The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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IAEA
International Atomic Energy Agency

2142-9

Advanced Conference on Seismic Risk Mitigation and Sustainable Development

10 - 14 May 2010

The SISMA-ASI project: an innovative approach for seismic hazard mitigation

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Agenzia Spaziale Italiana, Sezione Osservazione della Terra

SISMA new approach towards the understanding of earthquake generation and seismic hazard mitigation builds over three major concepts:

- taking advantage of the new generation of DINSAR and GPS deformation data at the Earth's surface in conjunction with seismic flow monitoring

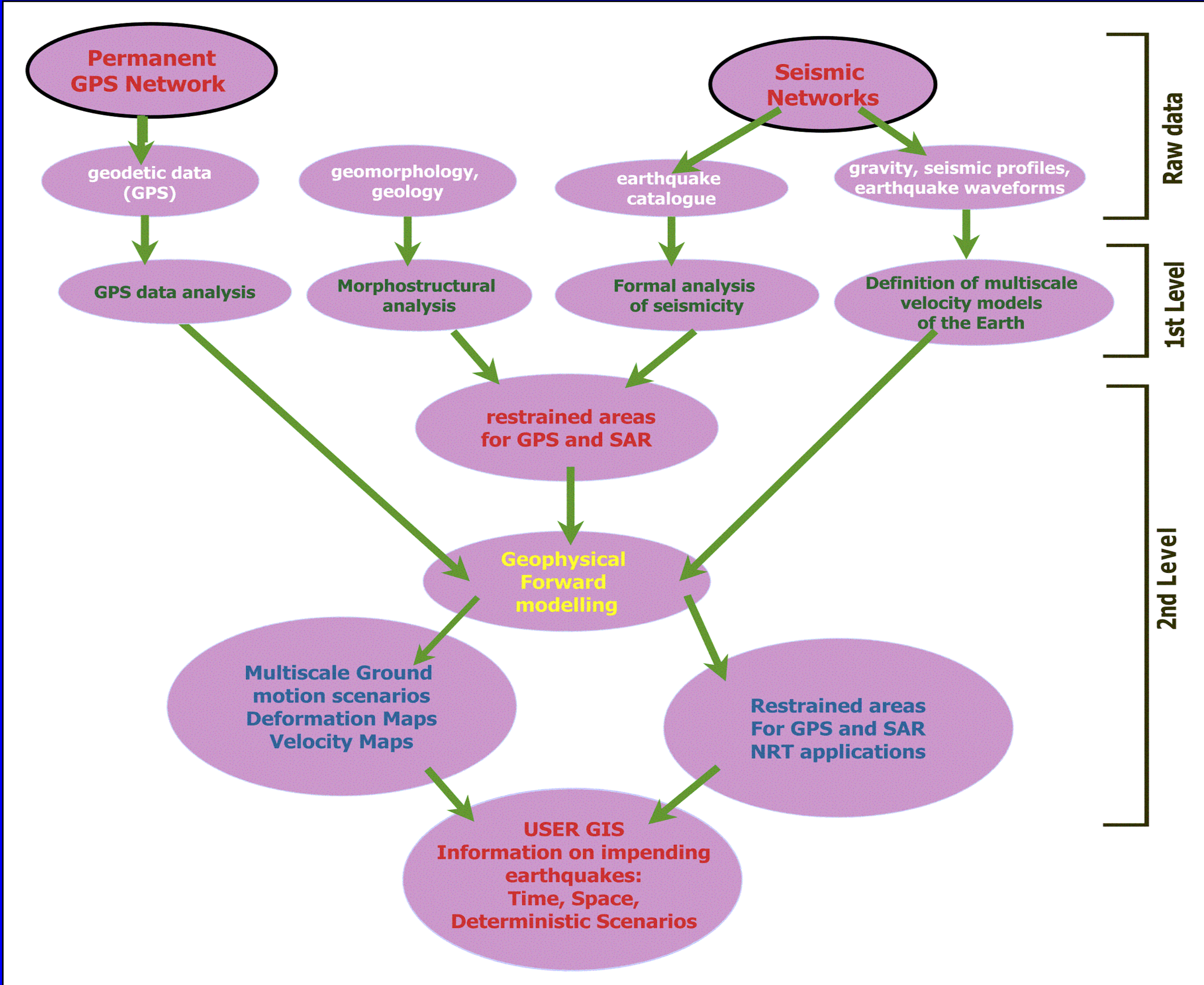
which in turn allow us

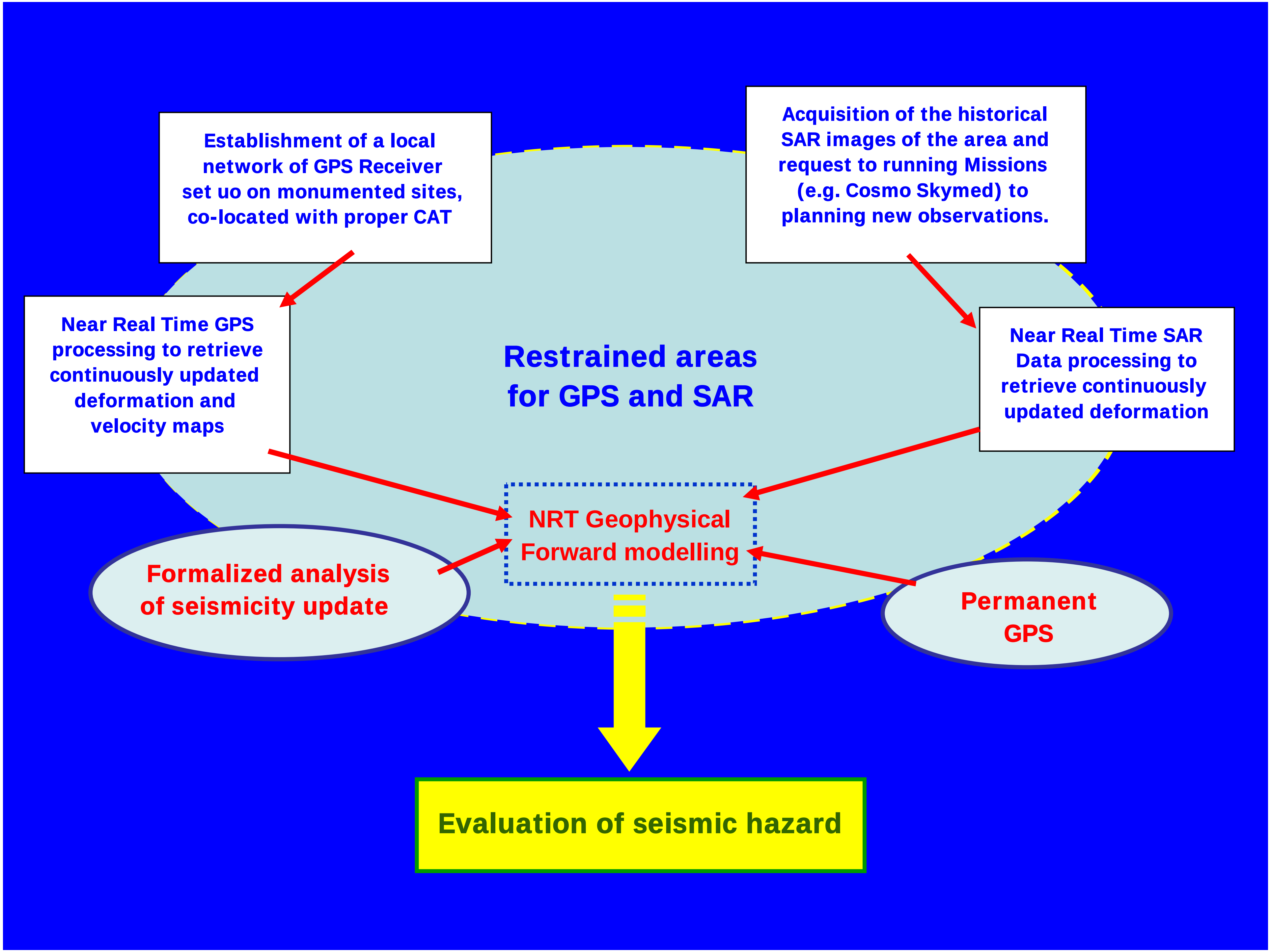
- building an integrated geophysical, geodetic and seismological scheme to disclose stress build up within the gouge of sesmic active faults for a deterministic approach of earthquake cycle description

which in turn allows us

- overcoming the obvious shortcomings of the old approach to seismic hazard mitigation based on a purely probabilistic approach

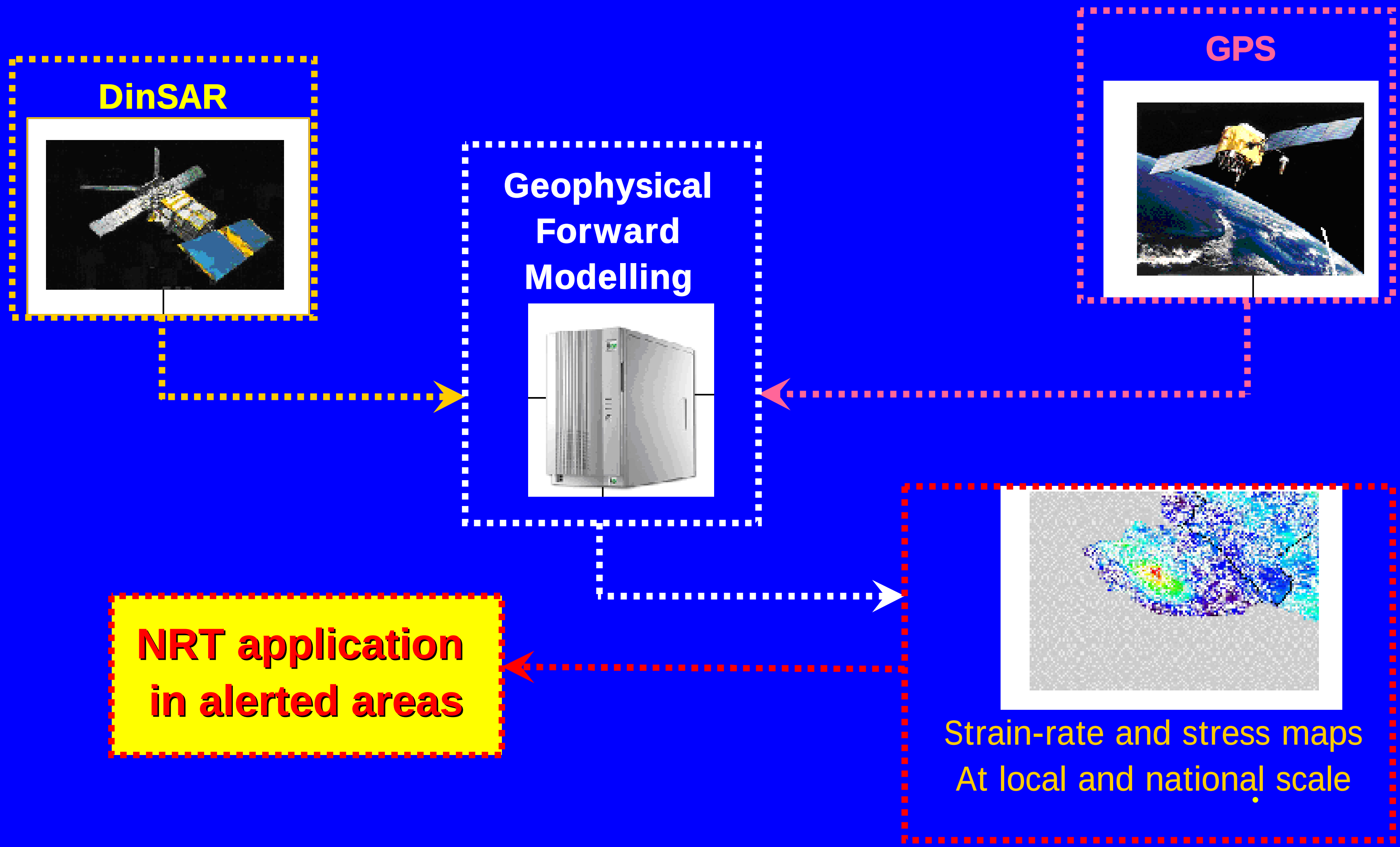
SISMA Overall Description




Establishment of a local network of GPS Receiver set uo on monumented sites, co-located with proper CAT
Acquisition of the historical SAR images of the area and request to running Missions (e.g. Cosmo Skymed) to planning new observations.
Near Real Time GPS processing to retrieve continuously updated deformation and velocity maps
Restrained areas for GPS and SAR
Near Real Time SAR Data processing to retrieve continuously updated deformation
NRT Geophysical Forward modelling
Formalized analysis of seismicity update
Permanent GPS
Evaluation of seismic hazard

- **Maps of alerted areas, prone to earthquake events with given magnitude, will be obtained through comparison of non-EO information, provided by seismological data analysis, and taking into account results provided by Geophysical Modelling based on EO information;**
- **EO observations, consisting of GPS and DinSAR images, will permit to draw deformation maps on the surface;**
- **Stress maps at the depth of the active faults will be obtained through integration of EO geodetic information into Geophysical Forward Modelling.**

EO Data in Near-Real-Time Application



Which is the contribution of Earth Observations?

- **Inter and pre-seismic phase:** monitoring of surface deformations, which is a possible indicator of stress build up on faults
- **Co-seismic phase:** improve understanding of the process taking place along the fault plane and permit estimating of the interactions of the stress field (modified after the seismic event) and nearby faults.
- **Post-seismic phase:** monitoring possible phenomena (e.g. afterslip, post-seismic relaxation) that may affect the stress field in the lithosphere

Three seismogenic zones,

Friuli-Venezia Giulia

Umbria-Marche

Pollino (Calabria)

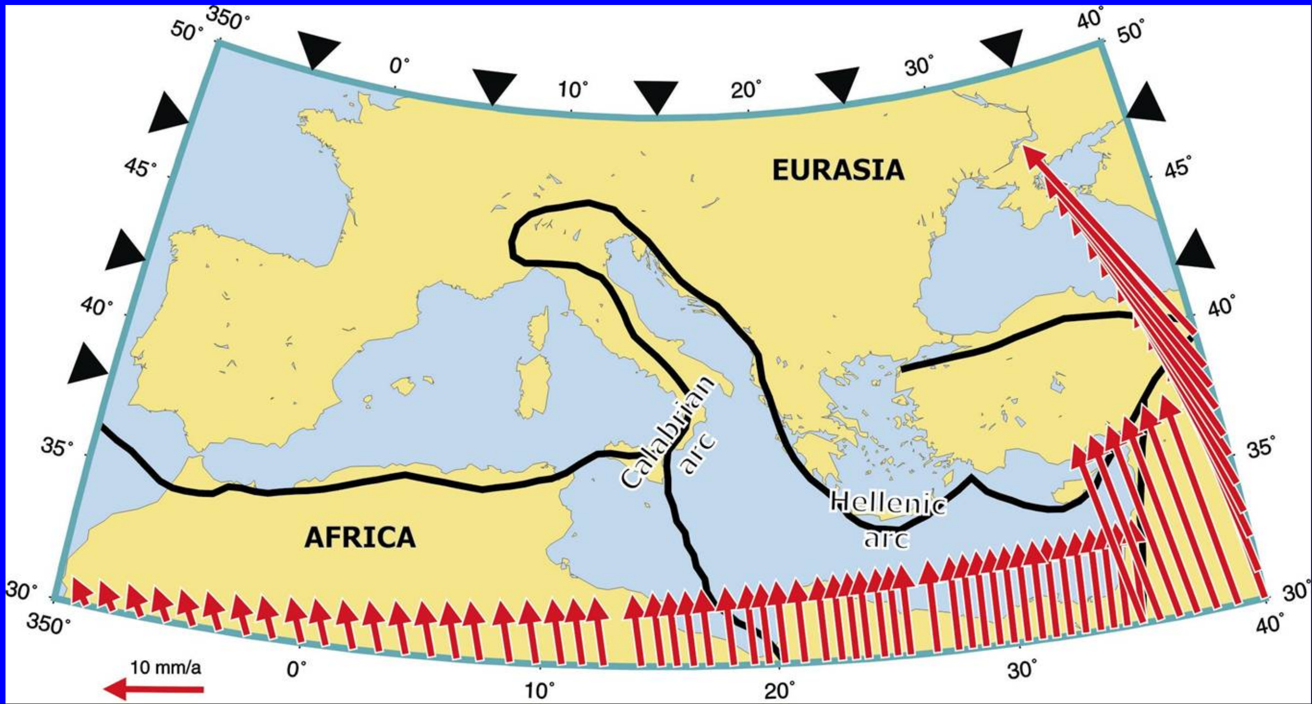
are test sites for SISMA applications.

These active seismogenic zones are embedded within the diffuse plate boundary between Africa and Eurasia, in the central Mediterranean

- SISMA

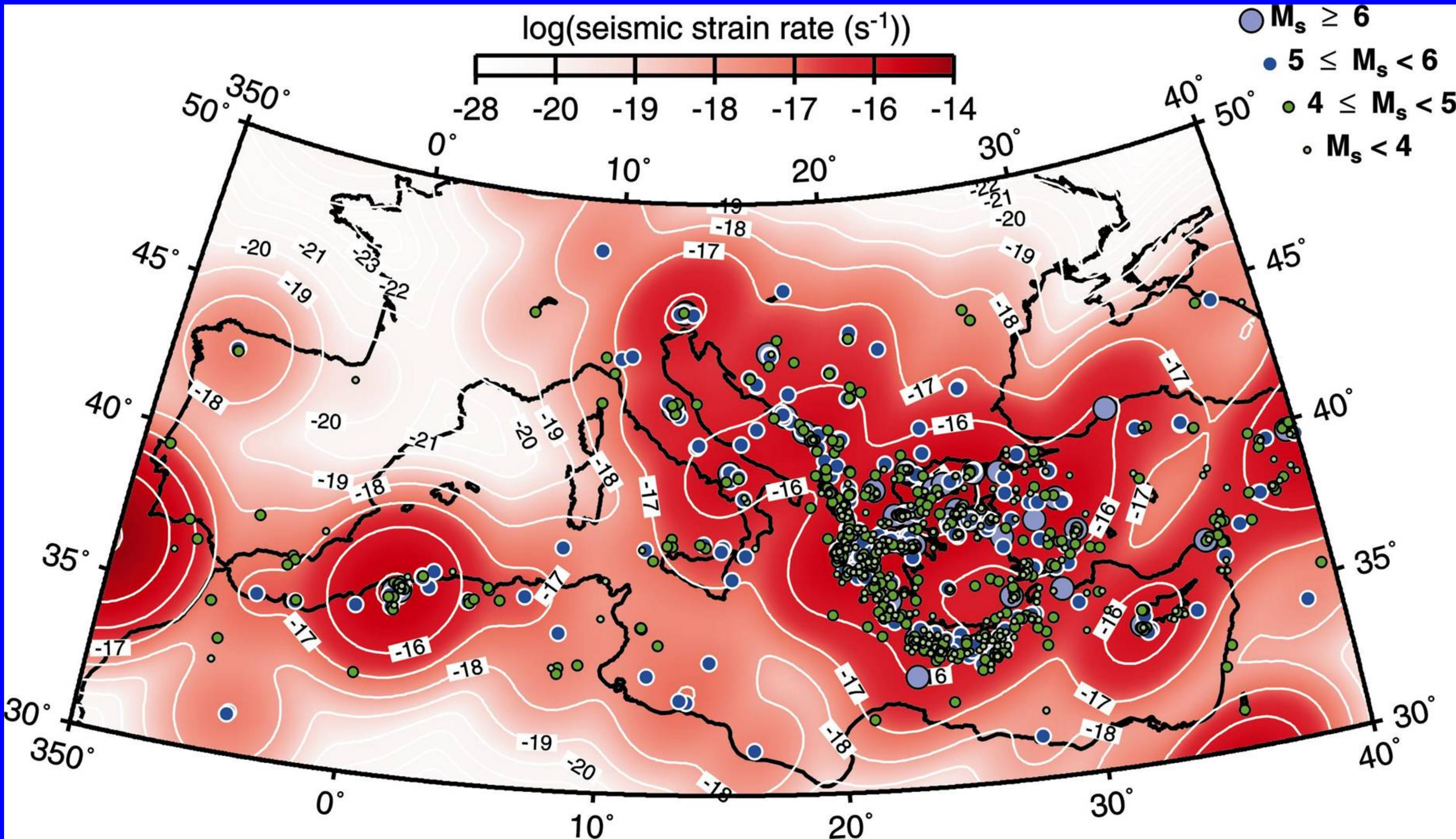
- National scale

Africa-Eurasia relative motion from paleomagnetic data (NUVEL-1A)



The selected test sites are embedded within an highly deforming Mediterranean, as shown by the strain-rate inferred from the cumulative deformation induced by the earthquakes of the NEIC catalog

Seismicity (Ms, NEIC 1903-1999) and calculated seismic strain rate

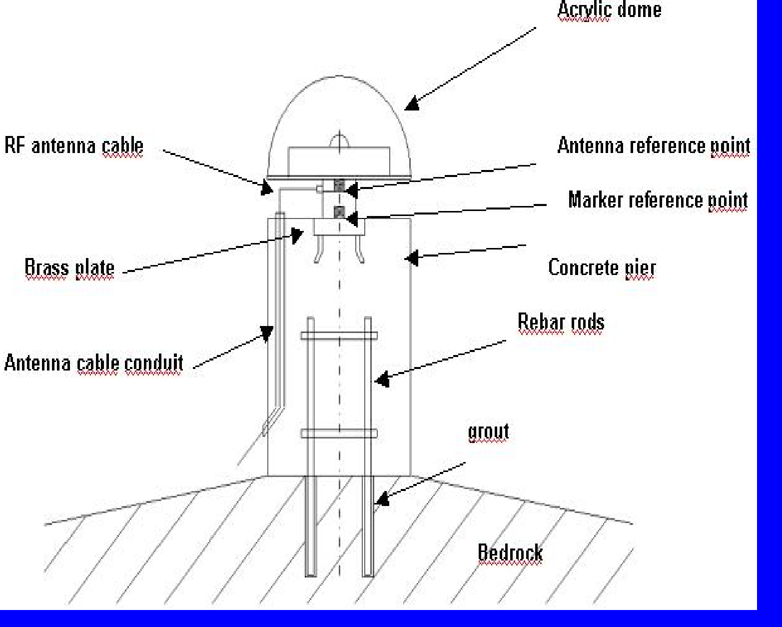


GPS implementation and GAIN network

The following two pictures show a typical implementation of a permanent GPS receiver on bedrock (Nocara, Calabria)

and

the GAIN network for the Alpine space, to be used within the development of SISMA

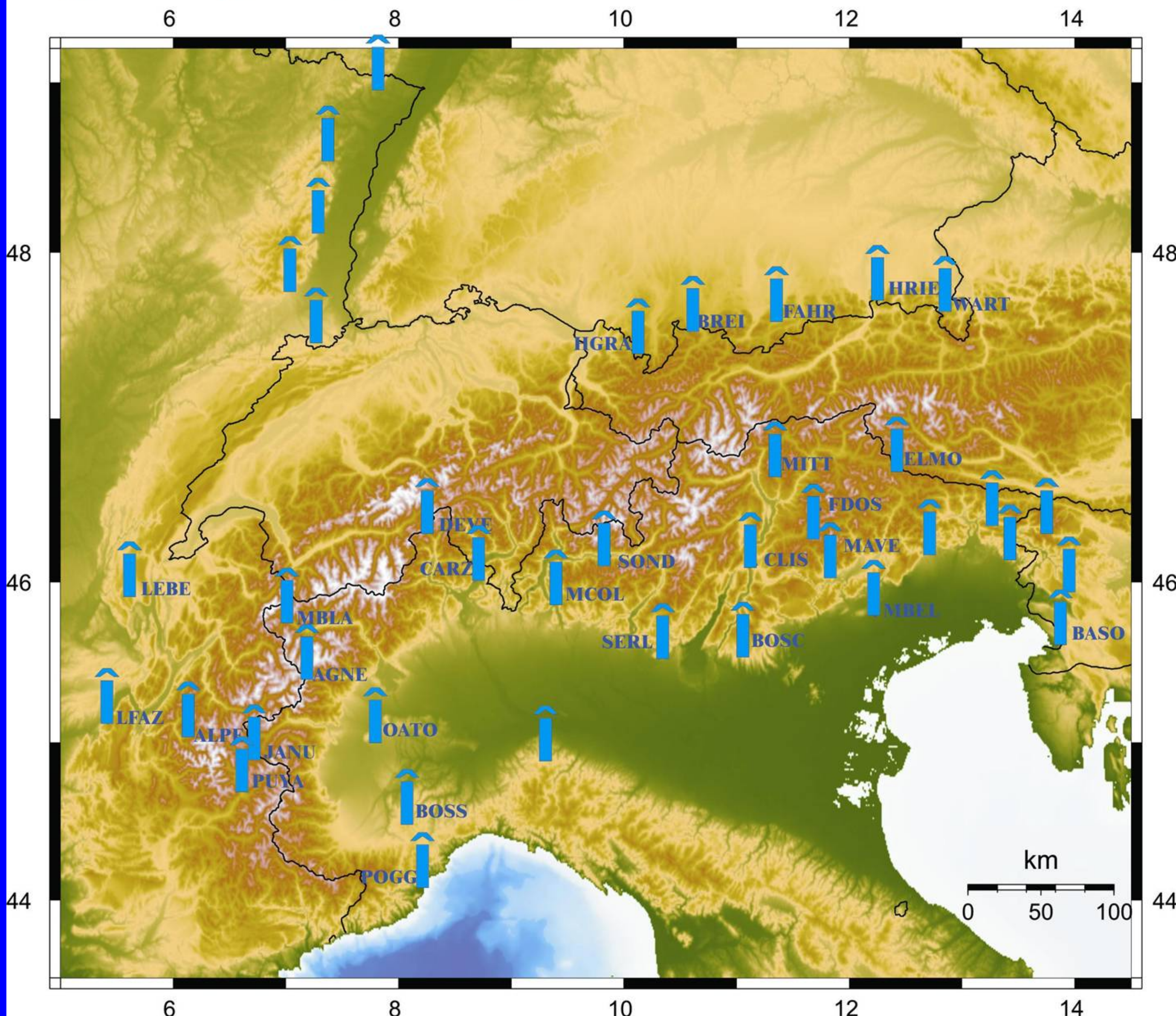


Acrylic dome
RF antenna cable
Antenna reference point
Marker reference point
Brass plate
Concrete pier
Rebar rods
Antenna cable conduit
grout
Bedrock

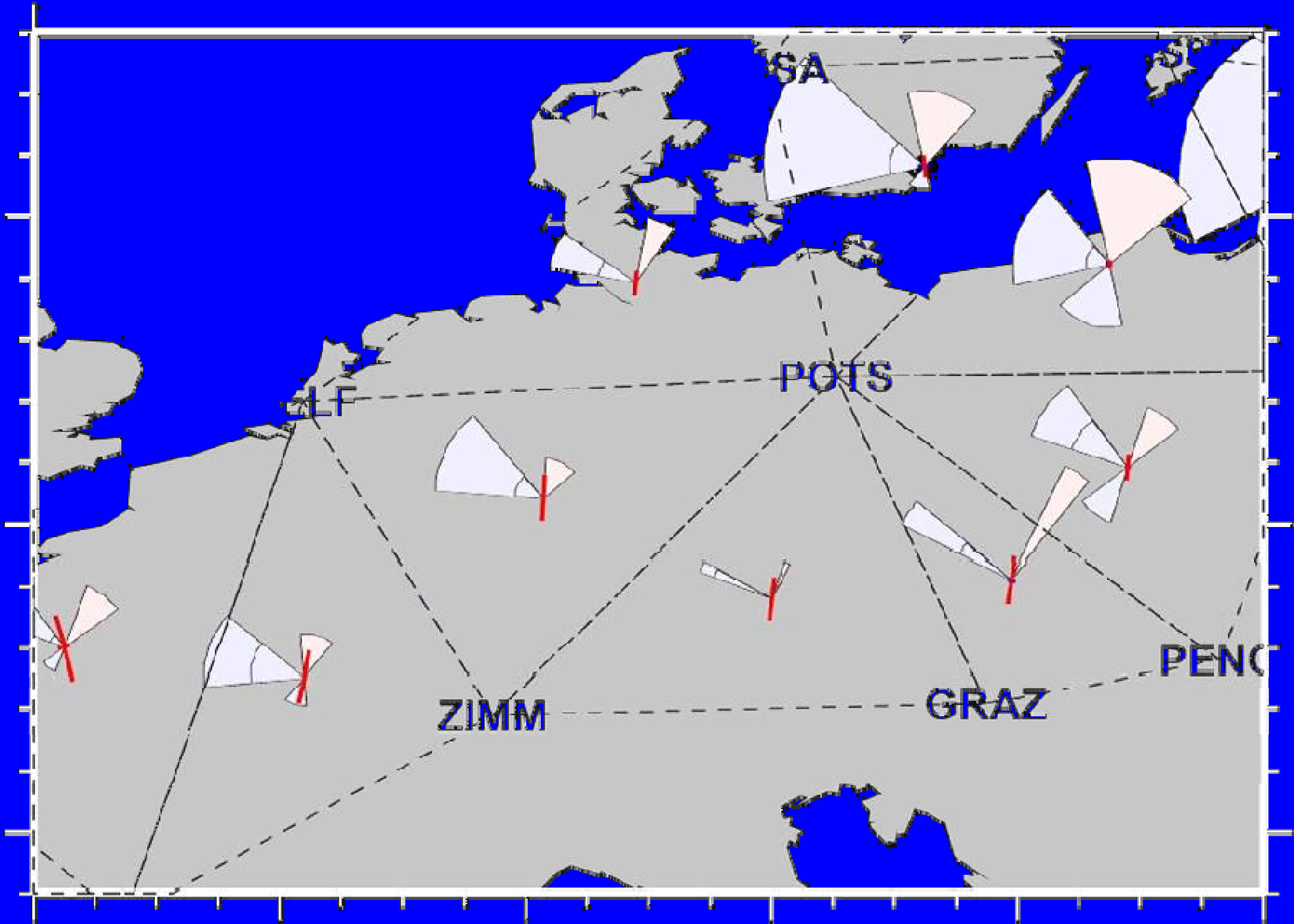
ALPS GPSQUAKENET

Interreg III B

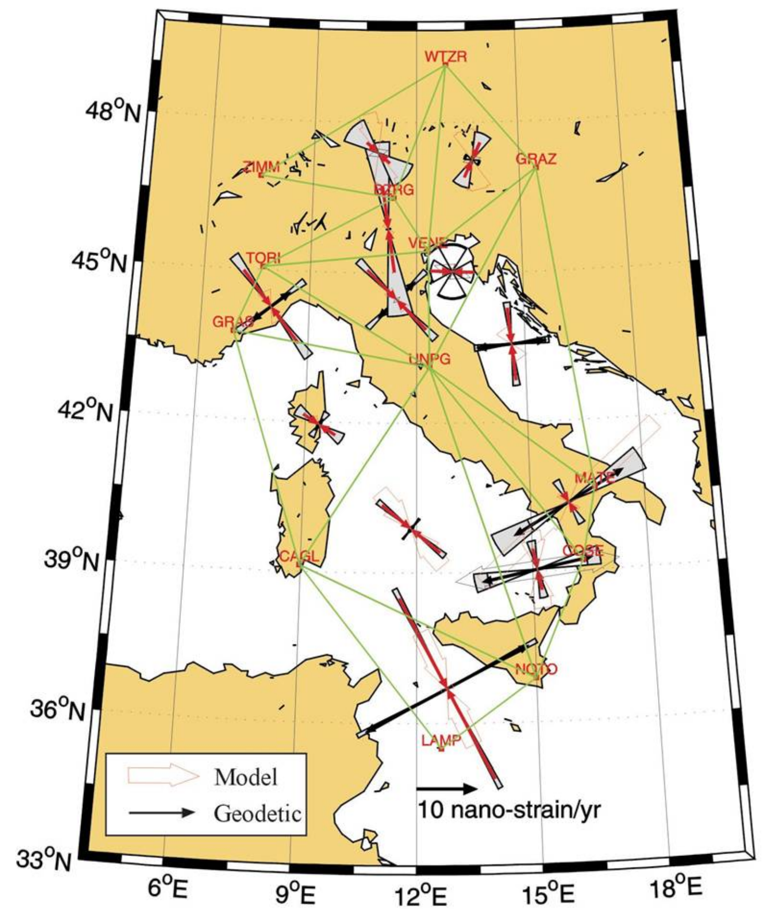
GAIN - Geodetic Alpine Integrated Network



Permanent GPS observations



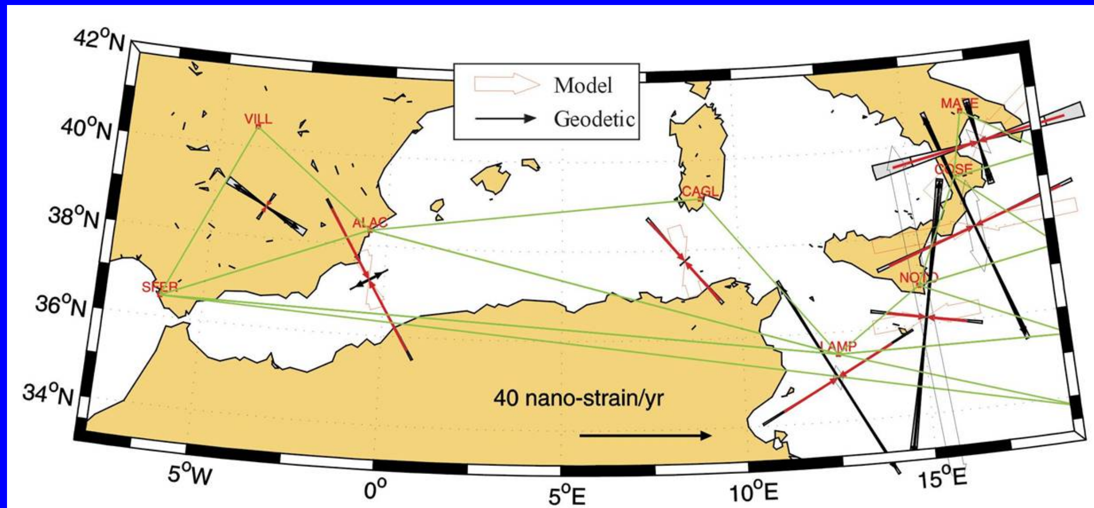
Marotta, A. M. and R. Sabadini, GJI 2004 – The signatures of tectonics and glacial isostatic adjustment revealed by the strain rate in Europe



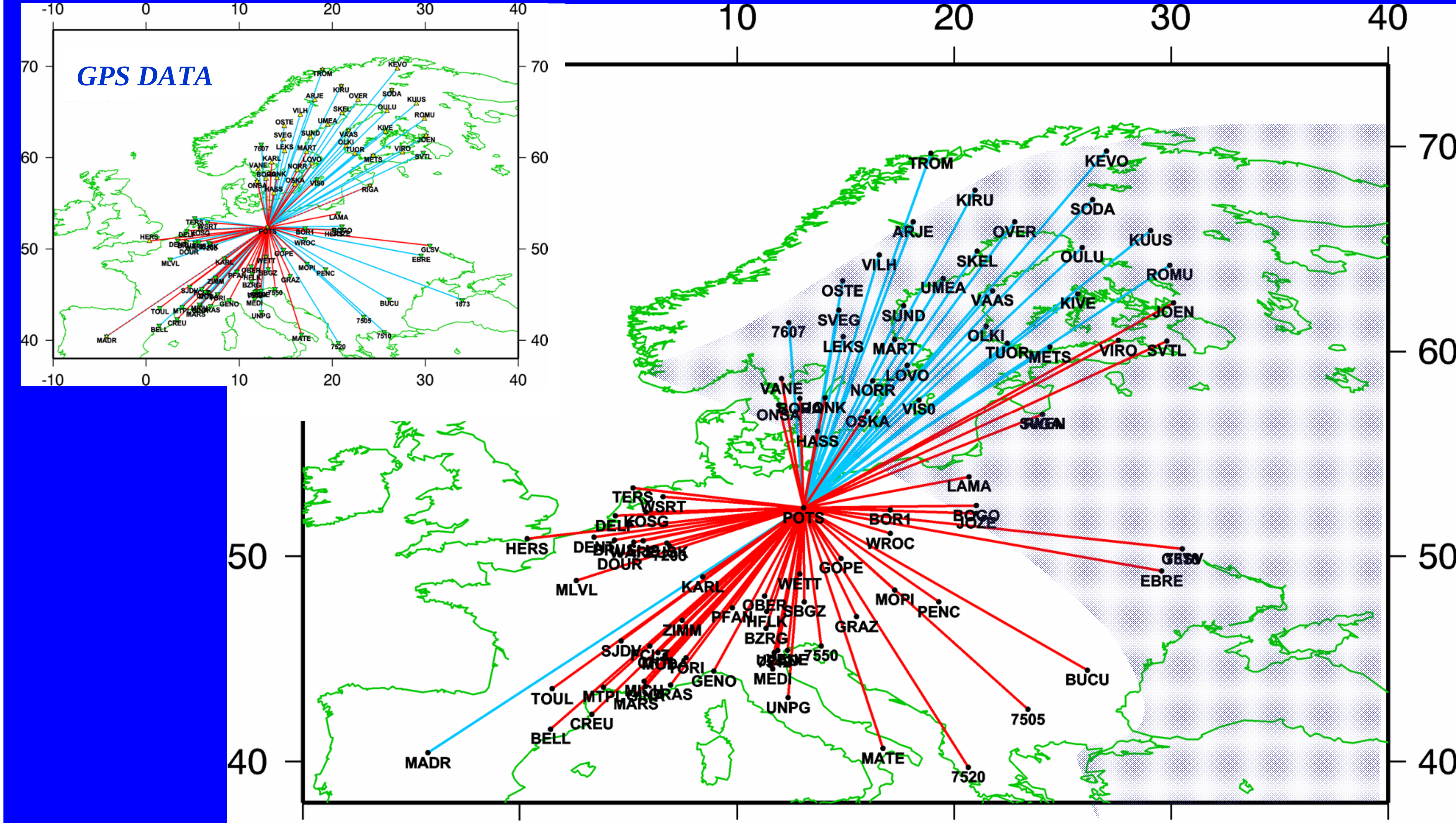
Horizontal principal strain rate tensor

Model B:
active convergence
+
subduction forces in the Hellenic (*deep slab*) and Calabrian arcs

Jimenez-Munt, I. et al., (2003) Active deformation in the Mediterranean from Gibraltar to Anatolia inferred from numerical modeling and Geodetic and seismological data



Comparison between predicted crust and lithosphere deformation patterns and GPS data to verify the feasibility of seismic hazard mitigation: baseline variations



Marotta, A. M. et al., JGR 2004 – Combined effects of tectonics and glacial isostatic adjustment on intraplate deformation in central and northern Europe: Application to Geodetic baseline analysis.

The probabilistic analysis supplies indications that can be useful but are not sufficiently reliable to characterize seismic hazard

Algorithms for middle-range intermediate-term prediction

Algorithms fully formalized and globally tested for prediction are:

- **CN algorithm** (*Gabrielov et al., 1986; Rotwain and Novikova, 1999*)
- **M8 algorithm** (*Keilis-Borok and Kossobokov, 1987; Kossobokov et al., 1999*)

They allow to identify the TIPs

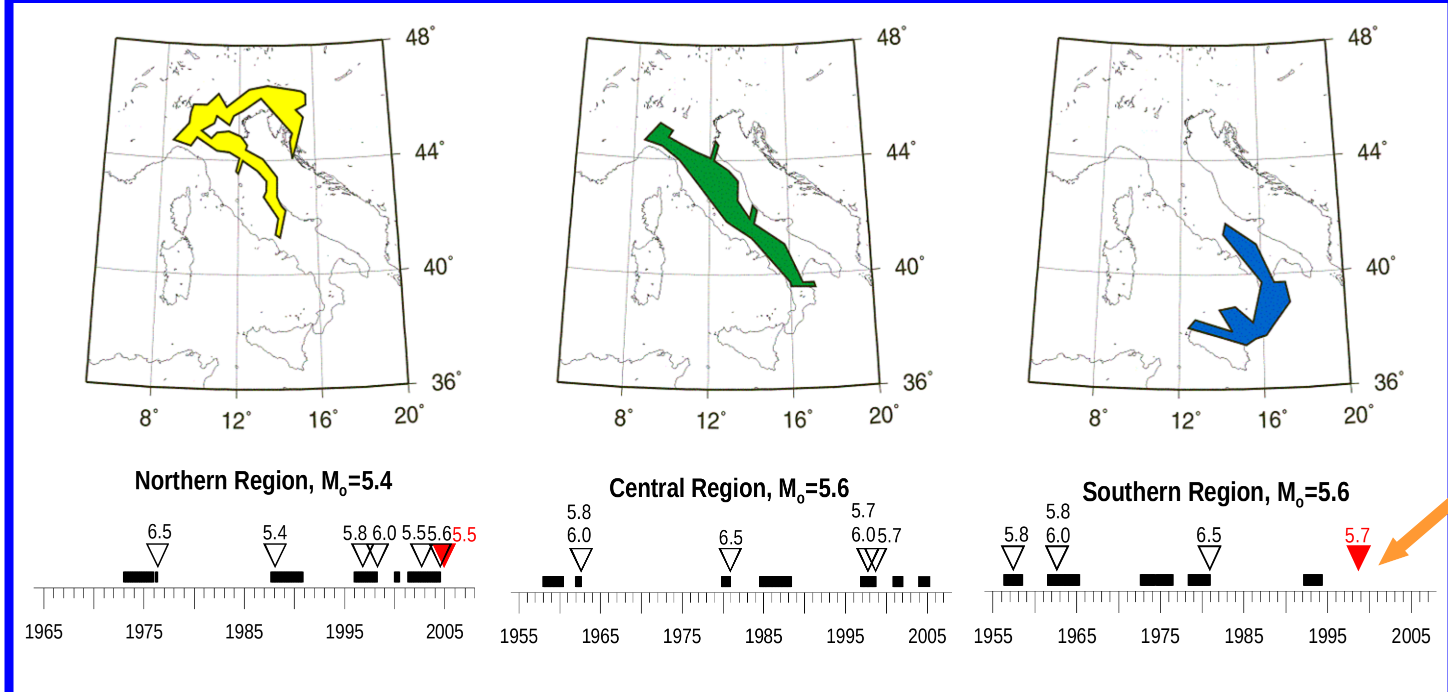
(Times of Increased Probability) for the occurrence of a strong earthquake within a delimited region

Algorithms for middle-range intermediate-term prediction

The algorithms are based on a set of empirical functions to allow for a quantitative analysis of the premonitory patterns which can be detected in the seismic flow:

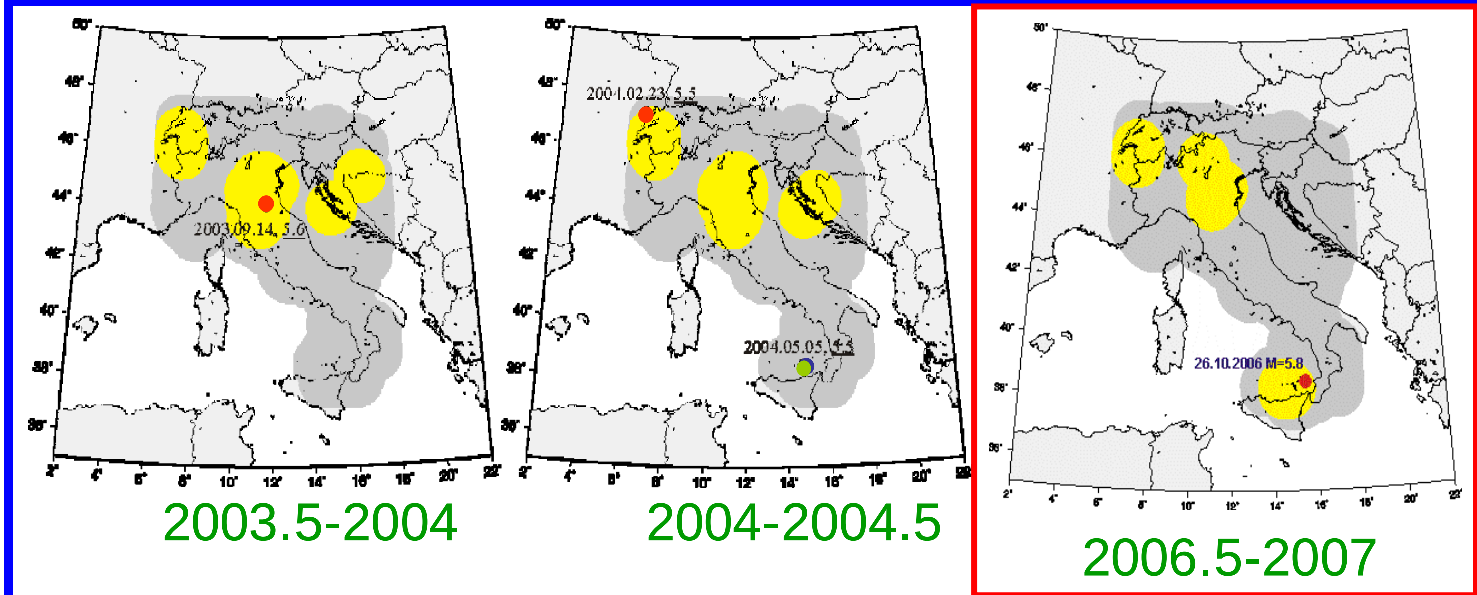
- Variations in the seismic activity
- Seismic quiescence
- Space-time clustering of events

These methods make use of detectable inverse cascade of seismic process, at different space and time ranges, to reduce consecutively space and time limits where a disastrous earthquake has to be expected.



CN algorithm

Times of Increased Probability for the occurrence of events with M>Mo within the monitored regions



M8S algorithm

Monitored region

Alerted region

Events with M_{max} ≥5.5 occurred since July 2003

Updated to March 1 2007

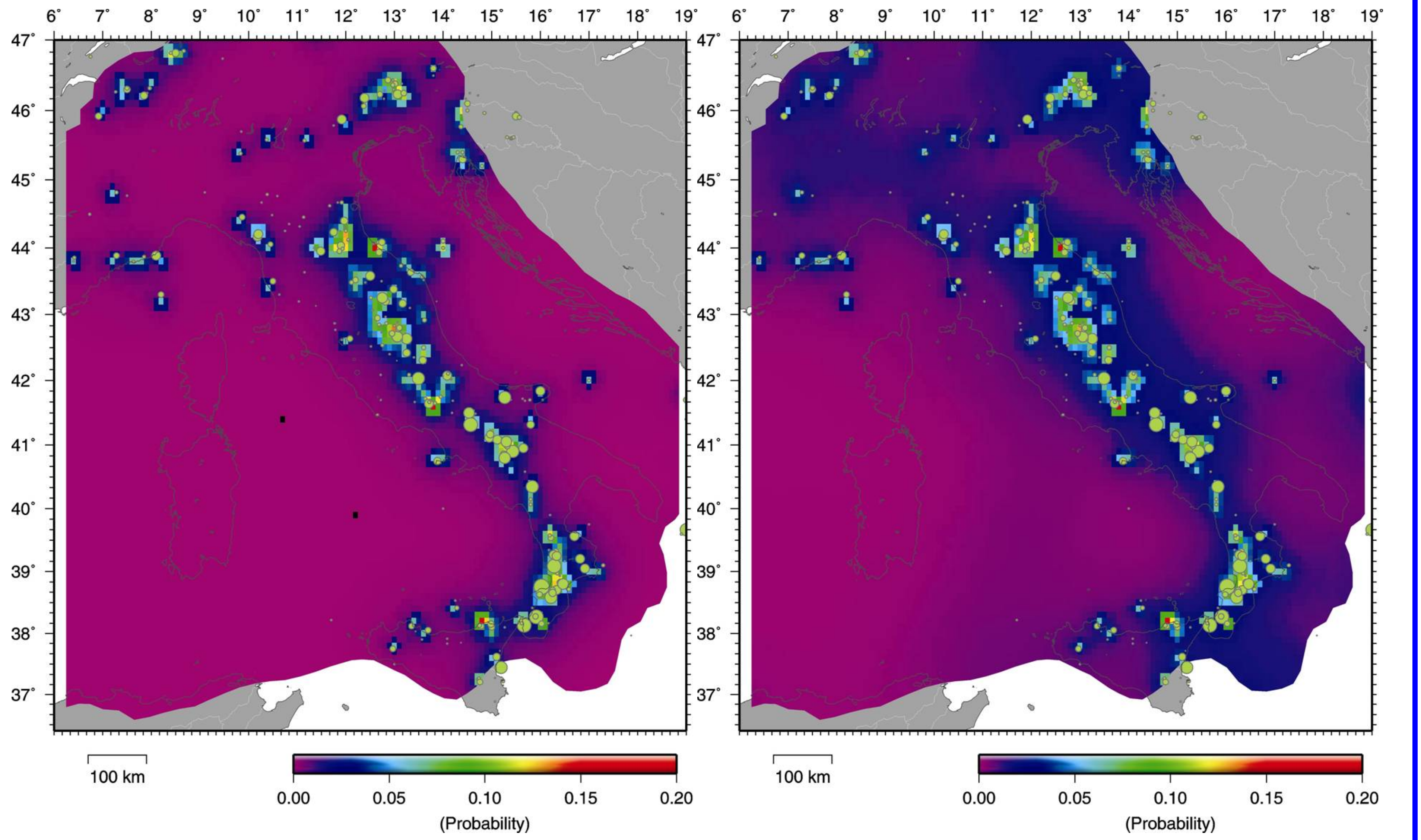
(*Peresan al., Earth Sci. Rev. 2005*)

Bayesan integration

SISMA foresees the integration of these middle-range, intermediate-term prediction algorithms with strain-rate patterns from GNSS (Global Navigation Satellite System) and GFM (Geophysical Forward Modelling) at the national level

A first example of Bayesan integration limited to historical seismicity and strain-rate from GFM is shown in the following picture

Feasibility of seismic hazard mitigation by means of
the synergic use of historical seismicity and geophysical modeling.



Probability of at least one earthquake with magnitude greater than 5.5 in fifty years in each cell.

•SISMA

•Local scale

•of the single seismogenic zone

A step ahead in Plate Tectonics

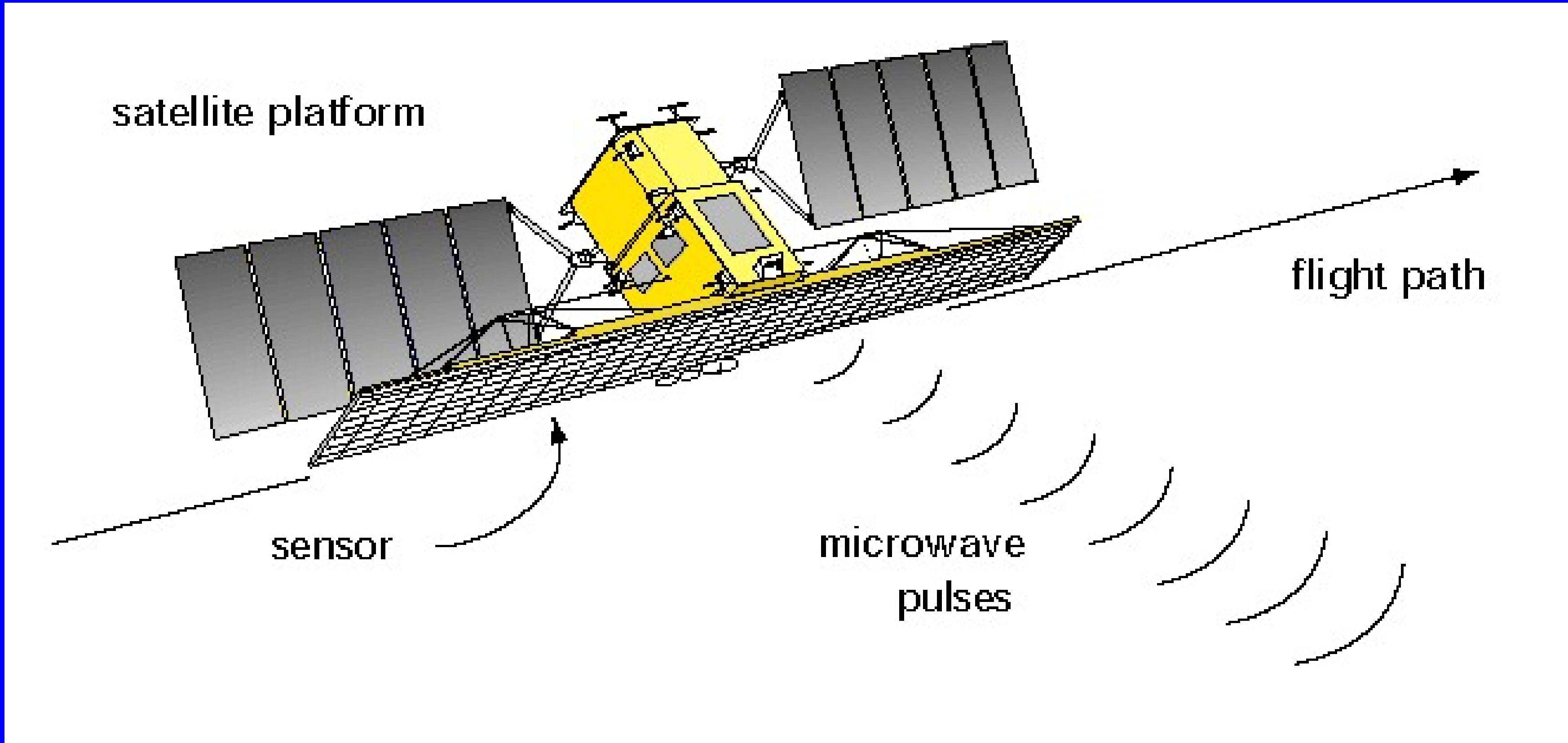
A key issue in our understanding of the Earth is the behaviour of active fault system at plate boundaries, during their inter-seismic phase. DInSAR and GPS techniques, and geophysical modelling, make nowadays possible to detect and to model the deformation style of the Earth's deforming zones at different spatial wavelengths and time scales.

From surface geodetic data, we can thus image stress-built up and deformation at the local scale of the fault gouge volume, embedded at depth within the regional deforming tectonic zone.

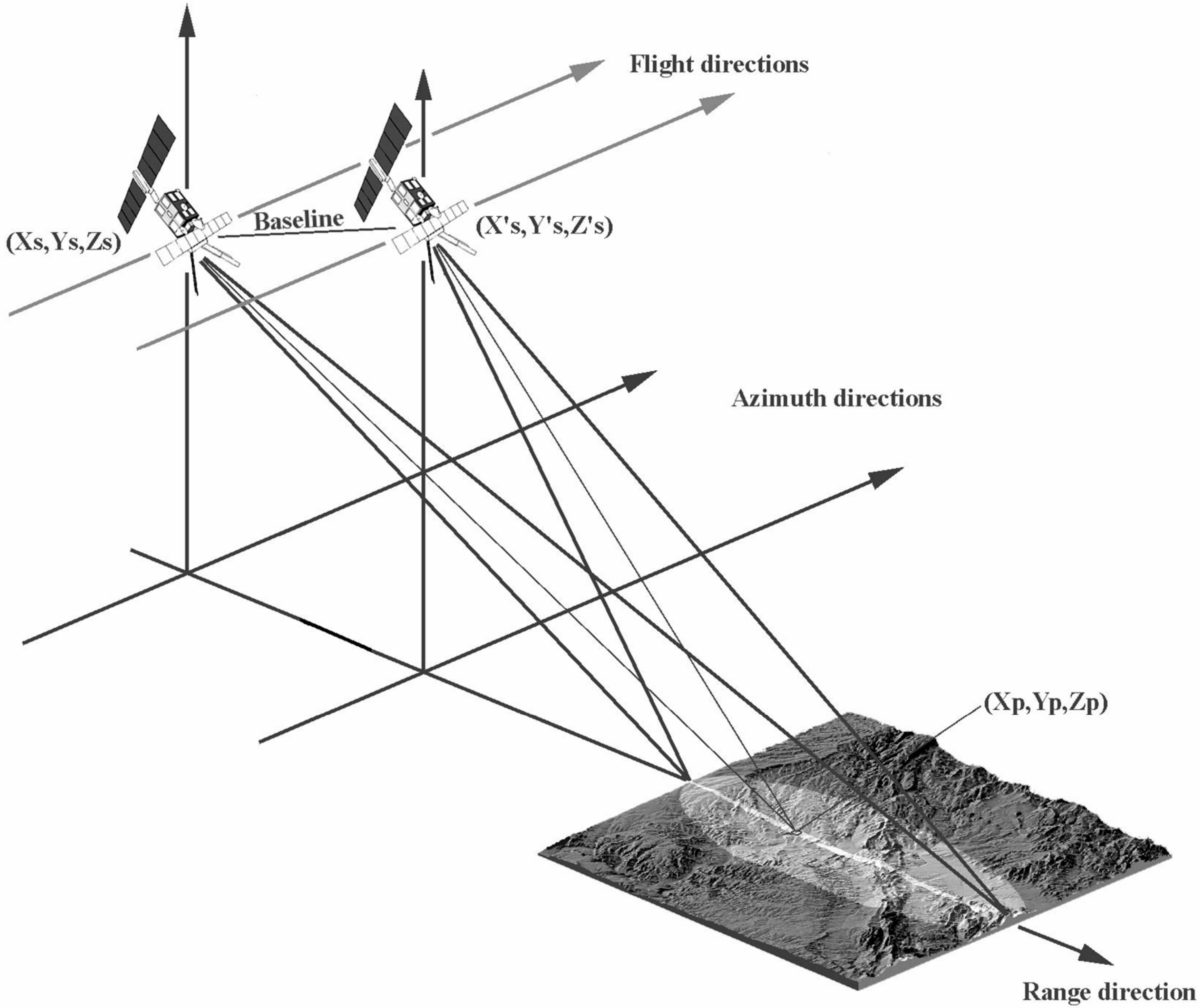
Plate tectonics can thus make a step ahead, from the kinematics of relative plate motion at the global scale inferred from paleomagnetic and global GPS data, to the regional and local spatial scale of active faults at plate boundaries, where horizontal and vertical deformation from GPS networks and DInSAR imaging constrain the deformation style of the Earth's crust to characteristic dimension as small as tens of kilometers, in an almost near real time fashion.

Such a fully integrated geophysical and geodetic approach is being tested within the Pollino area, in Southern Italy, in Friuli Venezia-Giulia and in the Umbria Marche region, all deforming zones characterizing the plate boundary between Africa and Eurasia in central Mediterranean.

DinSAR Data Acquisition

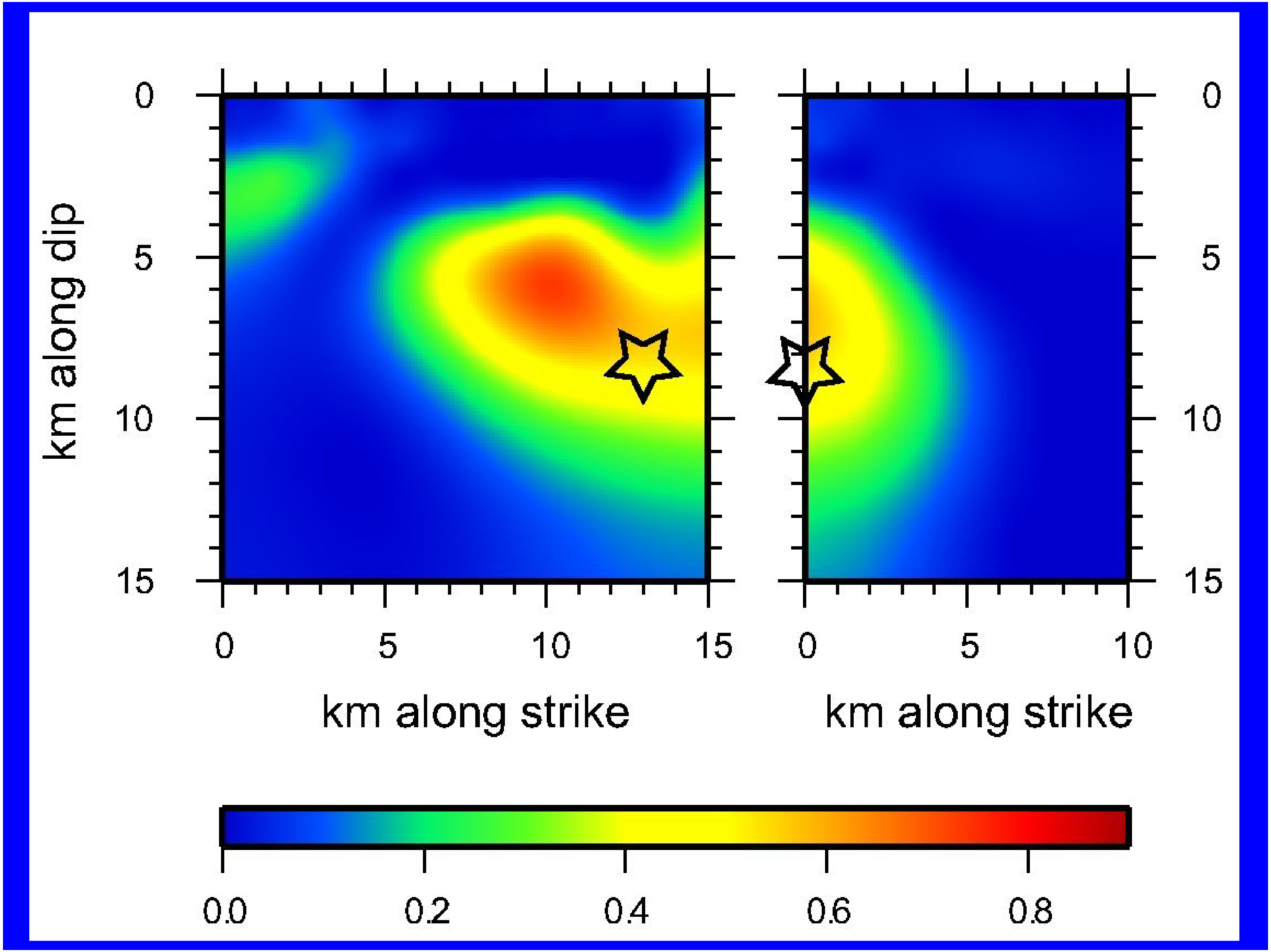


- Pulse transmission
- Propagation, interaction with surface ➔ echoes
- Acquisition of echoes, with a delay: $t = 2 R / c$
  ➔ the system measures distances
- Transmission of pulses along the orbit ➔ 2D sampling of terrain

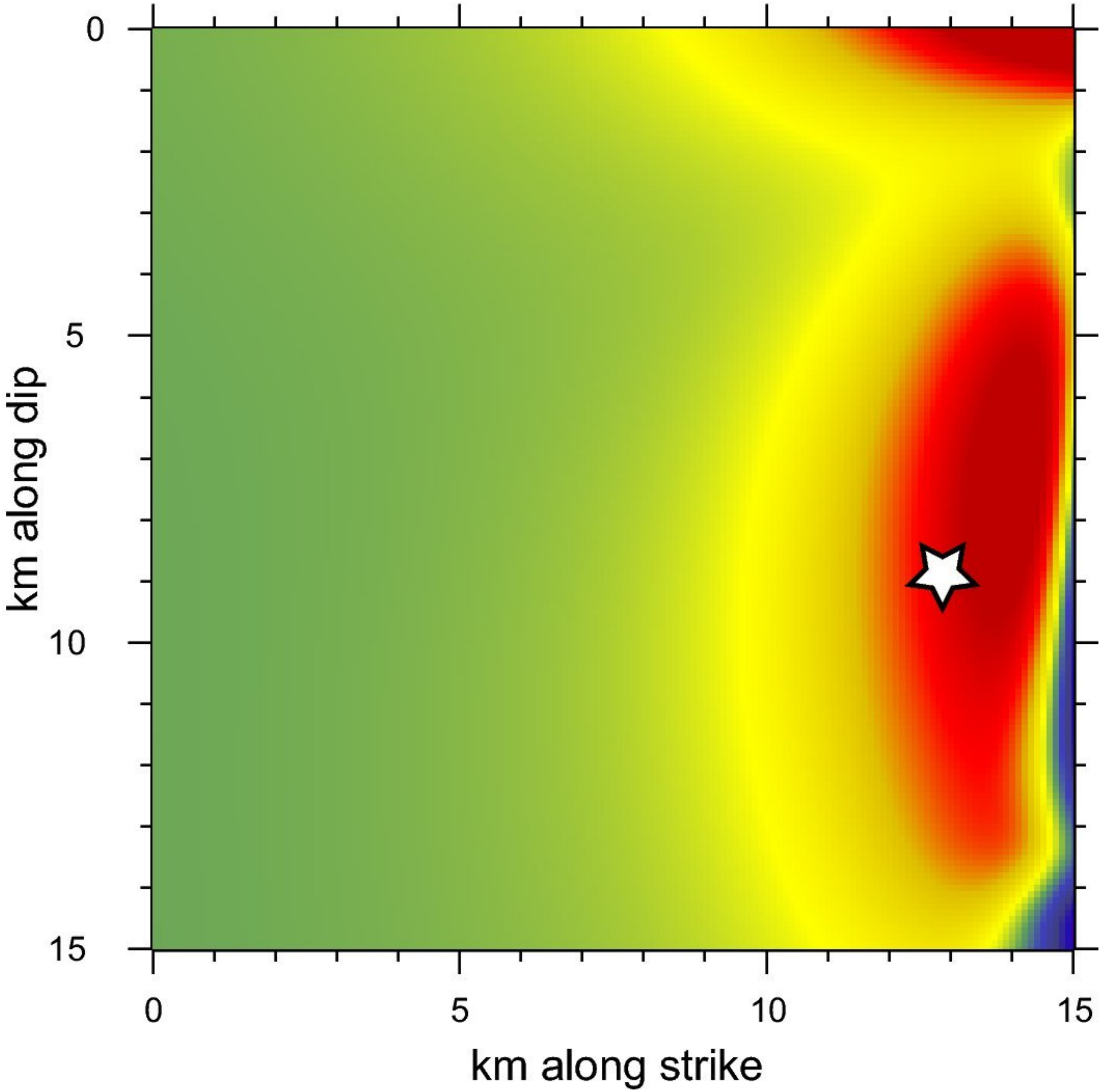

Flight directions
Baseline
(Xs,Ys,Zs)
(X's,Y's,Z's)
Azimuth directions
(Xp,Yp,Zp)
Range direction

Slip and stress changes during the 1997 seismic Colfiorito sequence

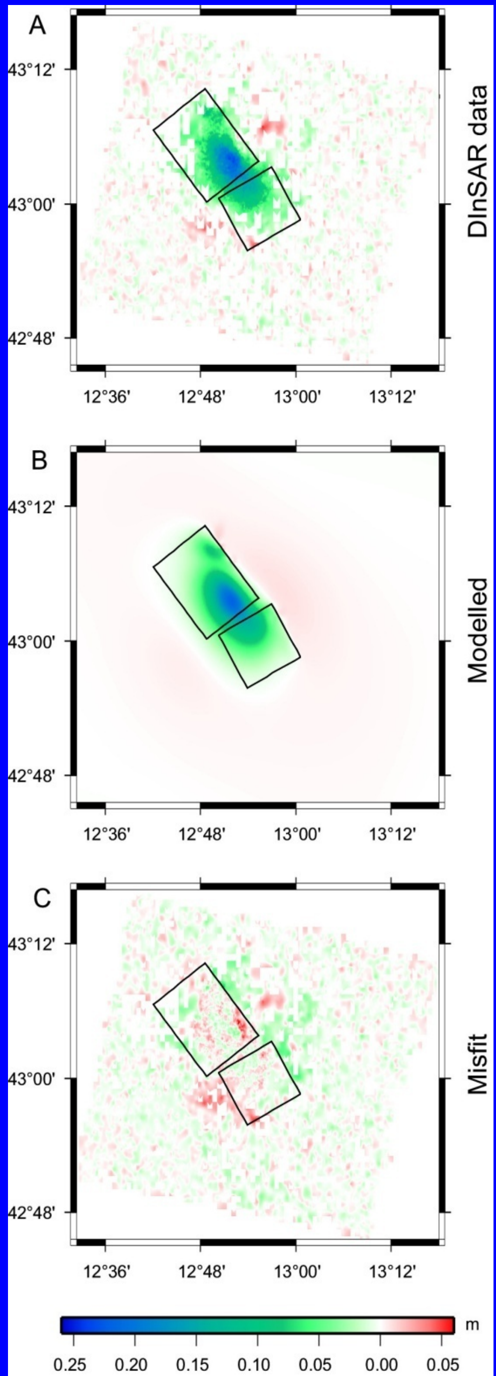
The following two pictures portray the newly generated slip DINSAR based inversion during the Colfiorito seismic sequence, corresponding to the two events of 00.33 (hh.mm) and 09.40 (hh.mm) of 97/09/26 and the CFF (Columb Failure Function) over the fault of the 09.40 (hh.mm) F2 event induced by the first F1 earthquake; stars denote the epicenters (Dalla Via et al., GRL, 2007).



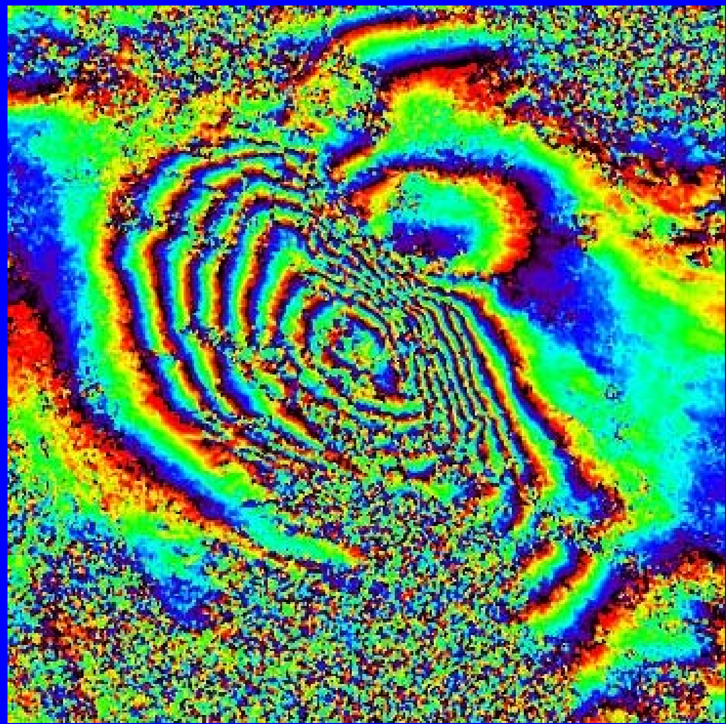
km along dip
0
5
10
15
0
5
10
15
km along strike
0
5
10
km along strike
0
5
10
15
0.0
0.2
0.4
0.6
0.8



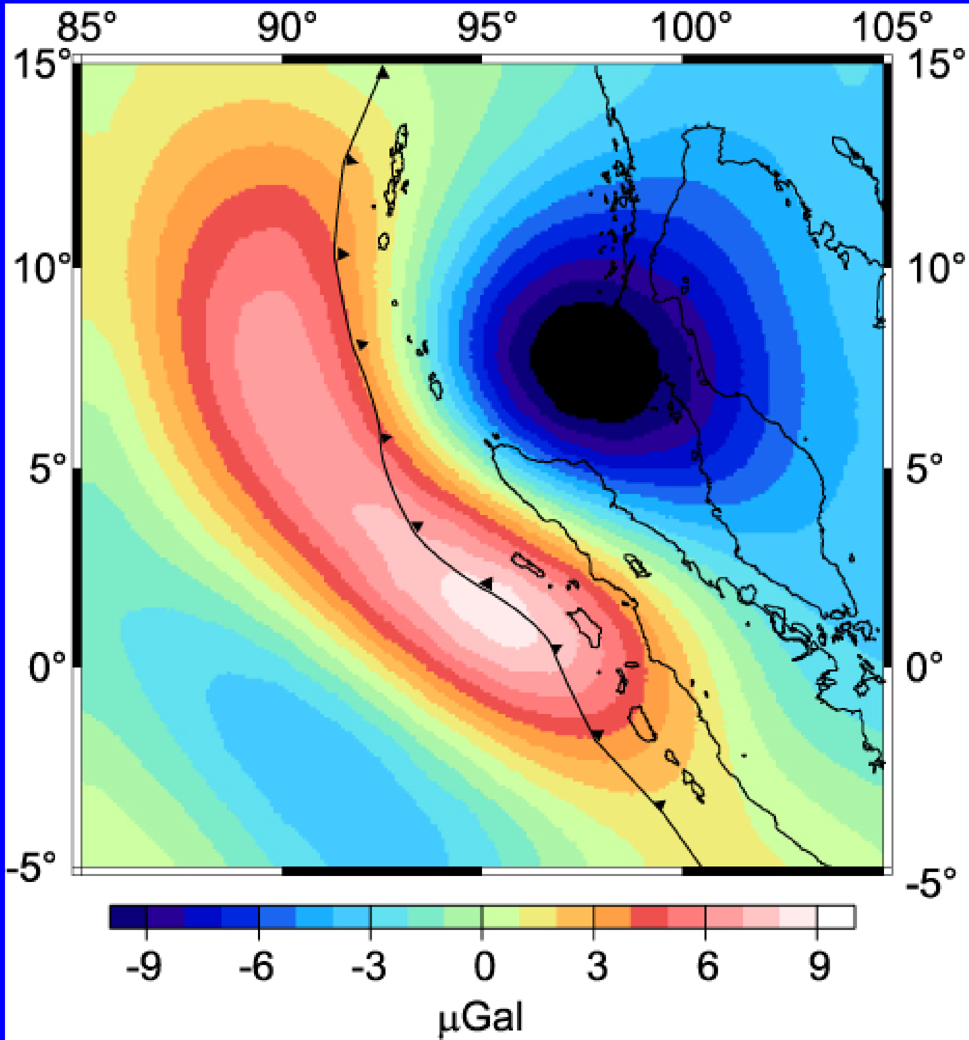
0
5
10
15
km along dip
0
5
10
15
km along strike


A
DInSAR data
B
Modelled
C
Misfit
43°12'
43°00'
42°48'
12°36'
12°48'
13°00'
13°12'
m
0.25
0.20
0.15
0.10
0.05
0.00
0.05

Co-sismico DInSAR L’Aquila



G
O
C
E


85°
90°
95°
100°
105°
15°
10°
5°
0°
-5°
-9
-6
-3
0
3
6
9
μGal

Analysis of surface displacements can suggest the ongoing dynamics of the fault.

- **DInSAR datasets**:
  from 1995 to 2000, 38 images,
  51 interferograms, 661 points

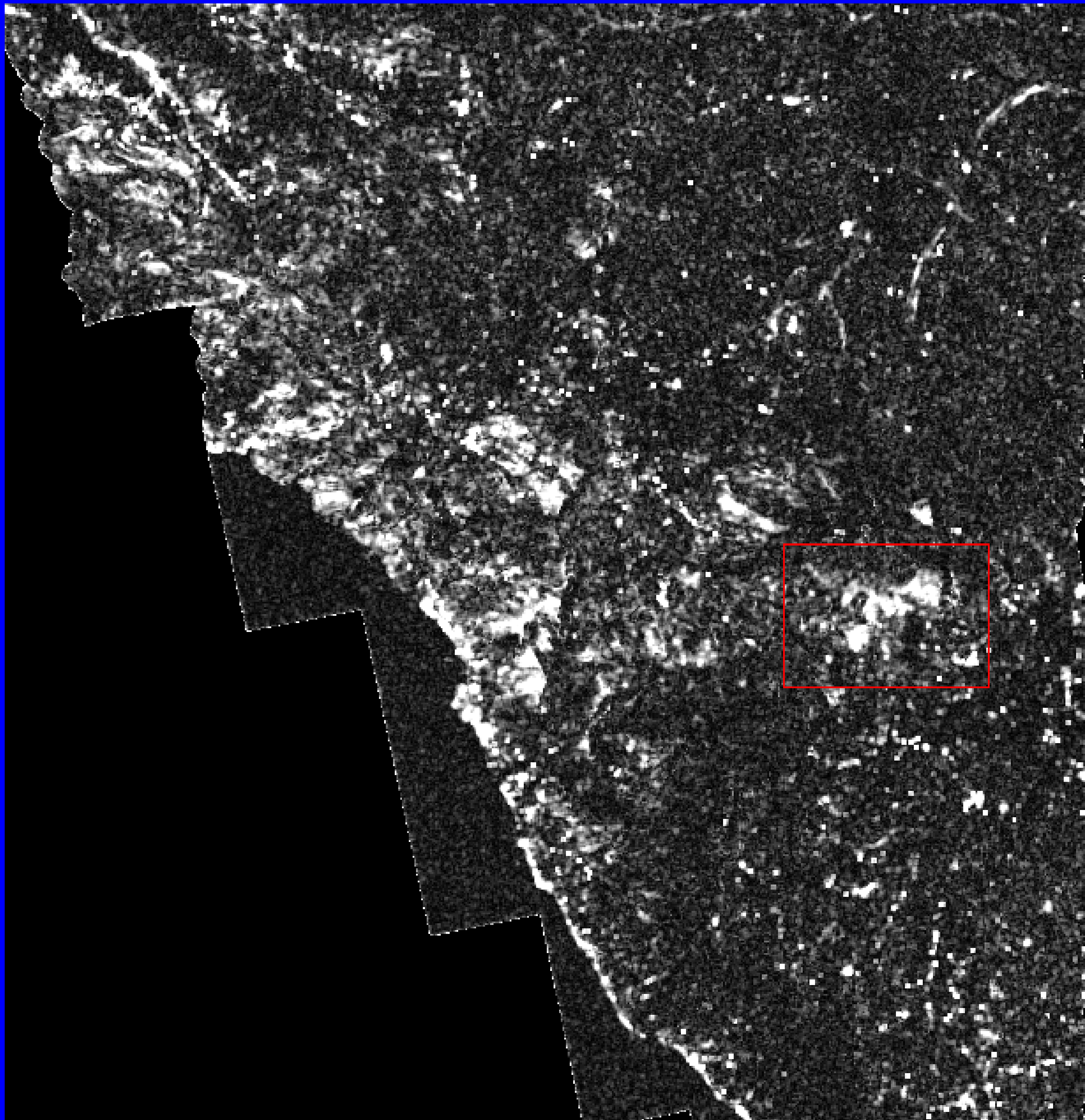
- **GPS datasets**:
  from 2003 to 2008,
  campaign network of 10 sites

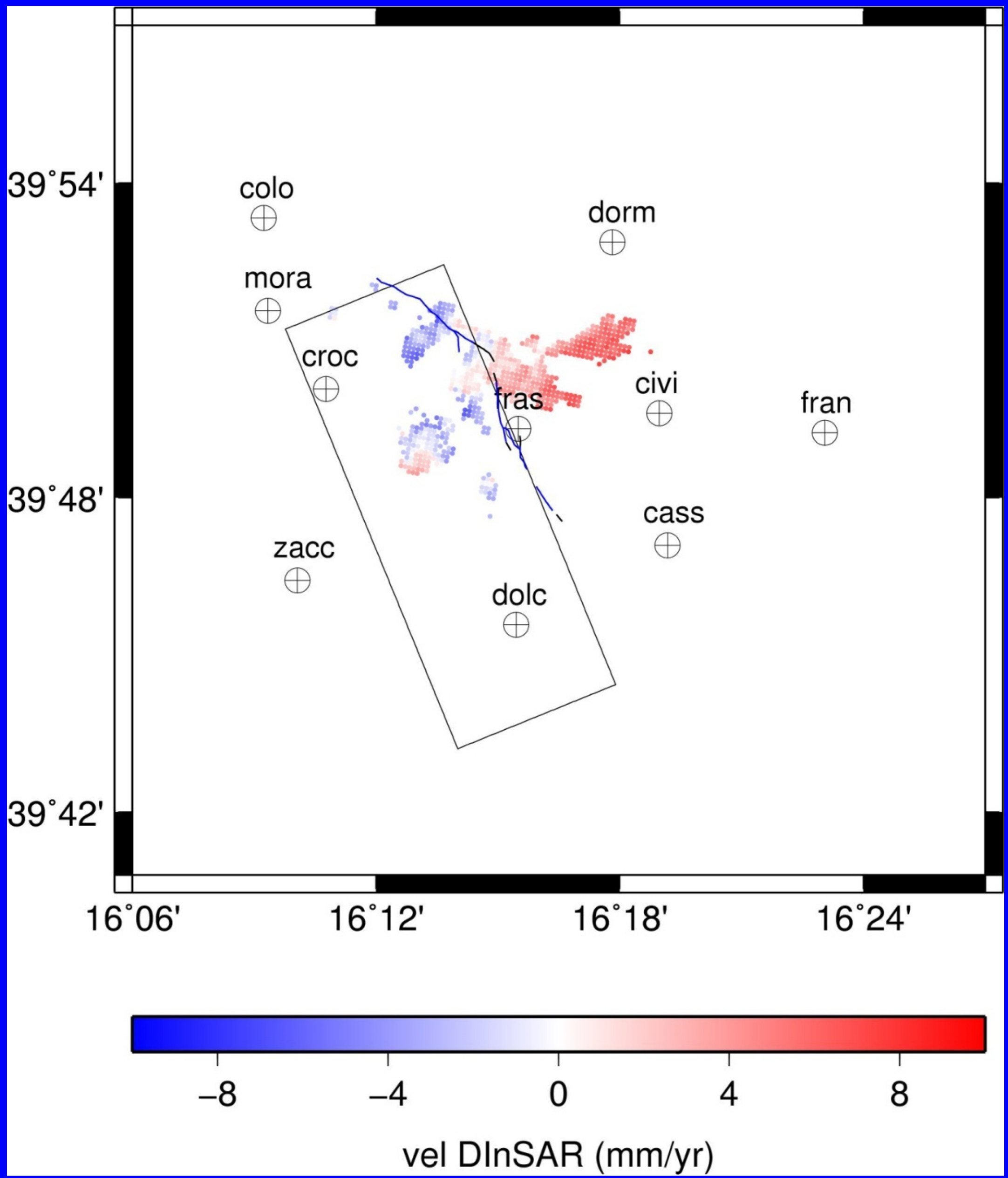
Modelling the Castrovillari fault:

- Length: 16km
- Width: 12km
- Top depth: 0km
- Strike: 157°
- Dip: 60°
- Rake: 270°
- 192, 1km x 1km patches

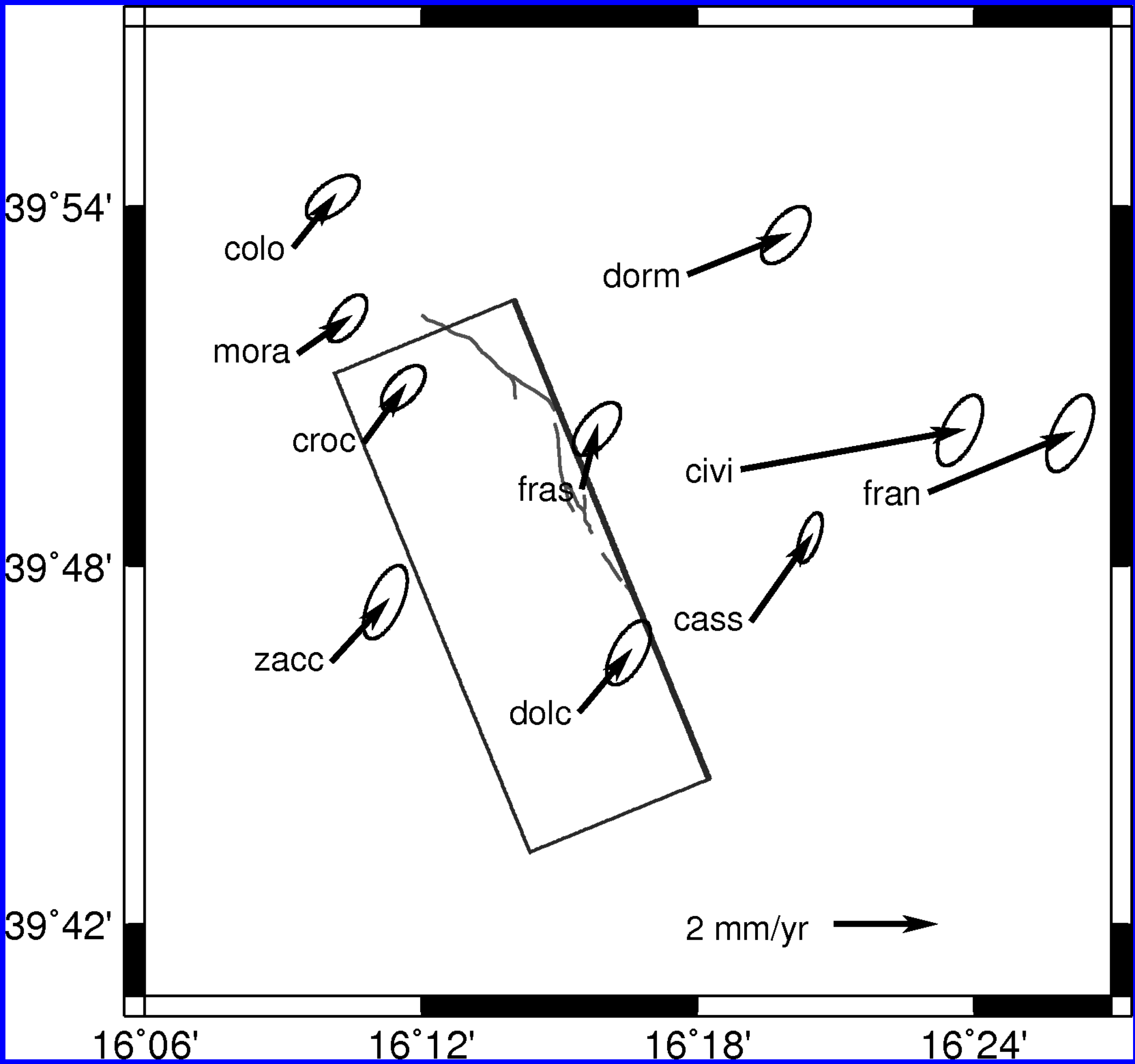
Half space Earth model (Okada 1992)

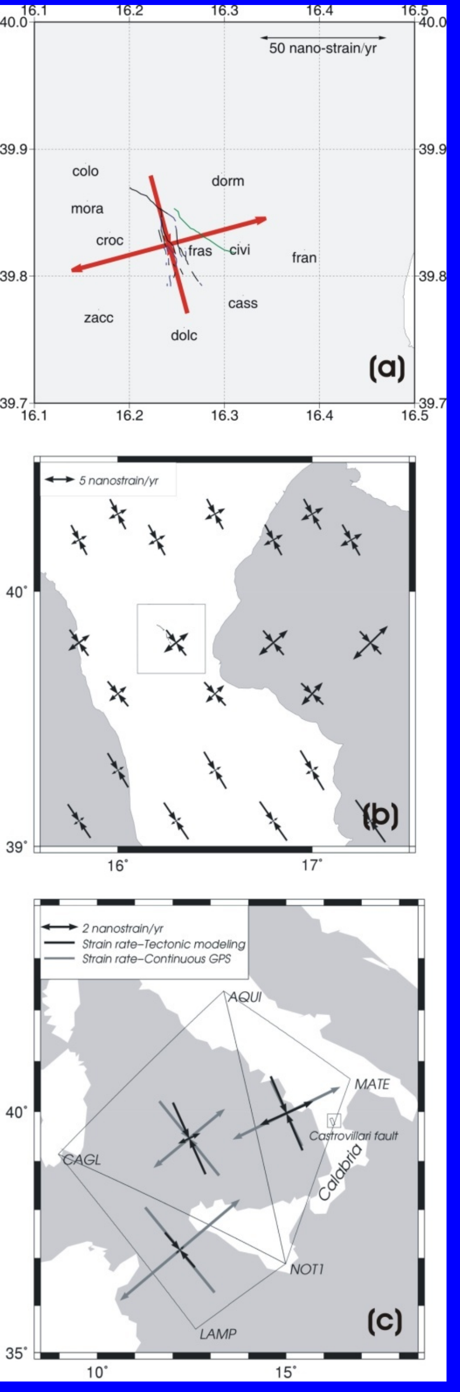
Occam's inversion scheme
(deGroot-Hedlin et al., 1990, Dalla Via et al., 2006)



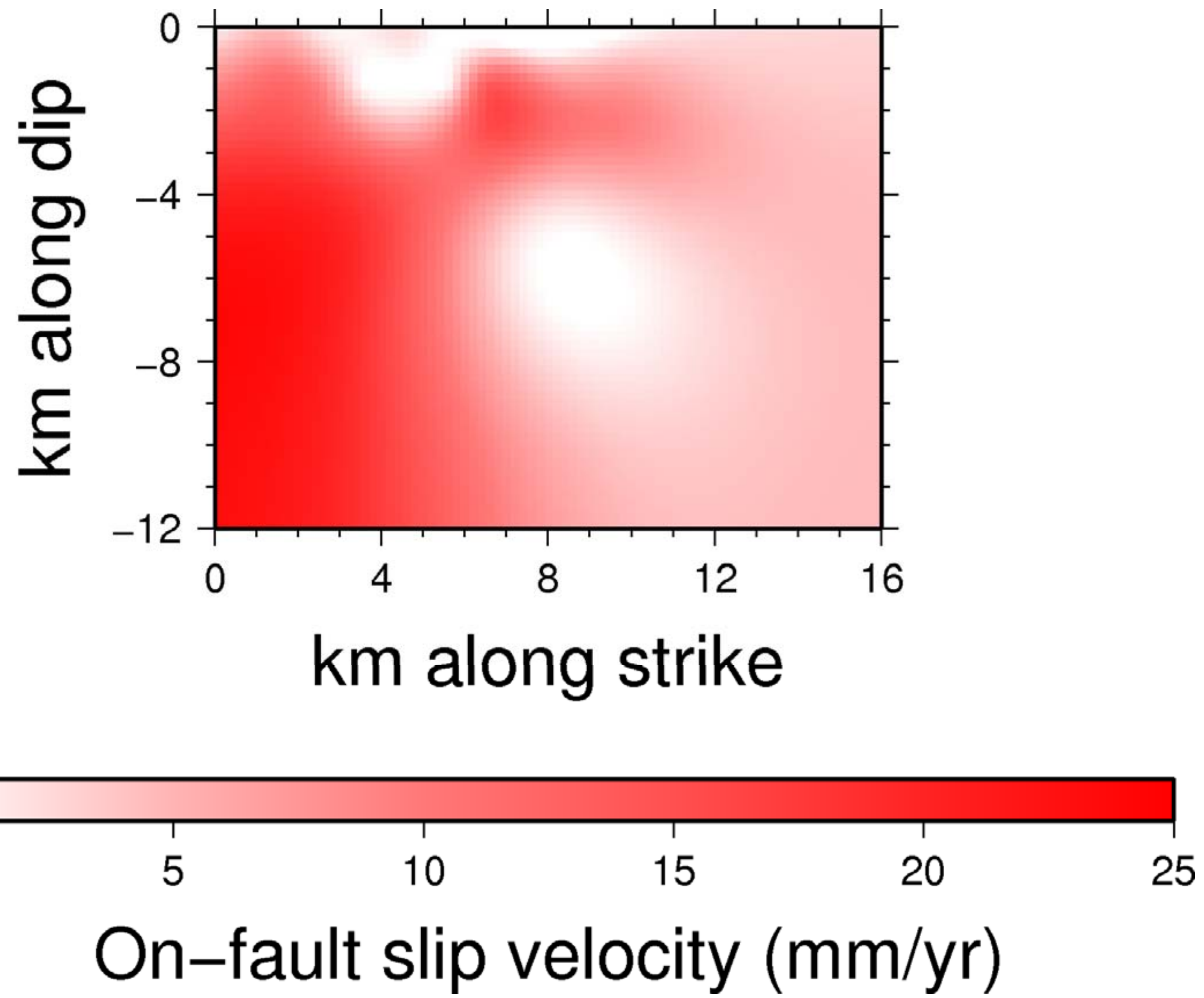


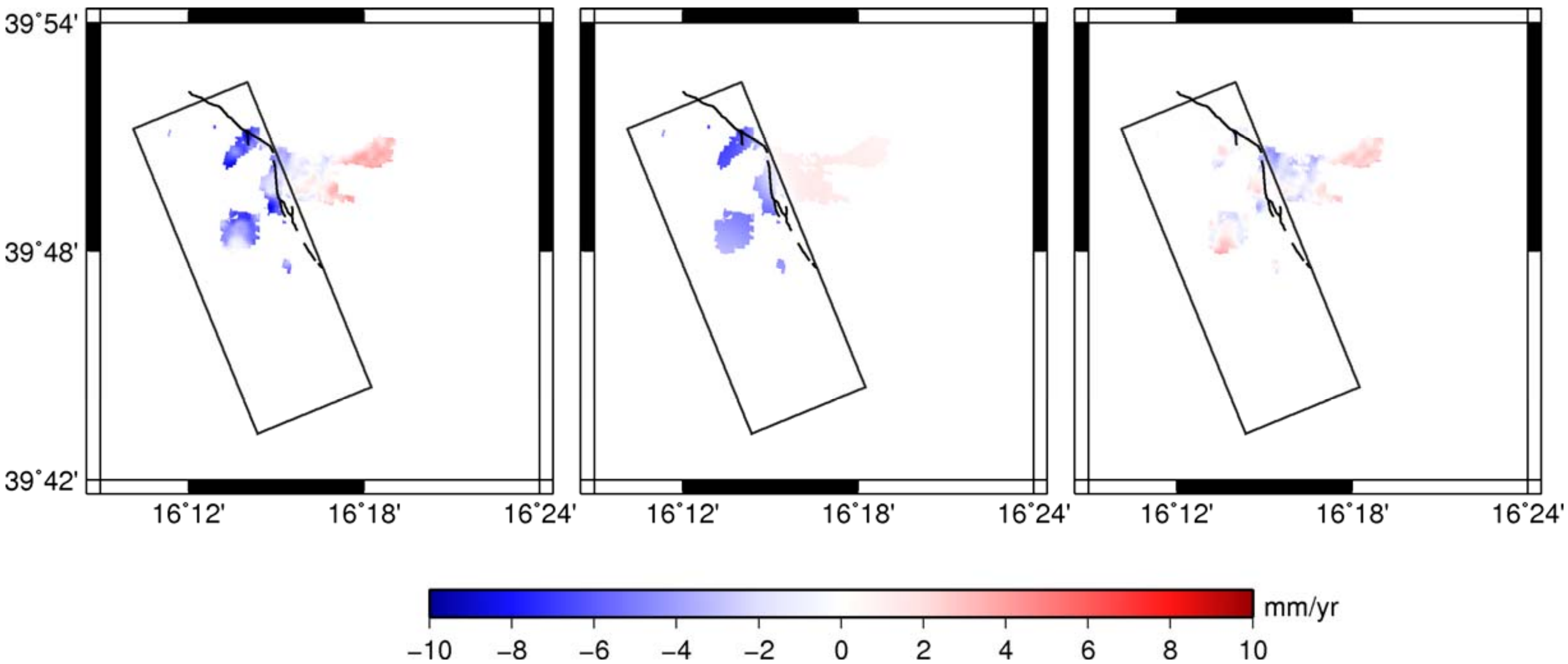
39˚54'
39˚48'
39˚42'
16˚06'
16˚12'
16˚18'
16˚24'
colo
dorm
mora
croc
civi
fras
fran
cass
zacc
dolc
−8
−4
0
4
8
vel DInSAR (mm/yr)


39°54'
39°48'
39°42'
16°06'
16°12'
16°18'
16°24'
colo
dorm
mora
croc
fras
civi
fran
cass
zacc
dolc
2 mm/yr

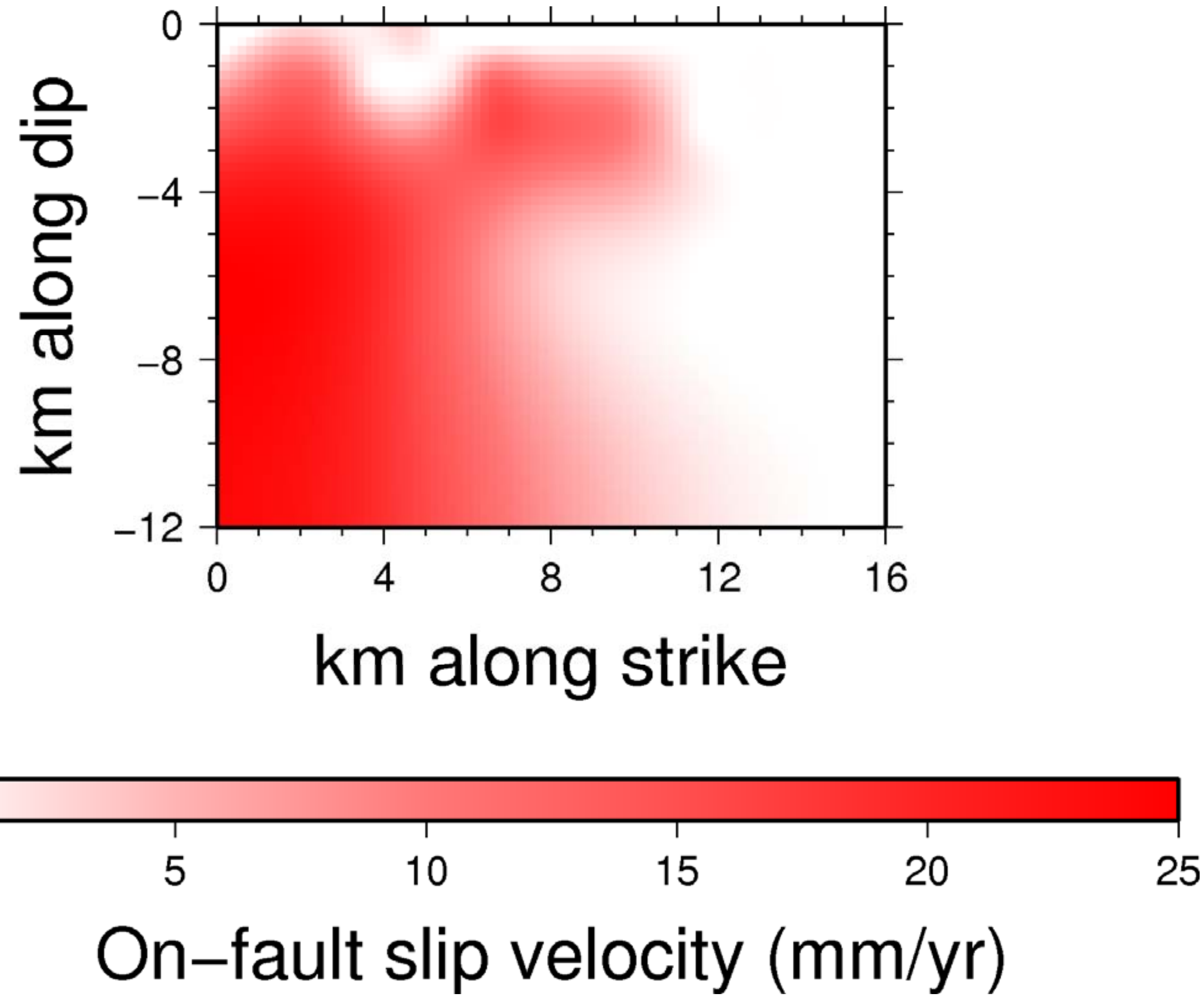


50 nano-strain/yr
colo
mora
croc
dorm
fras
civi
fran
cass
zacc
dolc
(a)
5 nanostrain/yr
(b)
2 nanostrain/yr
Strain rate-Tectonic modeling
Strain rate-Continuous GPS
AQUI
MATE
Castrovillari fault
Calabria
CAGL
NOT1
LAMP
(c)

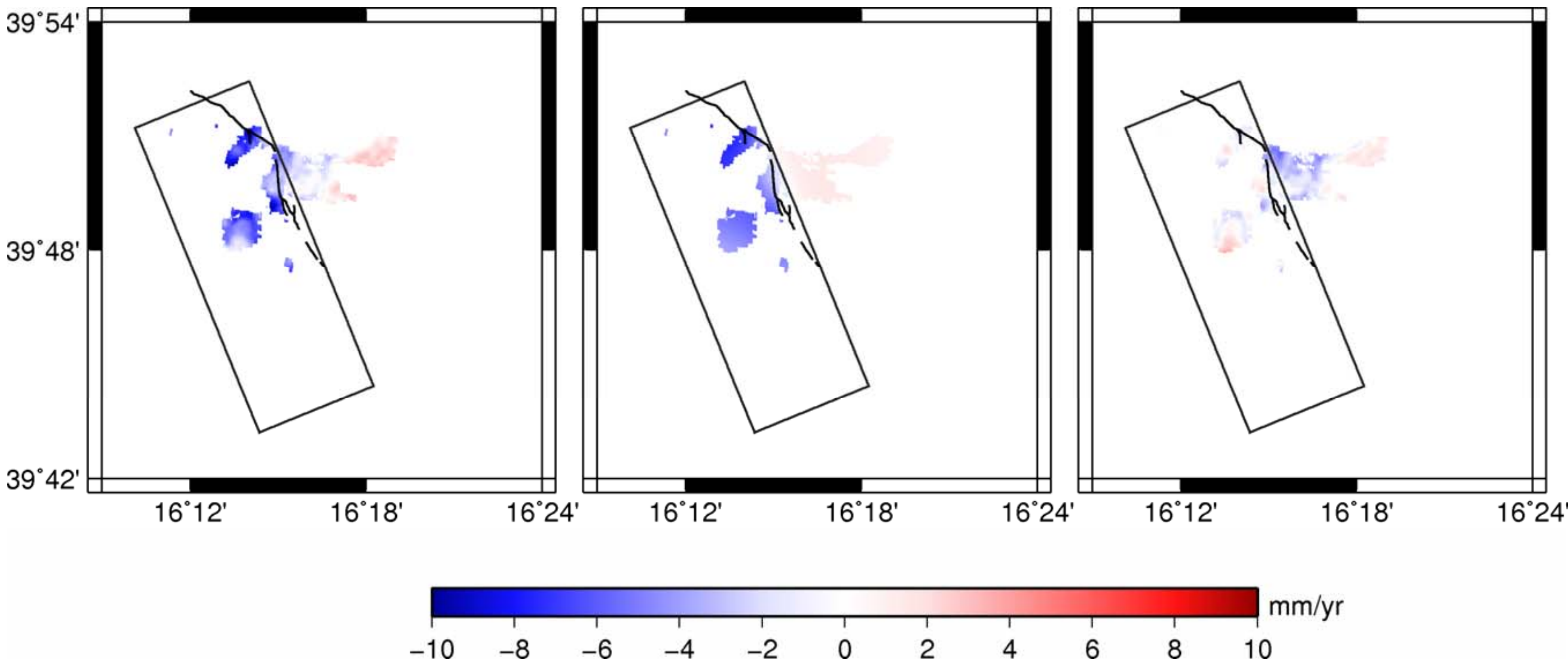

0
−4
−8
−12
km along dip
0
4
8
12
16
km along strike
0
5
10
15
20
25
On−fault slip velocity (mm/yr)

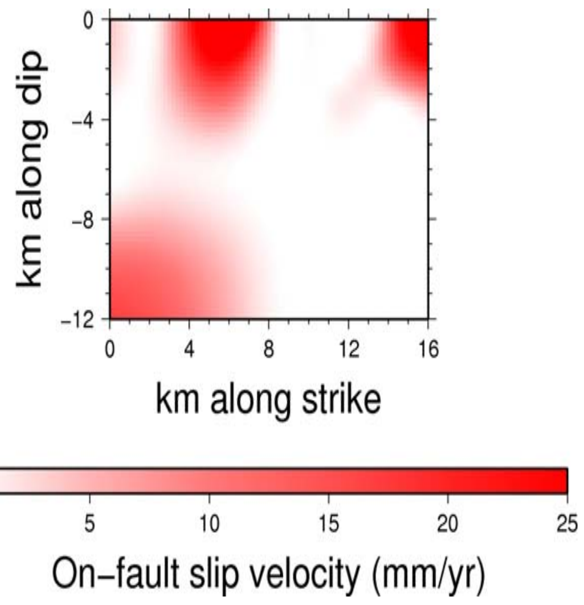


39°54'
39°48'
39°42'
16°12'
16°18'
16°24'
16°12'
16°18'
16°24'
16°12'
16°18'
16°24'
mm/yr
−10
−8
−6
−4
−2
0
2
4
6
8
10



0
-4
-8
-12
km along dip
0
4
8
12
16
km along strike
0
5
10
15
20
25
On-fault slip velocity (mm/yr)


39°54'
39°48'
39°42'
16°12'
16°18'
16°24'
mm/yr
−10
−8
−6
−4
−2
0
2
4
6
8
10


0
-4
-8
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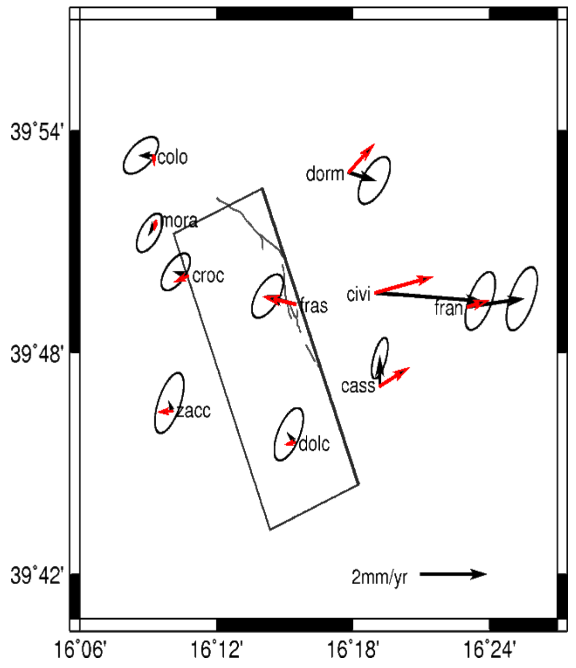
0
4
8
12
16
km along dip
km along strike
0
5
10
15
20
25
On–fault slip velocity (mm/yr)


39˚54'
39˚48'
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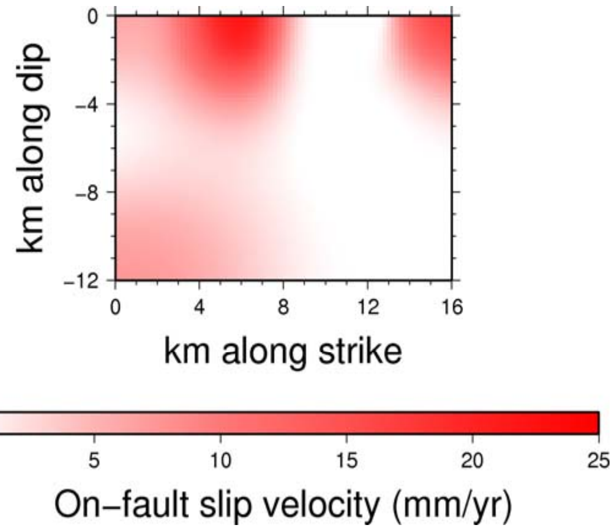
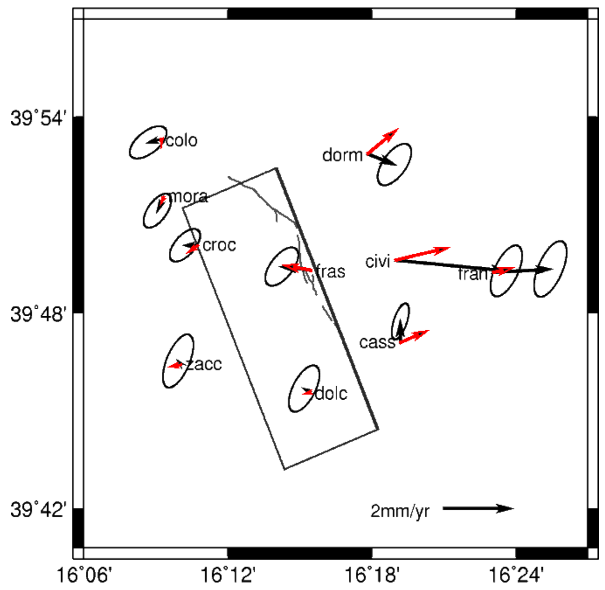
16˚06'
16˚12'
16˚18'
16˚24'
colo
dorm
mora
croc
fras
civi
fran
cass
zacc
dolc
2mm/yr


0
-4
-8
-12
km along dip
0
4
8
12
16
km along strike
0
5
10
15
20
25
On–fault slip velocity (mm/yr)


39˚54'
39˚48'
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16˚06'
16˚12'
16˚18'
16˚24'
colo
dorm
mora
croc
fras
civi
fran
cass
zacc
dolc
2mm/yr

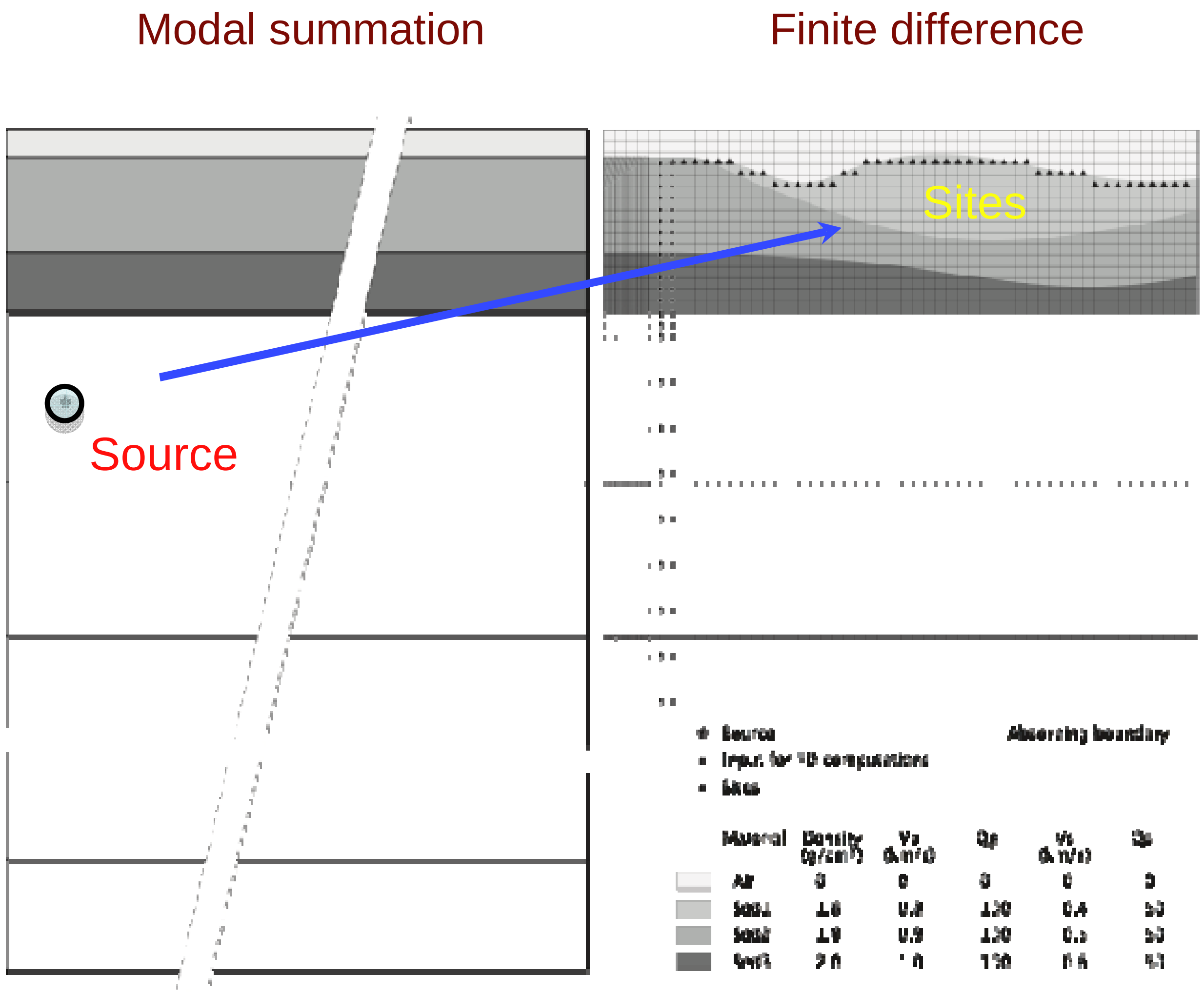
Regional scale modelling

- Computation of synthetic seismograms with the modal summation technique on the nodes of a grid that covers the study area
- Average structural properties
- Simple source model (scaled point source)
- Sources distributed in the alerted areas
- Cut-off frequency 1 Hz
- Maps of peak displacement, velocity and Design Ground Acceleration

Local scale modelling

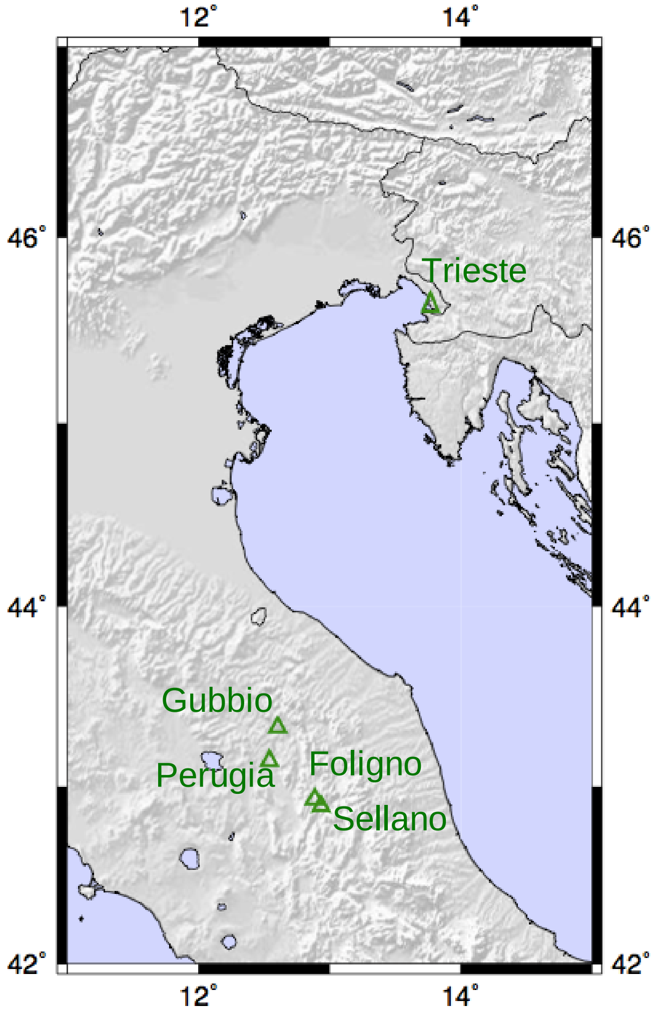
- Synthetic seismograms computed along selected profiles with a hybrid technique (modal summation plus finite difference)
- Detailed source model for selected faults(directivity included)
- Laterally heterogeneous structural models
- Cut-off frequency up to 10 Hz
- Maps of ground motion amplification

Local scale modelling: hybrid technique

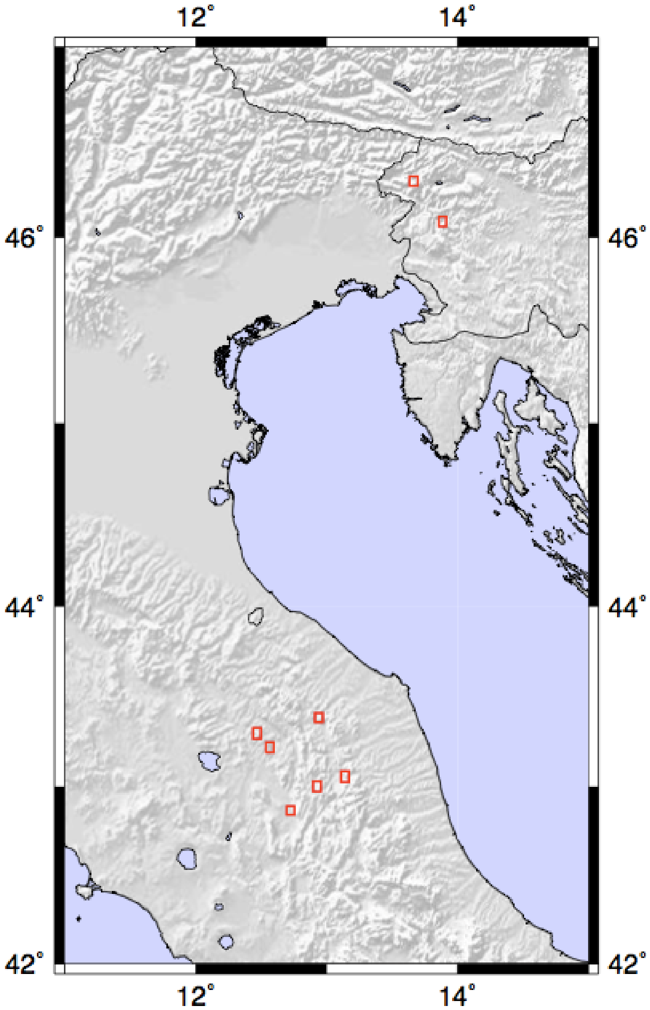


Local scale modelling: considered sites and sources

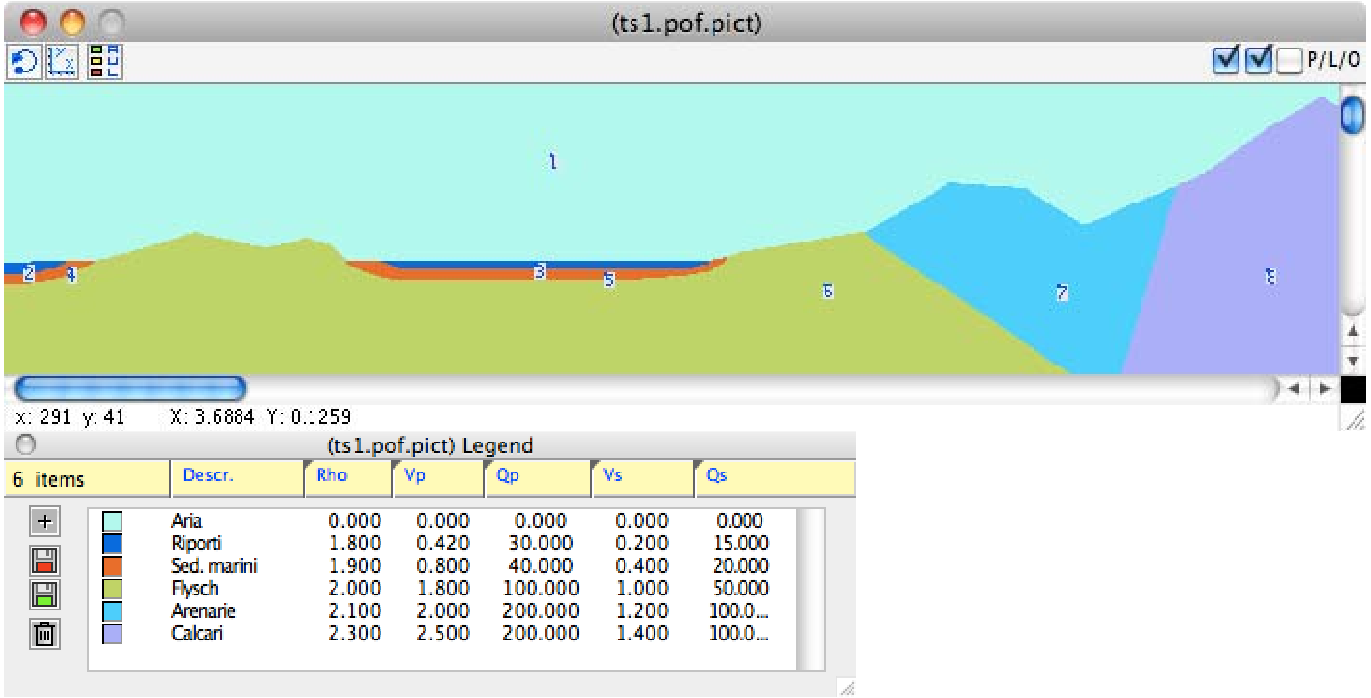
Cross-sections



Sources

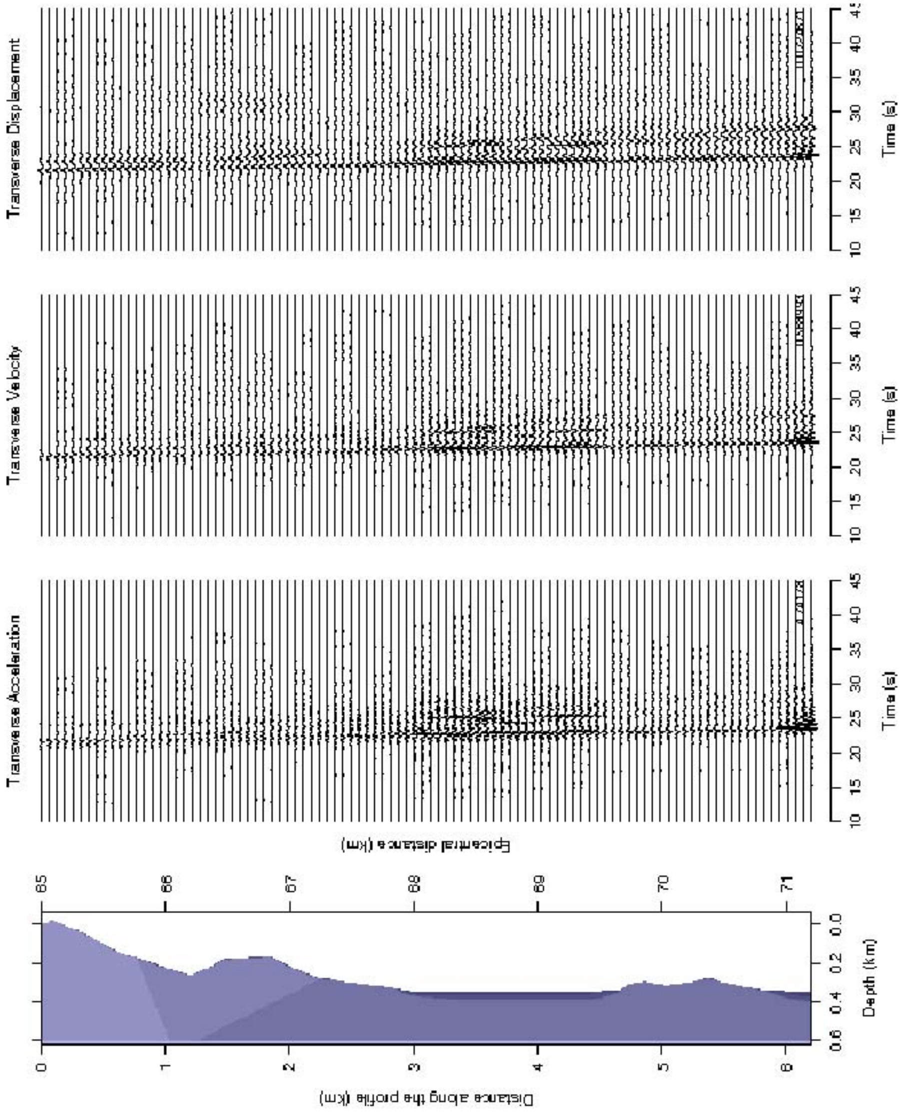


Local scale modelling: Trieste (6250x617 m)

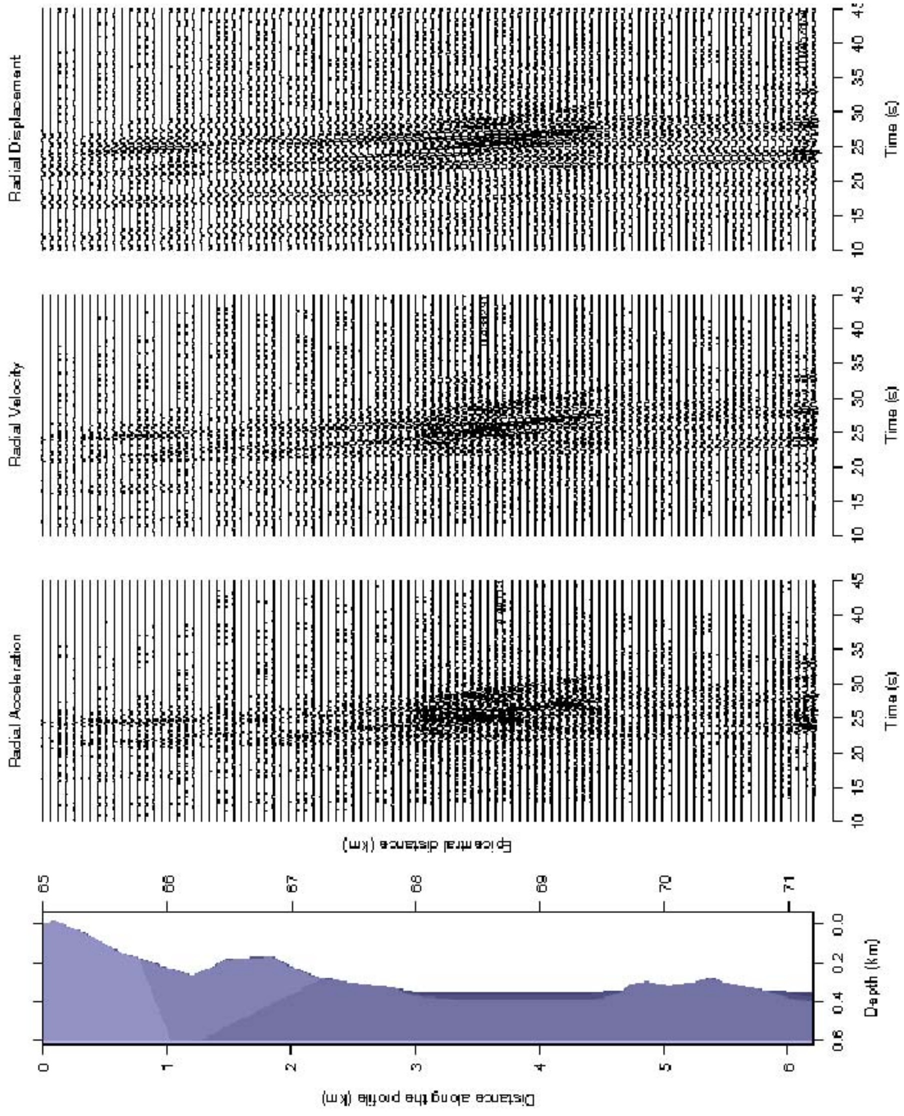


Local scale modelling: Trieste (waveforms)

Transverse component



Radial component



SISMA for inter-seismic and pre-seismic

Previous slides are representative of the concepts for SISMA developments targeted towards the detection of slip and stress changes during the inter-seismic and pre-seismic phases for monitoring the seismic potential in selected test sites and for alert when stresses over active faults overcome rupture threshold

CONCLUSIONS

- Although the seismic classification of the Italian territory has been recently revised, the evaluation of seismic hazard continue to be based on the traditional probabilistic approach, i.e. on the probabilistic analysis of earthquake catalogue and of ground motion information, retrieved by macroseismic observations and instrumental recordings, that may lead to severe underestimations of seismic hazard.

- Recently this approach showed its limitation in providing a reliable seismic hazard assessment, possibly due to the insufficient information about historical seismicity, which can introduce relevant errors in the purely statistical approach mainly based on the seismic history. Indeed, some areas where low seismic hazard was foreseen, and consequently were not included in the seismic classification, have been subsequently struck by relatively strong and damaging earthquakes (e.g. the Sicily, September 2002, and the Molise, October 2002, earthquakes).

CONCLUSIONS

- To overcome the mentioned limitations and, above all, to improve the pre-seismic information which may lead to an effective mitigation of seismic risk, we are proposing an innovative approach, that combines EO data and new advanced approaches in seismological and geophysical data analysis.

- The proposed system, in fact, is proposing a deterministic approach to the estimation of seismic ground motion, integrated with the space and time dependent information provided by EO data analysis through geophysical forward modeling. The reason of the proposed integration of different geophysical observables appears almost obvious analyzing the earthquake "life cycle", i.e. its process of preparation and occurrence: the lithosphere accumulates stress, according to strain and strain rates fields due to tectonic movements, which is partly released during the earthquake occurrence.