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Strain drop invariance indicated by a new global and complete catalogue of earthquake source time functions

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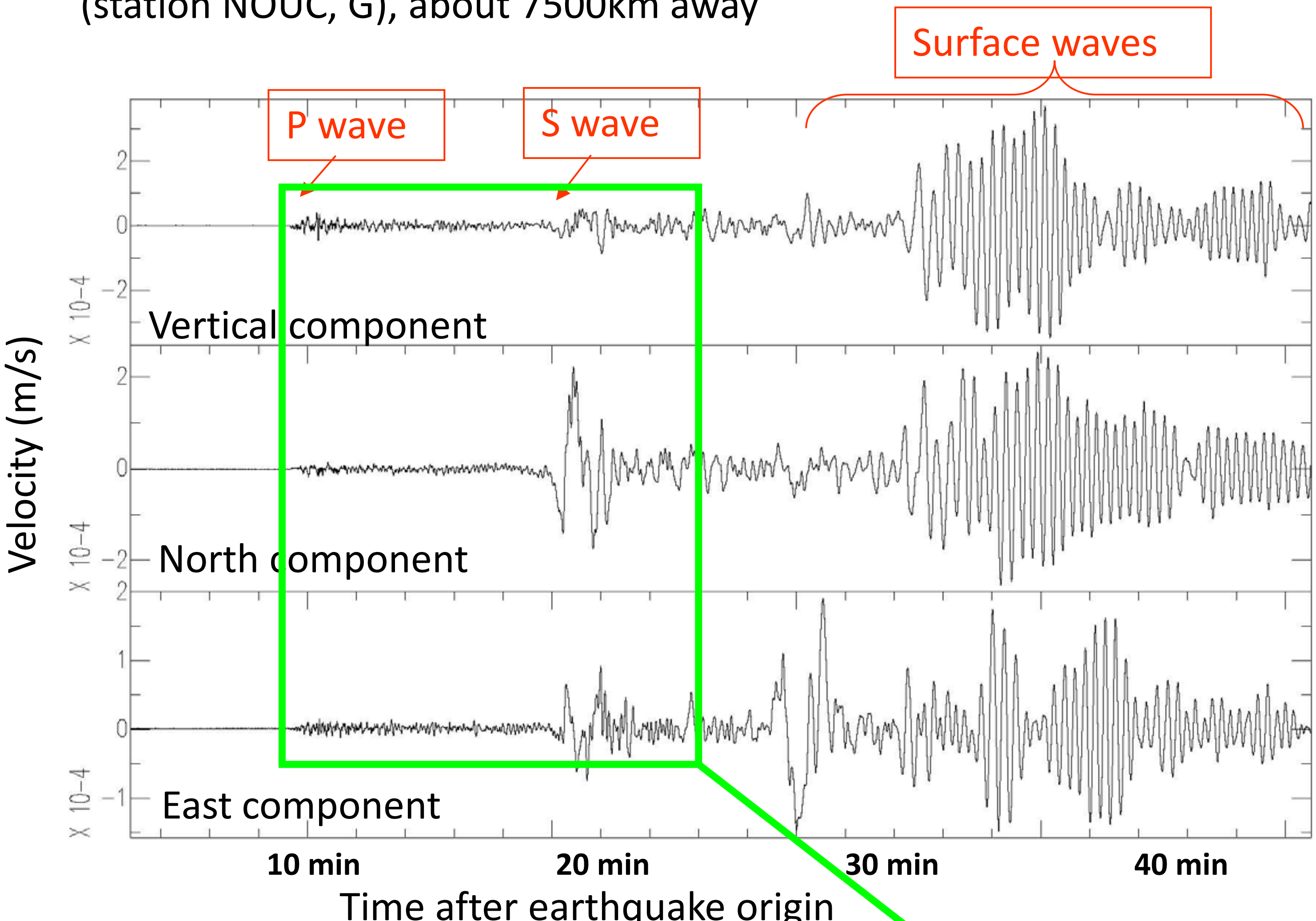
Work done at IPGP and Geoazur laboratories (Nice, France), with the support or IRD, CEA and european project NERA

Introduction on the SCARDEC method (*Vallée et al.*, 2011), used to retrieve the source time functions (STFs)

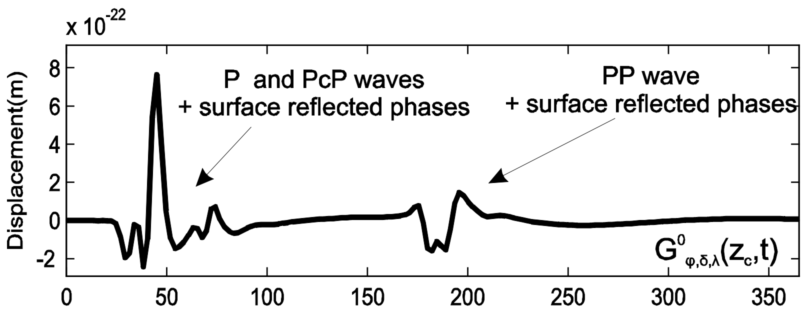
Waves generated by the Hokkaido earthquake (2003), recorded in New Caledonia (station NOUC, G), about 7500km away



Use of teleseimic body waves (P, PcP, PP, S, ScS) **to retrieve the source parameters, for all earthquakes in the magnitude range [6 – 9].**

Classical methods for source parameters determination at teleseismic distances

Illustration	*Physics*	*Parametrization*



« Point-source » radiation : depends on Earth structure, earthquake location and focal mechanism

4 to 9 parameters (« known » structure)

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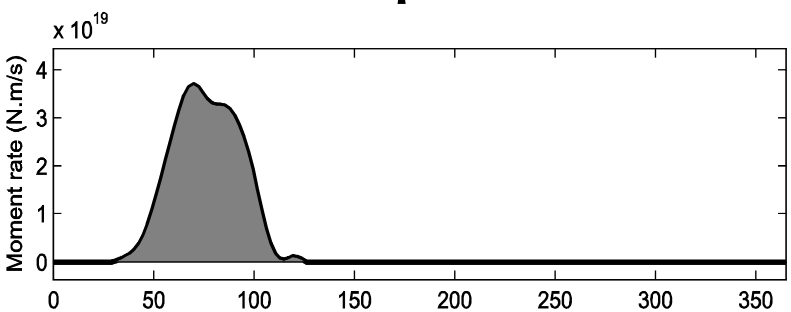

Spatio-temporal source term : Relative Source time function (RSTF)

A lot of parameters if all STF points are used as parameters. A few parameters if very simplified models are considered (for example gaussian shape)

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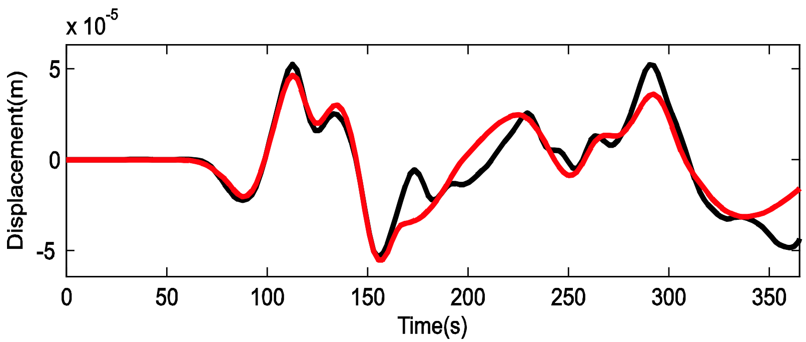
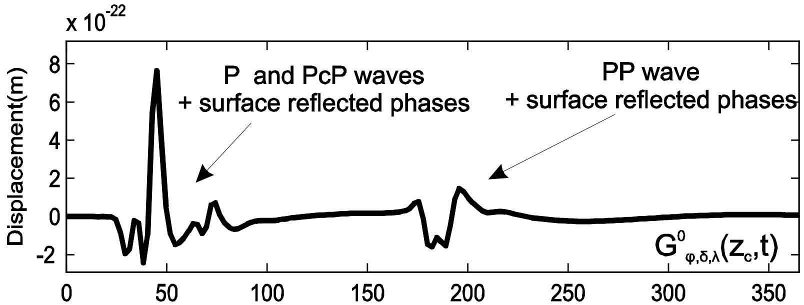


Observed seismic data : convolution between the source term and the point-source radiation

Inverse problem: Optimizing simultaneously the point-source radiation and the source term to fit the observed data

SCARDEC method for source parameters determination

Illustration	*Physics*	*Parametrization*



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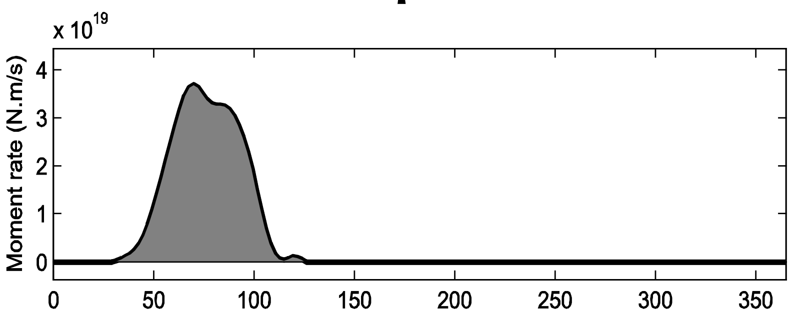

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Spatio-temporal source term : Relative Source time function (RSTF)

NO inverted parameters. Only imposing that the RSTFs are physical :

- ***positive***
- ***limited duration***
- ***causality***
- ***equal area (moment)***

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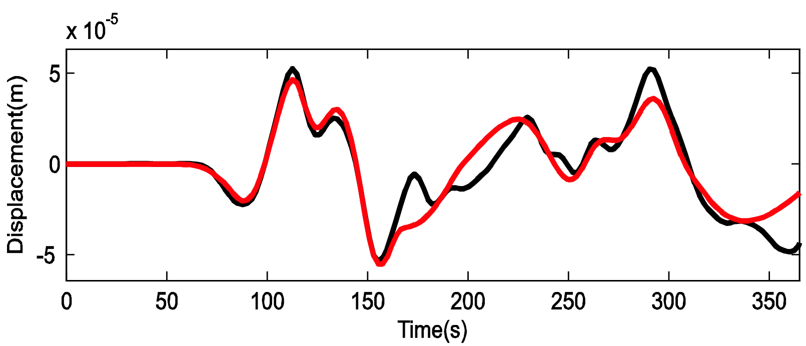

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Observed seismic data : convolution between the source term and the point-source radiation

Inverse problem: Optimizing the point-source radiation by fitting the observed data AND imposing physical RSTFs

Advantages of the SCARDEC method

- ***Source :***
  - The source time functions (STFs) can have an arbitrary complexity
  - The STFs can vary from station to station (RSTFs) – necessary for large earthquakes

- ***Methodology :***
  - Inverse problem depending only on strike,dip,rake and depth (2 other parameters if we allow for non-double-couple mechanisms)
  - Automated method : solution provided online, 45 minutes after an earthquake with M>5.5-6 (https://geoazur.oca.eu/SCARDEC)

Limitations :

- Very long earthquakes (> 150s) (2004 Sumatra earthquake)
- Strong focal mechanism variations inside the rupture
- Multiple events (body waves hidden by the stronger surface waves)

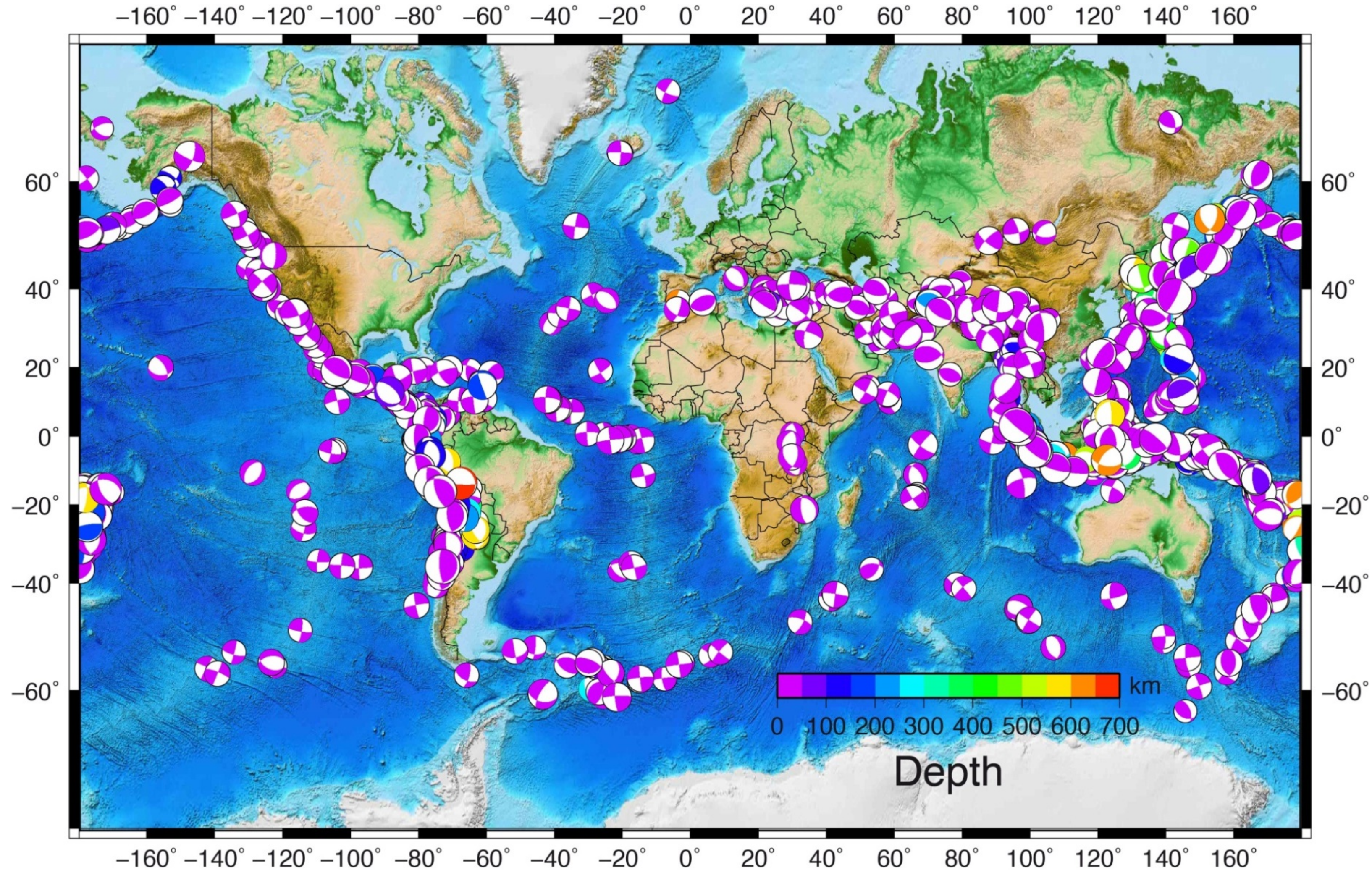
Why is it useful to determine precise STFs?

- **rapid determination of the source character (example : « tsunami earthquakes »)**
- **Precise STFs help the resolution of tomographic waveform inversions**
- **Systematic determination of STFs contains information on :**
  - **variability of the source contribution (useful for strong motion prediction)**
  - **variation of the nature of the source process**

Systematic analysis of the large earthquake characteristics

We analyse the ~ 2400 earthquakes with Mw>6 in the period 1992-2011, and extract about 1700 reliable source time functions for earthquakes of all depths.

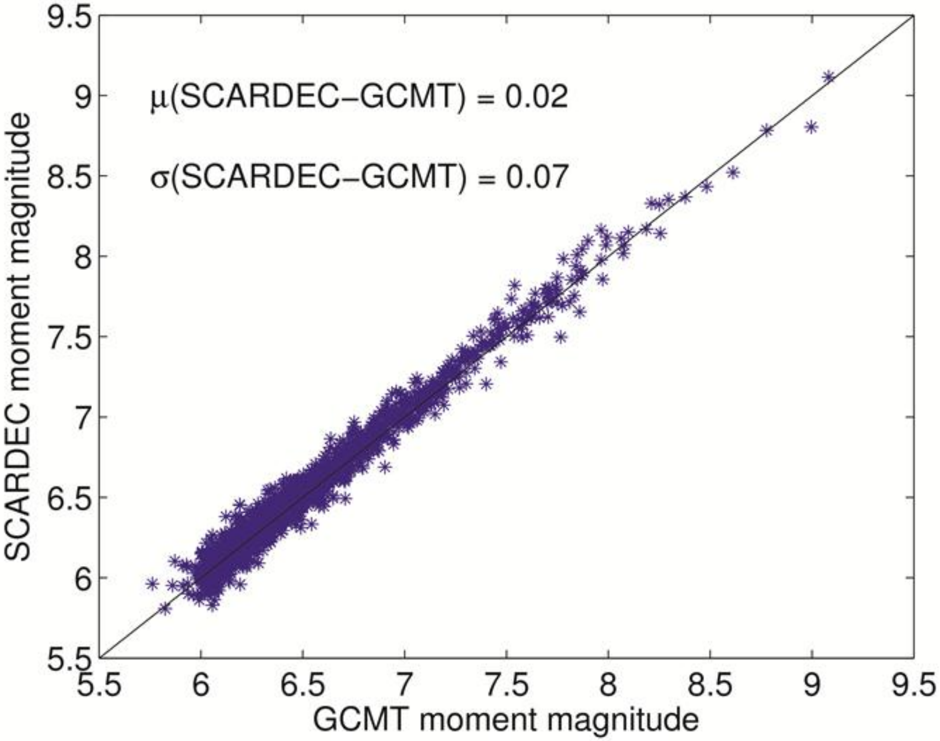
Larger and more complete catalog than previous STFs catalogs (Tanioka and Ruff, 1997; Houston, 2001; Bilek and Lay, 1999; Bilek et al., 2004…)



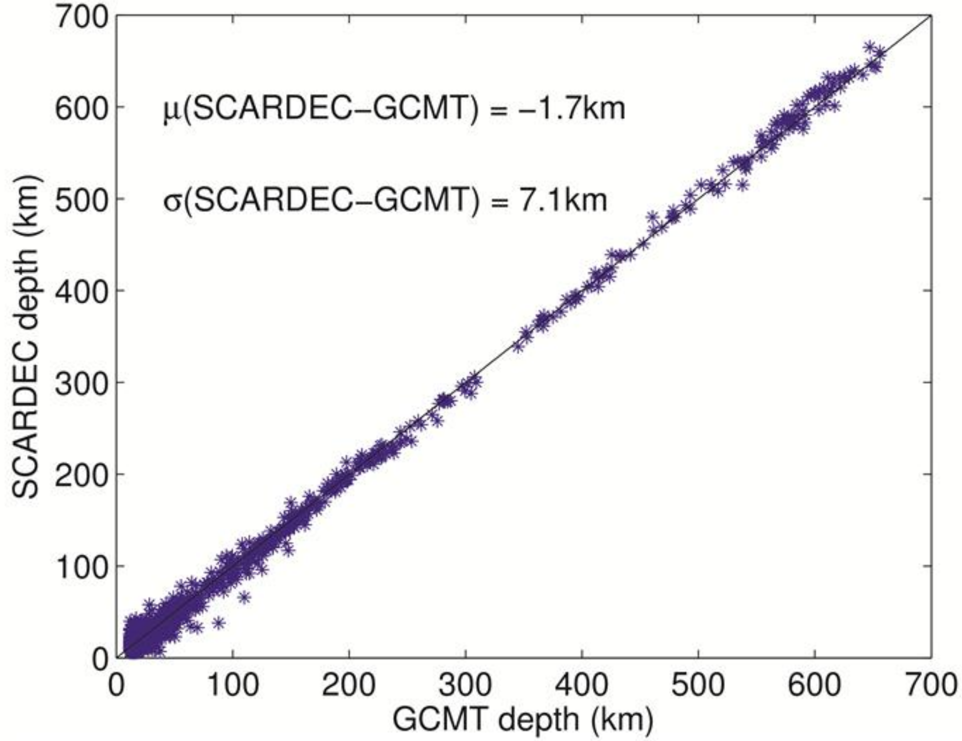
Determined mechanism and depth of the ~1700 earthquakes

Validations of SCARDEC characteristics with Global CMT catalog (Ekström et al., 2012)

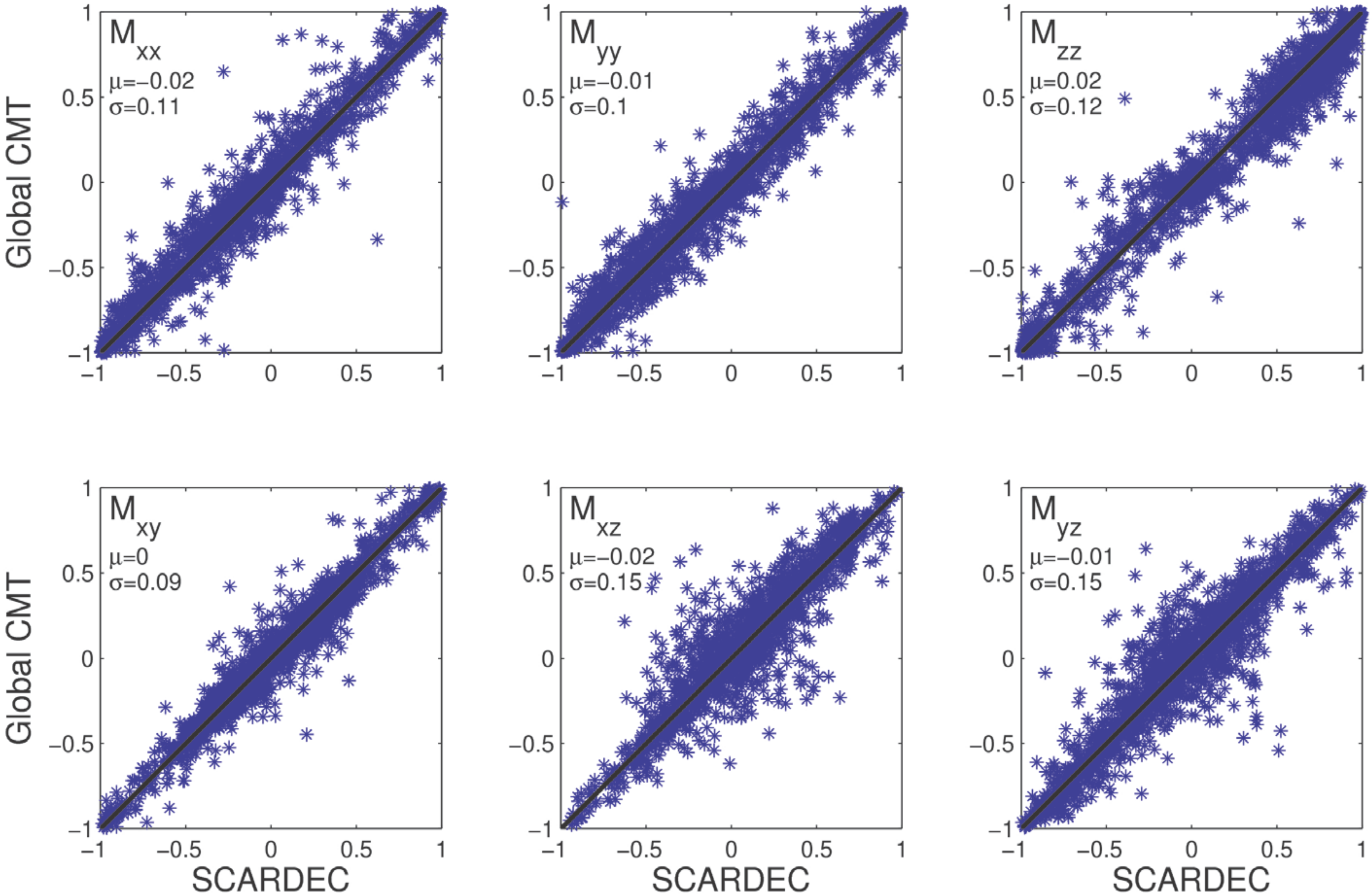
Moment magnitude



Depth



Moment tensor



4 examples of earthquakes with their source time functions Duration (T) and peak value (F_m) determination

Grey lines : individual RSTFs (from P waves)

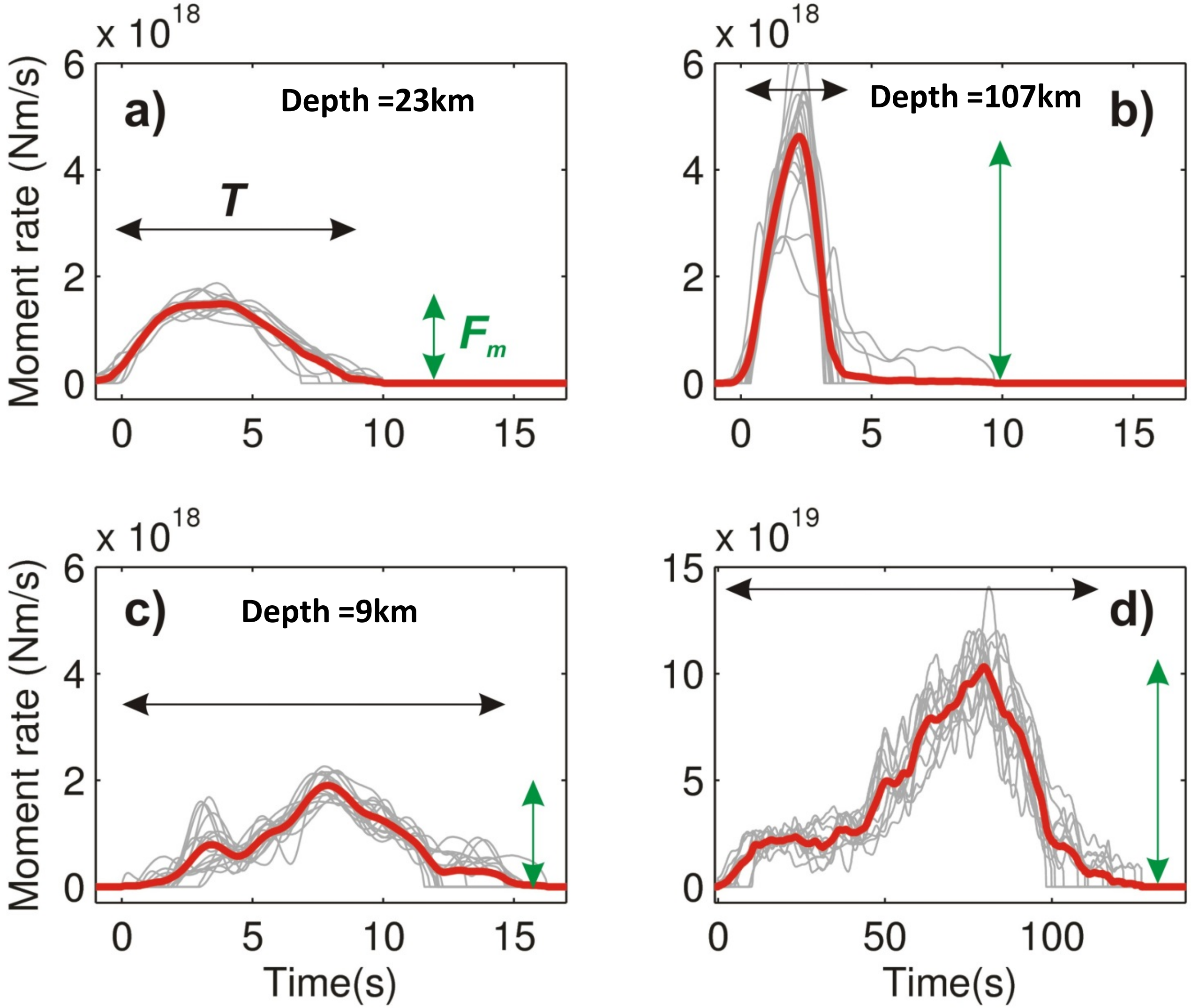
Red lines : average of RSTFs : good approximation of STF

a), b) and c) come from three earthquakes of Mw=6.6

a) is a simple shallow event
b) is deeper
c) is a more complex event

d) shows an example of a **very large event** (Peru 2001, Mw=8.4)

In all cases, duration (T) and peak (Fm) are measured. Note that Fm is a more objective measurement.



Relations between earthquake duration *T*, peak moment rate F_m and seismic moment M_0

$$M_o = \mu\, S\, A$$ μ rigidity; S slip ; A rupture area

In a bidimensional source model of characteristic rupture length *L* :

$$M_o \propto \mu \frac{S}{L} L^3$$

Strain drop Δε is proportional to $\frac{S}{L}$ and stress drop Δσ is proportional to μ $\frac{S}{L}$
In terms of strain drop :

$$M_o \propto \mu\, \Delta\varepsilon\, T^3\, V_r^3$$, where V_r is the rupture velocity

Considering V_r directly proportional to the shear velocity V_s , the duration ***T*** is related to the seismic moment (use of the relation μ = ρ V_S^2) by :

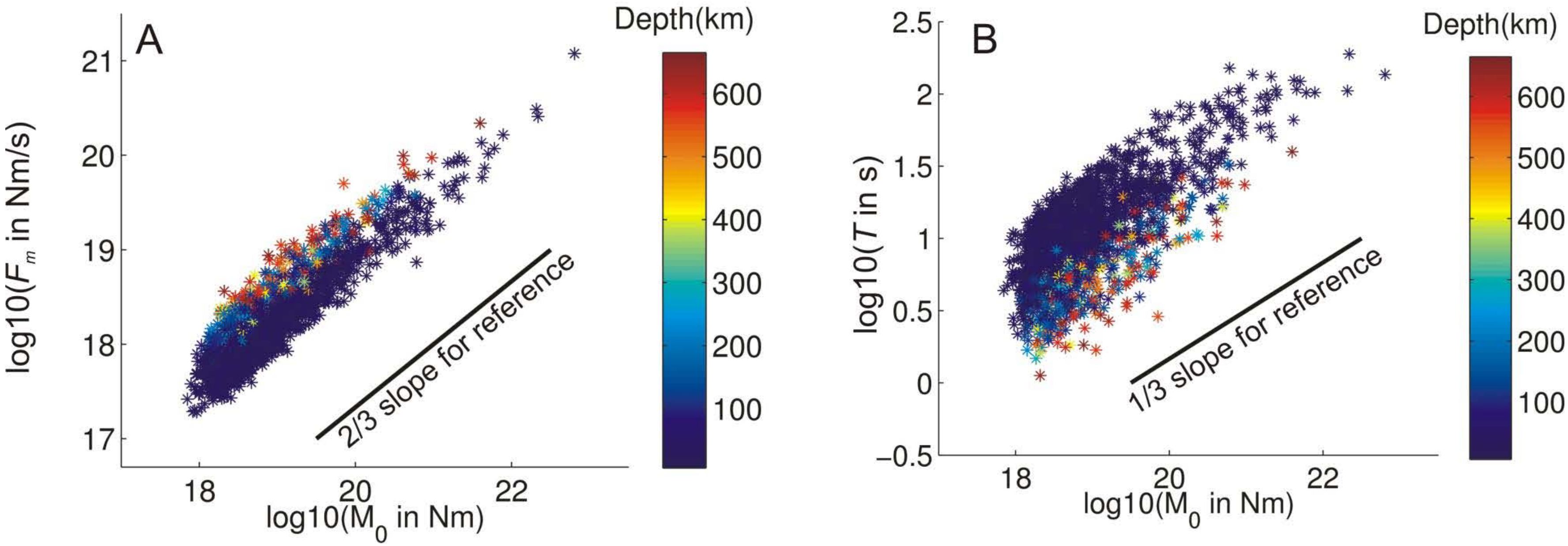
$$T \propto \frac{M_0^{1/3}}{\rho^{1/3}\, V_s^{5/3}\, \Delta\varepsilon^{1/3}}$$

On the other hand : $M_0 \propto T\, F_m$

This leads to the relation between peak value F_m and seismic moment :

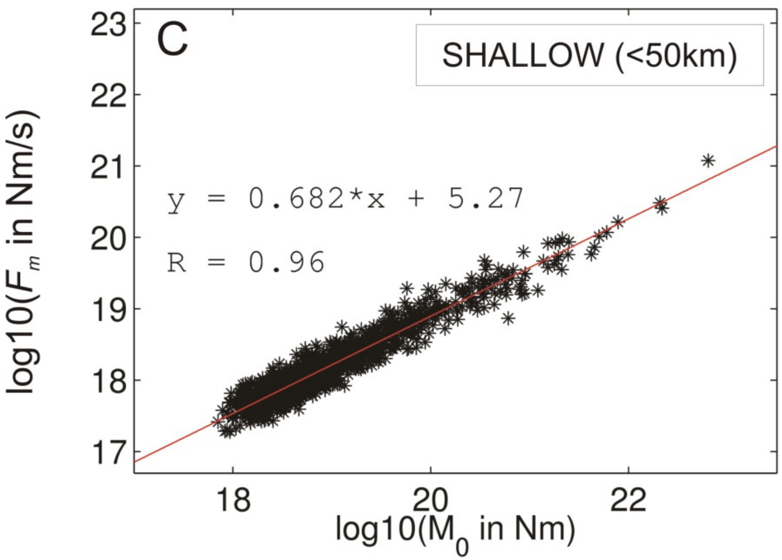
$$F_m \propto \rho^{1/3}\, V_s^{5/3}\, \Delta\varepsilon^{1/3}\, M_0^{2/3}$$

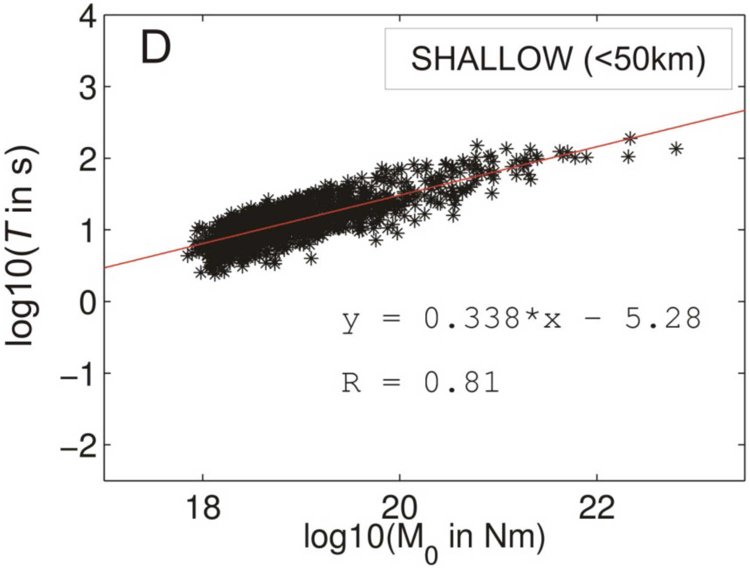
Observed relations F_m - M_0 and T- M_0



Observations: The 2/3 and 1/3 trends are well observed in the global STF catalog, with the value $\rho^{1/3} V_s^{5/3} \Delta\varepsilon^{1/3}$ (equivalently $V_s \Delta\sigma^{1/3}$) increasing with depth

Restraining the catalog to shallow depth earthquakes





The figure above indicates that at shallow depth (where ρ and V_s are not expected to vary in a systematical way):

- **F_m is very well fitted as evolving as M_0^{β} (with β close to 2/3)**
- **T is well fitted as evolving as M_0^{δ} (with δ close to 1/3).**

This indicates that at shallow depth, Δσ and Δε are independent on the seismic moment.

Let us consider the variations as a function of depth *z* ; z_0 represents shallow depth.

We have $\boldsymbol{F_m(z_0) = \alpha\, M_0^{\beta}}$, with α and β empirically determined

We can compute the scaled value of F_m : $\boldsymbol{\widetilde{F_m}(z) = \dfrac{F_m(z)}{F_m(z_0)}}$

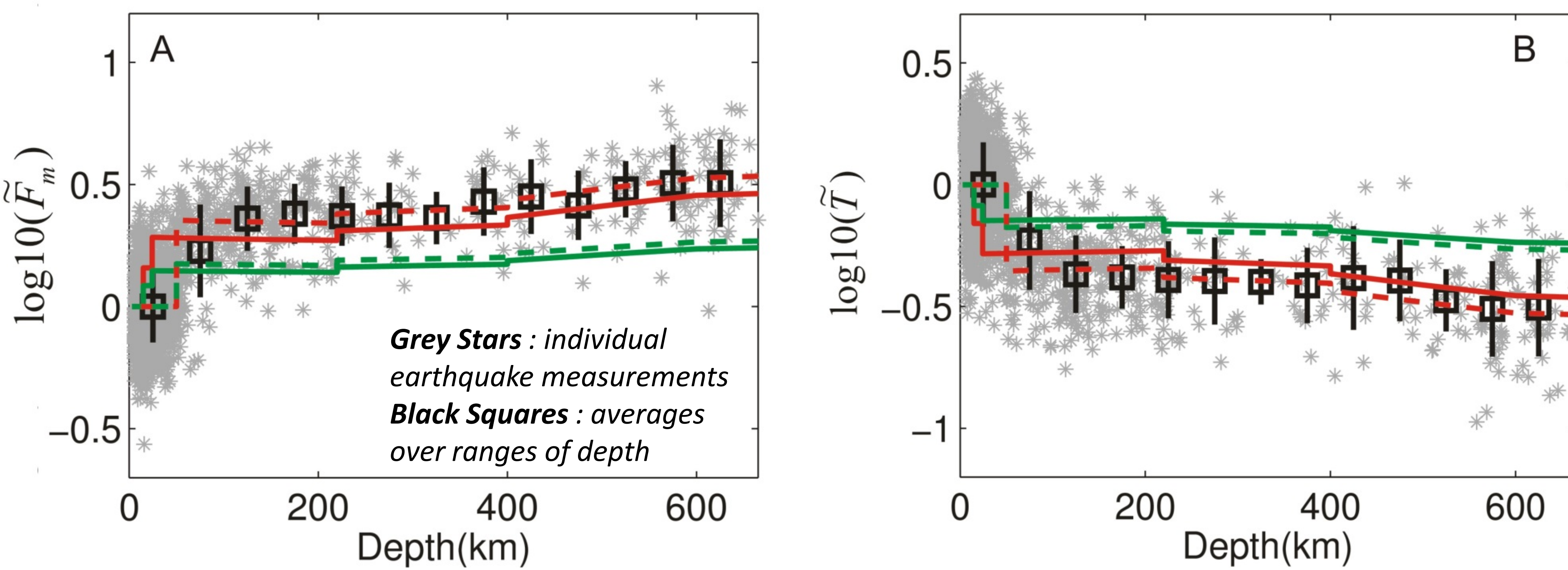
This scaled value is equal to : $$\boldsymbol{\widetilde{F_m}(z) = \frac{\rho^{1/3}(z)\, V_s^{5/3}(z)\, \Delta\varepsilon^{1/3}(z)}{\rho^{1/3}(z_0)\, V_s^{5/3}(z_0)\, \Delta\varepsilon^{1/3}(z_0)}} \quad \textbf{(1)}$$

Consider two simple models:

- **constant stress drop** : in this case $\boldsymbol{\widetilde{F_m}(z)} = \boldsymbol{\dfrac{V_s(z)}{V_s(z_0)}}$ **(2)**
- **constant strain drop** : in this case $\boldsymbol{\widetilde{F_m}(z)} = \boldsymbol{\dfrac{\rho^{1/3}(z)\, V_s^{5/3}(z)}{\rho^{1/3}(z_0)\, V_s^{5/3}(z_0)}}$ **(3)**

Similar derivations can be done for the scaled value of duration T; the ratios are simply inverted in equations (1),(2),(3).

Observed relations $\widetilde{F_m}(z)$ *and* $\widetilde{T}(z)$ and agreement with simple models



Green : expected variation of $\widetilde{F_m}(z)$ / $\widetilde{T}(z)$, in the PREM model, in the hypothesis of *constant stress drop*

Red : expected variation of $\widetilde{F_m}(z)$ / $\widetilde{T}(z)$, in the PREM model, in the hypothesis of *constant strain drop*

Stress drop increases with depth but strain drop appears to be little dependent on magnitude AND depth.

Discussion

- **Strain drop** (or in other words the ratio between characteristic slip and characteristic rupture length) **does not vary significantly with magnitude and depth.**

- Despite various efforts to detect some specific properties of **deep earthquakes**, they appear to be **very similar to their shallow counterparts**…

… A **common mechanism** (Roberts and Turcotte, 2000) ?

Other elements

- Under reasonable assumptions, **strain drop (S/R) inside the main slip patch** is on the order of **10^{-4}.**

- **Variability of strain (and stress) drop** at shallow depth is **less than previously inferred, by a factor of about 2**. This can reconcile some observations coming from strong motion variability (Cotton et al., 2013).