Disclosing Slow Active Tectonics from NGGM

Anna Maria Marotta

University of Milano

Workshop NGGM/MAGIC - January 26 2021

1. Activities and Heritage

GRAVITATIONAL SEISMOLOGY (GS)

Roberto Sabadini (PI)

G. Cambiotti, A.M.Marotta

(Activity Line 1: Scientific Data Exploitation) ESA ITT AO/1-9101/17/I-NB

Gravitational Seismology aims to quantify the **Gravitational Effects** of the Solid Earth processes leading to the Earthquakes of different magnitudes and characteristics (thrust, normal and/or strike slip) and in different tectonic environments (convergent, divergent and transform margins).

The **GS approach** builds on:

- a method developed in recent years at the University of Milano, combining the physico-mathematical modelling of active tectonics and of the seismic cycle with geodetic data in constraining the mechanisms responsible for crustal deformation and stress accumulation.

- the evidence that each phenomenon is categorized by distinctive time-varying gravity and geoid signals of different time scale and wavelength;

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Slow tectonics and earthquakes occur on different temporal and spatial scales

Short wavelengths	→	shallow features (e.g. earthquakes)
Short time scale	→	fast tectonic processes (e.g. earthquakes)
Long wavelengths	→	slow tectonic processes (e.g. subduction, extension)
Long time scale	→	slow tectonic processes (e.g. subduction, collision, extension)

Why understanding the mechanisms that regulate slow rate tectonic deformation is crucial in the context of the study of the earthquakes genesis?

Analyzing the slow time variation of gravity, deformation and stress fields in areas where the earthquakes occur allows characterizing the inter-seismic ***loading phase*** in terms of:

- *background crustal deformation and stress*
- *amount of coupling between interacting plate*
- *shallow and deep density/mass redistribution*
- *rheology controlling the inter-seismic loading*

Which tectonic processes are we interested to?

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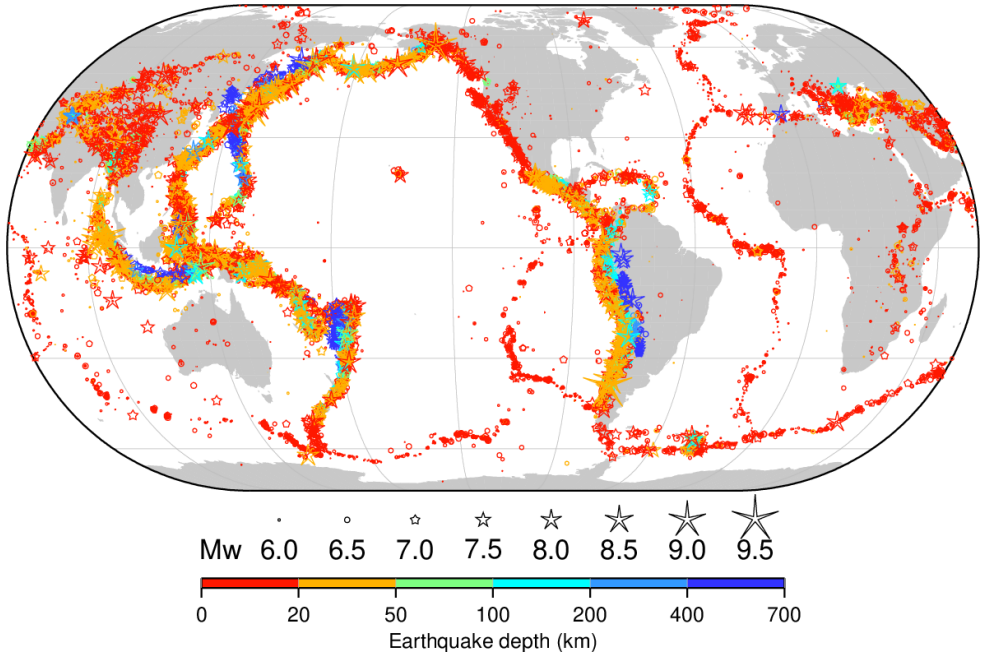
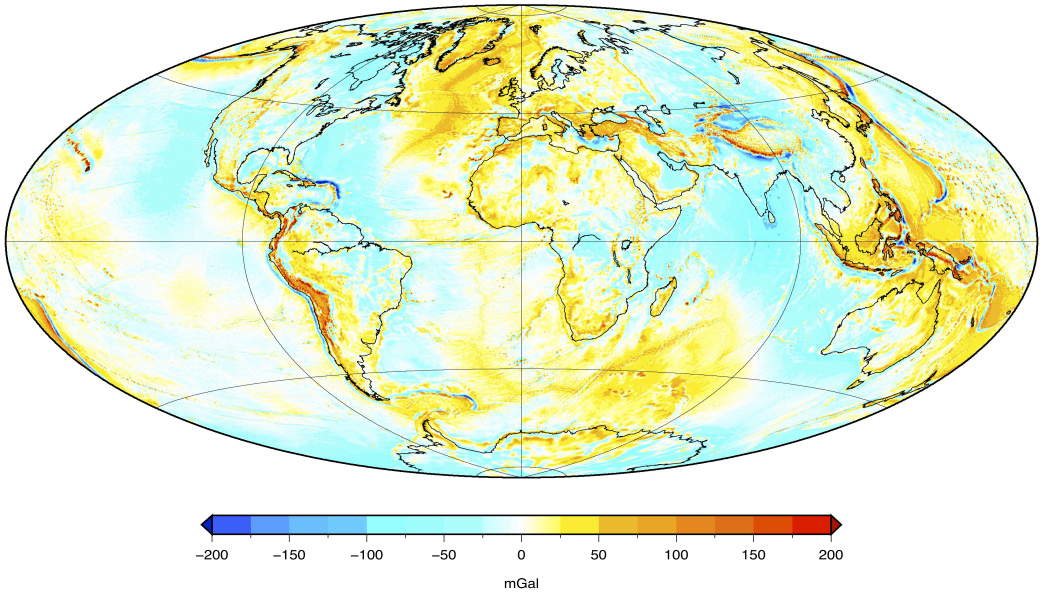
ISC-GEM Catalogue



Global map of the earthquakes listed in the Version 7.0 of the ISC-GEM Catalogue (about 39,400 earthquakes. (Storchak et al., 2013; 2015; Di Giacomo et al., 2018)

EIGEN-6C4 model



Global map of the gravity disturbance based on the EIGEN-6C4 model (the latest combined static global gravity field model including GOCE data up to degree and order 2190) (Forste et al. 2014).

SOLID EARTH TECTONIC PROCESSES

are the source of mass anomalies within the Earth, leading to gravitational signatures in a wide spectrum of spatial and temporal scales.

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In order to achieve the aforementioned goals, we developed physico-mathematical models to simulate the crust-mantle dynamics at both **CONVERGENT** and **DIVERGENT** margins, accounting for a detailed rheological and density distribution of the rocks.

Addressed questions:

1. Is the gravity signature of the slow tectonic processes constant?
2. Is the gravitational signatures of slow tectonics distinguishable from that due to earthquakes?
3. Can the gravitational signature of slow tectonics provide information on the plate coupling?
4. Is it possible to constrain the rheology controlling the seismic cycle (from the inter-seismic loading phase to the post-seismic phase?

We validated the model through the comparison between model results and the latest combined global gravity field models (EIGEN6C4).

This part of Gravitational Seismology deals with NGGM/MAGIC MRD 2.5 Solid Earth:

«*Tectonic processes leading to such catastrophic phenomena (earthquakes) are linked to deep mantle and crustal processes*», so NGGM allows «*creating a so called 4D Earth model which provides the capability to predict near-surface motion and deformation by the connection with geodynamic processes*».

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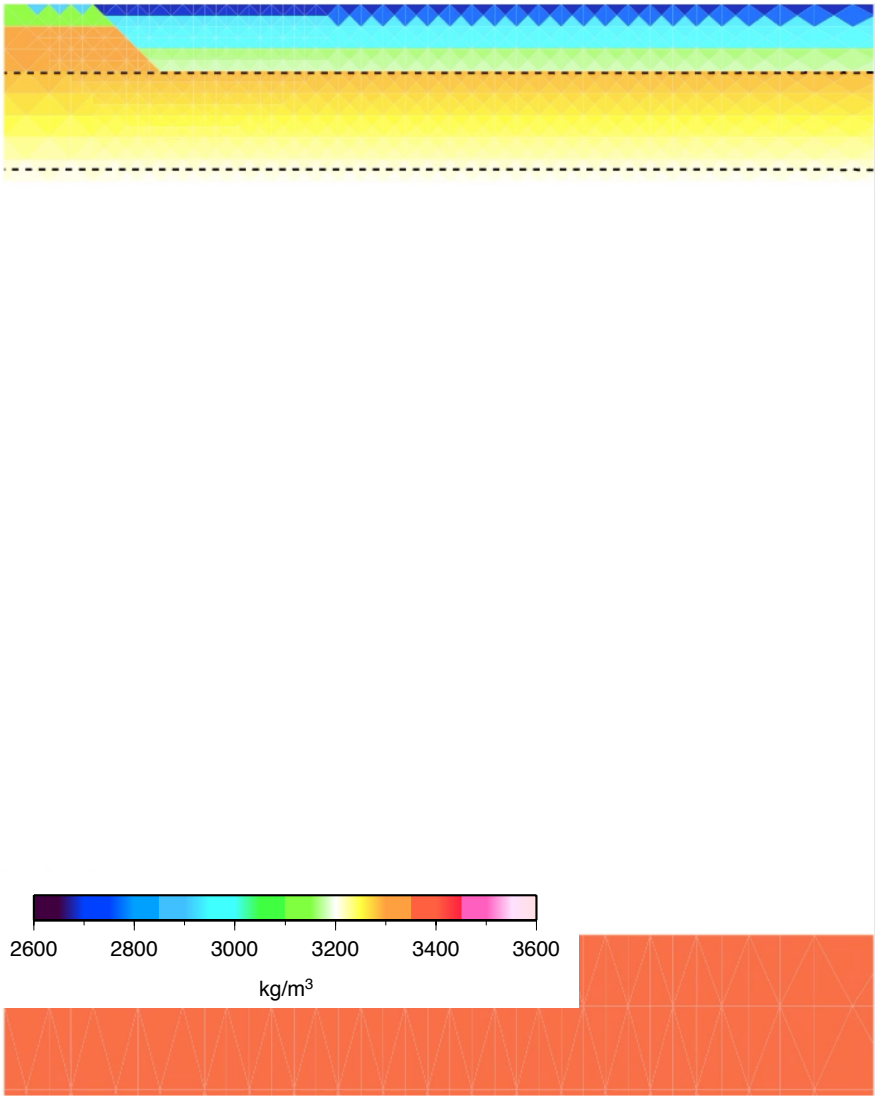
CONVERGENT MARGINS - SUBDUCTION LEADING TO MW=9 EARTHQUAKES

Markers distribution

Density



- crustal material, belonging either to the oceanic lower plate and scraped from the upper continental plate, subduces;
- the scraping effect is maximum within the first 5Ma, due to the strong coupling between the interacting plate;
- stationary configuration of the trench reached within few million of years;
- erosion/sedimentation mechanism is activated within few million of years;
- a huge amount of sediments fill the trench and sinks to great depths;
- After about 5Ma the PT conditions become favorable to activate mantle hydration and serpentinization in the wedge area.

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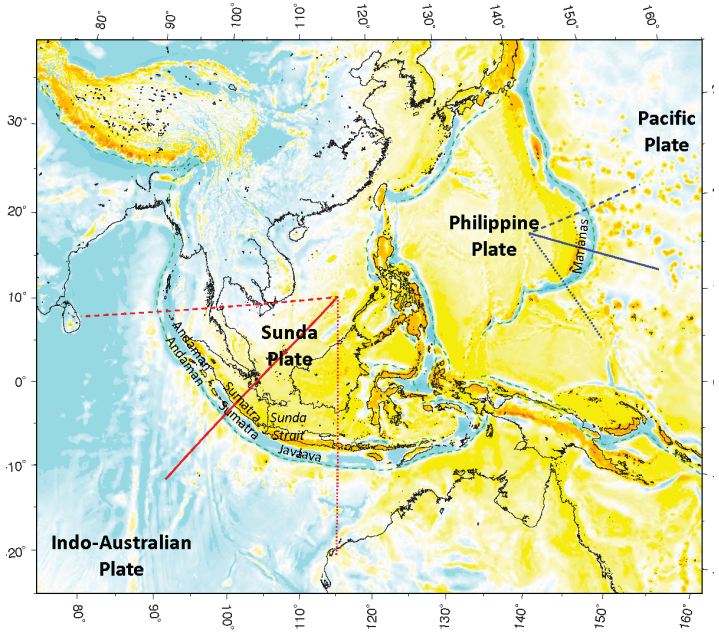
MODEL VALIDATION

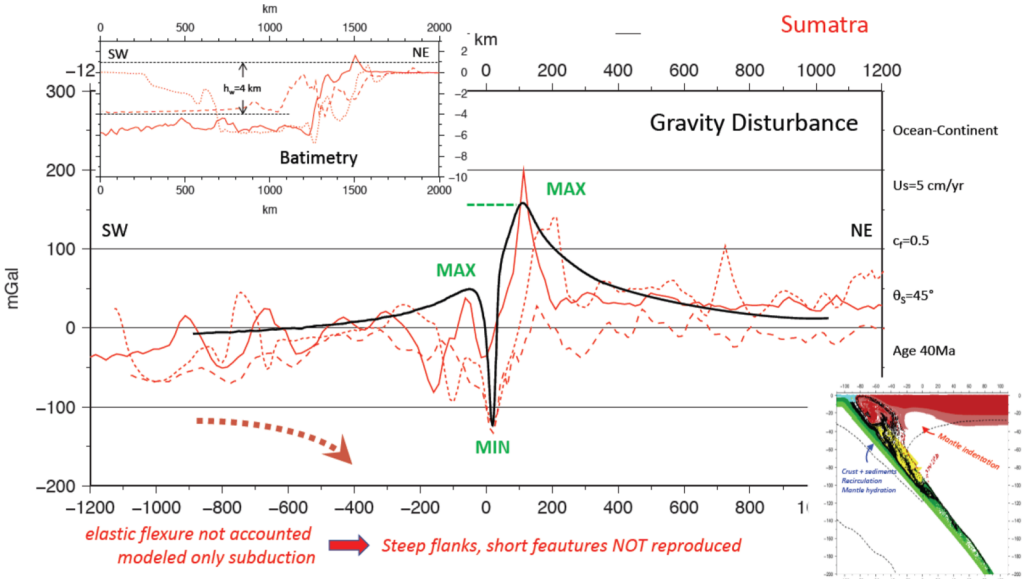
comparison between model results and the latest combined global gravity field models (EIGEN6C4).

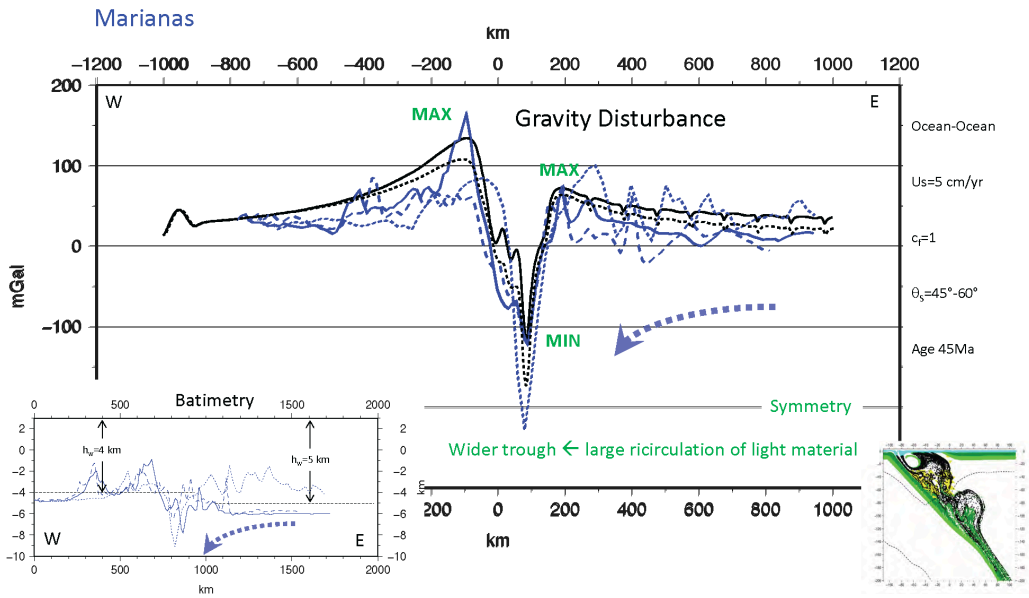
Sumatra – Marianas

SUBDUCTION LEADING TO MW=9 EARTHQUAKES

GRAVITY DISTURBANCE







Marotta, Restelli, Bollino, Regorda and Sabadini, 2020. The Static and Time-dependent Signature of Ocean-Continent and Ocean-Ocean Subduction: the case studies of Sumatra and Mariana complexes. Geophysical Journal International, doi:10.1093/gji/ggaa029.

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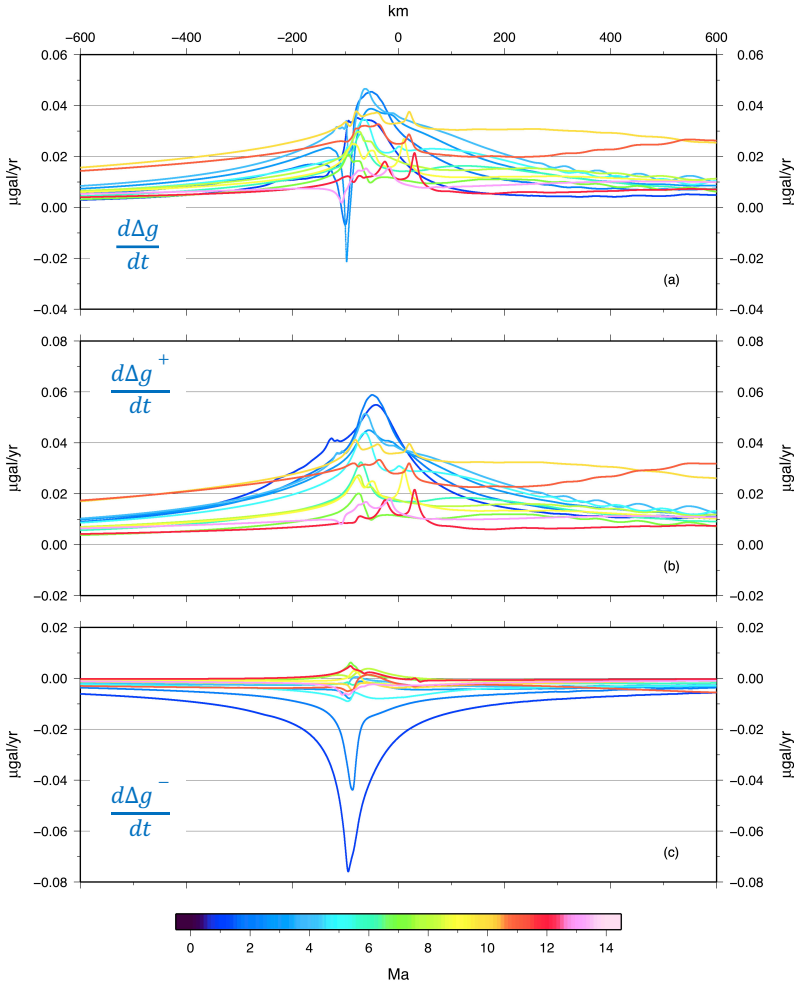
1. Activities and Heritage

Answers to Addressed questions

GRAVITY RATE OF CHANGE

U_s=5 cm/yr θ_s=45° c_f=1



Values averaged over a time span of 0.5 Ma

1. Is the gravity signature of Subduction constant? *NO*

   1.1 For subduction gravity signal varies from 0.05 μGal/yr during the early stages of subduction, to about 0.01 μGal/yr during the advanced stages of subduction.

   1.2 Rates of the order of 0.05 μGal/yr are seen by NGGM as linear trends, so we propose that a whole 10 yr mission duration is necessary to recover a signal comparable to 1 μGal, the accuracy of NGGM.

   1.3 Detection of these linear trends due to slow tectonics is among the most challenging, but very exciting, tasks of NGGM to score NGGM/MAGIC MRD 2.5 Solid Earth.

2. Is the gravitational signatures of subduction distinguishable from that due to earthquakes? YES

   Slow tectonics and earthquakes have different spatial (both shape and wavelength) and temporal patterns

   Wavelength of hundreds of kilometers for subduction/extension; tens of kilometers for earthquakes.

   Rate: difference of about one order of magnitude.

   Slow active tectonics contributes to changes in the static gravity field, at least during the 10 yr of NGGM flight duration. Its signal is about one order of magnitude smaller than that evaluated from the inter-seismic Mw=9 earthquakes, of the order of 0.5 – 1 μGal/yr.

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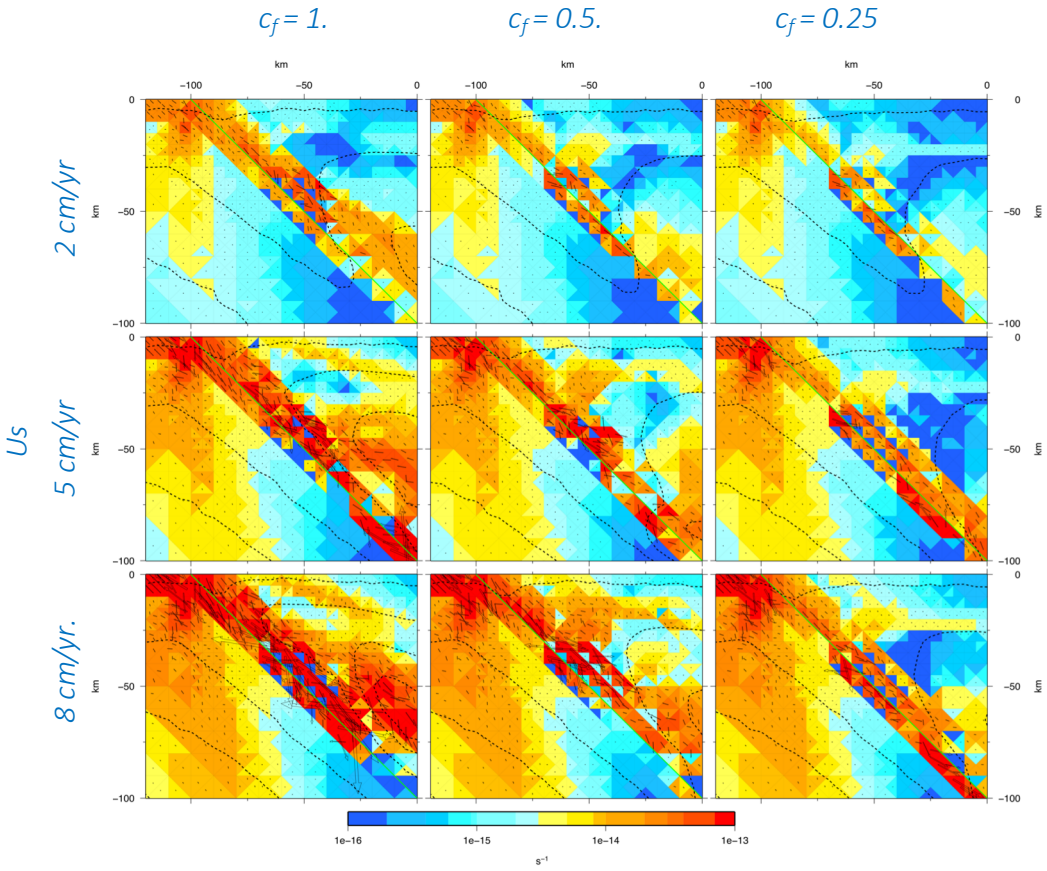
Answers to Addressed questions

MAXIMUM SHEAR STRAIN RATE IN THE WEDGE AREA



3. Can the gravitational signature of slow tectonics provide information on the plate coupling – important for establishing the seismogenic potential of subduction zones? → YES

- Comparison of model results and EIGEN6C4 model in two case studies allows constraining the amount of plate coupling, thus providing the amount of the seismic moment release.
- This may be relevant even for the Mediterranean subductions, such as the Calabrian one, whose amount of coupling is still completely unknown, which may be relevant for the estimate of the seismic potential of this earthquake prone area.

4. Is it possible to constrain the rheology controlling the seismic cycle, from the inter- to the post-seismic phase? → YES

The rheology can be obtained from the compositional and phase change processes occurring in the wedge area.

1. Activities and Heritage

The general pattern of the gravity gradients resembles to a certain extent the bipolar pattern of the gravity.

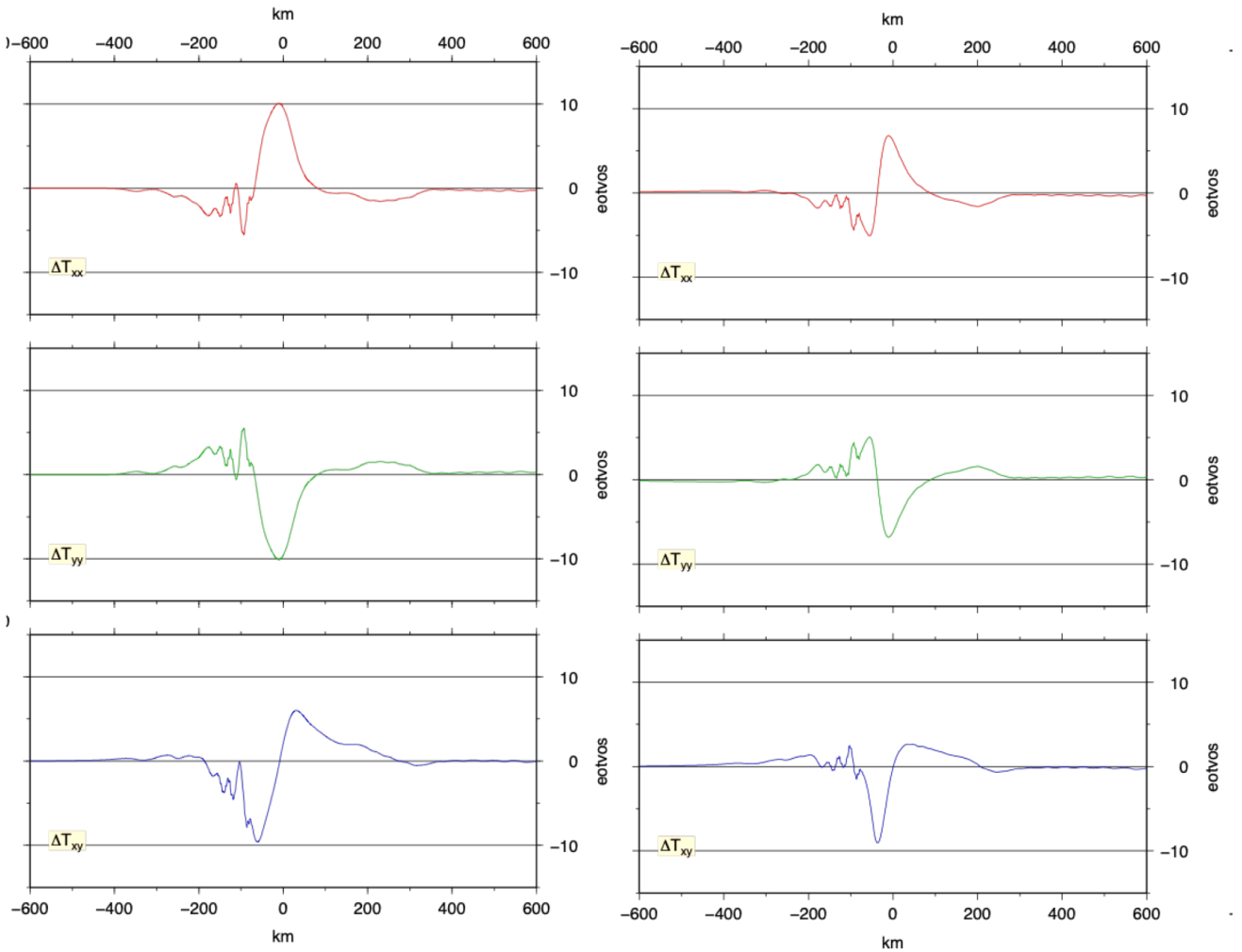
There is on the other hand a peculiar characteristic in the gravity gradients, which clearly portray an higher frequency content compared to the gravity in terms of short wavelengths.

This is due to the shallowest density anomalies in the wedge, the density structure in this region depending on the complex dynamic and convective processes characterizing this region.

This finding is very promising since it show that studying the gravity gradients at subduction zones, and in any active tectonic regions of the Earth from GOCE and in perspective of NGGM, will shed light on the physics of the processes characterizing the wedge region as well as on the rheology of these seismically important regions of our planet.

GRAVITY GRADIENTS

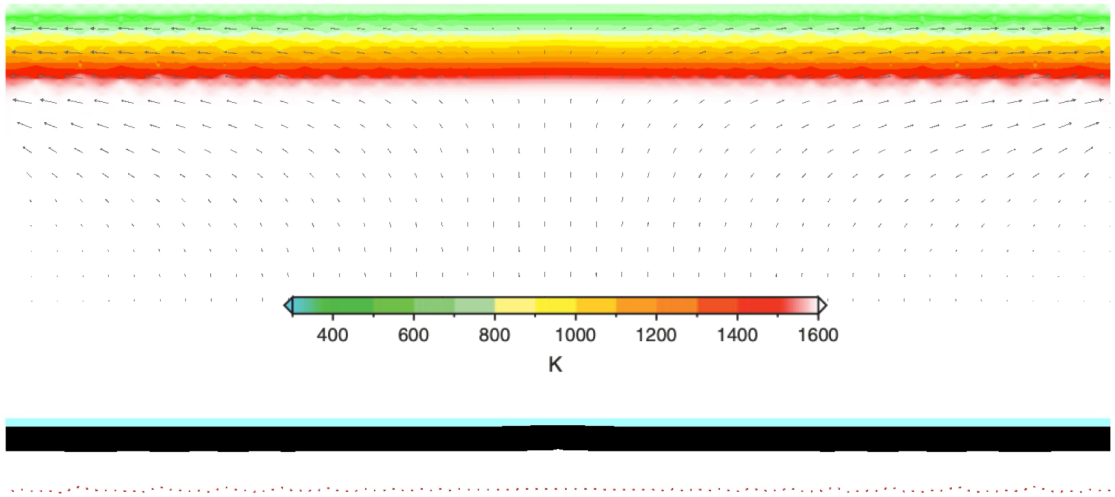
Us= 8 cm/yr *Us= 5 cm/yr*

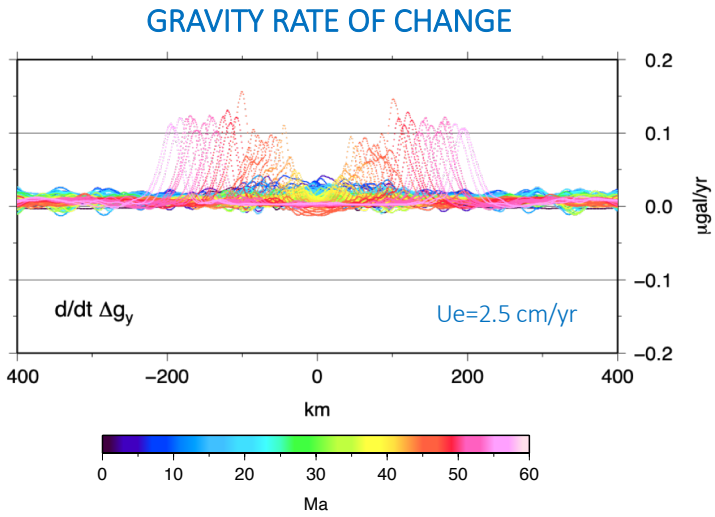


θ_s=45° c_f=1

2. Ongoing activities in relation to NGGM

1. *Extensional setting*





Water | Continental crust | Serpentinized mantle | Oceanic crust | Non serpentinized Oceanic mantle | Partial melting area

2. *Implementation of 3D slow-active tectonics model, starting from the 2D model → gravity gradients*

2. Ongoing activities in relation to NGGM

Slow-active Tectonics di Gravitational Seismology corresponds to **SRL4: Proof of concept**

4.5.1.1 Key questions to address

- Q: Is the scientific goal confirmed and translated into mission objectives, mission requirements and system requirements?

  A: Yes. The scientific goal is confirmed and translated into the FINAL REPORT of Gravitational Seismology, page 79/91, and in the NGGM/MAGIC MRD (citation RD8), in terms of 0.05 μGal/yr, which means a Mission Requirement of about 0.5 μGal over 10 yr of NGGM fly time: this represents a challenging Requirement in terms of capability of NGGM to detect linear trends, typical of slow tectonics.
- Q: Are Mission Requirements Document (MRD) and System Requirements Document (SRD) available with traceable requirements?

  A: Yes. The MRD is available with traceable requirements into the FINAL REPORT of Gravitational Seismology, page 79/91, and in the NGGM/MAGIC MRD (citation RD8).
- Q: Is a model (software package) available that allows the computation of measurements based on on observation input data?

  A: Yes. A software package exists that has been widely validated on several case studies.
- Q: Is the model technically and scientifically adequate and has it been independently reviewed?

  A: Yes. The model has been reviewed by peers (e.g. RD8).
- Q: Has the sensitivity of the measurements to the targeted geophysical parameter been demonstrated based on representative measurement data (e.g. campaign data) or in any other way?

  A: It is necessary to develop new advanced techniques of analysis of the temporal series able to distinguish the different signals (e.g the linear trends of the slow tectonics from the earthquakes signature)
- Q: Has a risk analysis been performed?

  A: NO.
- Q: Has a demonstration data set of measurements been produced?

  A: Yes, in terms of graphs and numerical values of model predictions.

3. Development plan of current/proposed activities

SRL4: Proof of Concept

The measurement concept is validated.
A model linking geophysical parameters and measurements is established.
Sensitivity of the measurements to the targeted geophysical parameter is demonstrated through extensive analyses by means of dedicated experiments but at least through simulations.

SRL5: End-to-End Performance Simulations

An end-to-end measurement performance simulator is developed, tested and validated using realistic and / or actual measurements1.
The performance model used is applicable to a predefined range of conditions (including realistic uncertainties of natural and observational nature) and can be used to address the needs originating from the science requirements in an end-to-end manner.
Retrieval algorithms applicable for a realistic range of error sources (both geophysical and technical) are demonstrated against a predefined performance metric reflecting observation and measurement requirements.

We foresee:

- Exploiting our model to 3D (or 4D with time)
- Feeding the geodetic simulator counterpart with gravity anomalies changing linearly in time over the fly time, in order to catch the linear trends from NGGM/MAGIC Mission Requirement Document, Par. 2.5 - Solid Earth, within a close-loop simulation, requiring squeezing the payload capabilities from the industrial counterpart.
- Linking the slow tectonic model, contributing to the inter- and pre-seismic earthquake phases, to the co-seismic and post-seismic models, considered still separately within *Gravitational Seismology: all the gravity signals, from the static, to the slow and fast ones must be self-consistently linked together*.
- Extending this modelling to the Central Mediterranean, in the Calabrian subduction complex, for the seismic hazard assessment of Mw=7 earthquakes.

STRATEGY

translating already established short-term **SRL5: End-to-End short-term** approach by UNIMI into a new **SRL5: End-to-End** long-term approach