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GO-Forward: Geothermal exploration and Optimization through FORWARD modelling and resource development

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ABSTRACT

Geothermal development in Europe faces challenges due to scarcity of subsurface information, particularly in densely populated urban areas, where data acquisition is more difficult. Traditional methods for predicting reservoir properties depend on high data density and spatial interpolation through geostatistical approaches.

The Horizon-Europe funded project GO-Forward seeks to facilitate a paradigm shift in this field by utilizing a coupled workflow of geological forward modelling techniques, comprising stratigraphic, diagenetic, fault and fracture modelling. This innovative approach allows for the physics-based modelling and prediction of reservoir heterogeneities in three dimensions, making it possible to derive valuable insights even in areas with limited data availability. By analysing the regional geological history of reservoir rocks, GO-Forward simulates the geological processes that have shaped these systems over time, thereby improving the accuracy of pre-drilling predictions.

The project integrates existing simulation tools and methods that have been previously applied in hydrocarbon exploration and adapts them to the complexities of geothermal environments. This comprehensive modelling framework not only enhances the understanding of geothermal plays but also significantly reduces pre-drill risk associated with exploration. The methods will be validated in regions with abundant subsurface information and production data. Once calibrated, the models will be utilized in greenfield areas, supporting the de-risking of geothermal exploration in these locations. GO-Forward emphasizes a combination of technology options tailored to the diverse geological settings representative of various geothermal plays across Europe, ultimately contributing to a more efficient and effective geothermal energy rollout.

1. INTRODUCTION

In the pursuit of achieving a net-zero greenhouse gas economy by 2050, geothermal energy stands out as a core component for baseload supply of the future energy system in Europe. Despite its potential, the widespread application of geothermal resources remains hindered by significant challenges, particularly due to limited availability of reliable subsurface data and the associated uncertainty of subsurface parameter distributions and high pre-drill risk. Further, exploration for geothermal resources is often bound to the vicinity of energy demand, ususally densely populated urban areas. There, acquisition of exploration data, e.g., by active seismic surveys or exploration wells, is especially challenging.

Current state-of-the-art approaches for modelling reservoir heterogeneities in 3D primarily employ geostatistical interpolation techniques that extrapolate properties from existing data. However, these methods require a certain data density and often fall short in accuracy and reliability at larger distances to data points, thus leading to increased drilling risks and suboptimal resource assessment. To address these challenges, the GO-

Forward project proposes a novel methodological framework that integrates advanced forward modelling techniques with a process-based understanding of the formation of geothermal reservoirs.

The motivation behind this research project is to enhance the precision of pre-drilling predictions of geothermal reservoir properties by simulating geological processes governing reservoir formation. By utilizing and integrating stratigraphic, diagenetic, and fracture forward modelling techniques, the project aims to develop accurate reservoir models even in regions with limited direct subsurface information, due to the consideration of additional geological knowledge and context. This innovative approach not only promises to reduce exploration costs and risks but also aims to increase the exploratory success rate by providing a comprehensive understanding of subsurface characteristics.

The anticipated impact of the GO-Forward project extends beyond the technical work to improve resource assessment. By querying societal engagement and public awareness from the early stages of exploration, the project aims to address the societal readiness level for development of geothermal projects. By integrating technological advancements with social science approaches, the project seeks to build public trust and acceptance, thereby facilitating the broader adoption of geothermal energy solutions.

In a nutshell, by combining advanced modelling techniques with proactive stakeholder engagement, the GO-Forward project represents the potential for a great step forward in geothermal exploration endeavours. The outcomes of this research hold the potential to significantly enhance the exploration and optimization of geothermal reservoir systems across Europe, ultimately contributing to a sustainable energy transition.

2. PROJECT OVERVIEW

The GO-Forward project is funded within the Horizon-Europe program Climate, Energy and Mobility, subprogram Energy Supply. Within GO-Forward, twelve partner institutions from eight different countries work together in developing and applying an integrated workflow of physics-based modelling of geothermal system development: from sedimentation over diagenesis to faulting and fracturing. Here, GO-Forward brings together experts from academia and industry. In addition to the technical expertise in interlocking these modelling approaches into one cohesive, reproducible and adaptable workflow, GO-Forward also aims at directly facilitating geothermal development, first in the target-sites within the project, second within Europe. Using surveys and interviews tailored to main stakeholders in the study regions, GO-Forward assesses the economical and societal perception, current awareness, but also needs for accelerating exploration and utilization of deep geothermal energy.

The main findings and updates about GO-Forward can be found, among others, on the project website: https://go-forward-project.eu.

The following table 1 provides a concise overview of GO-Forward key metrics:

Table 1: GO-Forward project data.

Start date	1 September 2024
End date	31 August 2028
Duration	4 years
Call	HORIZON-CL5-2023-D3-02
Partner countries	GER, DK, NL, AT, SP, UK, IT, CH
Partner Institutions	1. Fraunhofer Institution for Energy Infrastructures and Geotechnologies (IEG) 2. Geological Survey of Denmark and Greenland (GEUS) 3. Netherlands Organisation of Applied Scientific Research (TNO) 4. Geosphere Austria (GSA) 5. Institut Cartogràfic I Geològic da Catalunya (ICGC) 6. British Geological Survey (BGS) – United Kingdom Research and Innovation (UKRI) 7. Univerità degli Studi di Bari Aldo Moro (UNIBA) 8. University of Vienna (UVIE) 9. Technical University of Denmark (DTU) 10. SwissGeoEnergy SA (SGE) 11. Stiftung Risiko-Dialog (SRD) 12. EVN Wärme GmbH (EVN)
Project page	https://go-forward-project.eu/

3. METHODOLOGY

3.1 Enriching databases through Machine Learning

One key aspect of the presented GO-Forward approach is the utilization of well-calibrated forward models for prognosis of geothermal potential in areas without much pre-existing data. Key for achieving a suite of well-calibrated models is the quality and quantity of calibration data itself.

In GO-Forward, several approaches are tested and further developed to derive calibration data from diverse data sources, including among others: seismic data, well data (logs/cores/BHI) and surface/outcrop data (UAV photogrammetry, LIDAR). data. Different data sources are selected for extracting features and parameters like among others, lithofacies, porosity, shale content, faults and fractures.

One key aspect is to effectively minimize, by aid of ML approaches, the need for time-consuming manual interpretation and correlation of data. GO-Forward methods will significantly lower cost, enhance interpretation quality and facilitate reproducibility of results, for example by efficient segmentation and classification of image data, e.g. SEM images or thin sections, or joint correlation of identified lithofacies from seismic and wells using state-of-the art approaches like relative geological time.

Feature detection for fractures is important for calibrating fracture models, as fractures and faults can serve as fluid pathways and as such dramatically influence the potential of a reservoir. Automatic detection and classification of fractures from point cloud data (i.e., LIDAR), image data (i.e., BHI, seismic, 3D core scans), will be done by applying of recursive convolutional neural networks (RCNNs). Existing methods are improved by incorporating capabilities for not only identifying, but characterising properties of fracture features (i.e., aperture and orientation), in addition to automated differentiation of natural features and anomalies of non-geological features (i.e., fractures vs borehole breakouts in BHI).

3.2 Integrated Forward Modelling approach

Stratigraphic Forward Modelling (SFM)

SFM is a modelling approach that employs mathematical algorithms to create synthetic simulations of stratigraphic processes and products. By integrating equations that represent factors such as sediment transport, deposition, erosion, and compaction, SFM generates realistic models of sedimentary sequences. These models provide insights into the complex interplay between environmental conditions and geological dynamics that give rise to the diverse array of sedimentary successions observed in outcrops and subsurface data. Consequently, SFM yields insight in a realistic, 3D depositional architecture, on a local to basin scale which provides key information on the (lateral distribution of) reservoir quality through its prediction of reservoir facies (and grainsize) distribution. This sets them apart from geostatistical approaches, whose informative value drastically decreases beyond correlation lengths of datasets. GO-Forward will go beyond state of the art by novel application of existing SFM commercial software to geothermal exploration (hitherto limited for hydrocarbon exploration), extending existing SFM methods for different geological settings including reservoirs marked by syn-sedimentary faulting, and prediction of associated faulted reservoir flow properties.

Diagenetic Forward Modelling (DFM)

Complementary to SFM, DFM is used to simulate the effect of diagenetic events, such as compaction, dissolution, karstification, cementation, dolomitization, and their impact on flow properties (enhancement, destruction, compartmentalization). Both, early diagenetic processes related to the depositional environment and potentially leading to early reservoir compartmentalisation, and late, deeper burial processes related to temperature and pressure changes during burial or focused (fault-related) fluid flow are considered. These processes further increase the parametric heterogeneity already present in the depositional facies architecture based on SFM, potentially severely complicating exploration. While in petroleum reservoirs, reservoir properties could be exceptionally preserved due to hydrocarbon migration and shielding from burial diagenesis, this does not apply to brine saturated geothermal reservoirs. The GO-Forward workflow extracts necessary, appropriate input to state-of-the-art diagenetic models from SFM model results, rather than from geostatistically-derived or hand-drawn maps, combined with state-of-the-art basin modelling approaches to reconstruct temperature and effective stress histories. The output of diagenetic forward modelling will include grids containing lithology, porosity, permeability, temperature and pressure, which can be converted in turn to rock mechanical properties that form input to fracture forward modelling.

Fracture Forward Modelling (FFM)

Faults and natural fracture networks have a large impact on geothermal reservoir quality in various ways: Fracture density, size, aperture and interconnections are critical for fluid flow pathways determining flow performance in reservoirs marked by low matrix permeability. On the other hand, faults and fractures can act as flow barriers hampering matrix flow paths due to mineralization and smearing if marked by fault throw. Furthermore, reservoir faults are potential loci of induced seismic events, which are critical to assess in seismic hazard assessments, i.e. "Do No Significant Harm" (DNSH). Fractures (and small-scale faults) cannot normally be mapped directly in the subsurface, as they are below the resolution of geophysical data, and boreholes provide only very limited data coverage. Traditional solutions to this problem include building stochastic fracture models or matching measured fractal geometries in the boreholes or analogue outcrops. However, such results are unreliable to translate to (slightly) different lithological and burial and deformational history conditions for specific reservoirs. These challenges can be overcome by process-based geomechanical Fracture Forward Models (FFM) for nucleation, growth and interlinkage of fractures and faults. In GO-Forward we (a) adapt state of the art FFM software for geothermal reservoir rock types, including basement rocks, (b) constrain input on geomechanical properties for FFM from litho-stratigraphic layering and diagenetic alteration constrained by SFM and DFM, (c) enhance the FFM workflow for incorporation of tectonic stress histories and modelling of multiscale fault fabric , as well as the impact of significant thermal and chemical changes over geological timescales and during exploitation, hitherto not considered for hydrocarbon exploration and production. Jointly these methodological improvements provide a robust workflow for multiscale fault and fracture models facilitating significant reduction of uncertainty in pre-drill assessment of fracture dominated reservoir flow properties, identification of potential flow barriers related to fractures and faults, and providing key input for seismic hazard analysis.

3.3 Techno-economic assessment models

The resulting calibrated results of the modelling workflow (Figure 1), i.e. reservoir property models, will be used by DNSH and techno-economical models to evaluate and validate outcomes with existing production data. DNSH models will assess safe operational parameter envelopes for potential exploitation. The techno-economic performance assessment incorporates cash flow evaluation methods and stochastic models of Net Present Values (NPV) combined with determined Probability of Success (POS) of a project, as well as Value of Information (VOI) for potential exploration activities in a region (Van-Wees et al., 2020).

4. VALIDATION AND CALIBRATION SITES

The developed iterative modelling workflow (Fig. 1) will be validated in regions with abundant subsurface data necessary for calibration of the integrated forward models. An overview of these regions is presented in the following, and also in Figure 2.

4.1 Sandstone – Gassum Formation, Stenlille (DK)

The fluvial and shoreface deposits of the Upper Triassic-Lower Jurassic Gassum Formation are a proven geothermal reservoir in Denmark. At Stenlille this reservoir is used for natural gas storage for over 30 years, and therefore here the most complete subsurface dataset is available for proving the Go-Forward concept, including 2D/3D seismic, wells, logs, cores and decade’s worth of research. Elsewhere, data density of much poorer and reservoir architecture and properties rely heavily on geological models of the formation. Therefore, the study will provide crucial forward modelling parameters that aid better estimates for entire Denmark.

4.2 Sandstone – Nieuwerkerk Formation (NL)

The Upper Jurassic – Lower Cretaceous Nieuwerkerk Formation in the West Netherlands Basin consists of porous fluvial, costal to shallow marine siliciclastics. It hosts one of the most prolific geothermal aquifers (Willems et al., 2020) in the Netherlands with around 13 doublets drilled, and has significant potential for future growth. Data coverage from 2D-3D seismic, wells and logs is very good, but syn-sedimentary rift tectonics (Bouroullec et al., 2024; Weert et al., 2025) resulted in complex facies distribution, besides differential burial and uplift. Current stratigraphic models result in simplified predictions on reservoir quality, especially in the areas of interest, that are beyond the O&G legacy data.

4.3 Carbonates – Upper Jurassic Carbonates (AT / ESP)

Additionally, the Upper Jurassic carbonates of the Molasse basin in Germany, Austria and Switzerland are another example of a world-class geothermal reservoir with prominent examples of geothermal heat and electricity production in the greater Munich area. The carbonate platforms are characterised by reef-rimmed shelves and isolated carbonate build-ups. Reservoir facies is concentrated in karstified reef build-ups, whereas fine-grained facies in between build-ups is considered as non-reservoir zones. GeoSphere Austria developed a high-resolution reservoir model in the cross-border region between Germany and Austria, based on well and seismic data that will be made available for model calibration, providing initial bathymetry, seismic horizons and facies distribution.

The Kimmeridgian ramp within the Iberian Basin of northeastern Spain offers an unparalleled opportunity to investigate well-preserved sedimentary successions from Upper Jurassic times at the surface. This geological setting serves as an invaluable archive for calibration datasets in stratigraphic forward modelling. The ramp represents a transitional zone between coastal and open marine environments, which provides a unique opportunity for modeling the geothermal potential of carbonate systems, accounting for lateral and vertical facies variations. Forward modeling techniques will result in a comprehensive assessment of potential reservoir and seal rock distribution, aiding in understanding the temporal evolution of facies properties.

4.4 Granites – Hydrothermal fracture systems (UK)

The Cornwall granites are well known for high temperature hydrothermal mineralization associated with granite emplacement, mainly ENE-WSW striking mineral ‘lodes’. These are commonly displaced by NW-SE to NNE-SSW structures, many of which are reactivations of earlier strike-slip faults (Yeomans et al., 2019). The temperature of about 200 °C at 5 km depth, is locally enhanced by localized rising warm water. The NNW-SSE fault systems have significant permeability, and some of the more than 200 m wide fracture zones are current targets for geothermal exploitation – such as the United Downs Deep Geothermal Power project and the Eden Geothermal project. Data from the multiple research projects performed on the Cornwall granites, including old mine records, are made available for FFM within GO-Forward.

4.5 Crystalline Basement – Miocene fracture systems (IT)

Tuscany is part of the Inner Northern Apennines, piled up in the Cretaceous-Early Miocene. The region is the birthplace of modern geothermal industry, as numerous power plants have produced electricity from the Larderello-Travale field for more than 100 years. Outcrops of granite and basement rocks with abundant evidence of mineralisation resulting from the circulation of geothermal fluids at high (>250 °C) to medium-low (200 °C-100 °C) temperatures provide excellent analogue examples of deep-seated geothermal sites. The relationships between geological structures, granite location and fluid flow can be well-constrained at the surface. Given the existing knowledge on geological evolution, P-T conditions, stress field, permeability, fluid chemistry, fracture distribution and relation with geothermal fluid flow, Tuscany and the Tuscan archipelago (Elba Island) are chosen as one location to calibrate the GO-forward FFM approach.

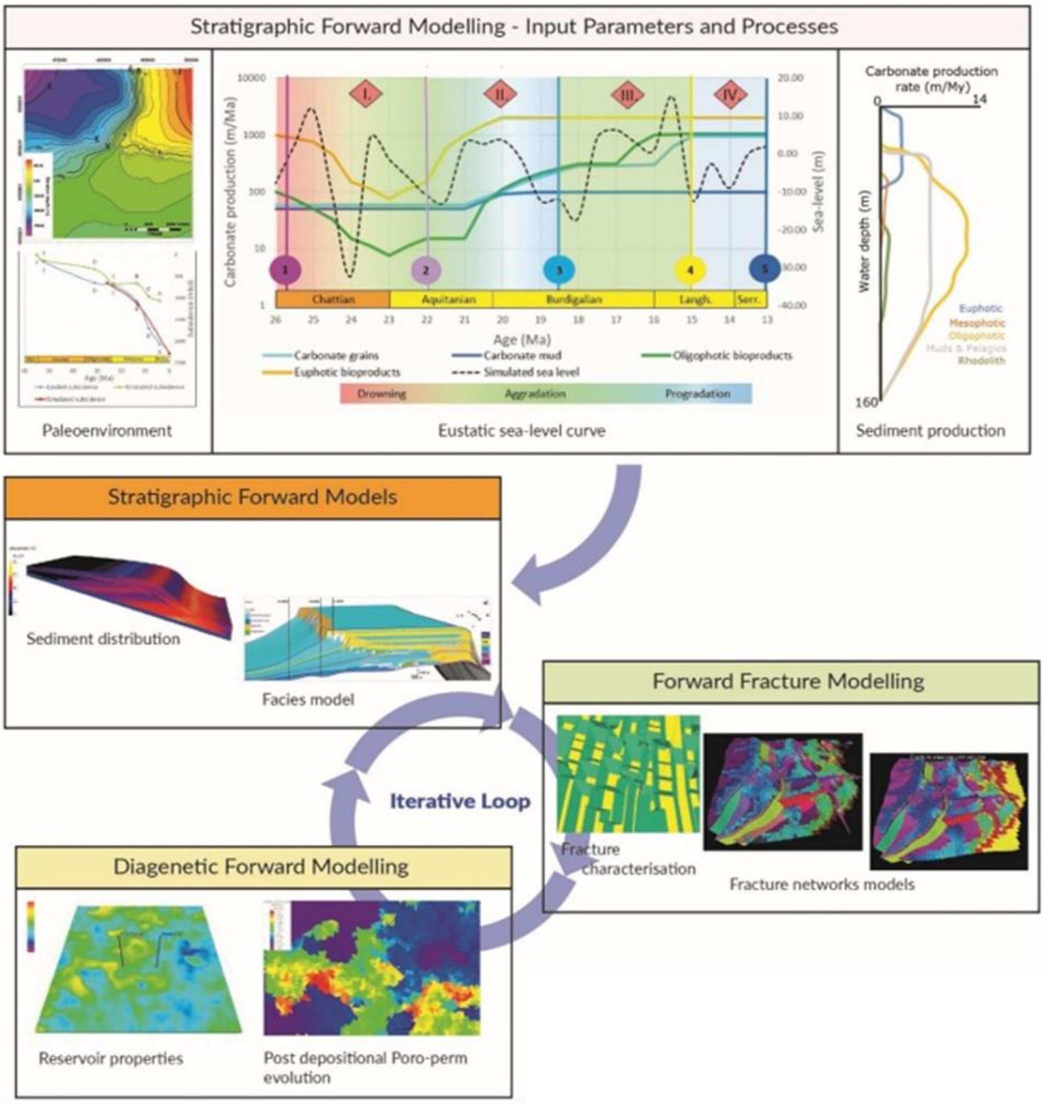

Figure 1: General workflow of integrated forward modelling envisioned in the GO-Forward project.

5. APPLICATION – TRANSFER OF WORKFLOW

Once the model workflow has been calibrated and validated in areas with abundant subsurface and reservoir information, it will be applied in areas with promising potential but much less available information and data.

5.1 Sandstone – Gassum Formation, Aarhus (DK)

A site in the Aarhus region, with little seismic data and no wells, is used to apply the Go-Forward concept. The Danish geothermal company Innargi plan to drill exploration wells and have recently concluded acquisition of 25 km of seismic lines. The site is ideal for applying the GO-Forward workflow, as predictions and evaluations based on the existing data can be blind-tested toward the new seismic and well data.

5.2 Sandstone – Neogene Upper North Sea Group (NL)

Shallow marine sediments of the Upper North Sea Group (Neogene) host various aquifers (Breda Subgroup, Oosterhout Formation) that are increasingly targeted for shallow geothermal exploration (temperatures up to ~55 °C) and for HT-ATES. The data density is low in large parts of the country where those formations occur at relevant depths (Houben et al., 2023). Seismic reprocessing and a process-based forward modelling workflow of facies and diagenesis could reduce the uncertainty on the distribution of potential flow and non-flow units to which reservoir parameters can be assigned, leading to an enhanced exploration success rate.

5.3 Carbonates – Triassic Carbonates, Southern Vienna Basin (AT)

Beneath this sedimentary basin and to the sides, the geological underground comprises, from NW to SE, the Flysch units, the Northern Calcareous Alps, the Greywacke Zone and the Central Alpine units. Especially the Triassic Northern Calcareous Alps are of interest for geothermal exploration, as they are fractured and water bearing over wide areas. They can be found in outcrops at the western border of the Vienna Basin. The main target for geothermal exploration are the "Wetterstein Formation", mainly limestones and dolomites, and the “Hauptdolomit”. The “Dachsteinkalk” consists predominantly of fine-grained limestone.

5.4 Carbonates – Devonian Massenkalk (GER)

Devonian limestones have been identified as major geothermal plays in Western Germany. While in the Netherlands, hydrocarbon exploration targeted these formations in some areas, the data coverage for these potential reservoirs in western Germany is scarce, especially for the Devonian “Massenkalk”. The exploration risk for these targets is high due to the high degree of spatial variability of reservoir facies on the carbonate platform. Recent studies on outcrop analogues confirmed that while matrix-permeability in the reservoir may be low, the occurrence of natural fractures characterize the Massenkalk carbonates as a natural fractured reservoir

5.5 Crystalline basement – Neogene fault- and fracture systems (ESP)

The Neogene Vallès Basin, in the central sector of the Catalan Coastal Ranges, is characterized by some identified fault-related hydrothermal systems located along the main extensional fault zone, the Vallès fault, associated with basement crystalline rocks. Multiple deformation stages affected the palaeozoic crystalline basement, resulting in a heterogeneous fracture distribution network, which favours the circulation of hydrothermal fluids. Very few legacy data of those reservoirs consist of geophysical and boreholes profiles, well test and geochemical data, mainly from the Cànoves-Samalús region, motivating the development of preliminary geothermal investigation. MT data and the available legacy borehole temperature data from this site suggest the potential existence of a deep target in the basement of the centre of the basin with temperatures >130 ºC at 3000 m depth.

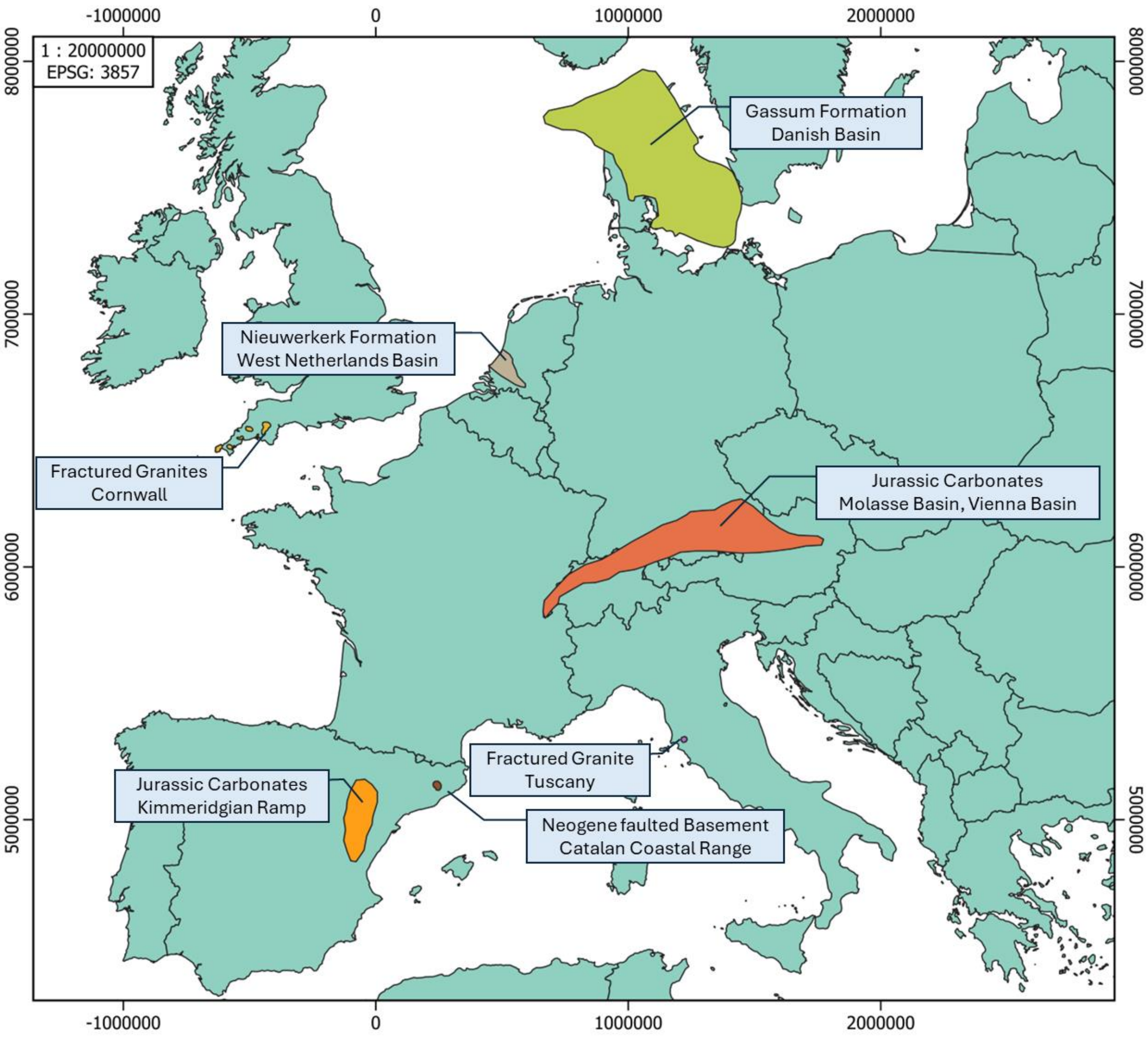

Figure 2: Overview of study regions used for model calibration in GO-Forward. Regions comprise potential reservoir types: siliciclastic sediments, carbonates, and crystalline formations.

6. PUBLIC ENGAGEMENT

For ensuring a target-oriented utilization of GO-Forward results, the project also includes assessment of societal and economic perception, awareness and needs for accelerating exploration and utilization of deep geothermal energy in the respective study regions. To this end, surveys and interviews, tailored to identified stakeholders in the respective regions, will be carried out to identify needs, but also concerns regarding expansion of geothermal energy utilization. The findings of this work package in conjunction with results of the technical and economic assessments will yield region-specific roadmaps for enhancing and facilitating development of geothermal energy with focus on the exploration phase.

7. OUTLOOK AND CONCLUSIONS

The GO-Forward project represents a significant advancement in geothermal exploration approaches, leveraging the innovative coupling of forward modelling techniques to enhance the accuracy of pre-drill predictions and reduce risks associated with geothermal resource development. By modelling geological processes shaping todays geothermal resources, the project aims to provide reliable assessments of geothermal reservoirs, particularly in regions with limited subsurface data.

With the European Union's ambitious goals for a net-zero greenhouse gas economy by 2050, geothermal energy will play a crucial role in the transition towards sustainable energy sources, especially in the heating sector.

As the project progresses, it is essential to align its outcomes with broader European developments in geothermal energy. This includes fostering collaboration with existing geothermal initiatives, participating in policy dialogues, and promoting societal acceptance of geothermal technologies. To this end, GO-Forward actively engages stakeholders and the public in study regions, to facilitate and accelerate developments in the geothermal sector, ultimately contributing to the EU's energy transition goals and supporting local communities in their energy needs.

In conclusion, GO-Forward is not only a project focused on technical innovation but also a catalyst for a sustainable energy transition in Europe, facilitating future geothermal exploration and development, thus bringing geothermal energy utilization forward.

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