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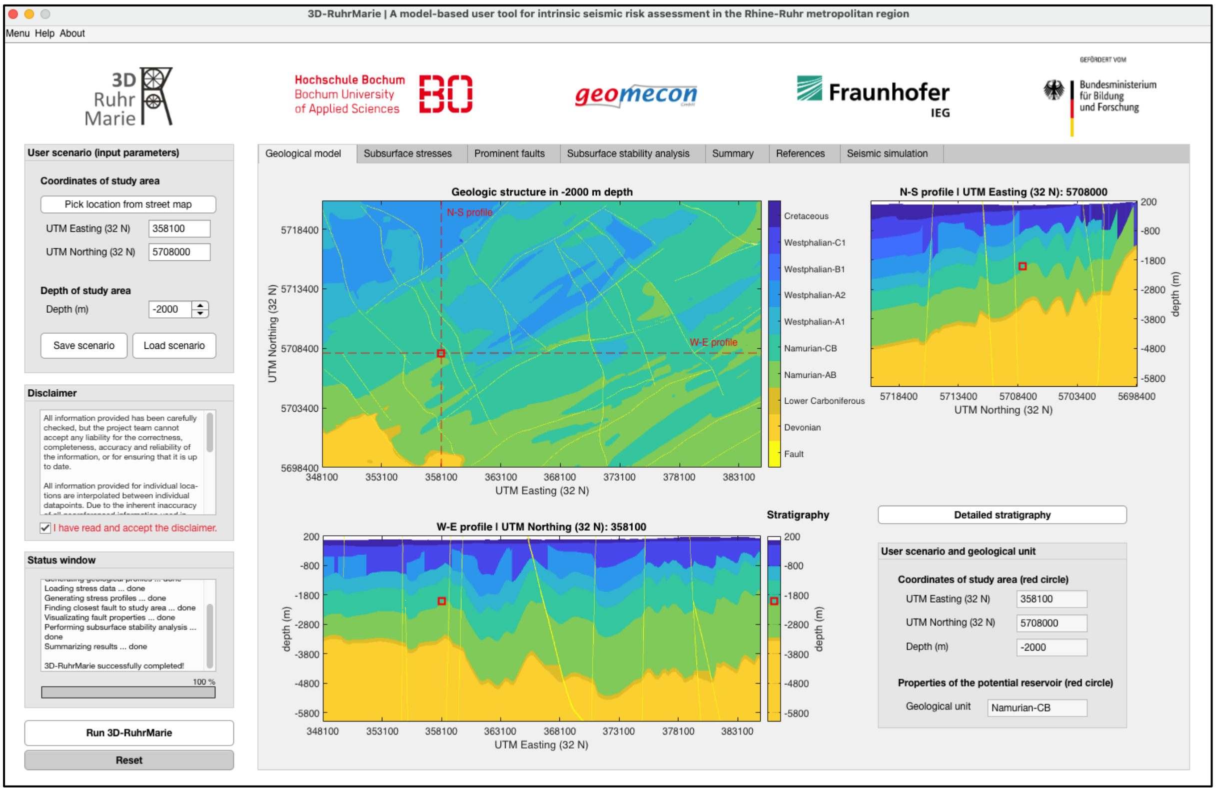
**3D-RuhrMarie (v.1)**
A model-based user tool for intrinsic seismic risk assessment in the Rhine-Ruhr metropolitan region

# USER MANUAL (v.1)




The interactive, model-based user tool **3D-RuhrMarie** for the risk analysis of the intrinsic seismic hazard in the Rhine-Ruhr metropolitan region was developed within the application-oriented research and development project of the same name. 3D-RuhrMarie is based on available three-dimensional structural-geological as well as seismotectonic data, which have been supplemented by new geomechanical subsurface modeling and laboratory-based measurements of geothermally relevant rocks. The user tool contains geological, experimental, and modeling assessment tools that facilitate risk analysis for seismicity induced by geothermal energy use.

## A | Disclaimer

All information provided has been carefully checked, but the project team cannot accept any liability for the correctness, completeness, accuracy, and reliability of the information, or for ensuring that it is up to date. All information provided for individual locations are interpolated between individual datapoints. Due to the inherent inaccuracy of all georeferenced information used in this study as well as complexity of the geological subsurface, the project team cannot ensure the site-specific validity of the interpolated results. Given information can be regarded as a first estimate but needs to be complemented with further information and detailed site-specific sensitivity studies. The project team does not accept any liability for any direct or indirect as well as tangible or intangible damage resulting from accessing, using, or not using of the user tool 3D-RuhrMarie or its content.

**Despite utmost care, no warranty is accepted for completeness, correctness or this manual being up to date. This version of the manual is in accordance with the 3D-RuhrMarie software-version v.1. Installation and use of 3D-RuhrMarie occurs at your own risk.**

## B | Installation files

The user tool 3D-RuhrMarie is a graphical user interface (GUI) developed in MATLAB® 2021a. It is deployed as a free standalone application that runs on Macintosh and Windows computer, for users that do not have MATLAB® licenses. Installation files were created specifically for both systems. 3D-RuhrMarie installations files can be downloaded directly free of charge from this repository: https://rockphysics.org/downloads.

After thorough examination of the installation files, it is still recommended to exit other open programs on your system and back up current data to maintain the data in the RAM before running the installation files. In all cases, a minimum of 8 Gigabyte of RAM and a display resolution of at least 1920 x 1080 pixels is recommended for the usage of 3D-RuhrMarie. If the software installer notices, that the MATLAB® Runtime 2021a (version 9.8) has not been installed on your computer, it will be installed. It may occur, that after the installation the first launch of 3D-RuhrMarie will be longer than usual. It is recommended to close all programs on your computer prior to starting 3D-RuhrMarie and do not open any applications or files while running the program to enable fast program execution.

## C | User interface of 3D-RuhrMarie

The 3D-RuhrMarie user interface is essentially composed of six elements, the structure and function of which are discussed below in the best possible way (Fig. 1). These elements include menu bar (C.1), user scenario (C.2), disclaimer (C.3), status window (C.4), run and reset buttons (C.5), and results tabs (C.6).

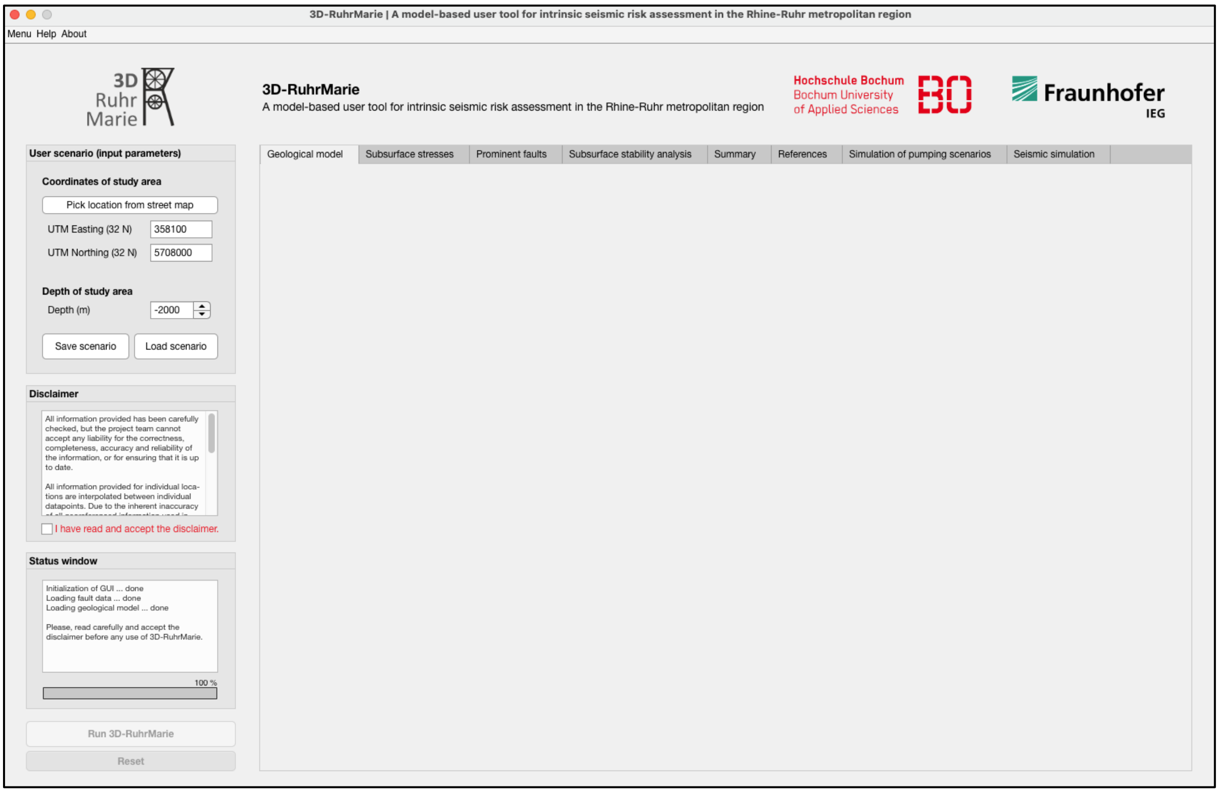



**Figure 1:** Graphical user interface of the user tool 3D-RuhrMarie. The user interface is essentially composed of six elements: (C.1) menu bar, (C.2) user scenario, (C.3) disclaimer, (C.4) status window, (C.5) run and reset buttons, and (C.6) results tabs. For a detailed functional description of these elements please refer to section C of this manual.

## C.1 | Menu bar

The menu bar, which is on top of the program, provides the user with three menu items ("Menu", "Help", and "About") including essential functions like opening and saving user setting (coordinates and depth of study area) in a text (.txt) file and quitting the program. Under the "Help" menu item the user will find options to receive assistance. Here, for example, the user manual can be opened as a PDF document outside the 3D-RuhrMarie program. It is also possible to contact the 3D-RuhrMarie team (3druhrmarie@rockphysics.org) here if the user is interested in laboratory measurements, stress modeling, and seismic modeling. The "About" menu item provides general information about the acknowledgments, the disclaimer, and the user tool 3D-RuhrMarie (e.g., software version).

## C.2 | User scenario (input)

The user tool allows the user to select specific coordinates or a freely selectable point via the map selection button "Pick location from street map" as well as a desired depth in the Rhine-Ruhr area with an area of 36900 m x 22400 m and a depth of 6000 m. The geological mode has a cuboid geometry with dimensions of 36900 x 22400 x 6000 m and extends from southwest to northeast:

| | |
|---|---|
| **UTM Easting (32 N):** | 348100 … 385000 |
| **UTM Northing (32 N):** | 5698450 … 5720800 |
| **Depth (m):** | -30 … -6000 m |

To use the "Pick location from street map" function, an existing Internet connection is required. Clicking this button opens a new modal window ("Study area of 3D-RuhrMarie (red area)"; Fig. 2) that displays the study area (red area) on a street map. The user can interactively zoom into the target area (e.g., mouse wheel or touchpad) and when the desired magnification is reached, the study area of interest can be selected via the "Pick Location" button using a crosshair. Afterwards the window "Study area of 3D-RuhrMarie (red area)" can be closed by clicking on the button "Close figure".
The buttons "Save scenario" and "Load scenario" can be used to either save or load the coordinates and the target depth of the investigation area (both as text file).

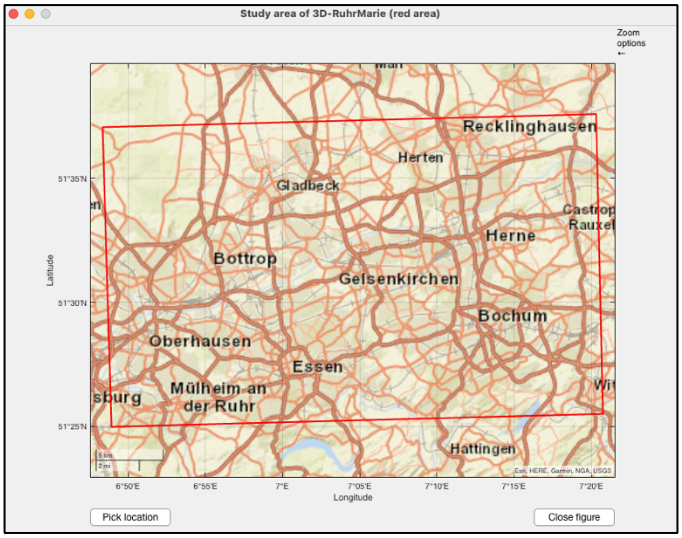



**Figure 2:** Optional free selection of the study area from an interactive street map. This window opens after clicking the "Pick location from street map" button, after the user has agreed to the disclaimer. The size of the integrated geological model is indicated by the red rectangle.

## C.3 | Disclaimer

To run 3D-RuhrMarie reading and accepting the disclaimer is mandatory. The disclaimer is also presented on page 2 of this manual (A) and can also be found in the menu bar (C.1). Click on the “I have read and accept the disclaimer” check box to confirm that you have done so. Now the fundamental functions of the program are released. The program can now be started by clicking on the button ”Run 3D-RuhrMarie” (C.5). As soon as the check box is deselected, the access to the fundamental functions is denied again.

## C.4 | Status Window

Changes to the status of the running program appear in the status window. In case of arising problems, it is helpful to follow the instructions in the status window.

## C.5 | "Run 3D-RuhrMarie" and "Reset" buttons

To run 3D-RuhrMarie reading and accepting the disclaimer is mandatory (C.3). With a click on "Run 3D-RuhrMarie" the calculation for the study area defined by the user is performed. The program can be reset to the original startup settings using the "Reset" button.

## C.6 | Result tabs (output)

After the program ("Run 3D-RuhrMarie") has been started, the user is informed about the predominant stratigraphic units (C.6.1), the nearest fault (C.6.2), the individual static stress components (C.6.3), as well as about the subsurface stability analysis (C.6.4) of the defined location in the results tabs. The most important findings or data of the study area selected by the user are summarized and evaluated in the "Summary" tab (C.6.5). Also, the references and data sources used are systematically listed in "References" (C.6.6). In addition to the listed main components of the user tool, additional exemplary modeling results have been included in the tool (C.6.7), which can be used to get an idea of the potential of the data set compiled in the project.

### C.6.1 Geological model

The data base for the 3D geologic subsurface model currently consists of nine stratigraphic horizons: Cretaceous, Westphalian-C1, Westphalian-B1, Westphalian-A2, West-phalian-A1, Namurian-CB, Namurian-AB, Lower Carbiniferous, Devonian, and faults. The "Geological model" result tab currently displays the geological unit of the study area and 4 figures showing the horizontal geologic structure at the target depth, the N-S and W-E profiles, and a simple stratigraphy through the target area (red box) (Fig. 3). The user is given the option to view a detailed stratigraphy (including the depth and thickness of each layer) in a new modal window. The detailed stratigraphy is opened by clicking the "Detailed stratigraphy" button.

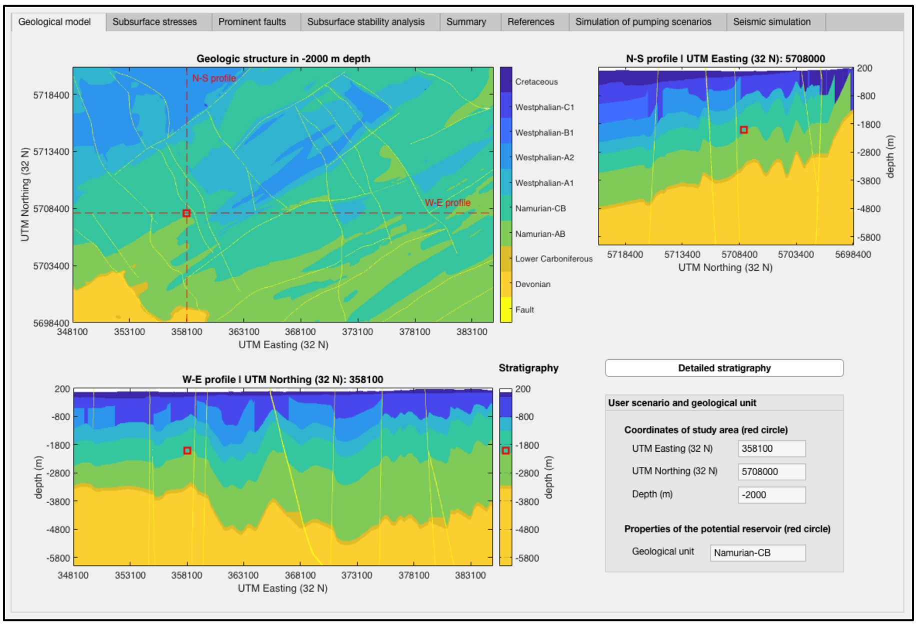



**Figure 3:** Example representation of the result tab "Geological model" for an exemplarily chosen study area in the geological unit Namurian-CB.

### C.6.2 Subsurface stresses

The "Subsurface stresses" tab is structured in the same way as the "Geological model" tab, but this tab now displays the stresses to be expected in the subsurface (Fig. 4). In the lower right area, exactly the stresses in the target depth are displayed. All the values listed here can be selected via the “Stress data” drop-down menu and displayed visually using the "Update figures" button. In addition, a 1D stress profile through the target area can also be selected in the drop-down menu.

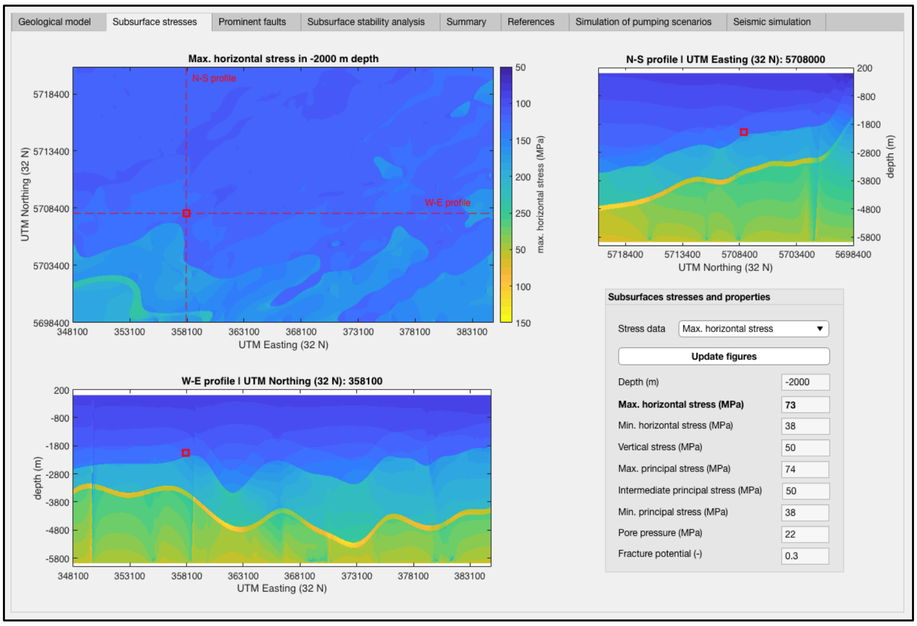



**Figure 4:** Example representation of the result tab "Subsurface stresses " for an exemplarily chosen study area in the geological unit Namurian-CB. This figure shows an example of the max. horizontal stress in the target depth, as well as N-S and W-E profiles through the user-defined study area.

### C.6.3 Prominent faults

The 3D-RuhrMarie dataset includes a total of 25 large-scale and prominent faults in the study area, whose fault properties are shown in the "Prominent faults" tab (Fig. 5). The minimum length of the faults included is 1000 m. The program automatically calculates the spatial distance between the study area and the closest fault (“Closest fault to study area”). The user can display two faults (“Selection of the fault and its properties to be visualized” drop down menu) side by side can freely choose between 6 fault properties to visualize. This selection is done via the "Fault property" drop down menus on the left and right side. The study area is displayed as a black circle in the left and right image. If desired, the user can also have a vertical drilling (black line) drawn from the surface to the study area (“Drilling to study area”). The study area can also be enclosed by a sphere with a freely selectable radius (“Sphere around study area”), which is helpful for spatial estimation of the distance. In future program versions there will be the option to determine the mean fault properties within this sphere. Below the figures the viewpoint (azimuth) can be adjusted to the fault orientation by means of a slider (“Viewpoint (azimuth)”). The adjustments made here are for visualization purposes only and have no influence on the results in the "Summary" tab. It is recommended that the user determines the best possible azimuth in this tab and enters it later in the "Summary" tab in

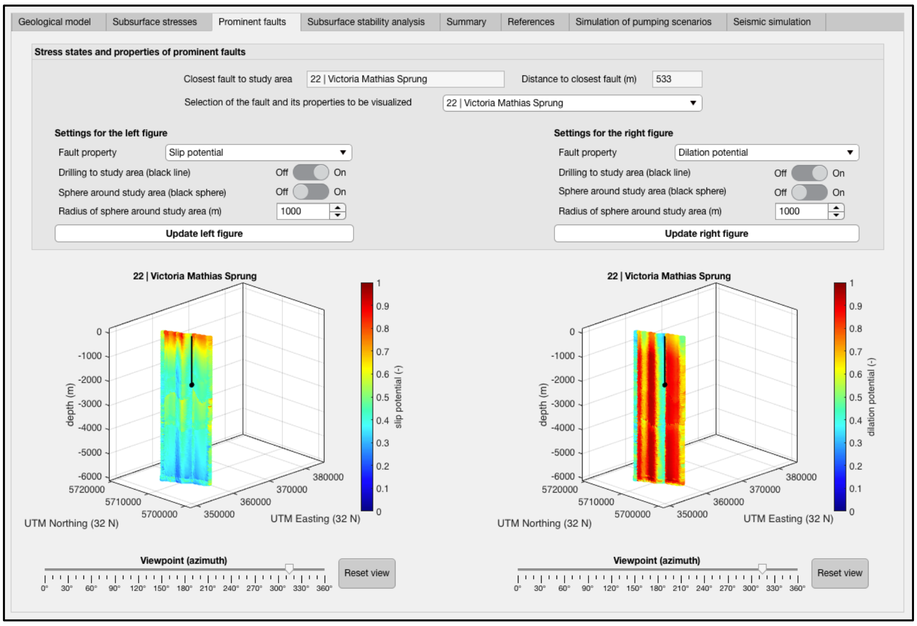



**Figure 5:** Exemplary representation of the spatial distribution of slip potential and dilation potential along the Victoria Mathias Sprung fault in the "Prominent fault" tab. In this example, the estimated distance between the user-selected study study area and the nearest fault amounts to approx. 533 m.

the "Viewpoint (azimuth) on fault (°)" field so that the faults are displayed in the best possible way in the automatically generated report.

### C.6.4 Subsurface stability analysis

Based on experimental test results from thermo-triaxial tests on rock samples from representative rock formations and the Mohr-Coulomb failure criterion or a linear friction criterion, the stability of the intact rock or fractured rock is estimated under in-situ conditions, respectively (Fig. 6). If Mohr circles are colored green or red the condition is stable or unstable, respectively. At the top right, the results of this stability analysis are summarized in various text boxes. The max. allowed overpressure indicates the pressure that can be applied in addition to the pore-fluid pressure assumed in the subsurface until the condition becomes unstable. To observe the influence of different usage scenarios, the user can adapt the analysis to underlying experimental conditions (e.g., the temperature or the pore pressure) himself. By clicking on "Update numbers" both graphics and the text boxes on the right side are adjusted accordingly.

If no experimental data on rock formations are available, simplified failure and friction criteria are estimated from re-evaluated in situ stress measurements. The simplified assumptions made are referred to as worst-case estimates. If the target area falls within a fault Byerlee's law (1978) is applied to estimate the subsurface stability. It is assumed that the rock in the fault is fractured and accordingly the option to estimate the stability of intact rock is missing. The experimental data set is constantly updated and will be included in new software releases.

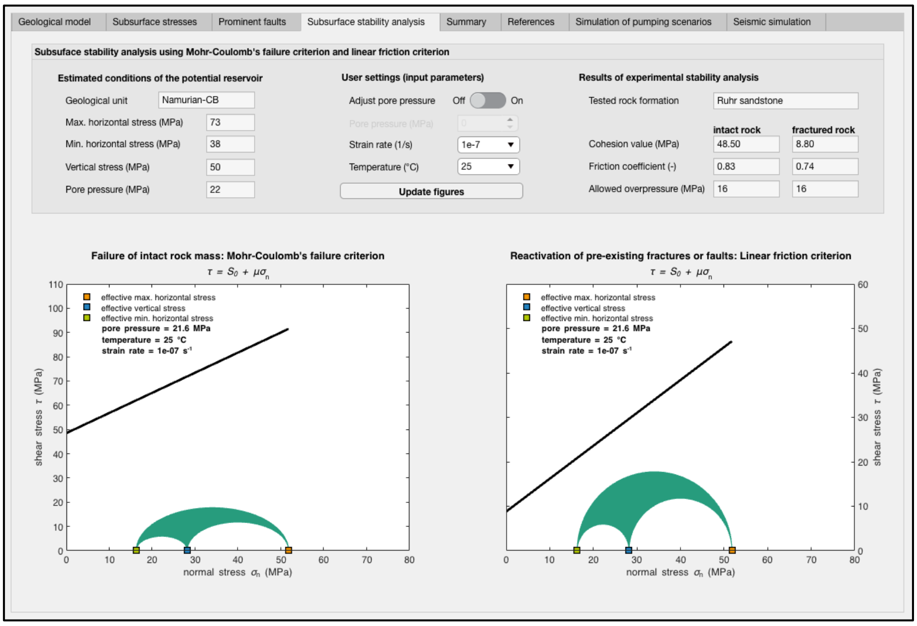



**Figure 6:** Analyses of surface stability of intact (left) and fractured (right) rock under estimated in situ conditions at user-selected coordinates and depths. In this example, the stability state of both intact and fractured rock has been estimated as stable (green color). Here, the stability analysis is based on experimental measurement results.

### C.6.5 Summary

The most important findings or data of the investigation study area selected by the user are summarized and evaluated in the "Summary" tab (Fig. 7). Currently, the seismic risk is estimated based on three important parameters: (1) the estimated distance of the study area to the closest fault (based on the structural geologic model), (2) the fracture potential of intact rock material in the study area (based on the stress model), and (3) a stability analysis of potentially intact or fractured rock in the study area based on laboratory measurements of representative rock samples, stress modeling results, or Byerlee's friction law (1978). The three geological, experimental, and model evaluation criteria of the potential seismic risk in the study area are shown as risk gauge scales on the right side of the tab. Detailed information on the evaluation criteria can be viewed by clicking on the "Estimated relative intrinsic risk for seismic hazard (details)" buttons located below the risk gauge scales.

The initial, automatically generated risk analysis can additionally be exported as an automatically generated PDF document (Fig. 8) by clicking “Create report in the study area analysis". It is recommended to provide a name (“Username or initials”) and title of a concept study (“Concept study”) so that the report can be categorized by the user afterwards. It is recommended that the user determines the best possible azimuth on the closest fault in the “Prominent faults” tab and enters this value in the "Viewpoint (azimuth) on fault (°)" field. This ensures that the fault properties are displayed in the best possible way in the automatically generated report. A save path (“Select save folder and name”) must be selected before the PDF document can be created. Note that first the individual pages of this report are saved separately before the program merges them into one report. This process may take

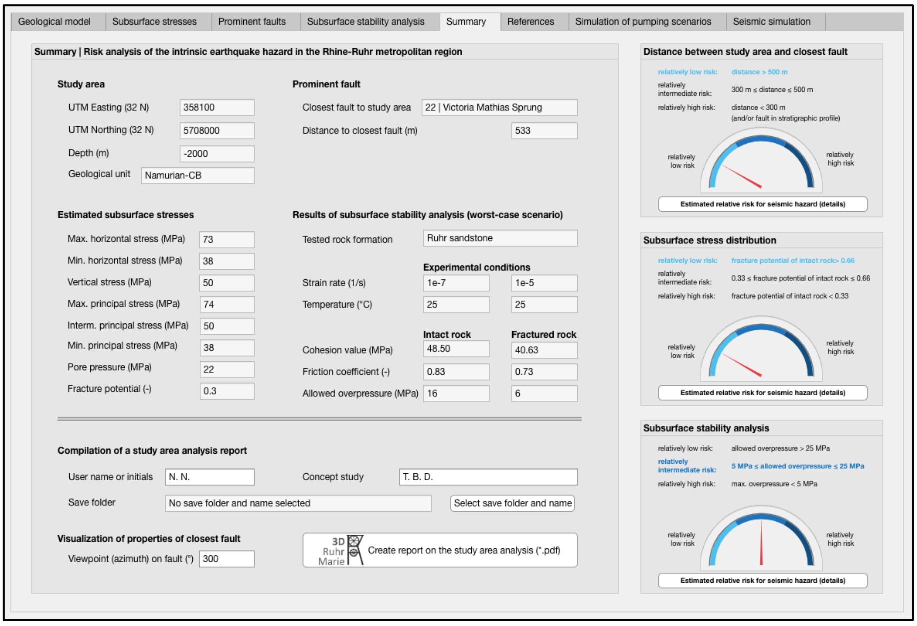



**Figure 7:** Summary of the most important data for the study area selected by the user in the "Summary" tab. The three geological, experimental, and model evaluation criteria of the potential seismic risk in the study area are shown as risk gauge scales on the right side of the tab.

some time. During this process, the individual report pages should not be deleted. When the report is finished, the individual document pages are automatically deleted.

The risk analysis will be supplemented by further criteria in the future. It should be noted that the risk analysis must be interpreted with due caution, as it is simplified, estimated, and interpolated data (see disclaimer). Due to the inherent imprecision of all georeferenced information used in this study and the complexity of the subsurface geology, the project team cannot guarantee the site-specific validity of the interpolated results. The risk analysis provides an initial rough guide to what can be expected at each site. Obviously, a final assessment of the site will require an additional and detailed study. Such a study cannot and does not in any way replace the given program.

### C.6.6 References

The tab "References" lists all references and used data sources that have been incorporated into the user-tool 3D-RuhrMarie (Fig. 9). The list is sorted based on the different methodological approaches and results tabs of the tool. With each further software version, this list will also be expanded.

**Please refer to this reference list if you would like to learn more about the respective sources of all graphics, values, and analyses presented in the results tabs and used in the automatically generated report.**

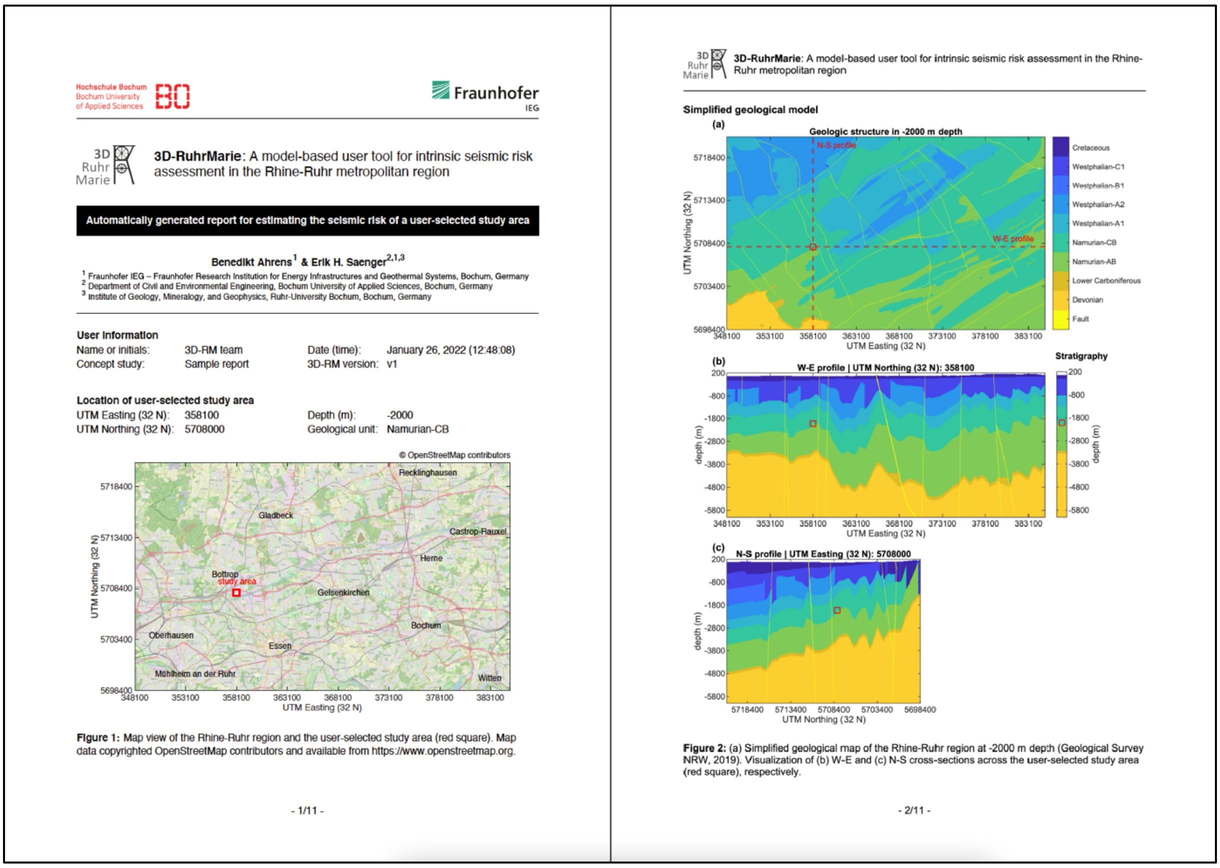
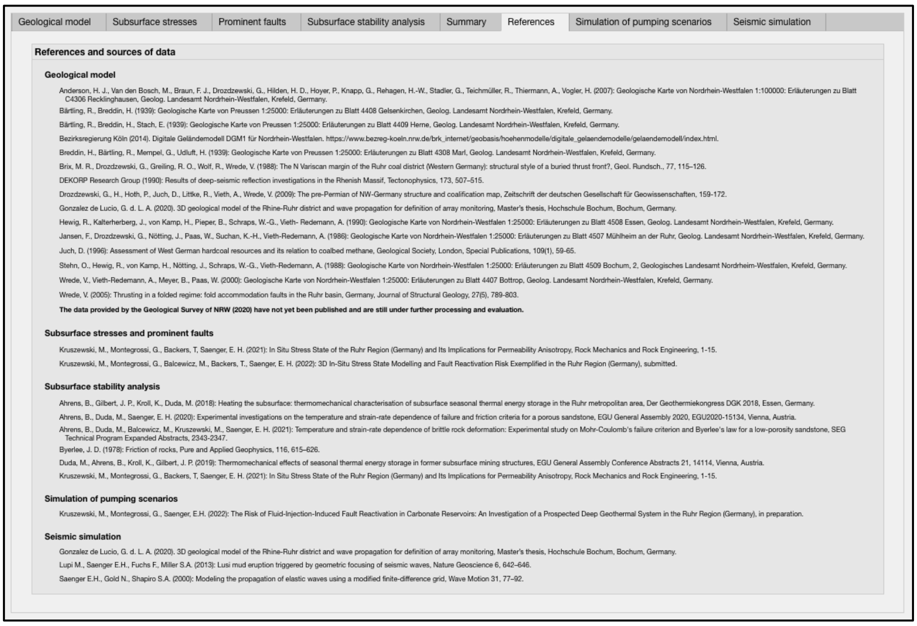



**Figure 8:** The first two pages of the automatically generated report on the study area selected by the user. The report is generated as a PDF document and is saved on the user's system.


Geological model | Subsurface stresses | Prominent faults | Subsurface stability analysis | Summary | References | Simulation of pumping scenarios | Seismic simulation

**References and sources of data**

**Geological model**

Anderson, H. J., Van den Bosch, M., Braun, F. J., Drozdzewski, G., Hilden, H. D., Hoyer, P., Knapp, G., Rehagen, H.-W., Stadler, G., Teichmüller, R., Thiermann, A., Vogler, H. (2007): Geologische Karte von Nordrhein-Westfalen 1:100000: Erläuterungen zu Blatt C4306 Recklinghausen, Geolog. Landesamt Nordrhein-Westfalen, Krefeld, Germany.

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Gonzalez de Lucio, G. d. L. A. (2020). 3D geological model of the Rhine-Ruhr district and wave propagation for definition of array monitoring, Master's thesis, Hochschule Bochum, Bochum, Germany.

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**The data provided by the Geological Survey of NRW (2020) have not yet been published and are still under further processing and evaluation.**

**Subsurface stresses and prominent faults**

Kruszewski, M., Montegrossi, G., Backers, T, Saenger, E. H. (2021): In Situ Stress State of the Ruhr Region (Germany) and Its Implications for Permeability Anisotropy, Rock Mechanics and Rock Engineering, 1-15.

Kruszewski, M., Montegrossi, G., Balcewicz, M., Backers, T., Saenger, E. H. (2022): 3D In-Situ Stress State Modelling and Fault Reactivation Risk Exemplified in the Ruhr Region (Germany), submitted.

**Subsurface stability analysis**

Ahrens, B., Gilbert, J. P., Kroll, K., Duda, M. (2018): Heating the subsurface: thermomechanical characterisation of subsurface seasonal thermal energy storage in the Ruhr metropolitan area, Der Geothermiekongress DGK 2018, Essen, Germany.

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**Simulation of pumping scenarios**

Kruszewski, M., Montegrossi, G., Saenger, E.H. (2022): The Risk of Fluid-Injection-Induced Fault Reactivation in Carbonate Reservoirs: An Investigation of a Prospected Deep Geothermal System in the Ruhr Region (Germany), in preparation.

**Seismic simulation**

Gonzalez de Lucio, G. d. L. A. (2020). 3D geological model of the Rhine-Ruhr district and wave propagation for definition of array monitoring, Master's thesis, Hochschule Bochum, Bochum, Germany.

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**Figure 9:** Screenshot of the "References" tab of the user tool. The references and data sources used and included are listed here systematically according to the tabs and the various methods in alphabetical order.

### C.6.7 Additional content

Furthermore, exemplary modeling results were added to the tool, which can be used to glimpse the potential of the data set compiled in the project. First, two different time-dependent thermo-hydraulic-mechanical simulation results of geothermal pumping operations along faults over a 20-year period are visualized (Fig. 10). Second, the results of forward seismic simulations of 5 hypothetical seismic events in the subsurface are presented as energy density at the surface, from which the relative surface motion can be estimated (Fig. 11).

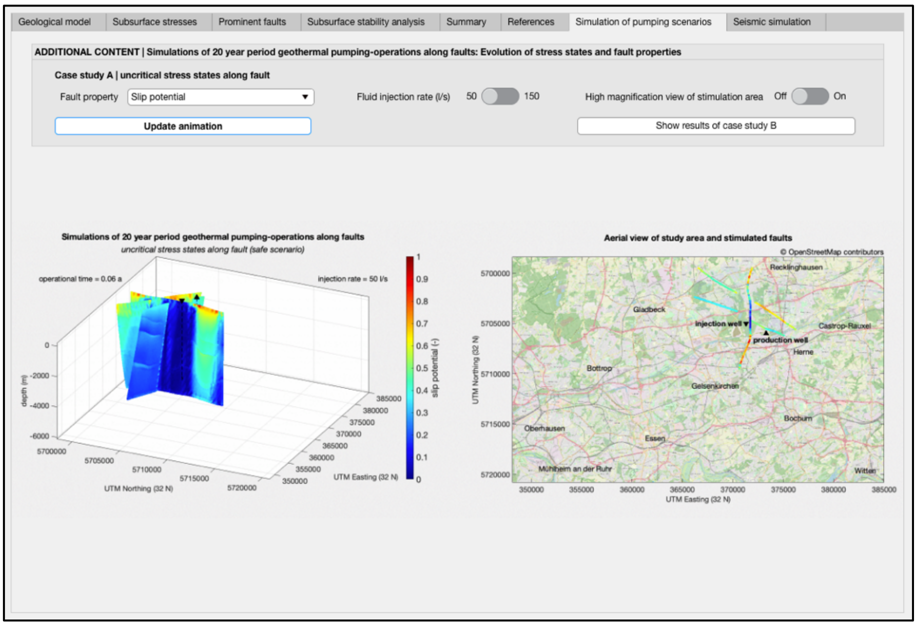


**Figure 10:** Time-dependent thermo-hydraulic-mechanical simulation results of geothermal pumping operations along faults visualized over a period of 20 years (modified after Kruszewski et al., 2022b).

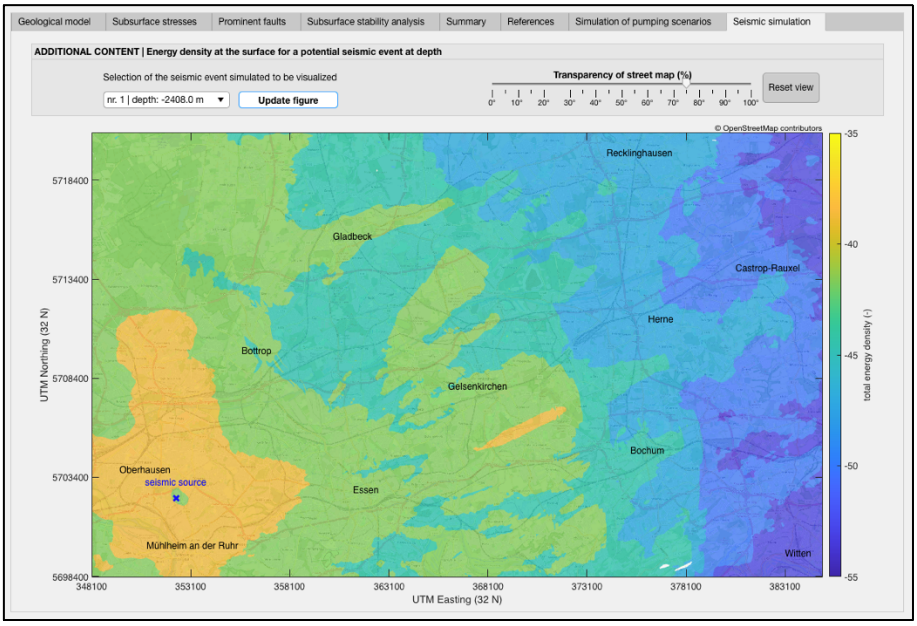


**Figure 11:** Illustration of energy density distribution at the surface of potential seismic events at depth (modified after Gonzalez de Lucio, 2020). The figures shown are the result of forward seismic simulations.

# D | References and sources of data

## D.1 | Geological model

Anderson, H. J., Van den Bosch, M., Braun, F. J., Drozdzewski, G., Hilden, H. D., Hoyer, P., Knapp, G., Rehagen, H.-W., Stadler, G., Teichmüller, R., Thiermann, A., Vogler, H. (2007): Geologische Karte von Nordrhein-Westfalen 1:100000: Erläuterungen zu Blatt C4306 Recklinghausen, Geolog. Landesamt Nordrhein-Westfalen, Krefeld, Germany.

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# E | Acknowledgements

The authors acknowledge generous funding by the Federal Ministry of Education and Research and geomecon GmbH for the project 3D-RuhrMarie ("FHprofUnt2016"). We gratefully acknowledge Petex for donating 10 Move academic software licenses to Hochschule Bochum for 3D-modelling and struc- tural analysis of the subsurface in the Rhine-Ruhr metropolitean area. Special thanks are due the Geological Survey of North Rhine-Westphalia for providing borehole data, geological maps and profiles. Furthermore, the authors acknowledge -and thank- the Geological Survey of North Rhine-Westphalia, Gabriela de los Angeles Gonzalez de Lucio, Martin Balcewicz, Michal Kruszewski, and Thomas Reinsch for fruitful and excellent discussions.