Forward Stratigraphic Modelling of Mesozoic Geothermal Carbonate Reservoirs in Central Europe: Sedimentological Constraints, Eustatic Controls and Permeability Heterogeneity

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INTRODUCTION

Carbonates constitute key geothermal reservoir formations for the exploitation of deep geothermal resources in Central Europe. Their complex facies architecture and heterogeneous distribution of petrophysical properties result in vast uncertainties in resource assessment. This issue is particularly pronounced in regions with limited or insufficient subsurface data, leading to exceptionally high exploration risks. **Forward Stratigraphic Modelling (FSM)** provides a precise and dynamic tool for generating realistic, process-oriented subsurface reservoir models in greenfield areas, mitigating the inaccuracies in prediction of reservoir thickness, lateral continuity, and petrophysical properties as typically derived from conventional (linear) interpolation between multiple datasets.

METHODOLOGY

FSM mainly relies on three fundamental input parameters that are essential for constructing geologically realistic and process-based representations of the subsurface: **(1) the initial bathymetry**, which defines the starting topography of the depositional environment; **(2) temporal variations in relative sea level** in response to subsidence, which together define the eustatic signal; and **(3) sediment production** rates as a function of water depth and time. Carbonate production strongly depends on the composition and ecological constraints of the producing biotic assemblages, which together define distinct carbonate factories. These biotas respond differently to environmental parameters such as light availability, water depth, nutrient levels, and hydrodynamic energy, leading to spatially and temporally variable depositional patterns. The definition of distinct carbonate factories and their depth-dependent production rates constitute the most important intrinsic parameter for generating FSM models (**Figure 1**). Sea-level fluctuations play a critical role in controlling accommodation space and consequently the volume available for sediment accumulation. Variations in accommodation space directly influence depositional architecture, facies distribution, and lateral continuity.

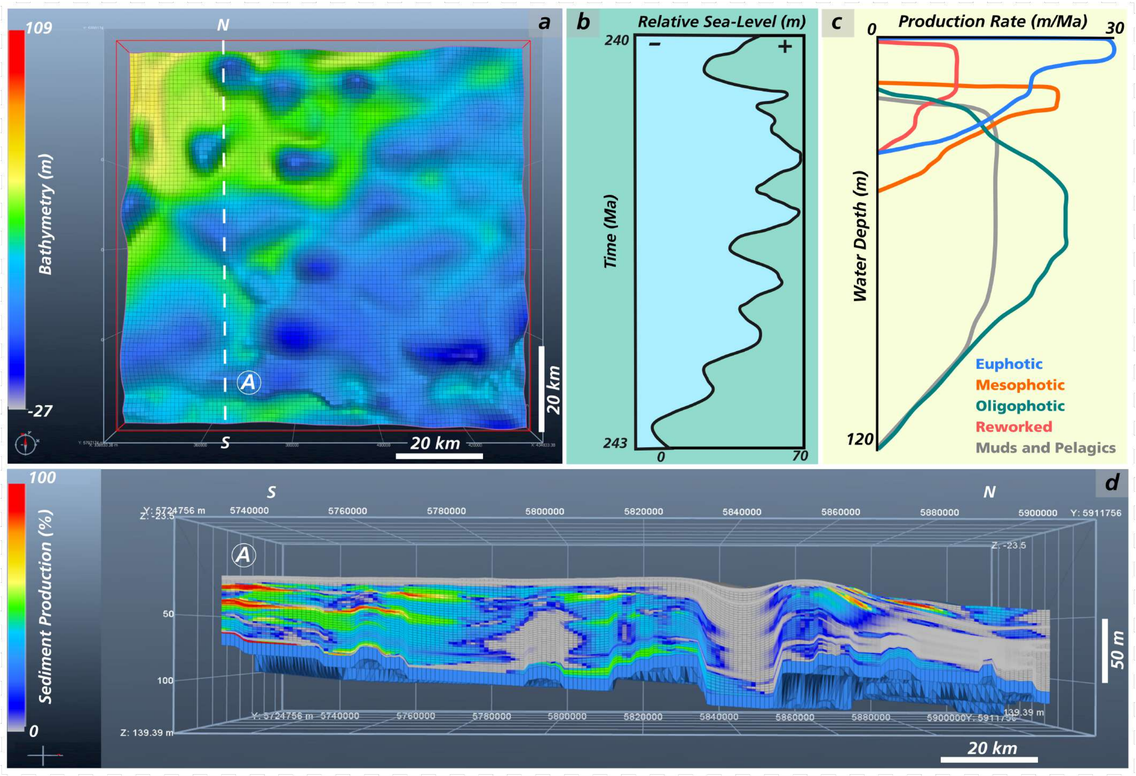


Figure 1. Model parameterization. a) Initial bathymetry at base of Lower Muschelkalk. b) Relative sea-level during modelling interval. c) Production versus water depth of modelled carbonate factories. d) Modelling result representing sediment production of euphotic factory

APPLICATION 1: MIDDLE TRIASSIC RESERVOIRS

The main carbonate reservoir target in the North German Basin consists of oolitic inner ramp deposits with moderate to high porosities (10–20%) and significant geothermal potential at depths of 2,000–4,000 m and temperatures of 80–130 °C. However, exploration is hindered by uncertainties in the subsurface distribution of the oolitic facies, as previous interpolation-based maps depict unrealistic geometries and thicknesses compared to modern ooid shoal systems. The study applies FSM to the Middle Triassic Lower Muschelkalk, incorporating ooid shoals, heterozoan and micritic deposits, each characterized by distinct depth-dependent production patterns. The results demonstrate that ooid shoals preferentially developed on pre-existing salt-induced topographic highs and that their thickness and distribution were strongly controlled by sea-level fluctuations (**Figure 2**). FSM results further explain the observed **southeast-to-northwest decrease in reservoir thickness** and provides a more realistic representation of subsurface ooid shoal geometries, which is crucial given that reservoir quality depends on both fracture systems and matrix porosity.

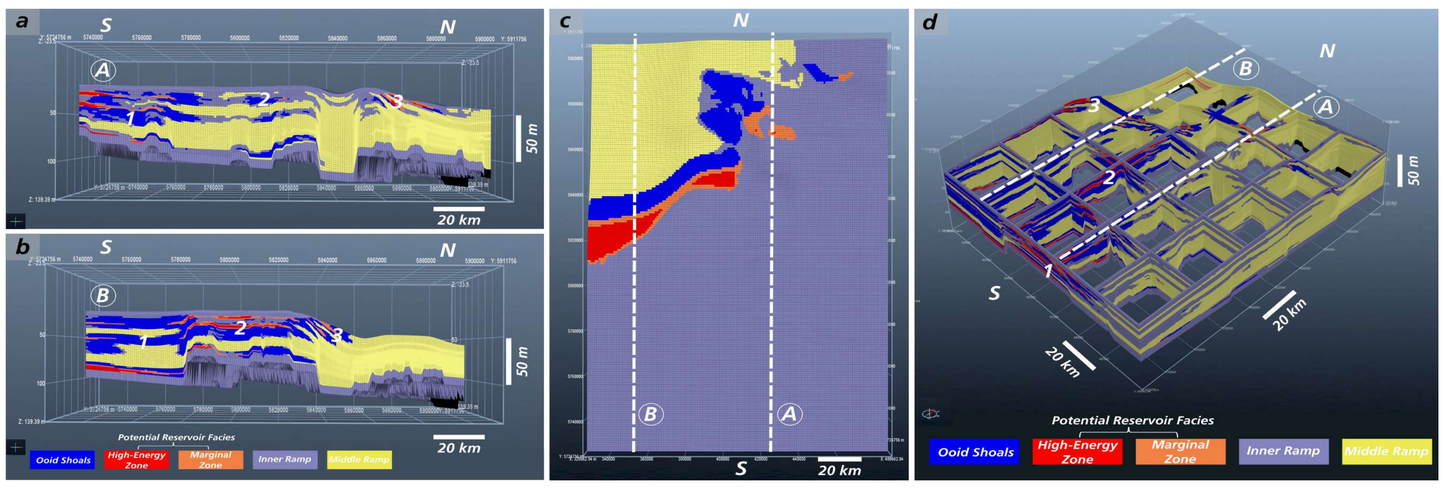


Figure 2. Lower Muschelkalk facies model. a) Profile A with distribution of oolitic reservoir facies. Numbers (1,2,3) indicate temporal subsequent phases of ooid shoal deposition. b) Profile B with distribution of oolitic reservoir. Note the higher abundance of oolite facies in phase 2 due to higher initial topography in the central part. c) Map view indicating positions of profiles A and B. d) Reservoir grid showing 3D distribution of oolitic reservoir facies. Note the SE to NW trend of oolite deposition from phase 1 to 3

Sea-level fluctuations strongly controlled facies development, with widespread sponge biostromes forming during Early Kimmeridgian transgression and intensified bioherm growth occurring during higher-frequency Tithonian sea-level changes (**Figure 4**). FSM enables a more accurate prediction of the spatial distribution and geometry of these key reservoir facies and associated diagenetic zones which are crucial for geothermal exploration because **zones of enhanced permeability** are mainly tied to karstification within the sponge-dominated units.

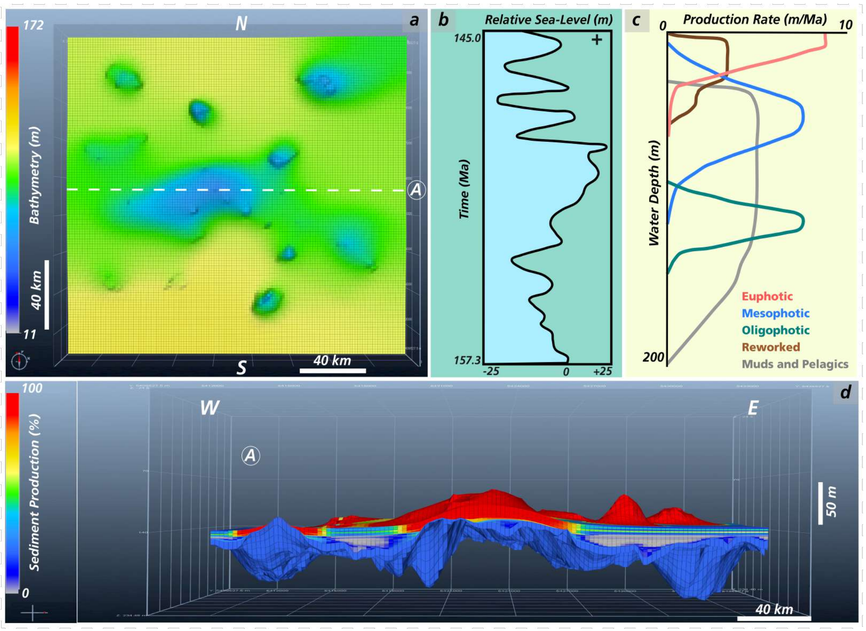


Figure 4. SFM Input Parameter a) Initial bathymetry at base Kimmeridgian with position of profile A. b) Sea level curve during modelling interval. c) Production versus depth for all sediment classes. d) Modelling results indicating production and location of spongue-mirobial bioherms

APPLICATION 2: UPPER JURASSIC RESERVOIRS

The Upper Jurassic Malm aquifer in the South German Molasse Basin is a major geothermal reservoir composed of fractured and karstified limestones and dolomites at depths of 2,000–4,000 m and temperatures of 80–140 °C. It developed on a distally steepened carbonate ramp and is characterized by a complex facies mosaic, with the main reservoir units consisting of Kimmeridgian Hexactinellid sponge biostromes and Kimmeridgian–Tithonian demosponge–microbial bioherms with minor coral deposits. FSM results show that the growth of bioherms required **pronounced initial seafloor topography** (70–140 m relief), as these buildups preferentially formed on structural paleohighs and were further enhanced by differential compaction (**Figure 3**).

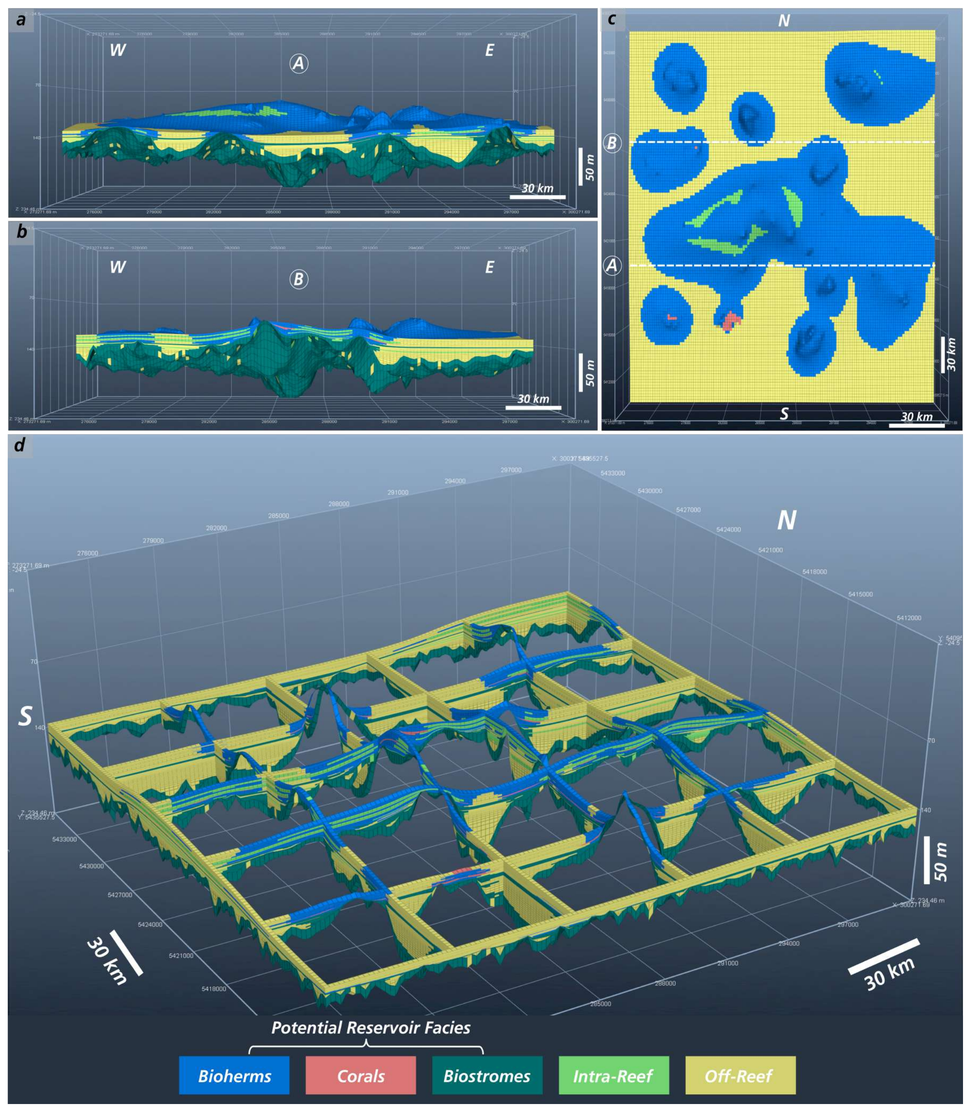


Figure 3. a) and b) Cross sections A and B of the facies model. c) Map view at final modelling time step of 240 Ma. d) Reservoir grid of the study area showing distribution of biostrome and bioherm reservoir facies. Note that bioherm facies and associated coral patch reefs are localized on top of antecedent topographic highs

CONCLUSIONS

This study presents detailed forward stratigraphic models of the major Middle Triassic and Upper Jurassic geothermal reservoir facies in Central Europe. The modelling approach systematically evaluates sedimentological processes, environmental controls, initial bathymetric conditions, and the response of carbonate systems to eustatic sea-level fluctuations. The resulting models provide **robust base-case scenarios for future investigations** of temporally equivalent geothermal carbonate reservoirs in greenfield areas, with current applications focusing on analogous successions in Switzerland, Austria, France, and Spain. A critical next step in reservoir assessment is the **integration of diagenetic processes through reactive transport modelling** within the FSM framework. The long-term objective is to establish an integrated reservoir model capable of realistically representing subsurface porosity and permeability distributions. Such an exploration model can only be reliably developed once reservoir facies are accurately reconstructed, as diagenetic alterations are fundamentally controlled by facies architecture as well as initial porosity and permeability conditions. Overall, the study demonstrates that forward stratigraphic modelling **significantly reduces uncertainties in reservoir characterization** by generating geologically consistent and process-based predictions of reservoir facies distribution.

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