

Geophysical Assessment and Productivity Zoning of Deep Geothermal Utilization in the Greater Munich Area using Multivariate Methods

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ABSTRACT

The North Alpine Foreland Basin in Bavaria, Germany, is a key region for deep hydrogeothermal energy, particularly in and around the city Munich, where hydrogeological conditions and heat demand align. Although significant potential remains untapped, plans for expanded geothermal development are underway. The 2020 “Report Masterplan Geothermal Energy” introduced a preliminary productivity zoning, but it requires refinement.

Using a dense drilling dataset, we applied multivariate statistical methods; principal component analysis (PCA) and hierarchical cluster analysis (HCA); to validate and improve this zoning. From 24 derived parameters, PCA identified key geological, hydrochemical, and technical factors, while HCA revealed five spatially distinct clusters that largely align with the original zoning of the “Report Masterplan Geothermal Energy”.

Our findings define three productivity types (A–C) from north to south, with differing outflow temperatures and porosity-depth trends. These results enhance the reliability of future productivity assessments and support the continued refinement of the Masterplan.

1. INTRODUCTION AND GEOLOGY

Geothermal energy is crucial for reducing carbon emissions in the heating sector (McCay et al. 2019). In Germany, the North Alpine Foreland Basin (NAFB) in Bavaria hosts the most developed deep hydrothermal reservoir, with high heat demand centered in Munich. Based on data from decades of drilling, 24 geothermal plants, 18 near Munich, are now operational. The “Report Masterplan Geothermal Energy” (Keim et al. 2020; Molar-Cruz et al. 2022) initially classified reservoir zones by transmissibility and porosity trends and additional hydrochemical information.

This paper condenses the results of our previously published work (Schölderle et al. 2025), aiming to refine the “Report Masterplan Geothermal Energy” zonation using multivariate statistical methods. The study field is the Greater Munich area, where data density allows deeper analysis of productivity parameters such as outflow temperature and porosity.

2. GEOTHERMAL IN MUNICH AND THE MASTERPLAN GEOTHERMAL ENERGY

The Greater Munich area currently hosts 21 hydrothermal geothermal sites, making it one of the most developed regions for deep geothermal energy in Europe. Of these, three projects in the southern part of the area failed due to low or unstable production rates.

Geothermal exploration began in 1982 with a repurposed hydrocarbon well northeast of Munich. Subsequent drilling increased significantly from 2002 onward, peaking in 2008/09 when 16 successful boreholes were completed. As of early 2024, 21 production and 21 injection wells are in operation, mostly in doublet configurations. Some sites required sidetracks or third wells due to technical complications or limited productivity.

To support future planning, Keim et al. (2020) published the “Report Masterplan Geothermal Energy” that introduced a regional productivity zonation based on available geological and hydraulic data. The zonation was developed using transmissivity values from pumping tests, porosity-depth regressions, and a regional geophysical facies model derived from seismic interpretation and borehole logs (see Figure 1, Zosseder et al. 2022). Zones were categorized according to estimated production ranges and assigned confidence levels based on data density and interpretive uncertainty and by implementing the hydrochemical zonation of Heine et al. (2021).

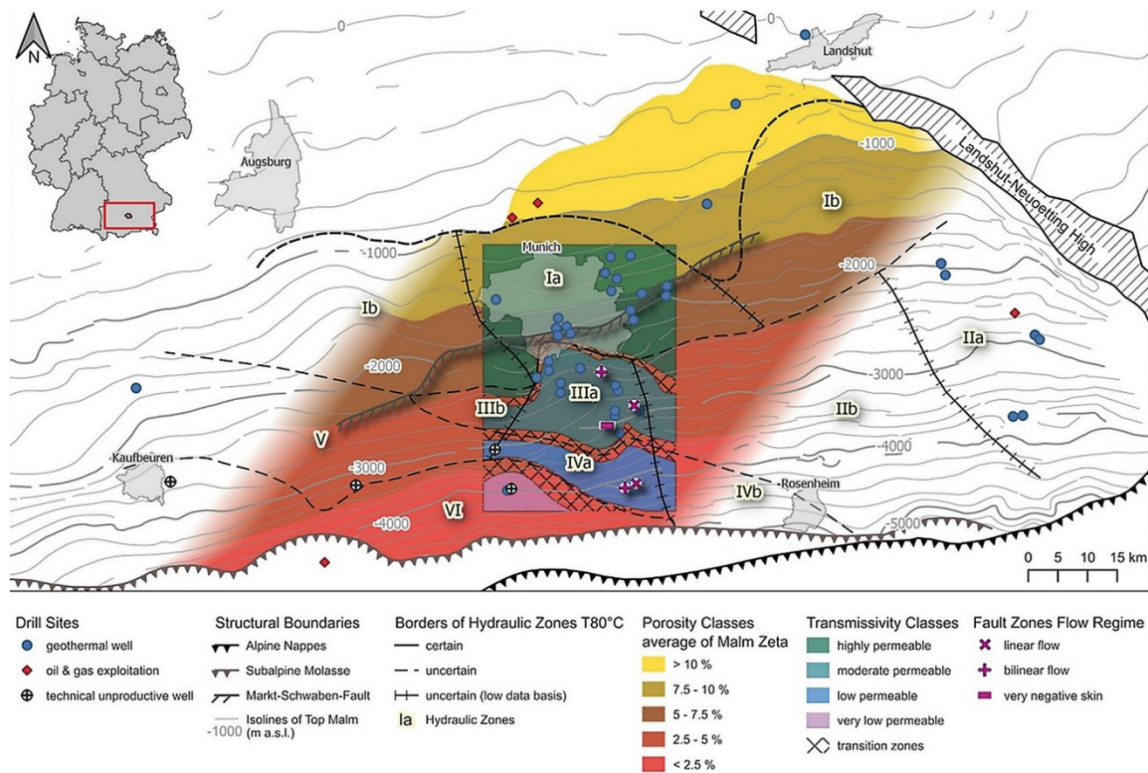


Figure 1: Greater Area of Munich and productivity zones of the study “Report Masterplan Geothermal Energy” with porosity trend and transmissivity/permeability zones. Taken from Zosseder et al. (2022).

3. DATA BASE

To assess geothermal productivity across the greater Munich area, we compiled a comprehensive dataset from 45 geothermal wells, including both producers and injectors. These data integrate 35 parameters grouped into:

- **Geological** (e.g., reservoir depth, porosity),
- **Hydraulic** (e.g., flow rate, productivity index),
- **Technical** (e.g., well deviation, filter area),
- **Hydrochemical** (e.g., pH, TDS, isotopic signatures).

Missing data were imputed based on proximity-weighted averages or global means, following statistical best practices.

3.1 Borehole Data

Due to cost and groundwater protection regulations, logging in geothermal wells is typically limited to basic tools such as gamma ray (GR) and resistivity. Neutron and density logs essential for porosity calculations are absent in geothermal wells in the north alpine foreland basin in Bavaria, though available in some legacy hydrocarbon wells. Sonic and image logs were used where available, though data quality is often reduced in fractured or porous zones due to borehole breakouts. Despite these limitations, hydraulic zones were identified in several wells via temperature profiles and

flowmeter PLT log data. All data were normalized to true vertical depth (TVD).

3.2 Technical Parameters

Technical factors, such as well completion, significantly influence geothermal well productivity. Older wells typically had smaller diameters (6-6.25") and were almost vertical, while newer wells (since 2015) have a standard 8.5" diameter and more deviated well paths. For the analysis, we included well completion details, reservoir section length, drill date, and well deviation parameters, as these factors directly impact productivity.

3.3 Geological and Thermal Parameters

The targeted reservoirs lie within the Lower Cretaceous and Upper Jurassic units ('Purbeck' and 'Malm Zeta-Epsilon-Delta') in depths of 1500–5000 m TVD. Stratigraphic markers and sequence boundaries were mapped using GR logs. Thermal parameters, outflow temperature, static formation temperature, temperature differences, and gradients, were derived from operational data, production tests, and fiber optic measurements.

3.4 Porosity Estimation

In the absence of neutron/density logs, porosity was calculated from sonic and resistivity logs, despite known limitations in carbonates due to complex pore systems. Vuggy porosity estimation was approached through indirect methods based on log discrepancies, supported by regional studies and literature models.

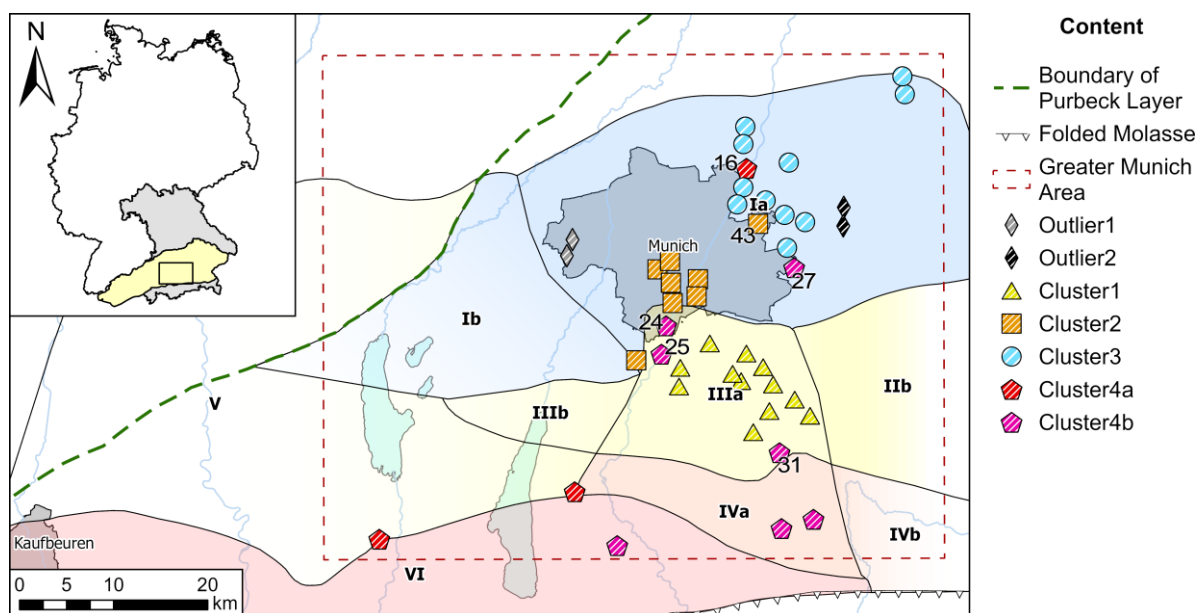


Figure 2: Mapped Clusters of Case B with Updated Zones Ia, b, IIb, IIIa, b, IVa, b, V, VI based on the Productivity Zones after Zosseder et al. (2022). Six points that spatially break out of the clusters are labeled with numbers (well identification). Taken from Schölderle et al. (2025).

3.5 Hydraulic and Hydrochemical Data

Flow zones were interpreted from flowmeter and temperature logs (available for 13 wells). Productivity indices were calculated from pump test data. Hydrochemical data pH, TDS, cations, anions, isotopes ($\delta^2\text{H}$, $^{87}\text{Sr}/^{86}\text{Sr}$), and DOC were compiled from recent studies (e.g., Winter and Einsiedl 2022). The groundwater shows low mineralization (<1000 mg/l TDS), attributed to mixing of meteoric, formation, and matrix waters, influenced by regional flow and geological history.

4. MULTIVARIATE STATISTIC METHODS

To refine the existing geothermal productivity zonation in the Greater Munich area, we applied a multivariate statistical framework with Principal Component Analysis and Hierarchical Cluster Analysis (PCA, HCA, e.g., Härdle and Simar 2015). The methods focused on reducing the dimensionality of the dataset while preserving the underlying variance structure relevant to geothermal productivity and to find correlations in the data set indicating different regional zones.

First, we conducted a PCA using a standardized correlation matrix (e.g., Härdle and Simar 2015). This approach helped identify the most influential variable groups and facilitated a meaningful reduction of 35 original parameters into six principal factors. These factors were interpreted as geological (fa1, fa4), hydrochemical (fa2), technical (fa3, fa5), and hydraulic (fa6) categories. Next, we performed HCA using single-linkage agglomeration and Euclidean distance metrics. The analysis was conducted both on the raw data (case A) and on PCA scores (case B) to avoid distortions caused by correlated variables. Clusters were determined using the dendrogram cutting method

and optimal cluster number was validated by elbow and silhouette analysis (e.g., Pedregosa et al. 2011).

5. RESULTS

To statistically refine the geothermal productivity zoning of the Greater Munich area, we conducted a HCA for two cases: A (raw data) and B (PCA-transformed data). The clustering was aimed at validating or updating the existing zonation from the “Report Masterplan Geothermal Energy”.

5.1 Cluster Analysis of Raw Data (Case A)

Using Single Linkage HCA, we identified two wells (no. 7 and 8) with significant distance from other sites, suggesting outlier status. Ward’s method identified four main clusters, each exhibiting clear spatial distribution patterns. For example, cluster 1 appeared in the northeast (zone Ia), characterized by high porosity and flow rates. Cluster 3 was located south of Munich and further subdivided into 3a (zone IIIa) and 3b (zones IV and VI), the latter being associated with lower productivity.

5.2 Principal Component Analysis (PCA) and Cluster Analysis (Case B)

PCA reduced the dimensionality to six main factors, explaining 80% of the variance. Geological parameters such as reservoir depth, outflow temperature, and porosity dominated factor 1 (fa1), while hydrochemical and technical parameters loaded onto fa2 and fa3, respectively.

The follow-up HCA based on PCA scores resulted in seven clusters as mapped in Figure 2. Outliers included wells with atypical hydrochemistry or extreme values in technical parameters. Spatially, the results revealed a strong north-south trend correlating with increasing

depth and temperature. Clusters corresponded closely to the geological structure, such as the distribution of karstified units and the presence of the ‘Purbeck’ layer.

5.3 Reservoir Types

The derived clusters corresponded to three main productivity types.

- **Type A** (corresponding to zones Ia/Ib of the “Report Masterplan Geothermal Energy”): shallow, high-porosity, productive,
- **Type B** (corresponding to zone IIIa of the “Report Masterplan Geothermal Energy”) (zone IIIa): medium-depth, moderate porosity,
- **Type C** (corresponding to zones IV–VI of the “Report Masterplan Geothermal Energy”): deep, low-porosity, and thermally favorable, but hydraulically risky.

Spatial outliers often reflected known site-specific challenges, such as poor or very good reservoir connection or altered hydrochemistry.

6. DISCUSSION AND CONCLUSION

6.1 Spatial Trends and Geological Validation

The cluster distributions confirm the validity of the north–south zonation in the “Report Masterplan Geothermal Energy”, which is primarily driven by geological depth and associated porosity/temperature trends (cf. Bohnsack et al., 2020). Factor fa1, which includes reservoir depth and temperature, dominated the cluster separation, emphasizing the critical role of geological controls.

In Figure 3, the three identified reservoir types A, B, and C from HCA are shown with the trends of outflow temperature and porosity.

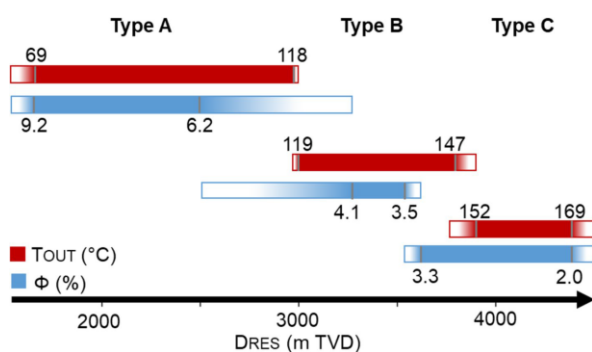


Figure 3: Three types of hydrothermal reservoirs (A, B, C) derived from hierarchical cluster analysis of the Munich Greater Area with calculated outflow temperatures and porosity. The values shown under the bars correspond to the cluster coverage within a type. Taken from Schölderle et al. (2025).

6.2 Hydrochemical Significance and Limitations

Hydrochemical parameters (fa2), while statistically distinct, showed weak correlation with productivity. However, they helped differentiate clusters with similar geological settings. For instance, cluster 2c differed from 2b only in hydrochemistry, possibly due to influxes from different formations (e.g., tertiary layers; cf. Heine et al., 2021).

Interestingly, pH values showed a depth-dependent trend and were grouped within the geological factor (fa1) rather than the hydrochemical cluster (fa2), suggesting indirect geological control. This observation may warrant further geochemical investigation.

6.4 Outliers and Subsurface Complexity

Outlier wells emphasize the complexity of subsurface systems. In these cases, differing hydrochemical or thermal profiles suggested either localized recharge anomalies or technical constraints. Their identification as distinct clusters or exclusions from the main groups increases the model’s interpretability and practical relevance for future developments.

This study demonstrates that multivariate methods provide a statistically robust tool for refining geothermal productivity zoning. Our re-zonation supports the validity of the “Report Masterplan Geothermal Energy” while adding resolution.

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Declarations

The results presented are an excerpt of the former published work Schölderle et al. (2025).

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