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Presented By:

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-TOPIC-

Carbon Capture and Storage in Algeria

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Dedication

To my dearest parents Nadia and Salim

To my sisters Yamina, Nada, Kenza, Khouloud and Assala, my brother Mohammed and my sunshine Razane

To my friends, everybody I appreciate and finally to myself

I dedicate this work.

Abstract

The In Salah Carbon Capture and Storage project in central Algeria is a world pioneering onshore carbon dioxide capture and storage project which has built up a wealth of experience highly relevant to carbon dioxide storage projects worldwide. This research focuses on the capture, transportation, and secure underground storage of carbon dioxide emissions. Through analyzing the project's design, risk assessment, monitoring techniques, and practical outcomes (including surface deformation and potential leakage), this study highlights the importance of further research to ensure the safe and effective implementation of carbon dioxide storage technology. The In Salah project provides an important case study for knowledge transfer to other major carbon dioxide storage projects in the planning and execution phases.

Key words: CO2 Storage, CCS, In Salah, Surface deformation, Monitoring, Risk assessment.

ملخص

يعد مشروع التقاط وتخزين غاز ثاني اكسيد الكربون في عين صالح في وسط تقدم تكنولوجيا احتجاز الكربون وتخزينه الجزائر مشروعًا رائدًا عالميًا لالتقاط وتخزين ثاني أكسيد الكربون على اليابسة. يركز هذا البحث على التقاط انبعاثات ثاني أكسيد الكربون ونقلها وتخزينها الآمن تحت الأرض ومن خلال تحليل تصميم المشروع وتقييم المخاطر وتقنيات المراقبة والنتائج العملية (بما في ذلك التشوه السطحي والتسرب المحتمل)، تسلط هذه الدراسة الضوء على أهمية إجراء المزيد من البحوث لضمان التنفيذ الآمن والفعال لتكنولوجيا احتجاز ثاني أكسيد الكربون وتخزينه ويوفر مشروع عين صالح دراسة حالة مهمة لنقل المعرفة إلى مشاريع احتجاز ثاني أكسيد الكربون وتخزينه الرئيسية الأخرى في مرحلتي التخطيط والتنفيذ.

الكلمات المفتاحية: تخزين ثاني أكسيد الكربون، احتجاز ثاني أكسيد الكربون وتخزينه، عين صلاح، تشوه السطح، المراقبة، تقييم المخاطر.

Résumé

Le projet de capture et de stockage du dioxyde de carbon d'In Salah se pose en véritable précurseur mondial du stockage terrestre de dioxyde de carbon. Ce projet a acquis une expérience inestimable, directement applicable aux initiatives de stockage de dioxyde de carbon à travers le globe. Cette étude se penche sur la capture, le transport et le stockage souterrain sécurisé des émissions de dioxyde de carbon. En analysant la conception du projet, l'évaluation des risques, les techniques de surveillance et les observations concrètes (déformations de surface, fuites potentielles), nous soulignons l'importance de la recherche future pour garantir une mise en œuvre sûre et efficace de la technologie de stockage de dioxyde de carbon. Le projet In Salah constitue une étude de cas précieuse, permettant le transfert de connaissances vers d'autres projets de grande envergure, dès les phases de planification et d'exécution.

Mots clés : Stockage du CO2, CCS, In Salah, Déformation de la surface, Surveillance, Évaluation des risques.

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CO2	Carbon Dioxide
GHG	Greenhouse Gases
CCS	Carbon Capture and Storage
ISG	In Salah Gas
IGCC-CCS	Integrated Gasification Combined Cycle with CCS
CCGT	Combined Cycle Gas Turbine
RFG	Recycled Flue Gas
ASU	Air Separation Unit
LPG	Liquefied Petroleum Gases
EOR	Enhanced Oil Recovery
ECBM	Enhanced Coalbed Methane Recovery
Kb	Krechba
Teg	Teguentour
Reg	Reguane
ICS	Integrated Control System
ESD	Emergency Shutdown System
MWD	Mesuring While Drilling
LWD	Logging While Drilling
DWAM	Drinking Water Aquifer Monitoring
JIP	Joint Industry Project
JV	Joint Venture
CDM	Clean Development Mechanism
InSAR	Interferometric Synthetic Aperture Radar
NW	Northen West
LBNL	Lawrence Berkeley National Laboratory
QRA	Quantified Risk Assessment
CPF	Central Process Facility
MMscf/d	Million standard cubic feet per day
Ppm	Particule per million

General Introduction

The Earth's climate is changing and the global climate is projected to continue to change over this century and beyond. The magnitude of climate change beyond the next few decades will depend primarily on the amount of greenhouse (heat-trapping) gases emitted globally and on the remaining uncertainty in the sensitivity of the Earth's climate to those emissions. With significant reductions in the emissions of greenhouse gases (GHGs), global annual averaged temperature rise could be limited to 2°C or less. However, without major reductions in these emissions, the increase in annual average global temperatures, relative to preindustrial times, could reach 5°C or more by the end of this century.

According to the Washington Post, earth's carbon dioxide levels hit record high; there probably is more carbon dioxide in the air now than at any time in 3 million years and it is still increasing. In order to prevent the worst effects of global warming it is essential to work on reducing the CO_2 emissions immediately and start investing in CO_2 reduction projects worldwide.

The 2020 Energy Transition Outlook estimates that oil and gas will account for 74% of world energy-related carbon dioxide (CO_2) emissions in mid-century. This is why it is imperative that the oil and gas industry reduces its emissions especially because the future of the industry depends on its ability to control these emissions.

The Carbon Capture and Storage is a versatile technology that can support the oil and gas industry's low-carbon transition. The oil and gas industry is one of the earliest adopters of the Carbon Capture and Storage (CCS) technology, this technology is an important geoengineering solution to control the CO_2 emissions. It consists on capturing the carbon dioxide (before it gets into the atmosphere); transporting it; and then storing it deep underground in geological formations. CCS is a way to stop global warming by minimizing the CO_2 emissions.[1]

This dissertation examines the technical aspects of CCS technology, drawing insights from a pioneering large-scale CCS project – the In Salah project in Algeria. Launched in 2004, this project aimed to capture CO2 emissions from a natural gas processing facility and store them underground in a saline aquifer. While initially hailed for its potential contribution to emissions reduction, the project faced several challenges, including an unexpected leakage incident as well as the surface deformation. This incident highlighted the difficulties involved in large-scale CCS operations and the need for a deeper understanding of the technical considerations and potential risks. The In Salah CCS project offers a number of learning lessons to the future CO2 storage projects and operations.

The methodology followed in this dissertation, is first giving an overview on the Carbon Capture and Storage technique, then presenting the In Salah Field as one of the largest gas producers in Algeria and lastly, it offers a review on technical details of the In Salah project, analysing the project's design, operational strategies, and the challenges encountered during CO2 injection, as well as the lessons learnt. By examining these aspects, we aim to:

- Offer an overview on Carbon Capture and Storage technique.
- Analyse the operational strategies employed at In Salah.
- Investigate the technical challenges encountered during the project's execution.
- Extract valuable insights into the technical considerations and potential risks associated with CCS projects (lessons learned).

The data used for this study were collected from different previous studies and In Salah Gas documents and presentations. Through a critical examination of the In Salah project, this dissertation aims to contribute to the broader development of safer, more reliable, and more efficient CCS technologies. This knowledge can play a pivotal role in mitigating climate change and paving the way for a more sustainable future.

Chapter I

Carbon Capture and Storage Literature review

I.1 Introduction

Climate change stands as one of the most pressing issues facing humanity today. The primary culprit in this crisis is the accumulation of greenhouse gases, particularly carbon dioxide (CO2), in the Earth's atmosphere. These gases trap heat, causing a gradual rise in global temperatures, disrupting weather patterns, and leading to a cascade of environmental consequences. The urgency of decarbonization – the significant reduction of greenhouse gas emissions – is now at a critical juncture.

This chapter delves into a comprehensive literature review on Carbon Capture and Storage (CCS) technology, a potential solution for mitigating the rise of atmospheric CO2 and achieving global decarbonization goals. The review offers a detailed overview of the CCS technology and its multifaceted supply chain. This supply chain encompasses various stages:

- **Capture Methods:** Exploring the different technological approaches to capturing CO2 emissions from various sources, such as power plants and industrial facilities.
- **Transportation Processes:** Examining the methods for transporting captured CO2 to storage sites, considering pipelines, ships, and other potential methods.
- **Geological Storage:** Evaluating the geological formations suitable for safe and long-term CO2 storage, along with the processes involved in injecting and securing the CO2 underground.

By analyzing a diverse range of research papers, reports, and books, this chapter synthesizes the current state of knowledge surrounding CCS technology. This comprehensive review aims to provide a clear understanding of the potential and challenges associated with CCS as a crucial tool in the fight against climate change.

I.2 CCS chain:

CCS technology is based on the implementation of a succession of processes that capture CO2 from industrial plant emissions, compress it and transport it to injection points and transport it to injection points, then introduce it in supercritical form for storage in a natural underground reservoir via injector wells, where, theoretically, it is supposed to remain trapped there for hundreds or even thousands of years.

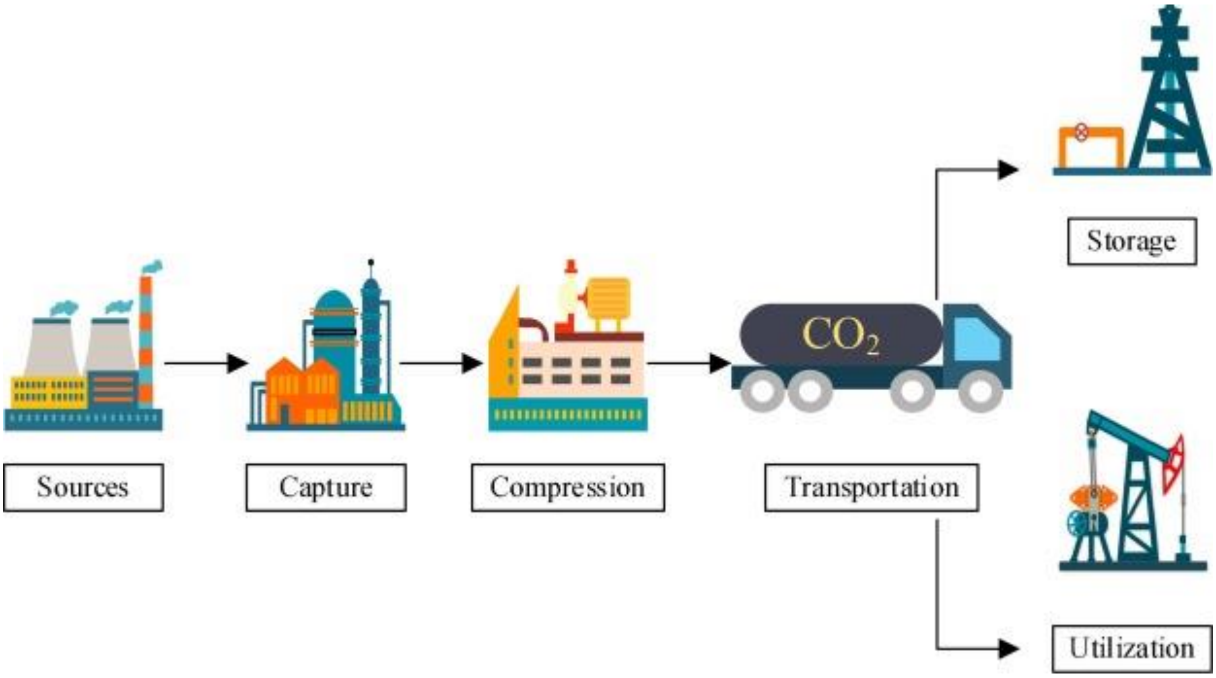


Figure I.1: CCS supply chain scheme.[2]

I.2.1 CO2 Capture:

Carbon Capture and Storage (CCS) encompasses a diverse range of technologies with varying degrees of development. Broadly, these technologies can be categorized into three main groups:

- Pre-combustion CO2 Capture: This approach removes CO2 before the fuel combustion process.
- Post-combustion CO2 Capture: This method captures CO2 after the fuel is burned, typically from the flue gas stream.
- Oxy-combustion CO2 Capture: This technology utilizes pure oxygen instead of air for combustion, resulting in a concentrated CO2 stream.

Regardless of the chosen capture method, all CCS technologies generate a high-purity CO2 stream. Following dehydration and potentially additional purification steps for oxy-combustion capture, the CO2 is directed to a multi-stage compression system with interstage cooling for transportation. The specifics of compression systems are not addressed further here.

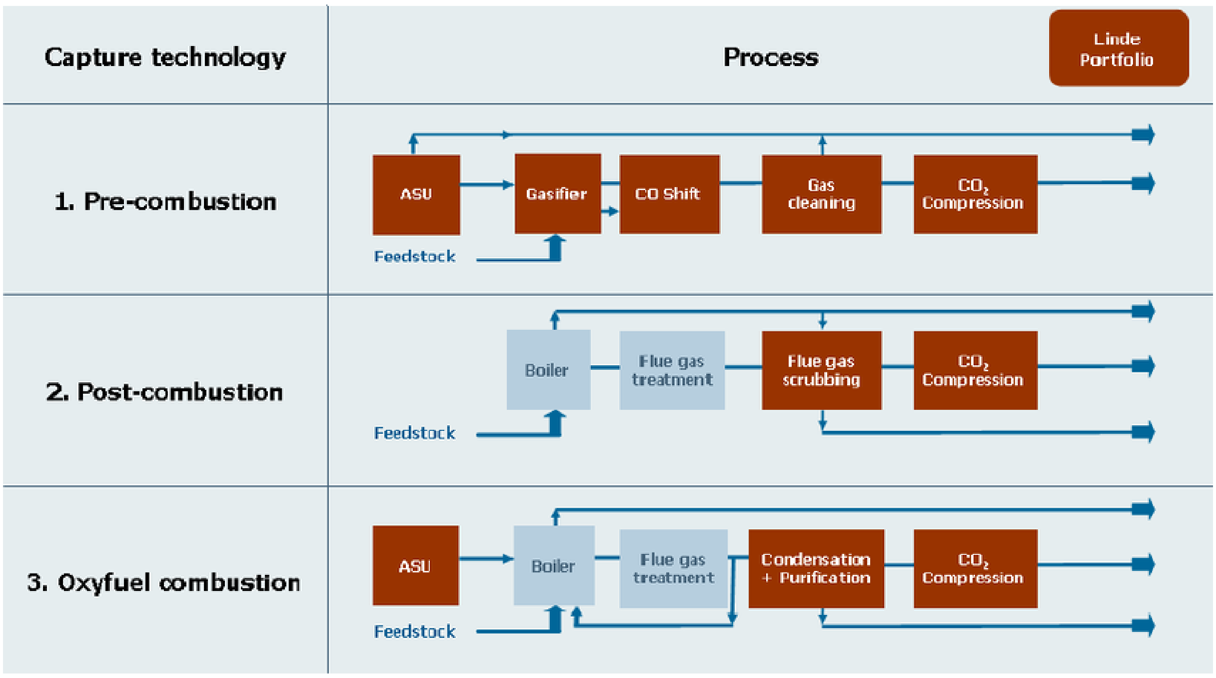


Figure I.2: Carbon capture processes considered in the energy sector.[3]

a. Pre-Combustion CO2 Capture:

While offering flexibility in fuel choice, IGCC-CCS presents limitations. The high capital cost of the gasification unit, due to its complexity, necessitates continuous operation at full load for syngas production. Additionally, the intricate design of an IGCC-CCS system makes it less suitable for flexible operations in power generation contexts. However, potential solutions exist, such as storing hydrogen, syngas mixtures, or even producing liquid fuels from syngas, enabling operation during periods of low electricity demand. This would allow the gasification process to function in a baseload manner, meaning it would operate continuously, while the Combined Cycle Gas Turbine (CCGT) could ramp up or down based on electricity demand, similar to a traditional natural gas-fired CCGT plant.

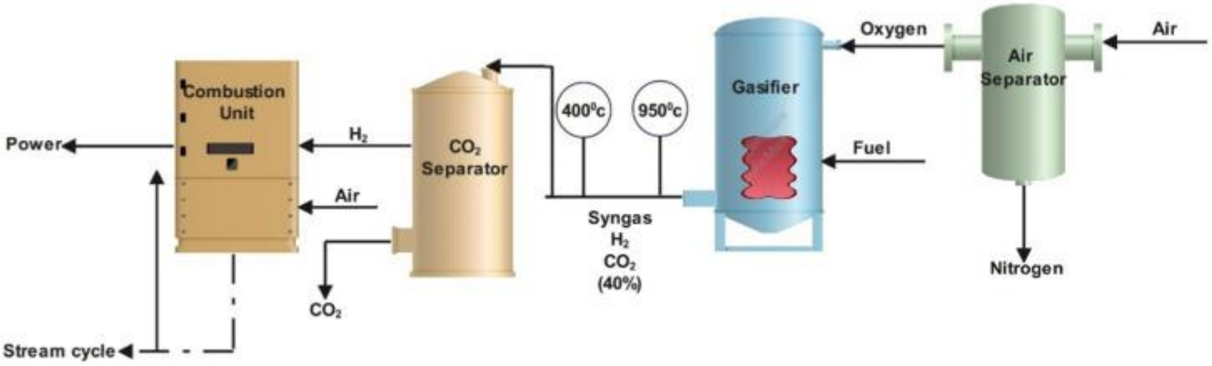


Figure I.3: Pre-combustion Technique.[4]

b. Post-Combustion CO2 Capture:

This technology offers a significant benefit: it's an "end-of-pipe" solution, similar to existing methods for controlling sulfur dioxide (SO2) emissions. Furthermore, integrating post-combustion capture into power plants, either during new construction or as a retrofit, has minimal impact on the required operational flexibility of these facilities.[5]

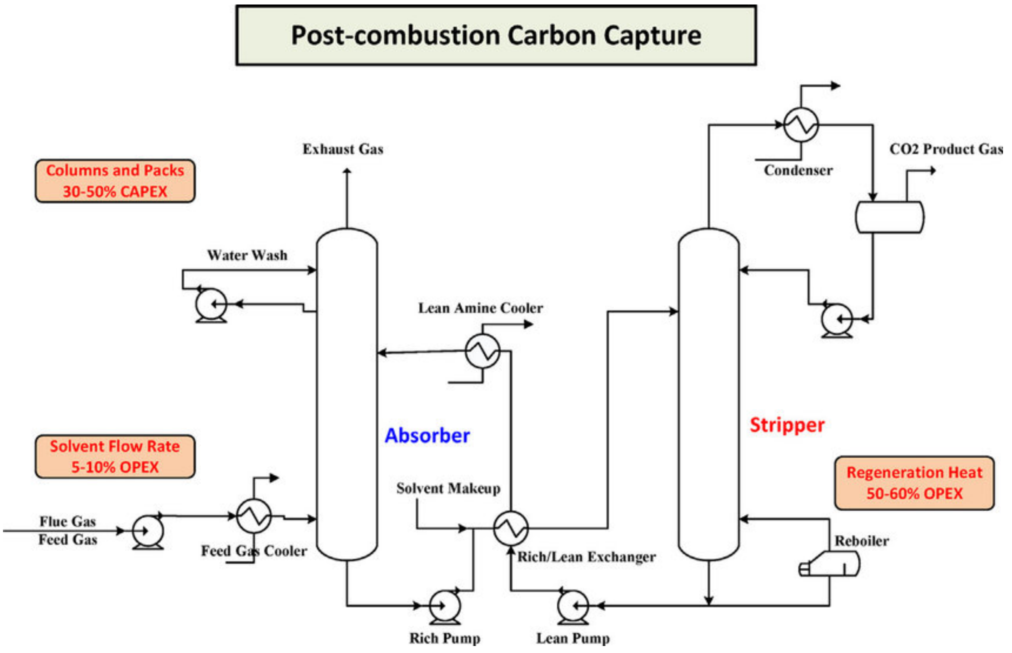


Figure I.4: Simplified diagram of a post-combustion capture process using reactive solvents.[5]

c. Oxy-Combustion CO2 Capture:

Implementing oxy-combustion capture necessitates significant plant modifications compared to air-fired plants. Additional units like a recycle loop, ASU, and a CO2 purification and compression unit become necessary. A preferred recycle ratio of 0.7 is employed to maintain flame and heat transfer characteristics similar to air-fired pulverized fuel (PF) boilers. Oxy-fuel combustion also requires stricter control over oxygen levels. While typical oxygen excess is around 15-20% for air-fired conditions, oxy-fuel operations maintain a lower excess (no more than 10%) to minimize ASU operational costs. Flue gas exiting the combustion process typically contains around 3% oxygen. Before being recycled, the flue gas stream undergoes cooling, scrubbing, and drying to remove particulates. Particle removal is critical to prevent buildup in the boiler and minimize wear on the flue gas recirculation fan and gas passages due to erosion.[6]

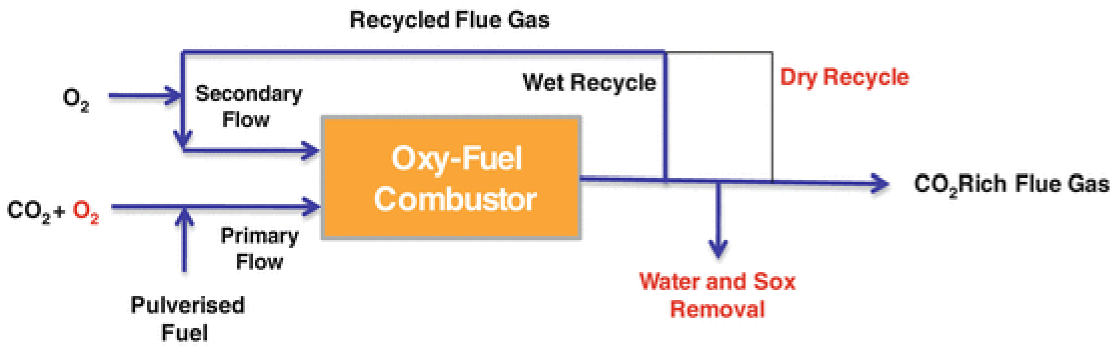


Figure I.5: Oxy-fuel Combustion for Carbon Capture and Sequestration.[6]

I.2.2 CO2 transport:

In most cases, the captured CO2 needs to be transported to the site where it will be stored, except when plants are located directly above a storage site.

Current Methods for CO2 Transportation:

CO2 transportation remains a mature technology within the pipeline market, serving as the primary method for moving captured carbon dioxide. Gaseous CO2 is typically compressed above 8 MPa to prevent two-phase flow and increase density, making transportation more efficient and cost-effective.

An alternative approach involves transporting CO2 as a liquid via ships, road tankers, or rail tankers. These vessels utilize insulated tanks to maintain CO2 at a temperature well below ambient and at significantly lower pressures compared to pipelines. The first long-distance CO2 pipeline became operational in the early 1970s.

- Pipeline Transportation.
- Ship Transport.
- Road and Rail Transport.

Advantage	Disadvantage
The transportation volume is large and the transportation cost is low.	The one-time investment of pipeline facilities is large.
Not affected by weather and traffic. No special railway facilities need to be built.	The requirements for gas source and destination are high, and they need to be close to the railway.
Not limited by source and destination. There is no need to invest in the construction of transportation facilities.	Transportation costs are high. Vulnerable to weather and traffic conditions. Fuel and labor costs are high.
Good economy. Transportation technology is mature.	The temperature and pressure control requirements of the transport equipment are high.

Figure I.6: Carbon dioxide transport methods advantages and disadvantages.[7]

I.2.3 Storage:

Storage is the last phase in the CCS chain, and is designed to last the longest. Because of its duration, storage will represent the most delicate phase to manage and will require very strict specifications.

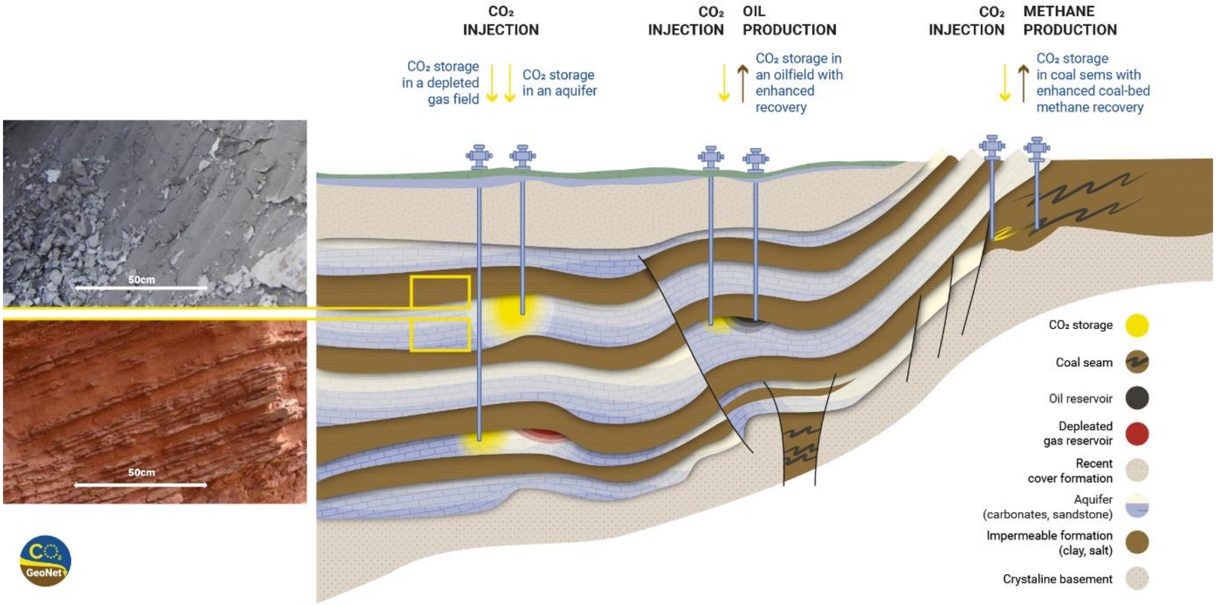


Figure I.7: Carbon dioxide storage.[8]

I.2.3.1 The mechanisms of CO2 storage in geological formations:

Trapping mechanisms; In terms of the pore space utilization, CO2 is preferably injected in a supercritical state (scCO2). This is because scCO2 is denser than gaseous CO2. scCO2 may undergo a phase change due to changes in pressure and/or temperature. Depending on the reservoir conditions, CO2 can be stored as compressed gas, as liquid, or in a supercritical phase. Most of the injected CO2 will reside in a mobile phase of CO2, free to move laterally or migrate vertically towards the caprock. Trapping of CO2 as residual gas occurs when formation water encroaches or invades the CO2 plume. It will also dissolve partially into the aqueous phase, leading to solubility trapping, and it can react with native minerals, resulting in mineral trapping. These trapping mechanisms are discussed in the following subsections.[8]

➢ **Hydrodynamic trapping:**

Buoyancy pushes CO 2 through rock formations to the surface. Because it is less dense than the fluids present in those formations, the CO 2 naturally rises until it encounters a caprock layer with low permeability, preventing it from escaping. This primary mechanism is particularly critical because it prevents immediate escape before other capture and storage opportunities emerge.[9]

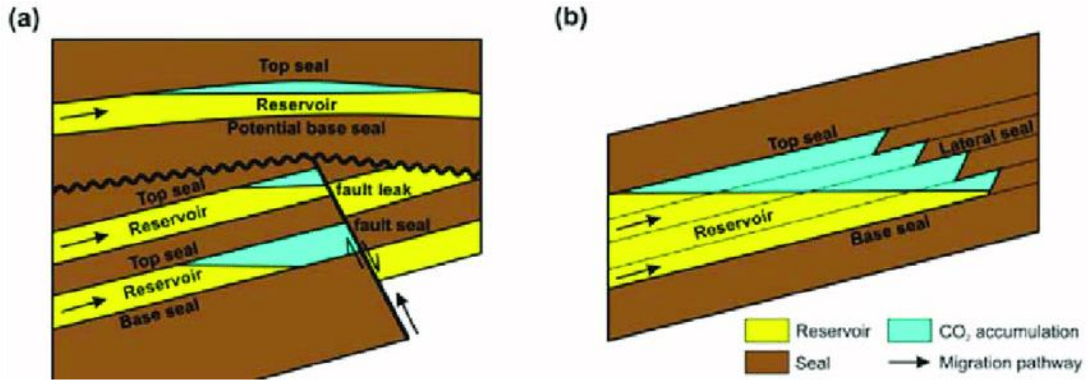


Figure I.8: Examples of (a) structural and (b) stratigraphic traps for CO2.[9]

➢ **Residual trapping:**

Brine, during the injection process, displaces a part of CO2 in a manner such that the solvent capacitances outside the pore's entry spaces leave a disconnected cluster that is entrapped in rock pores through capillary forces. Hence, this mechanism directly impacts CO2 storage reception behavior. This mechanism has been considered to be a contributory factor to the limitation of CO2 diffusion, estimated as 25% due to its large and widespread nature. Consequently, research has also revealed that residual trapping sums up to 25% or more of the total CO2 storage capacity, which depends on the factors such as the injection rate, reservoir heterogeneity and permeability ratios, and the final immobilized CO2 saturation.

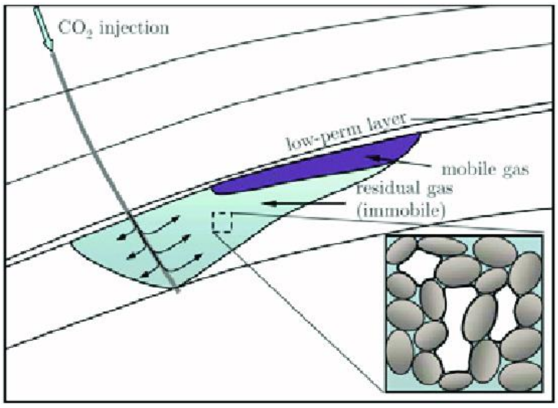


Figure I.9: Schematic of the trail of residual CO2 that is left behind because of snap-off as the plume migrates upward during the postinjection period.[10]

- **Solubility Trapping:**

CO2 addition increases density of formation fluids, which tend to flow downwards. This slowing down speeds up mixing and CO2 dissolution, which again increases storage capacity. How convection, a key to good mixing, is triggered, can also be achieved using amplification theory, global stability methods or linear stability analysis. This mechanism is supported by modelling and lab studies. Its potential to increase storage capacity has been shown. Moreover, the increased density of CO2-rich brine reduces the risk of it rising up through sealing caprocks.[10]

- **Mineral Trapping:**

Mechanism: Through chemical fixation, CO2 reacts with minerals and organic matter in the formation over geologic time to generate more stable carbonate minerals, thus immobilising CO2.Temperature, pressure, pH and the concentrations of other solutions have an impact on the reaction rate of minerals dissolving in high-pressure aqueous and non-aqueous CO2-water solutions, and as such the rate of dissolution and the fate of the CO2. Underground mineral dissolution can occur with aqueous and dry scCO2.Mineral trapping is a very slow process due to low reaction rates, but it’s the long-term, permanent storage of CO2 in geological formations that’s key.[10]

I.2.3.2 Types of geological formations suitable for CO2 storage:

Amongst CO2 storage options, geological formations offer a compelling solution due to their economic viability, safety considerations, and minimal environmental impact. Depleted oil and gas reservoirs, coal beds, and saline formations stand out for their ability to securely store CO2 over extended periods. Notably, depleted oil and gas reservoirs present an added benefit CO2 injection (EOR-CO2) can enhance oil recovery during the storage process. Additionally, other geological formations like salt caverns, basalt formations, and oil or gas-rich shales hold potential for future CO2 storage solutions.[11]

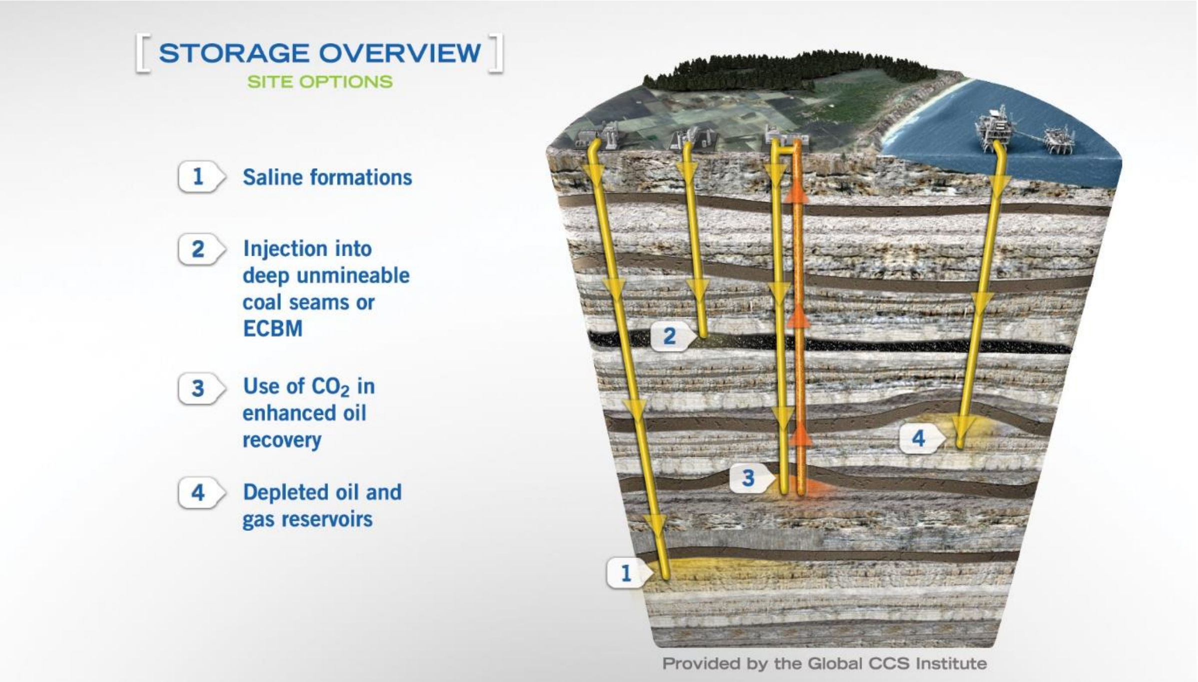


Figure I.10: Storage site options.[12]

- **Coal beds:**

Coalbeds have large internal surface area and strong affinity for gases such as methane (CH4) and carbon dioxide (CO2). Effective methods to release fully methane from tight coalbed resources have yet to be developed. Injection of CO2, so-called enhanced coalbed methane recovery (ECBM), is a means to increase the ultimate recovery as well as sequester greenhouse gases. Interestingly, most coals adsorb substantially more CO2 than CH4 at the same pressure. The mechanisms of gas adsorption, desorption, and transport through coal beds, however, are not yet elucidated to the same level of detail as mechanisms of gas injection into hydrocarbon reservoirs or saline aquifers.[13]

- **Depleted oil and gas reservoirs:**

Depleted oil and gas reservoirs Comparing to the other types of geological formations, CO2 storage in depleted hydrocarbon reservoirs is considered as the most suitable option. The main reason for this is the presence of least risk and uncertainty for possible leakage of CO2 due to a high degree of reservoir exploration, long period of production that means large number of reservoir data is collected, as well as an available production history that enables correct storage capacity estimate. The presence of infrastructure is very important, i.e. injection wells and surface facilities, since that significantly reduces storage costs. Possible CO2 migration paths to the surface at this type of storage could be many existing wells. The estimated storage capacity varies between 675 and 900 Gt CO2.[11]

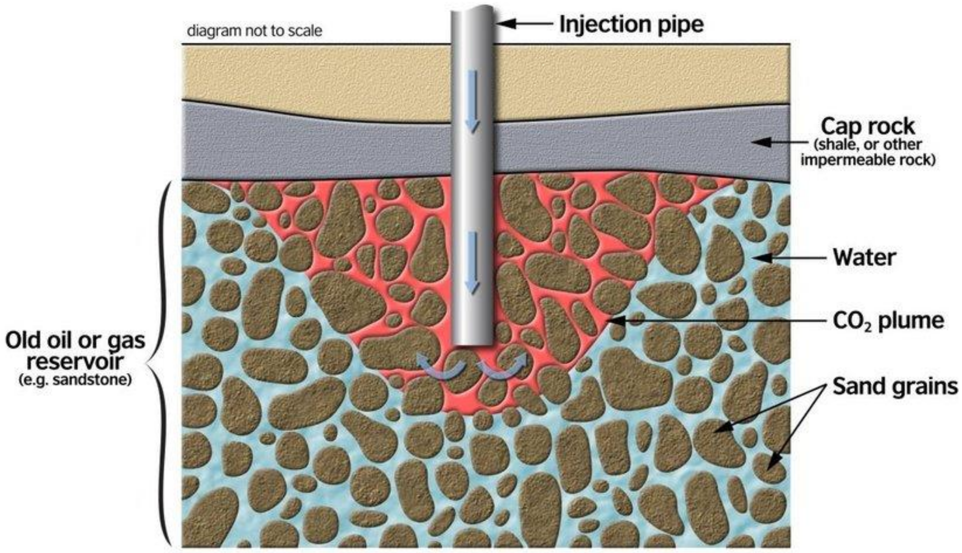


Figure I.11: Injection of carbon dioxide into depleted oil and gas reservoir.[11]

- **Saline Aquifers:**

The goal of CO2 sequestration is to store CO2 for centuries or thousands of years if not indefinitely. Our objective is to determine the time and length scales that characterize the sequestration of CO2 in saline aquifers. Accurate description of the physical mechanisms that control the behavior in these complex processes is necessary. Construction of mathematical and high-fidelity numerical models that accurately capture the relevant time and length scales is essential.[18]

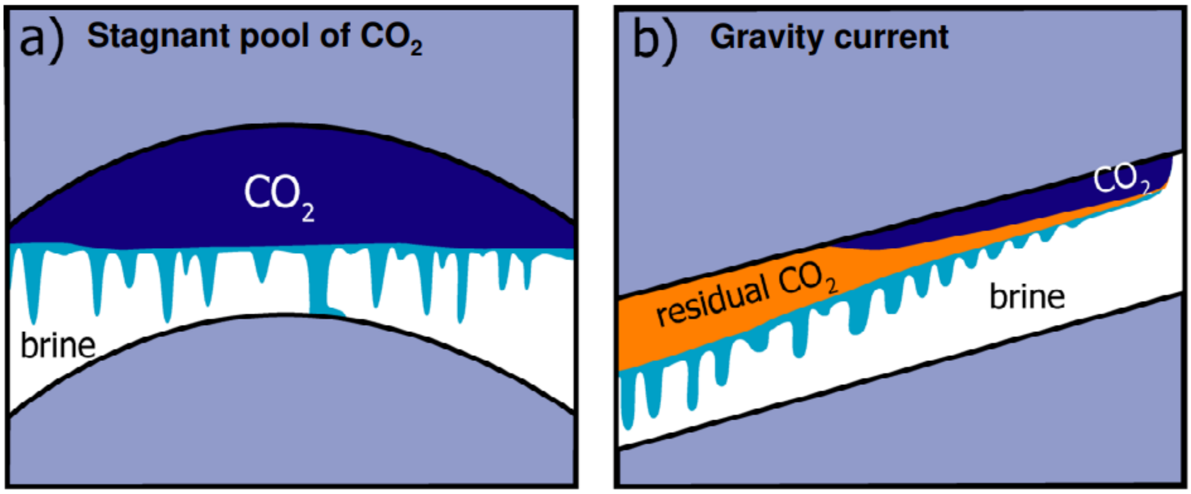


Figure I.12: Potential trapping mechanisms of CO2 injected into an aquifer.[13]

- **Enhanced oil recovery (EOR–CO2 method):**

CO2 injection method has been used in petroleum industry for over 40 years as an enhanced oil recovery method, but recently it represents a promising technology for mitigating greenhouse gas emission as a carbon storage method. [14]

I.2.3.3 Criteria for CO2 geological storage:

Understanding CO2 geological storage criteria is essential for identifying and selecting optimal storage sites that minimize environmental risks and ensure long-term CO2 containment. There are three main criteria to put in consideré

- **Physical (Thermobaric Conditions), Thermodynamic and Hydrodynamic Criteria:** This group focuses on the physical and chemical interactions between the injected CO2 and the storage formation. It considers factors like pressure, temperature, the formation's fluid properties.
- **Techno-Economic, Social and Regulatory Criteria:** These criteria address the practical and logistical aspects of CO2 storage projects. They include:
- **Techno-Economic:** Costs associated with site characterization, well drilling, CO2 capture and transportation infrastructure, operation and maintenance, and long-term monitoring.
- **Regulatory:** Legal and regulatory frameworks governing CO2 storage in the chosen region, including permitting processes, environmental compliance requirements, and liability issues.

By considering all three categories of criteria, we gain a comprehensive understanding of the technical feasibility, safety, environmental impact, and economic viability of a potential CO2 geological storage site.[11]

I.3 Conclusion:

This chapter has meticulously dissected Carbon Capture and Storage (CCS) technology, a promising solution in the fight against climate change. We embarked on a journey through the three fundamental stages of the CCS supply chain – capture, transport, and storage – uncovering the complexities and opportunities at each stage.

From delving into diverse capture methods, each with its advantages and limitations, to exploring the necessity for robust CO2 transportation infrastructure and pipeline safety, the chapter emphasized the multifaceted nature of this technology. Geological storage emerged as the crucial solution for long-term CO2 sequestration, highlighting the importance of selecting suitable sites with optimal capacity and secure containment measures.

By acknowledging the intricate details of each stage, we gained a profound appreciation for the potential of CCS as a weapon against climate change. While challenges remain, such as optimizing capture efficiency and minimizing upfront costs, ongoing advancements offer hope for a more cost-effective and efficient CCS future.

This exploration paves the way for a deeper understanding of CCS technology and its potential to contribute to a cleaner future. Through international collaboration, continued research and development, and the implementation of effective policies, we can unlock the full potential of CCS and accelerate the transition towards a low-carbon future. CCS, alongside other clean energy solutions, offers a compelling path for mitigating CO2 emissions and ensuring a more sustainable future for generations to come.

Chapiter II

In Salah Gas Project Overview

II.1 Introduction:

Algeria boasts a wealth of natural gas reserves, playing a significant role in the global energy landscape. This chapter delves into the heart of this resource potential, exploring two key projects: the In Salah Gas Project (ISG) and the Krechba field.

The In Salah Gas Project serves as a prime example of large-scale natural gas development in Algeria. We will explore the project's history, its technical aspects including well drilling and production processes, and its economic significance for Algeria. Understanding the In Salah project provides a foundational understanding of Algeria's natural gas industry.

Following this exploration, we shift our focus to the Krechba field, a site with a unique dual identity. While it contributes to Algeria's natural gas production, the Krechba field also holds immense potential for the future. This chapter will examine the geological and petrophysical characteristics of the Krechba field, including reservoir properties and formation characteristics. Understanding these characteristics is crucial for appreciating the field's suitability for a groundbreaking initiative – Carbon Capture and Storage (CCS) technology.

By exploring both the In Salah Gas Project and the Krechba field, this chapter paints a comprehensive picture of Algeria's natural gas resources. We will not only delve into the present state of production, but also lay the groundwork for the exciting advancements poised to transform the Krechba field in the fight against climate change

II.2 In Salah Gas Project Overview:

The In Salah Gas project (ISG) is a collaborative effort undertaken by three major energy companies: Sonatrach (Algeria), ENI (Previously, BP was also a partner, but ENI acquired BP's share in the project.), and Statoil (now Equinor). Located in the heart of the Sahara Desert in southern Algeria, the ISG project focuses on developing and extracting natural gas from seven distinct dry gas fields. The In Salah Complex conventional gas field recovered 60.52% of its total recoverable reserves, with peak production in 2013.

In Salah Complex conventional gas field ownership structure; These companies (SH-ENI-EQUINOR) hold shares in the project, with Sonatrach at 35%, BP at 33%, and Statoil contributing the remaining 32%.

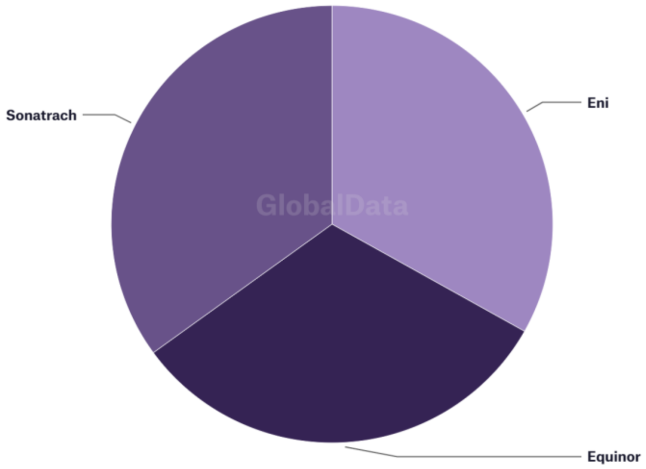


Figure II.1: In Salah Complex conventional gas field ownership structure.[15]

The objectives of this JV are: Exploration, Appraisal, Development and Joint Marketing of natural gas produced.

- First treated gas in July 2004,
- Estimated gas reserves: 340 bcm (230 bcm recoverable).
- Dry Gas production plateau: 9 bcm/yr for about 13 to 16 years
- Contract duration: until 2027.
- The global investment is around 2.7 billion US$ (1.7 billion US$ for Phase I).

II.2.1 Geographic Location and Layout:

a- Location:

Figure II.2: In Salah Gas project location in Algeria.[17]

b- Fields development:

The development of this project consisted of two phases:

- 1st Phase: Started in 2001 (first gas produced in 2004).
- 2nd Phase: after 2011.

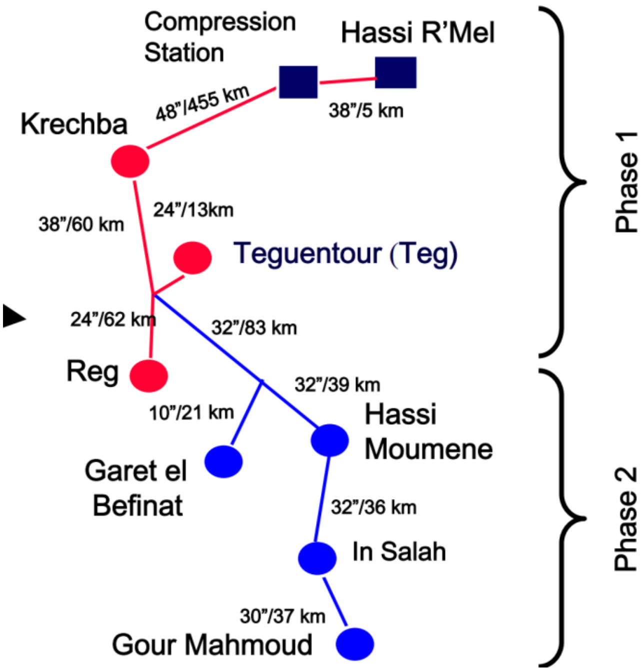


Figure II.3: Diagram illustrating the location of different ISG fields.[18]

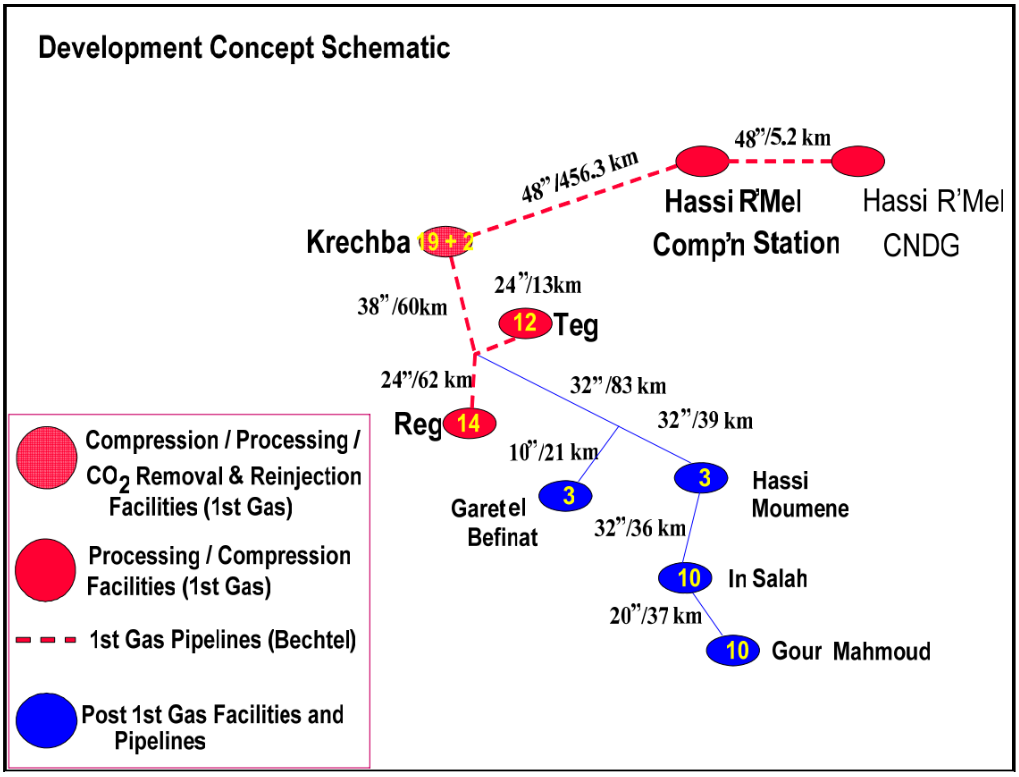


Figure II.4: ISG Development concept schematic.[20]

b-1- Development of the Fields: Phase 1:

- The first phase consists of the development of three fields: Krechba, Teg and Reg.
- Gas will be produced from two reservoirs at Krechba, Carboniferous and Deep Devonian.
- Teg is the largest field, with an initial production profile representing ½ of Teg, ¼ Reg and ¼ Krechba.
- Reservoir fluids are gas, with a small forecast amount of condensate at Krechba C - less than 5 barrels per mmscf.
- CO2 content varies between 1% and 9%, with a forecast average of 6.5%.
- Small amounts of H2S detected at Krechba, 15ppm H2S assumed in other fields.

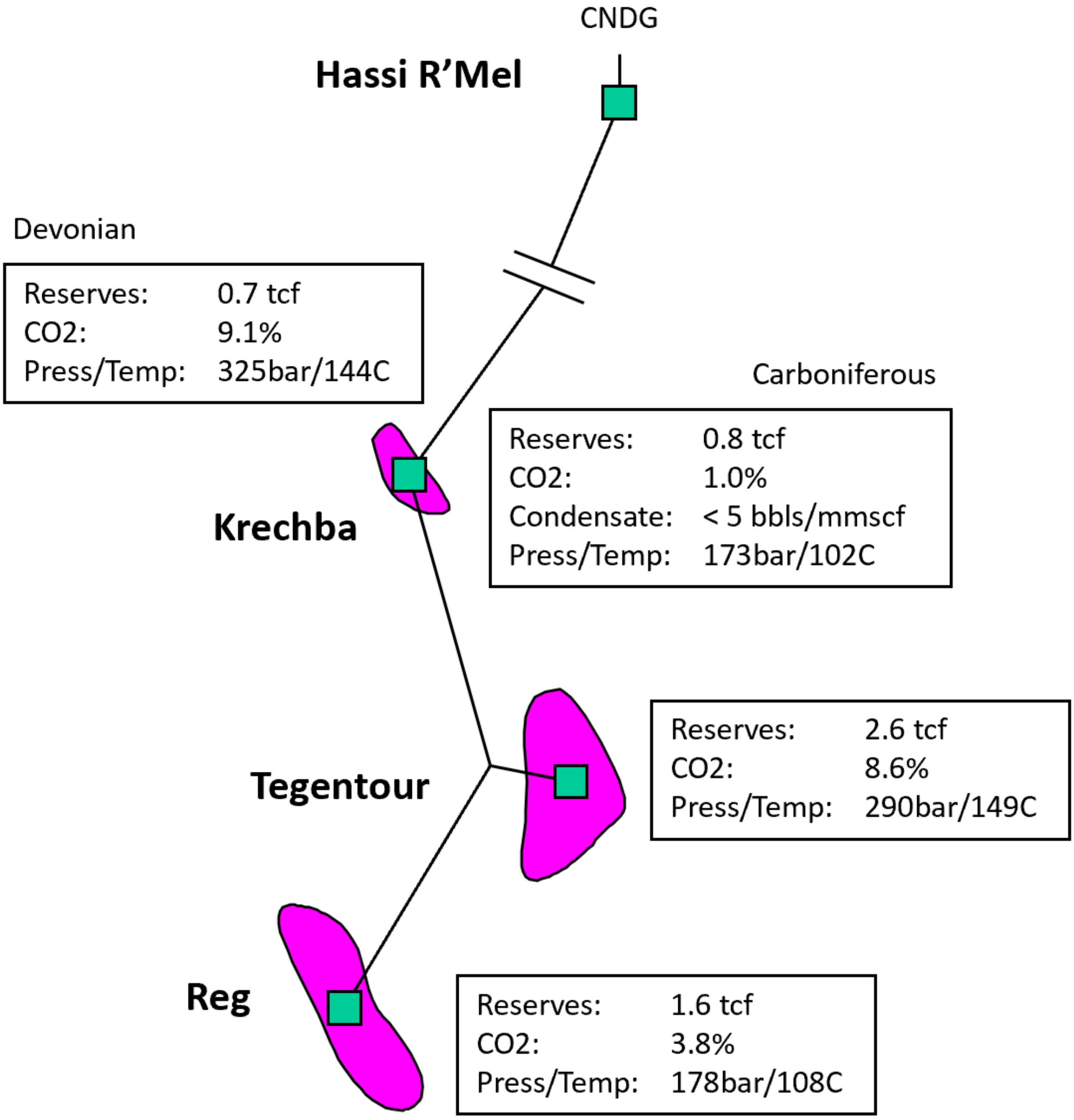


Figure II.5: Fields development phase 1.[21]

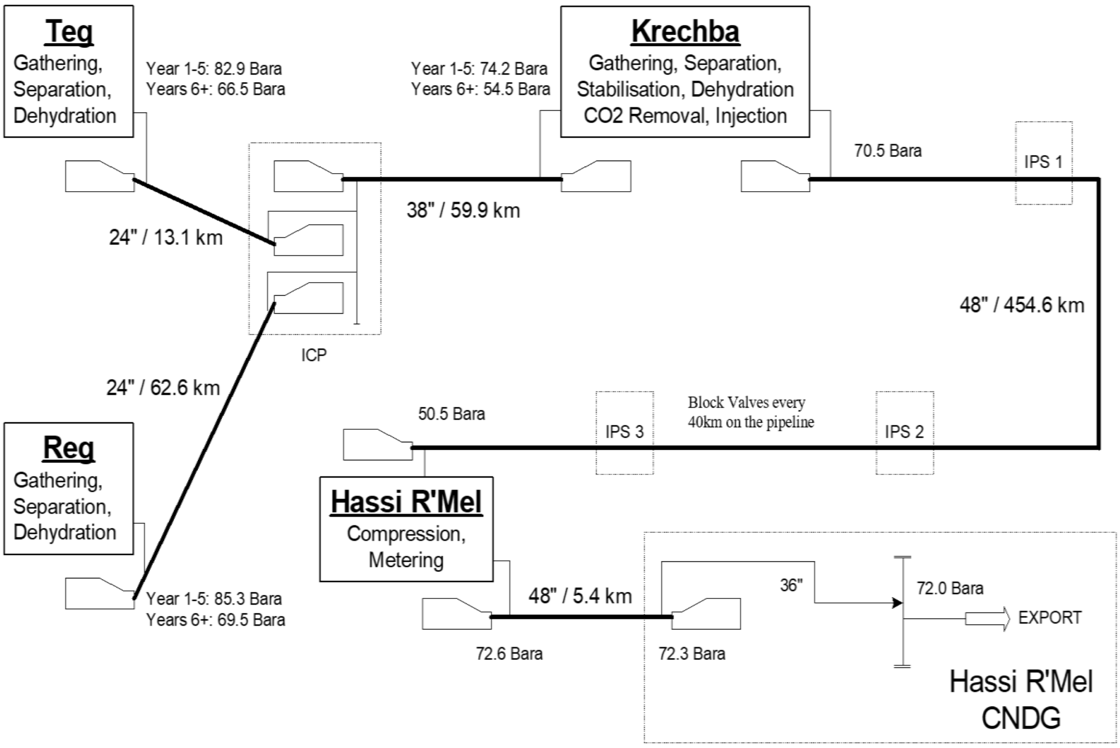


Figure II.6: Phase 1 general installations overview.[21]

b-2- Development of the Fields: Phase 2:

Phase 1 of the project initially consists of developing the 3 northern fields: Krechba, Teguentour (Teg), Reg, to ensure a marketing profile of 9,109 Cm3(1) per year. According to pressure decline forecast for these first three fields, the pipe system between the fields is planned to be extended to the other 4 southern fields: Gour Mahmoud, In Salah, Garet el Befinat and Hassi Moumene, which will be developed at a later date. The Boutraa field is an additional opportunity for the development.

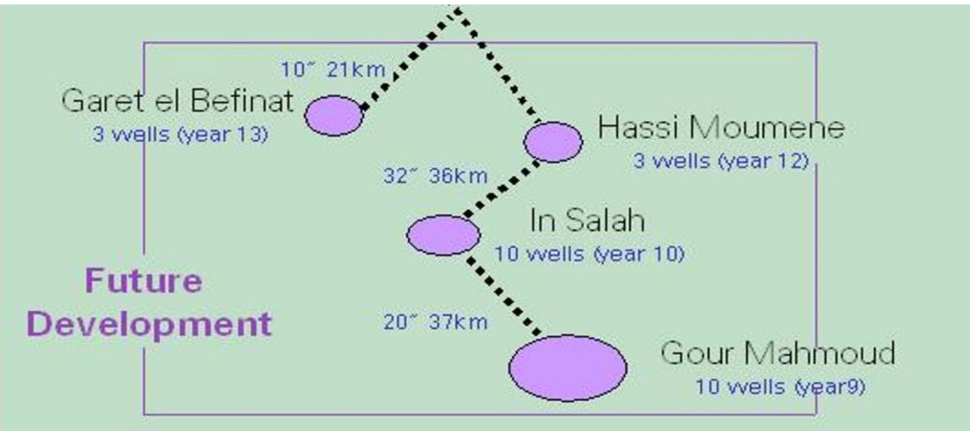


Figure II.7: Phase 2 fields development.

II.2.2 In Salah Gas fields :

The fields were uncovered in the following years:

Table II.1: Years of the fields discovery.

In Salah	1957
Teguentour	1957
Krechba field	1958
Reg	1962
Garet El Befinat	1983
Gour Mahmoud	1988
Hassi Moumene	1990
Boutraa	1999

Commercial production began in July 18, 2004. The gas sold is branded of the joint marketing company, In Salah Gas Limited. Gas sales are scheduled to continue until 2027 (contract end date).

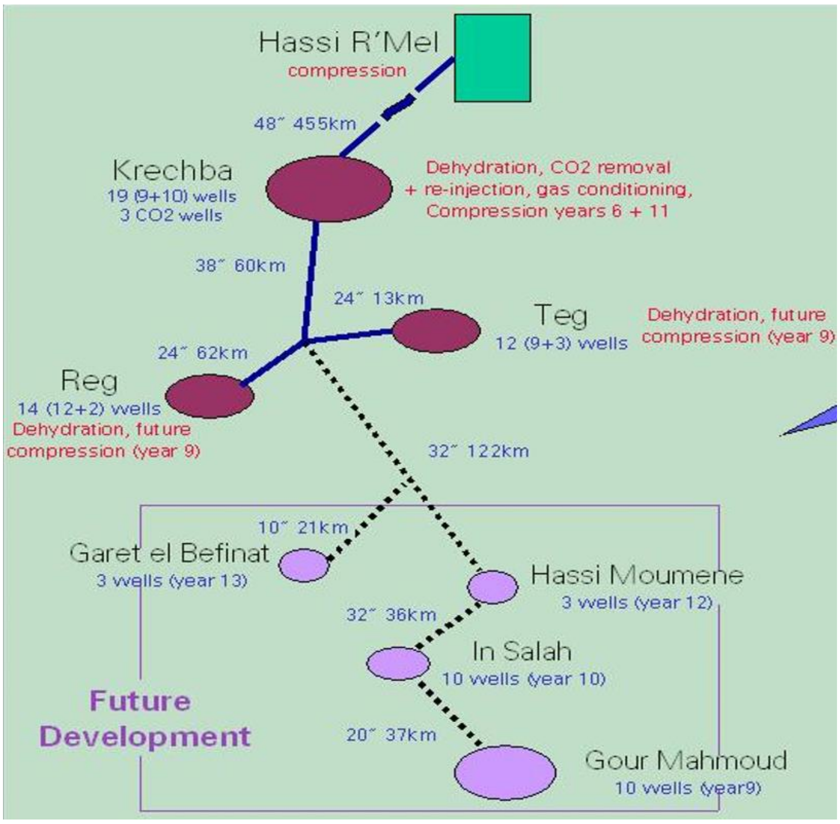


Figure II.8: ISG Fields.[21]

II.2.3 Production Facilities and Processing plant:

- Production Infrastructure Phase 1
  - 21 production Wells, 3 CO2 injection Wells and 1 produced water injection Well pre 1st gas.
  - 455 km 48 in export pipeline.
  - Production Facilities and Compressor station.
    - Krechba (main processing center).
    - Teg.
    - Reg.
    - Hassi R’Mel (export compressor station).
- Gas Sale Contracts and Transportation Agreements.
- Phase 2 Development of the 4 Fields in the South.

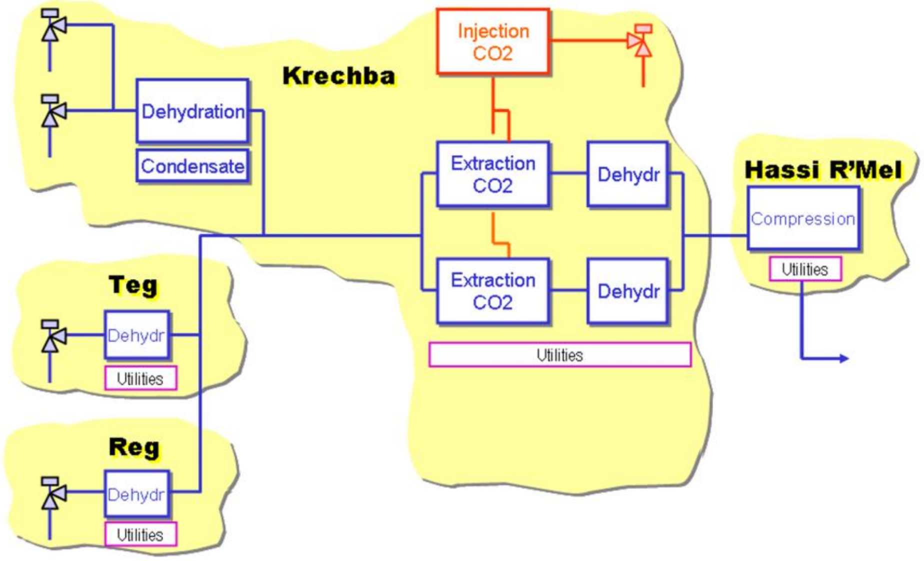


Figure II.9: Simplified PFD (Phase 1).[20]

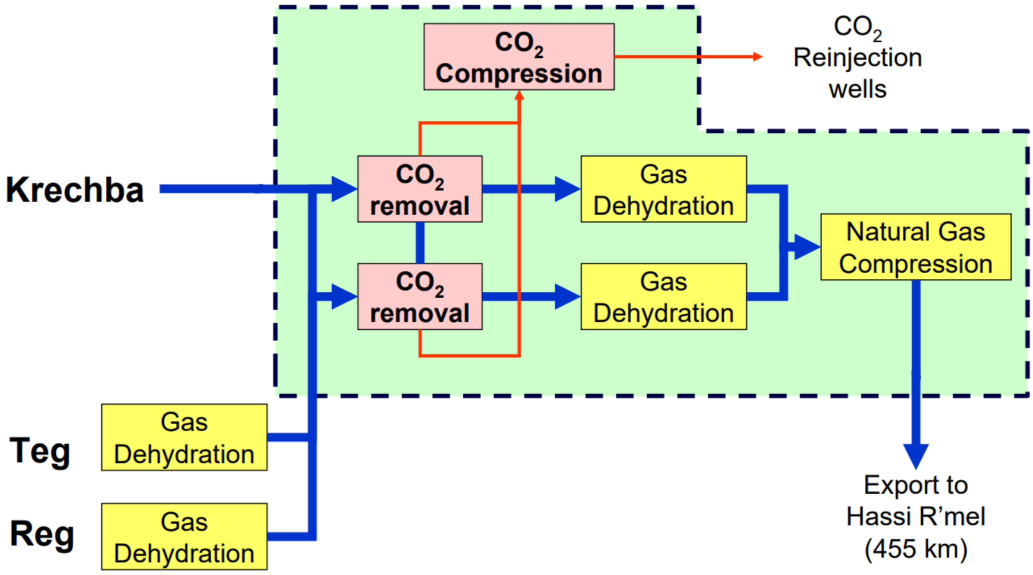


Figure II.10: In Salah Gas Processing Plant.[22]

II.3 Krechba field:

Krechba is one of eight fields in the In Salah Gas Development in Central Algeria. The field is in the northern part of the acreage retained for development, and consists of reservoirs in the Carboniferous and Devonian. The Carboniferous, Tournasian C10.2 sands are the main contributor to the gas production to date, being developed for first gas in 2004. The original field discovery made in 1957 was based on 2D seismic. Due to uncertainty on the top reservoir and the thin reservoir, a 3D seismic dataset of approximately 600 km2 was acquired in 1997. Seismic amplitudes were used to define accurately the presence and quality of the estuarine sands very well developed over the field. This reservoir consists of several stacked thinner sands, at depths ranging from 2800 m to 3400 m.

Figure II.11: Location of the Krechba (In Salah) gas field in central Algeria.[23]

II.3.1 Krechba geology:

The Krechba deposit is a large, simple, dome-shaped structure containing two natural gas reservoirs stacked on top of each other. The Carboniferous reservoir (upper layer) is a thick layer of sandstone deposited in an ancient valley, while the Devonian reservoir (lower layer) consists of multiple sandstone layers separated by clay.

The current structure of the deposit formed during a period of mountain building (Hercynian orogeny) that squeezed the rock layers and created the dome shape. Faults (cracks in the rock) also formed during this time.

The chapter describes the characteristics of each reservoir layer in detail, including:

- **Depth:** The Carboniferous layer is shallower (1700m) than the Devonian layer (2850m to 3350m).
- **Thickness:** The Carboniferous layer can be up to 24m thick, while the Devonian sandstones vary in thickness.
- **Porosity:** The Carboniferous layer has higher porosity (up to 22%) than the Devonian layers (up to 15%). Porosity refers to the amount of empty space in the rock that can hold fluids like natural gas.
- **Permeability:** Both layers have good horizontal permeability (up to 600mD), which allows fluids to flow through the rock.
- **Water Level:** The Carboniferous layer has a defined water level at 1330m, separating the gas from the underlying water.

II.3.2 Krechba seismic:

2009 Krechba seismic results:

- 14 horizons were interpreted during this seismic, from Ordovician to the Cretaceous.
- 3 groups of faults were interpreted: Ordovician, Devonian and Carboniferous.
- Carboniferous faults are small-scale, with limited offset and variable orientations. C20.1.
- No large-scale faults crossing the caprock: small-scale faults and fractures and fractures may exist.

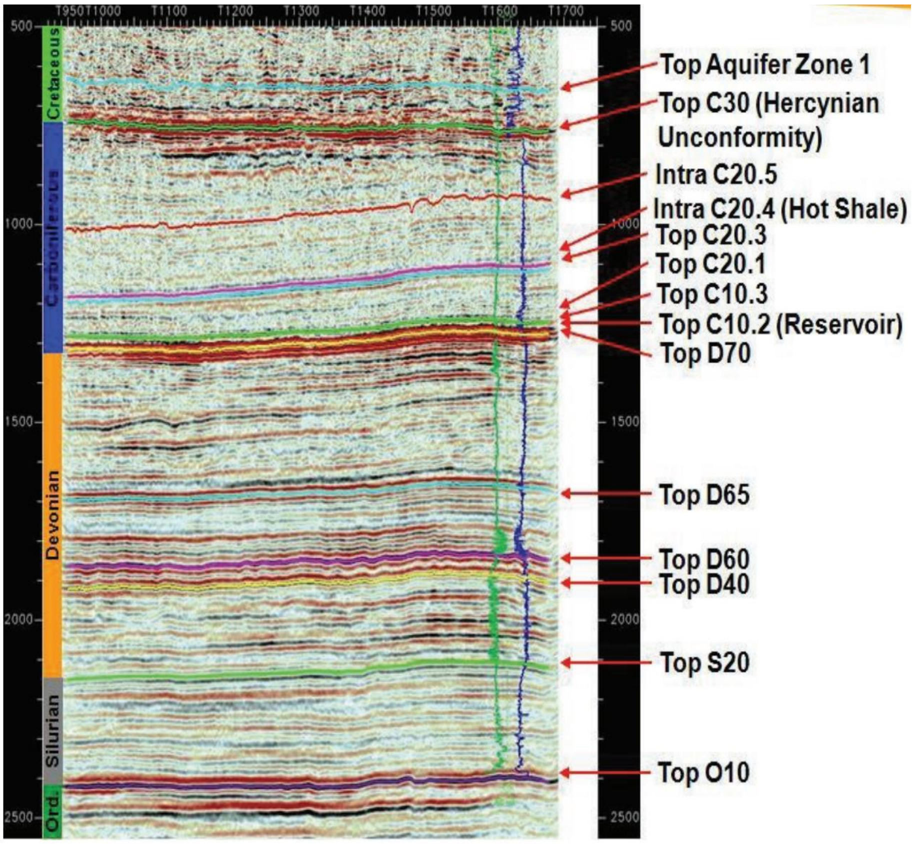


Figure II.12: Seismic interpretation: Geological stratigraphy of Krechba.[24]

II.3.3 Krechba wells:

In Krechba there are different types of wells, including:

- CO2 injection wells.
- Production wells.
- Water production wells.
- Abandoned wells.

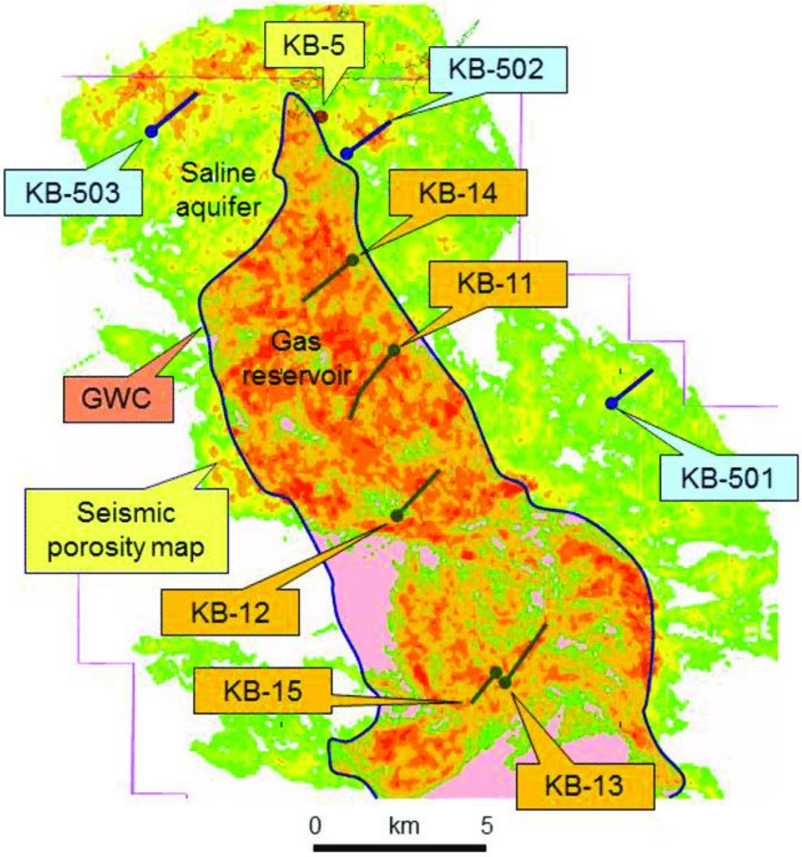


Figure II.13: Field layout: Krechba Carboniferous reservoir and saline aquifer, In Salah Gas Development.[25**]**

a. CO2 injection wells: (KB-501, KB-502 and KB-503)

There are three horizontal injection wells at Krechba, injecting up to 50 MMscfd of CO2. These wells were drilled using Geosteering technology (enabling measurement and logging while drilling: MWD, LWD: Mesuring While Drilling and Logging While Drilling), to keep the well inside the target formation and perpendicular to the maximum field, and therefore perpendicular to the dominant orientation of the fractures, in order to maximize injectivity capacity. Their horizontal length is 1800m.

The storage formation is 1950m below ground, 20m thick, with 13% porosity and 10mD permeability, and is overlain by 900m of impermeable layer. Wells KB-502 and KB-503 are located in a zone of high permeability, so injection is mainly via these two wells.
mainly through these two wells. On the other hand, well KB-501 has a low injectivity potential injectivity, as it was the first well drilled for the purpose of injecting CO2, and is located in a zone of low a zone of low permeability and porosity.

PS: the CO2 injection is currently suspended.

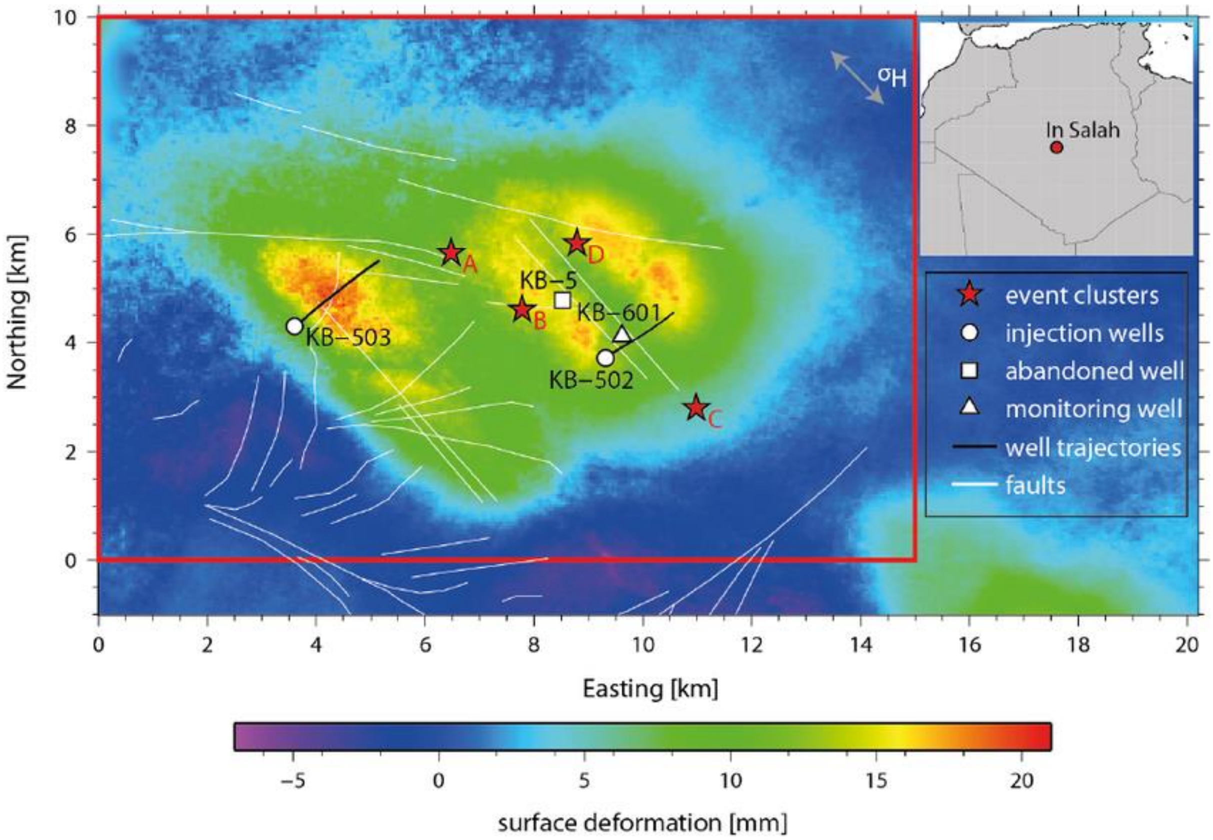


Figure II.14: Krechba field, In Salah, Algeria showing the location of two horizontal CO2. Injection.[26]

b. Production wells:

Early gas operations at Krechba are based on production from the Krechba Carboniferous reservoir only. Carboniferous reservoir only. After twelve months, production from the Carboniferous Krechba begins to decline and is supported by production from the Devonian Krechba reservoir.

At Krechba there are 08 production wells, divided into 02 groups: 05 Carboniferous wells and 03 Devonian wells.[24]

- **The Carboniferous wells** are: Kb-11, Kb-12, Kb-13, Kb-14, Kb-15 (all horizontal wells, due to the low vertical permeability of the reservoir and, above all, its average thickness of 20 m).
- **The Devonian wells** are 03 wells: Kb-6, Kb-16, Kb-17 (all vertical wells).

c. Observation and monitoring wells:

At Krechba, there is only one observation well, Kb-9. Its purpose is to observe CO2 breakthrough. On the other hand, there are 05 observation and monitoring wells for the intercalary aquifer continental aquifer (drinking water): Kb-601, Kb-602, Kb-603, Kb-604, Kb-605. These last wells are drilled near CO2 injector wells (except for Kb-605 and Kb-601, which are drilled in remote locations). all aim to monitor the salinity of drinking water by periodically taking samples and analyzing them in the laboratory. This is known as Drinking Water Aquifer Monitoring.

BAR-A and BAR-B are geophones placed in a 2m-deep hole, their purpose being to detect micro-fractures induced by injection of CO2 into the Carboniferous by triangulation, a monitoring method called Microseismic.

d. Former abandoned wells:

Sonatrach's abandoned wells are Kb-1, Kb-2, Kb-3, Kb-4, Kb-5, Kb-7, Kb-8, Kb10: These wells were drilled in the 80s by Sonatrach, for delineation and exploration purposes, they were then sealed with cement plugs, generally glass G cement. These wells cross the Carboniferous to Devonian.[24]

e. Drinking water production wells:

Kb-101, Kb-102, Kb-103: These wells are used to produce drinking water from groundwater.

and are used for domestic consumption.

Note:

In September 2023, another monitoring well (Kb-607) was drilled for investigation purposes, currently SLB is performing the sampling by DST.

II.3.4 Krechba Process Diagrams:

- **Krechba processing plant:**

As shown in (figure II.15), the naturl gas will be treated in the processing plant, where the CO2 will be removed and dehydrated and finally re-injected.

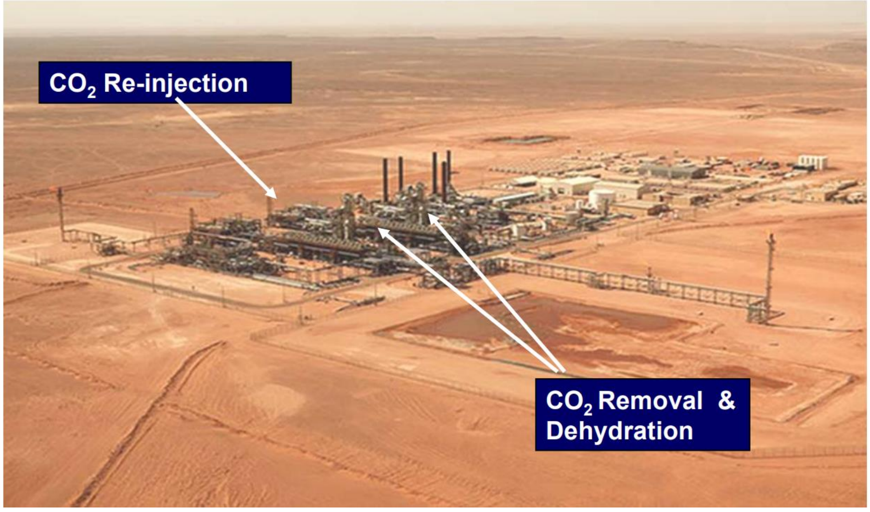


Figure II.15: Krechba processing plant (real view).[24]

➢ Gas Processing:

Natural gas coming from different fields will be treated in the Krechba processing plant; the process is further explained in the figure bellow.

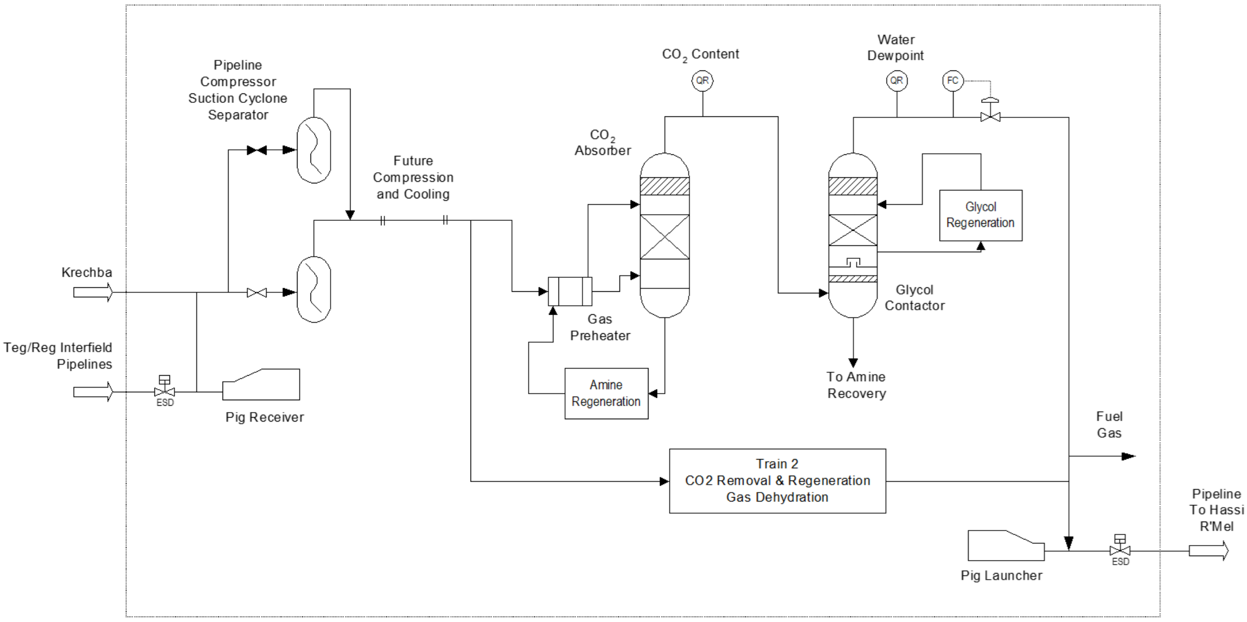


Figure II.16: Gas Processing diagram.[21]

➢ Decarbonation and Amine Regeneration:

Decarbonation and amine regeneration are crucial processes in Carbon Capture and Storage (CCS) projects. Decarbonation refers to the removal of CO2 from the flue gas stream, while amine regeneration involves the recovery of the amine solution used in the capture process.

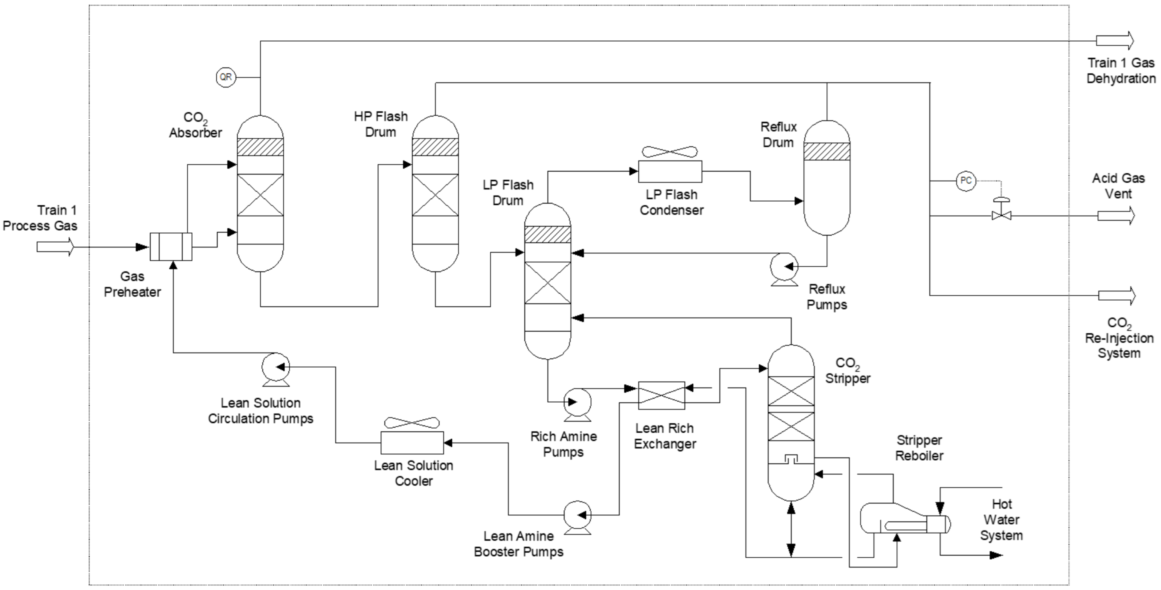


Figure II.17: Decarbonation and Amine Regeneration diagram.[21]

II.3.5 CO2 re-injection:

The Krechba gas field in Algeria is not only a significant natural gas resource, but it's also home to one of the world's first industrial-scale carbon capture and storage (CCS) projects. This project injects captured CO2 from the natural gas production process back underground into the depleted Devonian reservoir layer of the Krechba deposit. This innovative approach reduces greenhouse gas emissions associated with natural gas production and demonstrates the potential for CCS technology.

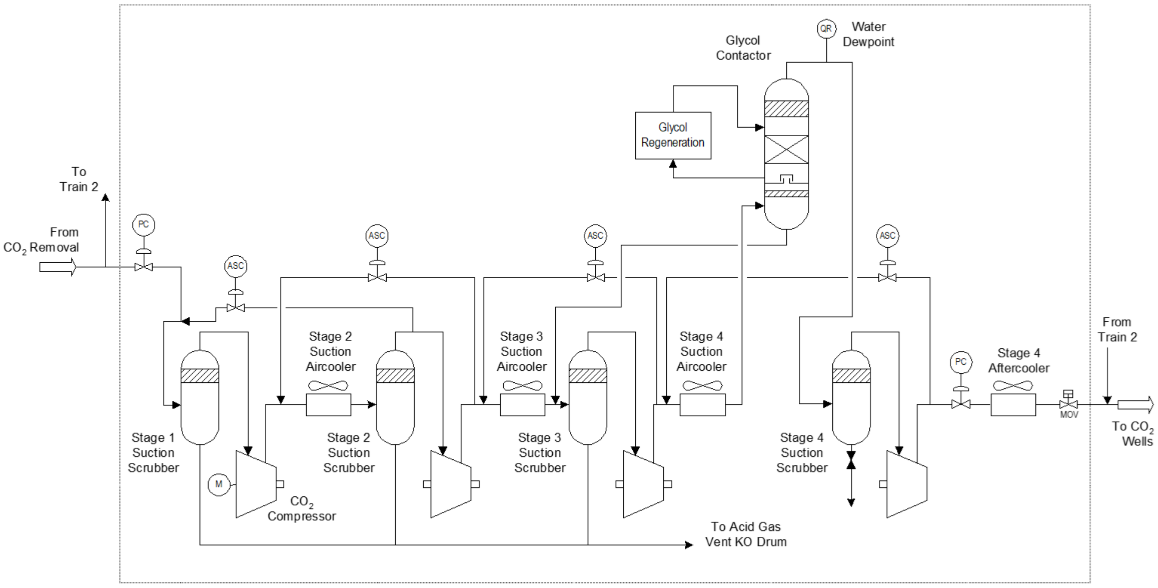


Figure II.18: CO2 re-injection diagram.[21]

II.4 Conclusion:

This chapter has explored the vast natural gas reserves of Algeria, with the In Salah Gas Project (ISG) as a prime example of large-scale development. We have examined the project's technical aspects, economic significance, and its role in solidifying Algeria's position as a major natural gas producer.

Our exploration then shifted to the Krechba field, revealing its dual identity. While currently contributing to Algeria's gas production, the unique geological characteristics of the Krechba field make it a promising candidate for a groundbreaking initiative – Carbon Capture and Storage (CCS) technology.

However, the story of Algeria's natural gas doesn't end here. The potential for CCS technology at Krechba presents a fascinating bridge between continued resource utilization and environmental responsibility. Chapter 3 will delve deeper into this transformative potential, analyzing the technical details of the CCS project and its broader implications for mitigating climate change.

By critically examining the future prospects of CCS in Algeria, we can illuminate a path towards a more sustainable future for the nation's natural gas sector. This future could involve utilizing CCS technology to minimize the environmental footprint of gas production while maintaining its economic importance.

Chapter III:

Surface Uplift and CO2 Leakage in the In Salah CCS Project

III.1 Introduction:

The In Salah CCS project is one of the first large scale demonstrations of CO2 injection into a saline aquifer. The project aimed to reduce the CO2 emissions through storing the CO2 coming from the natural gas processing facility. The project succeeded to store around 3.7 million tons of CO2 during its life time.

While the project initially garnered significant interest for its potential contribution to emissions reduction, its journey wasn't without challenges. In 2004, soon after CO2 injection began, unexpected leakage was detected at a nearby well. This incident highlighted the complexities involved in large-scale CCS operations and the need for a deeper understanding of the technical considerations and potential risks.

This chapter presents an overview of the technical aspects of the In Salah CCS project. The project’s design and operational strategies are presented in details in this chapter. I will also analyze the challenges encountered during CO2 injection, specifically the wellbore leakage incident, I will be focusing on the connection between the leakage and its connection to geological features.

Through a critical examination of the In Salah project, this chapter aims to:

- Unpack the technical details of large-scale CO2 storage in a saline aquifer.
- Analyze the operational strategies employed at In Salah.
- Investigate the challenges encountered during the project's execution.
- Extract valuable insights into the technical considerations and potential risks associated with CCS projects.

By dissecting the technical aspects of the In Salah project, we can gain valuable knowledge that can be applied to future CCS initiatives. This knowledge can contribute to the development of safer, more reliable, and more efficient CCS technologies, paving the way for a more sustainable future.

III.2 CCS in In Salah (ISG-CCS) project overview:

In 2004, the CO2 injection started as part of the In Salah project in Algeria, CO2 from several gas fields, which have a CO2 content of 5-10%, is removed from the production stream to meet the sales gas export specification of 0.3% CO2. Normally, in gas production plants the CO2 is vented in the atmosphere, but in this project the CO2 was injected via injection wells.The investors derive no commercial benefit from the CO2 storage at In Salah, so it is being used as an experimental and demonstration project – to learn about CO2 geological storage in deep saline formations.

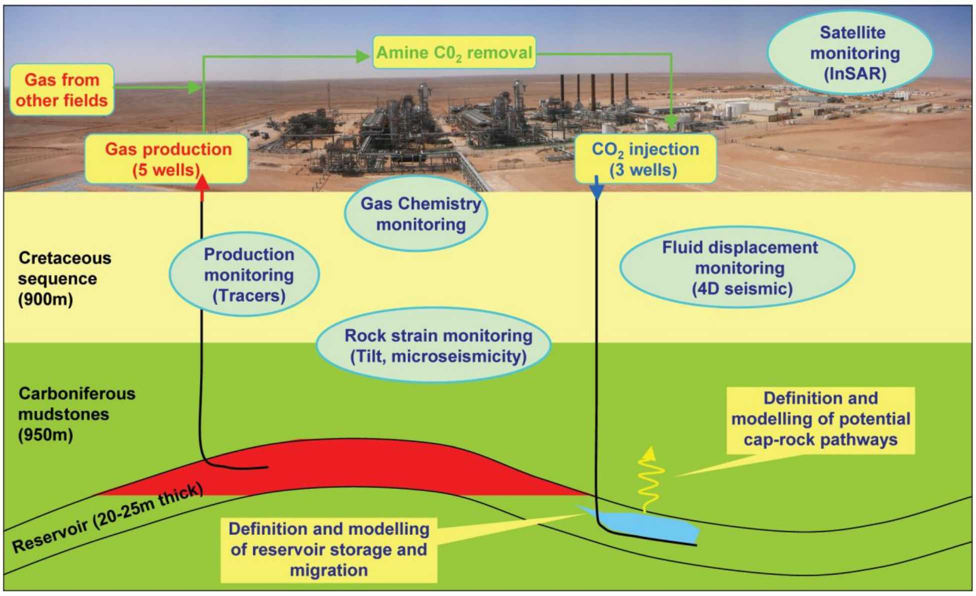


Figure III.1: Summary of the In Salah CO2 injection and storage site at Krechba with the main monitoring activities.[27]

The chosen CO2 storage site features a thick layer of Carboniferous sandstone. This sandstone formation lies nearly 1,900 meters underground and boasts a porosity of around 15%, indicating a good capacity to hold fluids. Additionally, its permeability of 10 millidarcies allows for efficient CO2 flow within the formation. To maximize injection capacity and minimize the risk of fracturing in unintended directions, three cutting-edge horizontal injection wells were drilled perpendicular to the existing stress field and dominant fracture orientation.By the end of 2008, this project successfully injected over 2.5 million tonnes of CO2 underground. To ensure safe and effective storage, a joint industry project (JIP) was established. This JIP utilized a combination of geochemical, geophysical, and production monitoring techniques for an initial period of five years. According to SONATRACH, The ISG-CCS project demonstrates large-scale geological storage of CO2, that aimed to capture and store **1 million tons** of carbon dioxide annually. Throughout the project's lifespan, a total of 17 million tons of CO2 was supposed to get re-injected underground. This impressive feat translates to a significant 60% reduction in greenhouse gas emissions for the project. The environmental impact is equivalent to removing 250,000 cars from the road or creating a vast 200 square kilometer forest. Despite the project's significant cost of **100 million US dollars**, the CO2 capture and storage itself comes in at a competitive price of only $6 per ton.[24]

The project’s objectives:

- Demonstrating to stakeholders that industrial-scale geological storage of CO 2 is a viable greenhouse gas (GHG) mitigation option.
- Assuring people that secure geological storage of CO 2 can be cost-effectively verified and that long-term assurance can be provided by short-term monitoring.
- Setting precedents for regulating and verifying geological storage of CO 2 - ultimately to allow eligibility for Clean Development Mechanism (CDM).[28]

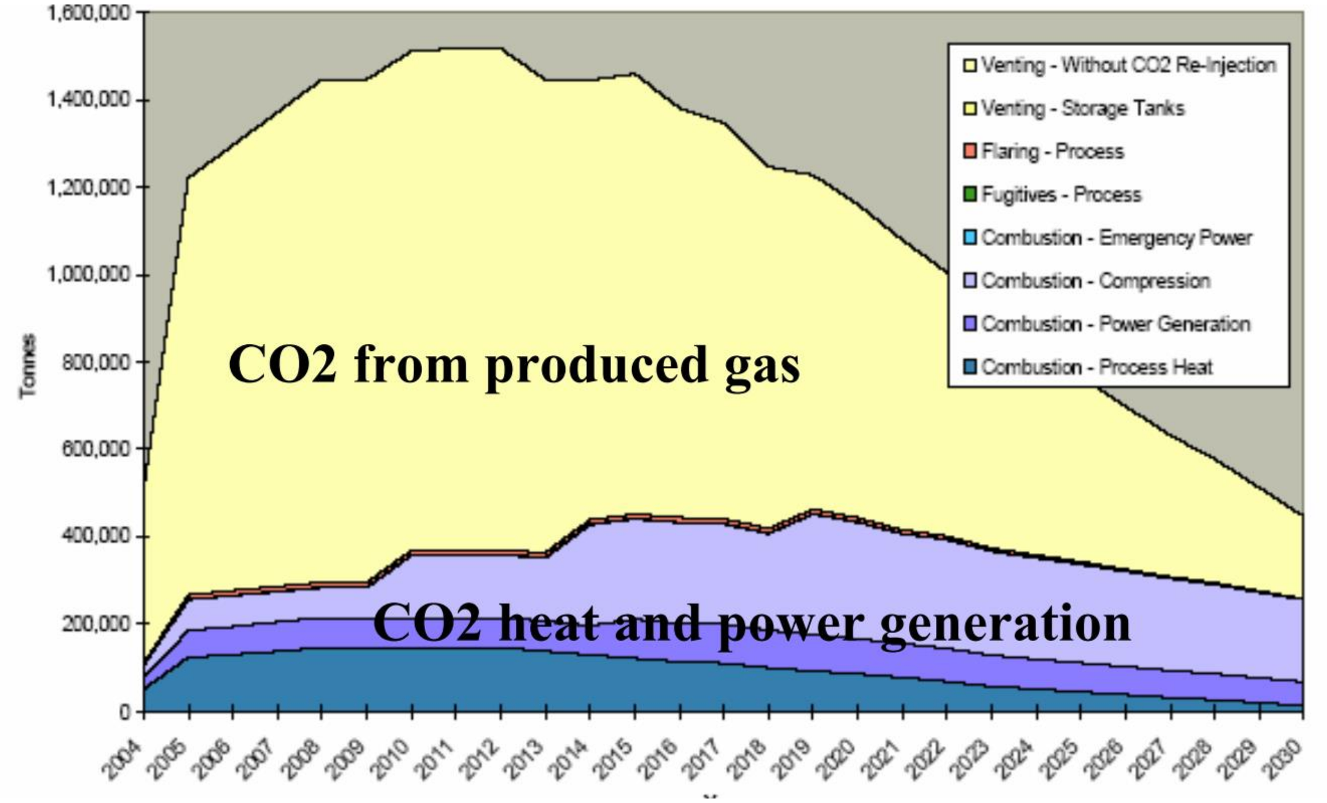


Figure III.2: In Salah Gas CO2 emissions by source In Salah Gas CO2 emissions by source.

Note: the CO2 coming from the produced gas is the one that will be stored underground.

The percentage of CO2 in In Salah fields varies, the highest levels are registered in Teguentour and in Krechba, detailed percentages are mentioned in the following table:

Table III.1: CO2 content in different In Salah fields.[50]

Fields	Reservoirs	CO2 %
Reg	Devonian	2 to 4
Krechba	Tournaisian (Carboniferous)	1
	Gedinian (Devonian)	9 to 10
Teguentour	Denovian	8 to 10

III.2.1 CO2 capture:

It requires two trains that are custom made for carbon capture for the purpose of this project. The process includes separating CO2 from the natural gas stream through counter-current absorptions with a particular type of chemical solvent that is a mixture of ethanol and primary amines. Consequently, this solvent acquires a propulsive ability to capture the CO2. After CO2 absorption, the solvent itself has a regeneration process that guarantees its reuse for further CO2 absorption. Last, a stage that is independent of the absorption system is used for the final stage of the dehydration of this natural gas with glycol. This means that natural gas is a CO2-free product produced without by-products.

III.2.1.1 The CO2 removal unit:

ACRU – a natural gas conditioning unit intended for CO2 and H2S removal from the gas. The unit has two parallel CO2 extraction trains operating at 50% loading to ensure. This unit receives a mixed stream from the REG and TEG and Krechba fields.

- **Process:**

Homogenization: A cyclonic separator is used for uniform flow delivery and mixing of the gas stream.

Preheating: Adsorption and Desorption Unit HA-028101 improves the temperature of feed gas to 55°C before entry to CO2 Absorber Column VE-028101.

CO2 Absorption: Lean amine solution flows downward through the CO2 Absorber Column on the other side as the preheated gas flows upward thereby absorbing CO2 gas. The amine solution reacts with CO2 and H2S gases in the amine solution.

Regeneration: CO2 and H2S absorbed into the rich amine solution from the absorber VE-028103 is stripped out through the rich amine solution and discharged in VE-028102 Regenerator Column. To regenerate the spent amine solution, the absorbing solution is heated in order to remove the absorbed gases. CO2 stripped lean amine solution is then regenerated and re-cooled before passing through to the absorber column of the CO2 unit.

Drying: The cleaned gas comes at the top of CO2 absorber column and passes to gas export drying facilities.

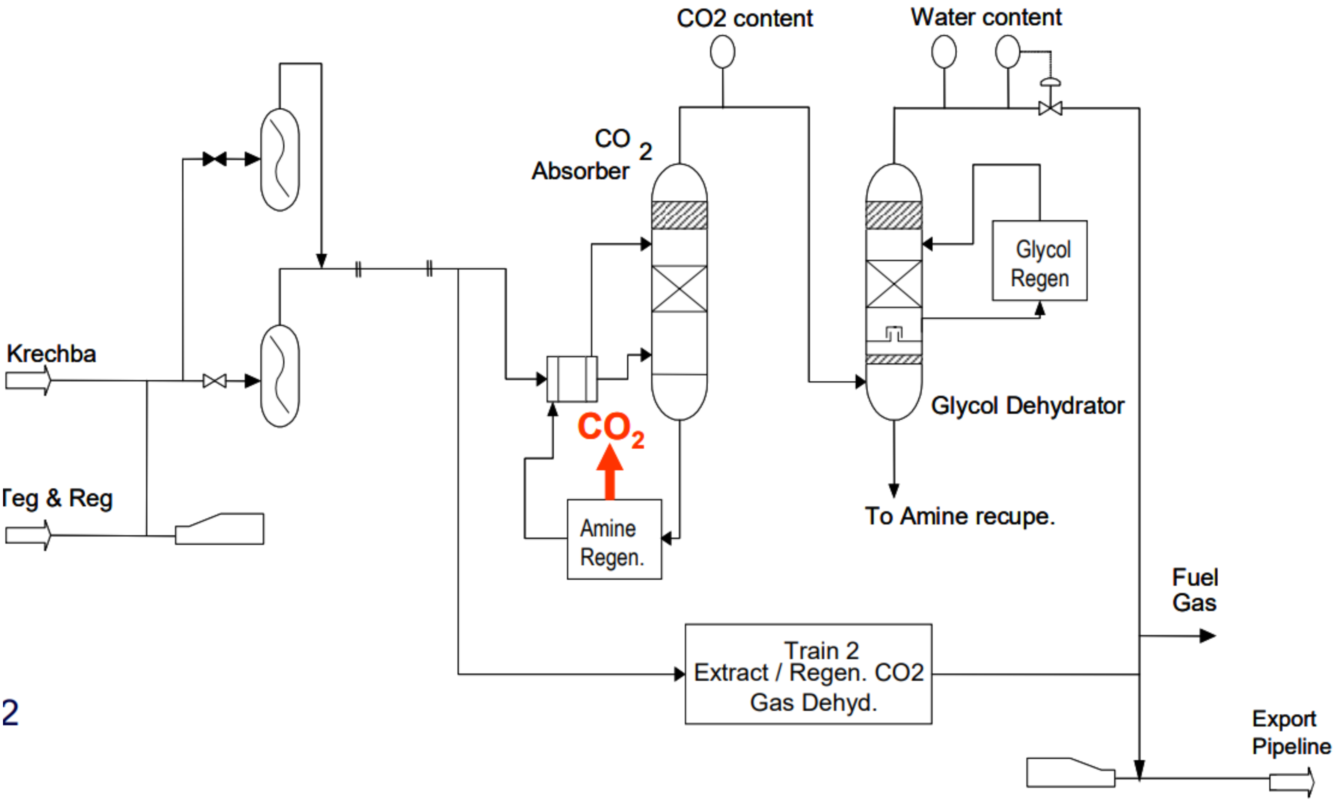


Figure III.3: CO2 Removal from natural gas process.

III.2.1.2 CO2 compression and dehydration:

The CO2 that is captured is compressed through a multi-stage process with 4 distinct compression stages before the final pressure reaches 200 bar. The CO2 has to be dehydrated in order to make the process of transportation and storage effective. This dehydration process comes after the third compressor and the medium used is triethylene glycol (TEG). The TEG separates any remaining water vapor in the CO2 stream, which is no longer gaseous upon exiting the TEG.

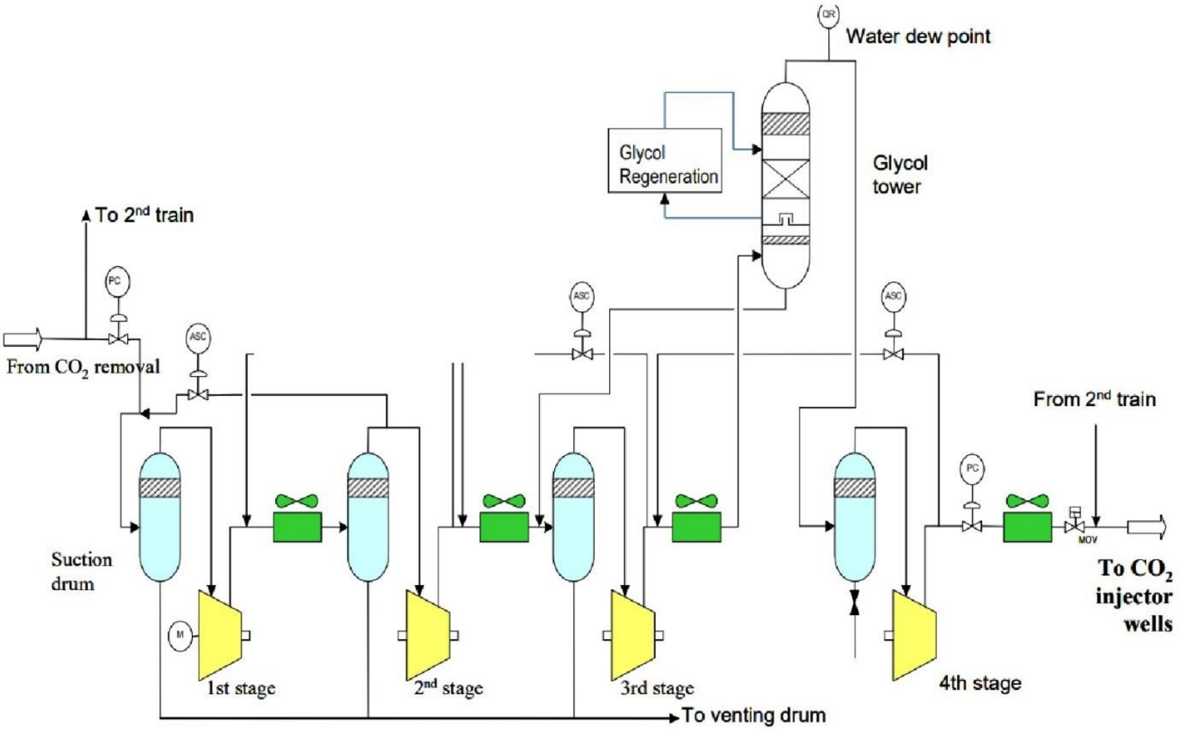


Figure III.4: CO2 compression and dehydration.

III.2.2 Transportation:

The dehydrated gas from the TEG and REG facilities is transported through **inter-field pipelines** and combines with the dehydrated and conditioned gas from the Krechba field's own treatment facilities.

III.2.3 Geological storage:

According to SONATRACH, during the design phase, various storage options were considered, including distributed storage units at each field and a centralized facility. The high cost and increased complexity of distributed storage, mainly due to the need for multiple CO2 stripping units at each location, made it an impractical option. Therefore, a single centralized facility emerged as the preferred solution, and the Krechba field was chosen as the optimal location.

III.2.3.1 Krechba the chosen storage site:

Krechba was chosen to be the preferred storage site by the In Salah Project, after the selection a number of reservoirs next to krechba field were investigated including the shallow Carboniferous and the deep Devonian structures. The selection was made according to several reasons, including:

a) The existence of exploration and appraisal wells.

b) The availability of seismic data.

c) All processin facilities are located in one site.
d) The shallowness of the Carboniferous structure.
e) The huge storage capacity of the reservoir.

Therefore, after the capture and the transportation of the CO2, it will be reinjected in the shallow Carboniferous.

The deep saline aquifer of the Carboniferous C10.2 reservoir in Krechba, just below the producing gas phase. This sandstone reservoir is characterized by low porosity (13-20%) and low permeability (10 mD) and has a thickness of 20 meters. The injection depth is between 1850 and 1950 meters below the surface

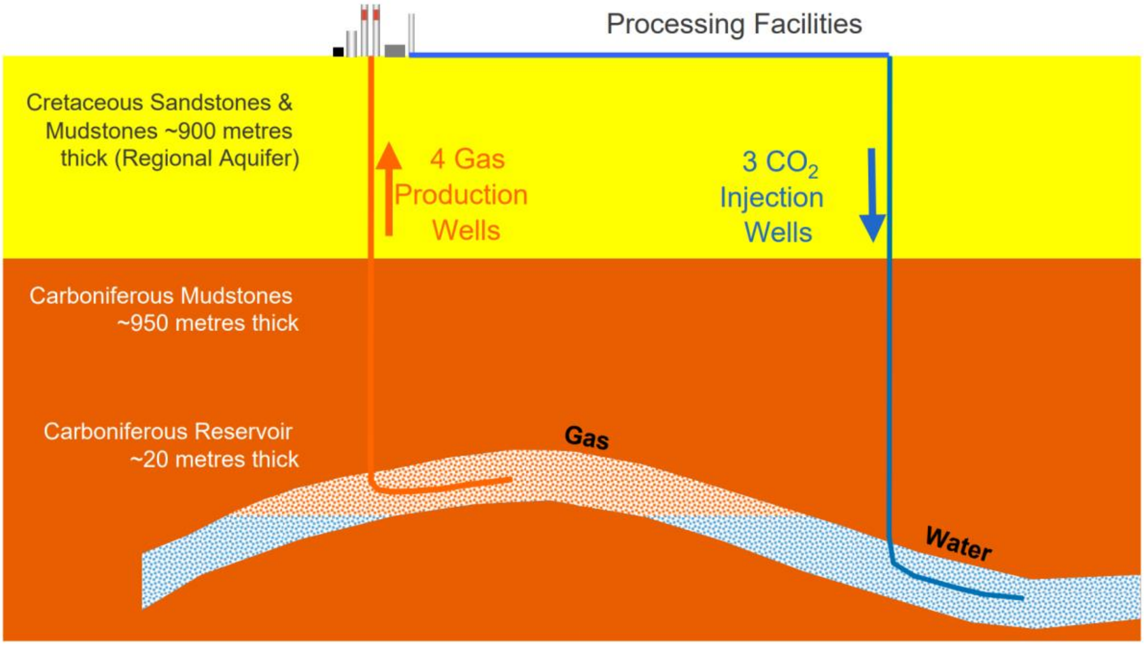


Figure III.5: CO2 storage at Krechba.

The trapping mechanisms are an important component that should be identified, as for the case of Krechba the CO2 initially displaces the surrounding water (Drainage) due to its higher mobility ratio. However, the process is gradual and not all CO2 dissolves immediately. This is attributed to the saturation of saline water by CO2 and the inverse relationship between CO2 dissolution and water salinity. As CO2 is less dense than formation water, it migrates upwards towards the caprock due to buoyancy. Over time, most of the CO2 remains trapped either by the caprock or as mobile CO2 within the reservoir.

III.2.3.2 CO2 injection in Krechba:

The CO2 was injected via three main horizontal wells (**Kb-501, Kb-502, Kb-503**) with a depth of 1500 to 1800m (4921 to 5905 ft) with an injection rate of 50 mmscfd, the wells were drilled using the Geosteering Technology.

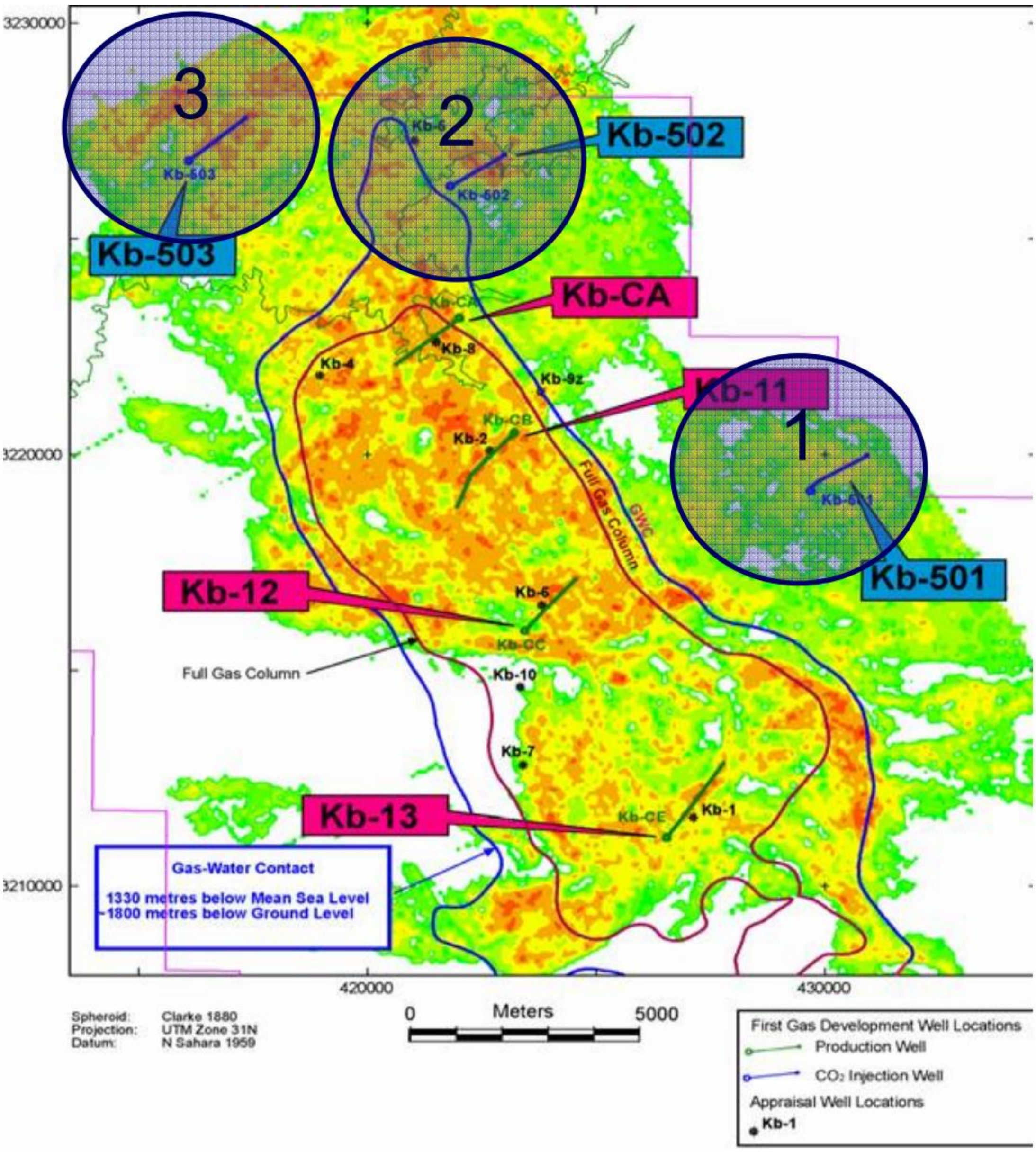


Figure III.6: CO2 injection wells location.

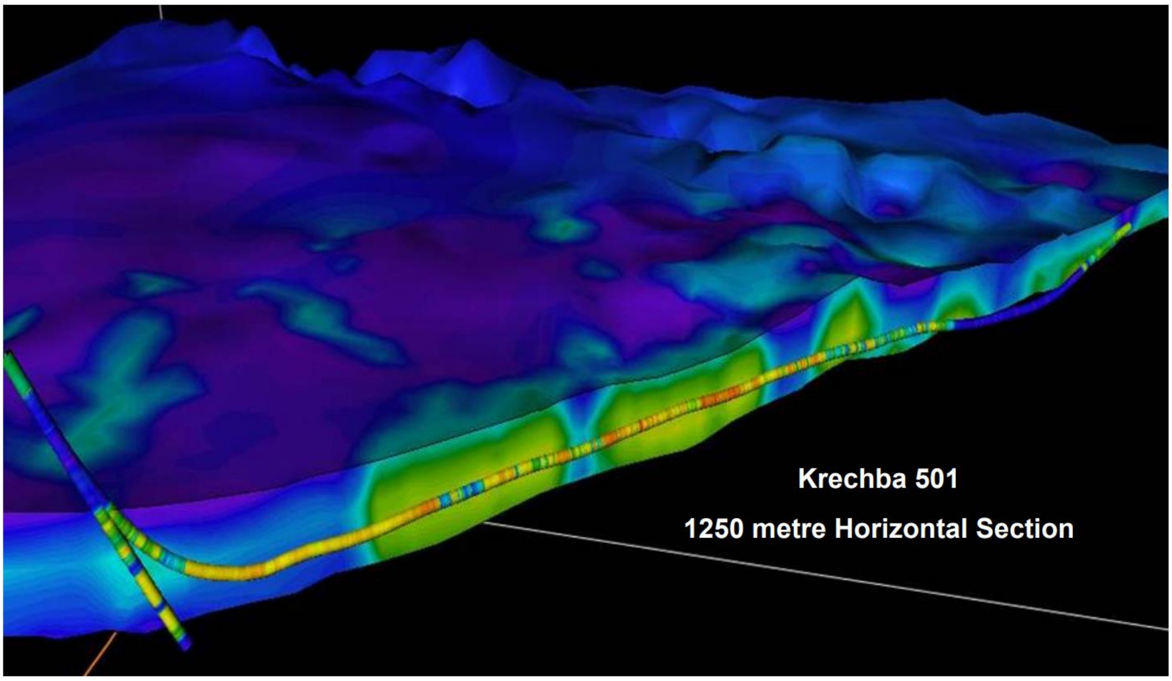


Figure III.7: Kb-501 one of the 3 injection wells.[22]

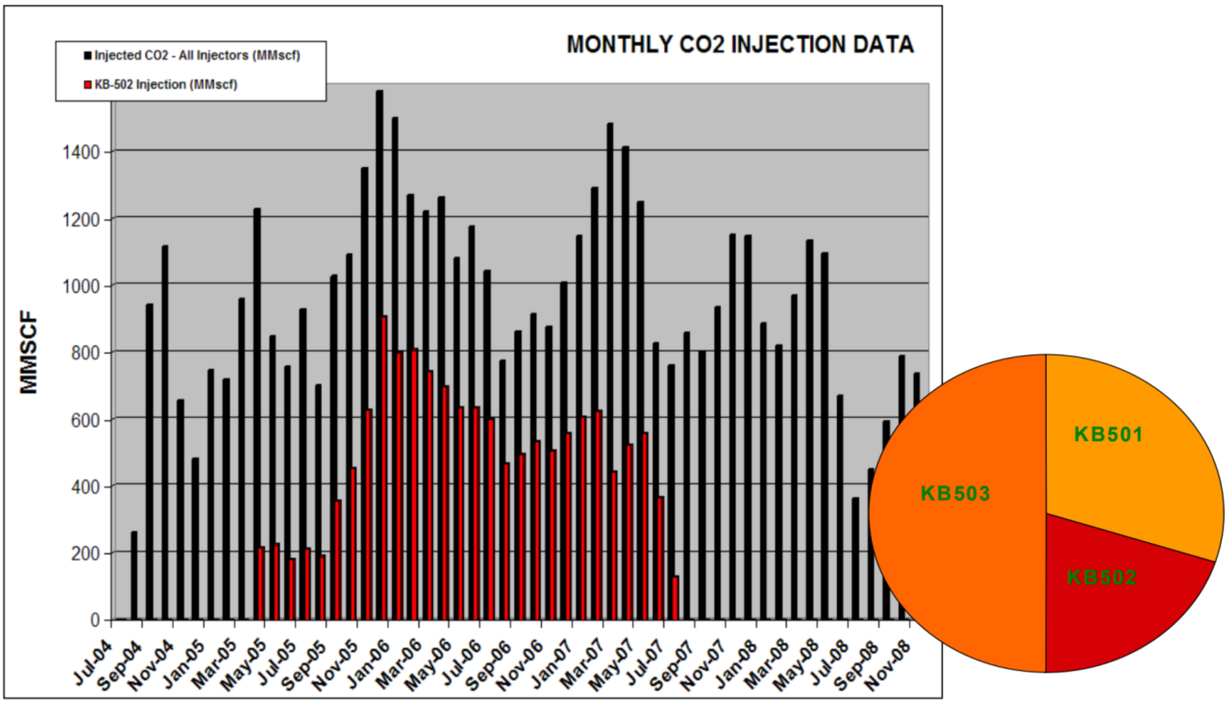


Figure III.8: CO2 injection history.[29]

III.2.4 Risk Assessment:

Risk assessment is a crucial part of the CCS project, before the injection started an investigation must be done to identify any potential risks. Starting from pre-injection data collection to identify any leakage pathways, moving to core analysis assessed the caprock’s integrity. The risk assessment is necessary to choose the monitoring methods that will work on detecting and addressing leakage risks.[30]

III.2.4.1 Leakage Risk Based on Pre-injection Information in Krechba:

- **Wells:**

Statistical data on well blowouts (defined as uncontrolled leakage from a well, no matter how small) from oil and gas operations in general can be used to estimate a likelihood of approximately 1% that a CO2 injector well will blowout in the project lifetime.[30]

There is low likelihood of CO2 contacting any of the inactive wells for a very long time excluding possibly KB-5 which was reported to have a slight leak and more so, KB-4 since it is near injection wells. Although, an occurrence of blowout from these wells is a rare event in terms of probability there is always the potential of a disastrous event occurring. Consequently, their credibility ought to be checked frequently while it is yet possible that they will need to be deactivated. It was found that the effect of proper abandonment procedures can reduce the amount of CO2 leakage by these wells to even negligible volumes. The leakage of brine is equally less of a concern because it is active by minimal pressure driving forces.[31]

- **Faults and Fractures:**

With respect to leakage through faults and fractures, the static and post-closure periods are not a concern due to the record of gas accumulation and the long-term pressure decline expected in the system due to gas production. However, the injection period will produce overpressures that are of concern.

Exploiting these existing natural access points, scientists intended to inject CO2 at a pressure that would further fracture the designated sedimentary formations specifically layers C10.2 and possibly C10.3 thereby enhancing its capability to receive CO2. Such pressure was applied to exclude the new fractures penetrating through C20 layer which contains significant emergent freshwater resources (USDW).

Some of this CO2 may transition upward through fractures which re-open in the sealed layer, and fill them, although the notion of leakage may not apply because the storage layer includes these layers. Thus, it can be noted that possible fractures may not be limited to the identified levels, but could also spread upwards. Due to this possibility, potential of leakage of CO2 from these fracture into the USDW is not high, though in the event it happens, it is fatal. Hence, using data from previous studies, the risk for leakage of CO2 through faults and fractures is regarded as being low.It is also important to clarify that brine leakage through these pathways is also viable at a minimal level.[31]

III.2.5 Monitoring methods:

Monitoring is an essential part of safe CO2 geological storage, in Krechba monitoring technologies were in place to ensure safety and to overcome all the possible risks.

A Joint Industry Project (JIP) was set up in 2005 to monitor the CO2 storage process using a variety of geochemical, geophysical and production techniques over a 5 year period. A pre-injection 3D seismic survey was acquired in 1997 but this was principally focused on imaging the reservoir section and not the overburden. This data was reprocessed in 2006 but this did little to improve the imaging of the overburden section.[32]

III.2.5.1 Screening and selecting monitoring technologies applied at In Salah:

Initial monitoring and verification program using the Boston Square.[26]

In addressing the challenge of monitoring storage, the In Salah CCS project used a very comprehensive approach. They first of all established the potential leakage risks that are possible in their firms and then adopted the chosen methods for detecting and managing the same. As the proposed project intended to be a large-scale pilot scale, techniques that offered useful information on CO2 behavior in the deep saline formations were preferred. Affordability was another important factor taken into account in order to guarantee that the selected techniques provide reasonable value for money. The project incorporated state-of-the-art monitoring practices to continually monitor the movement of the CO2 plume through the use of 4D seismic. This has provided a strong foundation for post-injection monitoring not only for the In Salah project but for any future CCS initiatives. It should be noted that each Boston Square assessment is unique to any given site.

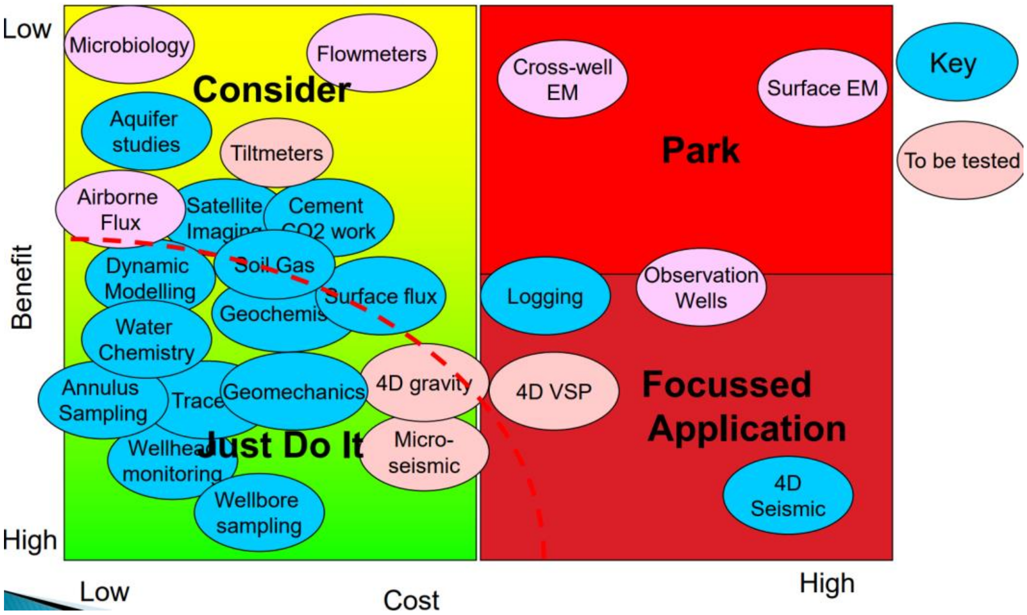


Figure III.9: Monitoring technologies evaluation. [33]

III.2.5.2 Monitoring in In Salah Project:

a. Pre-injection data acquisition:

Due to the challenges involved in ensuring that the chosen site is suitable for CO2 storage, prior to the injection of CO2 that began in August 2004, a series of pre-injection data collection program were initiated. Key activities in the gas field development were complemented by this program with the major elements emphasizing the aspects of CO2 storage. These consisted of some pre-injection investigations such as coring and geophysical logging to determine the characteristic of the reservoir units as well as the caprock viability and correlation, shallow water and soil gases surveys to set base line of leakage.

A pre-injection data collection programme was initiated prior to the start of injection in August 2004. This data collection programme was mainly focused on the gas field development, but with certain important components focused on CO2 storage. This included the baseline 3D seismic survey (1997), extensive core sampling and logging programmes (including image logs) in the new development wells and the CO2 injection wells, shallow aquifer sampling and headspace-gas sampling throughout the overburden sequence. A soil gas survey was also conducted around each of the new injection wells and samples were collected from the shallow aquifer water wells at the accommodation camp and the Central Processing Facility (CPF).[34]

b. Monitoring methods used in In Salah:

- **3D/4D seismic:**

In 2009, a new seismic survey was specifically acquired to gain a clearer picture of the rock formations above the CO2 injection zone (overburden). This survey was designed with a wider viewing angle and incorporated data from multiple directions (multi-azimuth) to better identify any potential fracture zones in the rock. The focus of this survey was on the northern portion of the storage site, where three CO2 injection wells, four existing wells, and two production wells are located. This emphasis makes sense considering that 75% of the injected CO2 was targeted for this northern area.

Integration of the seismic data with InSAR, micro seismic and subsurface datasets and models has allowed detailed models of the rock mechanical response to CO2 injection to be inferred.[35]

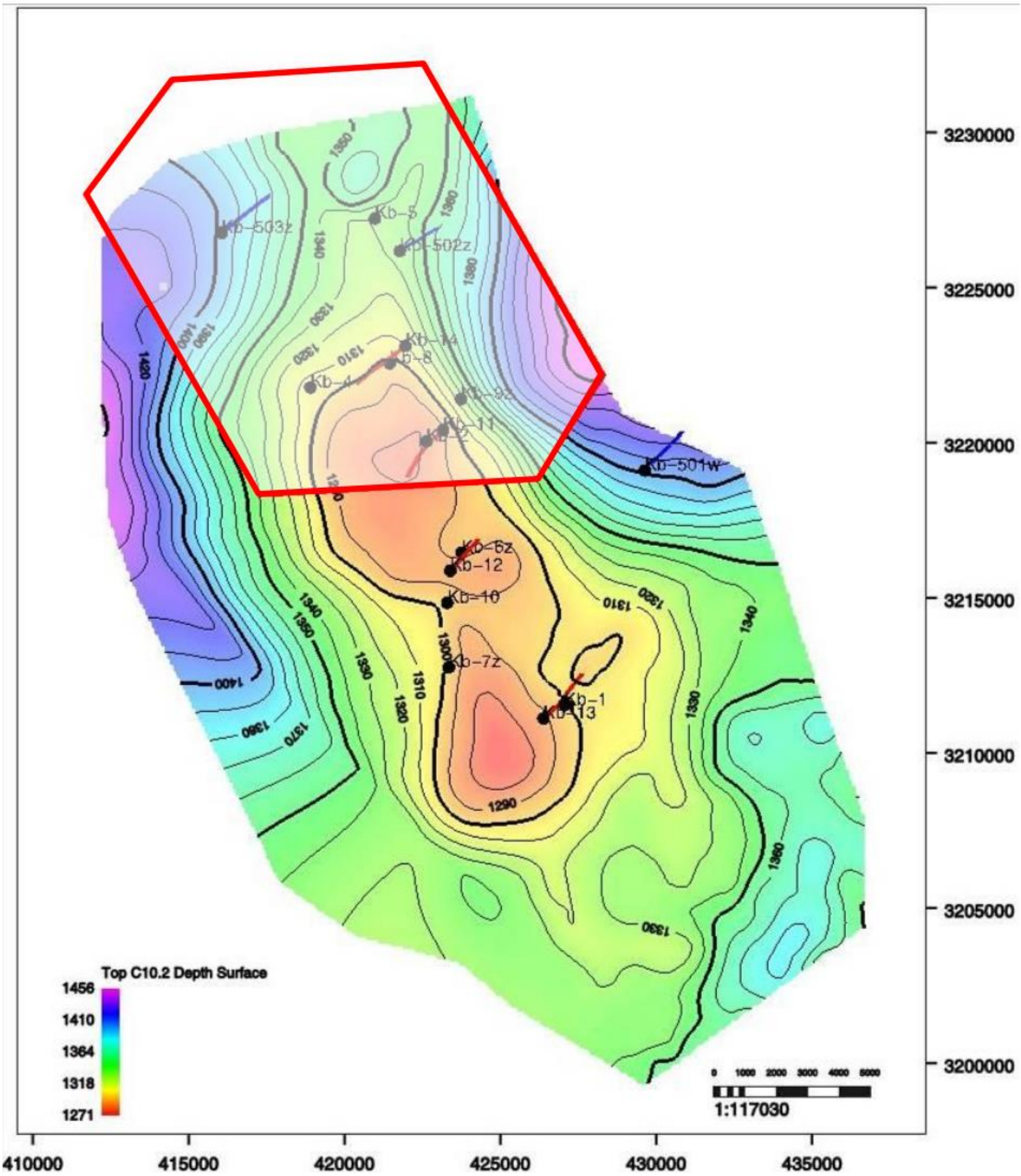


Figure III.10: Krechba 2009 seismic survey.[36]

- **InSAR (Interferometric Synthetic Aperture Radar):**

InSAR has been used for the CO2 storage monitoring in In Salah, [35]. Millimeter-scale ground movement detection is possible thanks to InSAR (Interferometric Synthetic Aperture Radar). This technology has proven particularly useful at the In Salah CCS site. By combining satellite data with computer models of rock mechanics, InSAR can monitor how the ground responds to pressure changes deep underground caused by CO2 injection. This capability addresses a crucial aspect of CO2 storage – managing injection pressure to ensure safe and secure storage. InSAR offers a cost-effective solution, allowing frequent surveys (every 8 to 30 days) to track injection-related ground movements. However, it's important to note that interpreting the results accurately requires careful data processing and robust rock mechanics models.

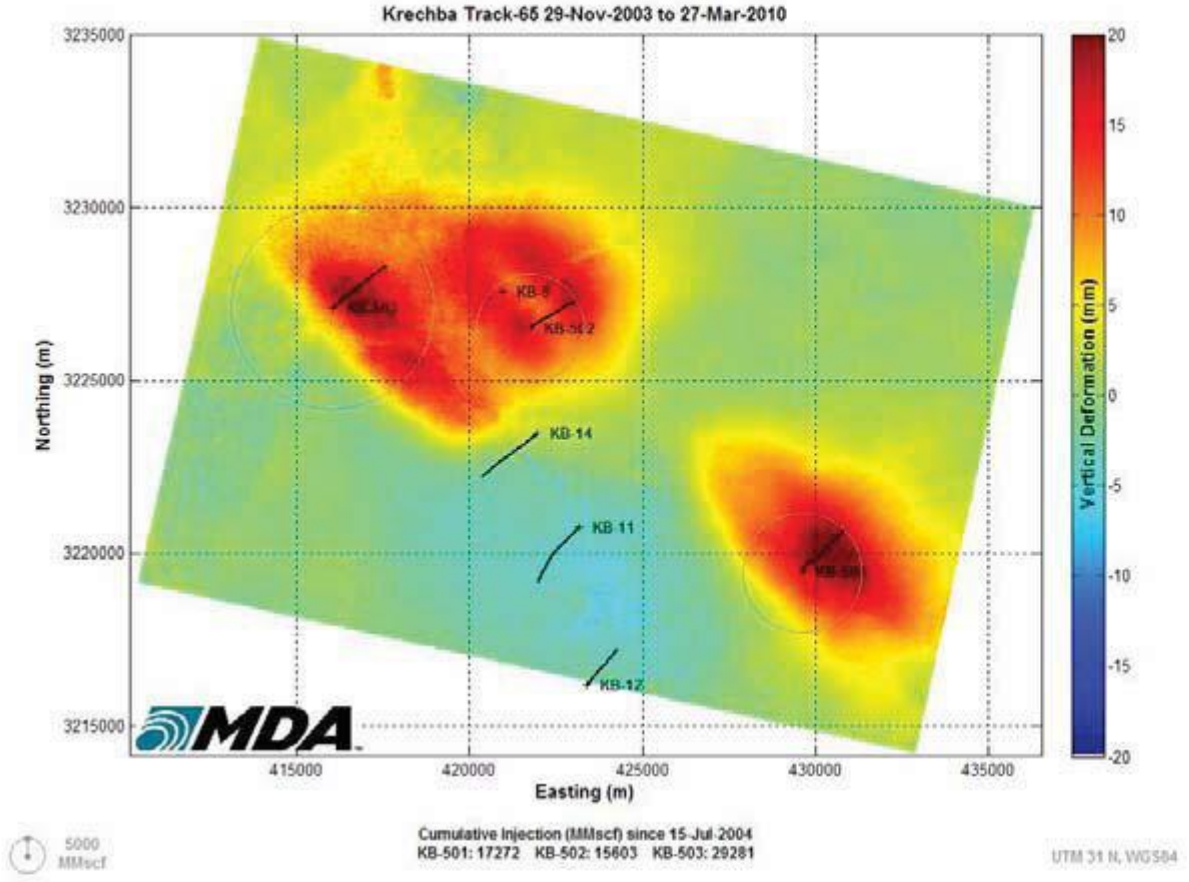


Figure III.11: Image generated by InSAR (at Krechba).

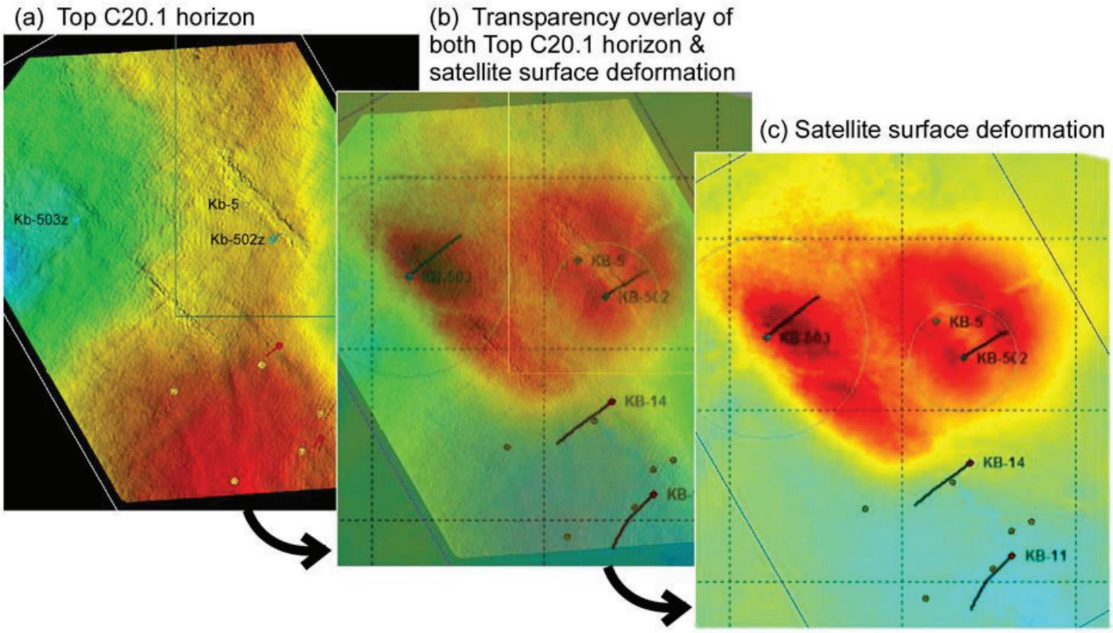


Figure III.12: NW-SE linear features seen on 2009 3D seismic data compared with InSAR surface deformation data.[36]

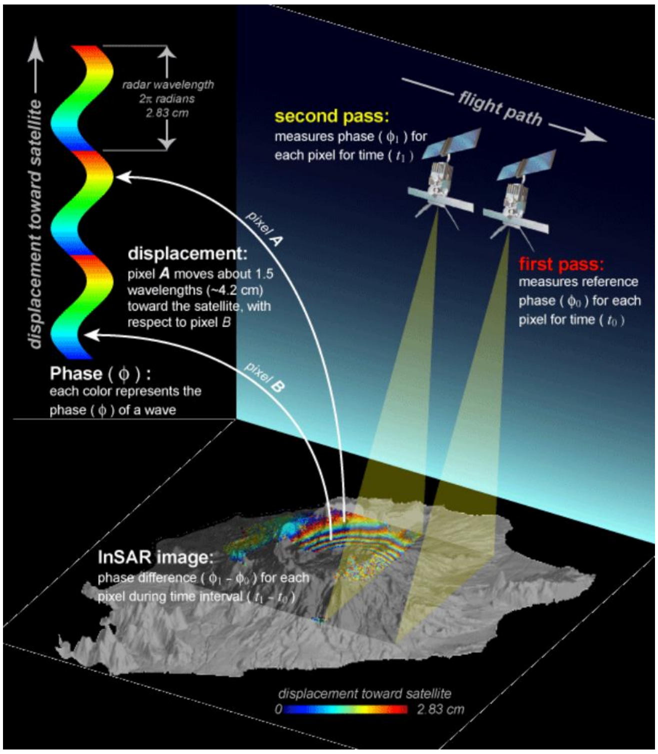


Figure III.13: Satellite imagery (by InSAR).[36]

- **Microseismic data:**

Microseismic monitoring was conducted using a pilot well drilled 500 meters above the injection well KB-502. This well housed a set of geophones that could detect tiny vibrations in the rock. Since mid-2009, the data has revealed over 1,000 microseismic events, most likely triggered by the CO2 injection process.[37]

While the current setup with a single well limits precise location of these events, analysis of the data, including arrival times of different wave types and event timing, suggests a strong correlation with CO2 injection. This information, combined with other monitoring data, provides valuable insights into the effectiveness of the injection process.

- **Wellhead sampling and CO2 tracers:**

To track CO2 movement and identify its source, a wellhead sampling program was established, collecting fluid samples every two months. To distinguish injected CO2 from natural sources, unique tracers were added to each injection well. This proved particularly useful in confirming that CO2 detected in production wells wasn't from the injection process. However, tracers also identified two instances of CO2 breakthrough: once to an appraisal well in 2007 (confirmed to be from a nearby injection well), and another to a production well in 2012 (as predicted by simulations).[38]

Other methods such as: **Core analysis, Shallow Aquifer wells** and **Surface flux Monitoring** were also used for CO2 monitoring purposes at Krechba.

III.2.6 Risks and monitoring:

After identifying the main risks that could be faced during the CO2 storage, a monitoring programme is planned.

Table III.2: Risks and monitoring at Krechba.[39]

Risk	Monitoring Technologies
Injection Well Problems	Ongoing pressure monitoring, continuous wellhead and annual downhole or through casing logging
Early CO2 Breakthrough	Modeling, tracers, seismic imaging, observation wells, fluid sampling, wellhead and annulus monitoring
Vertical leakage	Seismic imaging, microseismic, shallow aquifer monitoring, soil gas sampling,

	surface flux, gravity, tiltmeters, satellite imagery
Wellbore leakage	Annulus monitoring, soil gas sampling, through casing logging.
Old wellbore integrity	Annulus pressure monitoring and CO2 surface flux monitoring

Table III.3: Risks and monitoring (during operation).[34]

Risks	**Operational and Monitoring Response**
Risk of migration to the north (2008): InSAR data and updated reservoir modelling showed increasing risk of migration to the north(potentially outside the Krechba hydrocarbon lease).	Acquisition of 2009 3D seismic; continued InSAR monitoring programme; shut-in of northern injection well KB-502; integrated and updated reservoir modelling
Loss of well integrity (2010): CO2 detected at KB-5 wellhead indicated possible loss of well integrity.	Plug-and-abandon operation at KB-5; increased frequency of wellhead inspections; additional focus on well-bore cement and CO2 geochemical reactions.
Vertical leakage into the caprock (2010): The 2009 seismic data revealed new NW linear features aligned with the stress field, and InSAR data analysis indicated possible hydrofractures.	Reduction of CO2 injection pressures; seismic reprocessing; microseismic data upgrade and analysis; integrated geomechanical modelling studies.

III.2.6.1 Integration:

The development of a CO2 plume in for storage in a reservoir is far from uniform. Laminar flow profiles and gradients help characterize and model the reservoir and need high-resolution data to accommodate such complexities. It identifies the need for complex two or more-way models that simulate the effects of several factors affecting the movement of plumes such as fluid forces, rock fracturing behavior, changes in temperatures, and chemical interactions.

By elaborating their model, studies outlined the influence of faults and fractures at the Krechba site on the subsurface migration of CO2, pointing out that they were initially ignored. The JIP that oversaw the project realized that these were some of the missing pieces of information in understanding the movement of CO2 and implications for long-term storage safely and thus went on to conduct several studies.

III.2.6.2 Monitoring results:

- **Well Integrity – Wellhead and Annulus Monitoring:**

In 2007, high concentrations of CO2 were measured in the northerly KB-5 well (an old appraisal well drilled in 1980 into the Carboniferous aquifer and not cemented across that interval when suspended) which lies 1.4 km to the NW of the KB -502 injector.[26]

Following detection of the leakage from the KB-502 injection well into the KB-5 well through the tracer analysis, KB-5 well was subsequently killed and plugged, and abandoned forever. Revised injection in KB-502 was then done before the program was put on hold again until November, 2009. For maintaining safety, surface and soil gas is still cautious in regard with KB-502. There are also monthly inspection and sampling of both existing production and injection wells that are ongoing. Interestingly, wellhead pressure data revealed a contrast: consistently operating at a pressure of approximately 273 bar/g in KB-5 before its shutdown and a rate of 5 bar/g in KB-502 during the time it was shut in. The subsequent study established that this pressure drop was in fact a wellbore integrity problem and could not be specifically attributable to the injection of CO2.

- **Satellite Imaging:**

Surface uplift has been detected over all three of the In Salah CO2 injection wells (with corresponding subsidence also observed across the gas production area).[32]
They are capable of recording any kind of alterations in the Earth's surface that might occur due to the movements of the CO2 plume underneath the ground. For example, the circular deformation at the KB-502 well may be perhaps attributed to a single fault associating the KB-502 well with the nearest well, the KB-5 well.

Experimentalists have applied computer simulations to reach the same conclusions, proving that the observed changes in the surface correspond to the results provided by the model due to the pressure rise as a result of CO2 injection. This pressure increase causes some reactions in the rock's geomechanical design resulting into the observed surface movement.

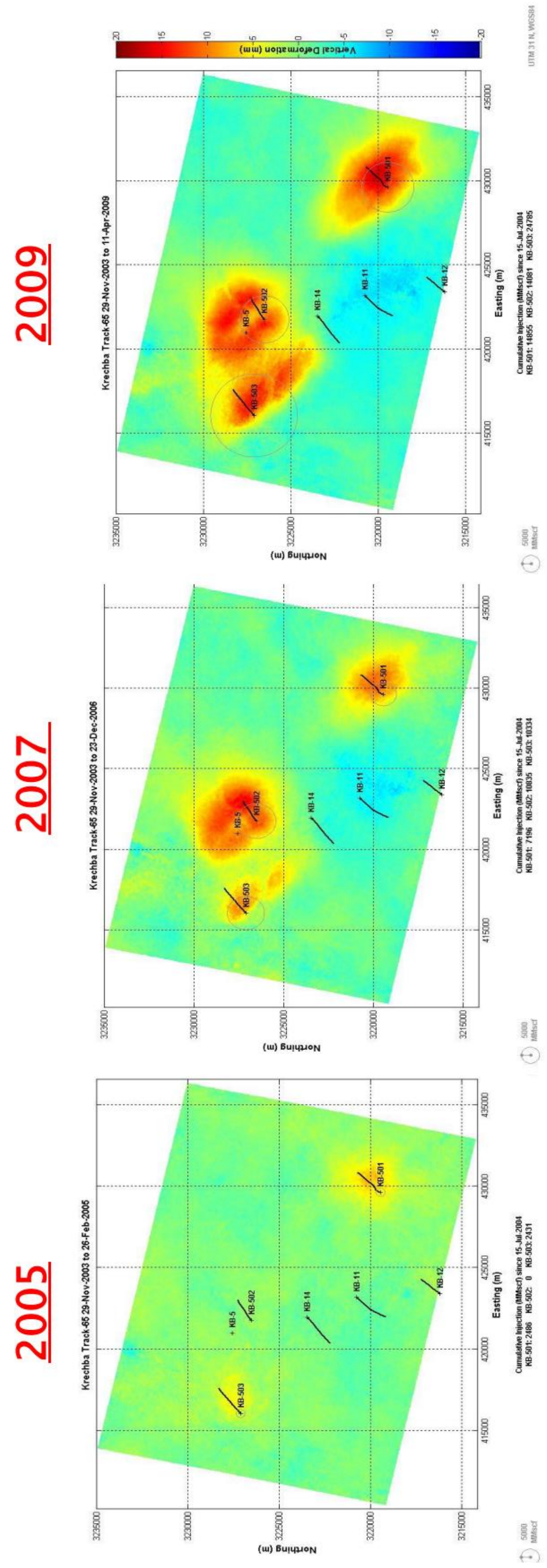


Figure III.14: Satellite imagery at Krechba throughout the years.

- **Repeat 3D Seismic:**

The 3D seismic was done again to offer an imaging of the overburden and the injection horizon, and it provided excellent results. Combining these results with the satellite data will better the monitoring programme.

Reservoir modeling and history matching of the CO2 breakthrough, new seismic data, wellhead and annulus sampling, pressure data and satellite deformation data have allowed the JIP to build up a detailed picture of the CO2 plume around injection wells KB -502 and KB-503.[40]

III.3 The project outcomes:

In this section we will analyse the complexities faced during the CO2 injection in Krechba, as well as identifying the key factors that led to the ground deformation and the CO2 leakage.

III.3.1 Krechba surface deformation:

The InSalah CCS project is one of the first CO2 projects in the world, where CO2 coming from several gas fields was injected through three injection wells (Kb-501, Kb-502, Kb-503).

To ensure adequate CO2 flow-rates across the low-permeability sand-face, the In Salah Gas Project decided to use long-reach (about 1 to 1.5km) horizontal injection wells.[34]

The permeability of the storage site was relatively low, therefore the need to use long reach horizontal wells was necessary to increase injection capacity by accessing a larger area of the reservoir.As mentioned before, InSAR (Interferometric Satellite Aperture Radar) was used to monitor the CO2 injection.In the fall of 2006, a preliminary reservoir-geomechanical analysis conducted at the Lawrence Berkeley National Laboratory (LBNL) using the TOUGH-FLAC numerical simulator indicated that surface deformations on the orders of centimeters would be feasible.[41]

Even though, at the beginning In Salah JIP viewed that no significant ground deformation will occur as result of the solid overburden and the deep reservoir.

Shortly after this, LBNM decided to use InSAR to detect any ground surface deformations related to the CO2 injection, InSAR data were acquired and analyzed by Tele-Rilevamento (TRE).[40]

In 2007 the results were published, and indeed a surface deformation was detected, this uplift could be clearly related with each injection well. with uplift bulges of several km in diameter centered around each injection well.

Measured uplift occurred within a month after start of the injection and the rate of uplift was approximately 5 mm per year amounting to about 1.5 cm in the first 3 years of injection.[33]

Several methods were used to detect the surface up lift and the results were close (The observed surface uplift rate is around 5 mm/year).

Forward and inverse modelling of the subsurface pressure increased.[33]

The increase of the subsurface pressure was mainly caused by the injection of the CO2, therefore what led to the surface to the ground up lift was the propagation of the subsurface pressure increase.

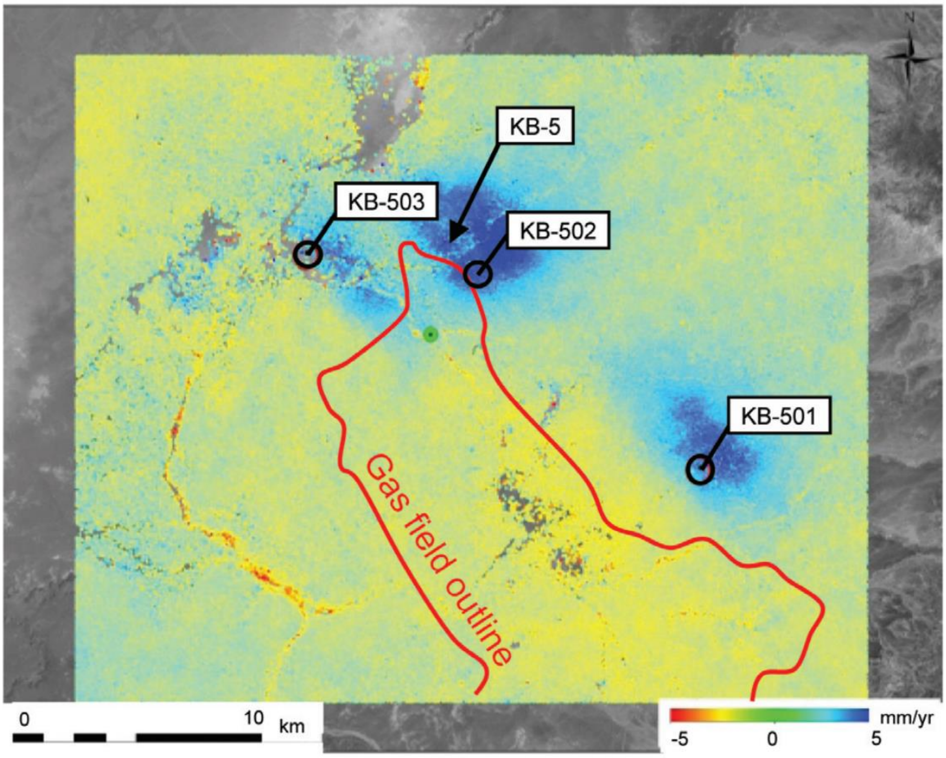


Figure III.15: PSInSAR velocity map (Envisat) over the In Salah area for the period December 2003 to March 2007**.** [42]

Previous studies focused on the Kb-502 injection well, where a double-lobe uplift pattern has been observed in the ground deformation data. The observed uplift patterns at KB-501 and KB-503 have single-lobe patterns,but they can also indicate a deep fracture zone mechanical response to the injection.[41]

To further explain this, the up lift that occurred in Kb-501 and Kb-503 was a single lobe uplift; which means the round rose in a single rounded bump, in the other hand at Kb-502 the ground surface rose in a pattern with two higher points, and this is called double lobe uplift pattern.

III.3.2 Surface deformation around the injection wells:

As discussed before, surface deformation was detected around the injection wells using InSAR, the uplift was detected nearby all three wells. A double lobe was observed around the injection well Kb-502 unlike the other two injection wells.

III.3.2.1 Kb-501 and Kb-503:

Studies has shown that the observed uplift nearby the two wells is related to poro-elastic caused by the injection of the CO2 in the reservoir (20 m). Results showed that a constant injection rate over a period of 3 years, with an overpressure in the reservoir in the order of 10 MPa, could result in a ground surface uplift of 1.2 cm. some pressure-induced deformations within a 100-m-thick zone of the lower caprock could play a significant role in the observed ground uplift.[43]

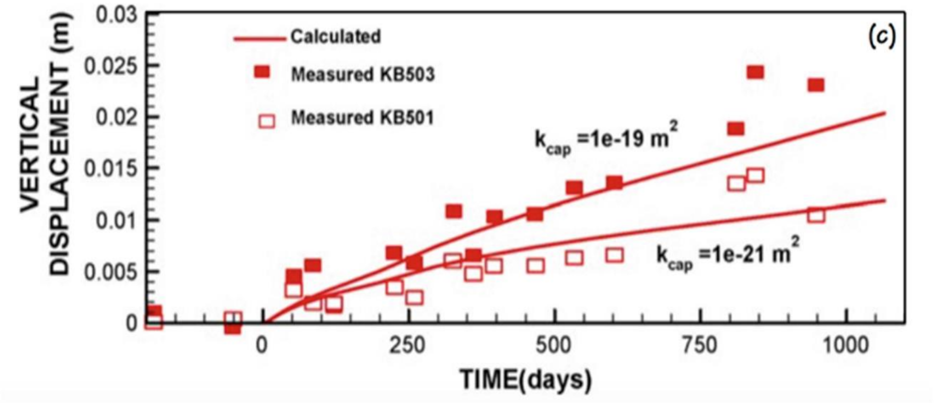


Figure III.16: Comparison with data at KB501 and KB503 for varying caprock permeability. [44]

Interestingly, when they set the caprock to be less permeable in their model (meaning fluids like CO2 would flow through it with difficulty), the ground movement could be entirely explained by the expansion of the CO2 storage zone. This matched the observations at the KB-501 injection well (see Figure 2c). On the other hand, if the caprock was more permeable (allowing easier fluid flow), the model predicted increased pressure within the caprock itself, causing more substantial ground uplift, which is what they saw at the KB-503 injection well.

III.3.2.2 Kb-502:

At the KB502, the injection scheme has been more complex with more variations of the injection rates and the uplift pattern is also more complex with two parallel uplift lobes rather than one single uplift lobe.[28]

The two uplift lobes were interpreted to be caused by pressure diffusion along two parallel permeable zones within the reservoir. An alternative interpretation of this pattern was presented that would signify the opening of a tensile fracture at the depth of the reservoir. That would suggest that permeability at KB502 is strongly heterogeneous affected by the degree of fracturing and perhaps by intersecting faults.

III.3.2.3 Summary of the KB-502 Injection Well Deformation:

This study analyses the ground movement (deformation) observed above the KB-502 CO2 injection well. Satellite data shows a unique double-lobed uplift pattern, different from the single-lobed pattern seen at other wells. Several interpretations suggest this pattern is caused by a vertical fracture zone opening due to increased pressure from CO2 injection. This interpretation is supported by recent 3D seismic analysis confirming the presence of such a zone intersecting the well.Studies by analysing injection data suggest a pressure increase triggered the opening (reactivation) of this pre-existing fracture zone around January/February 2006. This aligns with the timeframe when the double-lobed uplift pattern appeared in satellite data.The ground uplift increased steadily during injection, reaching about 15 mm after 2 years. Even after the well was shut in (stopped injecting) in mid-2007, some uplift remained (around 20 mm) and a slow subsidence phase began.

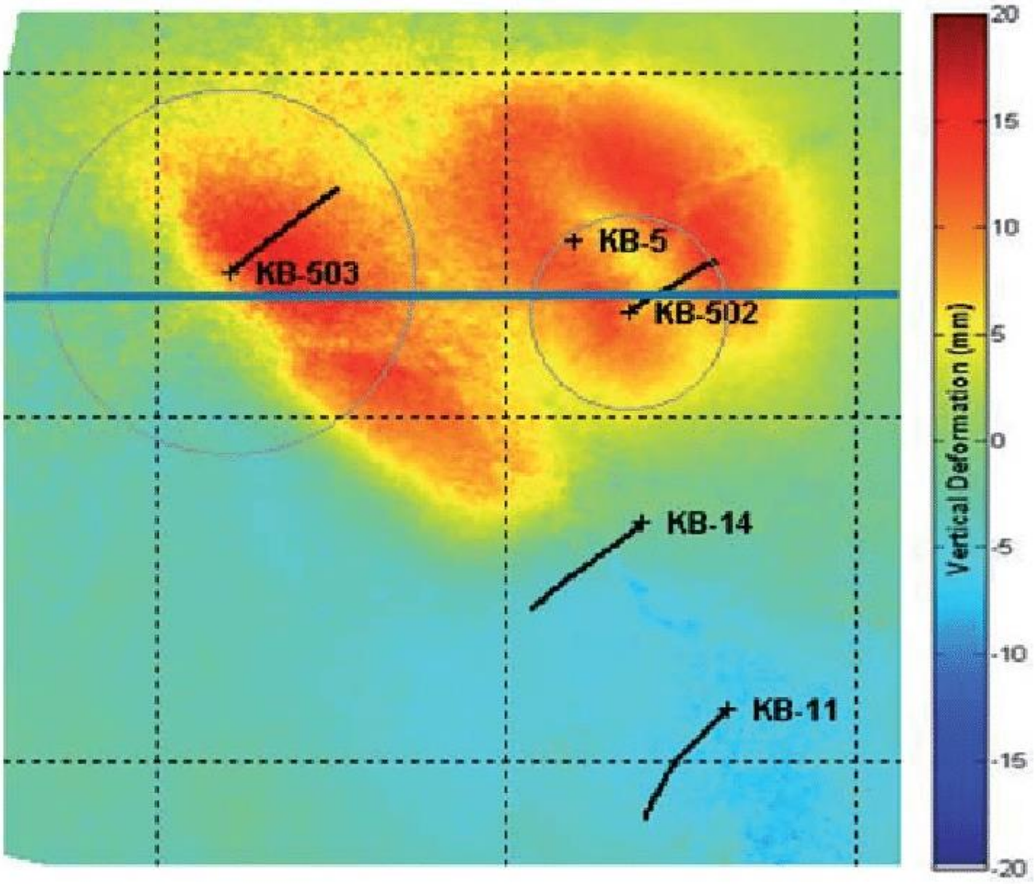


Figure III.17: injection wells (KB-502 and KB-503) and InSAR vertical surface displacement pattern.[45]

A further valuable constraint to the subsurface plume development was gained by the detection of CO2 breakthrough at a suspended appraisal well (KB-5) 1.3 km to the NW of injection well KB-502. Tracer analysis confirmed that the CO2 detected at KB-5 came from KB-502. Reservoir modelling and history matching of the CO2 breakthrough, pressure data, and satellite deformation data have allowed to build up a detailed picture of the CO2 plume around injection well KB-502. The detection of CO2 at the KB-5 wellhead has generated considerable interest, because the greatest risk of CO2 leakage from geological storage sites is expected to be associated with old wells.[40]

III.3.3 Ground uplift around the injection well Kb-502:

In 2007, an important leak was detected in KB-5, this abandoned well is situated the NW of injection well KB-502. It should be noted that the old wells always presented a weak point for CCS projects.Different tracer chemicals (perflurocarbons) have been used to ‘tag’ the CO2 injected at each injection well, so that any CO2 detected,can be differentiated from the natural CO2 in the subsurface and traced back to an individual injection well.[41]

Therefore, by the analusis of the tracres, it was confirmed that the CO2 breakthrough at Kb-5 comes from the injection well Kb-502.

III.3.3.1 Old wells and the efficiency of CCS projects:

As pointed before, old wells present a weak point for CCS projects, for multiple reasons; such as:

- Integrity Issues: Over time, well casings and seals can deteriorate due to exposure to harsh downhole conditions and corrosive fluids. This can create pathways for CO2 to leak upwards and escape the storage reservoir.
- Pre-Existing Pathways: These wells could have pre-existing weaknesses like fractures or incomplete cementation that could become leakage paths for CO2.
- Limited Knowledge: Information about the well's construction details, depth, and surrounding geology might be incomplete or outdated. This lack of knowledge makes it difficult to assess the well's integrity and potential leakage risks.
- Decommissioning Challenges: Properly decommissioning old wells for CO2 storage requires specialized techniques and procedures. If not done correctly, a decommissioned well could still provide a potential pathway for CO2 leakage.

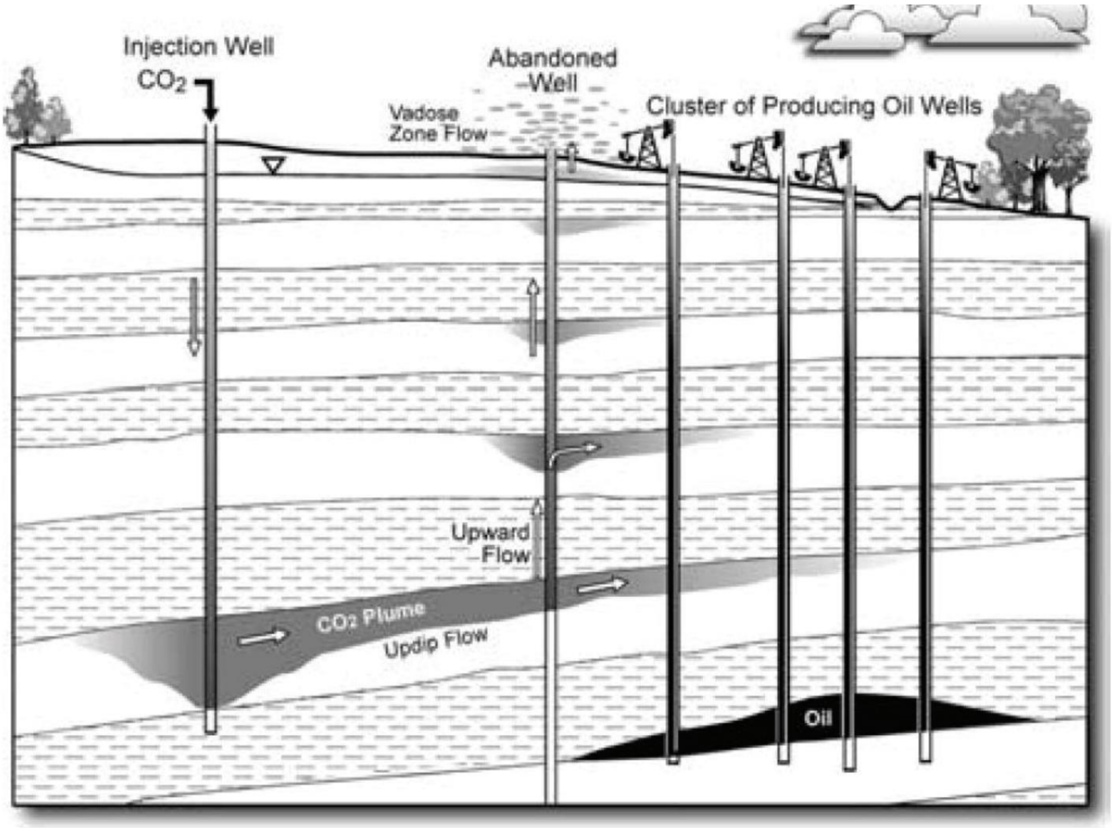


Figure III.18: scheme explaining the CO2 plume movement.

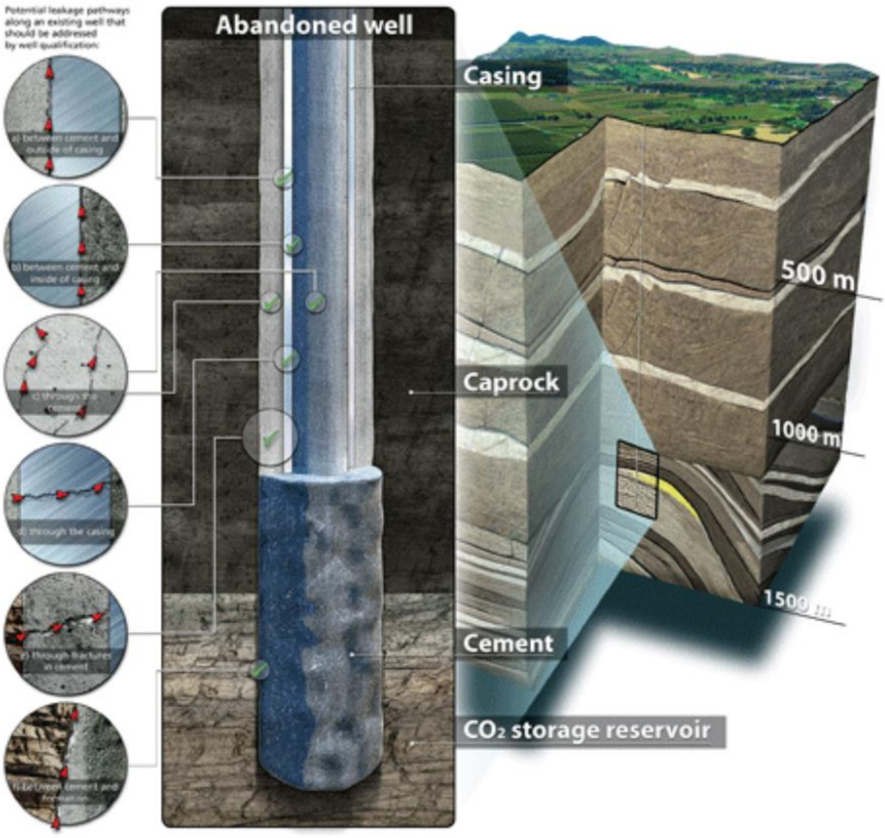


Figure III.19: old wells effecting the efficiency of the CO2 storage.[24]

In the case of In Salah CCS project, a number of old wells where in the Krechba site near the injection wells, and in this study, we will focus on the well Kb-5.

III.3.3.2 Kb-5 overview:

Kb-5 is an old well drilled in 1980 for exploration purposes by Sonatrach, this well is located in the north of Krechba CPF.

The drilling of this well ended in July 1980, and in October 1980 the well was abandoned by Sonatrach using 3 different cement plugs (3415 to 3210m (B1), 3200 to 2980 (B2) m and the third one 2850 to 2746m (B3)).

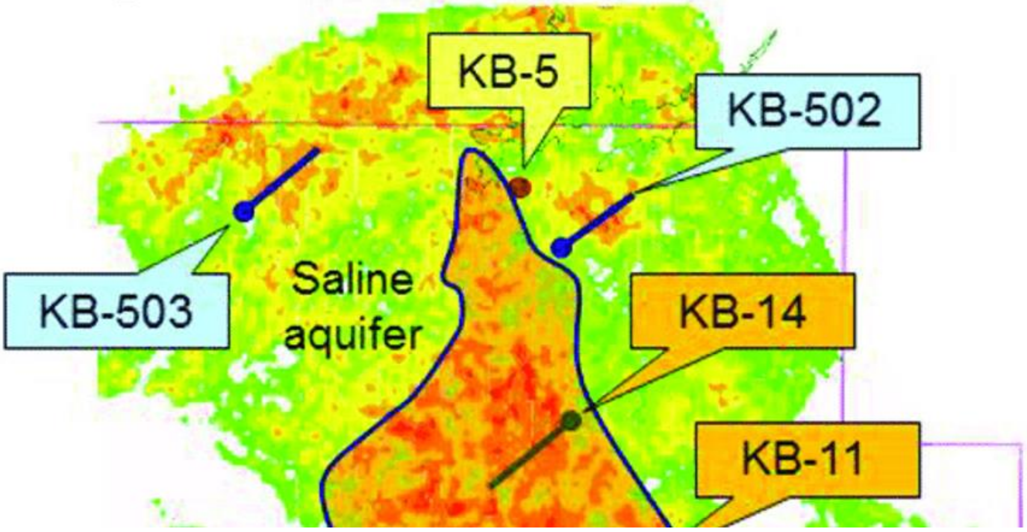


Figure III.20: Kb-5 location.

Figure III.21: Kb-5 well head after the abandonment in 1980.[24]

It should be noted that because the well is relatively old, there is lack in the documents.

Information about the well:

- Between August 2006 and June 2007, the CO2 breakthrough occurred.
- On 28 June 2007 a gas leak was noticed at the wellhead and the JV personnel immediately replaced a missing flange on the wellhead, which stopped the leak. The actual leakage at wellhead amounted to no more than a few ft3/day.
- Perfluorocarbon tracers were injected into the three CO2 injectors on 1 June 2007. The KB-502 tracer was first detected at KB-5 in March 2008 confirming that the source of the CO2 breakthrough was injected CO2. CO2 injection at well KB-502 started in April 2005.

As a precaution, the KB-502 injection well was temporarily shut-down and the compressed CO2 was injected only into the other two wells, KB-501 and KB-503. Injection at KB-502 recommenced soon after permanent decommissioning of KB-5. Still the injection was stopped again, and as for now the CO2 injection is suspended (all three wells).[40]

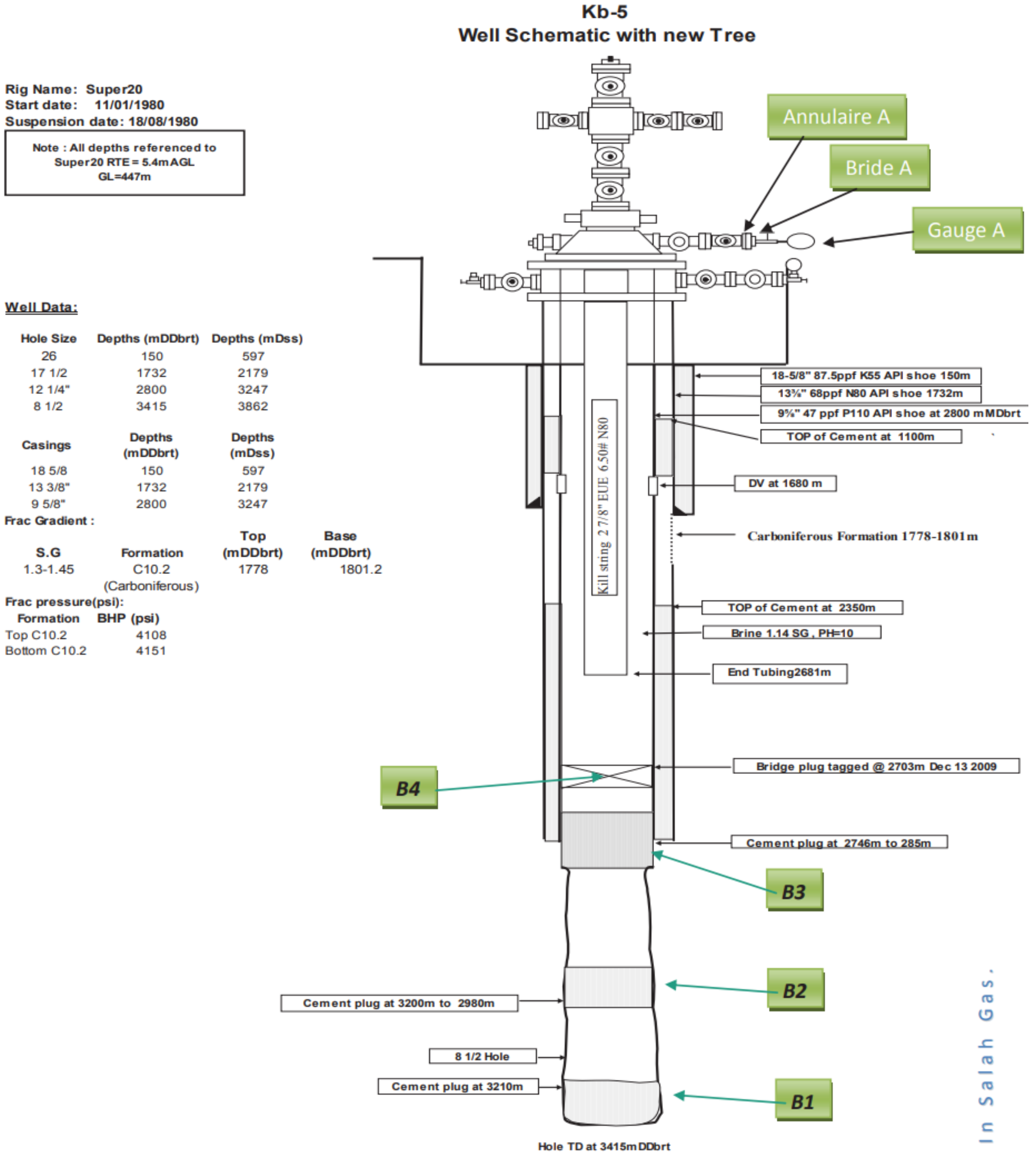


Figure III.22: Kb-5 completion after the abandonment in 1980. [38]

After the CO2 leak was detected in June 2007, the well was taken over by the JV until it was finally abandoned in 2009. This abandonment went through 3 main phases.

III.3.3.3 Summary of the KB-5 Well Leakage Scenario:

According to studies based on surface observations during abandonment operations and theoretical knowledge of CO2's impact on casing and cement, the most likely scenario for the KB-5 well leakage is:

a. **Pre-existing Corrosion:** The 95/8 casing was already corroded at the aquifer level well before CO2 injection due to the corrosive action of the saline and acidic aquifer water.

b. **Corrosion-Induced Connections:** This corrosion created connections between the aquifer and the annular space A.

c. **Acidification of Neutralizing Brine:** These connections allowed aquifer water to mix with the neutralizing brine in annular space A, causing the brine to become acidic.

d. **Further Casing Damage:** The acidic neutralizing brine deteriorated the mechanical properties of the steel casing through further corrosion.

e. **CO2 Accumulation:** CO2 arrived between 2005 and 2006 at KB-5 and accumulated in the annular space between the casing and the formation.

f. **Cement Degradation:** The supercritical CO2 reacted with minerals in the cement, causing it to degrade and crack.

g. **CO2 Migration through Cement Channels:** While carbonic acid from the CO2-water interface at the casing-formation space didn't have enough time to cause perforations, it enabled CO2 to migrate through cement channels to reach annular space B.

h. **Annular Pressure Increase and Casing Collapse:** Gaseous CO2 accumulated in annular space B, increasing pressure and causing the collapse of the already weakened casing due to acidic brine corrosion.

i. **CO2 Release to the Surface:** CO2 continued to accumulate in annular spaces A and B, eventually forcing the flange at the wellhead and leaking to the surface around July 2007.[24]

III.3.4 Deep Fracture Zone Reactivation:

According to studies, pre existing fractures were the main cause to create the pathways for the CO2 to migrate.

III.3.4.1 Fault and fracture characterization at In Salah:

In the exploration and early phase, the Krechba site was described as a low relief anticlinal structure with no significant faults. During drilling of horizontal injectors in 2002 it was recognized that fractures and small faults could play a role when the field began production. Some lost circulation zones were observed whilst drilling through the lower overburden and reservoir sections. Some of the wells encountered conductive fractures in the Visean (shale) section and the reservoir itself also shows the presence of fractures and small faults. Image logs from 4 wells were analysed and fracture interpretations performed. A strike-slip stress regime has been inferred, in agreement with regional data, where the maximum horizontal stress (NW-SE) is greater than the vertical stress. A potential fluid overpressure zone was also identified in a siltier mudstone layer in the lower Visean between 1720m and 1760m depth, having a pore pressure of 1.17 SG. The Tournasian C10 reservoir is sub-normally pressured. To date, there are no signs of fluid compartmentalisation within the Krechba gas reservoir. A stress analysis study indicated that the potential fracture shear failure pressure is around 2.1 MPa (in the current strike slip stress regime). Results from history matching the (Eclipse) reservoir simulation model appear to indicate the need for a significant permeability increase due to fractures.[46]

III.3.4.2 Deep Fracture Zone Reactivation at KB-502

Several studies investigated the unusual ground movement observed at the In Salah CO2 storage project. The complex surface uplift pattern, particularly the double-lobed shape seen at well KB-502, was attributed to the influence of pre-existing faults and fractures in the rock layers.

One study used a computer model to simulate the reactivation of a deep fracture zone under pressure from CO2 injection. Their model included a 50-meter-wide zone with a specific stiffness and predicted a maximum ground uplift of 2 centimeters after two years, with a double-lobed pattern spaced about 1.5 kilometers apart. This study also considered the potential for triggering small earthquakes due to the combined effects of pressure increase and cooling, but concluded this risk was likely low.[41]

Building on this initial work, another study developed a more detailed model of the fracture zone reactivation. This model incorporated a highly permeable and flexible zone within the rock layers, and included changes in permeability over time to better match the observed changes in pressure and ground movement. The simulated fracture zone was 80 meters wide and intersected the injection well. The model successfully reproduced the observed double-lobed uplift pattern from satellite data, with good agreement in both the shape and timing of the movement.[47]

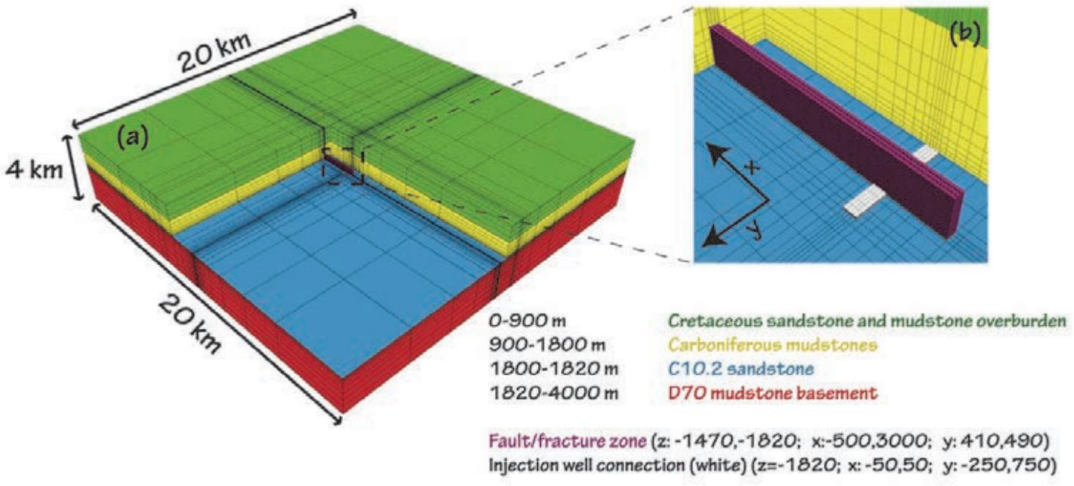


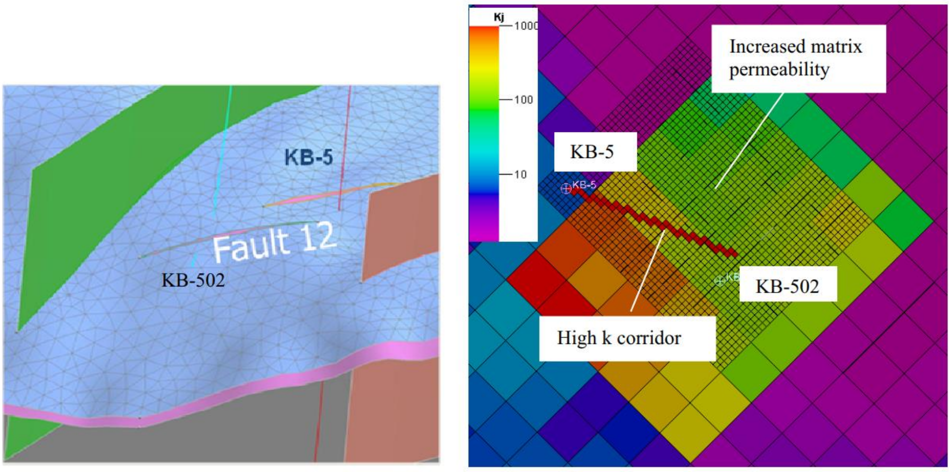
Figure III.23: (a) Computational domain by Rinaldi and Rutqvist. (b) The simulated fracture zone.[48]

To summarize, the analysis by Rinaldi and Rutqvist supported the notion of a fracture zone confined within the caprock. A sensitivity analysis confirmed that only a fracture zone confined within the caprock could allow matching of all available field information, including time evolution of pressure and deformation, and the 3D seismic indication of a CO2 saturated fracture zone extending for some thousand meters laterally.

III.3.4.3 History matching of CO2 breakthrough at KB-5:

A more complex model incorporating separate pathways for fluid flow (dual-permeability) better matched the pressure readings at the KB-502 injection well. However, it wasn't able to predict the CO2 leak at the KB-5 well within the two-year injection timeframe. Analysis by the project team suggests a pre-existing northwest-trending crack or fault intersecting the KB-502 well before CO2 injection began. This fault/fracture is likely more permeable due to its alignment with the main regional stress direction. Unfortunately, the quality of the original seismic survey data limits our understanding of the exact height of this fault/fracture.

To explore if this feature could have acted as a pathway for CO2, a simplified scenario was modeled. This involved adding a highly permeable zone connecting the KB-502 injector and the KB-5 well within the reservoir model. This model also used a refined grid around the wells for better accuracy. Additionally, the fault itself could be represented with much smaller cells compared to the original model. Based on the full-field simulation results, researchers decided to switch back to a simpler model with a single flow pathway for the reservoir. However, to account for the potential impact of fractures around KB-502, the model included increased permeability values in that specific area. These multipliers were applied differently in horizontal directions to reflect the idea that fractures might allow easier flow in certain directions.[49]



(a) (b)

Figure III.24: (a) Several faults have been identified around Kb-502 and KB-5, among which Fault 12 cuts across well KB-502; (b) A singlemedium model with enhanced local matrix permeability around KB-502, and a high permeability corridor connecting KB-502 and KB-5.[34]

Simulation was done using **TOUGH-FLAC** simulator linking the multiphase fluid flow **TOUGH2** and the geomechanical simulator **FLAC3D**.

III.3.5 Thermal Effects:

A recent study examined how temperature changes affect the behaviour of cracks (fracture reactivation) near the KB-502 injection well. Using a two-dimensional model and a specific modeling approach, the study was able to simulate the movement of the CO2 underground and suggested an earlier arrival of CO2 at the leaky well KB-5.

The study found that temperature changes likely reached the crack zone, but their impact on how easily CO2 could be injected (injectivity) was probably less significant compared to the influence of pressure. However, the study also showed that in situations with low pressure (like a very permeable reservoir), temperature stress could actually open up cracks more, leading to a pressure drop.

As mentioned in other research, these temperature stress changes might gradually weaken the cracks over time, potentially causing tiny earthquakes (microseismicity). The cooling effect, which arrives much later than the CO2 itself, squeezes the rock, opening existing cracks and making it easier to inject CO2.[50]

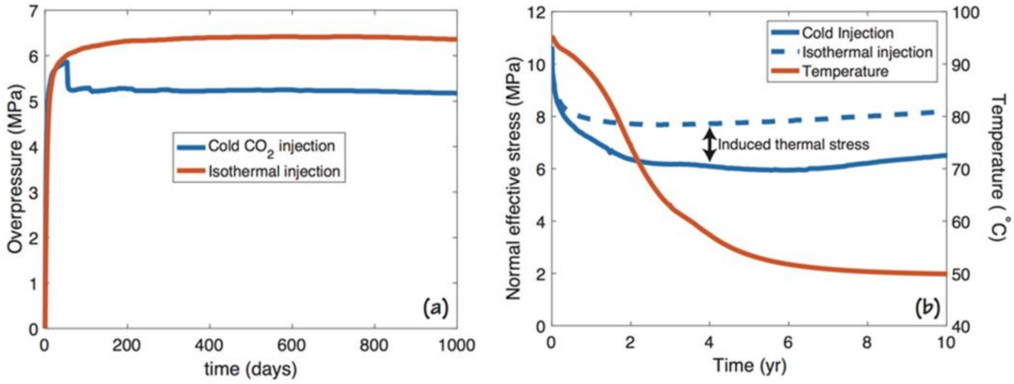


Figure III.25: Long term effect of thermal changes in a scenario similar to In Salah with low pressure injection. (a) Pressure changes highlight changes in injectivity. (b) Induced thermal stress changes that may result in microseismicity.[43]

III.3.6 The potential danger of the Kb-5 leak to potable ground water:

The potable ground water could be effected or contaminated by several factors such as, the carbon dioxide or/and saline brine.

The JIP monitoring program includes regular monitoring of the aquifer by sampling the five monitoring wells at the Krechba site. wells at the Krechba site, the April 2012 analytical results report indicated that the water aquifer had not undergone any change in its chemical, physicochemical or physical properties.[24]

Note:

As for today the project is still under investigation, all injection operations are suspended.

III.4 Conclusion:

- The In Salah CCS project is a world pioneering onshore CO2 capture and storage project, it is also the first onshore CCS project.
- The In Salah gas development project, initiated in 2004, involved the long-term storage of waste carbon dioxide associated with natural gas production at several central Algerian fields.
- The key risks in the Krechba site were injection well problems, early breakthrough of carbon dioxide at the gas production wells, vertical leakage in the formation, and well leakage
- Monitoring is an essential part of safe CO2 geological storage, in Krechba monitoring technologies were in place to ensure safety and to overcome all the possible risks.
- Surface deformation was detected around the injection wells, the uplift was detected nearby all three wells. The ground uplift occurred after few months of the injection.
- The old wells (such as Kb-5 in this case) represents a weak point for the CCS project.
- the CO2 leak at Kb-5 is primarily due to the poor state of the completion of this old well; water from the aquifer has corroded the casing over time perforations through which the neutralization brine comes into contact with the acidic aquifer water, leading to acidification of the neutralization brine, which is then thought to have corroded the internal of the casing, deteriorating its mechanical properties.[24]
- The leakage incident emphasized the importance of wellbore integrity throughout the CO2 injection process. Robust well integrity assessments and monitoring procedures are essential to minimize leakage risks.
- The project highlighted the potential impact of fractures and permeability variations within the reservoir. Future modeling efforts should consider incorporating these factors for more precise simulations.
- The importance of high-quality pre-injection geological data and continuous monitoring of pressure, seismic activity, and ground deformation was underscored. Early detection of potential issues allows for timely mitigation strategies.
- Satellite InSAR data has proven highly valuable to monitor subtle mm-scale surface deformation related to subsurface pressure changes caused by injection and production.
- The injection in Kb-502 was stopped temporally in 2007, but the injection started once again in 2008.
- The project was officially suspended in 2011, and still under investigation.

This study provides valuable insights into the technical aspects of the In Salah CCS project. However, limitations in available data, particularly regarding pre-injection reservoir characterization and long-term pressure monitoring, hinder a complete understanding of all factors influencing CO2 migration and potential leakage pathways. Future CCS projects can benefit from comprehensive pre-injection site investigations and robust monitoring programs to improve risk assessment and operational safety.

General conclusion

The fight against climate change demands a multi-pronged approach, with Carbon Capture and Storage (CCS) technology emerging as a promising contender. My dissertation has delved into the technical aspects of CCS, drawing valuable insights from the pioneering In Salah CCS project in Algeria.

Although In Salah project had problems, it serves as a valuable learning experience for future endeavors. We can use this knowledge to make CCS technology better and create safer, more dependable, and more effective ways to store CO2. Also, we need to keep studying long-term CO2 behavior, ways to monitor the environment, and how to educate the public about CCS technology.

Key learnings from In Salah:

- The In Salah project demonstrated the technical feasibility of large-scale CO2 storage in a deep saline aquifer. However, unforeseen operational challenges, including wellbore leakage and pressure-induced fault reactivation, highlighted the importance of thorough pre-injection assessments and well integrity monitoring.
- Monitoring should be part of the Field Development Plan (FDP) and routine field operation.
- QRAs should be carried out prior to injection and periodically throughout the operation.
- The main seepage risks are driven by: legacy well-bore integrity, cap-rock integrity and CO2 plume migration direction.
- Compared to hydrocarbon developments, CO2 storage projects require the integration of a wider-scope of datasets (InSAR, soil gas, seismic) over a greater aerial/vertical extent.
- Injection strategies, rates and pressures need to be linked to geomechanical modelling.
- CO2 plume development is not homogeneous and requires high resolution data for reservoir characterization and modelling.[49]
- Satellite InSAR data has been especially valuable in understanding the geomechanical response to CO2 injection, but needs to be integrated with high quality reservoir and overburden data and models.[50]
- The importance of flexibility in the design and operation of the capture, compression, and injection system.

This dissertation mainly focused on the technical aspects of CCS, recognizing limitations in data availability and the need for further research on long-term CO2 behavior and environmental impacts.

Overall, this dissertation emphasizes the potential of CCS technology for mitigating climate change while acknowledging the technical challenges that need to be addressed. By building upon the knowledge gained from projects like In Salah and dedicating further research efforts, CCS can contribute to a more sustainable future for generations to come.

Recommendations:

Future studies can explore economic considerations, social acceptance, and the integration of CCS within a broader climate change mitigation strategy.

CCS technology holds immense potential for mitigating climate change by capturing CO2 emissions from industrial sources and securely storing them underground. However, successful implementation hinges on overcoming technical challenges, ensuring environmental and social sustainability, and developing a robust regulatory framework. By addressing these aspects, CCS can play a pivotal role in the global fight against climate change and pave the way for a cleaner future.

References

[1] Anderson,S and Newell,R. Prospects for Carbon Capture and Storage Technologies.RESOURCES FOR THE FUTURE.4-29, 2003.

[2] Zhang, S., Liu, L., Zhang, L., Zhuang, Y., & Du, J. An optimization model for carbon capture utilization and storage supply chain: A case study in Northeastern China. Applied Energy, 231, 194–206. https://doi.org/10.1016/j.apenergy.2018.09.129

[3] Weikl, M. C., & Schmidt, G.Carbon capture in cracking furnaces. ResearchGate,2010.https://www.researchgate.net/publication/263272524_Carbon_Capture_in_Cracking_Furnace.

[4] Mahapatra, P. M., Aech, S., & Panda, A. K.Energy generation from coal and conversion technologies. In Elsevier eBooks,2023. https://doi.org/10.1016/b978-0-323-93940-9.00045-1.

[5] Liang,Z., Wichitpan,R., Recent progress and new developments in post-combustion carbon-capture technology with amine based solvents.ResearchGate.2015.

[6] Jurado, N., Darabkhani, H. G., Anthony, E. J., & Oakey, J. E. Oxy-fuel Combustion for Carbon Capture and Sequestration (CCS) from a Coal/Biomass Power Plant: Experimental and Simulation Studies. In Springer eBooks (pp. 177–192).2015. https://doi.org/10.1007/978-3-319-17031-2_14

[7] Lu, H., Ma, X., Huang, K., Fu, L., & Azimi, M. . Carbon dioxide transport via pipelines: A systematic review. Journal of Cleaner Production, 266, 121994.2020. https://doi.org/10.1016/j.jclepro.2020.121994

[8] THE EUROPEAN NETWORK OF EXCELLENCE ON THE GEOLOGICAL STORAGE OF CO2. CC BRGM-CO2GeoNet. https://co2geonet.com/explore-ccs/where-and-how-much-co2-can-we-store-underground/

[9] Zhang, D., Song, J.Examples of (a) structural and (b) stratigraphic traps for CO 2. . . (n.d.). ResearchGate. https://www.researchgate.net/figure/Examples-of-a-structural-and-b-stratigraphic-traps-for-CO-2-modified-from-10_fig1_260441587.2014

[10] Zhang, D., & Song, J. Mechanisms for geological carbon sequestration. Procedia IUTAM, 10, 319–327.2014. https://doi.org/10.1016/j.piutam.2014.01.027

[11] Tomić, L. T. CRITERIA FOR CO2 STORAGE IN GEOLOGICAL FORMATIONS. UNIVERSITY OF BELGRADE - FACULTY OF MINING AND GEOLOGY.2018.

[12] How do you store CO2 and what happens to it when you do? - Drax Global. Drax Global. (2021, May 14). https://www.drax.com/carbon-capture/how-do-you-store-co2-and-what-happens-to-it-when-you-do/

[13] Jessen, K.CO2 sequestration in oil/gas reservoirs, saline aquifers and coal beds. www.academia.edu.2006.https://www.academia.edu/115691366/CO2_sequestration_in_oil_gas_reservoirs_saline_aquifers_and_coal_beds

[14] IEA greenhouse gas R&D programme.Barriers to overcome in implementation of CO2 capture and storage. International Energy Agency.2000.

[15] Kgi-Admin, & Kgi-Admin. Oil & gas field profile: In Salah Complex Conventional Gas Field, Algeria. Offshore Technology.2021.https://www.offshore-technology.com/data-insights/oil-gas-field-profile-in-salah-complex-conventional-gas-field-algeria/?cf-view&cf-closed

[16] Hamida, H., Belkhatir A. localisation du site gazier In-Salah. Source : In-Salah Gas JV. (n.d.). ResearchGate. https://www.researchgate.net/figure/localisation-du-site-gazier-In-Salah-Source-In-Salah-Gas-JV_fig1_289130212

[17] Leung, D. Y., Caramanna, G., & Maroto-Valer, M. M. An overview of current status of carbon dioxide capture and storage technologies. Renewable & Sustainable Energy Reviews, 39, 426–443.2014. https://doi.org/10.1016/j.rser.2014.07.093

[18] Haddadji R,. The In-Salah CCS experience Sonatrach, Algeria.21 September 2006.

[20] In Salah Gas, ISG Operations, September 8,2007.

[21] In Salah Gas, Apercu technique, 2004.

[22] Haddadji R,. The In-Salah CCS experience Sonatrach, Algeria.21 September 2006.

[23] Newell, A., Kirby, G., Sorensen, J., & Milodowski, A. The Cretaceous Continental Intercalaire in central Algeria: Subsurface evidence for a fluvial to aeolian transition and implications for the onset of aridity on the Saharan Platform. Palaeogeography, Palaeoclimatology, Palaeoecology, 438, 146–159.2015. https://doi.org/10.1016/j.palaeo.2015.07.023

[24] Belkacem D., Haireche Y. L'efficacite du stockage du CO2 a Krechba-In Salah : Par l'investigation sur la fuite du CO2 au niveau du puits Kb-5, Master dissertation, Boumerdes University (Algeria), p.129, 2012.

[25] Ringrose, P., Mathieson, A., Wright, I., Selama, F., Hansen, O., Bissell, R., Saoula, N., & Midgley, J. The In Salah CO2 Storage Project: Lessons learned and knowledge transfer. Energy Procedia, 37, 6226

[26] Goertz-Allmann, B. P., Kühn, D., Oye, V., Bohloli, B., & Aker, E. Combining microseismic and geomechanical observations to interpret storage integrity at the In Salah CCS site. Geophysical Journal International, 198(1), 447–461.2014.

https://doi.org/10.1093/gji/ggu010

[27] Ringrose et.al. [2009] Plume development around well KB-502 at the In Salah CO2 storage site, First Break, 27, , 85-89.2009.

[28] Ringrose et.al. [2009] Plume development around well KB-502 at the In Salah CO2 storage site, First Break, 27, , 85-89.2009.

[29] Forsyth, J,. CCS operating flexibility experience from In Salah.

[30] Jordan, PD and SM Benson. Well blowout rates and consequences in California oil and gas district 4 from 1991 to 2005: implications for geological storage of carbon dioxide, Environmental Geology.2008.

[31] Oldenburg, C. M., Jordan, P. D., Nicot, J. P., Mazzoldi, A., Gupta, A. K., & Bryant, S. L.. Leakage risk assessment of the In Salah CO2 storage project: Applying the certification framework in a dynamic context.2011. Energy Procedia, 4, 4154–4161. https://doi.org/10.1016/j.egypro.2011.02.360.

[32] Mathieson, A., Midgely, J., Wright, I., Saoula, N., & Ringrose, P.In Salah CO2 Storage JIP: CO2 sequestration monitoring and verification technologies applied at Krechba, Algeria. Energy Procedia, 4, 3596–3603. 2011. https://doi.org/10.1016/j.egypro.2011.02.289

[33] Mathieson, A., Midgley, J., Dodds, K., Wright, I., Ringrose, P. and Saoula, N., CO2 sequestration monitoring and verification technologies applied at Krechba, Algeria. The Leading Edge; 216-221.2010.

[34] Ringrose, P., Mathieson, A., Wright, I., Selama, F., Hansen, O., Bissell, R., Saoula, N., & Midgley, J. The In Salah CO2 Storage Project: Lessons learned and knowledge transfer. Energy Procedia, 37, 6226–6236. 2013

https://doi.org/10.1016/j.egypro.2013.06.551

[35] Vasco, D. W., Rucci, A., Ferretti, A., Novali, F., Bissell, R. C., Ringrose, P. S. Mathieson, A. S. and Wright, I. W. Satellitebased measurements of surface deformation reveal fluid flow associated with the geological storage of carbon dioxide. Geophysical Research Letters; 37, L03303.2010.doi:10.1029/2009GL041544.

[36] Iain, W,.Up-scaling CCS-In Salah Lessons.

[37] Oye, V., Aker, E. Daley, T. M., Kühn, D., Bohloli, B., Korneev, V. Microseismic monitoring and interpretation of injection data from the In Salah CO2 storage site (Krechba), Algeria; 2012, Presentated at the GHGT11 Conference, www.sciencedirect.com.

[38] Jordan, PD and SM Benson. Well blowout rates and consequences in California oil and gas district 4 from 1991 to 2005: implications for geological storage of carbon dioxide, Environmental Geology.2008.

[39] Mathieson, A., Midgely, J., Wright, I., Saoula, N., & Ringrose, P. In Salah CO2 Storage JIP: CO2 sequestration monitoring and verification technologies applied at Krechba, Algeria. Energy Procedia, 4, 3596–3603. 2011. https://doi.org/10.1016/j.egypro.2011.02.289

[40] Mathieson, A., Midgely, J., Wright, I., Saoula, N., & Ringrose, P. In Salah CO2 Storage JIP: CO2 sequestration monitoring and verification technologies applied at Krechba, Algeria. Energy Procedia, 4, 3596–3603. 2011. https://doi.org/10.1016/j.egypro.2011.02.289

[41] Rutqvist, J., & Tsang, C. A study of caprock hydromechanical changes associated with CO2-injection into a brine formation. Environmental Geology, 42(2–3), 296–305. 2002.https://doi.org/10.1007/s00254-001-0499-2

[42] Rutqvist, J., Vasco, D. Coupled reservoir-geomechanical analysis of CO2 injection at In Salah, Algeria.2009. https://doi.org/10.1016/j.egypro.2009.01.241

[43] Rinaldi, A., Rutqvist J. Modeling ground surface uplift during CO2 sequestration: the case of In Salah, Algeria.2017.

[44] Rinaldi, A., Rutqvist J. Deep Fracture Zone Reactivation During CO2 Storage at In Salah (Algeria) – A Review of Recent Modeling Studies.2019. https://doi.org/10.1007/978-3-319-99670-7_49

[45] Gemmer, L., Hansen O. Geomechanical Response to CO2 Injection at Krechba, InSalah, Algeria.2012. 10.3997/2214-4609.20144113

[46] Mathieson, A., Midgely, J., Wright, I., Saoula, N., & Ringrose, P. In Salah CO2 Storage JIP: CO2 sequestration monitoring and verification technologies applied at Krechba, Algeria. Energy Procedia, 4, 3596–3603. 2011. https://doi.org/10.1016/j.egypro.2011.02.289

[47] Rinaldi, A., Rutqvist. Forward and inverse modeling of ground surface uplift at In Salah, Algeria.2014.

[48] Rinaldi, A., Rutqvist J. Modeling ground surface uplift during CO2 sequestration: the case of In Salah, Algeria.2017.

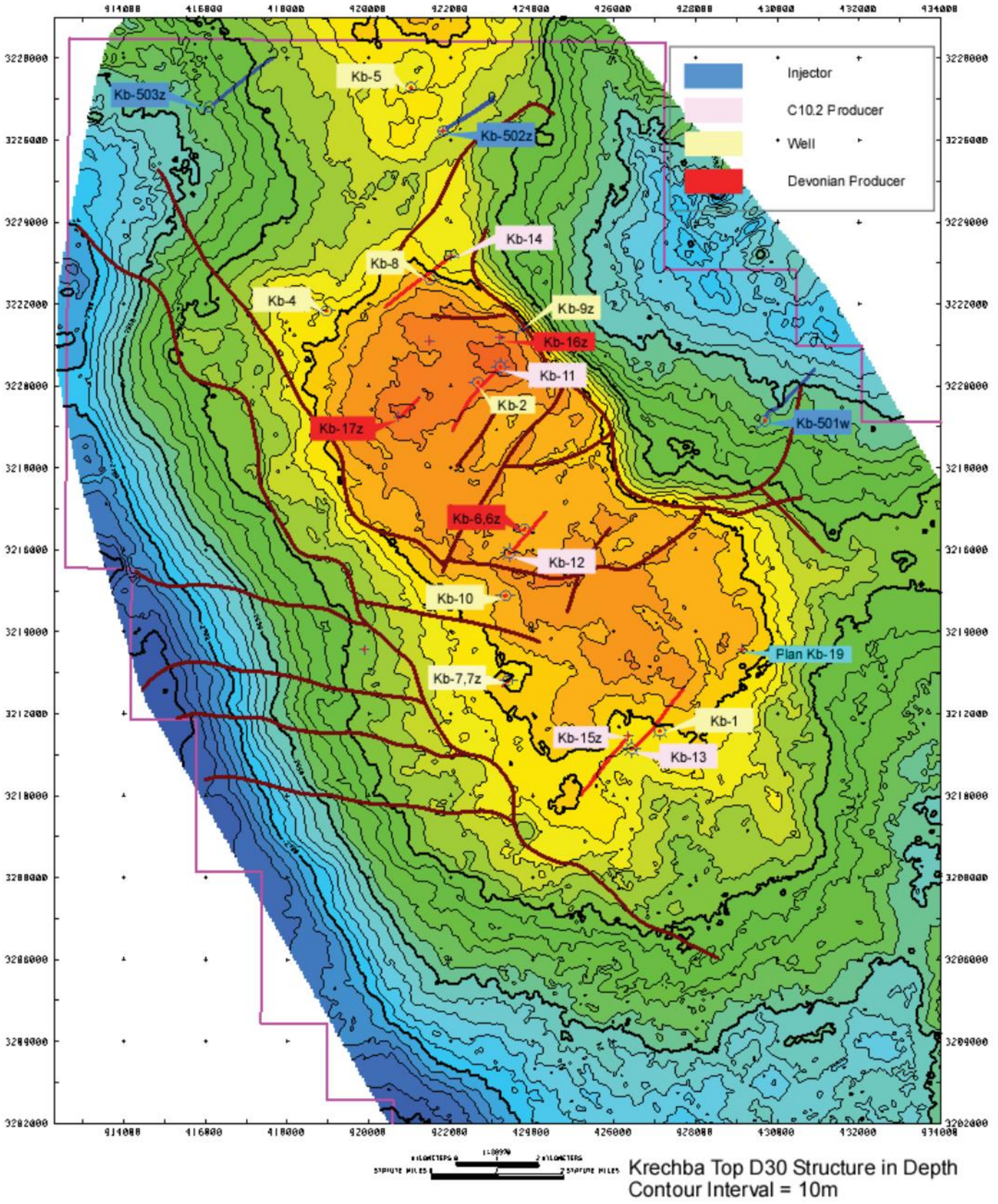
[49] Durucan, S., Shi, J., Sinayuc, C., & Korre, A. In Salah CO2 storage JIP: Carbon dioxide plume extension around KB-502 well–New insights into reservoir behaviour at the In Salah storage site. Energy Procedia, 4, 3379–3385. 2011.

https://doi.org/10.1016/j.egypro.2011.02.260

[50] Rinaldi, A., Rutqvist J. Deep Fracture Zone Reactivation During CO2 Storage at In Salah (Algeria) – A Review of Recent Modeling Studies.2019. https://doi.org/10.1007/978-3-319-99670-7_49

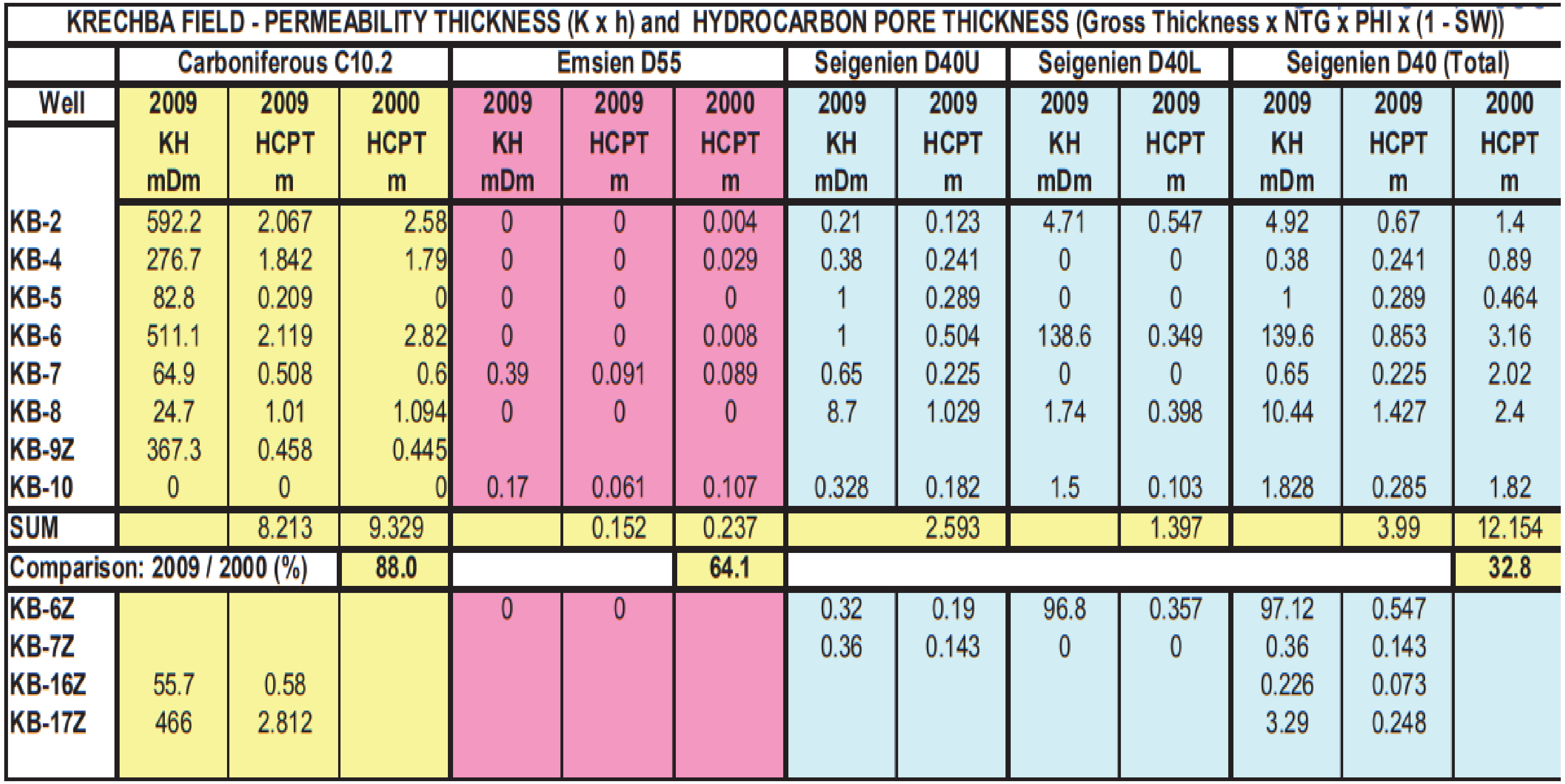
Appendix 1

Krechba Devonian reservoir 1997 3D seismic data.[51]



Appendix

Krechba petrophysics:



KRECHBA FIELD - PERMEABILITY THICKNESS (K x h) and HYDROCARBON PORE THICKNESS (Gross Thickness x NTG x PHI x (1 - SW))

	Carboniferous C10.2			Emsien D55			Seigenien D40U		Seigenien D40L		Seigenien D40 (Total)		
Well	2009 KH mDm	2009 HCPT m	2000 HCPT m	2009 KH mDm	2009 HCPT m	2000 HCPT m	2009 KH mDm	2009 HCPT m	2009 KH mDm	2009 HCPT m	2009 KH mDm	2009 HCPT m	2000 HCPT m
KB-2	592.2	2.067	2.58	0	0	0.004	0.21	0.123	4.71	0.547	4.92	0.67	1.4
KB-4	276.7	1.842	1.79	0	0	0.029	0.38	0.241	0	0	0.38	0.241	0.89
KB-5	82.8	0.209	0	0	0	0	1	0.289	0	0	1	0.289	0.464
KB-6	511.1	2.119	2.82	0	0	0.008	1	0.504	138.6	0.349	139.6	0.853	3.16
KB-7	64.9	0.508	0.6	0.39	0.091	0.089	0.65	0.225	0	0	0.65	0.225	2.02
KB-8	24.7	1.01	1.094	0	0	0	8.7	1.029	1.74	0.398	10.44	1.427	2.4
KB-9Z	367.3	0.458	0.445										
KB-10	0	0	0	0.17	0.061	0.107	0.328	0.182	1.5	0.103	1.828	0.285	1.82
SUM		8.213	9.329		0.152	0.237		2.593		1.397		3.99	12.154
Comparison: 2009 / 2000 (%)			88.0			64.1							32.8
KB-6Z				0	0		0.32	0.19	96.8	0.357	97.12	0.547	
KB-7Z							0.36	0.143	0	0	0.36	0.143	
KB-16Z	55.7	0.58									0.226	0.073	
KB-17Z	466	2.812									3.29	0.248	

	Gedinnian D30			Gedinnian D20			Gedinnian D10		
	2009 KH mDm	2009 HCPT m	2000 HCPT m	2009 KH mDm	2009 HCPT m	2000 HCPT m	2009 KH mDm	2009 HCPT m	2000 HCPT m
KB-2	64.6	1.734	2.4	12.8	0.34	0.61	2.57	0.213	1.58
KB-4	108.3	0.291	1.21	51.1	0.534	0.59	7.29	0.989	2.23
KB-5	255.5	0.878	0.3	59.5	0.507	0.38	15.3	0.088	0.17
KB-6	108.4	1.125	0.95	75.1	0.432	0.45	17.21	0.15	0.82
KB-7	595.4	2.047	1.728	5.75	0.396	0.415	43.1	0.593	1.769
KB-8	38.52	0.591	0.638	37.8	0.417	0.355	12.95	0.111	1.59
KB-9Z									
KB-10	79.38	1.27	1.57	12.76	0.189	0.209	0	0	0
SUM		7.936	8.796		2.815	3.009		2.144	8.159
Comparison: 2009 / 2000 (%)			**90.2**			**93.6**			**26.3**
KB-6Z	102.51	0.589		30.65	0.418		22.06	0.089	
KB-7Z	80.46	0.402							
KB-16Z	45.82	0.463		40.08	0.235		0.336	0.065	
KB-17Z	74.01	0.971		28.65	0.288				