

Towards Digital Twins for earthquakes: The experience of DT-GEO

Arnau Folch (GEO3BCN-CSIC, Spain)

Thanks to Johannes Kemper (ETHZ)

Toward Data Lakes for Recorded and Simulated
Earthquake Ground Motions

GFZ German Research Centre for Geoscience
Postdam, 2-4 September 2024



DT-GEO



This project has received funding from the European Union's Horizon research and innovation programme under the grant agreement No 101058129

Outline

01

DT-GEO in a nutshell

02

Towards a DT for earthquakes

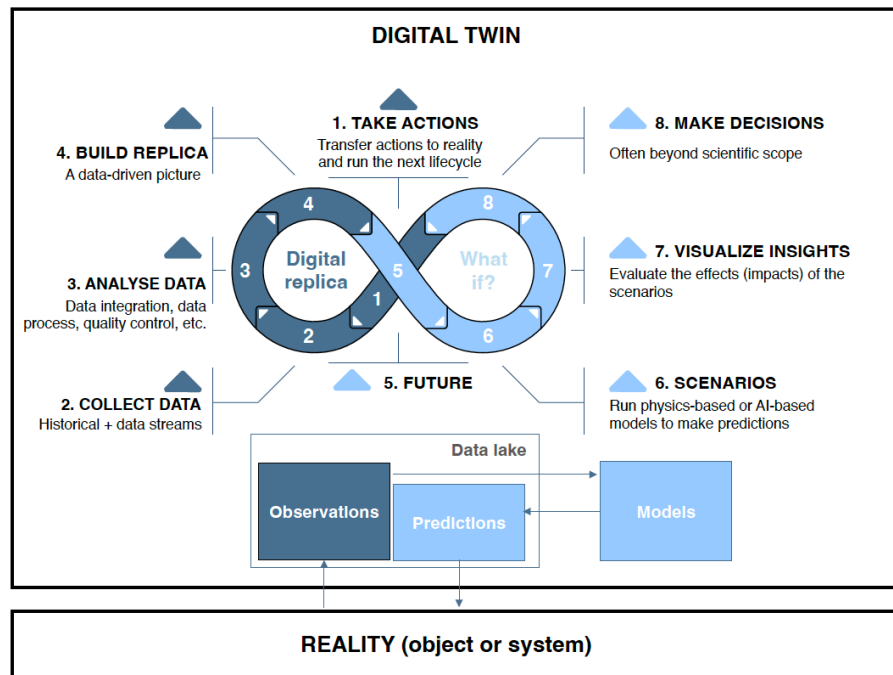
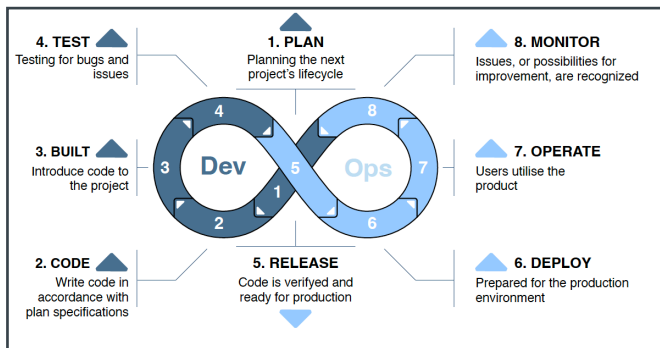
03

DT-GEO and Geo-INQUIRE: interactions and what's next?

The concept of Digital Twin (DT)

A Digital Twin is a **virtual lifecycle environment** that contains a data-informed **replica** of a real system, model-based **prediction** capabilities (scenarios) and, **ideally, can provide feedback** (decisions) to **modify** the real system (i.e. to close the lifecycle loop)

Analogy with the DevOps cycle is software engineering



HORIZON-INFRA-2021-TECH-01-01

4 HE digital twins projects funded

1

Biodiversity Digital Twin for Advanced Modelling, Simulation and Prediction Capabilities (BioDT)

Digital Twin providing advanced modelling, simulation and prediction capabilities across relevant research infrastructures, the BioDT project will be able to more accurately model interaction between species and their environment.

2

A Digital Twin for GEOphysical extremes (DT-GEO)

Deploy 12 Digital Twin Components (DTCs) embedding flagship simulation codes, AI layers, large volumes of (real-time) data streams, data assimilation methodologies, and overarching workflows for deployment and execution in centralised HPC and virtual cloud computing RIs.

3

An interdisciplinary Digital Twin Engine for science (interTwin)

Prototype of an interdisciplinary Digital Twin Engine (DTE), an open source platform that provides generic and tailored software components for modelling and simulation to integrate application-specific Digital Twins (DTs). Use cases for high-energy physics, radio astronomy, astrophysics, climate research, and environmental monitoring.

4

eBRAIN-Health - Actionable Multilevel Health Data (eBRAIN-Health)

Deliver a distributed research platform for modelling and simulating complex neurobiological phenomena of human brain function and dysfunction in a data protection compliant environment.

DestinE ?

Human brain

DT-GEO: numbers and objectives

Action	Horizon-RIA
GA No	101058129
Duration	3 years
Start Date	Sep 2022
End Date	Aug 2025
Budget	15,1 M€
Partners	26
Consortium	HPC RI Data RI Monitoring Research Academia Private

01

Deploy a pre-operational prototype of **Digital Twin (DT) on geophysical extremes** for its future integration in the Destination Earth (DestinE) initiative

02

Implement 12 **Digital Twin Components (DTCs)** addressing specific hazardous phenomena from volcanoes, tsunamis, earthquakes, and anthropogenically-induced extremes in order to conduct data-informed:

1. Early warning systems
2. Forecasts
3. Hazard assessments across multiple time scales.

03

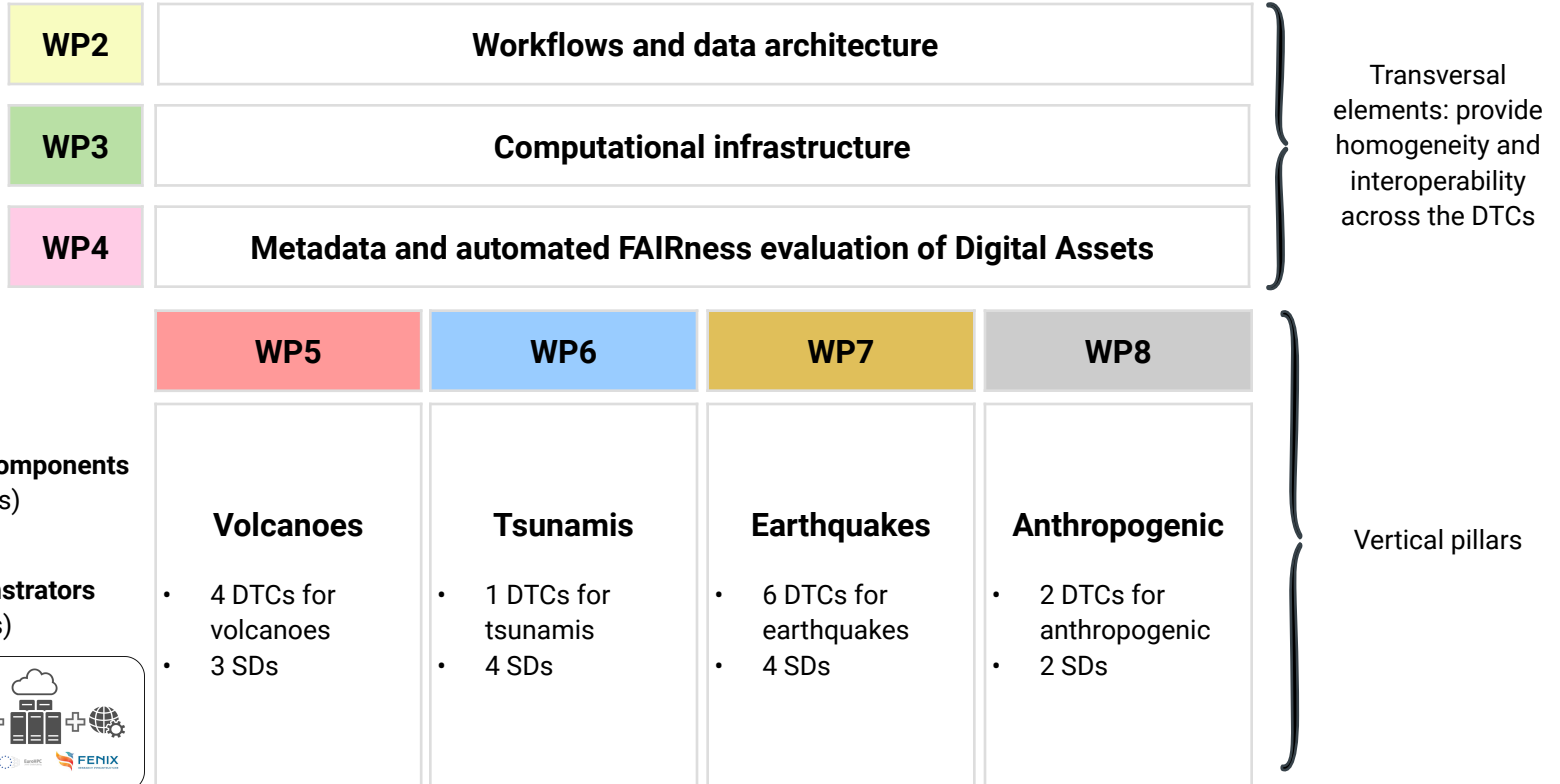
Provide a flexible framework for FAIR-validation of project Digital Assets (DAs) and its integration in 2 Research Infrastructures (RIs):

1. The European Plate Observing System (EPOS)
2. HPC/virtual cloud computing (EuroHPC/FENIX)

04

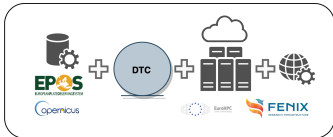
Verify the DTCs in operational environments at 13 **Site Demonstrators (SDs)** of particular relevance located in Europe and beyond

The DT-GEO structure



12
Digital Twin Components
(DTCs)

13
Site Demonstrators
(SDs)

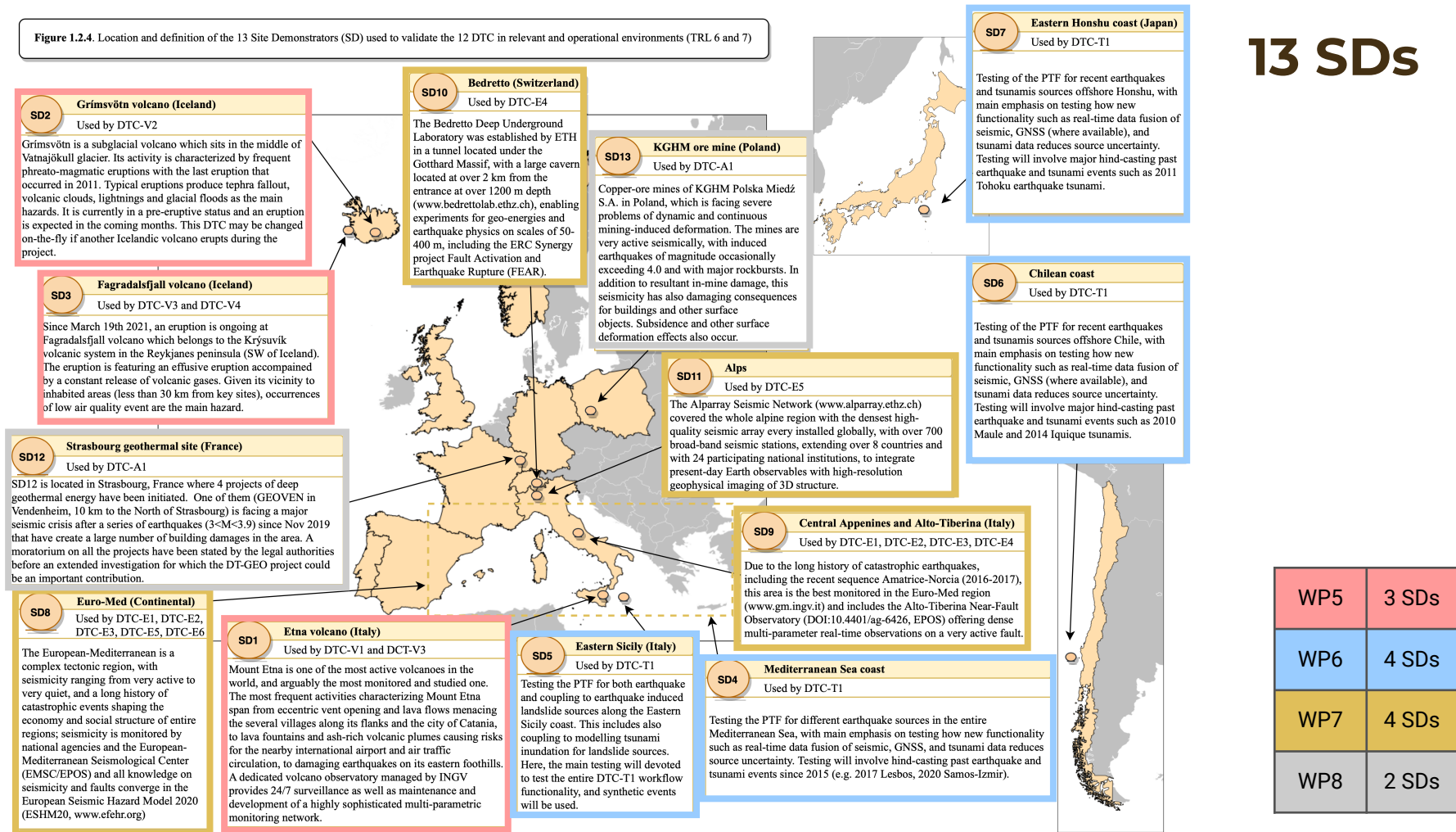


12 DTCs

DTC	Code	Hazard	Name	Target TRL
1	DTC-V1	Volcano	Volcanic unrest dynamics	6
2	DTC-V2		Volcanic ash clouds and deposition	7
3	DTC-V3		Lava flows	6
4	DTC-V4		Volcanic gas dispersal and deposition	7
5	DTC-T1	Tsunami	Probabilistic Tsunami Forecasting (PTF)	7
6	DTC-E1	Earthquake	Probabilistic Seismic Hazard and Risk Assessment	7
7	DTC-E2		Earthquake short-term forecasting	7
8	DTC-E3		Tomography and Ground Motion Models (GMM)	7
9	DTC-E4		Fault rupture forecasting	7
10	DTC-E5		Tomography and shaking simulation	6
11	DTC-E6		Rapid event and shaking characterisation	7
12	DTC-A1	Anthropogenic	Anthropogenic geophysical extreme forecasting (AGEF)	6



Figure 1.2.4. Location and definition of the 13 Site Demonstrators (SD) used to validate the 12 DTC in relevant and operational environments (TRL 6 and 7)

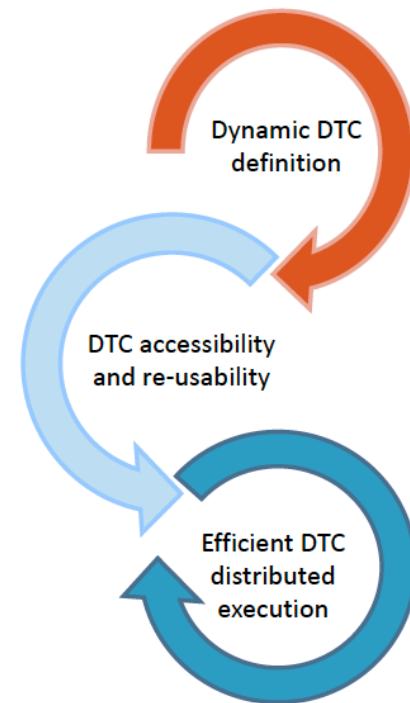
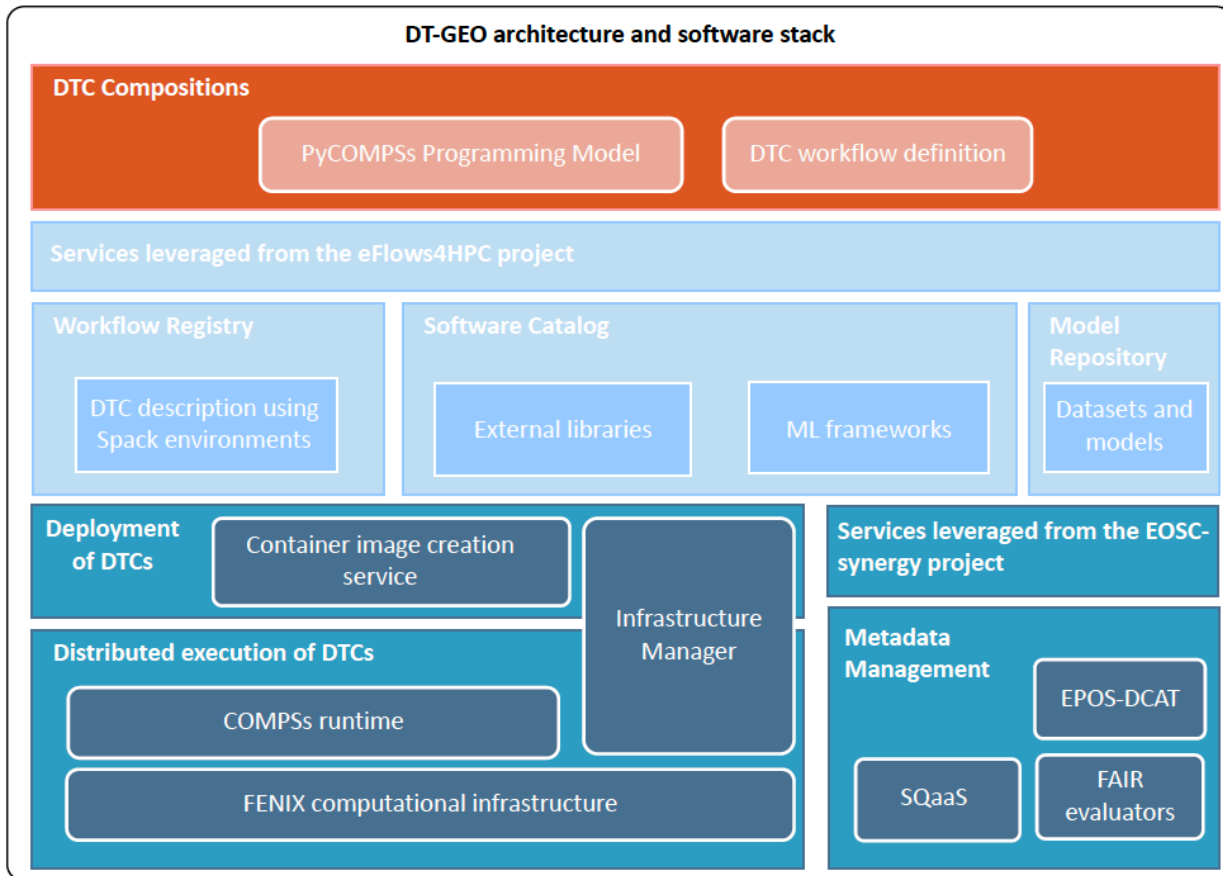


13 SDs

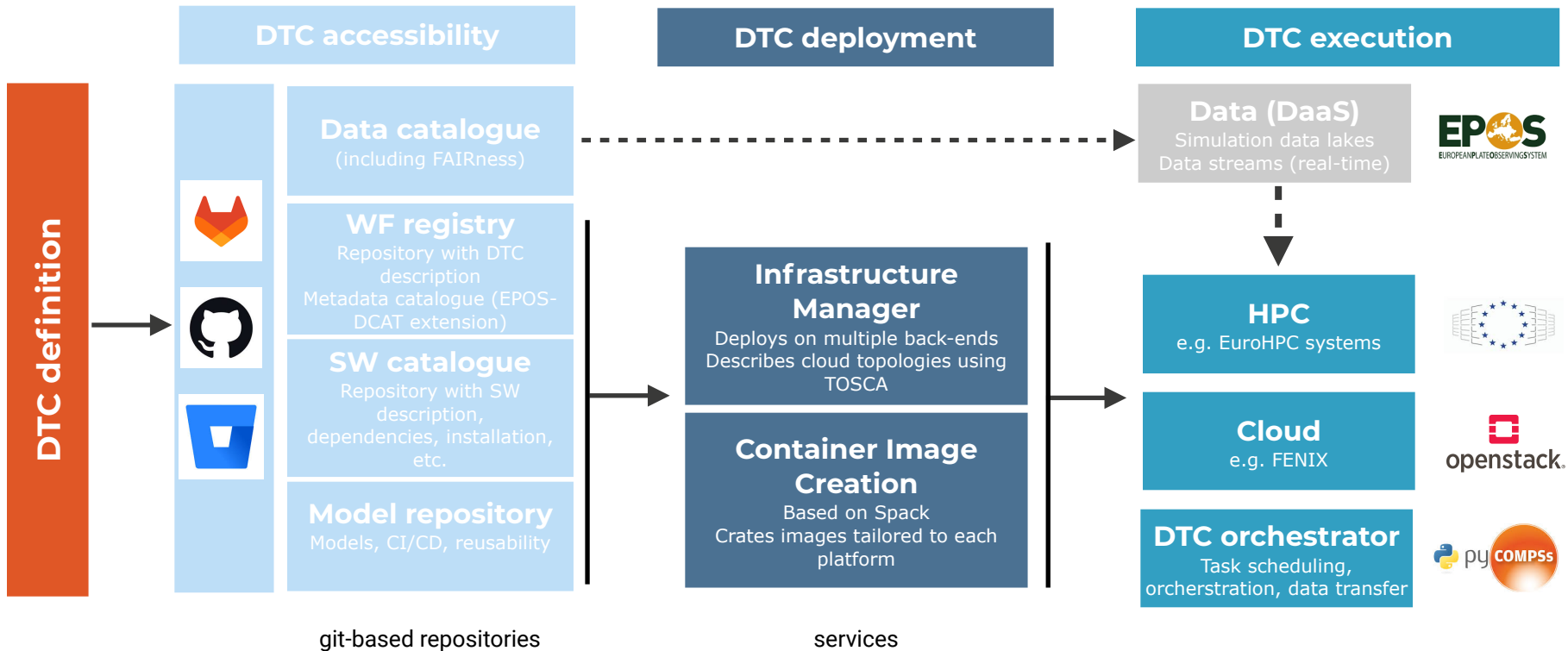
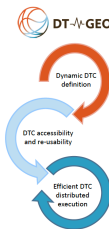
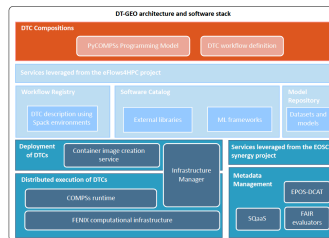
WP5	3 SDs
WP6	4 SDs
WP7	4 SDs
WP8	2 SDs

DT-GEO architecture

DT-GEO architecture and software stack



DT-GEO architecture

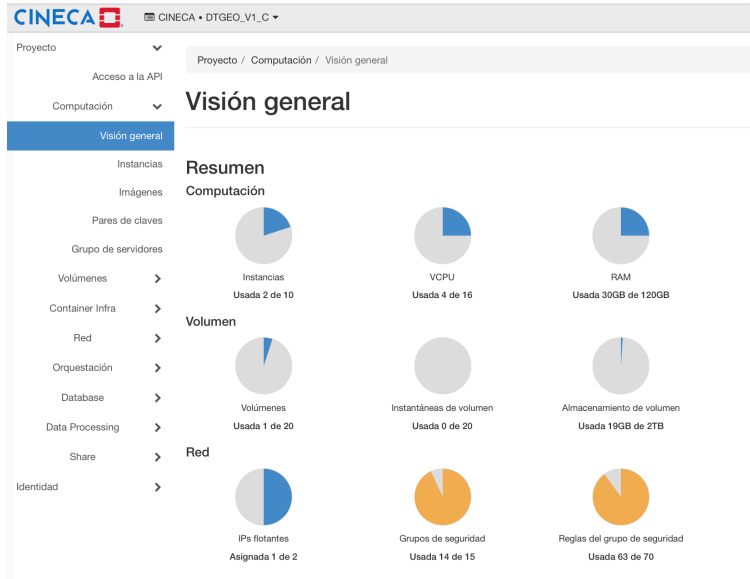


Computational architecture

- DT-GEO uses an **Infrastructure Manager** (IM) to deploy DTCs execution in cloud environments.
- Open stack @CINECA ADA cloud service (IaaS) for DTC testing (cloud).
- The DTC execution (SDs) relies on HPC.
- Configuration of Spack modules on the HPC clusters and support for PyCOMPSs module configuration.

ADA OpenStack dashboard: <https://adacloud.hpc.cineca.it>
Documentation: [link](#)

Interactive computing service: <https://jupyter.g100.cineca.it/hub>
Documentation: [link](#)



Interactive session parameters setting

? User Guide

Slurm Reservation: None

Slurm Account: dtgeo_v1

Number of cores: 1

Memory (MB): 4096

GPU configuration: None

Time (hours): 1,0

ICE4HPC Backend Environment: Release 2023.10

User interface: Jupyterlab

AVAILABLE COMPUTATIONAL RESOURCES

	Nodes	Total Number of cores	Total Free Memory (MB)
No available GPUs	0	/	/
1 available GPU	0	/	/
2 available GPUs	9	432	3.467.700

Start

FAIRness evaluation of DTCs

- Services for DTC reusability (catalogues, registries, and repositories), including the creation of a **Workflows Hub Registry**.
- Recording of workflow provenance: **capture the details of a DTC execution as metadata**.
- The interoperability of the generated metadata is guaranteed by the use of the RO-Crate specification.
- RO-Crate (Research Object Crate) is a method for aggregating and describing research data with associated metadata.

The screenshot shows the WorkflowHub interface for the project 'A Digital Twin for GEOPhysical extremes (DT-GEO)'. The page includes a search bar, navigation links (About, Help, Register, Log in), and a 'Related items' section. The 'Related items' section lists four work packages (WPS) with their descriptions, space information, and public web pages.

Work Package	Description	Space	Organisms
WPS - Anthropogenic geophysical extremes	Develop and implement 1 DTC for Anthropogenic Geophysical Extreme Forecasting (AGEF) with 4 workflow outcomes: forecasting of long-range responses of geoservisors (TC-AGEF1), forecasting of late responses of geoservisors (TC-AGEF2), modeling of the largest magnitude (TC-AGEF3), and induced seismic hazard map estimation (TC-AGEF4). Test the DTC-A through demonstrators at 2 relevant European sites: Strasbourg geothermal site in France (SD12) and KGRM copper ore mine in Poland (SD13).	Space: A Digital Twin for GEOPhysical extremes (DT-GEO) Public web page: https://dtgeo.eu/	Organisms: Not specified
WPS - Earthquakes	Provide an integrated, comprehensive, modular modelling and testing framework Develop multi-scale workflows applicable beyond the identified test-areas enabling improved physical understanding and progress beyond state-of-the-art in the earthquake process. Develop and implement 6 DTCs covering earthquake-related aspects over long and short time scales Test the 6 DTC-E at 4 relevant sites: Euro-Med (SD6), Central Apennines and Alto-Tiberina (SD8), Bedretto Lab (SD10) and the Alps (SD11).	Space: A Digital Twin for GEOPhysical extremes (DT-GEO) Public web page: https://dtgeo.eu/	Organisms: Not specified
WPS - Tsunamis	Develop and implement 1 DTC for data-informed Probabilistic Tsunami Forecasting (PTF) (DTC-T1) Test the DTC-T1 through demonstrators at 4 relevant sites: Mediterranean sea coast (SD4), Eastern Sicily (SD5), Chishan coast (SD6), and Eastern Honshu coast in Japan (SD7).	Space: A Digital Twin for GEOPhysical extremes (DT-GEO) Public web page: https://dtgeo.eu/	Organisms: Not specified
WPS - Volcanoes	Develop and implement 4 DTCs for volcano-related extremes: volcanic unrest (DTC-V1), threat of volcanic ash clouds and fallout (DTC-V2), lava flows (DTC-V3), and volcanic gases (DTC-V4). Test the 4 DTC-V through demonstrators at 3 relevant European sites: Mt. Etna in Italy (SD1), and Grimsvötn and Fagradalsfjall in Iceland (SD2 and SD3 respectively).	Space: A Digital Twin for GEOPhysical extremes (DT-GEO) Public web page: https://dtgeo.eu/	Organisms: Not specified

<https://workflowhub.eu/programmes/36#projects>

DT-GEO current status

1

Phase 1

2

Phase 2

3

Phase 3

From M1 to M12

From M13 to M24

From M25 to M36

KoM (Sep 2022)

1st review (Oct 2023)

2nd review (Oct 2024)

End (Aug 2025)

- ✓ Project setup
- ✓ Collection of requirements (MS1)
- ✓ Computational infrastructure (MS2)
- ✓ Blueprint of DT architecture (MS3)
- ✓ Metadata scheme
- ✓ FAIR quality-based ecosystem

- Beta implementation of the DTCs (MS5 and MS6)
- Early execution of SDs in the FENIX cloud infrastructure (testing/staging)
- Design and development of the DT architecture, second iteration loop

- Further implementation of the DTCs (some coupled)
- Run the Simulation Cases in operational environments using HPC (MS7, MS8 and MS9)

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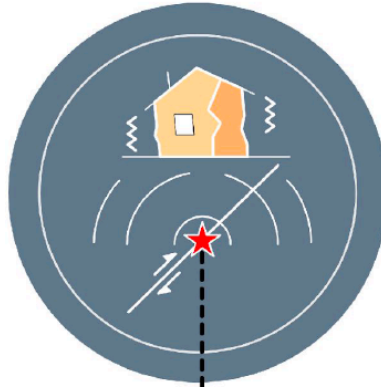
03

DT-GEO and Geo-INQUIRE: interactions and what's next?

Earthquake DTCs

Earthquakes sources and shaking span a large range of time and spatial dimensions.

The WP7 approach is to first develop individual DTC, and later link them in a single pipeline combining different time and spatial scales.



By positioning the new workflows in the existing agencies and infrastructures - local, national, regional, EPOS - we design the future architecture of seismology.

We cover long-term computational and tomography workflows and event-based low-latency workflows.

Decades

Years

Days to minutes

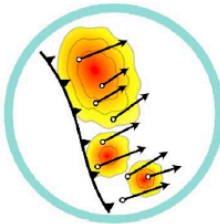
Seconds

Minutes to hours

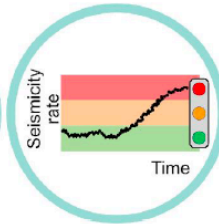
Hours to weeks



Long-term hazard mapping



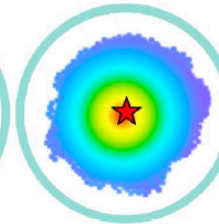
Long-term forecasting



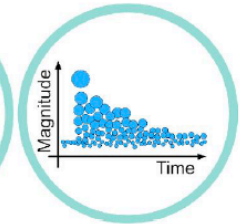
Short-term forecasting



Early warning

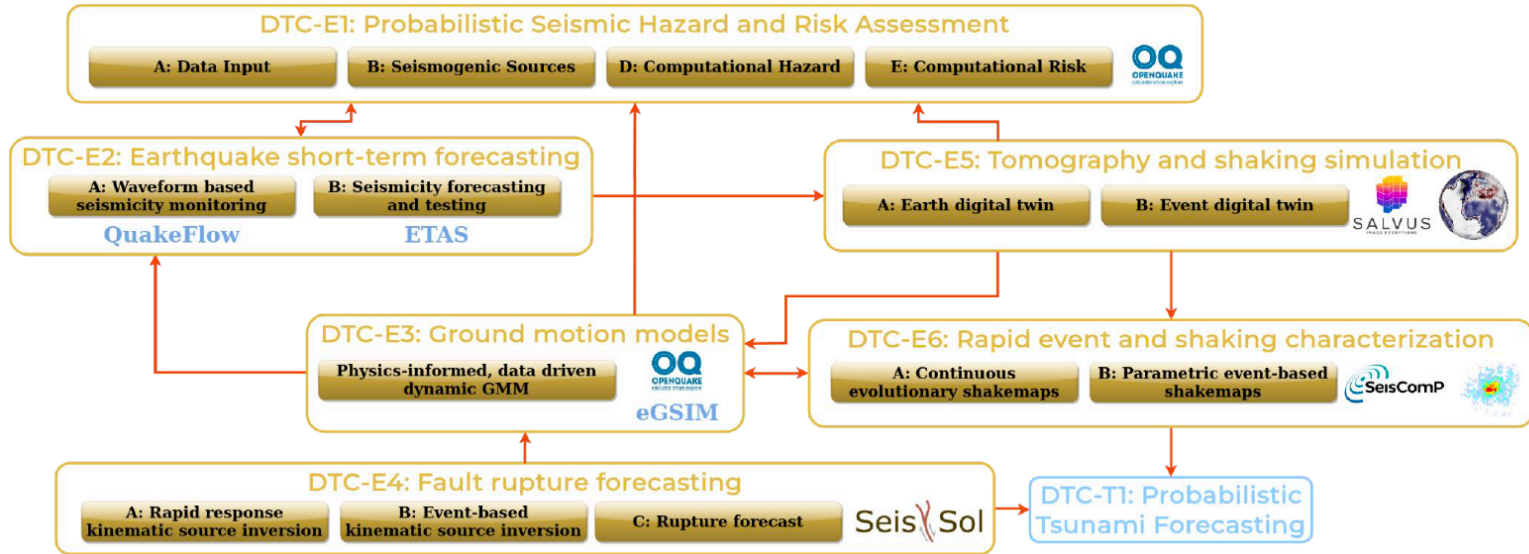


ShakeMap & rapid loss



Aftershock forecasting

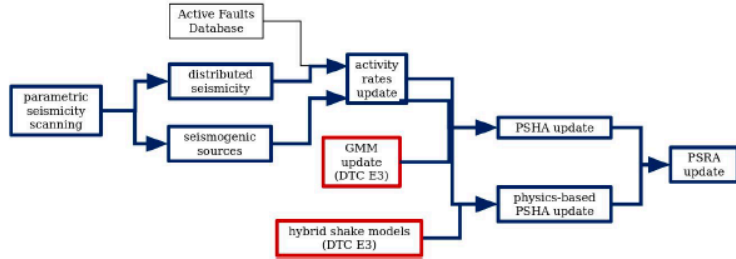
Earthquake DTCs: a set of interconnected WFs



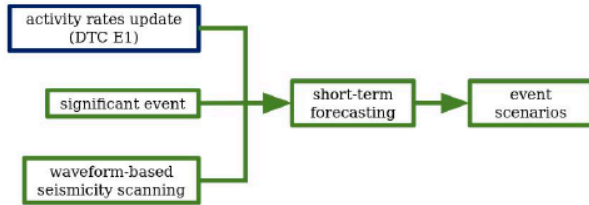
	DTC-E1	DTC-E2	DTC-E3	DTC-E4	DTC-E5	DTC-E6	Total
# of WFs	4	2	1	3	2	2	14
# of Steps	19	17	10	13	15	10	84

Earthquake DTCs: a set of interconnected WFs

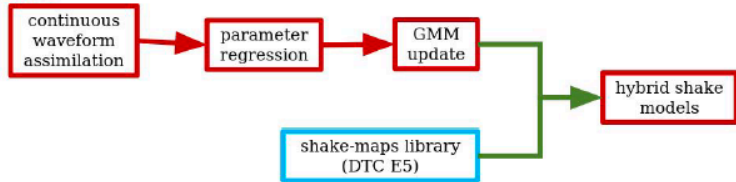
DTC E1: PSHA & PSRA



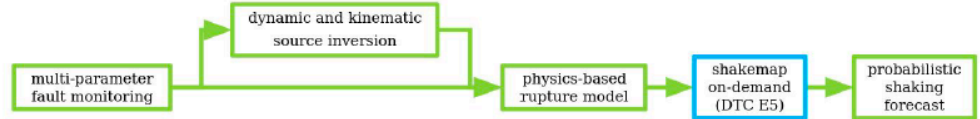
DTC E2: earthquake forecasting



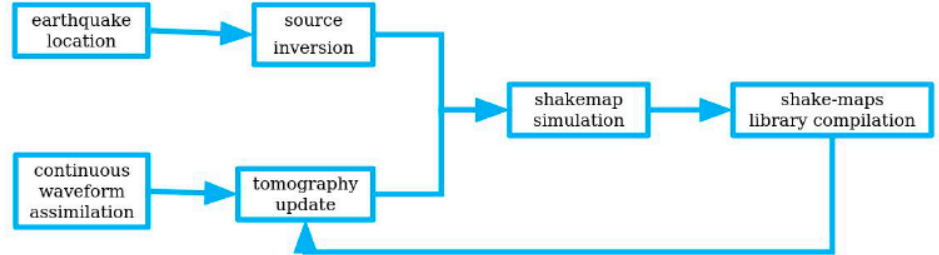
DTC E3: GMM



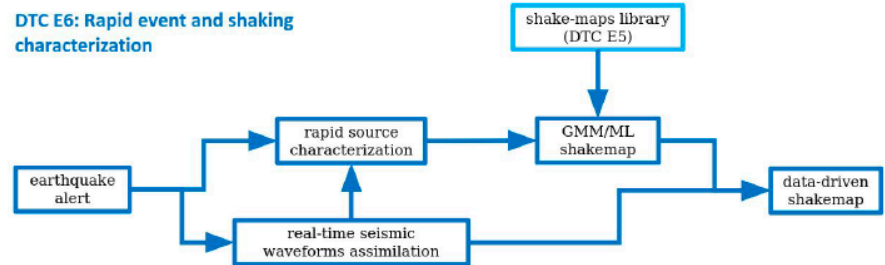
DTC E4: fault rupture forecasting



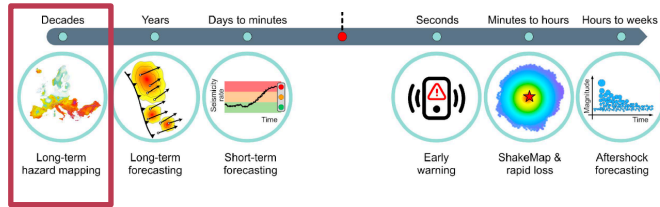
DTC E5: Tomography and shaking simulation



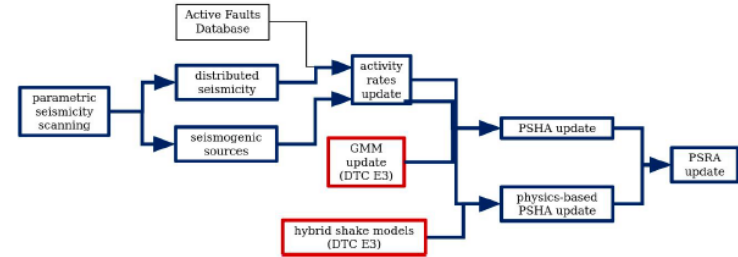
DTC E6: Rapid event and shaking characterization



DTC-E1: Probabilistic Seismic Hazard and Risk Assessment



DTC E1: PSHA & PSRA



Leader Participants

Laurentiu Danciu (ETH)

ETH Zurich: Nicolas Schmid, Carlo Cauzzi

INGV Rome: Roberto Basili

GFZ: Graeme Weatherill

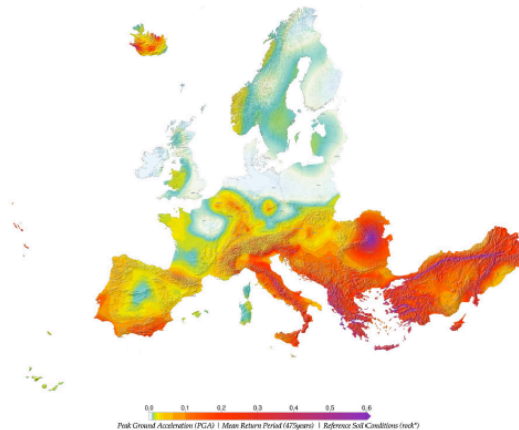
Objective

Assimilate on-going seismicity and update the activity rates used for the seismogenic sources and distributed seismicity components of the European Seismic Hazard Map (ESHM20).

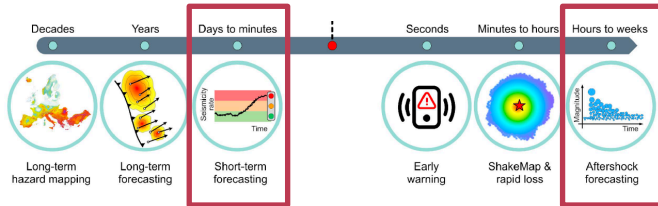
Probabilistic Seismic Risk Assessment will be computed from the two hazard branches using the OpenQuake vulnerability inventories.

Site Demonstrators

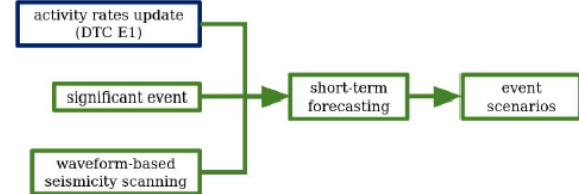
SD8: Euro-Med



DTC-E2: Earthquake short-term forecasting



DTC E2: earthquake forecasting



Leader

Stefan Wiemer (ETH)

Coordinator

Leila Mizrahi (ETH)

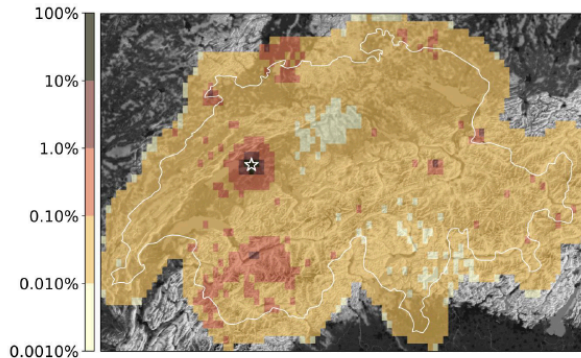
Participants

ETH: Marta Han, Nicolas Schmid, Men-Andrin Meier, Dario Jozinovic, Stefan Wiemer

UKRI: Margarita Segou, Brian Baptie

GFZ: Danijel Schorlemmer

INGV: Lauro Chiaraluze, Maddalena Michele



Objective

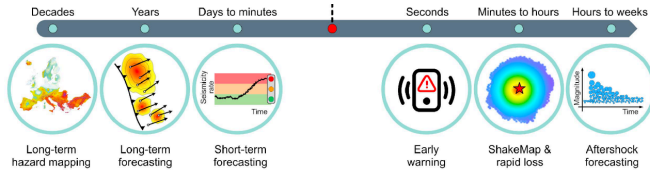
Process waveform data into high-resolution seismicity catalogues. Use ETAS models to produce short-term earthquake rate forecasts and tests them using standard earthquake catalogues.

Site Demonstrators

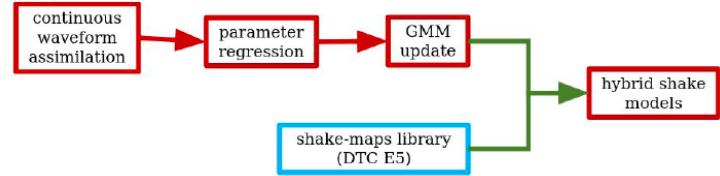
SD8: Euro-Med (Continental)

SD9: Central Apennines-Alto Tiberina

DTC-E3: Tomography and Ground Motion Models (GMM)



DTC E3: GMM

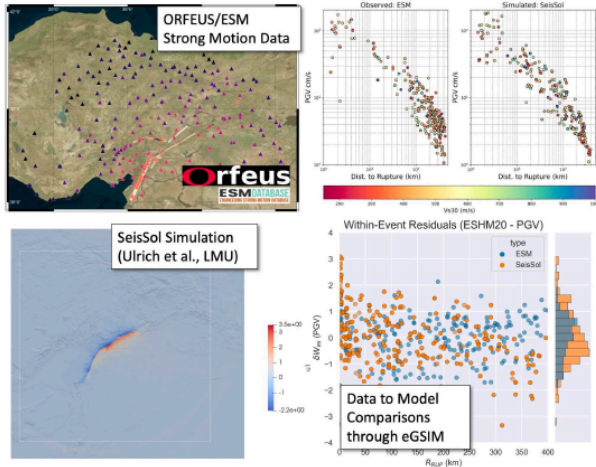


Leader Participants

Fabrice Cotton (GFZ)

GFZ: Graeme Weatherill, Dino Bindi, Riccardo Zaccarelli, Ssu-Ting Lai

ETH: Carlo Cauzzi, Laurentiu Danciu



Objective

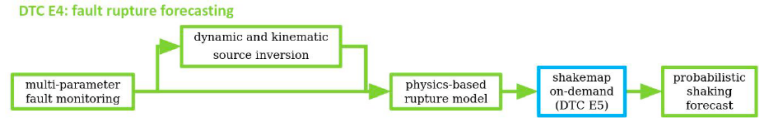
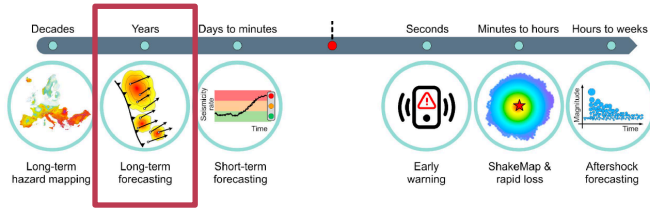
Provide ground motion models (GMMs) for Europe, using AI and physics-based ground motion simulations to create accurate, fine-resolution models of earthquakes.

Site Demonstrators

SD8: Euro-Med (Continental)

SD9: Central Apennines-Alto Tiberina

DTC-E4: Fault rupture forecasting



Leader

Alice Gabriel (LMU)

Coordinator

Mathilde Marchandon (LMU)

Participants

LMU: Nico Schliwa, Thomas Ulrich

INGV: Lauro Chiaraluce, Emanuele Casarotti

CNRS Geo-Azure: Jean-Paul Ampuero, Bertrand Delouis

ETHZ: Luca Dal Zilio

Rupture forecasting for the Alto Tiberina fault system

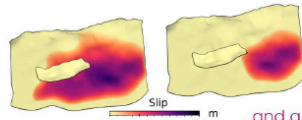
Multi-data constraints from Near-Fault Observatory
TABOO



SeisSol

3D dynamic rupture & seismic wave propagation

Catalog of **physic-based rupture scenarios...**



Objective

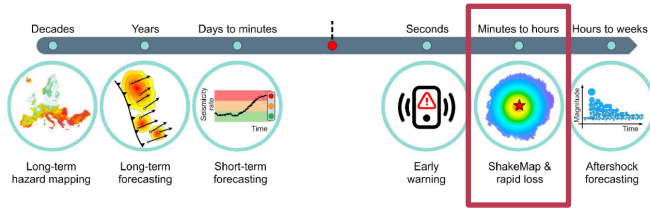
Model fault rupture complexities, including dynamic source inversion and forward dynamic modeling, multi-physics modeling for earthquake source processes, as well as path and site effects.

Site Demonstrators

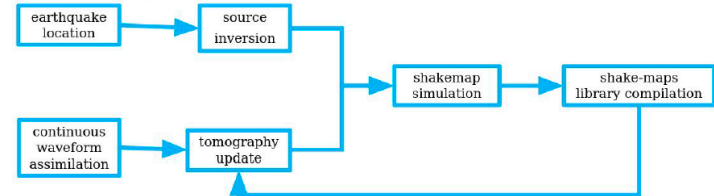
SD9: Central Apennines-Alto Tiberina (Italy)

SD10: Bedretto (Switzerland)

DTC-E5: Tomography and shaking simulation



DTC E5: Tomography and shaking simulation



Leader Participants

Marta Pienkowska (ETH)

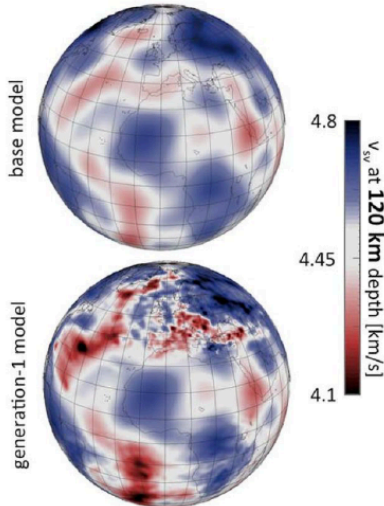
ETH: Andreas Fichtner, Sebastian Noe, Ariane Lanteri

Mondaic: Christian Boehm, Lion Krischer, David Sollberger, Lars Gebraad

BSC: Josep de la Puente, Marisol Monterrubio Velasco, Natalia Zamora, Cedric Bhihe, Claudia Abril

CNRS: Jean-Paul Ampuero, Cedric Twardzik, Bertrand Delouis

CSIC: Paula Herrero



Objective

Use seismic data to create a multi-scale model of the Earth, which is used to update the Collaborative Seismic Earth Model (CSEM).

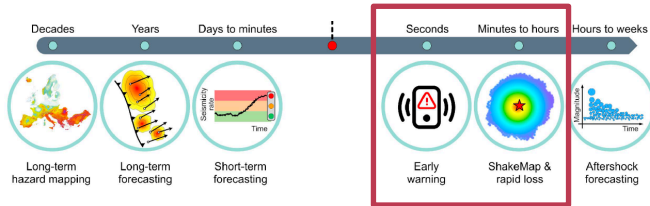
Generate maps of synthetic ground motion distributions for seismic sources at different time scales, and update them by incorporating new data.

Site Demonstrators

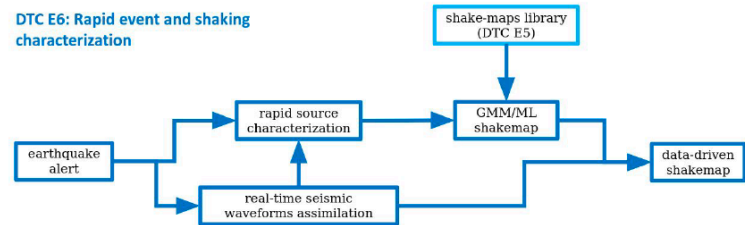
SD8: Euro-Med (Continental)

SD11: Alps

DTC-E6: Rapid event and shaking characterisation



DTC E6: Rapid event and shaking characterization



Leader

Maren Böse (ETH)

Participants

ETH: Savas Ceylan, Carlo Cauzzi, Frédéric Massin, John Clinton

INGV: Alberto Michelini, Licia Faenza

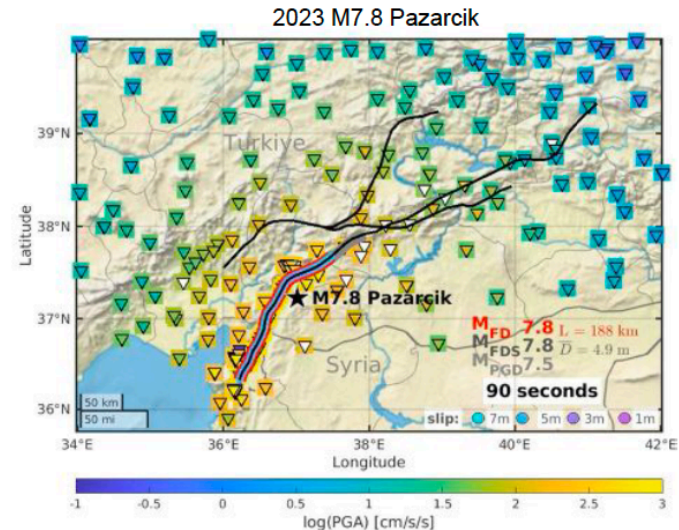
GFZ: Dino Bindi, Graeme Weatherill, Fabrice Cotton

Objective

Provide evolutionary data-driven maps of (strong) ground shaking (e.g., ShakeMaps), including a finite-fault source model characterization, for rapid information and warnings a few seconds to minutes after any significant ($M \geq 3.5$) earthquake in the larger Euro-Med region.

Site Demonstrators

SD8: Euro-Med (Continental)



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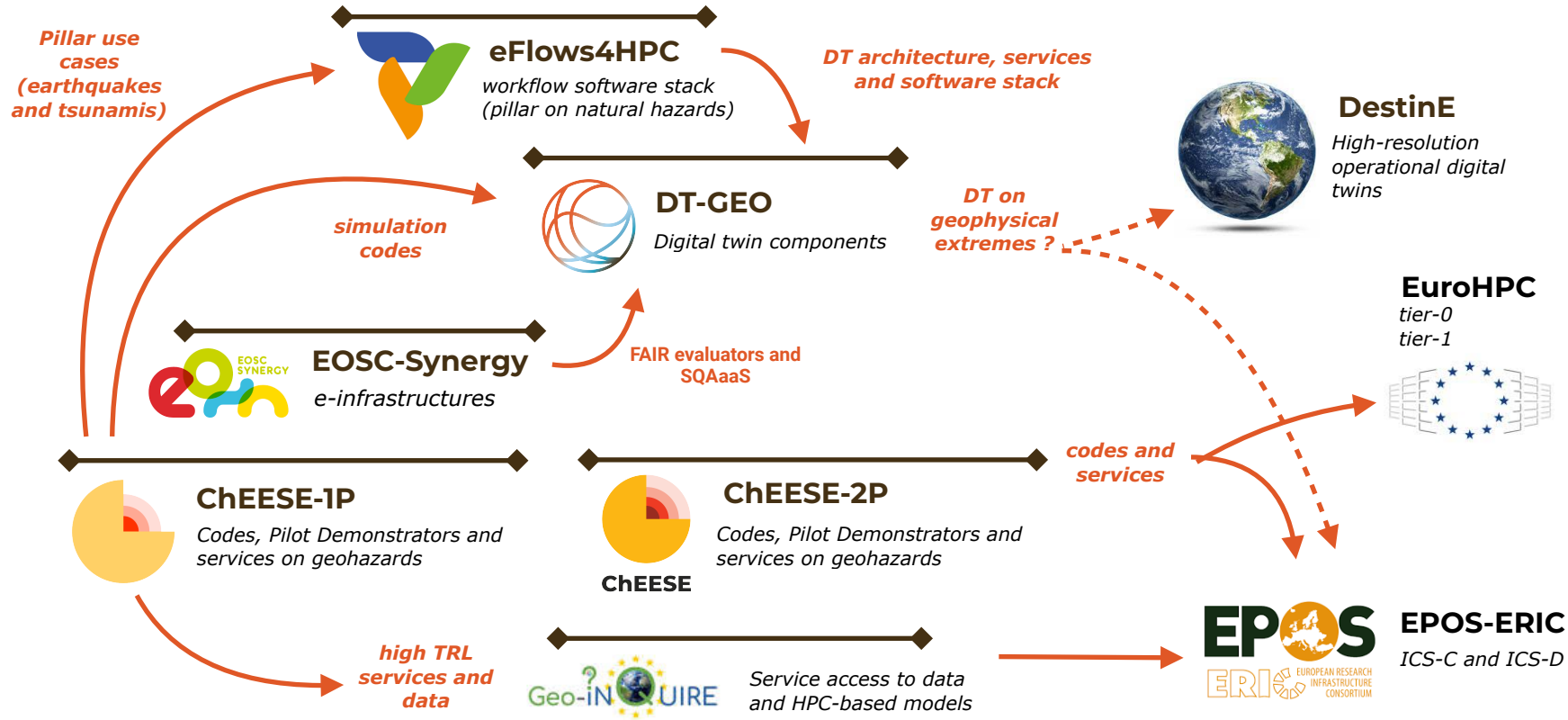
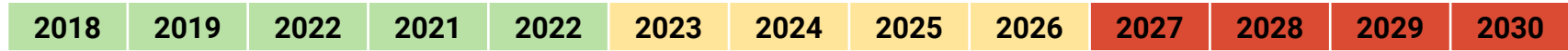
02

Towards a DT for earthquakes

03

DT-GEO and Geo-INQUIRE: interactions and “what’s next?”

ecosystem of European projects



DT-GEO consortium

(19/26 DT-GEO partners are shared with Geo-INQUIRE !)

No	Partner	Type		No	Partner	Type	
1	CSIC	COO	Consejo Superior Investigaciones Científicas	13	CNRS	BEN	National Center for Scientific Research
1.1	UPV	AFE	Universitat Politècnica de València	13.1	UNISTRA	AFE	UNIVERSITE DE STRASBOURG
2	INGV	BEN	Istituto Nazionale di Geofisica e Vulcanologia	13.2	UGA	AFE	UNIVERSITE GRENOBLE ALPES
3	IGF	BEN	Institute Geophysics - Polish Academy of Science	13.3	IRD	AFE	INSTITUT DE RECHERCHE POUR LE DEVELOPPEMENT
4	CIN	BEN	CINECA Consorzio Interuniversitario	13.4	OCA	AFE	OBSERVATOIRE DE LA COTE D'AZUR
5	BSC	BEN	Barcelona Supercomputing Center	13.5	UCA	AFE	UNIVERSITE COTE D'AZUR
6	NGI	BEN	Norwegian Geotechnical Institute	13.6	IPGP	AFE	INSTITUT DE PHYSIQUE DU GLOBE DE PARIS
7	UMA	BEN	University of Malaga	13.7	UP	AFE	UNIVERSITE PARIS CITE
8	GFZ	BEN	German Research Centre for Geosciences	14	EPOS	BEN	European Plate Observing System - ERIC
9	LMU	BEN	Ludwig-Maximilians Universität München	15	CYFRONET	BEN	ACK CYFRONET
10	IMO	BEN	Icelandic Meteorological Office	16	ETH	ASP	Swiss Federal Institute of Technology
11	UHAM	BEN	University of Hamburg	17	MON	ASP	MONDAIC
12	LIP	BEN	Lab of Instrumentation and Experimental Particle Phy.	18	UKRI	ASP	United Kingdom Research and Innovation

COO Coordinator

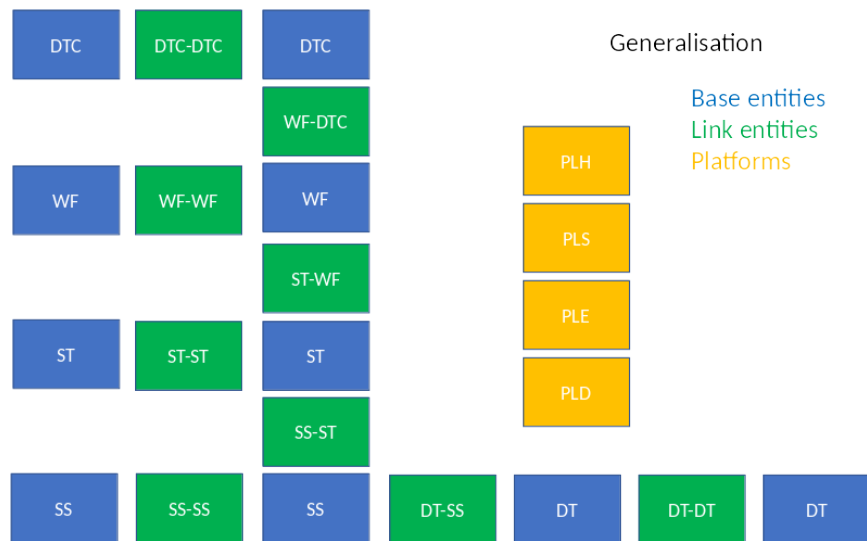
BEN Beneficiary

AFE Affiliated Entity

ASP Associated Partner

Data architecture: joint effort with Geo-INQUIRE

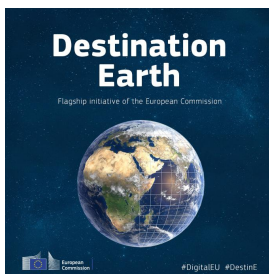
- Metadata schemes to characterise the DTCs and their relationships (aligned with geo-INQUIRE):
 - **DCAT**: Data Catalog vocabulary for publishing data catalogs on the web (<https://www.w3.org/TR/vocab-dcat/>).
 - **EPOS-DCAT-AP**: an extension of the DCAT Application Profile for Research Infrastructures in the solid-Earth domain based on the Common European Research Information Format (CERIF).
 - **DT-GEO**: further extension of EPOS-DCAT to accommodate metadata for new entities in the DT-GEO schema such as Workflow and Step.
- Adoption and extension of the EOSC-synergy SQAaaS platform for assuring quality on DAs (e.g. FAIR-EVA has been extended with a specific plugin to integrate with the EPOS-DCAT catalog).



Simulation Data Lake (SDL@CINECA infrastructure)

- Preservation, accessibility, and insightful exploration of results from numerical simulations.
- Curate existing simulation datasets and integrating new ones from various Virtual Access (VA) within the Geo-INQUIRE WP5.
- Ambitions to become a strategic asset within several geoscience domains and initiatives (e.g. ChEESE and DT-GEO).
- 500TB of storage; relies on the EUDAT Collaborative Data Infrastructure and its B2* service ecosystem.
- Working on metadata scheme (EPOS-DCAT extension).





Destination Earth

key elements

Flagship initiative of the EC

- European Green Deal (2019)
- European Data Strategy (2020)
- Shaping Europe's Digital Future (2020)

Objectives

1. Develop a digital twin of the Earth to monitor and predict environmental changes and human impacts
2. Evidence-based policy developments
3. Actionable predictions (downstream component)

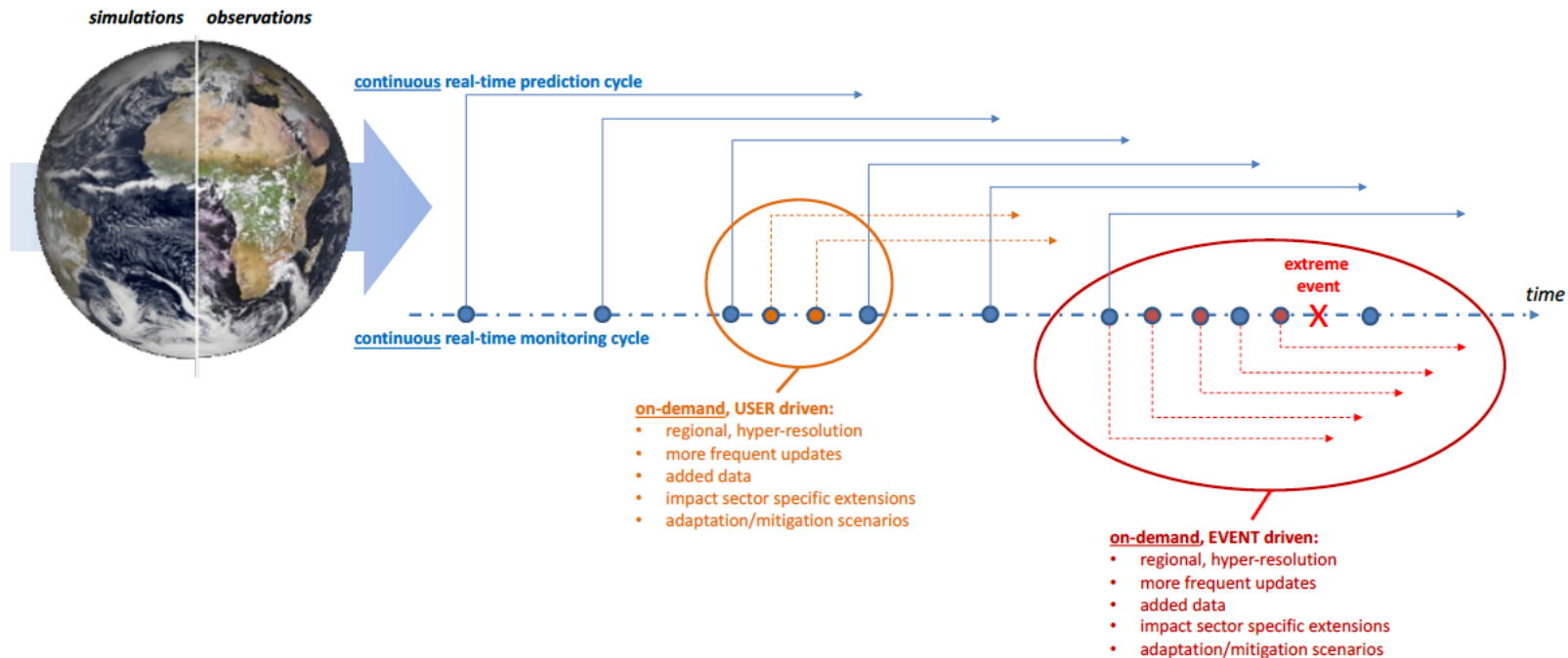
Three main ingredients

1. Data lake
2. Digital twin engine (continuous + on-demand)
3. DestinE Core Service Platform (DESP)

Funding

1. Digital Europe Programme of the Directorate-General for Communications Networks, Content and Technology (CNECT) - Tender for implementation
2. Horizon Europe - For additional R&I activities

DT engine production modes



Mode	Continuous	On-demand (user-driven)	On-demand (event-driven)
Resources	EuroHPC (10%)	DESP (cloud)	Urgent computing ?

Core Service Platform

- Use Cases demonstrate the capabilities of the DestinE infrastructure to provide actionable information and decision support to its end users.
- Up to 20 use cases by now...

The screenshot shows the 'Use Cases Catalogue' page on the DestinE website. The header includes the 'Destination Earth' logo and navigation links for 'About', 'Use Cases', 'Community', 'Procurements', 'News & Events', 'Multimedia', 'FAQ', 'Contact us', and a 'Visit DestinE Platform' button. The main content area features a search bar, a filter sidebar with categories like 'Organisation', 'Topic', and 'Scale', and a list of 20 search results. Three results are visible, each with a representative image, a title, a brief description, and a 'Read more' link.

Home - Use Cases Catalogue

Use Cases Catalogue

Discover the first set of selected End-to-End Use Cases in the DestinE Catalogue!

Each Use Case demonstrates the capabilities of the DestinE infrastructure to provide actionable information and decision support to its end users.

Search 20 results found Any

Organisation Topic Scale

Extreme Weather Flooding
Adaptation Modelling Framework
Developing an adaptation modelling framework supporting the EU Adaptation Strategy goals and enabling easier access to advanced hazard and impact models for decision-makers.
Procured by: [Read more >](#)

Extreme Weather Urban Heat
Adaptation Modelling Framework for Heat Stress Exposure
Developing a modelling framework that will facilitate the formulation of adaptation measures addressing heat waves.
Procured by: [Read more >](#)

Urban Heat
Addressing Urban Heat Island Effect
Providing high-resolution urban heat maps for cities across Europe to underpin urban climate adaptation measures.
Procured by: [Read more >](#)

Air Quality
Air Quality Forecasting Analysis System
Exploring ECMWF's digital twins applications for air quality analysis and forecasts.

What's next?

The Geophysical extremes DestinE twin

- Geophysics was on the radar since the ExtremeEarth-PP (DestinE embryo)...
- GEMINI proposal at HORIZON-INFRA-2024-TECH-01-03 call failed...
- And now?
 - Other calls...
 - The role of EPOS (distributed Data Lakes)
 - Lobby for tenders (DG-CNECT)

THANK YOU

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@dtgeo_eu



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