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Closed-Loop Geothermal Heat Recovery Predictions: Impact of Time-Dependent Gradient Decay and Fracture Thermal Resistance

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Abstract

This study examines the potential conversion of an abandoned well in the Krechba Field, Ahnet Basin, Algeria, into a closed-loop geothermal system using supercritical CO_2 as the working fluid. The research focuses on evaluating the effect of natural fracture properties on long-term heat extraction performance. A numerical model was developed to simulate conductive heat transfer along a 3000 m wellbore divided into 300 vertical segments, using geological, thermal, operational, and fracture-related parameters representative of the Krechba Field.

Sensitivity analysis was conducted over a 30-year simulation period to assess the effects of fracture density, water saturation, fracture filling type, mass flow rate, and stratigraphic layer properties. The results show that higher fracture density and water saturation improve heat extraction, while mineralized or gouge-filled fractures reduce thermal performance. The study also shows that mass flow rate affects outlet temperature and heat delivery, and that improving fracture properties across all layers gives the highest thermal output. Overall, the results confirm that closed-loop geothermal systems using supercritical CO_2 can provide stable long-term performance in mature petroleum fields.

Keywords: *Closed-loop geothermal system; supercritical CO_2; Krechba Field; Ahnet Basin; natural fractures; heat transfer; abandoned wells.*

الملخص

تهدف دراسة إلى بحث إمكانية تحويل بئر مهجورة في حقل كرشبة، حوض أحنات بجنوب جزائر، إلى نظام حراري أرضي مغلق باستعمال ثاني أكسيد كربون فوق حرج كسائل عامل. يركز بحث على تقييم أثر خصائص كسور طبيعية في أداء استخراج حرارة خلال مدة تشغيل طويلة. تم إعداد نموذج عددي لمحاكاة انتقال حراري بالتوصيل على طول بئر بعمق 3000 متر، مقسمة إلى 300 مقطع عمودي، مع اعتماد معطيات جيولوجية وحرارية وتشغيلية مرتبطة بحقل كرشبة.

أجريت دراسة حساسية خلال فترة 30 سنة لتحليل أثر كثافة كسور، تشبع ماء، نوع حشو كسور، معدل تدفق كتلي، وخصائص طبقات صخرية. بينت نتائج أن ارتفاع كثافة كسور وزيادة تشبع ماء يحسنان استخراج حرارة، بينما تؤدي كسور مملوءة أو معادن إلى خفض أداء حراري. كما أظهرت نتائج أن معدل تدفق يؤثر في درجة حرارة خروج وكمية حرارة مستخرجة، وأن تحسين خصائص كسور في جميع طبقات يعطي أعلى مردود حراري. عموما، تؤكد دراسة أن نظام حراري أرضي مغلق باستعمال ثاني أكسيد كربون فوق حرج يمكن أن يوفر أداء مستقرا في حقول بترولية ناضحة.

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كلمات مفتاحية: نظام حراري أرضي مغلق؛ ثاني أكسيد كربون فوق حرج؛ حقل كرشبة؛ حوض أهنت؛ كسور طبيعية؛ .انتقال حراري؛ آبار مهجورة.

Résumé

Cette étude examine le potentiel de conversion d'un puits abandonné du champ de Krechba, dans le bassin d'Ahnet en Algérie, en un système géothermique en boucle fermée utilisant du CO_2 supercritique comme fluide de travail. La recherche se concentre sur l'évaluation de l'effet des propriétés des fractures naturelles sur les performances d'extraction thermique à long terme. Un modèle numérique a été développé afin de simuler le transfert de chaleur conductif le long d'un puits de 3000 m subdivisé en 300 segments verticaux, en utilisant des paramètres géologiques, thermiques, opérationnels et liés aux fractures représentatifs du champ de Krechba. Une analyse de sensibilité a été réalisée sur une période de simulation de 30 ans afin d'évaluer les effets de la densité des fractures, de la saturation en eau, du type de remplissage des fractures, du débit massique et des propriétés des couches stratigraphiques. Les résultats montrent qu'une densité élevée de fractures et une forte saturation en eau améliorent l'extraction thermique, tandis que les fractures minéralisées ou remplies de gouge réduisent les performances thermiques. L'étude montre également que le débit massique influence la température de sortie et la quantité de chaleur extraite, et que l'amélioration des propriétés des fractures dans l'ensemble des couches stratigraphiques permet d'obtenir la production thermique la plus élevée. Dans l'ensemble, les résultats confirment que les systèmes géothermiques en boucle fermée utilisant du CO_2 supercritique peuvent assurer des performances stables à long terme dans les champs pétroliers matures.

Mots-clés : système géothermique en boucle fermée ; CO_2 supercritique ; champ de Krechba ; bassin d'Ahnet ; fractures naturelles ; transfert thermique ; puits abandonnés.

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List of Abbreviations

Abbreviation	Full Term
$scCO_2$	Supercritical Carbon Dioxide
CLG	Closed-Loop Geothermal
CLGS	Closed-Loop Geothermal System
FD	Fracture Density (fractures/m)
Sw	Water Saturation (dimensionless)
ORC	Organic Rankine Cycle
EGS	Enhanced Geothermal System
CCUS	Carbon Capture, Utilization and Storage
CCS	Carbon Capture and Storage
TPS	Total Petroleum System
TOC	Total Organic Carbon
FMI	Formation MicroImager
OBMI	Oil-Base MicroImager
DFN	Discrete Fracture Network
NIST	National Institute of Standards and Technology
Rc	Thermal Contact Resistance (m·K/W)
keff	Effective Thermal Conductivity (W/m·K)
Geff	Effective Geothermal Gradient (°C/m)
$\dot{m}$	Mass Flow Rate (kg/s)

cp	Specific Heat Capacity (J/kg·K)
KB-1	Krechba Borehole 1
KB-502	Krechba Borehole 502
ηORC	ORC Thermal Efficiency

General Introduction

The increasing global demand for sustainable and low-carbon energy resources has encouraged the development of alternative technologies capable of reducing dependence on conventional fossil fuels. Among these technologies, geothermal energy represents a promising solution because it provides a stable and continuous source of heat that can be used for power generation or direct thermal applications. However, conventional geothermal exploitation often requires favorable geological conditions, high permeability, and significant drilling investments. For this reason, the reuse of existing petroleum wells has become an attractive approach for reducing costs and improving the feasibility of geothermal projects (Budiono et al., 2022; Caulk & Tomac, 2017).

Closed-loop geothermal systems have gained particular attention because they allow heat extraction from deep geological formations without producing reservoir fluids (Alimonti & Soldo, 2016). In this configuration, a working fluid circulates inside a sealed wellbore system and absorbs heat mainly through conduction from the surrounding rocks. This makes the system more controllable and reduces risks related to fluid loss, induced seismicity, and reservoir contamination. The use of supercritical carbon dioxide as a working fluid can further improve system performance due to its favorable thermodynamic properties, including low viscosity and good heat transfer behavior under deep reservoir conditions (Adams et al., 2015).

In Algeria, the Ahnet Basin represents an important geological province because of its hydrocarbon potential, Paleozoic sedimentary succession, and structural complexity (Klett, 2000). Within this basin, the Krechba Field is of particular interest due to its previous role in the In Salah CO_2 storage project and the availability of geological and reservoir data (Ringrose et al., 2013). The presence of natural fractures in the field adds another important dimension to geothermal evaluation, since fractures can influence effective thermal conductivity, thermal resistance, and heat transfer behavior

This study focuses on evaluating the possibility of converting an abandoned well in the Krechba Field into a closed-loop geothermal system using supercritical CO_2 as the circulating fluid. The research investigates how fracture properties, including fracture density, water saturation, fracture filling type, and stratigraphic layer characteristics, affect thermal performance over a long-term operational period. In addition, the study examines the influence of mass flow rate on production temperature and heat delivered to the surface.

The main objective of this work is to develop a numerical methodology capable of assessing the thermal behavior of a closed-loop geothermal system under geological conditions representative of the Krechba Field. The study also aims to identify the most influential fracture and operational parameters controlling heat extraction performance. To achieve this, the wellbore is discretized into vertical segments, geological and thermal input parameters are assigned to each stratigraphic unit, and sensitivity analyses are conducted over a simulation period of 30 years.

The research is organized into three chapters. The first chapter presents the study area and its geological context, including the geographical location of the Ahnet Basin, its petroleum system, the Krechba Field, and the influence of fractures on heat transfer. The second chapter describes the conceptual framework, input data, governing equations, mathematical formulation, and computational workflow used in the simulation. The third chapter presents the case study, results, and discussion, with emphasis on fracture sensitivity analysis, fracture filling effects, mass flow optimization, and the impact of stratigraphic layer properties on heat extraction.

Through this structure, the study seeks to contribute to the evaluation of closed-loop geothermal potential in mature petroleum fields and to highlight the role of natural fractures in controlling long-term thermal

Chapter I: Study Area and Description

The Ahnet Basin exhibits very complex sedimentological and structural characteristics. The Paleozoic sedimentary sequence, which is nearly complete, is mainly composed of clays, sandstones, and limestones that rest unconformably on a Precambrian–Early Cambrian volcano-sedimentary basement, strongly structured by the effects of the Pan-African orogeny. Given the significant hydrocarbon potential of this basin, exploration efforts and development projects have been intensively prepared by geological experts, Sonatrach research groups, and other foreign companies based on reservoir studies (EIA, 2013).

1.1. Geographical Location and Boundaries

The Ahnet Basin is situated within the southern Algeria region, specifically forming part of the western province of the Saharan Platform (Fig. 1). Its boundaries are defined by the meridians 1°00′ and 3°00′ East, as well as the parallels 24°00′ and 27°00′ North, encompassing a total area of approximately 50,000 km² in (Kadri & Hacini, 2018). The basin lies about 1,200 km south of Algiers and 700 km southwest of Hassi Messaoud.

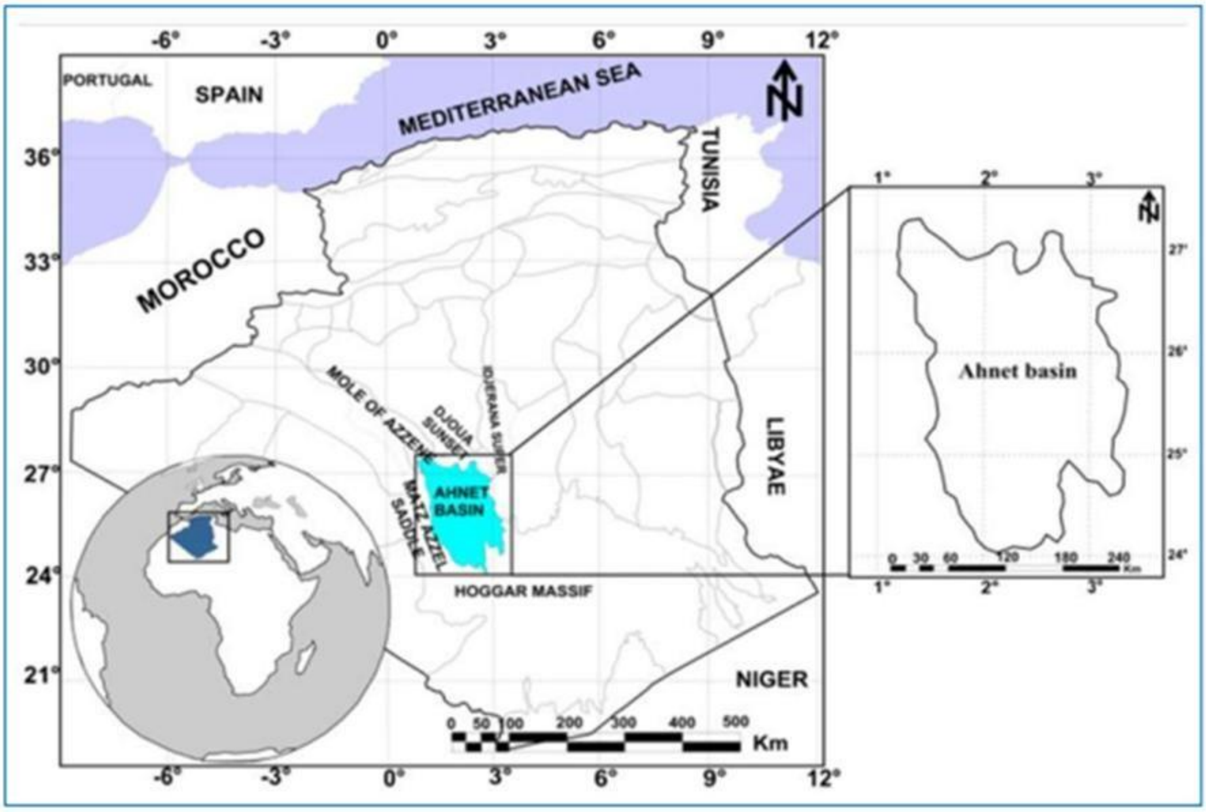

Figure 1: Geographical location of Ahnet basin, Algeria. Allaoui et al. (2022).

1.2. Geological Setting

Geologically, the Ahnet Basin is located in the Algerian Sahara, specifically to the northwest of the Hoggar Massif (Fig.2). This basin occupies a unique geographical position, endowing it with distinct structural characteristics (Mofredj et al., 2019). It is a north–south trending intracratonic basin containing a thick Paleozoic sedimentary succession exceeding 3,000 m, including organic-rich Silurian and Devonian shales. The structures take the form of large, elongate anticlines and domes formed as a result of Hercynian tectonic compression.

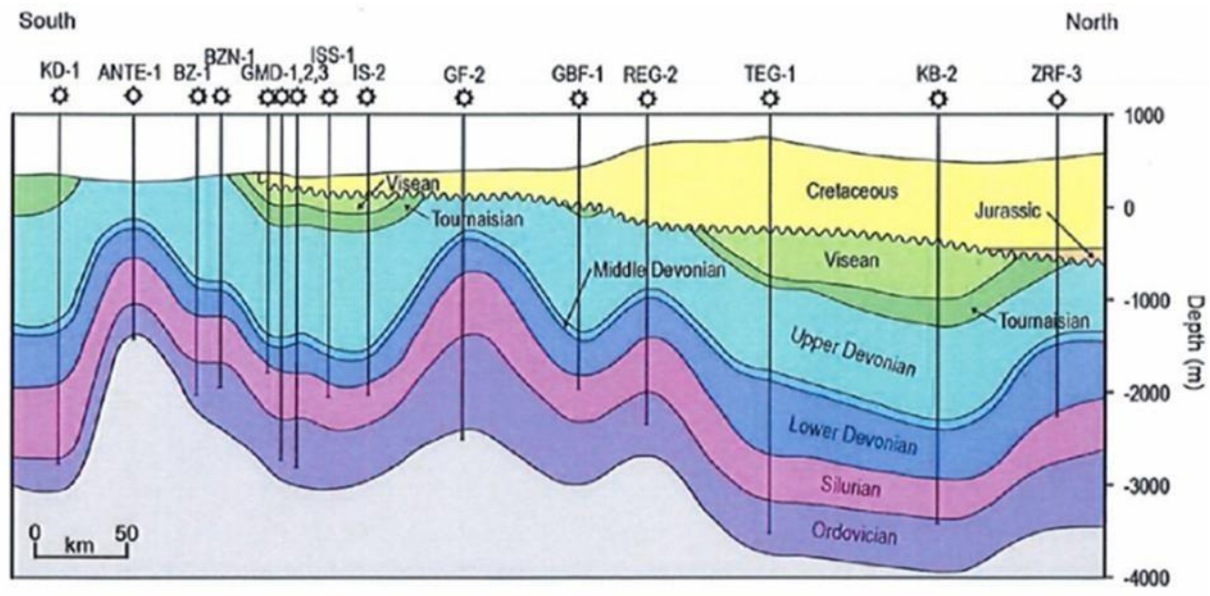

Figure 2: Schematic Cross Section of the Ahnet Basin, Algeria Sonatrach (2009).

1.2.1. Lithology

The Paleozoic deposits of the Ahnet Basin rest unconformably on a Precambrian substratum consisting of two distinct units: the basement and the upper Infra-Cambrian part. The basement is of volcano-metamorphic nature, composed of micaschists and amphibolites intruded by magmatic bodies. Overlying this, the Intermediate Series (Ahnet Purple Series) consists of arkosic and conglomeratic formations with fluvial facies (Fig.3). In the Ahnet Basin, the Paleozoic formations are relatively complete, ranging from the Lower Cambrian to the Carboniferous (WEC, 2007). The Cambrian begins with coarse conglomeratic sandstones in a fluvial environment, passing upward into finer sandstones with trace fossils (tigilites). The Ordovician is subdivided into lower, middle, and upper units. The Lower Ordovician includes Units III1 (Miribel sandstones, El Gassi clays, El Atchane sandstones), III2 (Hamra quartzites), and III3 (Ouargla sandstones, Tiferouine and Azzel clays). The Middle Ordovician (Unit VI) includes Oued Saret and El Goléa sandstones. Silurian deposits consist of black graptolitic shales. The Devonian is subdivided into Lower (Gedinnian, Siegenian, Emsian), Middle (Couvinian, Givetian), and Upper (Frasnian, Famennian, Strunian) subsystems.

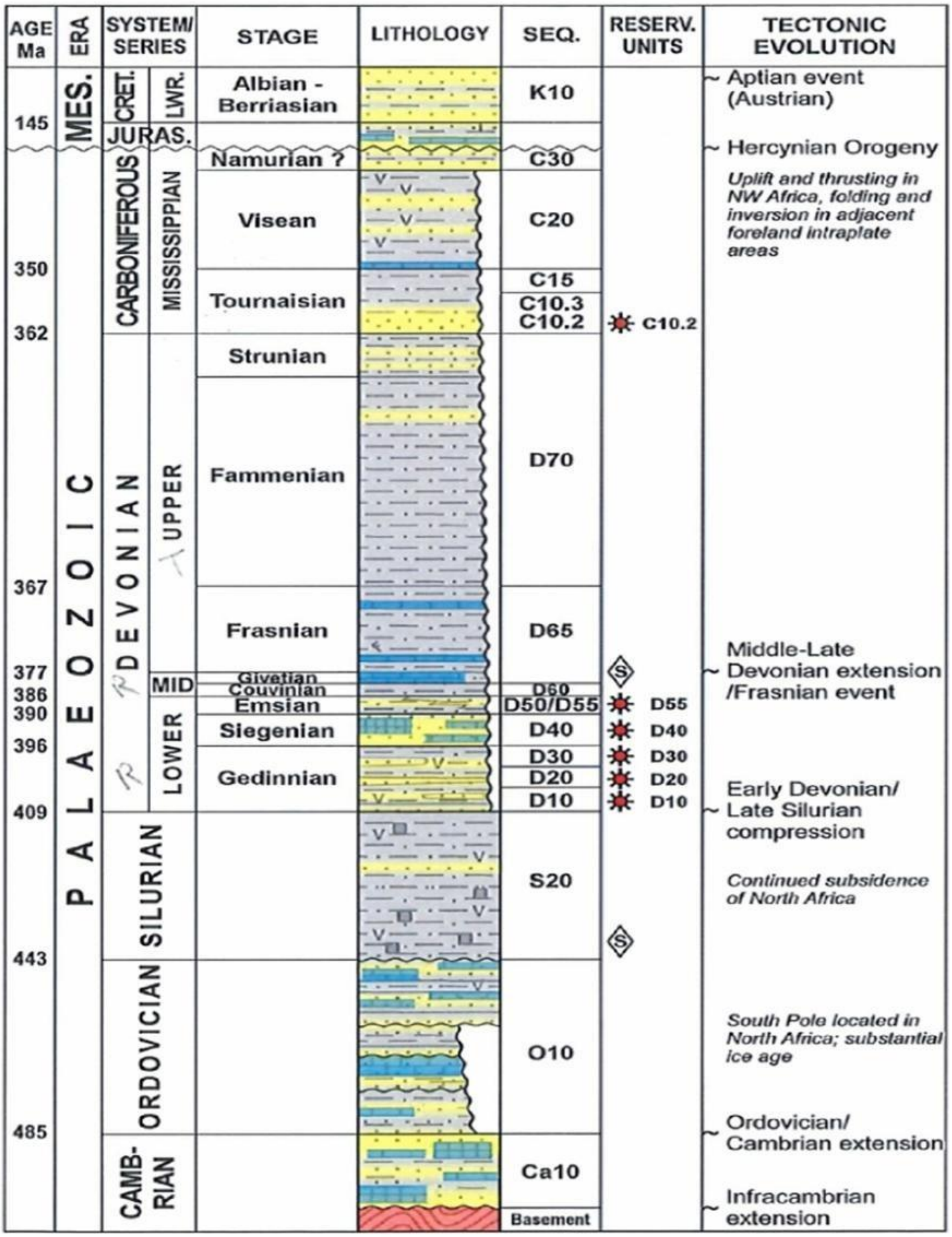

Figure 3:Lithology column of the Ahnet Basin. Modified from Sonatrach (2009).

1.2.2 Local Geology of the Krechba Field

The Krechba gas field, located in central Algeria, forms part of the In Salah CO_2 storage project. The primary storage reservoir is a Carboniferous quartz arenite sandstone approximately 20 m thick, situated at a depth of about 1800 m .The overburden consists of approximately 900 m of Carboniferous mudstone overlain by 900 m of Cretaceous sandstone and mudstone (Bjørnarå et al., 2018).

The reservoir is naturally fractured, with dominant fracture orientation in the NW-SE direction (Morris et al., 2011; White et al., 2014).A significant fracture zone (F12) intersects the injection well KB502; this zone is approximately 20 m thick, extends 450 m vertically, and 3 km laterally (Bjørnarå et al., 2018). The present-day stress regime is strike-slip, with σH (maximum horizontal stress) = 49.9 MPa oriented NW-SE, σv = 44.5 MPa, and σh = 30.8 MPa oriented NE-SW. The present-day stress regime is strike-slip, with σH (maximum horizontal stress) = 49.9 MPa oriented NW-SE, σv = 44.5 MPa, and σh = 30.8 MPa oriented NE-SW (Morris et al., 2011).

1.3. Petroleum System Overview of the Ahnet Basin

The Ahnet Basin forms part of the Tanezzuft-Ahnet Total Petroleum System (TPS), a classic Paleozoic petroleum system in North Africa. Its evolution was strongly influenced by the Hercynian orogeny (Klett, 2000). The elements and timing of this petroleum system are illustrated in Figure 4.

The primary source rocks are organic-rich marine shales of Silurian and Devonian age. The Tanezzuft Formation (Silurian Hot Shales) represents the main source rock, exhibiting high TOC content and Type II/III kerogen. Devonian shales, especially the Frasnian interval, provide a secondary but significant source. Hydrocarbon maturation occurred mainly during the Carboniferous, with subsequent modification by Hercynian uplift and erosion

Reservoir Rocks

- Cambrian–Ordovician: Thick quartz-rich sandstones of fluvial to deltaic origin, representing the most important conventional reservoirs.
- Silurian and Devonian: Sandstones and mixed clastic-carbonate units.
- Carboniferous: Sandstones with variable reservoir properties.

Seal Rocks

- Intraformational seals: Marine shales and mudstones within the Paleozoic sequence provide reliable local seals.
- Regional top seal: Triassic–Jurassic evaporites, mudstones, and carbonates overlying the major Hercynian unconformity.

Traps and Closures

- Elongated anticlines and domes formed by Hercynian compression and basement fault reactivation.
- Faulted anticlines and stratigraphic/combination traps in Carboniferous intervals.

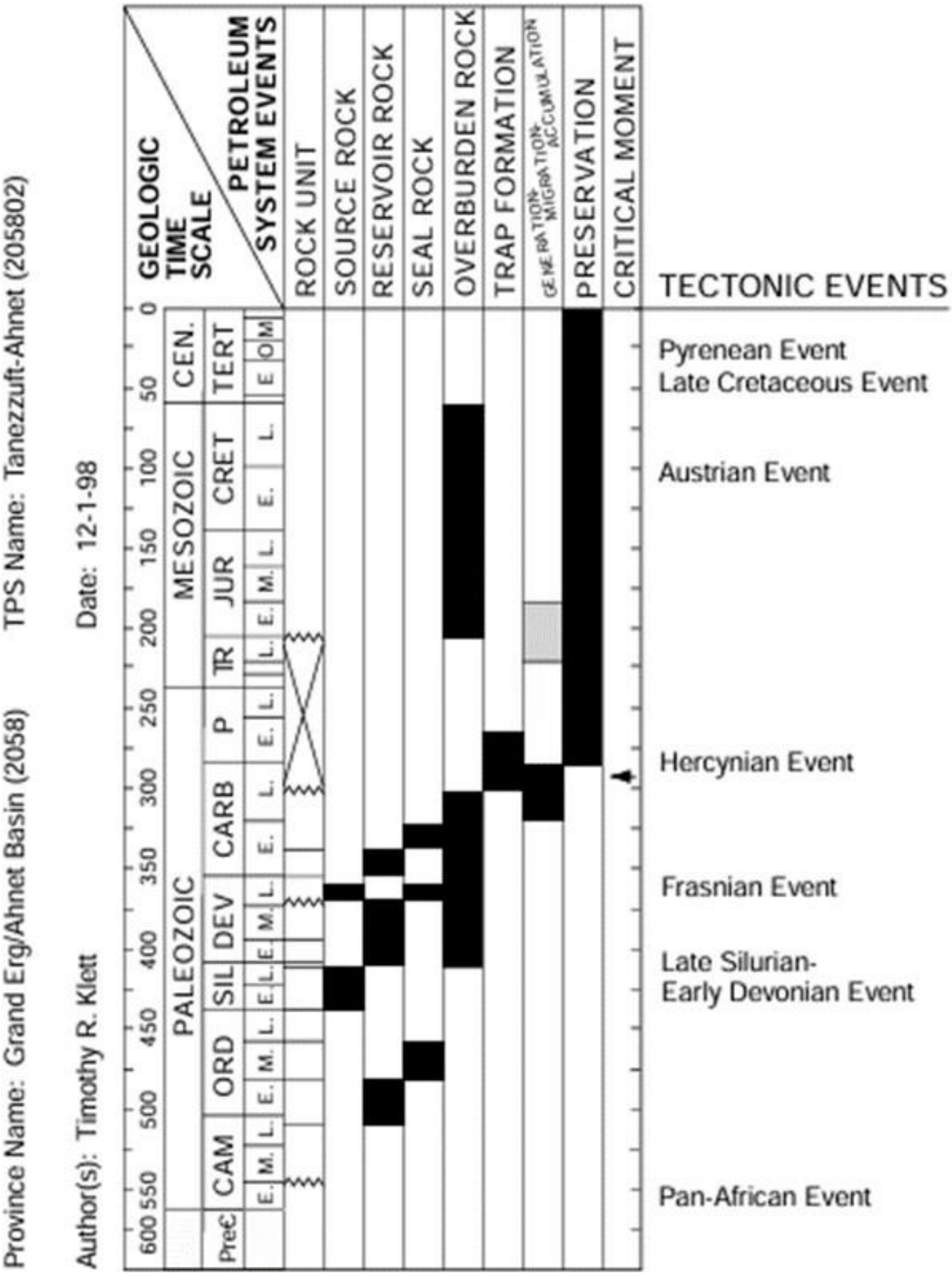

Figure 4: Events chart for the Tanezzuft-Ahnet Total Petroleum System (TPS) in the Grand Erg/Ahnet Province. Klett (2000).

1.4. The Krechba Field and the In Salah CCUS Project

The Krechba Field is one of the major gas fields in the Ahnet Basin, producing from Carboniferous sandstone reservoirs with low matrix permeability (typically 10^{-13} to 10^{-15} m²). The field gained international prominence through the In Salah CO_2 Storage Project (2004–2011), where approximately 3.8 million tons of CO_2 were injected into the saline aquifer portion of the reservoir **(Fig.6)**. Natural fractures play a dominant role in controlling fluid flow and permeability in this field (Ringrose et al., 2013; White et al., 2014).

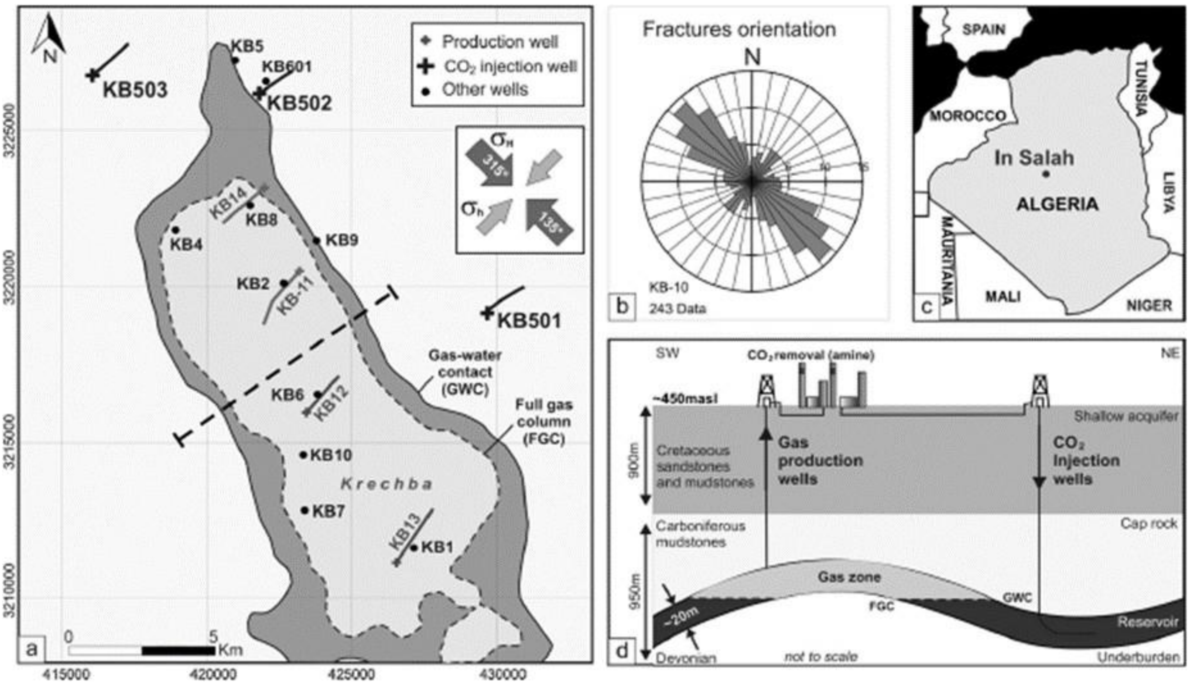

Figure 5: Composite figure: (a) Map of the In Salah CO_2 storage site; (b) Rose diagram of natural fracture strikes in well KB-10; (c) Regional location map; (d) Schematic cross-section. Modified from Baroni et al. (2011), White et al. (2014), and Mathieson et al. (2009).

1.5. Fracture Properties and Thermal Influence

In closed-loop geothermal systems (CLGS), heat transfer is primarily conductive. Natural fractures modify the effective thermal conductivity and introduce thermal anisotropy around the wellbore, even without direct fluid circulation between fractures and the working fluid (Fowler & McClure, 2021).

1.5.1. Fracture Orientation and Thermal Anisotropy

Fractures in the Krechba Field exhibit a dominant NW-SE orientation, sub-parallel to the present-day maximum horizontal stress (σH), with steep dips (>70–80°). A secondary, less frequent E-W set is also present (White et al., 2014). This preferred orientation induces significant thermal anisotropy in closed-loop configurations. Fractures aligned with the temperature gradient act as preferential pathways for conductive heat flow, resulting in elliptical rather than radial heat extraction patterns (Fowler & McClure, 2021).

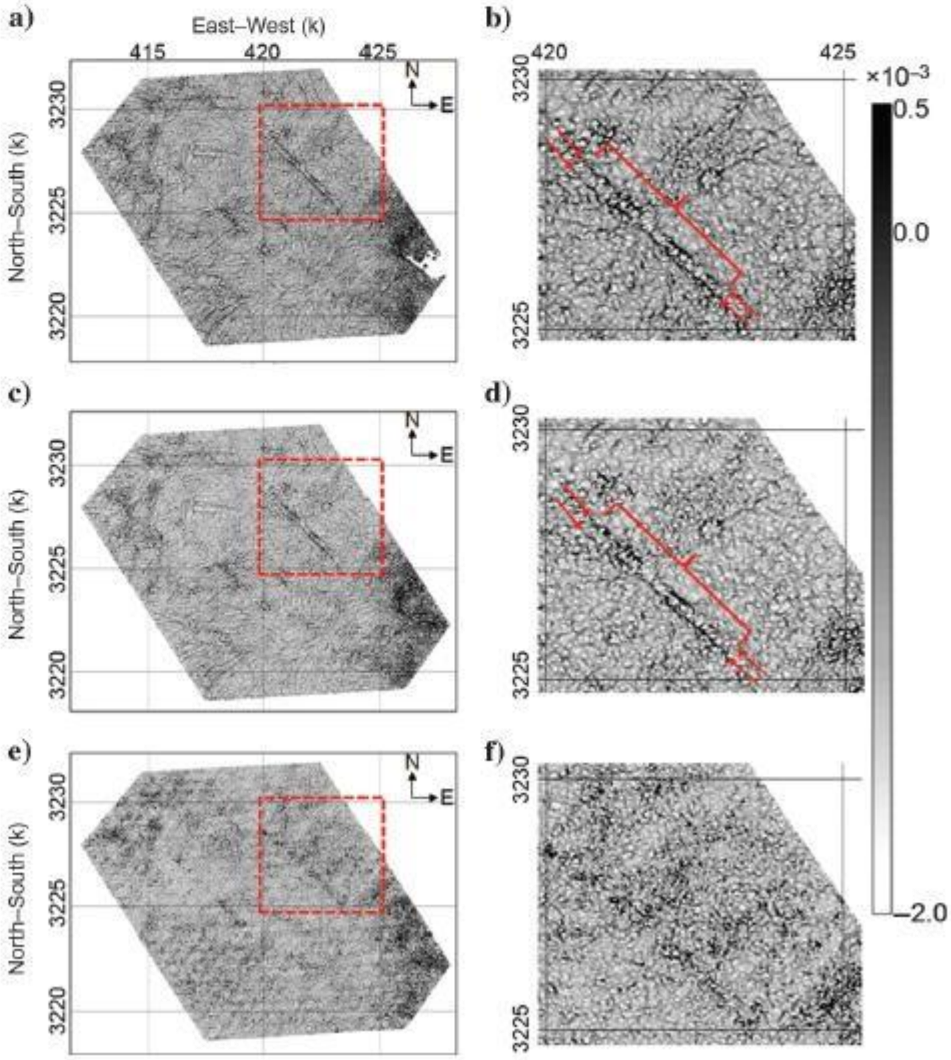

Figure 6:Most positive curvature attribute extracted at different horizons (C10.2, C20.1, and C20.4) showing the linear fracture zone above injection well KB-502. Source: Zhang et al. (2016).

Table 1:Estimated dimensions of the fracture zone above KB-502 (Zhang et al., 2016).

Parameter	**Value**	**Unit**
Fracture zone length	~3,500	m
Fracture zone width	~350	m
Fracture zone height	~80	m
Dominant orientation	NW-SE	—
Dip angle	>70–80	degrees

1.5.2. Fracture Density and Effective Thermal Conductivity

Fracture density is structurally and stratigraphically controlled, being higher near faults, fold hinges, and in brittle sandstone intervals, while lower in ductile clay-rich layers. In closed-loop systems, higher fracture density and greater length increase the rock volume contributing to conductive heat transfer, potentially enhancing overall heat extraction rates (Fowler & McClure, 2021).

1.5.3. Fracture Aperture, Filling, and Conductive Heat Transfer

Fracture apertures in the Krechba Field typically range from a few microns to 0.5–1 mm in conductive fractures. Partial mineral filling (calcite or silica) is common, reducing hydraulic conductivity but potentially enhancing thermal conductivity when filled with high-conductivity minerals (White et al., 2014). In CO_2-rich environments like Krechba, geochemical reactions may alter aperture and filling over time through dissolution or precipitation, affecting long-term thermal performance (Fowler & McClure, 2021).

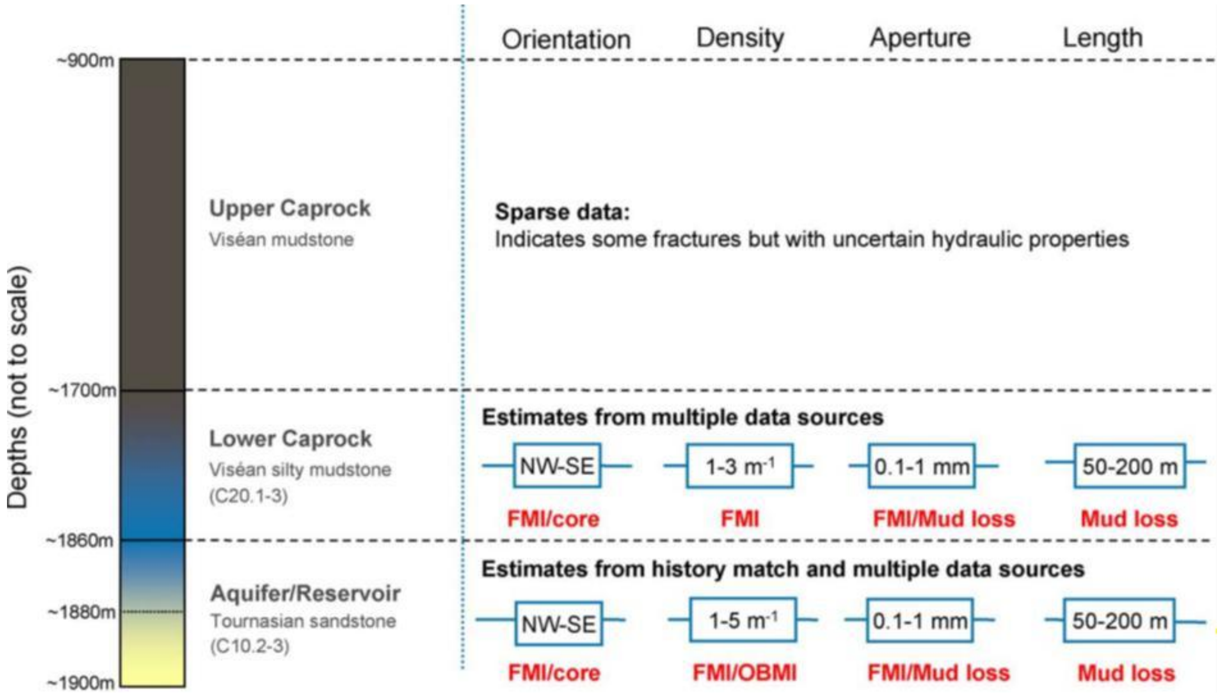

Figure 7: Sketch showing fracture parameters for the reservoir and caprock section (900–1900 m) inferred from FMI/OBMI image logs, core inspection, and mud loss data. Source: Iding & Ringrose (2010).

Chapter II: Conceptual Framework and Methodology

2.1. Conceptual Framework

The present study proposes the repurposing of abandoned wells in the Krechba Field (Ahnet Basin, Algeria) from CO_2 sequestration infrastructure into Closed-Loop Geothermal (CLG) systems using supercritical CO_2 ($scCO_2$) as the working fluid. This approach enables the isolation and rigorous quantification of the effects of natural fractures and time-dependent geothermal gradient decay on long-term heat recovery performance (Rocha & Zerpa, 2021; Fowler & McClure, 2021).

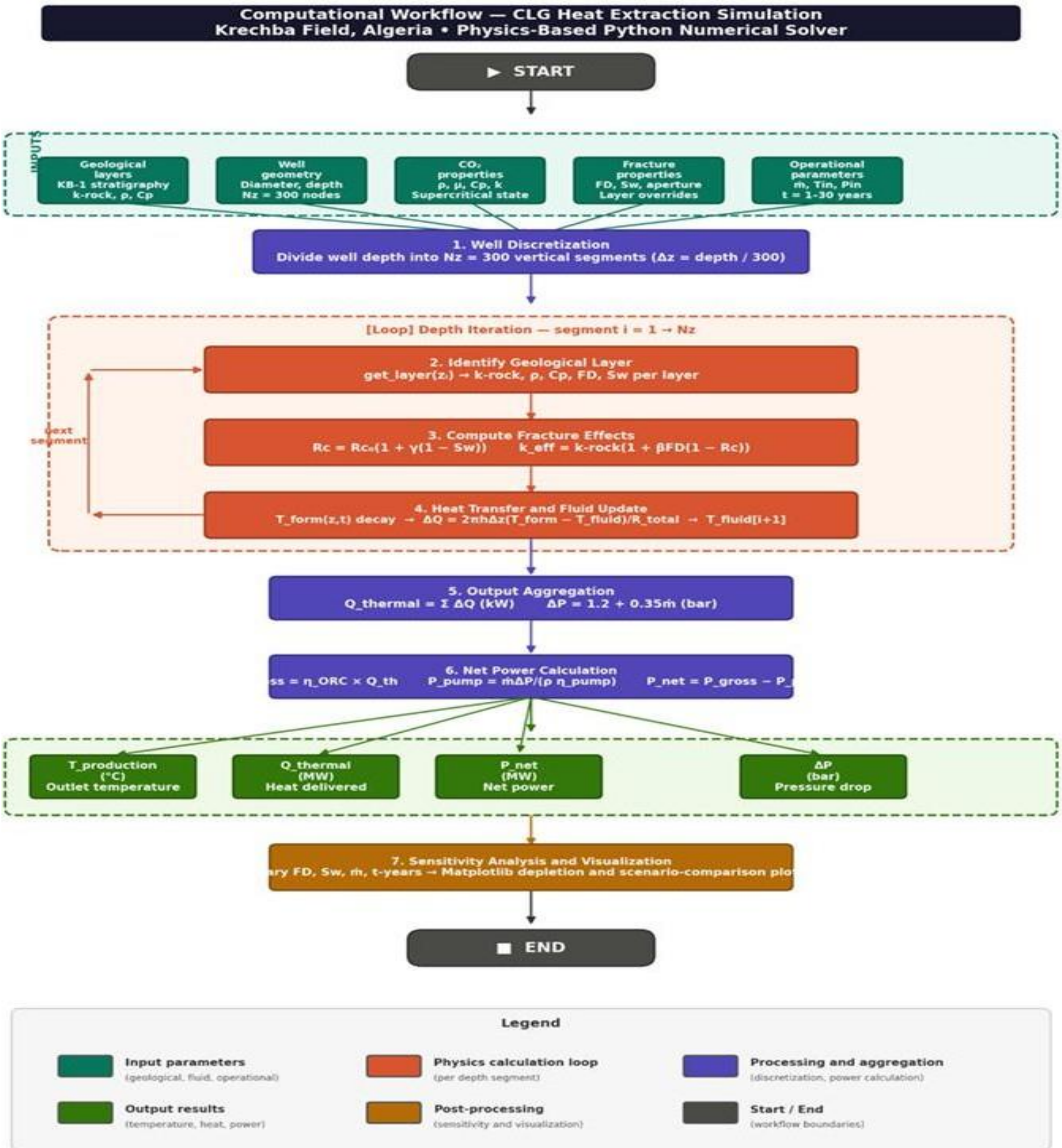

Figure 8: Conceptual Framework and Methodology Flowchart for Closed-Loop $scCO_2$ Geothermal Extraction in Abandoned Wells

2.1.1. Research Boundaries

This study is geographically limited to the Krechba Field in the Ahnet Basin. Technically, it focuses exclusively on closed-loop configurations in existing abandoned wells, using $scCO_2$ as the circulating fluid. The modeling emphasizes conductive heat transfer, time-dependent thermal depletion, and fracture thermal resistance. Open-loop systems, hydraulic stimulation (EGS), and full economic assessment are outside the scope of this research.

2.1.2. Advantages of Closed-Loop $scCO_2$ Systems

Closed-loop geothermal systems offer significant advantages, particularly in fractured reservoirs like Krechba (Rocha & Zerpa, 2021; Fowler & McClure, 2021):

- Complete isolation of the working fluid eliminates advective interference, allowing precise evaluation of conductive heat transfer and fracture effects.
- Utilization of $scCO_2$ leverages the existing CCS infrastructure from the In Salah project, creating synergy between carbon storage and geothermal energy.
- Superior thermophysical properties of $scCO_2$ (low viscosity, high density variation with temperature, excellent heat transfer) enable efficient natural thermosiphon circulation.
- Repurposing abandoned wells minimizes drilling costs and environmental impact.

2.1.3. Well Conversion Process

The conversion of an abandoned petroleum well in the Krechba Field into a closed-loop geothermal well involves standard petroleum engineering operations, as reviewed by Budiono et al. (2022) and illustrated in Figure 8.

The methodology centers on a closed-loop geothermal (CLG) system acting as a deep borehole heat exchanger. Cold $scCO_2$ is injected down the wellbore, absorbs geothermal heat through conduction from the formation, and rises to the surface for power generation via an ORC unit (Alimonti & Soldo, 2016). This closed-loop architecture decouples hydraulic interactions from thermal processes, isolating the heat transfer mechanism from the complex fluid flow dynamics of the fractured reservoir (Fowler & McClure, 2021).

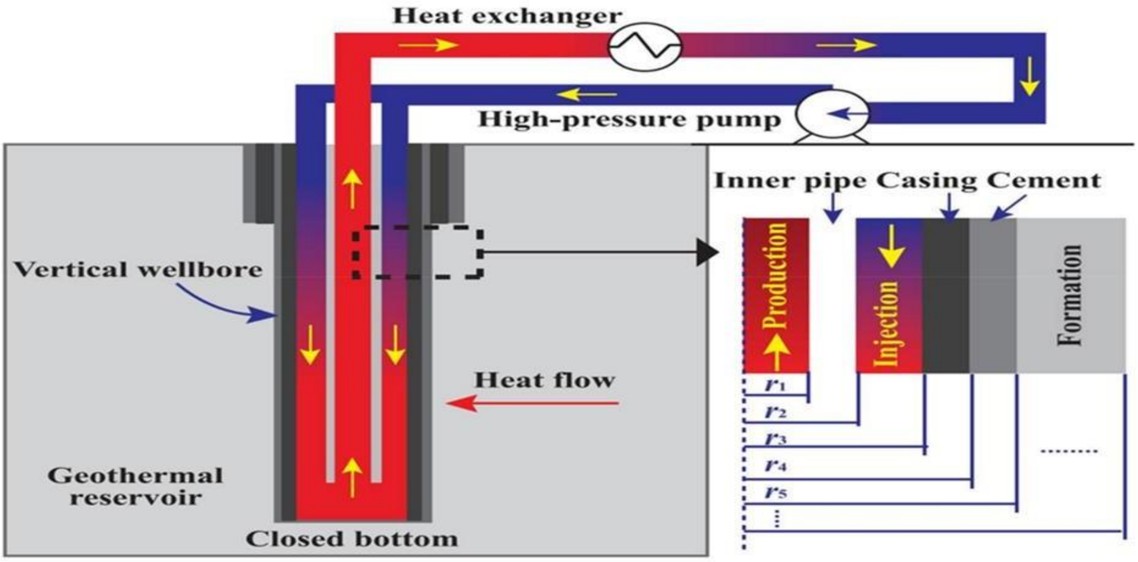

Figure 9: Schematic illustration of the conversion process from an abandoned well to a closed-loop geothermal system. Gluyas et al. (2021) and Caulk & Tomac (2017).

2.2. Input Data and Parameterization

2.2.1. Stratigraphic and Geological Inputs

The geological model is based on the lithological column of well KB-1 (Sonatrach JV Gas, 2005). The reservoir is discretized into seven stratigraphic units with distinct thermal and fracture properties, summarized in Table 2.

Table 2: Stratigraphic Input Parameters for Krechba Well KB-1 (Sonatrach JV Gas, 2005).

Stratigraphic Unit	Depth (m)	Lithology	k_rock (W/m·K)	ρ (kg/m³)	cp (J/kg·K)	FD (m⁻¹)	Sw (%)
Upper Cretaceous	0–163	Dolomite/Mudstone	1.8	2200	800	0.5	0.05
Lower Cretaceous	163–856	Sandstone/Mudstone	2.2	2300	850	0.8	0.10
Visean	856–1532	Mudstone/Siltstone	2.5	2450	880	1.2	0.15
Visean Hot Shale	1532–1846	Mudstone/Dolomite	2.0	2550	950	4.5	0.35
Visean Unstable	1846–1916.5	Mudstone/Limestone	2.1	2520	920	3.5	0.30
Base Visean	1916.5–1981	Mudstone/Limestone	2.3	2500	900	2.5	0.25
Tournaisian	1981–3500	Sandstone/Siltstone	2.6	2480	890	1.8	0.20

Note: The Visean Hot Shale is the primary thermal target due to its high fracture density.

2.2.2. Wellbore Geometry and Completion

The wellbore geometry was modeled as a coaxial closed-loop configuration. The geometric parameters, summarized in Table 3, were determined based on the actual completion data of the KB-1 well and standard petroleum engineering practices (Klett, 2000; Cheng et al., 2013).

Table 3: Wellbore Geometry and Completion Parameters.

Parameter	Symbol	Value	Unit
Total Depth	L	3000	m
Casing Inner Diameter	Dc	0.20	m
Inner Pipe Diameter	Di	0.10	m
Casing Thickness	tcsg	10	mm
Cement Sheath Thickness	tcem	30	mm
Cement Thermal Conductivity	kcem	1.5	W/m·K
Number of Nodes	Nz	300	—

2.2.3. Operational and Thermodynamic Inputs

The operational parameters represent a realistic base case for a deep geothermal system. The mass flow rate of 7.0 kg/s was selected based on optimization studies for deep borehole heat exchangers (Alimonti & Soldo, 2016). The simulation period of 30 years corresponds to the standard economic lifetime of geothermal power projects (Hu et al., 2020). The scCO_2 specific heat was evaluated dynamically from the NIST database (NIST, 2017), and the ORC efficiency of 14.5% is a conservative benchmark for low-temperature binary systems (Tchanche et al., 2011).

Table 4: Operational and Fluid Input Parameters.

Parameter	Symbol	Value	Unit
Mass Flow Rate	$\dot{m}$	7.0	kg/s
Injection Temperature	T_{in}	70.0	°C
Simulation Period	t	1–30	years
scCO_2 Specific Heat	c_{p,CO_2}	1050	J/kg·K
ORC Efficiency	η_{ORC}	14.5	%

2.3. Governing Equations and Mathematical Formulation

2.3.1. Fourier's Law of Heat Conduction

The fundamental mechanism governing heat transfer in the closed-loop system is conductive heat transfer, expressed by Fourier's Law (Incropera et al., 2017):

$$\boldsymbol{q} = -\boldsymbol{k} \cdot \nabla \boldsymbol{T} \qquad (2.1)$$

where q is the heat flux vector (W/m²), k is the effective thermal conductivity of the medium (W/m·K), and ∇T is the temperature gradient.

2.3.2. Time-Dependent Geothermal Gradient Decay

Continuous heat extraction causes progressive cooling of the near-wellbore region. This effect is modeled as (Al Saedi et al., 2019):

$$\boldsymbol{G}(\boldsymbol{z},\boldsymbol{t}) = \boldsymbol{G_0} \cdot [\mathbf{1} - \boldsymbol{a} \cdot (\mathbf{1} - \boldsymbol{e}^{(-t/\tau)})] \qquad (2.2)$$

where G_0 = 0.045 °C/m is the initial geothermal gradient, a = 0.085 is the thermal decay coefficient, and τ is the thermal relaxation time constant. This formulation captures the long-term decline in heat recovery potential due to thermal depletion.

2.3.3. Fracture Thermal Contact Resistance

Natural fractures introduce additional thermal resistance, quantified as (Garcia & Santamarina, 2021):

$$\boldsymbol{R_c} = \boldsymbol{R_c}\mathbf{0} \cdot (\mathbf{1} + \boldsymbol{\gamma} \cdot (\mathbf{1} - \boldsymbol{S_w})) \qquad (2.3)$$

where $R_c0 = 0.25m \cdot K/W$ is the baseline resistance, $\gamma = 2.2$ is the saturation sensitivity coefficient, and Sw is water saturation in the fracture. Water-filled fractures reduce thermal resistance significantly compared to dry fractures.

2.3.4. Fracture-Enhanced Effective Thermal Conductivity

The presence of fractures modifies the overall thermal conductivity of the rock mass (Garcia & Santamarina, 2021):

$$\boldsymbol{k_{eff}} = \boldsymbol{k_{rock}} \cdot (\mathbf{1} + \boldsymbol{\beta} \cdot \boldsymbol{FD} \cdot (\mathbf{1} - \boldsymbol{\lambda} \cdot \boldsymbol{R_c})) \qquad (2.4)$$

where β = 0.45 is the conductivity scaling factor, FD is fracture density, and λ = 0.30 is the resistance impact coefficient.

2.3.5. Total Thermal Resistance Network

The overall heat transfer from formation to fluid is limited by multiple resistances in series (Rocha & Zerpa, 2021):

$$R_{total} = R_{conv} + R_{pipe} + R_{casing} + R_{cement} + R_{formation} + R_c \quad (2.6)$$

$$R_{cement} = (r_{out}/r_{in})/(2\pi \cdot k_{cem}) \quad (2.7)$$

2.3.6. Heat Transfer Rate per Segment

The heat transfer rate from the rock formation to the working fluid in each discretized segment is (Rocha & Zerpa, 2021; Al Saedi et al., 2019):

$$\Delta Q = (T_{form} - T_{fluid}) \cdot \Delta z/R_{total} \quad (2.8)$$

The fluid temperature is then updated by the energy balance (Incropera et al., 2017; Alimonti & Soldo, 2016):

$$T_{\mathrm{fluid},\,i+1} = T_{\mathrm{fluid},\,i} + \frac{\Delta Q}{m\, c_{p,\mathrm{CO_2}}} \quad (2.9)$$

2.4. Computational Workflow and Sensitivity Analysis Strategy

The primary objective of the numerical simulation is to isolate and quantify the impact of natural fracture properties on the thermal performance of the CLG system using supercritical CO_2. To achieve this, the numerical simulation was implemented in Python (version 3.9), selected for its robust ecosystem of scientific libraries and flexibility in implementing custom physical models. The solver, named ***AdvancedCLG_Simulator***, utilizes a Finite Difference Method (FDM) to discretize the wellbore domain into 300 vertical nodes, ensuring sufficient spatial resolution across thin geological layers.

The computational framework relies on core libraries to execute the workflow: NumPy (Harris et al., 2020) was fundamental for handling vectorized array operations and solving the linear algebra required for the thermal resistance network. For structured data management, Pandas (McKinney, 2010) facilitated the organization of stratigraphic inputs and the export of simulation results. Visualization of thermal performance was achieved using Matplotlib (Hunter, 2007), while SciPy (Virtanen et al., 2020) was utilized for its statistical functions to analyze trends in temperature decline over the operational period.

The solver is built using an Object Oriented Programming (OOP) approach to ensure modularity. The code utilizes Python dataclasses to define structured inputs, where the **Layer** class encapsulates stratigraphic properties and the **CLG_Inputs** class manages operational variables. A critical feature implemented is the **fracture_overrides_by_layer** dictionary, which allows for the dynamic modification of fracture properties in specific stratigraphic units, such as the Visean Hot Shale, without altering the base geological model. The physics engine is encapsulated within the **effective_k_Rc** function, which dynamically calculates effective thermal conductivity (*keff*) and thermal contact resistance (*Rc*) based on fracture density and water saturation, as defined in Equations **2.3** and **2.5**. The simulation loop iterates spatially from the well bottom to the surface, identifying the geological layer at each node, applying user defined overrides, and solving the energy balance to update the fluid temperature profile, ultimately aggregating the heat balance to determine total thermal power.

2.4.1. Baseline Configuration

A base case scenario was first established using average values derived from the KB-1 well data (Table 2) (Sonatrach JV Gas, 2005). All geological layer properties, wellbore geometry, and operational parameters were fixed according to realistic field conditions in the Krechba Field. This base case serves as the reference scenario for comparing the effects of fracture variations.

2.4.2. Methodology of Variation

To specifically investigate the influence of fractures, the following controlled variation strategy was implemented

To accurately simulate the subsurface conditions, the input parameters were divided into fixed and variable sets. Wellbore geometry, surface boundary conditions, and basic operational constraints were kept constant. This allowed us to clearly isolate the physical effects of the reservoir. In contrast, the rock thermal properties particularly the effective thermal conductivity were modeled as dynamic variables. These properties varied spatially according to the lithology and fracture density of each geological layer, and they also changed over time as a result of progressive thermal depletion.

A single well **(KB-1**) was selected for this study for two primary reasons., modeling one well provides a controlled setting to rigorously evaluate the influence of natural fractures on heat transfer, without the added complexity of inter well interference, Well **KB-1** penetrates all the major geological formations in the Krechba Field, extending from the Upper Cretaceous down to the Tournaisian (C10) reservoir. This makes it an ideal representative stratigraphic column for studying vertical variations in thermal behavior.

All input data were sourced from authentic field records and peer-reviewed literature related to the In Salah CO_2 storage project. Geological layering and depth intervals (0 to 3431 m) were obtained directly from the **KB-1** well logs Sonatrach JV Gas, (2005). Rock properties such as thermal conductivity, density, and specific heat capacity were adopted from Bjørnarå et al. (2018) and Morris et al. (2011). Because FMI image logs were not available, fracture density values (ranging from 0.5 to 6.0 fractures/m) were estimated based on lithological descriptions, with higher densities assigned to brittle intervals such as the Visean Hot Shale. These estimates align well with the stratigraphic variability reported in the KB-1 logs Sonatrach JV Gas, (2005) and fractured zones identified by Zhang et al. (2016). Thermal contact resistance was calculated using correlations from Garcia and Santamarina (2021).

Operational parameters were chosen to reflect realistic field conditions. A geothermal gradient of 35–40°C/km was adopted, consistent with measured bottom hole temperatures of approximately 90–100°C at around 1800 m depth in the In Salah field. A mass flow rate of 5.0 kg/s was selected as a practical baseline for a single U-tube or coaxial configuration, while the injection temperature was set at 35°C to ensure the CO_2 remains in a supercritical state throughout the loop. Finally, two fracture scenarios were considered: Open fractures representing the ideal case, and Gouge filled fractures representing the more realistic situation where induced fractures contain debris, resulting in significantly higher thermal contact resistance.

- **Fracture Density (FD): 0.5 to 6.0 fractures/m**
  his range encompasses the stratigraphic variability reported in the KB-1 well logs (Sonatrach JV Gas, 2005). The base case values range from 0.5 m^{-1} (in the Upper Cretaceous) to 4.5 m^{-1} (in the Visean Hot Shale). The upper limit of 6.0 m^{-1} represents highly fractured zones or fracture corridors, as identified by Zhang et al. (2016) in their analysis of the KB-502 area.
- **Water Saturation (Sw):** The range of water saturation (Sw) from 0.0 to 0.8 was carefully selected to encompass the expected variability in fracture conditions across the different stratigraphic units in the Krechba Field. This parameter directly affects the thermal contact resistance (Rc) and, consequently, the overall heat transfer efficiency (Garcia & Santamarina,

2021). The lower bound (Sw = 0.0) represents dry fractures, which are typical in the depleted gas-producing horizons where the fracture voids are primarily filled with gas. Gas has relatively low thermal conductivity, leading to higher thermal resistance and thus the minimum heat transfer efficiency in the system. In contrast, the upper bound (Sw = 0.8) corresponds to highly water saturated fractures, characteristic of the saline aquifer intervals intersected by Well KB-1 (Iding & Ringrose, 2010; Ringrose et al., 2013). Since water exhibits significantly higher thermal conductivity than gas, this scenario provides the maximum heat transfer efficiency.

- **Layer-Specific Parameterization:** Given the geological heterogeneity of the Krechba field, where properties vary significantly with depth (Bjørnarå et al., 2018), applying uniform changes to the entire wellbore is unrealistic. To address this, the model incorporates a fracture_overrides_by_layer function. Technically implemented as a dictionary, this function maps specific stratigraphic names (Visean Hot Shale) to custom parameter values such as fracture density (FD) and water saturation (Sw). During the simulation loop, the solver identifies the geological layer at each node; if an override is defined for that layer, the default global values are dynamically replaced. This mechanism is essential for isolating the contribution of specific high-fracture zones like the Visean Hot Shale (Zhang et al., 2016) to the total thermal performance (Q th and T prod), ensuring that the sensitivity analysis reflects realistic geological scenarios rather than generalized averages.

2.4.3. Numerical Implementation

The simulation was implemented in Python using a custom-developed solver named AdvancedCLG_Simulator. The wellbore was discretized into 300 vertical nodes (Nz = 300) to ensure sufficient spatial resolution, particularly across thin geological layers. The transient numerical simulations were conducted over a **30 year** period to thoroughly assess the long-term thermal performance and sustainability of the closed-loop geothermal system. This extended timeframe was deliberately chosen for two main reasons. First, unlike conventional open-loop geothermal systems that often experience rapid thermal breakthrough within just a few years, closed-loop systems exhibit much slower thermal depletion because they rely primarily on conductive heat transfer from the surrounding rock. 30-year simulation window is therefore essential to properly capture the gradual, time-dependent decay of the geothermal gradient **(Eq. 2.2)** and to verify that the production temperature remains sufficiently stable and economically viable over the project's operational lifetime. Second, this duration is consistent with established practices in the literature on deep borehole heat exchangers. For instance, Alimonti and Soldo (2016) used multi-decade simulations to evaluate the long-term evolution of heat transfer in similar closed-loop configurations. By adopting a comparable simulation period, the results of the present study can be meaningfully compared and benchmarked against previous research in the field (Alimonti and Soldo, 2016).

Chapter III: Results and Discussion

The simulation was conducted for well KB-1 over a 30-year period. The selection of KB-1 was primarily driven by the availability of a complete stratigraphic log covering all target formations from the Upper Cretaceous to the Tournaisian (C10) reservoir making it a representative column for the field (Sonatrach JV Gas, 2005). While data from surrounding wells (e.g., KB-2) was available, the decision to model a single well was motivated by the need to isolate the physics of heat transfer. A single-well model avoids the uncertainty of inter-well connectivity and lateral boundary conditions, allowing for a rigorous sensitivity analysis on fracture properties (Bjørnarå et al., 2018).

3.1. Sensitivity Analysis of Fracture Properties

The primary objective of this study is to understand how fracture characteristics influence heat extraction. The sensitivity analysis module was used to vary Fracture Density (FD) and Water Saturation (Sw) independently.

3.1.1. Effect of Fracture Density (FD)

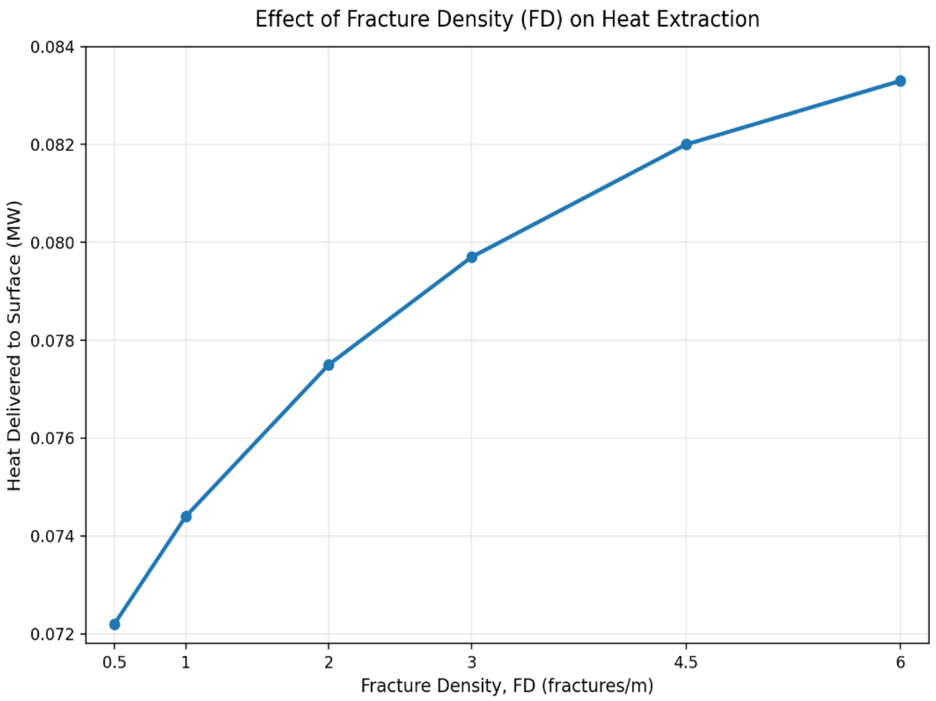

Figure 10: Effect of Fracture Density (FD) on heat extraction (thermal power delivered to surface).

Figure 9 illustrates the relationship between fracture density and the heat delivered to the surface. The graph exhibits a clear positive correlation: as fracture density increases from 0.5 to 6.0 fractures/m, the thermal output rises. This behavior is consistent with the effective thermal conductivity model (k_{eff}) presented in Equation 2.4. Higher fracture density increases the effective heat transfer surface area between the rock matrix and the wellbore, reducing the overall thermal resistance (Garcia & Santamarina, 2021). The curve shows a non-linear trend where the rate of increase slows at higher FD values, indicating that the thermal bottleneck shifts from formation conductivity to convective heat transfer of the fluid inside the pipe (Incropera et al., 2017).

3.1.2. Effect of Water Saturation (Sw)

Figure 10 demonstrates the critical role of moisture saturation within the fractures. The results show a significant improvement in heat extraction as Sw increases. This validates the Thermal Contact Resistance (R_c) model (Equation 2.3). Water has a much higher thermal conductivity (~0.6 W/m·K) compared to gas (~0.02–0.05 W/m·K). As Sw increases, fractures become thermally conductive bridges, lowering R_c and facilitating efficient heat flow from the deep formation to the wellbore (Garcia and Santamarina, 2021).

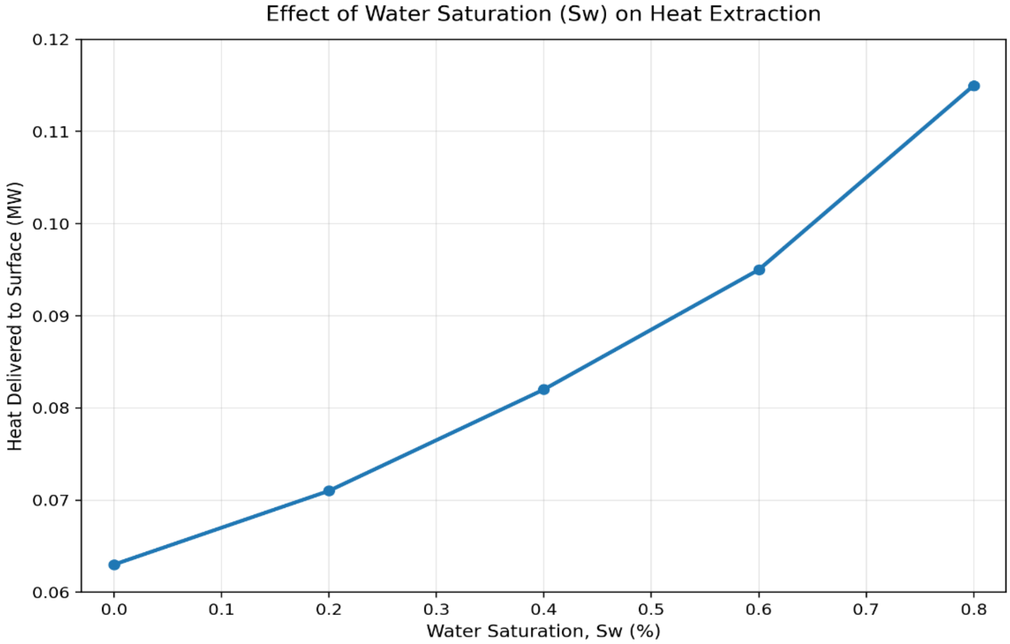

Figure 11: Effect of Water Saturation (Sw) on heat extraction.

3.2. Effect of Fracture Filling Type

In naturally fractured reservoirs, fractures are often filled with minerals or gouge. The model simulates five distinct filling scenarios using a Filling Factor (ff), ranging from 1.0 (fully open, CO_2-filled) to 0.05 (fully mineralized).

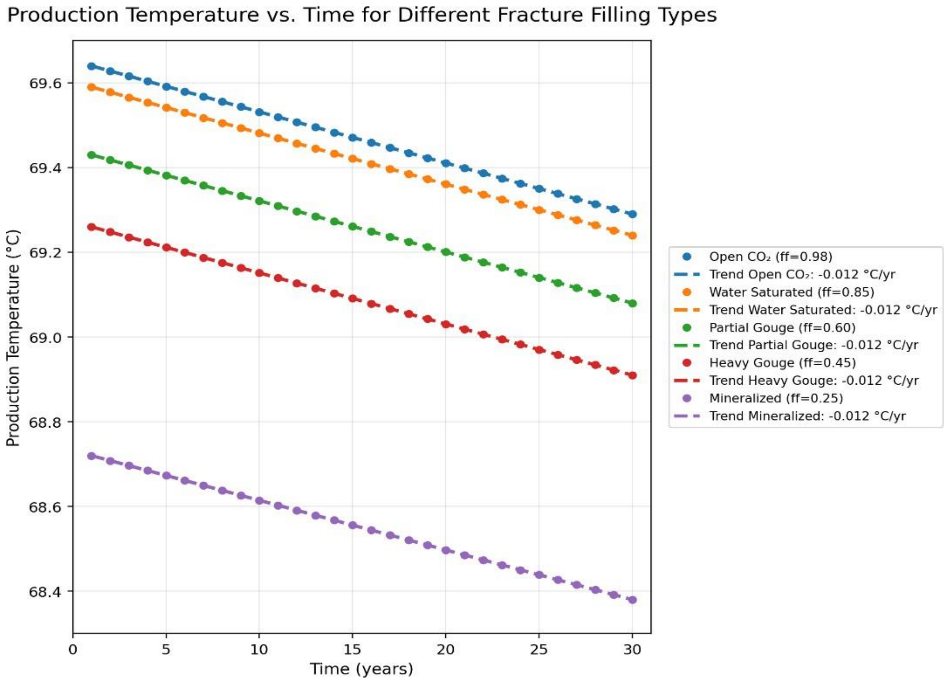

Figure 12:Production Temperature vs. Time for Different Fracture Filling Types.

Figure 11 compares the production temperature over 30 years for different filling types. The highest production temperatures are observed in Open CO_2 and Water Saturated scenarios, Intermediate performance is noted in the Partial Gouge and Heavy Gouge scenarios, where the presence of crushed rock or fines introduces additional thermal resistance. In contrast, the Mineralized scenario exhibits the lowest production temperature. While the thermal conductivity of mineral fillings depends on the specific mineralogy (e.g., quartz is highly conductive, whereas clay or carbonate mud is insulating), this scenario assumes low-conductivity mineral precipitates (such as clay gouge or fine carbonate cement), which act as a thermal barrier that severely impedes heat conduction (White et al., 2014). Although all scenarios show a gradual decline in temperature over time due to near-wellbore thermal depletion, the relative difference remains consistent, highlighting that fracture quality acts as a permanent constraint on system efficiency.

3.3. Operational Performance and Mass Flow Optimization

Increasing the mass flow rate directly increases the total heat extracted. The 9.0 kg/s scenario yields the highest power output. The curves show remarkable stability over the 30-year period, with only a slight decline due to gradient depletion. This suggests that the Closed-Loop system is resilient to rapid thermal breakthrough, unlike open-loop systems which often suffer from sharp temperature drops (Rocha & Zerpa, 2021; Alimonti & Soldo, 2016).

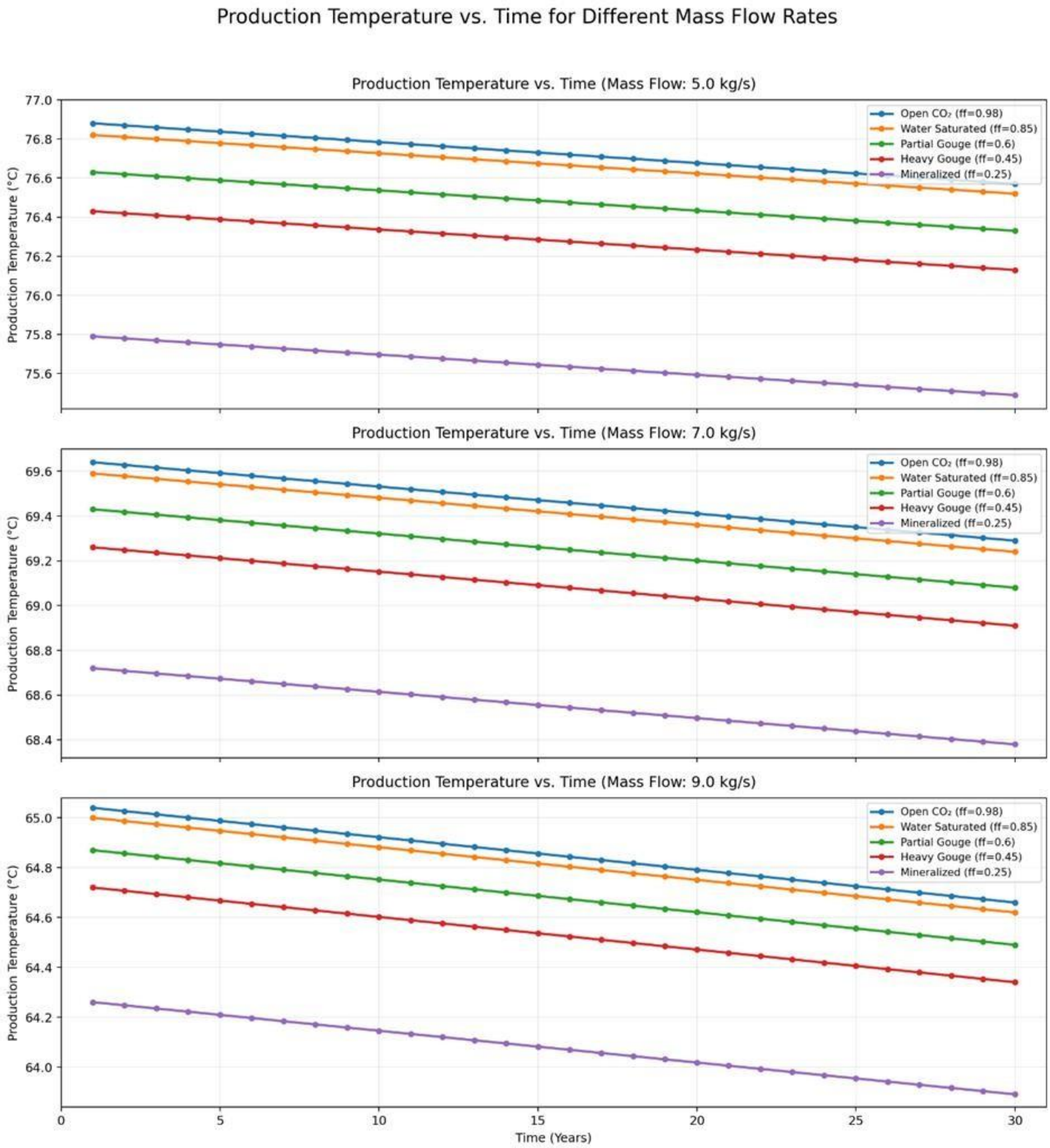

Figure 13:Production Temperature vs. Time for Different Mass Flow Rates.

3.4. Impact of Stratigraphic Layer Properties on Heat Extraction

To understand the geological controls on heat extraction, a comparative analysis was conducted using a layer-specific modification approach. Four distinct scenarios were simulated over a 30-year operational period: Base Case, Visean Hot Shale Improved, Visean Hot Shale Degraded, and the All Layers Enhanced.

3.4.1. Temporal Evolution of Thermal Performance

Figure 13 shows that all scenarios remain relatively stable throughout the 30-year simulation period. The performance ranking is clearly visible: All Layers Enhanced scenario provides the highest thermal output, followed by Visean Hot Shale Improved, then the Base Case, while Visean Hot Shale Degraded gives the lowest performance. The large difference between the All Layers Improved scenario and the others highlights the cumulative effect of improving fracture properties across the entire wellbore.

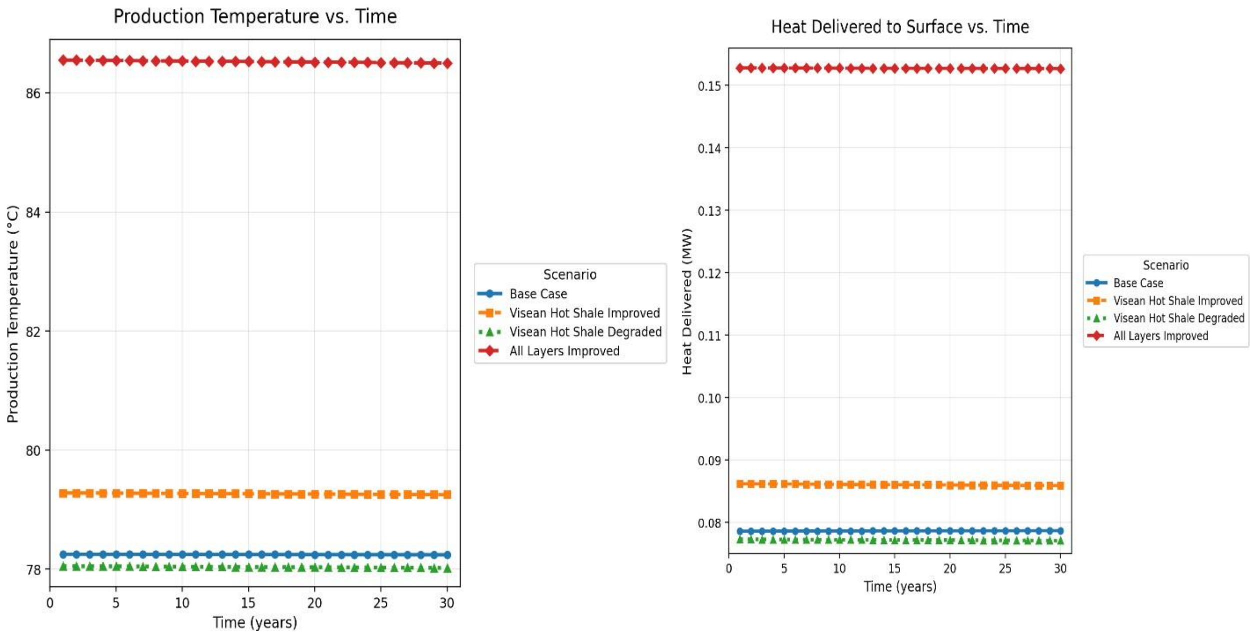

Figure 14: Comparison of Fracture Override Scenarios Over Time: production temperature (left) and heat delivered (right).

3.4.2. Quantitative Assessment of Layer Contribution

Table 5: Summary of Simulation Results at t = 30 Years.

Scenario	Production Temp (°C)	Heat Delivered (MW)	Relative Change (%)
Base Case	78.23	0.0786	—
Visean Hot Shale Improved	79.23	0.0859	+9.3%
Visean Hot Shale Degraded	78.03	0.0771	−1.9%
All Layers Improved	86.53	0.1527	+94.3%

The data suggests a non-linear relationship between fracture quality and heat extraction. Enhancing fracture properties specifically in the deep, high temperature Visean Hot Shale resulted in a +9.3% increase in thermal output, validating the hypothesis that deeper layers contribute more significantly to the overall energy balance (Al Saedi et al., 2019). The Visean Hot Shale Degraded scenario shows only a marginal decline (−1.9%), indicating inherent geological redundancy. The All Layers Enhanced scenario nearly doubles the heat output (+94.3%), underscoring the critical role of effective thermal conductivity (k_{eff}) across the entire well column.

General Conclusion

The comprehensive numerical investigation conducted in this study confirms the technical viability of repurposing the abandoned KB-1 well in the Krechba Field for Closed-Loop Geothermal (CLG) energy extraction using supercritical CO_2. The simulation results, spanning a 30-year operational lifecycle, demonstrate that the proposed system offers a stable and sustainable energy output, characterized by a gradual thermal drawdown rather than catastrophic depletion.

A critical finding pertains to the role of natural fractures in conductive heat transfer. The sensitivity analysis revealed a positive non-linear correlation between fracture density and heat extraction (Garcia & Santamarina, 2021). The analysis also highlighted the paramount importance of water saturation within fractures: water creates thermal bridges that significantly lower contact resistance, thereby enhancing heat flow. The comparative analysis of stratigraphic layers further underscored the system's inherent geological redundancy; while the Visean Hot Shale is a primary heat contributor, the system maintains robust performance even if this interval is degraded (Fowler & McClure, 2021).

Operational and Strategic Recommendations:

- Prioritize geological intervals with high water saturation ($S_w > 0.6$), using pre-drilling surveys to identify aquifer-bearing fractured zones.
- Optimize mass flow rates toward 9.0 kg/s, as the thermal reservoir possesses sufficient inertia to sustain higher extraction rates without severe long-term depletion.
- Utilize seismic curvature attributes to identify and avoid heavily mineralized fracture corridors, which act as thermal insulators.

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