

# Turkey's Geothermal Energy Potential: Investment Opportunities and Exploration Methods

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## ABSTRACT

Turkey hosts significant geothermal resources due to its unique tectonic setting at the convergence of the African, Eurasian, and Arabian plates. While conventional hydrothermal systems have been successfully developed over the past decades, much of the country's high-enthalpy potential remains untapped—especially in regions suitable for advanced exploration techniques and Enhanced Geothermal Systems (EGS). This paper presents a comprehensive overview of Turkey's geothermal landscape, highlighting its geological advantages, current exploration strategies, and sectoral trends. It further outlines the growing investment opportunities fueled by supportive regulatory frameworks, rising energy demand, and a national commitment to renewable energy expansion. By bridging geoscientific insights with private sector dynamics, the study offers a strategic roadmap for investors seeking scalable, long-term geothermal projects in Turkey.

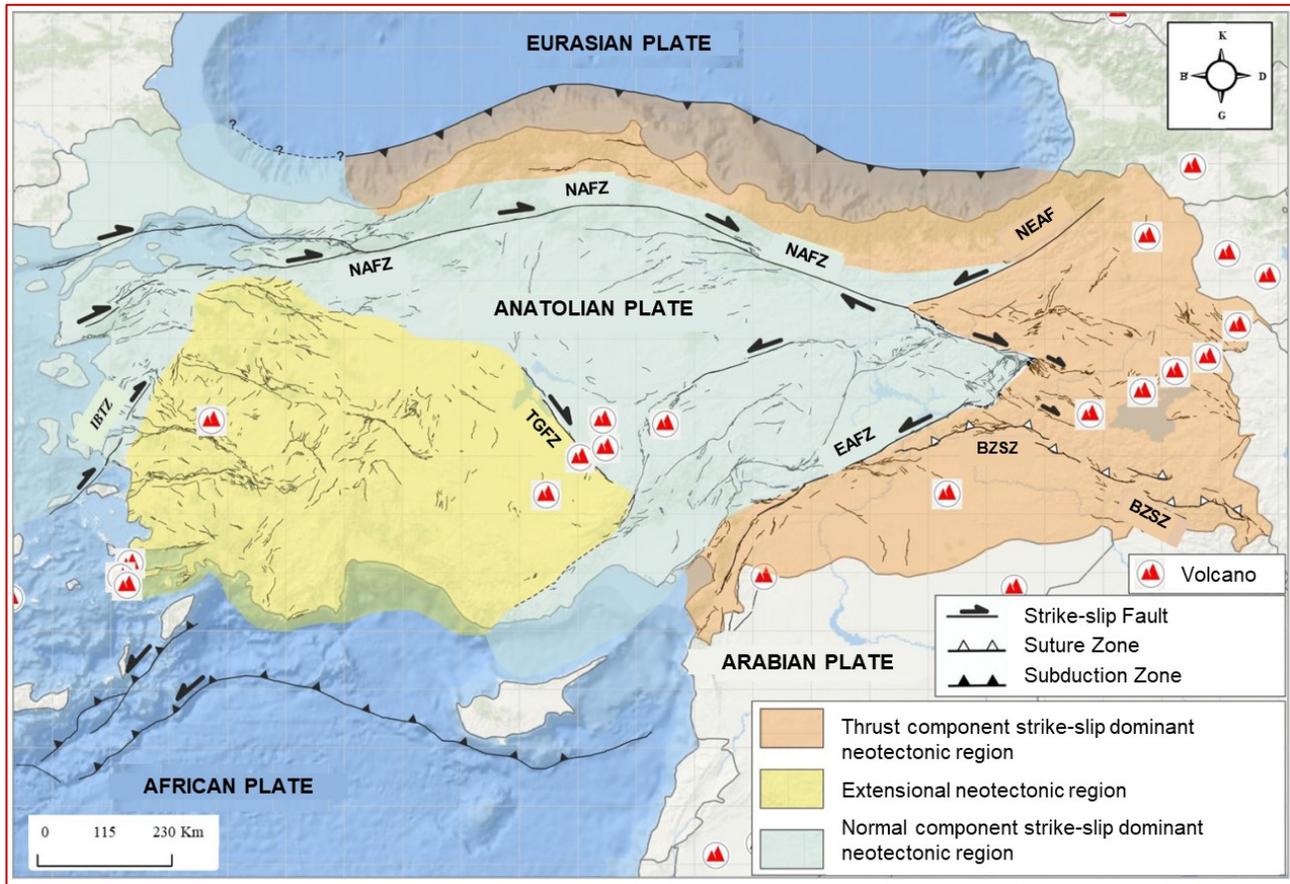
## 1. INTRODUCTION

Turkey has emerged as one of the world's leading countries in geothermal energy development over the past two decades. Favorable geological conditions, combined with supportive government policies and increasing energy demand, have positioned geothermal energy as a strategic component of Turkey's renewable energy portfolio. Unlike intermittent renewable sources, geothermal energy provides reliable baseload power, making it particularly valuable for countries with growing electricity consumption and energy import dependency.

As of today, geothermal development in Turkey has been predominantly concentrated in Western Anatolia, where extensional tectonics, high heat flow, and well-defined graben systems have enabled the rapid discovery and commercialization of geothermal resources. Regions such as the Büyük Menderes, Küçük Menderes, and Gediz basins host the majority of operating geothermal power plants, benefiting from shallow reservoirs, proven permeability, and extensive historical exploration (Kılınç, 2025).

However, the success of Western Anatolia has also led to increasing challenges. High license density, reservoir interference between neighboring fields, pressure decline, and reinjection-related operational issues are becoming more pronounced. In parallel, competition for new licenses in mature basins has intensified, increasing entry costs and limiting upside potential for new investors. These factors highlight the need to diversify Turkey's geothermal exploration focus beyond its traditional core areas.

Eastern Anatolia represents a fundamentally different but highly promising geothermal setting. The region is characterized by complex tectonics related to the Arabia–Eurasia collision, widespread Neogene–Quaternary volcanism, and evidence of elevated geothermal gradients. While large-scale commercial geothermal projects have not yet been widely developed in this region, multiple indicators—including thermal manifestations, altered zones, and regional heat flow studies—suggest significant untapped potential (Figure 1).



**Figure 1: The neotectonic regions and structural characteristics of the Anatolian Plate (modified from Şener, M. F., Uzelli, T., Akkuş, İ., Mertoğlu, O., Baba, A. 2023).**

From an exploration perspective, Eastern Anatolia can be considered a frontier to semi-frontier geothermal province. Such regions inherently carry higher geological uncertainty but also offer substantially higher value creation opportunities when exploration is conducted using modern, integrated methodologies. Advances in geophysical imaging, geochemical interpretation, and structural modeling now allow for more effective risk reduction compared to early-generation geothermal exploration approaches.

Within this broader context, the Muş region stands out as a representative case for evaluating geothermal investment opportunities in Eastern Anatolia. Its geological setting, structural framework, and early-stage exploration data provide an opportunity to assess how frontier geothermal areas in Turkey can be systematically explored and developed. This paper therefore uses the Muş geothermal licenses as a case study to demonstrate how Turkey's geothermal growth can expand eastward through disciplined exploration strategies and phased investment models.

## 2. GEOLOGICAL FRAMEWORK OF TURKEY'S GEOTHERMAL SYSTEMS

Turkey is located at the convergence of the Eurasian, African, and Arabian plates, resulting in one of the most tectonically active regions in the Mediterranean–Middle East domain (Bodur, 2025). This complex plate interaction governs the distribution, style, and characteristics of the country's geothermal systems. The geothermal framework of Turkey can be broadly explained through the interplay of tectonics, magmatism, crustal thinning, and deep fluid circulation.

### 2.1. Tectonic Regimes and Heat Flow

Turkey's geothermal resources are closely linked to its active tectonic framework, which can be divided into three principal regimes:

- **Western Anatolia – Extensional Regime**

Western Anatolia is dominated by N–S extension, leading to the development of E–W trending graben systems such as the Büyük Menderes, Gediz, and Küçük Menderes basins. Crustal thinning in this region results in elevated heat flow, shallow brittle–ductile transition depths, and enhanced permeability along normal fault systems. These conditions favor high-enthalpy, liquid-dominated geothermal reservoirs, many of which have been successfully developed for electricity generation.

- **Central Anatolia – Transitional Regime**

Central Anatolia represents a transitional tectonic domain influenced by both extension and strike-slip deformation. Geothermal systems in this region are often associated with volcanic complexes and caldera structures. Reservoirs tend to be structurally controlled, with permeability localized along faults and fracture networks rather than basin-scale graben systems.

- **Eastern Anatolia – Collisional and Post-Collisional Regime**

Eastern Anatolia is characterized by thickened crust related to the Arabia–Eurasia collision, followed by widespread post-collisional volcanism and localized lithospheric thinning. Despite the thicker crust, regional heat flow remains anomalously high due to mantle upwelling and magmatic intrusions. This unique tectono-thermal setting supports the development of deep, structurally controlled geothermal systems.

## **2.2. Role of Fault Systems and Structural Controls**

Faults play a critical role in Turkey’s geothermal systems by providing pathways for deep fluid circulation. In many regions, productive geothermal reservoirs are not defined by lithology alone but by fault-controlled permeability.

Key fault-related mechanisms include:

- Deep-reaching strike-slip and oblique faults enabling vertical fluid ascent
- Fault intersections acting as permeability enhancement zones
- Reactivated basement structures controlling reservoir geometry

In Eastern Anatolia, major fault zones such as regional strike-slip systems and their associated secondary fractures are particularly important. These structures facilitate the circulation of meteoric waters to depth, where they are heated and subsequently transported back toward the surface.

## **2.3. Magmatism and Heat Sources**

Magmatic activity is a fundamental heat source for many geothermal systems in Turkey, especially in Central and Eastern Anatolia. Neogene to Quaternary volcanism is widespread and includes stratovolcanoes, lava plateaus, and intrusive bodies.

Heat contributions arise from:

- Cooling magma bodies at mid- to lower-crustal levels
- Elevated geothermal gradients due to lithospheric thinning
- Radiogenic heat production in volcanic and metamorphic rocks

While not all geothermal systems are directly magmatically heated, the thermal influence of young volcanic activity significantly enhances regional heat flow and reservoir temperatures.

## **2.4. Reservoir Types and Fluid Characteristics**

Turkey hosts a wide range of geothermal reservoir types, reflecting its geological diversity:

**Graben-hosted reservoirs (Western Anatolia):** Shallow to intermediate depth, high permeability, liquid-dominated systems

**Volcanic-hosted reservoirs (Central Anatolia):** Fracture-controlled, often heterogeneous, with localized high-temperature zones

**Structurally controlled basement reservoirs (Eastern Anatolia):** Deep circulation systems, typically associated with fault zones and fractured metamorphic or volcanic basement

Geothermal fluids are predominantly meteoric in origin, with varying degrees of magmatic contribution. Geochemical signatures often indicate long residence times and high water–rock interaction, particularly in Eastern Anatolia, where deep circulation paths are common.

## **2.5. Implications for Exploration Strategy**

Understanding Turkey’s geological framework is essential for designing effective exploration programs. While Western Anatolia benefits from well-established exploration analogs, Eastern Anatolia requires a different approach focused on:

- Regional structural analysis rather than basin-scale models
- Deep-penetrating geophysical methods (e.g., MT)
- Careful geochemical interpretation to estimate reservoir temperature and depth

This geological diversity underscores the importance of region-specific exploration strategies and highlights why frontier areas, when approached with modern methodologies, can offer attractive opportunities for geothermal development.

### 3. EXPLORATION METHODOLOGY IN FRONTIER GEOTHERMAL AREAS

Exploration in frontier geothermal regions differs fundamentally from development in mature geothermal provinces. Limited historical data, absence of production wells, and poorly constrained subsurface conditions result in higher geological uncertainty. Consequently, exploration strategies in such areas must be structured to systematically reduce risk while preserving flexibility in investment and project design.

#### 3.1. Phased Exploration Concept and Risk Management

A phased exploration approach is essential in frontier settings. Each phase is designed to answer specific geological questions and to justify progression to higher-cost activities.

- **Phase 1 – Regional Screening:** Identification of prospective geothermal corridors using regional geology, tectonics, heat flow indicators, and surface manifestations.
- **Phase 2 – Prospect-Scale Evaluation:** Focused studies to define drillable targets, including detailed structural mapping and geophysical surveys.
- **Phase 3 – Pre-Drilling Integration:** Final target ranking and well design based on integrated interpretation of all available datasets.

#### 3.2. Geological and Structural Investigations

Geological studies form the foundation of geothermal exploration, particularly in regions where reservoirs are structurally controlled rather than stratigraphically defined.

Key activities include:

- Detailed surface geology and lithological mapping
- Identification of active and fossil fault systems
- Analysis of fault kinematics and stress regime
- Mapping of hydrothermal alteration zones

In frontier areas, special emphasis is placed on recognizing fault intersections, step-overs, and relay zones, which often act as high-permeability conduits for geothermal fluids.

#### 3.3. Geochemical Surveys and Reservoir Temperature Estimation

Geochemical investigations provide critical insights into subsurface conditions at relatively low cost. Sampling of thermal waters, cold springs, and gas manifestations allows for estimation of reservoir temperature, fluid origin, and circulation depth.

Typical analyses:

- Trace elements and major ions
- Stable isotopes ( $\delta^{18}\text{O}$ ,  $\delta\text{D}$ )
- Gas chemistry ( $\text{CO}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{N}_2$ ,  $\text{CH}_4$ )

Geothermometry results must be interpreted cautiously in frontier areas, as mixing, re-equilibration, and shallow cooling effects are common. Integration with geological and geophysical data is therefore essential.

#### 3.4. Geophysical Methods and Subsurface Imaging

Geophysical surveys play a central role in frontier geothermal exploration by providing indirect but spatially continuous subsurface information.

Commonly applied methods include:

- Gravity and magnetic surveys: Identification of structural trends, basement depth, and magmatic intrusions
- Magnetotellurics (MT): Imaging of conductive zones related to clay caps, fluid pathways, and potential reservoirs
- Seismic methods (where applicable): Structural imaging and fault characterization

In regions such as Eastern Anatolia, MT surveys are particularly valuable due to their ability to image deep structures beneath volcanic and complex terrains.

#### 3.5. Integrated Interpretation and Target Ranking

The greatest reduction in exploration risk is achieved through integrated interpretation. Geological, geochemical, and geophysical datasets are jointly evaluated to develop conceptual geothermal models.

Key outputs include:

- Identification of upflow zones and recharge areas
- Estimation of reservoir depth and temperature range
- Ranking of potential drilling targets based on risk and reward

This integrated model serves as the basis for deciding whether to proceed with exploratory drilling.

### 3.6. Exploratory Drilling Strategy

Exploratory drilling represents the highest-cost and highest-risk phase of geothermal exploration. In frontier areas, well objectives are typically designed to simultaneously test temperature, permeability, and fluid chemistry.

Strategic considerations include:

- Selection of well location based on integrated models
- Design of slim or full-diameter exploration wells
- Flexibility to adapt drilling strategy based on real-time data

Successful exploration wells not only confirm resource presence but also significantly de-risk subsequent development phases.

### 3.7. Implications for Frontier Geothermal Investment

When applied systematically, modern exploration methodologies enable frontier geothermal areas to transition from conceptual potential to bankable projects. While uncertainty remains inherent, disciplined exploration significantly improves success rates and supports phased investment structures, making such projects attractive to both strategic and financial investors.

## 4. THE MUŞ GEOTHERMAL LICENSES: REGIONAL SETTING AND KEY TECHNICAL FINDINGS

### 4.1. Regional Geological Setting

The Muş geothermal licenses are located within the Muş Basin in Eastern Anatolia, a region shaped by post-collisional tectonics associated with the Arabia–Eurasia convergence. The basin is bounded and dissected by regional-scale fault systems that have been active from the Neogene to recent times. These structures play a fundamental role in controlling subsurface fluid circulation and permeability development (Figure-2).

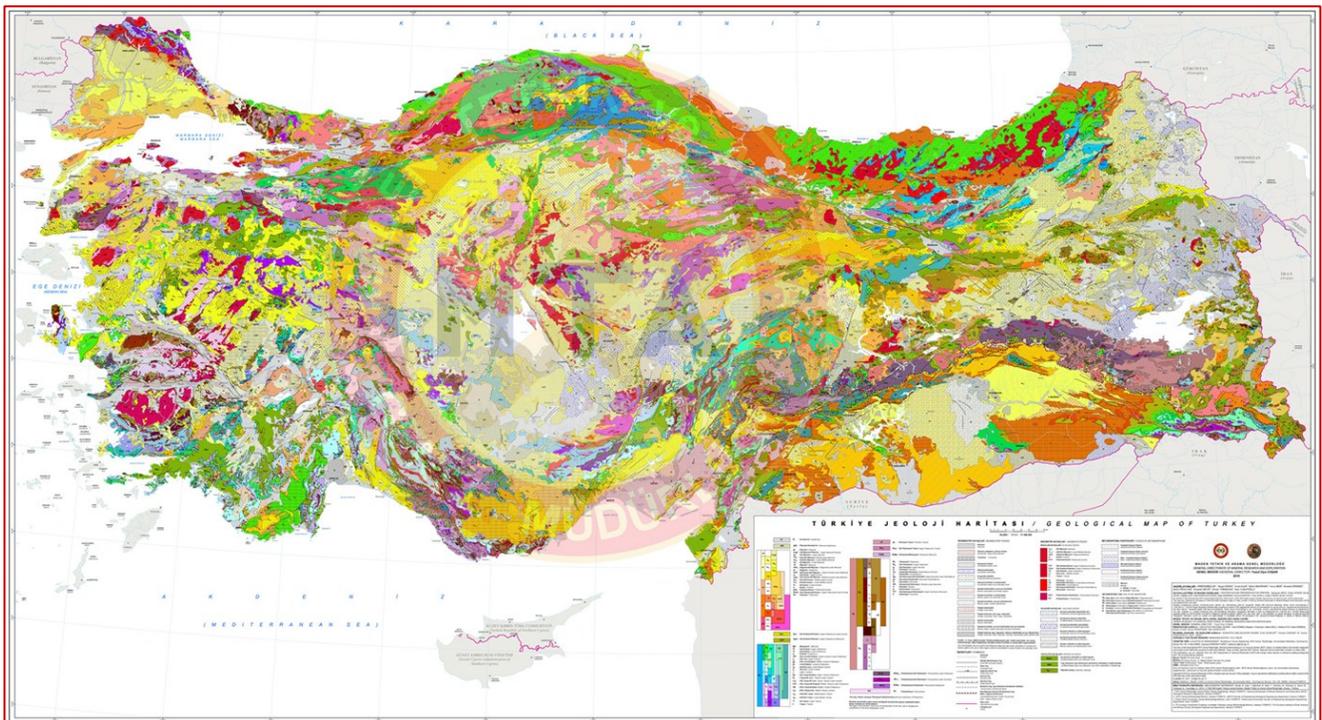


Figure 3: Geology map of Türkiye (MTA)

The regional geology is characterized by a basement composed of metamorphic especially marbel and volcanic units, overlain by Neogene–Quaternary sedimentary and volcanic sequences. The presence of young volcanic products and widespread faulting suggests a favorable geothermal setting driven by elevated heat flow and deep fluid circulation.

#### 4.2. Structural Framework and Permeability Controls

Structural analysis indicates that geothermal prospectivity within the Muş licenses is primarily controlled by fault architecture rather than lithological traps. The most prospective zones are associated with:

- Major strike-slip and oblique-slip faults
- Fault intersections and step-over zones
- Reactivated basement faults propagating into overlying units

These structures are interpreted as conduits that allow meteoric waters to penetrate to depth, where they are heated and subsequently ascend along permeable fault zones (Figure-3).

Stress regime analysis suggests that currently active faults are favorably oriented for permeability enhancement, increasing the likelihood of sustainable fluid flow.

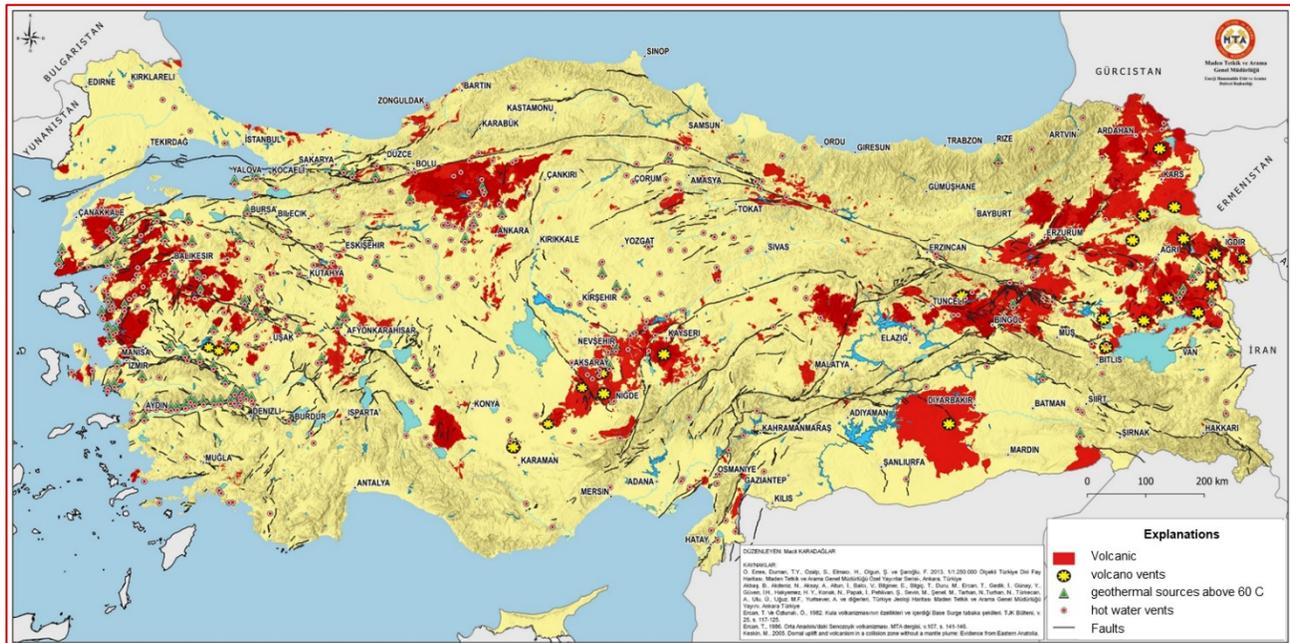


Figure 3: Tectonic map and volcanic areas in Türkiye (MTA)

#### 4.3. Geochemical Characteristics and Reservoir Temperature Indicators

Geochemical data from thermal and mineral water occurrences within and around the Muş licenses provide important constraints on reservoir conditions. Fluid chemistry indicates a predominantly meteoric origin, with evidence of deep circulation and significant water–rock interaction.

Key geochemical observations include:

- Elevated silica and alkali concentrations
- Stable isotope signatures consistent with deep circulation
- Gas compositions dominated by CO<sub>2</sub>, suggesting interaction with deep crustal or magmatic sources

Preliminary geothermometry results indicate reservoir temperatures potentially suitable for electricity generation and/or high-temperature direct-use applications. However, mixing with shallow groundwater and cooling during ascent are interpreted to affect surface discharge temperatures.

#### 4.4. Geophysical Data and Subsurface Interpretation

Geophysical surveys conducted over the Muş licenses include regional gravity and magnetic datasets, complemented by targeted magnetotelluric (MT) measurements.

Interpretation of these data suggests:

- Basement topography with significant structural relief
- Conductive zones at depth interpreted as clay-rich alteration caps
- Resistive bodies potentially corresponding to fractured reservoir zones or intrusive heat sources

MT sections reveal vertically extensive conductive anomalies aligned with major fault zones, supporting the interpretation of structurally controlled geothermal systems.

#### 4.5. Conceptual Geothermal Model

Integration of geological, geochemical, and geophysical datasets supports a conceptual model in which geothermal fluids are recharged at higher elevations, circulate to depths along major fault systems, and are heated by a combination of elevated geothermal gradient and possible magmatic heat sources.

Upflow is interpreted to occur along fault intersections within the license area, with lateral outflow into permeable stratigraphic units where present. The depth to the primary reservoir is expected to be greater than in Western Anatolia but within technically drillable ranges using modern drilling technology.

#### 4.6. Technical Uncertainties and Data Gaps

As with all frontier geothermal projects, key uncertainties remain, including:

- Precise depth and thickness of the geothermal reservoir
- Spatial continuity of permeability along fault zones
- Long-term productivity and sustainability of fluid flow

These uncertainties can be addressed through additional targeted geophysical surveys, refined geochemical sampling, and ultimately exploratory drilling.

#### 4.7. Summary of Technical Implications

The Muş geothermal licenses represent a structurally controlled, deep-circulation geothermal system characteristic of Eastern Anatolia. Existing technical data indicate a favorable geothermal setting, while the remaining uncertainties are consistent with early-stage exploration projects. From a technical standpoint, the area warrants further systematic exploration to confirm reservoir properties and development potential (Figure-4).

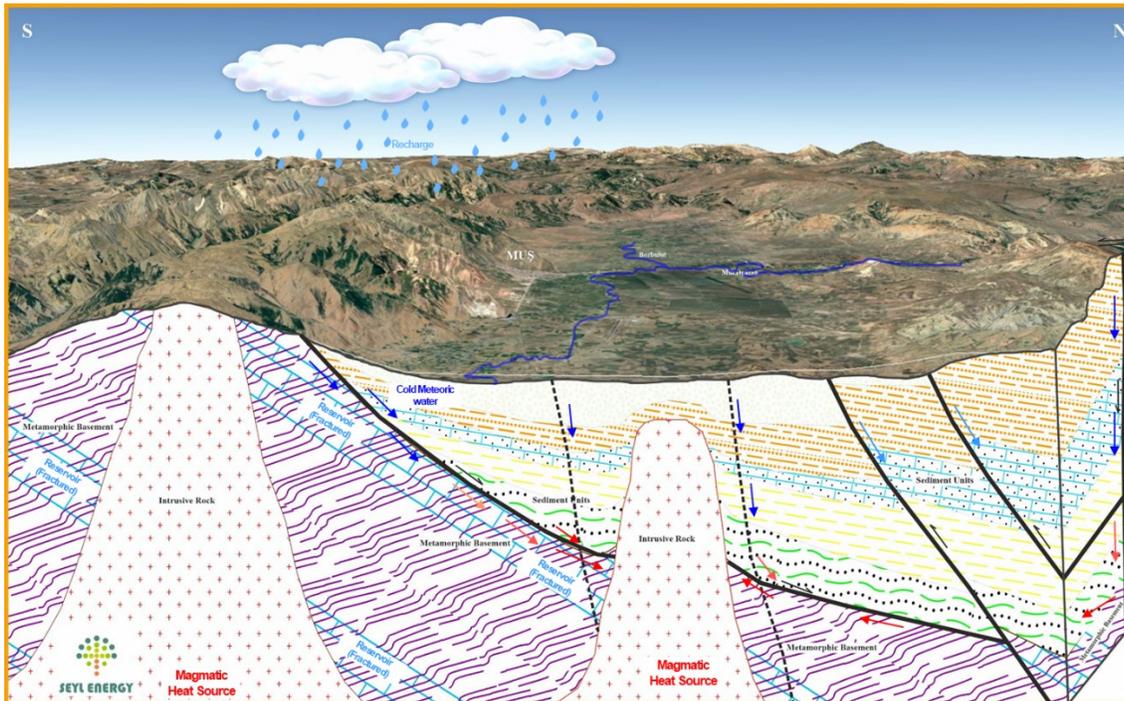


Figure 4: Mus basin subsurface 3D geological- geothermal model

## 5. INVESTMENT PERSPECTIVE

From an investment standpoint, Turkey remains one of the most established geothermal markets globally, supported by a clear licensing framework, long-term resource rights, and a track record of successful project development. The country's experience in geothermal power generation and direct-use applications has led to the formation of a skilled local supply chain, including drilling contractors, service providers, and technical consultants.

While Western Anatolia continues to attract the majority of geothermal investments, the maturity of these basins has gradually shifted the risk–reward balance. High entry costs, increasing operational complexity, and reservoir interference risks have reduced the upside potential for new entrants. In contrast, frontier regions such as Eastern Anatolia offer opportunities for value creation through early-stage participation, provided that exploration risks are managed systematically.

The Muş geothermal licenses exemplify this investment dynamic. The licenses cover a large contiguous area with multiple structurally controlled exploration targets, allowing for portfolio-style exploration within a single license group. Such configurations are particularly suitable for phased investment models, where capital deployment is aligned with the progressive reduction of geological uncertainty.

From a technical–economic perspective, the expected reservoir depths and temperature ranges suggest flexibility in development pathways. Depending on confirmed reservoir characteristics, projects may be developed for electricity generation, cascade direct-use applications, or hybrid schemes combining both. This optionality enhances project resilience under varying market and regulatory conditions.

Furthermore, the availability of risk-sharing structures—such as farm-out agreements, joint ventures, and staged equity participation—enables strategic and financial investors to tailor their exposure according to risk appetite. In this context, frontier geothermal licenses in Turkey provide a platform for disciplined capital allocation rather than speculative investment.

## 6. CONCLUSIONS

Turkey's geothermal sector has reached a stage of maturity where future growth increasingly depends on the systematic exploration of underexplored and frontier regions. While Western Anatolia continues to host the majority of operating geothermal fields, geological and technical evidence indicates that Eastern Anatolia represents a viable next phase for geothermal expansion when approached with modern exploration methodologies.

The Muş geothermal licenses, evaluated in this study, provide a representative example of a structurally controlled geothermal system in Eastern Anatolia. Integrated exploration activities conducted to date include geological mapping, geochemical analyses, geophysical surveys, and the interpretation of available 2D seismic data. These seismic datasets have enabled subsurface structural modeling, improving the understanding of fault geometries, basement configuration, and potential reservoir architecture beneath the license areas.

Geochemical observations, including a measured surface discharge temperature of approximately 98°C, confirm the presence of an active geothermal system and support interpretations of deep fluid circulation. Although surface temperatures are influenced by mixing and cooling effects, such values are considered significant indicators of elevated subsurface reservoir temperatures in frontier geothermal settings.

From a geological perspective, the interpreted reservoir framework is consistent with Paleozoic fractured marble, which are widely recognized as one of the principal geothermal reservoir formations in Turkey. These units, characterized by fracture and karst-related permeability, constitute the main producing reservoirs in several of Turkey's high-capacity geothermal fields. Their presence within the Muş region, combined with favorable structural controls, enhances the technical credibility of the geothermal play concept proposed in this study.

Integration of 2D seismic interpretation with geological and geophysical datasets has allowed the development of a preliminary subsurface geothermal model, defining potential upflow zones and priority drilling targets. While uncertainties remain regarding reservoir continuity, permeability distribution, and sustainable flow rates, these uncertainties are typical of early-stage geothermal projects and can be addressed through phased exploration and exploratory drilling.

In conclusion, the Muş geothermal licenses demonstrate that Eastern Anatolia holds technically sound geothermal potential supported by measurable surface manifestations, subsurface geophysical data, and regionally proven reservoir analogs. When evaluated through disciplined exploration strategies and supported by flexible investment structures, such frontier geothermal systems can contribute meaningfully to Turkey's long-term geothermal development and energy transition.

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