Seismic Arrays: Insight into Source Characteristics and Disaster Mitigation

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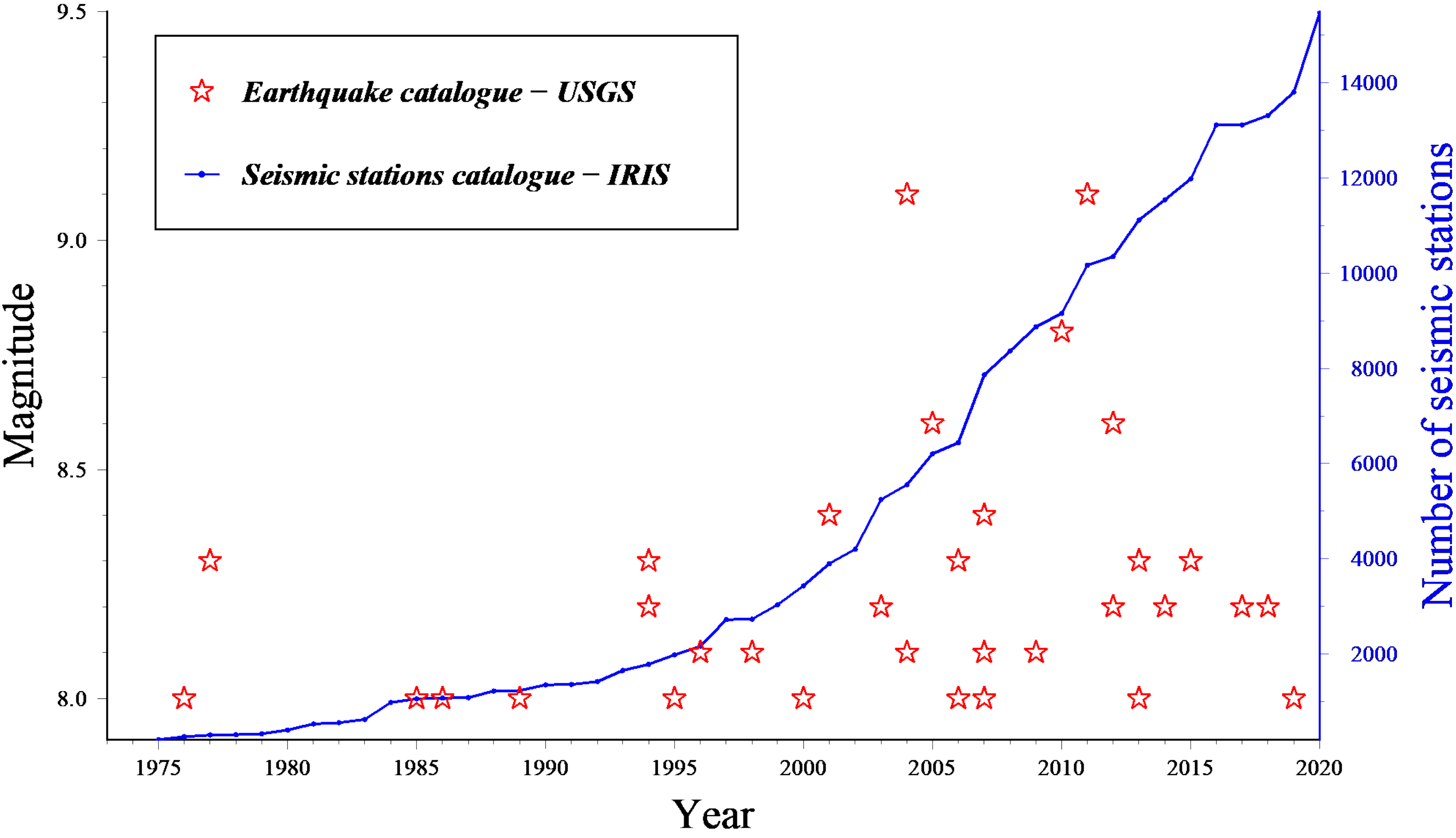
Online, 9 December, 2021

Booming of seismic observations



M > 8 earthquakes since 1973 (USGS)

Imaging source process of large earthquakes using seismic data recorded at dense arrays

Big data +Array technology

(Ishii et al., 2005， Nature)

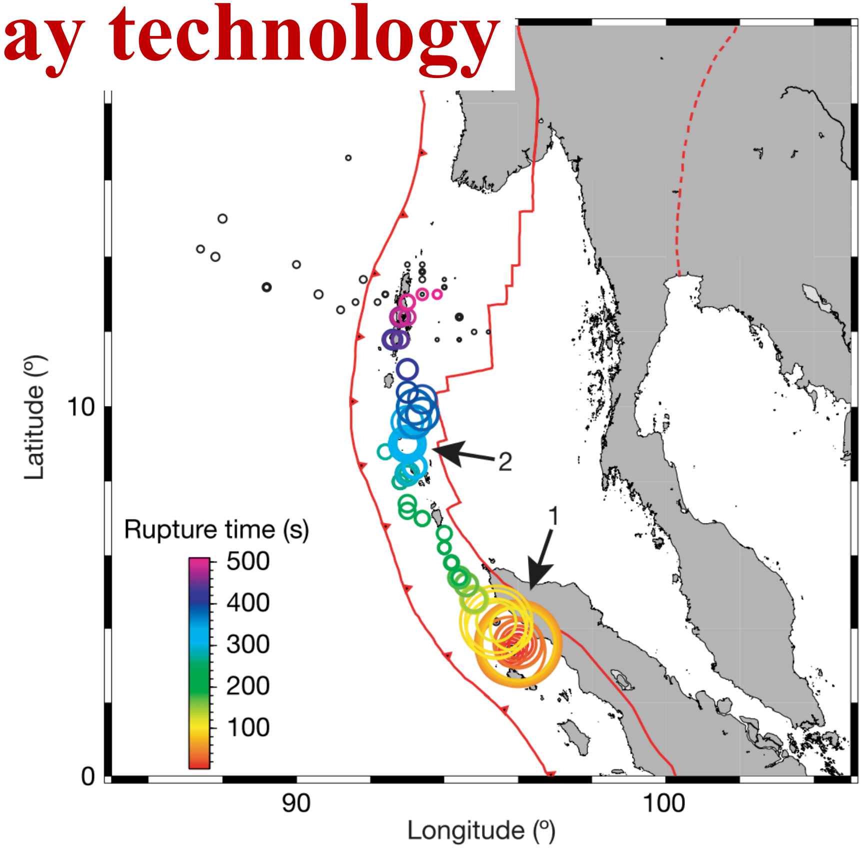
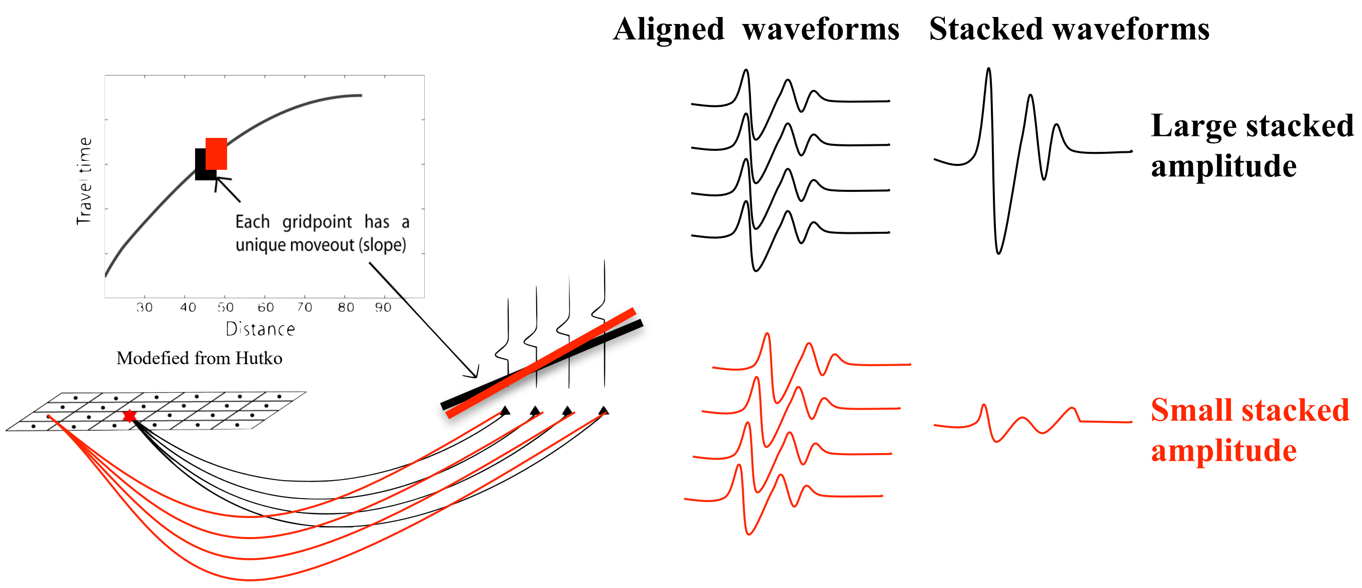


Figure 3 | Rupture trace of the Sumatra earthquake. Maxima of energy maps are shown in their spatiotemporal development by coloured circles. The width of the circles scales linearly with seismic energy; colour coding is proportional to the time since rupture initiation in the source region. Major tectonic lines are shown in red. Numbers 1 and 2 indicate the position of two major seismic energy releases.

(Kruger and Ohrnberger, 2005, Nature)

Back-projection

- **Search a grid of points to determine the best location for the source of seismic radiation in each designated time window of interested waves.**

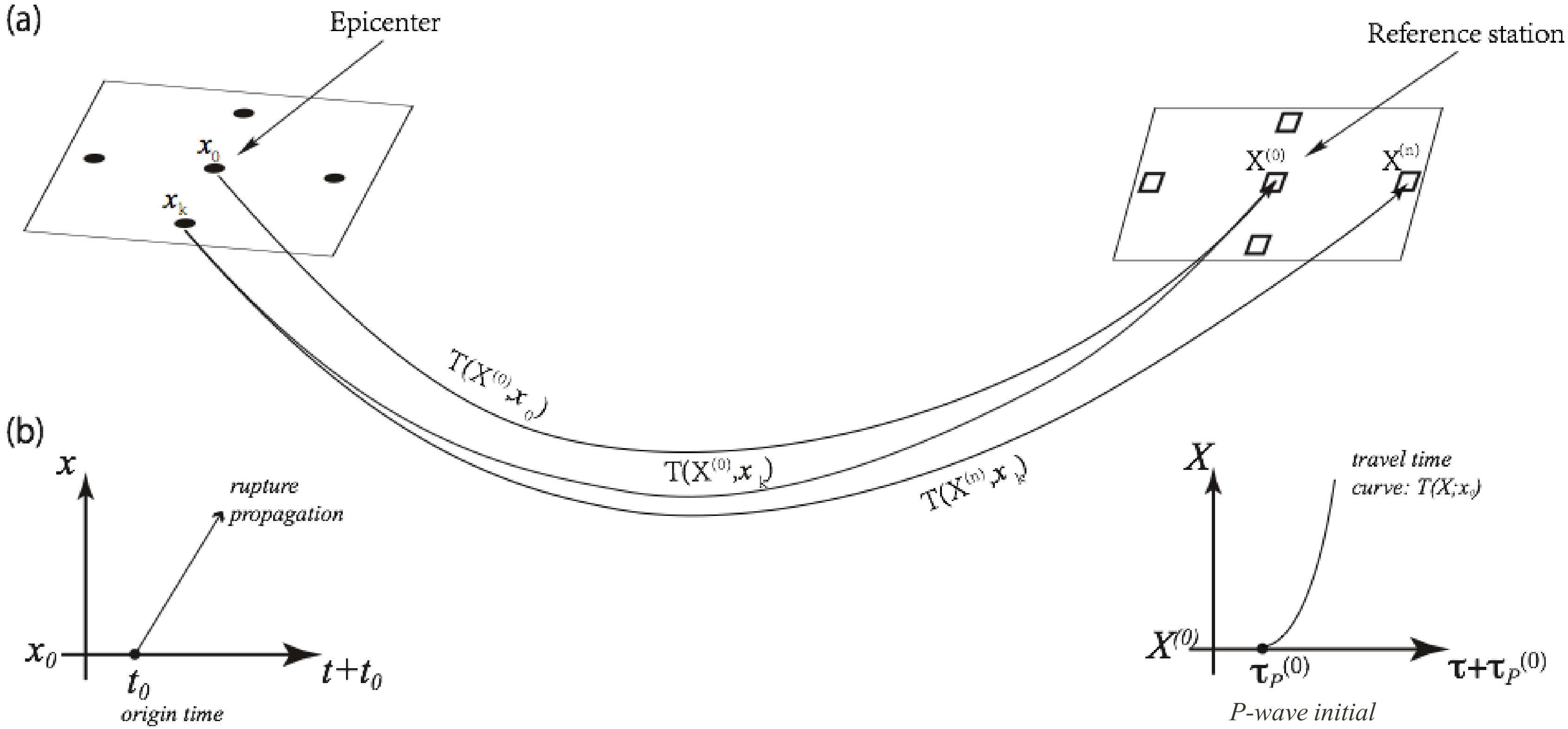


Two Back-projections

Standard back-projection | **Sliding window beampacking (Beamforming)**

Ishii et al., 2005, Nature

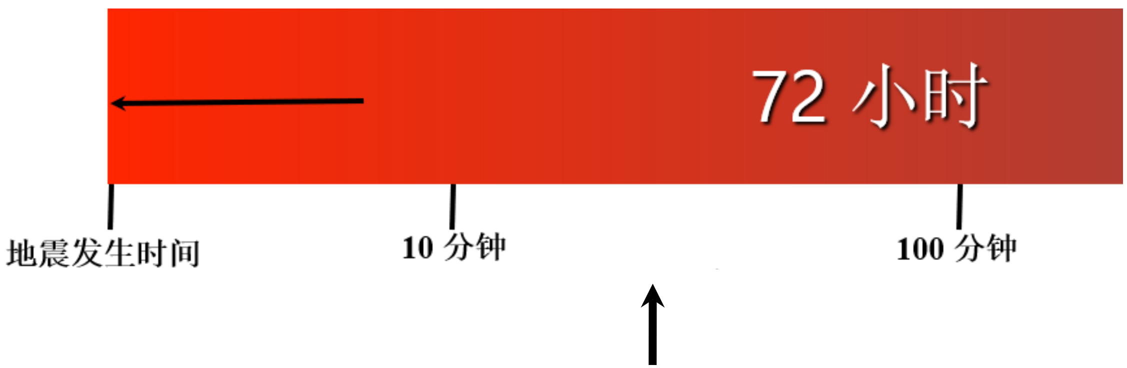
Krüger and Ohrnberger, 2005, Nature



(Wang et al., 2016)

Determining magnitude of large earthquakes

- **Rapidly and accurately determining magnitude of large earthquakes remains challenges**



The 2011 M9 Tohoku, Japan earthquake

美国地调局 (USGS)	5-13 min M_{Wp} 7.9	32 min M_W 8.9
日本气象厅 (JMA)	4-24min M_{Wp} 7.9 Tsunami warning base on M7.9	

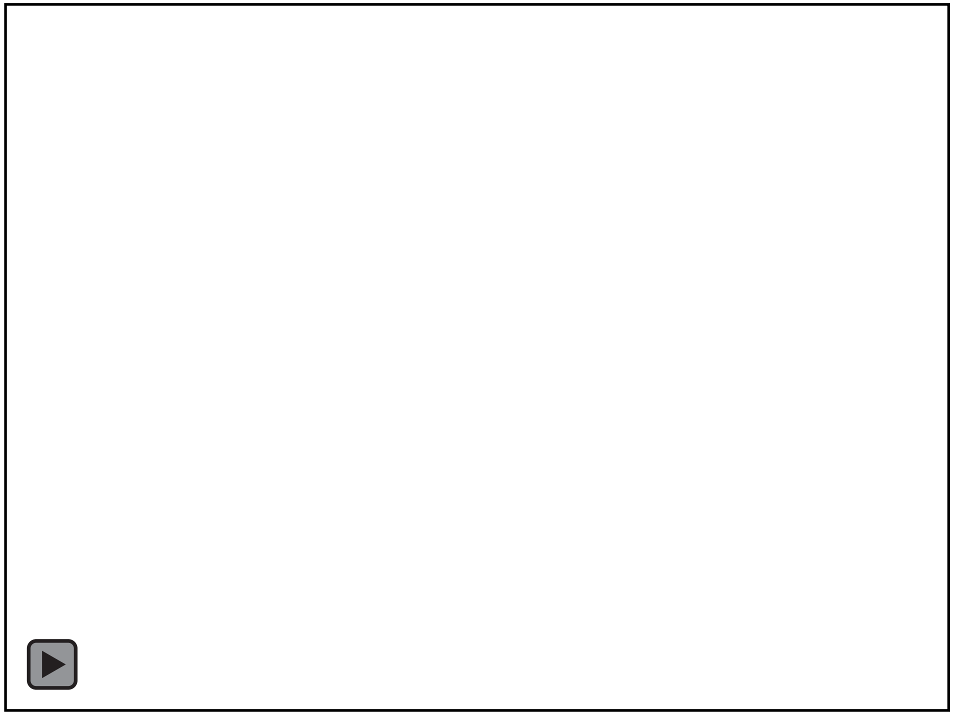
Hayes et al., 2011，SRL

Huge unexpected tsunami reached the Japan coast 25min after the earthquake

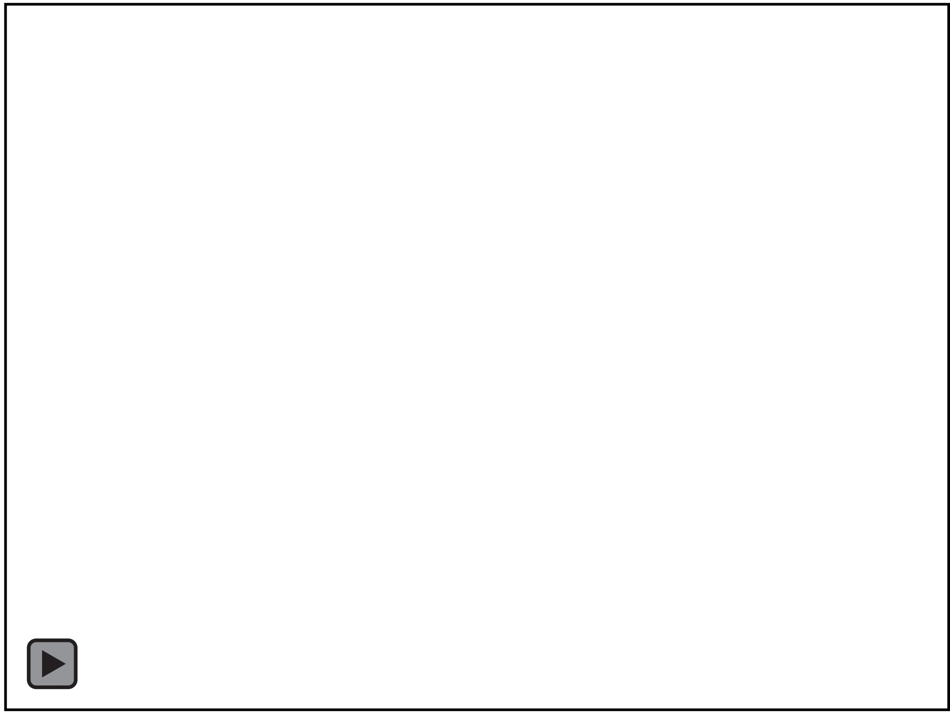
The importance of accurate magnitude for tsunami warning

(With Tung-Cheng Ho, Kyoto University)

M7.9

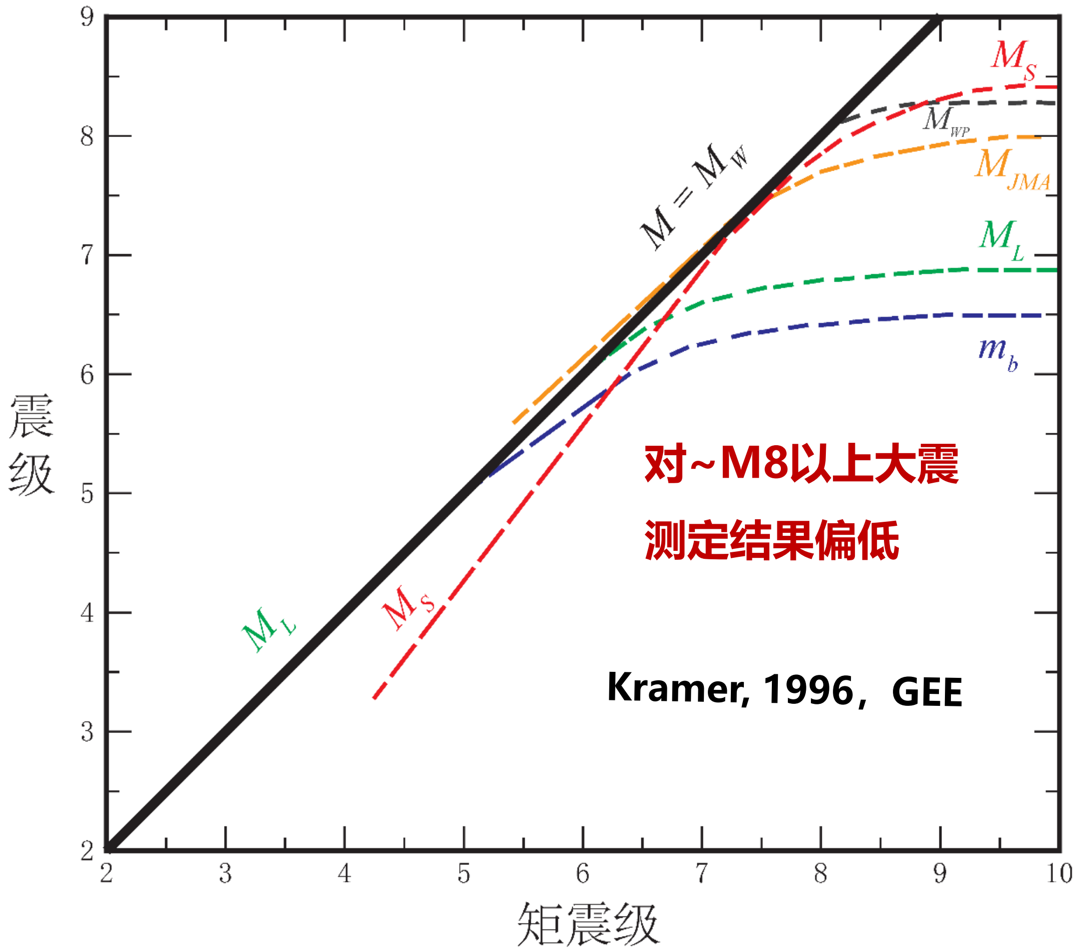


M9.1



Limitations of conventional methods

➢ M_L、M_S、M_{WP}，M_{JMA} Saturate for large earthquakes



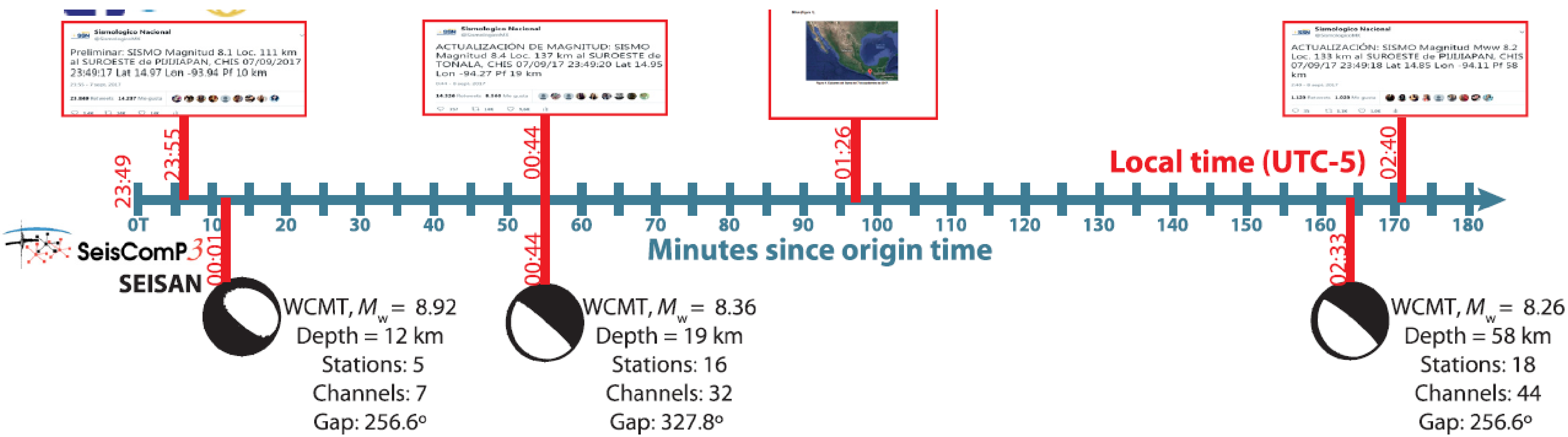
- M_L、M_S、M_{WP}、M_{JMA} saturate
- Ignoring source durations
- M_{ww} is obtained from inversion of W-phase data, which may encounter instable results with limited data in the early phase after earthquakes.

Sepetember 8, 2018 Mw 8.2 Mexico earthquake

~10 min
Mww 8.92

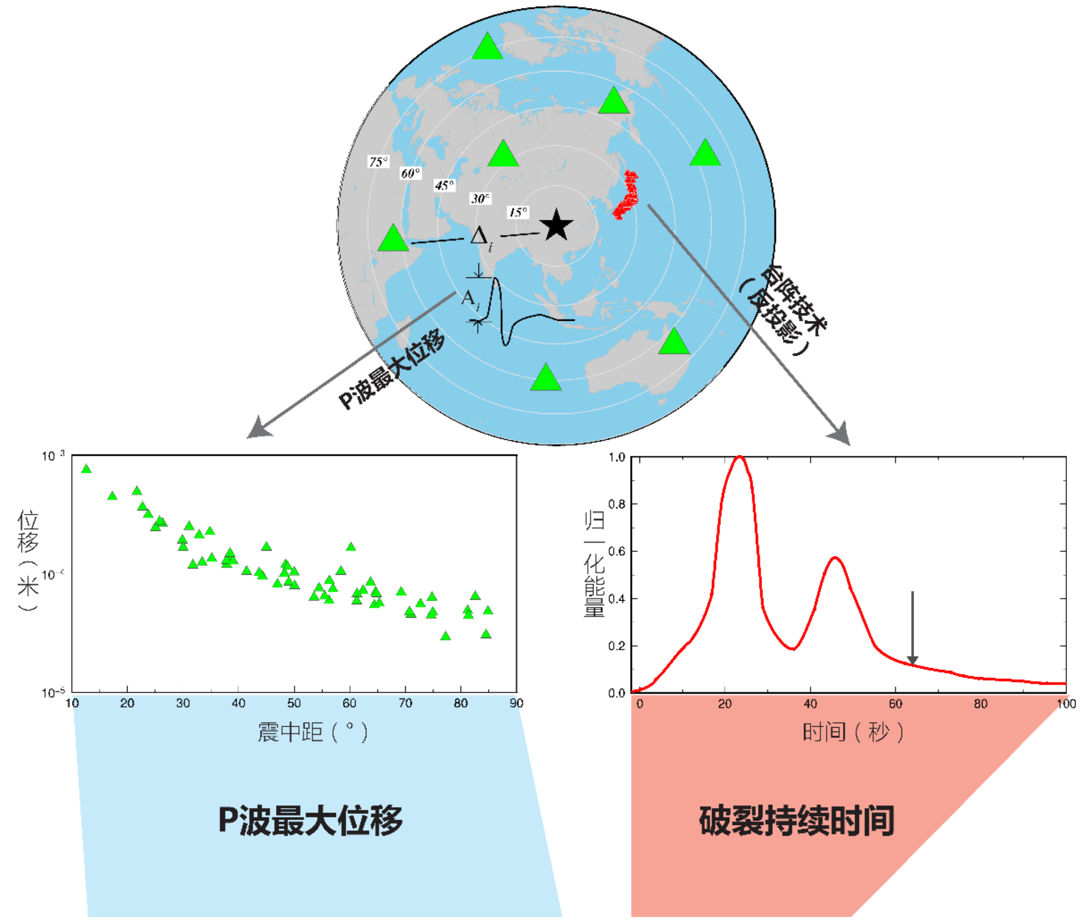
~1 h
Mww 8.36

~2 h
Mww 8.26



Pérez-Campos et al., 2020, SRL
Pérez-Campos et al., 2021, SSA meeting

A new magnitude scale (Hara, 2007; 2011; Wang et al., 2017)



$$M = \alpha \log A + \beta \log \Delta + \gamma \log t + \delta$$

GSN

+

Regional seismic array

- P-wave displacements + source duration
- Rapid and straightforward

Wang et al., 2017

M_{dt}: P-wave Maximum Displacement & Source Duration

$$M = \alpha \log A + \beta \log \Delta + \gamma \log t + \delta$$

empirical parameters

		10-40°	*40-85°*	*10-85°*
α:	0.79 ± 0.03,	0.53,	0.51,	0.55
β:	0.83 ± 0.05,	0.44,	0.01,	0.67
γ:	0.69 ± 0.03,	1.01,	1.05,	1.01
δ:	6.47 ± 0.17,	6.23,	7.89,	5.55

(Hara, 2007, 2008, 2011)

(Wang et al., 2017; Song et al., 2019; Yao et al., 2019)

Far-filed Displacement → Seismic Moment

$$\mathbf{u}(\mathbf{x},t) = \frac{1}{4\pi\rho\alpha^3}\mathbf{A}^{FP}\frac{1}{r}\dot{M}_0\left(t-\frac{r}{\alpha}\right) + \frac{1}{4\pi\rho\beta^3}\mathbf{A}^{FS}\frac{1}{r}\dot{M}_0\left(t-\frac{r}{\beta}\right)$$

P-wave displacement

S-wave displacement

Aki and Richards (2002)

- A^{FP} and A^{FS}: P- and S-wave radiation pattern correction terms
- ρ: rock density
- α and β: P- and S-wave velocity
- r: source–receiver distance
- M_0: moment rate function.

$$\mathbf{u}^P = \frac{1}{4\pi\rho\alpha^3}\mathbf{A}^{FP}\frac{1}{r}\dot{M}_0\left(t-\frac{r}{\alpha}\right)$$

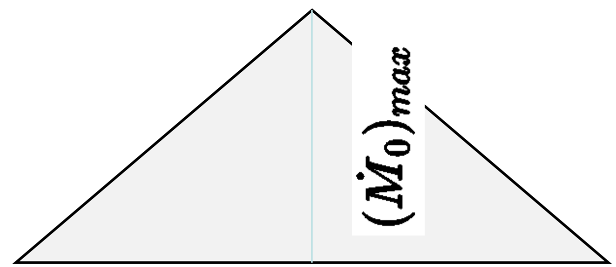
$$\dot{M}_0 = 4\pi\rho\alpha^3 r\frac{1}{\mathbf{A}^{FP}}\mathbf{u}^P$$

Far-filed Displacement → Seismic Moment

$$\dot{M}_0(\mathrm{max}) = 4\pi\rho\alpha^3 \cdot r \cdot u^p_{(\mathrm{max})}$$

Duration

$$M_0 = (4\pi p a^3 \cdot R \cdot A) \cdot D$$



Duration

$$M_0 = (4\pi p a^3 \cdot R \cdot A) \cdot D \cdot 1/2$$

In Mwp method:

- ρ, rock density: 3.4E+03 kg/m^3
- α, P velocity: 7.9 km/s

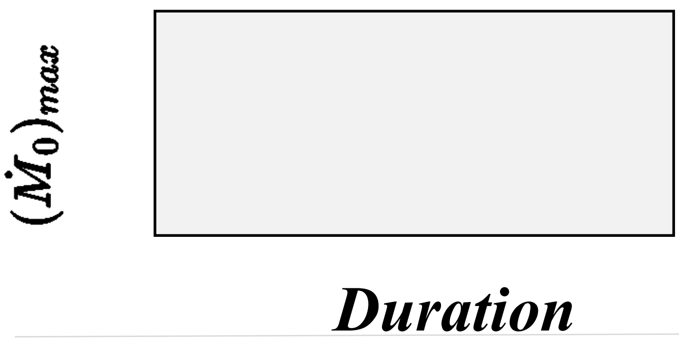
$$\mathbf{m * \ s * \ km * 4 * 3.14 * (3.4 * 10^3 \ kg/m^3) * (7.9 \ km/s)^3}$$

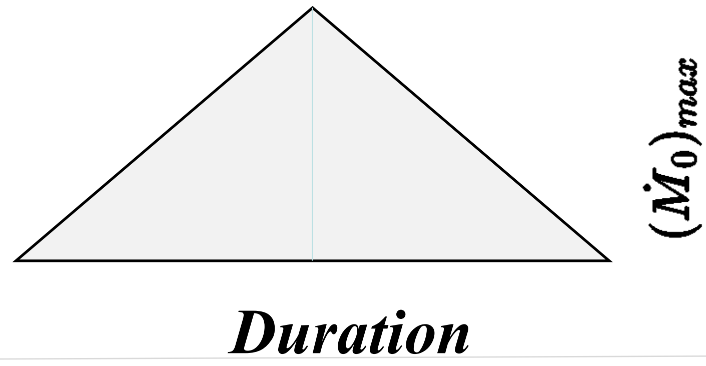
$$4 * 3.14 * 3.4 * 10^3 * 7.9^3 * (\mathrm{kg} * \ \mathrm{m/s^2}) * (\mathrm{km^4/m^3})$$

$$4 * 3.14 * 3.4 * 10^3 * 7.9^3 * 10^{12} Nm$$

$$2.1 * 10^{19} Nm$$

Far-filed Displacement → Seismic Moment





$$M_0 = (4\pi p a^3 \cdot R \cdot A) \cdot D$$

$$M_0 = (4\pi p a^3 \cdot R \cdot A) \cdot D \cdot 1/2$$

$$M = \frac{2}{3}\left[\log(M_0) - 9.1\right]$$

$$M_{dt} = \frac{2}{3}\left[\log\left(4\pi p a^3 \cdot R \cdot A \cdot D\right) - 9.1\right]$$

$$M_{dt} = \frac{2}{3}\left[\log\left(4\pi p a^3 \cdot R \cdot A \cdot D \cdot 1/2\right) - 9.1\right]$$

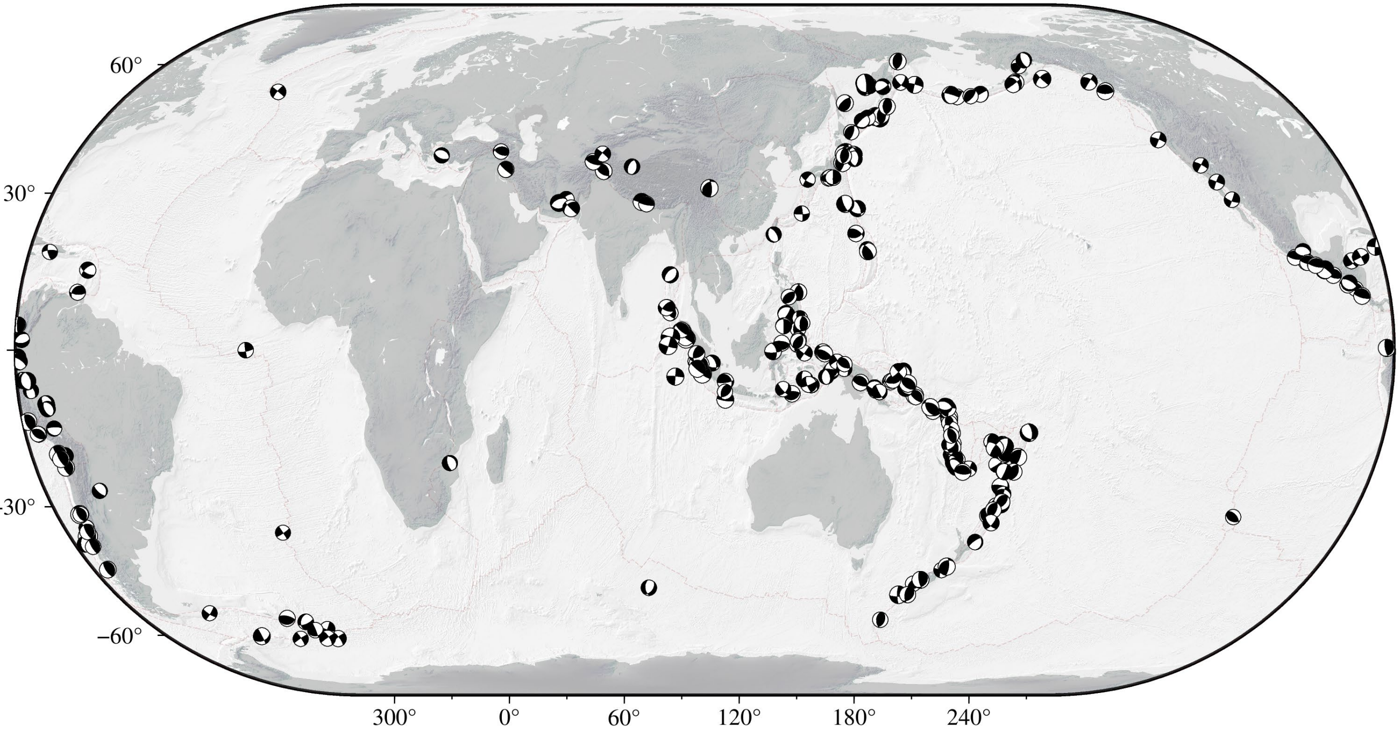
$$M_{dt} = 0.67 * logA + 0.67 * logR + 0.67 * logD + \delta$$

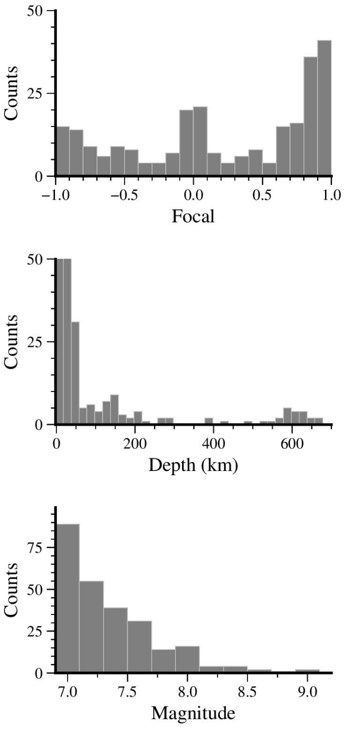
δ=6.81

δ=6.61

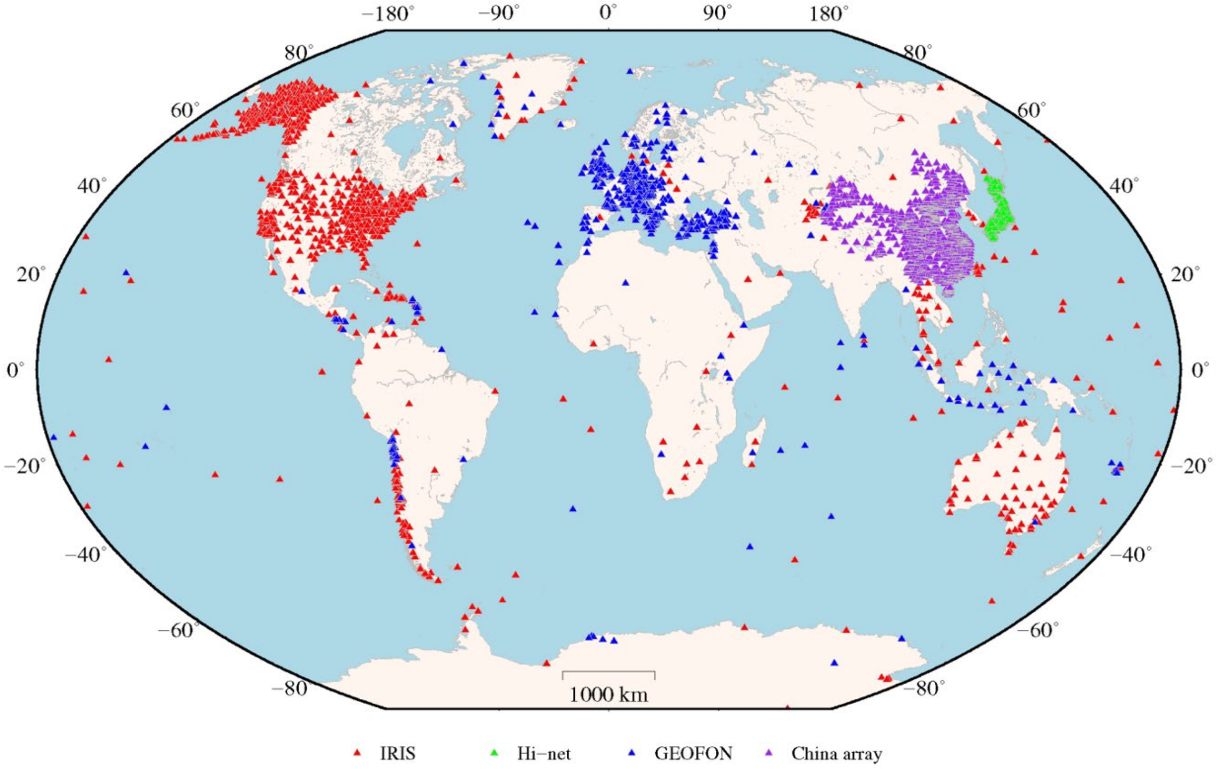
Magnitude estimation for large earthquakes (2004-2021)

2004-2021/03 M≥7 Earthquakes Worldwide (USGS)





Magnitude estimation for large earthquakes (2004-2021)



P Max. Disp.:
GSN 150+
Global &
Uniform

Duration by BP:
China Array
Japan Hi-net
Europe Array
US Array

Magnitude estimation for large earthquakes (2004-2021)

$$M = \alpha \log A + \beta \log \Delta + \gamma \log t + \delta$$

Fix α=β=ϒ=0.67

257 large earthquakes

5 seismic arrays(GSN, China array, Japan Hi-net, USarray, EUR array)

~ 450,000 waveforms

δ= 6.57

SD= 0.12

	10-40°,	40-85°,	10-85°
α: 0.79 ± 0.03,	0.53,	0.51,	0.55
β: 0.83 ± 0.05,	0.44,	0.01,	0.67
γ: 0.69 ± 0.03,	1.01,	1.05,	1.01
δ: 6.47 ± 0.17,	6.23,	7.89,	5.55
(Hara, 2007, 2008, 2011)	(Wang et al., 2017; Song et al., 2019; Yao et al., 2019)		

Magnitude estimation for large earthquakes (2004-2021)

$$\mathbf{u}^P = \frac{1}{4\pi\rho\alpha^3}\mathbf{A}^{FP}\frac{1}{r}\dot{M}_0\left(t - \frac{r}{\alpha}\right)$$

$$M_0 = \int_0^T \dot{M}_0 = 4\pi\rho\alpha^3 r \frac{1}{\mathbf{A}^{FP}}\int_0^T u^P$$

Mwp

$$M_0 = \int_0^T \dot{M}_0 = 4\pi\rho\alpha^3 r \frac{1}{\mathbf{A}^{FP}} Max\left(\int_0^T |u^P|\right)$$

$$M_{wp} = \frac{1}{1.5}(\log M_0 - 9.1)$$

Mdt

$$M_0 = (4\pi p a^3 \cdot R \cdot A) \cdot D \cdot k$$

$$M_{dt} = 0.67 * logA + 0.67 * logR + 0.67 * logD + \delta$$

Triangle

δ=6.61

Rectangle

δ=6.81

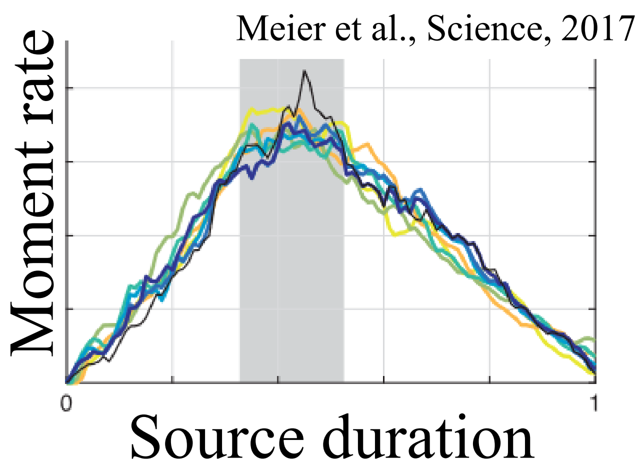
Regression Calculations: δ=6.57

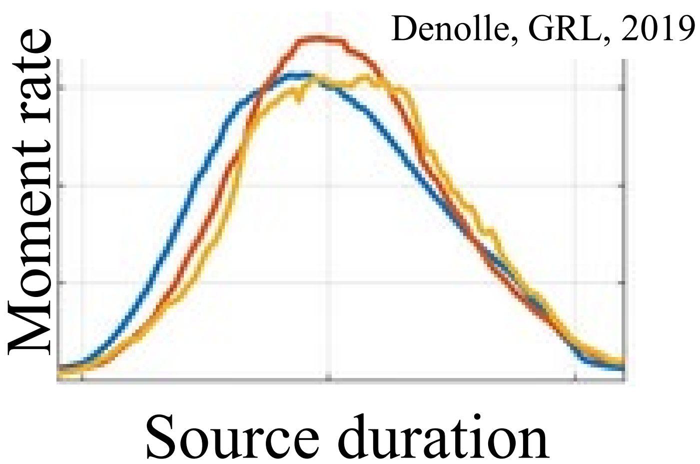
Magnitude estimation for large earthquakes (2004-2021)

$$M = \alpha \log A + \beta \log \Delta + \gamma \log t + \delta$$

Fix α=β=Υ=0.67 Fitting *δ*=6.57

Shape of moment rate function

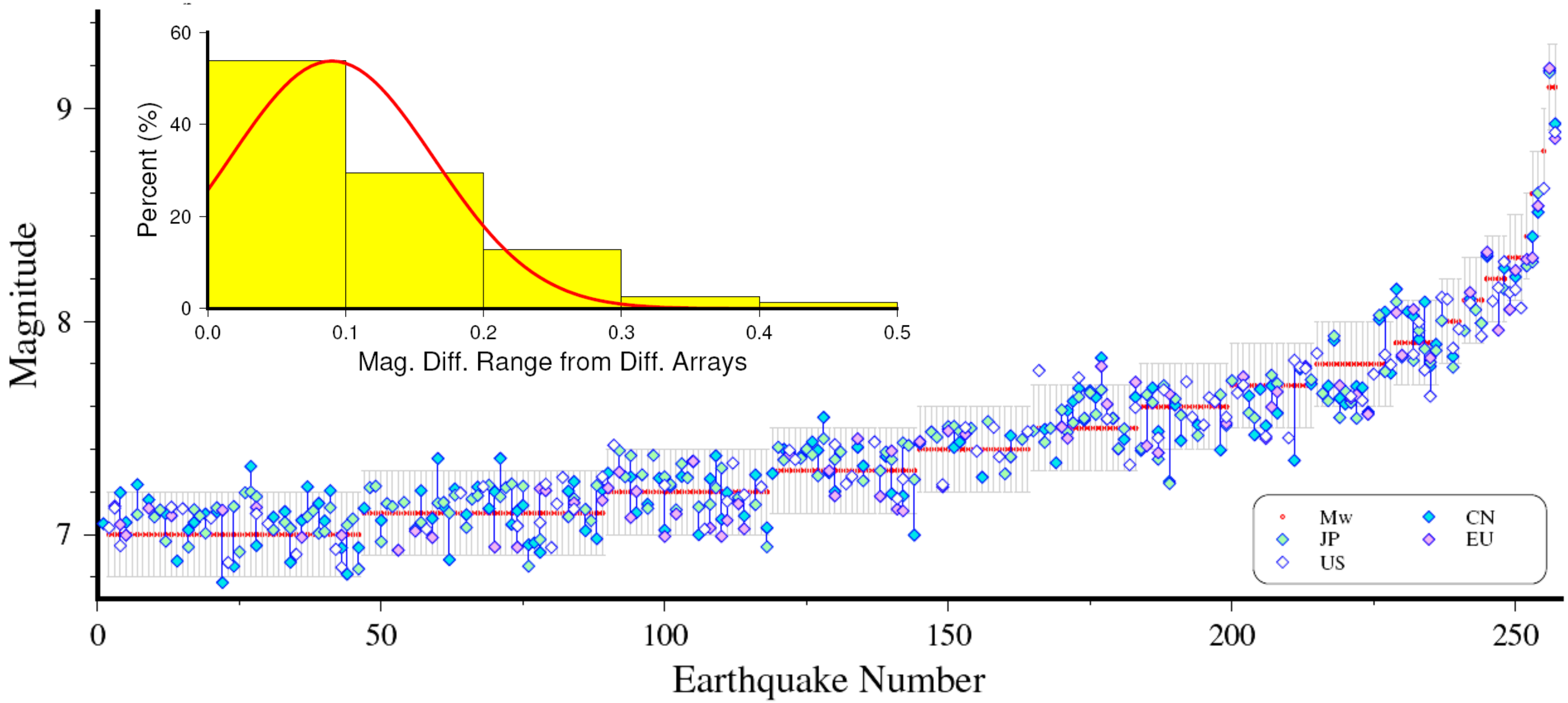




- ✓ Triangle: ***δ*=6.61**
- ✓ Rectangle: ***δ*=6.81**
- ✓ Skewed normal distribution: **6.61** < ***δ* < 6.81**

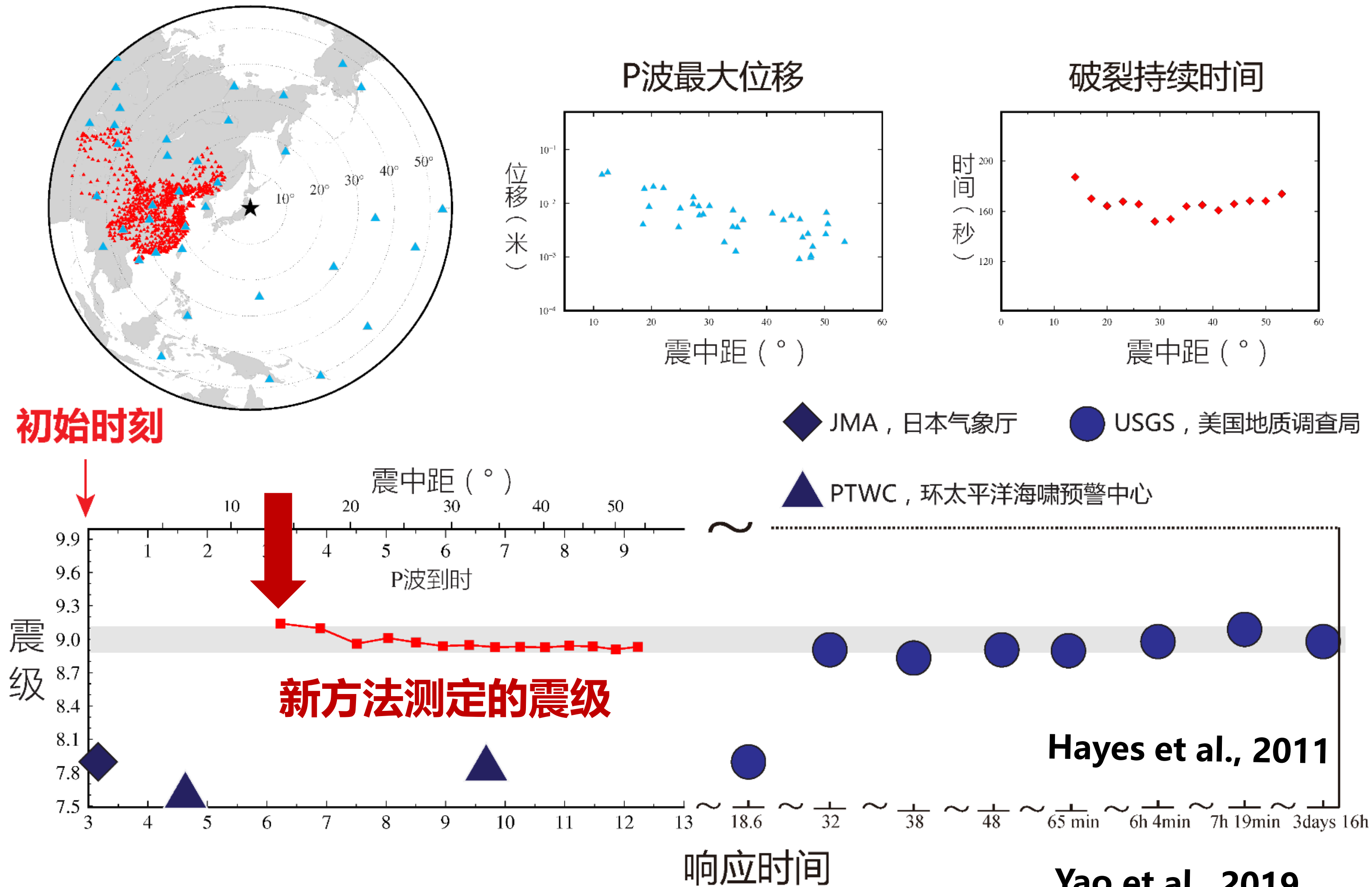
Magnitude estimation for large earthquakes (2004-2021)

➢Comparisons of Large Seismic Arrays



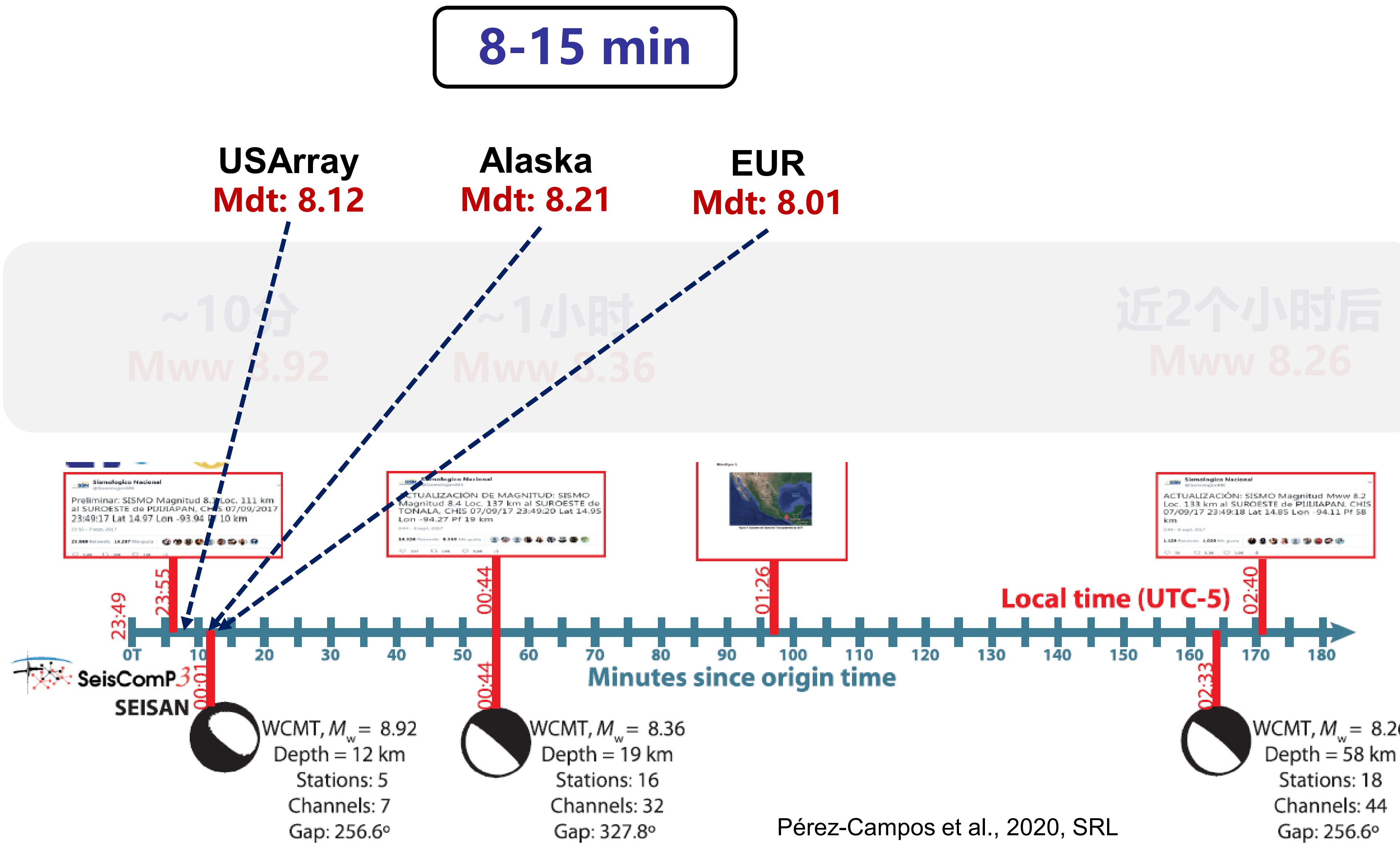
Determining the magnitude of the M9 Tohoku earthquake

M9.1 in 6-7 min after the O.T.



Yao et al., 2019

Determining the magnitude of the Mw 8.2 Mexico earthquake

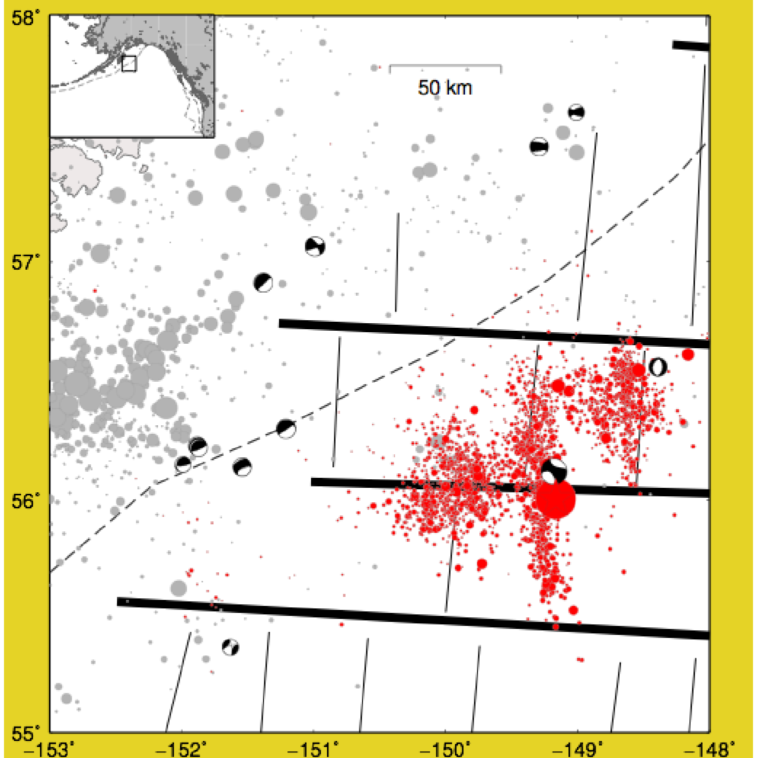


Pérez-Campos et al., 2020, SRL
Pérez-Campos et al., 2021, SSA meeting.

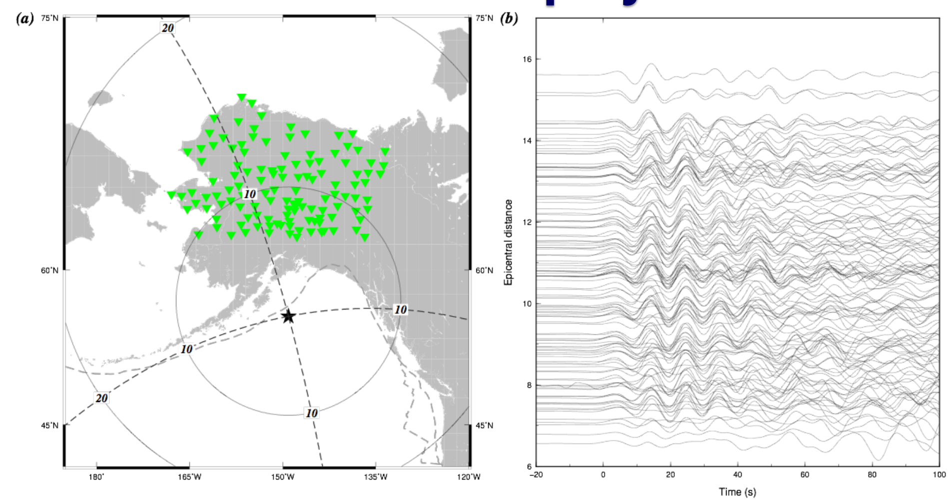
The 23 January 2018 Mw 7.9 Alaska earthquake

Our estimate	PTWC、USGS
3-4 min, M_{dt} 7.9	3 min， M 8.0-8.2 2 h， M7.9

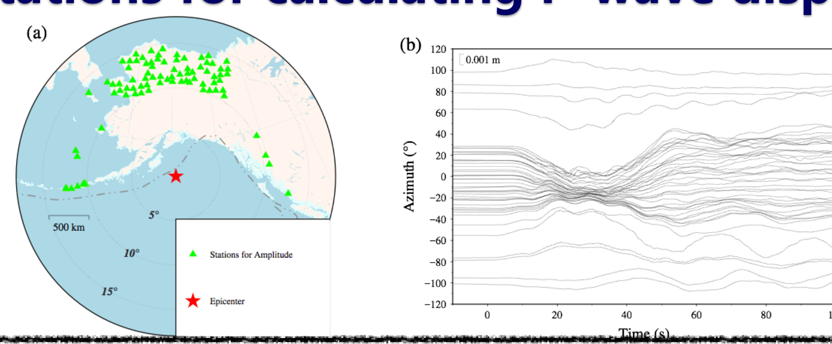
The earthquake sequence



Stations for back-projection

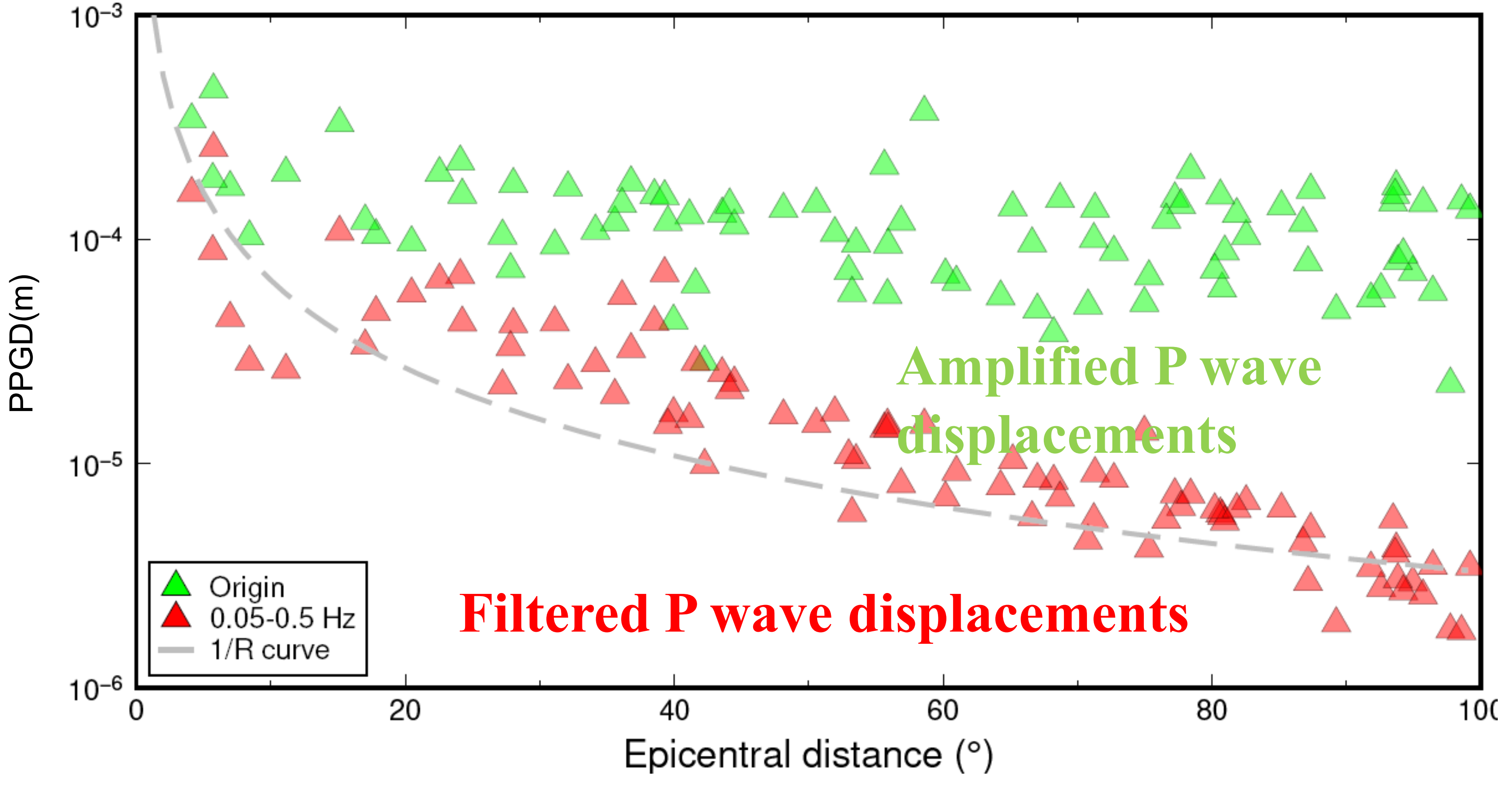


Stations for calculating P-wave disp.



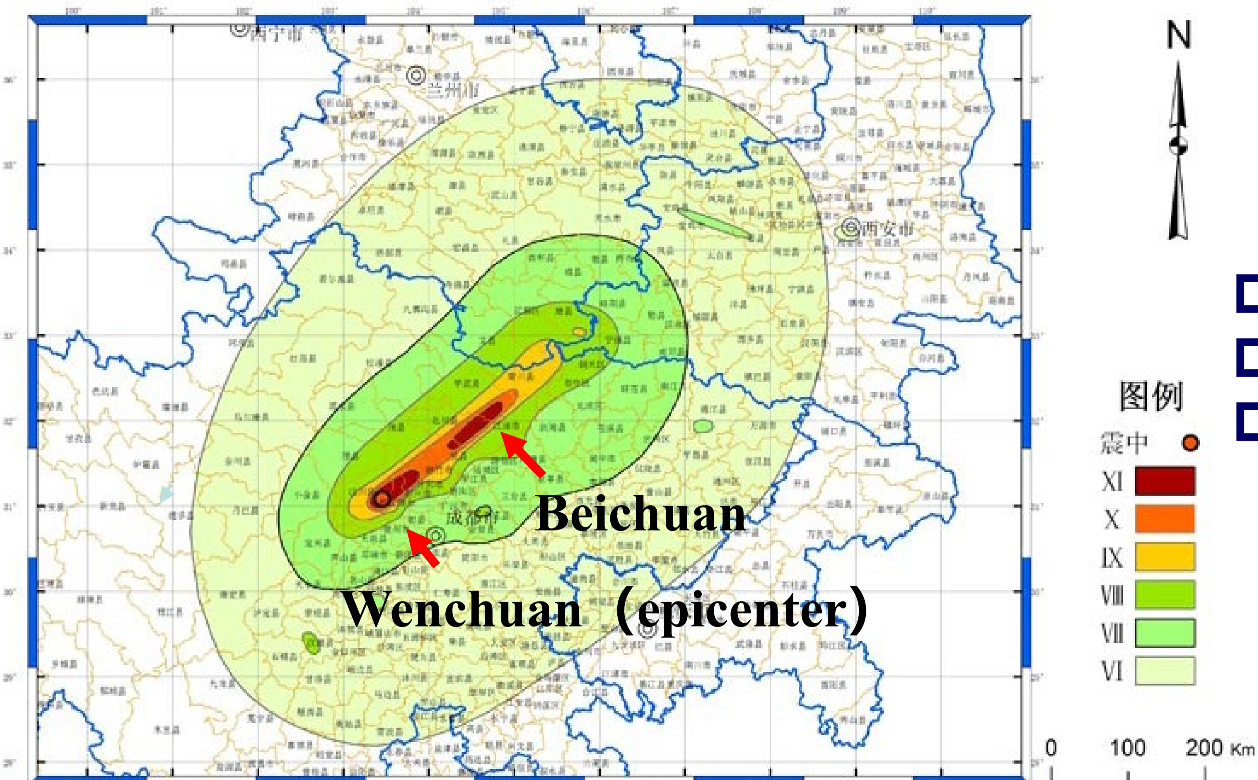
Magnitude estimation for large earthquakes (2004-2021)

- The 12, April, 2012 M_W 7 earthquakes (M6 Earthquake, 9 min before)



Seismic intensity map

Rupture fault qualifies damage areas



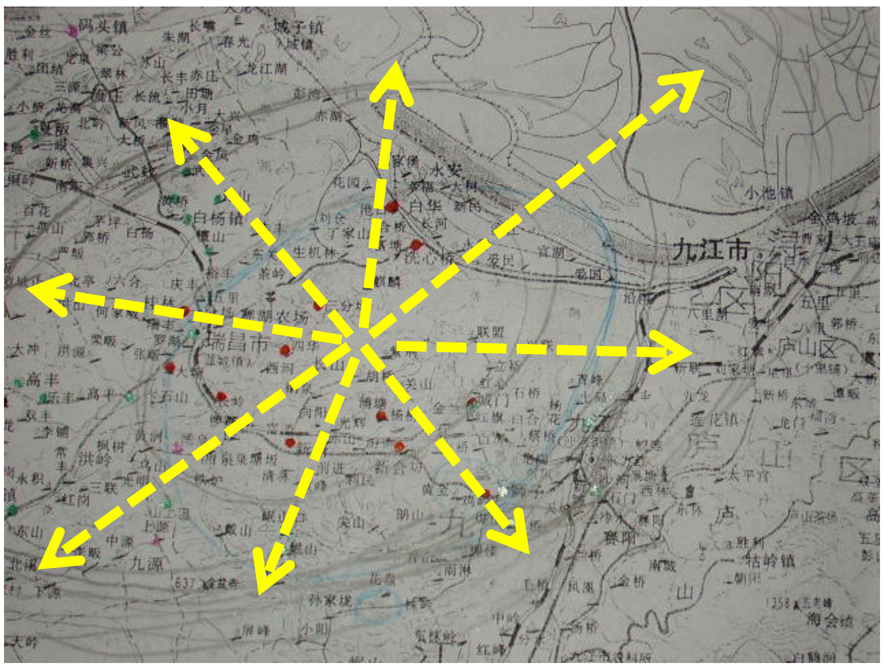
- Point source
- Damaging belt
- Wenchuan-Beichuan-Qingchuan

Seismic intensity map by field survey (CEA)

Estimating seismic intensities

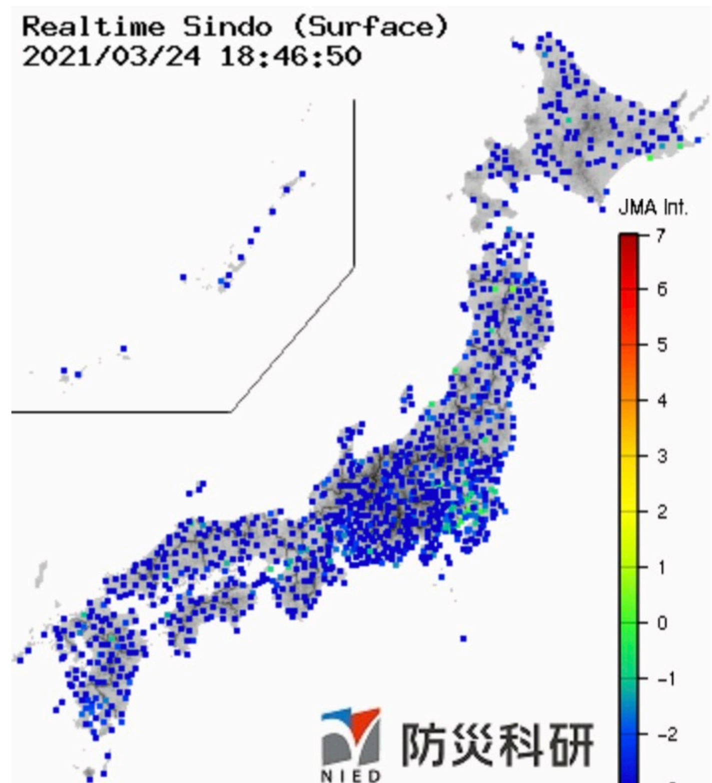
Conventional methods

High intensity: field survey
Low intensity: posting survey



Limited real-time observations

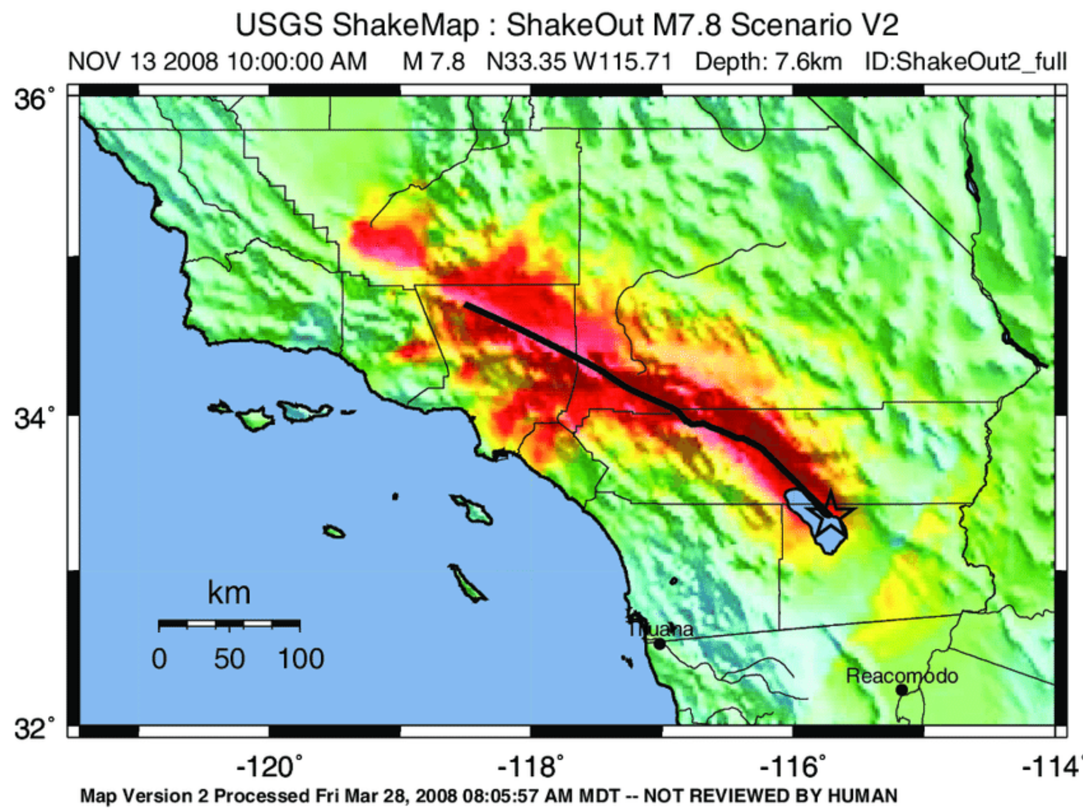
Measuring ground motions



Dense real-time observations

ShakeMap, USGS

Sparse observation+GMPEs+DYFI



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Unknown fault geometries will largely affect the results

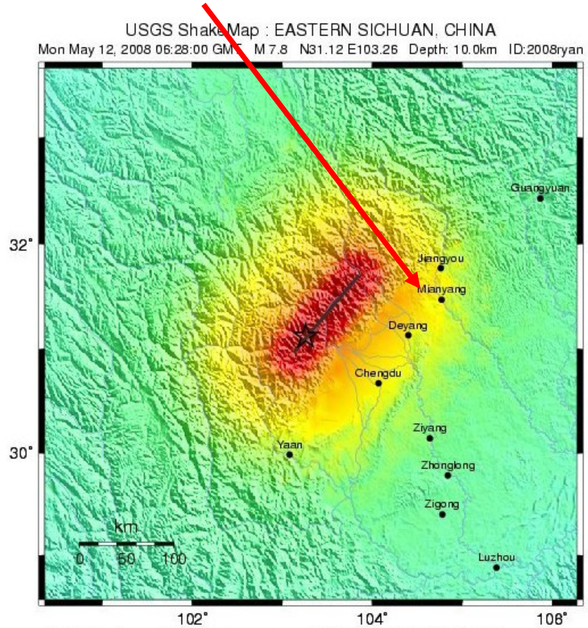
ShakeMap of the 2008 Mw 7.9 Wenchuan earthquake

Production time: (Beijing Time) **2008/05/12 17:42** **2020/06/04 05:23**

Origin Time:

2008/05/12 14:28

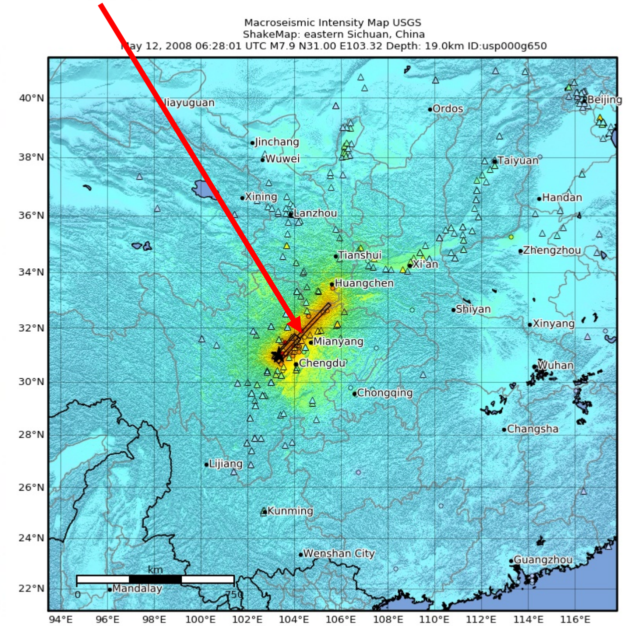
绵阳



Map Version 3 Processed Mon May 12, 2008 02:42:14 AM MDT -- NOT REVIEWED BY HUMAN

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

绵阳



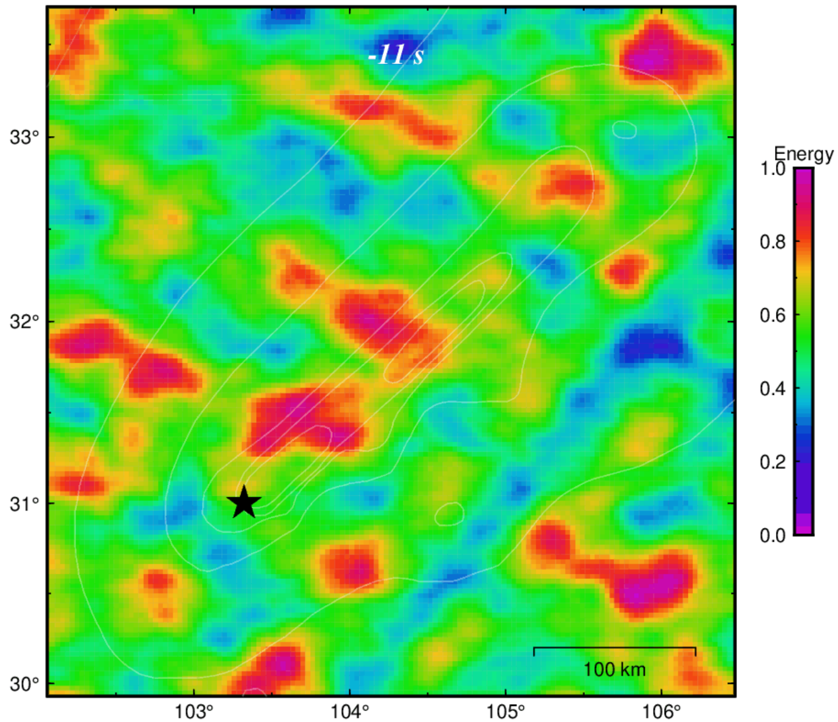
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA(%g)	<0.0464	0.297	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV(cm/s)	<0.0215	0.135	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden et al. (2012) Version 1: Processed 2020-06-04T05:22:56Z

△ Seismic Instrument ○ Reported Intensity ★ Epicenter ▭ Rupture

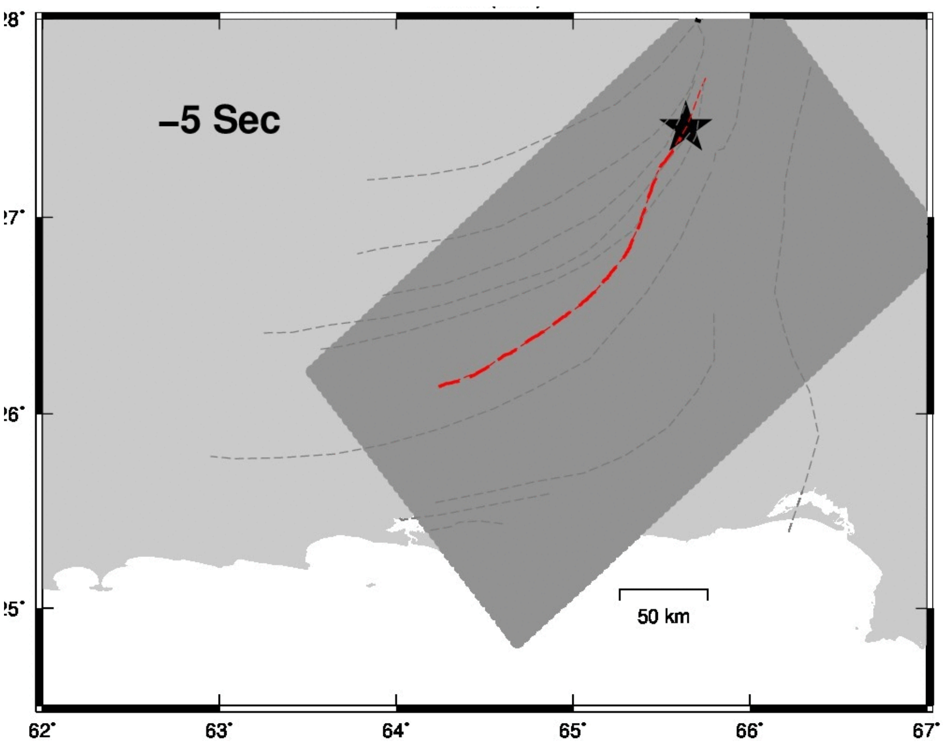
The 12 May 2008 Mw 7.9 Wenchuan earthquake

Data: EUR, band-pass filtered 0.5-2.0 Hz



The 24 September 2013 Mw7.7 Pakistan earthquake

Data: Hi-net, band-pass filtered 0.5-2.0 Hz

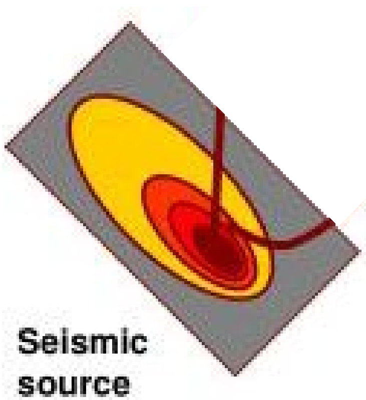


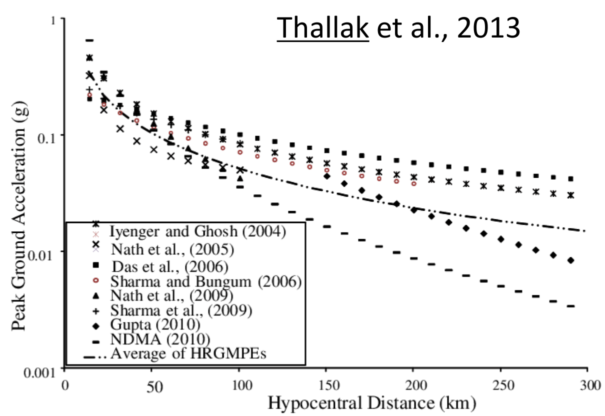
(Wang et al., 2016)

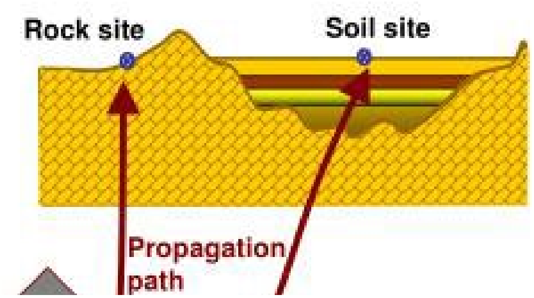
A novel method

- 实时测定地震断层空间展布
- 不依赖密集强震动观测数据
- 考虑不同场地特征

Energy radiations + **Attenuation** + **Site effect**







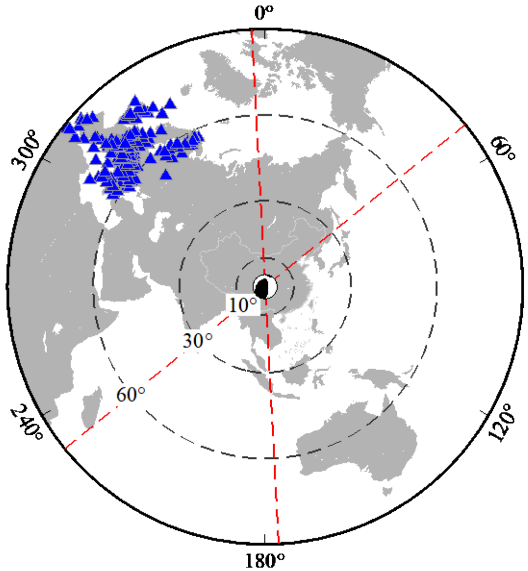
Back-projection

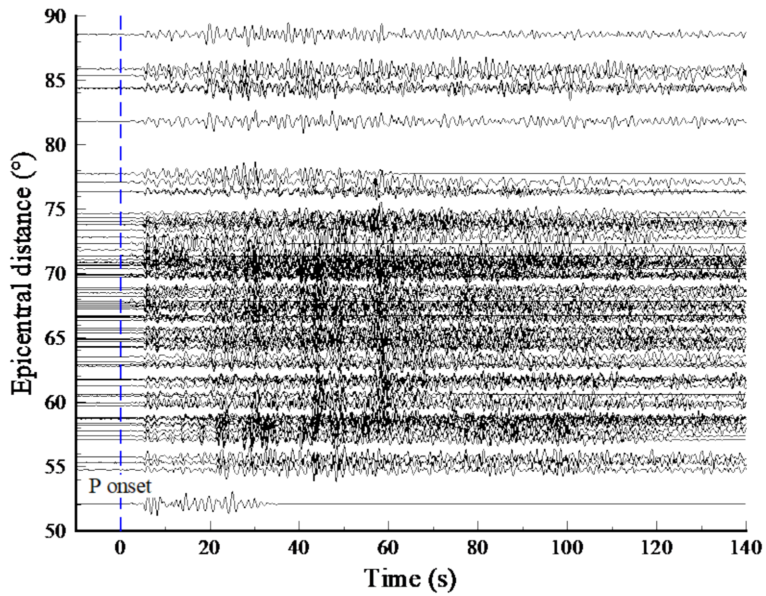
GMPEs

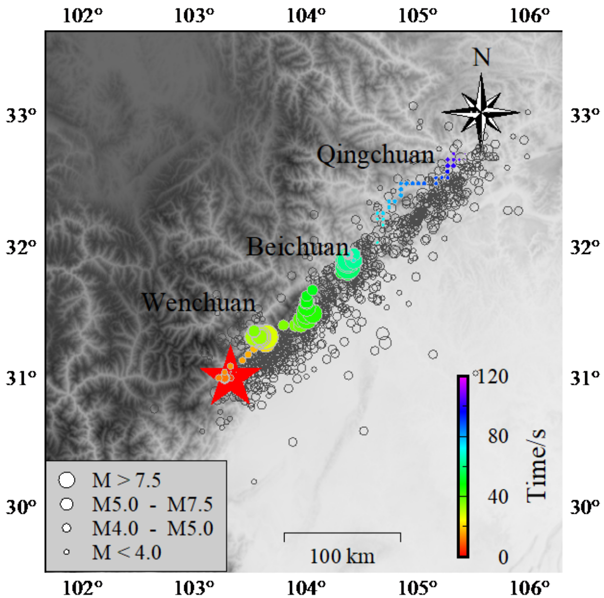
Site corrections based on V_s30

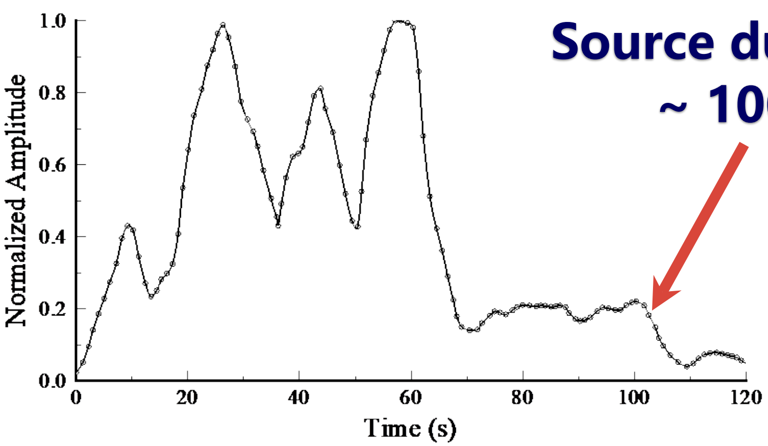
http://image1.slideserve.com

The 12 May 2008Mw7.9 Wenchuan earthquake









Source duration ~ 100 s

Chen et al., under revision.

Seismic intensity maps

PGA | **PGV** | **PGV** **site correction**

Model 1

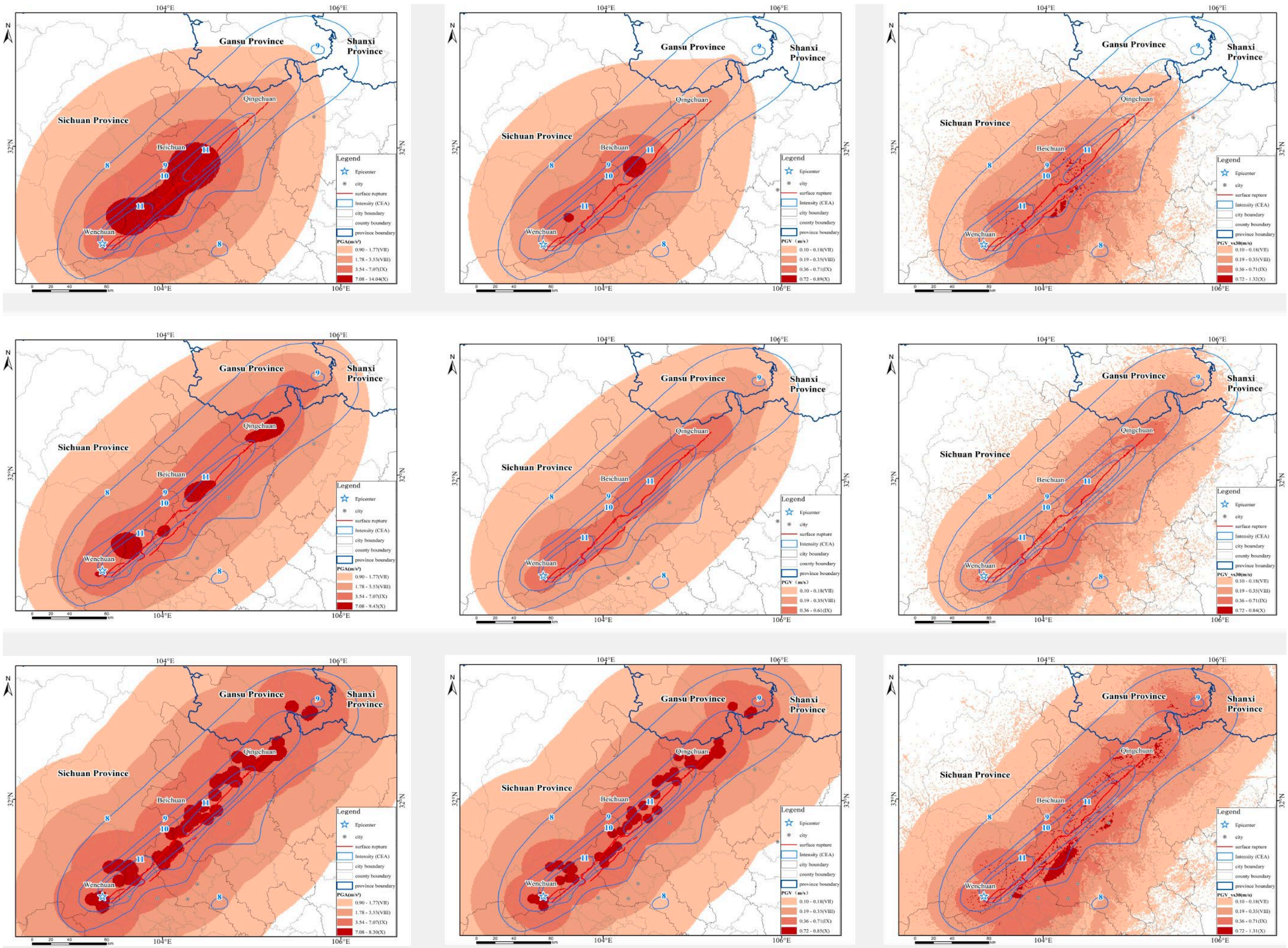
Intensity and locations of subevents

Model 2

locations of subevents Equal weight

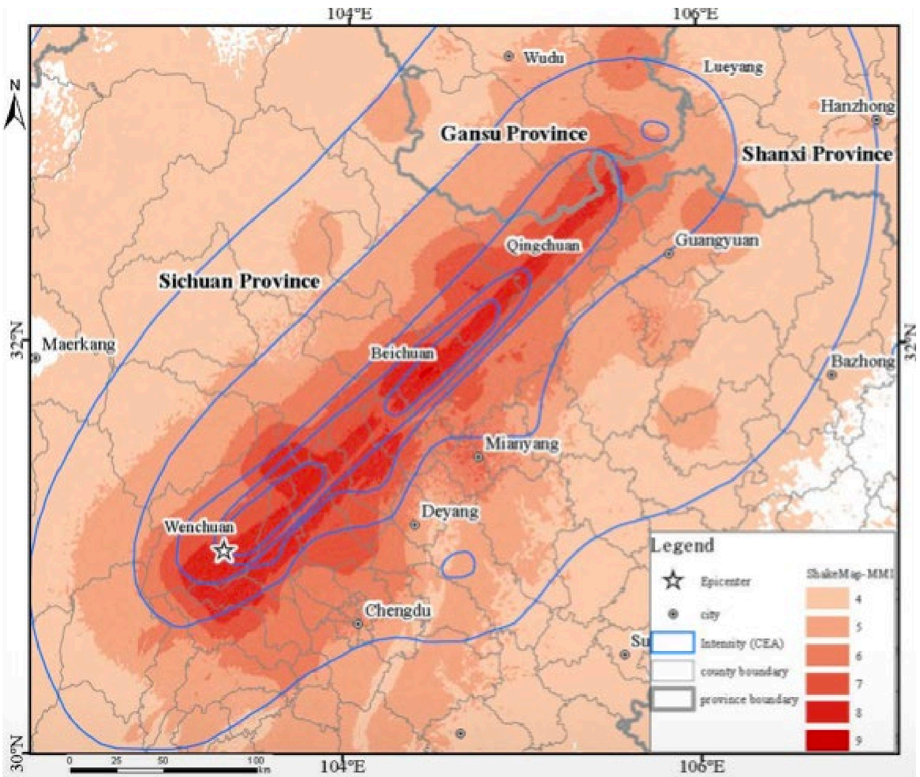
Model 3

Shortest distance to the fault plane



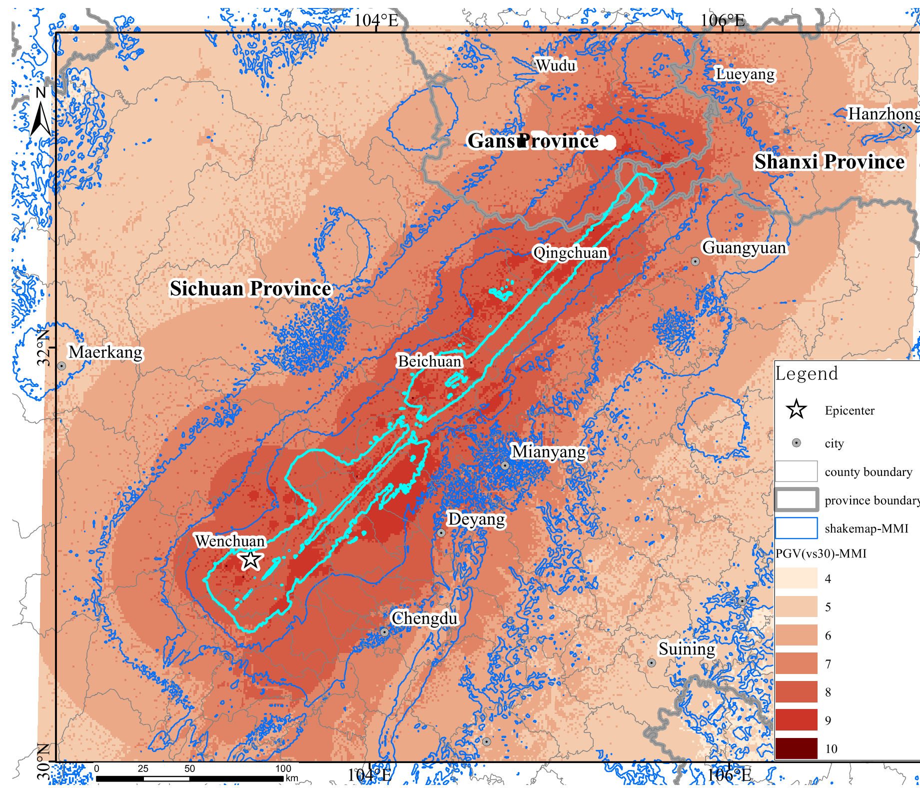
Comparisons among seismic intensity maps of CEA, ShakeMap, and our result for the 2008 Wenchuan earthquake

CEA & ShakeMap



蓝线：调查得到的地震烈度（CEA）
背景：ShakeMap结果（2020/06）

Our result & ShakeMap



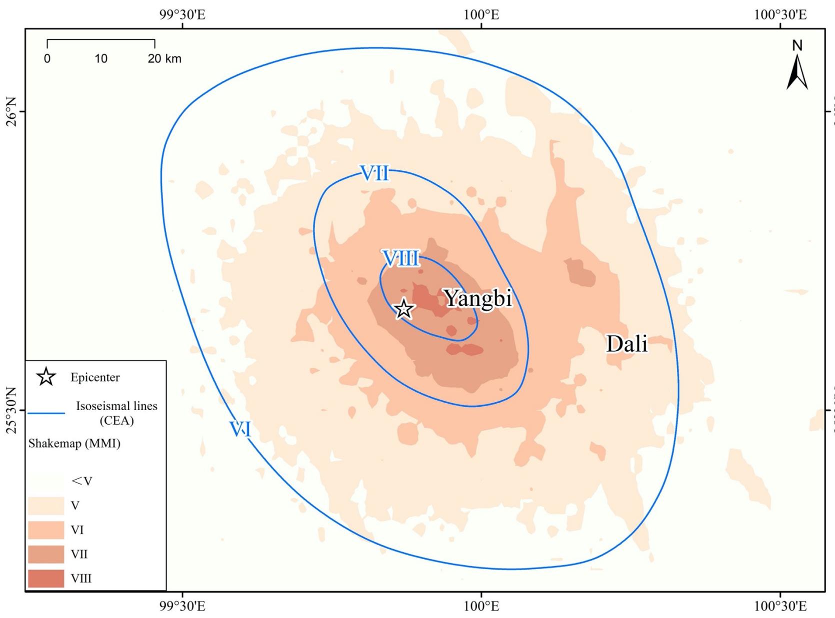
蓝线：ShakeMap结果（2020/06）
其中亮绿表示MMI Ⅷ和Ⅸ度区
背景：我们方法得到的烈度分布

The 2021 Mw 6.1 Yangbi, Yunnan, China earthquake

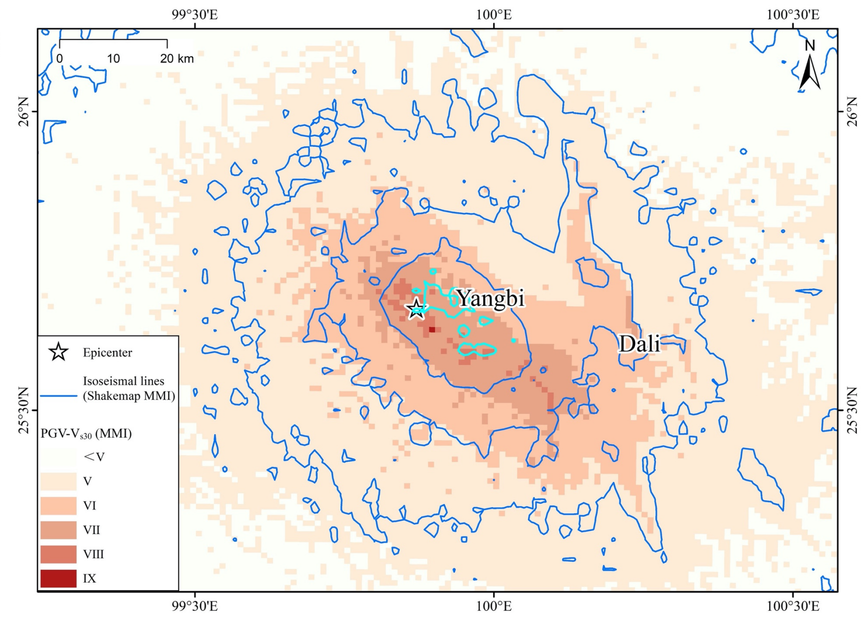
CEA&ShakeMap

ShakeMap&our result

(a)



(b)

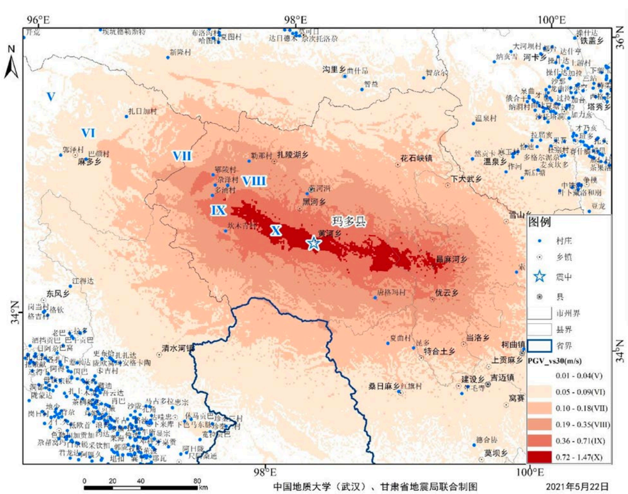


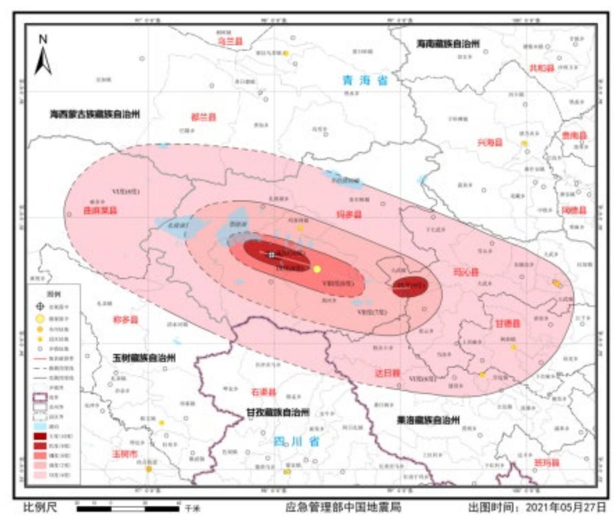
Accurate local Vs30 is important

The 22 May 2021 Mw7.3 Madoi, China earthquake

4 h after the O.T.

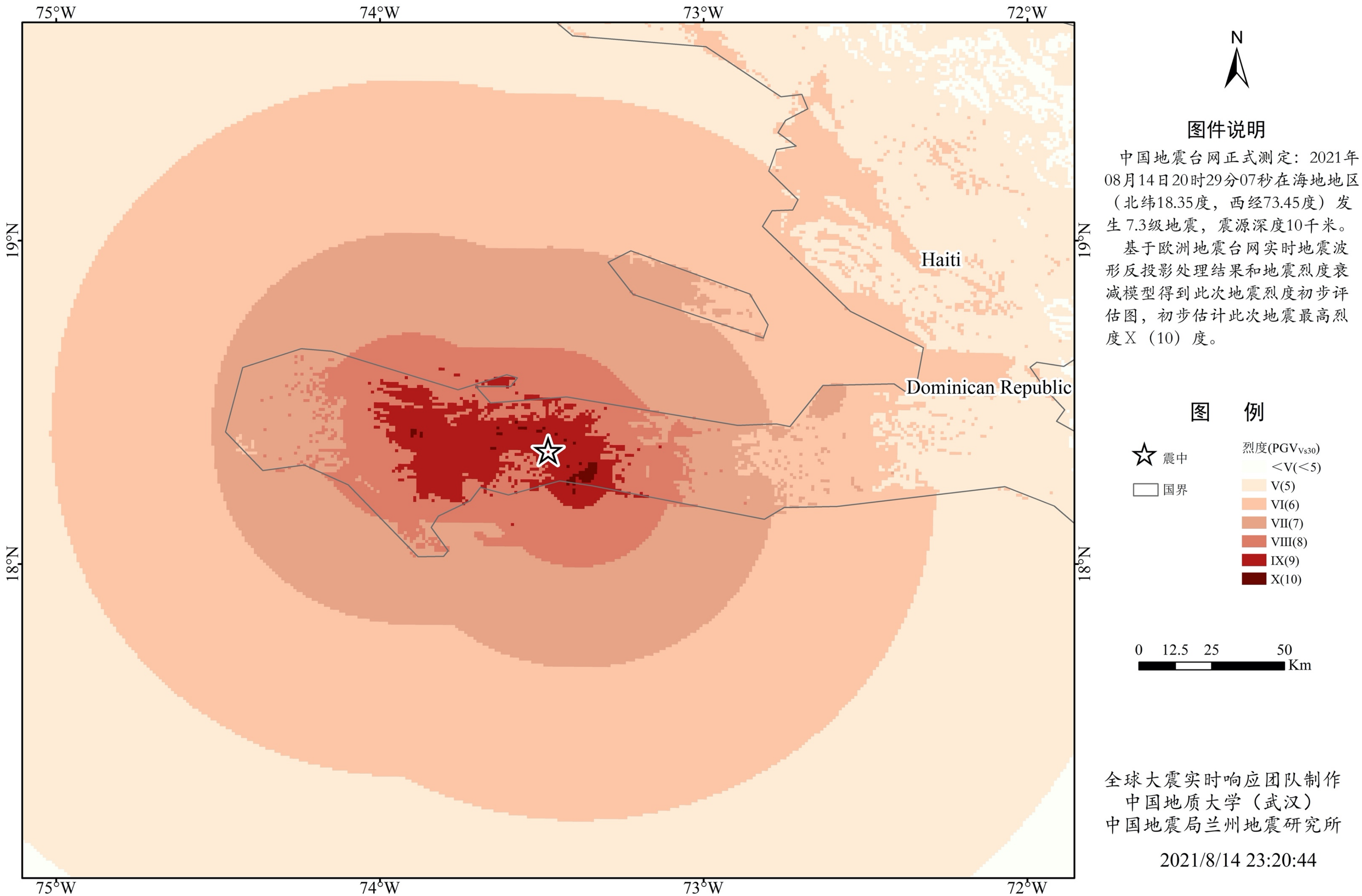
Field survey by the CEA





The 14 August 2021 Mw 7.3 Haiti earthquake

海地M7.3级地震烈度初步评估图V1.0



图件说明

中国地震台网正式测定：2021年08月14日20时29分07秒在海地地区（北纬18.35度，西经73.45度）发生7.3级地震，震源深度10千米。

基于欧洲地震台网实时地震波形反投影处理结果和地震烈度衰减模型得到此次地震烈度初步评估图，初步估计此次地震最高烈度X（10）度。

全球大震实时响应团队制作
中国地质大学（武汉）
中国地震局兰州地震研究所

2021/8/14 23:20:44

Time efficiency

Travel time+Source duration +Data delay+ processing time

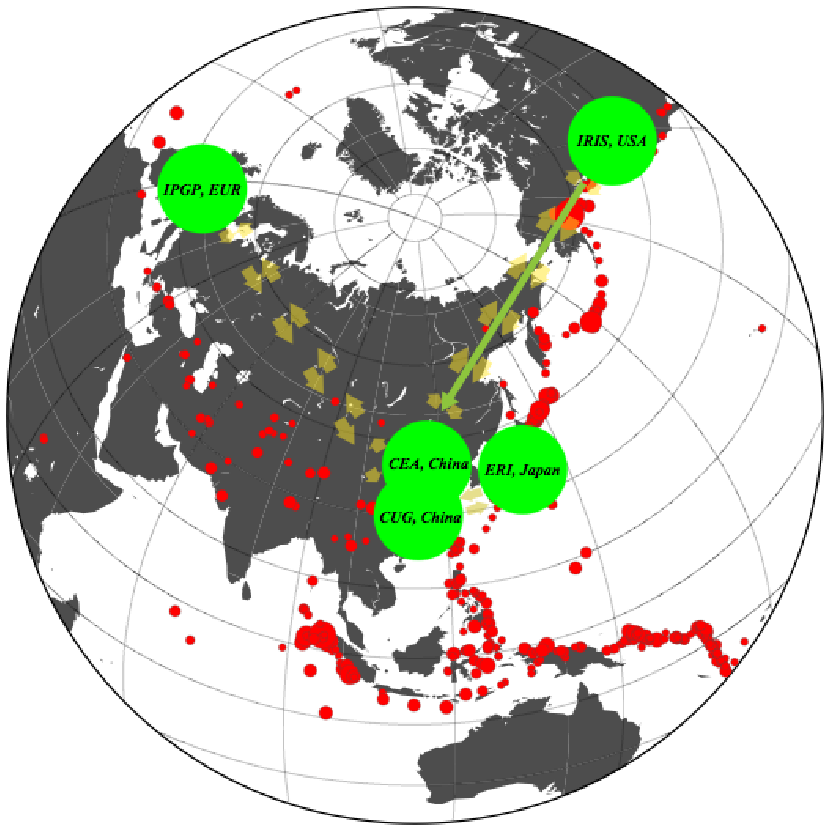
M9 3-9 min
M8 30s - 2 min
M7 ~10s

< 1 min + < 1 min

Distance (Deg.)	10	30	50	90
Distance (km)	1111.2	3335.7	5556	10000.8
Travel time (min)	*2-3*	*6*	*9*	*13*

Applying this system with three regional dense arrays that are located at Eurasia, China, Japan, and America , would help better earthquake emergency response and tsunami warning for global earthquakes.

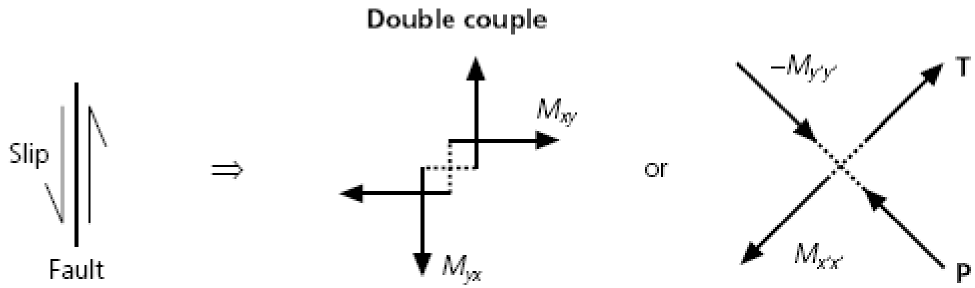
~10 min + Source duration

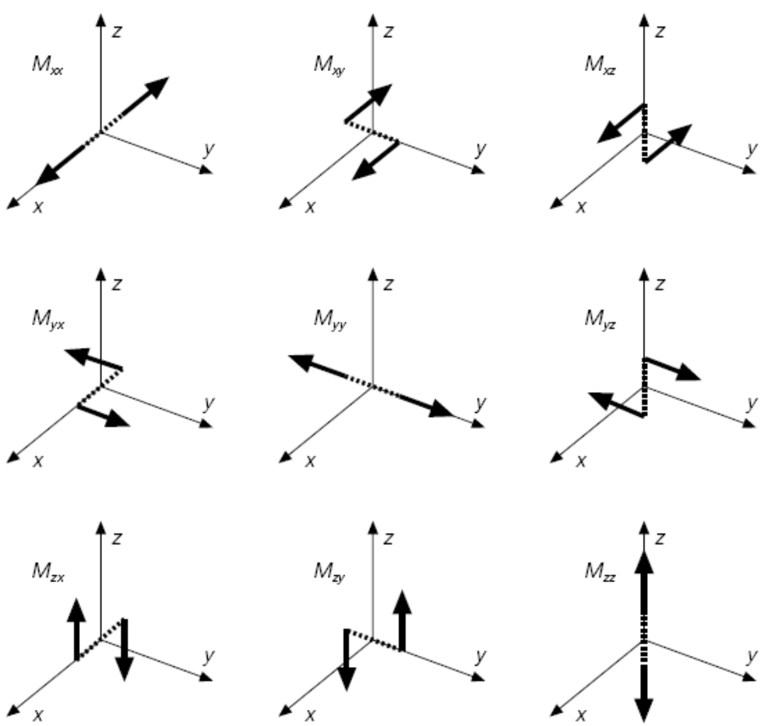


M ≥ 7.5, Depth ≤ 60 km, USGS catalog (1970-2014)

Thank you!

Moment tensor inversion → Seismic moment





$$\mathbf{M} = \begin{pmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{pmatrix}$$

$$M_0 = \frac{1}{\sqrt{2}}\left(\sum_{ij} M_{ij}^2\right)^{1/2}.$$

M_{WW}, W-phase, USGS, PTWC

M_{WC}, body- and surface-waves, GCMT

Moment Magnitude & Seismic Moment

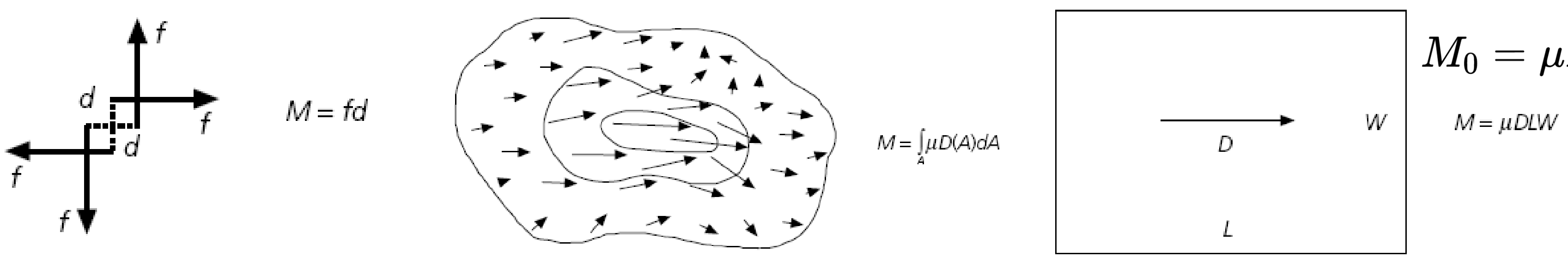
- **Shear module:** 3-6*10^4 MPa for crust-upper mantle
- **Stress drop:** 2-6 MPa for large earthquakes.

$$\log E = \log M_0 + \log \frac{\Delta\sigma}{2\mu} = \log M_0 - 4.3$$

$$\lg E = 1.5M_s + 4.8$$ Gutenberg & Richter, 1956

$$\mathrm{M_w} = (\log \mathrm{M_0} - 4.3 - 4.8)/1.5 = (\log \mathrm{M_0} - 9.1)/1.5$$

Kanamori (1977) and Hanks & Kanamori (1979)



$$M_0 = \mu \bar{D} S$$

Stein & Wysession, 2003