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COSEISMIQ-CH

COntrol SEISmicity and Manage Induced earthQuakes in Switzerland (Project no. 731117)

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Zusammenfassung

Die nationale Energiestrategie der Schweiz sieht vor, dass bis 2050 5-10% des Stroms aus der Tiefengeothermie gewonnen werden und ein wesentlicher Beitrag zum Wärmebedarf geleistet wird. Um dieses ehrgeizige Ziel zu erreichen und damit eine breite Nutzung der tiefen Geothermie in der dicht besiedelten Schweiz zu ermöglichen, müssen die Anlage und der Betrieb von geothermischen Reservoiren optimiert und gleichzeitig die induzierte Seismizität auf einem akzeptierten Sicherheitsniveau gehalten werden. Im Rahmen des Pilot- und Demonstrationsprojekts COSEISMIQ-CH wurden innovative Ansätze zum Management der induzierten Seismizität und zur Optimierung der Produktion in nahezu Echtzeit entwickelt und validiert. Das Projekt COSEIMQ-CH ermöglichte es Forschern des Schweizerischen Erdbebendienstes (SED) und der GeoEnergie Suisse AG, zusammen mit Partnern aus Island und Irland am EG GEOTHERMICA CoFund Projekt COSEIMIQ teilzunehmen. Wir haben das Hengill-Gebiet und das Kraftwerk Hellisheiði in Island, das drittgrößte geothermische Kraftwerk der Welt, als Demonstrationsstandort ausgewählt. Aufgrund der geringen Bevölkerungsdichte, der breiten Akzeptanz der Geothermie, der hohen Rate induzierter Seismizität und der laufenden Erschließungsprojekte mit mehreren Bohrlöchern konnten wir in einer kommerziellen Anwendung sicher testen, wie ein datengesteuertes, adaptives Echtzeit-Entscheidungshilfsmittel den geothermischen Betrieb unterstützen kann. Wir installierten ein seismisches Netzwerk von 23 Stationen in der Region Hengil und betrieben es etwa drei Jahre lang in Echtzeit, was zu einem einzigartigen Datensatz für die Entwicklung von Methoden und das Prozessverständnis führte. Wir optimierten und demonstrierten Arbeitsabläufe für die Analyse der Seismizität in Echtzeit, einschließlich der Bestimmung des Hypozentrums und des Momententensors, und diese Arbeitsabläufe sind nun bereit für den Einsatz in Projekten in der Schweiz. Wir demonstrierten, wie seismische Bildgebungsverfahren, die Erdbeben oder Umgebungsgeräusche als Quellen nutzen, sich gegenseitig ergänzen können, um ein hochauflösendes Bild der Strukturtemperatur im Hengill-Gebiet zu erhalten. Wir haben geomechanische Analyse- und Modellierungsabläufe kalibriert, die das Prozessverständnis verbessern, aber auch in einem prädiktiven Sinne genutzt werden können, um die Entwicklung des Reservoirs und der induzierten Seismizität vorherzusagen. Schließlich haben wir gezeigt, dass adaptive, datengesteuerte Ansätze zur Risikobewertung und Entscheidungsunterstützung sehr leistungsfähig sind. Sie verbessern das Situationsbewusstsein, informieren über Strategien zur Risikominderung und können die Erfolgschancen der Erschließung tiefer geothermischer Lagerstätten nicht nur in Island, sondern auch bei anstehenden Projekten in der Schweiz erhöhen. Ein Schwerpunkt von COSEIMIQ-CH war die Kommunikation der Ergebnisse, die Bereitstellung eines offenen Zugangs zu Daten, Methoden und Codes sowie der Wissenstransfer zwischen den verschiedenen Interessengruppen.

Résumé

La stratégie énergétique nationale suisse prévoit que 5 à 10% de l'électricité sera obtenue à partir de la géothermie profonde d'ici 2050, ainsi qu'une contribution substantielle à la demande de chauffage. Pour atteindre cet objectif ambitieux, et permettre ainsi une utilisation généralisée des ressources géothermiques profondes dans une Suisse densément peuplée, il faut optimiser la création et l'exploitation des réservoirs géothermiques, tout en maintenant la sismicité induite à un niveau de sécurité acceptable. Le projet pilote et de démonstration COSEISMIQ-CH a développé et validé des approches innovantes pour gérer la sismicité induite et l'optimisation de la production en temps quasi-réel. Le projet COSEIMQ-CH a permis aux chercheurs du Service sismologique suisse (SED) et de GeoEnergie Suisse AG de participer, avec des partenaires islandais et irlandais, au projet CoFund COSEIMIQ de la CE GEOTHERMICA. Nous avons choisi la région de Hengill et la centrale électrique de Hellisheiði en Islande, la troisième plus grande centrale géothermique du monde, comme site de démonstration. En raison de la faible densité de population, de la large acceptation de l'énergie géothermique, du taux élevé de sismicité induite et des projets de développement multi-puits en cours, nous avons pu tester en toute sécurité, dans une application à l'échelle commerciale, comment un outil d'aide à la décision adaptatif et basé sur des données en temps réel peut informer les opérations géothermiques. Nous avons installé un réseau sismique de 23 stations dans la région de Hengil et l'avons exploité en temps réel pendant environ 3 ans, ce qui a permis d'obtenir un ensemble de données unique pour le développement de méthodes et la compréhension des processus. Nous avons optimisé et démontré des flux de travail pour l'analyse de la sismicité en temps réel, y compris la détermination de l'hypocentre et du tenseur de moment, et ces flux de travail sont maintenant prêts à être déployés dans des projets en Suisse. Nous avons démontré comment les techniques d'imagerie sismique utilisant les tremblements de terre ou le bruit ambiant comme sources peuvent se compléter pour donner une image à haute résolution de la température des structures dans la région de Hengill. Nous avons calibré des flux de travail d'analyse et de modélisation géo-mécaniques qui améliorent la compréhension des processus mais peuvent également être utilisés de manière prédictive pour prévoir l'évolution du réservoir et de la sismicité induite. Enfin, nous avons démontré que les approches adaptatives et axées sur les données pour l'évaluation des risques et l'aide à la décision sont puissantes. Elles améliorent la connaissance de la situation, informent les stratégies d'atténuation des risques et peuvent augmenter les chances de succès du développement de réservoirs géothermiques profonds, non seulement en Islande, mais aussi dans les projets à venir en Suisse. COSEIMIQ-CH a mis l'accent sur la communication des résultats, sur le libre accès aux données, aux méthodes et aux codes, ainsi que sur le transfert de connaissances entre les différentes parties prenantes.

Summary

The Swiss National Energy strategy foresees 5-10% of electricity to be obtained from deep geothermal energy by 2050, as well as a substantial contribution to heating demands. Reaching this ambitious goal, and thus enabling the widespread use of deep geothermal resources in densely populated Switzerland, requires optimizing geothermal reservoir creation and operation, while at the same time keeping induced seismicity within an accepted level of safety. The Pilot and Demonstration project COSEISMIQ-CH developed and validated innovative approaches to manage induced seismicity and production optimization in near-real time. The project COSEIMQ-CH enabled researchers from the Swiss Seismological Service at SED and from GeoEnergie Suisse AG to participate with partners from Iceland and Ireland in the EC GEOTHERMICA CoFund project COSEIMIQ. We selected the Hengill area and Hellisheiði Power Station in Iceland, the third largest geothermal power station in the world, as the demonstration site. Because of the low population density, wide acceptance of geothermal energy, high rate of induced seismicity and ongoing multi-well development projects, we could test safely in a commercial scale application how a real-time data-driven, adaptive decision support tools can inform geothermal operations. We installed a seismic network of 23 stations in the Hengil region and operated it in real-time for about 3 years, resulting in a unique data set for method developments and process understanding. We optimized and demonstrated workflows for real-time seismicity analysis, including hypocenter and moment tensor determination and these workflows are now ready to be deployed in projects in Switzerland. We demonstrated how seismic imaging techniques using earthquakes or ambient noise as sources can complement each other to give a high-resolution picture of structure temperature in the Hengill area. We calibrated geo-mechanical analysis and modelling workflows that enhance process understanding but can also be used in a predative sense to forecast the evolution of the reservoir and of the induced seismicity. Finally, we demonstrated that adaptive, data-driven approaches for risk assessment and decision support are powerful. They enhance situation awareness, inform risk mitigation strategies and can increase the chances of success of deep geothermal reservoir development not only in Iceland, but also in upcoming projects in Switzerland. A string focus of COSEIMIQ-CH was on communication of the results, on providing open access to data, methods and codes, and also on knowledge transfer between different stakeholders.

Main findings

1. COSEISMIQ-CH has **advanced the state of the art in managing and controlling induced seismicity** related to deep geothermal energy by further developing - and demonstrating in Iceland - advanced traffic light concepts for seismic risk mitigation. These approaches are now applied in the Utah FORGE and Haute-Sorne Enhanced Geothermal System projects by academic partner (ETH) as well as industry partners (GeoEnergy Suisse AG).
2. COSEISMIQ-CH has **advanced seismic monitoring and analysis techniques** targeted at high resolution recording of induced seismicity. We have demonstrated in Iceland how our newly developed and largely automated earthquake analyses workflows, fully embedded into the professional and operational earthquake analysis system SeisComp, are capable of detecting and processing tens of thousands of earthquakes. These openly available workflows will now be used not only in upcoming EGS projects but are also operated in Switzerland as part of the monitoring of hydrothermal projects, in the context of the Swiss Geobest project.
3. COSEISMIQ-CH **has advanced seismic imaging techniques** that are based on noise interferometry, establishing firmly that these methods are often superior to classical seismic tomography methods. Seismic velocity changes are linked to structure, temperature, steam content and reservoir evolution, hence seismic imaging of fluid injections are an important element of reservoir characterization, reservoir optimization and risk mitigation. Our findings and methodological advances are now ready to be applied in future deep geothermal projects in Switzerland and worldwide.
4. COSEISMIQ-CH has **advanced the geo-mechanical modelling capabilities** of geothermal reservoirs. We have shown how injection histories, knowledge on faults and enhanced seismotectonic information (e.g., earthquake source mechanism) can be combined in computational models that are consistent and capability to forecast with some confidence the reservoir evolution and the evolution of the future seismicity. These computational geo-mechanical capabilities help to understand the Hengill geothermal area but are a valuable resource also for other geothermal projects.

To enable these main findings, the choice of Iceland as a demonstration site was ideal, owing to the high seismicity rate but very low seismic risk due to the negligible population density in the Hengill area. Equally important was the international collaboration and knowledge exchange, enable by embedding the project in the context of a EU Geothermica Cofund project.

1. Contents

2. Introduction

2.1 Background information and current situation

The EU energy strategy for 2030 aims to reach a 40% cut in greenhouse gas emissions and increase the share of renewable energy to at least 27% of consumption. If properly managed the exploitation of deep geothermal resources can give a valuable contribution to achieve this target. So far, geothermal induced seismicity has been a major setback and tremendous challenge to future deep geothermal energy exploitation, with the concern that industrial operations could cause damaging earthquakes. Enhanced Geothermal System (EGS) projects in deep crystalline rocks are especially under pressure because induced seismicity is strictly linked to permeability enhancement of the reservoir for creating an efficient heat exchanger. Large magnitude induced seismic events are a risk for the population and structures, as well as an obstacle for the development of new techniques for the exploitation of underground geo-resources. The problem of induced seismicity is particularly important for the future development of geothermal energy in Europe.

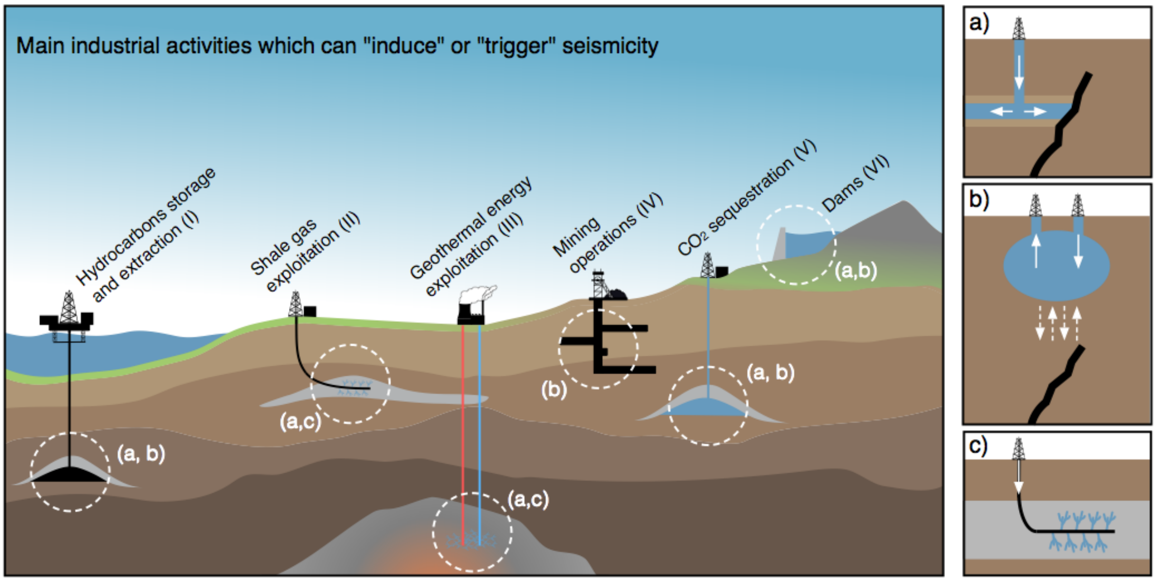


Figure 1: *Industrial activities which can "induce" or "trigger" seismicity (from Grigoli et al. 2017).*

Deep geothermal energy exploitation projects such as Basel (2006) and St Gallen (2013) have been aborted due to the felt induced earthquakes they created and an increasing risk aversion of the general population. Induced seismicity is thus an unwanted product of such industrial operations but, at the same time, induced earthquakes are also a required mechanism to increase the permeability of rocks, enhancing reservoir performances. Analysis of induced microseismicity allows to obtain the spatial distribution of fractures within the reservoir, which can help, not only to identify active faults that may trigger large induced seismic events, but also to optimize hydraulic stimulation operations and to locate the regions with higher permeability, enhancing energy production. Societal acceptance for deep geothermal projects in Switzerland has partially eroded, mostly because of earthquakes induced in past projects, and projects in Switzerland can be delayed by many years. To regain trust and acceptance, it is critically important to demonstrate the ability to control induced seismicity.

On the other hand, the operators need to address other challenges such a reducing costs by drilling wells with better knowledge of the subsurface temperatures and permeability and reducing the environmental impact by reducing the footprint of the power plant and increasing the efficiently. Seismic risk reduction and reservoir efficiency are in the case of EGS reservoirs coupled problems that needs to be addressed.

2.2 Purpose of the project

Despite the huge potential, geothermal energy is still a small fraction of the total energy produced from renewable sources. One of the main problems is that the high fluid pressures and the large fluid volumes injected during hydraulic stimulation operations may induce seismic events that can be felt by the population, reducing the public acceptance of a project. Thus, in urbanized areas deep geothermal resources can only be exploited if the problem of controlling induced seismicity is adequately addressed.

COSEISMIQ brings together a distinguished and interdisciplinary team of scientists and practitioners from across Europe committed to answer the challenges of EGS projects. We believe that innovations in geothermal risk governance are possible, through advancing seismic monitoring technologies and improving the modeling capabilities and process understanding.

The project COSEISMIQ integrates seismic monitoring and imaging techniques, geomechanical models and risk analysis methods with the ultimate goal of implementing innovative tools recently developed but yet untested. These adaptive, data driven approaches for reservoir optimization and for the control and management of induced seismicity represent a major contribution to safe and sustainable geothermal energy exploitation. In this context, one of the main aims of COSEISMIQ is to provide operators with a reliable decision tool to estimate the risk of induced seismicity following reservoir operations.

2.3 Objectives

The key objectives of COSEISMIQ-CH and COSEISMIQ overall are:

- To demonstrate that quantitative data-driven, adaptive traffic light systems (ATLS) are reliable and capable tools to assess, and control induced seismicity.
- To calibrate and apply ATLS concepts to geothermal plays in Iceland, demonstrating the contribution to ensuring safe operations and to provide enhanced decision support to operators of deep geothermal systems during all project phases (planning, permitting, stimulation operation and post-operation).
- To improve the economic performance of deep geothermal systems by allowing to balance heat revenues and seismic safety.
- To transfer the knowledge and software developed during the demonstration and validation application in Iceland to other EU countries.

3. Procedures and methodology

The project COSEISMIQ-CH (www.coseismiq.ethz.ch) executed from 2018 to 2021 integrated seismic monitoring and imaging techniques, geo-mechanical models and risk analysis methods. The key success criteria for COSEISMIQ-CH was the seamless integration into an European GEOTHERMICA project COSEISMIQ, the BFE allocated funding for SED and GES as part of the Pilot and Demonstration program financed the Swiss contribution to the GEOTHERMICA Cofund projects. The objectives of COSEISMIQ and COSEISMIQ-CH are closely aligned, and in this report, we use the two acronyms interchangeably. Integration into the GEOTHERIMCA project provided a framework for accessing the COSEISMIQ demonstration site, the Hengill area in Iceland (Figure 2). Here the two largest geothermal power plants of Iceland are in operation, the Nesjavellir and Hellisheiði power stations, producing up to 303 Megawatts of electricity and up to 400 Megawatts of thermal energy, the third largest geothermal power plant in the world. Both plants are operated by Reykjavik Energy which is one of the partners of COSEISMIQ and more than 30 wells exist down to a depth of 2200 meter.

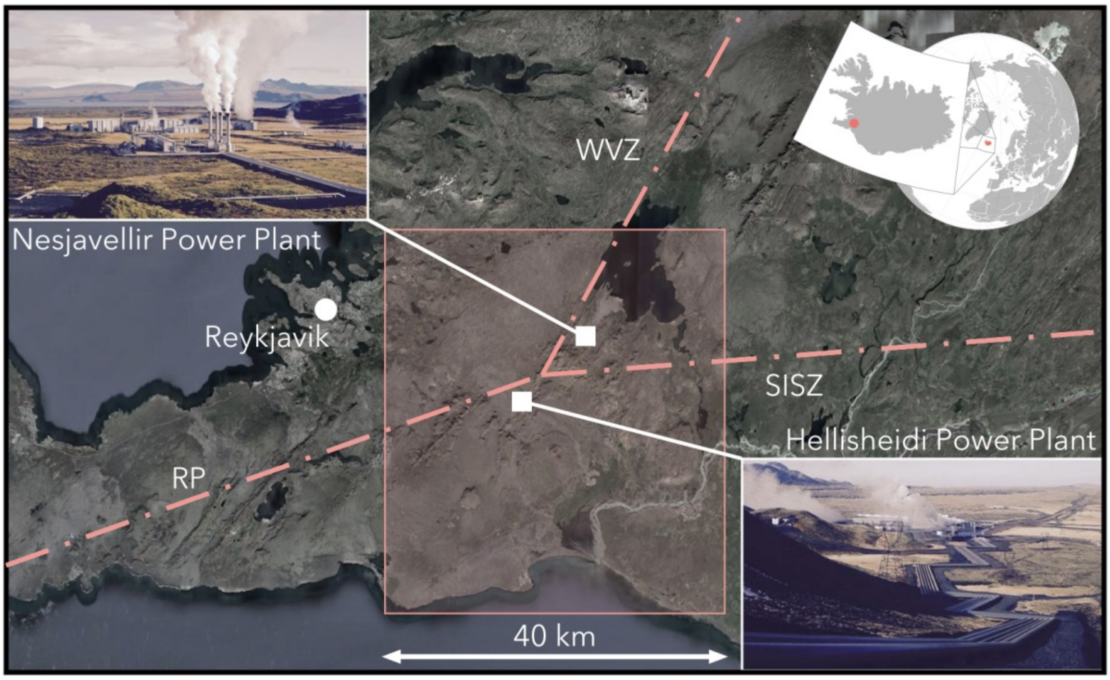


Figure 2: *Study area of COSEISMIQ in Iceland.*

The ultimate goal of COSEISMIQ-CH is implementing and demonstrating in industrial applications innovative tools for balancing risk and reservoir development. These adaptive, data driven approaches for reservoir optimization and for the control and management of induced seismicity represent a major contribution to safe and sustainable geothermal energy exploitation. Within the project COSEISMIQ, we aimed at demonstrating the potential of using real-time tools, with the overall goal of developing a Real-Time Induced Seismicity Controller (RISC) in a commercial scale application in Iceland.

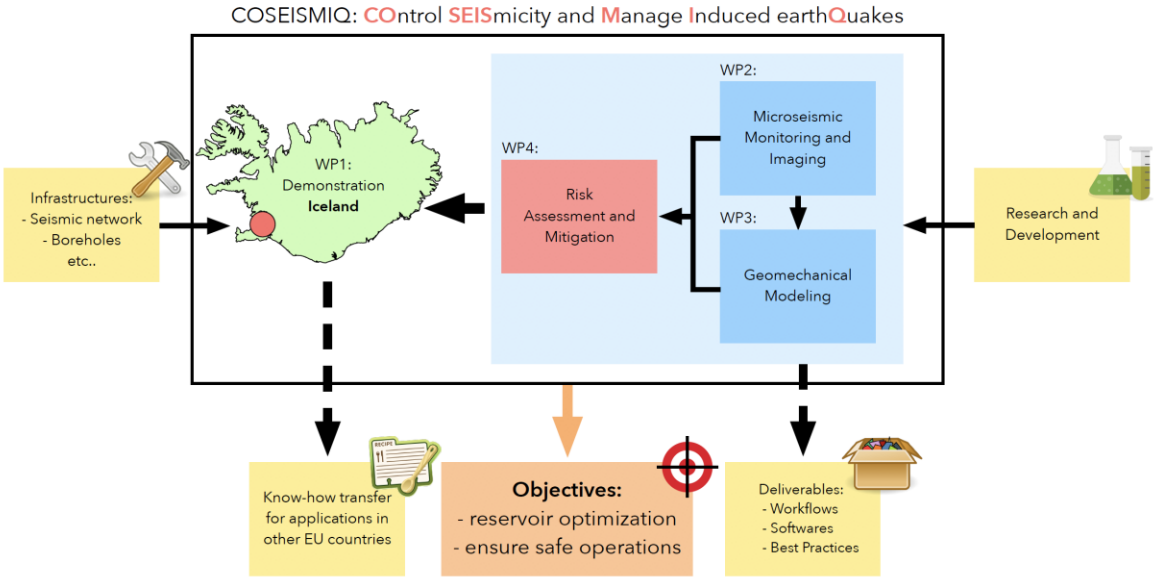


Figure 3: *Organizational structure of the COSEISMIQ project.*

The project was organized in four work packages (WPs, see Figure 3):

- WP1 Demonstration Case;
- WP2 Microseismic Monitoring and Imaging;
- WP3 Geomechanical Modeling;
- WP4 Risk Assessment and Mitigation.

The selected demonstration site in the Hengill region in Iceland, is ideal to test and validate COSEISMIQ technologies (WP1), given the distributed geothermal activities and abundant induced seismicity, combined with low population density and limited building fragility resulting in a small risk to people and buildings. The main activities of WP2 are the development of innovative full-waveform seismological methods for automated and real-time microseismicity analysis and reservoir characterization. A main objective is to develop tools to quickly obtain a detailed knowledge of the geometry of active faults and on the ongoing fracturing process during stimulation operations. WP3 focuses on the real-time implementation of geomechanical modeling tools to simulate and forecast induced seismicity in relation to injection scenarios. The development of inverse modeling capabilities allows a comparison between observed and simulated seismicity, and it is used to validate and update the geomechanical model to improve the seismicity forecasting performance. Finally, WP4 aims at merging the outputs of WP2 and WP3 in a tool for real-time risk analysis to ultimately controlling and managing induced seismicity.

The project structure of COSEISMIQ-CH is shown in Figure 4, along with the project staff at the start. The project was jointly overseen by Prof Stefan Wiemer (ETH) and Dr. Peter Meier (GES). The steering committee of the project was composed of the lead scientists of the GEOTHERMICA COSEISMIQ project, to ensure seamless integration of both projects.

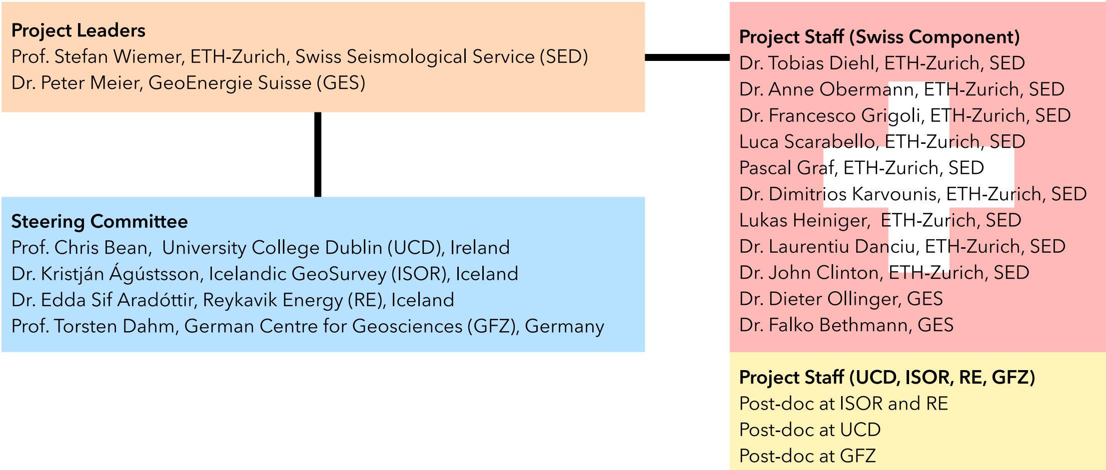


Figure 4: *Organizational structure of the COSEISMIQ-CH project and participants at the project onset.*

The following sections summarizes the achievements and results in each work package. More detailed scientific information can be found in the various deliverables and scientific publication, all available on the project website (http://www.coseismiq.ethz.ch/en/dissemination/deliverables/):

D1: Implementation of advanced micro-seismicity monitoring tools in SeisComp3 modules and workflows optimized for geothermal plays.

D2: Implementation of advanced imaging tools in workflows optimized for geothermal plays.

D3: Coupled geo-mechanical and reservoir modeling framework implemented within RISC, ready for real- time application and adapted to Icelandic conditions. Integration of the methods developed in the WP2, WP3 and WP4 in a single tool (the RISC tool).

D4: Risk and Safety assessment calibrated for Icelandic conditions and extended to allow the distinction between natural and induced seismicity.

D5: Offline calibration and performance evaluation of the RISC system

D6: Demonstration of the RISC decision support framework at the Hengill site in real time

D7: RISC tool ready for other commercial applications in Europe.

4. Description of activities and results

4.1 The COSEISMIQ seismic network: Installation and operation (WP1, Part1)

A major achievement and base of the project was the successful and year-round operation of a modern seismic network in the harsh Icelandic weather conditions. From Nov. 2018 to August 2021, we installed and operated 23 high-quality seismic stations (10 STS2 120s, 8 Lennartz 5s, 5 Guralp6D 30s) in the Hengill area (Figure 5, orange triangles). These stations complemented 10 permanent seismic stations (Lennartz 1s) from ON Power, and 8 stations of the regional network of the Icelandic Meteorological Office (7 Lennartz 5s, 1 Lennartz 1 s) (Figure 5, blue triangles). The network operated with real-time data transmission at 200 Hz and recorded about 6000 earthquakes with M>0.5 per year (Grigoli et al. 2022, Figure 6), forming a uniquely valuable dataset for our own analyses presented in subsequent chapters. The data is fully open to others, and hence form a valuable resource for other researchers, regulators and industry. The facilitate the use of the data, we have published a detailed description of the data, as well as access information, has been published by Grigoli et al. (2022) in the journal Nature Scientific Data.

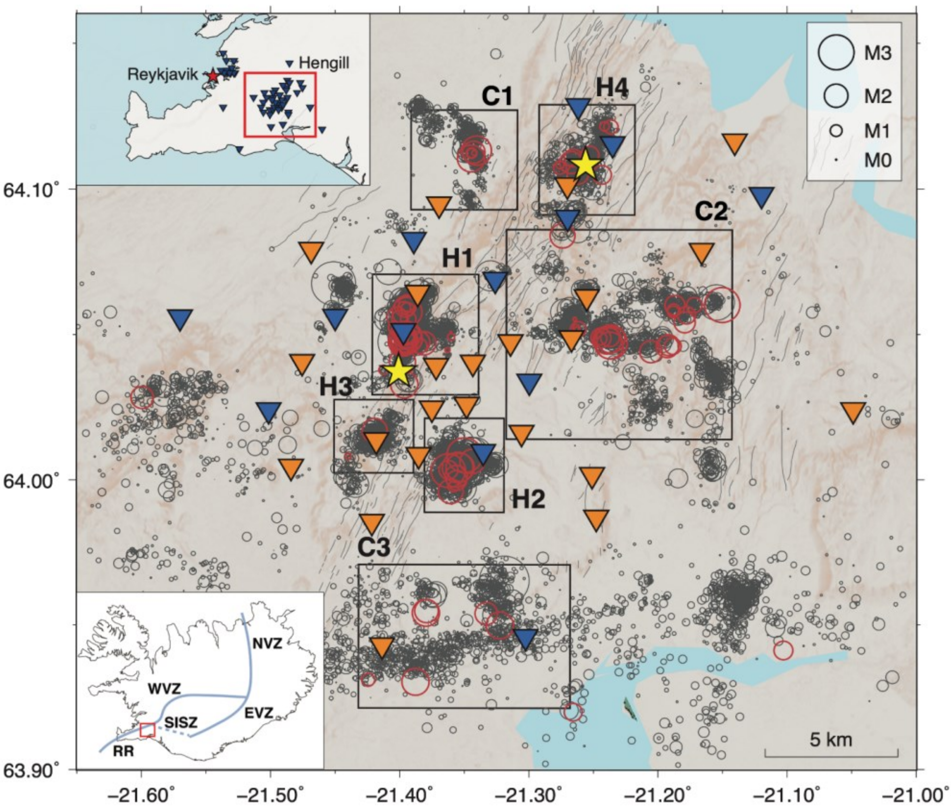


Figure 5: *Seismic network across the Hengill geothermal field. Permanent (blue triangles) and temporary COSEISMIQ stations (orange triangles) are shown. The yellow stars are the location of the Nesjavellir (North) and Hellisheidi power plants. From December 2018 to January 2021, about 15'640 earthquakes were reported by ISOR, grouping into several clusters. The clusters H1 to H4 are directly related with production or injection operations, while no such operations coincide with the clusters C1 to C3. The red events are used for the travel-time tomography. Lower Left: Location of the Hengill volcanic complex (red rectangle) at the triple junction of the Western*

Volcanic Zone (WVZ), the South Icelandic Seismic Zone (SISZ), and the Reykjanes Peninsula Oblique Rift (RR). Upper Left: Zoom into RR giving an overview of the seismic network.

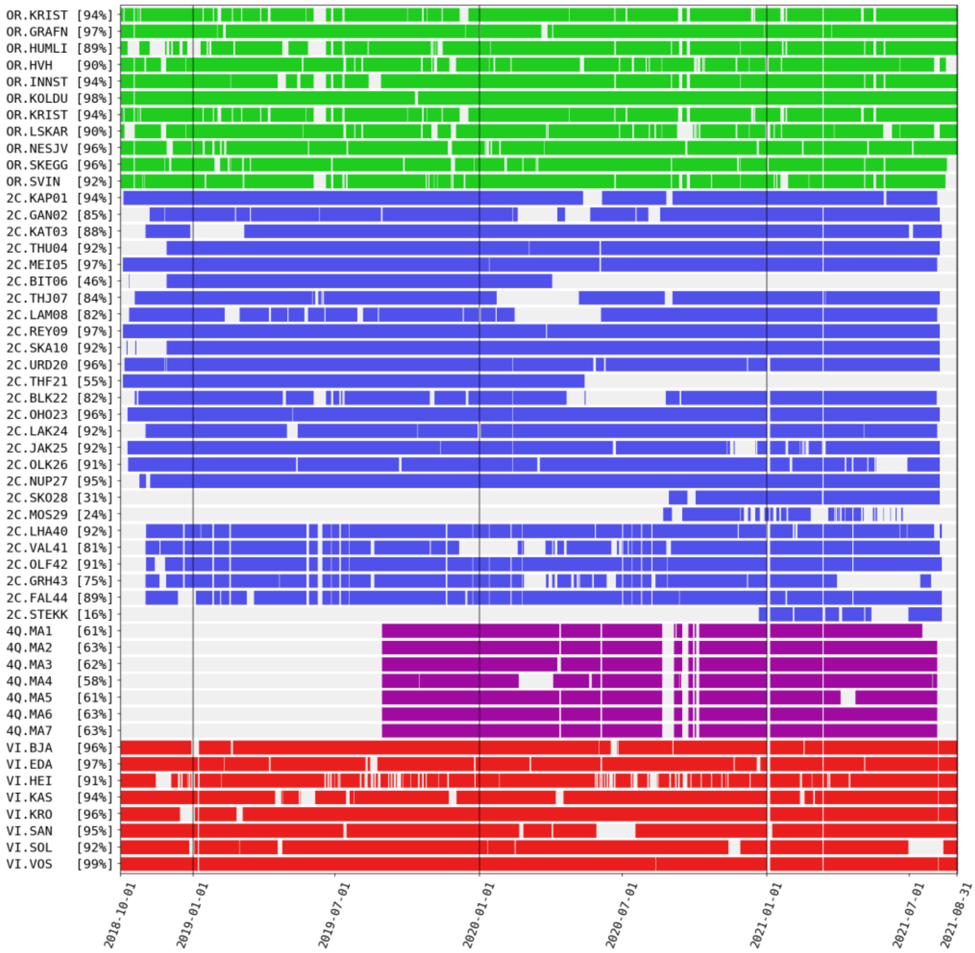


Figure 6: *Data completeness during the installation period of the seismic network.*

Within the 2C network, each station installation consisted of 2 solar panels and a wind turbine for power generation (Figure 7). The wind turbine was installed around 50 meters away from the sensor in order to avoid contaminating the seismic recordings with high-frequency noise. Data transmission was performed using WIFI or 4G network. The variable topographic gradient made the set-up of signal enhancing antennas often necessary. The seismic sensors are buried at least 50 cm into the ground to reduce the noise using vaults with a concrete socket and a thick layer of insulation material (Figure 7c).

We faced numerous challenges related to the harsh weather conditions in Hengill that caused data gaps in particular during the winter months (Grigoli et al. 2022). Despite this, we achieved an overall excellent data retrieval of about 90% during the period of the study (Figure 6). The repeated changes between freezing and thawing led to several vaults being filled at least partially, sometimes completely, with water. The definite cause of how the water got into the vaults is not obvious, but one possibility is that it entered through the cable connector on the barrels. Sealing the connector with sealant provided a temporary solution, but it tended to break loose from the barrel wall. The amount of sealant then made it extremely difficult to get the cables out so this solution is not recommended. Lightning decimated the number of functional Taurus digitizers. Another challenge was the strong winds that regularly caused fuse blows at the wind generators. This problem was improved by removing every second blade. Additional lessons learned were that an effort should be made to arrange maintenance trips in the month of June, a drain system should be installed in the barrel, and carefully choose sites for installations. These lessons learned and improved designs are now also being used by other installations in the area, they also form important lessons learned for site selection and site building in Switzerland.

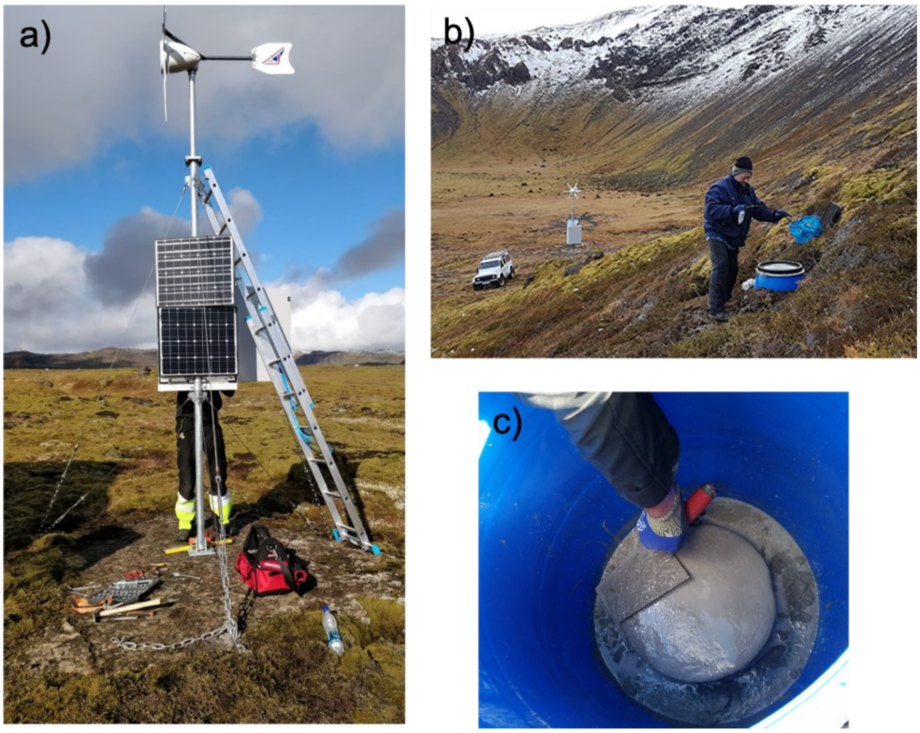


Figure 7: *Impressions of the field installations for the COSEISMIQ stations. a) Mast with wind turbine and solar panels for power generation to enable real-time data transmission. b) Vault with seismic sensor at about 50m distance from the mast. c) Concrete socket within vault.*

4.2 Advances in Microseismic Monitoring and Imaging (WP2)

Microseismic monitoring in the Hengil area

The seismic data recorded by the COSEISMIQ network (section 4.1) formed the baseline of advances in the advances in seismic monitoring and seismic imaging techniques. We designed a fully automated seismic processing workflows as part of the professional-grade real-time seismic monitoring system SeisCompP (https://www.seiscomp.de) that is used by dozens of seismological services worldwide, including IMO and ISOR in Iceland and the SED. It is also use by an increasing number of geothermal operators. The aim of these workflows is to enhance the robustness, reduced the hypocenter location uncertainty and extend the detection ability to smaller magnitudes. A schematic view of the workflows is shown in Figure 8. The SED is using SeisCompP for monitoring of all geothermal projects in Switzerland, and it will form the backbone of the monitoring in the upcoming EGS in Haute Sorne also. The enhances achieved in COSEIMQ are thus highly valuable for Swiss geothermal projects.

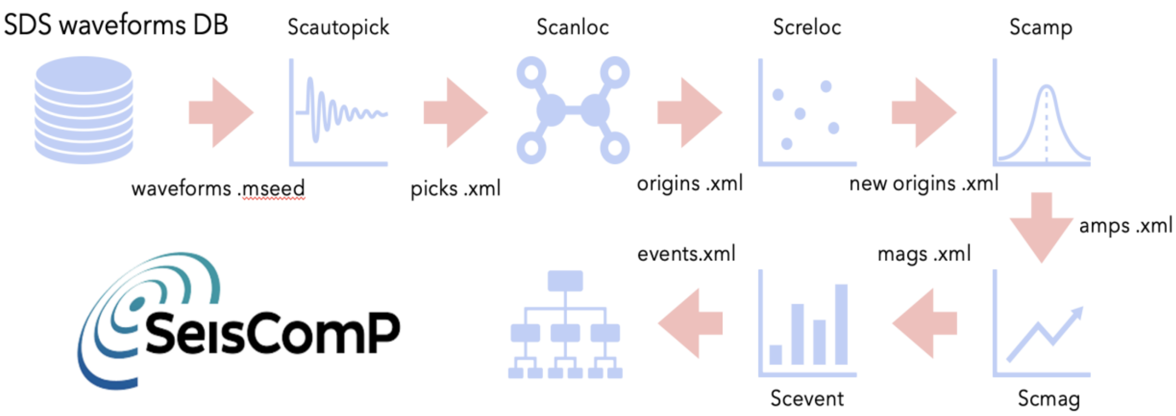


Figure 8: *Schematic view of the workflows implemented in SeisCompP.*

Microseismic monitoring operations within the COSEISMIQ project were based on the use of two mirrored SeisComP servers operating both at ETH and ISOR. Each SeisComP module has been optimally tuned to maximize the performance of the automatic routine processing. In a subsequent step, a catalog of absolute location is used to generate a double difference relocated catalog using a new SeisComp module developed within COSEISMIQ (rtDD, https://github.com/swiss-seismological-service/scrtdd/). While the tuning operations were performed in off-line mode, our SeisComp system operated in real-time during the entire duration of the project. Some additional and more sophisticated analyses were still performed in off-line mode.

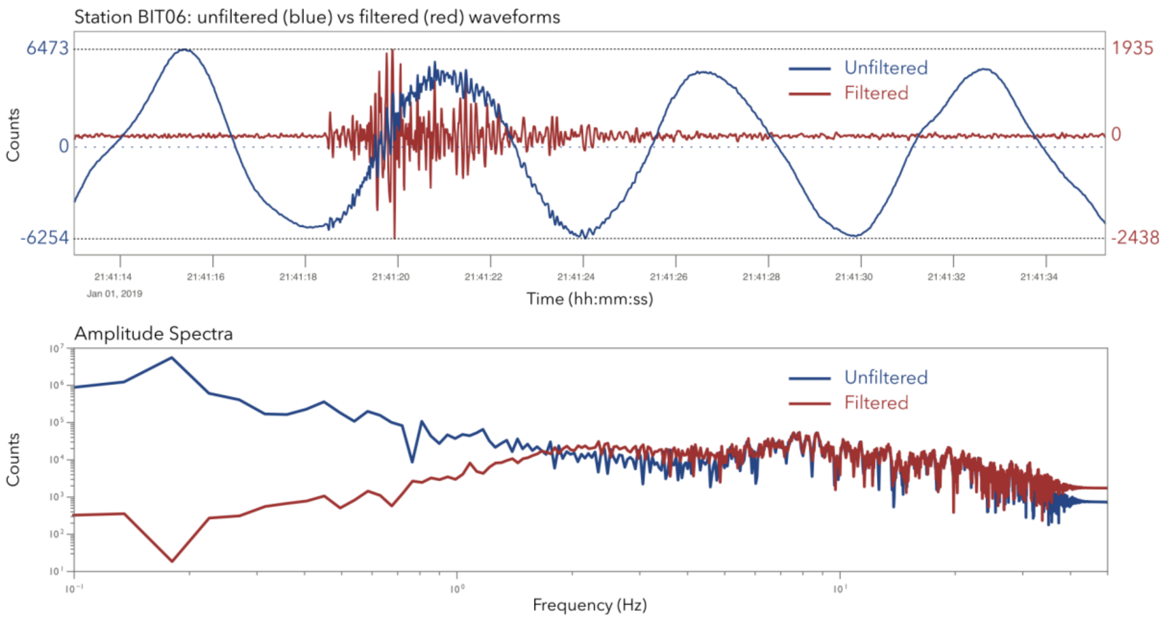


Figure 9: *Seismic waveforms and amplitude spectra of the event occurred on 01 January 2019 with magnitude 1.1 recorded by the broadband STS-2 at the station BIT06. The raw, unfiltered waveforms and the amplitude spectrum are shown in blue; the red lines refer to the waveform and amplitude spectrum after filtering between 2–50 Hz.*

An important issue we encountered when processing the seismic data from the Hengill area is related to the strong ambient noise contamination of the broadband waveforms that affects local magnitude computation. This makes magnitude estimation challenging and without addressing this issue, for events below Ml ~1.0 the energy content of the noise is generally larger than that from the events. In order to reduce the impact of the strong microseismic noise, we used a 4th order Butterworth filter in the range of 2-50 Hz. The importance of this filtering process is illustrated in Figure 9, Figure 10 shows the impact of applying the filter on the frequency-magnitude distribution. For details please refer to Grigoli et al. (2022) and Obermann et al. (2022).

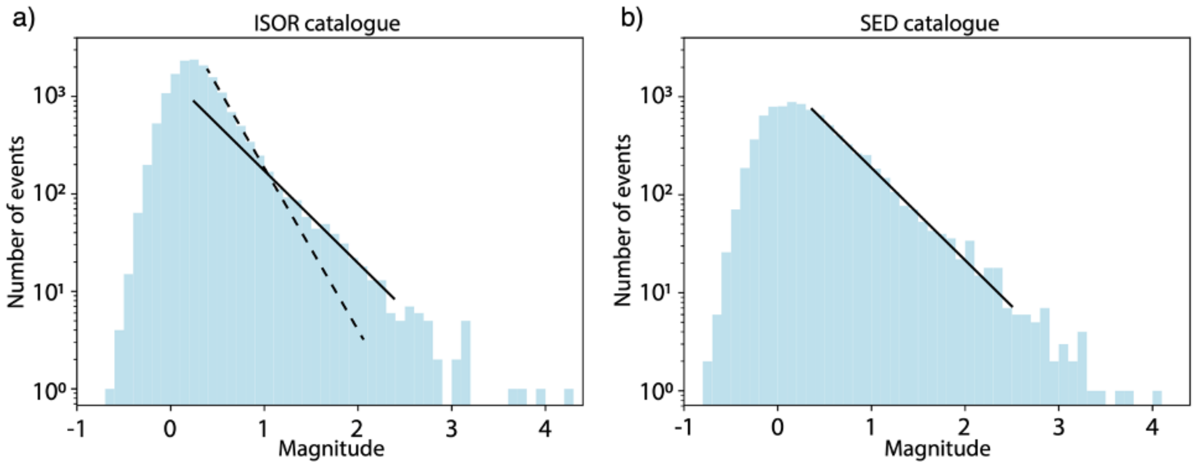


Figure 10: *Richter local magnitude (M_L) distribution in the ISOR (a) and SED HQ (b) catalog. The ISOR catalog shows a bias of M_L for events <1.0 introduced by the strong microseisms that can be mitigated with an additional high-frequency pass filter (b (from Obermann et al. 2022).*

The micro seismic data collected during the 3-year COSEISMIQ recording period were analyses in great detail using manual inspections, and repeated optimisations of automated workflows. After many months of optimization, we produced four seismic catalogs suitable for different scopes and publicly accessible at: http://coseismiq.ethz.ch:8080/fdsnws/event/1/

The catalogs contain seismic events within the following geographical region: 63.9° ≤ Latitude (North) ≤ 64.2° and -21.7° ≤ Longitude (East) ≤ -20.9° and are quality sorted (see Grigoli et al 2021, for details) in the following way:

- **Low Quality (LQ)** catalog (about 12’000 events), contains events with at least 10 phase picks. This catalog is characterized by lower detection threshold but larger location uncertainties for smaller events. This catalog is suitable for earthquake statistics (e.g., seismicity rate or b value analysis)
- **Medium quality (MQ)** catalog (about 9’900 events). This catalog is a subset of the LQ catalog characterized by a quality score >-5.
- **High quality (HQ)** catalog (about 8’800 events). This catalog contains only events with a quality score >-1. This catalog is suitable to identify the main tectonic structures and can be used as a starting point for more detailed seismological analysis.

Figure 11 shows the locations of seismic events related to each different catalog. Finally, we released an additional catalog (DDHQ) containing the same events of HQ catalog but with a refined location obtained using rtdd (Fig 12). These catalogs are the input for subsequent seismotectonic analyses, seismic imaging but also for reservoir modeling.

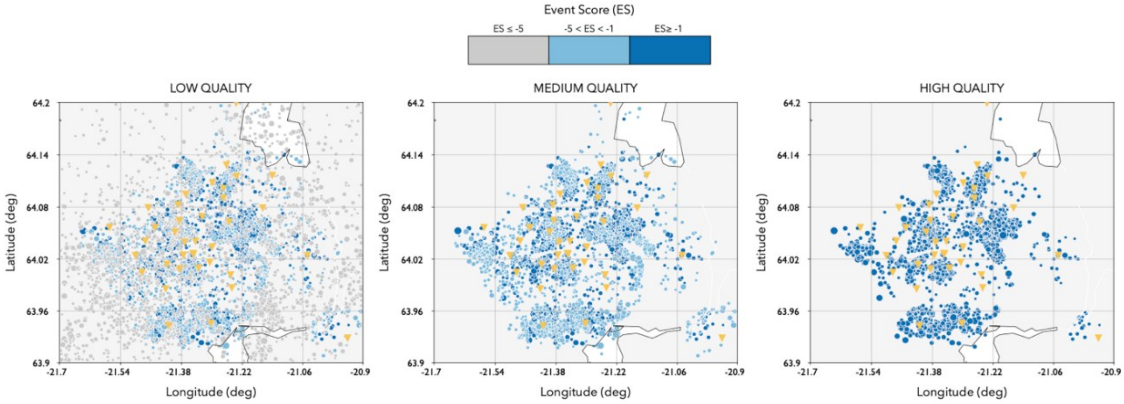


Figure 11. *Seismicity location for the low (left panel), medium (central panel) and high (right panel) quality catalogs. Event score associated with each event is color coded, in gray events with an event score S 5, in light blue the events with events score 5 < S < 1, and in dark blue the events with events score S 1. Location of seismic stations in yellow (from Grigoli et al. 2022).*

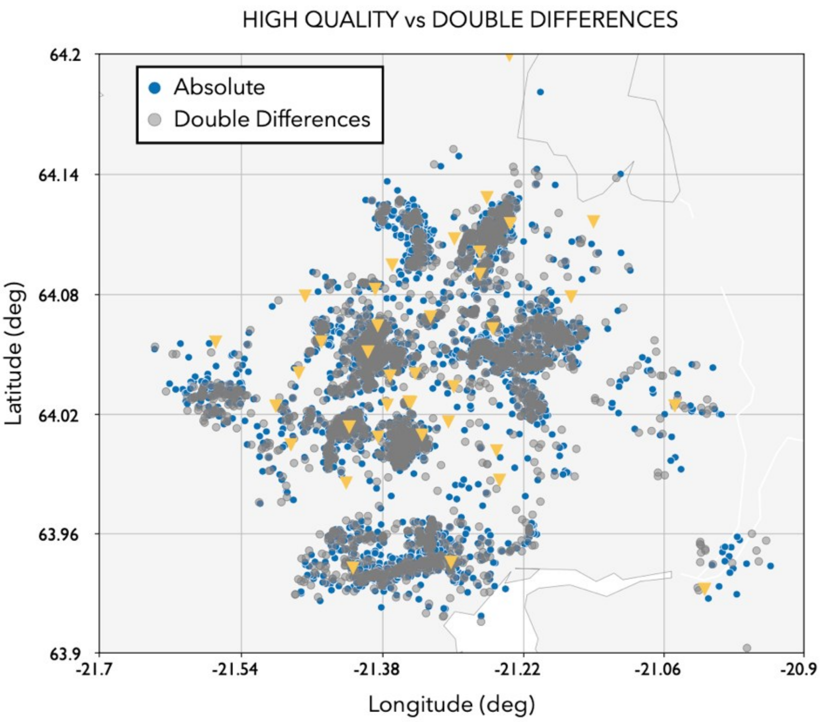


Figure 12. *Comparison of locations from the absolute (high quality) and double difference catalogs. The location of the seismic stations is indicated by yellow triangles.*

4.3 Rapid microseismic source-parameter estimation using supervised deep learning

In addition to the magnitudes and hypocenter, the most useful information that can be extracted from earthquakes is the Moment Tensors (MT) that describes the rupture orientation. Moment tensors inform geothermal operators on the stress state in the reservoir and the orientation evolution of the fracture network; they are therefore important input for operational decision making and for controlling risks. For these classifications to be effective ideally, they should be undertaken in quasi-real-time. Despite advances in seismological techniques, automatic source characterization for microseismic earthquakes remains difficult since current inversion and modeling of high-frequency signals are complex and time consuming. This mitigates against complete real-time classification, especially if the seismicity rates are high with, for example, many 10s of events per minute, as can be the case in geothermal fields. In this COSEISMIQ work we design and implement a Deep Learning scheme to address this problem, demonstrating how it can circumvent the difficulty in achieving quasi-real-time information. Specifically, we turn the data inversion problem into an image recognition task and use deep Convolutional Neural Networks (ConvNets) to determine microseismic source parameters (location, magnitude and Moment Tensor components) with speed-up factors in the 10s to 100s of thousands, over conventional inversion approaches. For each seismic event the scheme returns results, without human intervention, in a fraction of a second. The advantage of such a scheme in a production setting is that it would allow operators to 'keep up with' the analysis of rapid streams of incoming seismicity, and hence it aids operational decision making in real time.

A key element of the approach that we have developed is that the ConvNet is trained on synthetic data based on numerical forward modeling of synthetic seismicity. A key innovation is the way in which we add noise to these data, honouring field noise as seen on field seismic stations, from the area of interest. An added bonus of this approach is that the ConvNet scheme can be fully available in advance of any geothermal operations, even in geographical locations with low seismicity rates, making it highly suited to future geothermal production activities. The results of this study are published as Nooshiri et al. (2021).

In this work, we design a multi-branch, multi-target regression ConvNet to estimate the source parameters of micro-seismic earthquakes recorded by a seismic network (Fig. 13). The idea of designing a multi-branch neural network (NN) is to combine time-domain waveforms with other input data types and perform joint inversion of waveform attributes to improve the stability of solutions. As input data, we use time domain waveforms and kurtosis-based characteristic functions to train the NN.

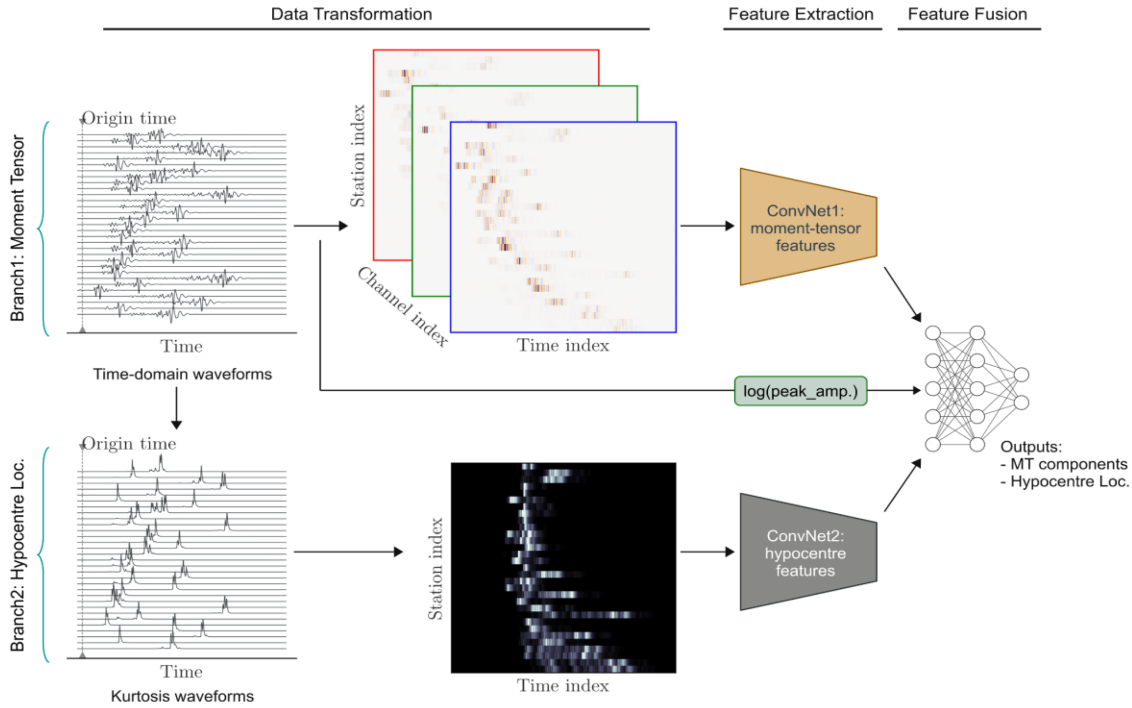


Figure 13: *Schematic diagram of the overall workflow, showing the NN inputs, feature extraction, feature fusion and the outputs. The NN is designed as a multi-branch model that carries out parallel ConvNets (from Nooshiri et al., 2021).*

Our approach builds a training data set by calculating synthetic seismograms from a population of randomly generated micro-seismic sources. The seismic sources are uniformly distributed in the space of all moment tensors and located in a particular monitoring volume which must be determined in advance. We then calculate a set of three-component seismograms for every source recorded on the COSEIMQ network deployed. To provide a more realistic training set, we develop a work-flow to incorporate realistic noise within the synthetic seismic data. We apply a statistical modeling method to obtain a more accurate characterization of real seismic noise and use field noise recorded on the COSEISMIQ seismic network in the Hengill area to condition that statistical model.

Once the synthetic dataset is built, we use 80% of the data to train the NN. When the NN is trained, we evaluate its predictive performance on the remaining 20%, which is used as a hold-out test set. Fig. 14 shows the distributions of differences between ground-truth and NN-predicted source parameters for the events in the synthetic test set. It can be seen that there is no systematic trend in predicted localizations as indicated by the high degree of symmetry of the distributions. Moreover, from the histogram of distances between true and predicted moment-tensors shown in Fig. 14(d), we find that 95% of the distances are below 0.1, denoting a high degree of similarity between predicted and true moment-tensors in both source type and orientation. Visual comparison of resulting source mechanisms corresponding to a random batch of outputs is shown in Fig. 15. Corresponding focal-mechanism plots match almost perfectly well, indicating that the NN is able to satisfactory invert for seismic moment tensor.

We also invert waveform data from micro-seismic events in the Hengill geothermal area that occurred inside our monitoring volume. ‘Manual’ moment-tensor solutions are already available for these events and have been obtained by using two different inversion tools; Grond (Heimann et al. 2018) and FociMT/HybridMT (Kwiatek et al. 2016). The comparison shows that the NN results are a very good match to the manual inversion solutions (Fig. 15, 16). These are example "recorded" events in the Hengill geothermal area that occurred inside our monitoring volume. We chose these events because ‘manual’ moment-tensor solutions are already available for them. The solutions predicted by the NN show very similar patterns in both source type and orientation to the manual inversion solutions. Overall, the performances of the NN are very consistent with standard techniques, but with the big advantage of providing rapid solutions. For example, the solutions from Grond inversion tool were obtained in tens of minutes per event, while our trained NN is able to produce similar results within a fraction of a second. Moreover, the time required to obtain manual solutions is an estimate only after having tuned the input parameters and found the best settings, whereas when applying the NN setting adjustments and manual pre-processing are not required and the solutions are obtained automatically. These features offer the potential for automatic and rapid real-time information on micro-seismic sources in a deep geothermal context, which renders the system suitable for seismic monitoring applications not only in Iceland but also in other geothermal projects, such as projects in Switzerland.

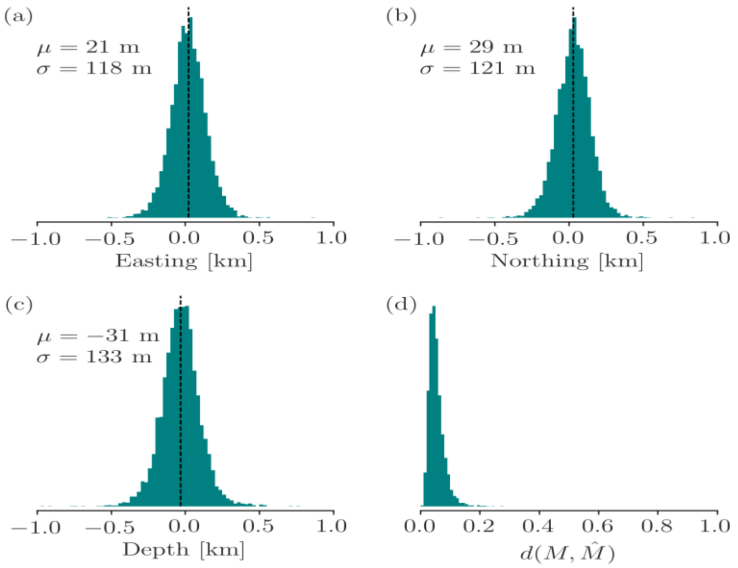


Figure 14: *(a)-(c) Differences between ground-truth and NN-predicted locations for 5000 events in the test set in easting, northing, and vertical directions, respectively. (d) Distances between ground-truth and NN-predicted moment tensors for 5000 test events.*

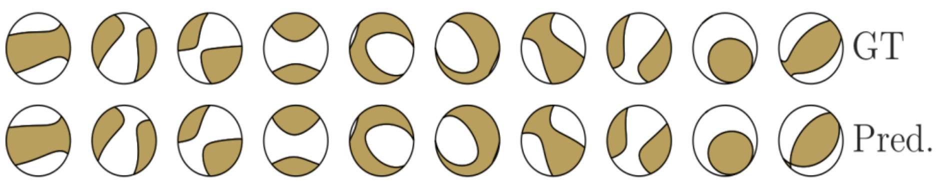


Figure 15: *Focal-mechanism plots for 10 randomly chosen seismic events in the hold-out test set: (top panel) ground-truth (GT) mechanisms for the micro-seismic events generated using forward modeling, and (bottom panel) mechanisms for the same events predicted by the NN.*

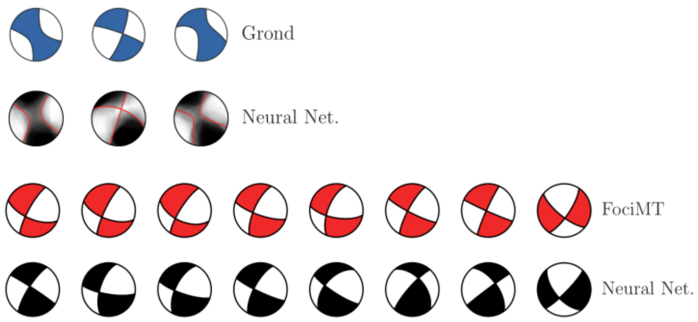


Figure 16: *Focal mechanism comparisons between NN predictions and manually inverted solutions obtained by using (two top panels) Grond and (two bottom panels) FociMT/HybridMT inversion tools.*

4.4 Building and testing a manual Moment Tensor database for COSEISMIQ

We also investigated and optimized the capabilities of existing, traditional approaches to determine moment tensors. We deployed the FociMT/HybridMT inversion algorithm (Kwiatek et al., 2016), a well-tested MT inversion method that is specifically tuned for local microseismicity such as the one recorded within COSEISMIQ. We produce a dataset that can be both used by the wider COSEISMIQ team for other purposes, and for ground truthing the NN approach to MT inversion, as outlined above.

We initially selected a small subset of 67 events of magnitude >=0.8 from the high-resolution earthquake catalog (Figure 11) that are both in the center of the deployment and defined as high quality picks. We find that in the Hengill area, where strong ambient noise affects the seismograms, the design of the filter has important effects on the displacement waveform needed for picking and inversion: causal filters struggle to clean the strong low-frequency noise, and acausal filters cause artifacts that can bias the first P-wave arrivals (Figure 17). We find that a very sharp, high-order, causal filter is required to clean the data. After fine-tuning the event preprocessing on the event subset, we select a larger database of 197 events from the COSEISMIQ catalog across the whole study area, including several seismicity clusters at the edge of the deployment. We pick and invert these events first with FociMT, then cluster them based on their location using K-means clustering, and finally re-inverted the clusters using HybridMT. The results from the single-event inversion, shown in Figure 18, show good correlation between neighbouring earthquakes, suggesting a reliable inversion. The clustered inversion changes some MT solutions significantly, greatly reducing the intra-cluster MT variance for most clusters and showing separate clusters forming more distinct trends on the source type plot. Interestingly, three event clusters show increased variance after the HybridMT inversion, indicating substantially different source mechanisms within a small area.

The FociMT/HybridMT methods investigated and optimized for COSEISMIQ were also used in the EGS stimulation in Helsinki and are now being tested for data from Bedretto and Utah FORGE as part of the DEEP project. Given the positive results we obtained here in COSEISMIQ, we anticipate that the same approach will be used for future Swiss projects by both GES and SED,

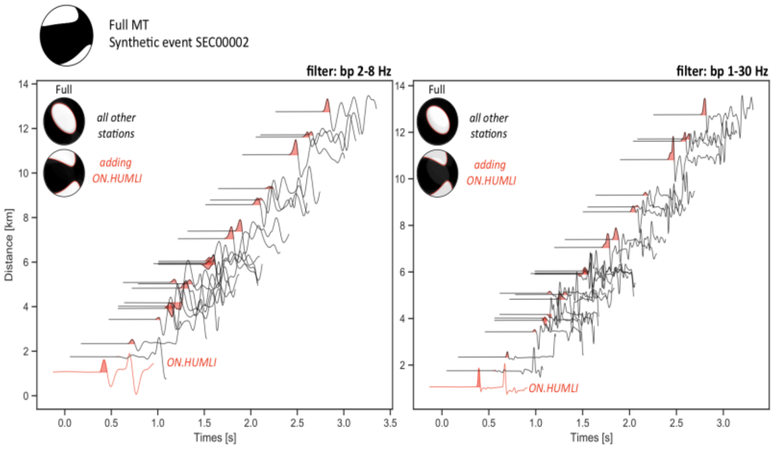


Figure 17: *Effects of changes of filter band and picked stations on the manual inversion of synthetic data. Reference focal mechanism is plotted on top. Left panel shows picks and results for waveforms filtered 2-8 Hz, right panel 1-30 Hz. In both panels the top focal mechanism is inverted using only the black waveforms and the bottom one the results when adding the records from an additional station (ON.HUMLI). The picked area beneath the first P arrival is shown in red.*

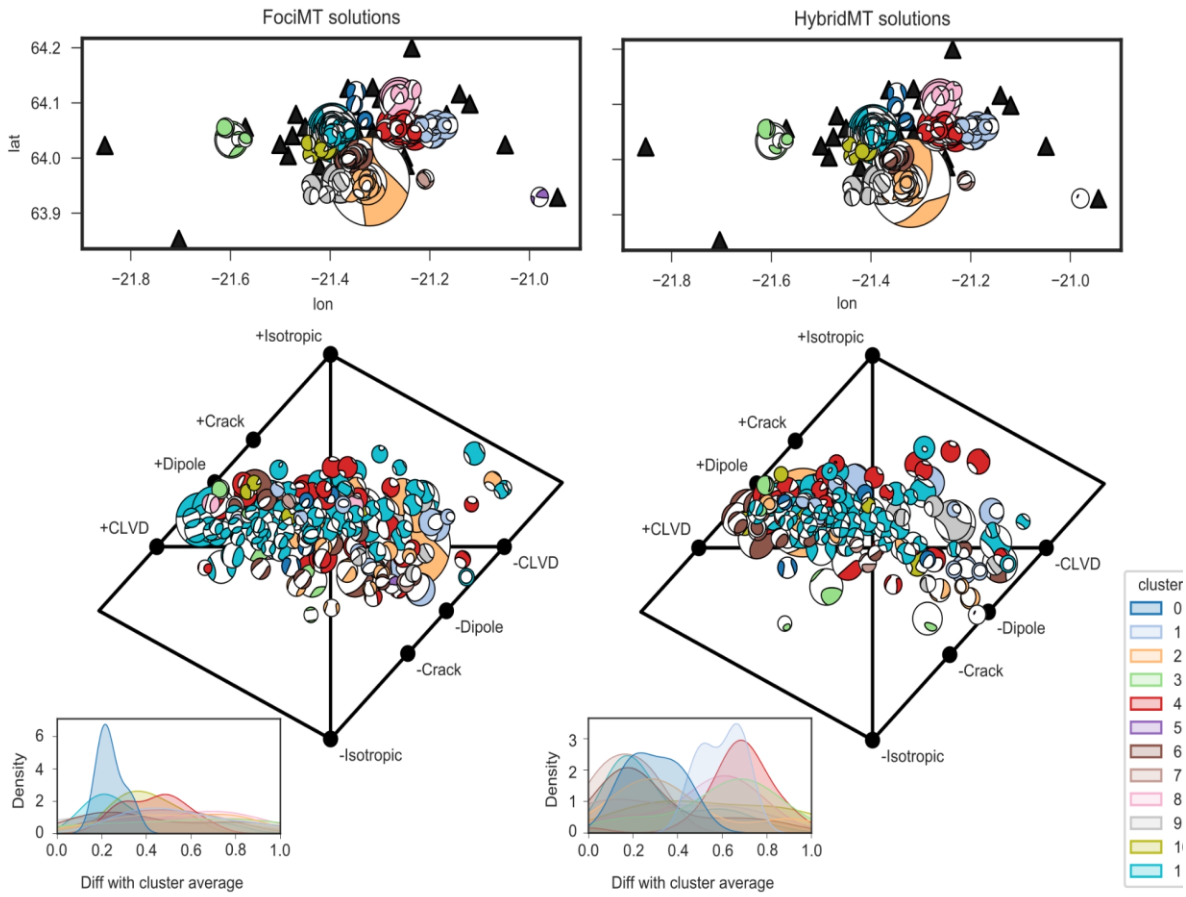


Figure 18: *Results of the inversion of 197 real events. Left panels show the results using FociMT, right panels the results using HybridMT. For each set of solutions, we plot geographic locations, the MT difference from the cluster average and the source type (Hudson) plots. All MTs are coloured by the cluster ID based on their location using K-means clustering.*

4.5 Enhancing Seismic Imaging capabilities using local earthquake data

Imaging seismic velocities in the underground can serve several purposes: It can help to resolve structure as well as physical properties such as temperature, pressure and fluid content and it can also be used in time lapse imaging to resolve changes in reservoir properties that relate to stimulation or production, s well as to seismotectonics. Because seismic imaging and earthquake location are coupled problems, enhanced resolution of velocities also translates in more precise earthquake locations, leading to sharper seismotectonic analysis capabilities. Seismic imaging is hence potentially a very powerful tool, but often the resolution power is insufficient to draw unambiguous conclusions. Within COSEISMIQ, we used seismic imaging first to better understand the Hengill reservoir and to inform modelling and risk assessment. We also strived, however for methodological advances and optimized workflows that enhance the potential of seismic imaging, for example when applied to Swiss geothermal or CO_2 storage plays.

For our analysis we use the high-resolution earthquake catalog to image the shallow crustal structure and analyze the local seismicity. The results are summarized in Obermann et al. (2022) With a subset of 6300 high-quality manually picked P- and S-phases, we compute initially a minimum 1-D model for the Hengill region. Our results suggest that for the Hengill geothermal field the most consistent and accurate hypocenter locations are derived from a joint inversion of P and S arrival times. We use this minimum 1-D model in combination with detection and location algorithms to produce a fully automated high-quality earthquake catalog of the entire period of the experiment. As magnitude estimations for events with M_L<1.0 are biased by the strong microseisms, we implement an additional butter-worth filtering procedure to present a seismic catalog with consistent micro-seismic magnitude estimations (Figure 9).

The seismicity occurs at depths of 2 km in the central part of the geothermal field and is concentrated at depths greater than 4 km in the southern and the northern Nesjavellir region. These differences in focal depths are likely indicators of lateral changes in the brittle-ductile boundary. Three-dimensional crustal imaging of V_P, V_S, V_P/V_S shows below average V_P/V_S ratios together with positive V_P and V_S anomalies beneath the central volcanoes in the first 2 km, which are interpreted as solidified magmatic intrusions (Figure 19). At greater depth, we observe an elongated high-velocity anomaly trending NE-SW that we interpret as a single intrusive body, crossing the rifting zone between Mt. Hengill and Grensdalur. A spatial analysis of b-values shows slightly increased values in areas with numerous injection wells and slightly decreased values in production areas. For details, please refer to Obermann et al. (2022) and to the ETH PhD thesis of Alejandro Duran (2021)

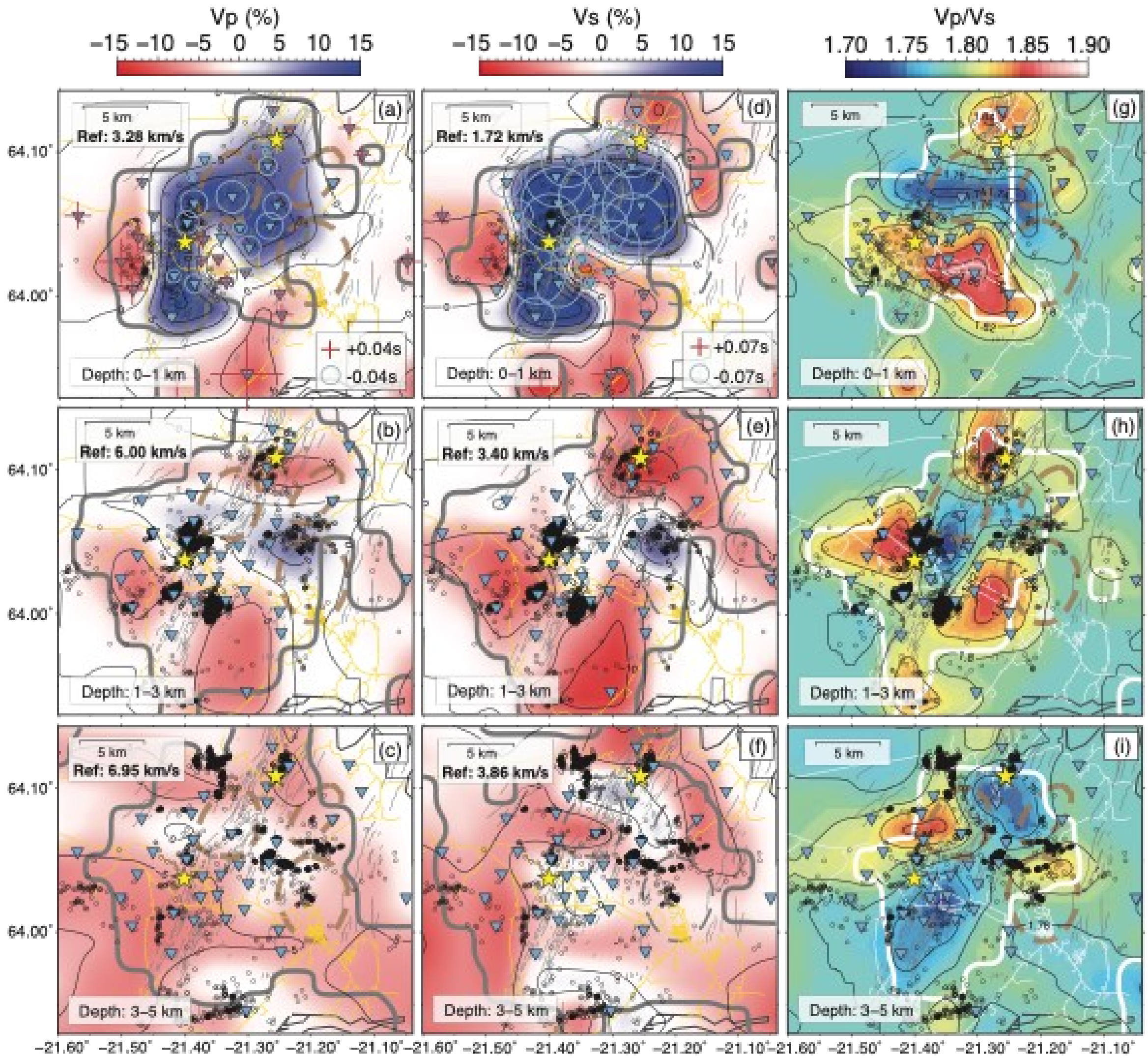


Figure 19. *Horizontal cross-sections of the Vp, Vs and Vp/Vs velocity models at 0, 2 and 4 km depth presented as relative change (in %) with respect to the reference 1-D model. The reference velocity of each layer is shown on the upper left-hand side of each figure. The average Vp/Vs is 1.79 in the study area. The thin black lines show velocity contour lines. Dashed lines outline the central volcanoes: Hengill, Hrómundartindur and Grensdalur. Crosses (red) and circles (blue) in a) and d) correspond to station-delay times of the minimum 1-D model for Vp and Vs, respectively (Fig. 4). Black circles indicate seismicity according to the automatic HQ catalog located within the indicated depth ranges. The yellow and white lines mark the major roads that are important for orientation. The thick line marks the well-resolved areas with an RDE>0.7.*

4.6 Exploring the potential of imaging with ambient seismic noise

An alternative powerful method for seismic imaging makes use of the ambient noise field recorded at the COSEISMIQ seismic network. The advantage of ambient noise interferometry is that it is independent from the rate and spatial distribution of micro-earthquakes and can be based on shorter installation of dense arrays, but so far there are few comparative studies that compare ambient noise based and earthquake base seismic imaging. COSEISMIQ addresses this gap, and we show in Sanches et al. (2021) that ambient noise-based image can indeed be applied with excellent spatial resolution in the uppermost 4 km of the crust (Figure 20). We obtain a Vs velocity model that is in excellent agreement with previous local earthquake tomography studies discussed in the previous section as well as with knowledge on the local geology. The achieved resolution of ambient noise imaging is in many places superior to the earthquake-based tomography and allows for example to the identification of small-scale seismic velocity anomalies that could not be resolved in previous studies, such as the low-velocity anomaly in Hverahlíð, where the most powerful injection/production wells in the area are located. This suggest that future geothermal projects in Switzerland would greatly benefit from an a-priori seismic imaging campaign based on noise interferometry as a powerful and cost-effective addition.

In comparing the tomography results with the resistivity model derived from the joint 1D-inversion of Magneto-Telluric and Electro-magnetic data in the Hengill area, we observe that both models respond similarly to the petrophysics and geological features and show an excellent overall correlation in the Hengill area. Some small discrepancies were observed in areas thought not to be in thermal equilibrium. We argue in Sanches et al. (2021) that the combination of seismic noise tomography together with resistivity data can assist in identifying current temperature anomalies in geothermal reservoirs. A joint inversion would improve the interpretation of the architecture of the geothermal area in question. In conclusion, seismic noise tomography shows great potential as a complementary tool for the exploration of high-enthalpy geothermal fields. For details please refer to Sánchez-Pastor et al. (2021).

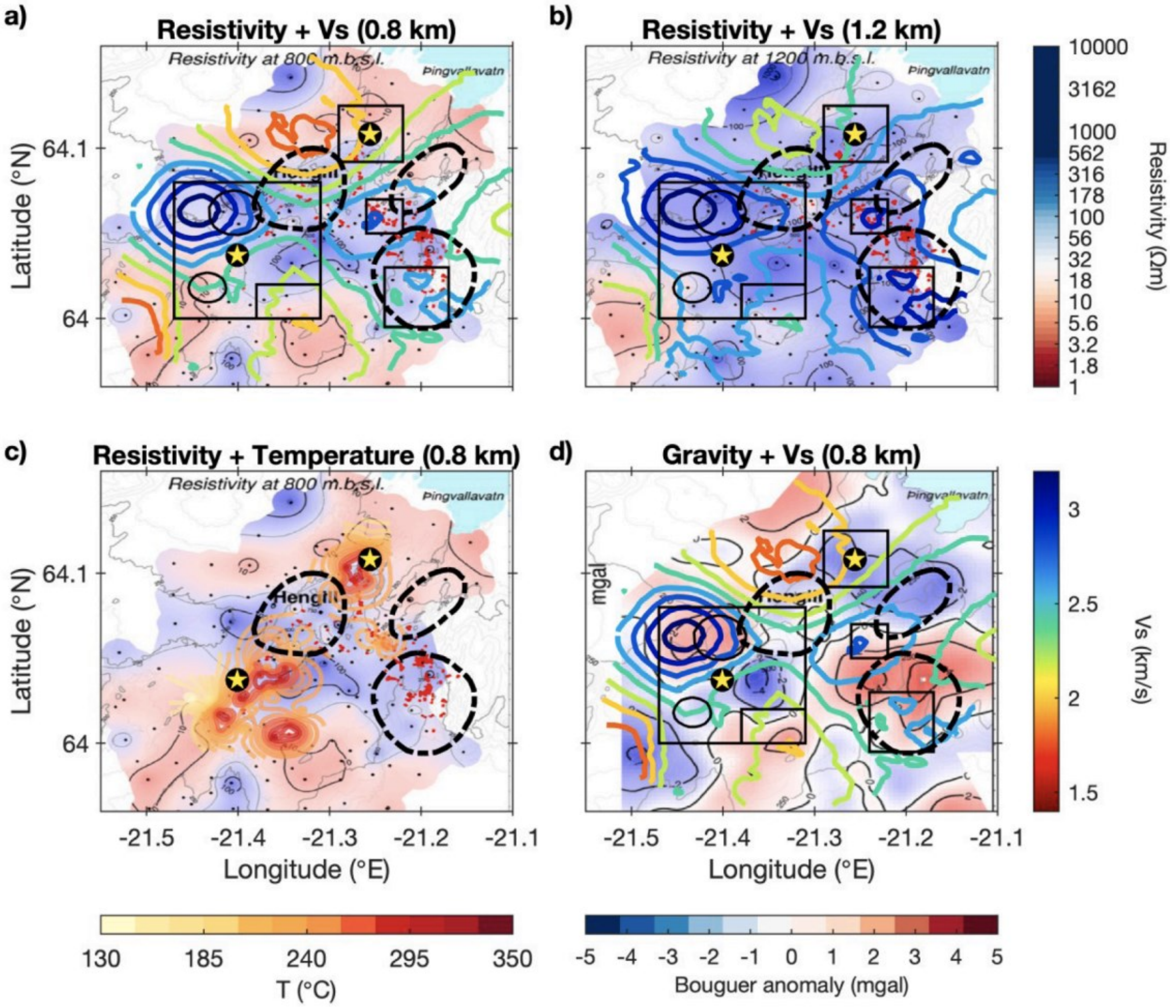


Figure 20: *Comparison between the 3D shear-wave velocity model (in all panels plotted as contour lines on top) and the joint 1D inversion of TEG and GT resistivity data at (a) 0.8 km and (b) 1.2 km depth. (c) Joint 1D inversion of TEG and GT resistivity data at 0.8 km depth and the formation temperature at 1 km depth. (d) Residual Bouguer gravity map and tomography model at 0.8 km depth. (Figures modified from Arnason et al., 2010). Note that the colour scales corresponding to the resistivity and velocity estimations are equal for all panels. Red dots in a) - c) are geothermal surface manifestations and black dots indicate the location of the GT soundings. The geothermal fields and reinjection areas are represented in a) – c) as thin black lines.*

4.7 Advancing Geomechanical Modeling Capabilities (WP3)

Geomechanical modeling is the tool to understand and forecast the evolution of a geothermal reservoir, both in terms of the hydraulic properties relevant for the economic viability and in terms of the seismicity. In COSEISMIQ our objectives are three-fold: 1) We advance the capability and utility of Geomechanical modeling tools overall, with a specific focus on their deployment in near-real time; 2) We use these tools to advance the understanding of the Hengill reservoir, 3) We transfer the knowledge gained by task 1 and 2 to other projects, including sites in Switzerland. To achieve these objectives, Work Package 3 of COSEISMIQ (entitled: "*The real time implementation of geomechanical modeling tools to simulate induced seismicity in relation to injection scenarios*") focused mainly on two aspects:

- The analysis of the geological and mechanical conditions in Húsmúli and,
- The calibration of numerical models.

Reinjection of spent geothermal fluids in Hengill is distributed mainly in two areas: Gráuhnúkar and Húsmúli, comprising respectively 6 and 5 wells. Húsmúli is located West of the Hellisheiði field (Northern cluster of injection wells in Fig. 21), its five wells range in depth from 1.4 to 2.4 km true vertical depth. Gráuhnúkar is located further South, its six active injection wells measuring between 1.2 and 2.2 km true vertical depth. Given the complexity of the Hengill area, WP3 concentrated its work on the main reinjection area in Húsmúli for which we gathered an understanding of the physical parameters on the generation of injection-induced seismicity. The analyzed parameters include injection flow rate, injection/extraction duration, pore pressure changes, fracture distributions etc. Differences in natural pre-drilling and induced seismicity between Húsmúli and Gráuhnúkar mirror the differences observed during drilling and injection. This could indicate structural differences (e.g., presence/absence of structures, size of structures, orientation). Multiple publications have or will result from this work on top of Deliverables 3 and 5 (Ritz et al., (2021), Kristjánsdóttir et al., (in prep), Ritz et al., (in prep), Yu et al., (in prep)).

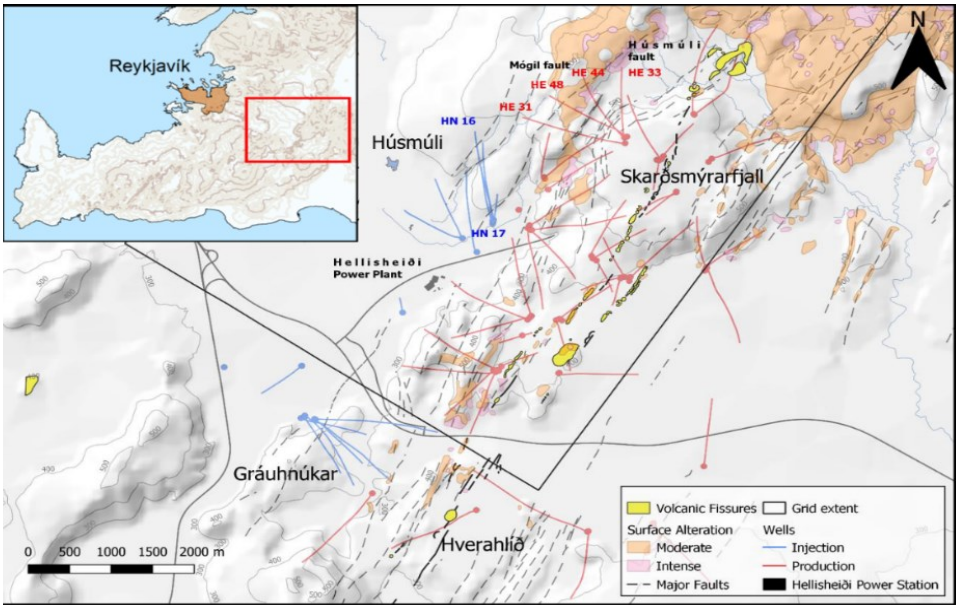


***Figure 21**. Map of the Hengill area showing the production wells of the Hellisheidi geothermal area with the Húsmúli and Gráuhnúkar reinjection areas.*

Geology and tectonic setting: Both injection areas (i.e. Húsmúli and Gráuhnúkar) lie to the south-west extension of the Hengill Volcanic System (Figure 15). While Húsmúli sits near the main volcanic centre, Gráuhnúkar lies further south. Lithology in the area can be divided in two main units:

- Hyaloclastites formed during sub-glacial volcanic eruptions extend from the surface to a depth of ca. 1500 m. Intercalated inside this hyaloclastites unit are lava flows of variable extent.
- A basaltic basement below the hyaloclastites unit.

The interface between these two units is deeper than 1800m in Gráuhnúkar while it is found at 1200m in Húsmúli. Two wells in Húsmúli reached the basaltic basement (HN-09 and HN-11). None of the wells in Gráuhnúkar reach the basement basaltic series, although terminal depths are very similar to the Húsmúli wells. The Hengill area sits in the intersection of two major tectonic trends:

- The Hengill fault system with major structures trending mostly in NE-SW direction (N30°) and confined to the Hengill volcanic zone
- A set of conjugated fault systems associated with the SISZ (South Iceland Seismic Zone) characterized by N0° to N10° and N60° to N80° structures.

Seismicity analysis: The initial analysis in COSEIMIQ was carried out before the COSEISMIQ catalog was available. Two different catalogs were used:

- The catalog from the Icelandic national seismic station network (SIL) available for the whole of Iceland from 1995. Locations on this catalog are not precise enough for certain analyses (e.g., definition of structures) but it can be used to analyze seismicity before the onset of injection.
- A detailed catalog from ISOR covering the period September 2011-May 2012. This catalog was put together combining data from the SIL network and a temporary seismic network deployed between 2011 and 2012 (Kristjánsdóttir et al., in prep). The locations on this catalog are precise enough to analyze the spatial distribution of induced seismicity and derive detailed structural observations.

Seismicity before the onset of injection (1995-2006): In the 10 years' period before the onset of injection, seismicity in the areas of Grauhnukar and Husmuli present important differences in terms of frequency of events and total released Mo (figures 22 and 23). The area around Husmuli is considerably more active with up to 150 events/month while in Grauhnukar the monthly frequency is below 10 events/month. On June 17, 2000 at 15:40, a 6.4 Mw earthquake located 50 km east of Husmuli marked the beginning of a sequence of strong events after 90 years of relative seismic quiescence in this region. The same day at 17:09 a 4.7 Mw event occurred in the Husmuli. This sequence of strong seismic events did not significantly affect the Grauhnukar area. At the onset of injection in Grauhnukar, a total of 1400 events had been detected in the Husmuli area since 1995 while in the same period, only ca. 80 events had been detected in Grauhnukar.

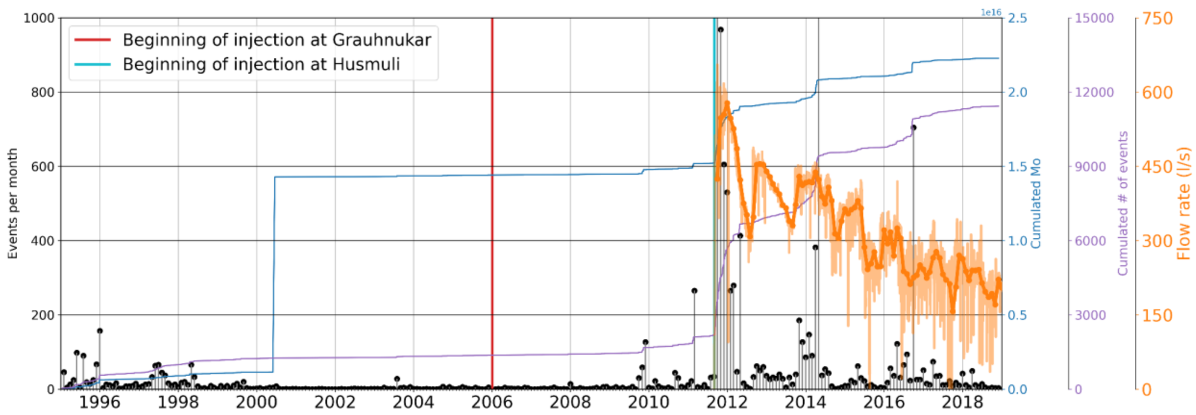


Figure 22. *Evolution of seismicity vs. total injection rate in Husmuli*

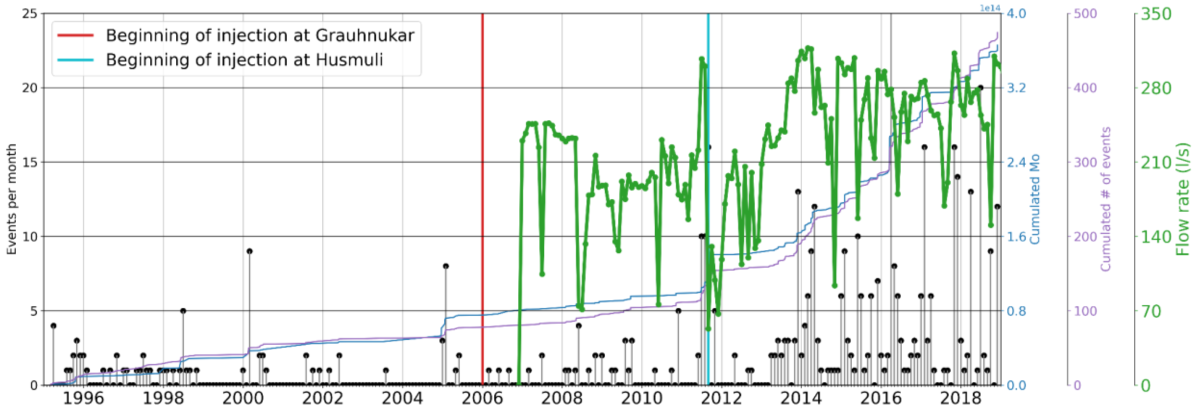


Figure 23. *Evolution of seismicity vs. total injection rate in Grauhnukar.*

Induced seismicity during September 2011-May 2012: Induced seismicity in Húsmúli is localized around the wells between 1km and 4km, occurring mainly at depths consistent with the basaltic series, which could suggest a link between injection into the deeper faults and induced seismicity. The analysis of seismicity in the detailed ISOR catalog revealed details of a fault network that had only been coarsely revealed by the SIL catalog previously available. A principal deformation zone (PDZ) oriented N0°-10° is clearly expressed in the general trend of 3 main seismic clouds. Riedel structures (blue and yellow in figure 16) are revealed by focal mechanisms derived from master events and expressed in internal lineations inside the main seismic clouds. A set of normal faults oriented N45° are clearly shown by focal mechanisms near the north and southern tip of the main seismic cloud. This pattern of normal faults near the tip of the main seismic cloud fits a model of horse-tail terminations on a dextral strike-slip system (Figure 16).

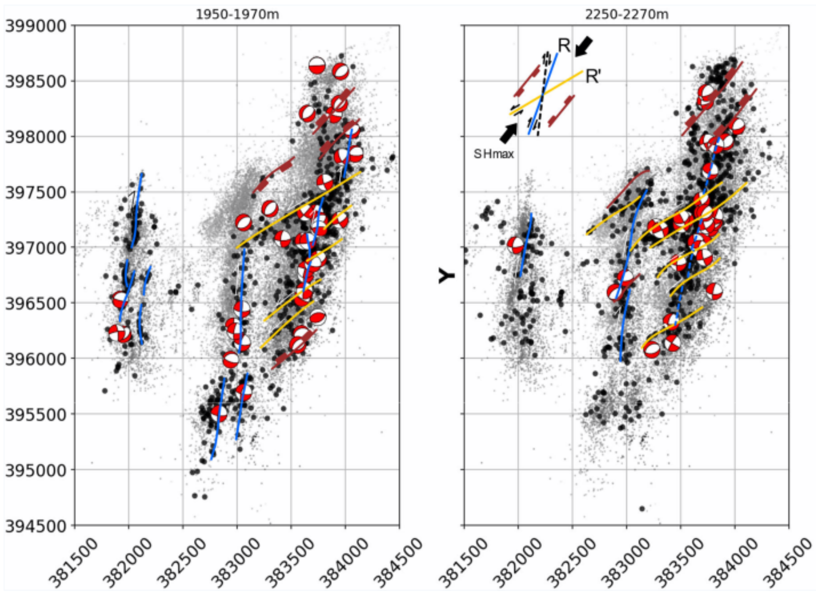


Figure 24. *Structures highlighted by the seismicity and focal mechanisms in Húsmúli for selected depth (catalog Kristjánsdóttir 2011-2012 - from Kristjánsdóttir et al., (in prep)). Grey dots are all seismic events available in the detailed ISOR catalog while black, thick dots are those that fall in the depth interval indicated in the title of the plots.*

4.8 Influence of physical parameters on the induced seismicity

Temperature: The Hellisheiði area is characterized by a thermal anomaly associated with magmatic activity and fluid circulations along major Hengill faults. The temperature of rock formation influences frictional movements and then influences slip and seismic behaviour. From geological models, well-logs and drilling reports, we extracted temperature data for each well in both Gráuhnúkar and Húsmúli, showing a significant temperature difference between the reinjection sites. Characterized by a hydrothermal up-flow Gráuhnúkar presents very high temperatures, with wells surpassing 270°C at 700m depth. Húsmúli, on the edges of the Hengill system, sits in a cooler region, with wells reaching ~250°C at 1500m depth. These temperature differences between the reinjection areas could explain in part the different seismic behaviours, with Gráuhnúkar flirting with the brittle-ductile transition zone.

Stress: The intense tectonic activity in Iceland implies that stresses can change with both space and time in association with local events (e.g. major earthquakes, magmatic activity, increased hydrothermal circulation, etc.). From scarce stress measurements and focal mechanisms (from literature and from Kristjánsdóttir et al. (in prep)), we analyze the stress state in the reinjection areas. From a semi-regional point of view, we can conclude that the stress state near the Húsmúli and Gráuhnúkar injection fields is strongly influenced by the crustal spreading processes taking place in the Hengill system. It is therefore very likely that, at least at seismogenic depths, the stress field is characterized by EW to NW-SE extension.

Injection rate: If a first order temporal correlation between injection operations and seismicity is easy to draw, the daily variation of the injection rate does not explain changes in the seismicity patterns. This absence of direct correlation is a result of the multi-wells injections coupled to a complex fracture/fault network at depth. We are investigating the contribution of individual wells to the induced seismicity using a machine learning approach in Húsmúli for the period 2015-2021 (Yu et al., (in prep), see Fig. 25).

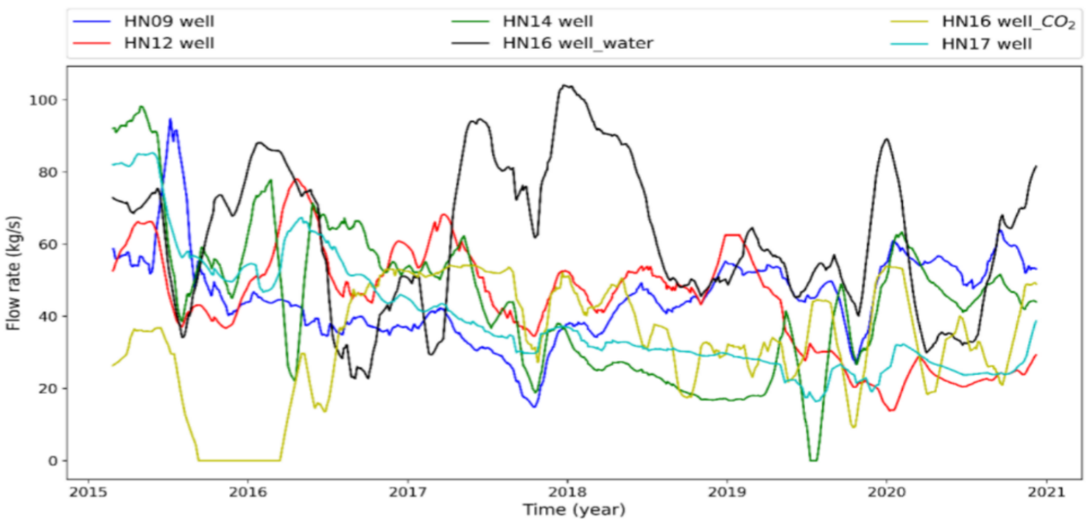


Figure 25. *Injection history in Húsmúli used for the machine learning feature extraction in Yu et al., (in prep)*

4.9 Calibration of geomechanical models

TOUGH2-Seed model

TOUGH2-Seed is a hybrid hydro-geomechanical-stochastic model coupling TOUGH2, and a “Seed” model developed at ETH. We were provided a regional scale TOUGH2 model of the Hengill area by Reykjavik Energy that had been calibrated on well data, pressure drawdowns and production logs since the 1990s. The regional model does comprise the Húsmúli region, however it is located outside the refined center and thus has quite coarse grid cells. This regional model was nonetheless tested with the Seed coupling on the onset of reinjection in Húsmúli (September 2011 - April 2012, Fig. 26-A), integrating all data on stresses, fault orientations and seismicity locations gathered throughout the geomechanical analysis. This regional model however performed quite poorly due to a sharp permeability boundary blocking all fluids from migrating North of the wells (Figure 26). We have since acquired a refined TOUGH2 model of the Húsmúli area from Reykjavik Energy and Carbfix. The calibration of this new refined model is ongoing and will allow us to better understand the fluid migration and seismicity as this model includes major hydraulic faults in the TOUGH2 matrix.

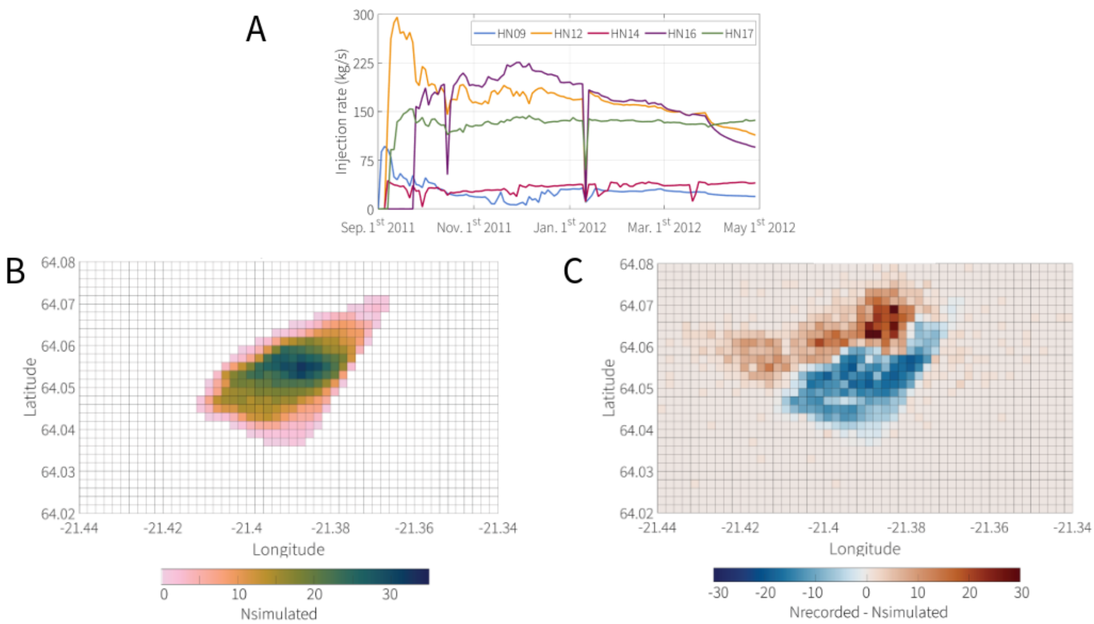


Figure 26. *Seismicity produced by the TOUGH2-Seed model during the first 9 months of injection. A- Injection history for the five active wells in Húsmúli. B- Number of events simulated. C- comparison simulated vs. observed seismicity (red = more observations than predicted / blue = model overshoots)*

Calibrated structural and hydraulic models based on HFR-Sim

HFR-Sim is the in-house Enhanced Geothermal Systems (EGS) simulator of ETH Zurich (Karvounis and Jenny 2015, Deb and Jenny 2018). It is especially designed for simulating dynamically changing fractured reservoirs and it employs discrete fracture modeling for large, important fractures. An optimized version of HFR-Sim has been optimized by the SED for probabilistically predicting injection-induced earthquakes (Karvounis and Wiemer, 2022). For the needs of COSEISMIQ, a workflow is developed that is based on HFR-Sim, produces a hydraulically calibrated structural model for Húsmúli, and satisfies the needs of the ATLS for real time calibrations. The workflow utilizes with high fidelity a wide range of structural field observations (e.g., images of wells and their inflow zones), employs unsupervised machine learning techniques for extracting important structural information from the recorded seismicity, and calibrates the properties of the updated structural model to reproduce both the hydraulic and the seismic response of the reservoir.

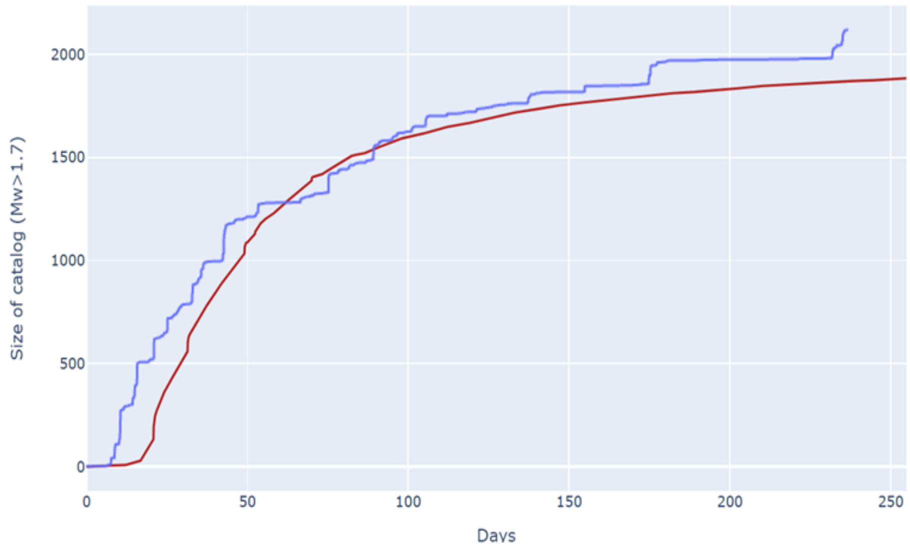


Figure 27. *Number of seismic events with Mw>1.7 in Húsmúli (blue curve) and simulated number of events (red curve) as a function of days since first reinjection started in Húsmúli.*

The model is calibrated using the rich observations over a 9-month period, from September 2011 until the end of May 2012. The resulting HFR-Sim model reproduces the later inflow rates in Húsmúli, the declining trend of it, and the rate of simulated seismicity for the observed relocated hypocenters (Kristjánsdóttir et al., (in prep)). The structural model consists of deterministic fractures from the wells, alignment fractures extracted from the spatiotemporal evolution of the seismic cloud, and one fracture for every seismic event that is optimally oriented for the stress field and the observed focal planes in Húsmúli (Karvounis et al., (in prep)). The rate of seismicity in the calibrated model is presented in Figure 27.

Seismogenic index model

The Seismogenic Index model is a simple empirical approach linking injected volume to the number of events expected above completeness ($N_{exp,\geq Mc} = V_{inj}(t) \cdot 10^{\Sigma - bMc}$). Very few geomechanical information can be integrated in such a simple model. However, with the analysis of the seismicity distribution and of the orientation of faults that can potentially carry fluids, the distribution of volumes can be tailored to the Húsmúli area.

The comparison of the Seismogenic Index and TOUGH2-Seed models, calibrated for the Húsmúli reinjection with 0.005 degrees (latitude and longitude), are compared in Figure 28 for the September 2011-April 2012 period. More details can be found in Deliverable 5.

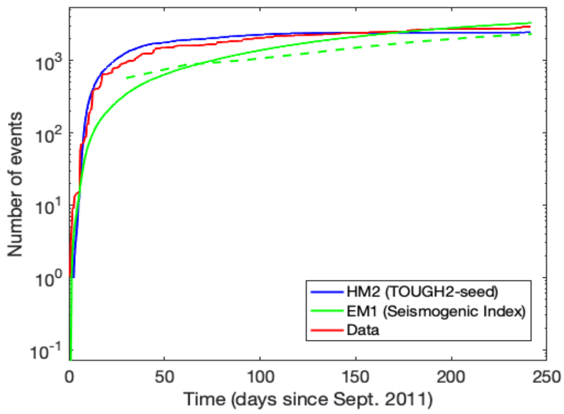


Figure 28. *Comparison of TOUGH2-Seed and Seismogenic Index model for history matching of the first eight months of injection in Húsmúli*

4.10 Risk Management Framework (WP4)

Here we present the results of the implementation of automated and adaptive risk assessments in near real-time for fluid-induced seismicity in the Hengill region of Iceland. Specifically, we report the workflow to determine the estimation of the prior risk and the real time updating strategy. The following results exploited synergies with a real-time test of adaptive traffic light systems during a stimulation near Reykjavik (Geldinganes) in the fall of 2019 (a DESTRESS funded project). Methodologies developed in COSEISMIQ could hence best tested in real time during a single well stimulation in Iceland.

We summarize here the methods and tools for the a priori hazard and risk assessment, and the Bayesian updating scheme to integrate real-time monitoring with online hazard and risk updating. For a detailed description of these activities, please refer to Broccardo et al. (2019). In addition, we here present a summary of the real time application of the adaptive traffic light system for the Geldinganes stimulation. Below, we introduce the hazard module, the risk module and the adaptive traffic light system updating strategy applied in Geldinganes project.

The hazard model

COSEISMIQ employs a time-variant Probabilistic Seismic Hazard Analysis (PSHA) to manage fluid-induced seismicity (Grigoli et al., 2017; Bommer et al., 2015; Broccardo et al. 2017a; Lee et al., 2019). Briefly, in this context, PSHA aims at the computation of the rate of exceeding a given intensity measure (IM) at a given distance from the injection site. This rate depends on the number of events above a given minimum magnitude, the frequency distribution of the magnitude (namely the truncated Guttenberg-Richter distribution), and an empirical ground shaking attenuation function. Usually, there are two key parts to be defined: the probabilistic characterization of the seismogenic source model, and the ground motion characteristic model. The first gives the temporal and spatial forecast of the seismic events, while the second is characterized by Ground Motion Predictive Equations (GMPEs), which relates magnitudes and distances to a given Intensity Measure, IM (e.g., Peak Ground Velocity, PGV, Peak Ground Acceleration, PGA, etc.).

At this level of analysis, to include alternative models (i.e. epistemic uncertainties), we implemented a logic tree with weighted branches. The first level of the logic tree describes the epistemic uncertainty related to the selection of the seismogenic source parameters while the second level on the uncertainty relates to the GMPEs. The upper bound of the Gutenberg-Richter distribution is fixed, for Icelandic conditions, to (Kowsari et al., 2019). The details of the logic tree are reported in Broccardo et al. 2019.

The source model

The model SM1 is based on the empirical evidence that the volume affected scales with the volume of fluid injected; this implies a relation between the expected number of earthquakes $E[N]$ and the volume injected V, which read as

$$E[N(t); M > m] = 10^{a_{fb}-bm}\dot{V}(t), \qquad t \leq T_{in} \ ,$$

$$= 10^{a_{fb}-bm}\tau \, exp\left(-\frac{t-T_{in}}{\tau}\right)\dot{V}(T_{in}), \quad t > T_{in}$$

where a_{fb} is the so-called seismogenic index or underground feedback parameter, b is the b-value in a Gutenberg-Richter distribution, T_{in} is the injection duration, and τ is the mean relaxation time of a diffusive process (Mignan et al., 2017, Dinske and Shapiro, 2013; van der Elst et al., 2016; Mignan, 2016; Broccardo et al., 2017b). It is important to observe that this model only applies to positive flow rates. While the underground feedback parameters a_{fb} and b can be estimated during the stimulation (Mignan et al., 2017; Broccardo et al., 2017b), a priori knowledge on those parameters is largely limited and the range of possible values is very wide.

The model SM2 introduces a first-order physical process into the forecasting. This is given by modelling pressure diffusion through a fractured media containing randomly distributed earthquake faults, which are named seeds. Here, the HFR-sim (Section 1.3) is employed both for modelling flow in a fracture network with dynamically changing permeability (Karvounis and Jenny, 2016) and for simulating the source times of randomly pre-sampled scenarios of hydro-shearing events at certain hypocenter (Karvounis et al., 2014). The resulting seismicity rates can be converted into static equivalents rates (like for SM1) and compared with SM1. Specifically, Figure 19 shows the results together with case of synthetic catalogue with predefined parameter matching Icelandic conditions.

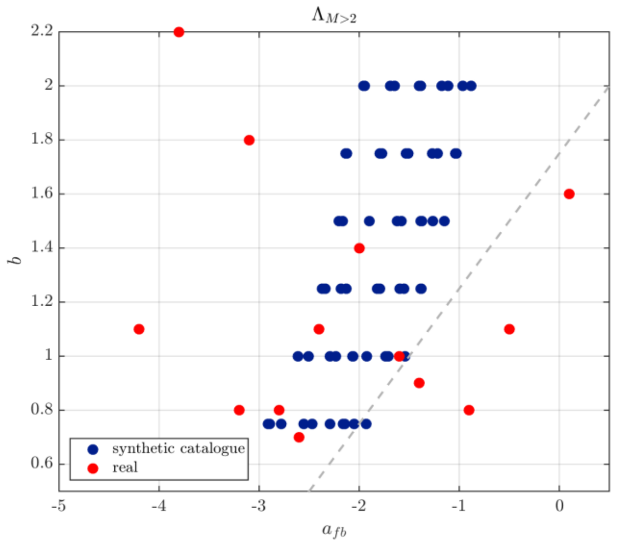


Figure 29. *Distribution of - values for the real dataset (red dots) synthetic catalogue (blue dots). Details can be found in Broccardo et al. 2019.*

Ground motion prediction equations

The relationship between the site source characteristics and the ground shaking intensity measures, is given by 7 GMPEs. The selection is based on the study of Kowsari et al. (2019), in which they recalibrate existing GMPEs to the Icelandic strong motion data set. Then, we convert the PGA into the European Macroseismic Scale (EMS98, Grünthal, 1998) using Ground Motion to Intensity Conversion Equations (GMICE) for small-medium intensities. The GMICE used in this work are introduced by Faccioli and Cauzzi (2006) and Faenza and Michelini (2010). Details of the GMPEs selected and about the conversion are reported in Broccardo et al. (2019). Provided with the source model and the GMPEs, the PSHA outputs are obtained by the classical total probability integration. Figure 30 shows the PSHA outputs based on the Macroseismic scale. In red are reported the real data and in blue the model SM2.

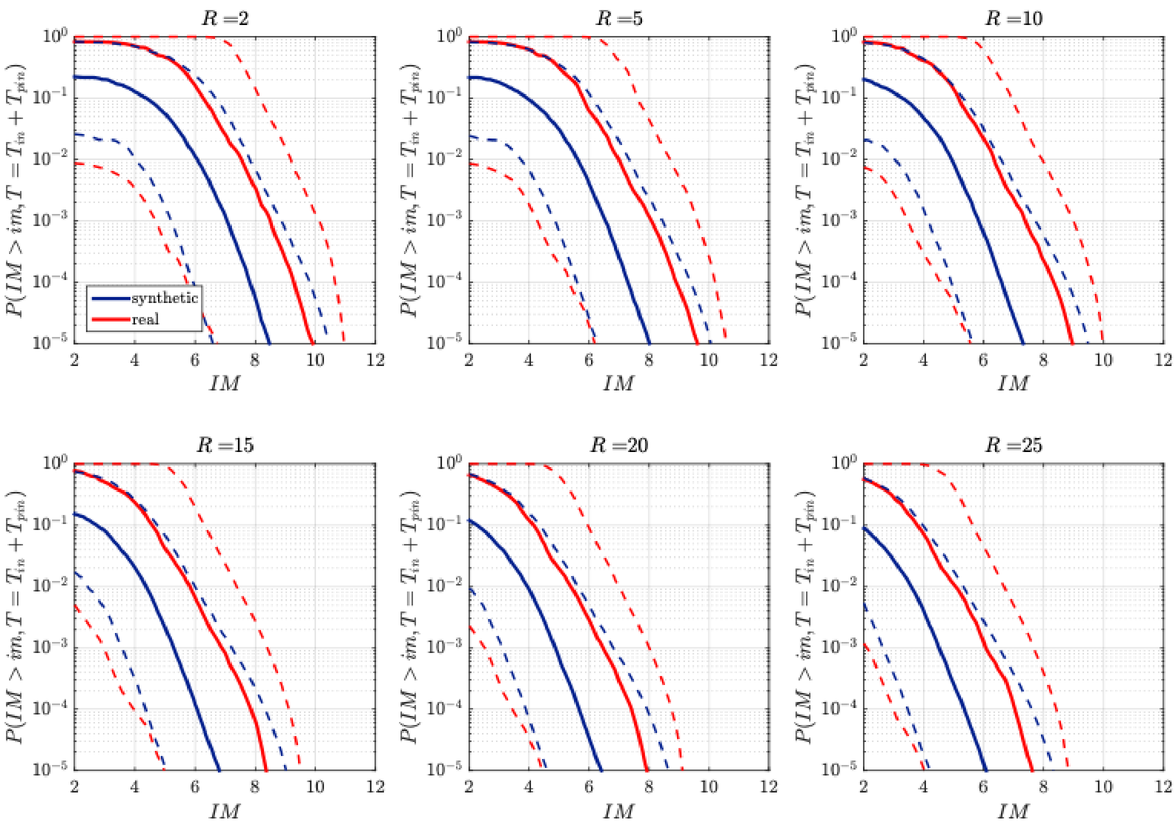


Figure 30. *PSHA analysis comparison between source model SM1 and SM2 (synthetic catalogue) for different source-to site distance, R. Solid lines: medians; dashed lines 10% and 90% quantiles. Intensity measure.*

The risk model

In this project, we propagate the hazard analysis into the risk domain for a virtual Icelandic type of building. We use a virtual building because the area is not densely populated, making it a perfect virtual test site. Seismic risk is computed by convolving a vulnerability model for the relevant building typologies with the exposure model. In the adaptive traffic light system, we use as risk measure the individual Risk (IR). The IR is based on the vulnerability models that follow the macroseismic approach for damage assessment (Lagomarsino and Giovinazzi, 2006) and modified in Mignan et al., (2015) for the induced seismicity case. In practice, the *IR* is computed by integrating the hazard with the vulnerability model and the conditional probability of fatalities for a given damage grade. Figure 31 shows the *IR* for different building classes. Median and quantiles are computed considering a 50% weight for the SM1 model and 50% weight for SM2 model for the selected set of parameters.

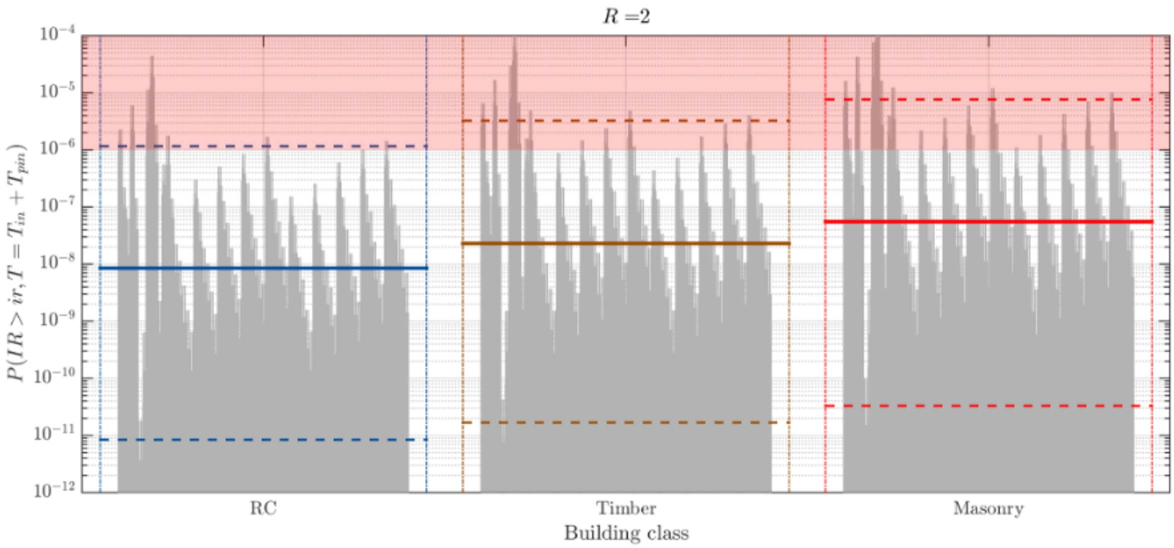


Figure 31. *IR for 2 km distances based on the final model (combined SM1 and SM2). The solid horizontal lines represent the weighted median values of the vertical gray lines. The dashed horizontal lines represent the 10 and 90% epistemic quantiles.*

Online updating of the adapting traffic light system

This section discusses the updating of the rate model (i.e., only of [a_{fb}, *b*]) related to the DESTRESS project in Geldinganes, Reykjavik. Updating the join probability model of [a_{fb}, *b*] is crucial since it allows to compute and control online the variation of *IR,* and, ultimately, narrow down the uncertainties. The real-time updating strategy uses a classical Bayesian learning strategy integrated with a Non-Homogeneous Poisson Process (Broccardo et al., 2017). Specifically, we use the parameter estimates of the rate model SM1 to define a joint prior distribution. In this case, we include expert knowledge to determine the bounds of the prior. Once the seismicity data has been recorded, the Bayesian framework allowed the computation of the posterior distribution for the model's parameters, the formulation of predictive models, and a robust forecasting strategy. The inference strategy for the empirical model proposed in this project and the predictive model for the number and magnitude of fluid-induced events are described in detail in Broccardo et al. 2017. In the Geldinganes project, we also integrated the hazard and risk computation but not the updates of the ground motion prediction equations because data on peak ground acceleration and velocity were not available. After testing the adaptive traffic light system on a synthetic case study based on the SM2 model, we applied it to the stimulation in Geldinganes in near-real-time. The stimulation consisted of two macro-stages (with each macro-stage divided into two substages). In the first macro-stage, no seismicity has been recorded. Although no data were available, the Bayesian updating strategy formulated a posterior distribution and reduced the uncertainty on the rate model and the final risk computation. Figure 22 shows the joint prior distribution and the joint posterior after updating the first stage. Figure 23 shows an iso-risk contour plot together with the posterior distribution. This plot shows explicitly the "safe" and "risky" domain and the epistemic uncertainty evolution around the parameters a_{fb} and b. Finally, Figure 24 shows the online evolution on IR together with the epistemic uncertainty reduction on its value. The risk was computed near-real-time with the planned injection profile. The details of these "seemingly" surprising results (updating with no data) are reported in a manuscript under preparation. Next, we used the posterior distribution of the first stage and mixed it with the prior distribution of the first stage to formulate a robust prior distribution for the second macro-stage. In the second macro stage, seismicity has been recorded, and the final updates are reported in Figures 25 and 26. In the Geldinganes project, the adaptive traffic light system guided the operator to modulate the injection profile. The updated injection profiles were discussed and elaborated during the project (i.e., there were not a list of alternative profiles). In particular, it made quantitatively and explicitly clear that the risk level associated with the injection was very low and, therefore, it allowed to increase the injected volume compared to the original plan.

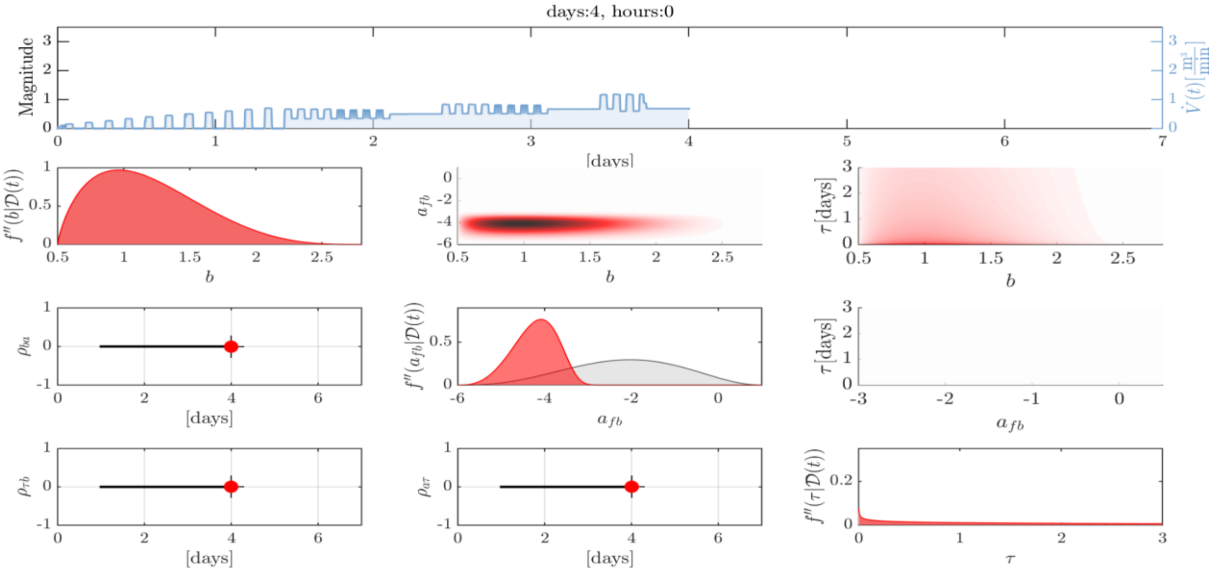


Figure 32. *First macro-stage. Starting from the top, the first subplot reports the recorded injection profile and Magnitudes. The bottom matrix plot reports in the diagonal the marginal distribution of the parameters. Specifically, gray represents prior distributions, red represents posterior distributions. The upper diagonal of the matrix plot represents the joint distributions. The lower diagonal of the matrix plot reports the correlation coefficient between the model parameters.*

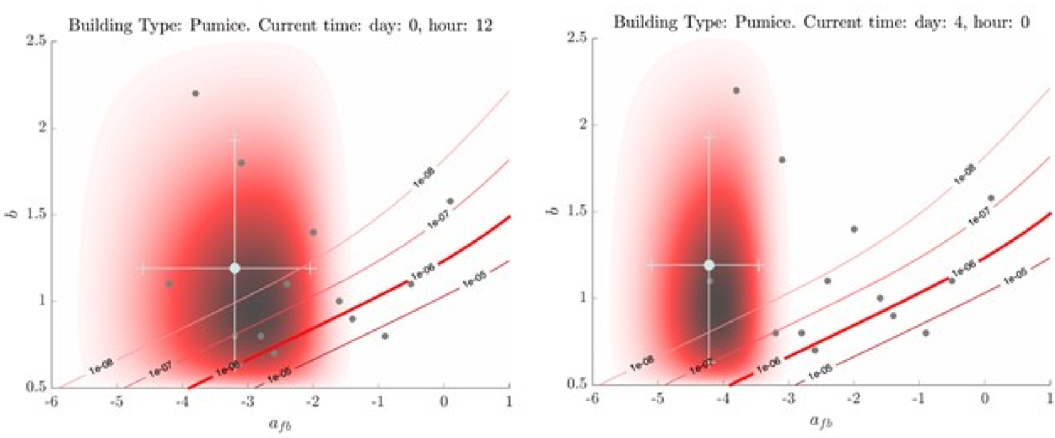


Figure 33. *First macro-stage set for a virtual masonry building. Iso-risk curve and posterior distribution, left panel first updates, right panel last updates*

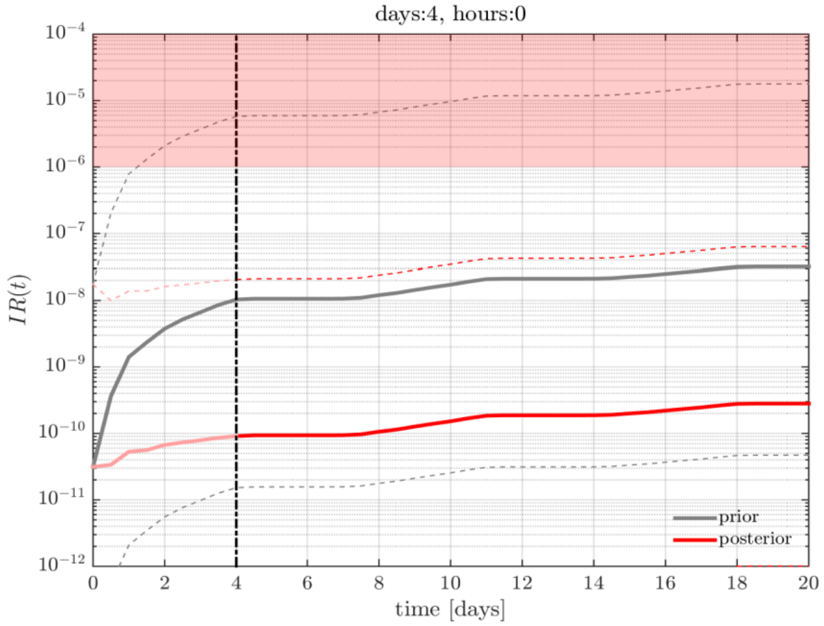


Figure 34. *Risk updates and epistemic uncertainty reduction after 4 days of the updates. Solid line mean risk, dashed lines 5-95% quantiles. Gray lines computations based on prior uncertainties; red lines computations based on 4 days' posterior. Observe the large uncertainty reduction.*

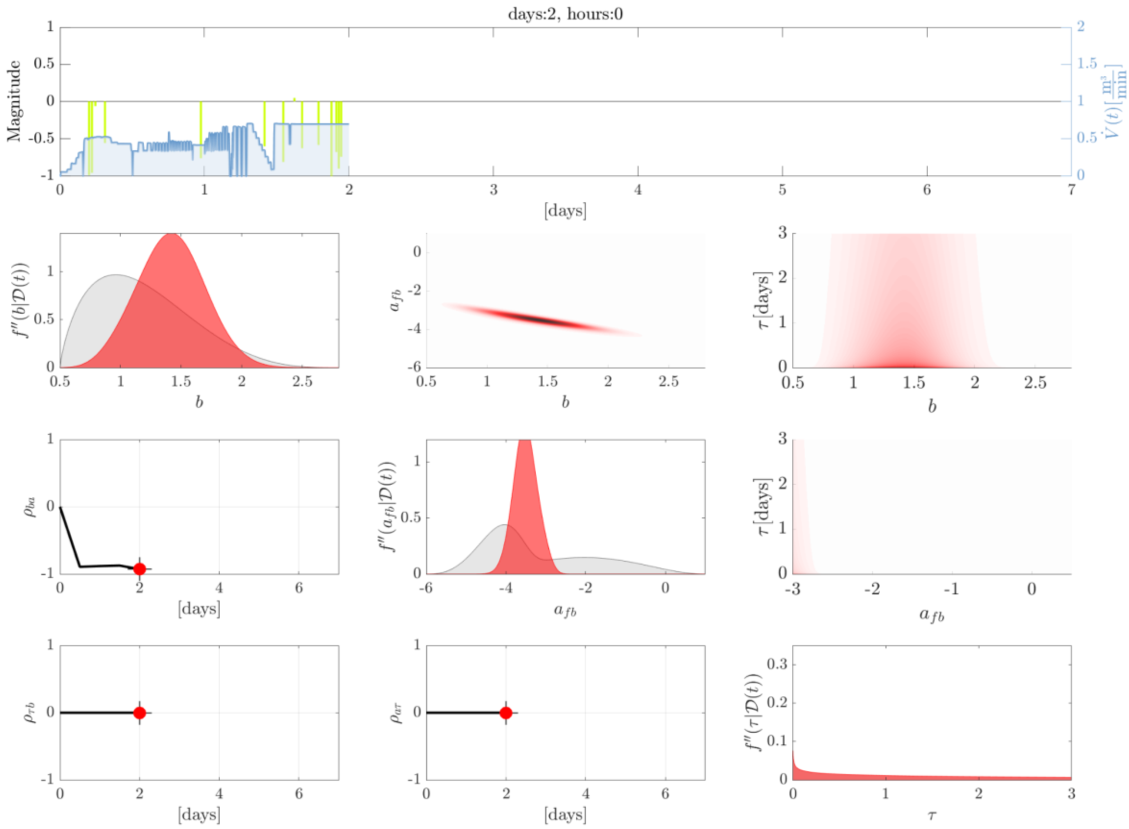


Figure 35. *Second macro-stage. The figure represents the same quantities of Figure 32.*

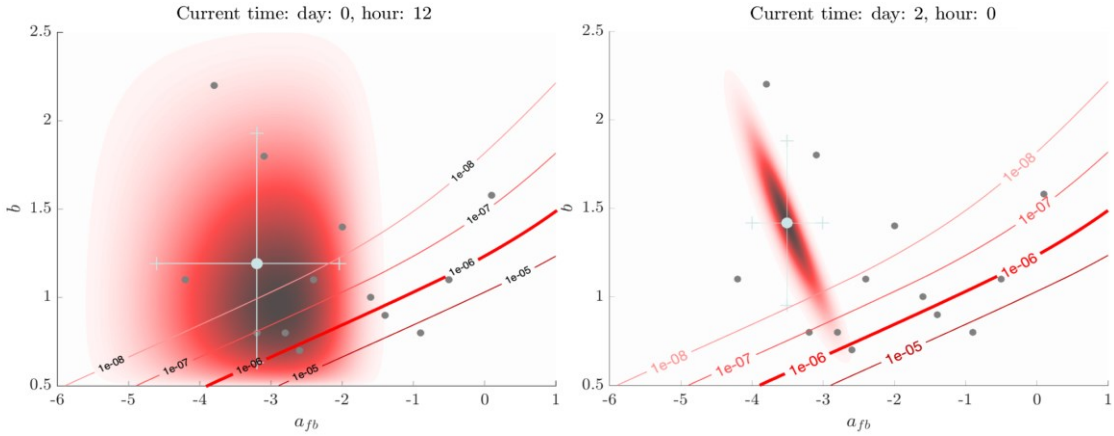


Figure 36. *Second macro-stage risk update for a virtual masonry building. Iso-risk curve and posterior distribution, left panel last update fist macro-stage, right panel last updates second macro-stage.*

4.11 Demonstration of the RISC Decision Support Framework & Tool (WP1 – Part2)

The risk management framework presented in the previous paragraph Is not critically needed in the Hengill area given its remoteness. The RISC (**R**eal-Time **I**nduced **S**eismicity **C**ontroller) tool is then most useful for understanding the number of events generated in the area and how they are linked to the human operation. Here, we summarize a potential use of the COSEISMIQ data for forecasting seismicity and comparing forecasting models. Such models are compared with state-of-the-art approaches to calculate the information gain, with respect to a null hypothesis. The models implemented in here are tuned to forecast seismicity in the entire Hengill geothermal field and are the following: a basic ETAS model (the null hypothesis), a more advanced ETAS version (EM2, deliverable 6), and the EM1 model as implemented and calibrated in the past months (deliverable 5). For simplicity, we decided to test the models in a pseudo-forecast exercise, leading to a comparison of models via a Cumulative Information Gain (CIG). Application in real-time of the current approach could be easily implemented, assuming the hydraulic and seismic data flow is correctly working.

Dataset input to pseudo-forecasting models

The seismic catalog is the same as described above (and in Deliverables 2 and 5). We used the middle quality catalog (evscore>-5). A statistical analysis of the whole dataset shows that the overall magnitude of completeness (Mc) is 0.3 (Figure 27 a), with a b-value of 0.93 (Figure 37 b). For all models, we assume the Mc=0.3 and filter the catalog above this magnitude. The hydraulic data only covers up to December 2020, and we assumed the same level of injection/production after that period to the end of the dataset (August 2021). The injection/production rate at the various wells were distributed by means of Gaussian kernel to obtain a spatial distribution of injection/produce fluid volumes to be linked with seismicity. More details can be found in Deliverable 6.

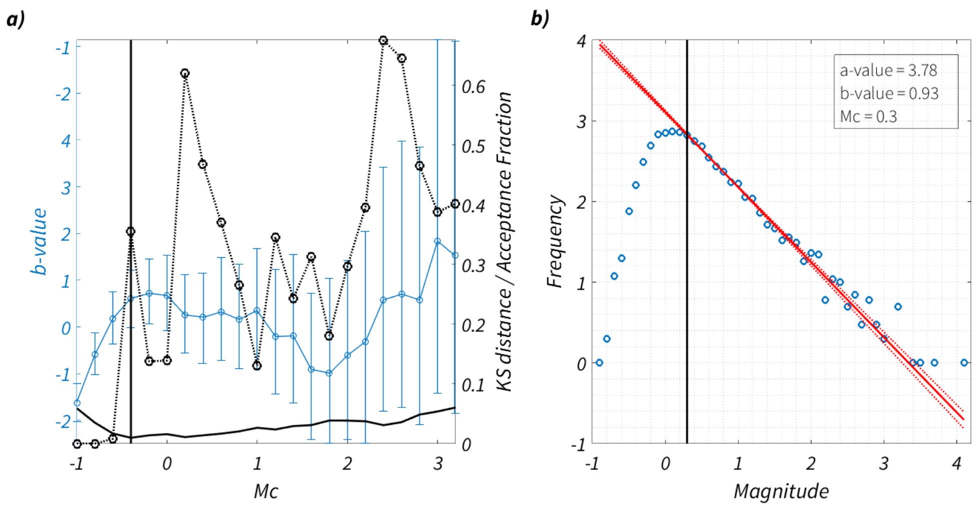


Figure 37. *COSEISMIQ catalogue between December 2018 and February 2021. Statistical catalogue analysis for the determination of a-value, b-value and Mc using a KS distance optimization function.*

Pseudo forecasting and model performance comparison

We performed a pseudo-forecasting modeling by employing three different models:

1. A model exploiting an empirical relationship between injection/production rate and seismicity (referred to as Shapiro's model, EM1);
2. A standard ETAS model, purely based on seismic catalog (the null hypothesis; EM2 - null);
3. A modified ETAS to account for spatially variable background (EM2- Var1)

More details about the models (1 to 3) can be found in Deliverable 6 and Deliverable 7. For each model, we take as a base Learning Period (LP) all the data recorded up to Feb. 1st, 2020. Using this data, we calibrate all the competing models. Then we perform a forecast for the next 30 days and update the LP with the additional information. We do this process of training and forecasting repeatedly until the end of the dataset, which for this deliverable is set to end of January 2021. Figure 38 shows the results for each individual model and we also computed for each model the so-called "N-test" by comparing the number of simulated events with the observation. We calculate for each pseudo-forecast (12 in total) the Log-Likelihood for each space bin in our computational domain. Such a Log-Likelihood is simply assumed to be the Poissonian for EM1, while exploiting the full probability distribution for the ETAS models (EM2-Null and EM2-Var1). The information gain is then calculated for both EM1 and EM2-Var with respect to the null hypothesis (EM2-Null), and for each forecast period (12 in total, each of 30 days). We have for each model a time-series illustrating how the information gain may change as new data are included in the LP. Figure 39 allows us to directly compare the models and provides then the basis for a weighing scheme.

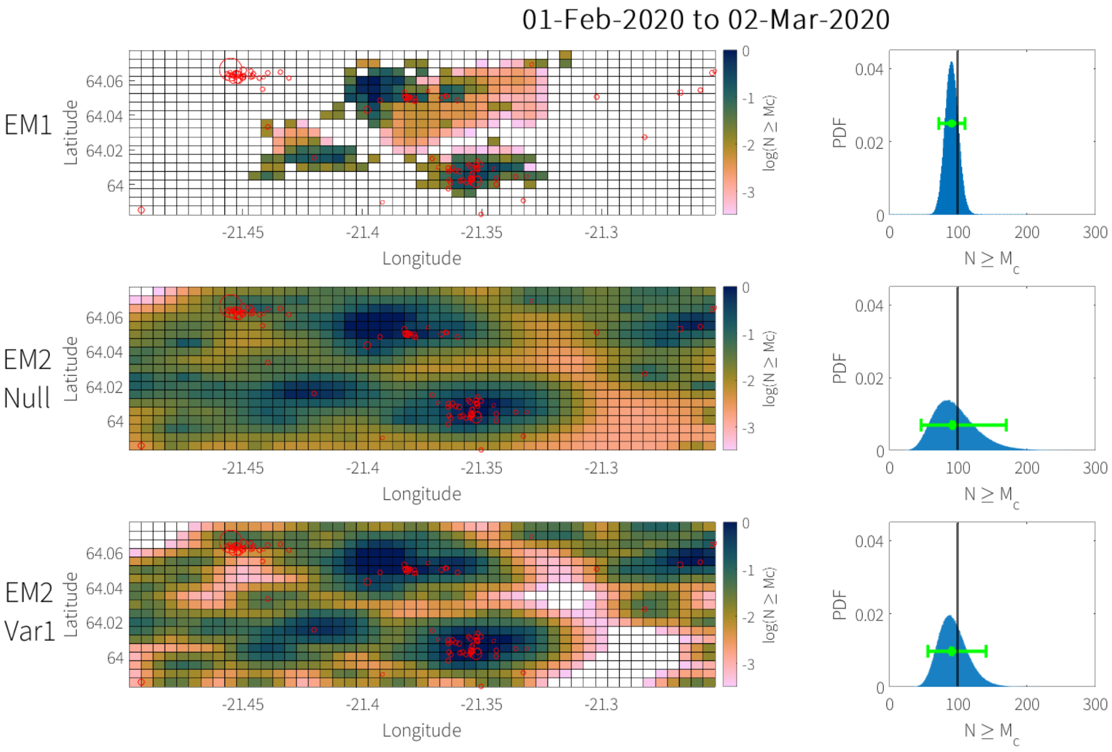


Figure 38. *Pseudo-forecasting results for period 01-Feb-2020 to 02-Mar-2020 (EM1 = Seismogenic index, EM2 = ETAS). On the rates maps (left) the red dots represent the recorded seismicity above completeness (size scaled with magnitude). The N-tests (right) show the output of each model (number of events) as a probability density function with its median and 5-95 quantiles in bright green, and the actual recorded number of events above completeness as a vertical black line.*

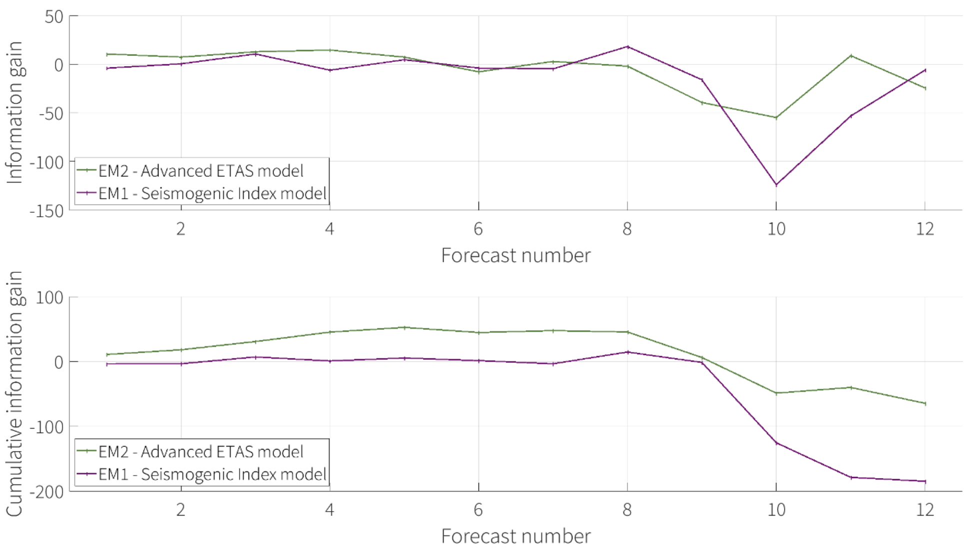


Figure 39. *Information gain for EM1 (purple) and EM2-var (green) - calculated relative to the null hypothesis (EM2 - null) for each successive 30 days forecast. For the comparison between EM1 and EM2-null we account for the log-likelihood computed only for the cells with active injection/production wells. Punctual information gain (top) and cumulative information gain (bottom).*

Both models show limited information gain compared to the null hypothesis, with the advanced ETAS model being slightly better for the first forecasts, and the EM1 model sometimes performing better. Both EM1 and EM2-var perform significantly worse in the forecasts corresponding to the periods with high seismic rates. Note that for this period all models fail the N-test. This means that the models are not efficient in handling sudden changes in the seismicity rate. A reduced forecasting period (e.g. only a few days) will help improve performance of ETAS models for high seismicity periods, while it is not yet clear whether these periods are linked to any human operation as EM1 does not capture any trend. The description of the repository is provided in Deliverable 7, codes and data needed for this pseudo-forecasting exercise are available at the following link:

https://github.com/RitzVanille/HengillSeismicityForecastingModels

The new hybrid model: ETAS+Hydro

An ETAS model views the seismicity as composed of background earthquakes and triggered earthquakes. To the classical ETAS seismicity kernel (g(x,y,t)), we add a new background that is linked to injected/produced volume:

$$\lambda(t,x,y,m|\mathcal{H}_t) = \boldsymbol{\mu_{hydro}(x,y,t)} + \mu + \sum_{i:t_i<t} g(t-t_i, x-x_i, y-y_i, m_i)$$

Where, $\boldsymbol{\mu_{hydro}(x,y,t)}$ is the induced seismicity rate that is linked to the injection rate at point (x,y,t):

$$\boldsymbol{I(x,y,t)} = \sum_{w=1}^{N} \frac{\boldsymbol{I_w}\left(t - \frac{\Delta r_w}{\boldsymbol{v}}\right)}{\left(1 + \frac{\Delta r_w}{\boldsymbol{\delta}}\right)^{1+\varphi}}$$

Where, *w* is the index of the well, Δr_w is the distance between the (*x,y*) and well location, (x_w, y_w). $\Delta r_w/v$ is the time taken by the fluid injected at the well *w* to reach (*x,y*) and parameters δ and φ control how the felt injection intensity decreases in space.

This model formulation allows to probabilistically distinguish:

- Events that are triggered by past seismicity.
- Spontaneously occurring background events
- Events induced by hydraulic injection.

Preliminary inversion results show that ~87% of events M≥0.3 are triggered by past seismicity, and only 13% is background seismicity. Of this background ~60 % of the events are linked to injection/production activities. The inverted diffusion speed v of the perturbation is of the order of ~110 m/ day. This research will continue into early 2023, as part of the PhD thesis of Vanille Ritz.

5. Discussion and Conclusions

COSEISMIQ-CH was conceived as a partner project to the EC COFUND GEOTHERMICA project COSEISMIQ, that was also coordinated by ETH Zurich (PI: Stefan Wiemer). The international dimension was extremely useful for the success of the project and enabled us to address important questions related to the Swiss geothermal roadmap in Iceland, a place with high induced seismicity but low seismic risk. The GEOTHERMICA framework allowed access to one of the most interesting geothermal sites on earth, so we could optimize our tools and methods and gain valuable hands-on experience while geothermal projects in Switzerland, such as the Haute Sorne project, were delayed. It also ensured knowledge transfer and collaboration of Swiss scientists and operators with some of the most experience scientists and operates in geothermal energy worldwide. The important lessons learned and valuable tools and knowledge developed in Iceland, as summarized in the previous chapters, could only be gained by working in Iceland, yet, they are universally valuable for geothermal projects worldwide, and they are particularly valuable for advancing the Swiss geothermal roadmap.

In our self-assessment, COSEISMIQ and COSEISMIQ-CH had a substantial and sustained impact in various dimensions, well in line with the expectations in the original proposal. Specifically, we like to highlight the following results:

- We demonstrated the successful operation of a high-quality dense seismic network in a geothermal area, under difficult environmental conditions. The lessons learned from the network design, maintenance and operation will influence future networks in Iceland and other geothermal areas, including Switzerland, they influence the way ISOR is operating seismic networks, and the influence the requirements and expectation of industry partners (OR and GES) on such networks so that the meet the needs of operators.
- We performed high resolution seismic imaging of the region using classical tomographic methods as well as ambient noise-based approaches; interpretations linked to structure, temperature, steam content and reservoir evolution. Results are documented in several peer reviewed publications (Sanches et al., 2021; Obermann et al., 2022). The results help OR to understand their geothermal resource and plan the optimized future use. Our analysis has advanced the state of the art in imaging geothermal resources and these advances will be used in future geothermal projects. The data and methods already form a key input for the GEOTHERMICA project DEEPEN (https://www.or.is/en/about-or/innovation/deepen/) coordinated by OR and targeted at De-risking Exploration for geothermal Plays in magmatic Environments.
- We produced a high-resolution earthquake catalog for the region, spanning nearly 3 years, forming the baseline for subsequent analyses of our team but also a highly useful resource for other researchers and future analysis (Grigoli et al., 2021). The catalog is open-access and published online on COSEISMIQ website; the catalog creation process and the catalog itself is documented in a Scientific Data publication to be fully reproducible and useful resource for future studies.
- We implemented an important improvement of the automated earthquake analyses workflows, fully embedded into the professional and operational earthquake analysis system SeisComp3 used at ISOR and SED, but also many other institutions worldwide. These tools are used for improved picking, association, template matching, cross-correlation and relative earthquake location. SeisComp3 and the new modules and workflows we developed are open source and hence a legacy of COSEISMIQ that will support numerous geothermal operations worldwide.

These improved procedures will for example support the seismic monitoring and analysis of SED and GES in the upcoming Haute-Sorne EGS project in Switzerland.

- We developed an enhanced geo-mechanical modeling and model testing framework for the Hengill area that promotes understanding of induced seismicity in the region but also forms the baseline for automated risk assessment and control as input for decision support of geothermal operators (foremost OR and GES in our case). By establishing which models can best forecast induced seismicity, we are giving the operators a solid baseline for planning and monitoring future field operations, balancing seismicity, and geothermal energy output. The modelling and testing framework is openly available and can be used by other operators and regulatory agencies.
- We developed a new generation of tools for determining earthquake source mechanics, exploiting the power of machine learning for a fast and reliable estimator faulting (Nooshiri et al., 2021). Understanding source mechanisms in near-real time is critically important for understanding the evolution of a geothermal resource, and the methods we introduced will be widely adopted, including the application to upcoming geothermal projects in Switzerland.
- We made substantial progress in developing and implementing workflows for automated and adaptive risk assessment in near real-time (ATLS: Adaptive Traffic Light System). A full probabilistic formulation of the seismic hazard and risk in the Hengill area that considers uncertainties in data and models in quantitative ways was implemented and tested. This work has benefitted from synergies with a real-time test of adaptive traffic light systems during a stimulation near Reykjavik (Geldinganes) in the fall of 2019 (with support from the EC FP7 project DESTRESS, Broccardo et al., 2020). These updated procedures and lessons learned have now firmly established ATLS approaches as a useful and sometimes required extension of classical traffic light approaches. They are now ready to be tested in future deep geothermal projects, such as Haute Sorne, and the findings and codes developed in COSEISMIQ also form the baseline of the GEOTHERMICA project DEEP (www.deepgeothermal.org) that support the Utah FORGE project.

6. Outlook and next steps

Managing induced seismicity while at the same time optimizing the reservoir properties of a deep geothermal system is a highly challenging and site- and project specific task. Balancing seismic risk and economic output are key objectives of all deep geothermal projects worldwide and especially needed in densely populated Switzerland, a country with a history of failed hydrothermal and EGS projects. We believe that COSEISMIQ has substantially advanced the state of the art in this domain in several respects outlines in previous chapters, but it would be presumptuous to assume that we have 'solved' the problem. In this respect, selected follow-up actions are suggested, and some of these are already well on the way:

- The adaptive traffic light approach should be further refined and tested in real-time conditions. A specific focus should be on Enhance Geothermal Systems (EGS) in crystalline basement because there the induced seismicity is a tool needed and the controllability of the systems is larger than in hydrothermal projects. EGS are also the one technology that is most promising for electrical power generation in Switzerland. This task has been up by the GEOTHERMICA project DEEP (www.deepgeothermal.org) (Figure 40), coordinated also by ETH but now extending the collaboration to partners from the USA. DEEP specifically targets knowledge transfer from the US Department of Energy P&D site FORGE to the EGS project in Haute Sorne (Jura).

***Figure 40**. DEEP Project Public Website*

- Machine Learning techniques have proven to be a powerful method for automated and rapid seismicity analysis via waveform scanning and for forecasting of the reservoir evolution. These innovative approaches, spearheaded in COSEIMQ for focal mechanism, are now being explored in the DEEP projects.
- Seismic imaging techniques can exploit the information from dense nodal arrays, and the EC GEOTHERMICA project DEEPEN (https://www.or.is/en/about-or/innovation/deepen/) aims to better understand the roots of magmatic geothermal systems through observations and modelling, as well as to develop techniques and work flows to find such deep and superhot resources. The project is a multinational collaboration among several universities, institutes, and energy companies (Figure 41) and it builds to a large part on the lessons learned from the imaging within the COSEIMQ project.

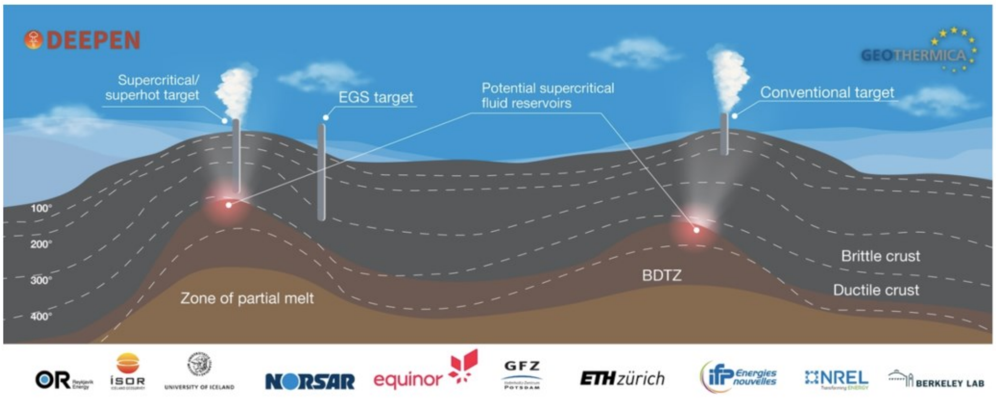


Figure 41. *Magmatic geothermal systems, in the context of DEEPEN schematic view of several plays (i.e., subsurface resources) in the same region.*

- Continued knowledge transfer to Swiss geothermal projects is an urgent and continuous need. The knowledge and software gained in the COSEISMIQ project is for example used directly in the context of the GEOBEST2020+ projects (Figure 42), sponsored by *energieschweiz*, to enhance the seismic monitoring capabilities of seismic networks but also to inform risk management and mitigation strategies.
- The Haute Sorne project operated by GES is now proceeding again, overcoming several years of standstill in light of public opposition. This is a highly important EGS projects, a key element of the Swiss geothermal roadmap. The achievement of COSEISMIQ will be used by GES, but also by the SED, to enhance the seismic safety of the projects and to improve the economic output.

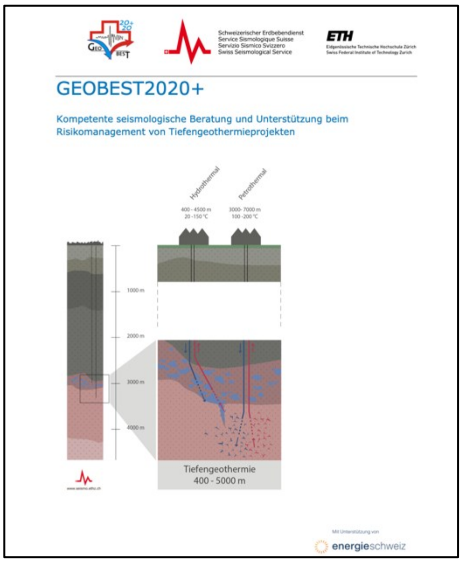


Figure 42. *GEOBEST 2020+*

7. National and international cooperation

COSEISMIQ was, as explained before, designed to be an international collaboration project, bringing together leading institutions from Iceland, Ireland, Germany, and Switzerland (Figure 43). The consortium contained academic partners as well as industry partners. The two Swiss representatives, GeoEnergie Suisse AG (GES) and the Swiss Seismological Service (SED) worked very closely together in the project, with intense knowledge and tool exchange for mutual benefit.

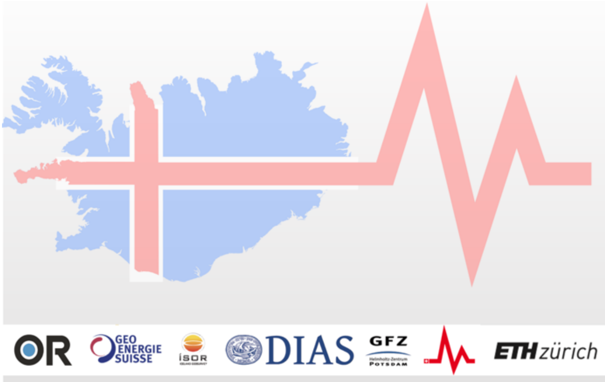


Figure 43. *COSEISMIQ Partners*

The Consortium Agreement has been signed between the partners in May 2018, which is based on the DESCA model. The purpose of this Consortium Agreement is to specify with respect to the Project the relationship among the parties, in particular concerning the organization of the work between the partners, the management of the project and the rights and obligations of the partners. In our opinion, the project has been well managed, the CA has been followed by all partners and the cooperation between partners has been good.

The project started with the Kick-Off Meeting in Reykjavik in 2018, and the first annual meeting has been held in Zurich. Even after the hit of the pandemic, the national and international COSEISMIQ teams have been collaborating very well, by frequent zoom meetings of the whole consortium. The project meetings of the whole group with their timeline are listed in Figure 44. The project meetings helped tracking the project's progress, the timeline and budget, strengthened the knowledge transfer between partners and enabled the dialogue between academic and industrial partners. The agenda of the meetings have been shared prior to the meeting with the project participants, the meeting minutes have been taken and shared by the whole group through the project's Intranet.

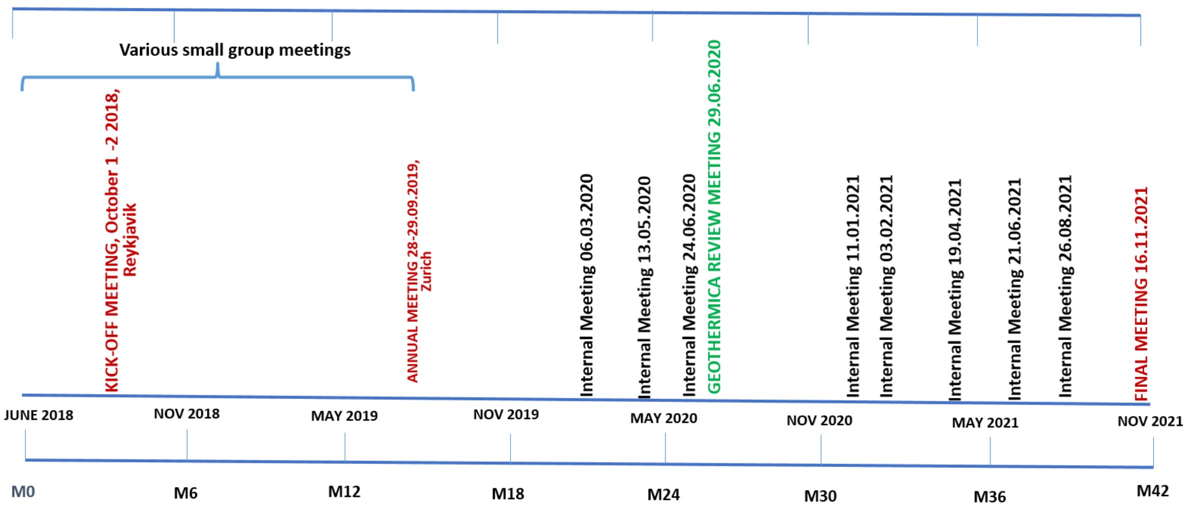


Figure 44. *The project meetings that are held throughout the project.*

The project management created an Intranet on Alfresco platform (Figure 45) to share project information such as agreements, guidelines, reports, deliverables, presentations, meeting minutes etc. The main purpose of the intranet is to provide a common space to share project documents, therefore it is the main document repository for COSEISMIQ. We used the Intranet not only as a project repository, but also a space to support the timely implementation of the project by keeping all project information together under one site, to keep track of events, tasks, deadlines related to the COSEISMIQ project. The participants could follow the progress and deadline of the deliverables and milestones under the "Site Data Lists". A snapshot from the project's intranet is shown below.

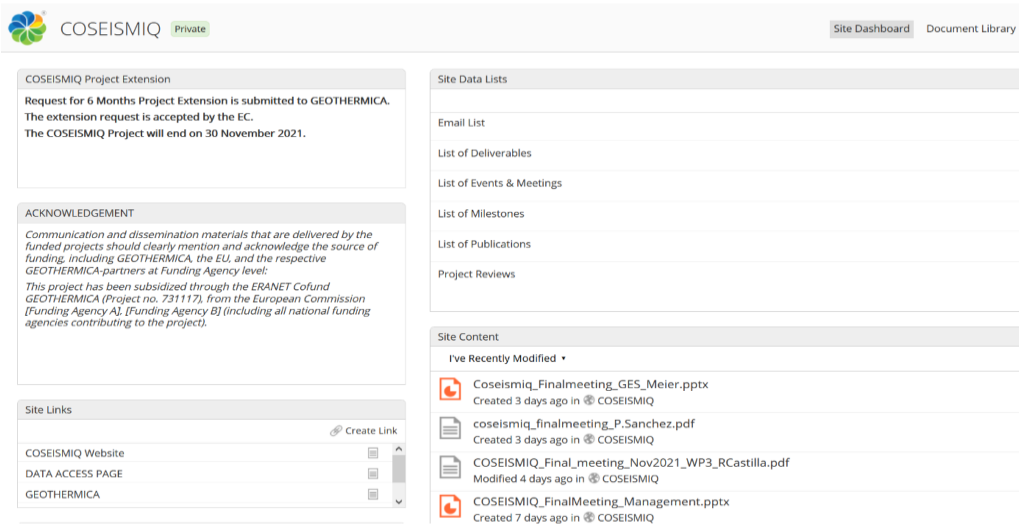


Figure 45. *Snapshot from the project's internal document and information sharing platform (intranet), Alfresco-Coseismiq site*

The project management was responsible for tracking the project's progress; the reporting, the timely submission of the deliverables and achievement of the milestones. The responsible partners have been sent reminders in advance of the reporting deadlines. Overall, the project's progress has been timely, with minor delays in certain activities that are reported in the half yearly traffic light reports (TLRs).

8. Communication

We created the COSEISMIQ website http://www.coseismiq.ethz.ch/ (Figure 46). On the website, we share general project information such as project overview, description of work packages, partners' information, funding information and dissemination. The major dissemination information shared on the website currently includes the COSEISMIQ seismic network, station information, the seismic catalogs created during the project, and the deliverables. The publications will also be shared on the website as they become available. All the open access tools and software will be linked to the website under project dissemination.

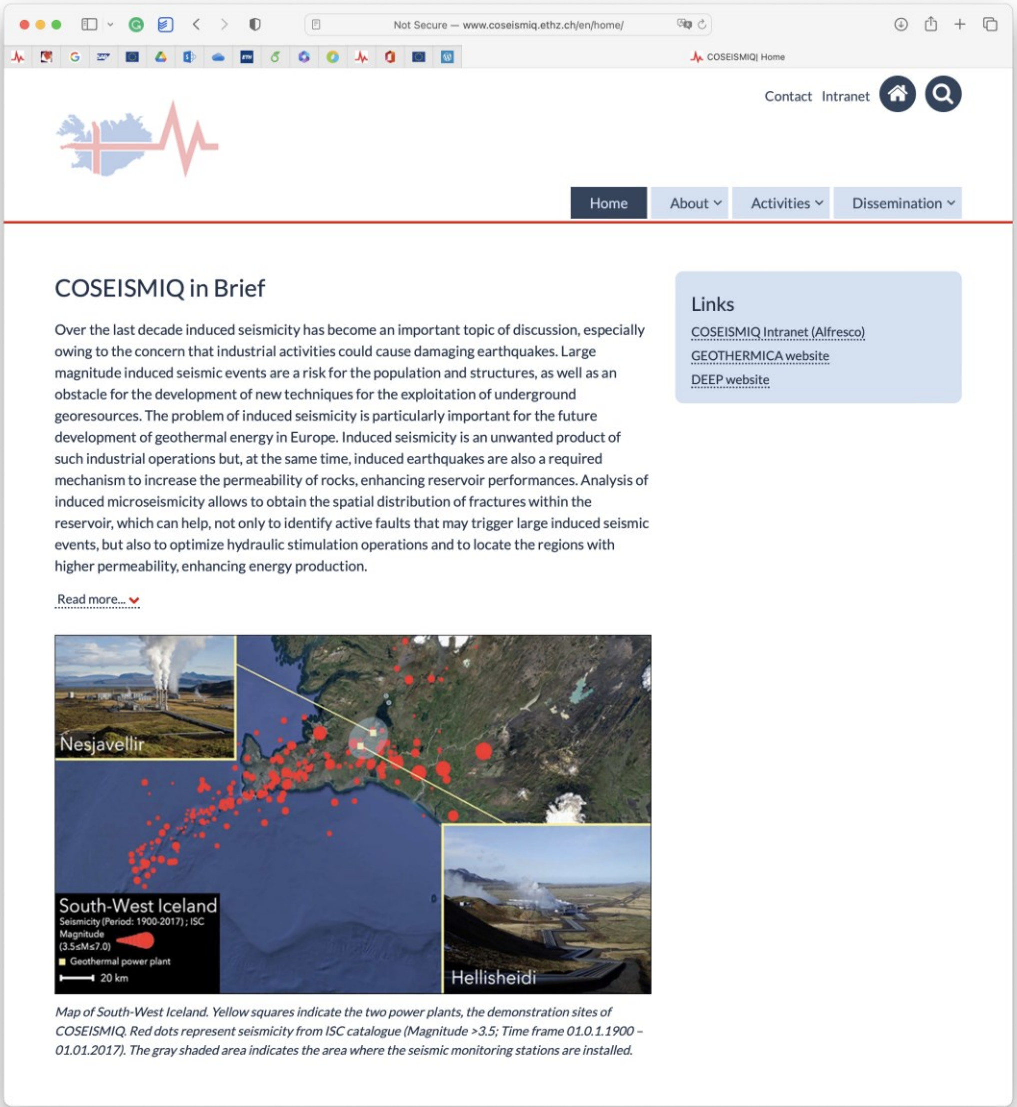


Figure 46. *Snapshot from the COSEISMIQ website, http://www.coseismiq.ethz.ch/*

To present COSEISMIQ, many presentations were given at national and international workshops and meetings, and we are continuing to promote COSEISMIQ results.

1. Internal presentation for the staff at ISOR – Kristjan Agustsson, Oct. 2018
2. Presentation at the 2018 Hengill workshop at the Icelandic Meteorological Office – Thorbjorg Agustsdottir, Dec. 2018
3. Presentation at the 2019 Hengill workshop at Reykjavik Energy – Sigridur Kristjansdottir, Dec. 2019
4. Presentation at the 2019 Schatzalp Workshop on Induced Seismicity – Thorbjorg Agustsdottir, Mar. 2019
5. Presentation at the 17th Swiss Geoscience Meeting (Fribourg) - November 2019
6. Presentation at the EGU General Assembly (online) - May 2020
7. Conference paper for the American Rock Mechanics Association 54th Symposium "Modelling Induced Seismicity with a Hydraulic-Mechanical-Stochastic Simulator: Review of Case Studies." - 2020
8. Conference paper for the World Geothermal Congress "Preliminary Modelling Activities for an Adaptive Traffic Light System for the Hengill Geothermal Field" - 2020/2021
9. Nooshiri, N., Bean, C. J., Grigoli, F., and Dahm, T.: Towards Real-Time Moment Tensor Inversions in a Data Rich Micro-Seismic Environment using Deep Learning, EGU General Assembly 2021, online, 19–30 Apr 2021, EGU21-12686, https://doi.org/10.5194/egusphere-egu21-12686, 2021.

We also published several internal reports:

1. 2019 Yearly report for the Icelandic Technological Fund – Sigridur Kristjansdottir, 2019
2. 2020 Yearly report for the Icelandic Technological Fund – Sigridur Kristjansdottir, 2020
3. Final report for the Icelandic Technological Fund - Sigridur Kristjansdottir, 2022
4. 2018 Midterm report for the Icelandic Technological Fund – Kristjan Agustsson, 2018
5. 2019 Midterm report for the Icelandic Technological Fund – Sigridur Kristjansdottir, 2020
6. 2020 Midterm report for the Icelandic Technological Fund – Sigridur Kristjansdottir, 2020
7. Swiss Annual Report to BFE, 2019
8. Swiss Annual Report to BFE, 2020
9. Swiss Final Report to BFE, 2021

A total of 7 deliverables are openly available from the COSEISMIQ web site:

D1: Implementation of advanced micro-seismicity monitoring tools in SeisComp3 modules and workflows optimized for geothermal plays.

D2: Implementation of advanced imaging tools in workflows optimized for geothermal plays.

D3: Coupled geo-mechanical and reservoir modeling framework implemented within RISC, ready for real- time application and adapted to Icelandic conditions. Integration of the methods developed in the WP2, WP3 and WP4 in a single tool (the RISC tool).

D4: Risk and Safety assessment calibrated for Icelandic conditions and extended to allow the distinction between natural and induced seismicity.

D5: Offline calibration and performance evaluation of the RISC system

D6: Demonstration of the RISC decision support framework at the Hengill site in real time

D7: RISC tool ready for other commercial applications in Europe.

9. Publications (status 7/2022, additional publications are being prepared).

1. Broccardo, M., Mignan, A., Grigoli, F., Karvounis, D., Rinaldi, A. P., Danciu, L., Hofmann, H., Milkereit, C., Dahm, T., Zimmermann, G., Hjörleifsdóttir, V., and Wiemer, S.: Induced seismicity risk analysis of the hydraulic stimulation of a geothermal well on Geldinganes, Iceland, Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2019-331, 2020.
2. Nooshiri, N., Bean, C. J., Dahm, T., Grigoli, F., Kristjánsdóttir, S., Obermann, A., & Wiemer, S. (2021). A Multi-Branch, Multi-Target Neural Network for Rapid Point-Source Inversion in a Micro-Seismic Environment: Examples from the Hengill Geothermal Field, Iceland. *Geophysical Journal International*, ggab511, https://doi.org/10.1093/gji/ggab511
3. Sánchez-Pastor, P., Obermann, A., Reinsch, T., Ágústsdóttir, T., Gunnarsson, G., Tómasdóttir, S., Hjörleifsdóttir, V., Hersir, G. P., Ágústsson, K. and Wiemer S. (2021) Imaging high-temperature geothermal reservoirs with ambient seismic noise tomography, a case study of the Hengill geothermal field, SW Iceland, Geothermics, 96, https://doi.org/10.101H/j.geothermics.2021.102207
4. Ritz, V. A., Rinaldi, A. P., Karvounis, D., Castilla, R., Colas, E., Meier, P. M., Wiemer, S., Hjörleifsdóttir, V., Gunnarsson G., COSEISMIQ team. (2021) Preliminary Modelling Activities for an Adaptive Traffic Light System for the Hengill Geothermal Field. Proceedings World Geothermal Congress 2020+1, 2, 3861-3869.
5. Ritz, V.A., A. P. Rinaldi, S. Nandans, S. Wiemer, and the COSEISMIQ team.Model comparison for induced seismicity in Hengill. The journal is not decided yet but maybe JGR or GRL. In preparation.
6. Grigoli, F., Clinton, J., Diehl, T., Kaestli, P., Scarabello, L., Ágústsdóttir, T., Kristjánsdóttir, S., Magnusson, R., Bean, C., Broccardo, M., Cesca, S., Dahm, T., Hjörleifsdóttir, V., Mena Cabrera, B., Milkereit, C., Nooshiri, N., Obermann, A., Racine, R., Rinaldi, A.P., Ritz, V., Sánchez-Pastor, P., Wiemer, S. (2022) Monitoring microseismicity in the Hengill Geothermal Field, Iceland, Scientific Data, 9, 10.1038/s41597-022-01339-w.
7. Obermann, A., Duran, A., Ágústsdóttir, T., Diehl, T., Wu, S.-M., Sánchez-Pastor, P., Kristjansdóttir, S., Hjörleifsdóttir, V., Wiemer, S., Páll Hersir, G. Seismicity and 3-D body-wave velocity models across the Hengill geothermal area, SW Iceland, Frontiers in Geosciences, in press.
8. Rossi, C., Grigoli, F., Cesca, S., Heimann, S., Gasperini, P., Hjörleifsdóttir, V., Dahm, T., Bean, C., Wiemer, S., Scarabello, L., Nooshiri, N., Clinton, J., Obermann, A., Ágústsson, K., Ágústsdóttir, T. (2020) Full-Waveform based methods for microseismic monitoring operations: An application to natural and induced seismicity in the Hengill geothermal area, Iceland, Advances in Geosciences, 54, 129-136, doi: 10.5194/adgeo-54-129-2020

The following deliverables are submitted throughout the project:

Deliverable 1: Implementation of advanced micro-seismicity monitoring tools in SeisComp3 modules and workflows optimized for geothermal plays.

Deliverable 2: Implementation of advanced imaging tools in workflows optimized for geothermal plays.

Deliverable 3: Coupled geo-mechanical and reservoir modeling framework implemented within RISC, ready for realtime application and adopted to Icelandic conditions. Integration of the methods developed in the WP2, WP3 and WP4 in a single tool (the RISC tool).

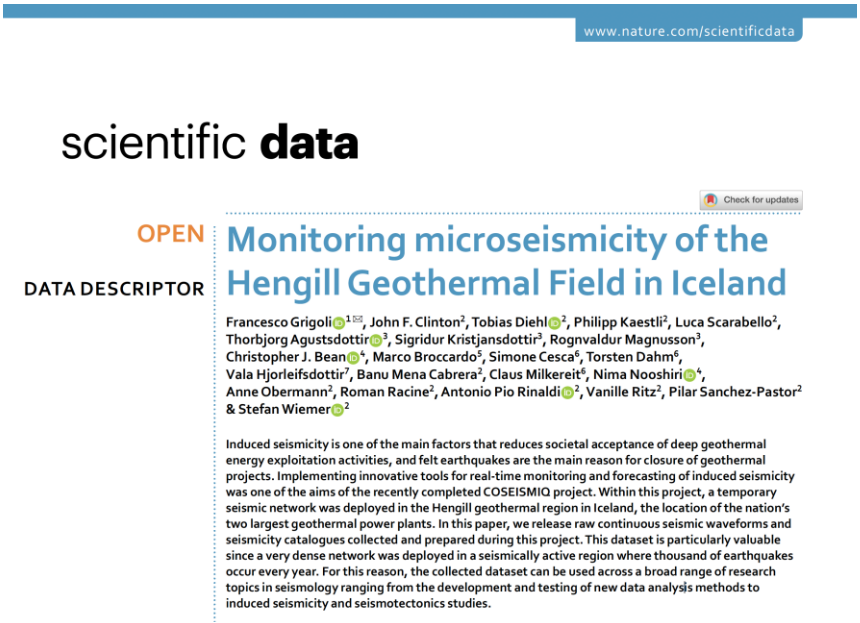
Deliverable 4: Risk and Safety assessment calibrated for Icelandic conditions and extended to allow the distinction between natural and induced seismicity.

Deliverable 5: Offline calibration and performance evaluation of the RISC system

Deliverable 6: Demonstration of the RISC decision support framework at the Hengill site in real time

Deliverable 7: RISC tool ready for other commercial applications in Europe

The seismic data collected by the project was published in scientific data (Figure 47), including all relevant access information and meta-data.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DATA DESCRIPTOR

Monitoring microseismicity of the Hengill Geothermal Field in Iceland

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Induced seismicity is one of the main factors that reduces societal acceptance of deep geothermal energy exploitation activities, and felt earthquakes are the main reason for closure of geothermal projects. Implementing innovative tools for real-time monitoring and forecasting of induced seismicity was one of the aims of the recently completed COSEISMIQ project. Within this project, a temporary seismic network was deployed in the Hengill geothermal region in Iceland, the location of the nation's two largest geothermal power plants. In this paper, we release raw continuous seismic waveforms and seismicity catalogues collected and prepared during this project. This dataset is particularly valuable since a very dense network was deployed in a seismically active region where thousand of earthquakes occur every year. For this reason, the collected dataset can be used across a broad range of research topics in seismology ranging from the development and testing of new data analysis methods to induced seismicity and seismotectonics studies.

Figure 47. *Snapshot from the COSEISMIQ website, http://www.coseismiq.ethz.ch/*

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