

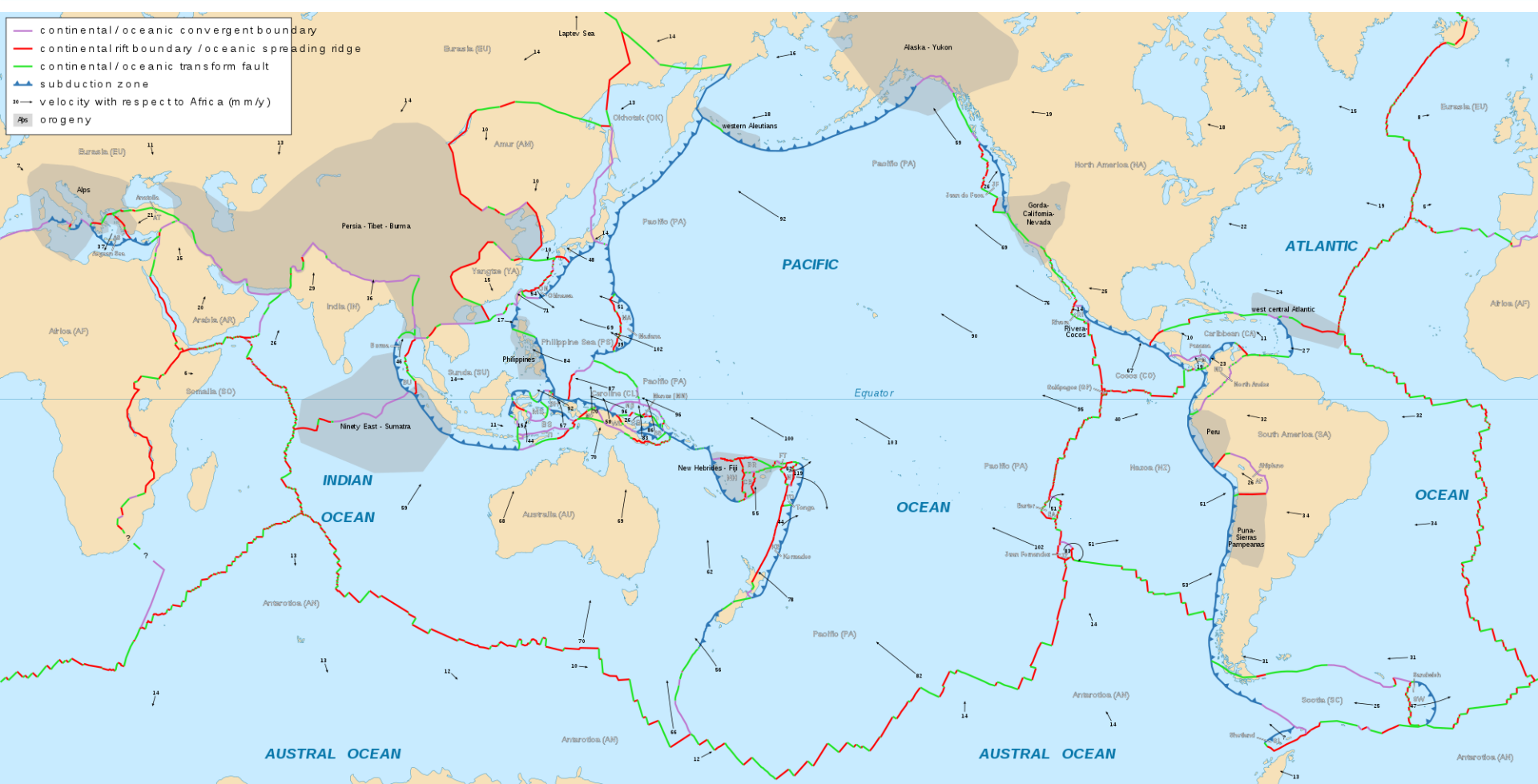
USE OF SPACE-BASED DATA FOR PLATE TECTONICS APPLICATIONS

*F. Sarti (ESA), A. Mouratidis (AUTH, Greece),
G. Pezzo (INGV, Italy), S. Salvi (INGV, Italy)*

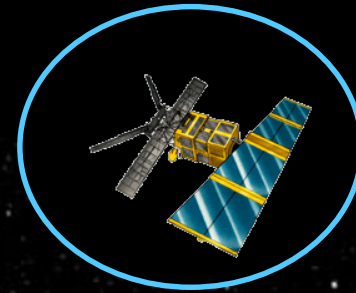
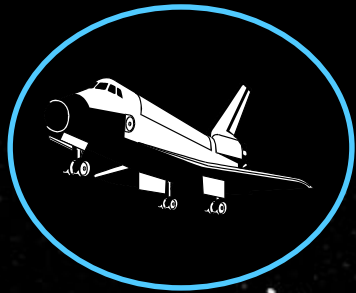
Francesco.Sarti@esa.int

1. Introduction (Plate Tectonics, EO, GNSS)
2. Advances: Mapping
3. Advances: DEM
4. Advances: Land cover
5. Advances: Displacements (GNSS, InSAR, SLR, VLBI)
6. Other Applications
7. Summary and Conclusions
8. References
9. Further reading

Introduction – Plate Tectonics



Introduction – Earth Observation (EO)



- Earth Observation (EO) from space and airborne imagery provides new insights and tools for plate tectonics and in general, for all Earth Sciences.
- Better understanding and modeling of the Earth's crust
- Identification of features related to processes at different scales

Operational & Near-future EO missions: *The Sentinels (Copernicus, former GMES)*



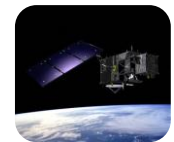
1. Sentinel-1: SAR mission for land and ocean services



2. Sentinel-2: Optical high resolution land mission



3. Sentinel-3: Medium resolution land and ocean mission



4. Sentinel-4: Geostationary atmosphere mission



5. Sentinel-5: Low Earth orbit atmosphere mission



ESA Sentinel 1 Mission



C-band SAR Mission

Sentinel-1A (3/4/2014)

Sentinel-1B (25/4/2016)

Applications:

- Ice and marine/land monitoring;
- Mapping in support of humanitarian aid in crisis situations.

Main features:

- C-band (5.4 GHz) SAR
- Daily coverage of high priority areas;
- Bi-weekly global coverage;
- 12 days repeat cycle (6 days with both Sentinels 1A and 1B operational);
- 7 years design life time (consumables for 12 years).

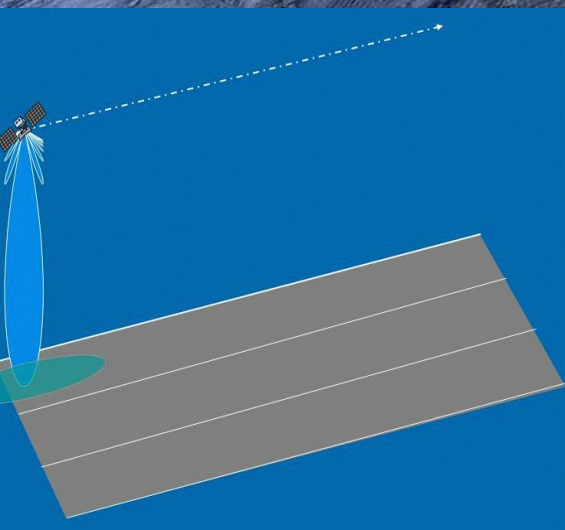


Modes	Resolution	Swath Width	Polarization
Stripmap (SM)	5 x 5 m ²	> 80 km	HH+HV or VV+VH
Interf. Wideswath (IW)	5 x 20 m²	> 250 km	HH+HV or VV+VH
Extra Wideswath (EW)	25 x 100 m ²	> 400 km	HH+HV or VV+VH
Wave (W)	5 x 20 m ²	20 x 20 km ² @ 100 km spacing	HH or VV

Image Acquisition in Interferometric Wide Swath mode (IW)



Terrain Observation
by Progressive Scans
(TOPS)

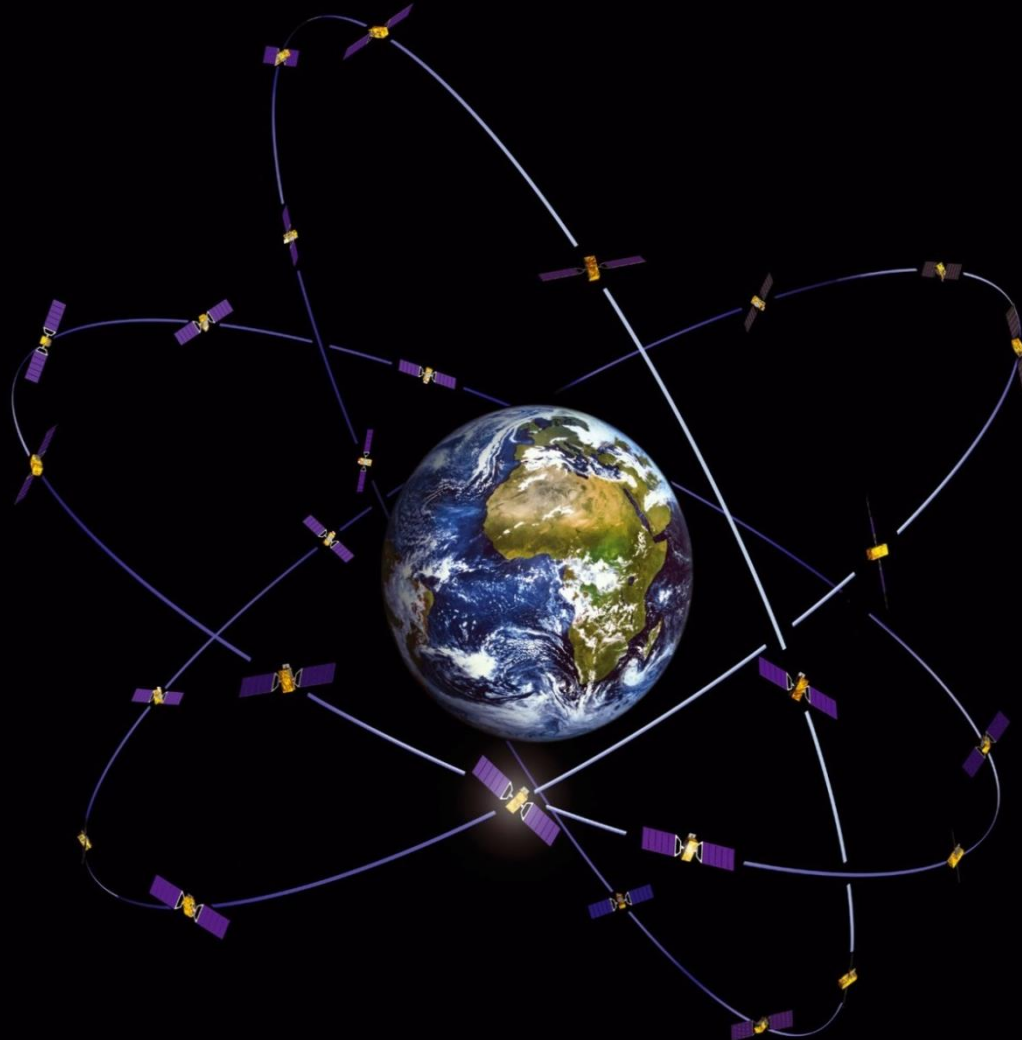


Two dozen satellites hovering thousands of miles out in space are allowing people to locate themselves on the earth's surface with remarkable precision

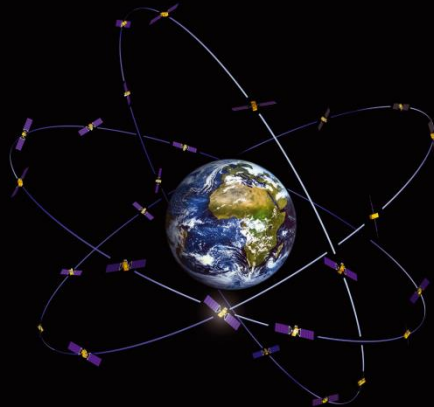
by Thomas A. Herring

(Scientific American, February 1996)

Introduction – Global Navigation Satellite Systems (GNSS)



Introduction – Global Navigation Satellite Systems (GNSS)



What is Galileo?

Introduction – Global Navigation Satellite Systems (GNSS)



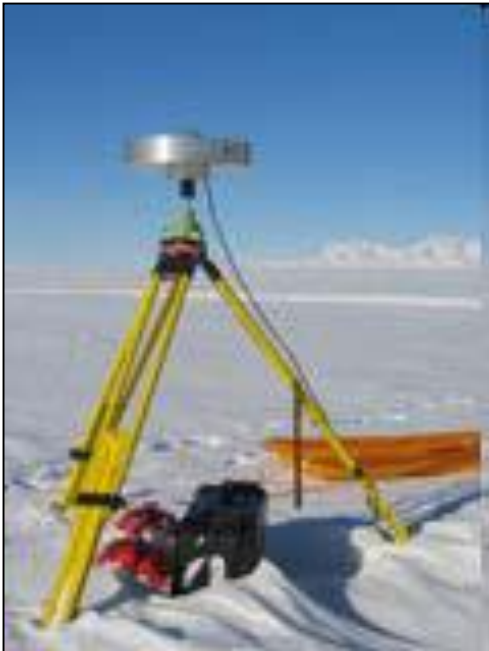
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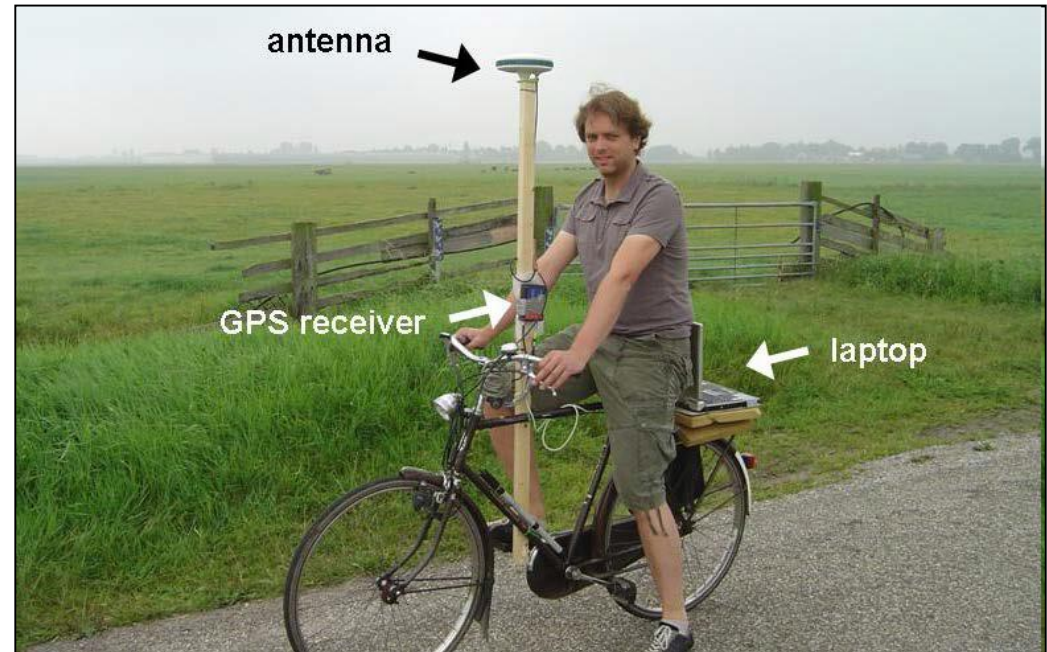
2003-8-21 10:4

Introduction – Global Navigation Satellite Systems (GNSS)

Static



Kinematic



Introduction – Global Navigation Satellite Systems (GNSS)



https://gssc.esa.int/navipedia/index.php/Main_Page

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“The reference for Global Navigation Satellite Systems.”

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- [GPSWorld news](#)
- [GNSS Science Support Centre news](#)

Quick References

- [GALILEO Brochure \(ESA\)](#)
- [Current and Planned Global and Regional Navigation Systems \(UNOOSA-ICG\)](#)
- [Galileo IOV Factsheet](#)
- [Galileo FOC Factsheet](#)
- [ESA GNSS Data Processing Book](#)



- Until a few years ago, lack of systematic EO acquisitions
- Nowadays, regular, systematic acquisitions and short revisit time of EO missions
- EO has become a fundamental tool, together with Global Navigation Satellite Systems (GNSS) and in-situ-measurements
- Space data allow mapping & measuring small-scale crustal deformation over large areas with high spatial resolution, contributing to our **understanding and modeling of active**

Introduction

See video n.1 or show it from
youtube (next slide)



On October the 30/10/2018, the European Commission granted the legal status of European Research Infrastructure Consortium to EPOS (European Plate Observing System) <https://www.epos-ip.org/>

EUROPEAN RESEARCH INFRASTRUCTURE ON SOLID EARTH

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EPOS - The European Plate Observing System

A Research Infrastructure for Solid Earth Science

<https://www.youtube.com/watch?v=ORbPjESluUg>

INTRODUCING EPOS

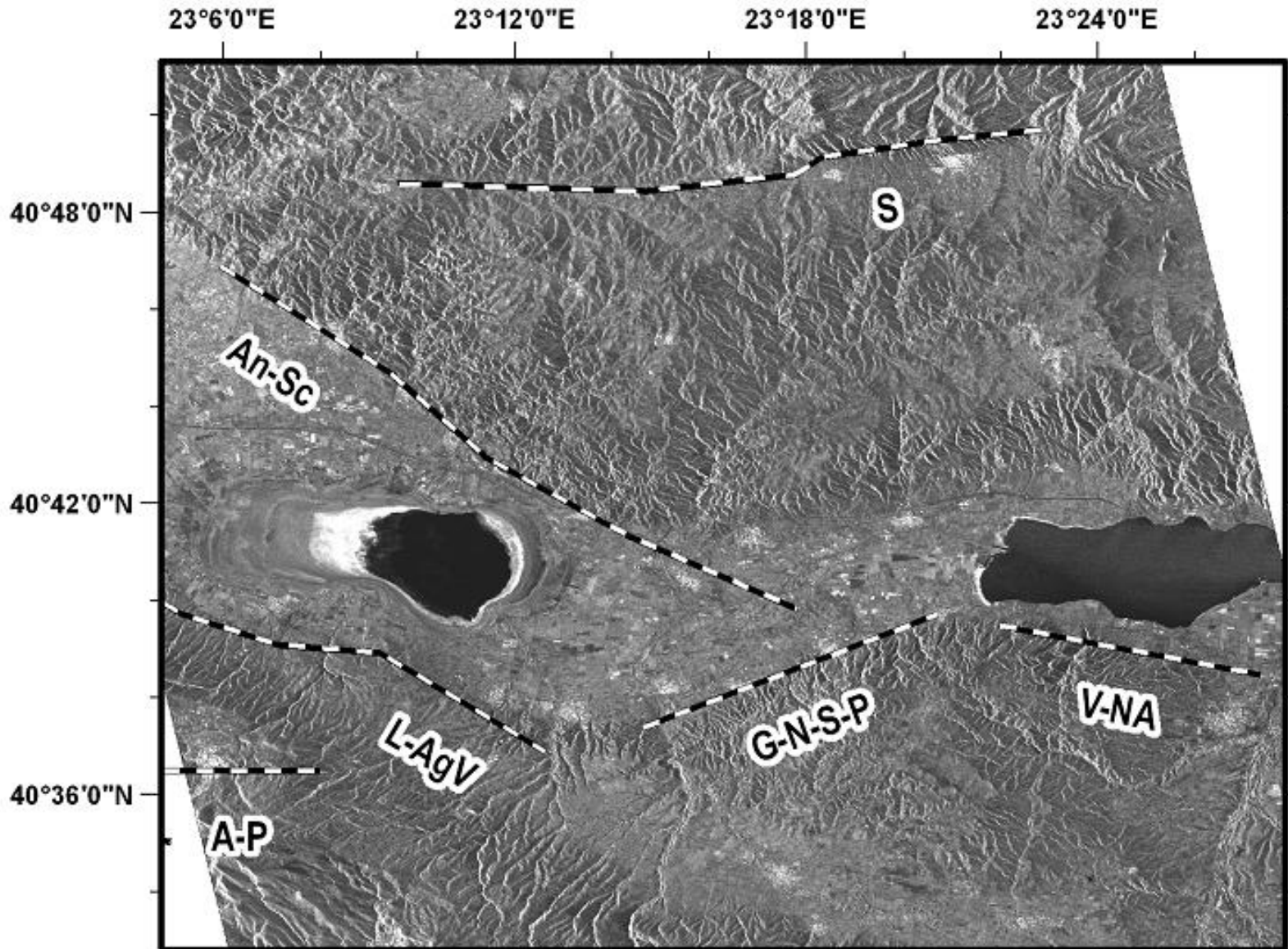
Viable solutions to tackle solid Earth grand challenges



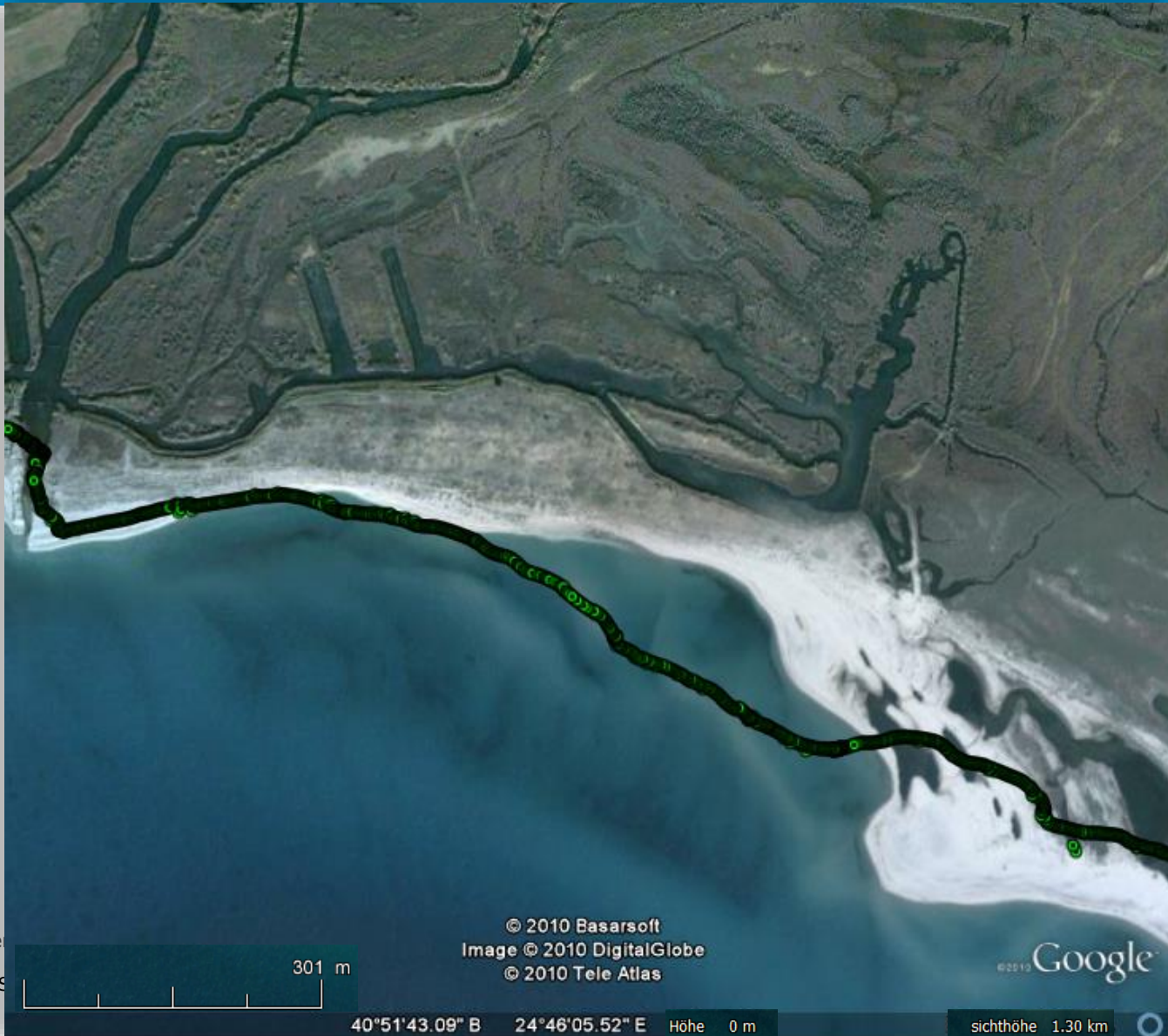
- Geomorphological and topographical features like mountains, valleys and rifts, which shape the “face of the Earth”, can be successfully observed and modeled (with an increasingly higher resolution) using optical and radar (SAR) imagery from space.
- Synthetic Aperture Radar (SAR) and/or optical satellite data are powerful tools for surface and deep geological and tectonic structures detection, especially where seismic data are not available



Advances: Mapping of tectonic lines (faults) ESA



Advances: Mapping of changes



| Earth Obser
ESA UNCLASS

© 2010 Basarsoft
Image © 2010 DigitalGlobe
© 2010 Tele Atlas

© 2010 Google

European Space Agency

40°51'43.09" B 24°46'05.52" E Höhe 0 m

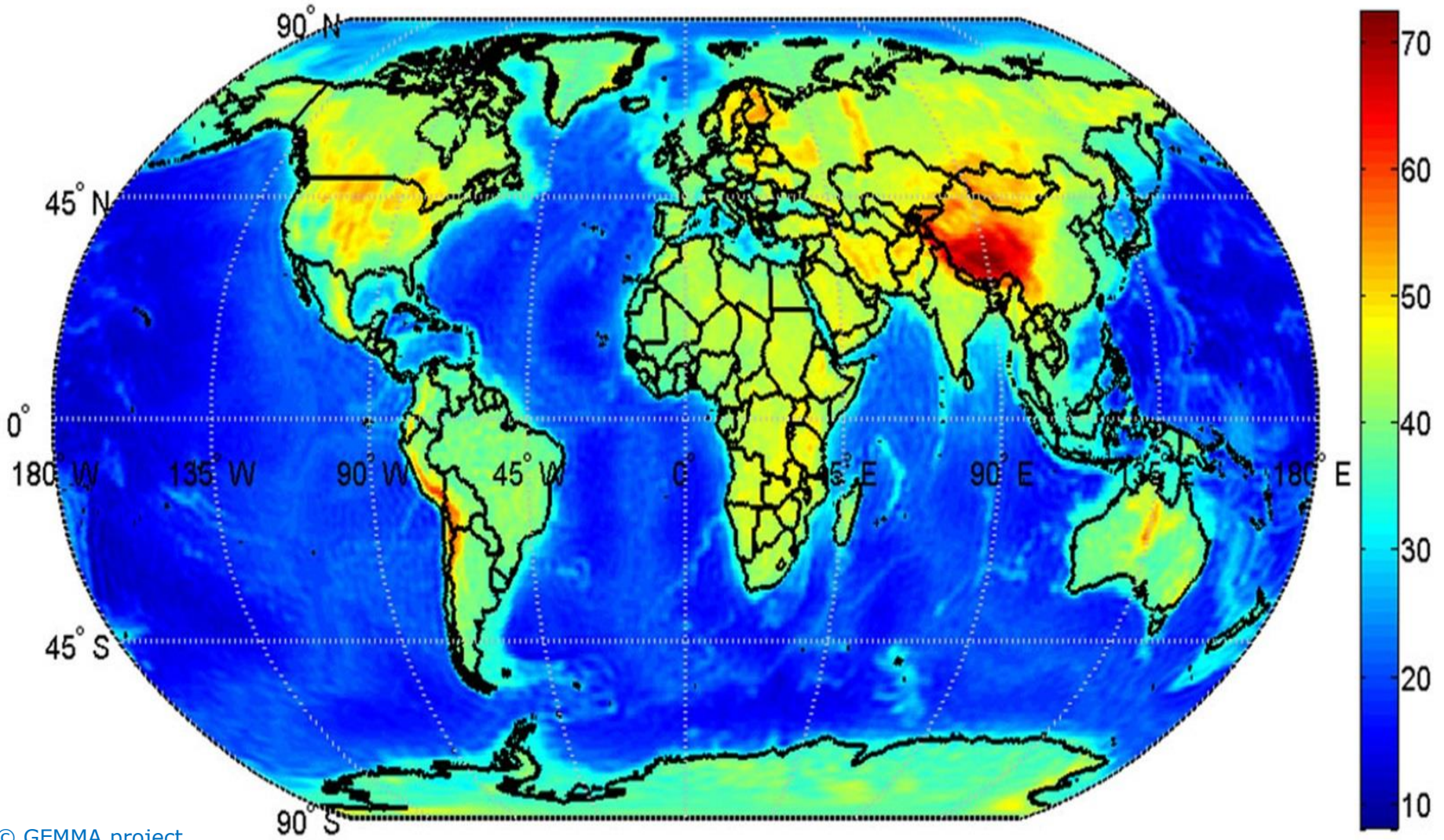
sichthöhe 1.30 km

GOCE Maps Moho



See details on:

http://www.esa.int/Our_Activities/Observing_the_Earth/GOCE/Mapping_the_Moho_with_GOCE



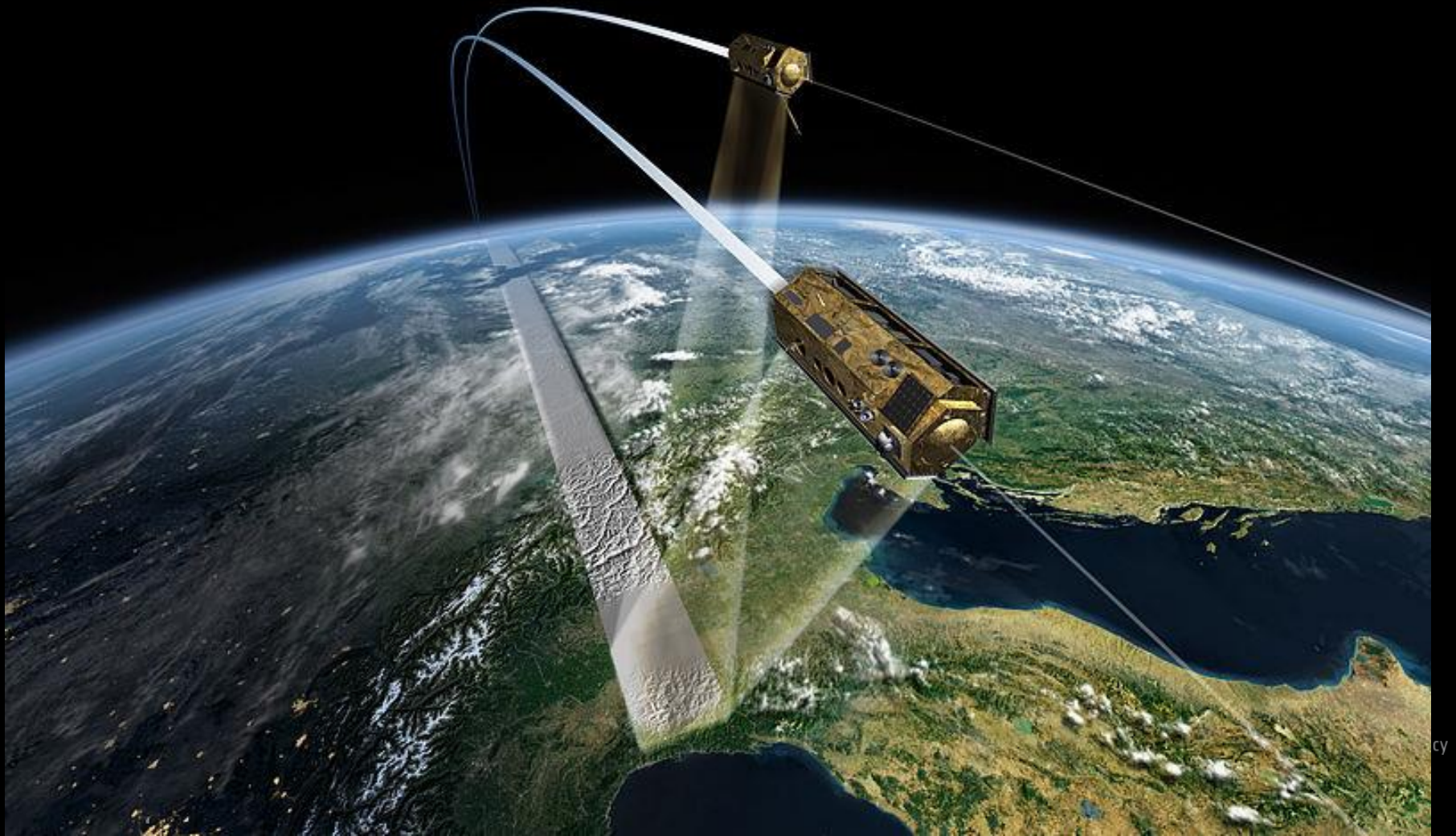
© GEMMA project



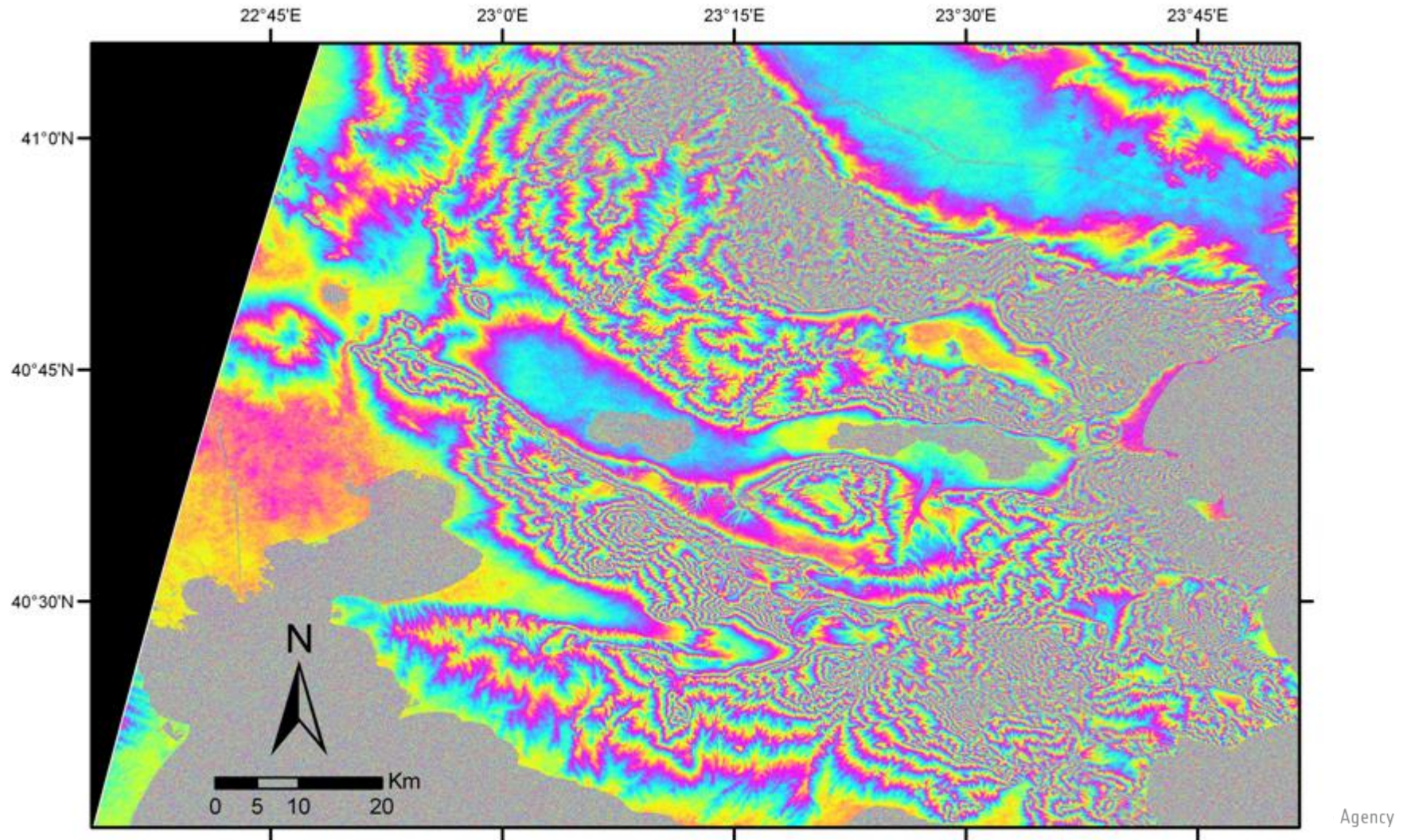
European Space Agency

- Stereo optical data and simultaneous radar acquisitions (e.g. SRTM and Tandem-X missions) have allowed the creation of finer and more precise Topographic Models (Digital Elevation Models/DEMs) worldwide.

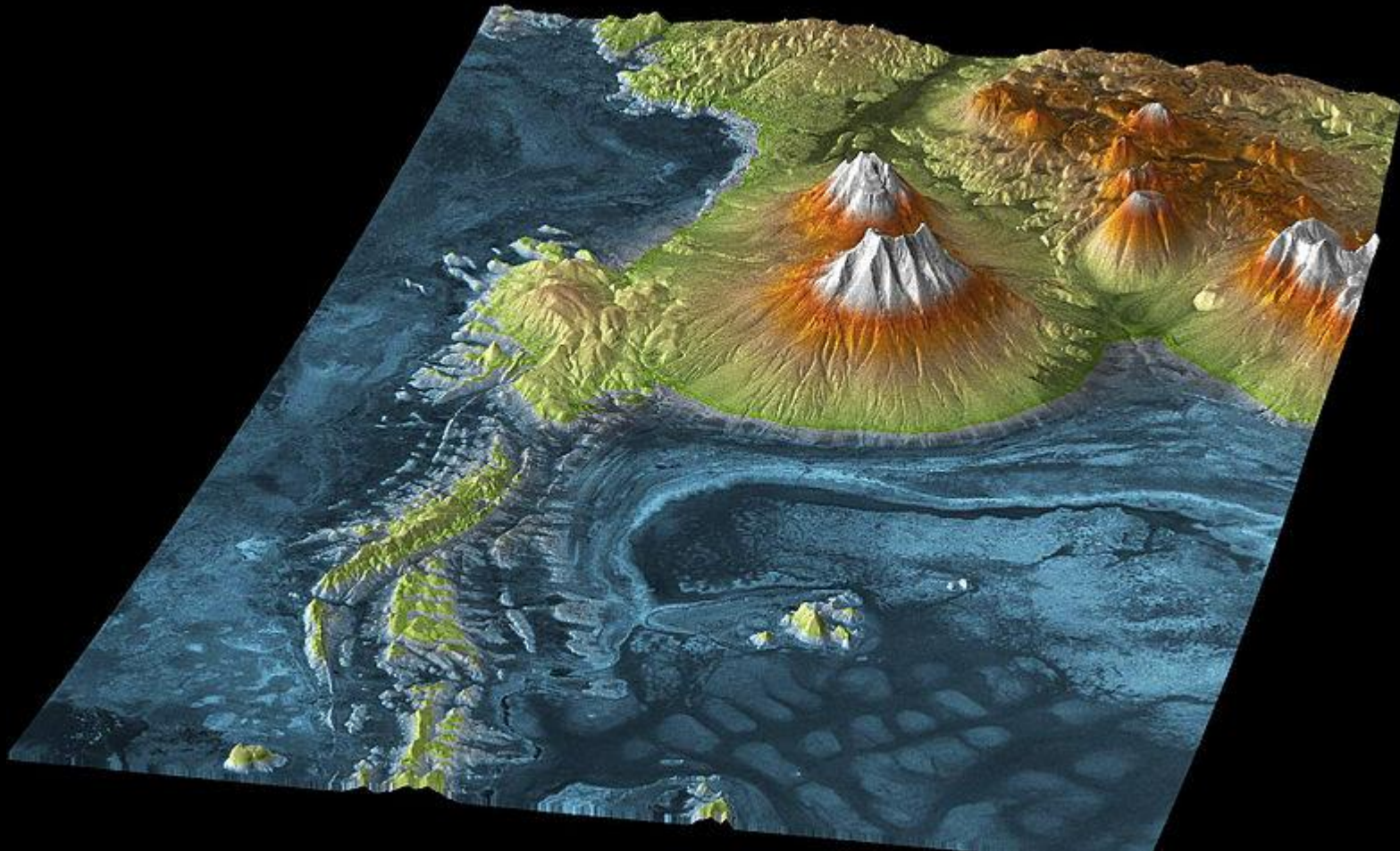
Advances: DEMs



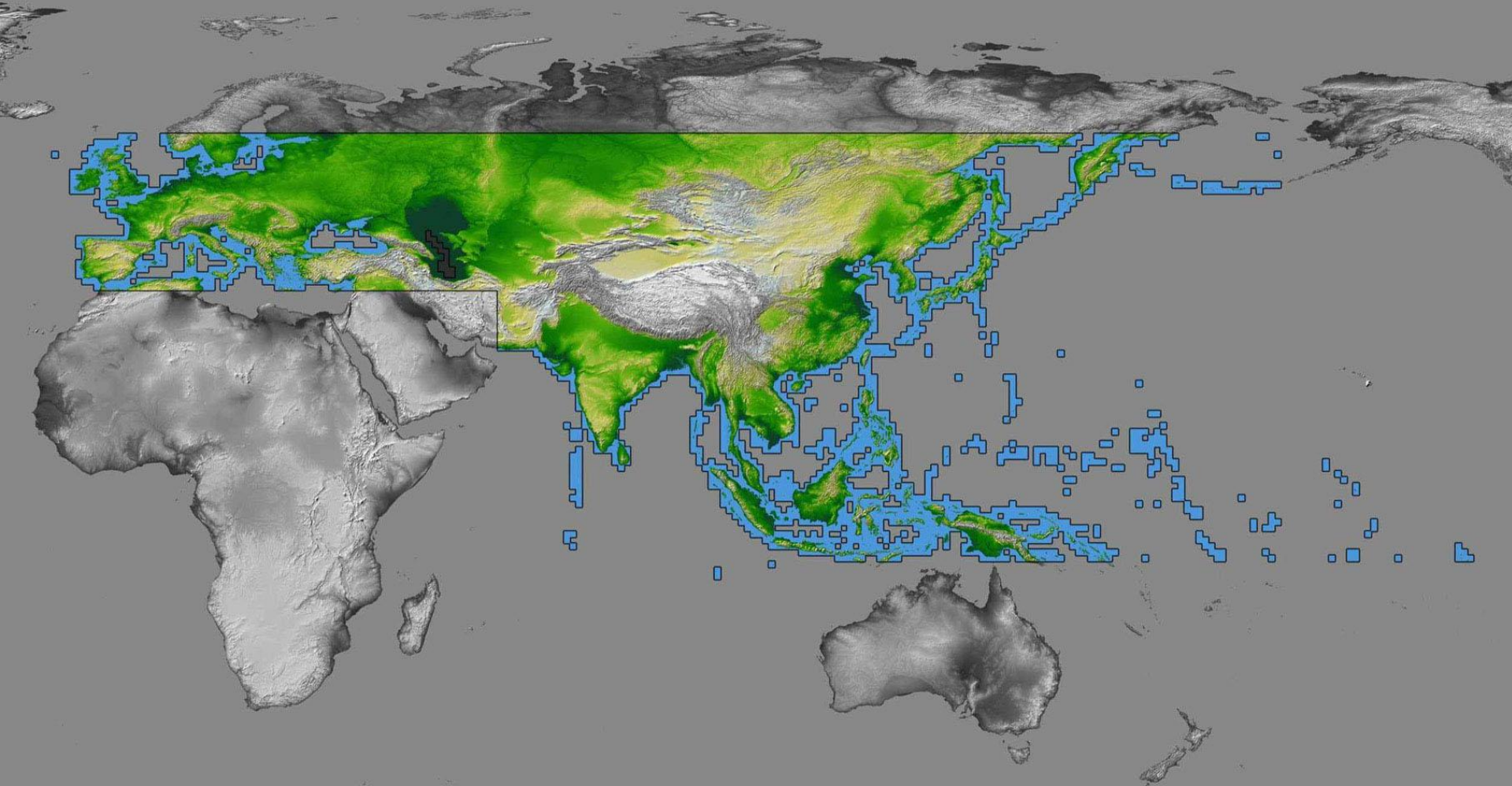
Advances: DEMs



Advances: DEMs










Advances: DEMs

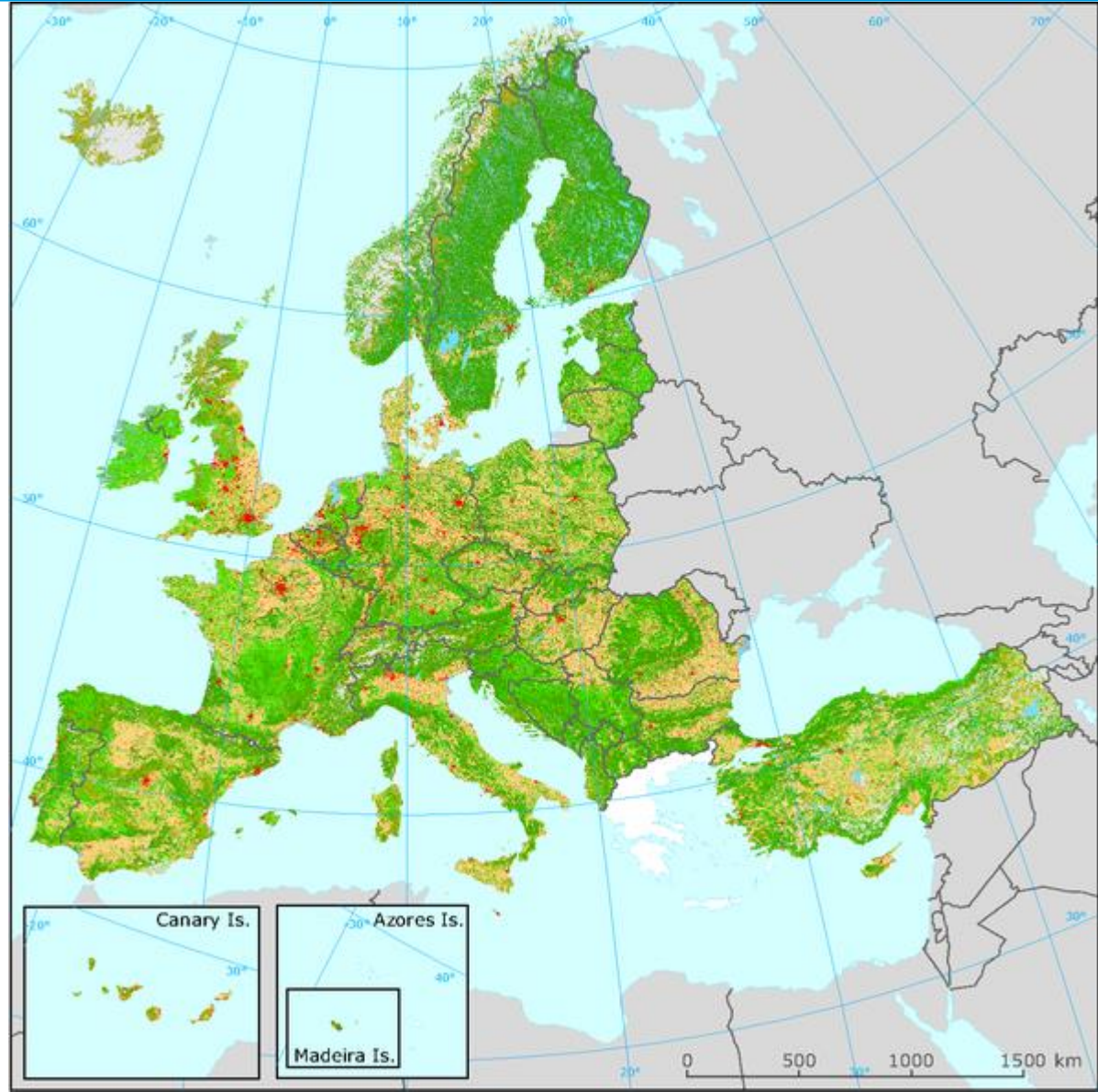


- Multispectral satellite data presently allow classifying land cover, whereas it is expected that the analysis and mapping of soil properties, including minerals, will soon benefit from forthcoming hyperspectral missions.

Advances: Land Cover

Corine Land Cover types - 2006

-  Artificial areas
-  Arable land and permanent crops
-  Pastures and mosaics
-  Forested land
-  Semi-natural vegetation
-  Open spaces/bare soils
-  Wetlands
-  Water bodies
-  No data
-  Outside data coverage



- GNSS and SAR Interferometry (InSAR), allow to measure accurately ground displacements.
- Since many years, GNSS provide useful and very precise (mm) displacement measurements over long and continuous periods, essential for geodesy applications and active tectonics studies. However, these systems provide punctual data, at the location of GNSS stations, which also need being installed in the field and maintained/inspected regularly.

GNSS
receiver/antenna

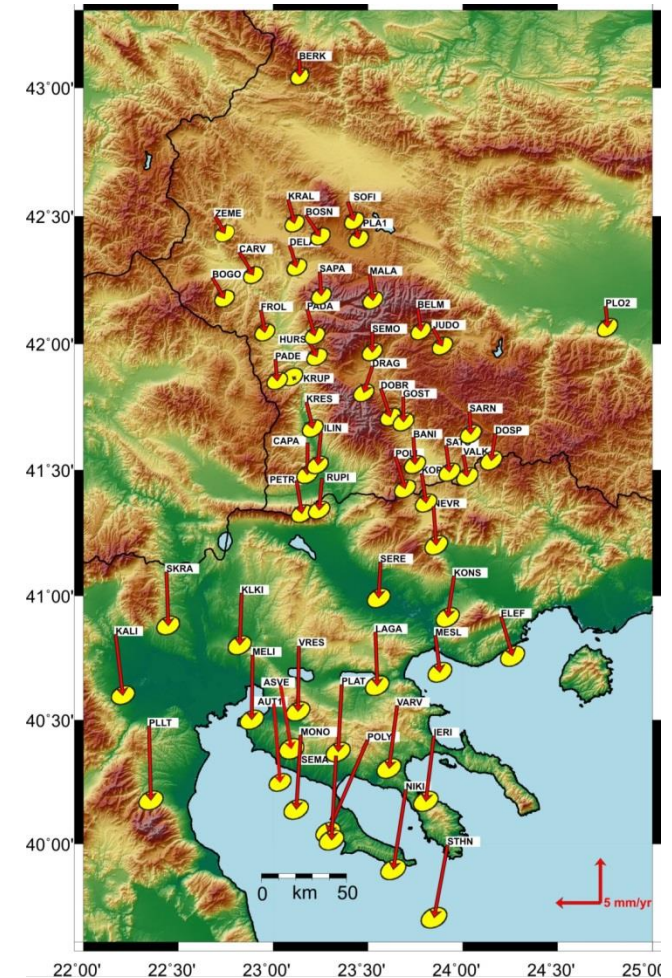
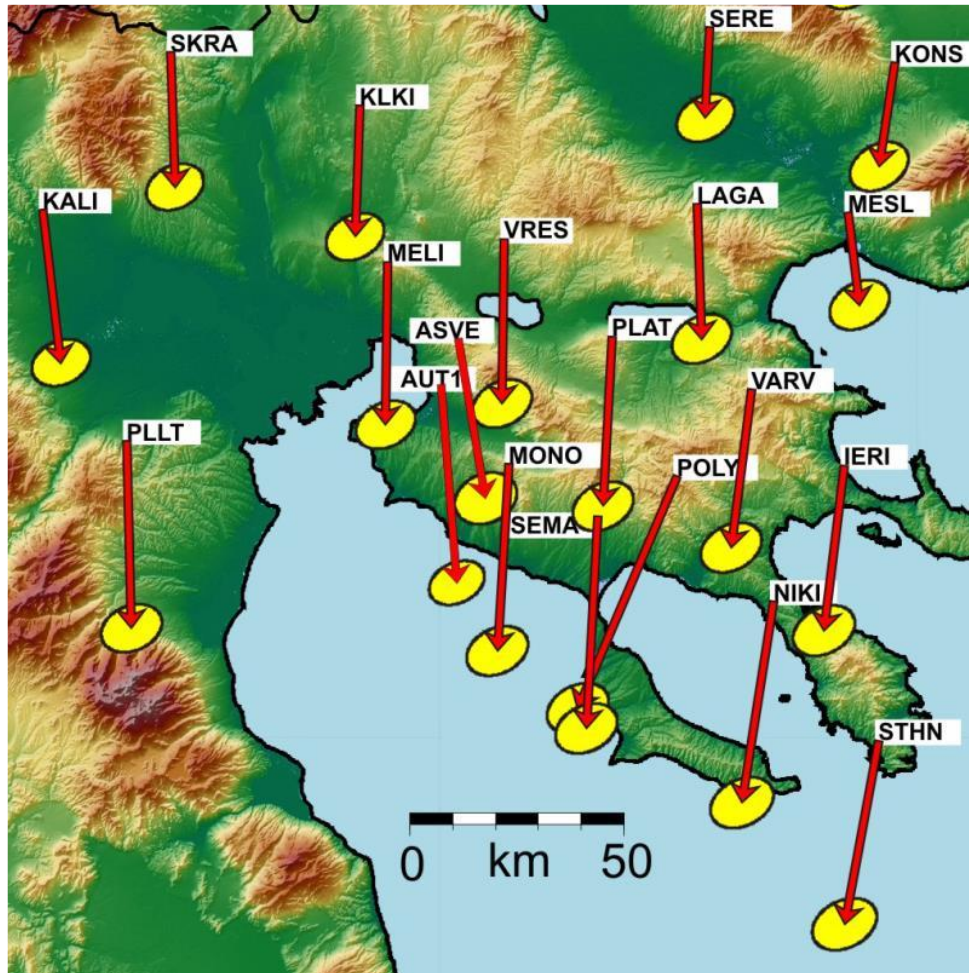


- Since 1991, however, with the launch of ERS-1, followed by ERS-2, the information provided by GNSS can be enriched and complemented with large scale ground displacement maps computed from InSAR (SAR Interferometry).
- Based on the difference of two non-simultaneous SAR phase images InSAR allows to compute the maps of ground displacement over large regions with an accuracy of a few cm (or even a few mm), from a height of 800km!!

Abandoned area due to subsidence phenomena near Thessaloniki, Greece

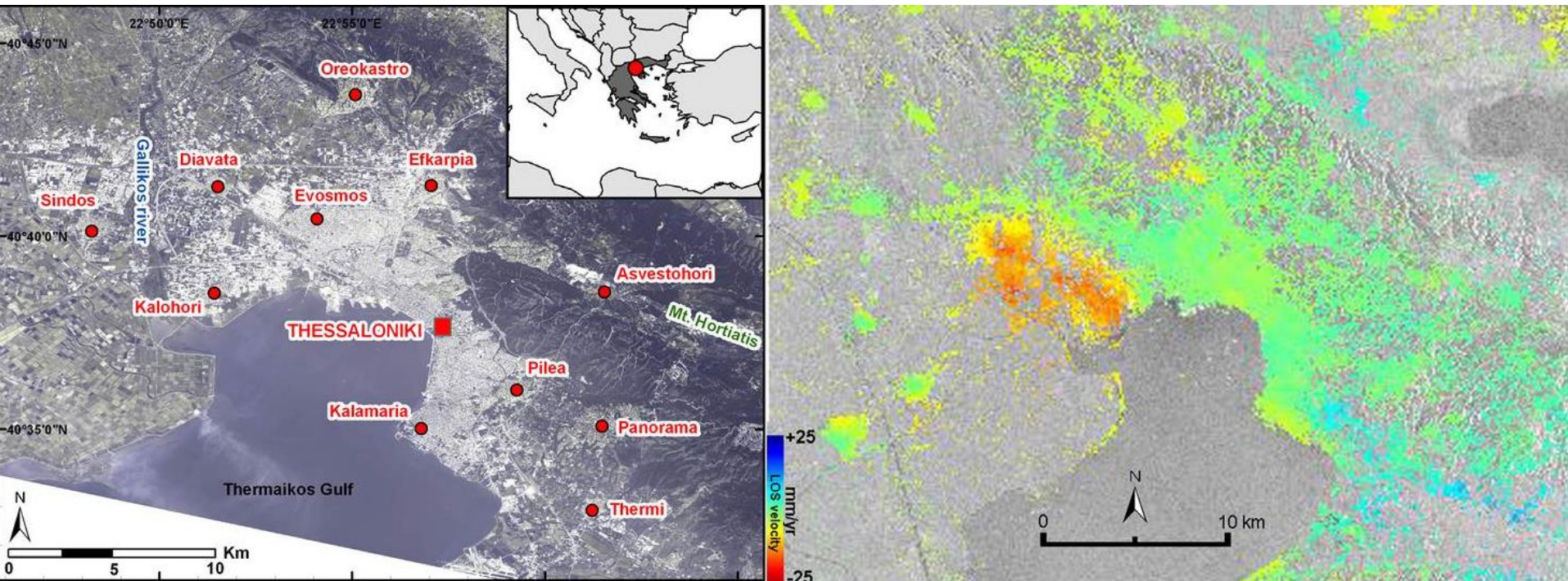


Advances: Displacements (GNSS)



Horizontal displacements in Northern Greece and Bulgaria, measured through repetitive GNSS campaigns (*Mouratidis, 2010; Matev, 2011*)

Advances: Displacements (INSAR)

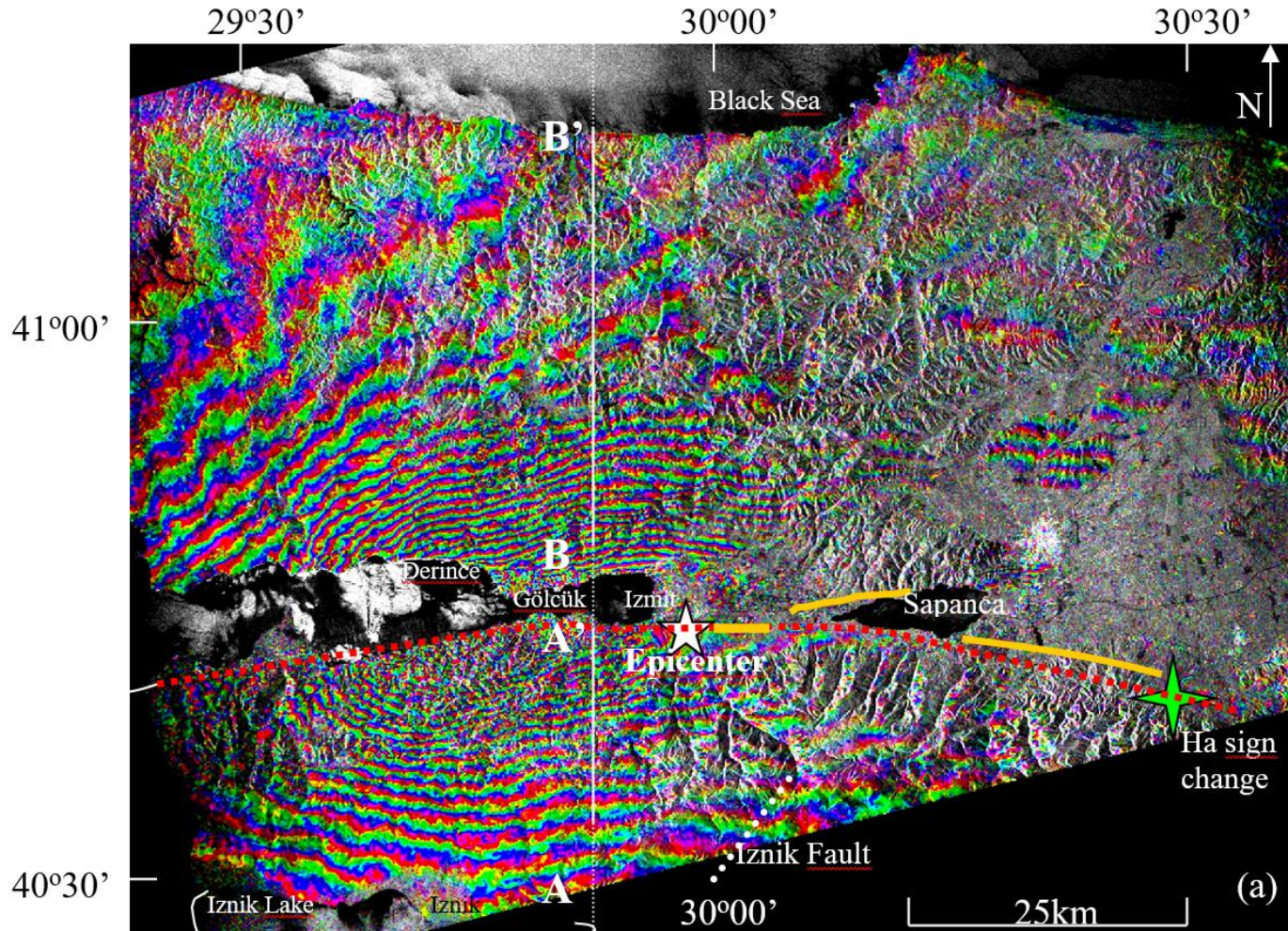


2004-2010 subsidence monitored by PS InSAR, using Envisat/ASAR data
(Mouratidis and Costantini, 2012)

- Nowadays, with new generation satellites, like Sentinel-1 (A and B), the revisit time, therefore the temporal frequency of observation (temporal resolution) has gone down from 35 days to 6 days, whereas the width of the images has increased from 100 to 250 km (S-1 IW mode, regularly used in acquisitions over land).
- The horizontal sampling of the measurement can be greatly reduced (metric or sub-metric level) using satellites like Radarsat-2, Terrasar-X or Cosmo-SkyMed.

- Displacement accuracy and noise depend on the sensor wavelength. Nowadays the availability of various SAR missions with different radar bands (X, C, L, with radar signal wavelength around 3, 5.6 and 23 cm respectively) allows to select the sensitivity of the targeted displacement measurement
- Mapped displacement is along the Line of Sight (LoS) of the radar signal and mainly reveals the vertical component (uplift or subsidence)

Advances: Displacements (InSAR)



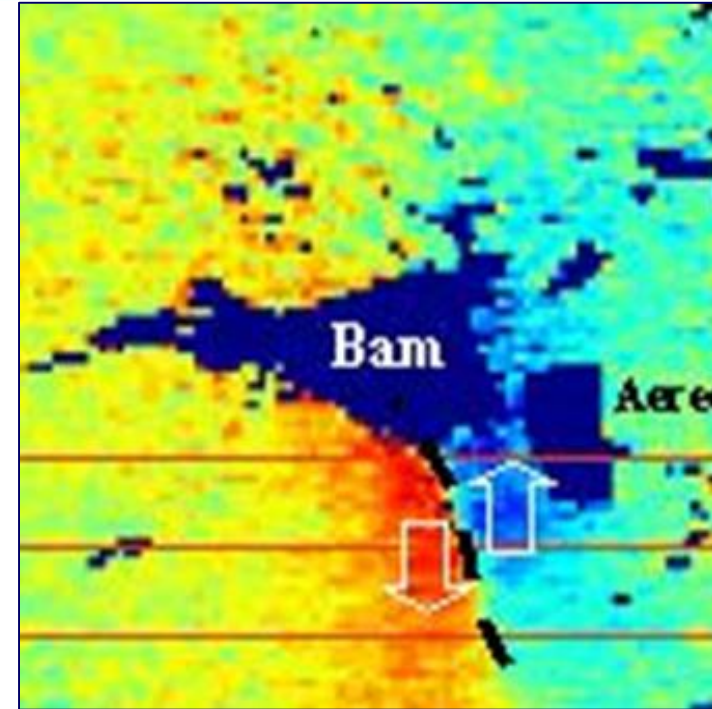
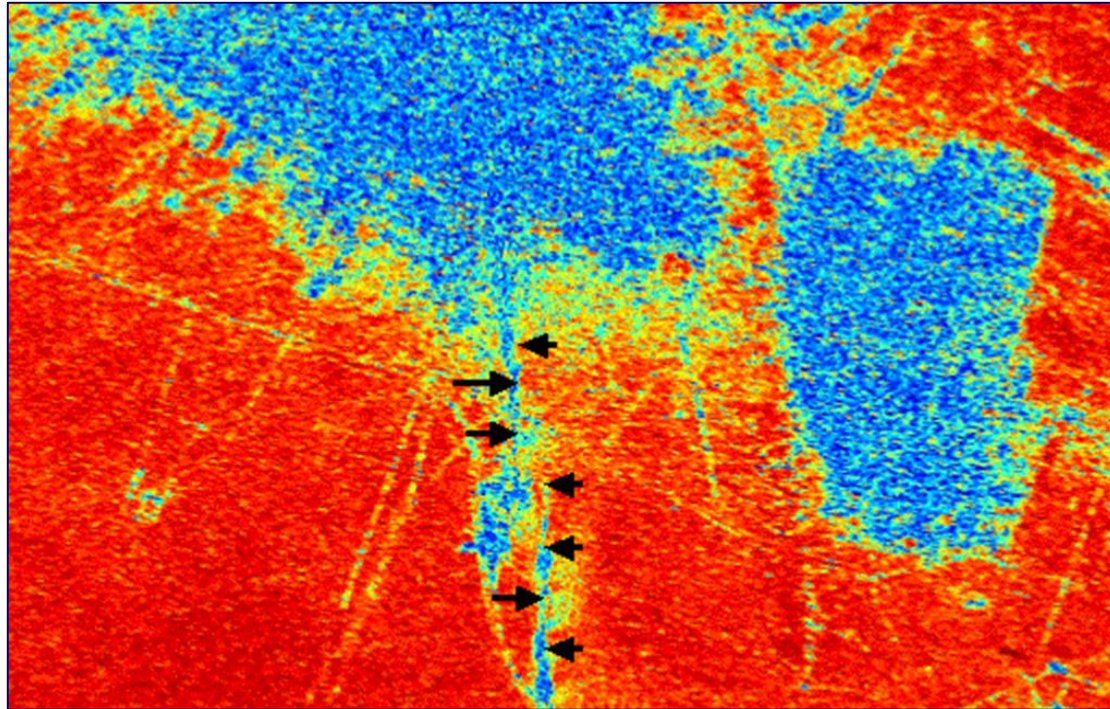
ERS-2 interferogram of the Izmit earthquake (1999)

- The smaller the displacement, the better the accuracy. In the case of large earthquakes, the accuracy of the observed displacement decreases approaching to the surface fault rupture, where the displacement is too large to be observed with this technique.
- In these cases, near the fault, other techniques like SAR correlation or even optical correlation can be used, to infer the horizontal component.



Ground observation of the “blind fault” rupture southern of the city of Bam, following the Bam earthquake of 2003.

Called “blind” since barely observable at the surface. This “blind” was detected from space (using SAR correlation and similar techniques) – see next slide



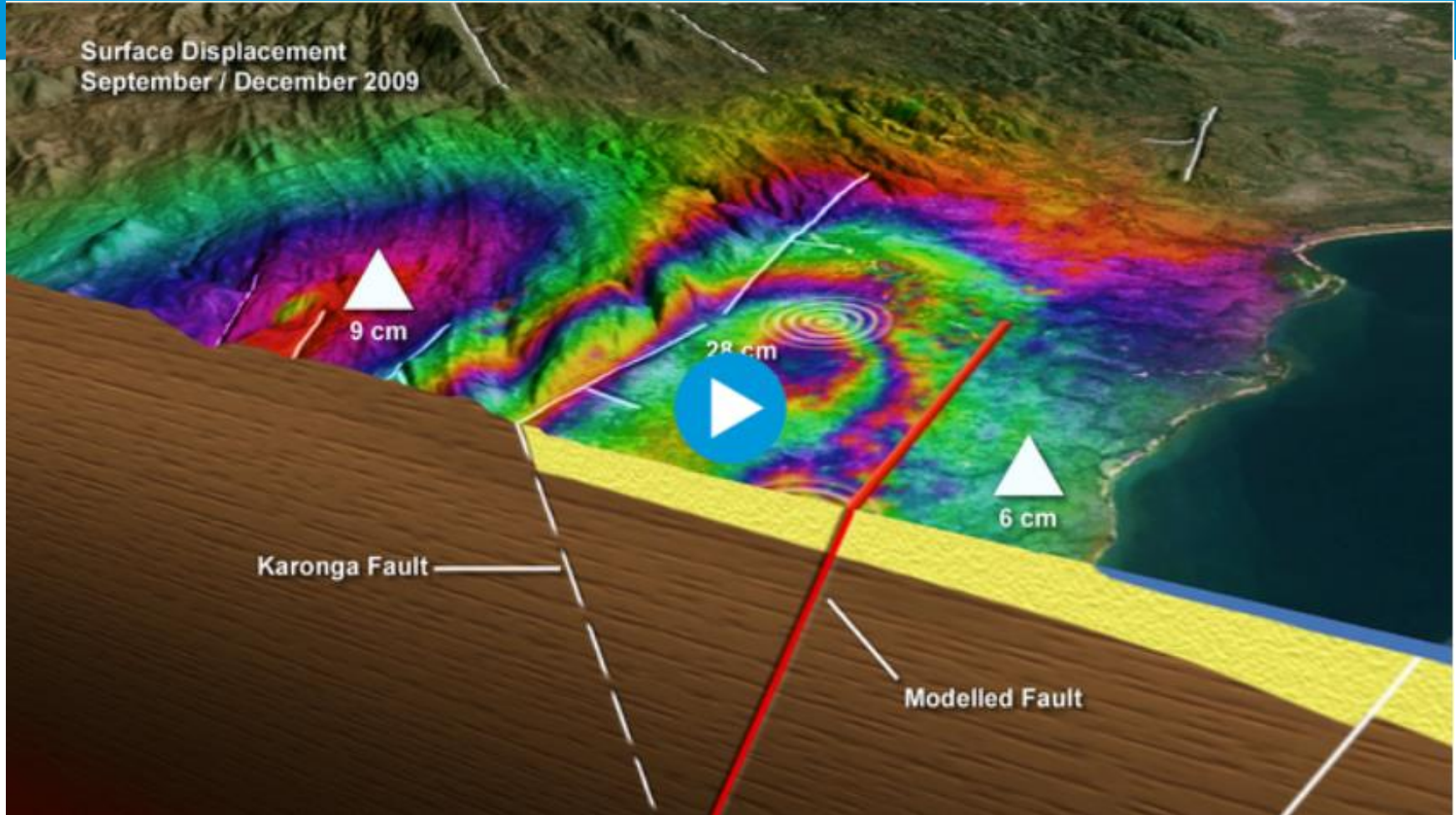
Fault rupture observed on an ASAR coherency image (left) and on an azimuth shift map (right) obtained by precise correlation of the ASAR pair (Bam Earthquake, 2003).

Fault modeling allows scientists also to compute stress transfer onto surrounding faults, and/or to map new faults triggered by an earthquake

- The accuracy of InSAR can be improved in the case of long temporal series of acquisitions (**multitemporal InSAR**): in this case even very slow deformation rates of stable points over several years / decades can be measured.
- For example, these techniques can be used to measure not only coseismic deformation but also slow **intersesimic deformation** of a few cm/year or mm/months typical of various (non-locked) faults.

- Using multitemporal InSAR, scientists have been able to detect surface displacement with cm accuracy over several years, thus monitor the moving apart of the two tectonic plates in the East African Rift, revealing that the dormant Mount Longonot in Kenya rose by 9 cm between 2004 and 2009 (see video in the next slide)
- Tectonic activity such as the movement of magma underground may have caused this deformation of the surface above.

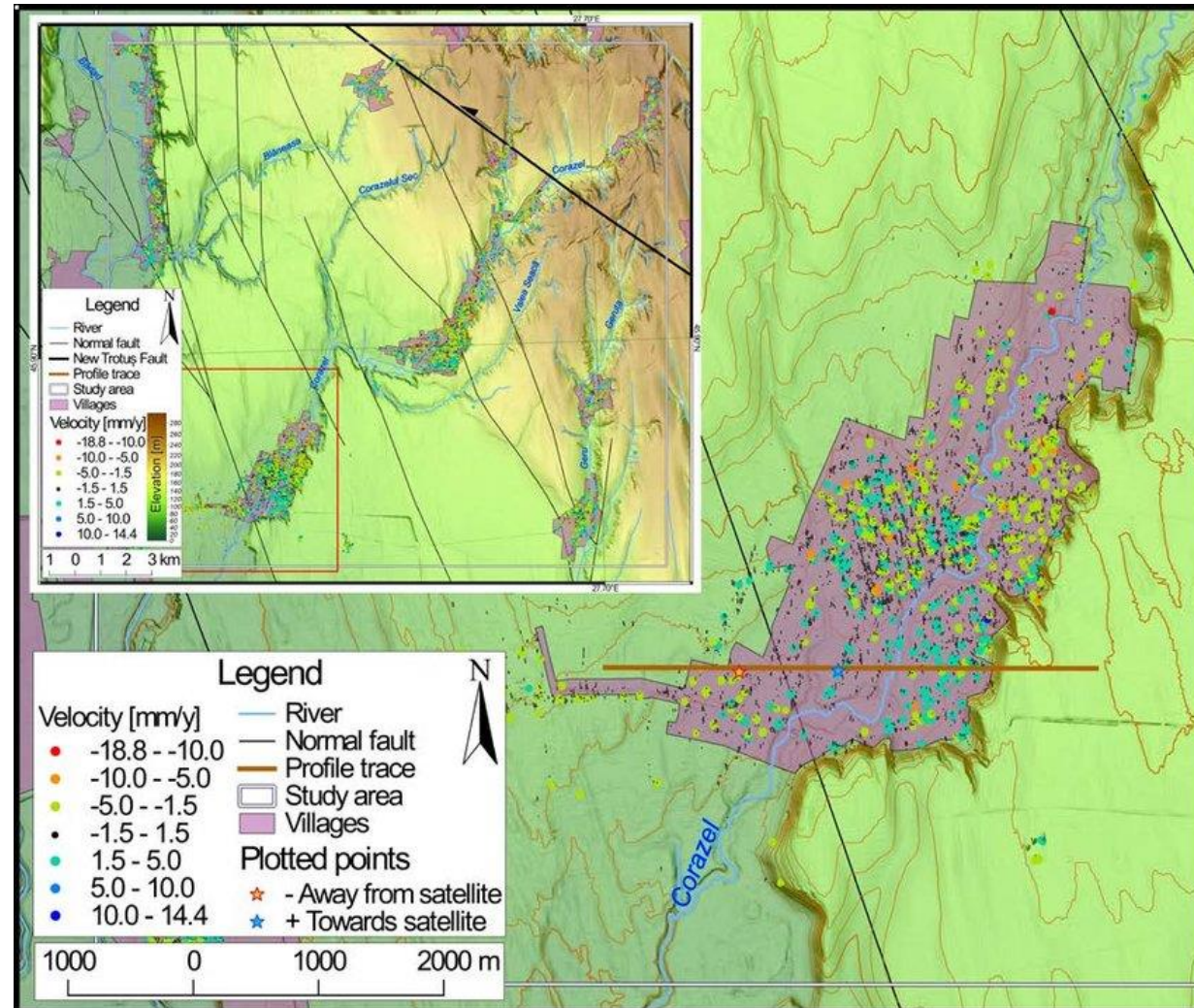
Advances: Displacements (InSAR)



https://dlmultimedia.esa.int/download/public/videos/2013/08/001/orig-1308_001_AR_EN.mp4

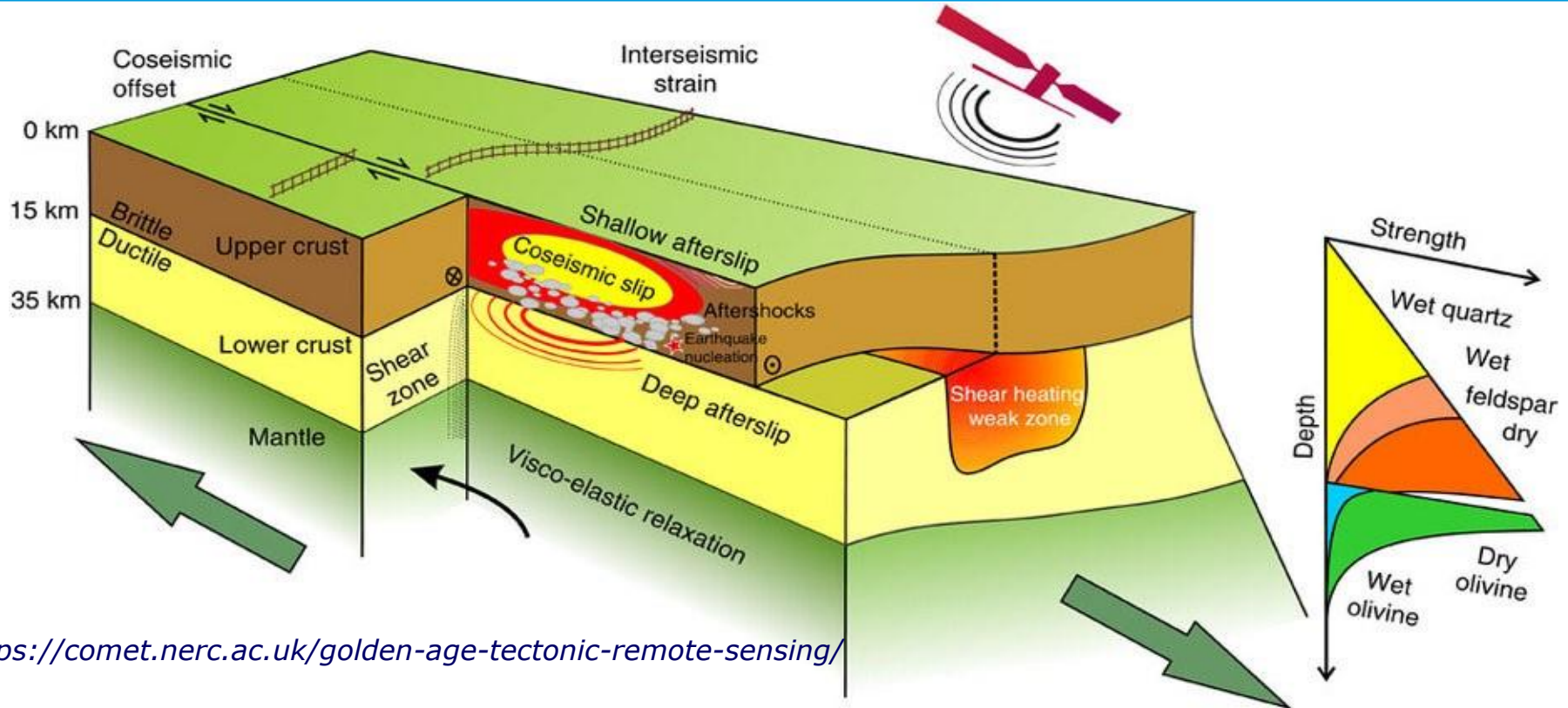
Advances: Displacements (InSAR)

In another case, PS-InSAR stacking of Sentinel-1 dataset allowed the detection of fractures induced by neotectonics in Eastern Romania, characterized by blocks movement in opposite direction around 5-10 mm/year.



- All this different information can be **assimilated into seismic and tectonic models, helping scientists to better understand the entire earthquake cycle** and to estimate (the probability of) future hazards occurrences

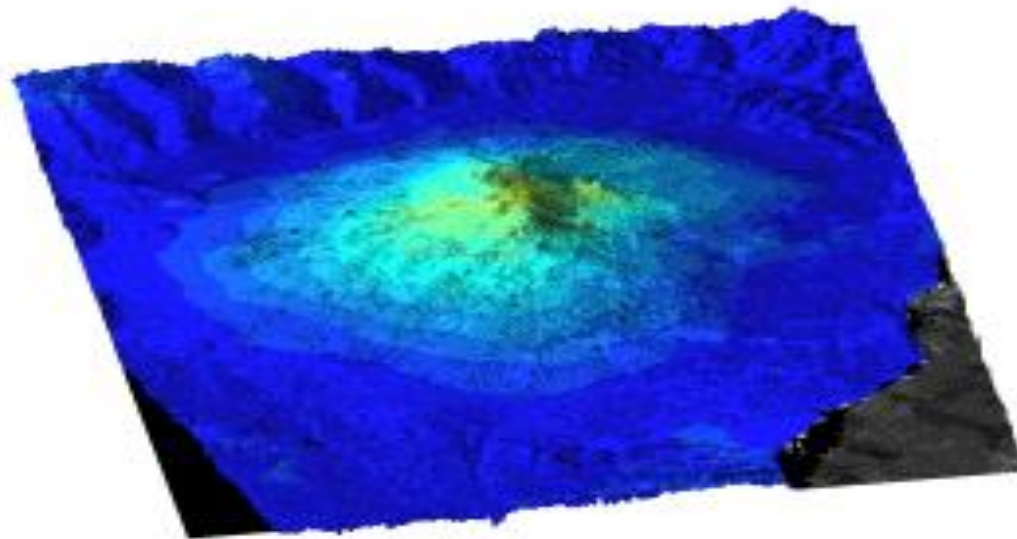
Advances: Displacements



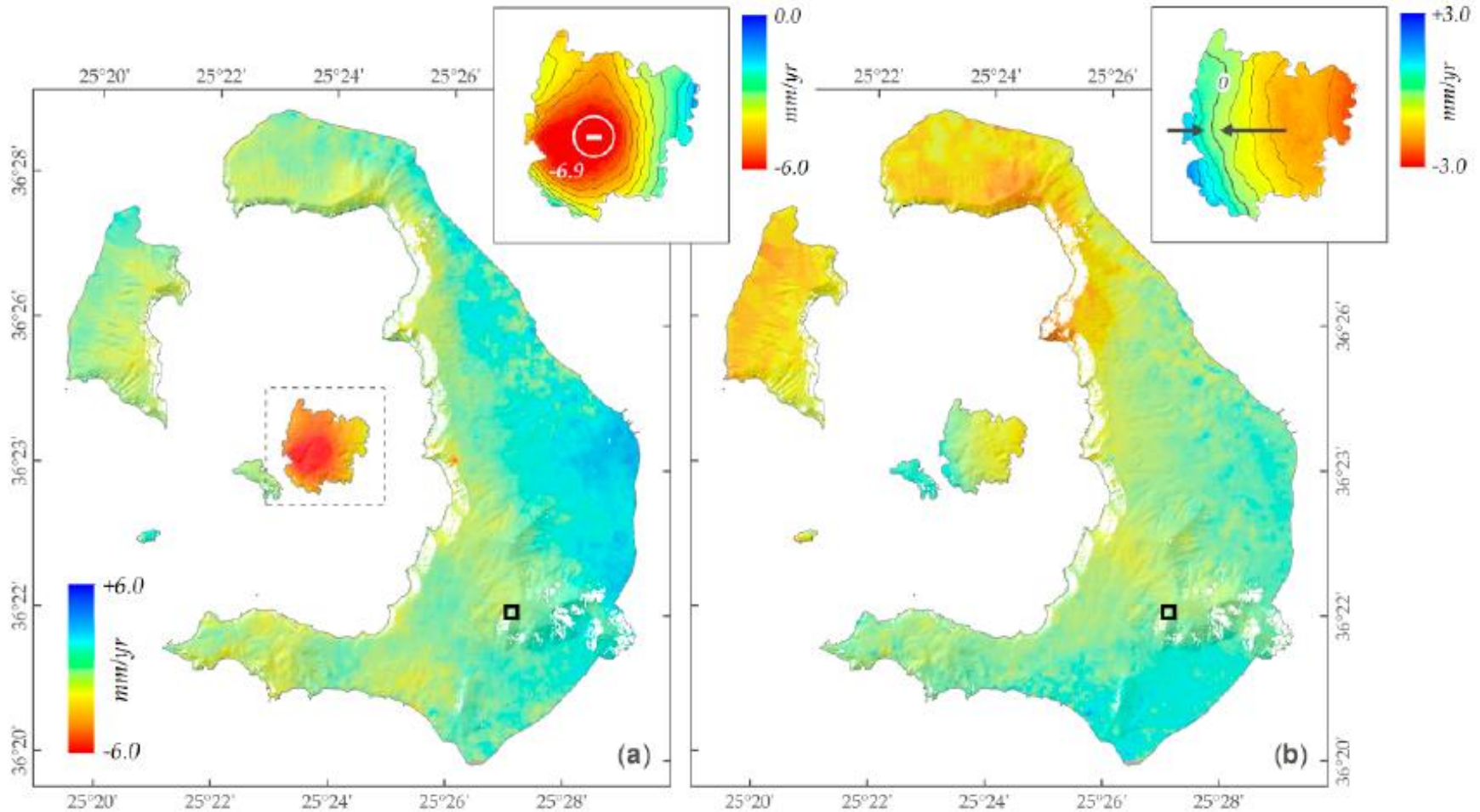
<https://comet.nerc.ac.uk/golden-age-tectonic-remote-sensing/>

Satellite geodesy offers the opportunity to measure the complete earthquake cycle: from slip in the upper crust, its relationship with aftershocks and fault segmentation; to postseismic deformation and interseismic strain accumulation across fault zones between earthquakes.

- Similar information about inflation and deflation of volcanoes can be obtained using the same technique.
- This information can be related to phenomena taking place in the magmatic chambers of volcanoes and, together with a variety of different measurements and in-situ measurements, can help to improve volcanic models.



Deformation over Etna, measured by InSAR.



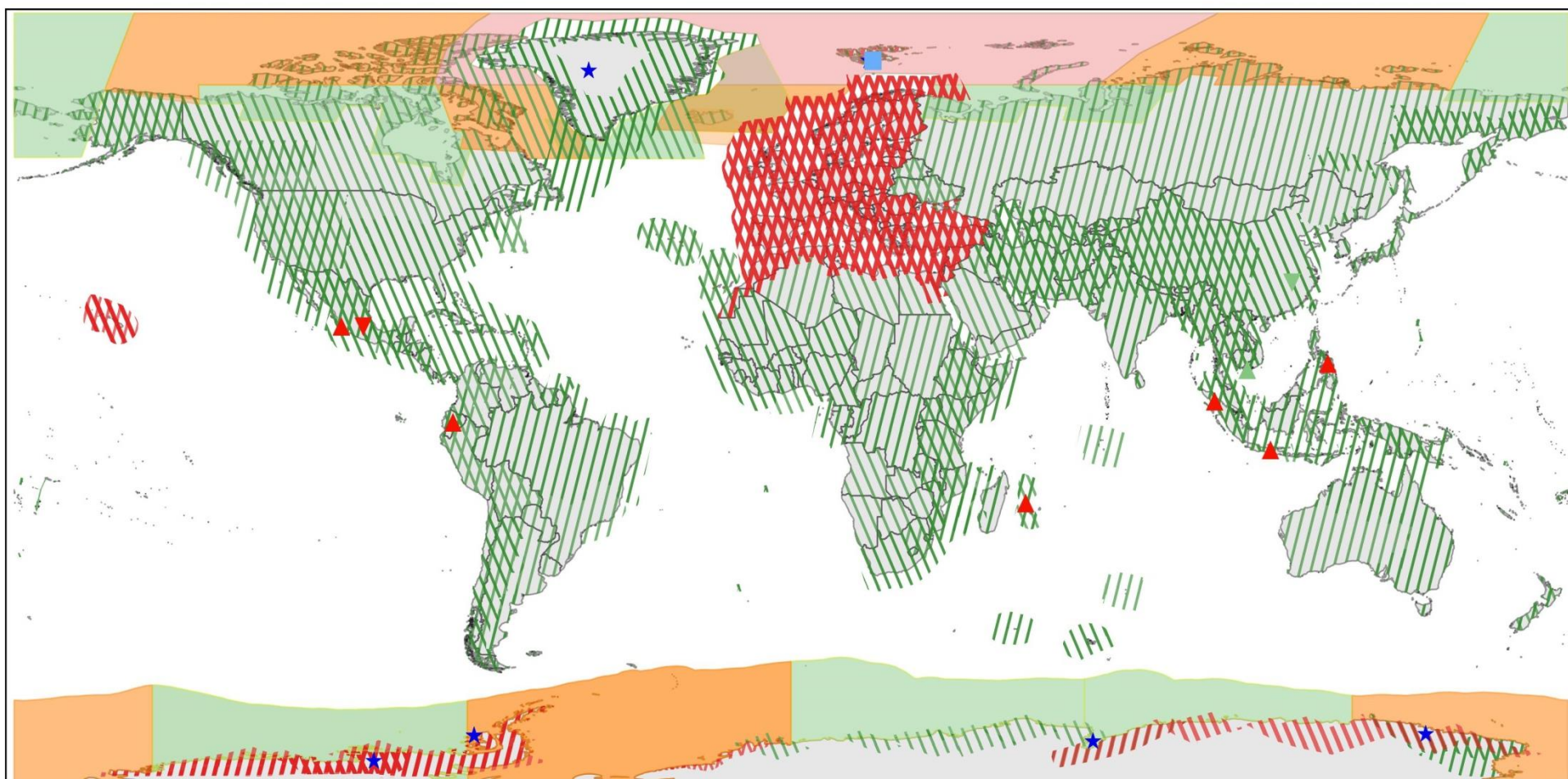
(a) Vertical and (b) East-West displacement rate maps of Santorini volcano for the period 2014–17, from combined Sentinel-1 observations. Displacement rates are given relative to the reference point, marked by a rectangle (Papageorgiou et al. 2019).

- For this reason, the acquisition strategy of ESA SAR missions (presently, Sentinel -1) is such that **frequent regular acquisitions over all major seismic and volcanic areas in the world are acquired**, thus building up a huge archive of data complementing similar archives obtained by the previous SAR missions (ERS-1, ERS-2, ENVISAT ASAR).
- Examples of such regions are the whole Andean region, S. Andreas' fault in California, Israel, Japan, mount Etna, Campi Flegrei and Yellowstone (the so-called "super-volcanoes") and many others.

Sentinel-1 Constellation Observation Scenario: Revisit & Coverage Frequency



validity start: 02/2018



PASS	REVISIT	FREQUENCY *	COVERAGE	FREQUENCY **	REFERENCE DATA SITES (6d repeat)
ASCENDING	6 days	12 days	1 days		Highly active volcanism
DESCENDING	6 days	12 days	1-3 days		Fast subsidence
	6 days	12 days	2-4 days		Short growth cycle, intensive agriculture
					Fast changing wetlands
					Fast moving outlet glaciers
					Permafrost & glaciers

* coverage ensured from same, repetitive relative orbits
 ** coverage not considering repetitiveness of relative orbits

- **Volcanology and tectonics institutes worldwide** (like e.g. IPGP in France, INGV in Italy and ISMOSAV in Greece) **receive, process and assimilate constantly SAR data acquired over main active volcanoes and seismic areas** (together with GNSS and many other data) **into their models, aiming at improving the forecast of eruptions and the estimation of seismic hazards.**

Although InSAR provides very useful information about tectonic phenomena at local/regional scale, **other space-based techniques, have been used to analyse plate motion at larger or even global scale.** On top of the already mentioned GNSS techniques, Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) ought to be mentioned.

Different results from all possible different techniques (VLBI, GNSS, DORIS and PRARE systems) are integrated within international network of space geodetic observatories.

Advances: Displacements (SLR - Satellite Laser Ranging)



In SLR a **global network of observation stations** measures the round trip time of ultrashort light pulses sent from ground to retro-reflectors on board **satellites**. Range measurements of mm accuracy are then used to derive accurate measurement of orbits and, in turn, to obtain **accurate measurements of the motion (mm/year) of station motion on a global scale**



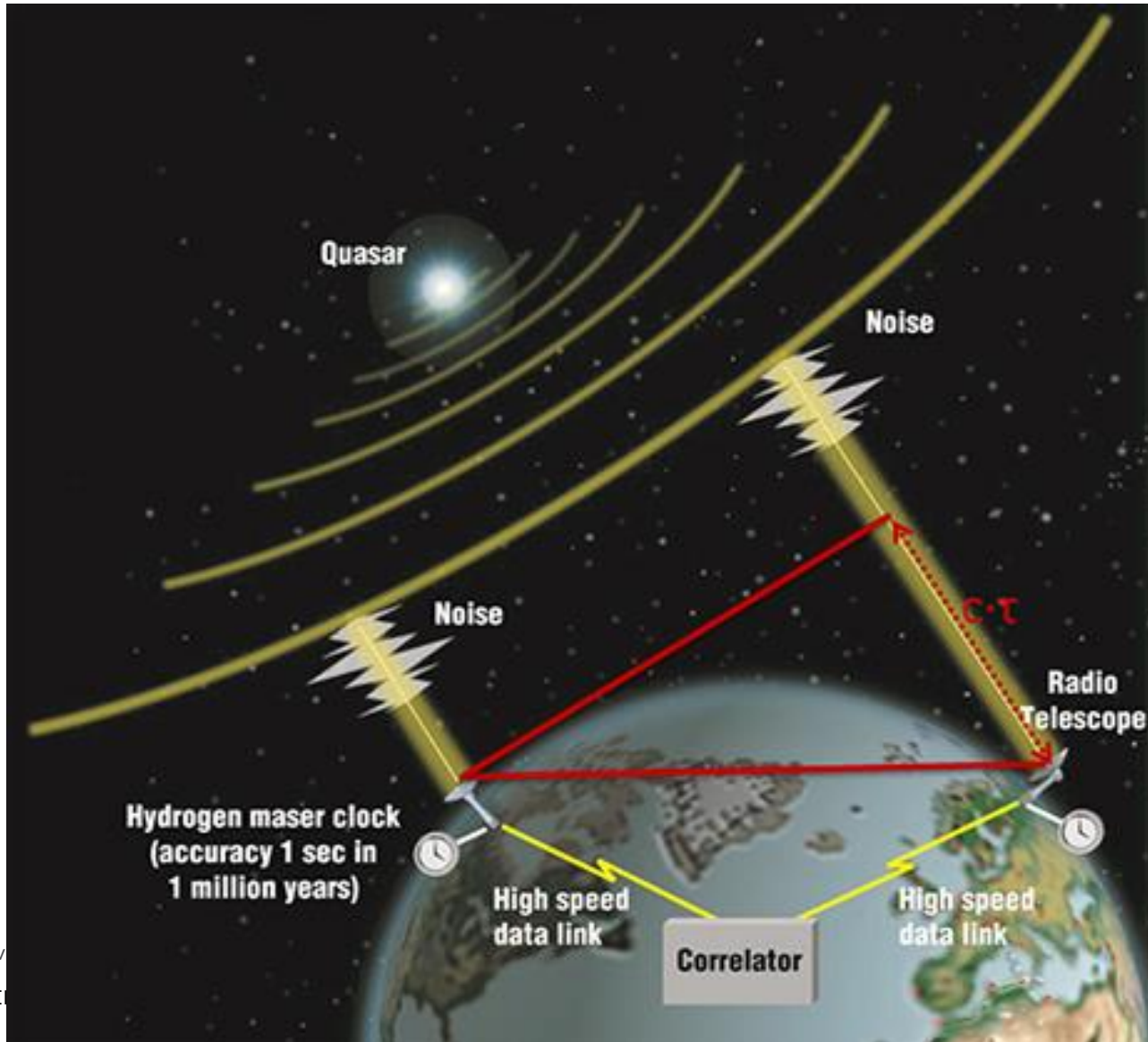
Laser Ranging System of the geodetic observatory Wettzell, Bavaria

Advances: Displacements (VLBI - Very Long Baseline Interferometry)



- VLBI is a geodetic space-based technique, not based on satellite data but rather on a **worldwide array of radio telescopes** simultaneously collecting data from different radio sources in the sky.
- Using one single radio source in the sky, the relative time-of-arrival of signals from that source to each telescope can be very accurately determined
- By observing many radio sources spread widely over the sky over long time periods, very precise measurements of the relative 3-dimensional position of globally distributed telescopes is achieved with mm accuracy, thus allowing the measurement of motions of the Earth's tectonic plates.

Advances: Displacements (VLBI - Very Long Baseline Interferometry)

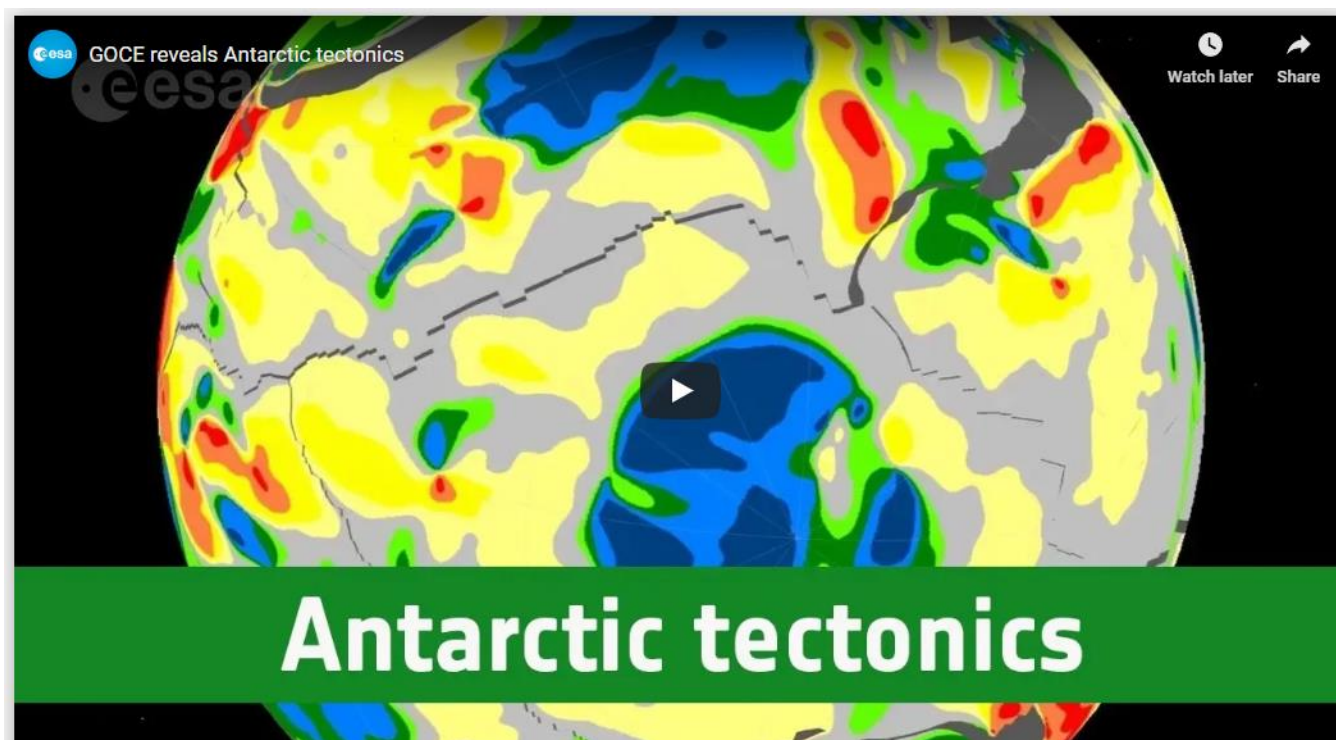


- it is interesting to remark that space-based measurements can also help to investigate paleo-geology, paleogeography and thus paleohistory of our planet.
- An example: impact craters detection using space based data (next slides)

Other Applications: gravity and lithosphere



Satellite gravity gradients measured by GOCE satellite (ESA) can be used to assess different characteristics of the lithosphere. It **reveals relics of ancient continents under Antarctica**



See video at:

https://www.youtube.com/watch?time_continue=1&v=2YcAAyUPId4

More details at: <https://eo4society.esa.int/2018/11/07/goce-gravity-gradients-reveal-relics-of-ancient-continents-under-antarctica/>

Earth Observation Store 04 63

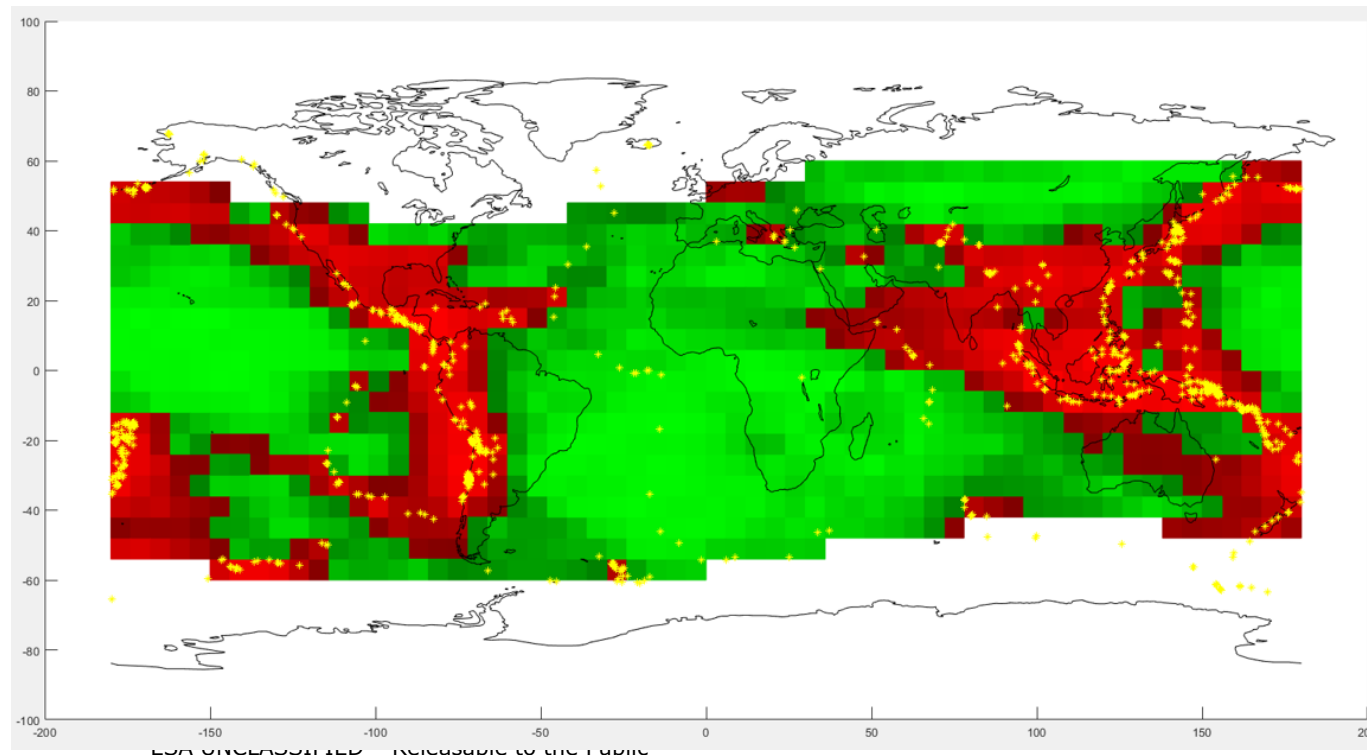
European Space Agency

ESA UNCLASSIFIED - Releasable to the Public

Other Applications: earthquakes and ionospheric magnetic field



A recent study based on Machine Learning techniques analysed magnetic field data measured by the **SWARM** ESA mission (first 2 years), investigating the **relationship between ionospheric magnetic field perturbations and earthquakes worldwide** (full USGS catalogue).



Seismic active regions on Earth identified from magnetic field measurements in the ionosphere. Colour scale shows the probability that a cell is interested by seismic activity

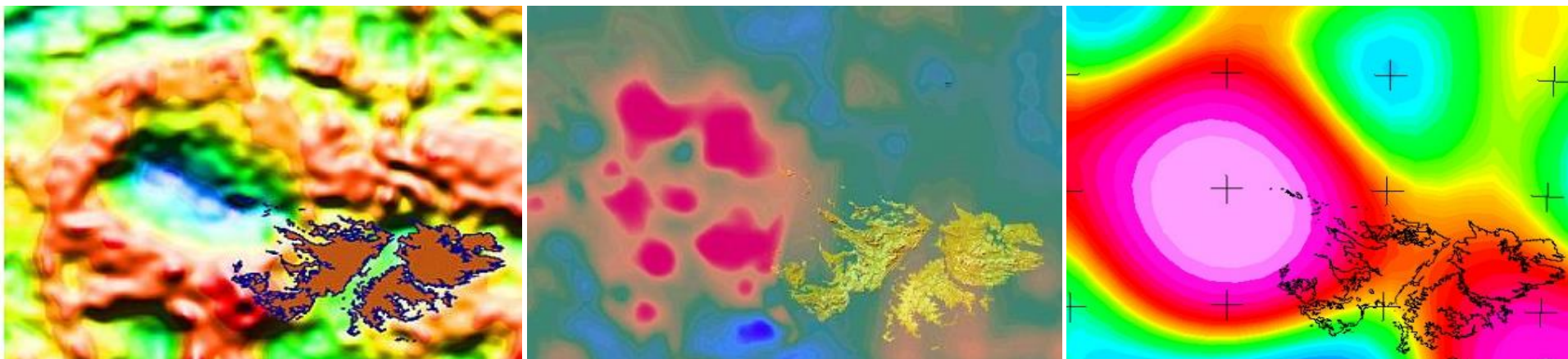
Other Applications: impact craters and gravity/magnetic anomalies



The analysis of anomalies in the gravitational field (the most recent and most accurate model is presently derived from the ESA GOCE's mission) as well as in the magnetic field (like the one provided by the ESA Mission SWARM) can be used to research patterns of ancient impact craters on Earth.

Anomalies of this kind were recently spotted western of the **Falkland** islands, **possibly (but not necessarily) related to the impact crater of the Great Dying event, 252 millions years ago**, at the Permian-Triassic transition, before Pangea started to split apart). Similar phenomena can be spotted over the Chicxulub impact crater (Mexico, slightly less than 66 million years ago at the Cretaceous–Paleogene boundary)

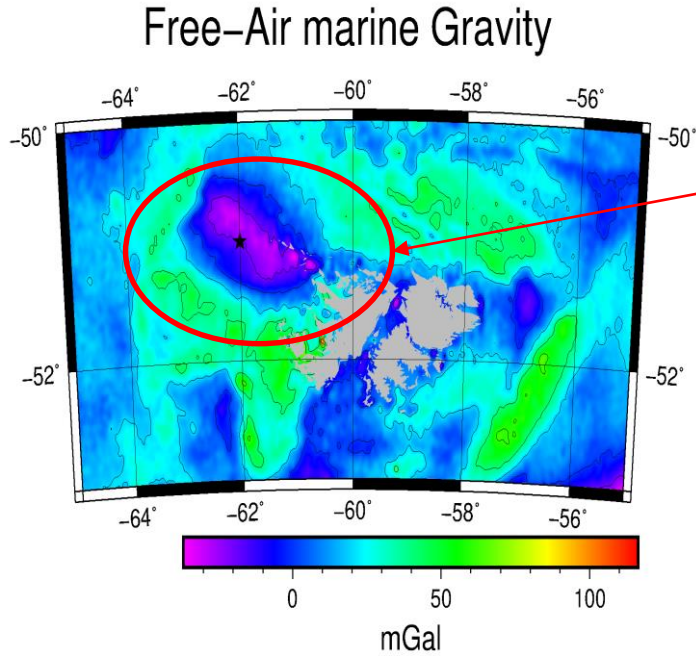
Other Applications: impact craters and gravity/magnetic anomalies



Left and middle: Gravity anomalies and magnetic anomalies western of Falkland Islands.

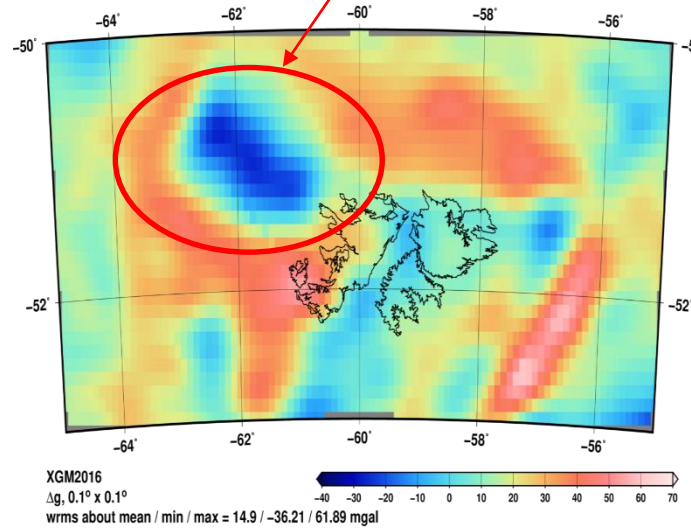
Right: magnetic anomalies over the same region measured by SWARM (ESA).

Fakland/Melvinas plateau: gravity anomaly



Altimetry data

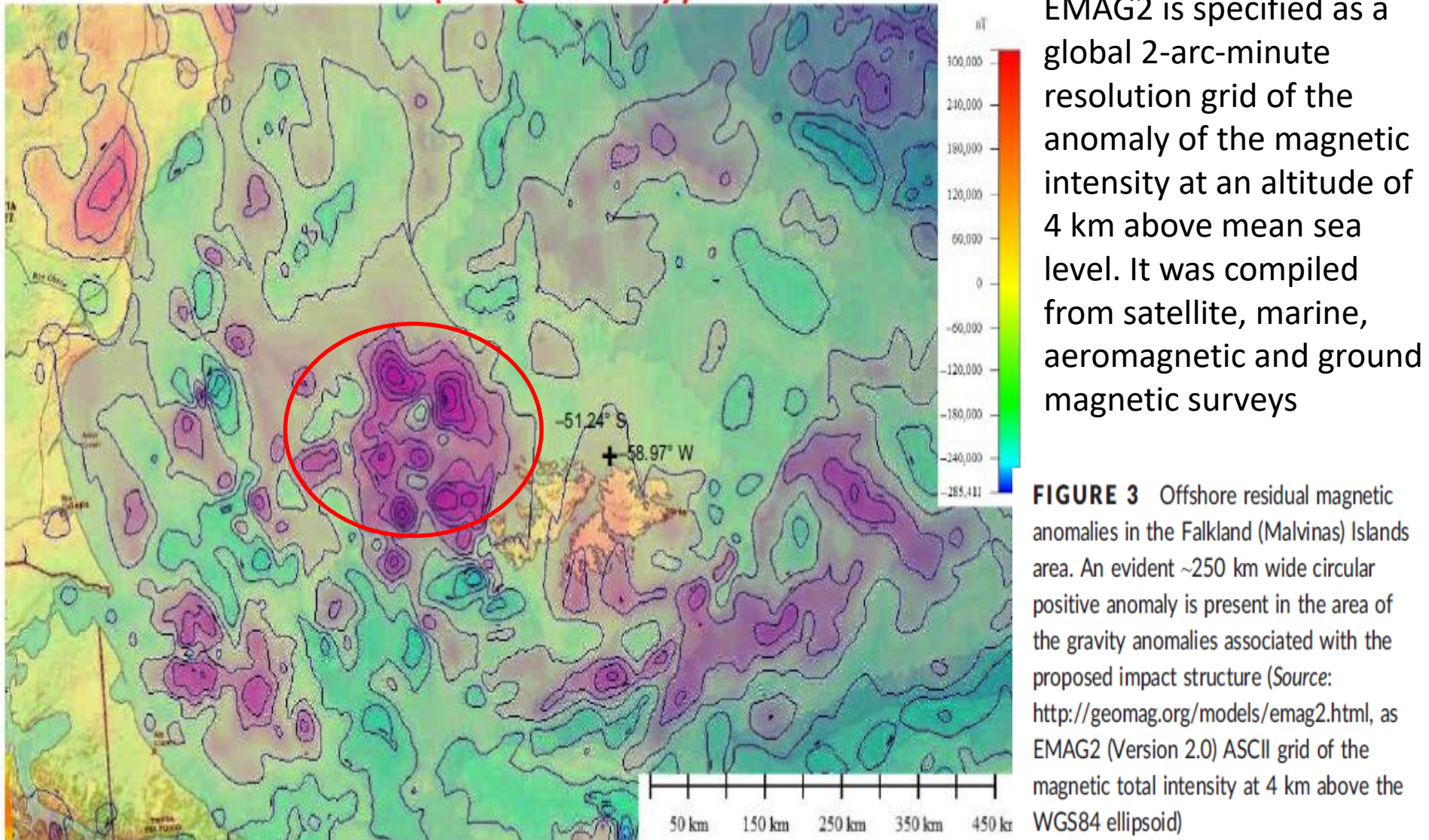
There is an elongated **gravity anomaly** low to the north-east of the island, which coincides with the location of the proposed crater



[ICGEM, GFZ Potsdam, Thu Jan 24 14:29:31 2019](#)

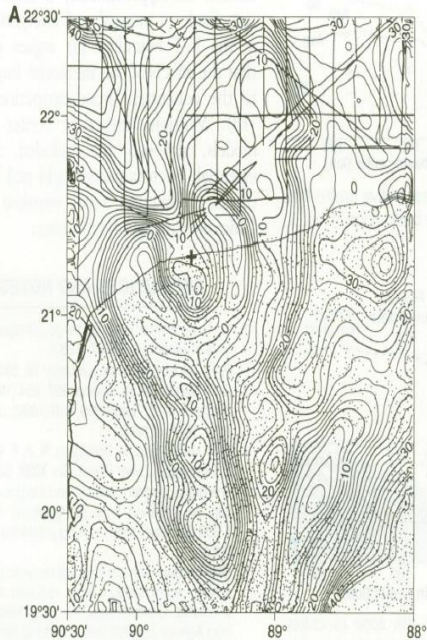
XGM2016 (experimental geopotential model)

Fakland/Melvinas plateau: magnetic anomaly



Courtesy of Joerg Ebbing & Agnes Wansing (Univ. Kiel)

Chicxulub impact crater



region shown in Fig. 1 viewed obliquely from approximately 60° above the surface looking north.

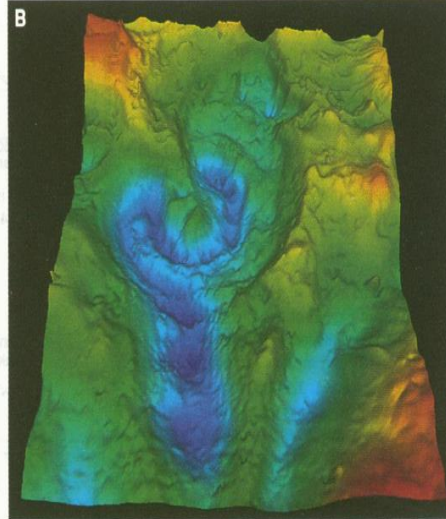


Fig. 2. (A) Contoured gravity anomaly data for the region shown in Fig. 1. Center of the Chicxulub impact basin lies at (+). Small dots are gravity stations and offshore measurements (δ). Before contouring, we smoothed the gridded data by an 11 by 11 (7.2 km by 7.2 km) convolution filter. The contour interval is 2 mgal. (B) Relief-shaded gravity anomaly data for the region shown in Fig. 1 viewed obliquely from approximately 60° above the surface looking north. Artificial lighting is from the south.

SCIENCE • VOL. 261 • 17 SEPTEMBER 1993

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Sharpton et al. **Chicxulub Multiring Impact Basin: Size and Other Characteristics Derived from Gravity Analysis**

Classical, geophysical studies show the **gravity anomaly** associated with the outer ring of the crater as well as the central peak, which is also clearly seen in the **magnetic anomaly**.

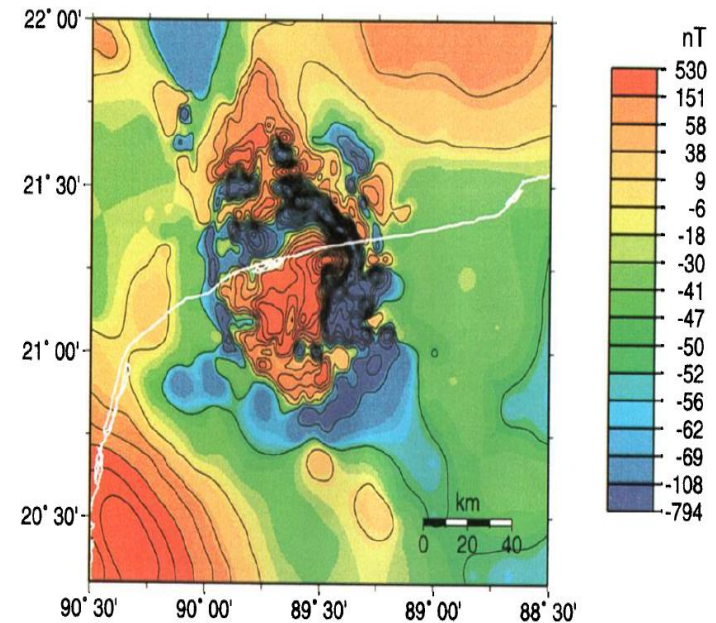


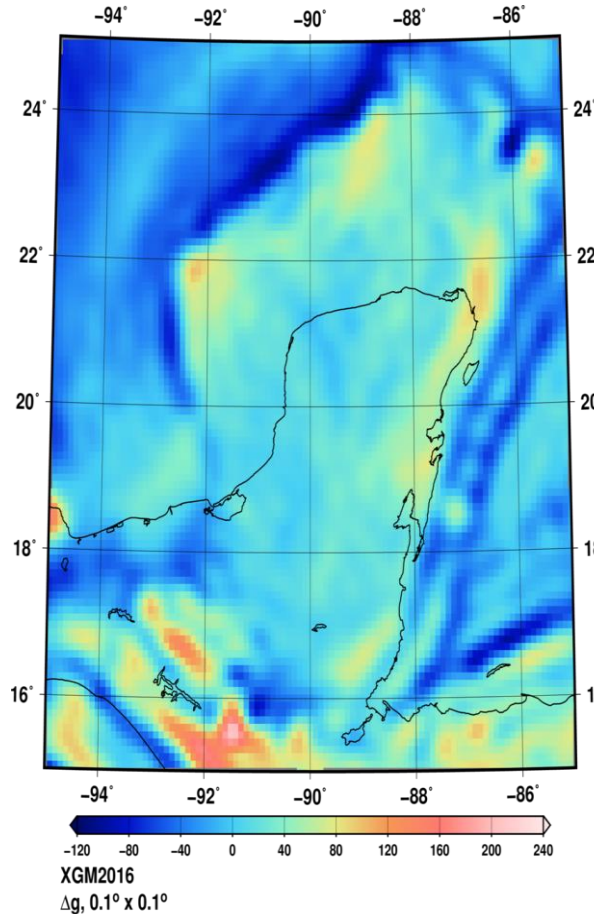
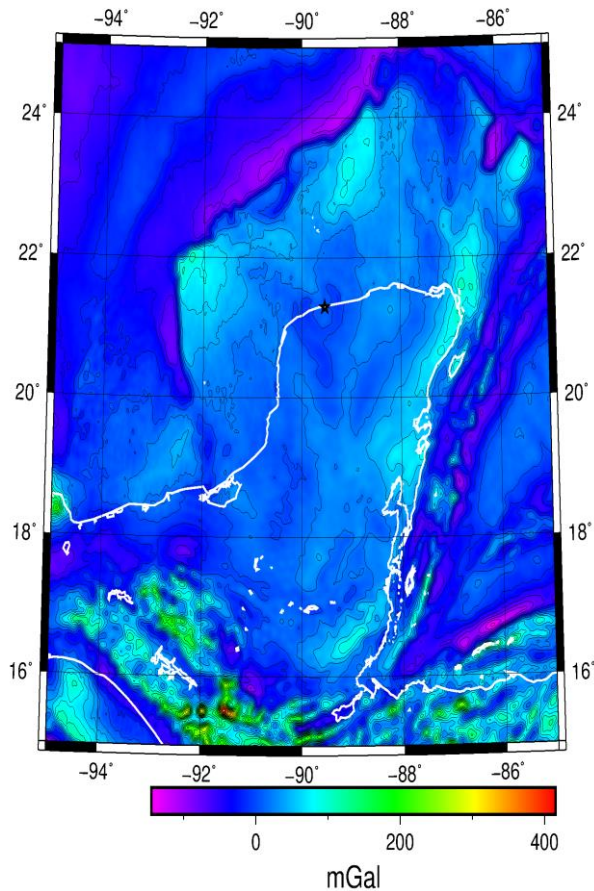
Plate 1. Total magnetic field observed over Chicxulub after a base level of 48380 nT has been removed. Data are a 1-km-gridded data set from a Pemex aeromagnetic survey. The contour interval is 50 nT; the white line indicates the Yucatán coastline.

Three-dimensional magnetic imaging of the Chicxulub Crater, M. Pilkington & A. Hildebrand, 2000

Chicxulub impact crater – Gravity anomaly



Free-Air marine Gravity



Chicxulub is clearly seen in both the altimetry data as in the combined gravity model based on GOCE data

Circular feature could be enhanced by a slightly better colour scale

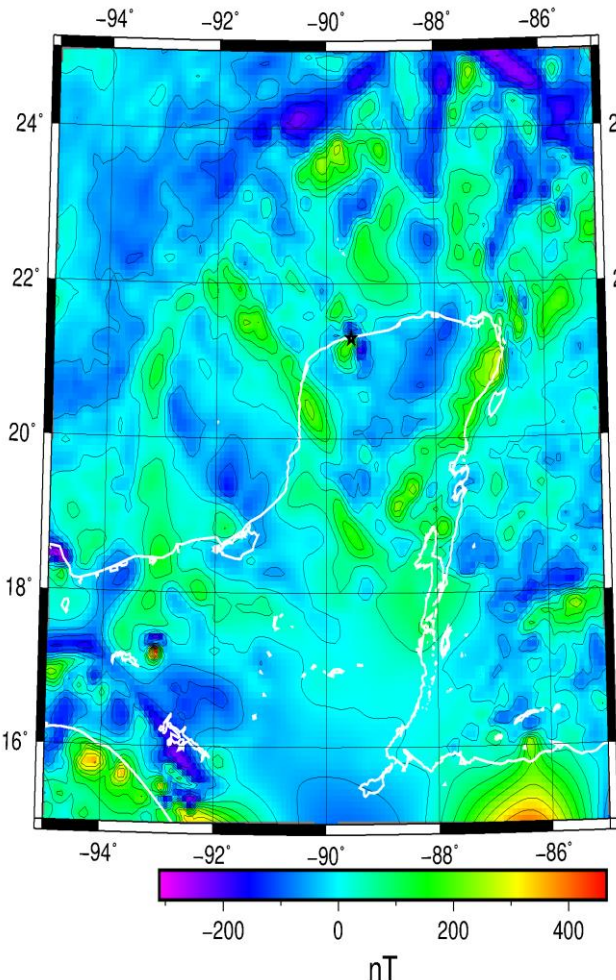
Altimetry data

XGM2016 Satellite model

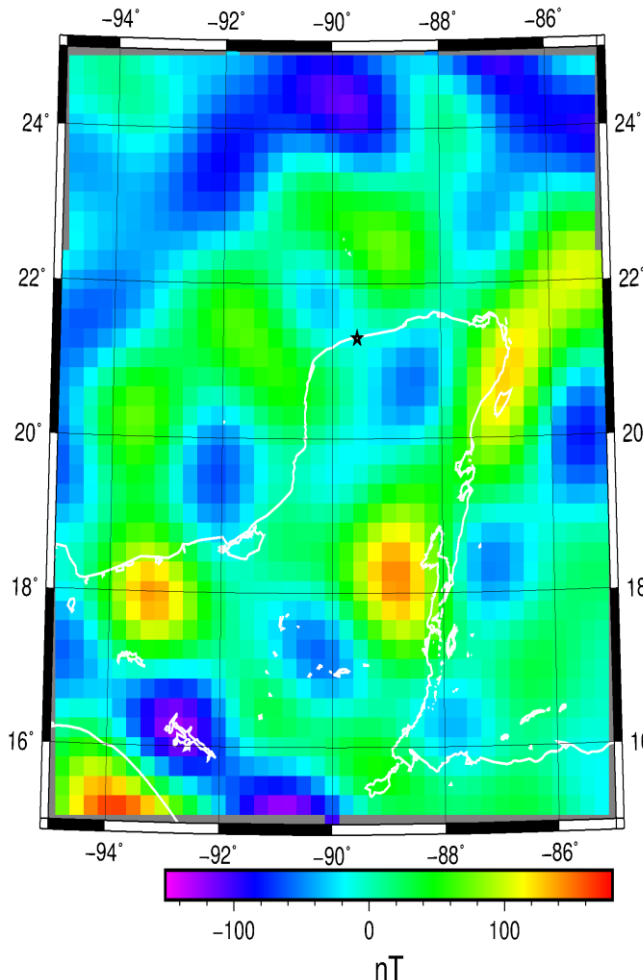
Chicxulub impact crater – Magnetic anomaly

Chicxulub is clearly seen in the EMAG2 data set

EMAG2 magnetic data



LCS-1 magnetic data

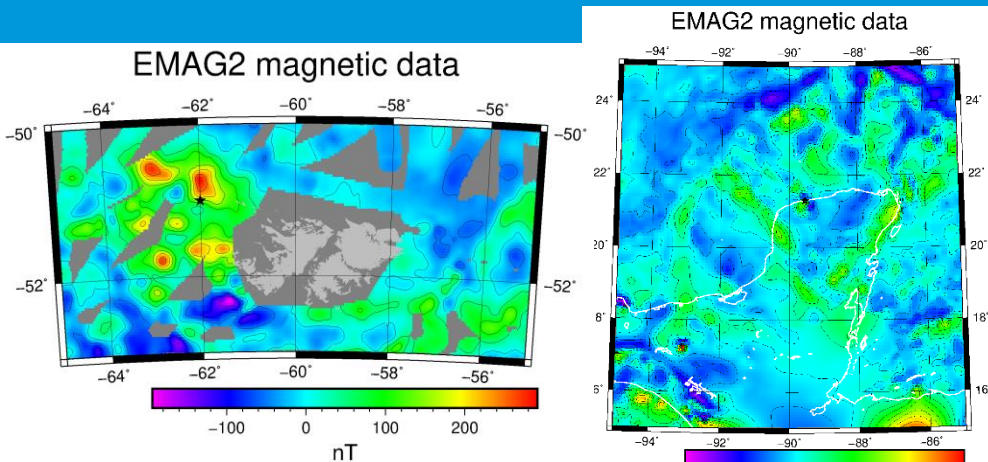


Anomaly is located over the central peak. EMAG2 is based on satellite as well as terrestrial magnetic data

No visible anomaly in the LCS-1 magnetic model based on Swarm data

- Despite the extension of the crater of 140-160km, the magnetic anomaly correlates with the central peak, which only has an extension of <60 km
- 60 km is below the resolution of satellite magnetic data

Comparison Falkland/Melvinas plateau – Chicxulub



- An anomaly is seen both in the gravity and magnetic data over the Falkland-Melvinas plateau

- Correlation of magnetic and anomaly would indicate a common source

- Impact crater of this size would be expected to have a complex form, with a central peak

Chicxulub Multiring Impact Crater

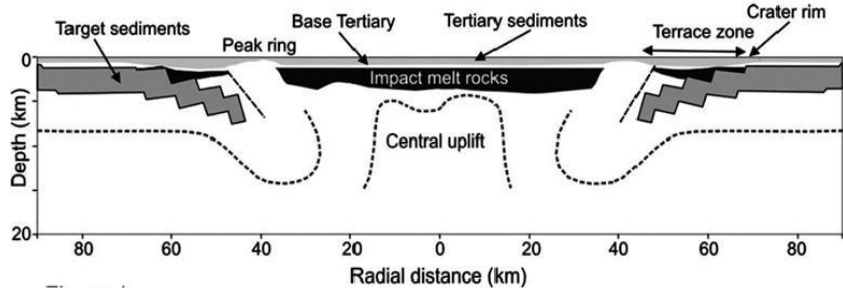


Figure 23. Schematic model for Chicxulub deep structure (taken from Collins *et al.*, 2008).

- If Falkland/Melvinas plateau is impact crater, the size of the inner peak would be in the order of 100km, making the crater one of the largest, if not the largest on Earth....

- But a tectonic origin for the anomalies appears also possible/likely

Some impact craters can also be seen on space-based topography models (TanDEM-X DEMs)

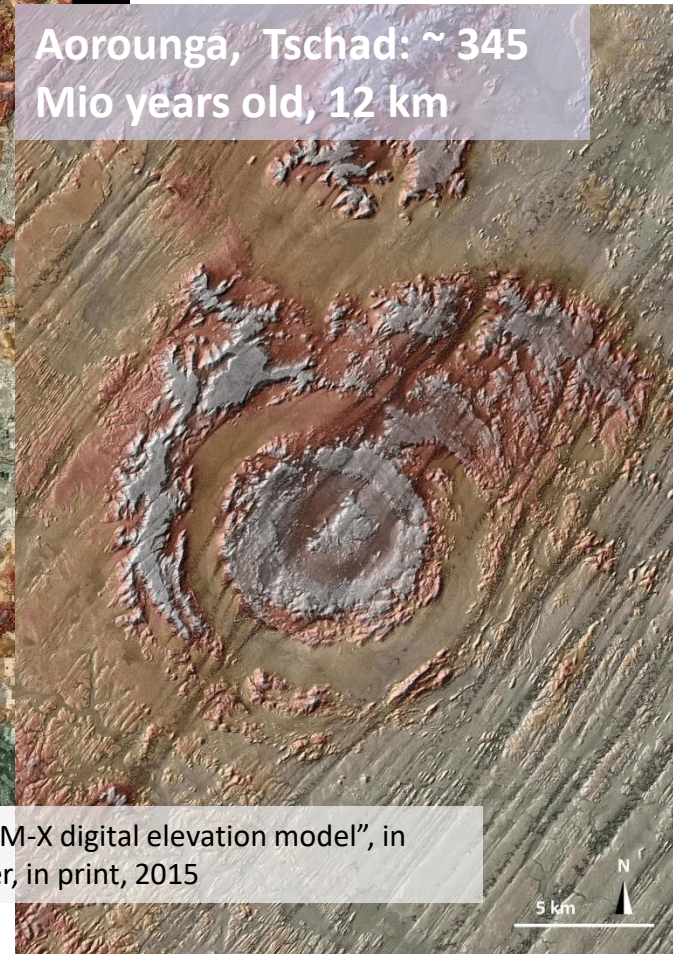


Barringer, Arizona, 50.000 years old, 1.2 km



Ries, Germany, 15 Mio years old, 24 km

7.5 km N



Aorounga, Tschad: ~ 345 Mio years old, 12 km

5 km N

Gottwald, M. et al., "Mapping terrestrial impact craters with the TanDEM-X digital elevation model", in "Large Meteorite Impacts and Planetary Evolution V", GSA Special Paper, in print, 2015

- Rapidly evolving EO, GNSS and other space-based technologies
- Data and techniques relevant for plate tectonics applications
- Ever-growing accuracy, reliability and density of space-based measurements/information
- Data, software and tools freely available
- Need for relevant geospatial education (and therefore appropriate resources) already at school level!

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- (Ref. 1) Elliott, J. R., Walters, R.J., and Wright, T.J. (2016) "The role of space-based observation in understanding and responding to active tectonics and earthquakes", Nature Communications, doi: 10.1038/ncomms13844
- (Ref. 2) <https://comet.nerc.ac.uk/golden-age-tectonic-remote-sensing/>
- (Ref. 3) https://www.esa.int/Our_Activities/Observing_the_Earth/Highlights/Africa_s_ups_and_downs
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- (Ref. 5) Sarti F. (2014), PhD thesis: "Potentiel de la télédétection optique-radar pour le suivi des changements et déformations de la surface terrestre : application à la gestion des risques naturels" <http://www.theses.fr/2004TOU30289>
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<https://www.haystack.mit.edu/edu/pcr/Data/pdf/Introduction%20to%20plate%20tectonics,%20geodesy%20and%20VLBI-final.pdf>
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- (Ref. 11) Fabiano Costantini, Antonios Mouratidis, Giovanni Schiavon & Francesco Sarti (2016) Advanced InSAR techniques for deformation studies and for simulating the PS-assisted calibration procedure of Sentinel-1 data: case study from Thessaloniki (Greece), based on the Envisat/ASAR archive, International Journal of Remote Sensing, 37:4, 729-744, DOI: 10.1080/01431161.2015.1134846
- (Ref. 12) Papageorgiou, E.; Foumelis, M.; Trasatti, E.; Ventura, G.; Raucoules, D.; Mouratidis, A. Multi-Sensor SAR Geodetic Imaging and Modelling of Santorini Volcano Post-Unrest Response. Remote Sens. 2019, 11, 259.

Further reading



- <http://www.isprs.org/proceedings/XXXV/congress/comm4/papers/394.pdf>
- <https://www.geospatialworld.net/news/remote-sensing-satellites-help-monitor-tectonic-plates/>
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- <http://www.esa.int/esapub/bulletin/bullet102/Silvestrin102.pdf>
- <https://www.nature.com/articles/ncomms13844>
- <https://www.tandfonline.com/doi/full/10.1080/01431161.2018.1423741> (see ex. of Los Angeles)
- [file:///C:/Users/fsarti/Desktop/Downloads/01favretto%20\(1\).pdf](file:///C:/Users/fsarti/Desktop/Downloads/01favretto%20(1).pdf)
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