Basic project information

Project number TKI:	TKI-2021-02-GE
Project title:	Seismicity Potential Dinantian geothermal reservoirs – implications of case study Balmatt for projects in the Netherlands (SeiMoD)
Coordinator:	TNO
Partners in NL:	VITO, Californië Wijnen Geothermie, EBN
Project period:	15 May 2021 – 1 September 2022

Introduction SeiMoD

Motivation

Dinantian carbonates (Lower Carboniferous, ca. 360-330 Ma) are considered a target for the production of geothermal energy in the Netherlands and Belgium. Geological characteristics of these reservoirs are quite different compared to the 'conventional' sandstone reservoirs that are commonly targeted. The geological characteristics, tectonic setting, reservoir properties, karstification and fractured nature will affect the flow, heat transport and the mechanical response of rocks to geothermal operations in the Dinantian carbonates. These factors have an influence on the potential occurrence of induced seismicity when operating in the Dinantian rocks.

So far, two geothermal doublets have been operated in the Dinantian carbonates in the Netherlands, both in the southeastern part of the country. During operations a limited number of seismic events were recorded in the past years which have led to a suspension of geothermal operations. Unambiguous conclusions about the relation between geothermal operations and seismic events are hampered by the lack of data and understanding of causal mechanisms. Such relations are crucial for assessing and managing risks of induced seismicity, and for designing geothermal operations with minimum risks of induced seismicity. Data, models and experiences from the Balmatt geothermal doublet in Mol (Belgium), also being drilled in the same Dinantian carbonate system, can provide insights in relations between geological setting, geothermal operations and induced seismicity specifically for operations that target the Dinantian carbonates. A better understanding of these relations is of great value for developing Dutch Dinantian geothermal systems.

Goals

Ambitions to accelerate development of geothermal energy production as outlined in the 'Masterplan Aardwarmte' require accelerated development of geothermal projects, including new targets such as the Dinantian carbonates. Geothermal projects targeting the Dinantian carbonates in the Netherlands have been mostly successful in terms of heat production, but concerns related to induced seismicity have been a showstopper for development. A better mechanistic understanding of relations between geothermal operations and seismicity is crucial for assessing and managing seismic risks associated with these projects. Modelling approaches are required that provide quantitative forecasts of stress changes and associated induced seismicity.

SEIMOD aimed at (a) using the unique dataset from the Balmatt geothermal project to develop and validate induced seismicity models, (b) establishing a mechanistic knowledge base underpinning relations between geothermal operations and seismicity, and (c) assessing implications for Dinantian carbonate systems in the Netherlands by taking into account experiences from the Californië Wijnen Geothermie project.

Short activity description
Based on geological and reservoir engineering data and models from the Balmatt geothermal project, project partners set up a coupled reservoir - geomechanical model to assess the effects of geothermal operations due to changes in pressure, temperature, fault stress and associated seismic response of faults. Coupled reservoir - geomechanical models were validated by the catalogue of seismic events and results of seismicity studies from the Balmatt project. Likewise, forecasts of the models for seismic events were evaluated. Data and experiences from the Californië Wijnen Geothermie project were combined with recent literature studies to assess differences of key factors causing seismic activity at the Balmatt and Californië geothermal sites.

Results to be realized
SEIMOD was supposed to provide a comprehensive overview of geological, geohydrological, geomechanical and seismicity characteristics of Dinantian rocks at Balmatt and Californië geothermal sites. These data should be completed with some new experimental data on thermo-mechanical parameters for Dinantian rocks. Further, a validated 3D-geomechanical and seismicity model was planned to be built for the Balmatt site. Relevant factors and mechanisms that control seismic activity of Dutch Dinantian reservoirs were supposed to be defined.

Expected impacts
The project should (a) lead to a better understanding of causal relations between geothermal operations and induced seismicity, (b) result in an improved knowledge base and modelling toolbox for the assessment of seismic risks of Dinantian geothermal projects, and (c) enable a more reliable de-risking of future geothermal projects and implementation of mitigation measures in Dinantian reservoirs.

Technical report

The technical report is available as separate document from the coordinator (address see below). The summary of the technical report is printed below.

Summary of the technical report
Concerns about induced seismicity are currently hampering development of geothermal projects targeting the Dinantian carbonates in the Netherlands. It is therefore of the utmost importance to properly assess the induced seismicity potential and manage seismic risks associated with projects in the Dinantian carbonates. Assessment of induced seismicity potential for the Dinantian carbonates in the Netherlands is challenging. Limited data is available on the spatial distribution and properties of the formations. There are also only two existing geothermal projects in the Netherlands targeting them (i.e. the Californië projects CWG and CLG in the south-eastern part of the country, near Venlo), and only a limited number of hydrocarbon wells were drilled that encountered the Dinantian carbonates. The Balmatt geothermal project near Mol in Belgium targets the Dinantian carbonates, and allows relation between geological setting, reservoir properties, operations and induced seismicity to be analysed.

This project aims to advance the understanding of the mechanisms controlling induced seismicity in Dinantian carbonate reservoirs, and to develop models to forecast induced seismicity in these reservoirs. The specific aims are:

(1) To use the Balmatt data to develop and validate induced seismicity models.
(2) To establish a mechanistic basis underpinning relations between operations and seismicity.
(3) To assess implications for Dinantian carbonates targets in different parts of the Netherlands taking into account experiences in the Californië Wijnen Geothermie project (CWG).

The geological setting, reservoir properties, operations and induced seismicity were characterised for the Balmatt site near Mol in Belgium, and for the Californië (CWG and CLG) sites near Venlo in the Netherlands. Several different numerical and semi-analytical modelling approaches were used to simulate end-member scenarios for mechanisms leading to induced seismicity. We distinguished two end-members for flow: 1) fracture-dominated flow (analytical single fracture model) and 2) flow through porous media (numerical model of layered medium of single porosity rocks with high permeability layers). Model simulations focus on investigating (i) the onset of seismicity soon after the start of injection operations, (ii) the occurrence of post shut-in seismicity (and in-between injection tests), (iii) reoccurrence of seismicity at lower injection rates during second injection phase, (iv) the areal extent of seismicity, and (v) typical ranges of magnitudes and stress drops.

Seismicity at Balmatt is likely mainly caused by direct pore pressure effects caused by injection into a highly permeable network of faults and fractures linking to a strike-slip fault zone at a few hundred meters distance of the injection well. In terms of timing of seismicity, a fracture-dominated flow model (analytical single fracture model) appears to better reproduce the characteristics of seismicity than the (numerical) porous reservoir flow model. Model results in the single fracture model combined with a seismicity model indicate the reactivated fault was probably initially close-to-critically stressed, since model simulations only produce seismicity after shut-in, in between injection cycles and after restart (as observed in practice) if in-situ stress conditions on the fault are initially near-critical. Post shut-in seismicity and seismicity after restart was found to be strongly correlated with hydraulic diffusivity for direct injection into a close to critically-stressed fault zone, with the post shut-in and reoccurrence of seismicity being promoted by lower diffusivities. However, as hypothesized by Kinscher et al. (2022) the late post-injection seismicity and the delay between injection operations and seismic response may also have been a consequence of aseismic slip occurring along fault planes. In an extensive analysis of the seismicity data of Balmatt, Kinscher et al. (2022) showed the occurrence of multiple seismic repeaters, which are often associated to aseismic creep on faults. The mechanism of aseismic creep is currently not incorporated in our models. Model results show that poroelastic effects are expected to be much smaller than the direct pressure effect (by a factor of 4 to 5, depending on Biot's coefficient), and stabilize the fault during injection periods (destabilize the fault near the production well). Constantly increasing pressure levels of subsequent injection phases recorded at the first seismic event detection during the first injection period from December 2018 to July 2019 seem to suggest a Kaiser effect on triggering seismicity, but this effect is less obvious during the second period after restart of injection in April 2021, with seismicity occurring at lower injection rates and pressures than during the first period. The extension of the monitoring network early 2021 may have led to the detection of small events at lower levels. Modelling results of the analytical single fracture model suggest other dynamics than the Kaiser effect may play a role in triggering seismicity after restart, such as stress transfer and the varying magnitude of the prestress on the fault due to its surface roughness.

The single fracture model also appears to better reproduce the characteristics of seismicity than the numerical porous model in terms of areal extent, distribution of magnitudes and stress drops. The areal extent of seismicity can cover the entire fault area (up to 3 km from the injection well) in semi-analytical single fracture models with ranges of magnitudes and locations of events along the fault plane, depending on model input parameters (e.g., fault roughness). The numerical model generally only produced low magnitude seismicity clustered around the injection well, except for very smooth faults with high friction drops which caused 'runaway rupture' over the entire fault, culminating in one single large magnitude event. Event magnitudes from all simulations based on the single fracture model range between M -1.5 to M 5.0 with larger magnitudes (M > 4) requiring specific combinations of fracture transmissivity and diffusivity leading to 'runaway' slip on the entire fault plane. For most combinations of input parameters event magnitudes are between M -1.5 to M 2.0, which is in the same order of magnitude as the observed seismicity. The numerical model either generates only small seismic events or one single large magnitude event. Stress drops in the single fracture model vary between 0 and 2.5 MPa. Stress drops based on analysis of seismic source parameters are typically in the range of 0.1-2 MPa with a limited number of events reaching values up to more than 10 MPa. Cooling and thermal contraction of rocks around the injection well cannot explain the reactivation of the fault at the Balmatt site, due to the short duration and limited amount of fluids injected during the operations. Cooling and thermal contraction around the injection well were identified as the cause of induced seismicity at Californië with a temporal relation between seismic activity and significant reductions in flow rate, in particular at times when reservoir pressure returned to or near pre-operational levels.

A combination of laboratory triaxial deformation and acoustic (compressional and shear wave) velocity measurements was performed on outcrop samples of Dinantian (Visean and Tournaisian) carbonates to evaluate the relation between dynamic and static Young’s modulus and Poisson’s ratio. When applied to sonic log derived dynamic values, the relations suggest significant differences with existing values that were based on a relation between static and dynamic Young’s modulus for oil-producing limestones in Iran at unconfined conditions.

Implications for Dinantian carbonate targets in different parts of the Netherlands are mostly based on comparison of regional geological settings. In general, the lack of data for the Dinantian carbonates in most regions in the Netherlands is hampering direct application of findings to other regions or specific project locations in the Netherlands. Of particular importance for regional induced seismicity potential is data on the stress state of faults and reservoir properties. Areas may exist in the Netherlands that are less prone to induced seismicity and have lower induced seismicity potential than near the Balmatt and Californië sites because faults are further away from a critically-stress state. As it may not always be straightforward to determine the detailed location and stress state of faults prior to operations (given resolution of seismic surveys and uncertainties in stress field), a site-specific critical distance of operations to major faults may be considered in selecting future project locations, based on model forecasts that account for uncertainty in parameters. Also, a clear threshold for induced seismicity that is accepted for geothermal projects in the Netherlands would help management of seismic risk in future geothermal projects targeting the Dinantian carbonates.

Execution of the project

Coordination of the project

The coordination of the SeiMoD project was in hands of TNO. There was regular contact with the project partner main contacts about organizational matters e.g., collecting information for the progress reports.

Collaboration with project partners

The collaboration with the project partners (Californië Wijnen Geothermie, VITO, EBN) was very pleasant and constructive. Data needed to carry out the projected work was provided by partners quickly after project start. From the beginning, the executing team held a monthly technical meeting where progress, research questions and solutions were critically discussed. These meetings helped to keep partners informed and to receive a critical view on the research approaches and results.

Challenges and modifications

The project was carried out according to plan. Only challenge was the time line originally projected. One year was obviously not enough to plan, carry out and report project activities and results. Therefore, the consortium requested twice an extension of the project time by altogether 3 months. The extension was granted by TKI Nieuw Gas. The projected budget and of TNO and VITO was completely used.

Contribution of the project to the goals of the funding program
One of the goals of the innovation program Geo-Energy within TKI New Gas is the safe use of the subsurface for the production and storage of energy. The SeiMoD project significantly contributed to our understanding of processes in the subsurface that control induced seismicity for example, by geothermal operations.

Spin off within and outside the geothermal sector
This study was carried out on geological, geomechanical and seismic data from the Dinantian carbonate reservoir at the Balmatt site in Belgium. However, the knowledge base derived from the project in principle can be applied also to other regions in Europe, including the Netherlands, with existing or planned geothermal activities in order to assess the risk of induced seismicity.

Dissemination
Beside the public technical report results of the study have been submitted by partners TNO and VITO to the Proceedings of the European Geothermal Congress: Pogacnik, J. et al. (2022) Pressure response in the Balmatt geothermal wells, Mol, Belgium. Proceedings European Geothermal Congress 2022, 7 p. and ter Heege, J. et al. (2022) Geological controls on induced seismicity potential for geothermal projects targeting Dinantian carbonates in the Netherlands. Proceedings European Geothermal Congress 2022, 10 p. Further results, specifically the modelling results, will be published later in 2022 and 2023. We also plan to share project results with relevant stakeholders in the Netherlands and Belgium.

Additional information

For questions, supplementary information or a digital copy of the technical report please contact Holger Cremer (holger.cremer[at]tno.nl) or Brecht Wassing (brecht.wassing[at]tno.nl).

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