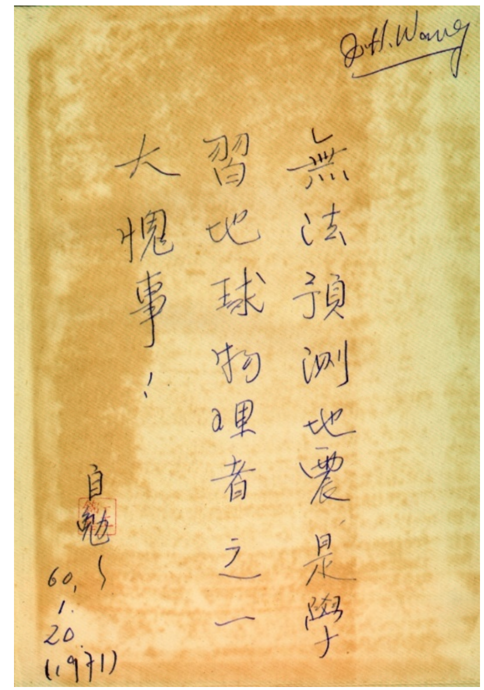
Earthquake Prediction: Fact or Fiction?

地震預測：
地震科學的
極終目標



國立中央大學地球科學系（2021/12/10)

(王錦華 中央研究院地球科學研究所 Senior PostDoc)

明天過後…


FROM THE DIRECTOR OF INDEPENDENCE DAY
THE DAY AFTER TOMORROW
MAY 28 WHERE WILL YOU BE?

Four Types of Earthquake Prediction

- **Time-independent Seismic Hazards**
- **Time-dependent Seismic Hazards**
- **Earthquake Forecasting**

  (⇒ Seismic Potential Evaluation)

- **Deterministic Prediction**

  (⇒ Earthquake Prediction)

成功的地震預測
時間: 誤差正負三天
地點: 誤差三十公里
規模: 誤差正負0.5

文獻記載

地震六端
（寧夏「隆德縣志」）

- 井水本湛靜無波，倏忽渾如墨汁，泥渣上浮。
- 池沼之水，風吹成荇交縈，無端泡沫上騰，若沸煎茶。
- 若風日晴和，颱颶不作，海水忽然繞起，洶湧異常。
- 夜半晦黑，天忽開朗，光明照耀，光異日中。
- 天晴日暖，碧空清淨，忽見黑雲如縷，蜿如長蛇，橫亘空際，久而不散。
- 在盛夏，驀覺清涼如受冰雪，冷氣襲人，肌為之栗。

第一次地震預測
（山西省「虞鄉縣志」）

- 年代：清朝嘉慶二十年(西元一八一五年)。
- 地點：山西平陸地區。
- 現象：從八月六日到九月九日間，「盆傾擔注」地下雨，九月九日後，天大熱。
- 專家：一群老人。
- 原理：霪雨後天大熱，預防地震。
- 結果：九月二十日午夜二時，發生強烈地震。

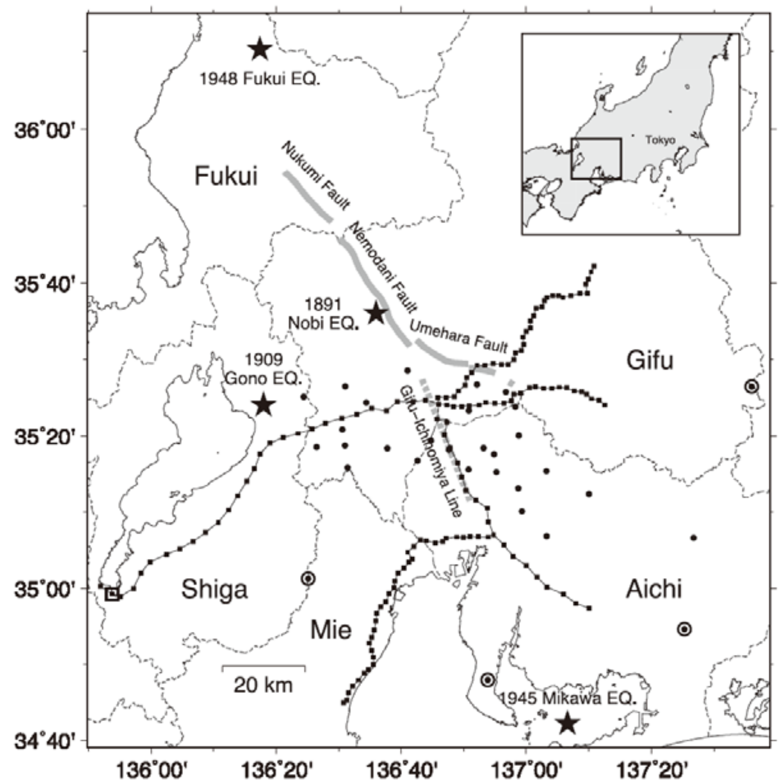
英籍日本東京帝國大學米勒教授(1880)首先指出地震預測的問題，並討論可能的前兆現象（例如：天氣、動物行為、電效應、地震光、地潮、溫泉的水溫和微震等） (‘Even since seismology has been studied one of the chief aims of its students has been to discover some means which enable them to foretell the coming of an earthquake….’)

Earthquake Prediction in Japan

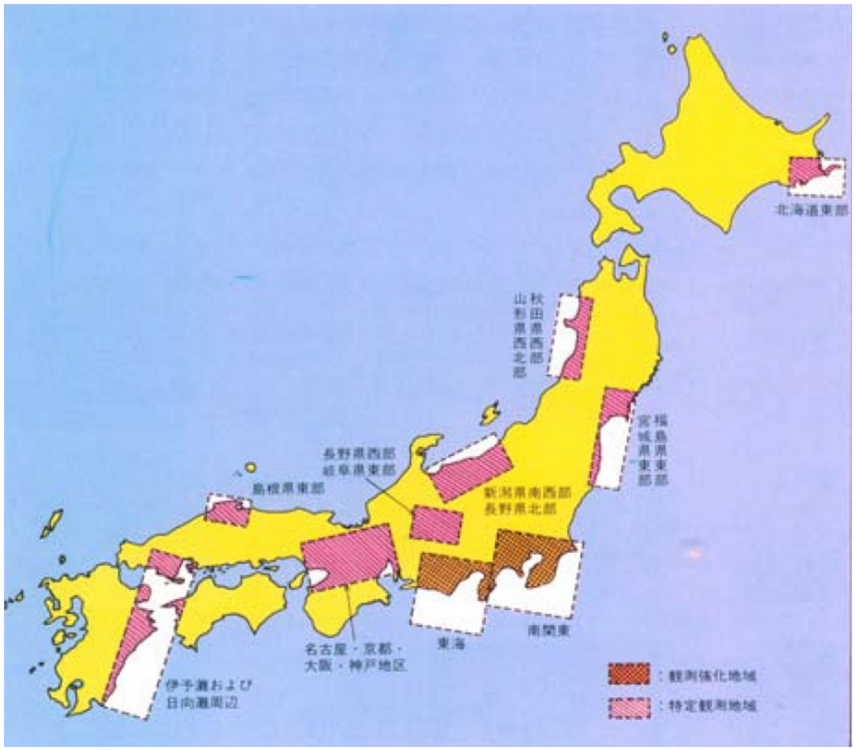
Brief History

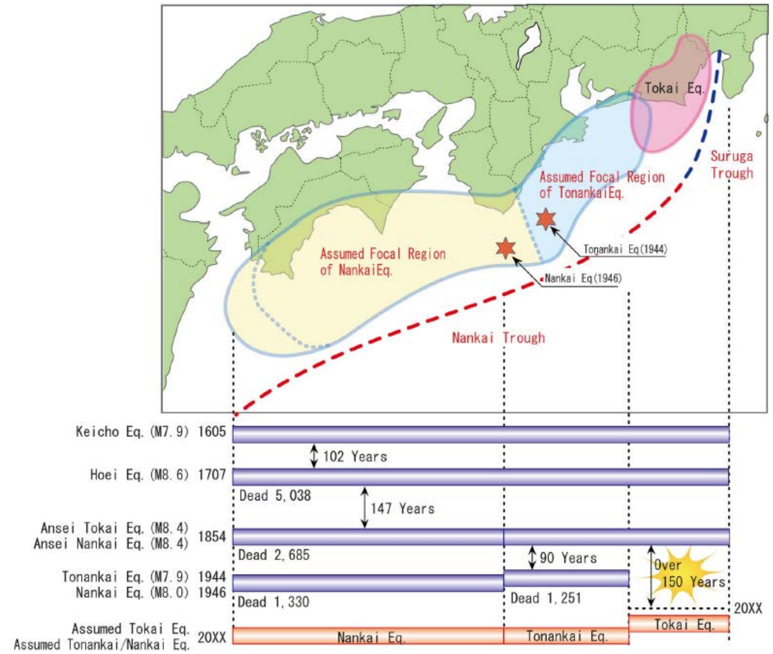
- **After the Oct. 28, 1891 M8.0 Nobi (美濃尾張Mino-Owari) earthquake, Japanese founded the Imperial Earthquake Investigation Committee (Ref.: Imamura, A., 1937. Theoretical and Applied Seismology, Maruzen, Tokyo).**
- **The 'Blueprint' finished by Tsuboi, Wadati and Hagiwara (1962) was the basis for Japan's prediction program.**
- **In 1980's and 1990's, budget was ~USD100 million a year.**

The 1891 Nobi Earthquake



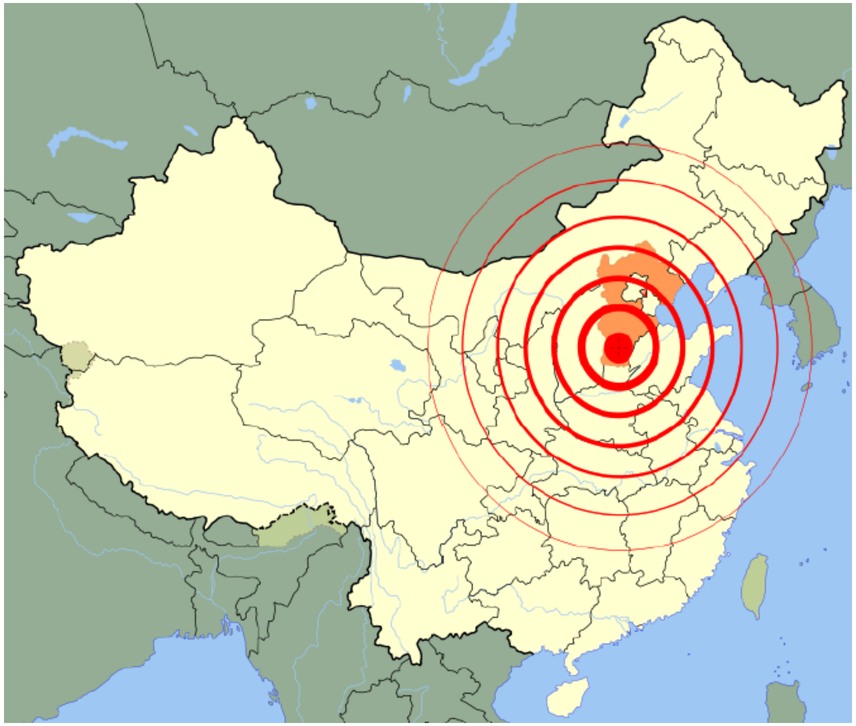
Areas for Potential Large Earthquake in Japan



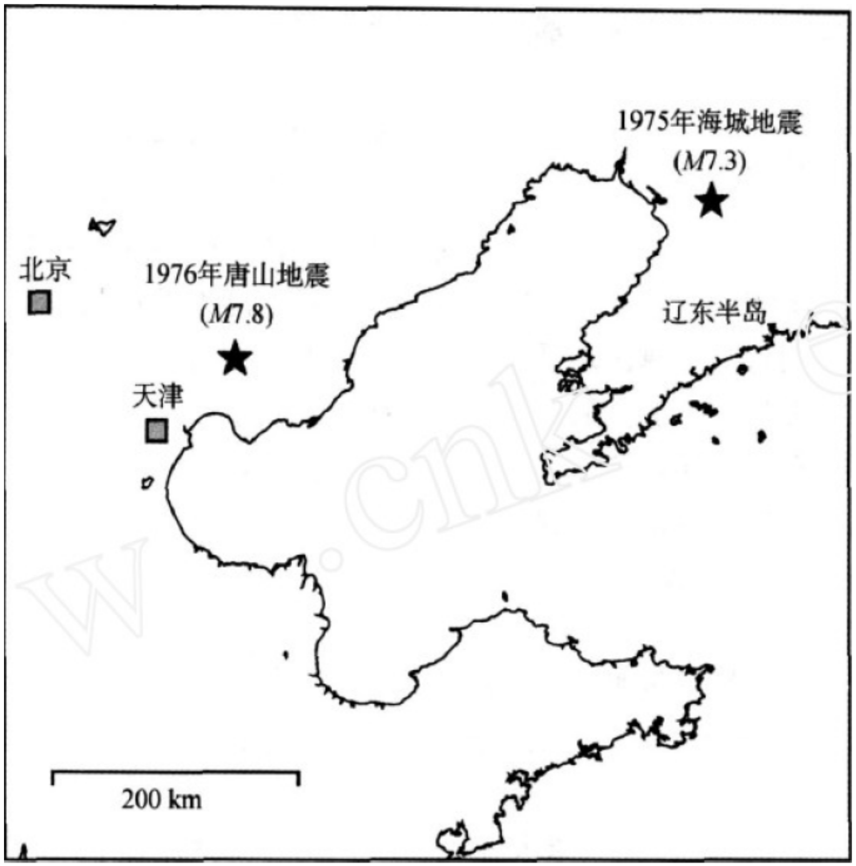


China's Program

- **After the March 22, 1966 M7.2 Xingtai earthquake (8,064 dead, 38,000 injured and more than 5 million destroyed houses), an extensive earthquake research program (including earthquake prediction) was developed**.



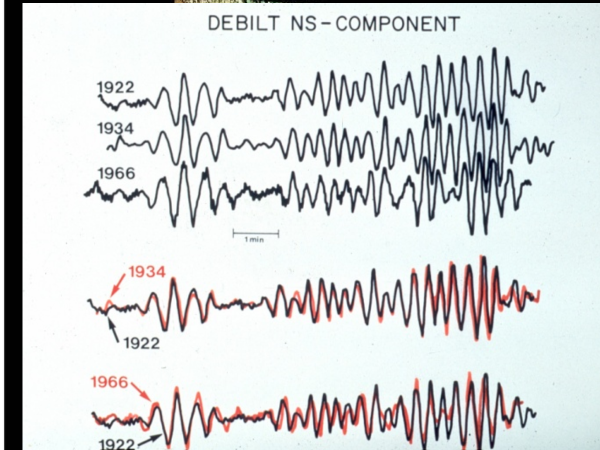
1975年2月4日M7.3海城地震

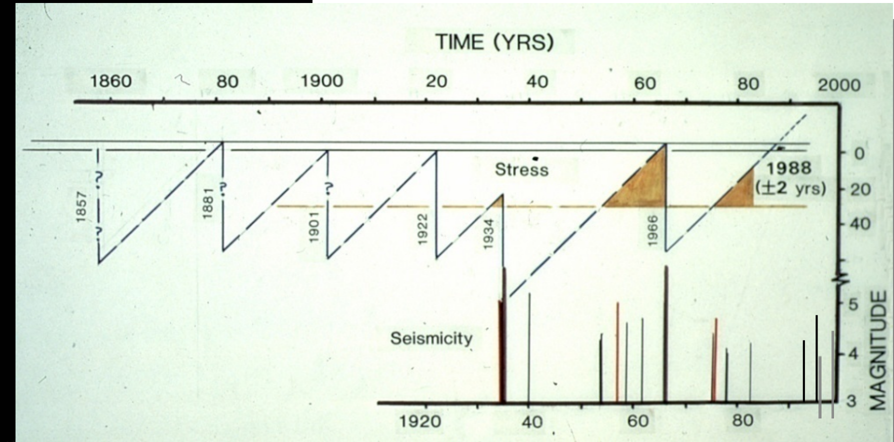


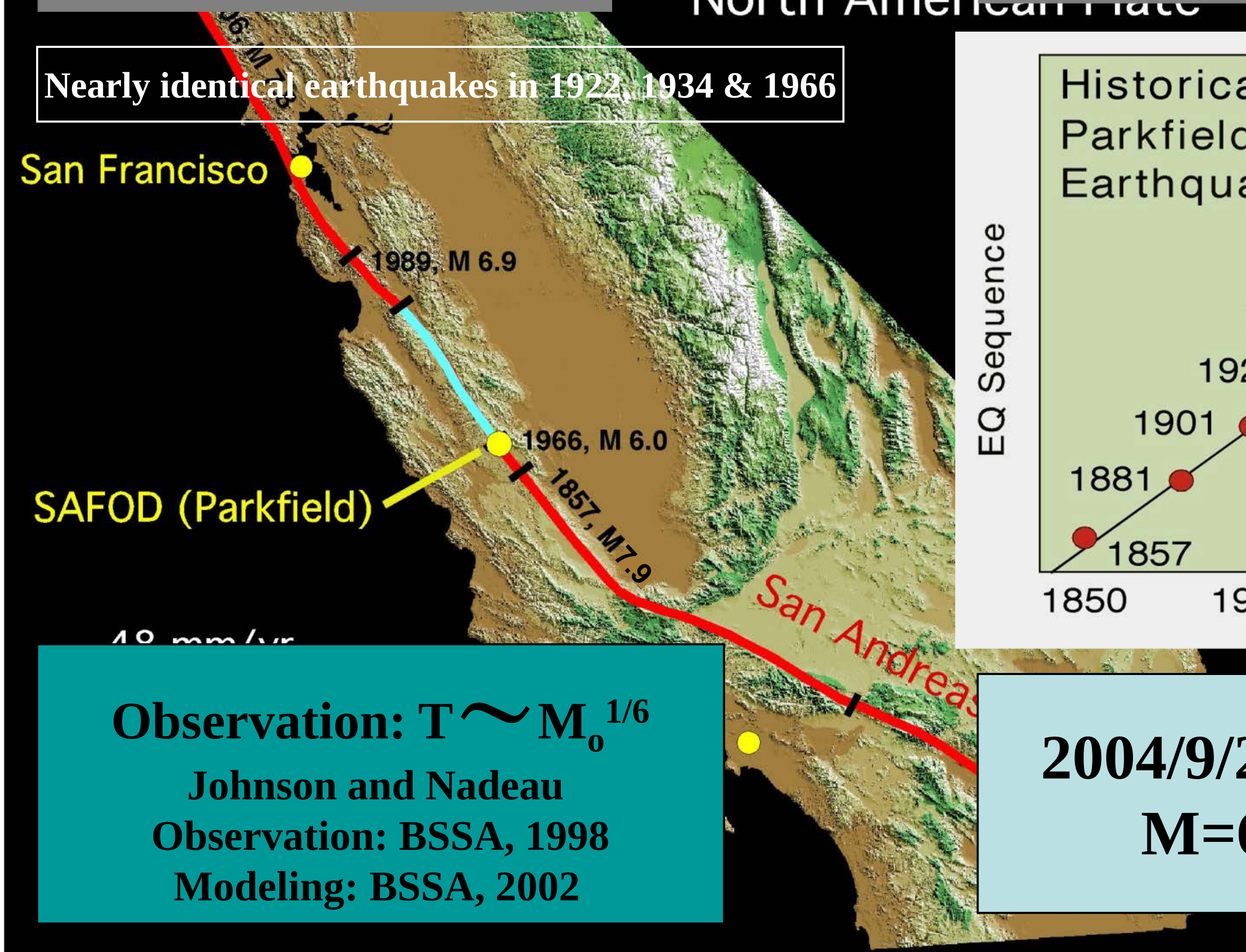
- 时间：19点36分
- 地点：中国辽宁省海城、营口县一带(北纬40度41分、东经122度50分)。
- 震源深度16.21公里，震中烈度为9度强。
- 在地震烈度7度区域范围内，有鞍山、营口、辽阳三座较大城市，人口167.8万；还有海城、营口、盘山等11个县，人口660万。合计人口834.8万，其中城市人口占20%，人口平均密度为每平方公里1000人左右。
- 全區人員傷亡共18308人，佔總人口數的0.22%。其中，死亡1328人，佔總人口數的0.02%，重傷4292人，輕傷12688人，輕重傷佔總人口數的0.2%。

USA's Earthquake Prediction Program

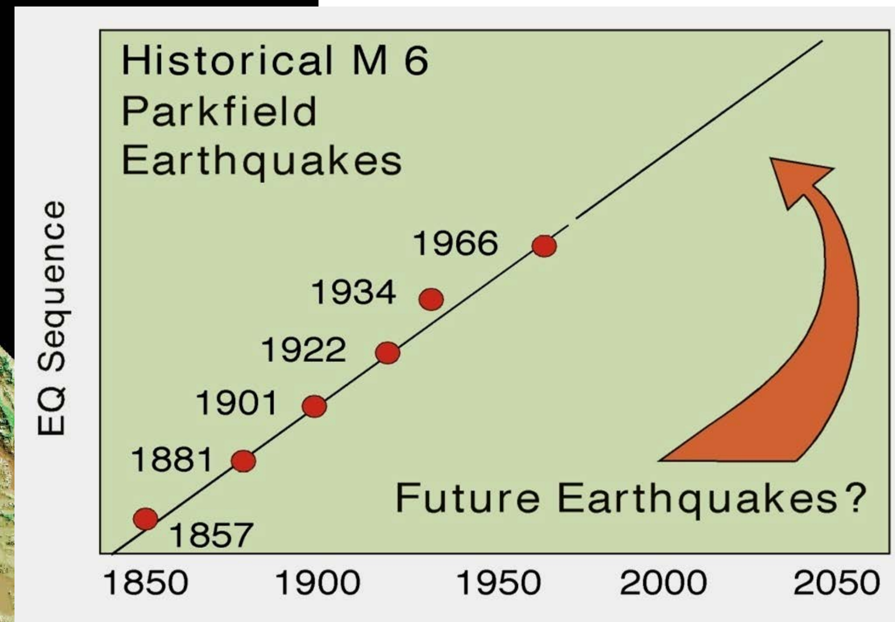
- **An Ad Hoc Committee (Press et al., 1965) proposed a large-scale empirical search for precursors.**
- **A panel of the US National Research Council (Allen et al., 1976) made the recommendation to US government for earthquake prediction.**
- **During the mid-1970s, optimism of earthquake prediction was prevalent in US.**
- **Allen (1982) commented "…we must face up to the fact that our progress during the past 5 years in short-term earthquake prediction has not been as rapid as we had envisaged when the program started…"**
- **The Parkfield Earthquake Prediction Experiment (1985–1993), coordinated by Prof. McEvilly of UC Berkeley, was issued by the Director of USGS on April 5, 1985.**







Nearly identical earthquakes in 1922, 1934 & 1966



Observation: T $\sim$ $M_o^{1/6}$

Johnson and Nadeau

Observation: BSSA, 1998

Modeling: BSSA, 2002

2004/9/28 17:15:24 (UTC)

M=6, Depth=8 km

EOS, TRANSACTIONS, AMERI
VOLUME 74 NUMBER 47 NOVEMBER 23, 1993

EOS

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NO

Waiting for Parkfield to Quake

After dark on November 16, a media van collided with a cow while driving through earthquake country near Parkfield, Calif. That may have been the most damaging incident to occur during the 72-hour earthquake alert issued, on November 14, by the state's Office of Emergency Services (OES).

Officials issued the Level A alert—meaning there was a one in three chance of a magnitude-6 quake within 3 days—following a 4.8-magnitude quake in the town of Parkfield, on the San Andreas fault. The probability of a bigger quake dies off rapidly with time. And, although the anticipated tremor never came, seismologists wrote another chapter in earthquake analysis and prediction in this seismically perilous state.

Parkfield, population thirty-four, lies midway between Los Angeles and San Francisco. It is cradled in the bucolic beauty of rolling hills and ranches. However, the town's main claim to fame is its seismic history—impressive, if not for its kick, at least for its consistency.

A magnitude-6 earthquake has struck the area, on average, every 22 years since 1857. In 1985, scientists predicted that history would repeat itself once more, and that the next magnitude 6 would strike again by 1993, give or take 5 years. (See *Eos*, March 30, 1993.)

That deadline has come and gone. Meanwhile, other equally valid statistical models predict a greater uncertainty in the timeline for the next magnitude 6, said John Langbein, chief scientist for Parkfield research at the U.S. Geological Survey in Menlo Park.

When the most recent tremor hit Parkfield this month, Langbein's team, which alerted the OES, had good reason to think it might be a foreshock of a larger quake.

For one thing, in previous Parkfield earthquakes, a foreshock of magnitude 4.8–5 has heralded the main quake about half the time, said Lucille Jones, a seismologist with the USGS in Pasadena. Two of these foreshocks each occurred just 17 minutes prior to the big quake.

Furthermore, "a fundamental hypothesis of the Parkfield prediction is that all six earthquakes were in the same place," she said. Therefore, scientists expect the next magnitude 6 to start close to the last one (which struck in 1966). Additionally, seismologists have established that foreshocks occur in basically the same place as the main shock, said Jones. And Langbein calculated that the November 14 quake was within 1 km horizontally and 1.5 km vertically from the 1966 site.

The prediction, however, drew on more than the historical patterns. Beginning in 1985, the USGS and the California Division of Mines and Geology turned Parkfield into the

Parkfield (cont. on page 554)

Famous Publicly Announced Predictions

世界公認中國預測成功一九七五年二月四日M7的海城地震。中國地震局認定一九九五年七月十二日雲南孟連M7.3地震、一九九六年二月三日M7麗江地震和一九九八年八月二十七日M6.4伽師地震的預測成功。世界上其他的地震預測都失敗或可疑。

- **In Los Angeles, USA, by Gribben (1971)**
- **In North Carolina, USA, by David Stewart (1975−1976)**
- **In Los Angeles, USA, by Henry Minturn (1976)**
- **In Oaxaca, Mexico, by a crank person (1978)**
- **In Peru, by Brian Brady (1981)**
- **In Missouri, USA, by Iben Browing (1990)**
- **In Greece, by P. Varotsos et al. (using VAN's Method) (1991)**
- **In Central California, USA, by C.G. Sammis (1995)**
- **In Tokyo, Japan, by a JMA's retired employee (1995)**
- **In Tokyo, Japan, by an earth scientist (2009)**

(The names in red color are earth scientists)

Debate of Two different viewpoints:

Omori's School: Un-predictable and Random

Immamura's School: Predictable

(They were both famous professors of seismology in Tokyo Imperial University. Before 1923, they debated the possibility of occurrence of an big earthquake in the Kanto area.) ⇒ The M7.9 Kanto Earthquake occurred on September 1, 1923

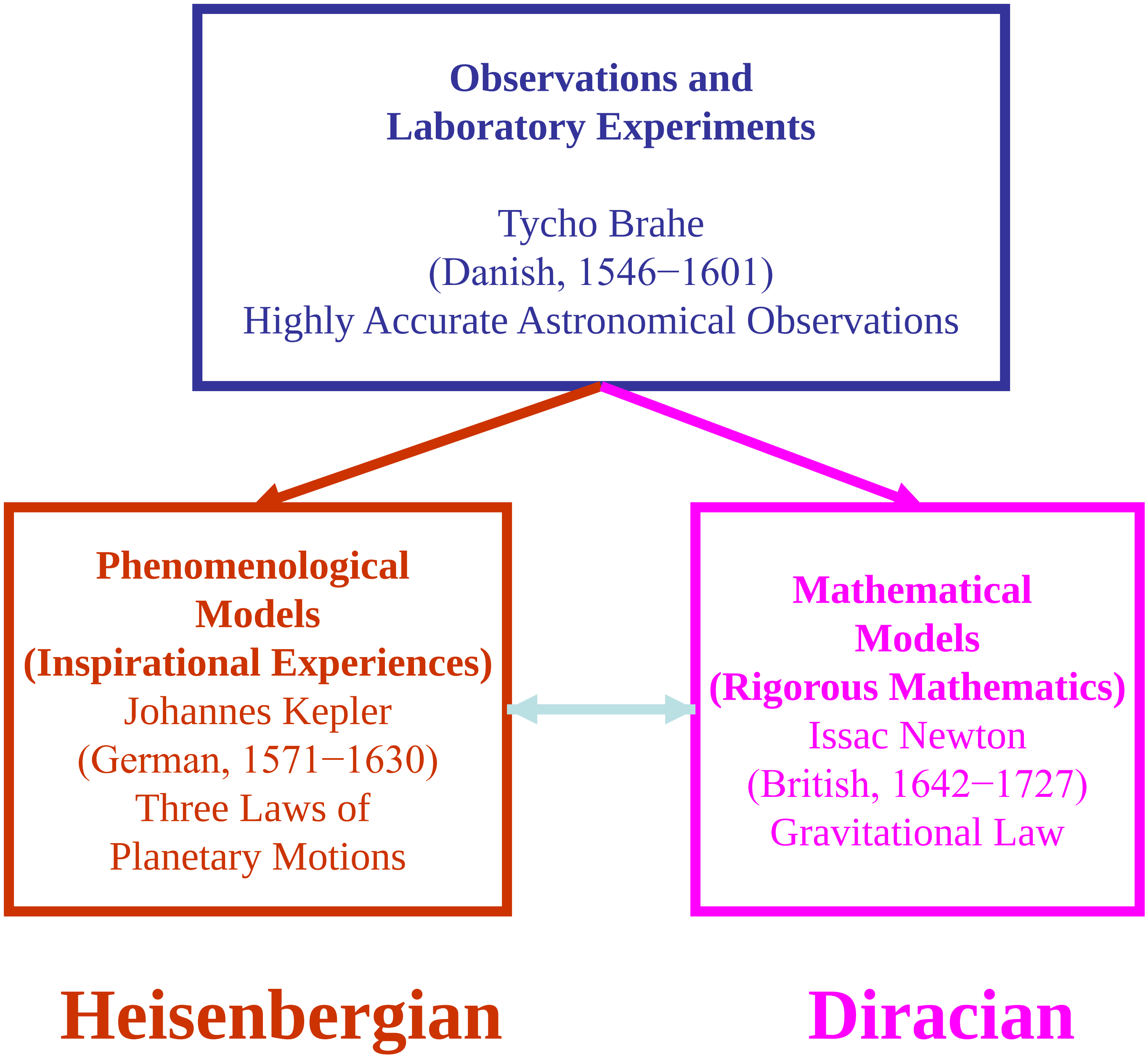
⇒ Problem? Do the imminent, short-, intermediate-, and long-term precursors exist?

Nature, Feb – April 1999

Forum: Debates about Earthquake Prediction

Week 1: Robert Geller (×), Max Wyss (○), Pascal Bernard (?)
Week 2: Andrew Michael (?), Christopher Scholz (○)
Week 3: Leon Knopoff (○), Robert Geller (×), Max Wyss (○), Pascal Bernard (?), Per Bak (?)
Week 4: David Jackson (××), Robert Geller (×), David Bowman & Charles Sammis (○), Francesco Biagi (○)
Week 5: Andrew Michael (○), Robert Geller (×), Max Wyss (○), Stuart Crampin (○), Zongliang Wu (○)
Week 6: Christopher Scholz (○), Robert Geller (×), Max Wyss (○)

(Geller, R.J., 1997. Earthquake Prediction: A Critical Review, Geophys. J. Int., 131, 425-450.)



Observations and
Laboratory Experiments
Tycho Brahe
(Danish, 1546−1601)
Highly Accurate Astronomical Observations
Phenomenological
Models
(Inspirational Experiences)
Johannes Kepler
(German, 1571−1630)
Three Laws of
Planetary Motions
Mathematical
Models
(Rigorous Mathematics)
Issac Newton
(British, 1642−1727)
Gravitational Law
Heisenbergian
Diracian

Earthquake Precursors

Four Categories of Precursors

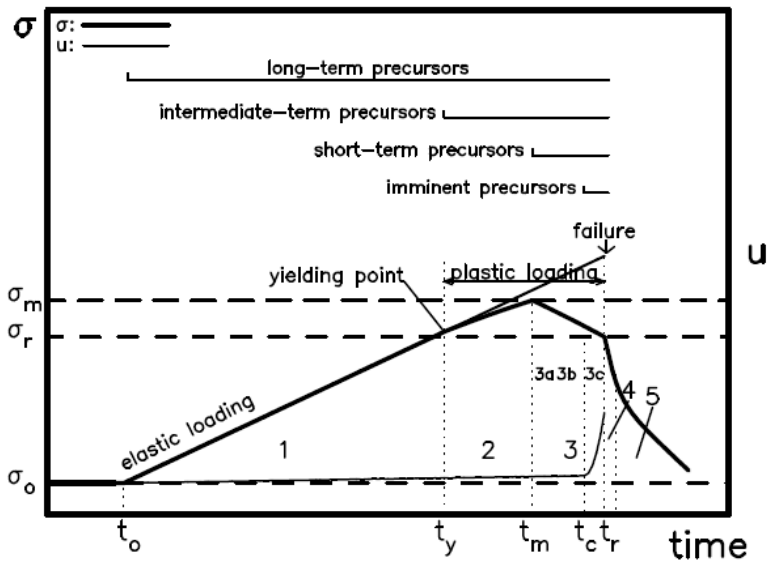
- **(1) Mechanical precursors: paleoseismicity, stress orientation changes, crustal deformations, seismicity pattern changes, seismic quiescence, foreshock activities, *b*-value anomalies, fractal dimension changes, changes of seismic-wave velocities, anisotropy changes, hydrological changes, slow-slip events, infrasound, gravity, heat, entropy, nucleation phase, etc.**
- **(2) Electromagnetic (EM) precursors: anomalous ground electric resistivity and conductivity, earthquake lights, thermal infrared emissions/long-wave radiation, geoelectric fluctuations, geomagnetic fluctuations, cloud-to-ground lightning, electromagnetic emissions from extremely low frequency (ELF) to very high frequency (VHF), anomalous sub-ionospheric VLF/LF signals, anomalies of total electron content (TEC) and f_oF_2, etc.**
- **(3) Chemical precursors: changes of geochemical compositions, radon concentration changes, gamma (γ) ray emissions, etc.**
- **(4) Biological precursors: anomalous behavior of animals, humans, and plants.**

Five Types of Earthquake Prediction and Time Windows

- **Very-long-term prediction (T>10 years or longer);**
- **Long-term prediction (T=3 to 10 years);**
- **Intermediate-term prediction (T=6 months to 3 years);**
- **Short-term prediction (T=8 days to 6 months);**
- **Imminent prediction (T≤7 days).**

Temporal Variations in Stress and Pre-seismic Slip

(Main and Meredith, 1989)



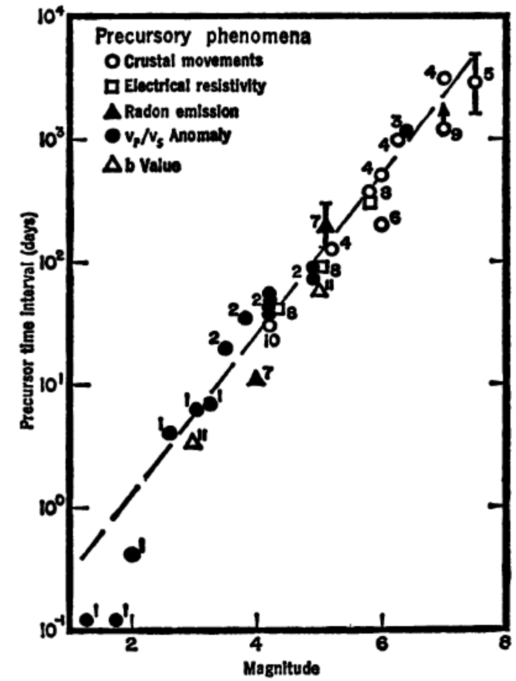
EM anomalies, infrasound, slow-slip events, anomalous animal activities, nucleation phase, etc. appear mainly in steps 3b and 3c, i.e., the short-term and imminent precursors. **Hydrological (for example groundwater level) and geochemical anomalies may appear from the later time of Stage 2, i.e., the intermediate-term, short-term, and imminent precursors.**

- **1. Elastic buildup of strain energy ⇒ long-term precursors**
- **2 . Inelastic strain hardening due to dilatancy;**
- **3. Precursory stress drop or strain softening: (a) microcrack linkage, (b) pore fluid diffusion, and (c) quasi-static slip on the fault between asperities;**
- **4 . Fracture of asperity at time t_f, fault rupture and dynamic slip of the fault behind the crack tip;**
- **5. Transient stimulation of further stress drop by aftershocks.**

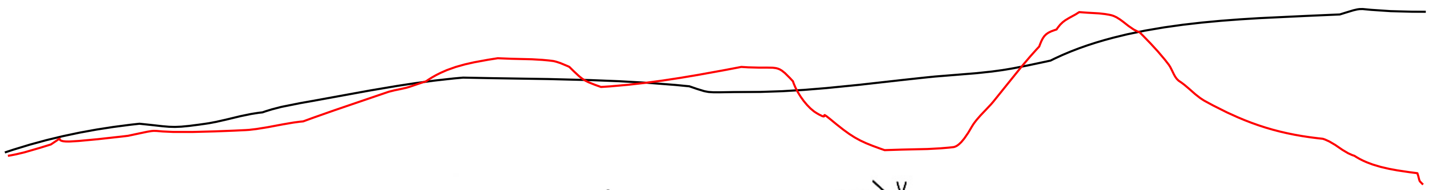
How T versus M?
(Linearity versus Nonlinearity)

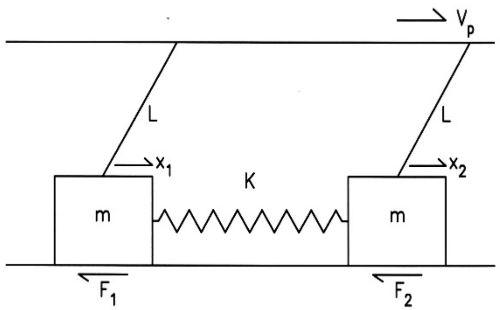
- **Linear 1D Difference Equation: $dn/dt=-\lambda n(t)$ → $dn/dt=-\lambda n(t)$ (without the memory effect) → $n(t)\sim \exp(-t/\lambda)$**
- **Non-linear 1D Difference Equation: $dn/dt=-\kappa n(t)n(t-\delta t)$ → $dn/dt=-\kappa n^2(t)$ (with the memory effect) → $n(t)\sim \kappa t^{-1}$**
- **Whitcomb et al. (1973) assumed $T\sim L^{\gamma}$ where L is the fault length of the forthcoming earthquake and γ is the scaling exponent. This gives $\log(T)\sim \gamma\log(L)$.**
- **Due to $M\sim \beta\log(L)$, we have $\log(T)\sim bM$.**
- **The first log(T)−M relationship: $\log(T)=3.75+0.65M$ (Scholz et al., Science, 1973).**

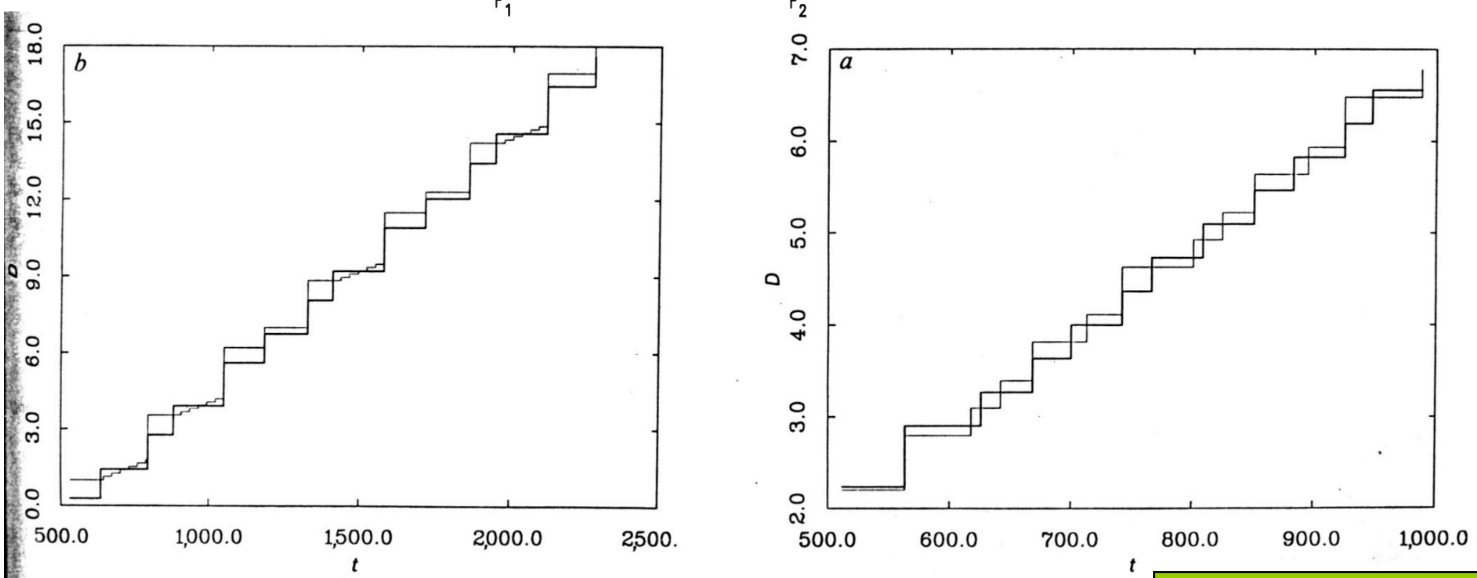
$\log(T)=3.75+0.65M$
(Scholz et al., Science, 1973)



Characteristics of Nonlinearity:
1. Sensitive to Initial Conditions (SIC)
2. Capable of Generating Chaos (Unpredictable)







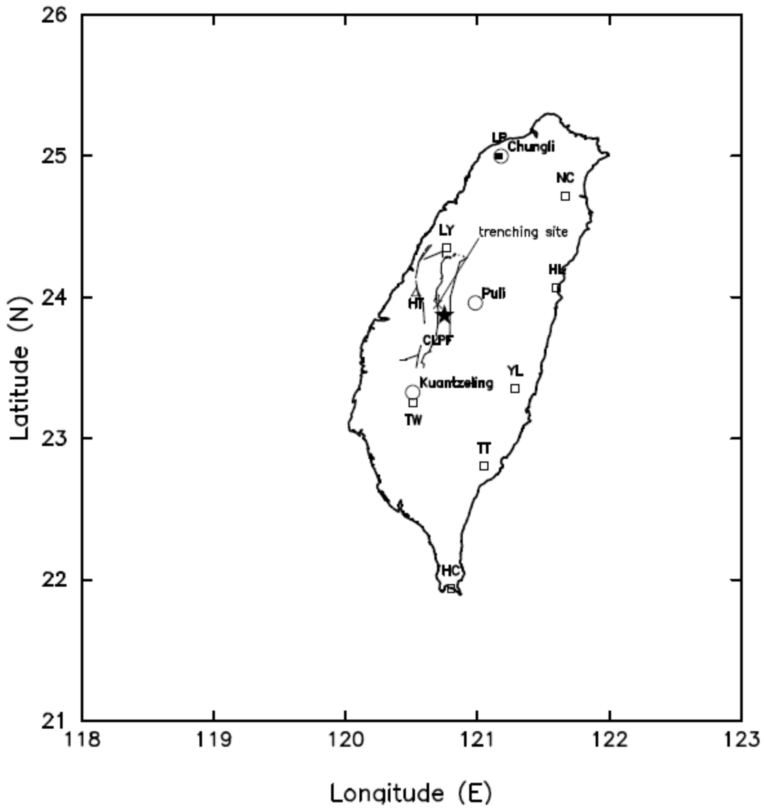
Huang and Turcotte [1995]

國內地震前兆的研究計畫

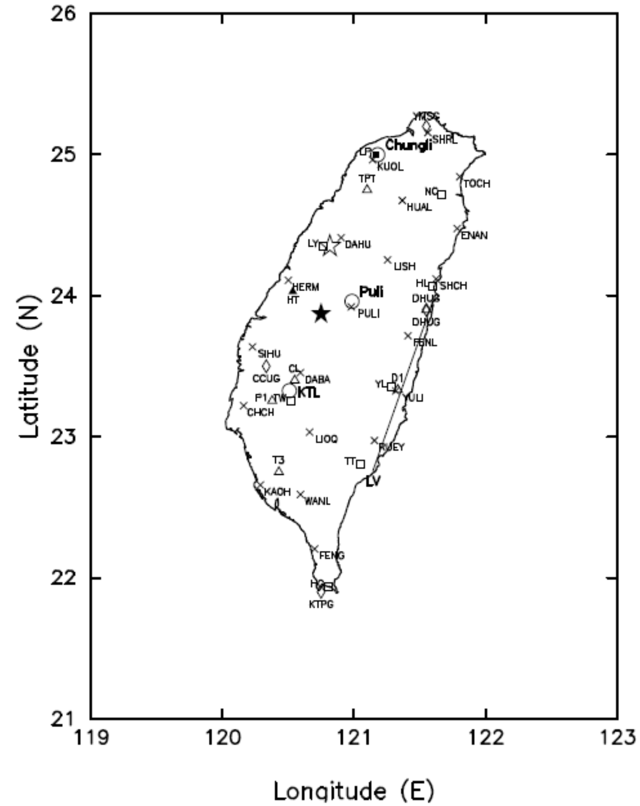
- 中央研究院地球科學研究所(1979－1980)
- 教育部及國家科學委會:「地震電磁前兆研究」(2002－2006)(中央大學地球科學院)
- 經濟部水利署:「地震發生前後地下水水位異常變化之研究」(2000－2005?)(成功大學防災研究中心)
- 經濟部中央地質調查所:「環境地球化學及斷層潛勢分析觀測」(2000－2021)(台灣大學地質科學系)
- 交通部中央氣象局:「地震電磁前兆研究」計畫(2002－2021)(中央大學地球科學院、成功大學地球科學系);「由全球衛星定位系統連續監測台灣地區地震前後地殼變形」計畫(2000－2021)(中央研究院地球科學研究所)
- 科技部:「地震電磁前兆研究(?)」(2021－2026)(中央大學地球科學院)
- 科技部(國家科學委會):幾項個別型計畫

Stations for Monitoring Precursors

Before 2000

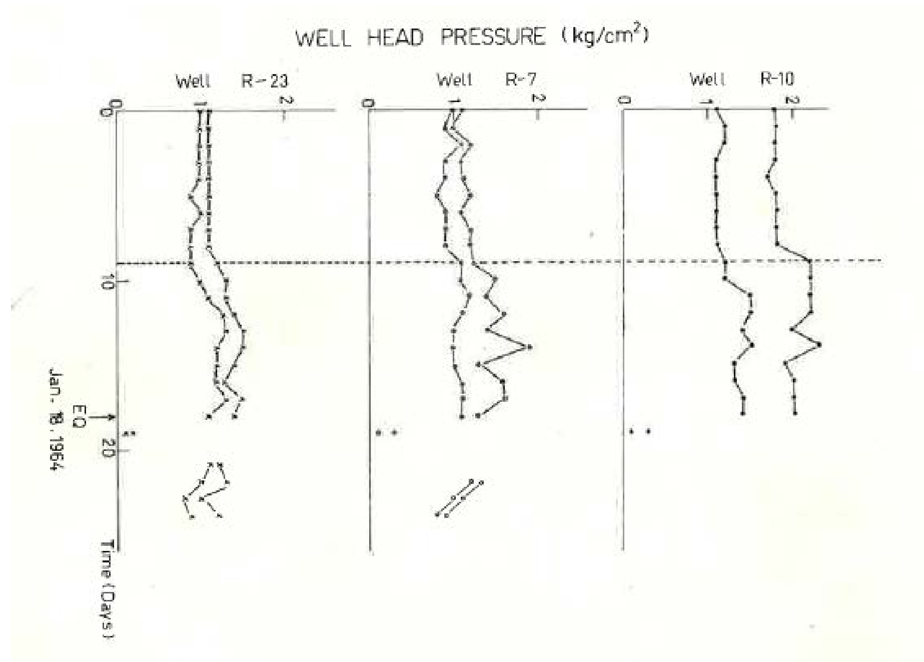


After 2000



The First Observed Precursor in Taiwan: Gas well pressure fluctuation

- **Wu (1975) and Wu and Feng (1975) reported that the gas well pressure fluctuations occurred about 9 days before the January 18, 1964 M_L6.3 Tainan-Chiayi (Baiho) earthquake.**
- **106 dead, 650 injured, 4923 totally destroyed houses, and 10885 partly damaged houses; landside, fissures, sand craters, etc.**



國內地震前兆的研究成果

- 在過去數十年的歲月中，台灣的地震科學家及相關學者，致力於收集這五項前兆的資料。對於這些觀測資料，蔡義本先生和他的共同研究者曾發表了四篇論文(Tsai et al., 1983, 2004, 2006, 2018)。第一篇文章僅回顧中央研究院地球科學研究所成員在1983年以前所做的初步前兆研究成果。第二、三篇文章則以中央大學所執行的教育部和國科會共同支持之iSETP前兆研究計劃的成果為主要內容。第四篇文章除了前述的結果外，並包含台灣大學所執行之地震化學前兆的成果。雖然如此，仍然有許多其他單位學者的前兆研究成果並未包含在這四篇文章中。
- 對於個別前兆的研究，也有幾位學者完成回顧性文章:劉等人(Liu et al., 2000, 2004, 2006, 2018)的台灣地震的電離層前兆研究；劉等人(Liu et al., 2006)的台灣地震之地磁異常前兆研究；陳等人(Chen et al., 2004)之台灣地震的地磁異常前兆的研究；陳等人(Chen et al., 2013)之台灣地震的地下水水位異常前兆的研究；傅和李(Fu and Lee, 2018)的台灣地震前之化學前兆研究。
- 除了蔡等人針對一九九九年集集大地震有較多項前兆的整合性研究外，其他的文章則不涉及單一地震的不同前兆之整合性研究，而且也較不討論這些可能前兆的物理和化學的原理及可靠性。

Table 1. Precursory times, T, of long-term, intermediate-term, short-term, and imminent precursors for earthquakes occurring in Taiwan. In the table, M_L is the local magnitude determined by the CWB.

Types	Precursors	T	Remarks
Long-term	Mechanical Precursors		
	Stress Orientation Changes	9 years (M_L=7.3)	Wu et al. (2010); Hsu et al. (2010)
	Changes of seismicity patterns	3−6 years (M_L=7.1, 7.3)	Wu and Chen (2007); Wu et al. (2008)
	Variation in b-values	3−6 years (M_L=6.4−7.3)	Chen and Wang (1984); Chen et al. (1990); Tsai et al. (2006); Wu et al. (2008)
	Changes in P-wave travel-time residual	6 years (M_L=7.3)	Lee and Tsai (2004)
Intermediate-term	Mechanical Precursors		
	Surface deformations	3 years (M_L=7.3)	Tsai et al. (2006)
	Seismic quiescence	9−21 months (M_L=7.1, 7.3)	Wu and Chen (2007); Wu and Chiao (2006); Kawamura and Chen (2013, 2014)
	Groundwater level changes	250 days (M_L=7.3)	Chen et al. (2013b, 2015)
	Foremers	8 months (M_L=6.4)	Chen and Wang (1984); Chen et al. (1990)
	EM Precursors		
	Geomagnetic annual changing rate	2 years (M_L=7.3)	Chen et al. (2004)
	Geochemical precursors	7 months (M_L=7.3)	Song et al. (2003)
Short-term	Mechanical Precursors		
	Crustal extension rate	4 months (M_L=6.4)	Fu et al. (2017b)
	Aseismic crustal strain	2.5−3 months (M_L=5.4−6.4)	Kuo et al. (2010)
	Variation in b-value	1 month (M_L=5.2)	Lin (2010)
	Variation in Q_p	2 months (M_L=6.2)	Wen et al. (2015)
	Groundwater level changes	10 days (M_L=6.2)	Yu and Mitchell (1988)
	Subsurface deformations	≤8 days (M_L≥5.0)	Chen et al. (2011b, 2013a)
	Gas well pressure change	9 days (M_L=7.3)	Wu (1975); Wu and Feng (1975)
	EM Precursor		
	ULF signals	2 months (M_L=7.3)	Akinaga et al. (2001)
	Geomagnetic anomalies	1.1 months (M_L=7.3)	Yen et al. (2004)
		1 month (M_L≥5.0)	Liu et al. (2006)
		10 days (M_L≥4.0)	Chen et al. (2009)
	Geoelectric field anomalies	5−80 days (M_L≥5.0)	Chen and Chen (2016, 2017)
	Thermal infrared radiation	2−15 days (M_L≥6.0)	Fu et al. (2020)
	Lightning	1−30 days (M_L≥5.0)	Liu et al (2015)
	Geochemical precursor		
	Chemical compositions	0.1−28.1 days (M_L=4.1−6.7)	Yang et al. (2006); Walia et al. (2013)
	Radon concentration	54−171 days (M_L=5.0−6.4)	Kuo et al. (2006a,b, 2010, 2017, 2018, 2019)
		21 and 60 days (M_L=5.9 and 6.4)	Fu et al. (2017b)
		4−51 days (M_L=4.6−5.8)	Liu et al. (1984)
		1−23 days (M_L≥4.0)	Fu et al. (2019)
		0.2−17.4 days (M_L=3.2−6.8)	Fu et al. (2017a)
		0.49−14.2 days (M_L=3.7−6.7)	Chyi et al. (2001, 2005); Yang et al. (2005); Fu et al. (2017c)
		few days	Fu et al. (2009)
	γ-ray emissions	2−20 days (M_L=2.8−6.7)	Fu et al. (2015, 2019)
	Animal anomalies (for some animals)	>7 days (M_L=7.3)	Chen et al. (2000)
Imminent	Mechanical precursors		
	Foreshocks	5 days (M_L=5.0−6.5)	Lin (2009)
		4 days (M_L=6.4)	Chen and Wang (1984); Chen et al. (1984)
		0.3−few hours (M_L=5.2)	Lin (2012)
	Slow slip	5 days (M_L=7.3)	Lin (2012)
	Infrasound	3 days (M_L=7.3)	Xia et al. (2011)
	Duration ratio	4 days (M_L=6.4)	Wang (1988)
	EM precursors		
	TEC and f_oF_2	3−5 days (M_L=6.0−7.3)	Liu et al. (2001,2008, 2004a,b); Chuo et al. (2002)
	Geomagnetic anomalies	few days (M_L≥5.0)	Wen et al. (2012)
	Lightning	4 days (M_L=7.3)	Tsai et al. (2006); Liu et al. (2015)
	Atmospheric electric field	2−4 days (M_L=6.8)	Kamogawa et al. (2004)
	ULF/ELF signals	4 hours (M_L=7.3)	Ohta et al. (2001)
	Earthquake light	few hours (M_L=7.3)	Chen et al. (2000)
	Geochemical precursor		
	Chemical compositions	1− 5 days (M_L≥5.0)	Song et al. (2006); Walia et al. (2009)
	Animal anomalies (for some	≤7 days (M_L=7.3)	Chen et al. (2000)

Wang, J.H. (2021a). A review on precursors of the 1999 M_w7.6 Chi-Chi, Taiwan, earthquake, Terr. Atmos. Ocean. Sci., 32(3), 275-304. doi:10.3319/TAO.2021.03. 24.0

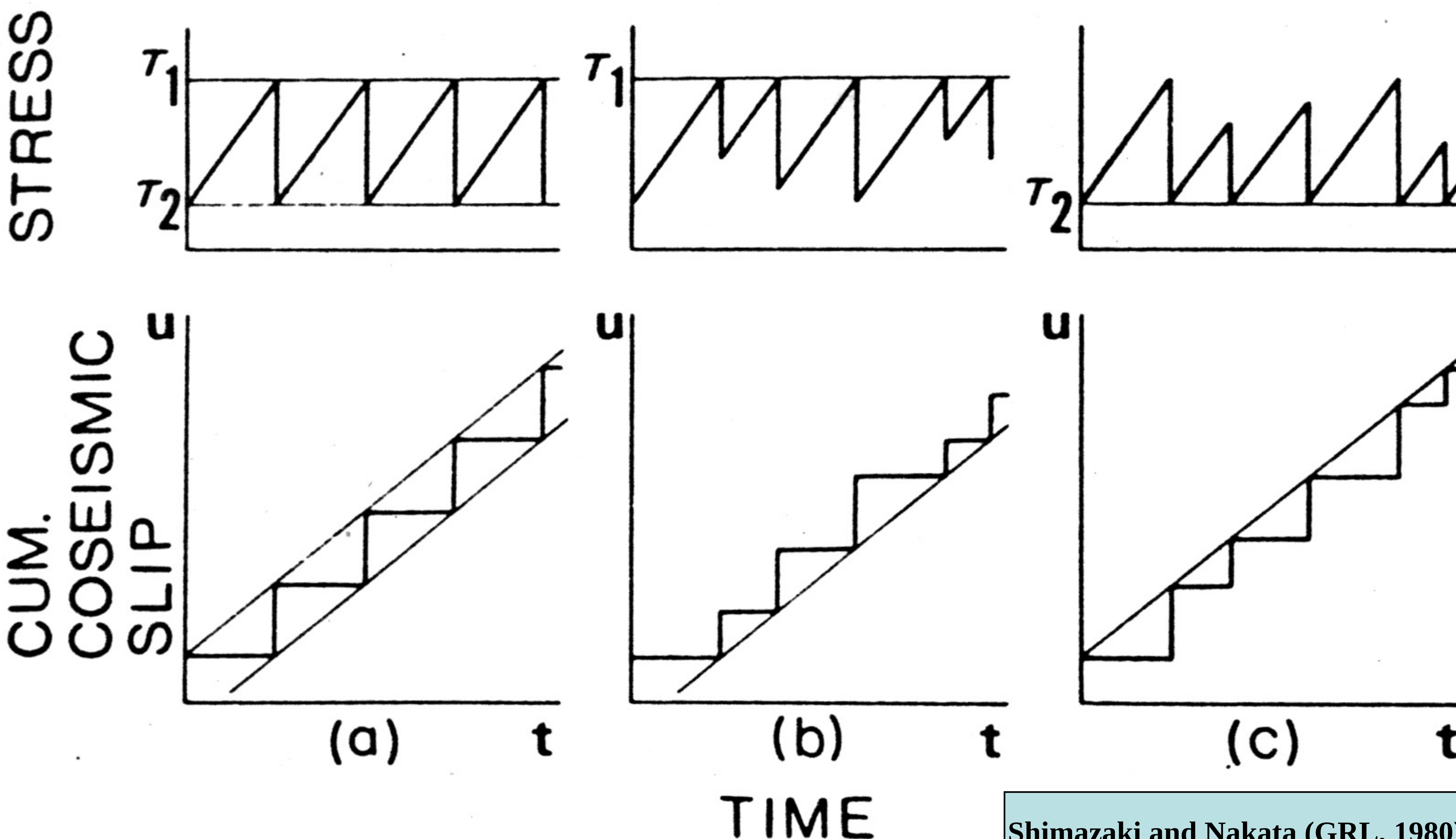
Wang, J.H. (2021b). A compilation of precursor times of earthquakes in Taiwan. Terr. Atmos. Ocean. Sci., 32 (in press).

Table 2. The precursory times of anomalies of different animals before the 1999 Chi-Chi earthquake reported by Chen et al. (2000). (after Wang, 2021b)

Animals	Weeks	Days	Hours	Time Window
Ants	1 and 8−10	1 and 2−3		Short-term
Cicada	4−6			Short-term
Diplopods	1−2	1−2		Short-term
Earthwarms	1−2	1		Short-term
Fishes	1−2	1		Short-term
Birds	1	1−2		Imminent
Roach		3		Imminent
Dogs		1	1 and a few	Imminent
Cats		1		Imminent
Turtles		1		Imminent
Palm civet-like			a few	Imminent
Snakes			2	Imminent

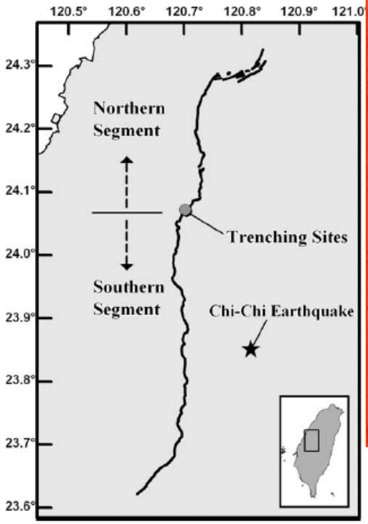
Very-long-term Prediction

時間-位移可預測模型　時間可預測模型　位移可預測模型



Shimazaki and Nakata (GRL, 1980)

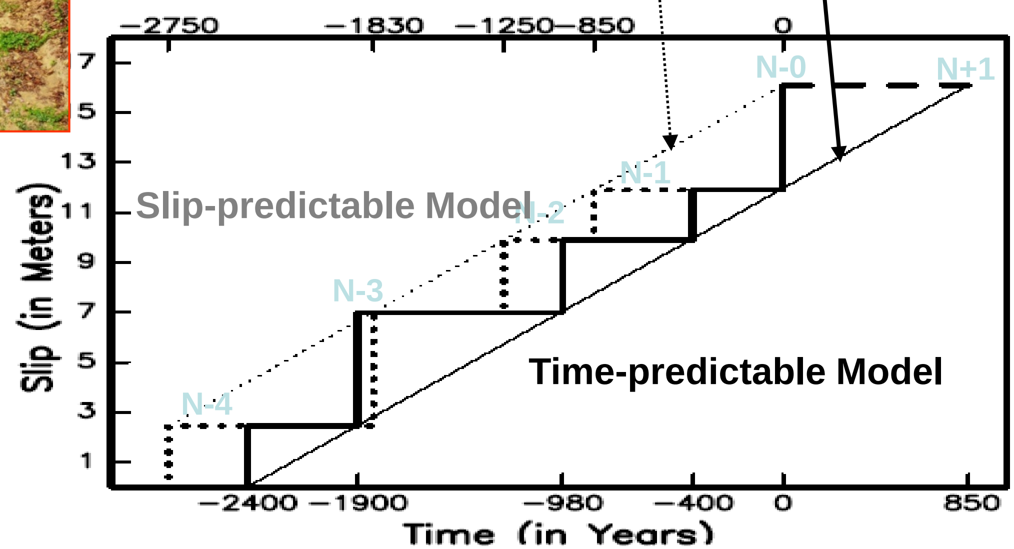
Slip History at a Pineapple Field on the Southern Segment of the Chelungpu Fault



Chen et al. (QR, 2004)

	N-0	N-1	N-2	N-3/N-4
BP (before the present)	0	150 – 430 yrs 300 – 500 yrs	700 – 800 yrs (?)	1900 yrs
Vertical Offset	1.6 – 2.1 m (1.9 m)	0.75 – 1.0 m (0.875 m)	1.0 – 1.1 m (1.05 m)	2.15 – 2.3 m (2.225 m) N-3: 1.3 m
Average Net Slip	4.2 m	2.0 m	2.9 m	7.0 m N-3: 4.55
M	7.44	7.18	7.31	7.5

V_W=4.97 mm/yr

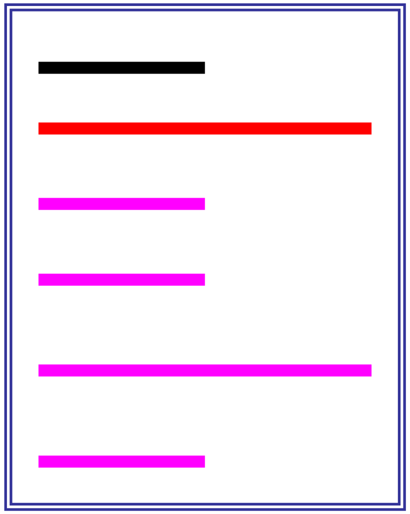


Wang (GRL, 2005)

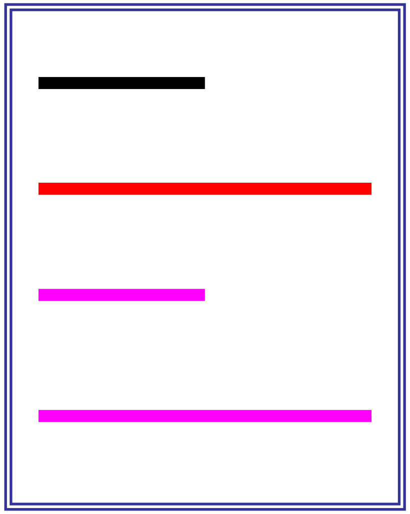
Long-term Earthquake Activity

S N

From stress drops, Wang (TAO, 2003) assumed that the Chi-Chi earthquake might be either a starting event or an ending one of an earthquake cycle including two smaller events only rupturing the southern segment and a big one breaking the whole fault.



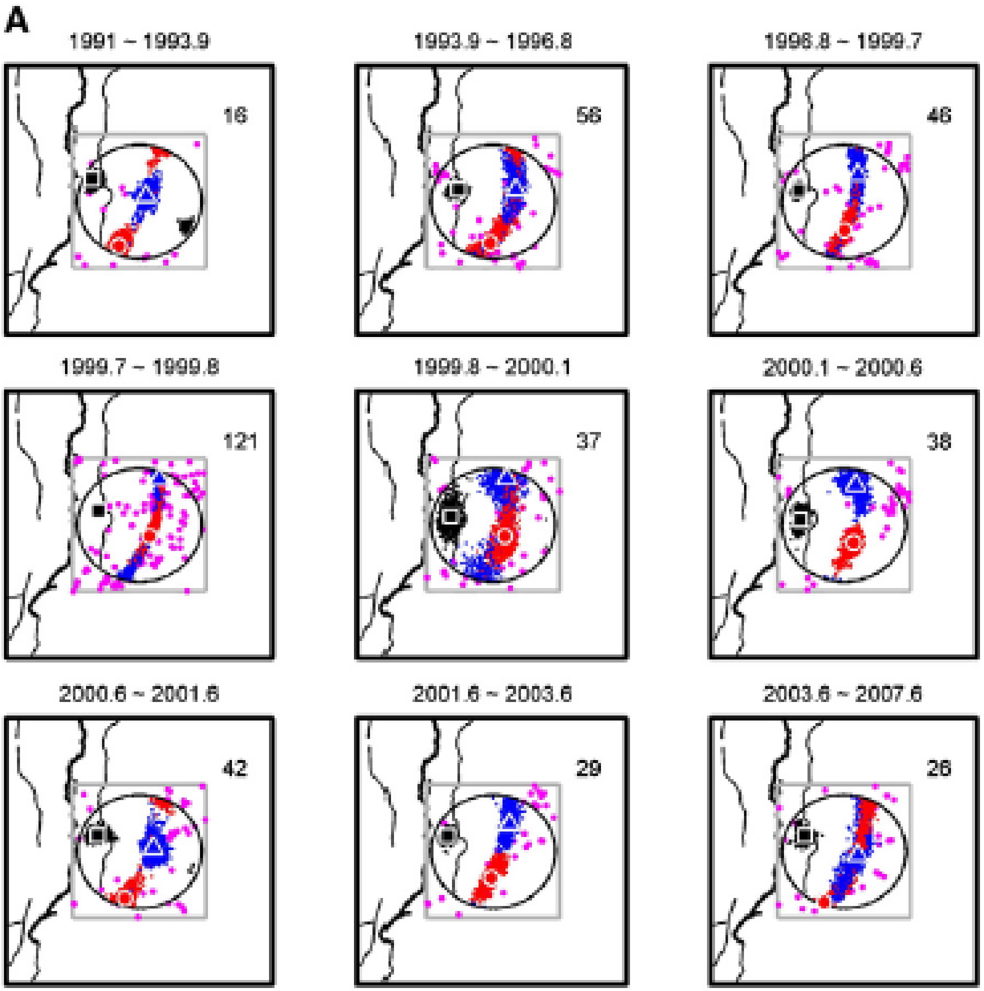
From the trenching data at Fengyuan site on the northern segment of the Cheungpu fault, Ota et al. (TAO, 2007) found two events, i.e., the 1999 Chi-Chi earthquake and an older event. Their earthquake cycle could be:



Long-term Prediction

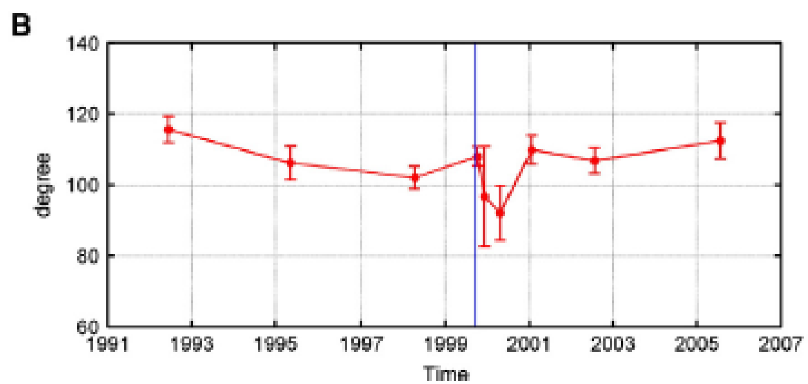
Stress Orientation Changes (T=9 years)

(Wu et al., EPSL 2010)



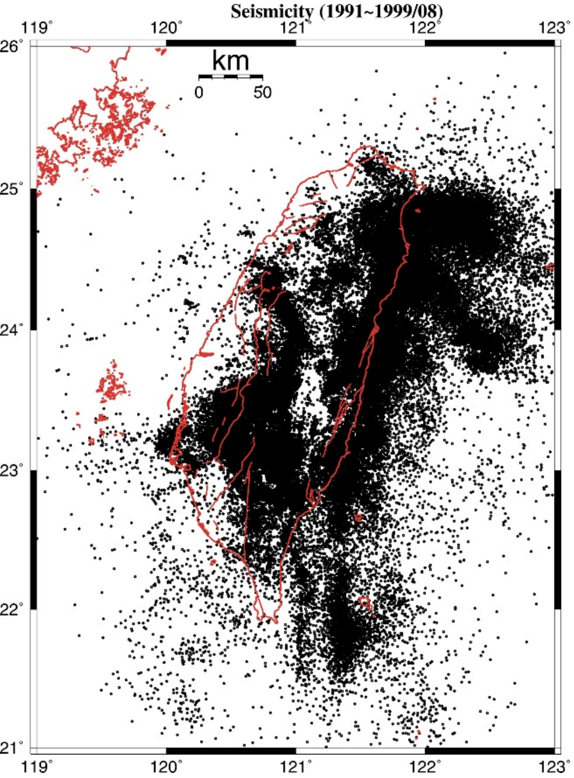
SH: The orientation of the maximum horizontal compressive stress axes

The 20˚ anticlockwise rotation of SH from the Longitudinal Valley (LV) to western Taiwan is probably caused by the left-lateral motion on the LV Fault that has consumed part of the oblique motion of plate convergence.

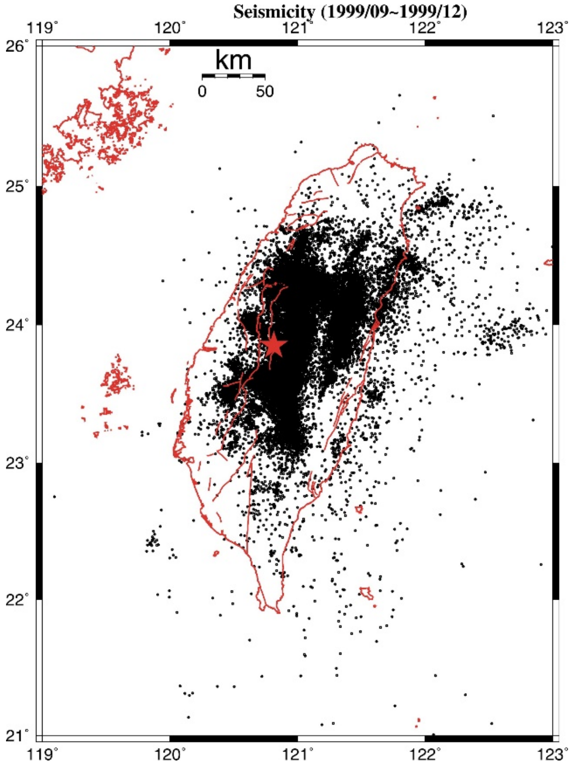


Seismicity Changes of M≥2 Events before and after the 1999 Chi-Chi Earthquake (T=6years)

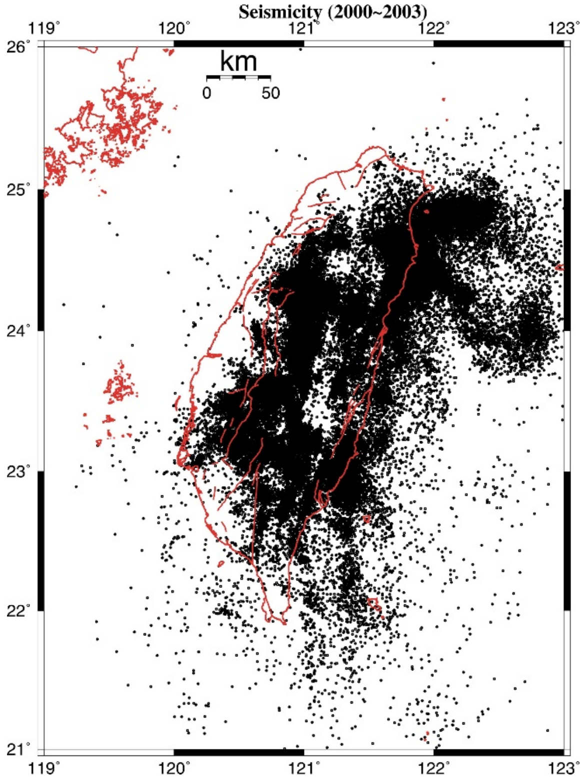
(Chen et al., 2005)



1991–1999



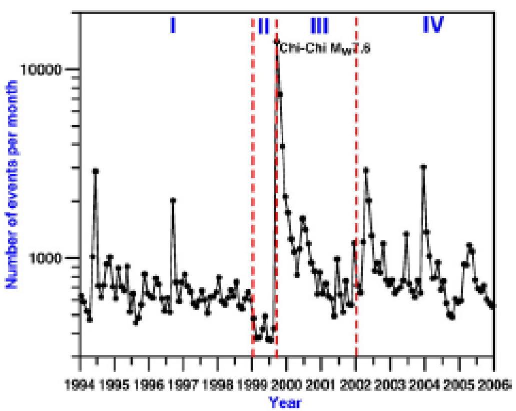
September–December 1999



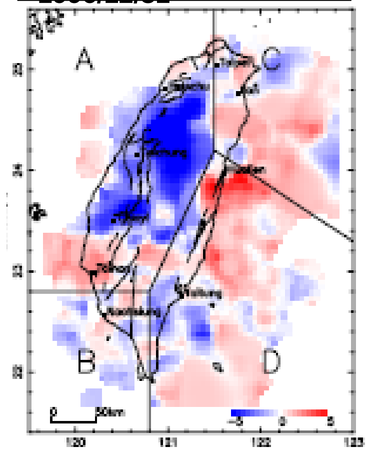
2000–2003

Maps of Seismicity Activity Z-Index for M≥2 Events before and after the Mainshock (T=6 years)

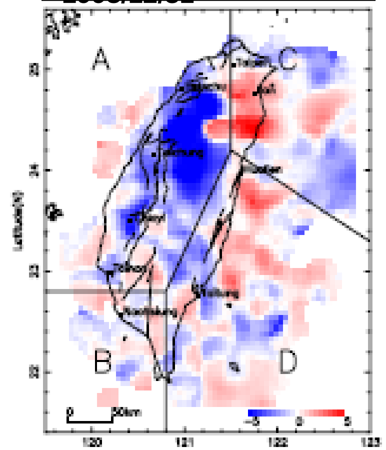
(Wu and Chen, Tectonophys., 2006)



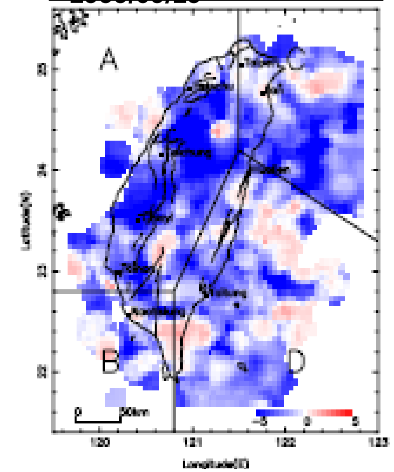
1994//01/01 to 1996/12/31



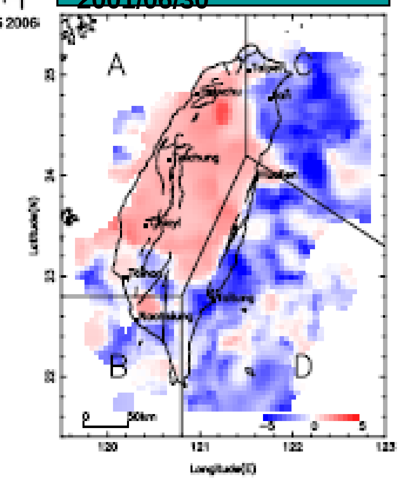
1997//01/01 to 1998/12/31



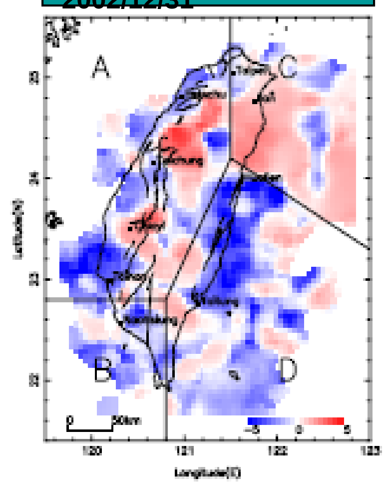
1999//01/01 to 1999/09/19



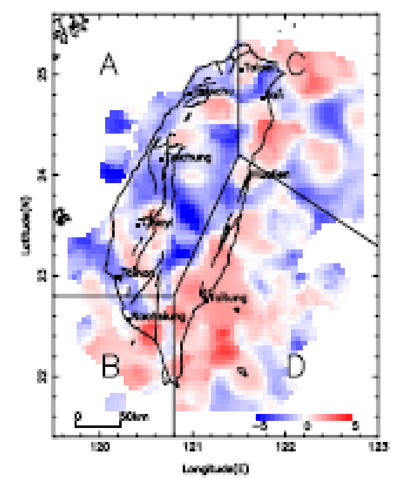
1999/09/20 to 2001/06/30



2001//07/01 to 2002/12/31

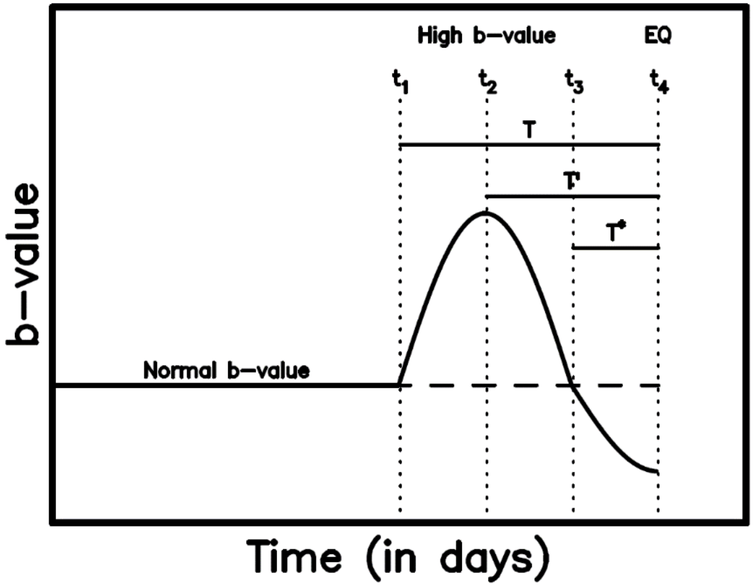


2003/01/01 to 2005/05/31



Temporal Variation in Abnormal b-values Prior to a Main-shock

(Wang, et. al., J. Seismol., 2016)



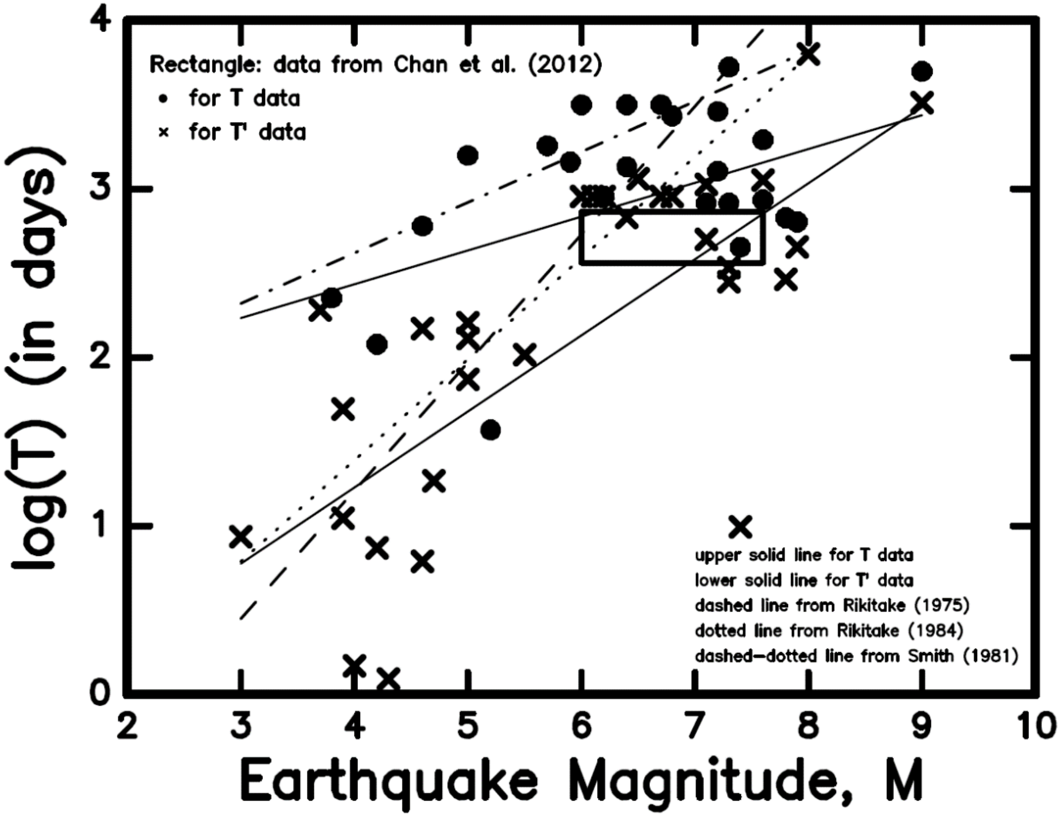
- **1st kind of precursor time: $T=t_4-t_1$**
- **2nd kind of precursor time: $T'=t_4-t_2$**
- **Waiting time: $T^*=t_4-t_3$**
- **Time of the presence of anomalies: $T-T^*=t_3-t_1$**
- **Time of the increase in anomalies: $T-T'=t_2-t_1$**

Plot of log(T) versus M

Upper solid line: For T, log(T)=(1.59±0.46)+(0.20±0.02)M

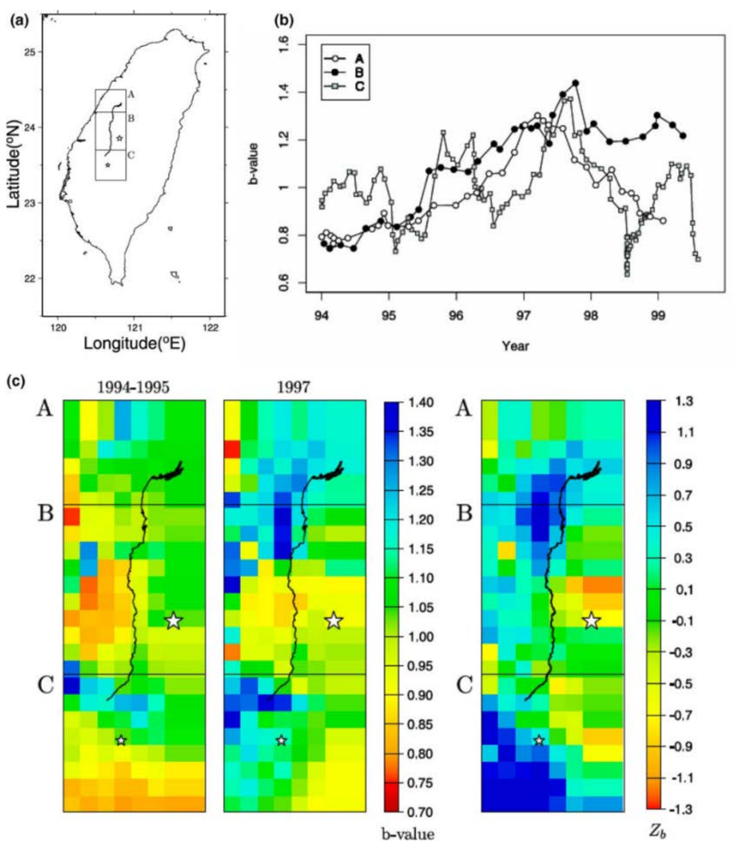
Lower solid line: For T', log(T')=(-0.57±0.69)+(0.45±0.01)M

(Wang et al., J. Seismol., 2016)

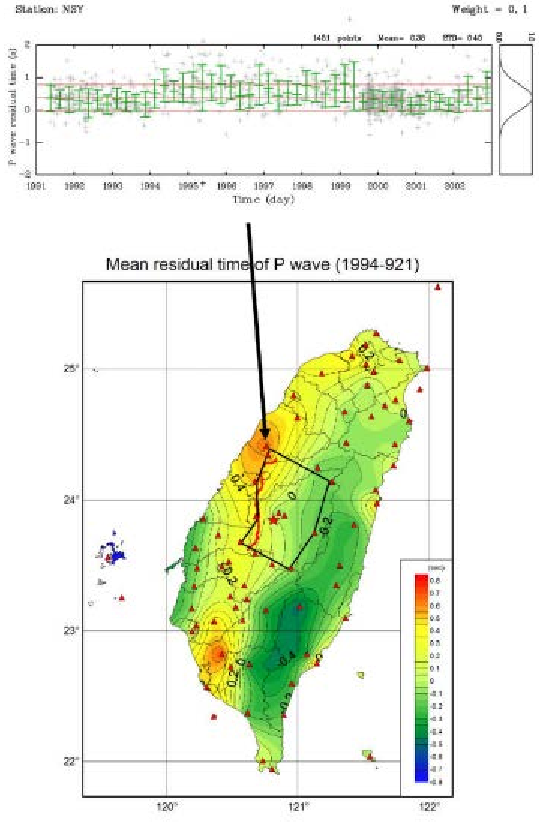


Temporal Variations in b-values and P-wave Travel Time (δt_p) (T=6 years)

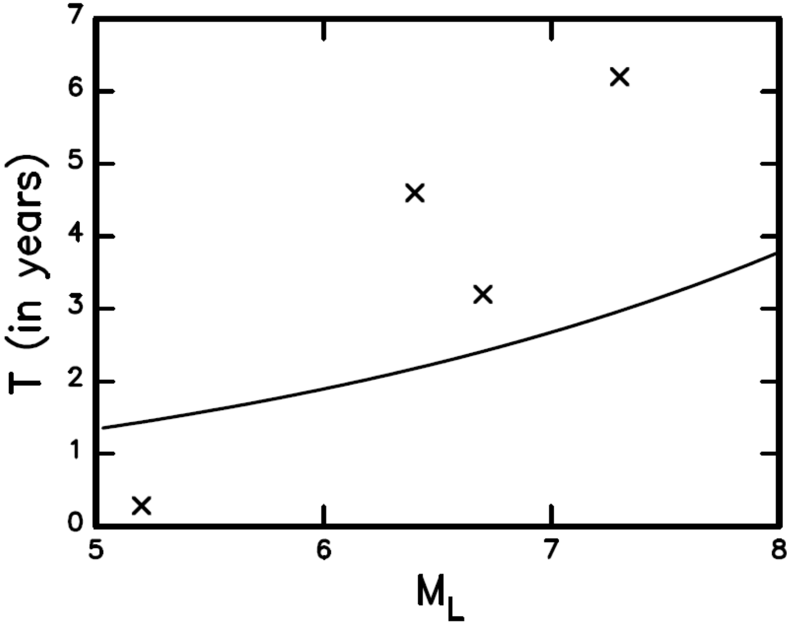
b-value (Tsai et al., 2006)



δt_p (Lee and Tsai, 2004)



T versus M_L for b-value Anomalies
Solid line: $\log(T)=1.94+0.15M_L$ (Wang et al., 2016)



- Before the May 20, 1983 M_L6.4 (or M_D5.7) Taipingshan earthquake, Chen and Wang (1984) and Chen et al. (1990) estimated the average b-value in every one year from 1973 to 1982.
- Tsai et al. (2006) studied the temporal variations of b-values for $M_L \geq 2.0$ events with $d \leq 40$ km before the 1999 Chi-Chi earthquake.
- Wu et al. (2008) studied the temporal variation in b-values for the December 26, 2006 Pingtung offshore doublet earthquakes with M_L=6.7 and 6.4
- Lin (2010) estimated the b-values of background seismicity and foreshocks before the March 4, 2008 M_L5.2 Taoyuan earthquake.

Intermediate-term Prediction

Crustal Deformations

From the GPS data
(Yu et al., 2001)

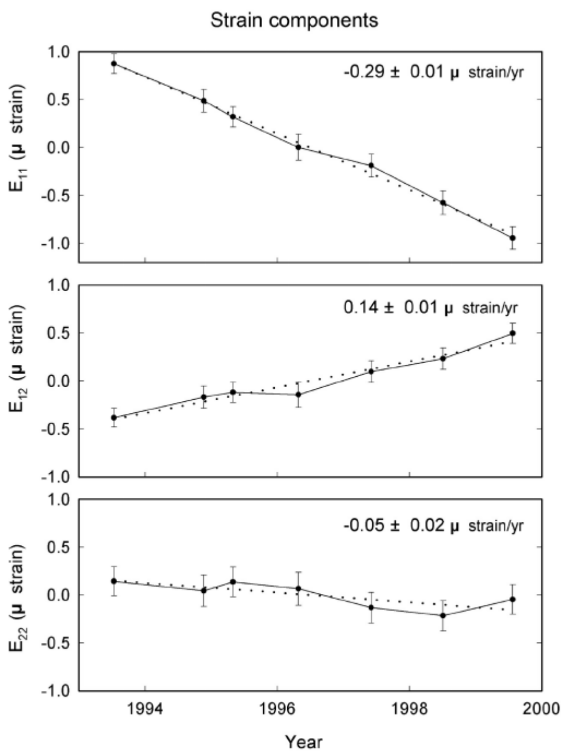
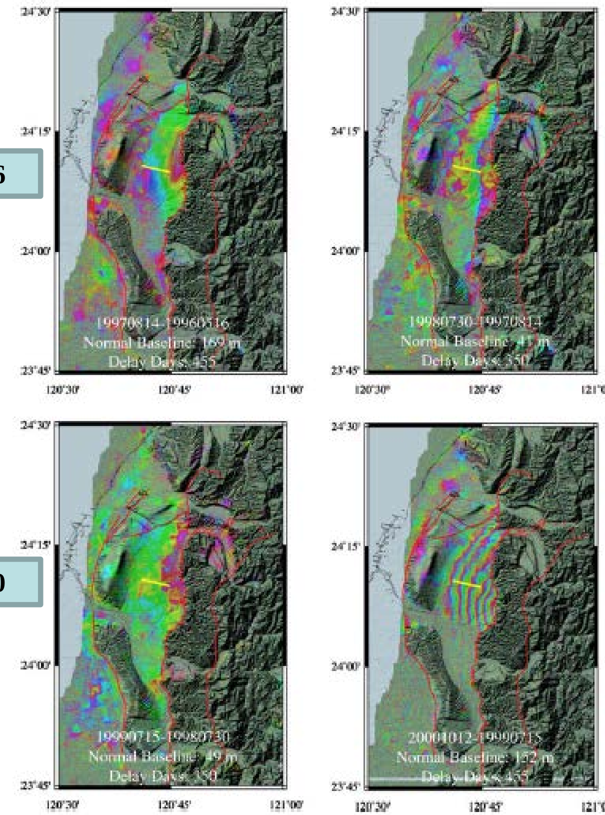


Fig. 4

From the InSar data (T=3 years)
(Tsai et al., 2004)



19970814-19960516

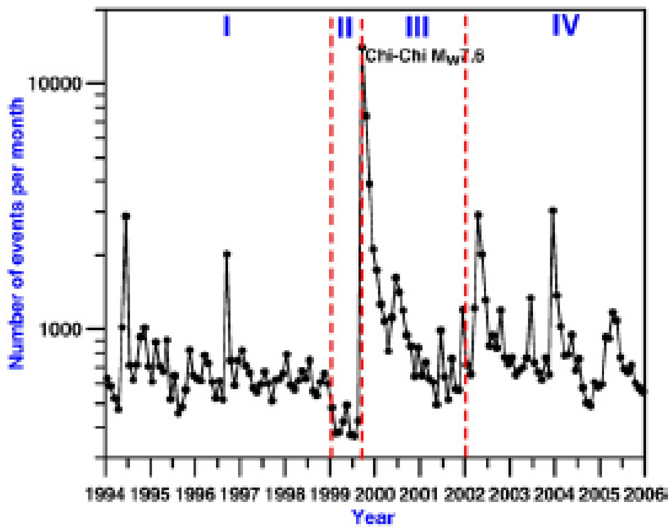
19980730-19970814

19990715-19980730

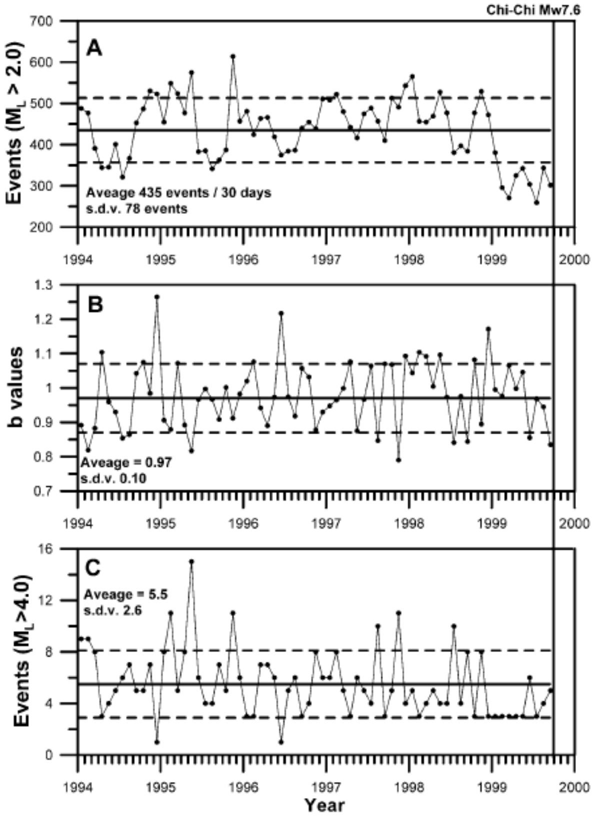
20001012-19990715

Seismic Quiescence (T=9 months)

Wu and Chen (2007)

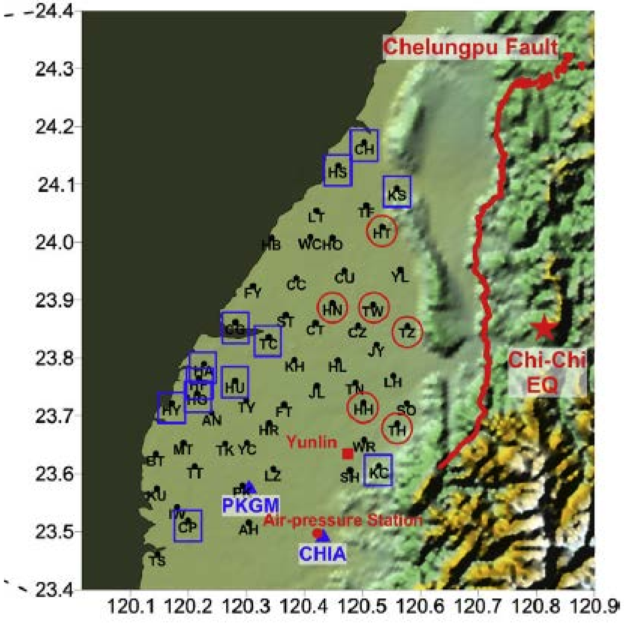


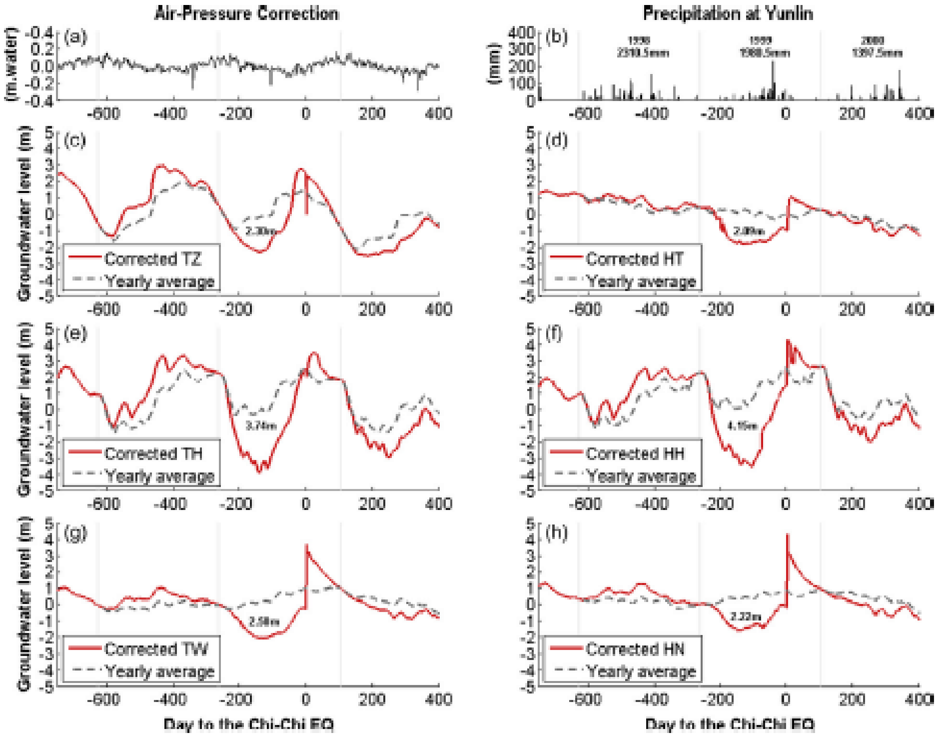
Wu and Chiao (2006)



Groundwater Level Change before the 1999 Chi-Chi Earthquake (T=250 days)

(Chen et al., 2015)





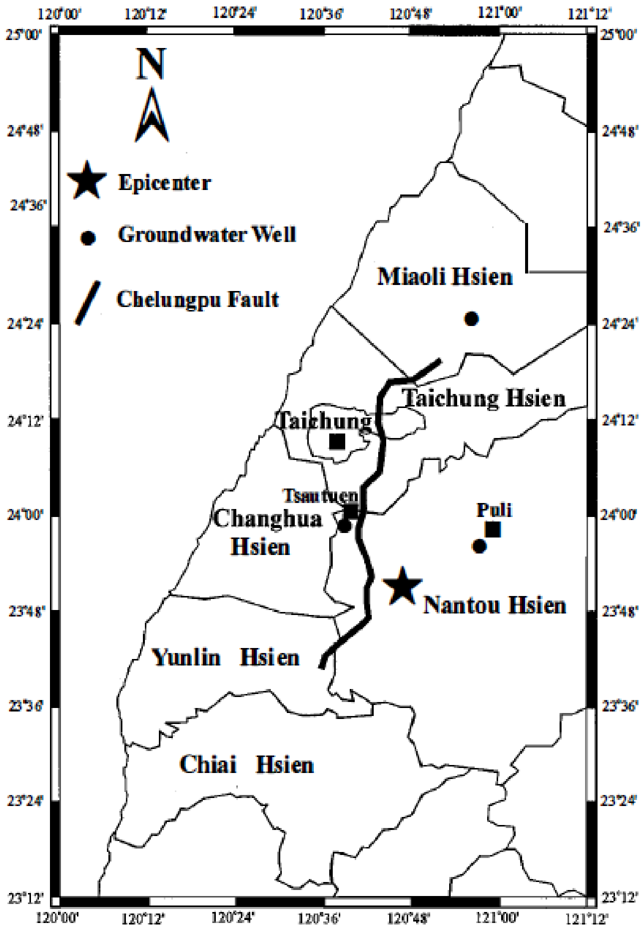
Groundwater Level

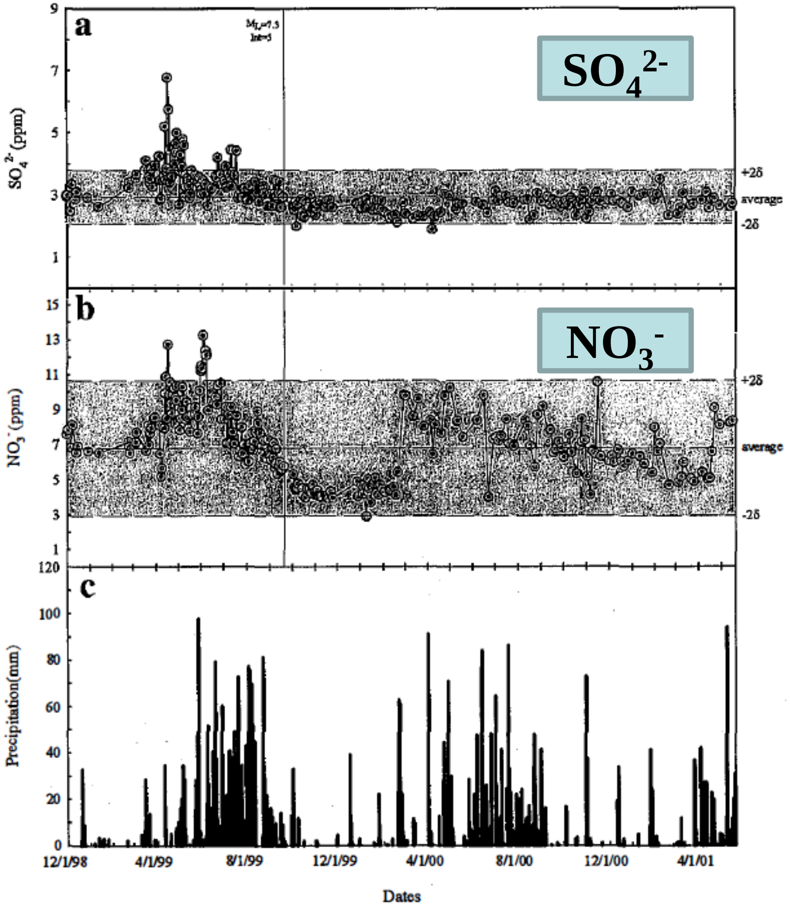
(Chen et al., 2015)

- **Chen et al. (2013b) examined variations of amplitude at a particular frequency band between 0.02 day^{-1} and 0.04 day^{-1} for M_L>6 earthquakes in Taiwan from August 1, 1997 to December 31, 2009. They found that the enhanced amplitudes in the frequency band were consistently observed prior to the July 27, 1998 M_L6.2 Rei-Li and November 5, 2009 M_L6.2 Ming-Jian earthquakes during the 12.5-year study period. However, they did not provide the precursor time.**
- **Yu and Mitchell (1988) observed groundwater level change at a well, which has a depth of 500 m and is located at the Chingshui River in northeastern Taiwan. This phenomenon appeared about 10 days before the January 16, 1986 M_L6.2 offshore Ilan earthquake. The precursor time is 10 days.**

Change of Geochemical Compositions (T=7 months)

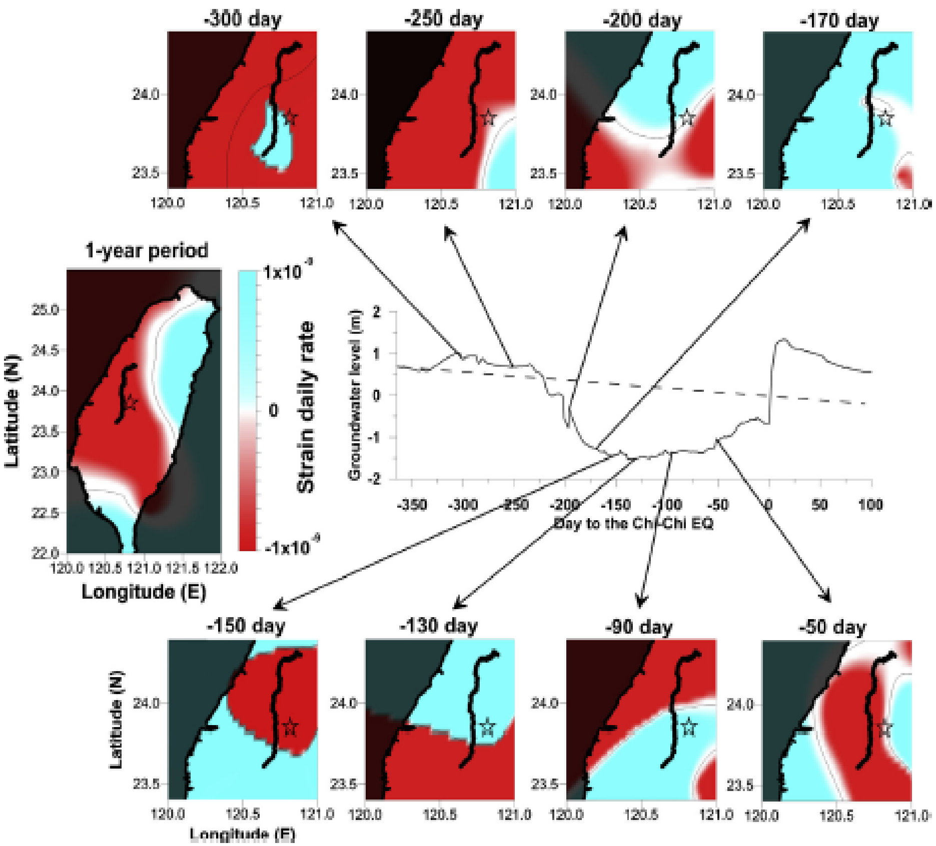
(Song et al., TAO, 2003)





Daily Strain Rate, έ
Red for έ<0 and Blue for έ>0

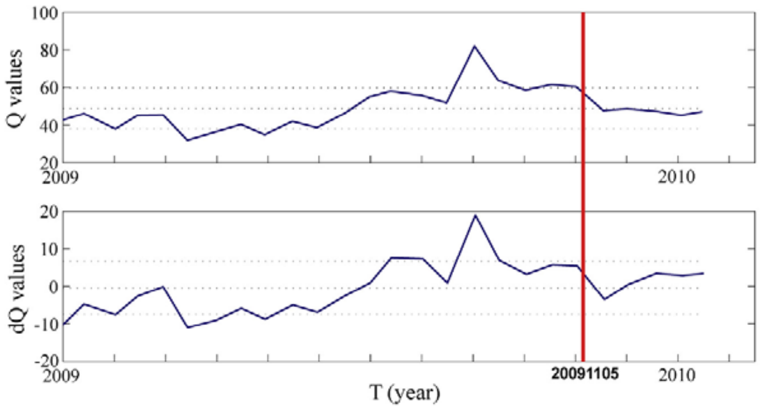
(Chen et al., 2015)



Short-term Prediction

Q_p Changes (T=5 months)

- Wen et al. (2015) measured the temporal variation in Q-factor of P-waves, i.e. Q_p, from January 2009 to January 2010 before and after the November 5, 2009 M_L6.2 Ming-Jen earthquake based on the first cycle of vertical-component of P-waves recorded by the CWB Seismic Network. Results show that the Q_p began to decrease for all stations about 2-months before the mainshock.

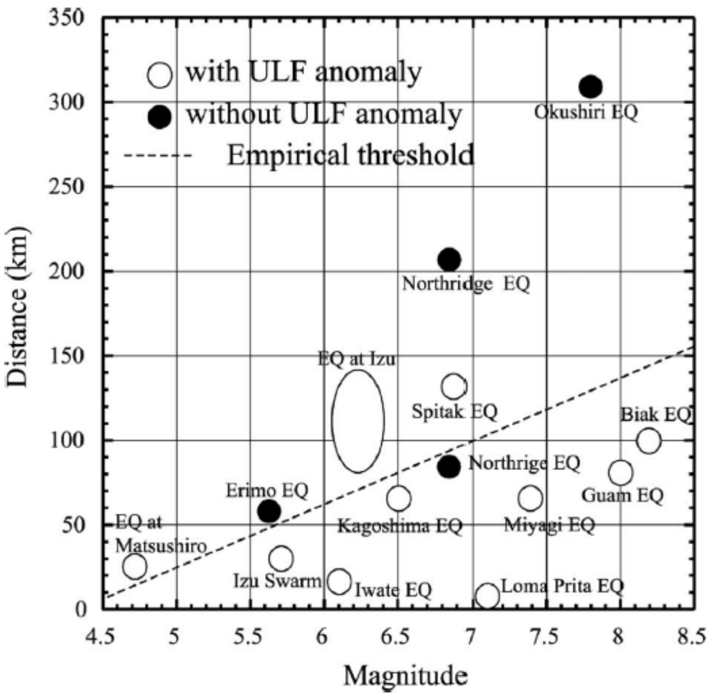


Electromagnetic Emissions

Classification

Designation		Frequency	Wavelength
ELF	extremely low frequency	3Hz to 30Hz	100'000km to 10'000 km
SLF	superlow frequency	30Hz to 300Hz	10'000km to 1'000km
ULF	ultralow frequency	300Hz to 3000Hz	1'000km to 100km
VLF	very low frequency	3kHz to 30kHz	100km to 10km
LF	low frequency	30kHz to 300kHz	10km to 1km
MF	medium frequency	300kHz to 3000kHz	1km to 100m
HF	high frequency	3MHz to 30MHz	100m to 10m
VHF	very high frequency	30MHz to 300MHz	10m to 1m
UHF	ultrahigh frequency	300MHz to 3000MHz	1m to 10cm
SHF	superhigh frequency	3GHz to 30GHz	10cm to 1cm
EHF	extremely high frequency	30GHz to 300GHz	1cm to 1mm

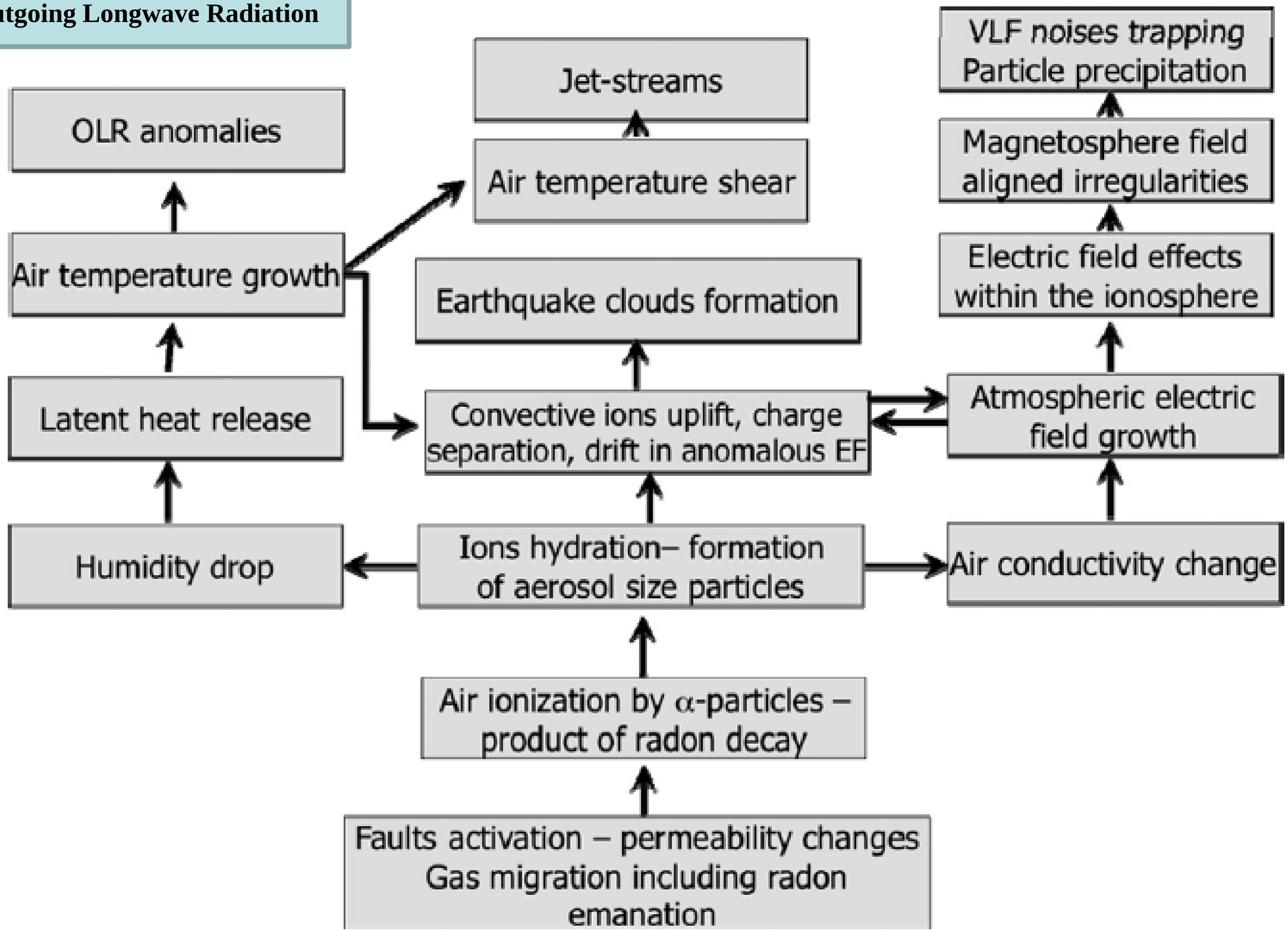
Distance vs. Magnitude for Seismo-ULF Emissions (Hayakawa and Hobra, 2010)



Schematic Presentation of Lithosphere-Atmosphere-Ionosphere-Magnetosphere Coupling

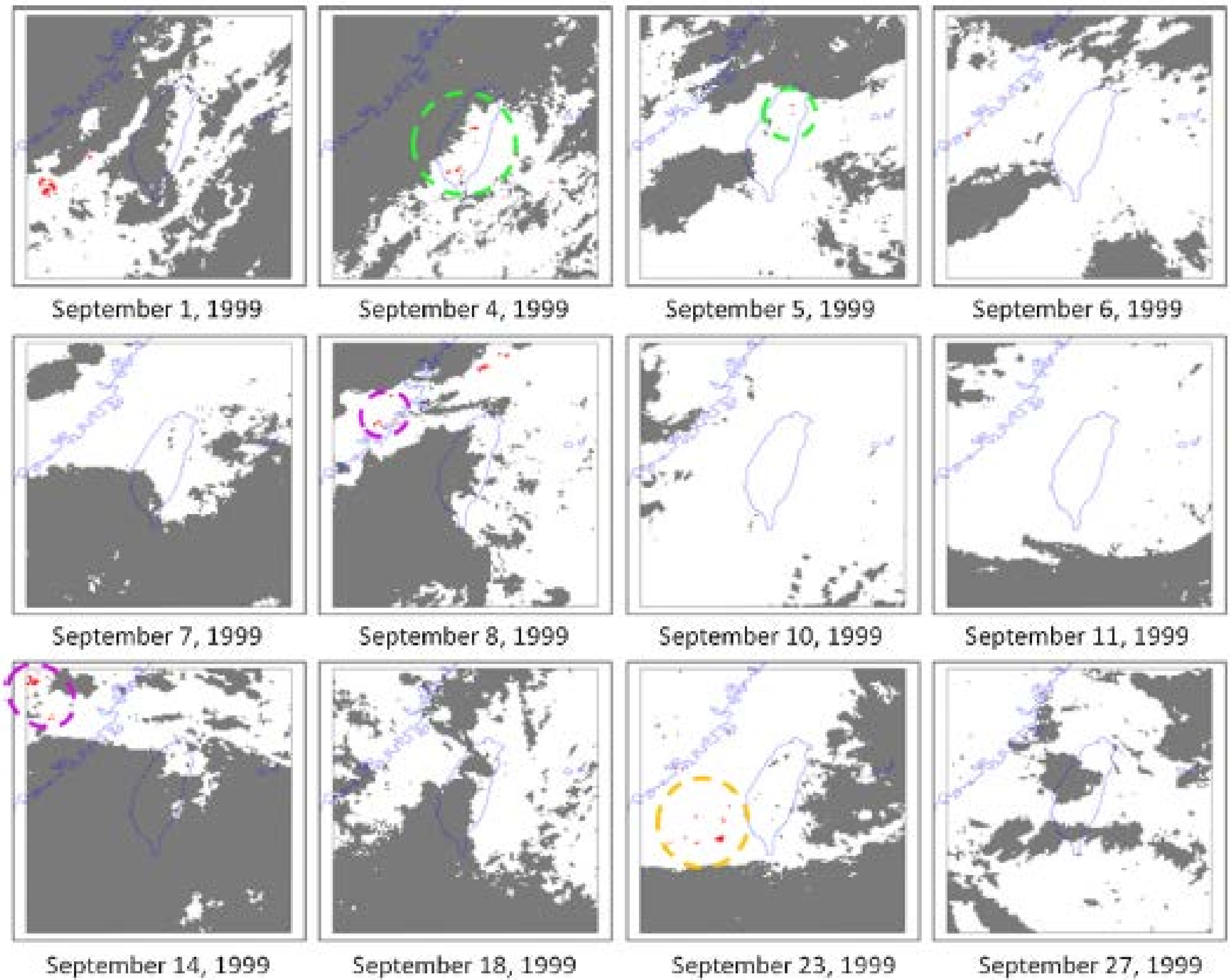
(Pulinets and Ouzounov, 2011)

OLR: Outgoing Longwave Radiation



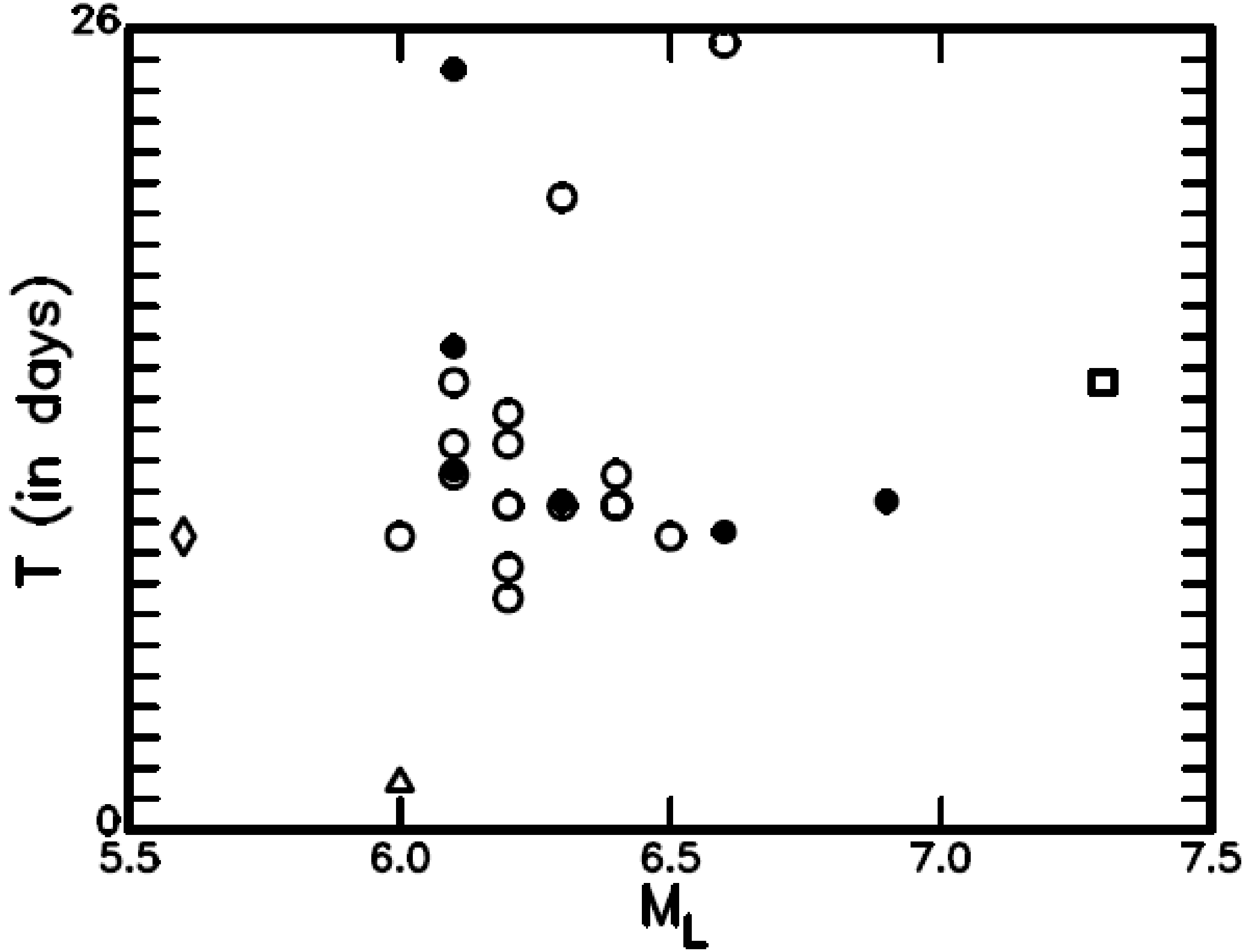
An Example of OLR for the M_L7.3 Chi-Chi Earthquake of September 20, 1999

(Genzano et al., 2015)



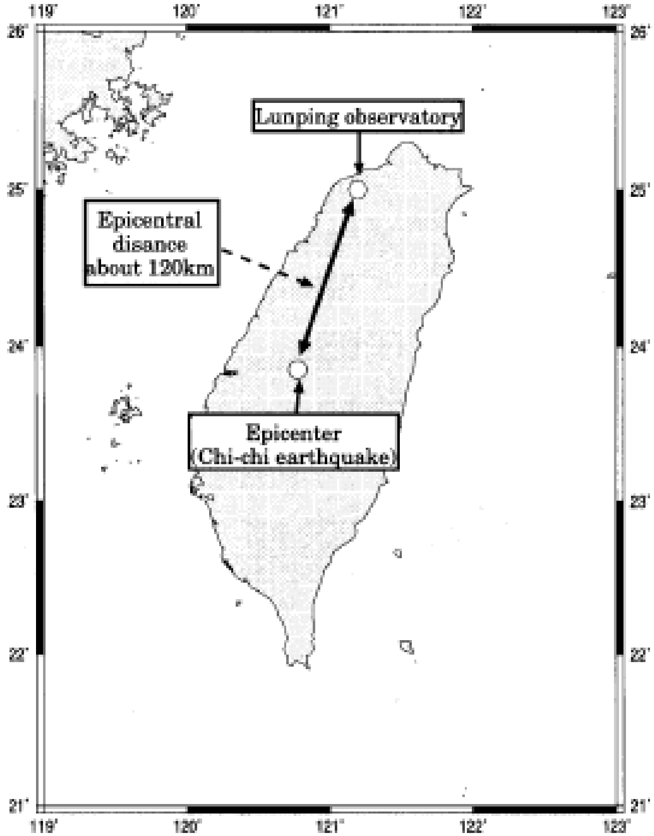
T versus M_L for Thermal Infrared Radiations

(Open symbols for the events with d≤40 km and Solid symbols for those with d>40 km)



ULF Signals before the 1999 Chi-Chi Earthquake (T=2 months)

(Akinaga et al., NHESS, 2001)



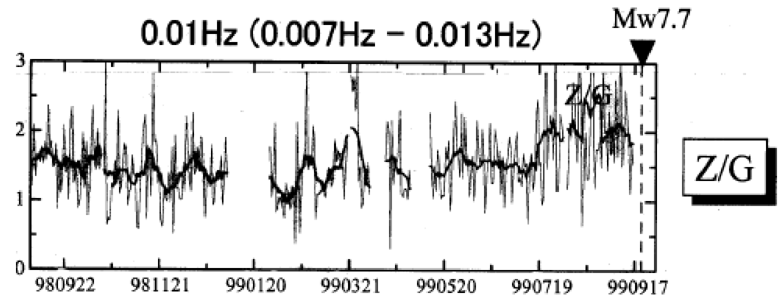


Fig. 2. Temporal evolution of the polarization (Z/G) at a frequency of 0.007 Hz–0.013 Hz during the whole analyzed period. A significant enhancement in the polarization is seen for two months before the quake.

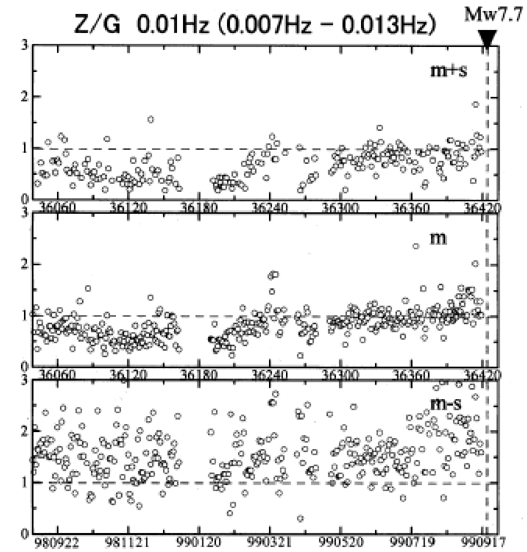
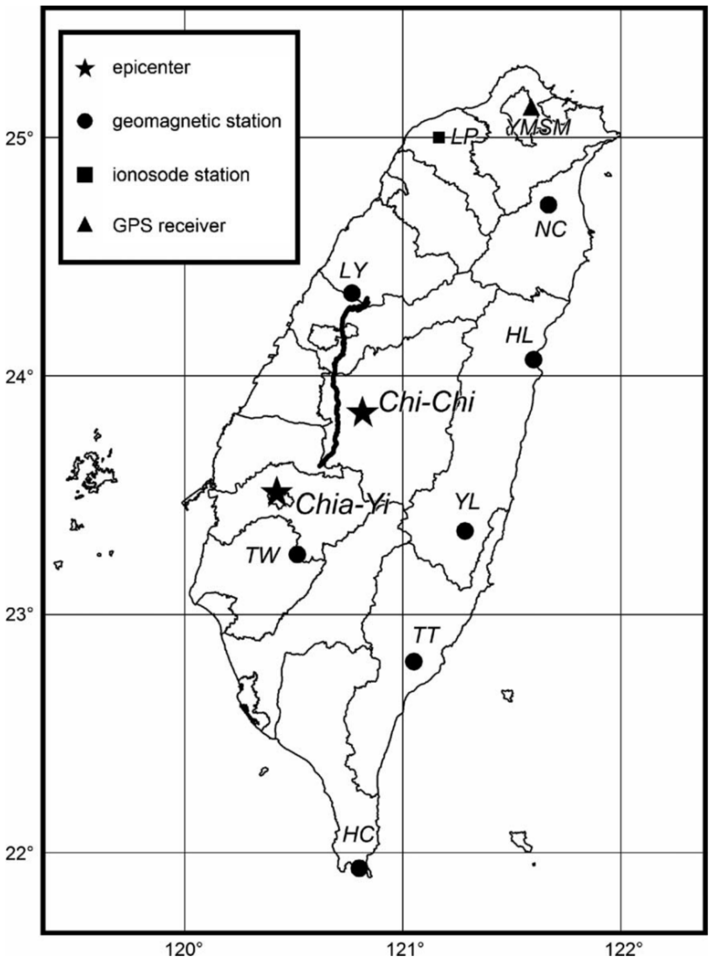
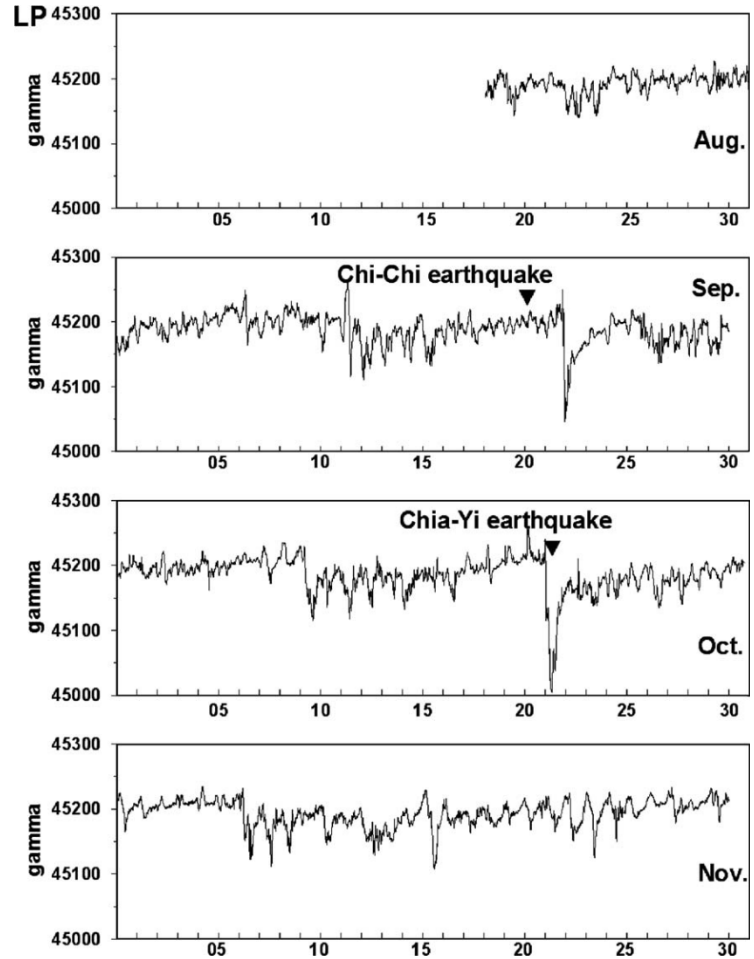


Fig. 3. Effect of changing the threshold on intensity on the temporal evolution of polarization (Z/G) at the same frequency in Fig. 2. The threshold in the top panel is $m + s$ (m : mean and s ; standard deviation), m for the middle panel and $m - s$ for the bottom panel.

Geomagnetic total intensity data recorded at the reference station (LP) from August to November 1999 (T=1 month)

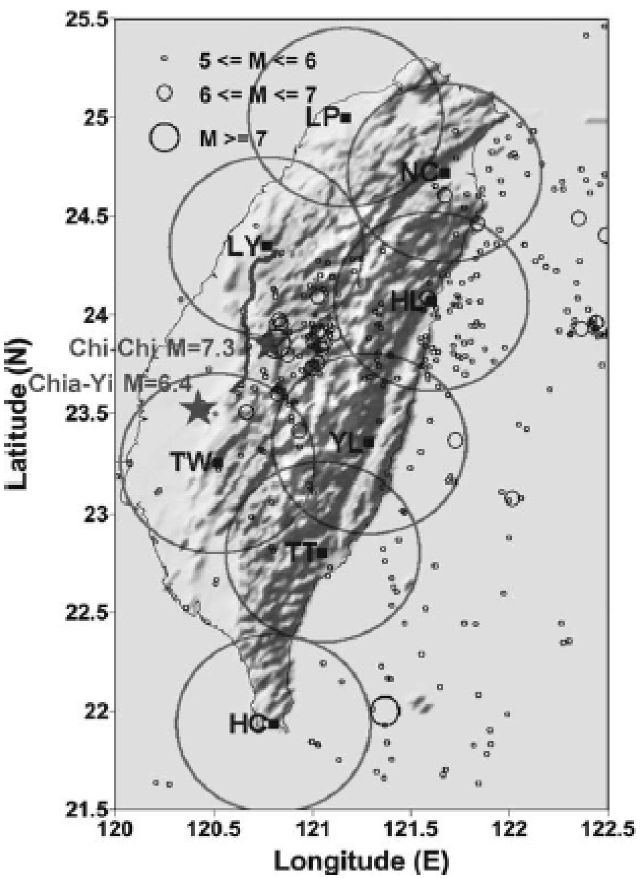
(Yen et al., EPS, 2004; and Chen et al., 2015)

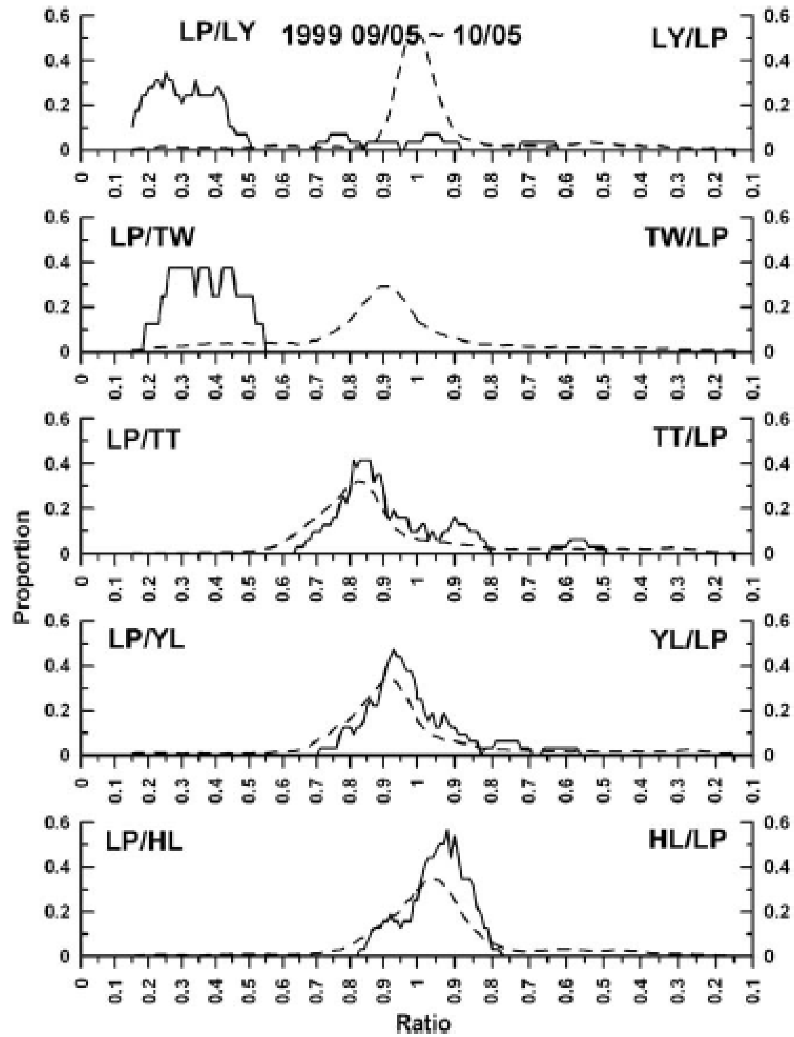




Geomagnetic Field Change (T=1.1 months)

(Liu et al., PCE, 2006)



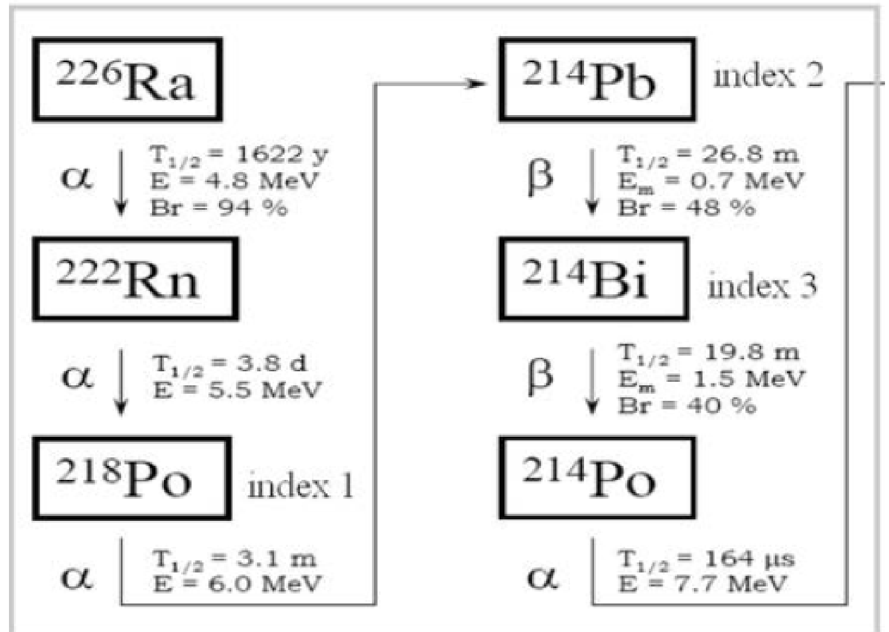


DDR: the diurnal range ratio between the LP station and the LY station

Decay of ^{226}Ra and ^{222}Rn

(Scholten et al., 2013)

- **^{222}Rn first decays, with a half time of 3.8 days, to ^{218}Po and then again decays, with a half time of 3.85 minutes, to ^{214}Pb.**
- **During the two decaying processes, there are α-particle (^{4}He) emissions with energy release of 5.49 MeV in the first step and 6 MeV in the second one. In addition, there is energy release by γ-ray emissions.**
- **This is a direct way to release heat and thus increase the temperature on the ground surface.**

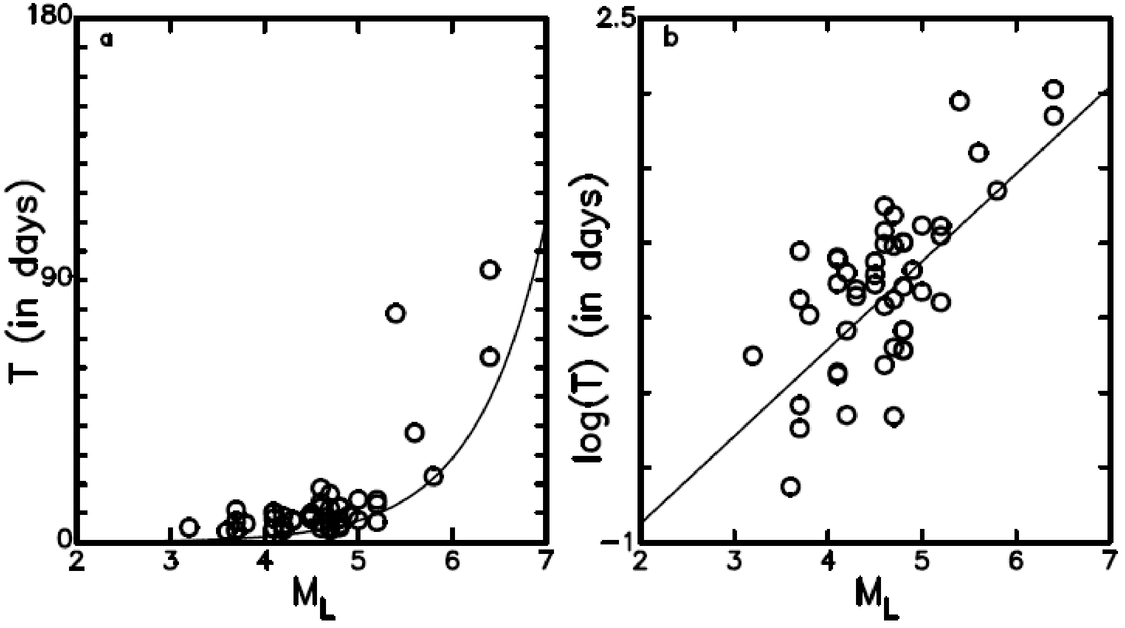


$$^{226}_{88}\mathrm{Ra} \longrightarrow {}^{222}_{86}\mathrm{Rn} + {}^{4}_{2}\mathrm{He} + {}^{0}_{0}\gamma$$

radium-226 → radon-222 + alpha particle + energy

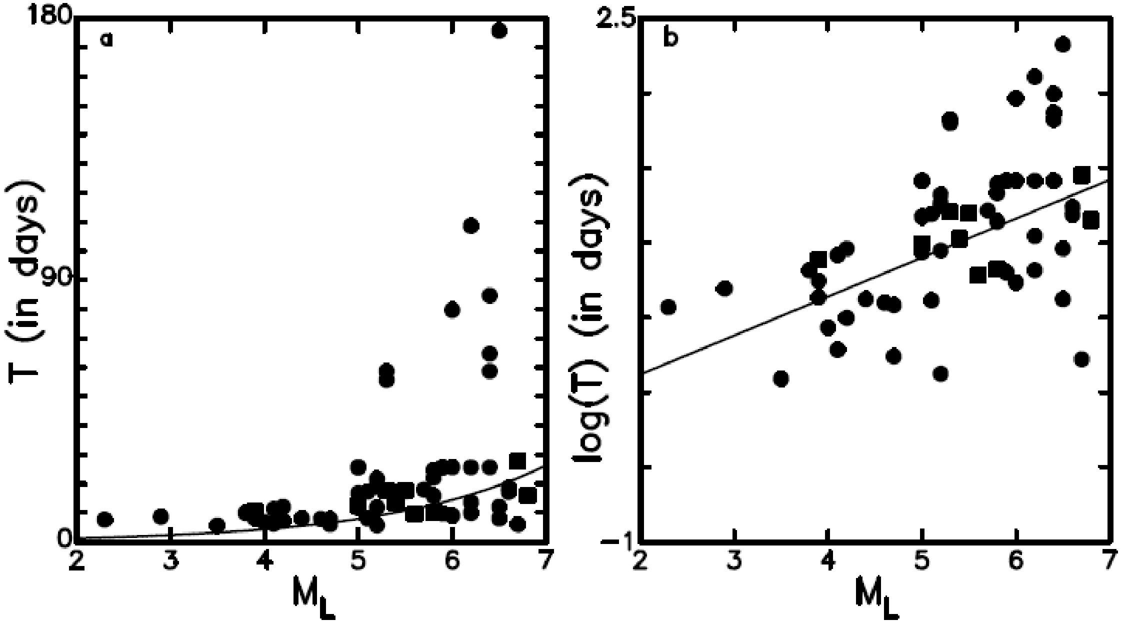
$$^{222}_{86}\mathrm{Rn} \longrightarrow {}^{218}_{84}\mathrm{Po} + {}^{0}_{0}\gamma + {}^{4}_{2}\mathrm{He}$$

T versus M_L for Rn Concentrations:
$\log(T)=(-2.05\pm0.40)+(0.58\pm0.01)M_L$ (d≤40 km)



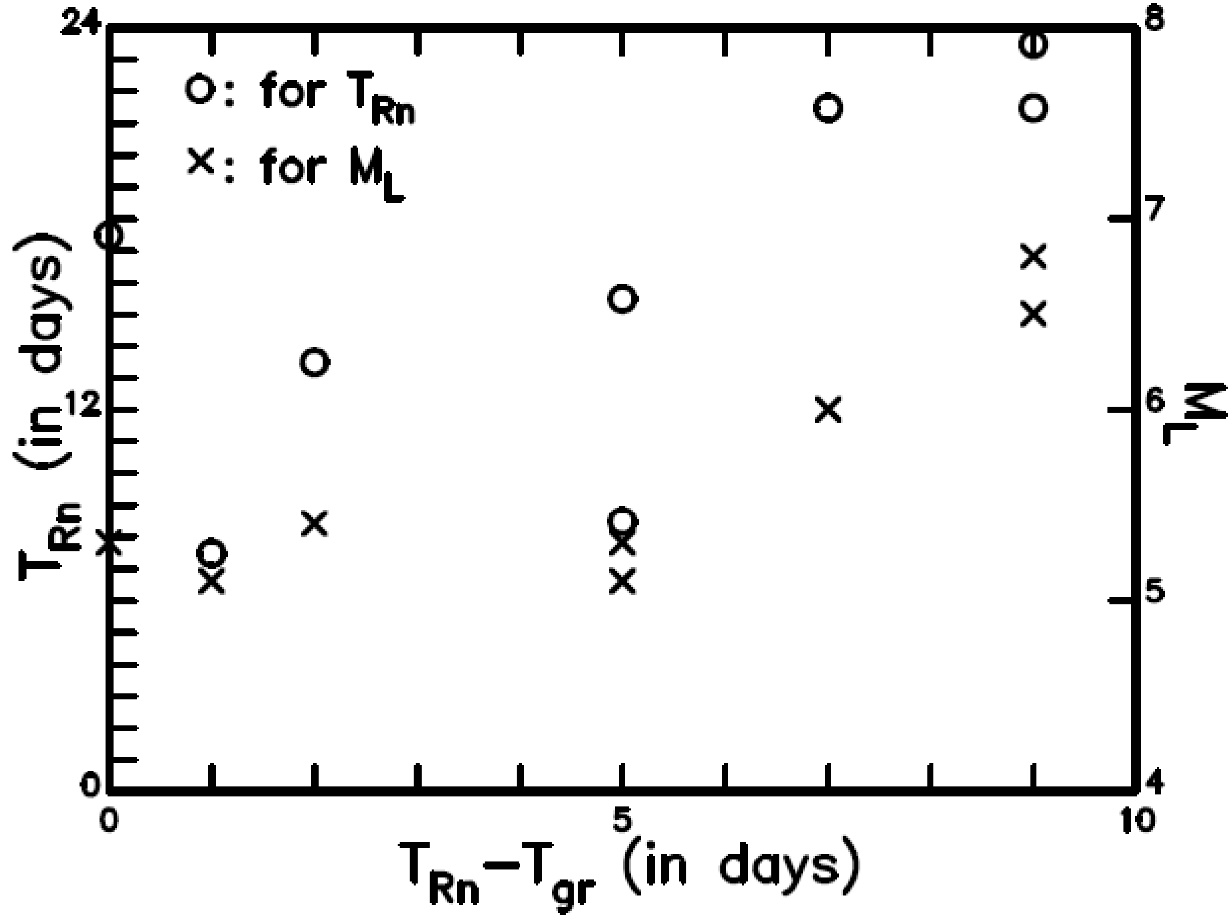
T versus M_L for Rn Concentrations:

$\log(T)=(-0.40\pm0.42)+(0.26\pm0.01)M_L$ (d>40 km)

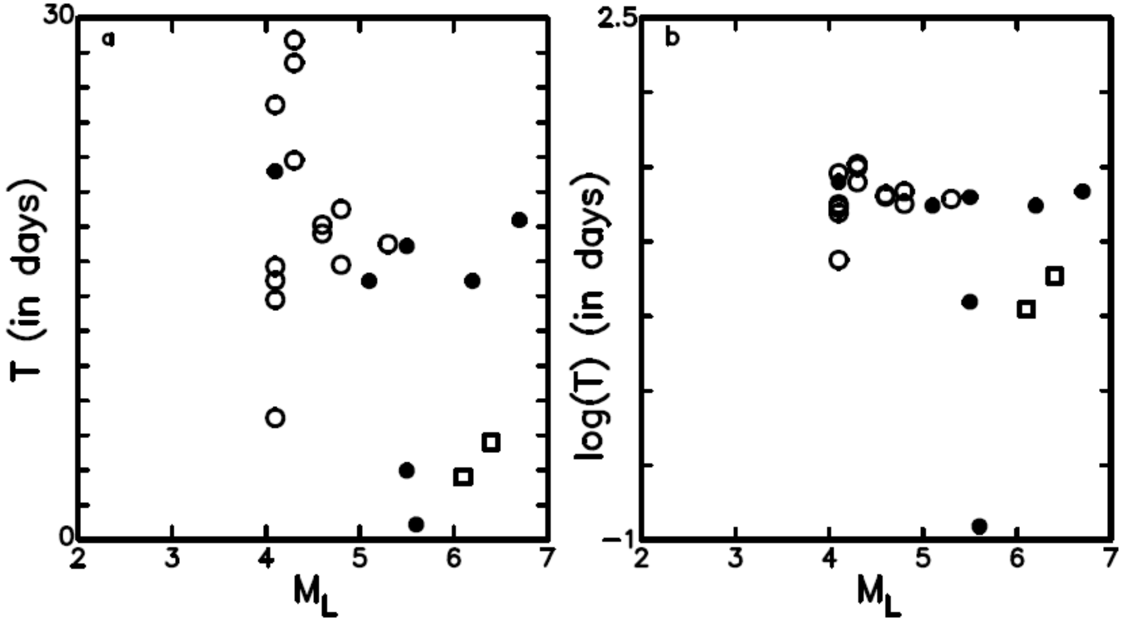


T_{Rn} and M_L versus T_{Rn}-T_{gr}

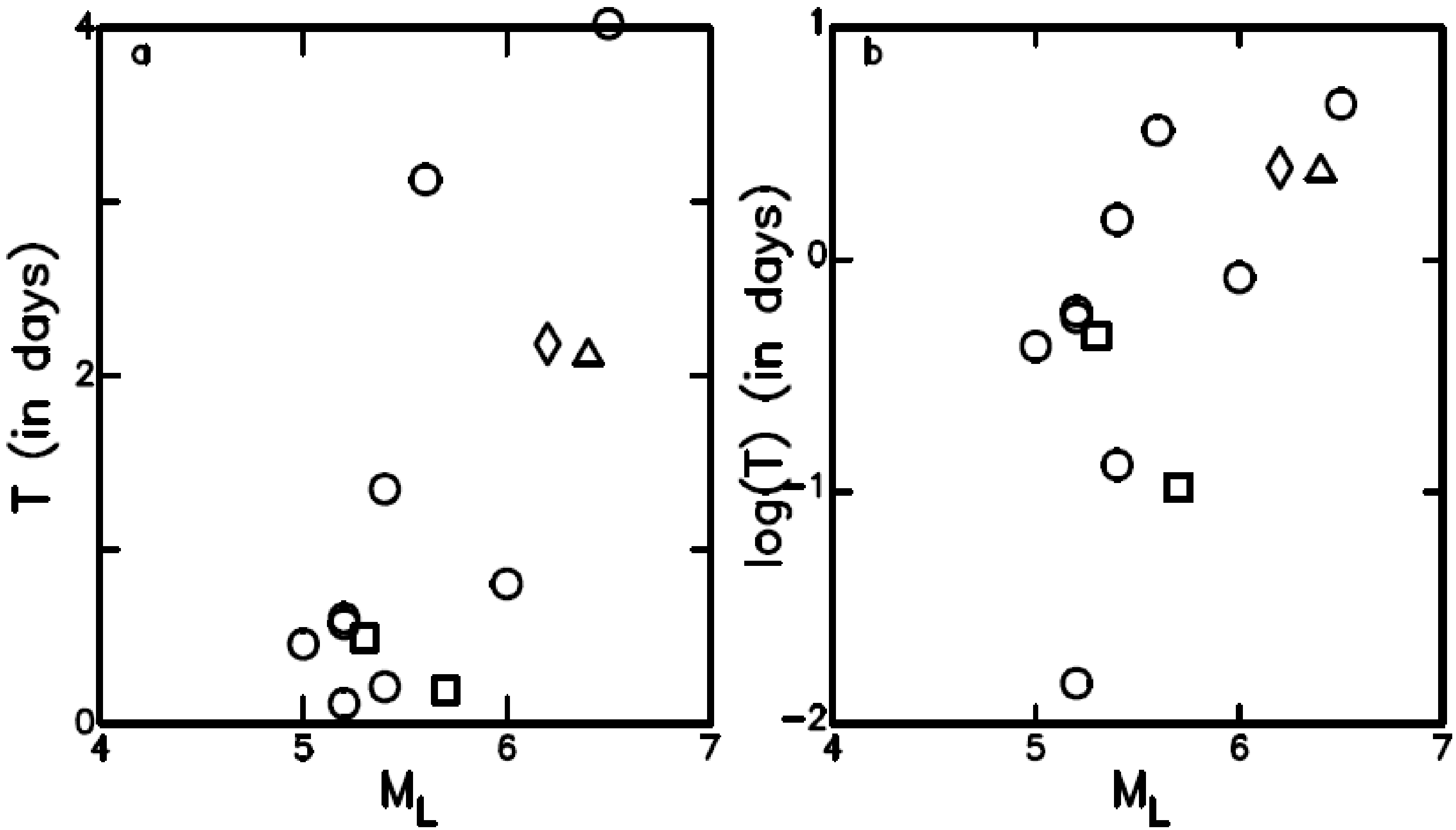
(Wang, 2021c)



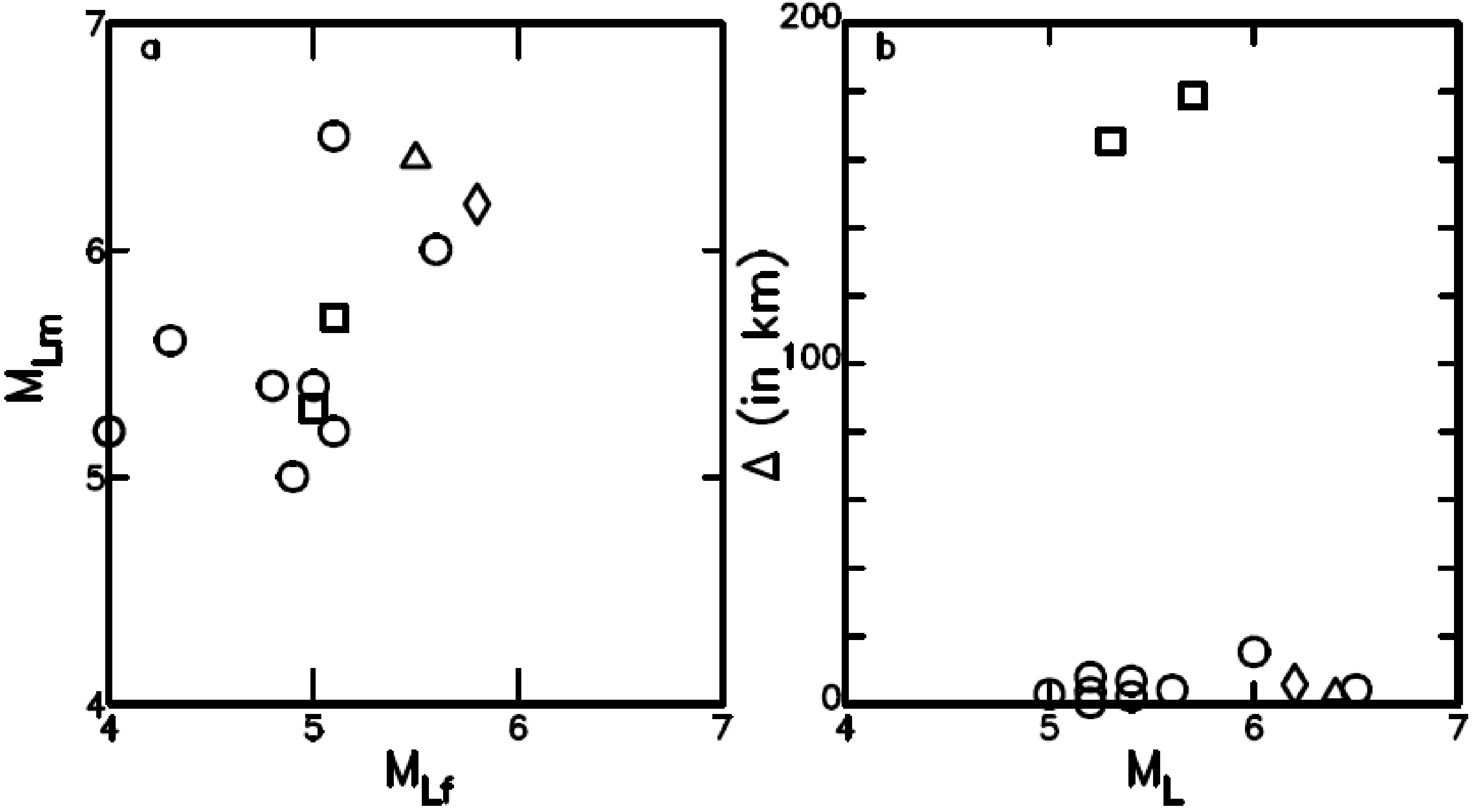
T versus M_L for Geochemical Compositions



(a) Plot of T versus M_L and (b) plot of log(T) versus M_L for the largest foreshocks



(a) Plot of M_L for mainshocks versus M_L for foreshocks, and (b) the epicentral distance (in km)

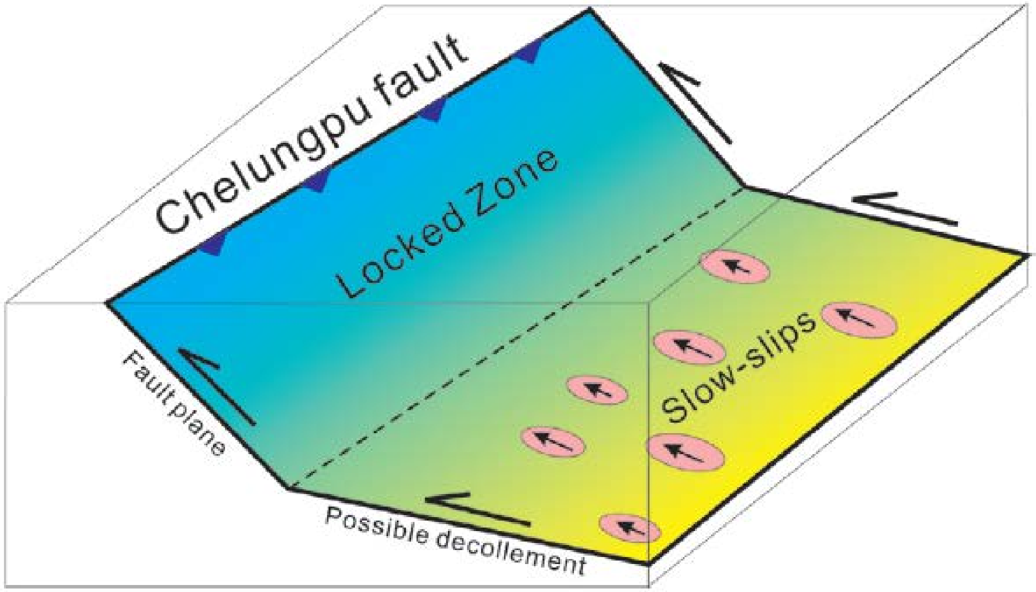


Imminent-term Prediction

Slow-slip Events (5 days)

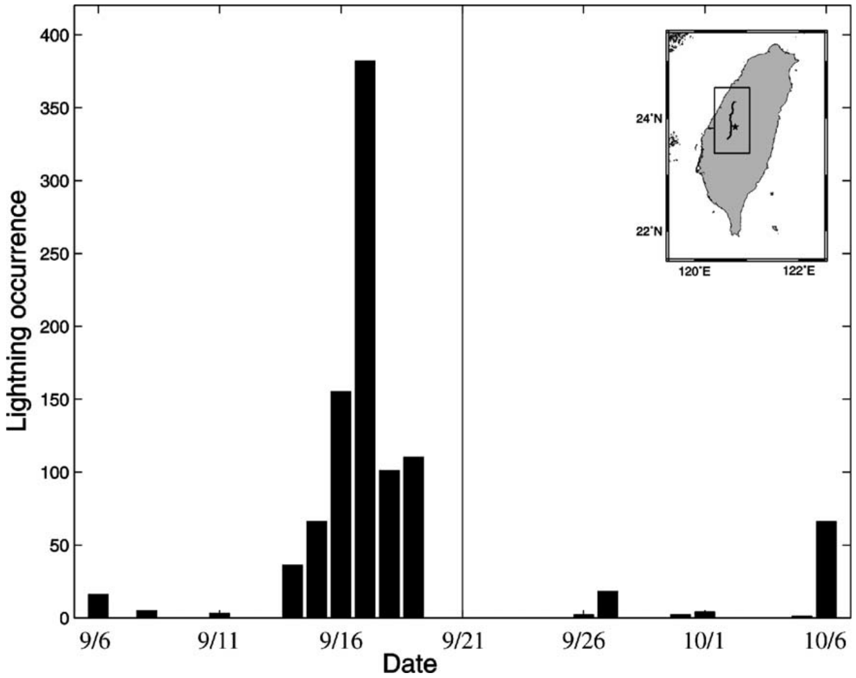
(Lin et al., 2012)

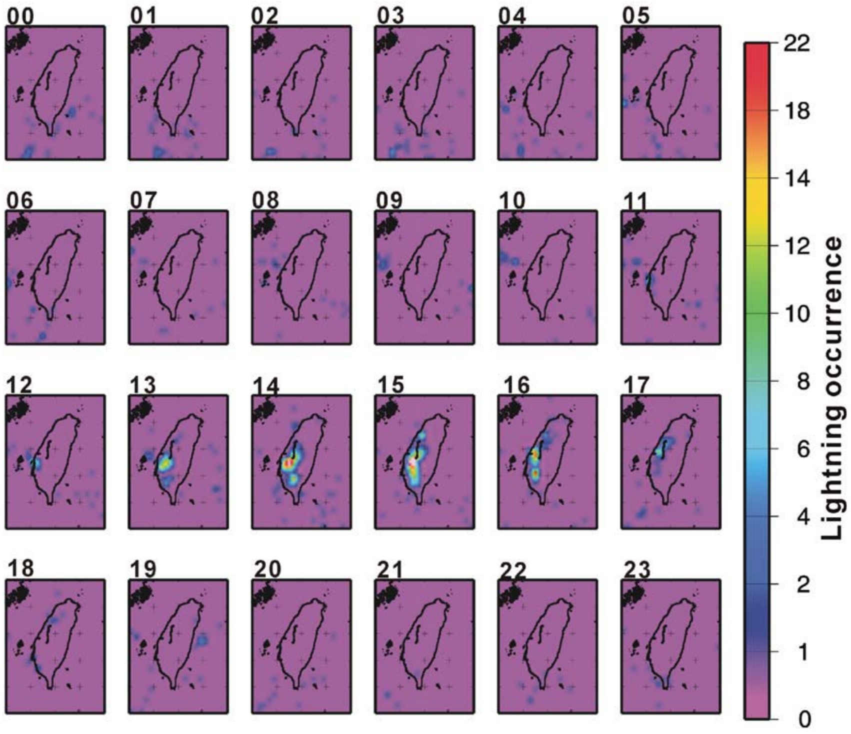
Event \ Fault	Depth (km)	Slip (m)	Dip (deg.)	Rak (deg.)	Fault Plane (km²)	Time (M/day)	Disp. at SSLB (mm)	Disp. at NACB (mm)
15	12	16	5	90	10 × 10	9/15	+0.48	-0.19
16	12	16	5	0	10 × 10	9/16	-0.22	+0.29
17	12	16	5	0	10 × 10	9/17	-0.32	+0.08
18A	10	9	5	90	10 × 10	9/18	-0.32	~
18B	12	6	5	90	10 × 10	9/18	~	-0.56
19A	10	20	5	90	10 × 10	9/19	-0.40	~
19B	12	5	5	90	10 × 10	9/19	~	-0.24



Cloud-to-ground Lightnings (T=4 days)

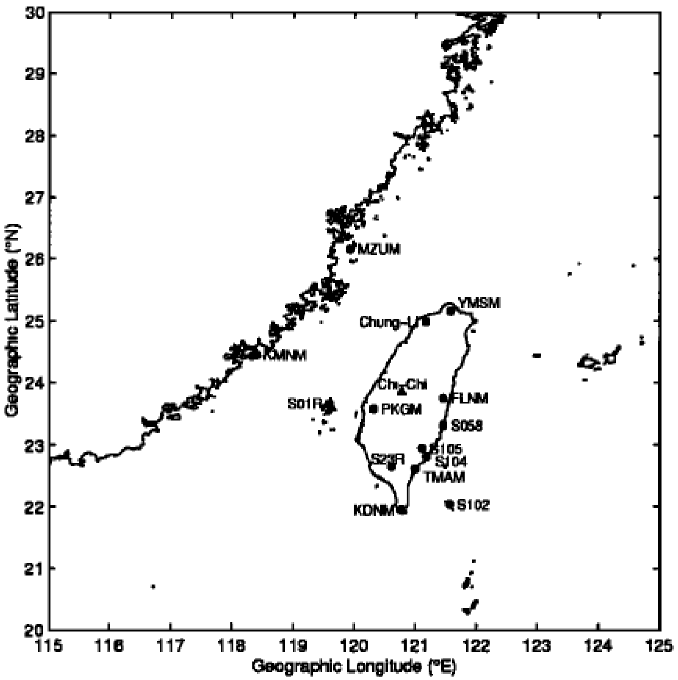
(Liu et al., 2015)

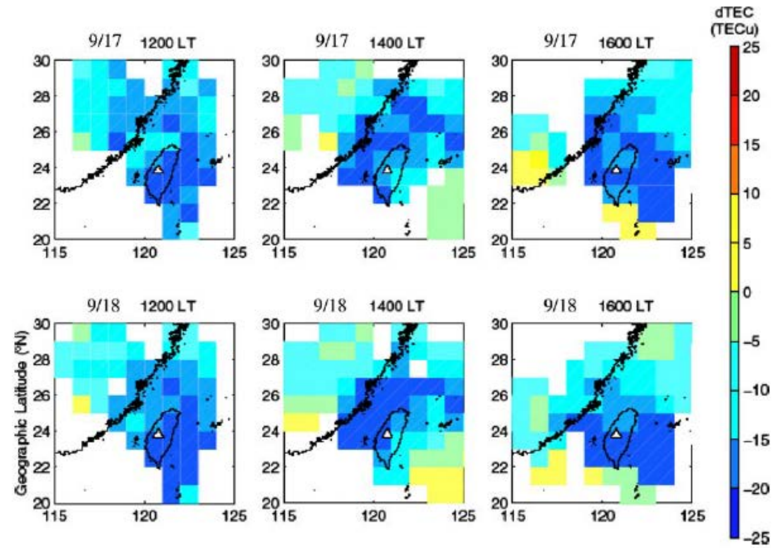


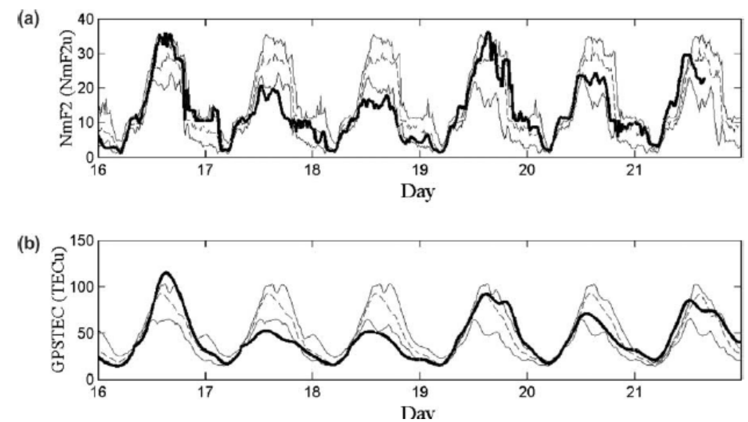


Variations of Ionospheric Total Electron Content (TEC) before the Mainshock (T=4 days)

(Liu et al., GRL, 2001)

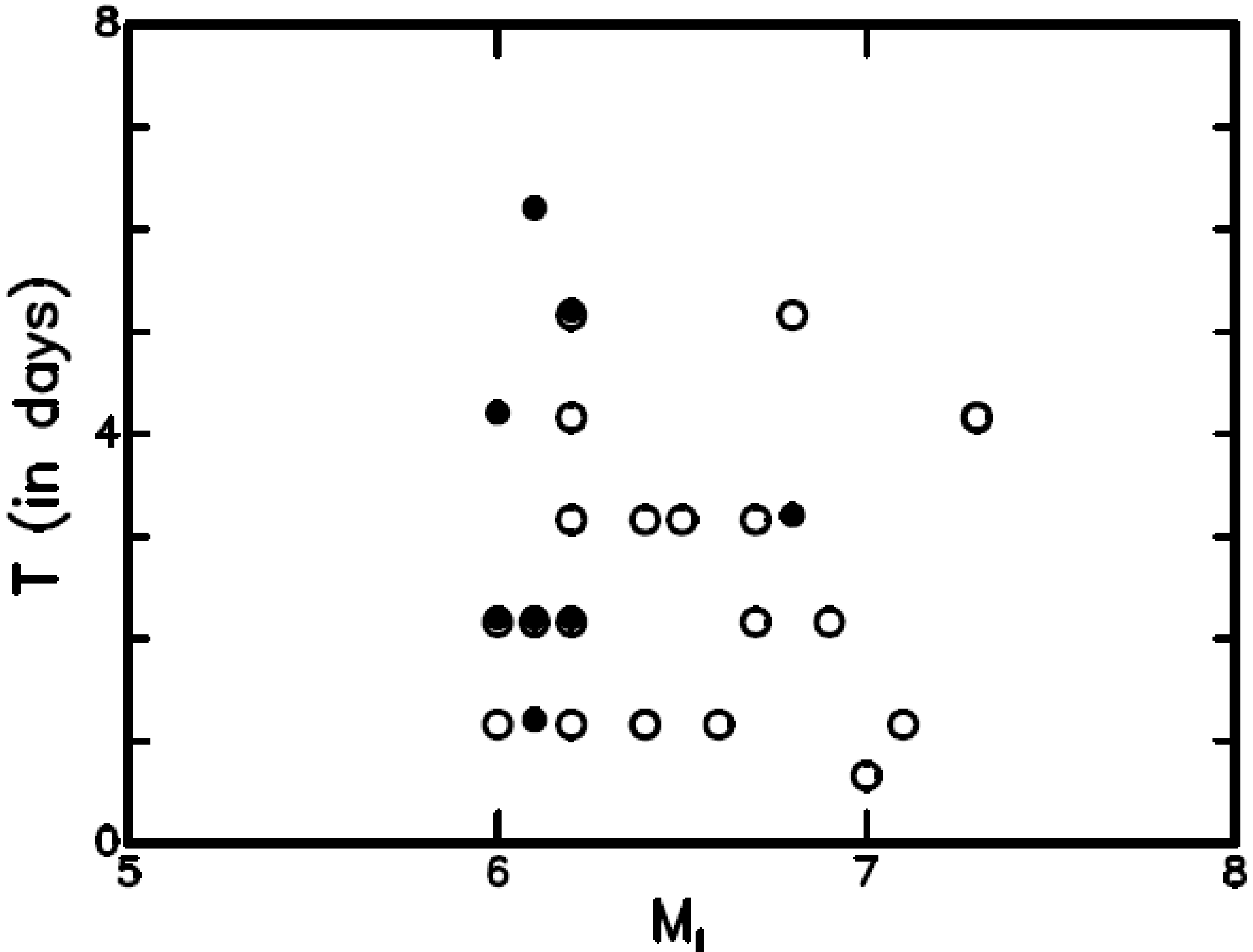






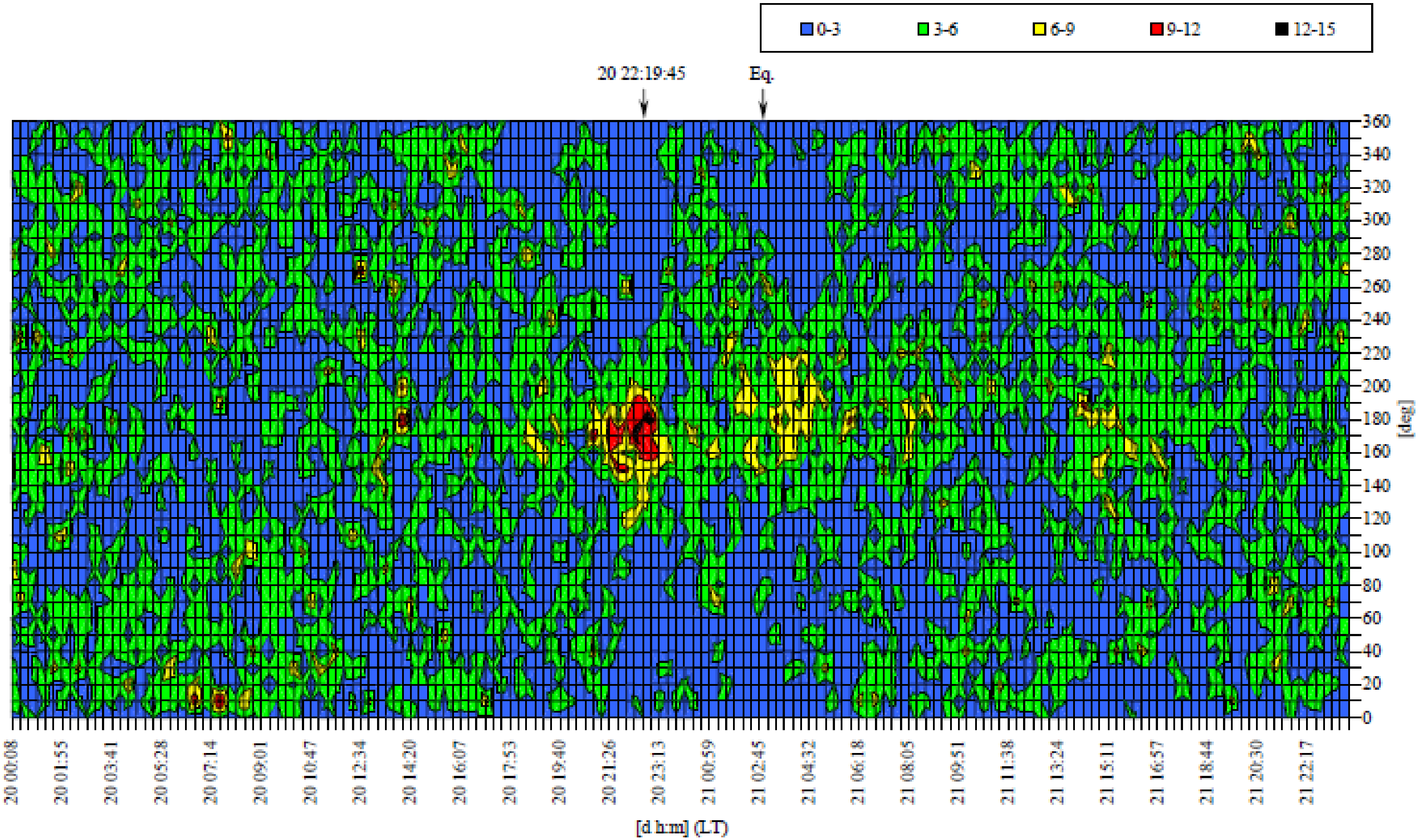
T versus M_L for TEC Anomalies

(Liu et al., 2000, 2004)



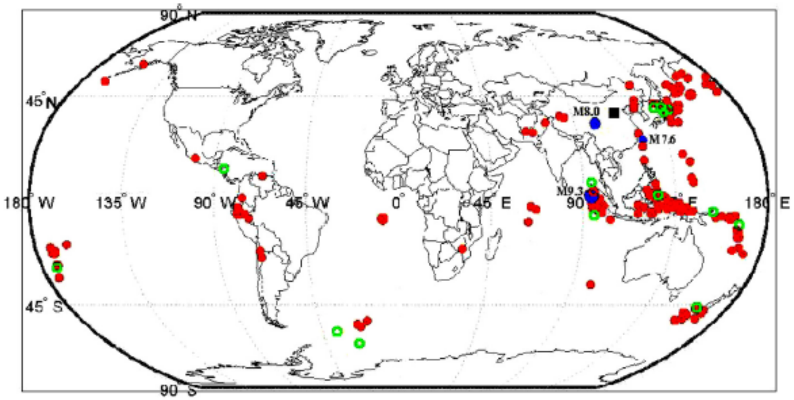
ULF/ELF Signals (T=4 days)

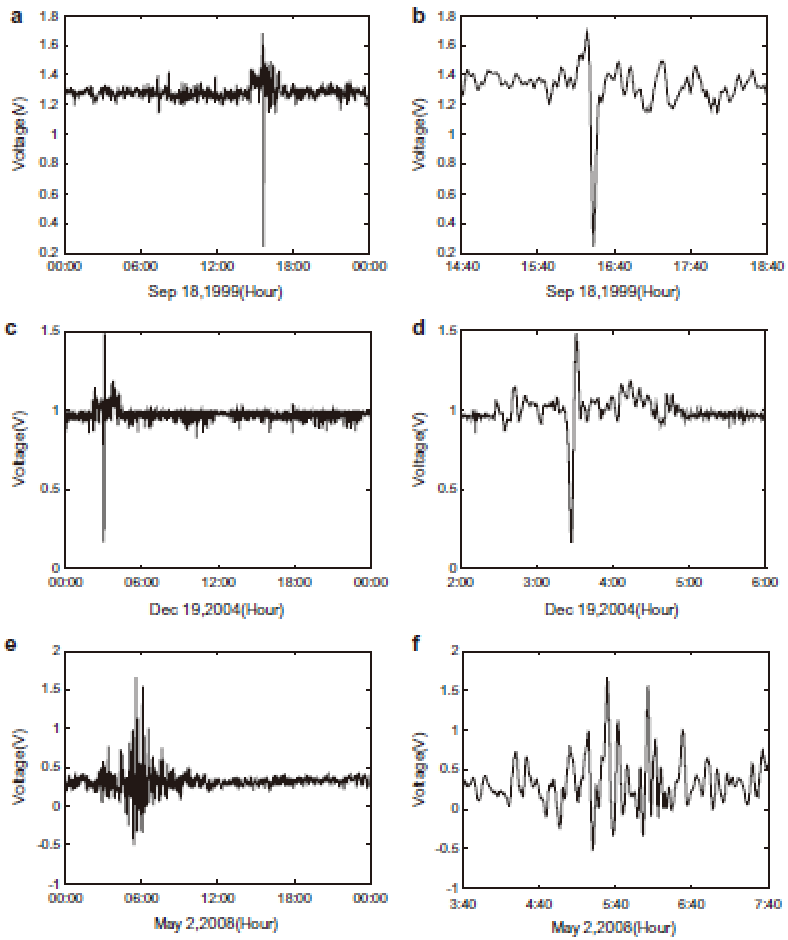
(Ohta et al., 2001)



Infrasound Signals (3 days)

(Xia et al., 2011)

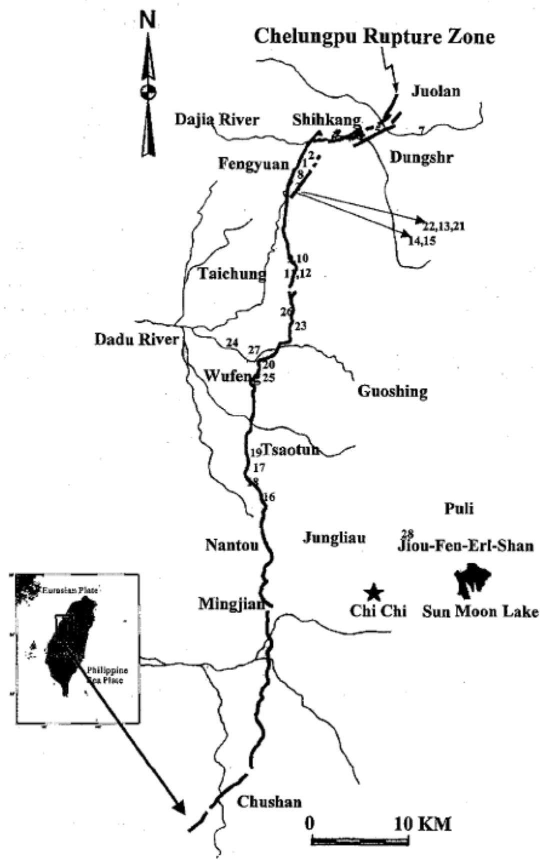




Infrasound, sometimes referred to as low-frequency sound, is sound that is lower in frequency than 20 Hz that is the normal limit of human hearing.

Anomalous Physical Phenomena before the 1999 Chi-Chi Earthquake (Short-term Precursors)

(Chen et al., TAO, 2000)



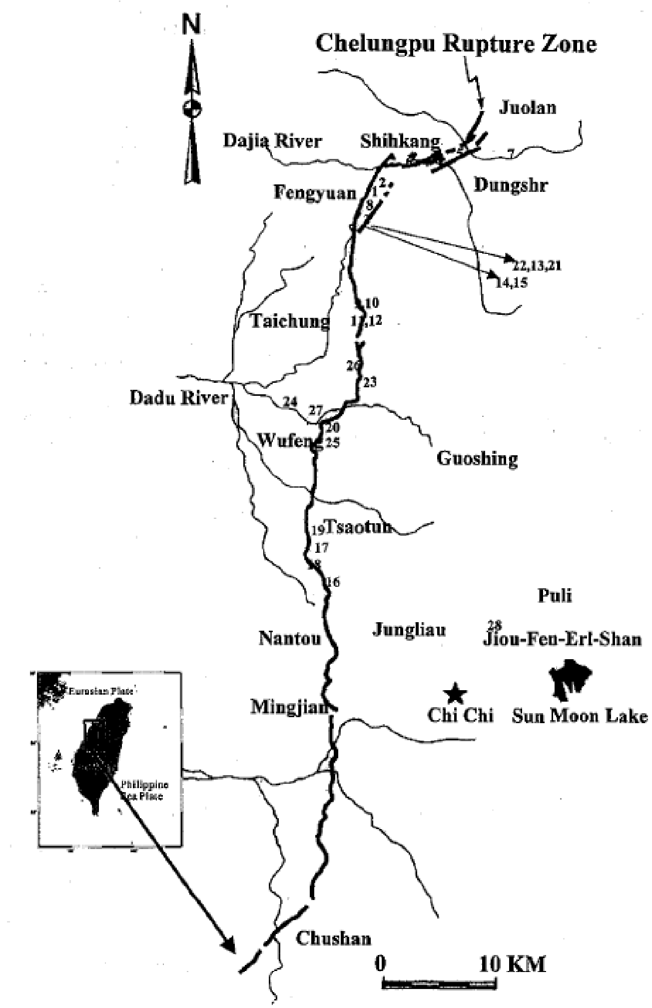
Items	In # of days	In # of hrs	Description
Wind L.7,9-15,17,18,20-22,24-27	Generally 1 day		Strong
Skylight L.3,8,11,13-15,19,24		a few	Red or colorful sky seen
Seismic light L.1		coseismic	Emission of green light
Sound L.1,2,4,20,21,24,25		coseismic	Distant thunder/ Passing truck- like sounds
Smell L.22		coseismic	Gaseous odors
Initial motion		coseismic	88% for lateral and 12% for vertical first

Earthquake Lights (T=few hours)

(Derr, BSSA, 1973)

Anomalous Animal Phenomena before the 1999 Chi-Chi Earthquake (Short-term Precursors)

(Chen et al., TAO, 2000)



Items	In # of weeks	In # of days	In # of hrs	Description
Ant L.4	8 to 10			Built new nest on tree
L.7		1		Moved & gathered beneath a shoe
L.21		2 to 3		Moved & gathered
L.24	1			Built new nest on tree
Dog L.16		1		Barked nervously
L.19			1	Barked forcibly
L.20			A few	Cried on hill top
		1		Refused to go the hill
L.21			A few	Cried on the roof
Cat L.16		1		Disappeared
Earthworm L.17	1 to 2	1		Climbed up onto ground surface in large numbers
L.19		1		Same as above
Diplopod L.16		1 to 2		Same as above
L.17	1 to 2			Many migrated indoors
Fish L.17		1		Jumped out of the water
L.28	1 to 2			Migrated downstream
Bird L.17	1			Diminished
L.20		2		Disappeared
L.24		1		Chirped nervously
Palm civet- like L.1			A few	Screamed nervously
Snake L.12			2	Appeared
Turtle L.16		1		Appeared
Cicada L.17	4 to 6			Ceased croaking
Roach L.24		3		Appeared

Biological Anomalies

(Chen et al., 2000)

Animals	Weeks	Days	Hours	Time Window
Ants	1 and 8−10	1 and 2−3		Short-term
Cicada	4−6			Short-term
Diplopods	1−2	1−2		Short-term
Earthwarms	1−2	1		Short-term
Fishes	1−2	1		Short-term
Birds	1	1−2		Imminent
Roach		3		Imminent
Dogs		1	1 and a few	Imminent
Cats		1		Imminent
Turtles		1		Imminent
Palm civet-like			a few	Imminent
Snakes			2	Imminent

Why log(T) versus M?

(Wang, 2021d)

$\log(T_i)=a_i+b_iM$ ($T_i=t_r-t_1$: t_r=the occurrence time of an earthquake and t_i=the appearance time of the i-th precursor)

For the 1st precursor, $\log(t_r-t_1)=a_1+b_1M \rightarrow t_r=t_1+10^{(a1+b1M)}$

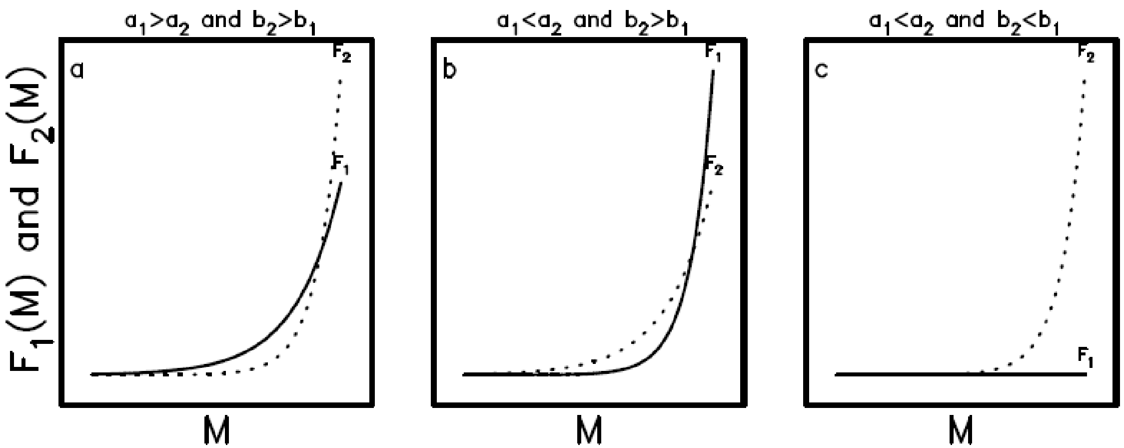
For the 2nd precursor, $\log(t_r-t_2)=a_2+b_2M \rightarrow t_r=t_2+10^{(a2+b2M)}$

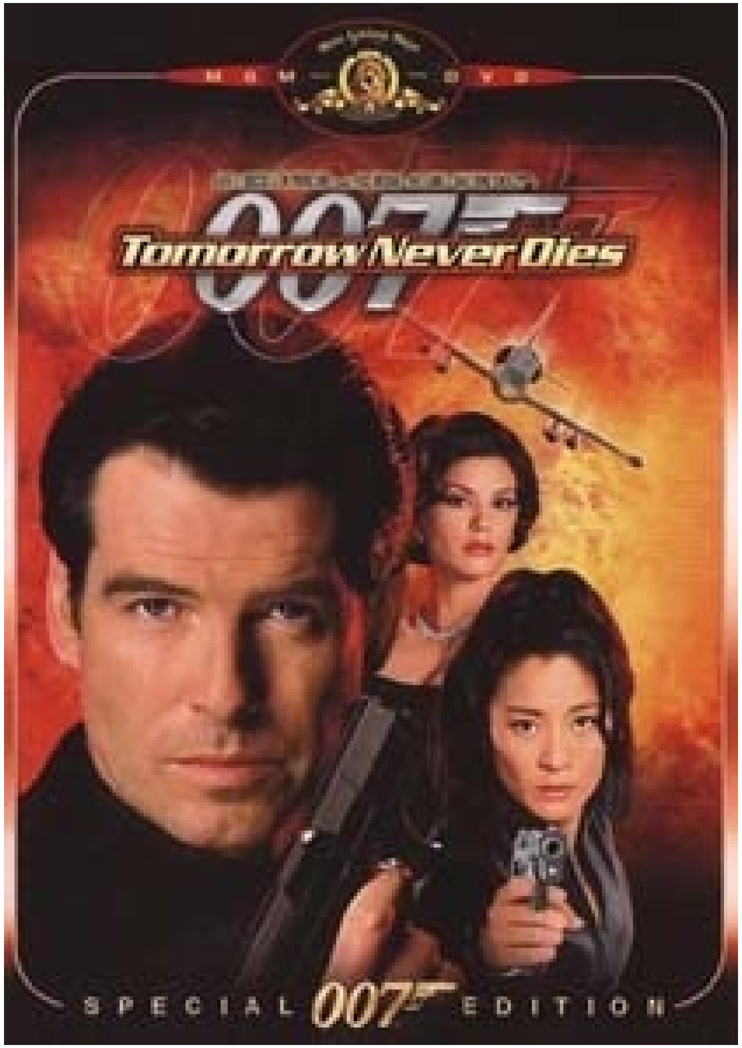
$\rightarrow t_1+10^{(a1+b1M)}=t_2+10^{(a2+b2M)}$ or $t_1-t_2=10^{(a2+b2M)}-10^{(a1+b1M)}$

$\rightarrow$ to evaluate M and then to calculate $t_r=t_i+10^{(ai+biM)}$

Disadvantage: The source area cannot be predicted from this method.

$t_1>t_2$





逢凶化吉

If all things are well-prepared before an impending earthquake, everybody 'Tomorrow Never Dies.'

謝　謝

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