

Resource Characterization and Conceptual Modeling of the Rico Geothermal System to Support Thermal Energy Network Development

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ABSTRACT

The Rico geothermal system in southwestern Colorado represents a promising low- to medium-temperature resource with potential to support a community-scale Thermal Energy Network (TEN). Surface manifestations include three thermal springs from historical artesian mining wells with discharge temperatures ranging from 38–46 °C and flow rates up to 0.95 l/s. However, geothermometry and historical data suggest subsurface temperatures up to 120–140 °C.

To evaluate the feasibility of utilizing this resource for direct-use heating, Teverra, with support from Seequent Ltd., developed a preliminary 3D geological model in Leapfrog Energy. This model integrates geological information, mapped fault structures, geophysical datasets, and known hydrothermal features to characterize the subsurface geometry and identify key controls on permeability and fluid flow. Early modeling results indicate a structurally complex but favorable setting for geothermal circulation, with fault networks that may enhance reservoir connectivity and recharge. The ongoing conceptual modeling effort incorporates additional datasets, including spring temperature and geochemistry, historic mining data, resistivity and magnetotelluric surveys, and thermal gradient anomalies, to refine the resource characterization and develop a conceptual model for the geothermal system.

This integrated approach will guide future exploration and infrastructure planning, laying the foundation for a resilient, locally sourced geothermal energy solution tailored to Rico’s heating needs. By systematically compiling legacy and newly acquired data into a coherent conceptual framework and 3D resource model, this work establishes a technically defensible pathway toward confirmation drilling, reducing subsurface uncertainty and increasing confidence for subsequent investment and development decisions

1. INTRODUCTION

Geothermal resources capable of supporting direct-use heating and TEN are increasingly recognized as a critical component of decarbonization strategies for small and mid-sized communities, particularly in cold-climate regions where space heating dominates energy demand (Herrerias Martínez et al., 2025). Unlike high-temperature geothermal systems developed for electricity generation, TEN-oriented resources can be economically viable at relatively modest subsurface temperatures when coupled with modern heat pump technologies. As a result, regions exhibiting anomalously high geothermal gradients, even in the absence of large surface manifestations, represent attractive but often underexplored opportunities for community-scale geothermal development.

The Town of Rico has a rich mining history owing to its unique geological setting, having housed more than 5,000 people in the past, but the decline in mineral operations has caused a drastic decrease in the town’s population and economic opportunities. As a result, the Town is now inhabited by around 300 people, and its economy reliant on tourism and infrastructure. The rising interest among residents in finding sustainable economic development opportunities prompted the exploration of geothermal energy utilization from the town’s local geothermal resources. The geological conditions of Rico, located in the western San Juan Mountains of southwestern Colorado, present one such opportunity. The town of Rico lies atop the Rico Dome, a structural uplift formed through a combination of intrusive activity, doming, and faulting that has played a central role in local mineralization and hydrothermal circulation (Knight, 1974). The Rico Dome is characterized by complex structural deformation, including intersecting north–south and northwest–southeast trending fault systems, and by the presence of Paleozoic carbonate units, notably the Leadville Limestone and Hermosa Formation, which are regionally recognized for their capacity to host permeable hydrothermal reservoirs and mineralization. These geological characteristics, in addition to the presence of known geothermal manifestations, have long suggested elevated subsurface heat flow and structurally focused fluid circulation beneath the town.

Evidence for active geothermal processes at Rico includes the artesian discharge of warm to hot thermal water from historic mining-era boreholes, elevated geothermal gradients documented in legacy temperature logs, and the presence of extensive travertine deposits near the river valley south of town. Measured spring temperatures range from approximately 40 to 46 °C, while geothermometric estimates and historical records suggest subsurface fluid temperatures on the order of 120–140 °C. These values imply geothermal gradients substantially above typical continental background levels. Importantly, however, surface thermal manifestations in Rico are spatially limited and do not, on their own, fully capture the extent or character of the subsurface thermal anomaly. Travertine deposits south of town, anomalous temperature gradients in mining boreholes, and geophysical evidence for laterally extensive conductive zones suggest that the geothermal anomaly may be broader than the geothermal system discharging at the historical boreholes indicate.

Previous investigations of the Rico geothermal system have largely focused on documenting surface expressions, mining-era thermal observations, and geophysical anomalies, but have not fully integrated these datasets into a unified subsurface framework suitable for evaluating development potential (e.g., Oerter, 2011; Dunnington et al., 2018). This study addresses these gaps by developing an integrated geological and conceptual model of the Rico geothermal system explicitly oriented toward evaluating its suitability for supporting a community-scale TEN. Using a 3D geological framework constructed in Leapfrog Energy coupled with geoscientific-driven conceptual modeling, the work synthesizes stratigraphic interpretations, mapped fault geometries, surface thermal data, historical mining records, and available resistivity and magnetotelluric datasets. The objectives of this paper are to (1) clarify the geological and structural setting of the Rico Dome as it relates to geothermal circulation, (2) characterize the likely depth, extent, and temperature range of the geothermal system while explicitly acknowledging data limitations and uncertainty, and (3) develop foundational conceptual models that can guide future exploration, confirmation drilling, and phased TEN infrastructure planning.

Rather than presenting a definitive resource estimate, this paper emphasizes conceptual understanding and uncertainty-aware interpretation appropriate for an early-stage geothermal prospect. By situating the Rico system within a broader framework that includes both localized convective upflow and a wider conductive thermal anomaly, the study highlights development pathways that extend beyond surface manifestations alone. In doing so, it aims to provide a technically robust foundation for decision-making as the Town of Rico considers geothermal energy as a long-term, locally sourced solution for meeting its heating needs.

2. GEOLOGICAL SETTING

The Rico geothermal system is located in the western San Juan Mountains of southwestern Colorado, a region characterized by a complex tectono-magmatic history involving Laramide deformation, Cenozoic intrusive activity, and widespread volcanism (Pratt et al., 1969). As highlighted in Figure 1, this geologic evolution produced a structurally heterogeneous crust marked by faulting, doming, and lithologic contrasts that strongly influence subsurface fluid flow and heat transport. Across the broader San Juan region, elevated heat flow has been attributed to a combination of magmatic heat input, crustal thinning, and deep fluid circulation along regional fault systems, creating favorable conditions for the development of hydrothermal systems even where surface manifestations are limited (Geldon, 1989).

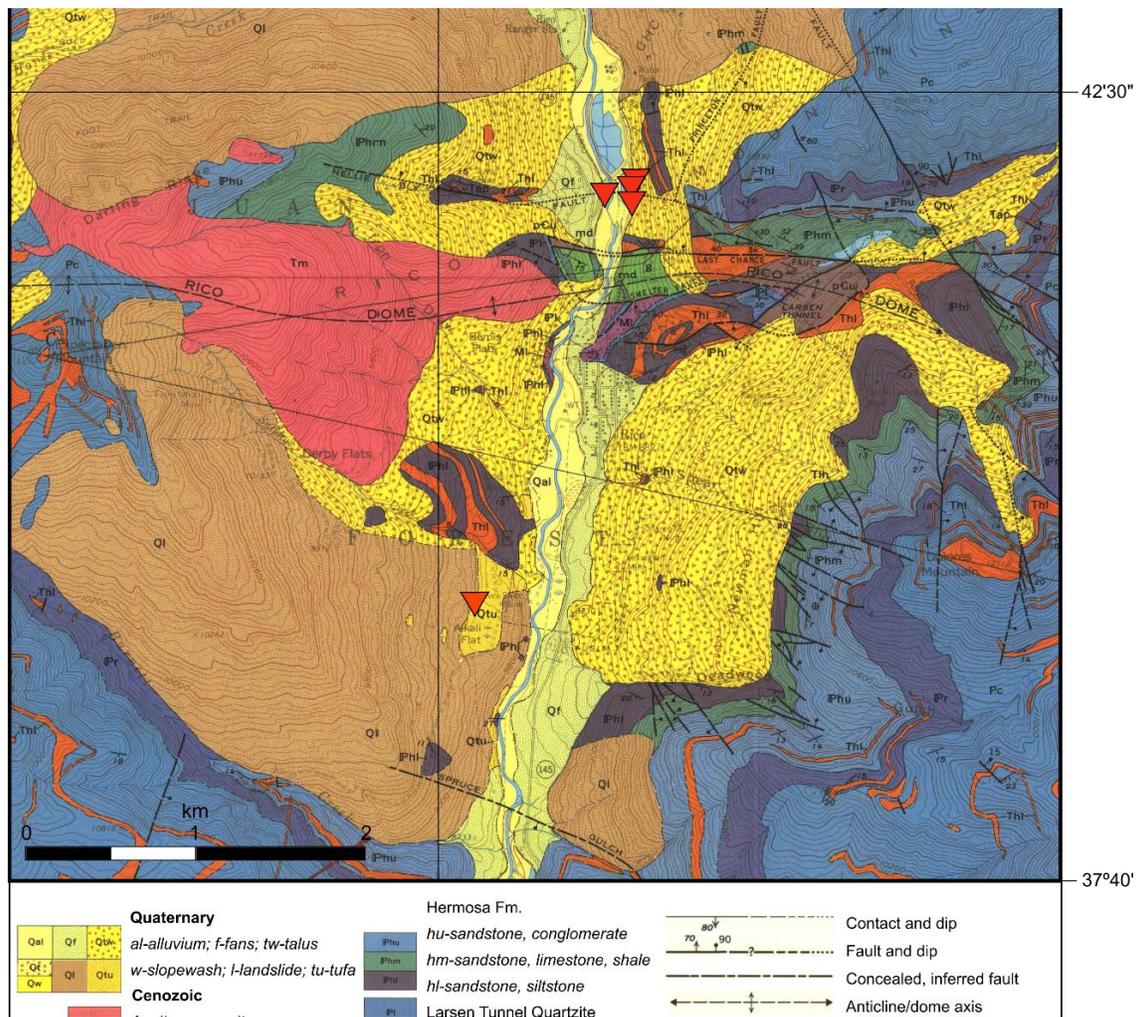


Figure 1: Geological map of the Rico area, with geothermal manifestations. Artesian boreholes are denoted by red triangles (modified from Pratt et al., 1969).

Within this regional framework, the Rico area occupies a structurally elevated position associated with the Rico Dome. The dome forms a prominent structural feature within the western San Juan Mountains and has long been recognized for its role in local mineralization and hydrothermal alteration (Pratt et al., 1969). Its geological complexity and history of fluid circulation make it a natural focus for geothermal exploration.

2.1 The Rico Dome: Structure and Origin

The Rico Dome is a structural uplift defined by outward-dipping stratigraphy surrounding the town of Rico and is interpreted to have formed through a combination of intrusive emplacement, doming, and subsequent faulting (Pratt et al., 1969). Regional geologic mapping indicates that Paleozoic sedimentary units were deformed into a domal geometry, with Mesozoic and younger volcanic units locally preserved along the flanks. Although the precise timing and relative contributions of intrusive versus tectonic processes remain debated, the doming event is widely accepted to have produced significant fracturing and faulting that enhanced permeability within the subsurface.

The dome is dissected by multiple fault systems, including north–south and northwest–southeast trending structures that intersect near the center of the uplift (Pratt et al., 1969). These faults played a critical role in the localization of ore deposits during historic mining and are inferred to have similarly influenced the migration of hydrothermal fluids. The spatial coincidence of mapped faults, mineralized zones, and present-day thermal manifestations suggests that the Rico Dome continues to act as a locus for fluid circulation, providing pathways for both deep recharge and upward discharge of heated fluids (Medlin, 1983; Oerter and Sares, 2010).

From a geothermal perspective, the Rico Dome is important not because it represents a singular heat source, but because its structural architecture promotes fluid flow and heat redistribution. Doming and faulting increase fracture density, create permeability anisotropy, and facilitate vertical connectivity between deeper heat sources and shallower reservoirs, a structural configuration commonly associated with hydrothermal geothermal systems hosted in carbonate terrains (Geldon, 1989).

2.3 Stratigraphic Framework Relevant to Geothermal Circulation

The stratigraphy beneath Rico comprises a succession of Paleozoic carbonate and clastic units overlain by Mesozoic sedimentary formations and locally intruded or covered by Cenozoic igneous and volcanic rocks (Pratt et al., 1969). Among these units, the Mississippian Leadville Limestone and the Pennsylvanian Hermosa Formation are of particular relevance to geothermal development due to their carbonate composition and propensity for secondary porosity development through fracturing, dissolution, and karstification.

The Leadville Limestone forms a regionally extensive carbonate platform and is widely recognized as a productive aquifer and hydrothermal reservoir elsewhere in Colorado (Geldon, 1989). In the Rico area, its depth varies due to doming and faulting, becoming exposed along the flanks of the Rico Dome but eroded beneath the town, based on integration of surface mapping, cross sections, and geophysical constraints (Pratt et al., 1969; Dunnington, 2018). The Hermosa Formation, which overlies the Leadville Limestone, consists of interbedded carbonates and clastics and may also participate in fluid circulation, either as a secondary reservoir or as a transmissive interval linking deeper and shallower units (Oerter and Sares, 2010).

Overlying volcanic and intrusive units, including sills and dikes associated with Cenozoic magmatism, locally act as low-permeability barriers that can impede vertical fluid flow (Pratt et al., 1969). These units may contribute to the confinement of geothermal fluids within carbonate reservoirs, enhancing lateral heat retention and promoting the development of laterally extensive conductive thermal anomalies.

2.4 Structural Controls on Reservoir Development

Structural deformation associated with the Rico Dome exerts a first-order control on geothermal circulation. Major faults, including the Last Chance, Nellie Bly, Smelter, and Blackhawk faults, define the primary permeability architecture of the system (Pratt et al., 1969). These faults vary in orientation, displacement, and inferred hydraulic behavior, with some structures acting as preferential fluid conduits and others functioning as partial barriers to flow (Dunnington, 2018).

Fault intersections are of particular importance, as they are commonly associated with enhanced fracture permeability and focused hydrothermal upflow. The alignment of surface thermal springs with mapped fault intersections supports the interpretation that present-day discharge is structurally controlled (Medlin, 1983; Oerter, 2011). At depth, these same structures are inferred to facilitate vertical connectivity between deeper, hotter formations and carbonate reservoir units, enabling sustained geothermal circulation.

Not all faults contribute equally to permeability, and mineralization or fault sealing may locally reduce transmissivity. Consequently, the subsurface is likely compartmentalized, with hydraulic boundaries that influence reservoir extent and flow direction. Understanding the geometry and hydraulic role of these structures is therefore essential for predicting reservoir behavior and identifying favorable drilling targets (Dunnington, 2018).

2.5 Implications on Geothermal Resource Development

The geological setting of the Rico geothermal system, characterized by domal uplift, permeable carbonate stratigraphy, and intersecting fault networks, creates conditions conducive to the development of both convective and conductive geothermal regimes. While localized convective upflow is expressed at the surface as artesian thermal wells, the broader geological framework supports the existence of a more extensive subsurface thermal anomaly that may not be fully captured by surface manifestations alone (Medlin, 1983; Oerter and Sares, 2010). Extensive alluvial Quaternary deposits cover much of the southern half of the Town, concealing potential structures that control the flow of mineralized and mildly thermal waters associated with extensive travertine deposits. However, bedrock exposures at high

elevations indicate that the southern flank of the Rico Dome is also intensely fractured in a predominant WNW-ESE direction, in addition to structural discontinuities resulting from the contact between Cenozoic intrusives and Paleozoic units (Pratt et al., 1969).

This combination of structural complexity and favorable lithology underpins the conceptual models developed in this study and informs subsequent sections addressing thermal data, geophysical interpretation, and three-dimensional geological modeling. Importantly, it also underscores the suitability of the Rico system for direct-use geothermal applications, where moderate temperatures, distributed heat extraction, and uncertainty-tolerant development strategies are compatible with community-scale TEN deployment.

3. STRUCTURAL CONTROLS ON FLUID FLOW

Structural permeability exerts a first-order control on the geometry, connectivity, and sustainability of the Rico geothermal system. The intersection of multiple fault sets within the Rico Dome has created a structurally complex subsurface in which faults act variably as fluid conduits, flow barriers, or compartment boundaries. Understanding the hydraulic role of these structures is therefore central to evaluating both the extent of the geothermal resource and its suitability for sustained thermal extraction.

3.1 Major Fault Systems

Geologic mapping of the Rico Quadrangle identifies several major fault systems that dissect the Rico Dome, including the Last Chance, Nellie Bly, Smelter, and Blackhawk faults (Pratt et al., 1969). These structures exhibit predominantly north-south and northwest-southeast orientations and intersect beneath and adjacent to the town of Rico. Faulting associated with domal uplift produced zones of intense fracturing that historically localized ore deposition and are inferred to similarly influence hydrothermal fluid migration.

Among these structures, the Last Chance and Nellie Bly faults are of particular importance due to their spatial association with artesian thermal flows from mining-era boreholes (Medlin, 1983; Oerter and Sares, 2010). These faults are interpreted to provide vertical permeability linking deeper heat sources with shallower carbonate reservoirs. In contrast, the Blackhawk Fault forms a prominent structural boundary on the northern side of the system and is inferred to act as a partial hydraulic barrier, potentially limiting northward fluid migration and contributing to reservoir compartmentalization (Dunnington, 2018).

3.2 Faults as Conduits and Barriers

Faults within geothermal systems commonly exhibit heterogeneous hydraulic behavior, depending on factors such as displacement magnitude, fracture density, mineralization, and stress state. In the Rico system, available geological and geophysical evidence suggests that some faults act as preferential conduits for fluid flow, while others impede or redirect circulation.

Resistivity and magnetotelluric (MT) surveys reveal conductivity contrasts aligned with mapped fault traces, suggesting zones of enhanced fluid saturation, hydrothermal alteration or mineralization along certain structures (Dunnington, 2018). These conductive features are interpreted to correspond to permeable fault zones that may facilitate fluid movement. Conversely, more resistive fault-bounded domains likely reflect sealed or low-permeability structures, potentially due to mineral precipitation, intrusive contacts, or absence of conductive materials. Such contrasts imply that the geothermal system is hydraulically segmented rather than uniformly connected across the subsurface.

This dual role of faults, as both conduits and barriers, introduces uncertainty into predictions of reservoir continuity and performance. However, it also creates opportunities for localized heat accumulation where permeable pathways are bounded by low-permeability structures, promoting both convective upflow and lateral conductive heat retention within carbonate units.

3.3 Fault Intersections and Fluid Upflow

Fault intersections represent zones of particular importance for geothermal circulation due to their enhanced fracture connectivity and increased permeability. In the Rico area, surface geothermal springs are spatially associated with intersections between major fault trends, supporting the interpretation that focused upflow occurs where structural pathways converge (Medlin, 1983; Oerter, 2011). These intersections likely serve as pressure release points where ascending geothermal fluids reach shallow depths or discharge at the surface.

At depth, fault intersections are inferred to promote vertical connectivity between deeper heat sources and carbonate reservoir units such as the Leadville Limestone and Hermosa Formation. The coincidence of elevated thermal gradients, artesian discharges, and structural complexity in these zones suggests that fault intersections play a critical role in sustaining convective circulation within the system. Similar structural focusing of geothermal upflow has been documented in other carbonate-hosted geothermal systems in the Rocky Mountains, reinforcing the plausibility of this interpretation (Geldon, 1989).

3.4 Structural Controls on Fluid Flow Direction and Reservoir Extent

Integration of structural mapping with geophysical interpretations suggests that fluid flow within the Rico geothermal system is not radially symmetric about the dome but instead exhibits preferred orientations dictated by fault geometry. MT inversions indicate laterally extensive conductive zones aligned with major fault trends at depths of approximately 500–1,000 m and with a conductive connection to surface, consistent with structurally guided fluid circulation within carbonate units (Dunnington, 2018).

The Blackhawk Fault appears to define a northern hydraulic boundary to the system, beyond which conductive anomalies and thermal indicators diminish. This boundary condition is consistent with conceptual models that invoke fault-bounded reservoir compartments rather than a laterally unconfined geothermal system. South of town, the presence of travertine deposits and elevated geothermal gradients suggests that fault-controlled circulation may extend beyond the presently active springs, implying a broader geothermal anomaly and

additional blind and hidden geothermal system than those forming the present surface expressions (Pratt et al., 1969; Medlin, 1983; Oerter and Sares, 2010).

3.5 Implications for Geothermal Development

The structurally controlled nature of the Rico geothermal system has direct implications for exploration strategy and TEN development. Productive zones are most likely to occur where permeable faults intersect carbonate reservoir units at depth, rather than being uniformly distributed beneath the town. As a result, drilling success will depend on accurately targeting structurally favorable locations rather than simply pursuing maximum depth or proximity to surface springs.

At the same time, structural compartmentalization introduces uncertainty regarding reservoir connectivity and long-term sustainability of subsurface development expansions. These uncertainties underscore the need for confirmation drilling, downhole temperature measurements and flow testing, and refined structural characterization to validate conceptual models. Nevertheless, the presence of multiple intersecting fault systems, combined with a favorable carbonate stratigraphy, supports the interpretation that the Rico geothermal system possesses favorable structural conditions to sustain both localized convective upflow and broader conductive heat transport that could support a community-scale TEN.

4. THERMAL MANIFESTATIONS AND TEMPERATURE DATA

Thermal data provide the primary evidence for active geothermal processes within the Rico Dome and form a critical constraint on conceptual models of heat transport and fluid circulation. Available thermal observations include surface spring temperatures, historical mining-era borehole records, artesian thermal discharge, and indirect temperature estimates derived from geothermometry. While these datasets are spatially and temporally heterogeneous, their collective interpretation indicates the presence of both localized convective upflow at or near the edges of the Rico Dome and a broader subsurface thermal anomaly.

4.1 Surface Thermal Manifestations

The principal surface expressions of geothermal activity in Rico consist of three historic mining-era boreholes located north of the town center that discharge thermal waters under artesian conditions. Measured discharge temperatures range from approximately 40 to 46 °C, with reported flow rates up to 0.95 L/s (Oerter, 2011). Seasonal variability in spring temperature is limited, generally within 1–2 °C, suggesting a relatively stable thermal source with only minor dilution from shallow meteoric groundwater.

Although modest in temperature and flow, these manifestations provide direct evidence of upward fluid migration from depth. Importantly, their spatial association with mapped fault intersections supports a structurally controlled discharge mechanism rather than diffuse conductive heat loss. The limited number of surface geothermal features should not be interpreted as indicative of a small geothermal system, as surface discharge represents only localized points of hydraulic connection to the surface.

Travertine deposits and anecdotal accounts of snow-free grounds and sulphurus, mildly thermal springs located south of the town provide additional evidence for additional geothermal systems. These deposits are interpreted as fossil but recent spring outlets, indicating that thermal discharge locations have shifted over time in response to evolving structural or hydraulic conditions (Pratt et al., 1969; Medlin, 1983). Their presence implies that additional geothermal systems may be present over a broader area than the immediacy of the artesian thermal boreholes, thus resulting in a larger potential for the utilization of geothermal resources near the town.

4.2 Historical Borehole and Mining Temperature Data

Historic mining activity within the Rico Dome generated boreholes that provide valuable subsurface thermal information. Several mining-era wells encountered artesian flows at depths of a few hundred meters, with reported thermal gradients reaching up to approximately 114 °C/km (Medlin, 1983). In addition to thermal fluids, some wells reported gas emissions, including CO₂ and H₂S, consistent with deep hydrothermal circulation.

Temperature–depth profiles from mining boreholes indicate geothermal gradients ranging from approximately 90 to 140 °C/km, substantially exceeding typical continental background gradients of ~25–30 °C/km. While these boreholes do not penetrate to depths typically associated with geothermal reservoir development, they provide strong evidence for anomalously high heat flow beneath the town. Thirteen historic boreholes with usable temperature or gradient information were compiled for this study, with bottom-hole temperatures estimated where direct measurements were unavailable.

The quality and documentation of these data vary, and uncertainties arise from unknown well conditions, incomplete records, and potential thermal disturbance during drilling. Nevertheless, the consistency of elevated gradients across multiple boreholes supports the interpretation that the observed thermal anomaly is not an isolated artifact but reflects a genuine subsurface conductive heat anomaly.

4.3 Geochemical Constraints and Geothermometry

Geochemical analyses of spring waters provide additional information on reservoir temperature and fluid–rock interaction. Previous studies indicate chemical signatures consistent with interaction between geothermal fluids and carbonate lithologies, including the Leadville Limestone and Hermosa Formation (Oerter and Sares, 2010). These interactions support the interpretation that carbonate units serve as the primary geothermal reservoir, or that substantial storage within carbonate units occur.

Geothermometric estimates utilizing silica geothermometers suggest subsurface equilibration temperatures on the order of at least 120–140 °C, with a relatively consistent water chemistry across sources. However, these estimates are subject to uncertainty due to fluid mixing

with shallow groundwater, re-equilibration during ascent, presence of higher-solubility mineral phases, and the limited number of available samples. As such, geothermometry is best viewed as providing a hypothetical estimate of reservoir temperature rather than a precise measurement.

4.4 Implications for the Thermal Structure of the System

Taken together, surface manifestations, borehole temperature data, and geochemical indicators support a conceptual model in which localized convective upflow is superimposed on a broader conductive thermal anomaly. Elevated gradients observed in mining boreholes suggest that heat is distributed over a larger volume than indicated by surface manifestations alone. This interpretation is consistent with the presence of extensive travertine deposits and with geophysical evidence for laterally extensive conductive zones at depth.

From a development perspective, this thermal anomaly is well suited to direct-use geothermal applications. Even in the absence of widespread high-temperature discharge, moderate subsurface temperatures at relatively shallow depths can be effectively exploited using open-loop developments or heat pump technology, particularly when integrated into a TEN designed to balance loads across multiple buildings.

5. GEOPHYSICAL CONSTRAINTS ON RESERVOIR GEOMETRY

Geophysical investigations conducted within and around the Rico Dome provide important constraints on the depth, lateral extent, and structural controls of the geothermal system. Electrical resistivity tomography (ERT) and magnetotelluric (MT) surveys offer indirect but spatially continuous information on subsurface properties, complementing sparse thermal and geological datasets.

5.1 Resistivity and Magnetotelluric Surveys

Electrical resistivity surveys carried out across the Rico Dome identified zones of anomalously low resistivity at shallow depths below the artesian thermal boreholes, interpreted as regions of increased fluid saturation, hydrothermal alteration, or both (Dunnington, 2018). Subsequent MT surveys expanded coverage to greater depths and provided an expanded view of subsurface electrical responses.

MT inversion results reveal a laterally extensive low-resistivity zone at depths of approximately 500–1,000 m and having a small extension to surface beneath the location of the thermal manifestations. This conductive body is spatially correlated with a shallow conductive region in the ERT and the trace of major fault systems, suggesting that it represents the location of the primary geothermal upflow or a thermally altered halo surrounding it.

5.2 Interpretation of Conductive Anomalies

Low resistivity in geothermal settings can arise from multiple causes, including elevated temperature, saline fluids, clay alteration, mineralization, or conductive lithologies. In the Rico system, integration with geological mapping indicates that the conductive anomaly is unlikely to be solely lithologic in origin. Instead, its geometry and alignment with fault structures suggest a strong hydrothermal component.

Earlier interpretations tentatively associated resistive zones with reservoir units; however, incorporation of stratigraphic constraints within a three-dimensional geological framework indicates that some resistive bodies are more plausibly associated with igneous or greenstone lithologies rather than permeable, fluid-bearing carbonates. This highlights the non-uniqueness of geophysical interpretations when considered in isolation and underscores the importance of integrated modeling.

6. 3D GEOLOGICAL MODELING

To integrate disparate datasets and support resource characterization, a three-dimensional geological model of the Rico geothermal system was developed using Leapfrog Energy. The objective of this model is not to define a fully resolved geothermal reservoir, but rather to provide a coherent spatial framework within which geological, structural, thermal, and geophysical information can be interpreted consistently and iteratively refined.

6.1 Model Inputs and Data Integration

The 3D model incorporates stratigraphic contacts derived from regional geological mapping, as well as surface and subsurface fault interpretations, historical mining records, borehole data, thermal spring locations, and geophysical survey results (Figure 2). Stratigraphic units explicitly modeled include the Hermosa Formation, Leadville Limestone, Molas Formation, and overlying sedimentary units, as well as intrusive bodies associated with the Rico Dome uplift (Figure 3). Due to the scarcity of published geological data from this region, the model is heavily based on the geological map of Pratt et al. (1969).

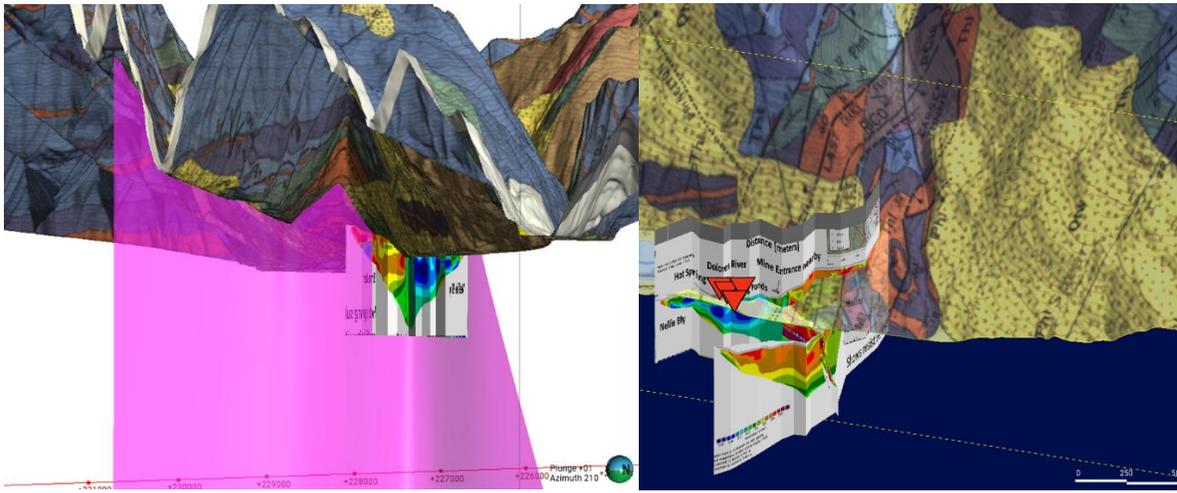


Figure 2: Northwest to Southeast cross-section incorporated into the 3D geological model (left). Oblique down-to-the-northeast view (right) of the Rico 3D geological model, including geophysical data, geological map, and geothermal manifestations of the Rico thermal artesian boreholes (red triangles).

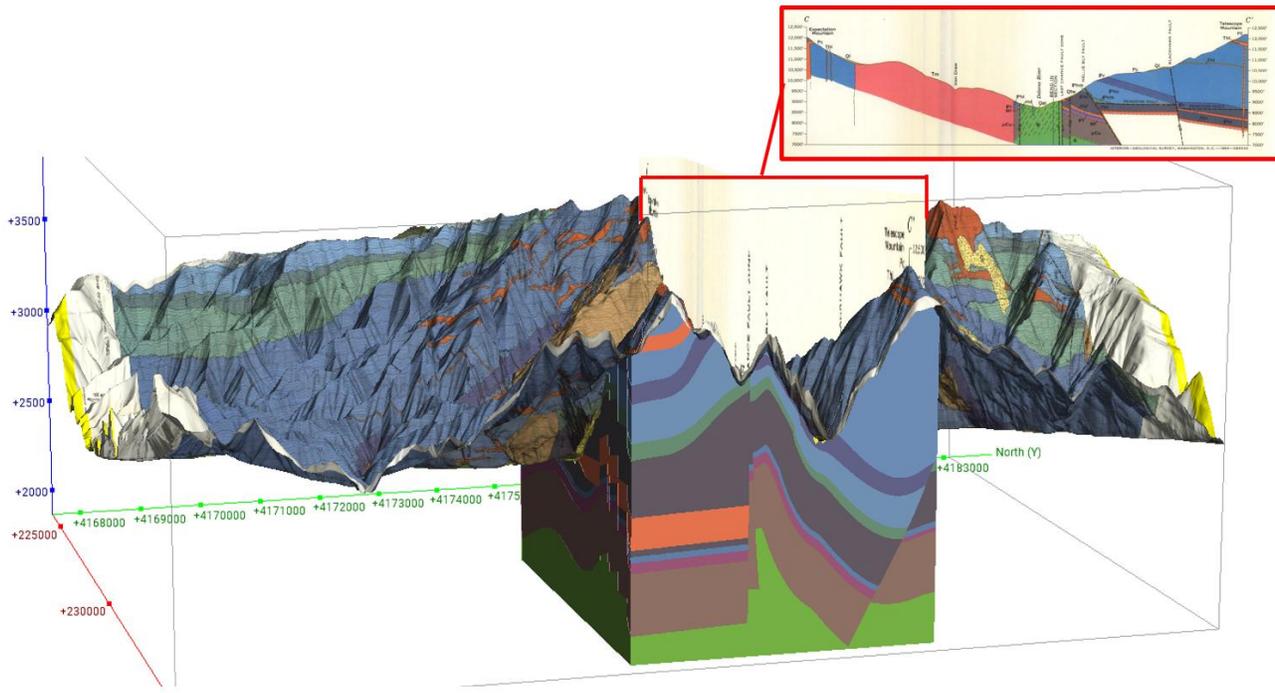


Figure 3: Preliminary 3D geological model of the Rico area showing stratigraphic units and structure derived from various input data. For example, the geological map and cross-sections from Pratt et al., (1969) are orientated in 3D and directly feed the geological model.

Structural inputs focus on the major mapped faults, including the Last Chance, Nellie Bly, and Blackhawk faults, which were modeled as discrete surfaces where sufficient control exists. Where fault geometry is poorly constrained at depth, fault surfaces are extrapolated conservatively using surface traces, dip estimates from topographic traces, and geophysical lineaments. These uncertainties are preserved within the model and explicitly acknowledged rather than smoothed or artificially resolved.

Thermal and geochemical datasets are not directly interpolated as continuous fields but are instead used qualitatively to guide interpretation of reservoir zones and circulation pathways. This approach avoids overfitting sparse or uncertain data while still allowing thermal information to inform the conceptual framework.

6.2 Model Architecture and Resolution

The model domain extends laterally beyond the immediate town of Rico to capture the broader structural and thermal context of the Rico Dome. Vertically, the model extends from the surface to depths exceeding 2 km to encompass the full range of inferred geothermal gradients and potential reservoir intervals.

Resolution is intentionally non-uniform, with higher detail in areas proximal to thermal manifestations and fault intersections, and lower resolution in peripheral zones. This scale-appropriate resolution reflects both data density and development relevance, ensuring that model complexity is aligned with available constraints and intended application.

6.3 Role of the Model in Resource Characterization

The 3D geological model serves three primary functions. First, it provides a consistent spatial reference for integrating and visualizing heterogeneous datasets. Second, it enables systematic evaluation of alternative conceptual models by allowing different assumptions about fluid pathways and heat sources to be tested geometrically. Third, it supports early-stage development planning by identifying zones where drilling could most effectively reduce uncertainty.

Importantly, the model is not treated as a predictive tool in isolation. Instead, it functions as a hypothesis-testing framework that highlights data gaps and guides prioritization of future investigations, including confirmation drilling and targeted geophysical surveys.

7. CONCEPTUAL MODEL OF THE RICO GEOTHERMAL SYSTEM

Based on integrated geological, structural, thermal, and geophysical evidence, several conceptual models can be proposed for the Rico geothermal system. Below we present a single conceptual model, where others may exist to represent different aspects of a complex, evolving hydrothermal system.

7.1 Observational Constraints

Several features of the Rico system are well supported by available data. These include: (1) anomalously high geothermal gradients relative to regional background; (2) active thermal discharge localized along fault structures; (3) geochemical evidence for fluid interaction with carbonate units; and (4) geophysical indications of laterally extensive, vertically connected conductive zones at depth.

Conversely, key uncertainties remain regarding the dominant heat source, the continuity of permeability within reservoir units, and the spatial extent of economically useful temperatures. The conceptual model must therefore remain flexible and avoid reliance on a single controlling mechanism.

7.2 Fault-Controlled Convective Circulation

The most strongly supported concept involves fault-controlled convective circulation within carbonate reservoir units, primarily the Leadville Limestone and possibly portions of the Hermosa Formation. Here, deeply circulating meteoric fluids are heated at depth and ascend along high-permeability fault zones, discharging where hydraulic connectivity to the surface exists.

This interpretation is consistent with the spatial coincidence of thermal springs and fault intersections, elevated geothermal gradients observed in mining-era boreholes, and geochemical signatures indicative of carbonate interaction (Figure 2). The Last Chance–Nellie Bly fault system likely plays a central role in focusing upflow, while the Blackhawk Fault may act as a lateral boundary to fluid movement.

7.3 Conductive Heat Anomaly with Localized Upflow

An alternative but complementary concept emphasizes a broad conductive thermal anomaly beneath the Rico Dome, with localized convective upflow occurring only where structural conditions permit. In this framework, elevated geothermal gradients result from enhanced heat flow associated with uplift, intrusive bodies, or deep regional circulation, while faults serve primarily as conduits rather than drivers of heat input (Figure 2).

This is supported by the lateral extent of elevated gradients and conductive zones imaged by MT surveys, as well as the presence of fossil travertine deposits south of town that indicate historical thermal discharge beyond current spring locations.

7.4 Heat Source Considerations

The ultimate heat source driving the Rico geothermal system remains uncertain. Potential contributors include residual and radiogenic heat associated with intrusive bodies related to the Rico Dome, advective heat transport via deep regional fault systems, and localized crustal thinning or uplift-related heat flow anomalies.

Current data do not allow these mechanisms to be distinguished conclusively. However, for direct-use applications, the precise origin of heat is less critical than the presence of sustained, accessible temperatures at drillable depths. As such, conceptual models are evaluated primarily in terms of their implications for reservoir accessibility and sustainability rather than their tectonic origin.

8. IMPLICATIONS FOR TEN DEVELOPMENT

The characteristics of the Rico geothermal system are well aligned with the requirements of a community-scale TEN. TEN systems prioritize moderate temperatures, reliability, and distributed heat extraction over high-temperature power generation, making them particularly suitable for low- to medium-temperature geothermal resources.

8.1 Resource Suitability for Direct-Use Applications

Surface discharge temperatures alone would support only limited direct-use heating. However, subsurface temperatures inferred from geothermometry, thermal gradients, and geophysical constraints suggest that significantly higher temperatures may be accessible at depth. When coupled with heat pump technology, these temperatures are sufficient to meet a substantial fraction of community heating demand.

8.2 Development Risks and Uncertainties

Key risks to development include uncertainty in reservoir permeability, variability in fault transmissivity, and limited direct temperature measurements at depth, in addition to economic viability. These uncertainties underscore the importance of phased development, beginning with confirmation drilling designed to reduce the highest-impact uncertainties before committing to full network deployment.

The 3D geological model provides a framework for identifying drilling locations that maximize information gain, particularly near fault intersections where upflow is most likely. Integration of drilling results into the model will allow rapid refinement of both conceptual understanding and system design.

8.3 Broader Implications for Small Community Geothermal Projects

The Rico case study illustrates how legacy mining data, modern geophysics, and three-dimensional modeling can be combined to evaluate geothermal potential in data-limited settings. While uncertainties remain, the integrated approach supports informed decision-making and reduces the risk of over- or underestimating resource potential.

Moreover, the presence of a potentially extensive geothermal anomaly beyond current surface manifestations suggests that development potential may exceed initial expectations. Recognizing and evaluating this broader system is essential for long-term planning and highlights the value of conceptual modeling even when data is sparse.

9. LIMITATIONS AND DATA GAPS

Despite encouraging indicators, the current assessment of the Rico geothermal system is subject to several important limitations that constrain confidence in resource size, sustainability, and development timelines. These limitations primarily reflect the early-stage nature of the investigation and the uneven quality and spatial distribution of available data.

First, there are no modern, purpose-drilled geothermal wells within the study area. Subsurface temperature estimates rely heavily on historical mining-era boreholes, which were not designed for thermal characterization and often lack continuous temperature logs, documented equilibration times, or precise depth control. As a result, geothermal gradients derived from these data are subject to uncertainty and should be interpreted as indicative rather than definitive.

Second, reservoir permeability remains poorly constrained. While fault-controlled flow is strongly suggested by structural mapping, spring locations, and geophysical lineaments, the transmissivity, continuity, and hydraulic connectivity of these fault zones at depth are unknown. Carbonate units such as the Leadville Limestone are likely to exhibit significant heterogeneity in fracture density and karst development, introducing additional uncertainty in reservoir performance.

Third, geophysical interpretations are inherently non-unique. Low-resistivity anomalies imaged by electrical resistivity and magnetotelluric surveys may reflect elevated temperature, fluid saturation, hydrothermal alteration, or lithologic contrasts. Although integration with geological and thermal data reduces ambiguity, geophysical datasets alone cannot uniquely define reservoir boundaries or predict producible flow rates.

Fourth, geochemical datasets are limited in number and temporal coverage. Existing water chemistry analyses provide useful constraints on fluid-rock interaction and approximate reservoir temperatures but mixing with shallow groundwater and potential re-equilibration during ascent complicate geothermometric interpretations. Additional sampling, including isotopic analyses and repeat measurements, would improve confidence in subsurface temperature estimates and circulation models.

Finally, the broader extent of the geothermal anomaly, suggested by elevated gradients and fossil travertine deposits south of town, remains largely unexplored. While this may represent a significant upside for development potential, it also introduces uncertainty regarding the spatial scale and connectivity of the system relevant to a TEN centered on the town of Rico.

Recognizing these limitations is essential for responsible development planning. Rather than diminishing the value of the current work, they underscore the importance of a phased exploration strategy in which targeted confirmation drilling, focused geophysical surveys, and iterative model updates are used to systematically reduce uncertainty and inform investment decisions.

While this study focuses on technical resource characterization and conceptual modeling, non-technical factors represent an important parallel limitation to geothermal development in Rico. Community acceptance, stakeholder engagement, and socioeconomic considerations may ultimately exert a greater influence on project viability than subsurface conditions alone.

Rico's history of mining activity, environmental remediation, and land-use sensitivity has shaped local perceptions of subsurface development. Concerns related to drilling impacts, groundwater protection, construction disruption, and long-term system ownership may affect public support for geothermal infrastructure. In addition, uncertainties related to project financing, utility governance structures, and equitable distribution of benefits introduce risks that are not addressed by technical modeling alone.

These factors are not treated in detail here, but their importance is recognized. Experience from comparable geothermal direct-use projects indicates that early, transparent community engagement and clear communication of both benefits and risks are critical to sustained project momentum. As Rico advances toward confirmation drilling and system design, integration of technical planning with community-driven decision-making will be essential to project success.

10. CONCLUSIONS AND NEXT STEPS

This study presents an integrated geological and conceptual assessment of the Rico geothermal system with the explicit goal of evaluating its suitability for supporting a community-scale TEN. By synthesizing geological mapping, structural interpretation, thermal and geochemical observations, geophysical data, and three-dimensional geological modeling, the work establishes a defensible early stage understanding of the system while explicitly acknowledging the substantial uncertainties that remain.

The analysis suggests that the Rico geothermal system is characterized by anomalously high geothermal gradients relative to regional background, structurally controlled fluid circulation, and strong evidence for interaction between geothermal fluids and carbonate reservoir units. Surface thermal manifestations, elevated gradients observed in boreholes, and geophysical indications of laterally extensive conductive zones collectively support a conceptual model in which localized fault-controlled convective upflow is superimposed on a broader conductive thermal anomaly beneath the Rico Dome. While the precise heat source and internal reservoir architecture remain unresolved, the convergence of independent datasets indicates that subsurface temperatures suitable for direct-use geothermal applications are likely accessible at drillable depths.

Importantly, this study demonstrates that surface expressions alone significantly underrepresent the potential scale of the geothermal system. Fossil travertine deposits south of town, elevated gradients beyond the active springs, and geophysical evidence for structural continuity suggest that the geothermal anomaly extends beyond the presently active discharge zones. This broader system perspective is particularly relevant for TEN development, which can accommodate spatially distributed heat extraction and does not require concentrated high-temperature upflow, necessarily.

Rather than attempting to define a definitive resource estimate, the work emphasizes interpretation constrained by uncertainty appropriate for early-stage geothermal development. The three-dimensional geological model developed herein serves as a hypothesis-testing framework that integrates disparate datasets, identifies key data gaps, and informs prioritization of future exploration activities. In doing so, it provides a technical foundation for phased development strategies aligned with both geological risk and community-scale infrastructure planning.

Building directly on the findings of this study, the project has advanced into a Phase II investigation supported by the Colorado Energy Office's Geothermal Energy Grant Program (GEGP). Phase II activities are designed to systematically reduce the highest-impact uncertainties identified in this paper and to translate conceptual understanding into actionable development planning. Key next steps include targeted confirmation drilling to directly measure subsurface temperature and permeability, refinement of geological and thermal models using newly acquired field data, and development of a preliminary TEN design informed by confirmed resource conditions. As Rico moves toward securing funding for confirmation drilling and advancing the system design through refining the 3D resource model with new data, international experience highlights that successful geothermal projects depend equally on robust technical strategies and comprehensive community engagement (Butler and Pick, 1982; Simmons et al., 2025). Therein, continued community engagement, land access coordination, and preliminary cost and emissions analyses will be undertaken to ensure that technical progress remains aligned with stakeholder priorities and socioeconomic feasibility.

Together, these efforts represent a transition from conceptual resource characterization toward pre-feasibility evaluation. The Rico geothermal system illustrates how legacy mining data, modern geophysical techniques, and three-dimensional modeling can be leveraged to evaluate geothermal potential in data-limited settings. More broadly, it demonstrates that low- to medium-temperature geothermal systems can play a meaningful role in decarbonizing heating demand in small mountain communities, creating a repeatable framework for use beyond Rico, Colorado.

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