Hidden System Identification: Basin Modeling as a Tool for Examining Sedimentary Geothermal Resource Potential

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ABSTRACT

Three-dimensional (3D) geologic and temperature models have been developed for the onshore U.S. Gulf Coast. The results from these models identify areas of moderate- to high-temperature (90°-150°C and >150°C; respectively) geothermal resources at depths <6 km. This modeling study addresses the fundamental challenge of predicting where opportune temperature and lithology coincide. Unlike traditional geothermal systems with surface expressions of hydrothermal circulation (e.g., hot springs, fumaroles, sinter), sedimentary geothermal systems (SGS) are generally hidden. Historically, simplified efforts to predict subsurface temperatures in sedimentary basins have focused on linear temperature extrapolation that does not consider the variable thermal properties of different lithologies or lithologic changes with depth (e.g., compaction, lithification). Therefore, the need to understand basin architecture and predict temperatures in 3D within SGS is paramount to identifying geothermal resources and determining economic feasibility. Basin modeling software has long been used to characterize the subsurface conditions of sedimentary basins, including temperature, in the pursuit of finding hydrocarbons. This tool can also be adapted to evaluate the potential of geothermal resources in a sedimentary basin by predicting the confluence of desirable temperatures and reservoir lithologies. In this work, PetroMod basin modeling software was used to create a regional geologic model of the onshore U.S. Gulf Coast, covering over 500,000 km^2 calibrated to temperature data from wells. Inputs include structural surfaces from commercial databases, lithology information derived from published literature, and corrected bottom-hole temperatures (BHT) from over 6,000 wells. The resulting 3D geologic model can be used to predict temperatures throughout the basin. Maps were exported showing the depth, depositional unit, and reservoir lithology at which temperatures of 90°C and 150°C were reached, revealing over 400,000 km^2 of moderate- to high-temperature resources at depths <6 km. These maps function as a first-order screening tool to identify areas where low-, moderate-, or high-grade resource potential may exist, based on temperature and if optimal reservoir lithologies or depositional units of interest are present. Depending on the success criteria of a project, the same maps can be exported for any isotherm or incorporate other

subsurface properties. The methodology employed in this work can be applied in any sedimentary basin with available subsurface data. Further calibration incorporating other data, including pressure and porosity, can expand the utility of basin modeling for geothermal evaluations. Basin modeling is a powerful but underutilized tool for identifying prospective geothermal resources in sedimentary basins.

1. Introduction

Basin modeling provides a numerical representation of the geologic history of a sedimentary basin, including tectonic and depositional processes. Geoscientists use basin modeling to better understand the formation and evolution of sedimentary basins and to predict the characteristics and distribution of sedimentary rocks within them. Basin models have long been used as a screening tool in the search for hydrocarbons where the thermal history of a basin is a key factor in determining if a resource is economic. Basin modeling can also be applied to exploration for sedimentary geothermal systems (SGS) by predicting where high temperatures and potential reservoirs may be present within economic drilling depths in a sedimentary basin. A simplified temperature prediction for detecting SGS by linearly extrapolating a temperature gradient from the shallow subsurface does not account for lithologic changes with depth which affect heat flow. Moreover, this simplified approach may not detect hidden geothermal systems. Hidden systems are geothermal resources that lack obvious manifestations at the surface, such as hot springs or a high measured heat flow, making their identification more difficult despite containing substantial geothermal resource potential. SGS sometimes occur in areas of low permeability, where hot geothermal fluids are trapped in subsurface reservoirs and cannot reach the surface. The integrated nature of sedimentary basin modeling, combining the structural, stratigraphic, and thermal history of a basin into a predictive temperature model, provides a promising tool for the exploration of hidden geothermal systems in sedimentary basins. For this study, a regional basin model over the onshore Gulf Coast basin was created using structural surfaces, maps of depositional environments, and corrected bottom-hole temperature (BHT) values to screen for SGS over this region (Figure 1).

2. Methodology

Models representing sedimentary basins typically include at least three main components: a structural framework, a stratigraphic model, and thermal history. The structural framework represents the basin's subsurface structure which may include faults, folds, and other deformational features. Detailed basin models may calculate the migration of fluids along faults and quantify accumulations within hydrocarbon traps. A stratigraphic model details the composition and arrangement of sedimentary strata within the basin. It describes the depositional environments across the basin through time and determines what compaction rates and conductive properties are used in calculations for the lithology assigned to cells throughout the model. The thermal history describes the burial history of sediments and the resulting temperature changes. The history of temperatures in the basins is critical for determining the thermal stress on strata through time and the resulting effects on reservoir quality, hydrocarbon source rock maturity, and present reservoir temperature. A thermal history may be calibrated with data such as BHT values and thermal maturity indicators, including organic maceral fluorescence, programmed pyrolysis, or biomarker parameters (Curiale and Curtis, 2016).

In this study, a simple three-dimensional (3D) sedimentary basin model of the onshore Gulf Coast was built in PetroMod 3D software from the metamorphic basement to the present-day ground level. The sedimentary fill of the Gulf Coast basin was divided into informal, genetically related units of major depositional episodes (Figure 1A). To construct the structural framework, surfaces created from IHS Markit (2022) well data were used to constrain the thickness and age of the depositional units. For a depositional model, paleogeographic maps at each time step were sourced from literature (Ambrose, 2017; Cicero and Steinhoff, 2013; Enomoto et al. 2012; Galloway, 2008; Hull and Loucks, 2010; Pearson, 2011; Salvador, 1991) to estimate lithologies and the thermal properties of each layer (Figure 1B). These paleogeographic maps from multiple sources were compared and standardized so that the same lithologies could be consistently assigned to each depositional environment through time. Finally, the model was calibrated to >6,000 corrected (BHT) values (Kinney and Pearson, 2016; Waples et al., 2004).

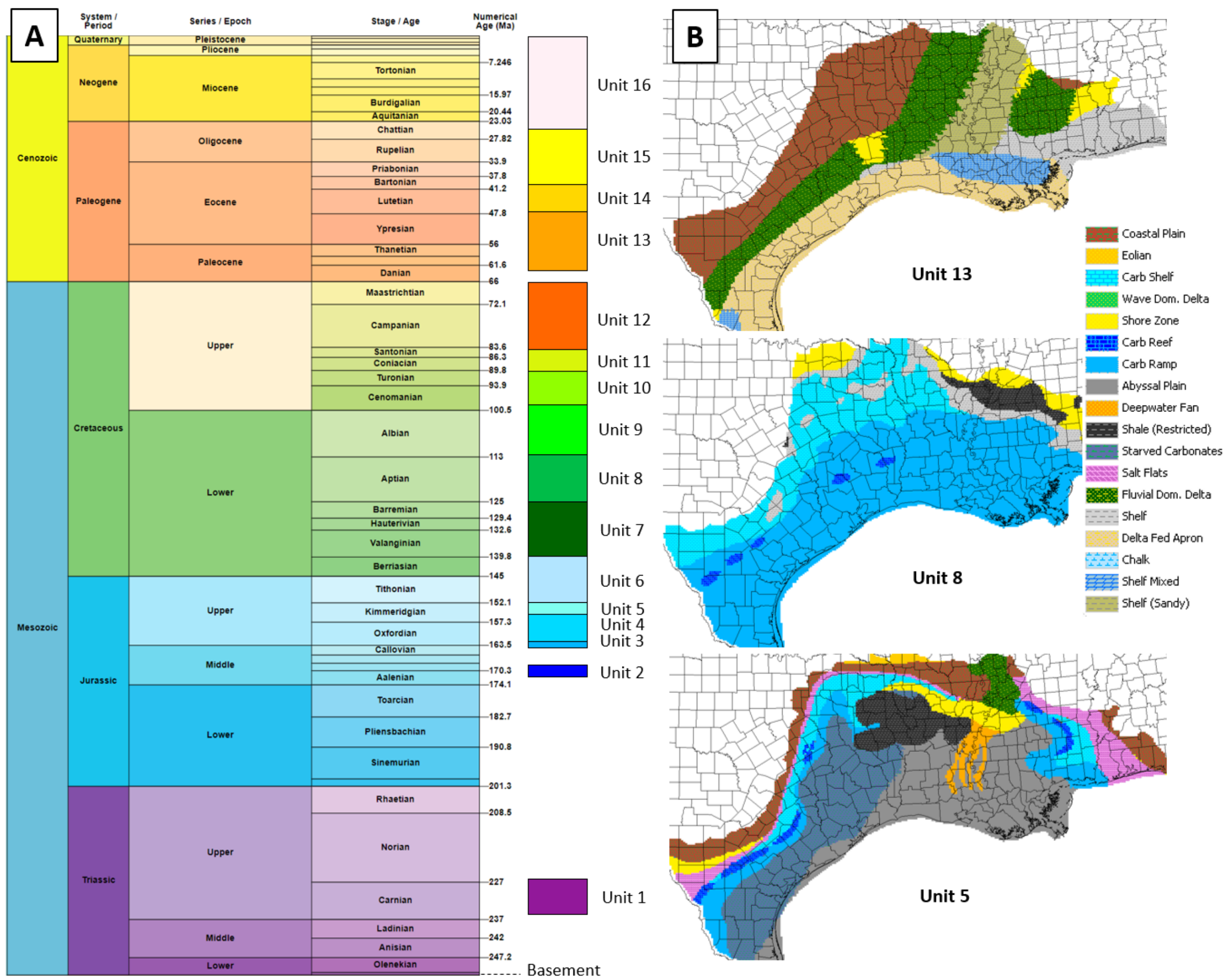

Figure 1: A – a stratigraphic chart showing the age of the depositional units used in the model (modified after Cohen et al., 2013 and Sneddon and Galloway 2019). Empty time between depositional units signifies erosion or non-deposition in the basin. B – examples of the lithology inputs used for some of the depositional units.

To generate additional temperature data for more robust calibration, additional BHT values for wells without parameters necessary to use the Waples correction approach (Waples et al., 2004) were corrected using a correlation based on the dataset compiled by Kinney and Pearson (2016). A cross plot of uncorrected and Waples corrected BHT values showed a mostly linear relationship with little scatter (Figure 2). The slope of a line fit through these data (forced through the origin) was 1.2, indicating that corrected BHTs are ~20% higher than those reported across the onshore Gulf Coast (Birdwell et al., 2022). This result was unexpected, and the limited availability of more reliable subsurface temperature data (e.g., temperature logs, drill stem tests, etc.) made it difficult to test the validity of this simple correlation-based correction. We propose caution and do not endorse the general adoption of this approach. Therefore, although many more BHT measurements are available, for this model, only Waples corrected BHTs were used for calibration.

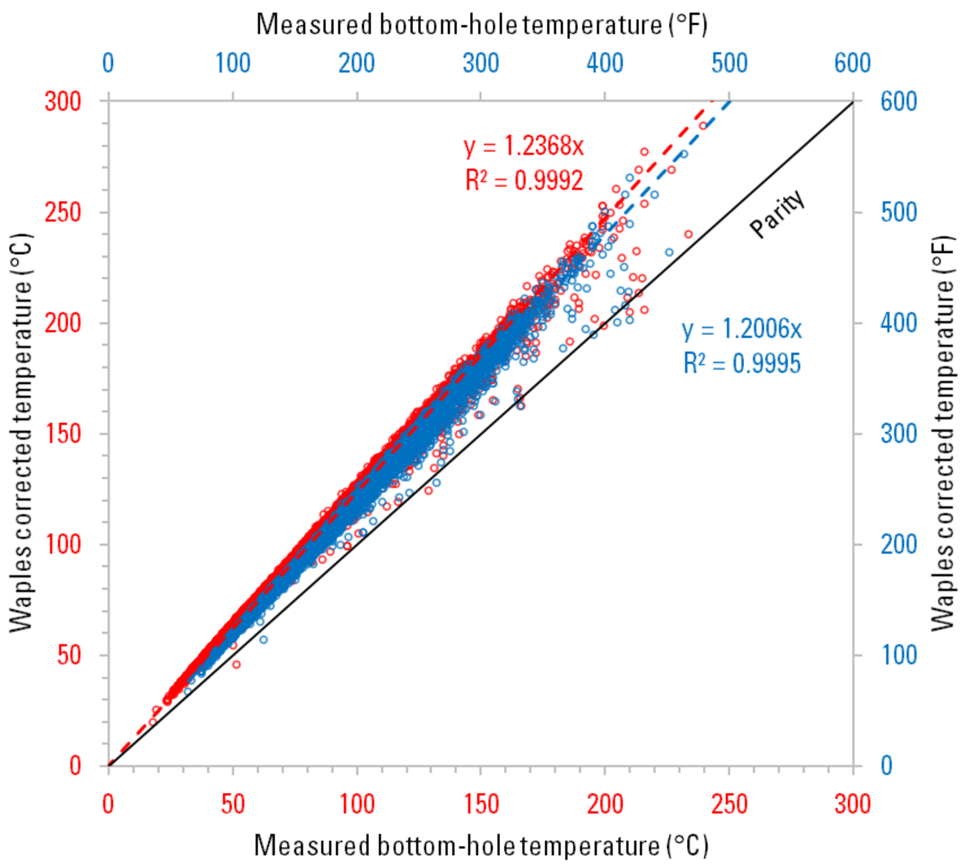

Figure 2: Comparison of uncorrected bottom-hole temperatures to Waples corrected temperatures (°C shown by red symbols and axes labels, °F shown by blue symbols and axes labels). Red and blue dashed lines represent linear correlations (with slope and correlation coefficients) and the solid black line represents parity between uncorrected and corrected temperatures.

3. Results

The completed product is a 3D geologic model calibrated to temperature from which many possible maps can be extracted depending on the criteria desired for SGS screening. Isotherm maps at 90°C (Figure 3), and 150°C (Figure 4) were exported to illustrate where each depositional unit intersects those isotherms which are commonly used for evaluating moderate- (90-150°C) and high-temperature (>150°C) sedimentary geothermal resources. These maps indicate that over

400,000 km^2 of the model area in the Gulf Coast contains a potential moderate- to high-temperature geothermal resource at an approachable target depth of less than 6 km. These potential geothermal resources can be considered hidden systems given the general lack of surface expressions of hydrothermal circulation in the Gulf Coast.

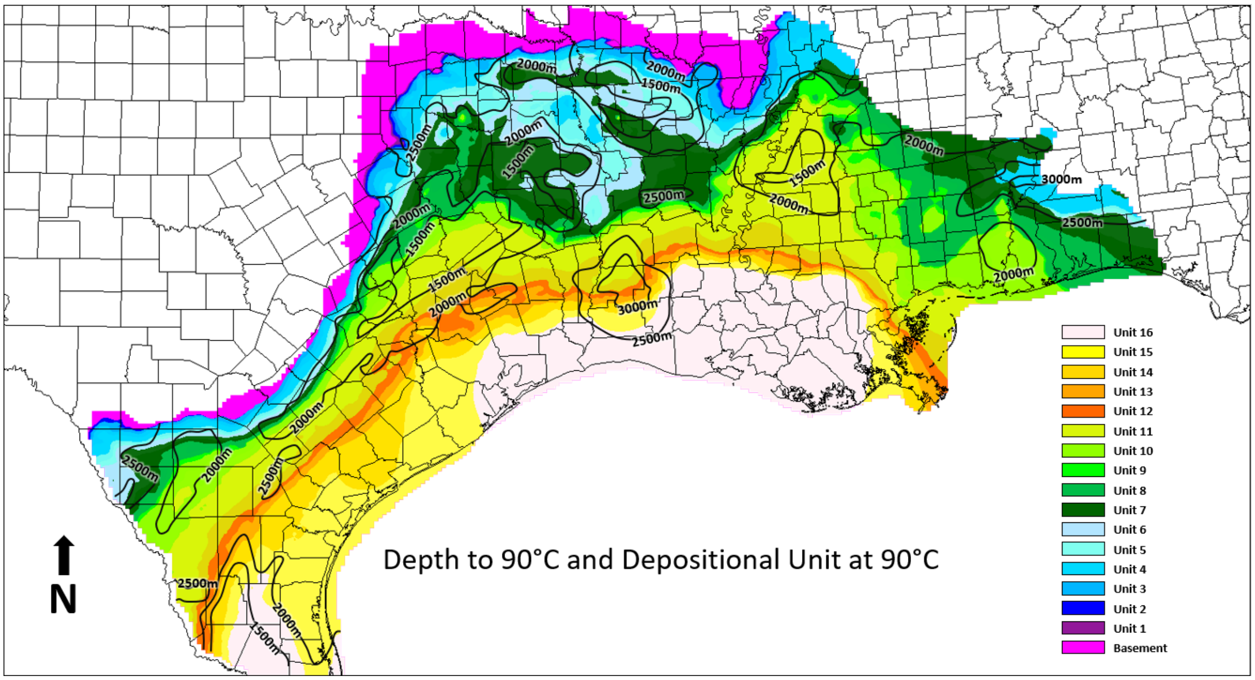

Figure 3: Map of depositional units intersecting a 90°C isotherm overlain with depth to 90°C contours.

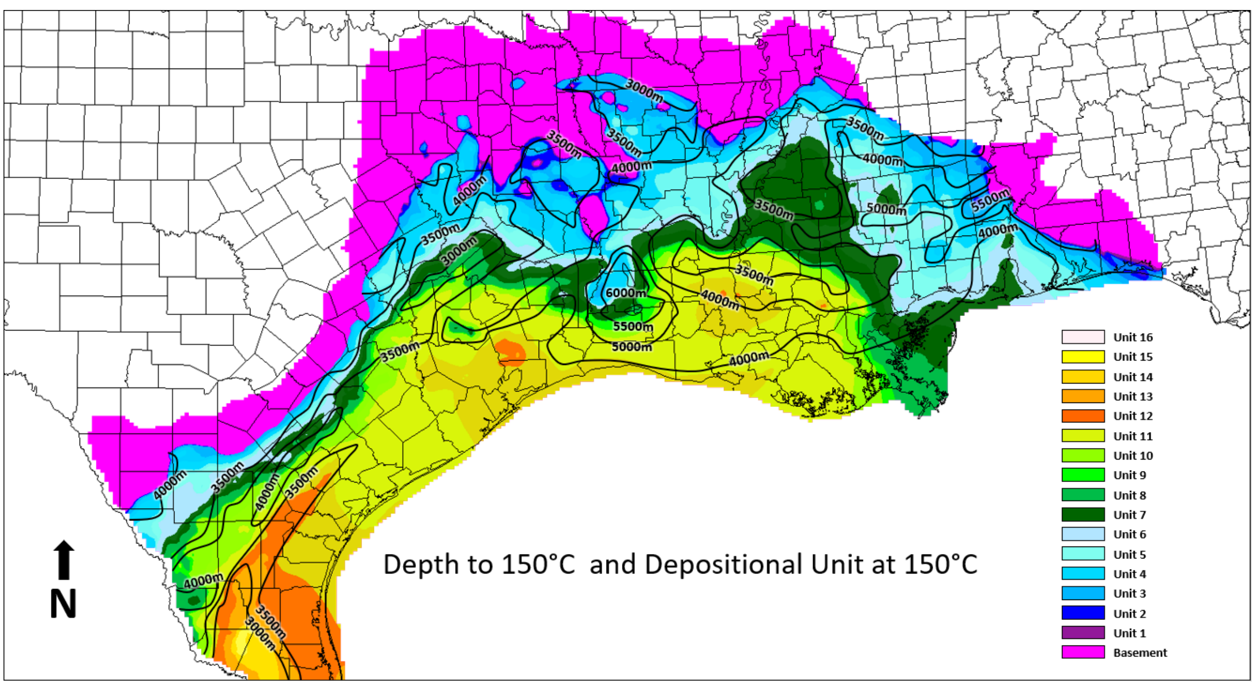

Figure 4: Map of depositional units intersecting a 150°C isotherm overlain with depth to 150°C contours.

Additional detail about the lithologies at any given temperature can be determined at the depositional unit level (Figure 5). Using this approach, areas where potential reservoir quality facies are found at temperatures conducive to geothermal resource development can quickly be identified. This information can be combined with infrastructure data to high grade areas for more detailed study. Porosity and pressure are also calculated by the model, but in this study, these properties were not calibrated to well data.

The utility of this model could be improved by using additional calibration data: porosity, pressure, and thermal maturity. Additionally, incorporating faults and modeling fluid migration could also predict additional geothermal resources. Using additional calibration data and adding the complexity of faults and fluid migration would require considerable detailed work and is something appropriate for more focused modeling work over a smaller area after a prospect has been identified and not the regional first-order temperature screening achieved by this work.

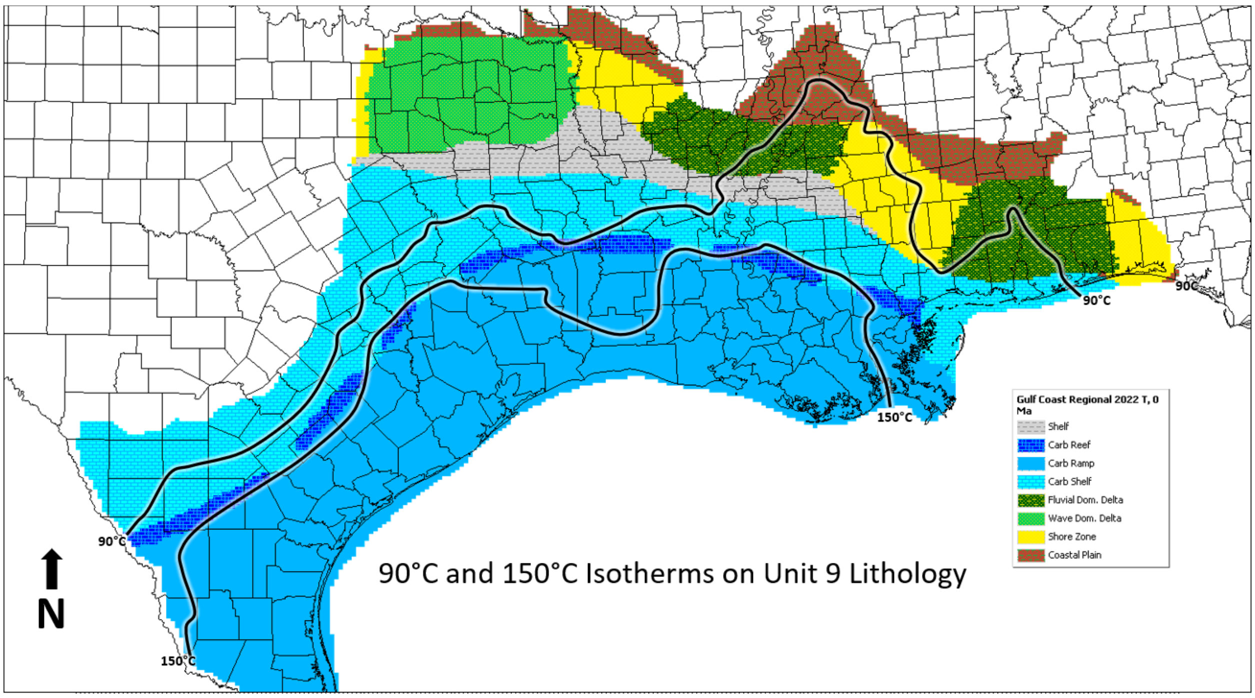

Figure 5: Lithologic map of Unit 9 overlain with 90°C and 150°C isotherms to show which lithologies are found at what temperature range. Areas of high potential for reservoir quality can be high-graded as potential candidates for conventional geothermal projects.

4. Conclusions

Sedimentary basin modeling is a powerful tool for detecting potential geothermal resources in sedimentary basins without hydrothermal surface expressions. Maps exported from a calibrated model can be customized to identify potential sedimentary geothermal resources according to whatever screening criteria are required for which mappable data is available. These outputs can also be used in conjunction with other data such as maps of existing oil and gas wells that can be converted to geothermal, power grid infrastructure, and heating/power demand to further screen for attractive targets for development. The methodology used in this work can be easily applied by practitioners with access to basin modeling software to model any sedimentary basin that has sufficient subsurface data for producing a structural framework, stratigraphic model, and thermal calibration. Further detail and calibration of other subsurface properties can be added to increase the resolution and utility of the model.

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