Geothermal Reservoir Characterization of the Karstified Upper Jurassic Aquifer in the South German Molasse Basin as basis for reduction of production risks and evaluation of interference between wells

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ABSTRACT

The GIGA-M project seeks to quantify the geothermal potential of the South German Molasse Basin in the greater Munich area, where high heat demand conveniently coincides with a high temperature anomaly in the subsurface. In most productive wells, hydraulically active zones are associated with karstified intervals in the Upper Jurassic-Lower Cretaceous (Malm & Purbeck) aquifer; however, fractures and matrix porosity may also contribute. Hence, improving our understanding of the spatial distribution of karstification in the Upper Jurassic aquifer is crucial for more reliable well interference models and for future exploration efforts. To this aim, we identify seismic features that hint at the extent and intensity of karstification, by correlating detailed mapping of secondary porosity in electric borehole images, with a reviewed sequence stratigraphic model and seismic interpretation.

We quantified the distribution of secondary porosity, from cm-scale vugs to m-scale karst bodies, using a semi-automated process in all existing wells with sufficient data coverage. Borehole image segmentation yields a detailed map of small-scale porosity associated with vugs and fractures. This shows that the identified heavily karstified intervals are typically concentrated at sequence boundaries, and algal boundstone facies of the regressive hemisequence of the Purbeck, highlighting the importance of a detailed stratigraphic model for predicting reservoir quality. It further provides a robust framework for improved seismic facies interpretation.

Despite seismic data resolution typically identifying only two facies—massive and bedded—we can refine the reservoir wide sequence stratigraphic model by integrating geophysical logging data and seismic interpretation. Amplitude Versus Offset (AVO) analysis is applied to differentiate between limestone and dolomite lithologies and identify karst features. Additionally, we use AVO inversion and Extended Elastic Impedance (EEI) analysis to estimate elastic properties, linking impedance to lithology.

Our model incorporates porosity distribution, calibrated against facies models and sonic logs, to enhance the predictability of heterogeneities and permeability distribution in the reservoir. This approach highlights the potential of integrating geophysical logs, borehole images, flowmeter logs, and seismic data to improve exploration strategies in karstified carbonate systems. Our findings will feed into a decision support model for reservoir management and thereby inform future strategies for intensified and sustainable exploitation of the geothermal field under the greater Munich area.

1. INTRODUCTION

The South German Molasse Basin is the most developed deep geothermal reservoir in Germany (BVG, 2025), producing 65-160°C hot water from the Malm (Upper Jurassic, chiefly Tithonian and Kimmeridgian) and Purbeck (lower Cretaceous, Berriasian) aquifer. Reservoir transmissivity, and therefore production and interference potential, in these units is primarily controlled by the paleokarst system (Hörbrand et al., 2025). Additional potential from the matrix, faults, and fractures is only of minor relevance in few locations, especially closer to the alpine front in the south (Konrad, 2022). As part of the GIGA-M project, this study focuses on improving reservoir characterisation in the greater Munich area using seismic attributes and well logs analysis to support high-resolution geological modelling. Six wells from the Schäflarnstraße geothermal site, in the centre of Munich, within the GRAME 3D seismic area provide detailed log data, enabling secondary porosity mapping, facies interpretation, stratigraphic interpretation and calibration. To enhance the geological model, the project aims at identifying hydraulically active features by correlating flowmeter and fiber-optic data from Pfrang et al. (2022) and Schölderle et al. (2023) with geophysical wireline and image logs, promoting a more realistic assessment of flow pathways and reservoir heterogeneity. The resulting geological model will form the basis for dynamic flow simulations to inform geothermal system optimisation, particularly for future drilling design and well targeting.

2. METHODS

2.1 Sequence Stratigraphy Framework

A sequence stratigraphy framework based on Wolpert (2020) was used to distinguish the Malm and Purbeck formations, which differ in facies architecture and reservoir potential. Key sequence stratigraphic features, such as stratigraphic surfaces (e.g., unconformities), bed thickening/thinning trends, and facies stacking, were mapped across multiple geothermal wells using electric borehole image logs, gamma-ray, sonic, and resistivity data. Massive, bedded, debris and dolomitised facies, as previously interpreted by the energy service provider SWM, were used to refine sequence facies, stratigraphic zonation and correlate karst intervals, improving the lateral prediction of facies distribution and reservoir heterogeneities.

2.2 Secondary Porosity Heterogeneities

Secondary porosity is mapped in electric image logs via segmentation between conductive, drilling-mud filled features and the more resistive rock matrix. Image segmentation based on manually determined thresholds yields highly faithful binary feature maps. Both the static and dynamic image are segmented, and the two interpretations are merged according to the general brightness distribution in the static image, which is evaluated on a blurred version of the static image. The segmentation of the dynamic image is used in the very bright and very dark parts, usually between 0.2–0.4 and 0.6–0.8, respectively (note the reverse polarity of brightness to conductivity mapping in image logs). Finally, the vertical gaps between image logger pads/flaps are filled (pore space pixels at both edges are linked horizontally), and individual insular pixels are removed using binary closing and opening with a square 3x3 pixel kernel.

From the resulting 2D map we can calculate the vertical (1D) porosity variation in the well—the ratio of segmented versus total pixels in each data row-—and identify trends at different scales by extracting the relevant frequency bands from a Fourier Transform. Additionally, each individual coherent feature in the 2D porosity map is labelled and characterised by its geometric parameters such as area, aspect ratio (major axis/minor axis), roundness (area/convex area), continuity (area/filled area), or tilt (major axis deviation from horizontal), and the number of features per depth increment are counted. These data are then smoothed to the 4-m--scale via a Fourier Transform to aide visualisation and remove noise from small-scale local heterogeneity.

2.3 Seismic-Well Calibration

High-resolution seismostratigraphic interpretation of the GRAME 3D seismic volume, located in southern Munich and containing the six wells of the Schäflarnstraße geothermal plant was used to map sequence boundaries, stratigraphic geometries, and lateral facies transitions. Sequence boundaries are interpreted through amplitude and facies contrasts and are tied to the well-based stratigraphic zonation, refining and extending the existing work of Wolpert et al. (2022). This well-to-seismic integration improves lateral correlation of sequence boundaries and helps delineating stratigraphically controlled karstified zones across the seismic volume.

2.4 Seismic Attribute with AVO analysis

Seismic attribute analysis that includes amplitude versus offset (AVO), was employed to tackle challenges associated with reservoir heterogeneity. This technique aims to provide a broader view of the spatial distribution of the reservoir, support large-scale sequence stratigraphy interpretation.

Starting with raw prestack time migrated gathers of the GRAME 3D seismic, a post-processing workflow was applied to suppress noise, eliminate multiples, and correct for Residual Normal Moveout (RNMO). A band-pass filter with corner frequencies of 15 Hz/10 dB to 70 Hz/10 dB was employed to enhance resolution by attenuating unwanted frequencies and revealing key geological features. This was followed by spectral balancing to further improve signal clarity. A Radon filter was then applied to suppress deeper coherent noise, while a Radial Trace Transform Filter (RTTF) filter was used to remove ground roll noise. Finally, RNMO correction was performed to align reflection events more accurately. A complete AVO analysis workflow was then conducted to make up for the lack of well coverage to improve the large sequence stratigraphy interpretation.

3. RESERVOIR CHARACTERISATION

We applied a multi-disciplinary approach to characterise reservoir heterogeneity and identify karst-related flow zones within the Purbeck and Malm carbonate sequences. This integrated interpretation draws on well logs, borehole image analysis, AVO analysis, and seismostratigraphy to map stratigraphic controls on porosity and permeability.

3.1 Well log interpretation

Initial stratigraphic characterisation confirms that sequence boundaries, particularly those associated with exposure surfaces and unconformities, exert a strong control on the development of karst and associated porosity (Fig. 1A & B). The bottom of the Purbeck formation (mapped as Large Sequence 4) is

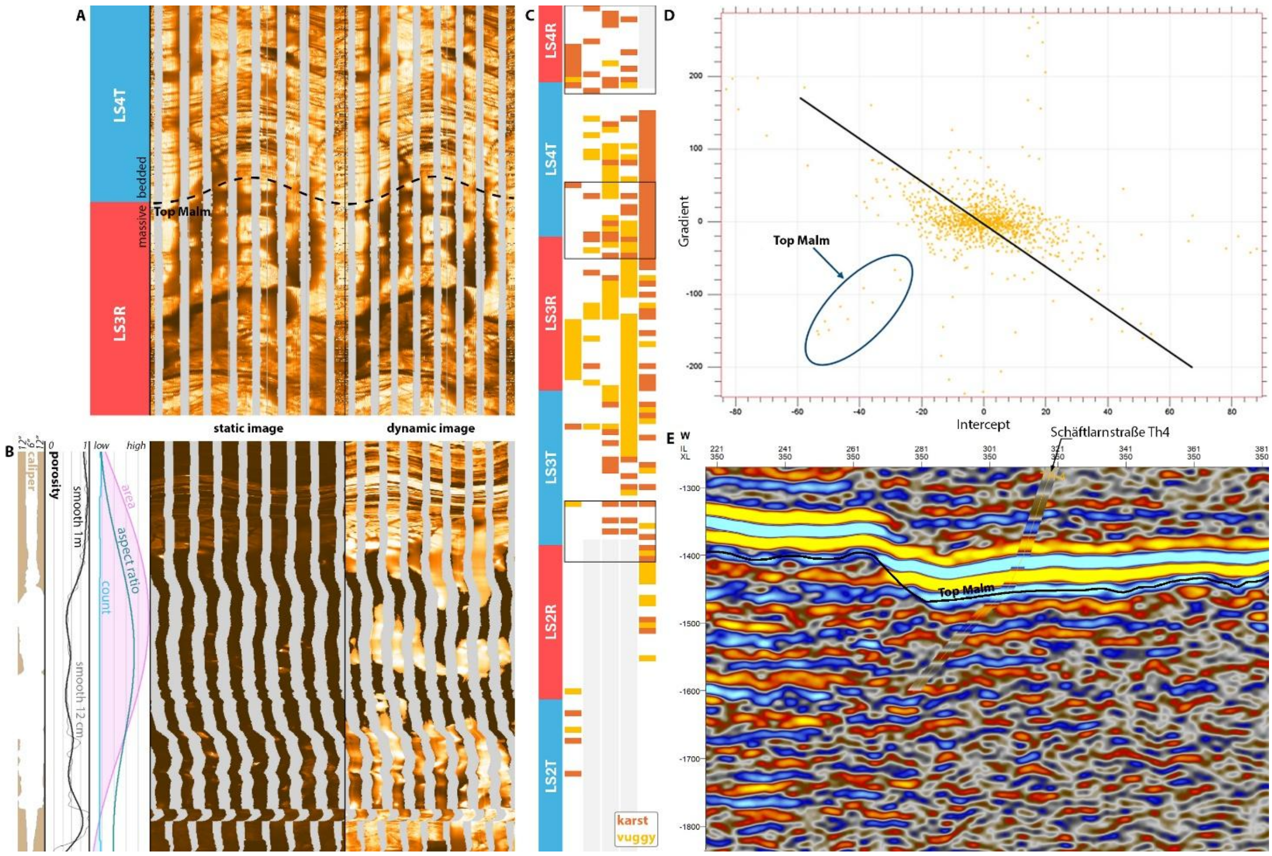

Figure 1: (A) Example of the transition from the massive shallow-marine carbonate facies of Large Sequence 3 Regressive (LS3R) to the bedded brackish facies of Large Sequence 4 Transgressive (LS4T), marking the boundary between the Upper Jurassic (Malm) and Purbeck, as seen in the electric image logs of Sls-Th4. (B) Secondary dissolution features can be identified from the geometric feature parameters extracted from the segmented images. Karst is typically associated with a high porosity, feature area, aspect ratio, and a low feature count. (C) The occurrence of secondary dissolution features (vugs in yellow; karst in orange) can be correlated with the sequence stratigraphy, with extensive karstification in LS4R, at the LS3R-LS4T transition, and in the lower LS3T (black rectangles). (D) Key stratigraphic horizons, such as Top Malm can be identified and (E) mapped throughout the seismic cube via their AVO properties, providing the base for a seismic scale stratigraphic framework.

consistently identifiable in well logs and marks a key transition in the depositional environment. Wireline and image log data support subdividing the reservoir into brackish facies (Purbeck, Large Sequence 4–LS4) and shallow marine carbonate facies (Malm; LS1–LS3).

Karst features are generally characterised by high area and aspect ratio coinciding with low feature count (Fig. 1B); sections with vuggy porosity with high feature count and, possibly, elevated porosity. We could not yet identify a parameter combination that reliably indicates highly fractured borehole sections.

Heavily karstified intervals are particularly common in, but not limited to, the brackish LS4R (regressive), and at the transitions from regressive to transgressive sequences (i.e., the sequence boundaries) as well as in the lower parts of the transgressive sequences (Fig. 1C). Intervals with vuggy porosity are mostly hosted in limestone, but are distributed more randomly with regard to the sequence stratigraphy.

3.2 Well-Seismic Integration

Seismic interpretation of the GRAME 3D volume enables the lateral extrapolation of the stratigraphic zonation defined in the six wells of the Schäftlarnstraße geothermal plant. As shown in the intercept seismic section (Fig. 1E), strong parallel high-amplitude reflectors (PHA) are consistently associated with the bedded Purbeck sequence (LS4), while more chaotic seismic patterns (CAR) align with the biohermal Malm facies (LS1-LS3). These facies interpretations correspond well with borehole image and log data.

Key stratigraphic markers, such as the Top of Malm (Top LS3) and the overlying Top of Purbeck (Top LS4), are clearly distinguishable in both the seismic amplitude response and associated well log data. This seismic–well integration provides a verification of the seismostratigraphic framework, improving confidence in the lateral continuity of hydraulically active stratigraphic intervals and zones with enhanced reservoir potential.

3.3 AVO Interpretation

AVO analysis reveals a clear seismic anomaly at the top of Malm (Top LS3), characterized by negative intercepts and gradients on the intercept-gradient crossplot (Fig. 1D). This anomaly aligns with a sharp facies boundary between the underlying massive biohermal Malm facies (LS3) and the overlying bedded brackish deposits of the Purbeck sequence (LS4). The AVO response is interpreted as a result of this transition from dense, high-velocity carbonates to fine-grained and possibly clay-rich lower-velocity sediments.

Borehole image logs from the Schäftlarnstraße wells support this interpretation, confirming a facies transition at the sequence boundary (Fig. 1A), that can be traced along its distinct AVO signature across the seismic volume. This highlights the potential of AVO analysis as a tool for mapping stratigraphic discontinuities and extra-/interpolating seismostratigraphic interpretations from wells.

3. CONCLUSIONS

By integrating borehole imaging, well logging, and advanced seismic interpretation, including AVO, we significantly improve the understanding of karstified geothermal systems in the South German Molasse Basin. This multidisciplinary workflow supports the identification of spatial heterogeneities and hydraulically active zones critical for geothermal exploitation.

The application of sequence stratigraphy, calibrated with well data and seismic facies, provides a predictive framework to map porosity trends, compartmentalise flow units, and differentiate between Purbeck and Malm reservoir facies. The strong correlation between karst features and stratigraphic surfaces such as unconformities and flooding surfaces supports the zonation of high-transmissivity intervals critical for geothermal production.

This integrated reservoir model enhances the spatial predictability of flow zones and provides a robust basis for reducing drilling risk, evaluating potential well interference, and optimising production strategies. Future steps include the full integration of seismic-scale stratigraphic features and structural elements to refine reservoir models across the basin.

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