Enhancing Geothermal Exploration Success: Leveraging Geothermal Play Fairway Analysis to Target Anomalous Heat Mechanisms and Optimize Gradient Predictions

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ABSTRACT

Geothermal energy development faces significant challenges due to subsurface uncertainties, particularly in identifying economically viable plays where elevated temperatures occur at accessible depths. Geothermal Play Fairway Analysis (GPFA) emerges as a powerful risk-reduction framework, adapted from petroleum exploration, to systematically integrate geological, geophysical, and thermal data at basin and play scales. By mapping Common Risk Segment (CRS) and Composite Common Risk Segment (CCRS) elements, GPFA highlights prospects with anomalous heat mechanisms that elevate local geothermal gradients beyond regional norms, enabling high-temperature resources at shallower depths and thereby slashing drilling costs while boosting return on investment (ROI).

Anomalous heat mechanisms often drive these localized thermal enhancements. For instance, salt diapirs act as thermal conductors, funneling heat upward and creating hotspots in sedimentary basins. Overpressured zones can advect deeper, hotter fluids toward shallower reservoirs, amplifying gradients through convective heat transfer. In extensional settings like the Basin and Range province, high-permeability faults linked to deep crystalline basement rocks—such as granites or igneous intrusions—facilitate upward circulation of hot fluids, yielding gradients far exceeding background levels. GPFA's data-driven approach, incorporating borehole temperatures, seismic interpretations, and permeability models, identifies these features by quantifying their impact on heat flow, reservoir quality, and fluid pathways. This targeted identification allows operators to prioritize prospects where temperatures suitable for power generation (>150°C) are achievable at depths under 4 km, reducing capital-intensive deep drilling and enhancing project economics.

A critical pitfall in geothermal assessment is the misuse of geothermal gradients for temperature extrapolation. Linear gradients, derived from bottom-hole temperatures (BHT), cannot be reliably extended beyond well control, as they overestimate deeper temperatures. Gradients inherently decrease with depth due to rising thermal conductivity in compacted, less porous rocks—governed by the equation: gradient = heat flow / thermal conductivity. This leads to flawed temperature-depth profiles; for example, a projected 200°C at 3 km might actually yield only 150°C, inflating drilling budgets and jeopardizing projects amid high upfront costs.

To mitigate this, GPFA incorporates 1D basin modeling, simulating heat flow from the lithosphere-asthenosphere boundary (at ~1330°C) upward through a stratigraphic column parameterized with lithology-specific thermal conductivities. This physics-based method accurately predicts non-linear gradients, accounting for radiogenic heat production and conductive/convective processes. Case studies from the Texas Gulf Coast demonstrate how GPFA, augmented by such modeling, has de-risked plays with anomalous gradients, improving success rates by 20-30% and optimizing ROI through shallower, cost-effective developments.

Additionally, the current developing "Methodology for Adaptive Geothermal Heat Flow Model with Variable Conductivity" offers a sophisticated yet accessible approach to extrapolate temperatures from shallow well data to greater depths, accounting for radiogenic heat production and varying rock properties.

In summary, GPFA not only pinpoints anomalous heat mechanisms for superior play selection but also enforces rigorous gradient modeling to avoid overestimation pitfalls, paving the way for sustainable geothermal expansion.

1. INTRODUCTION – GEOTHERMAL SYSTEMS

Geothermal energy stands as a pivotal component in the global transition toward sustainable power sources, providing reliable baseload electricity with a low carbon footprint. Despite its promise, the sector grapples with substantial subsurface uncertainties, such as heterogeneous heat distribution, variable reservoir permeability, and complex fluid dynamics, which often hinder the identification of economically viable resources (Blackwell et al., 2016). The challenge is particularly acute in locating plays where temperatures surpass 150°C at depths amenable to current drilling technologies, typically less than 4 km, to ensure cost-effectiveness and minimize environmental impact (Nielson et al., 2015).

To address these issues, Geothermal Play Fairway Analysis (GPFA) has been adapted from established petroleum exploration techniques, offering a structured, data-integrated approach to risk assessment and prospect prioritization (Siler et al., 2023). GPFA systematically evaluates critical elements at basin and play scales, utilizing Common Risk Segment (CRS) and Composite Common Risk Segment (CCRS) maps to delineate areas of high probability of success (PoS). This methodology not only reduces exploration risks but also enhances return on investment (ROI) by focusing on anomalous heat mechanisms that deviate from regional thermal baselines, facilitating access to high-temperature resources at shallower depths (Faulds et al., 2017).

This article delves into the GPFA framework, emphasizing its application in targeting anomalous heat mechanisms, including salt diapirs, overpressured zones, and shallow granitic plutons. Drawing from case studies in the Texas Gulf Coast region, we discuss how GPFA integrates geological and geophysical data to de-risk plays. Furthermore, we examine common pitfalls in geothermal gradient extrapolation and advocate for the incorporation of 1D basin modeling to achieve accurate temperature predictions. Through these discussions, we demonstrate how GPFA contributes to 20-30% improvements in exploration success rates, paving the way for broader geothermal adoption.

2. GEOTHERMAL PLAY FAIRWAY ANALYSIS: FRAMEWORK AND APPLICATION

Geothermal Play Fairway Analysis (GPFA) represents a methodical adaptation of petroleum play fairway analysis to geothermal exploration, focusing on the integration of multidisciplinary data to mitigate risks and enhance discovery rates (Nielson et al., 2015). GPFA begins at the regional or basin scale, progressively narrowing to the play scale, where it scrutinizes critical risk elements to identify prospects with the highest likelihood of success. This process is particularly effective in geothermal contexts, where systems are classified by reservoir equilibrium (dynamic vs. static), fluid type (liquid- vs. vapor-dominated), temperature (low <150°C vs. high >150°C), host rock lithology, and heat source (volcanogenic vs. non-volcanogenic), all of which influence resource viability and application (e.g., direct-use heating or electricity generation) (McCarthy, 2025).

The foundational workflow of GPFA involves several key steps. First, data compilation gathers evidence layers from geological, geophysical, and thermal sources, such as heat flow measurements, seismic profiles, and borehole temperatures. Quality control (QC) ensures data reliability, followed by interpolation techniques like Inverse Distance Weighting (IDW) or Triangulated Irregular Network (TIN) to create continuous surfaces. Operator-defined cutoff values then classify these surfaces into risk categories—high (red), medium (yellow), and low (green)—forming individual CRS maps for elements like heat, permeability, recharge, and seal (DeAngelo et al., 2016).

For instance, in geothermal systems, the heat element is paramount, analogous to the source rock in petroleum plays; without sufficient heat, no viable system exists (Rybach, 1981). Risk cutoffs for heat might include temperature gradients of 0-60°C/km (high risk), 60-80°C/km (medium), and >80°C/km (low), or heat flow values of 55-70 mW/m² (high), 70-85 mW/m² (medium), and >85 mW/m² (low). These CRS maps are then composited into a CCRS map using weighted sums or products, highlighting areas where all elements align favorably. In the Tularosa Basin example, GPFA reduced a 6500 km² area to eight high-graded prospects by stacking CRS layers for heat, fracture permeability, groundwater risk, and overall favorability (Shervais et al., 2023).

Applications of GPFA demonstrate its efficacy in risk reduction. In the Snake River Plain, Idaho, it identified favorable zones using gravity, magnetics, and heat flow data, leading to targeted drilling that confirmed anomalous gradients >50°C/km (Shervais et al., 2023). Similarly, in Washington State, GPFA delineated plays with elevated heat and permeability, achieving 20-30% risk reductions (Ansari et al., 2015). By quantifying impacts on heat flow, reservoir quality, and fluid pathways through borehole temperatures, seismic interpretations, and permeability models, GPFA enables operators to prioritize prospects achieving >150°C at <4 km depths, thereby slashing exploration costs and boosting ROI (Witter et al., 2022).

The elements required for an unconventional petroleum play or "petroleum system" are inherently different from a conventional system as the source rock is also the reservoir (Figure 2). The low permeability organic rich shale reaches required thermal maturity to produce hydrocarbons which are then produced through hydraulic fracturing (artificial permeability network).

3. ANOMALOUS HEAT MECHANISMS IN GEOTHERMAL EXPLORATION

Anomalous heat mechanisms are deviations from regional conductive heat flow regimes (typically 40-60 mW/m² in stable sedimentary basins), resulting in localized thermal enhancements that are critical for geothermal viability (Rybach, 1981). These mechanisms, often tied to geological structures or processes, can elevate geothermal gradients beyond background levels, making them prime targets for GPFA. Identifying such anomalies through initial heat resource screening is essential, as it allows for the prioritization of areas with functional geothermal systems before full-scale analysis (Siler et al., 2023). The following subsections detail key mechanisms—salt diapirs, overpressured zones, and shallow granitic plutons—drawing from regional examples like the Gulf Coast, where public borehole data reveal temperatures >300°C at 8 km depths, underscoring the potential for electricity generation above 120°C within 4 km (McCarthy, 2025).

In practice, GPFA employs evidence layers to quantify the impact of these mechanisms on overall system dynamics. For example, in dynamic equilibrium systems with convective heat transfer, anomalies can sustain long-lived resources, whereas static systems rely on conductive heat from radiogenic sources (Faulds et al., 2017).

For an unconventional petroleum system, here are some examples of the critical risk elements and their associated risk cutoff values (Figure 5). Note the asterisk for EGS next to the % clay critical risk parameter. In an unconventional petroleum system that requires fracturing, if the % clay gets too high, the rock is too ductile, and the fractures will not remain open. The same would apply to EGS, which requires the generation of a fracture network.

3.1 Salt Diapirs as Thermal Conductors

Salt diapirs, prevalent in sedimentary basins such as the Gulf of Mexico, serve as efficient thermal conductors due to their high thermal conductivity ($k \approx 4$-6 W/m·K at 20-250°C), contrasting sharply with surrounding sediments (1-2 W/m·K) (Robertson et al., 2022). This conductivity contrast induces refractive heat flow, where flux lines bend toward the diapir, concentrating heat at the crest and flanks and elevating local temperatures by 20-50°C (Nagihara, 2003). Governed by Fourier's law ($q = -k \nabla T$), this "chimney effect" can increase gradients by 10-30°C/km, as modeled in 3D simulations showing peak anomalies at the diapir top (O'Brien et al., 1983).

In the Texas Gulf Coast, salt diapirs (fig. 1) are integral to anomalous heat, where they act as "thermal wicks" transferring basal heat upward. Cross-sections from Oklahoma to the Gulf Coast reveal diapirs extending to 10 km depths, wicking temperatures from deep sources to shallower levels with minimal loss due to high k (Pearson, 2012). In the Haynesville region, diapirs correlate with heat flow >60-85 mW/m², far exceeding regional averages, and contribute to gradients of 60-90°C/km near structures versus 35-40°C/km ambient (Gray and Nunn, 2010). GPFA incorporates seismic and gravity data to map diapir geometry, assigning high weights (0.3-0.5) in heat CRS maps, as seen in North German Basin analogs where diapirism enhances reservoir temperatures (Ruppel et al., 2025).
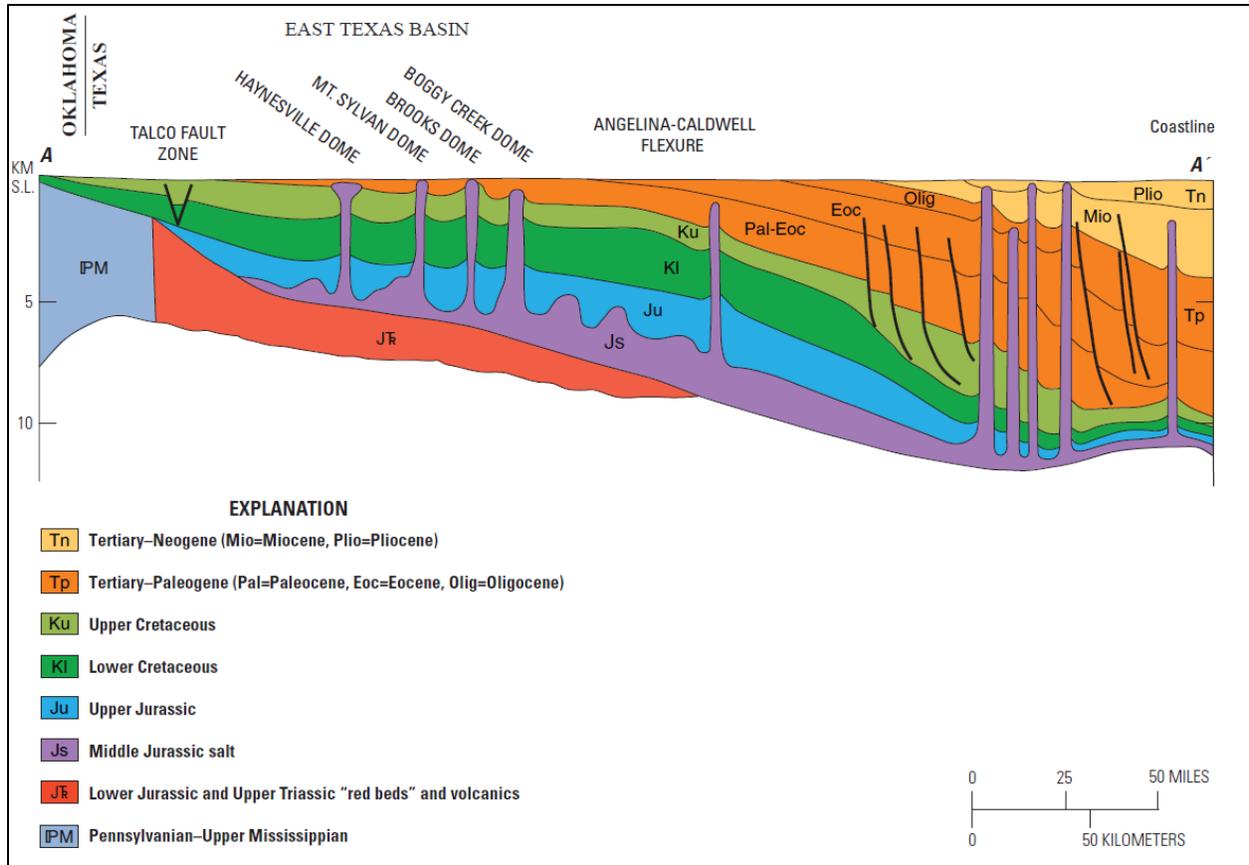
Figure 1: Cross section A-A´ with salt diapir structures from OK to the TX Gulf Coast (Pearson, 2012).

However, challenges include potential salinity impacts on fluid chemistry and drilling risks from ductile salt. Despite this, targeting diapir flanks reduces depths for >150°C resources, improving economics, as evidenced in Gulf Coast studies where anomalies support repurposing oil/gas wells for geothermal (Nagihara et al., 2003). Further research on lateral extent of these effects could refine GPFA models for broader application.

3.2 Overpressured Zones and Convective Heat Transfer

Overpressured zones, characterized by pore pressures exceeding hydrostatic levels (>0.7 psi/ft), facilitate convective heat transfer by advecting hot fluids upward along faults or permeable strata (Bebout et al., 1973). Fluid flow follows Darcy's law ($v = - (\kappa/\mu) \nabla(P - \rho g)$), with heat transport incorporating an advective term in the equation $\rho c \, \partial T/\partial t + \rho_f c_f v \cdot \nabla T = \nabla \cdot (K \nabla T) + Q$, leading to Peclet numbers >1 indicating convection dominance (Zhao et al., 2008). This can amplify gradients twofold, as fluids carry thermal energy from deeper, hotter reservoirs.

In the Texas Gulf Coast, overpressure is a key anomalous mechanism (fig. 2), particularly in the Eagle Ford region where rapid deposition creates geopressured conditions. Studies correlate shallower overpressure tops with reduced depths to 300°F, yielding gradients >50°C/km (Cornelius, 2020). In the Frio Formation, fault-driven advection elevates BHTs, supporting >150°C at <4 km (Garven et al., 2014). GPFA integrates pressure logs and seismic velocities into permeability CRS, weighting convective effects to boost PoS (Liu et al., 2023). Transient modeling via finite elements predicts sustainable flow, though risks like seal breach require careful assessment (Pruess, 1987).
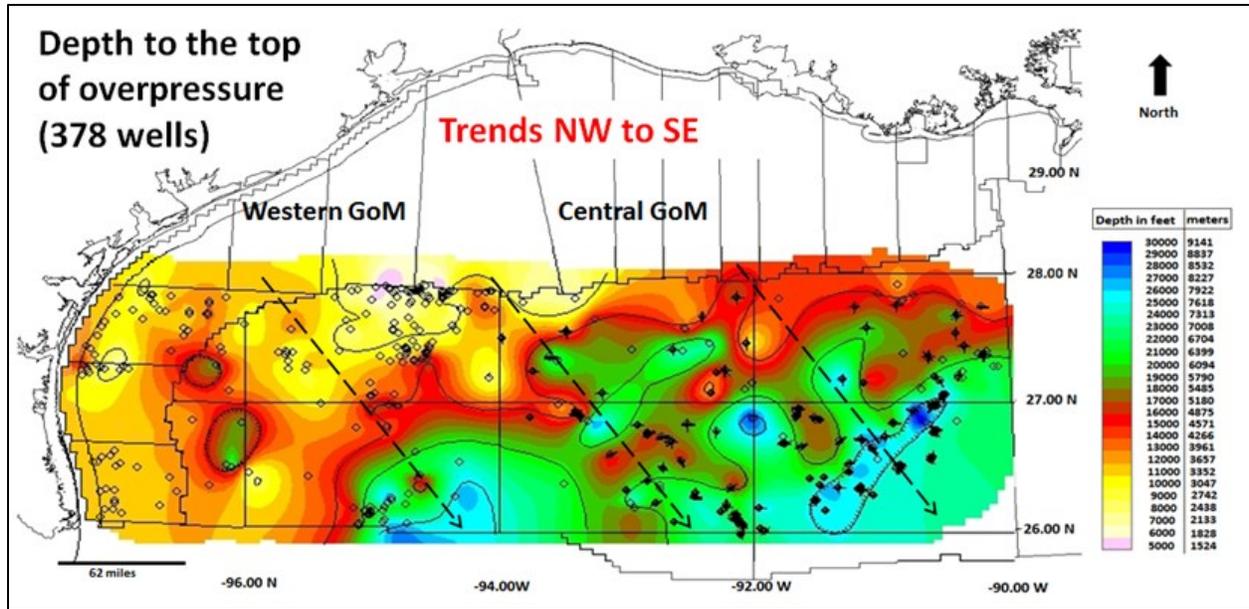
Figure 2: Depth to the top of overpressure (in ft and m) from geopressure gradients computed from 378 wells located in both the western and central GoM (Cornelius, 2020).

This mechanism thrives in compressive tectonics, where faults enhance migration, as in Bohai Bay analogs (Hartmann et al., 2025). In Gulf Coast applications, overpressure complements salt diapirs, creating hybrid anomalies that GPFA maps for optimized repurposing of wells, potentially generating 1-2 MWth per well (McCarthy, 2025).

3.3 Shallow Granitic Plutons and Radiogenic Heat Production

Shallow granitic plutons in extensional settings like the Basin and Range contribute to anomalous gradients (fig. 3) primarily through radiogenic heat production (RHP) from U, Th, and K decay, calculated as $A = \rho\ (0.0992\ U + 0.0263\ Th + 0.00348\ K)$ $\mu W/m^3$ (Rybach, 1981). RHP declines exponentially with depth ($A(z) = A0\ exp(-z/D)$, $D \approx 10\text{-}15$ km), adding 20-50% to crustal heat flow in high-heat-producing granites (Brady et al., 2006). Combined with high thermal conductivity (2.5-3.5 W/m·K), these plutons facilitate efficient conduction, enhancing surface expressions (Li et al., 2025).
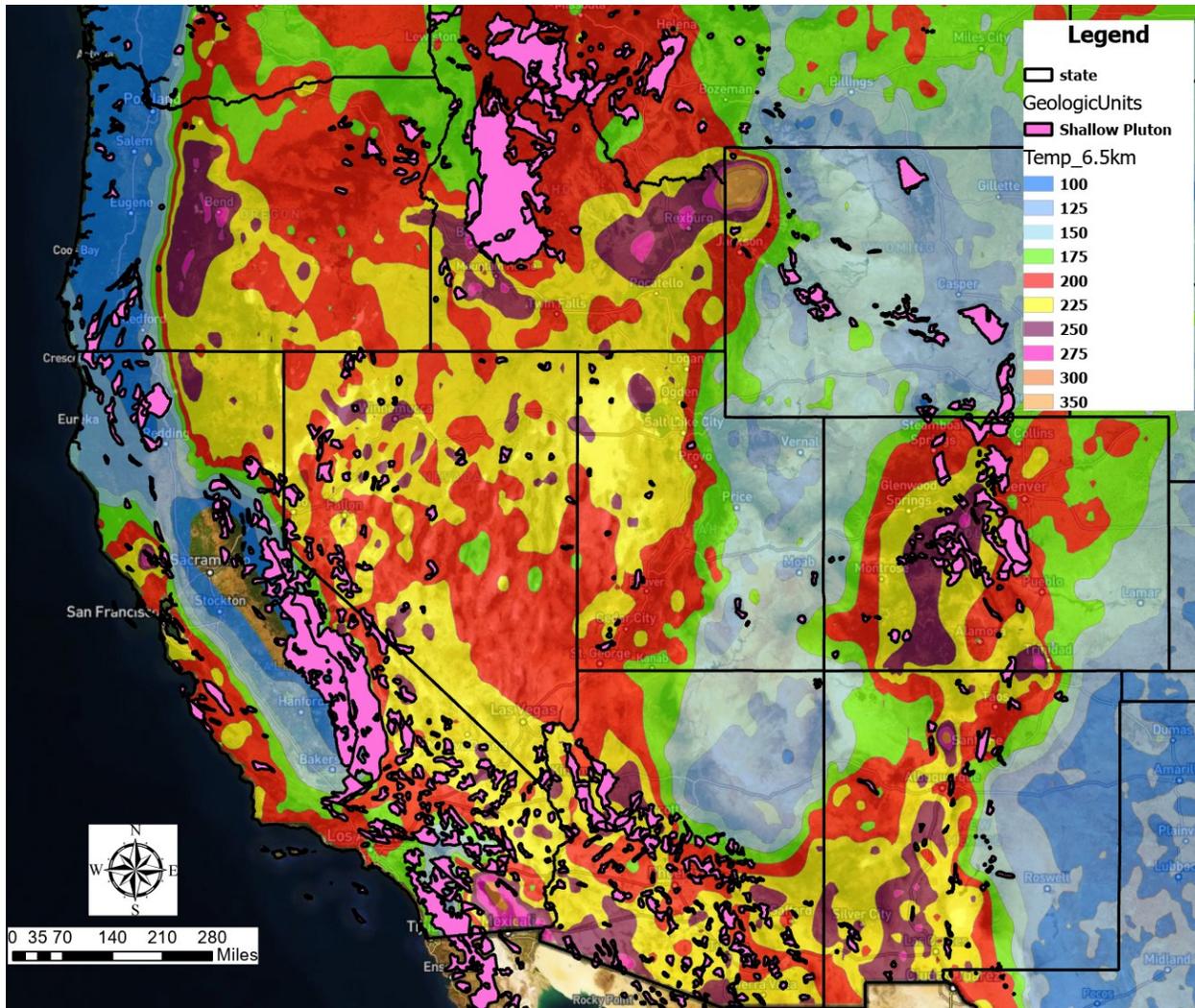
Figure 3: Shallow plutons across the Western United States showing correlation to elevated subsurface temperatures/geothermal gradients.

Correlations are strong: In the Sierra Nevada, RHP of 2-6 µW/m³ correlates with gradients >50°C/km (Wollenberg and Smith, 1964). In Jos Plateau, Nigeria, similar granites yield 40-60°C/km (Musa et al., 2024). Subduction-related cooling, however, suppresses this in forearcs like the Cascades, where slab dehydration lowers heat flow (Lewis et al., 1988). In the Texas Gulf Coast, igneous intrusions in the Haynesville region provide elevated RHP, contributing to heat flow >85 mW/m² and gradients amenable to geothermal repurposing (Yilmaz Sahin et al., 2023).

GPFA targets plutons using gravity/magnetic data for depth mapping, weighting RHP heavily in heat CRS (0.4-0.6) (Wang et al., 2022). This approach aligns with the emphasis on heat as the primary element, ensuring prospects in extensional regimes are prioritized for EGS or hydrothermal development (Nadin et al., 2016).

4. PITFALLS IN GEOTHERMAL GRADIENT EXTRAPOLATION

The extrapolation of geothermal gradients from bottom-hole temperatures (BHTs) is fraught with limitations, often leading to overestimations of deeper temperatures and flawed resource assessments (Rajmon, 2024). Linear assumptions presume constant dT/dz, ignoring the inherent non-linearity where gradients decrease with depth (fig. 4) due to increasing thermal conductivity (k) in compacted rocks—from ~1.5 W/m·K in shallow sediments to ~3 W/m·K in basement—per the relation $dT/dz = q / k$ (Blackwell, 1978). This can result in errors exceeding 20°C/km, as lithological variations, RHP, and fluid effects are overlooked (Ibrahim, 2018).

GEOTHERMAL GRADIENT °C/KM

50 °C/km

Heat Flow/Thermal Conductivity = Geothermal Gradient

KEY TAKEAWAY
Extrapolation of geothermal gradients beyond well control (BHT) will result in overestimated predicted in-situ reservoir temperatures. Geothermal gradients are not <u>constant,</u> they are an average (red oval) of a continually decreasing gradient with depth due to increasing thermal conductivity. To accurately predict gradients beyond well control, a 1D lithosphere thermal basin model must be applied.

Geothermal gradient (°C/km) = (BHT − 15°C)/TVD

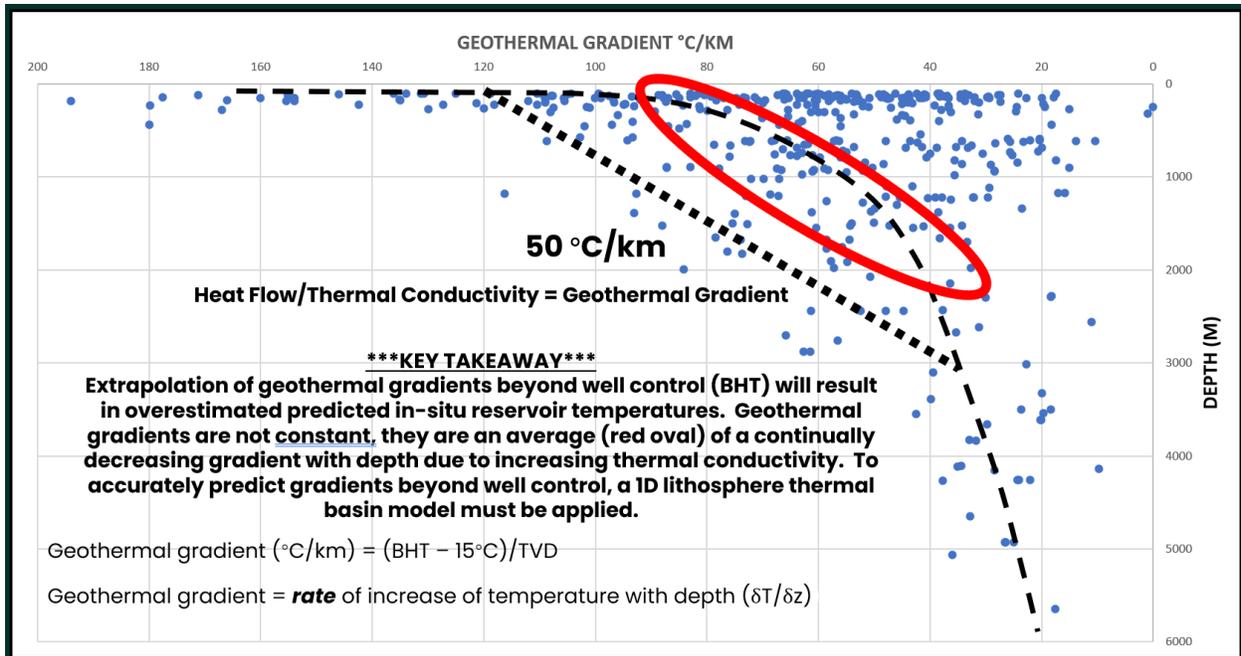Geothermal gradient = *rate* of increase of temperature with depth $(\delta T/\delta z)$

Figure 4: Geothermal gradients are not linear, they decrease with depth due to variables like RHP and increased thermal conductivity.

In the Texas Gulf Coast context, gradients below 60°C/km may require Organic Rankine Cycles (ORC) for viability, while <40°C/km render projects uneconomical due to excessive drilling depths (McCarthy, 2025). For example, in southern Louisiana, linear extrapolations would overestimate temperatures, necessitating drills to 10 km for 150°C, inflating costs beyond feasibility. Non-linear models, such as autoregressive (ARx) or neural network-based (NNARx), offer better fits by incorporating these factors, validated through cross-validation to prevent overfitting (Martinez et al., 2019).

GPFA mitigates these issues by mandating physics-based simulations over simplistic linear methods, as linear overestimations (e.g., 200°C vs. actual 150°C at 3 km) can jeopardize projects with drilling expenses >$5M/km (Chekhonin et al., 2023). Accurate gradient assessment is crucial for distinguishing viable plays, particularly in regions with anomalous mechanisms.

5. INTEGRATING 1D BASIN MODELING IN GPFA

To overcome extrapolation pitfalls, GPFA incorporates 1D basin modeling (fig.5), which simulates steady-state heat flow via the equation d/dz [k dT/dz] = -A(z), integrated upward from the lithosphere-asthenosphere boundary (LAB, T≈1330°C) (An et al., 2015). This approach parameterizes stratigraphic columns with lithology-specific k and RHP, accounting for mantle heat flow (25-30 mW/m²) and crustal contributions (20-40 mW/m²) (Gosnold et al., 2012). In convective regimes, effective k adjustments simulate fluid effects, yielding non-linear geotherms with <5% errors when calibrated (Negara et al., 2015).
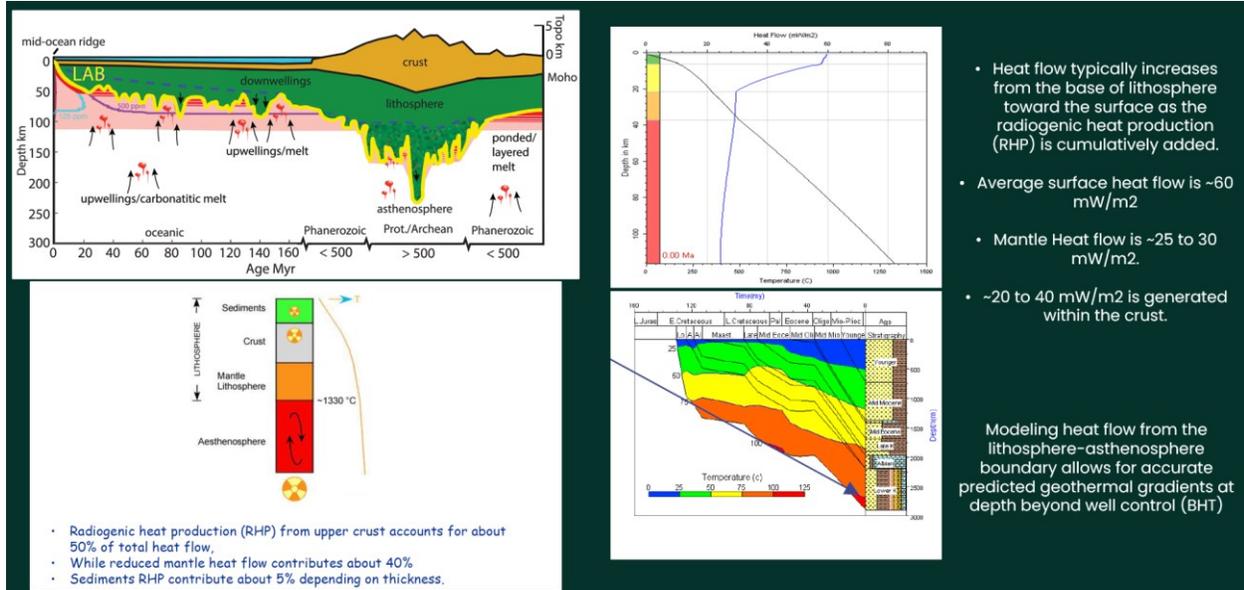
Figure 5: 1-D basin modeling from the lithosphere-asthenosphere boundary (LAB) accurately predicts geothermal gradients at depth.

In the Texas Gulf Coast, this integration is used during initial screening, using models to predict temperatures beyond BHT control and refine CRS maps (Marzano et al., 2025). For instance, in overpressured zones, modeling incorporates advective terms to forecast elevated gradients accurately. Extensions to 3D, as in the Williston Basin, reveal hot aquifers at 3-4 km, supporting EGS favorability (Crowell et al., 2024). Validation against well logs ensures reliability, reducing uncertainties to 2-10°C/km (Kirkby et al., 2024). By embedding 1D modeling, GPFA enhances PoS mapping, as seen in Gulf Coast applications where it de-risks plays for repurposing.

6. METHODOLOGY FOR ADAPTIVE GEOTHERMAL HEAT FLOW MODEL WITH VARIABLE CONDUCTIVITY

This methodology is under development as a free Python-based tool, serving as an alternative to proprietary basin modeling software and paid databases. By integrating Fourier's law with adaptive heat flow and variable thermal conductivity, the model achieves high fidelity in simulating geotherms in diverse basin types, with potential errors reduced to under 10% when calibrated properly.

At its core, the model is grounded in the one-dimensional steady-state heat conduction equation, modified to incorporate variable thermal conductivity ($k(z)$) and adaptive heat flow adjustments with exponentially decaying radiogenic heat production. The heat production is defined as:

$$A(z) = A0 \cdot \exp(-z/D)$$

where (A_0) is surface heat production, (z) is depth, and (D) is the characteristic decay length (typically 10-15 km for continental crust) [2], [3]. The governing equation is:

$$\frac{d}{dz}\left[k(z)\frac{dT}{dz}\right] = -A(z)$$

This is solved by integrating twice to yield the temperature profile:

$$T(z) = T_0 + \int_0^z \left(\frac{q_0}{k(\zeta)} - \int_0^\zeta \frac{A(\xi)}{k(\zeta)}\,d\xi\right)d\zeta$$

where (T_0) is surface temperature and (q_0) is basal heat flow [4], [5]. This formulation allows for realistic

geotherms in sedimentary basins, where ($k(z)$) may vary due to lithology changes, such as decreasing from 3 W/mK in granites to 1.5 W/mK in shales. The model's potential lies in its ability to extrapolate from shallow data (e.g., <1 km BHTs) to EGS-relevant depths, predicting temperatures with uncertainties as low as 2-5°C/km when incorporating site-specific data (e.g. temperature logs). The model significantly reduces errors from simplistic linear extrapolations that often exceed 20°C/km in complex basins. Studies have validated similar models against well logs in the Appalachian Basin, demonstrating improved accuracy over constant-k assumptions (Stutz et. al, 2012). As shown in Figure 6, a typical temperature-depth profile highlights the non-linear gradient influenced by variable (k) and heat production.
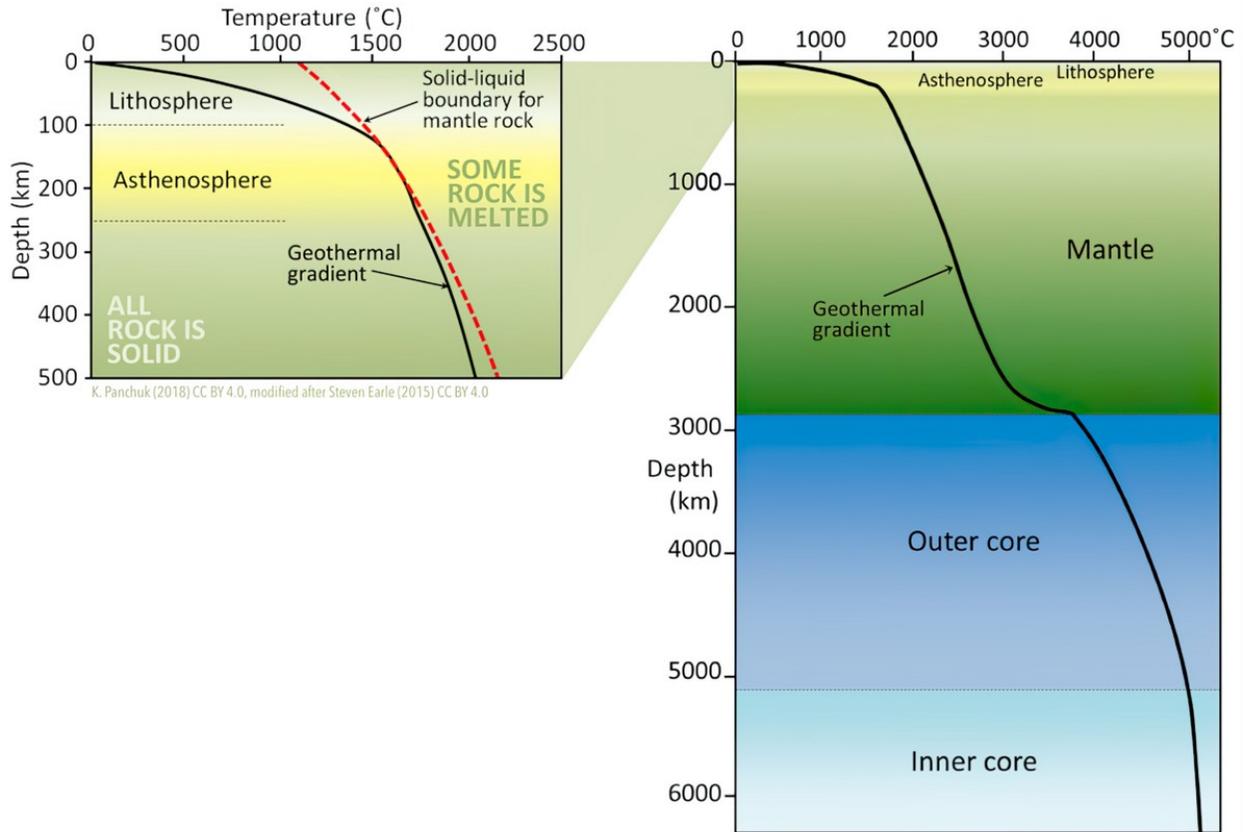

Figure 6: Temperature-depth profile in geothermal settings.

7. CASE STUDIES: TEXAS GULF COAST APPLICATIONS

The Texas Gulf Coast exemplifies GPFA's practical utility, where prolific oil/gas drilling (187,401 active oil wells, 98,709 gas wells) provides extensive data for geothermal assessment (Erdlac, 2022). Public borehole logs reveal temperatures >300°C at 8 km, with economic viability above 120°C within 4 km (Batir et al., 2020). Initial heat screening (fig. 7) identifies high-gradient regions in the Eagle Ford (overpressure-driven) and Haynesville (RHP from igneous intrusions and salt diapirs), reducing exploration areas and focusing on high-PoS prospects.
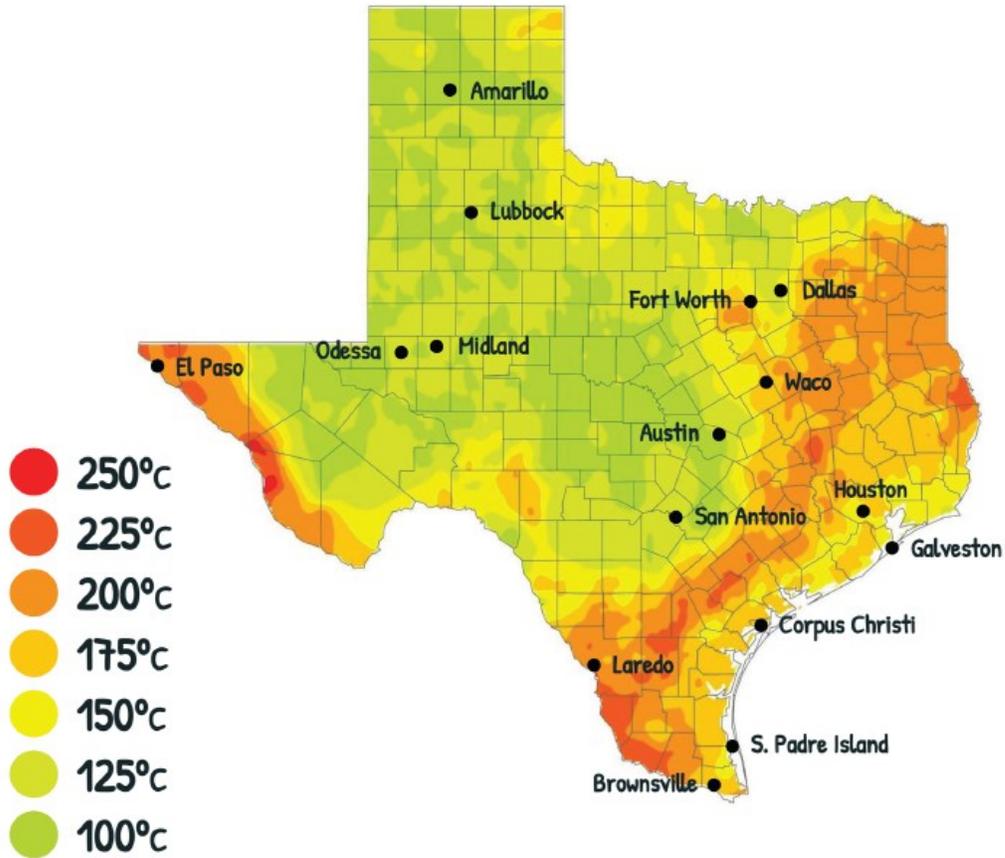
Figure 7: Texas geothermal resources at 6.5 kilometers depth (impactcp.org, 2023)

In the Haynesville, heat flow >60-85 mW/m² correlates with salt diapirs and igneous RHP, yielding gradients 60-90°C/km (Gray and Nunn, 2010). GPFA's CRS maps (fig. 8) for geothermal gradients (using cutoffs like >50°C/km low risk) composite with permeability and recharge layers, identifying wells for repurposing that could generate 1.27 MWth each (McCarthy, 2025). Similarly, Eagle Ford overpressure advects heat, with shallower overpressure tops linking to reduced depths for 300°F (Cornelius, 2020). 1D modeling refines predictions, achieving 20-30% success rate improvements and ROI optimization through shallower developments (McCarthy et al., 2016). These cases validate GPFA's role in transitioning oil/gas infrastructure to geothermal, supporting carbon neutrality.
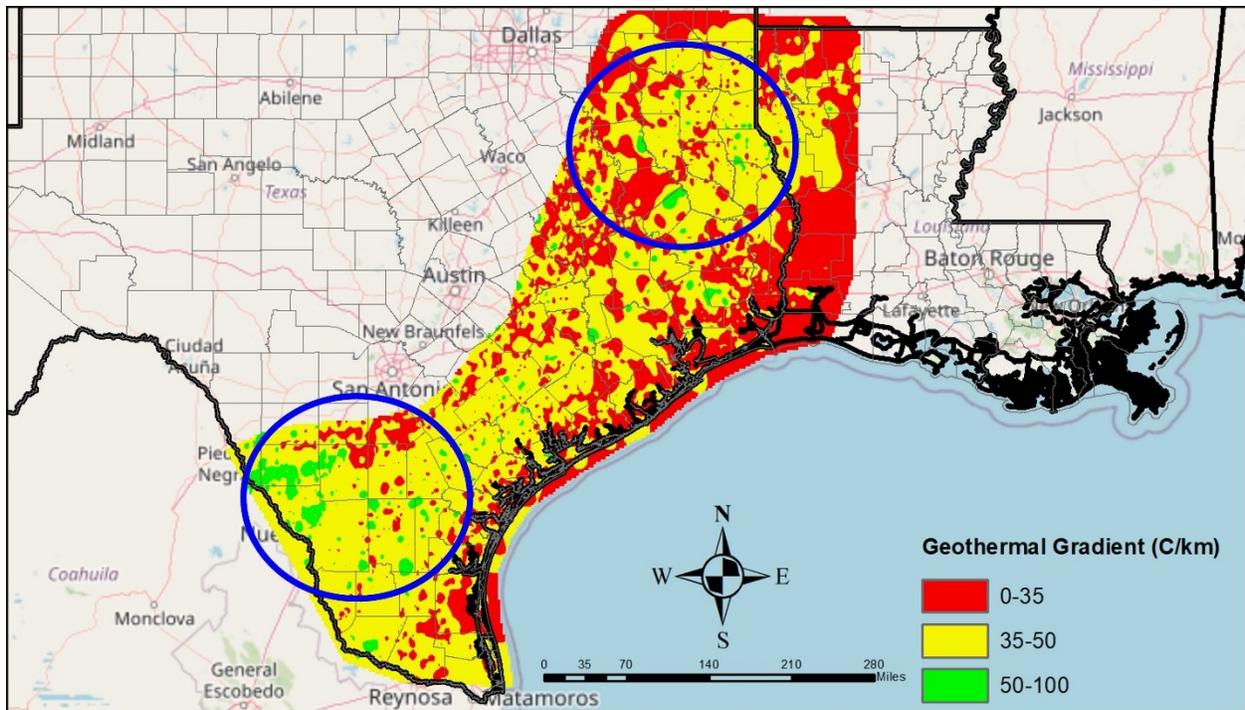
Figure 8: Regional TX/LA Geothermal Gradient CRS Mapping.

8. CONCLUSIONS

GPFA, by systematically targeting anomalous heat mechanisms and integrating 1D basin modeling/Adaptive Geothermal Heat Flow Model with Variable Conductivity, addresses key challenges in geothermal exploration, as evidenced in the Texas Gulf Coast and geothermal prospects across the Western United States. This framework not only de-risks plays but also enhances economic viability, with demonstrated success rate gains of 20-30%. Future advancements, including machine learning for uncertainty quantification, could further refine GPFA, accelerating sustainable geothermal deployment in high-potential regions (Witter et al., 2022).

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