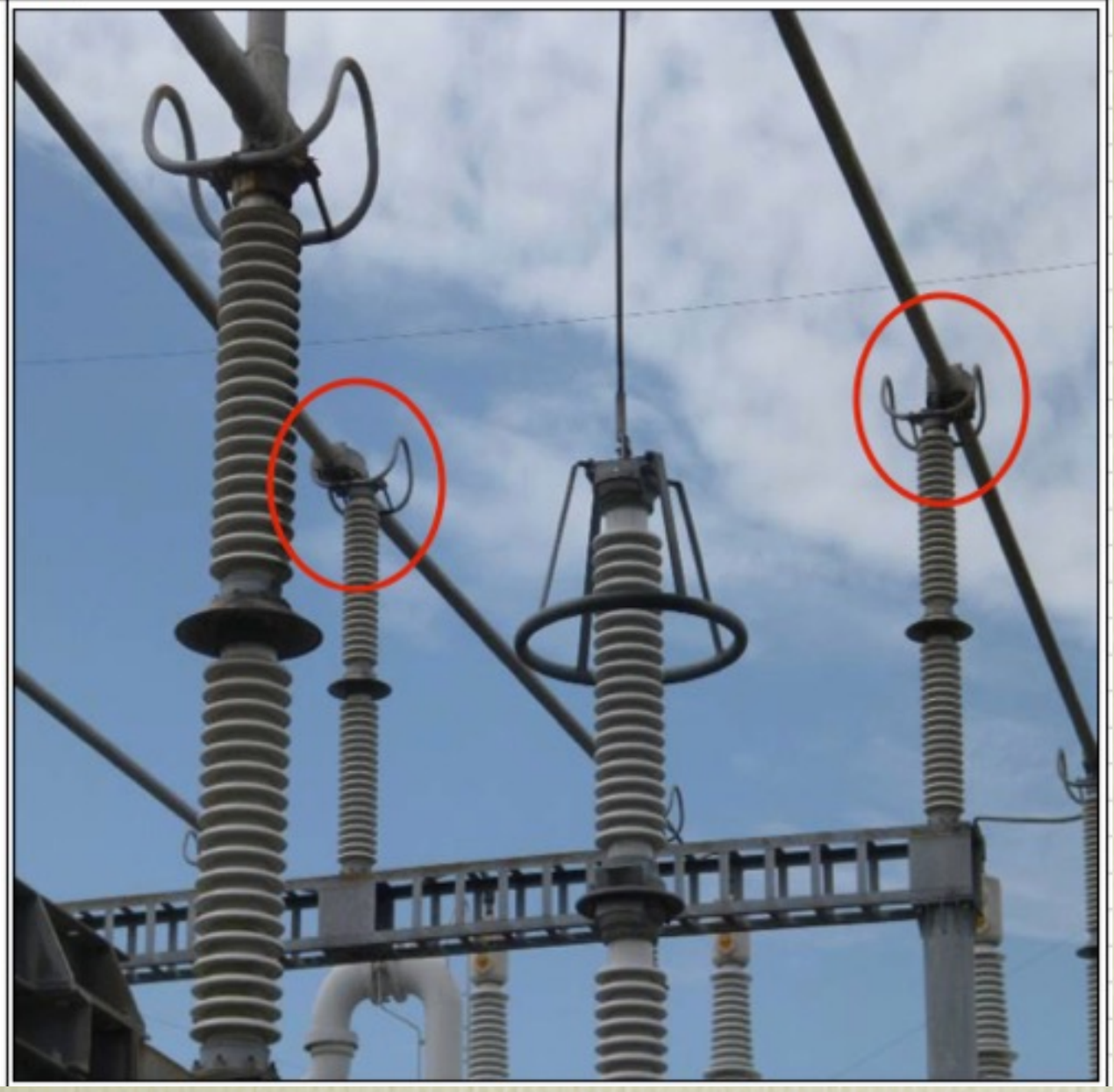
April 14 2016 Kumamoto B 500 - 220 kV



21



22	

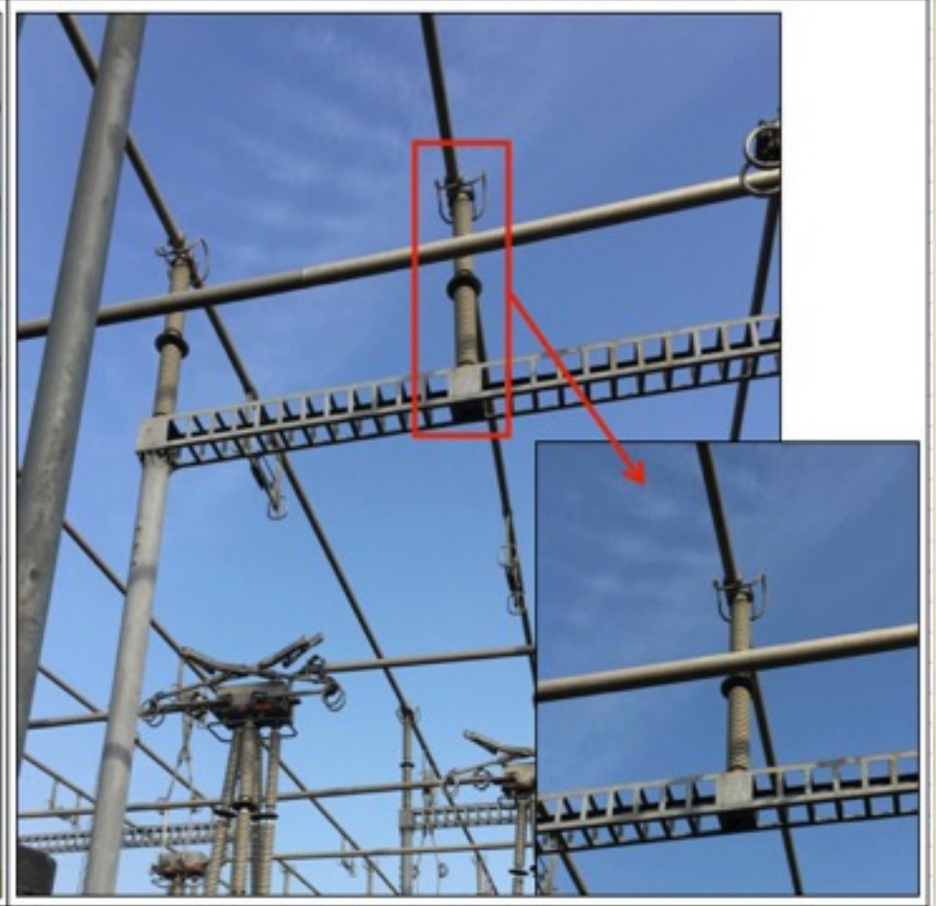


1

2

3

4



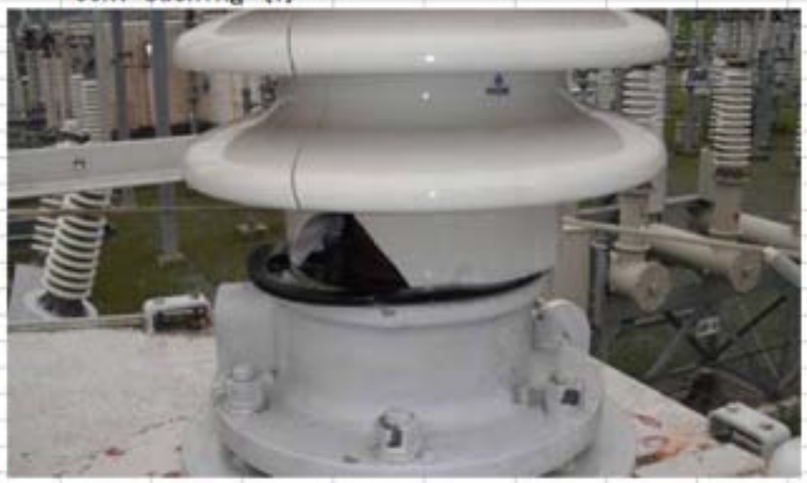
5

6

Minami Kumamoto 66kV #4 Shunt Reacter

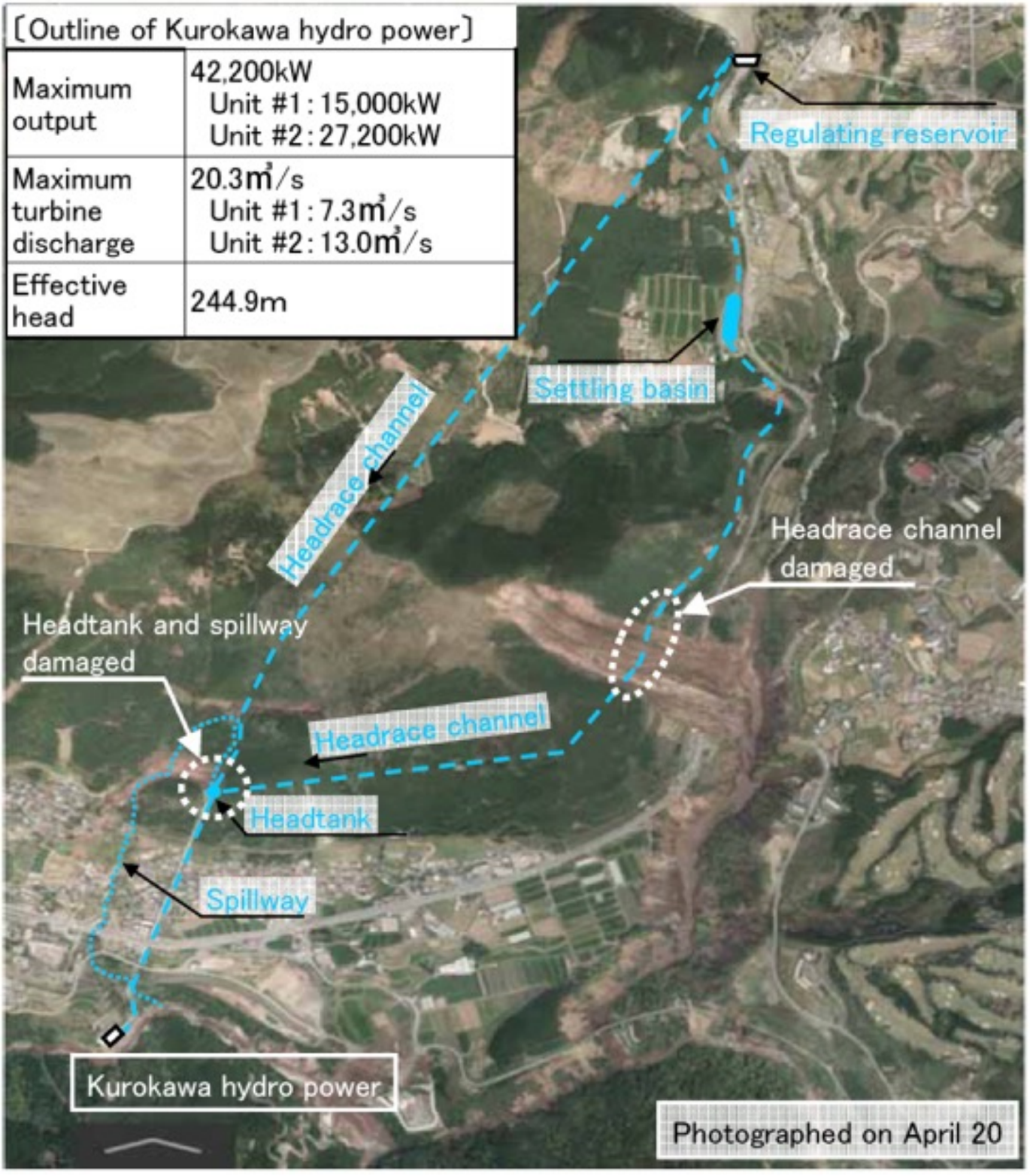
66kV bushing (S)

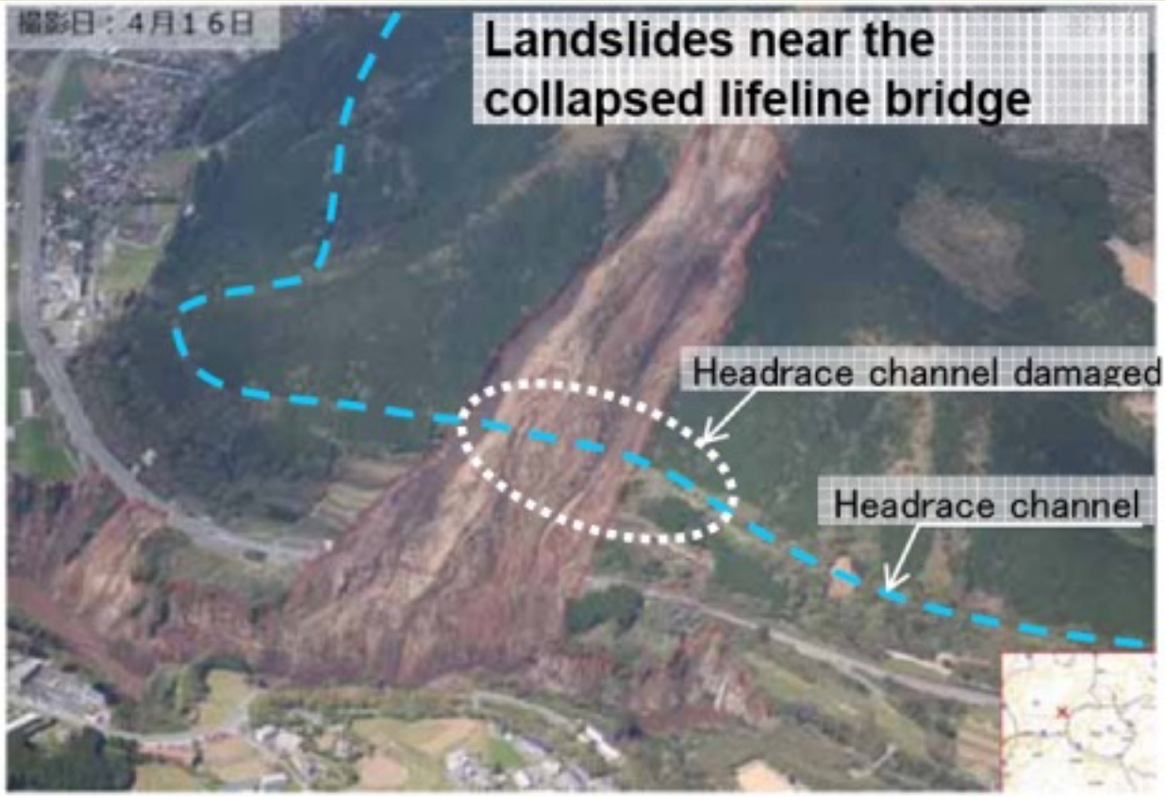
66kV bushing (T)



oil leakage

Kyushu Electric. Hydro Issues





JNC Company. Produces Fertilizer
Owns 13 Hydroelectric Power Plants

Turbine Building Failed. Repair after the landslide along the access road is repaired (July 2 2016, t+77 days)

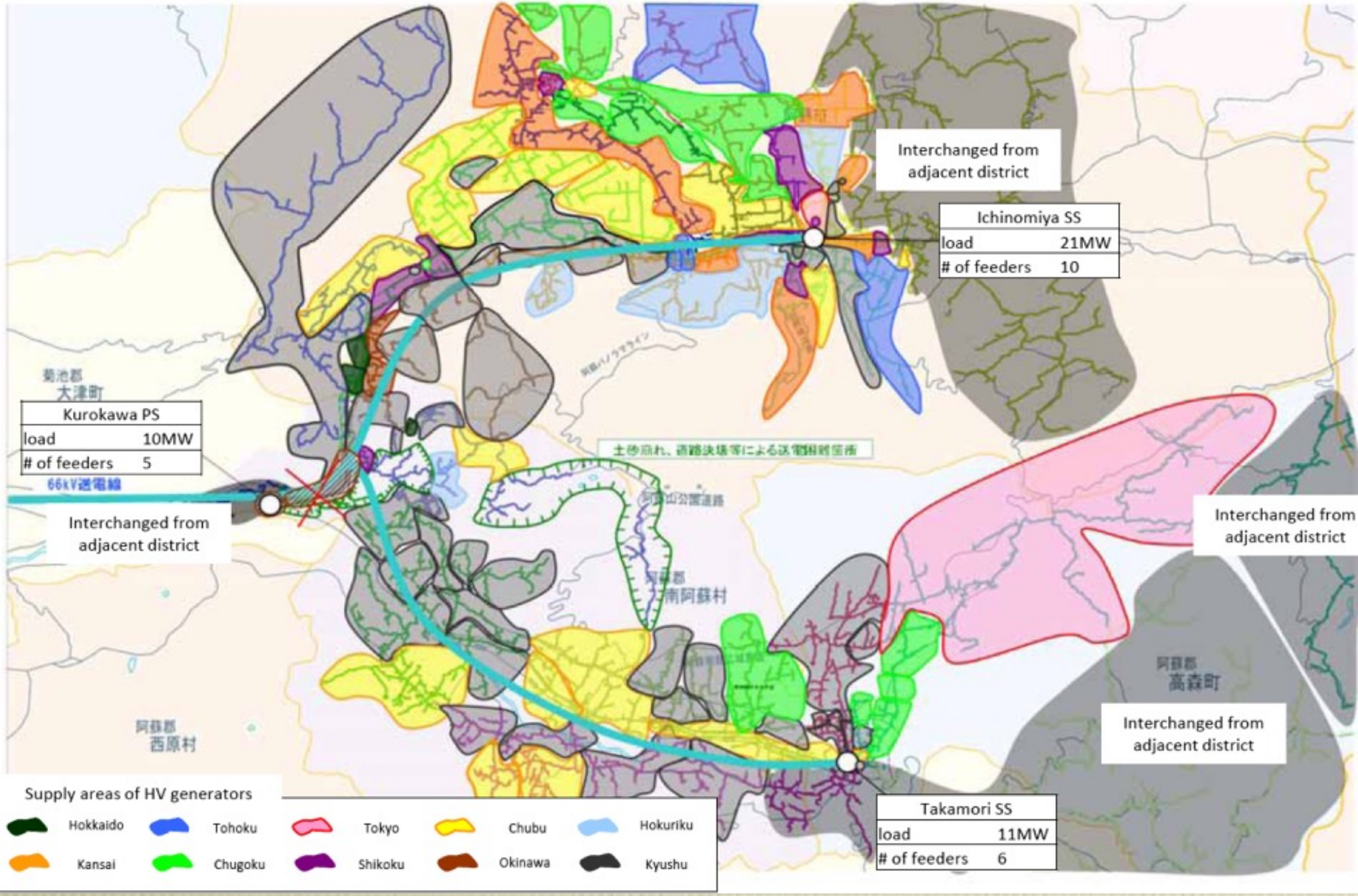
Distribution

Kyushu Electric. Distribution Issues

Kyushu Electric. Distribution Issues

Kyushu Electric. Distribution Issues

The other 9 electric power companies provided enormous assistance in outage restoration.



Kyushu Electric. Distribution Issues

Kyushu Electric. Distribution Issues

Mobole HV generator fueling

Generator fuel storage site

Common Distribution Pole

Reinforced Concrete Tube

Primary is Commonly 6.5 kV

Wood Poles are Rare

Cross Arms are steel

Attachments use metal friction clamps

Pulldowns + PGDs sometimes rotate the clamps, leading to faults

Attachments use metal friction clamps

Cross Arms are steel


ISUZU
TEPCO


ISUZU


ISUZU
MOVIDEN
災害復旧車
四国電力


関西電力
災害復旧用


ISUZU


PC
92
00kVA高圧発電機車
九州電力

Nuclear Power Plants

Sendai: In operation at the time of the earthquake.

・Sendai Nuclear Power Station

	Date and Time	JMA Seismic Intensity (Satsumasendai City, Kagoshima pref.)	Sendai Nuclear Power Station (Kyushu Electric Seismic Intensity)			
				Lowest floor of auxiliary building (on base rock)	Upper floor of auxiliary building (1st floor)	Ground surface
①	16 April 2016 01:25 JST	4	Seismic Intensity	3	3	3
			Maximum Acceleration (gal)	8.6	12.6	30.3
②	16 April 2016 01:46 JST	2	Seismic Intensity	1	1	2
			Maximum Acceleration (gal)	2.5	3.0	5.3
③	16 April 2016 03:55 JST	1	Seismic Intensity	0	—	1
			Maximum Acceleration (gal)	0.8	—	1.2
④	16 April 2016 09:48 JST	2	Seismic Intensity	1	1	1
			Maximum Acceleration (gal)	1.4	1.7	2.4

2 x 890 MW (1984, 1985). All PWR


31.8336, 130.1897

Genkai: Not in operation at the time of the earthquake.

・Genkai Nuclear Power Station

	Date and Time	JMA Seismic Intensity (Karatsu City, Saga pref.)	Genkai Nuclear Power Station (Kyushu Electric Seismic Intensity)			
				Lowest floor of auxiliary building (on base rock)	Upper floor of auxiliary building (1st basement floor)	Ground surface
①	16 April 2016 01:25 JST	4	Seismic Intensity	3	3	3
			Maximum Acceleration (gal)	20.3	30.1	23.5
②	16 April 2016 01:46 JST	3	Seismic Intensity	2	2	2
			Maximum Acceleration (gal)	7.7	15.0	9.8
③	16 April 2016 03:55 JST	2	Seismic Intensity	1	1	1
			Maximum Acceleration (gal)	2.6	4.7	2.6
④	16 April 2016 09:48 JST	2	Seismic Intensity	1	2	1
			Maximum Acceleration (gal)	3.3	7.6	3.1

2 x 559 MW (1975, 1980) + 2 x 1180 MW(1993, 1996). All PWR


33.5159, 129.8372

Questions?

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