Time Dependent Seismicity Along the Western Coast of Canada

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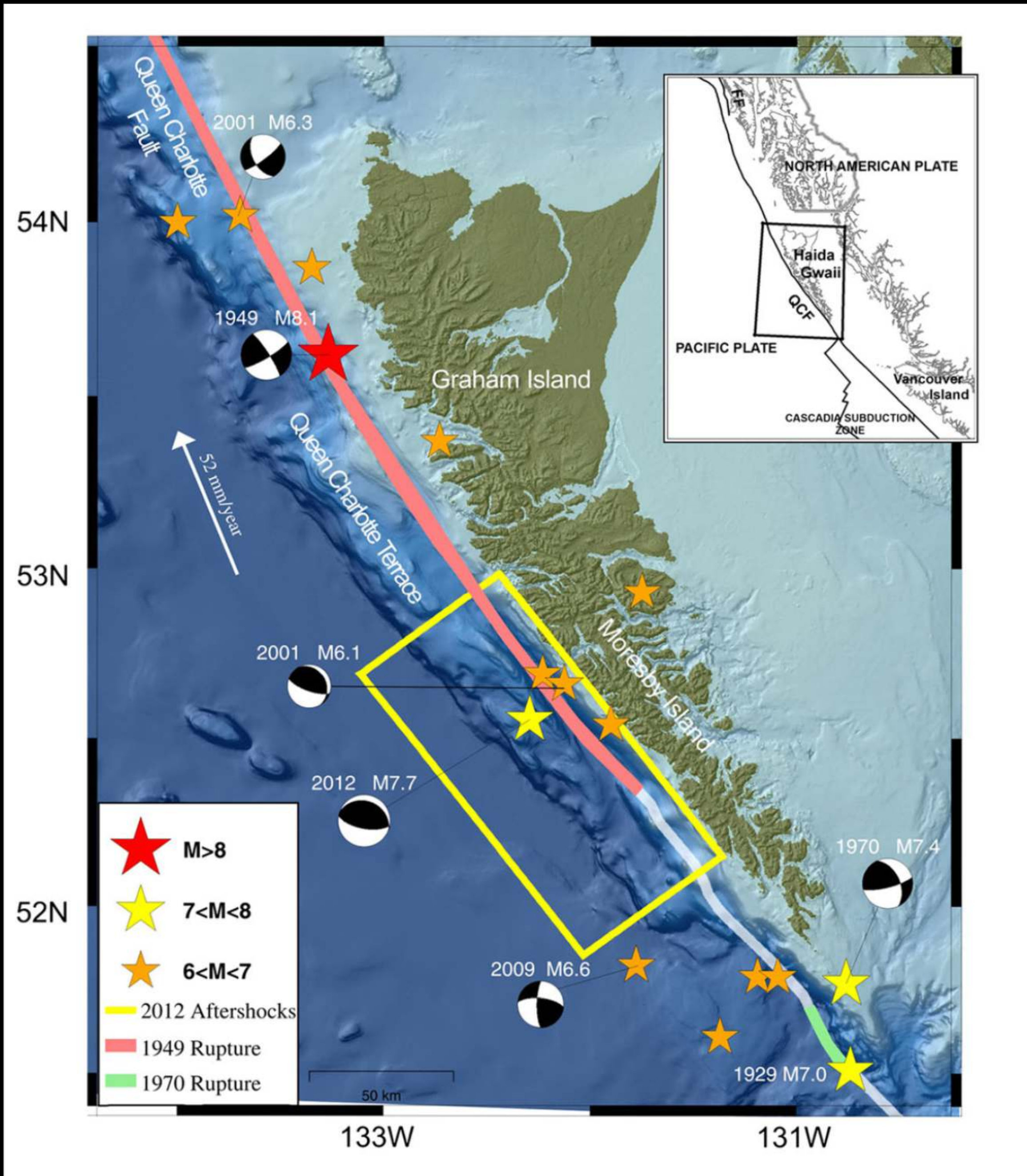


The 28 October 2012, M_w=7.7 Haida Gwaii earthquake generated the largest tsunami recorded in the world in 2012 (Cassidy et al. 2014).

The Cascadia Subduction Zone - CSZ - is a 1000 km long "megathrust" fault that stretches from the Northern Vancouver Island to Cape Mendocino- California.

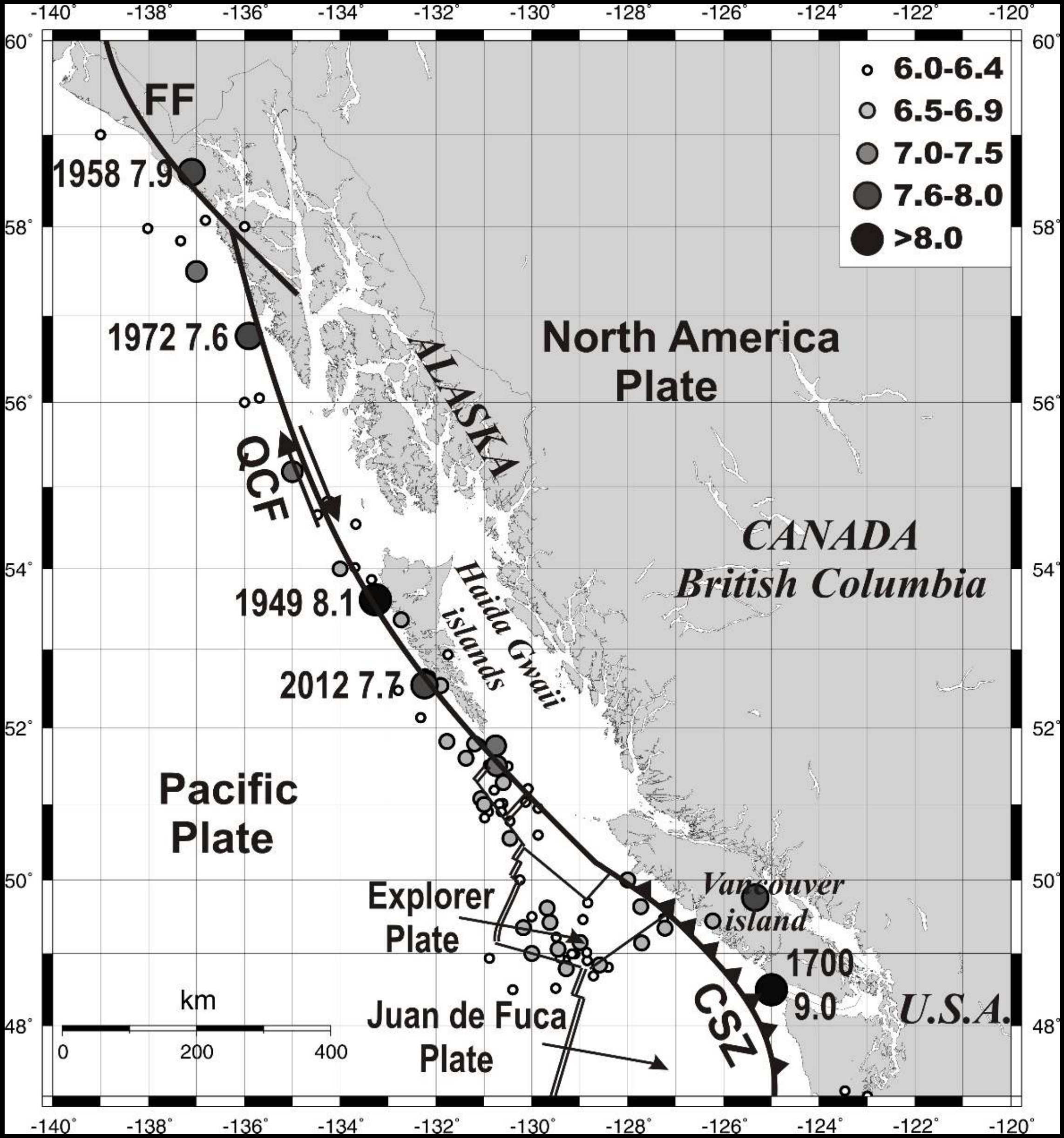
Separates the Juan de Fuca & North America plates.

Subduction, or underthrusting of the Juan de Fuca oceanic plate beneath the continent at a rate of 3.81 cm/yr produces three kinds of earthquakes:

I. Megathrust earthquakes (1700 AD, Cascadia, M=9.0; 1992, Cape Mendocino, M=7.0; 2012, Haida Gwaii, M=7.7)

II. Inslab earthquakes, whose magnitude is usually less than 7 {2001 magnitude M=6.8 Nisqually earthquake}.

III. Shallow earthquakes on crustal faults in western Oregon and Washington (900 AD Seattle, M ≥ 7; 1993, Scotts Mills, M=5.6, Klamath Falls, M=6), whose magnitude may exceed seven (M > 7) in some cases.



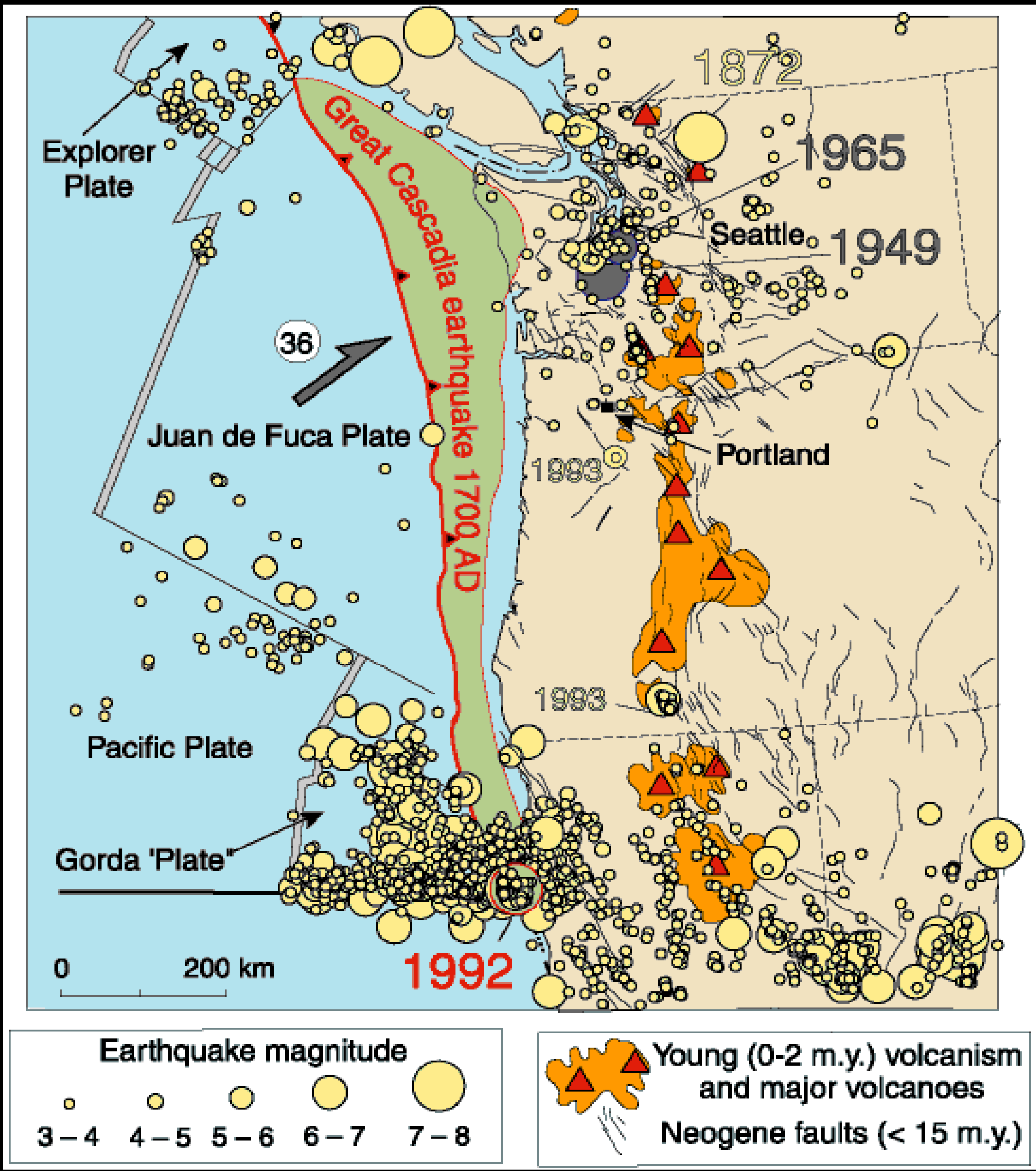
Earthquakes with M≥6.0 that occurred along the west coast of Canada since 1912. The epicenter of the giant M=9 Cascadia earthquake of 1700 is also shown

Although the Queen Charlotte Fault (QCF) is a predominantly strike-slip transform boundary, there is a component of oblique convergence between the Pacific and the North America plates off Haida Gwaii (Cassidy et al., 2014).

FF: Fairweather Fault

QCF: Queen Charlotte Fault

CSZ: Cascadia Subduction Zone



January, 1700 AD, Cascadia, M=9.0 : the last known megathrust earthquake in the Cascadia Subduction Zone.

Return Interval of M=9 earthquakes : 300 - 400 years.

Shallow earthquakes in the Cascadia Subduction Zone. (R.E. Wells et al., 2000).

Data Sources

- Seismic Hazard Earthquake Epicentre File (SHEEF) (Halchuk, 2009) for the period 1627-1991.

- National Resources Canada on-line bulletin (http://earthquakescanada.nrcan.gc.ca/stndon/NEDB-BNDS/bull-eng.php recently accessed: July 23, 2014) for the period 1992-2014.

All magnitudes were converted to the **moment magnitude** scale.

m_b and $M_s \Rightarrow M_w$ by the global relations of Scordilis (2005, 2006).

$M_L \Rightarrow M_w$ by the relations of Ristau (2004) for western Canada.

The Decelerating-Accelerating seismic Strain model (D-AS)

- Decelerating strain in the narrower (seismogenic) region
- Accelerating strain in the broader (critical) region
- Cumulative strain in both regions follows a power-law with the time to the mainshock:

$$S(t) = A + B(t_c - t)^m$$ *(Bufe and Varnes, 1993)*

S(t): cumulative Benioff strain, E_i is the seismic energy of the *i*th preshocks and *n(t)* is the number of preshocks occurred up to time t

$$\sum_{i=1}^{n(t)} E_i(t)^{1/2}$$

t_c: the mainshock occurrence time.

A, B, m: parameters calculated by the available data

Empirical Relations with Predictive Properties

- Global data:

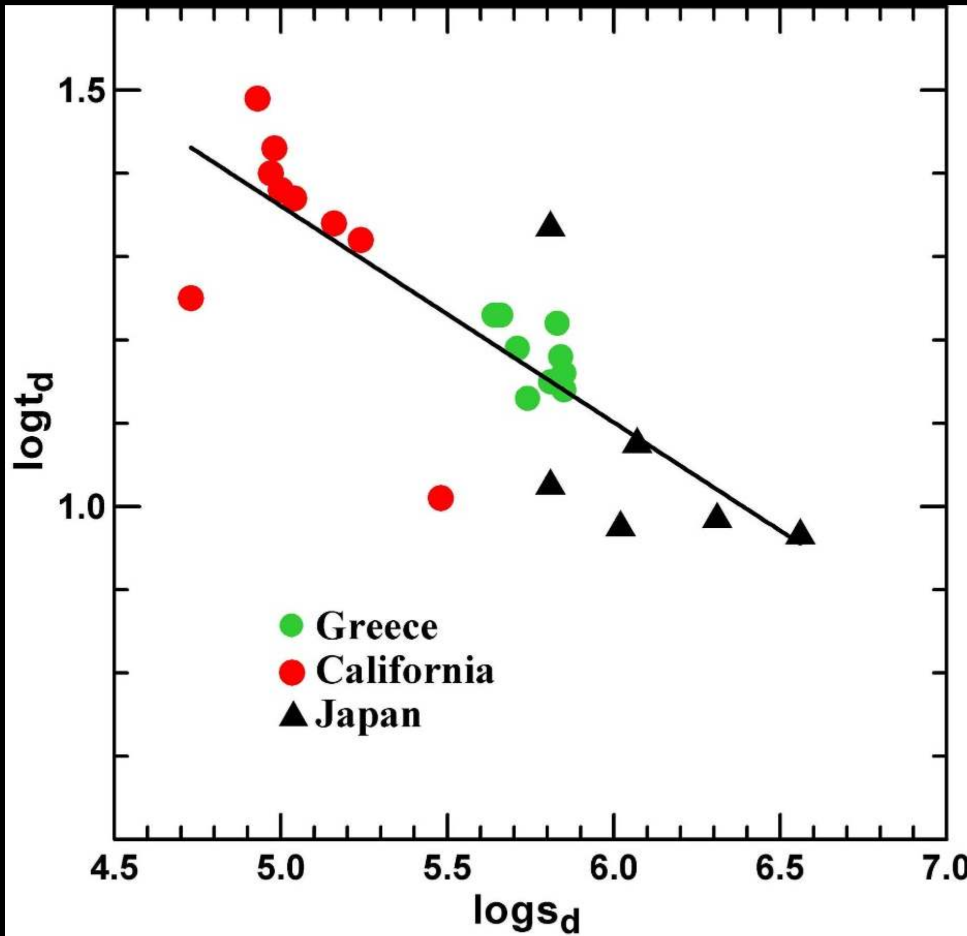
  Aegean
  California
  Japan
  Himalayas
  Anatolia
  Adriatic

- Scaling of dimension, R (in Km), of both regions with the mainshock magnitude, M, and the long-term seismicity rate, s (in $Joule^{1/2}/yr.\ 10^4 Km^2$)

- Scaling of durations (in yrs) of both preshock sequences with the long-term seismicity, rate, s

- Model uncertainties

Relations for Decelerating Preshocks in the Seismogenic Region



$$S(t) = A + B(t_c - t)^m \quad (1)$$
$$m > 1 \qquad (\overline{m} = 3.0)$$

$$\log r = 0.23M - 0.14s_d + 1.40 \qquad \sigma=0.15 \quad (2)$$

$$\log(t_c - t_{sd}) = 2.95 - 0.31\log s_d \qquad \sigma=0.12 \quad (3)$$

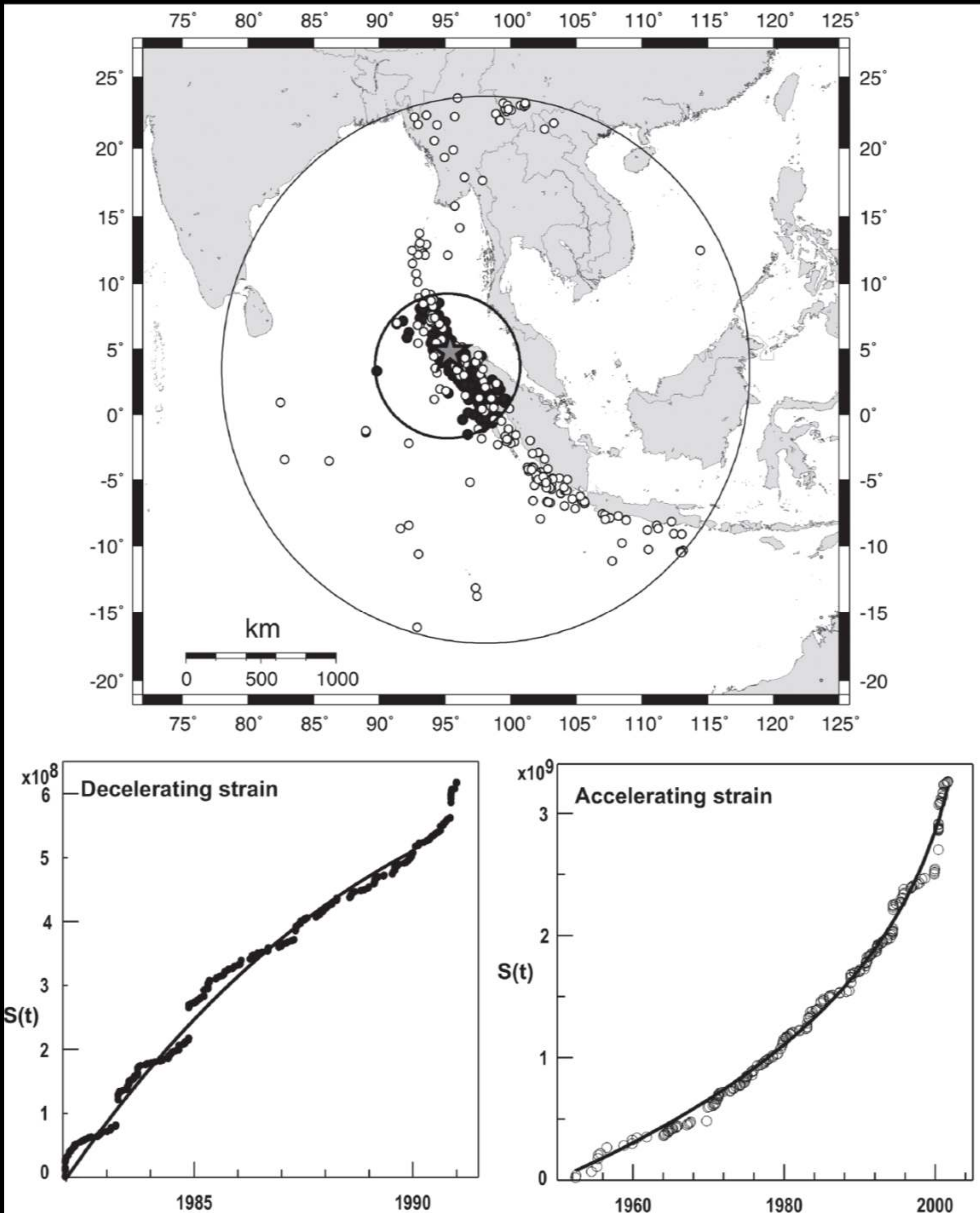
r (in km): axis of the circular seismogenic regions
M: mainshock moment magnitude
s_d: long-term strain rate (in $Joule^{1/2}$ /yr. 10^4Km^2)
t_c (in yrs): mainshock origin time
t_{sd} (in yrs): start time of decelerating preshocks

Papazachos et al. (Tectonophysics, 2006)

Similar relations hold for the accelerating preshocks that occur in the critical region:

$$\log R = 0.42M - 0.30s_a + 1.25 \quad (4)$$

$$\log(t_c - t_{sa}) = 4.60 - 0.57\log s_a \quad (5)$$



Decelerating-accelerating seismicity which preceded the Sumatra great earthquake (26.12.2004, M=9.0). (Upper part) Dots and small open circles are epicenters of decelerating and accelerating preshocks which are included in the circular seismogenic and critical regions, respectively. The star shows the mainshock epicenter. (Lower part) Plots of the time variation of the decelerating and accelerating Benioff strain, S(t), along with the best fit curves (Papazachos et al., 2014).

Selection criteria: optimization not only on the basis of the curvature parameter **C**.

$$\text{quality index} \quad q_d = \frac{Pm}{C}$$

m: exponent in relation (1) (m=3.0)

C: curvature parameter (Bowman et al., 1998)

P: the probability with which a decelerating pattern fulfils relations (2) and (3)

The Time and Magnitude Predictable Regional model (TIMAPR)

TIMAPR is based on the interevent times of mainshocks.

Since such events, that occur on a single fault, usually have recurrence times much larger than the relatively short span of the earthquake catalogues used, it is preferable to consider **seismogenic sources**, i.e. circular regions that include, in addition to the main fault where the largest mainshock occurs, other smaller faults where smaller mainshocks occur (Papazachos et al. 1997).

$$\log T_t = 0.19 \cdot M_{min} + 0.33 \cdot M_p - 0.54 \cdot \log S_d + q \qquad (6)$$

$$M_f = 0.73 \cdot M_{min} - 0.28 \cdot M_p + 0.46 \cdot \log S_d + w \qquad (7)$$

T_t: interevent time till the next mainshock with magnitude $M \geq \mathbf{M_{min}}$

M_p: the magnitude of the previous mainshock

M_f: the magnitude of the next mainshock

S_d: long-term seismicity level, i.e. the seismic strain rate in $Joule^{1/2}$ per year

q,w: parameters calculated by the available data

Identification of mainshocks within a seismogenic source after declustering

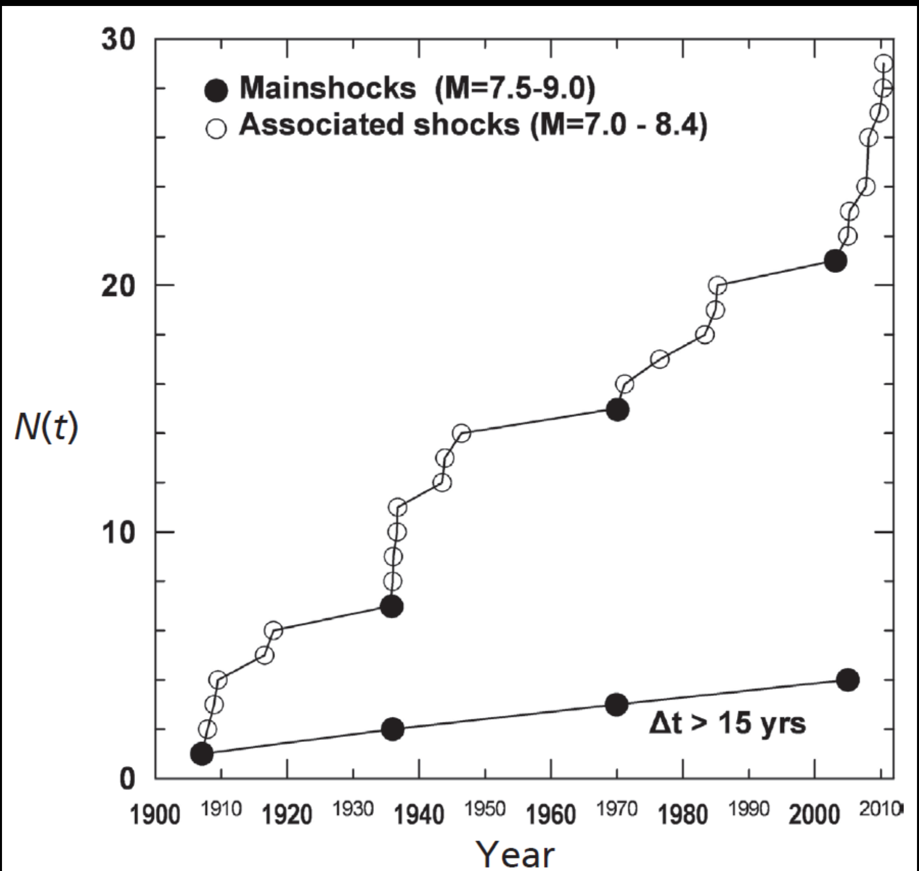
The interevent times of mainshocks show quasi-periodic behaviour when

$$\frac{\sigma}{T} < 0.5$$ *(Kagan and Jackson, 1991)*

T is the mean intervent time of the mainshocks in a seismogenic source.

σ its standard deviation.

Finding the optimum time window Δt to decluster an earthquake catalogue.



Time variation of the cumulative number, N(t), of shocks in the seismogenic region of the Sumatra 2004 great earthquake (M=9.0), for the complete (upper part) and the declustered (lower part) catalogue, respectively.
Mainshocks are denoted by black circles (M=7.5-9.0) and associated shocks (aftershocks etc.) by open circles (M=7.0-8.4) (Papazachos et al., 2014).

Selection criteria for the definition of the seismogenic source: optimization factor $OP = \frac{\sqrt{N}}{\sigma_q}$

N: number of interevent times

σ_q: standard deviation in relation (6)

Procedure

D-AS

- The area bounded by the two parallels $\phi \pm 3^o$ NS and the meridians $\lambda \pm 3^o$ EW around the mainshock epicentre, E(φ, λ), is covered by a dense grid of points (e.g. $\pm 0.2^o$ NS, $\pm 0.2^o$ EW).
- Each of these points is considered as the center of a circular seismogenic/critical region with radius r/R.
- For various r/R, M_{min} and t_{sd}/t_{sa} start times the respective quality indexes q_d/q_a are calculated. The highest values of these indexes correspond to the centers of the seismogenic/circular regions.

TIMAPR

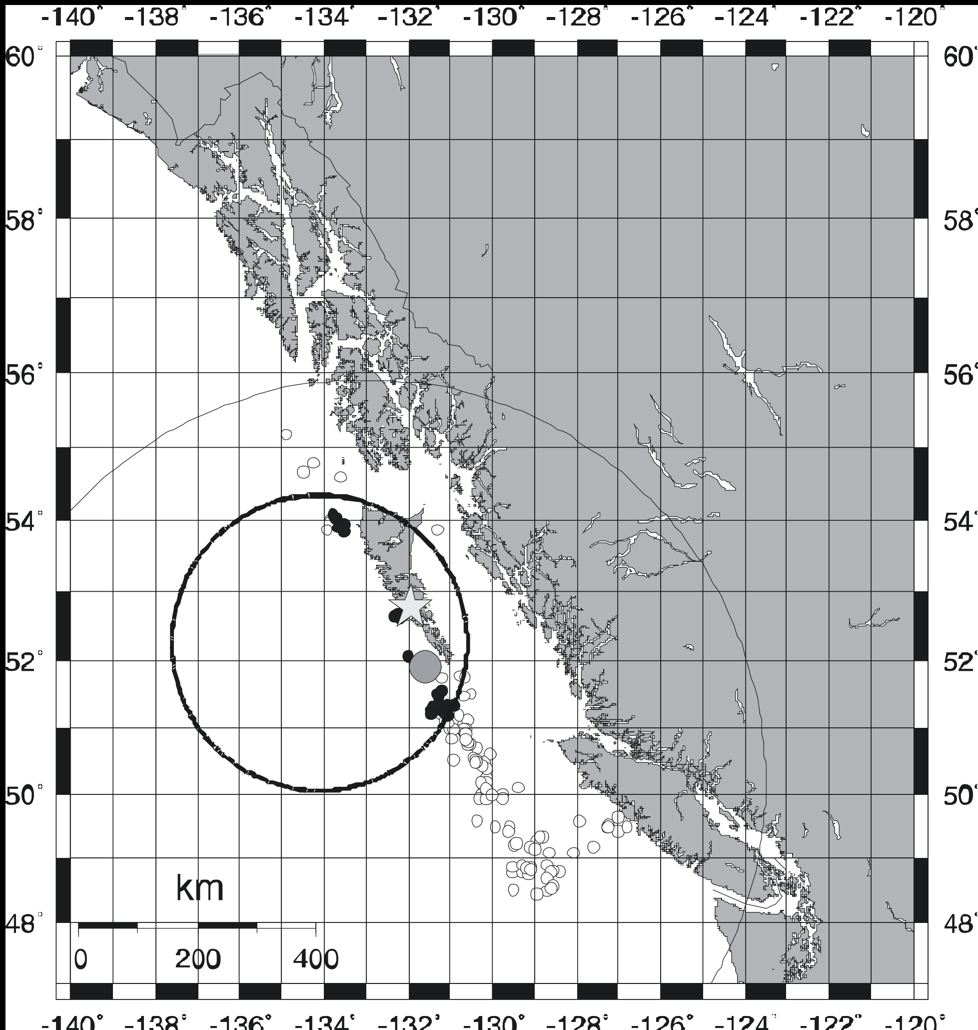
- The same area (see above) is covered by a grid of points.
- Each of these points is considered as the center of a circular seismogenic source.
- For various R-values of these sources the mainshocks are found (after declustering) and the optimization factor OP is calculated. The point/circle where the highest OP value is found, corresponds to the optimum seismogenic source.

Determination of the origin time, t*, of a retrospectively predicted (or expected) mainshock, its magnitude, M*, and epicenter E*

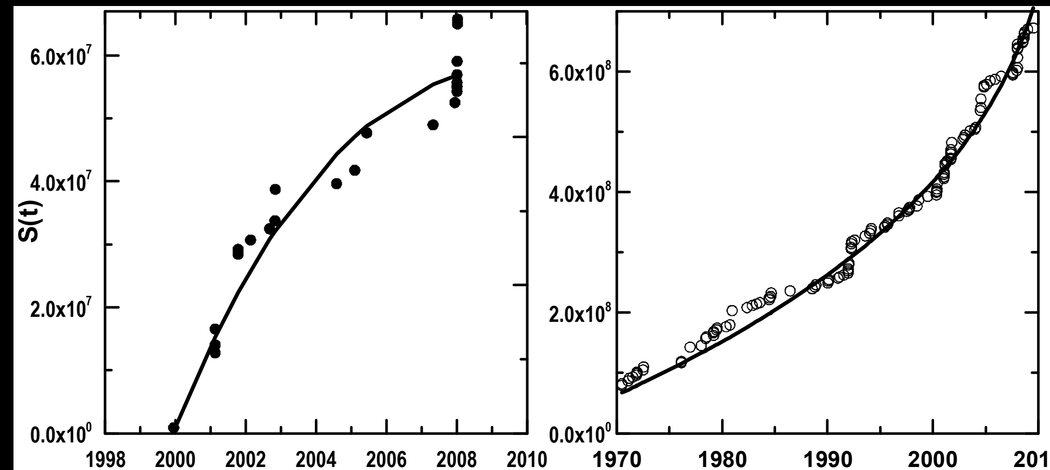
- **The origin time, t***, is the mean value of the times calculated by the relations (3), (5) and the (6) (the recurrence interval, T_t, calculated by the last relation, is added to the origin time of the previous mainshock that occurred in the region, e.g. 1992, M=6.7).

- **The magnitude, M***, is the mean of the magnitude values calculated by the relations (2), (4), and (7).

- **The epicenter, E*(φ,λ),** is the mean of two geographic points: (a) the mean epicenter of the decelerating preshocks, (b) the mean epicenter of the mainshocks which resulted after declustering in the seismogenic source.



Results for the 2012 mainshock

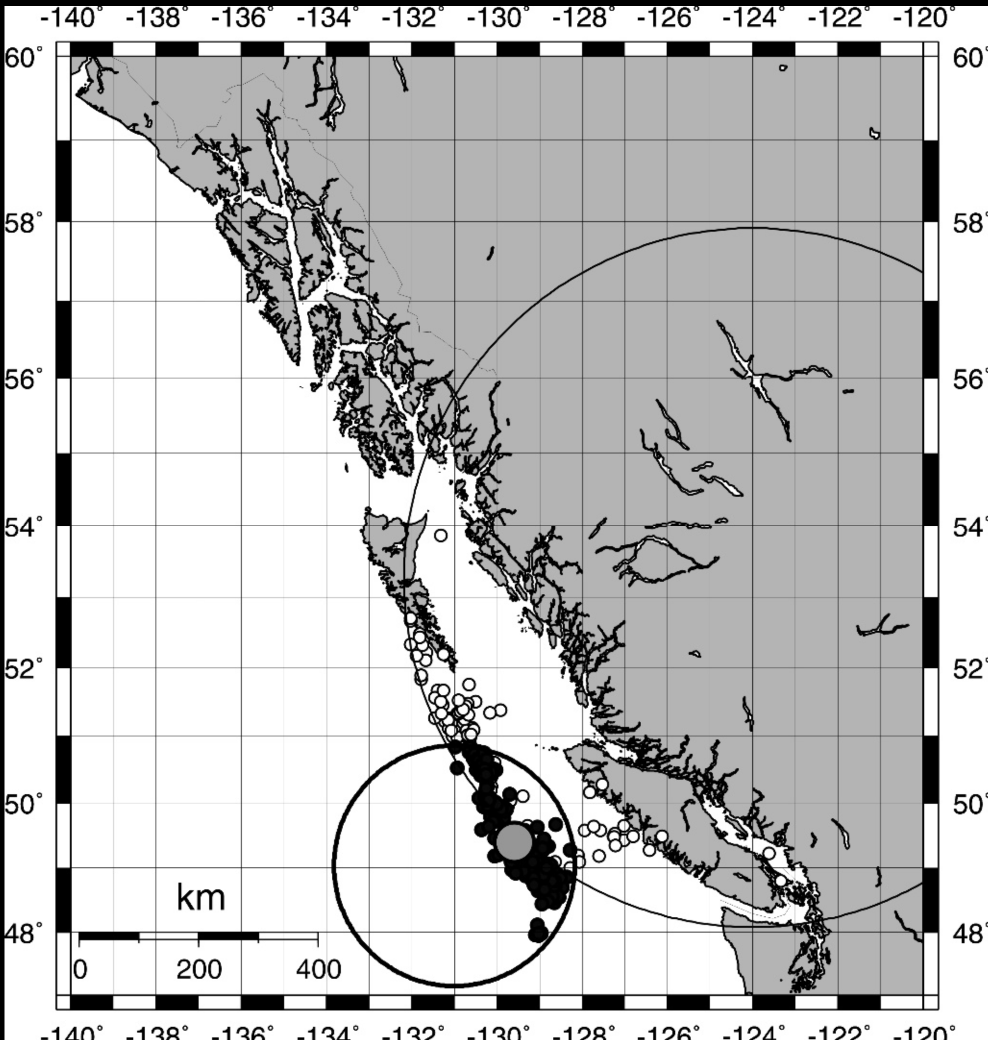


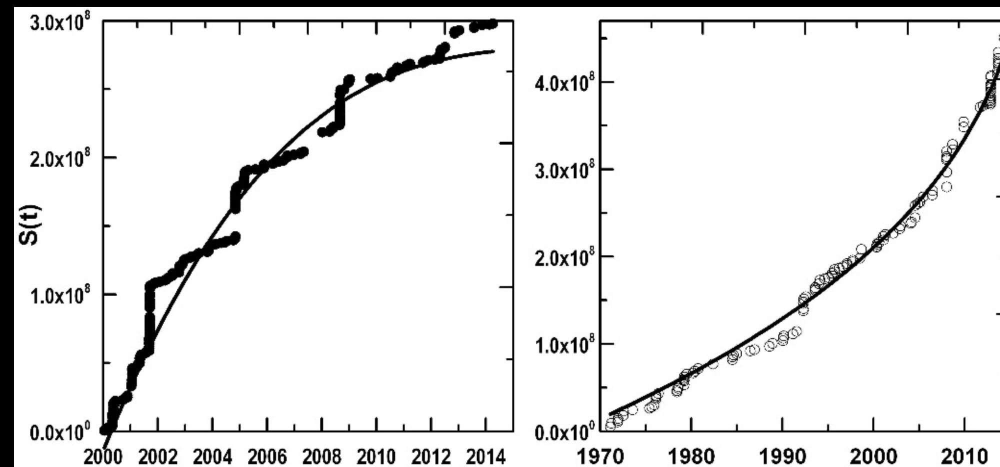
Plots of the time variation of the decelerating (left) and accelerating (right) Benioff strain, S(t), along with the best fit curves of relation (1).

Note: Decelerating and accelerating sequences are hardly recognizable in circular regions **centered** at the mainshock epicenter (low q_d and q_a values), in accordance with the results of Hardebeck *et al.* (2008) after tests on synthetic earthquake catalogues, since optimization procedures were based solely on the values of the curvature parameter C.

Dots and small open circles are epicenters of decelerating (M≥4.6, 1998-2009) and accelerating (M≥5.3, 1968-2009) preshocks which occurred in the circular seismogenic and critical regions, respectively. The star denotes the 2012 M7.7 mainshock epicenter, E, whereas the grey circle is the epicenter estimated in the present work.*

Forward test in the area 47ºN-57ºN, 122ºW-138ºW





Plots of the time variation of the decelerating (left) and accelerating (right) Benioff strain, S(t), along with the best fit curves of relation (1).

Decelerating preshocks: $M \geq 4.4$, 2000-2014

Accelerating preshocks: $M \geq 5.1$, 1971-2014

Currently observed decelerating (dots) and accelerating (small open circles) seismicity patterns along the west coast of Canada. The grey circle corresponds to the epicenter of the probably ensuing earthquake ($M^*=7.1$, $t_{c*} \approx 2022.5$, $E^*[49.4^o,-129.6^o]$).


Thank you for your attention !!