Committee on
Earth Observation Satellites

Seismic Demonstrator, highlights and successes

Arthur Delorme – Institut de physique du globe de Paris (IPGP)

CEOS WG Disasters Meeting 18 – Université Côte d’Azur (UCA), Nice, France

3 October 2022

Satellite optical image correlation for surface deformation measurement

Method developed at the french Alternative Energies and Atomic Energy Commission (CEA) in the late 1990s (Michel et al., 1999)

MicMac: free open-source software for photogrammetry, developped at the National Institute of Geographic and Forest Information (IGN) since 2003

Since 2012, IGN-IPGP collaboration, with support from TOSCA (CNES):

- 2014:
  - MicMac correlator ready to measure surface deformation (Rosu et al., 2015)
  - Workshop on DSM calculation – Benchmarking of existing solutions (40 participants, 12 teams)
- 2016:
  - Satellite image geometry is now supported in MicMac (Rupnik et al., 2016)
- 2020:
  - Post-processing tool to perform measurements on displacement maps

MicMac

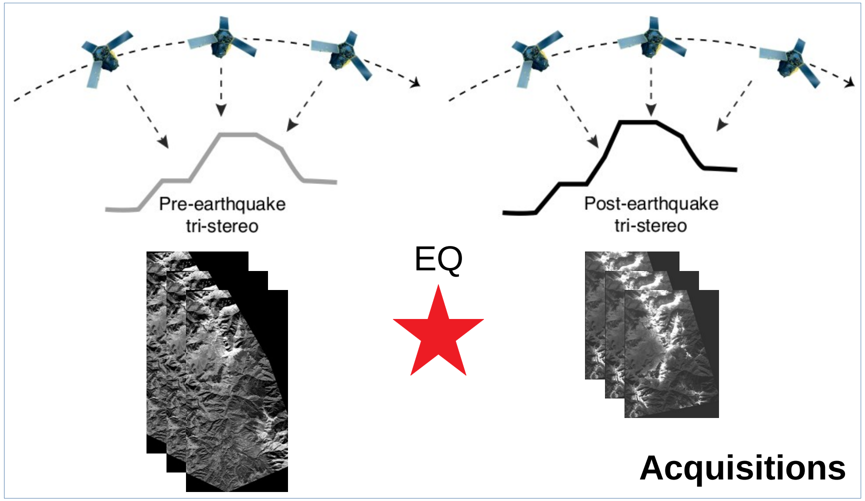
micmac.ensg.eu

Currently involves: 4 researchers, 1 engineer, 1 post-doc, PhD and internship students

The DSM-OPT and GDM-OPT DataTerra on-demand calculation services are based in part on these developments

Processing for the calculation of displacement maps

Processing for the calculation of displacement maps



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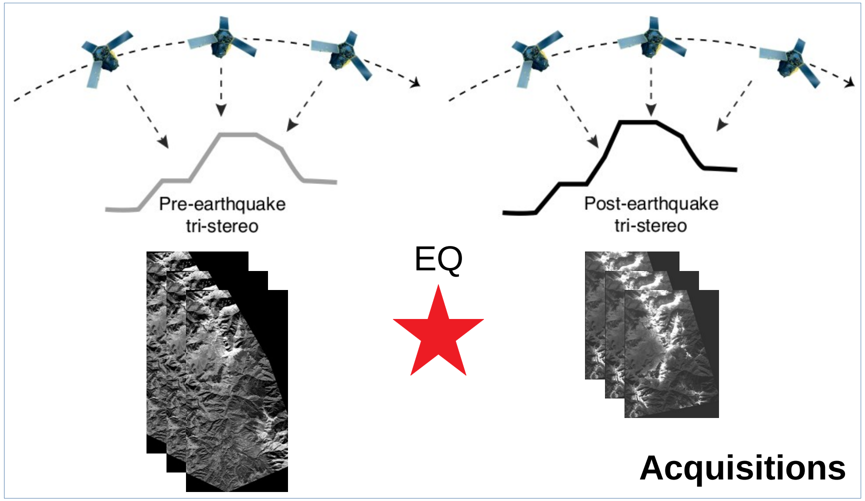
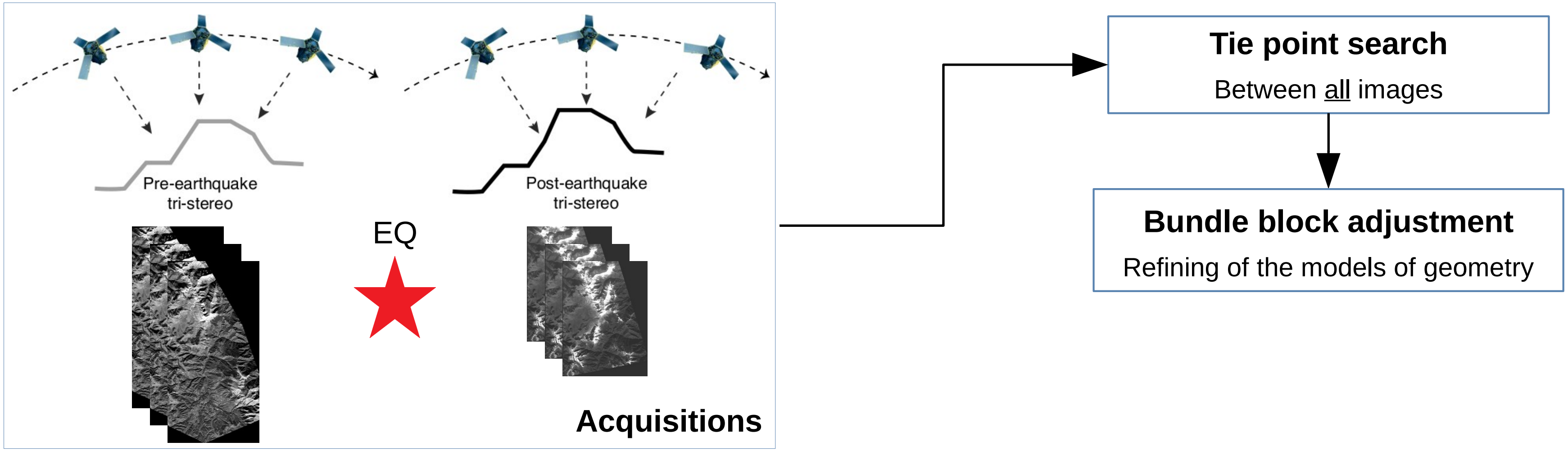


Tie point search

Between all images

Processing for the calculation of displacement maps



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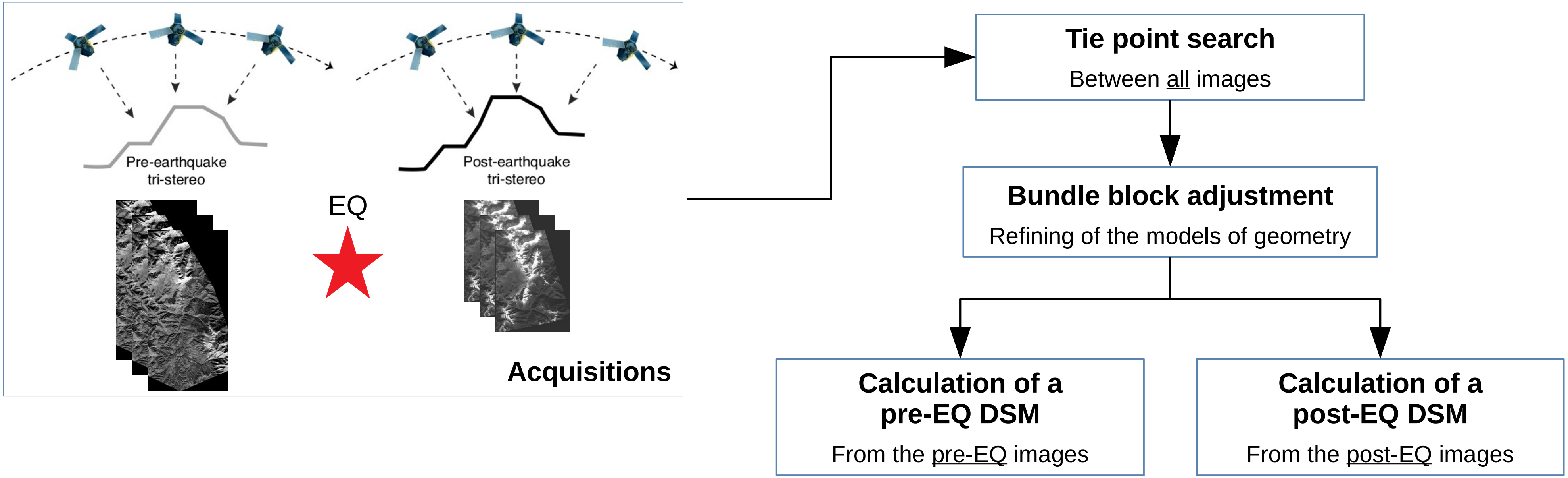

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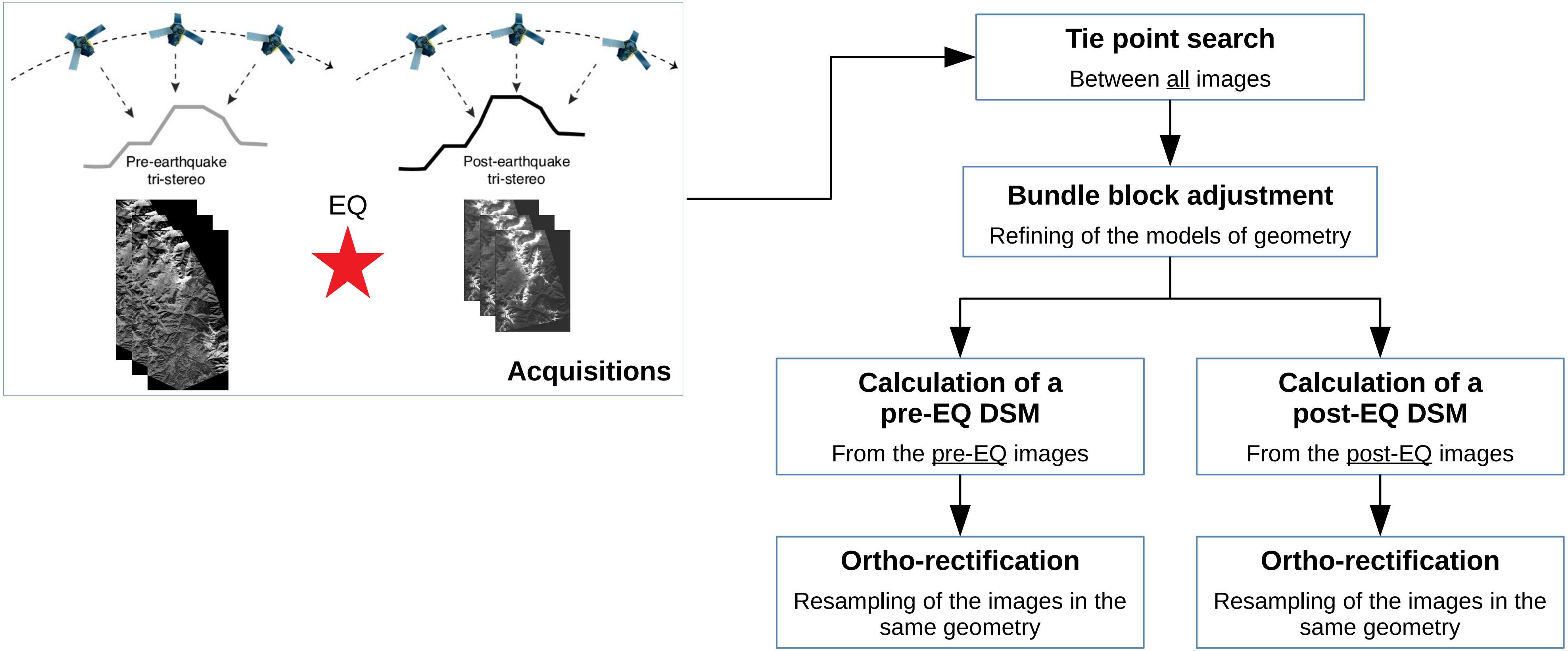
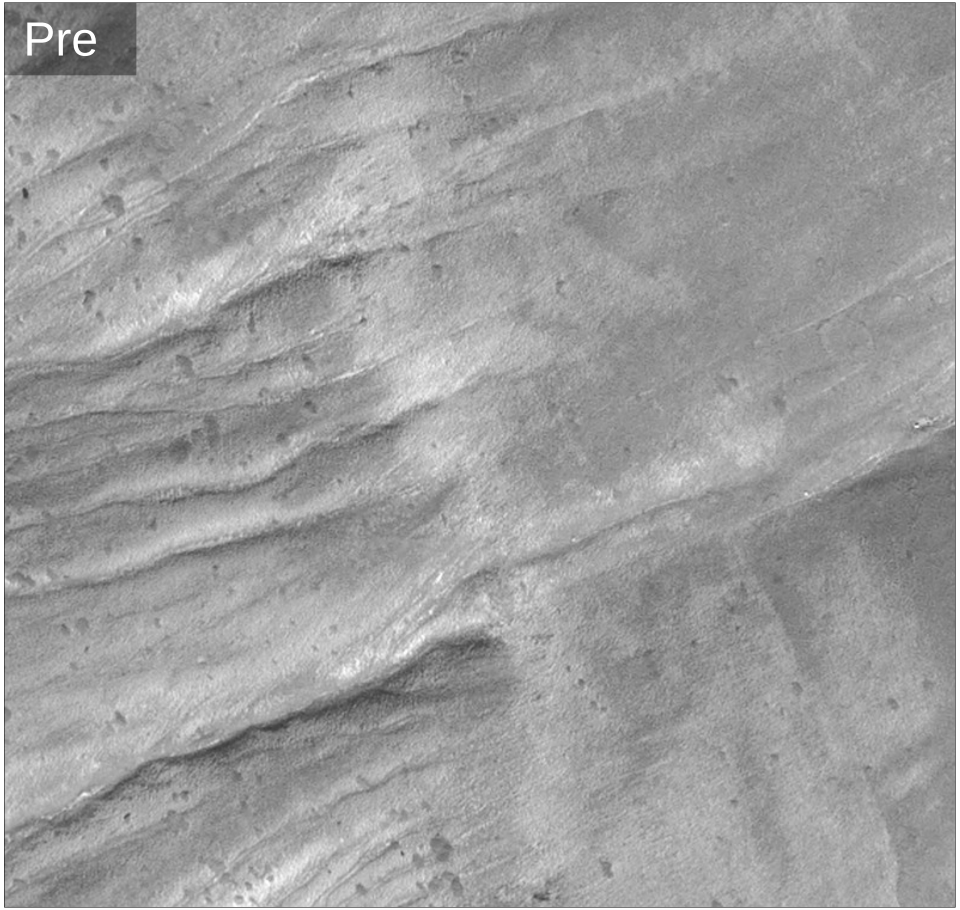


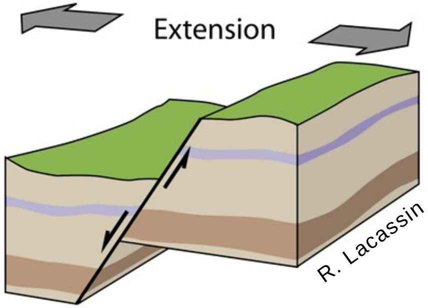
Parallax in the raw images

Caused by:

- Topography
- Image perspective
- And the EQ!



Pléiades satellite raw image (extract)



A normal fault

Norcia earthquake (Italy, 2016)

Delorme et al., 2020

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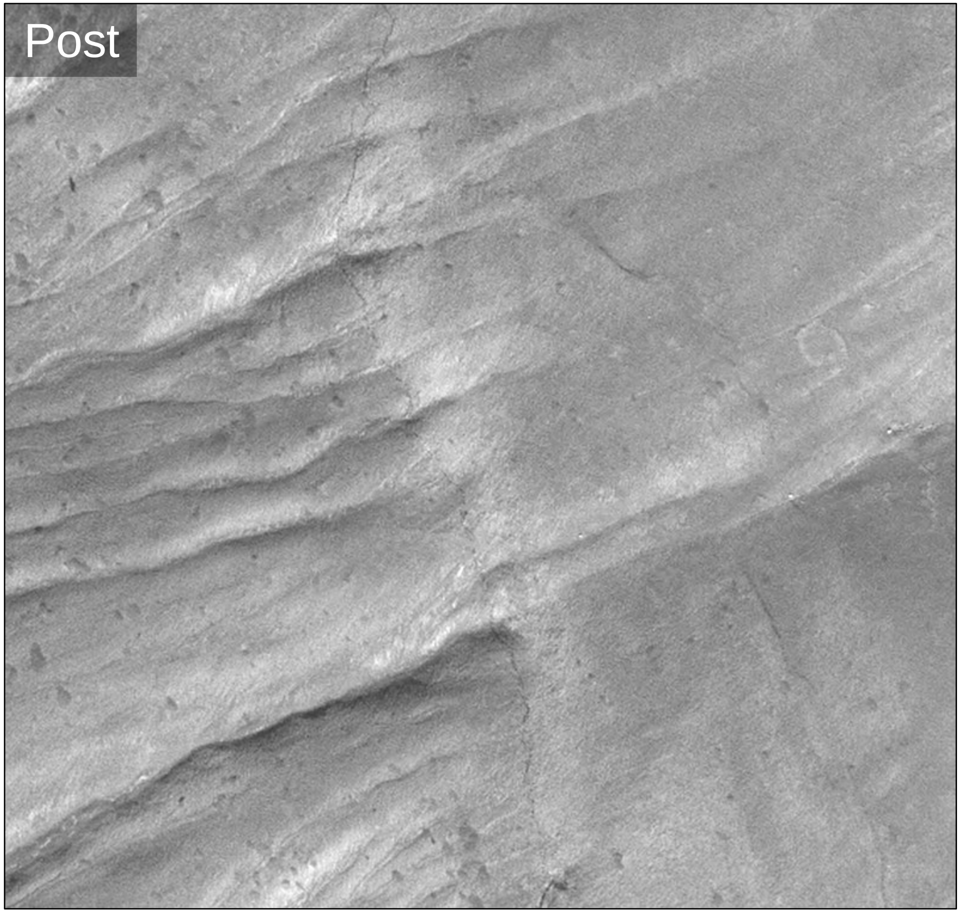

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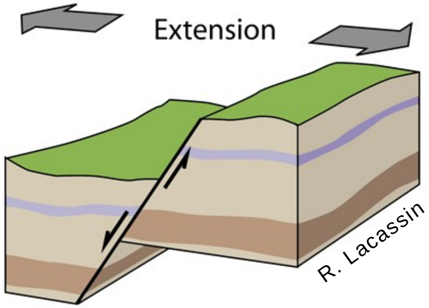

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Once ortho-rectified...

Caused by:

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- ~~Image perspective~~
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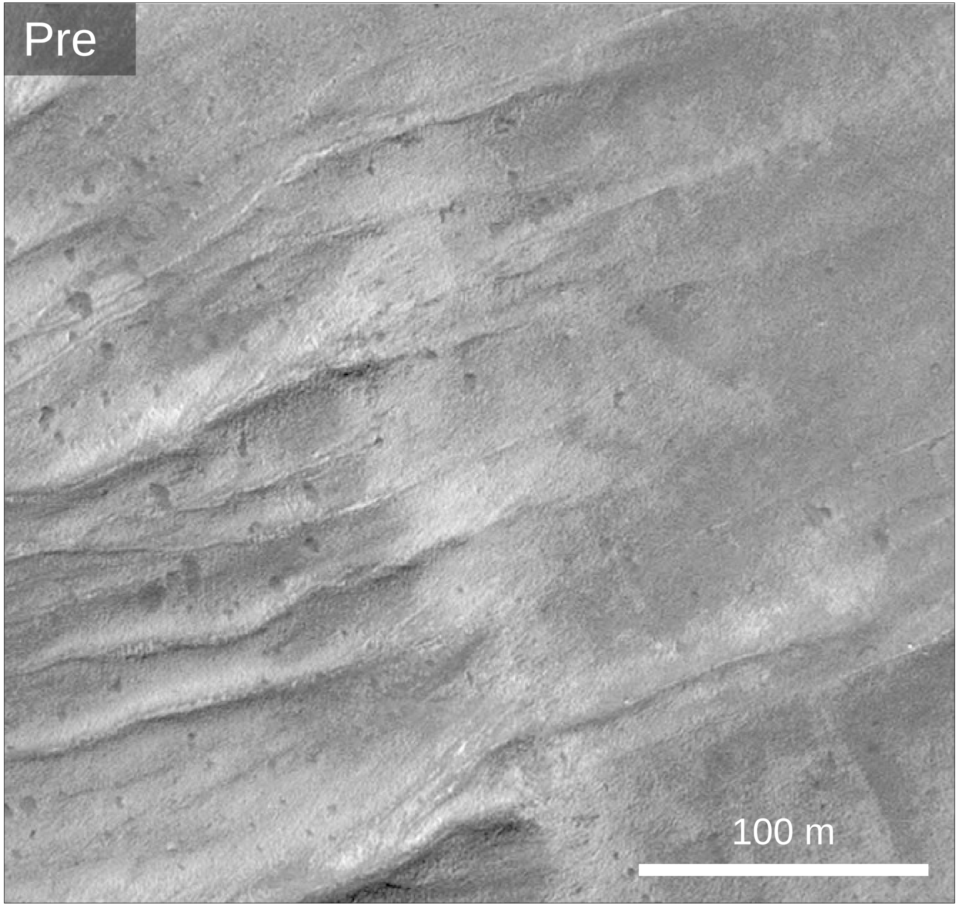
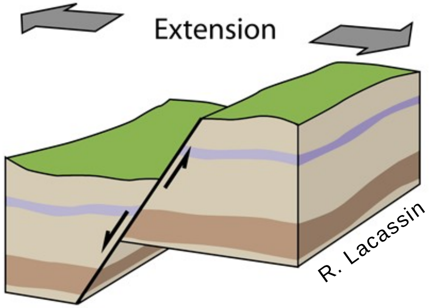


Pléiades satellite ortho-image (extract)



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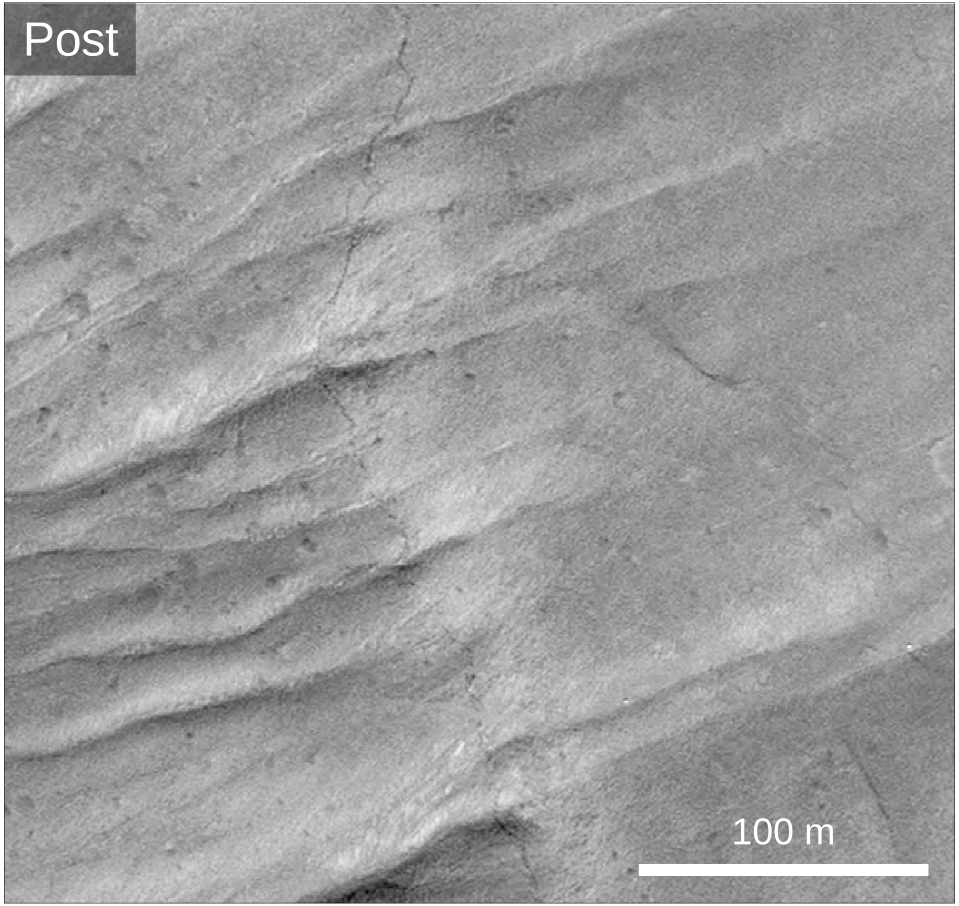

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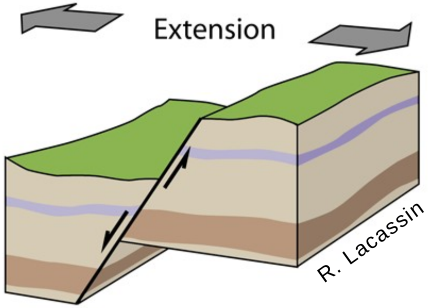

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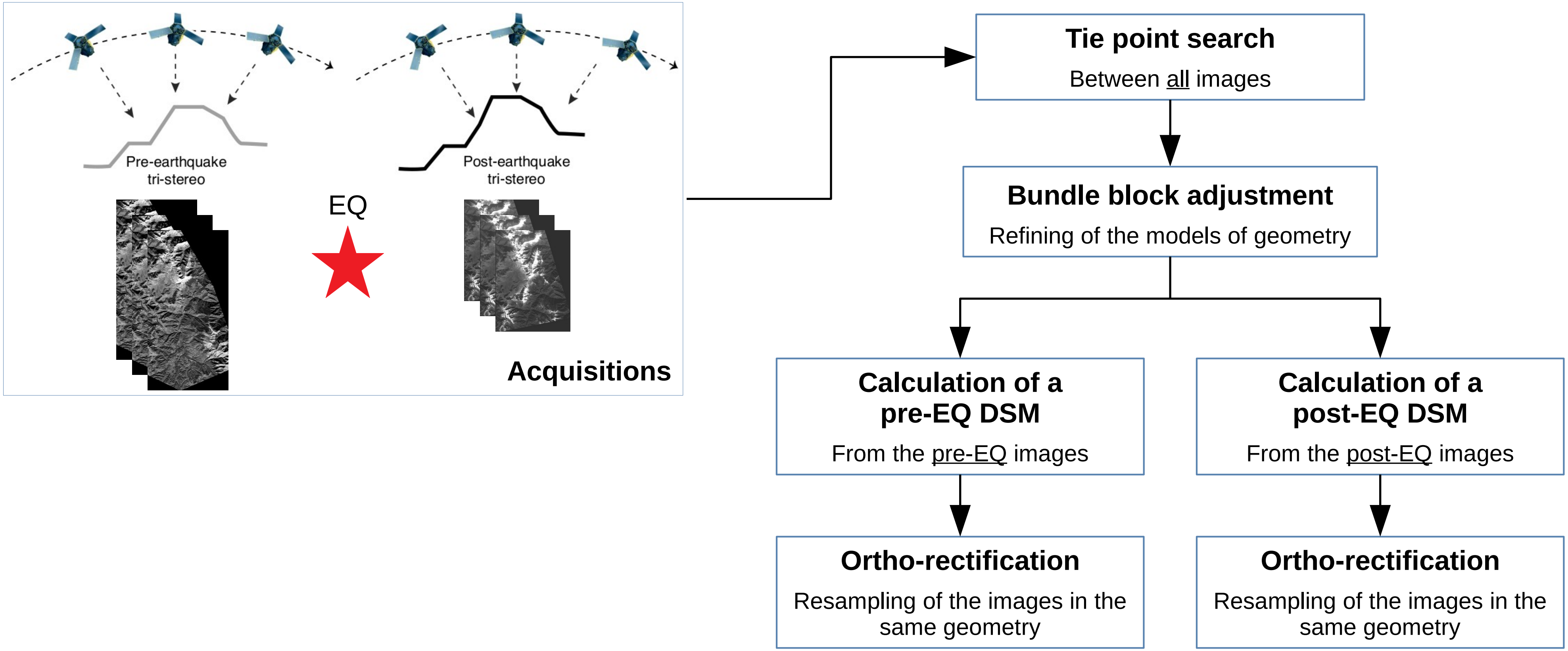
Processing for the calculation of displacement maps



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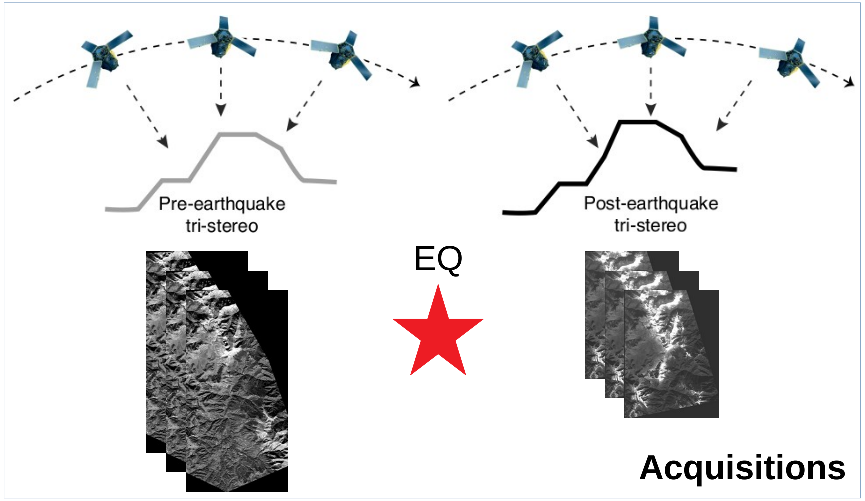


Tie point search

Between <u>all</u> images

Bundle block adjustment

Refining of the models of geometry

Calculation of a pre-EQ DSM

From the <u>pre-EQ</u> images

Calculation of a post-EQ DSM

From the <u>post-EQ</u> images

Ortho-rectification

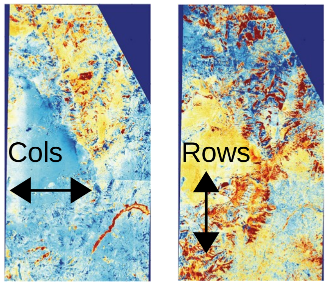
Resampling of the images in the same geometry

Ortho-rectification

Resampling of the images in the same geometry

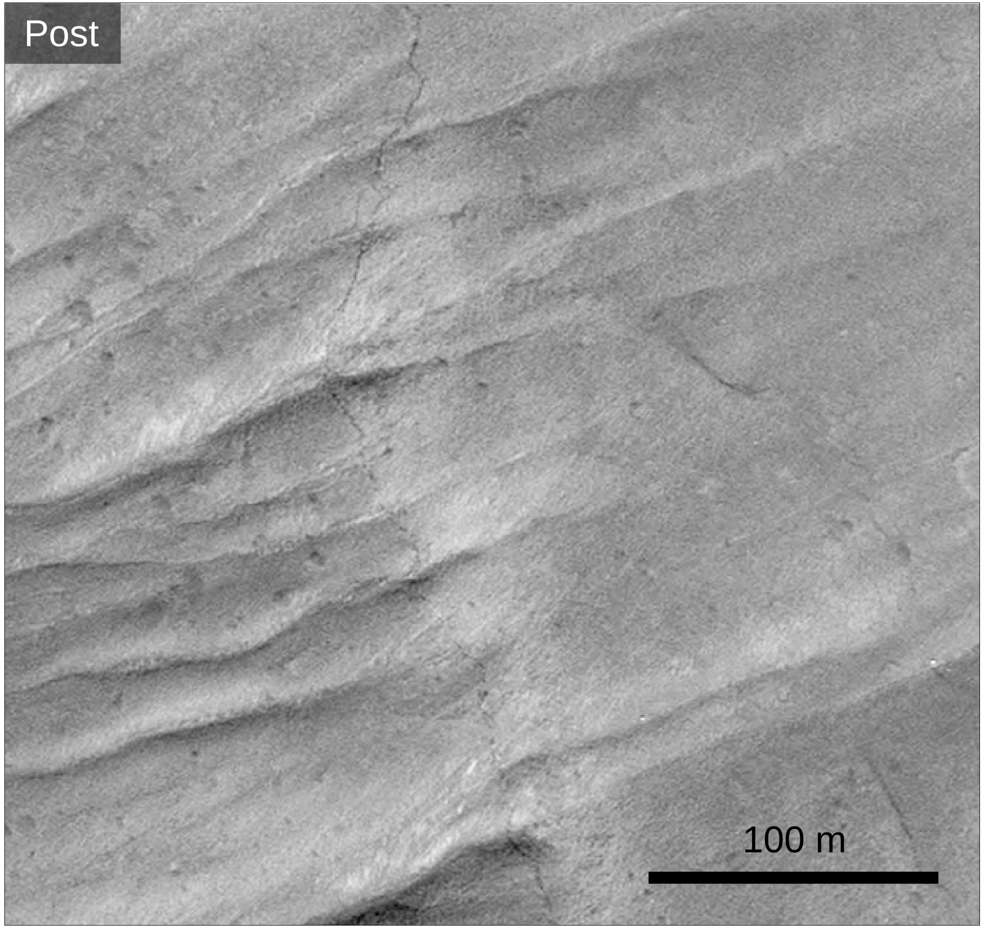
« 2D » dense matching

By image correlation



Maps of the horizontal displacement

Maps of horizontal pixel displacement

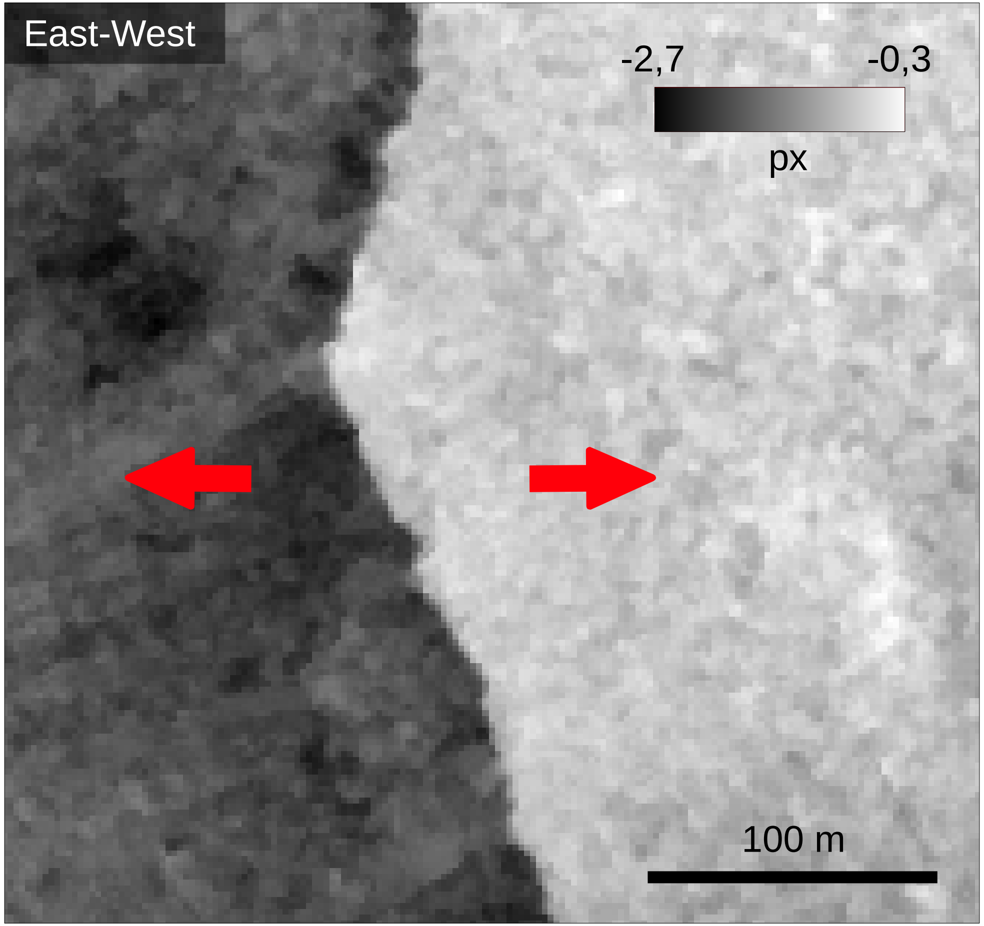


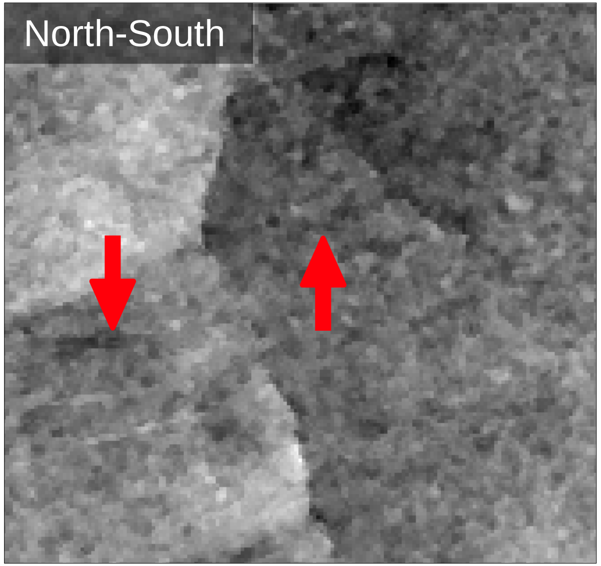
Post-EQ Pléiades ortho-image (extract)

Norcia earthquake (Italy, 2016)

Delorme et al., 2020

Maps of horizontal pixel displacement



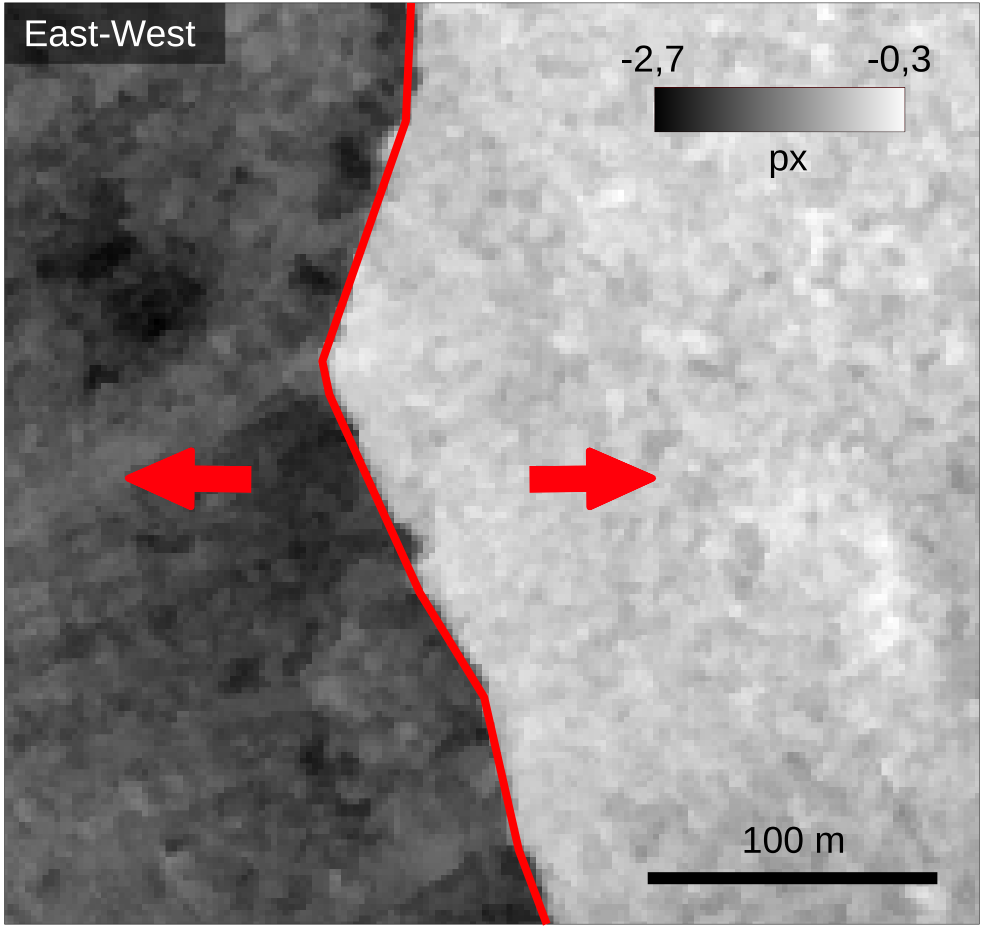


Displacement detection threshold: ~1/10 px

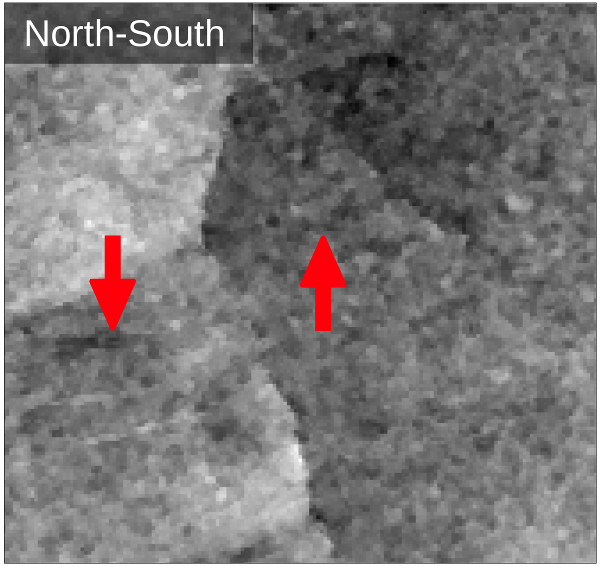
Norcia earthquake (Italy, 2016)

Delorme et al., 2020

Maps of horizontal pixel displacement



Map surface ruptures



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Delorme et al., 2020

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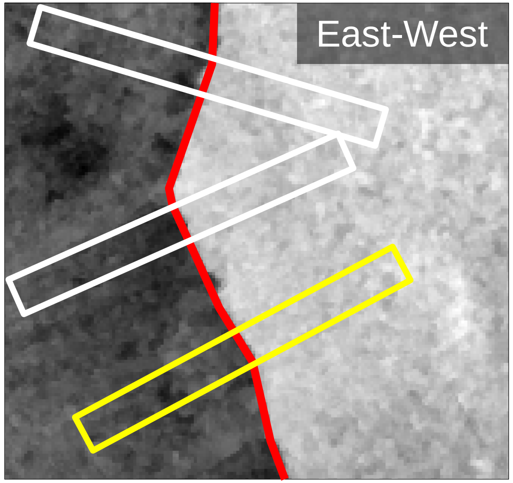
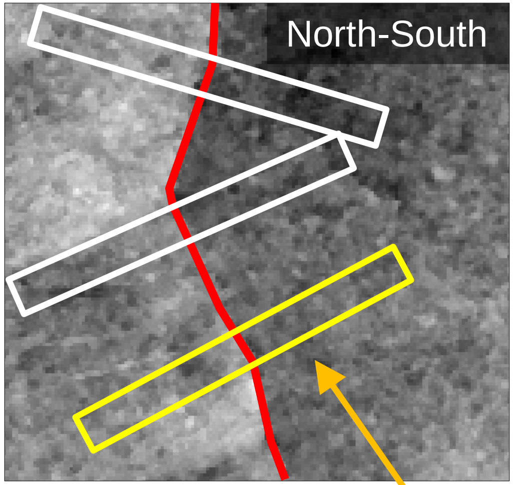
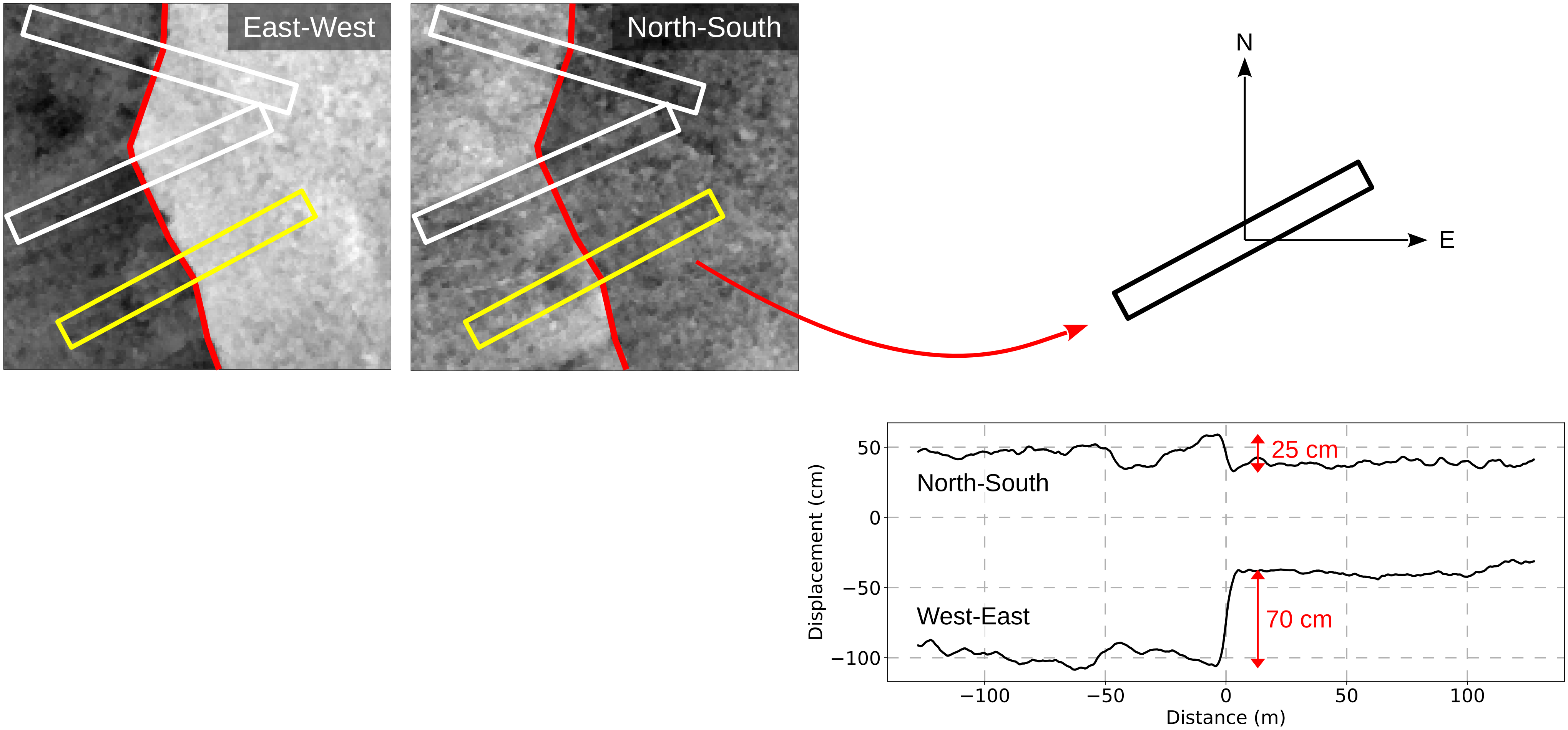




One stack of N parallel profiles
=> one averaged profile with increased S/N ratio

Norcia earthquake (Italy, 2016)
Delorme et al., 2020

Maps of horizontal pixel displacement



Norcia earthquake (Italy, 2016)

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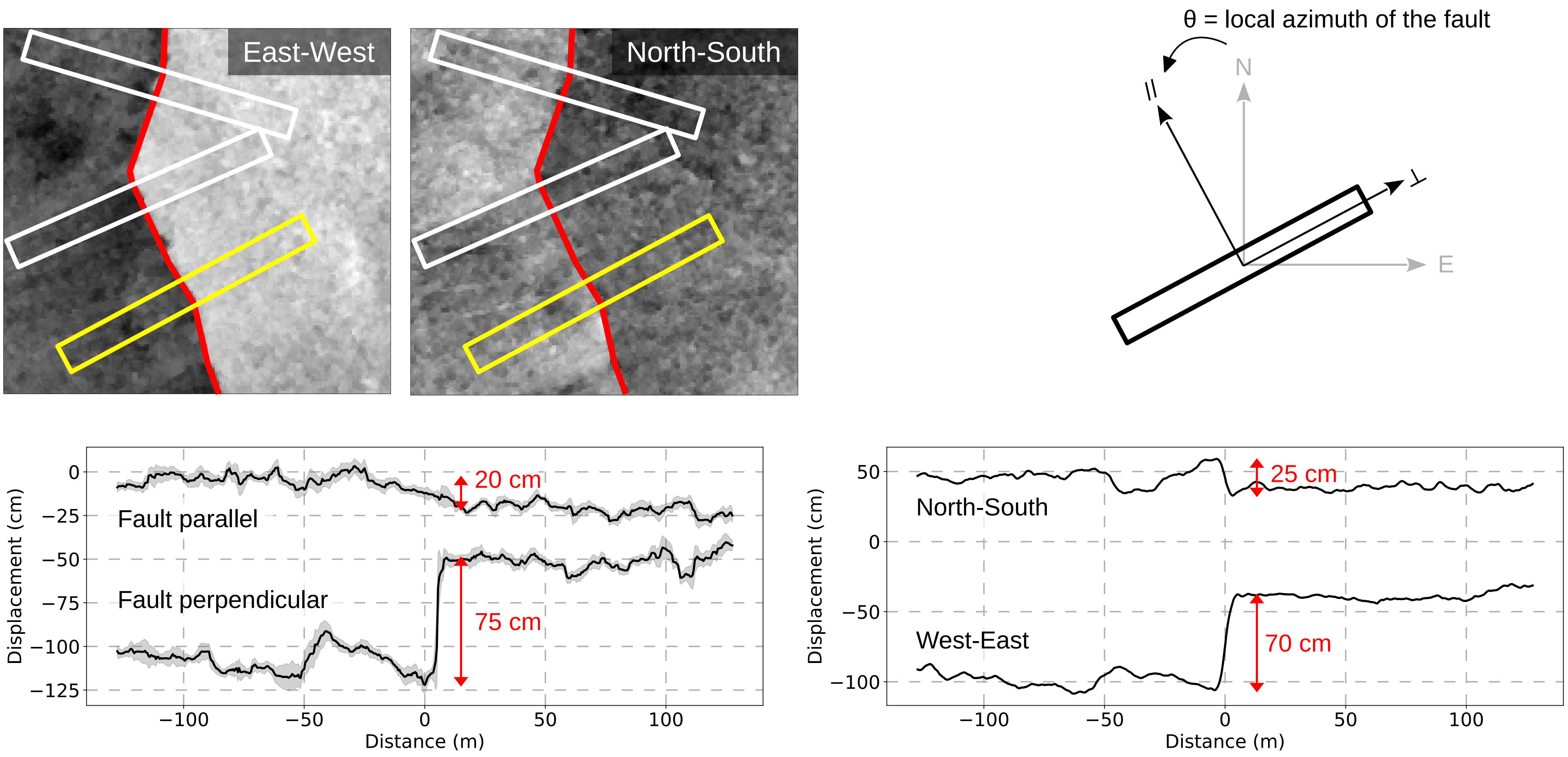

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Delorme et al., 2020

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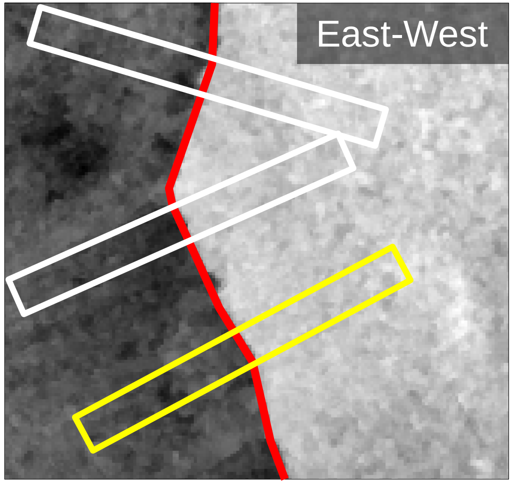

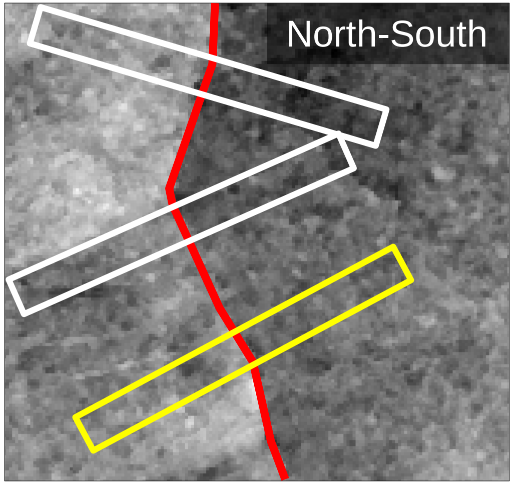

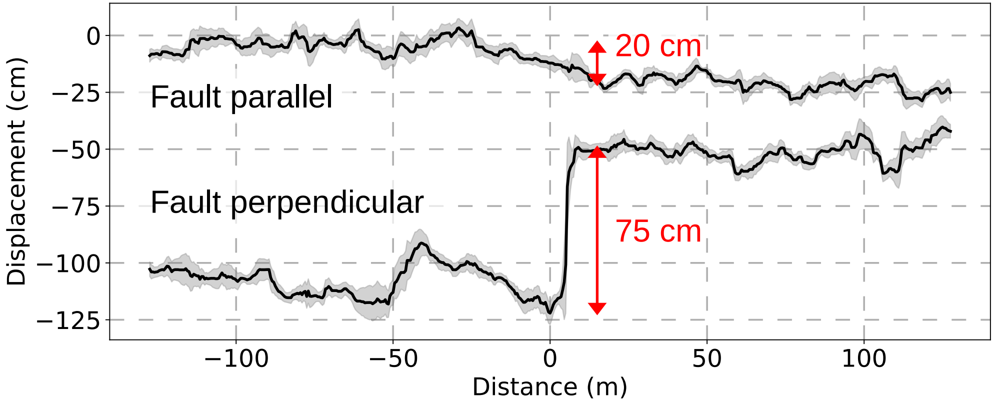

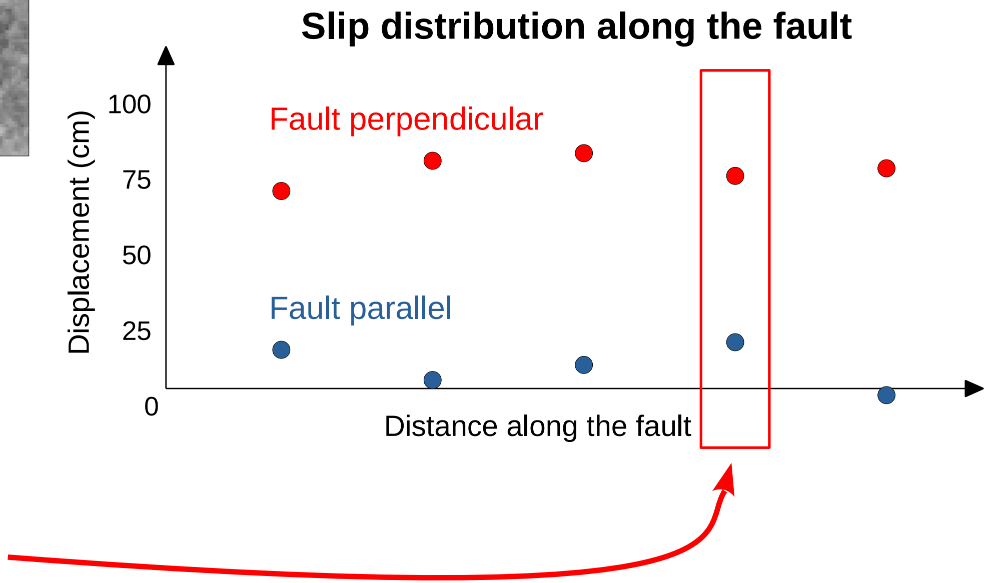

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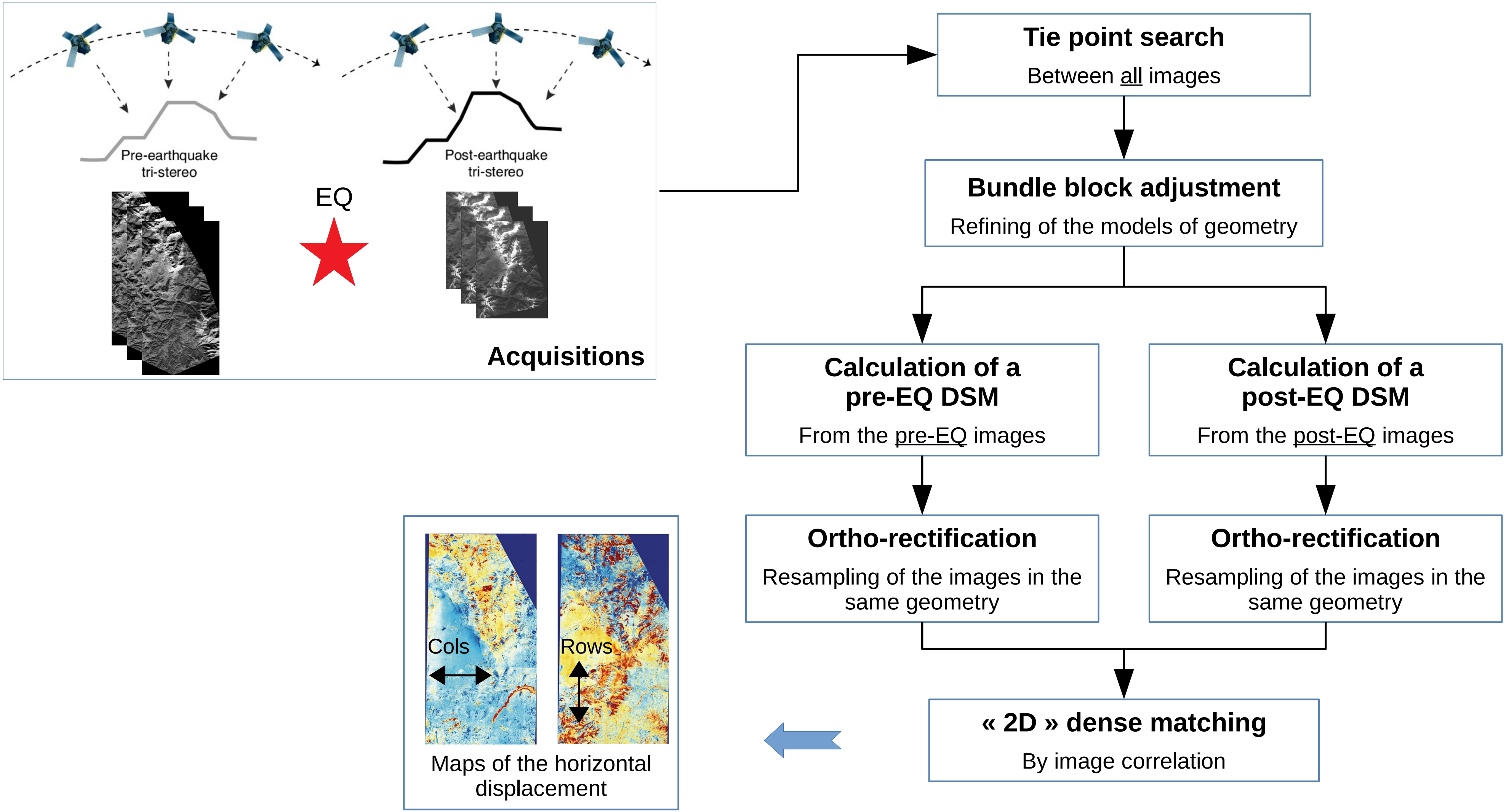

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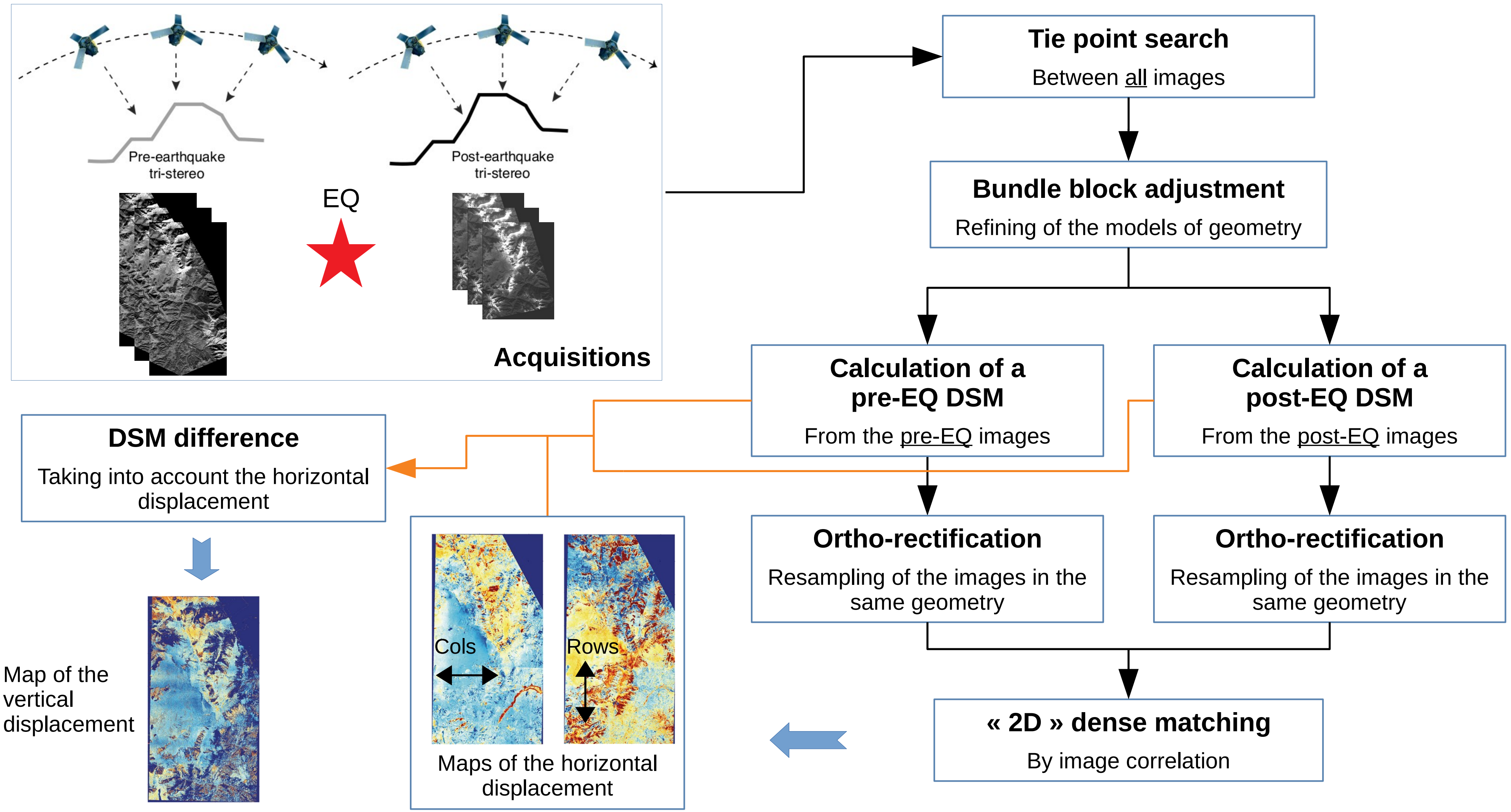
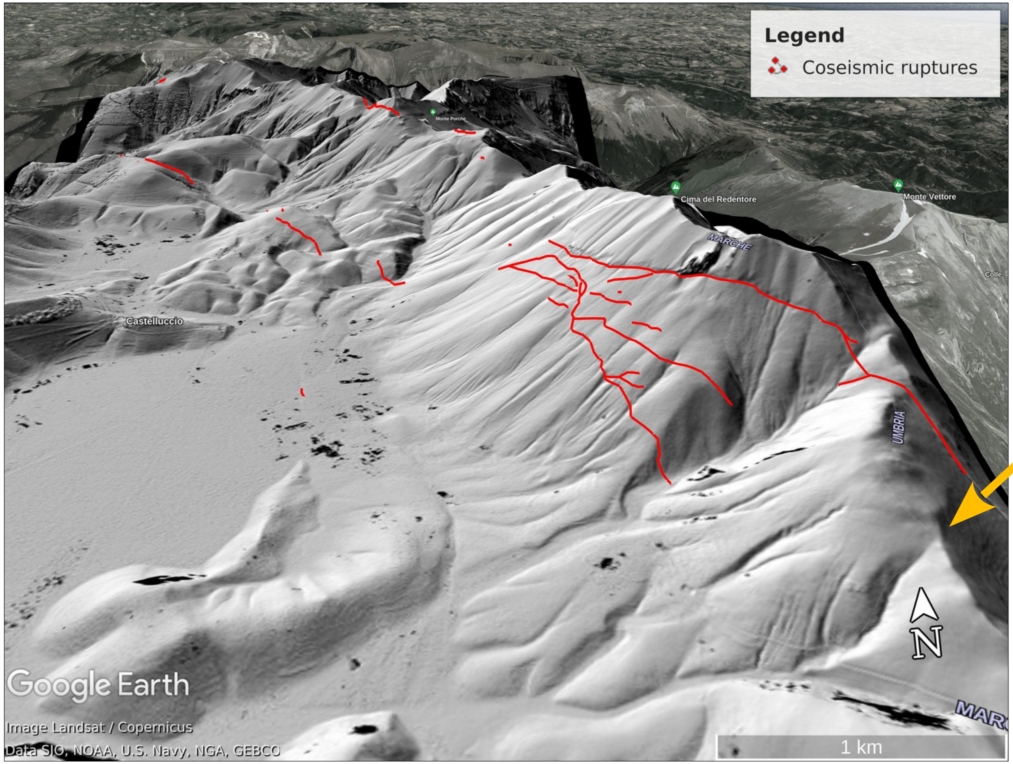


The Norcia earthquake (Italy, 2016, M_w 6.5)

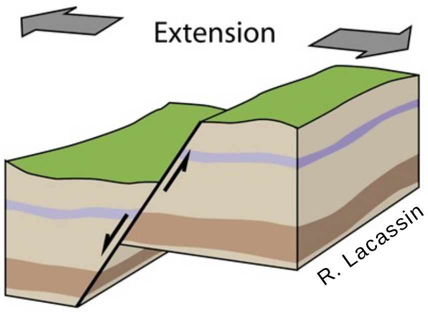
Delorme et al., 2020



Activation of the CEOS Seismic Hazards Pilot
=> Pléiades satellite images from CNES

High resolution DSM calculated from Pléiades data, accessible to the scientific community

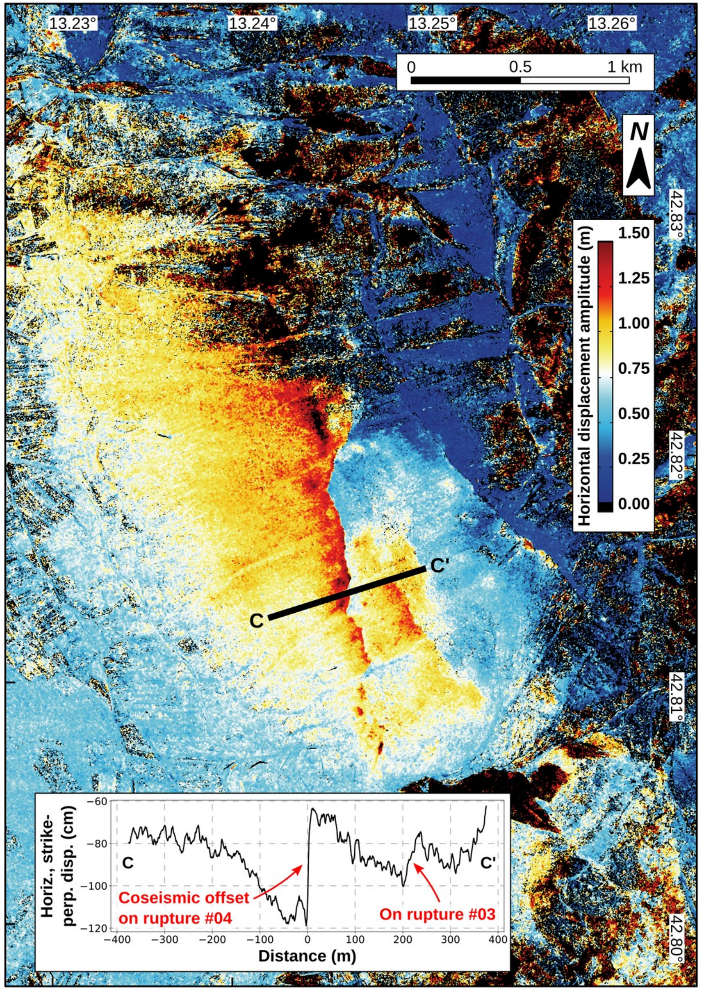
50 cm GSD
=> Displacement detection threshold: up to 5 cm



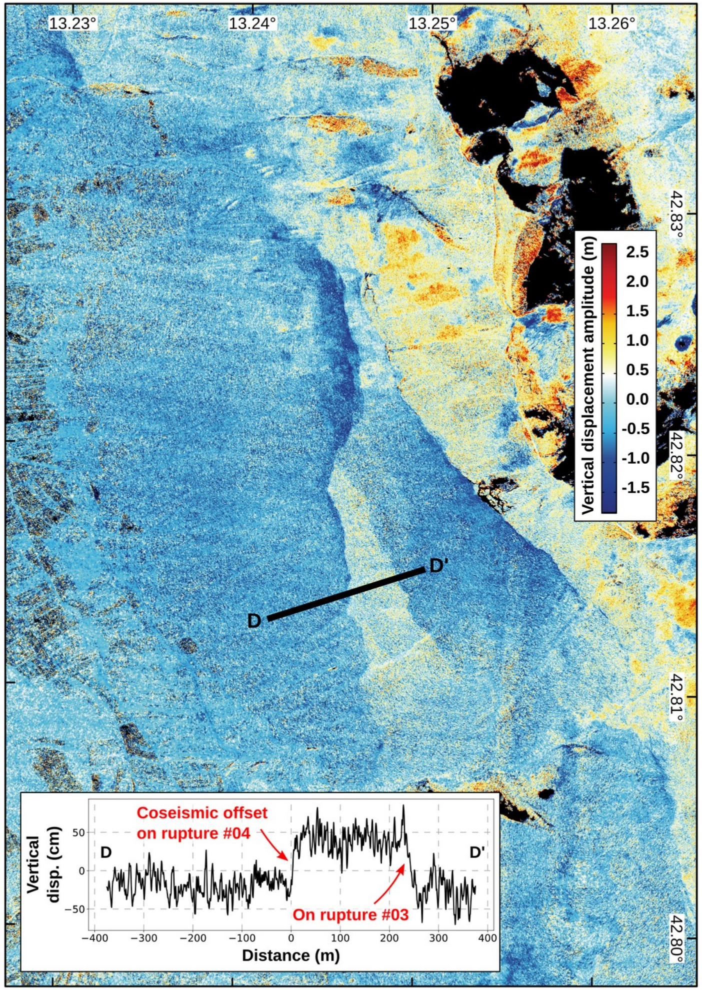
A normal fault

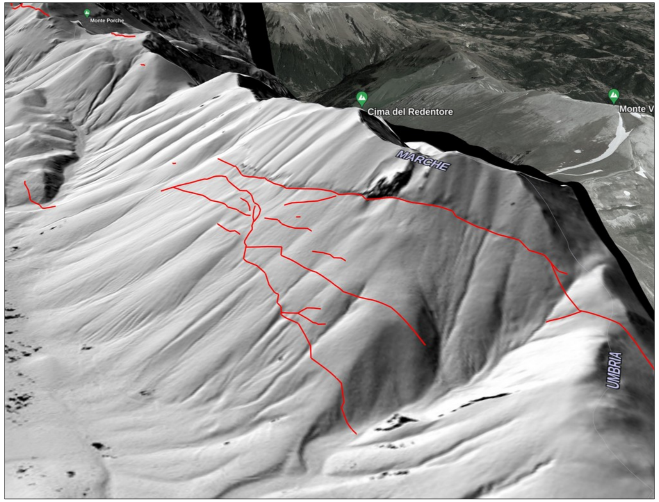
The Norcia earthquake (Italy, 2016, M_w 6.5)

Horizontal displacement



Vertical displacement

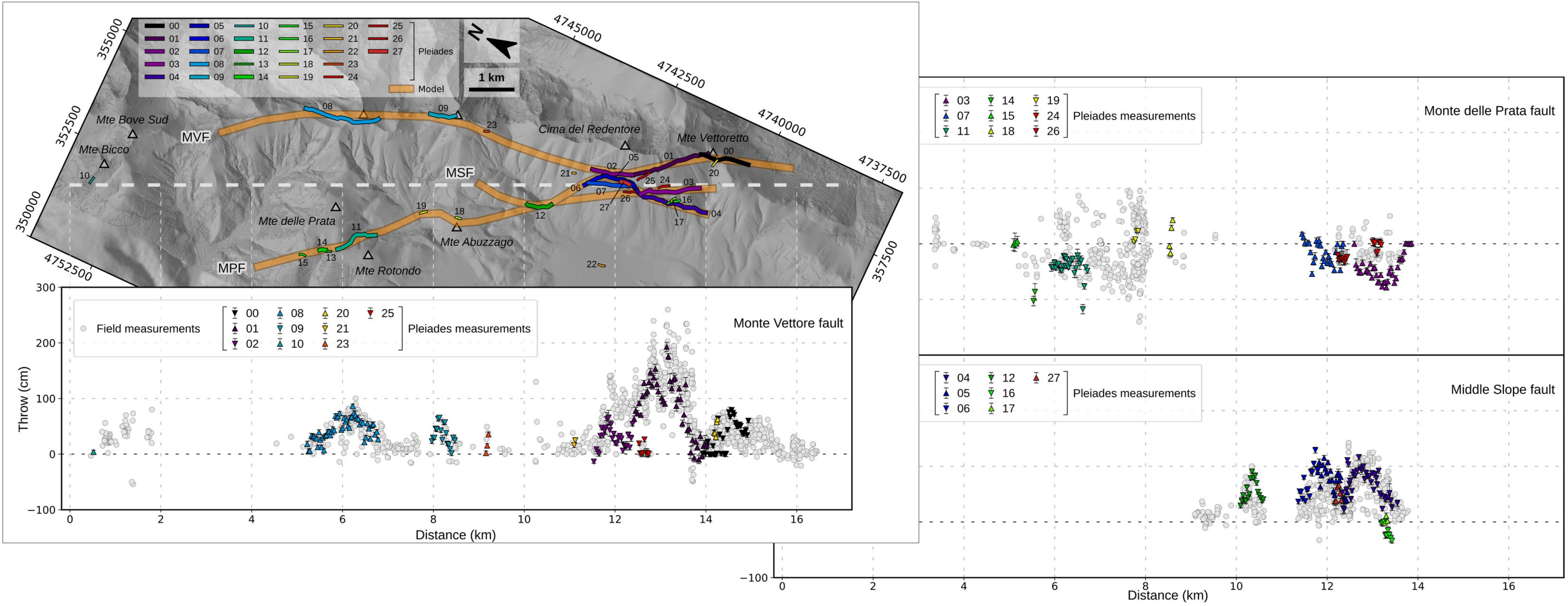




Cima del Redentore area

Delorme et al., 2020

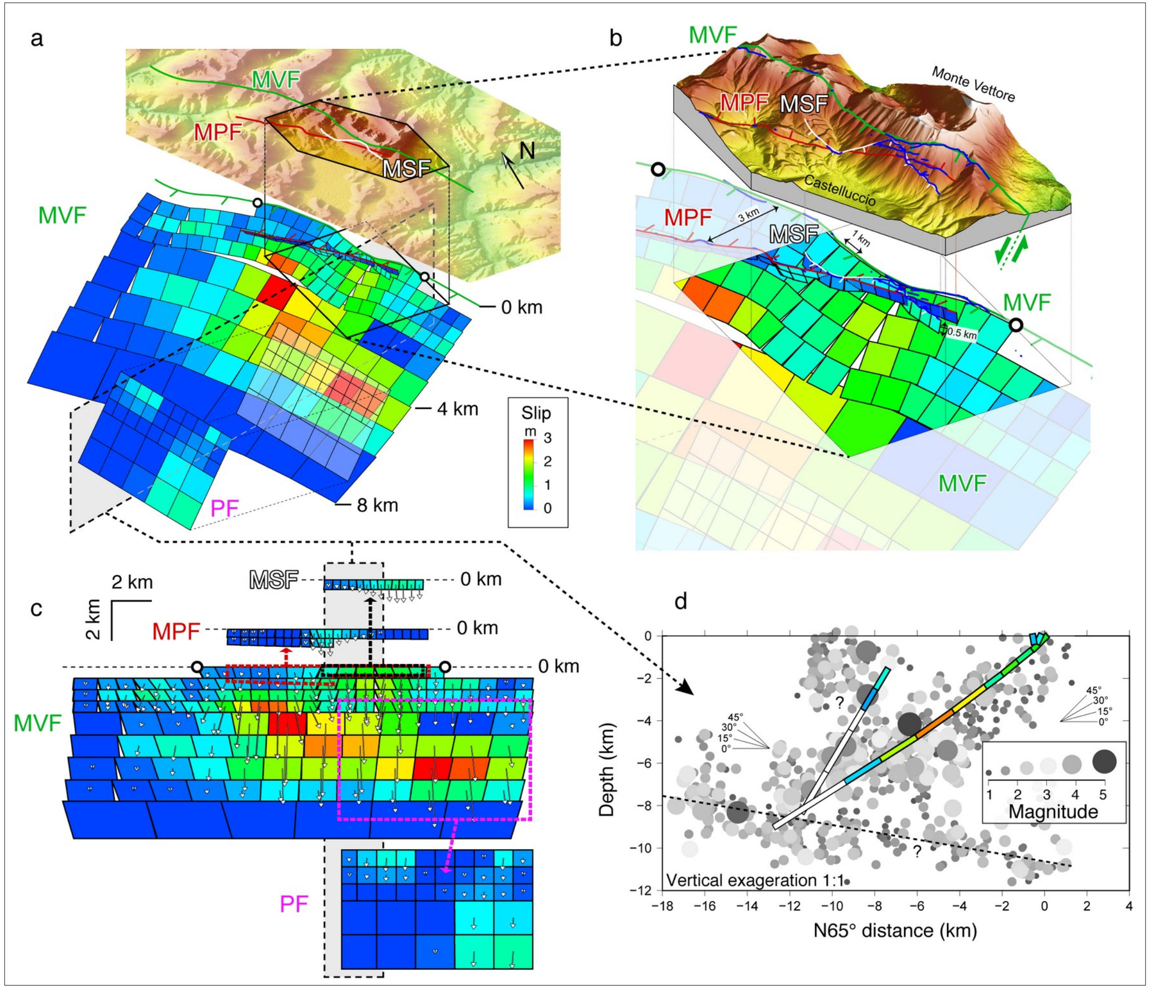
The Norcia earthquake (Italy, 2016, M_w 6.5)



Comparison between measurements from displacement maps (colored symbols) and from the field (gray dots)

Delorme et al., 2020

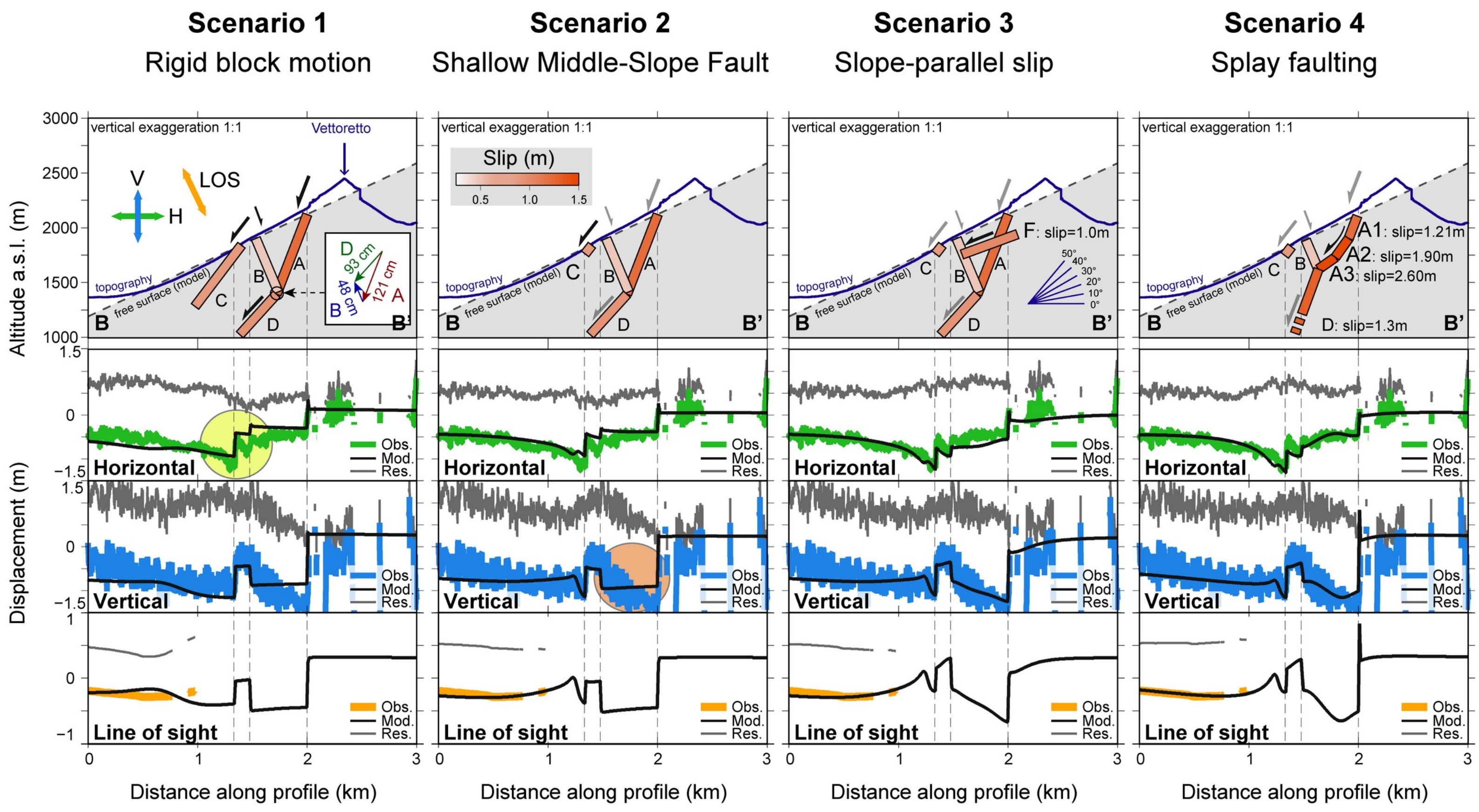
The Norcia earthquake (Italy, 2016, M_w 6.5)



Modeling: slip distribution on the fault planes, from the joint inversion of InSAR, GPS and optical data

Delorme et al., 2020

The Norcia earthquake (Italy, 2016, M_w 6.5)

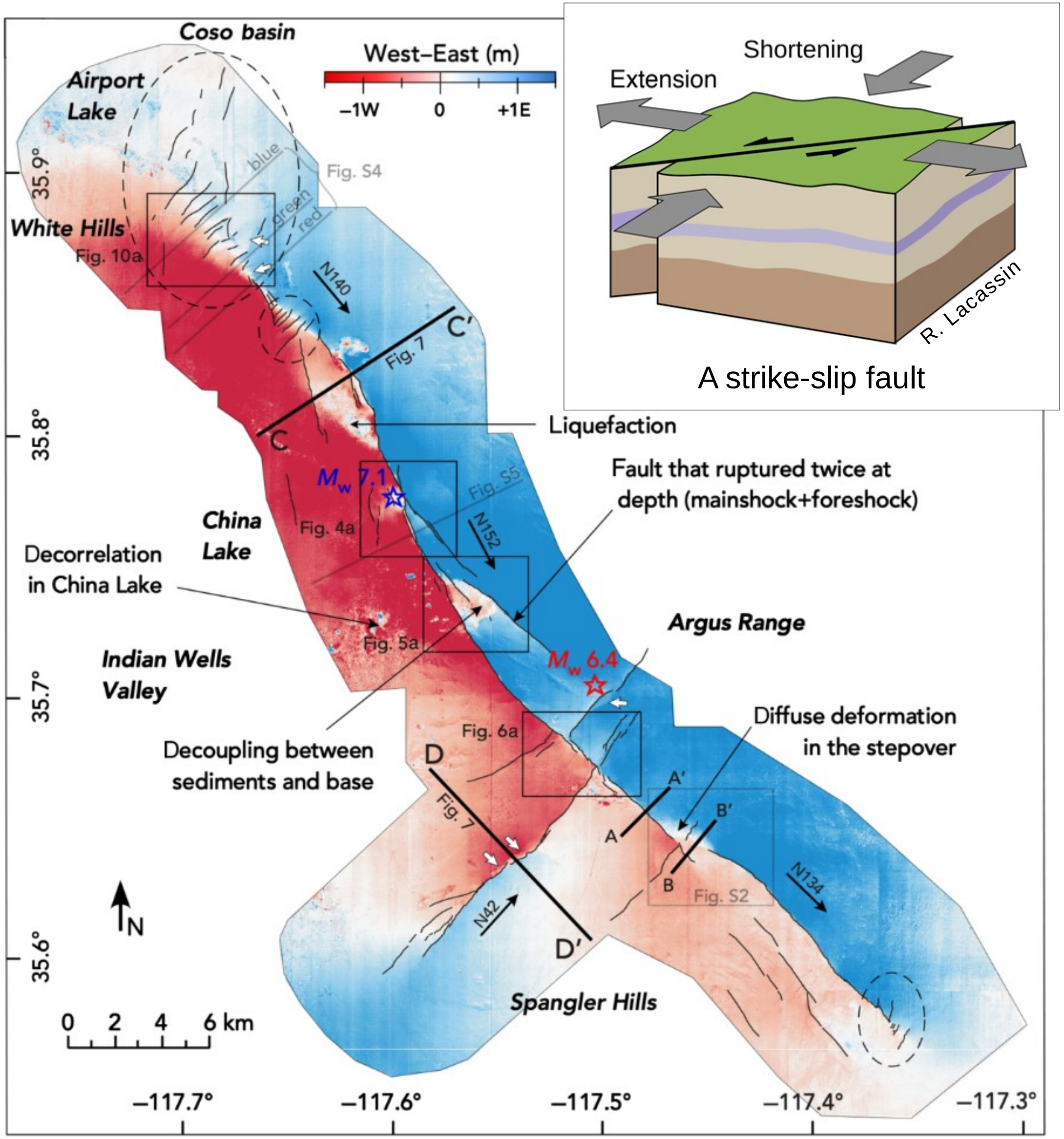


Modeling: near-fault simulations of surface displacement using four scenarios of fault geometry and slip at depth

Delorme et al., 2020

The Ridgecrest earthquake sequence (California, 2019, M_w 6.4 & 7.1)

Antoine et al., 2021

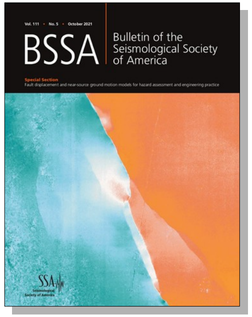


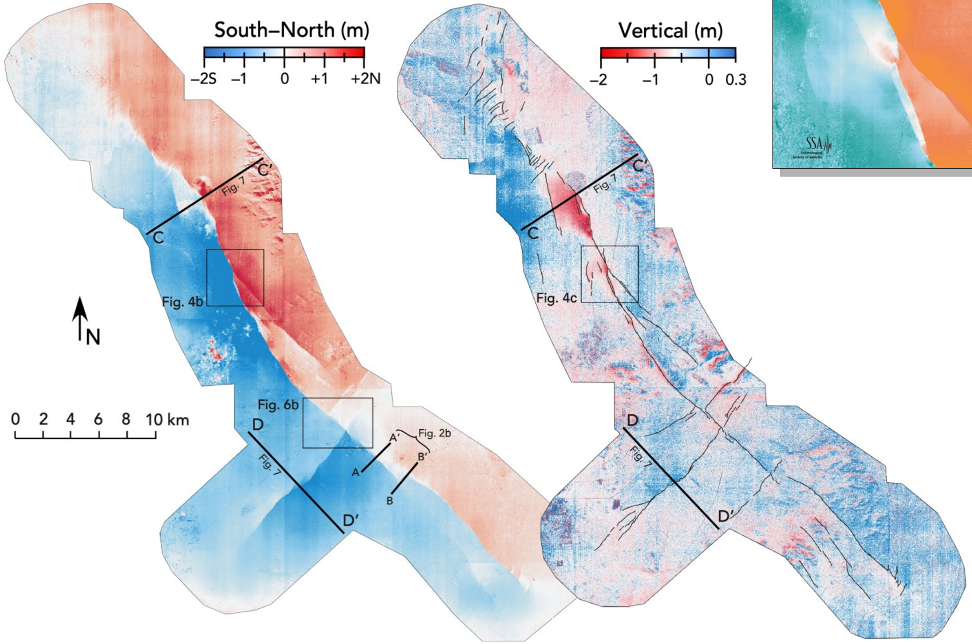
Pléiades-WV multi-sensor correlation

Pléiades images (CEOS Seismic Pilot - CNES)

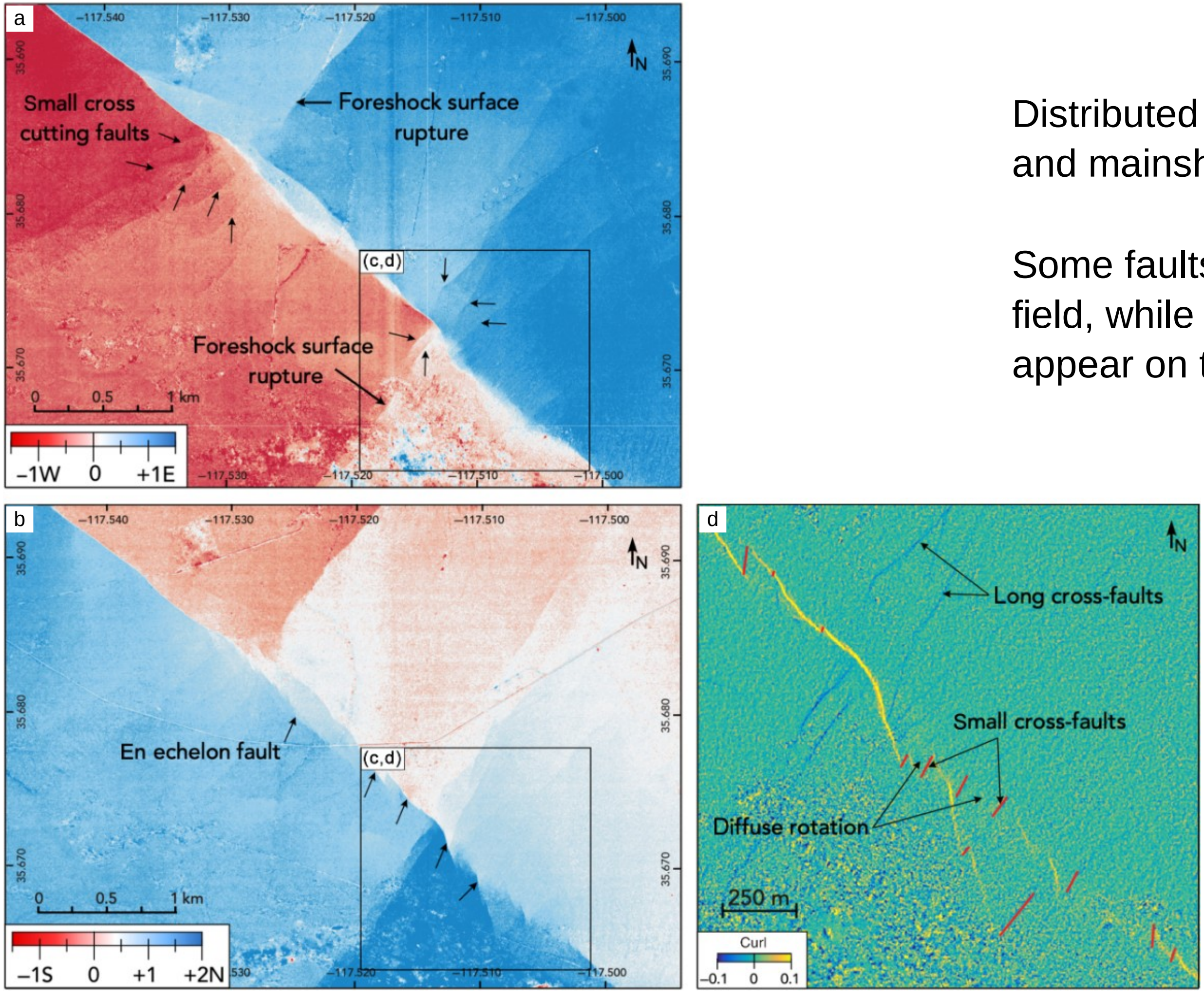
Worldview images (NextView license)

50 cm GSD





The Ridgecrest earthquake sequence (California, 2019, M_w 6.4 & 7.1)

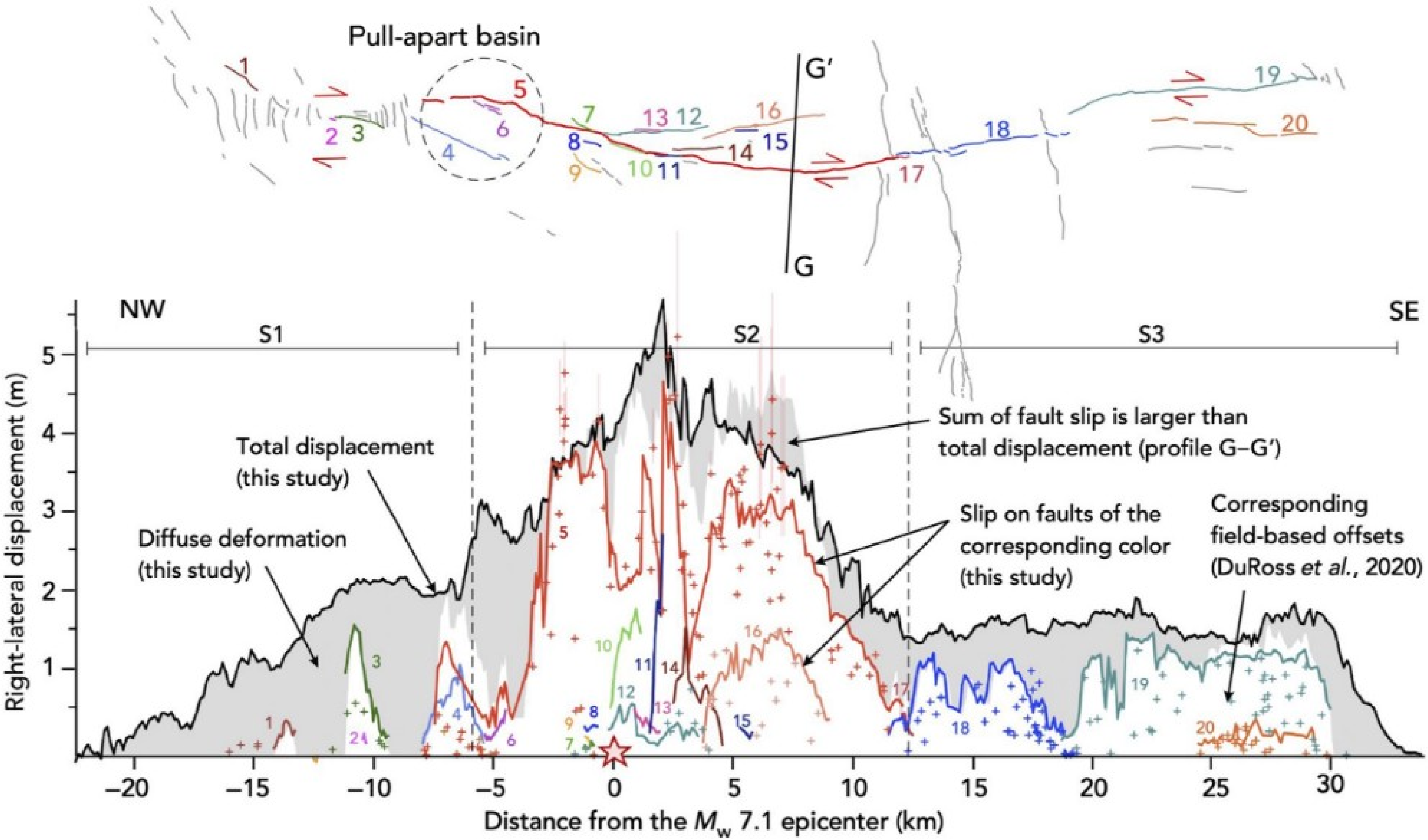


Distributed deformation along the foreshock and mainshock ruptures

Some faults had already been mapped in the field, while others were not detected, but appear on the displacement maps

Antoine et al., 2021

The Ridgecrest earthquake sequence (California, 2019, M_w 6.4 & 7.1)



Antoine et al., 2021

IPGP studies using CNES Pléiades data from CEOS Seismic Pilot:

- Kaikoura earthquake, New Zealand, 2016 (Klinger et al., 2018)
- Haiyuan fault, China (Matrau et al., 2019)
- Norcia earthquake, Italy, 2016 (Delorme et al., 2020)
- Ridgecrest earthquake sequence, California, 2019 (Antoine et al., 2021)
- Maduo earthquake, China, 2021 (in progress)

Conclusion

Correlation of high resolution optical images makes it possible to:

- Quantify the distribution along the rupture of the 3D surface deformation – both localized on the rupture and distributed around it – bringing new constraints to the models
- Detect small displacements on structures that are hard to detect in the field or with lower resolution images
- Bring new elements to current debates in the field of tectonics (e.g. the potential presence of inelastic deformation in the medium)

Current developments in MicMac, related to Earth sciences:

- Tie points extraction for historical images (L. Zhang)
- Learning methods for calculating deformation maps (A. Delorme)

CIEST^2 – Cellule d'Intervention et d'Expertise Scientifique et Technique

In the event of a disaster, the Charter acquires data for operational purposes, usually in Pléiades' monoscopic mode

The CEOS Pilots provide images to respond to specific requests from scientists, usually after the crisis

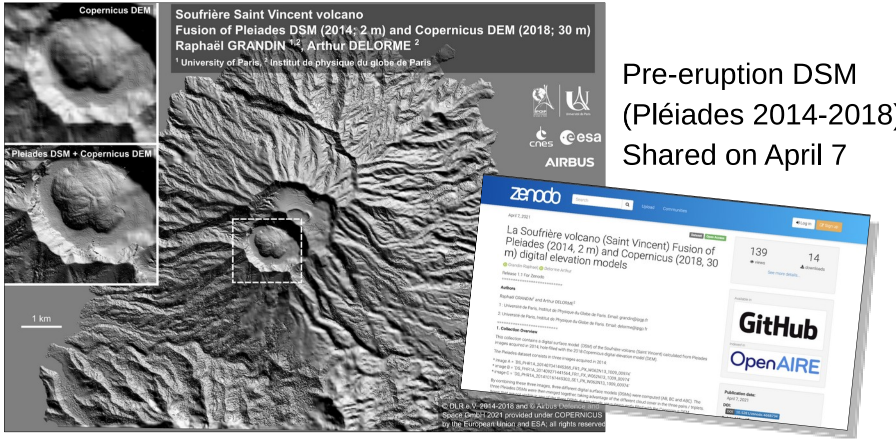
The CIEST^2 fills a gap by acquiring crucial Pléiades data in the course of the crisis (landslide, glacier collapse, earthquake, volcanic eruption, ...) with great reactivity. A direct channel is established between the scientific community and CNES (> 10 activations since 2021)

Scientific contact:
R. Grandin (IPGP, U. Paris Cité)
CIEST2_ComitePilotage@poleterresolide.fr

Complementary to CEOS Pilot activities

Example of the eruption of Soufrière Saint-Vincent:

- Formation of a dome (Dec 2020 → Apr 2021)
- Increase of eruptive activity (1 Apr → 9 Apr) → Activitation of CIEST^2: 08 Apr 23:00
  - => Start of eruption: 09 Apr 12:30
  - => 1st acquisition: 09 Apr 14:30
- Explosive phase (9 Apr → 23 Apr)
- Formation of a crater + ash / tephra deposits



Pre-eruption DSM
(Pléiades 2014-2018)
Shared on April 7