COntrol **SEIS**micity and **M**anage **I**nduced earth**Q**uakes (**COSEISMIQ**)

Deliverable 5

Deliverable 5: Offline Calibration and Performance Evaluation of the RISC System

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Contents

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Summary

The operation of the Coseismiq Network is extended until Summer 2021. Excellent data is being collected and fully automated real-time processing chain is developed. There is significant improvement in seismic processing with the new configuration, especially on the detection of magnitudes. There is substantial improvement on the catalogue; the robustness and completeness of the catalogue are being significantly enhanced. A high-resolution earthquake catalogue for the region is complete and the new catalogue is tested to adopt full automation. This forms the baseline for subsequent analyses.

An enhanced geo-mechanical modelling framework for the Hengill area that promotes understanding of induced seismicity in the region has been developed. We adjusted our existing tools and workflows developed in the past two years and enhanced in WP2-4 to Icelandic geothermal play conditions, calibrating them on past geothermal sequences and seismic data. This is done in a pseudo-prospect sense, replaying offline the seismic and hydraulic data such that the systems are adapting as new data become available. We compared the currently implemented built-in empirical model with the enhanced geo-mechanical model and conclude that no modifications are needed for a large-scale application. This will form the baseline for automated risk assessment and provides input for decision support of geothermal operators.

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Data

In this section we summarized the seismic and hydraulic data that have been collected during the COSEISMIQ project. The seismic data accounts for the events collected at the COSEISMIQ stations in the Hengill area, while hydraulic data were provided by the Icelandic partner OR (Reykjavik Energy).

Seismic data

COSEISMIQ catalogue

High accurate hypocenter locations and magnitude estimates are needed to better understand the relationship of injection and induced seismicity in the Hengill geothermal field, SW Iceland. In order to obtain reliable seismic event locations, we need to have an accurate velocity model, which well represents the study area. Here we built this model by solving the coupled hypocenter-velocity problem using a subset of 130 high-quality manually picked events from November 2018 to September 2020 occurred in the Hengill area (Figure 1). We then use the Hengill 1-D model to calibrate the automatic seismic data analysis workflow introduced in the previous deliverable (2.1) and relocate hypocenter parameters. For the determination of the minimum 1D model we manually picked 7647 Pg and 5260 Sg phases with $ML \geq 1.5$, following the guidelines of Diehl et al. (2012). Each phase is classified according to its uncertainty (picking error). Phases with larger uncertainty classes would have lower weights during the joint hypocenter-velocity inversion (e.g., Kissling et al. 1994).

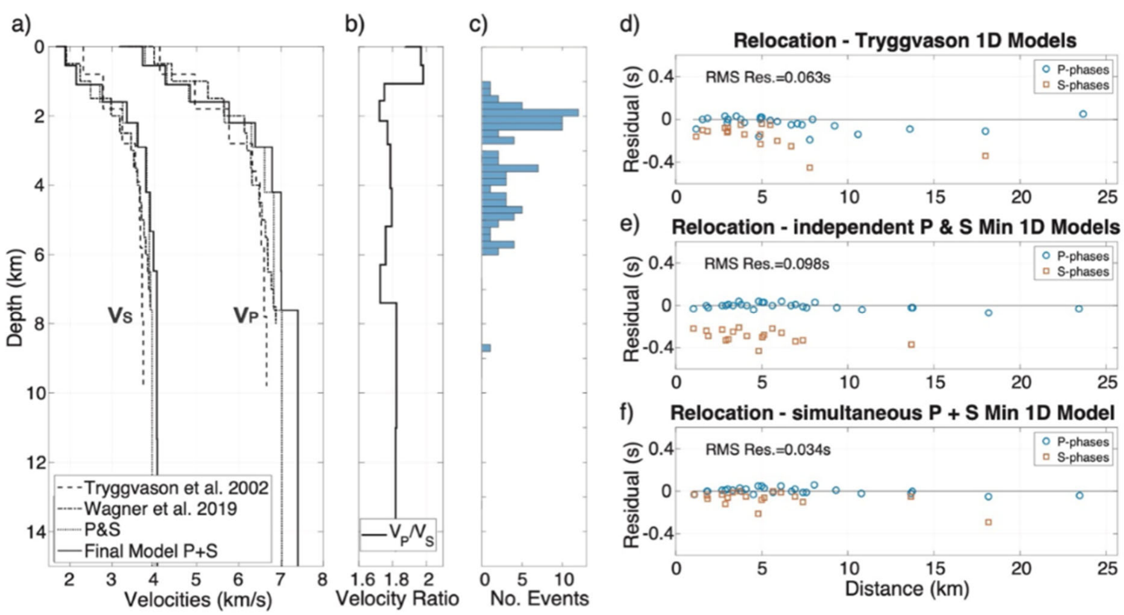

Figure 1: a) Different 1-D velocity models used in the relocation of events: The model from Tryggvason et al. (2002) used as the routine location model of ISOR, Wagner et al. (2019), P and S (P&S) independent 1-D models and P+S models from simultaneous inversion of P and S data. b) Vp/Vs ratio of the models obtained by the simultaneous P+S inversion. c) Focal-depth distributions derived from a simultaneous P+S inversion. d)-f) Travel-time residuals for the relocation of an arbitrary event (17.06.2020 – 02:55:25, $1.4M_L$) in the Hengill region. (d) using the model of Tryggvason et al. (2002), (e) using P and S (P&S) independent 1-D models and (f) using P+S models from simultaneous inversion.

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Finally, to detect, locate and estimate the magnitude of seismic events we used the open-source software package SeisComP. In this project we make use of SeisComP's modular structure to implement a workflow for automated offline analysis of seismicity. In this implementation SeisComP modules for phase picking, phase association, event detection, location and magnitude estimation are applied in sequential order with the output of the first being the input of the second. The workflow starts with the automatic phase picking module based on the Akaike Information Criteria (AIC picker) for both P and S phases (e.g., Zhang et al., 2003). Phase association and event detection is then performed using the module SCANLOC (Grigoli et al., 2018), while a refined location is estimated using the SCRELOC module, which uses the NonLinLoc algorithm (Lomax et al., 2000) combined with minimum 1-D velocity models (e.g., Kissling, 1988; Kissling et al., 1994) developed within this project. Finally, event magnitude and a location quality score are calculated. The final automated catalogue consists of about 16000 events (for the period 01/12/2018-01/09/2020) of which about 6000 are characterized by a high-quality location (Figure 2).

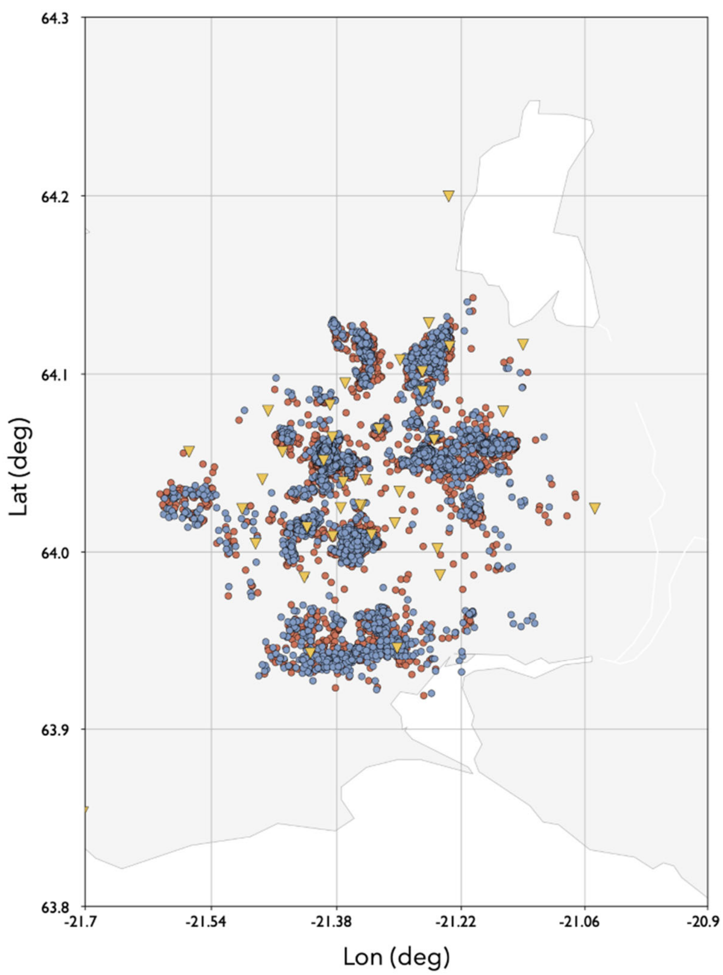

Figure 2: Comparison between high quality (score >-1) automated locations (red dots) with manual locations (blue dots) extracted from the ISOR catalogue for the period 01/12/2018-01/09/2020

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The distribution of the seismic events is highly clustered as previously shown in Figure 2, with most of clusters coinciding with production and injection areas. We observe that 41% of the seismic events are clustered at around 2 km depth and 16% at around 4 km depth. Additionally, there are no events in the very shallow regions above 1 km depth.
Figure 3 shows the frequency-magnitude distribution for a medium quality catalog (i.e. with and event-score >= -50, RMS<=0.2 s, number of observation per event >=0, distance to closest station <=10 km and a gap <250˚). The b-value, calculated with the software ZMAP (Wiemer, 2001) is 0.94, with a magnitude of completeness Mc=0.

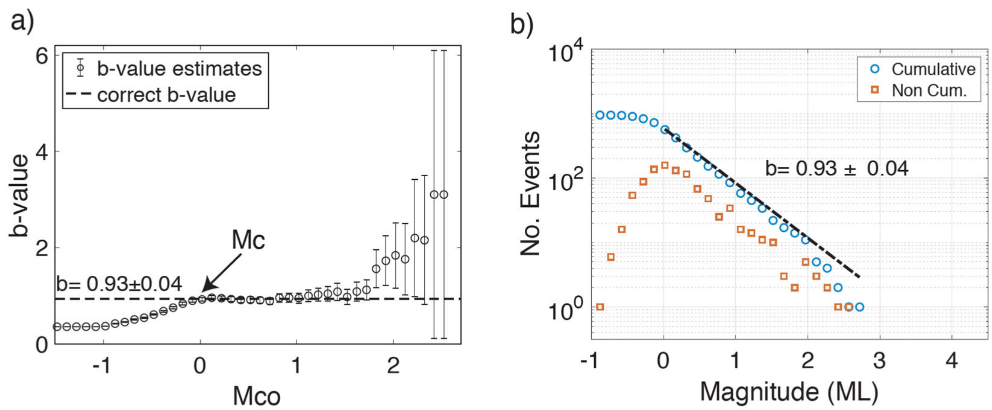

Figure 3: Frequency Magnitude Distribution of the catalogue for December 2018-September 2020

SIL catalogue 2011-2012 for Húsmúli

To calibrate some of the model, in particular for the reinjection areas, it is useful to analyse the seismicity at the starting of the injection operation. Injections at the Húsmúli reinjection zone started consistently in 2011, hence we used the SIL catalogue for the period Sept. 2011-April 2012. Those first eight months of consistent injection have seen a very strong seismic response. Figure 4 shows the frequency magnitude distribution, with b-value and Mc estimate. Further details about the seismicity of this period can be found in Deliverable 3.

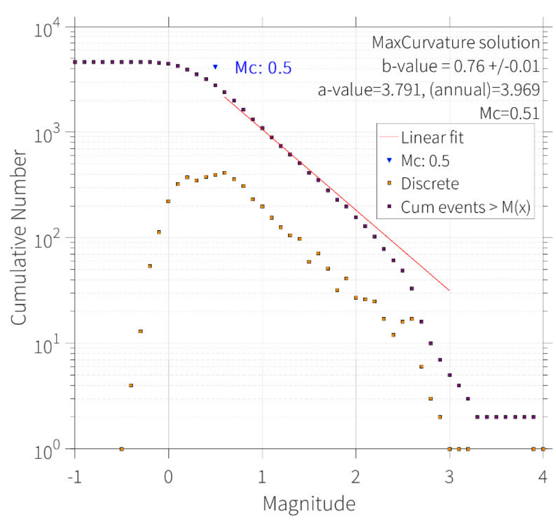

Figure 4: Frequency Magnitude Distribution of the SIL catalogue for Húsmúli September 2011 to end of April 2012 (Zmap)

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Hydraulic data

Hydraulic data covering the COSEISMIQ period were only obtained in December 2020. Data covers all re-injection activities up to early December 2020 (10 minutes data), while production data are limited to the period up to December 2019 and only with a monthly frequency). Table 1 summarizes the available hydraulic data provided by RO.

Table 1: Availability of hydraulic data for 2019

Zone	Well	Type (for 2019)	Q (flow rate, kg/s)	P (pressure, bar)	T (temperature, °C)	Frequency
Húsmúli	HN09	Injection	✓	✓		10 minutes
	HN12	Injection	✓	✓		10 minutes
	HN14	Injection	✓	✓	✓	10 minutes
	HN16	Injection	✓	✓		10 minutes
	HN17	Injection	✓	✓		10 minutes
Sleggja	HE05	Production	✓	✗	✗	monthly
	HE46	Production	✓	✗	✗	monthly
	HE13	Injection	✓	✗	✓	10 minutes
	HE40	Injection	✓	✓	✓	10 minutes
	KH01	Injection	✓	✓	✓	10 minutes
Skarðsmýrarfjall	HE23	Production	✓	✗	✗	monthly
	HE24	Production	✓	✗	✗	monthly
	HE25	Production	✓	✗	✗	monthly
	HE38	Production	✓	✗	✗	monthly
	HE37	Injection	✓	✓	✗	10 minutes
	HE39	Injection	✓	✓	✗	10 minutes
Gráuhnúkar	HN03	Injection	✓	✓		10 minutes
	HN05	Injection	✓	✓		10 minutes
	HN06	Injection	✓	✓	✓	10 minutes
	HN07	Injection	✓	✓		10 minutes
	HN08	Injection	✓	✓		10 minutes
	HN10	Injection	✓	✓		10 minutes
Hverahlíð	HE36	Production	✓	✗	✗	monthly
	HE53	Production	✓	✗	✗	monthly
	HE54	Production	✓	✗	✗	monthly
	HE60	Production	✓	✗	✗	monthly
	HE61	Production	✓	✗	✗	monthly
Hellisheiði	HE03	Production	✓	✗	✗	monthly
	HE04	Production	✓	✗	✗	monthly
	HE06	Production	✓	✗	✗	monthly
	HE07	Production	✓	✗	✗	monthly
	HE09	Production	✓	✗	✗	monthly
	HE11	Production	✓	✗	✗	monthly
	HE12	Production	✓	✗	✗	monthly

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	HE14	Production	✓	✗	✗	monthly
	HE15	Production	✓	✗	✗	monthly
	HE16	Production	✓	✗	✗	monthly
	HE17	Production	✓	✗	✗	monthly
	HE18	Production	✓	✗	✗	monthly
	HE19	Production	✓	✗	✗	monthly
	HE27	Production	✓	✗	✗	monthly
	HE29	Production	✓	✗	✗	monthly
	HE31	Production	✓	✗	✗	monthly
	HE32	Production	✓	✗	✗	monthly
	HE33	Production	✓	✗	✗	monthly
	HE34	Production	✓	✗	✗	monthly
	HE41	Production	✓	✗	✗	monthly
	HE42	Production	✓	✗	✗	monthly
	HE44	Production	✓	✗	✗	monthly
	HE45	Production	✓	✗	✗	monthly
	HE47	Production	✓	✗	✗	monthly
	HE48	Production	✓	✗	✗	monthly
	HE50	Production	✓	✗	✗	monthly
	HE51	Production	✓	✗	✗	monthly
	HE56	Production	✓	✗	✗	monthly
	HE58	Production	✓	✗	✗	monthly
	HE59	Production	✓	✗	✗	monthly

Given the constraint in hydraulic data availability, we focus here only on the data for 2019. Figure 6 shows the cumulative volume injected/produced in the Hengill geothermal area in the entire year. The largest volume is being injected at Húsmúli, reaching about 5 million m^3 over the one-year period. Given the large scale of the field, we assume in Figure 5 that the fluid is homogenously distributed around each injection/production well, and averaged over a grid with spacing of 0.005˚ (~ 500 m).

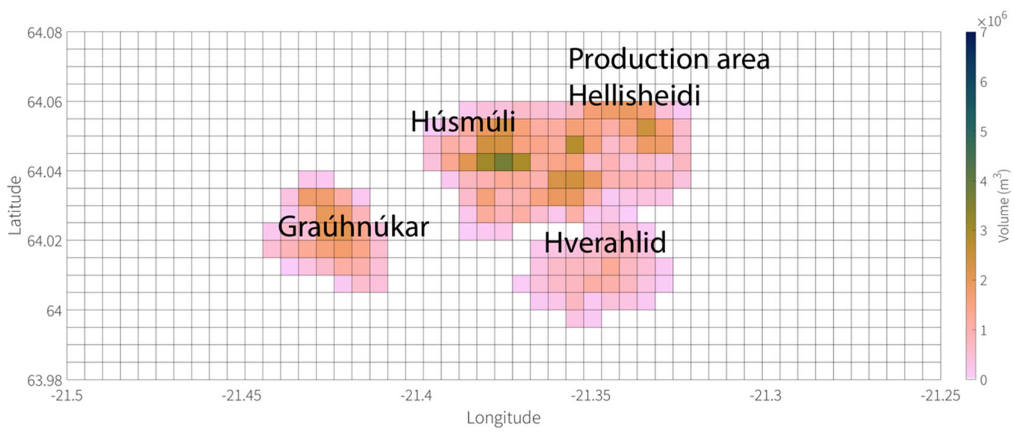

Figure 5: Fluid volume injected/produced in the entire Hengill area.

Reinjection at Húsmúli 2011-2012

While the calibration of the model is focused for the duration of the COSEIMIQ project, as highlighted above we use the data for the reinjection area of Húsmúli for validating the model. During the period Sept. 2011-April 2012. The injection rates (Figure 6-A) show dominance of well HN12 at the beginning of the reinjection, then picked up by wells HN16 and HN17. The deepest well, HN09, has a relatively low injectivity due to it penetrating the consolidated basaltic layer and thus having low injectivity.

The distribution of the volume in space depends on some assumptions: if assuming homogeneous permeability around each well, then a circular averaging is better suited (Figure 6-B), while assuming a fracture system NS, an elliptic averaging would better represent the permeability anisotropy in the direction of the fracture network (Figure 6-C). Given the small scale of the Húsmúli reinjection area, we average the injected volume in a grid with spacing 0.02˚ (200 m).

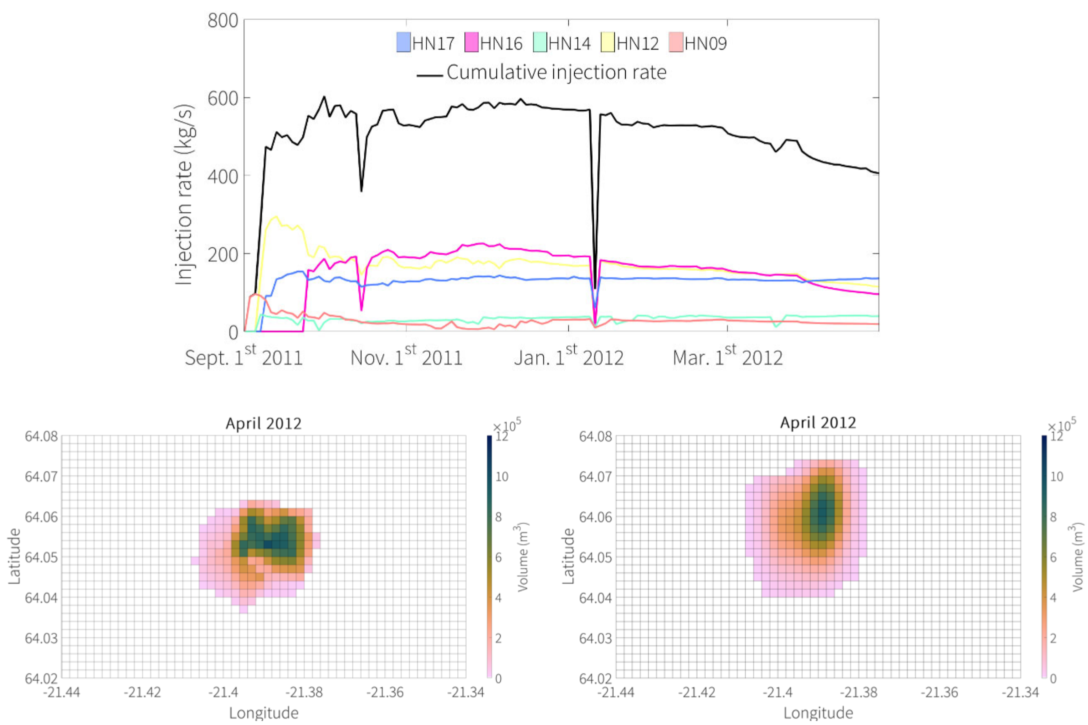

Figure 6: (top) Injection rate for the individual wells and cumulative injection rate of the Húsmúli reinjection zone; (bottom) distribution of volume accounting for elliptic averaging approximating the NS fracture network (Deliverable 3)

Induced Seismicity Forecasting Models

In this section we briefly summarize the models used during the testing phase for COSEISMIQ. Table 2 shows all the model variations planned for future development of the RISC tool. At the moment only two models are operative for real-time application: EM1 (Seismogenic Index Model) and HM1 (1D fluid-slow simulator and pressure-based seismicity). All the other models are available as scientific software, and are particularly useful for testing various hypothesis and to validate simplified approached. In COSEISMIQ we have used the model HM2 (TOUGH2-seed) for modelling the reinjection area of Húsmúli for the period 2011-2012. In this deliverable we calibrate the model EM1 for both the field scale and the small scale of Húsmúli and for this latter we provide a comparison of the real-time model with a physics-based approach provided by HM2. We neglect model HM1 as it is not developed for multi-well configuration, and it is therefore not usable for COSEISMIQ.

Table 2: Summary of models currently being developed/considered for the RISC tool. For COSEISMIQ, EMs have been evaluated as the most suitable given the several wells and seismicity related to both production and re-injection activities.

Models		**EM1**	**EM2**	**HM1**	**HM2**	**HM3**
Forecasts		deterministic	probabilistic	deterministic	probabilistic	probabilistic
Flow modelling	*Simulator*	None	None	Transin	TOUGH2	HFR-Sim
	Reservoir dimensions			1D Fractured Continuum	3D Fractured Continuum	3D Discrete Fractured
	Multiphase			no	yes	no
Seismicity modelling		Shapiro-like/Static Stress Transfer	Epidemic-Type Aftershock Sequence (ETAS)	Kernel Distributions for Converting Any Pressure to Seismicity (KD_CAPS)	Seeds or KD_CAPS	Seeds

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EM1 – Seismogenic index model

This model is based on a purely empirical relationship between the injected volume and the seismicity. Various versions exist in the literature after the pioneering work of the Shapiro's group (e.g. Shapiro, 2018). Other forms account, for example, for the injection rate rather than the injected volume, as well as for an exponential decay of the seismicity after shut-in (Mignan et al., 2017; Broccardo et al., 2017). A similar model was described in Deliverable 4. The proposed model provides a deterministic forecast with no flow model, and the expected number of events follow the relationship:

$$N_{exp,\geq m_c} = V_{inj/prod}(t)10^{\Sigma - bm_c}$$

Here for simplicity, we do not account for the seismicity decay after shut-in (as the injection is still current) and consider both the injected and produced volume (Figure 5-6). Given its simplicity, this model is ideal for real-time application, in particular for large scale region like the Hengill area where both injection and production activities occur.
The three model parameters are estimated independently: b and m_c are estimated from the seismic catalog, while the seismogenic index Σ is estimated by minimizing the residual in the temporal evolution with a least squares approach. More sophisticated method accounts for maximum likelihood and/or Bayesian parameter estimates (Broccardo et al., 2017), and will be used in the future.

HM2 – TOUGH2-Seed hybrid model

This model accounts for a hybrid approach coupling two modules for simulating fluid flow and seismicity. The flow module is based on TOUGH2: a multiphase multicomponent fluid flow simulator in a porous fractured media. The seismicity module is a stochastic geomechanical code (Rinaldi & Nespoli, 2017). The large scale TOUGH2 model for the Hengill geothermal field was provided by Reykjavik Energy. The model for Hengill covers an area of 50 km by 50 km with a depth of 3000 m. It comprises nearly 43.000 elements categorized into 43 reservoir domains. The mesh is centred around the production areas West of Húsmúli, with a refinement of the grid in the centre. 129 production and 31 injection time series cover multiple decades of hydraulic data (source/sinks since the 1970s, production since the 1990s). In this part, we focus on the Húsmúli reinjection area between September 2011 and May 2012., by accounting for the flow rate shown in Figure 6.
The seismicity is simulated by means of a seed-based model: a random distribution of hypothetical hypocentres that reactivates when failure conditions are satisfied. We run 48 single realisations (i.e. single distribution of the seeds) with the same pressure solution and average the results on the set of realizations, by stochastically varying the seeds position, orientation, friction coefficient, and local stress conditions. More details about the pressure distribution in the model, as well as the parameter setting for realistic simulation of the Húsmúli area were already provided in Deliverable 3.
Here we focus on calibrating the seismicity to reproduce the observations and with the goal of validating the EM1 model already implemented for real-time applications. Calibration was achieved by means of an inverse modelling tool minimizing a least squares objective function with gradient descend. Among the various TOUGH2-SEED parameters, we performed the inversion for the number of seeds, average coefficient of friction and cohesion. At the current stage, the inversion was performed only accounting the total temporal evolution of the seismicity.

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Model Calibration for the RISC Tool

As highlighted above, given the real time need for the RISC tool, only empirical models (EM1 and EM2) are foreseen as possible tools. We will test EM2 in the future applications, although it is not yet implemented in the RISC tool.
In this deliverable we modify and evaluate the model EM1 first for the whole Hengill geothermal field, and then we refine the model by comparing it with the local model of Húsmúli (e.g. Deliverable 3).
Notwithstanding the model parameter calibration, it is also important to define standardized averaging spatial procedure. For the field scale we use a spacing of about 500 m, and averaged all the variables in the same discretization. Each element of the grid is then treated individually.

Field scale model calibration for the COSEISMIQ period

The parameters calibration for the field scale is performed by using the data from the COSEIMIQ period. Given limitation in hydraulic data, we focused only on the year 2019 (Jan to Dec).
As highlighted before the parameters are considered independent. First, we calibrate the FMD parameters by means of a standard software (ZMAP - Wiemer, 2001). The entire year is used for b-value and Mc estimate, and the final spatial distribution for both variable is shown in Figure 7.
Given the Mc map, we then evaluate the number of events with magnitude above completeness for grid block (Figure 8).

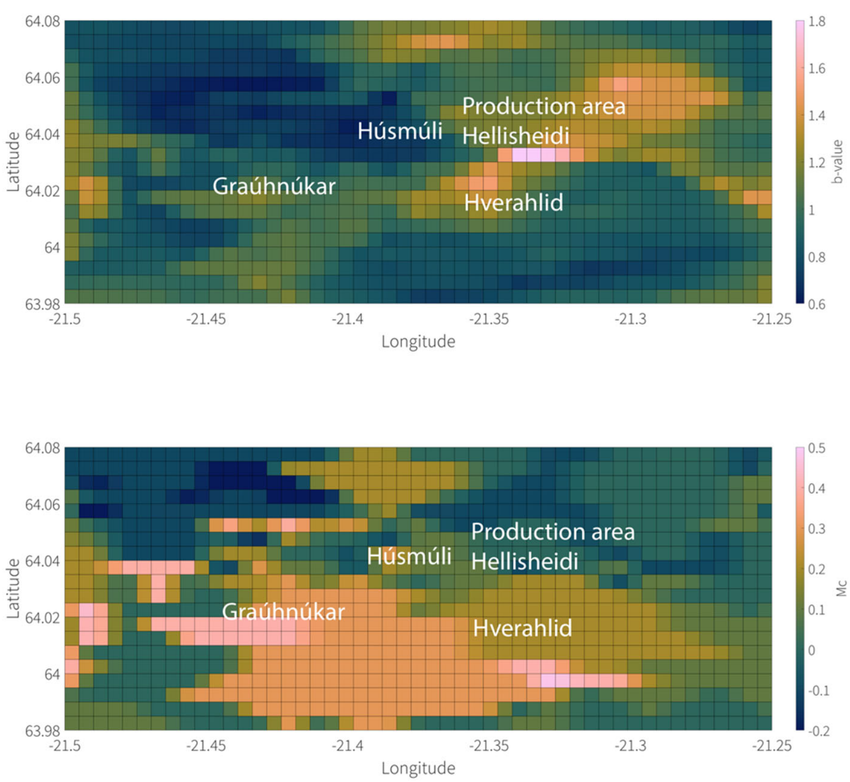

Figure 7: (top) b-value mapping from Zmap for 2019; (bottom) magnitude of completeness mapping from Zmap (Maximum curvature method) for 2019

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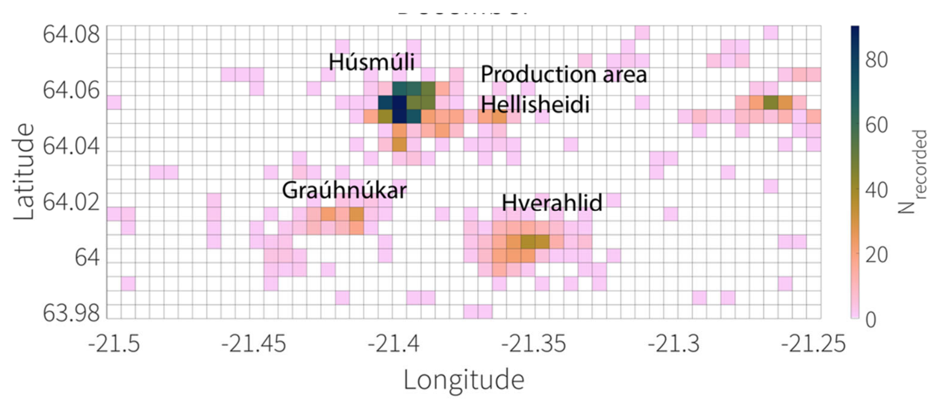

Figure 8: COSEISMIQ catalogue recorded number of events above Mc for 2019

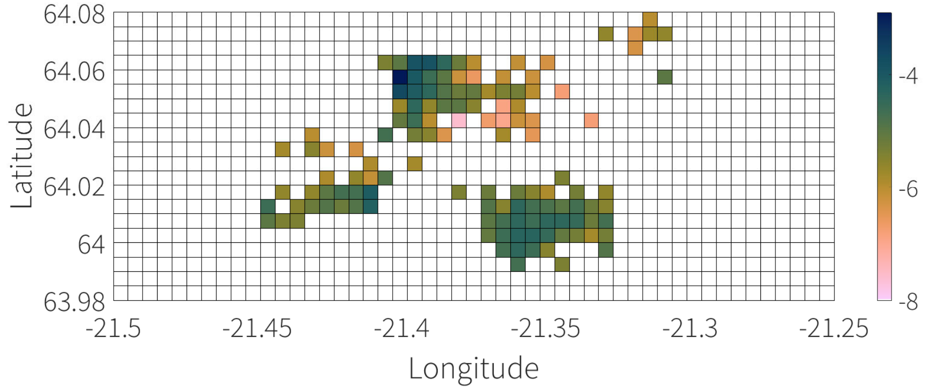

Figure 9: Productivity ∑ spatially optimised for 2019

Finally, we estimate the parameter ∑ (seismogenic index) for each grid block by accounting for the variable flow rate. We employ a time step of 1 month, given the current hydraulic dataset. Figure 9 shows the estimated seismogenic index for the whole Hengill geothermal field, which was estimated by minimizing the temporal misfit (least square) between recorded and simulate events for each block individually.

A comparison between recorded and simulated number of events is shown in Figure 10. The model well reproduces at different stages the evolution of seismicity. Differences arise in the Húsmúli region (Lat 64.06; Lon -21.4) and for a cluster of possible natural seismicity in the east (Lat 64.06; Lon -21.25).

For the Húsmúli region, there could be several reasons for the misfit, but the most apparent seems the distribution of the injected volume. Indeed, the seismicity seems to distribute North of the 5 wells in the sub-region (Deliverable 3).

Overall, model EM1 reproduces the field seismicity well, as also confirmed by the cumulative time evolution of seismicity. Figure 11 shows the good match between modelled and recorded number of events. A further validation comes from analysing the fit individually for few monitoring points (i.e. a few individual blocks), as shown in Figure 12.

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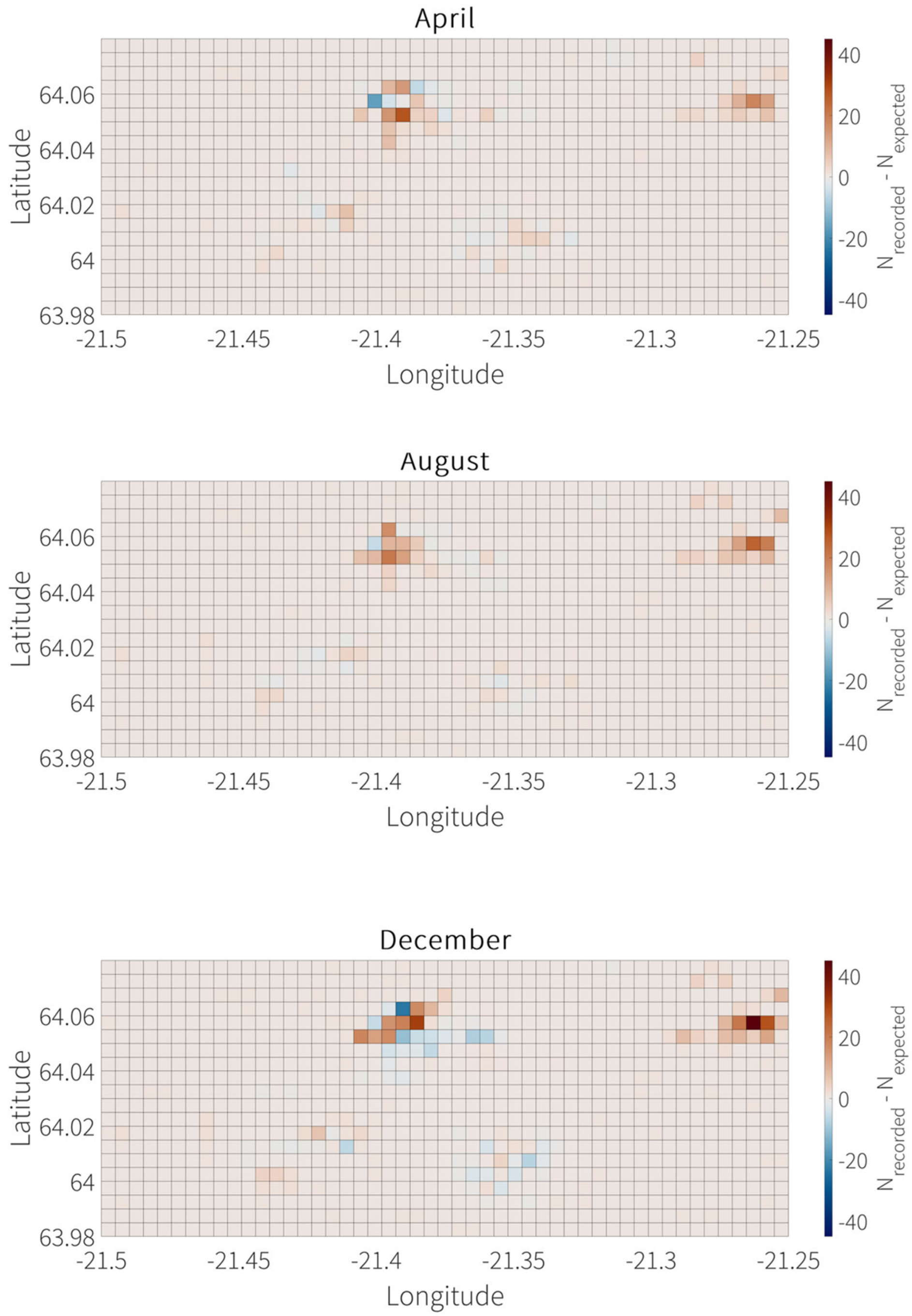

Figure 10: Comparison seismogenic index versus recorded seismicity (model undershooting - red, model overshooting - blue)

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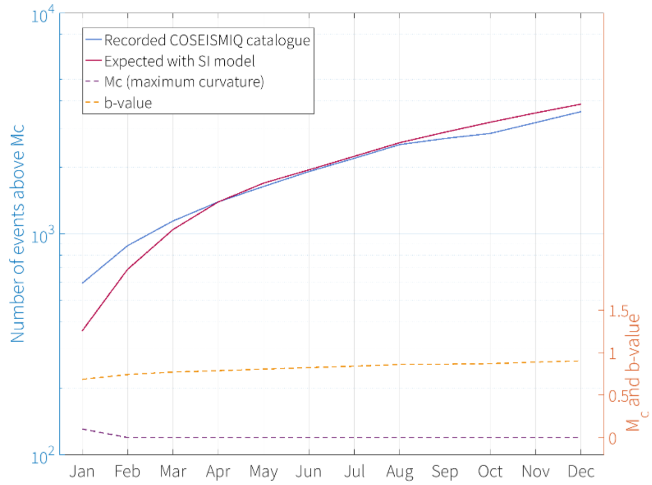

Figure 11: Whole field expected number of events compared to recoreded cumulative event for 2019

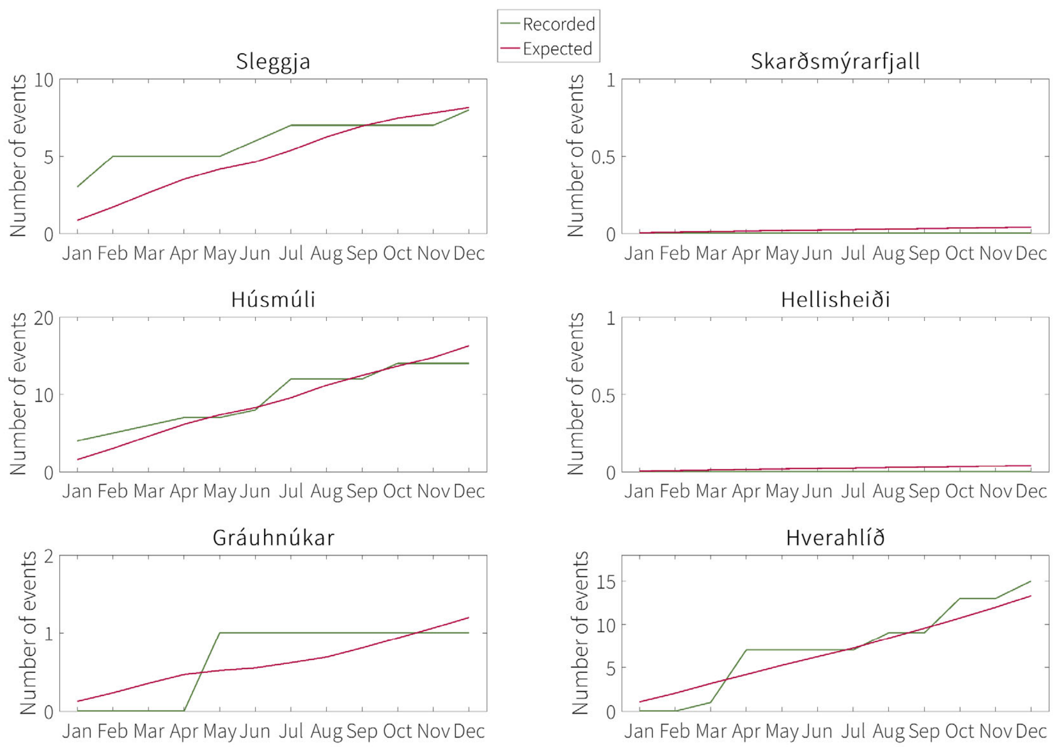

Figure 12: Monitoring grid-block comparison between the seismogenic index model and recorded seismicity for each zone

Comparison of models at Húsmúli during the period Sept. 2011 – Apr. 2012

In order to investigate more in details, the differences between recorded and simulated number of events for the Húsmúli subregion, we employed two different modelling approach, by using both EM1 and HM2. For this comparison we focus in the period Sept. 2011- Apr. 2012, i.e. when operations became substantial at Húsmúli. Investigating the initial evolution of the seismic cloud could shed light on how to improve the EM1 model.

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As shown in Figure 13a,c,e, the assumption of flow limited in a circular region around each injector is probably biasing the results. Indeed, EM1 estimates a very little number of events in the area north of the injection wells.

However, the region is strongly affected by the NS fracture network (Deliverable 3), hence the assumption of a circular averaging is physically wrong. To address this, we assume that the injected fluid is distributed elliptically to the north from each injection well (Figure 13b). This results in a better estimate of the number of events in the entire region (Figure 13d), minimizing the misfit with the observed seismicity (Figure 13f). The model however does not explain the cluster of seismicity occurring west of the injection wells (Lat 64.06; Lon -21.42).

When comparing the models EM1 and HM2 in reproducing the temporal evolution of seismicity, they agree only to a certain extent (e.g. roughly total number of events). The evolution of the recorded seismicity seems to be better described by HM2 model, which employs a pressure-based threshold for the seismicity (Figure 14). EM1 systematically underestimates the seismicity for both case of cumulative (solid green line in Figure 14, i.e. all wells considered as one,) or spatially distributed method (dashed green line in Figure 14, i.e. cumulating the individual blocks in Figure 13 d).

HM2 however fails completely in reproducing the spatial pattern of seismicity (Figure 15a-d). While it is true that the model inversion did not account for the spatial distribution, the result is certainly biased by a layer of low permeability that prevent pressurization of the area north of the injection wells (Figure 15e-f).

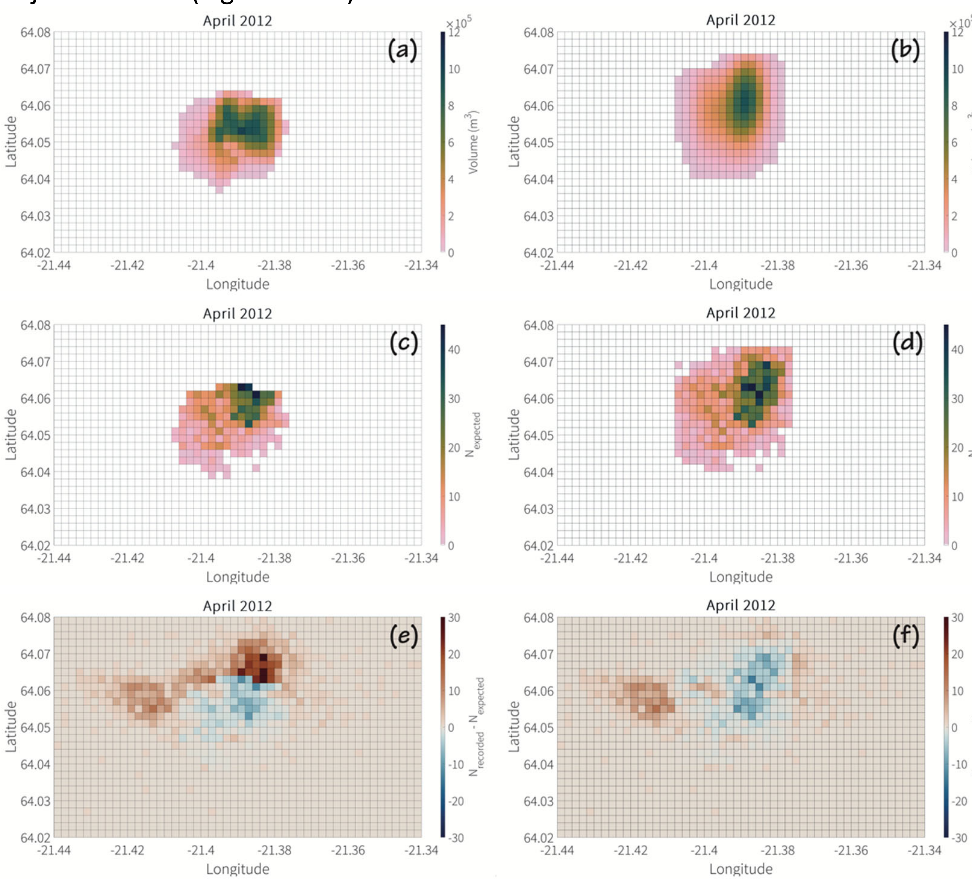

Figure 13: Method of the volume interpolation comparison. A- Circular interpolation B- Ellipsoid bivariate gaussian distribution. C and D - expected number of events for the two interpolation methods. E and F - difference between expected and recorded events

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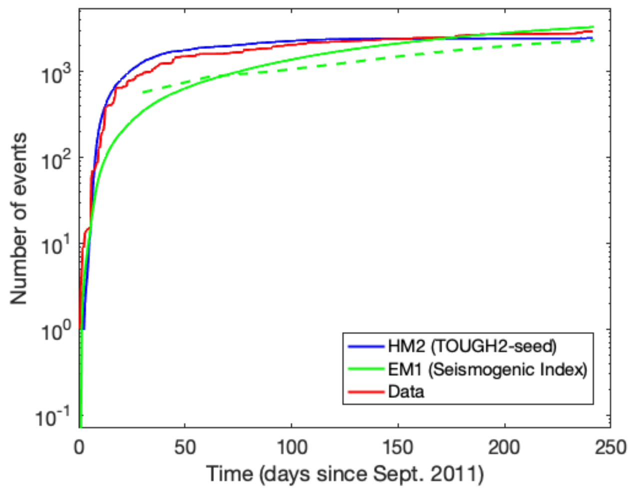

Figure 14: Comparison between EM1, HM2, and the recorded time evolution of seismicity

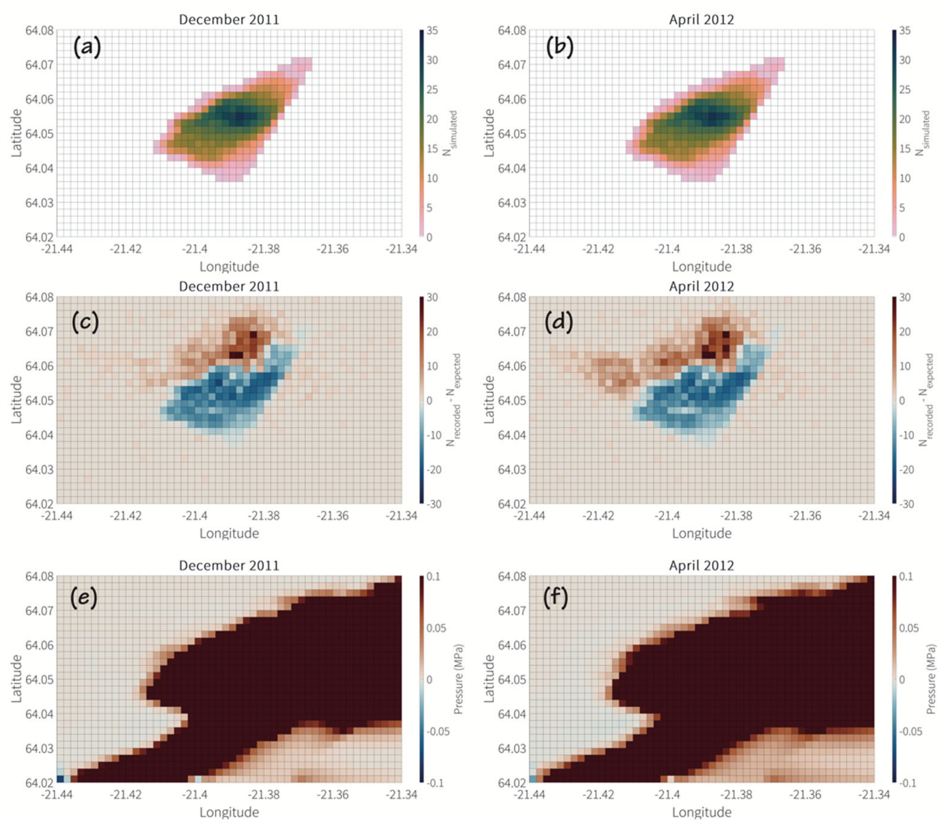

Figure 15: (a,b) Simulated number of events with TOUGH2-seed (average over 48 realizations) for two time snapshots. (c,d) Comparison between number of simulated and recorded events. (e,f) Pressure changes saturated at 0.1 MPa to highlight the absence of pressurization in the northern region.

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Next Steps towards full demonstration of a first-order "RISC Tool"

Having implemented the automatic seismicity detection/locator in SeisComP, and having calibrated at least one model for the whole Hengill area, constitutes already a first-order RISC tool potentially providing a forecast of seismicity.
The whole chain, from data acquisition to prediction, relies of course on data flowing, and a future real time application will strongly depend on this: this is true for COSEISMIQ, but also for future research projects (e.g. DEEP or Bedretto). In particular, the current bottleneck for COSEISMIQ seems to be the real-time availability of the hydraulic data.
However, it must be noticed that for the Hengill area the scale of the entire field is different from previous offline test of the RISC tool (e.g. Basel), and hence the real-time concept is stretched in time. Due to the temporal scale of injections/production and the occurrence of relative low seismicity per injector/year, a first-order tool can imply forecast and updates to it every few months rather than few hours.
In any case, even a first-order tool, needs to base forecast on injection/production plan, which are even more difficult to retrieve in a large field like the one in Hengill. However, in a future demonstration for COSEISMIQ, it could be assumed that the injection/production rate for the future months will be similar to the ones recorded in the latest year, making than possible to provide some forecast without relying on the actual availability of such information.
Another option for a first-order tool is to implement models that are not replying on hydraulic data (e.g. EM2), which requires further development in the modelling approach and calibration.
The current deliverable showed that models could potential help in predicting the future seismicity in the overall field, albeit with uncertainties due to exact location of the pressurized area.
The current status accounts for the pseudo-real time tools to characterize the seismicity, while some development is needed for the modelling approach.
This latter development will focus in the future in:

- Introduction of at least a second large scale model, aka the EM2 model based on probabilistic forecasts (ETAS).
- Introduction of new methods to calibrate the EM1 model, in particular the development of the maximum Likelihood method and Bayesian approach to calibrate parameters and estimate uncertainties.
- Finally, the most important development will be on model comparison: the current plan foresees the use of existing concepts borrowed from the Collaboratory for the Study of Earthquake Predictability (CSEP).

In parallel, we will continue modifying the physics-based model HM2, by adding more physical constrain. In particular, a more refined model is needed to overcome the limitation of the low permeability layer north of the wells. he addition of dynamic permeability changes could also help in reducing the misfit with the data. Finally, in the future we will account for the spatial distribution of seismicity in the inverse modelling to estimate the model parameters. This model constitutes the basis for comparison/evaluation for the other models in phase of calibration, in particular to understand when a certain physical mechanism could bias the forecast performance, and it is fundamental to determine modification to account in the empirical models.

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List of figures

List of tables

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