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THEME

Co2 Monitoring On the Continental Intercalare Aquifer at Krechba In Salah, Algeria

Presented by:

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In front of the jury:

:

- Examiner: **Dr Boulmaize Tayeb**
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Promotion 2021

DEDICATION

I dedicate this modest work to:

First of all, to my dear parents

My dedications are also addressed to my wife and dear brothers.

To all my sisters and to all of my family:

BEDJADJ

Also, I dedicate this work to all my teachers and dear friends

To all my Friends from Ghardaïa University.

To all my working friends at the IN SALHA GAS.

Thanks

My thanks go first of Allah

who gave us strength

To complete this modest work.

our teachers from Ghardaïa University, in particular,

those of the department **HYDRAULIC**

Rethinks to all the teachers who helped us

all along our university course and in particular ***Dr. H Boutelli, T. Boulmaiz, S. Boubli, and C. Oulabelkhir***

I express my gratitude and respect to the jury members

who agreed to judge my work

Our last thanks go to all

those who have contributed from near or far

at the end of this work.

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Abbreviation	**Total name**
ISG	In Salah Gas
CI	Continental intercalare
GHG	greenhouse gas
CSC	carbon dioxide capture and storage
PCRD	European Research and Development Framework Program
OUCH	the International Energy Agency
JIP	Joint Industry Project
THMC	thermo-hydro-mechanical-chemical
SCC	Joint Marketing Company
OOC	the Joint Operations Body
EWT	Extendend Well Test
GME	Gestore mercati energetici
OPS	Depardon operations
JV	Joint venture
PCRD	European Research and Development Framework Program
QRA	Quantitative Risk Assessment
THMC	thermo-hydro-mechanical-chemical
Expro	The slick line team

S U M M A R Y

Climate change partially due to emission of greenhouse gas is now a fact recognised by many scientists and governments. Carbon dioxide is responsible for over 60% of the "enhanced greenhouse effect", the Carbon storage can take place in hydrocarbon deposits, oceans, coal seams, and saline aquifers.

The In Salah Gaz project is joint venture between Sonatrach, British Petroleum and Staitol (Equinor) located in the central region of Algeria, is the first continental industrial-scale CO2 storage project in the world. The natural gas produced from the area is rich in CO2 and this last is returned to the earth for geological storage. Almost 3.8 million tonnes of CO2 have been injected since August 2004 till 2010 relating to relatively low permeability, 20 m thick, carboniferous filled with water.

In order minimise the risks associated with CO2 storage in this area and understand their behaviour underground, it is necessary to study multiple techniques for monitoring and analysing CO2 storage for many years specially his effect on the underground waters, in our case is the Continental intercalare.

Till now with the monitoring plan implemented there is no evidence of CO2 leakage in the aquifer, this will drove us to keep more focus on, and by involving some new methods on the monitoring plan.

ملخص

أصبح تغير المناخ الناجم جزئيًا عن انبعاث غازات الاحتباس الحراري حقيقة معترف بها من قبل العديد من العلماء والحكومات. ثاني أكسيد الكربون مسؤول عن أكثر من 60٪ من "تأثير الاحتباس الحراري المعزز".تتمثل اهتمامات التقاط وتخزين ثاني أكسيد الكربون في الحد من الاحترار العالمي عن طريق تقليل انبعاثات ثاني أكسيد الكربون في الغلاف الجوي ، ويمكن أن يحدث تخزين الكربون في رواسب الهيدروكربون والمحيطات وطبقات الفحم ومستودعات المياه الجوفية المالحة.

مشروع عين صالح غاز (مشروع مشترك بين سوناطراك وبريتيش بتروليوم وستات أويل هايدرو) الواقع في المنطقة الوسطى من الجزائر ، هو أول مشروع قاري لتخزين ثاني أكسيد الكربون على نطاق صناعي في العالم. الغاز الطبيعي المنتج من المنطقة غني بثاني أكسيد الكربون ويعاد ثاني أكسيد الكربون إلى الأرض للتخزين الجيولوجي. تم حقن ما يقرب من 3.8 مليون طن من ثاني أكسيد الكربون منذ أغسطس 2004 حتى 2010 فيما يتعلق بنفاذية منخفضة نسبيًا ، بسماكة 20 مترًا ، مليئة بالكربون المملوءة بالماء.

من أجل تقليل المخاطر المرتبطة بتخزين ثاني أكسيد الكربون في هذه المنطقة وفهم سلوكهم تحت الأرض ، من الضروري دراسة تقنيات متعددة لرصد وتحليل تخزين ثاني أكسيد الكربون لسنوات عديدة ، وخاصة تأثيره على المياه الجوفية ، في حالتنا هذا هو التكوين القاري البيني.

حتى الآن مع تنفيذ خطة المراقبة ، لا يوجد دليل على تسرب ثاني أكسيد الكربون في الخزان الجوفي ، وهذا سيدفعنا إلى التركيز بشكل أكبر ، ومن خلال إشراك بعض الأساليب الجديدة في خطة المراقبة.

RÉSUMÉ

Le changement climatique partiellement dû à l'émission de gaz à effet de serre est maintenant un fait reconnu par de nombreux scientifiques et gouvernements. Le dioxyde de carbone est responsable de plus de 60% de «l'effet de serre renforcé», le stockage du carbone peut avoir lieu dans les gisements d'hydrocarbures, les océans, les veines de charbon et les aquifères salins.

Le projet In Salah Gaz est une joint-venture entre Sonatrach, British Petroleum et Staitol (Equinor) situé dans la région centrale de l'Algérie, est le premier projet continental de stockage de CO2 à l'échelle industrielle dans le monde. Le gaz naturel produit dans la zone est riche en CO2 et ce dernier est retourné à la terre pour être stocké géologique. Près de 3,8 million de tonnes de CO2 ont été injectées d'août 2004 à 2010 pour une perméabilité relativement faible, 20 m d'épaisseur, carbonifère rempli d'eau.

Afin de minimiser les risques liés au stockage de CO2 dans cette zone et de comprendre leur comportement sous terre, il est nécessaire d'étudier plusieurs techniques de suivi et d'analyse du stockage de CO2 pendant de nombreuses années notamment son effet sur les eaux souterraines, dans notre cas est l'intercalare continental.

Jusqu'à présent, avec le plan de surveillance mis en œuvre, il n'y a aucune preuve de fuite de CO2 dans l'aquifère, cela nous conduira à rester plus concentrés et en impliquant de nouvelles méthodes dans le plan de surveillance.

GENERAL INTRODUCTION

The In Salah Gas project (ISG) represents one of the largest gas production projects in Algeria and contributes significantly to national gas production. The high CO_2 content of the gas produced at In Salah led the project partners to find a compromise to treat the CO_2 gas and store it in adjacent geological formations. The main concern of storage is to ensure that CO_2 remains in the formation where it was initially injected to avoid contamination of groundwater.

The In Salah Gas project is an important gas field development project in the In Salah region. The development will consist of the sequential exploitation of the gas reserves of the seven (07) fields, the treatment and transport of this gas to Hassi R' Mel located 450kms north of Krechba. the In Salah Gaz project will be laded by the Joint Operations Body (OOC), an association between Sonatrach, BP and Staitol (Equinor). the first gas of the project after comply with gas sales contracts is from August 2003. The sales profile was set at 9x109Cm3 (billion cubic meters' contract) per year. The production range will extend over 13 years and gas sales will continue until 2027. These gas fields contain CO_2 concentrations between 1-10%, well above the gas export specification of 0.3% and therefore require decarbonation facilities.

The Krechba field is a unique project by the nature of the reservoir where the re-injection is done in the salt aquifer of the gas reservoir, has low porosity and permeability and a very small thickness of the reservoir layer (only 20 m with three sub-layers) in addition to the proximity of an aquifer (continental intercalary) located 900 m from the reservoir.

The objective of our thesis is:

- to focus on study, multiple technics and methods were implemented.
- The monitoring of CO_2 behaviour before, during and after the storage in the krechba field (project In Salah Gas).
- The possibly of affect the continental intercalare in the case of CO_2 leakage.

C H A P T E R I

Presentation Of The In Saleh Gas Project And Krechba Field

1 Introduction:

The In Salah Gaz project is a pioneer in the gas industry in terms of CCS (Carbon Capture and Storage). It has been in service since 2004, more than 3.7 million tonnes of CO2 have already been injected in a deep saline formation nearly two (02) kilometres below the surface of the Earth. This chapter is devoted to the presentation of the field of study and project concerned for this last.

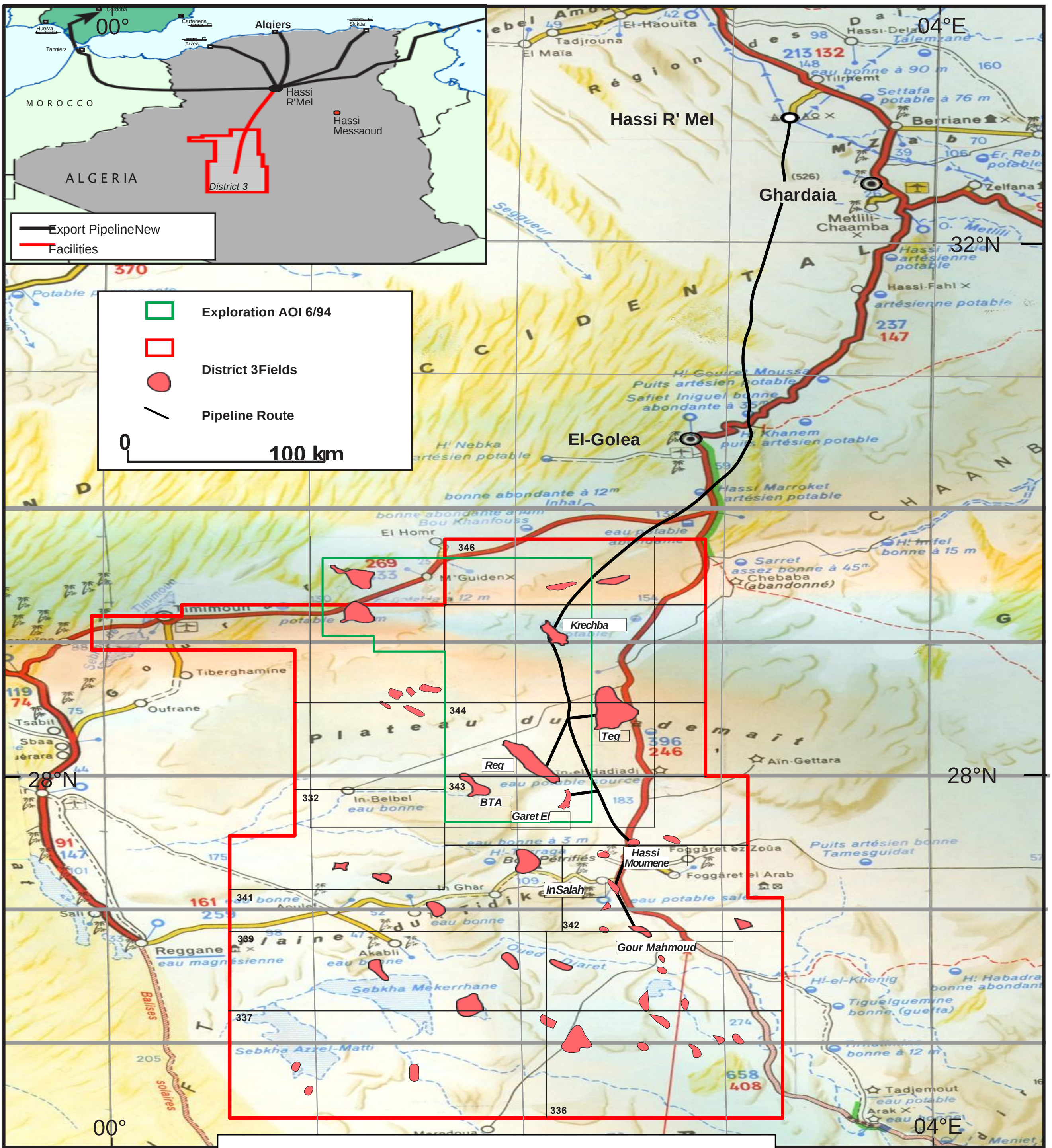


Figure I.1: location of the In Salah Gaz

2 Presentation of the In Salah gas project:

The In Salah Gaz project is a major development project for gas fields in the In Salah region. The development will consist of the sequential exploitation of the gas reserves of the seven (07) fields, the treatment and the transport of this gas to Hassi R 'Mel located 450 km north of Krechba. In accordance with the association contract between Sonatrach and BP, the In Salah gas project will be led by the Joint Operations conjoint (JOC), an association between Sonatrach, BP and Staitol The CO2 is confined as part of a natural gas production process, operated by the Sonatrach, BP and Statoil group, in the central Algerian Ahnet-Timimoune basin. Operational since 2004, the gas field contains approximately 160 billion cubic meters of gas over an estimated operating life of 20 years.

The fields are large simple anticlinal structures with reservoirs provided by sandstones of Devonian and Carboniferous age. Fields typically comprise multiple reservoir units and are laterally extensive (covering areas of 50 to 500 km2). There are variations in reservoir type and quality between fields which are reflected in development well design and numbers for each field.

The 3 northern fields of Krechba, Teguentour and Reg were initially appraised by Sonatrach and have been extensively evaluated by the JOB Exploration and Appraisal phase, undertaken in accordance with the Contract of Association and completed in February 1999. The OOC appraisal programme, which included 3D seismic acquisition and the drilling and testing of 5 appraisal wells, has successfully reduced uncertainty on reserve estimates, well deliverability and reservoir connectivity, allowing a development well spacing to be established.

The four southern fields of Garet el Befinat, Hassi Moumene, In Salah and Gour Mahmoud are less well understood. They were appraised by Sonatrach but were not included in the JOB appraisal programme. Whilst they are smaller than the 3 northern fields they comprise similar reservoirs so results from the northern fields have been applied to help determine reserves, development well numbers and development well design.

The hydrocarbon gas in all fields is dry, comprising 90 - 98% methane. Carbon dioxide levels are less than 1% in Carboniferous reservoirs and variable from approximately 4% to 10% in the Devonian reservoirs.

the contractual specifications of the export gas require a content of 0.3% of CO2, hence the need for the gas treatment using Amine solution (MDEA). Two de-carbonation trains are designed for this purpose in the CPF (Centre process facilities) of Kreachba, the CO_2 extract is sent to the compression system then to the three CO2 injection wells (horizontal wells) located in the eastern and northern perimeters of the Krechba reservoir. The re-injection started in 2004 with two injection wells (KB-501 and KB-503) followed by a third KB-502 injection well in April 2005 (see figure I-2). The reservoir is composed of carboniferous sandstone with a depth of 1950 m and a rock cover of 950m. (1)

3 Surface Facilities and Infrastructure:

The capacity of the production facilities will allow delivery of an Annual Contract Quantity (ACQ) of 9 x 109 Cm3 Algerian sales gas. The Maximum Hourly Rate (MHR) for the facilities, defined by the anticipated load factors in the gas sales contracts, is 1,184,157 Cm3/h. The availability for the facilities is expected to be 95%.

Gas produced from the development will be gathered and processed though surface facilities capable of delivering sales gas (meeting the gas specification set out in Table 1) to tie-in at the Point of Entry to the Northern Natural Gas Transportation Network (NGTN) located at Hassi R'Mel. An analyser system assembly will be installed at the RNTG Entry Point. (North Natural Gas Transport Network).

The equipment will ensure adequate accuracy to meet fiscal standards. The main equipment of this system will include:

- calorimeter,
- gas chromatograph,
- sulphur component analyser,

- dew point analyser in water,
- laboratory chromatograph (the existing Sonatrach laboratory will be used),
- carbon dioxide analyser,
- gas density analyser recorder.
- calibration equipment and consumables.

Table I-1: In Salah Gas Export Gas Specification

Parameter	**Specification**
CO2 content	0.3% mole
Water dew-point	Less than 80 ppm(v)
H2S	Less than 1.4 ppm(v)
Wobbe	11400 - 12350 $Kcal/Cm^3$
Total sulphur content	Less than 35 ppm(v)
Calorific Value	8700 -9650 Kcal/Cm3
Oxygen	maximum 0.2% mole

4 Discovery history:

The dates of discovery of the fields are as follows

- Teguentour 1957
- In Salah 1957
- Krechba 1957
- Reg1 1962
- Garet el Befinat 1983
- Gour Mahmoud 1988
- Hassi Moumene 1990

5 Description Of Fields:

5.1 Krechba:

Krechba field is located in the northern part of District 3, about 70km north of the Teguentour field. Since its discovery in 1958, 09 wells have been drilled there, including 02 appraisal wells drilled by the Joint Operations Organ (JOC) in 1998. The Krechba deposit is presented as a large closed structure, structurally simple. The gas productions of this deposit come from the sandstone reservoirs of the Carboniferous C10-2 (Tournaisian) and the Devonian (Siegénien and Gédinnien)

The Carboniferous sandstones are located at a depth of 1700 m, they were deposited in an environment of paleo valleys (probably estuary deposits). Sandstones are well developed (up to 24m total thickness) over a large part of the deposit but they are absent in parts of the west and south of the deposit. The Carboniferous sandstones are of good quality, with porosities of up to 22% and permeability of up to 200mD. The free body of water at the Carboniferous level is at the absolute coast of -1330m, which gives a closed surface of 130km² with a vertical amplitude of 70m. (2)

5.2 - Teguentour:

The Teguentour deposit appears as a large closed structure, structurally simple, with few significant faults. There are four (4) reservoir sequences in the Devonian: D20, D30, D40 and D55 and one limited expansion reservoir in the Tournaisian, sequence C10.2. At the level of the Devonian reservoirs, the deposit covers areas ranging from 150 km² at the level of the D30 and up to 500 km² at the level of the D55 (these areas are delimited by the water bodies recognized in each of the reservoirs). The petro-physical quality in the sequences of the main reservoirs, D40 Lower, D55 and D30, is good, with porosities reaching 27% and permeability up to 150 mD. The water saturations in all the reservoirs are of the order of 5 to 25%.

Gas from Devonian reservoirs contains on average 90% methane and 8 to 12% CO_2 and 5 to 7 ppm H_2S. The Carboniferous C10.2 sequence consists of shallow marine sandstones encountered at a depth of about 1500m (equivalent to 900m). This shallow reservoir (generally <5 m) presents only isolated areas of thicker and better quality reservoirs.

5.3 - Reg:

The Reg deposit corresponds to a large anticlinal structure, elongated in a NW-ES direction and covering an area of up to 350km². It is characterized by its faulty structure in a considerable way. The Devonian sandstone reservoirs are saturated with gas between depths of 1490m and 2030m (equivalent to -860m to -1400m). The main tank sequences are D30, D40 and D55. There are small additional amounts of gas in the D10 and D20 sequences. The total thickness of the Lower Devonian exceeds 500m and presents several sandstone levels constituting the reservoirs. These levels extend laterally over the entire deposit and were deposited in a fluvial to shallow marine or estuarine environment. The gas is contained in multiple porous intervals (up to 15 levels) varying in thickness from 1 to 5 m. The best reservoir qualities are found in the D55 and D30 sequences, with average porosities of up to 13% and permeability of up to 150 md.

The large fault network observed at the level of the Reg structure does not seem to have compartmentalized the deposit but must have an impact on productivity. This impact can be positive by promoting connectivity or negative by forming barriers to lateral flow. This should be the subject of a detailed study during the development phase. The gas from Reg Devonian reservoirs is dry (94% methane) and contains on average 2-4% CO_2 and 1-2ppm H_2S.

5.4 - Garet El Befinat:

The Garet El Befinat (GBF) field is a relatively small gas accumulation located 5km southeast of the Reg. It is presented as an anticlinal inversion structure, faulted and complex, covering an area of 32km². The top of the structure is at a depth of 1730m (equivalent to -1300m). The structure seems to extend north and south but this remains to be confirmed. The main reservoir corresponds to the shallow sea sandstones of the Emsian (D55) which are continuous across the field with a total thickness of about 25m. The average porosity is 12.8%. There are significant variations in the quality of the D55 reservoir across the field (average porosities vary from less than 5% to 17%). The permeability of medium porosity rocks is generally around 10mD.

5.5 - Hassi Moumene:

The structure of Hassi Moumène (HMN) is presented as a large, closed, simple structure, with small reverse faults on the hinge only. The main reservoir corresponds to the D55 sequence of the Devonian encountered by drilling at varying depths from 1130 to 1330m (coast from -718m to -918m).

The quality of the reservoir in its sandstones is very good, with average porosities of up to 16% and permeability of up to 1000mD. By analogy with neighbouring fields, it is assumed that the gas from reservoir D55 contains approximately 94% methane and less than 4% CO_2.

5.6 - In Salah:

The In Salah deposit is made up of a pinched anticlinal structure 3 km wide and 30 km long. It has two axis directions, the first oriented NNW-SSE in the northern half of the structure and the second oriented NNE-SSW in the southern half. The structure which covers an area of 90km² is not affected by significant faults at the level of the reservoir. The main tanks are made up of the D10 and D55 sequences, but there is also a small additional amount of gas in the D20 and D30. The total interval has a thickness of about 330m, and the reservoirs are in the interval between 1830 and 2220m deep (absolute coasts -1530 and -1920m).

Reservoir quality is best developed in the D10 sequence, with average porosities up to 22% and core permeability reaching 200mD. Gas composition data is very limited for the In Salah field; however, they indicate that the gas contains around 94% methane and less than 4% CO_2.

5.7 - Gour Mahmoud:

The Gour Mahmoud deposit consists of a large closed structure, structurally simple, with a large fault limiting the structure to the west. This NW-SE orientation structure covers an area of 130km² and has a 140m closure. There are 05 reservoir sequences in the Devonian: D10, D20, D30, D40 and D55 which were deposited in a fluvial to shallow marine environment. The reservoirs are extended laterally across the entire deposit, with the exception of the D55 which is only well developed to the northwest of the structure.

The reservoirs are encountered in the interval between the depths of 1700 to 2000m (equivalent to -1400m to -1700m). The qualities of the main tanks, D10, D30 and D55, are good, with average porosities exceeding 15% and average permeability generally greater than 10mD. By analogy with neighbouring fields, it is assumed that the gas for the GMD field mainly contains methane with a CO2 concentration of up to 4% and a negligible H2S concentration.

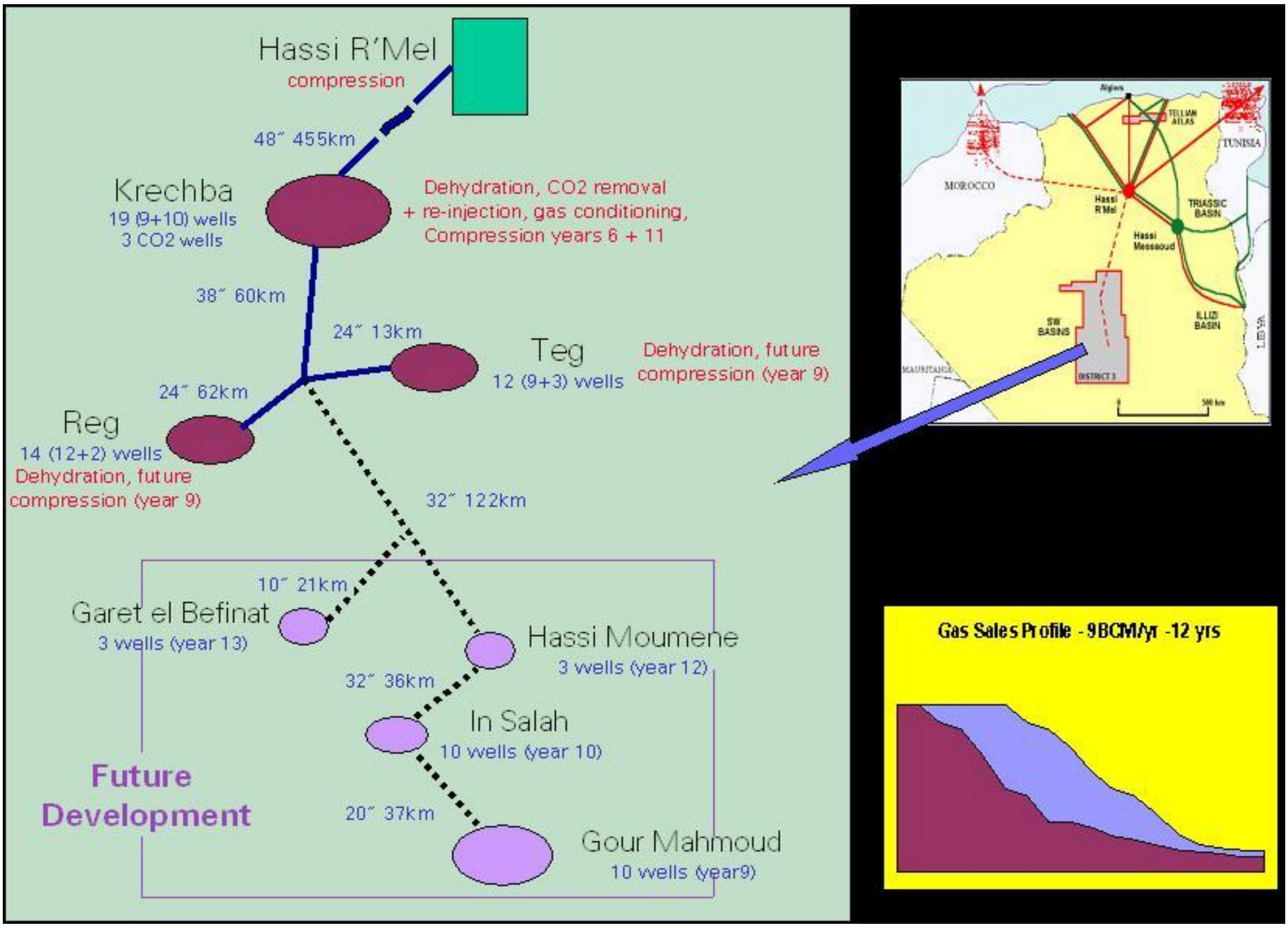


Figure I.2. Distribution of the fields of the In Salah GAZ Project

6 Presentation of In Saleh gas wells:

Total wells will be required for the operation of the three fields Krechba, Tegantour and Reg is 25well to supply a 9x109 Cm³ plateau per year of gas intended for sale. When the productivity of the first three fields was decreases, the four southern fields, Gour Mahmoud, In Salah, Hassi

Moumène and Garet El Befinat, are developed. A total of 75 wells will be drilled or resumed throughout the duration of the contract and across all fields including:

- 58 wells will be drilled for gas production,
- 13 wells will be taken over for gas production,
- 3 wells will be drilled for the injection of CO_2
- 1 well will be used for the injection of produced water.
- Figure I.2: location of the In Salah Gaz project.

7 Stratigraphic section of Krechba field:

. Devonian:

The Devonian reservoirs are located at a depth of between 2850 and 3350m (-2400m to -2900) and include multiple levels of sandstone stacked and separated by clay levels. These sandstones appear to be deposited in a shallow to marginal marine environment. The Gedinnian sandstones (D30 to D10) have a significant lateral extension and are of average quality, with porosities of up to 15% and permeability of up to 150 mD. The gas present in the Carboniferous reservoir C10.2 contains approximately 91% of methane and 1% of CO_2, its condensate content is of the order of 11.2 to 28.1 m3 / 106 m³ (2 to 5bbls / mmscf) No trace of H_2S has been recorded during the analyses carried out to date.

7.2 Carboniferous:

The Krechba Carboniferous reservoirs will be developed before the First Gas through horizontal wells. On the other hand, the Devonian reservoir will be developed later. The Carboniferous reservoir (C10.2) is well known since: 9 wells have already been drilled on this deposit, including 2 during the Exploration and Appraisal phase; a very good quality 3D seismic campaign has been acquired. For Premier Gaz, Krechba's development will targetonly reservoir C10.2 where 4 horizontal wells will be drilled. The expected production rate is 6.65 x 106 m³ / d (235 mmscf / d). To maintain the field's production plateau, 4 other horizontal wells will be drilled after the First Gas. The structural and amplitude maps derived from the 3D seismic campaign made it possible to study the locations of the horizontal wells in the C10.2 reservoirs. The data obtained from the 3D seismic campaign were used to determine the orientation of the horizontal drains that will be NE-SW in order to maximize the probability of crossing any open fracture, perpendicular to the orientation of the maximum stress in situ. (3)

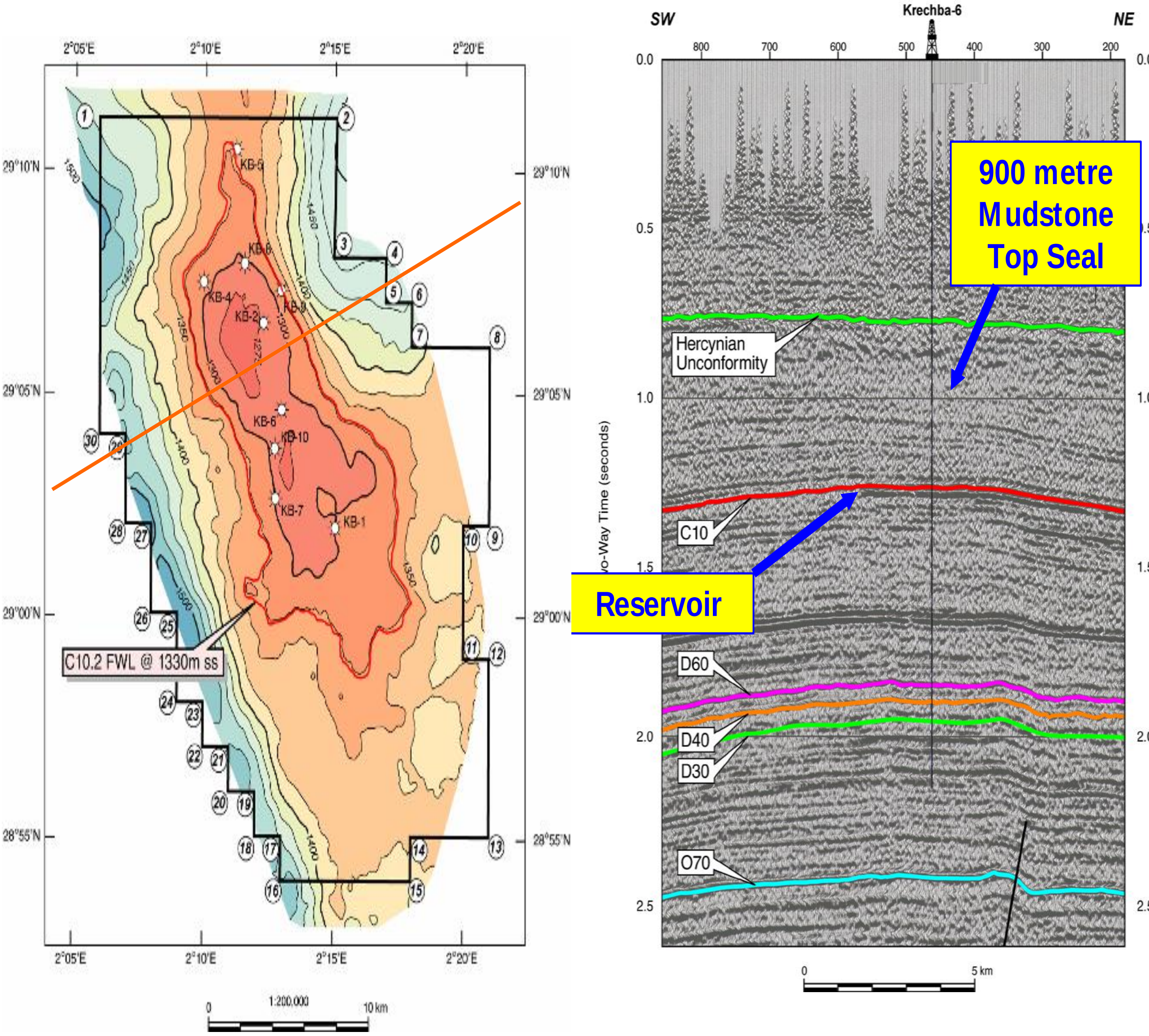


Figure I.3: Krechba field (Carboniferous reservoir).

8 Treatment of hydrocarbons from the Krechba field:

The gas from the two reservoirs will be collected in a collection network and sent to a centre production facility (CPF). At this treatment centre, the dew points of the gas for water and hydrocarbons will be reduced to reach the levels defined in the specifications of the gas intended for sale. This treatment will be carried out by:

- proven and conventional gas treatment units.
- Well fluids will enter a separator operating at a pressure greater than 80 bar to remove any condensate production water and condensate (if any).
- The condensate thus extracted will then be stabilized and stored for use as fuel in the boilers and any excess will be evacuated on site by tanker truck.

8.1 Cooling by air coolers:

Cooling by air coolers, and gas dehydration, then cooling by expansion in order to meet the necessary conditions in terms of dew point in hydrocarbons.

Krechba's dehydrated gas will then be mixed with gas from fields in the South. To be processed together in common gas processing facilities. When the flow pressure at the wellhead becomes insufficient to allow free flow in the inter-field pipeline network and the Discharge Pipe, one or more centrifugal compression units will also be installed. These units will be reconfigured, at a later stage in the life of the fields, to better manage the decline in wellhead pressures in flow. Common facilities The following facilities will be installed in Krechba, the main treatment and compression centre

8.2 Gas compression:

Dehydrated gas from fields to the south will be mixed with Krechba gas which has been dehydrated. The gas will be compressed to a sufficient pressure for its decarbonation and transport. A compressor station will be in due course to compensate for the pressure drop of the deposits. The Base case provides that it will be built 5 years after the First Gas.

8.3 De-carbonation:

The main function of the Krechba treatment facilities will be to achieve the required specification for CO2. The gas will arrive at Krechba with an average content of 5 to 7.5 mol% CO2. Two 50% de-carbonation units will be installed. The CO2 will be extracted with a chemical solvent (amine). This solvent will then undergo thermal regeneration and most of the CO_2 will be released at low pressure. The circulation of the solvent will be ensured by centrifugal pumping units with several stages driven by electric motors. The amine can then return to the absorber.

8.4 Dehydration:

The de-carbonation process humidifies the gas. Therefore, glycol dehydration of this gas in 2 units at 50% will be necessary. After measurements and sampling in the equipment, the gas will be sent to Hassi R'mel.

8.5 CO2 Reinjections:

The CO_2 extracted from the amine will then be compressed by 2 50% re-injection units driven by electric motors. The dense phase CO_2 will then be dehydrated before undergoing a new compression pumping for its re-injection. It will then be transported to the north of the field to be injected into the aquifer connected to the carboniferous production formation.

8.6 Produced Water:

The water separated at Krechba from the gas from the Carboniferous reservoir will be directed to an evaporation quagmire located near the treatment centre. Once the Devonian reservoir is put into production, all the water produced and separated from the Krechba field will be reinjected into the well.

8.7 Utilities Products:

Consumables planned at Krechba include air, nitrogen, fuel, safety vents and waste drains, chemical storage, firefighting water distribution and water supply, treatment and disposal thereof. The air will be produced by simple compression dehydration units, which also provide the charge for the nitrogen production units. The vents are divided into High Pressure, Low Pressure and sour gas vents. Electric power will be provided by two turbo-generators; a backup diesel generator is provided for emergency starts.

A substantial heating medium system exists for the supply of heat primarily for use in re-boilers for the regeneration of the CO_2 solvent. This heat is mainly produced by energy recovery boilers which are located in the electricity generation area or by independent boilers which are fed by gas or condensate. (4)

8.8 Reinjections Schema Description:

Gas produced from the In Salah Gas fields is gathered and process at the central processing site of Krechba. Typically, the average content of CO2 in the combined feed gas is 5.5% (volume), and this content must be reduced to 0.3% in order to meet the specification required for entry into the gas transportation system. This is achieved by contacting the feed gas with activated amine solution (aMDEA) in the absorber column, after which the gas is dehydrated before entering the export pipeline. The amine solution is regenerated, and circulated back to the absorber. As part of the regeneration process a CO2 stream of over 98% purity is produced at low pressure. See figure I.4.

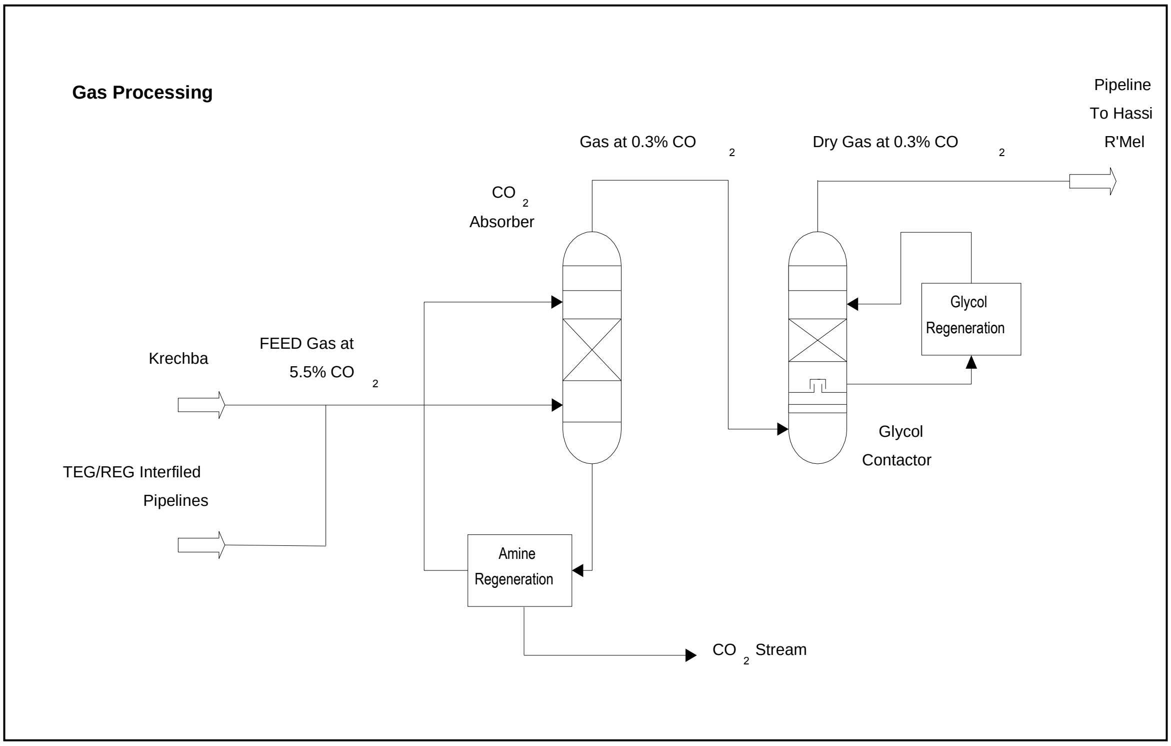


Figure I.4: CO2 Process.

Traditionally low pressure CO2 is vented to atmosphere. For In Salah however, additional facilities have been provided for the re-injection of the CO2 by-product. These facilities consist of electric motor driven compressors with CO2 dehydration, CO2 pipelines and CO2 well pads and wells, as shown in figure I.5. There are two trains of re-injection compression with dehydration, each compressing 50% of the CO2 from amine regeneration. The CO2 is compressed from about 1.4 bara to about 145 bara over 4 stages of compression. At the third stage the CO_2 is dehydrated (to avoid corrosion in the CO_2 pipeline) using a small slipstream of glycol from the main process. A total of about 20 km of 8” carbon steel pipeline transports the CO_2 to up to three wells for re-injection. (5)

Only two wells may be required if injectivity is confirmed to be good. The CO_2 compressors are electric drive, so incorporation of the scheme into the facilities design led to two 18 MW gas turbine generators to provide the re-injection compressor power requirements (24 MW) and gas production power requirements (12 MW).

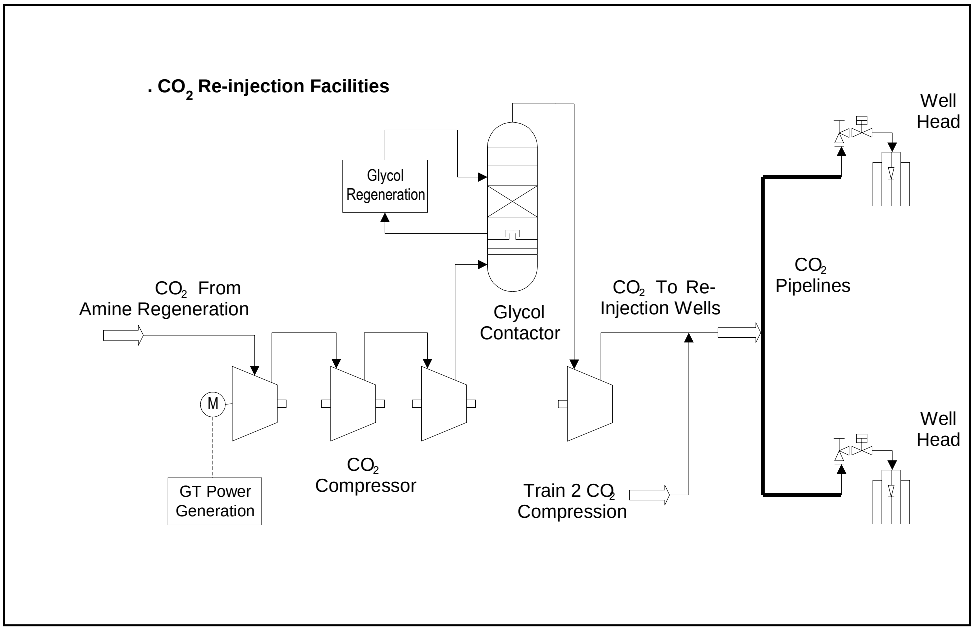


Figure I.5: CO2 Reinjections Facilities.

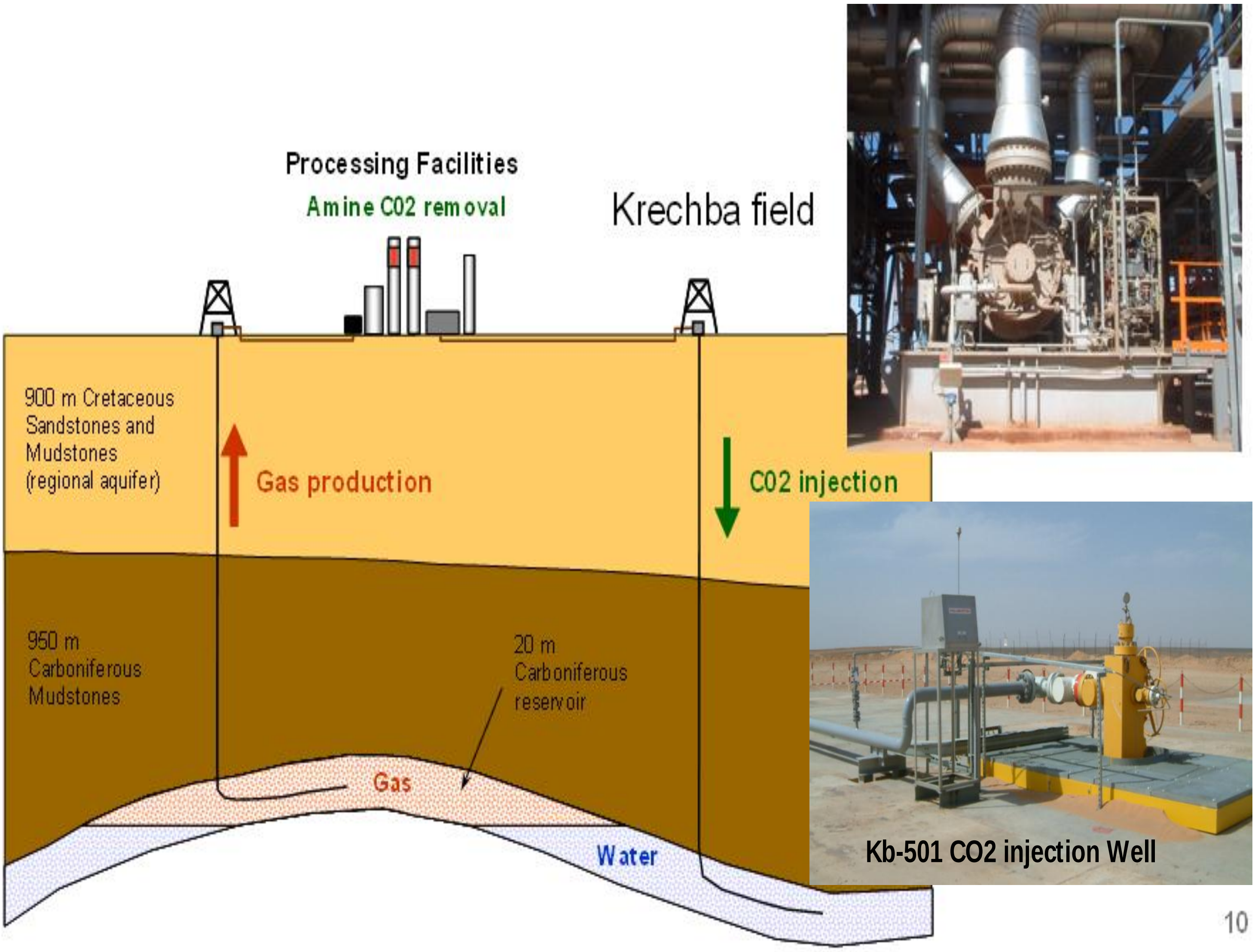


Figure I.6: Cycle of re-injection CO2.

9 Conclusion:

In this chapter we present the In Saleh project with his eight fields, and the main facility that exist at Krechba field, the utility and the CO2 reinjection system.

We present also the stratigraphy of the Krechba reservoir Devonian and Carboniferous, and his petrophysics parameters. The reinjection of CO2 is done the deep Carboniferous.

For good monitoring the behaviour of CO2 on the reservoir multiple methods were implemented, that methods are our topic in chapter II.

CHAPTER II

Methods Of Co2 Surveillance In Krechba Field

Introduction:

The In Salah gas project in Algeria is an industrial-scale CO_2 storage project that has been in operation since 2004. CO_2 from several gas fields, which have a CO_2 content of 1-10%, is removed from the production stream to meet the sales gas export specification of 0.3% CO_2. Rather than vent the separated CO_2 to atmosphere (as was normal industry practice for such gas plants), the Joint Venture (JV) partners, BP, Sonatrach and Statoil, invested incremental capital of $100 million in a project to compress, dehydrate, transport and inject that CO_2 into a deep saline formation down-dip of the producing gas horizon. A Joint Industry Project (JIP) was set up in 2005 to monitor the CO_2 storage process using a variety of geochemical, geophysical and production techniques, which consist in the static measurement of the downhole pressures of injectors, gas sampling points, sampling of tracers as well as monitoring of static levels of aquifers.

For this, this chapter contributes to highlighting the stapes and methods of injection and storage of CO_2 as well as the methods and techniques of monitoring used in this project.

Design and construction of injection wells:

Each well is drilled vertically in the target area, then redirected horizontally over more than 1.8 Kilometres to end up in areas of high rock porosity and thus facilitate the subsequent injection of CO_2 through the sand. State-of-the-art MWD "measure-while-drill" measurement techniques were used, which allowed the instruments to cross-cut rock porosities at intervals. The resulting 3D seismic image and borehole data from Algeria were transmitted live to the UK, allowing the wells to be 'geo-directed' remotely from BP's technology centre in Sunbury throughout the training.

The vertical portion of the well - the metal tube or casing - is surrounded by cemented completions to prevent CO_2 leakage to the sides. In theory, cement can be dissolved by CO_2, but in fact the gas reacts chemically on the surface of the cement to form a barrier (like toothpaste). This therefore prevents contact with the cement structure below this barrier and degradation of the cement envelope.

The horizontal portions are well filled along their entire length with a liner riddled with slits or perforations to help CO2 exit the well and permeate the rock formation. Under these conditions of high pressure and temperature (the injection pressure at the wellhead level 141 bar and the temperature 31 °c (, CO2 is a supercritical fluid, which has the density of a liquid but the viscosity of a gas.

The horizontal CO2 injection wells are located on the eastern and northern perimeters of the Krechba reservoir; there are three wells in total to achieve good spatial coverage, contact through the rock formation as well as increased gas production levels. Horizontal drilling was a major challenge for two reasons, local rock formations have very low permeability (only 10 to 20 milli-darcies) and the porous and saline rock formation comprising the target area is only 20 meters thick and lies two (02) kilometres below the surface, requiring horizontal drilling and a high degree of precision.

Location of wells is a critical factor The objective was to locate the wells in order to allow CO2 to be pumped into the sequestration formation approximately five (05) kilometres “down-dip” - a position within a slope, or "dip", the layers below the top of a geological structure resulting from gas-water contact. Natural gas is extracted from the “up-dip” gas accumulation - located higher up the slope of the same structure.

Three injection wells are used to obtain good spatial coverage and allow high CO2 flow rates (Kb501, Kb502 and Kb503). CO2 is a supercritical fluid at these pressure and temperature conditions. It diffuses through the sifted envelopes but its forcing through sand and rock is more difficult, so its speed drops. Once in place, it should stay trapped permanently.

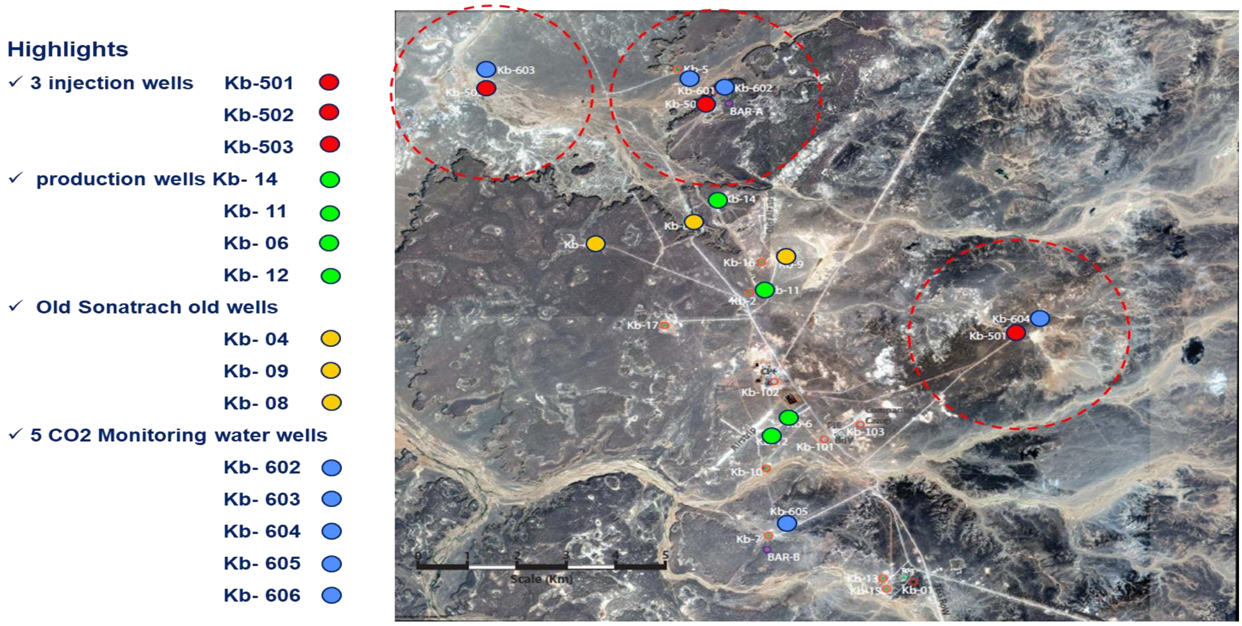


Figure II.1: Krechba Wells.

Monitoring objectives and CO2 injection status:

A key function of any surveillance program is its ability to use surveillance data to respond to field performance and any changes in operational activities. The In Salah demonstration project was an important example to understand the value of different monitoring methods put in place. Several Quantified Risk Assessments (QRA) were carried out during the operational phase, integrating all available data to assess both the integrity of the repository and the efficiency of the repository complex. After the 2010 QRAs, the decision was taken to reduce CO2 injection pressures in June 2010.

Subsequently, the analysis of the seismic and geomechanical data of the reservoir led to the decision to suspend the injection of CO2 in June 2011. The future injection strategy is currently under review and the monitoring program of the complete site is maintained in execution.

A monitoring program is in place with the aim of collecting and analysing data in order to understand the movements and behaviour of the injected CO2. After the suspension of the CO2 injection, the monitoring program continued, and should plan for the next few years. Provide assurance that the secure geological sequestration of CO2 can be economically verified and that long-term assurance can be provided by short-term monitoring. To demonstrate to partners that industrial geological sequestration of CO2 is a viable option for greenhouse gas mitigation. To set a precedent for the regulation and verification of the geological sequestration of CO2, enabling eligibility for greenhouse credits. In recognition of the importance of the project, the JIP receives assistance from the US Department of Energy, the EU's Directorate of Research and collaborates with leading technology providers around the world.

Monitoring methods:

The suite of technologies that may be deployed at any CO2 storage site for monitoring and verification purposes is readily available and utilizes mainly existing standard oilfield and environmental monitoring techniques and practices. However, each site will require a site specific suite of cost effective and focused technologies to provide the maximum benefit – there is no ‘cookie cutter’ approach when it comes to designing a Monitoring and Verification program.

A data collection programme was initiated prior to the start of injection in August 2004. This included extensive sampling and logging programmes (including image logs) in the new development wells, saline aquifer sampling and headspace gas sampling throughout the overburden. A soil gas survey was also conducted around each of the new wells and samples were collected from the shallow aquifer water wells at the accommodation camp and the Central Processing Facility (CPF).

The initial modelling work suggested that monitoring the movement of the injected CO2 in the reservoir would be difficult using anything other than observation wells drilled through the injection horizon. Monitoring of the overlying Carboniferous and Cretaceous sequences was considered to be just as important, if not more so, than the reservoir. An initial suite of around 29 monitoring technologies and techniques was placed on a Boston Square decision matrix to assess the perceived cost-to-benefit of each technology for use at Krechba.

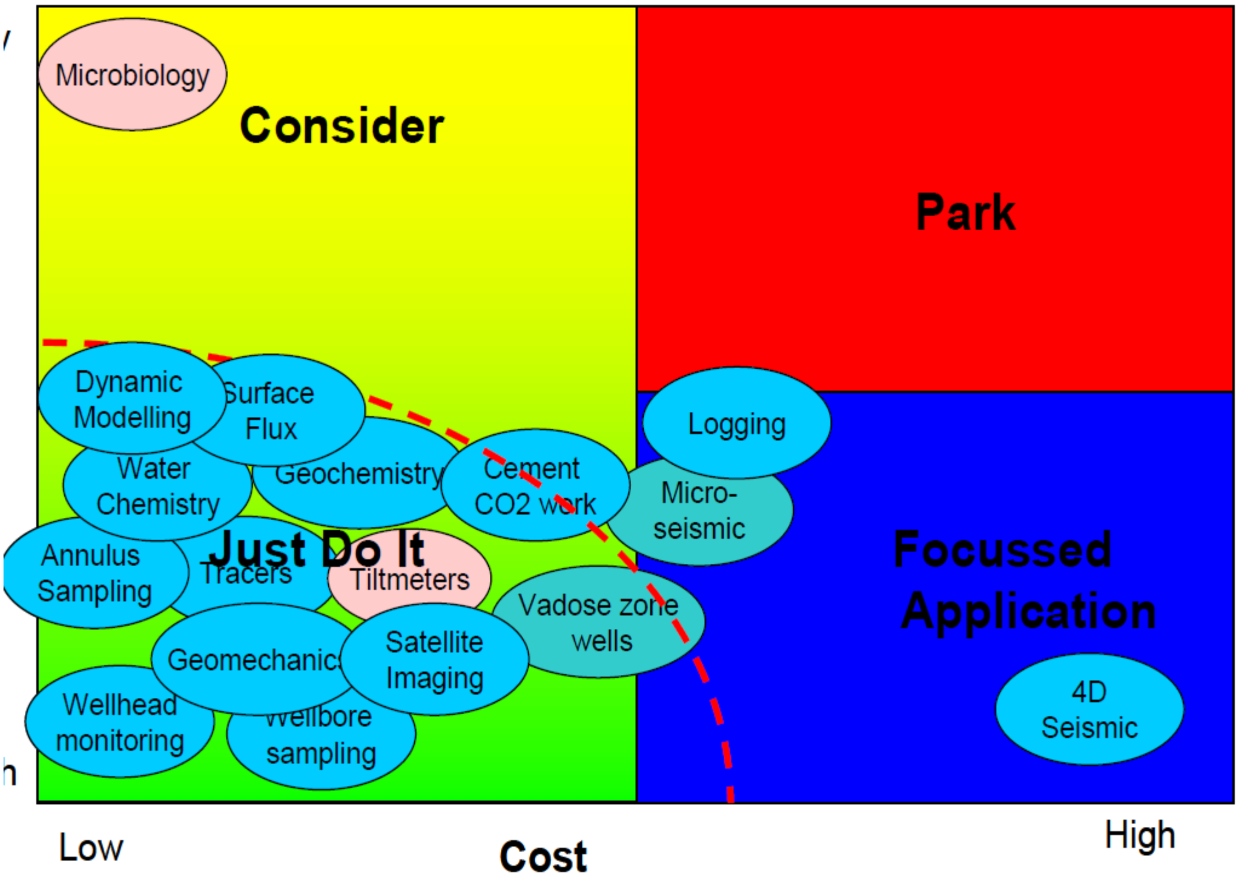


Figure II.2: Actual technologies applied at Krechba

. Satellite Imaging

Perhaps the most valuable, and initially surprising, monitoring method so far has been the use of Satellite based interferometric synthetic aperture radar (InSAR) to detect subtle ground deformation changes by comparing phase differences from successive satellite passes. There are several sophisticated signal processing methodologies being employed, including Permanent Scatterer Interferometry (PSInSAR™) which is a multi-interferogram image processing approach developed by Tele-Rilevamento Europa (TRE) of Italy, and "network inversion" and "persistent scatterer interferometry" developed by MDA (MacDonald Dettwiler and Associates). These provide a means to compare data from multiple satellite passes in order to enhance the deformation and suppress the influence of multiple noise sources due to atmospheric effects. These provide an accuracy of around 5mm/year and up to 1mm/year for a longer term average. In Salah has provided an excellent opportunity to evaluate the different approaches from the evolving satellite technologies and the signal processing from TRE, MDA and JGI/Japex. Satellite data was collected and interpreted on an on-going basis using Radarsat2, Envisat and TerraSAR-X by MDA/Pinnacle Technologies and TRE on behalf of the JIP.

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). Figure ? shows one of the recent deformation images from MDA/Pinnacle (Envisat data) based on the surface deformation observed since the period before injection started up to up to 18 September 2010. The red areas indicate uplift while the blue areas denote subsidence. The observed surface uplift rate is around 3-4mm/year. While not significant in terms of the local environment, the rate and pattern of surface deformation is being evaluated by numerous of our research partners and the JIP to provide an understanding of both the subsurface movement of the CO2 plume and the geo-mechanical response to the injection of CO2 at Krechba.

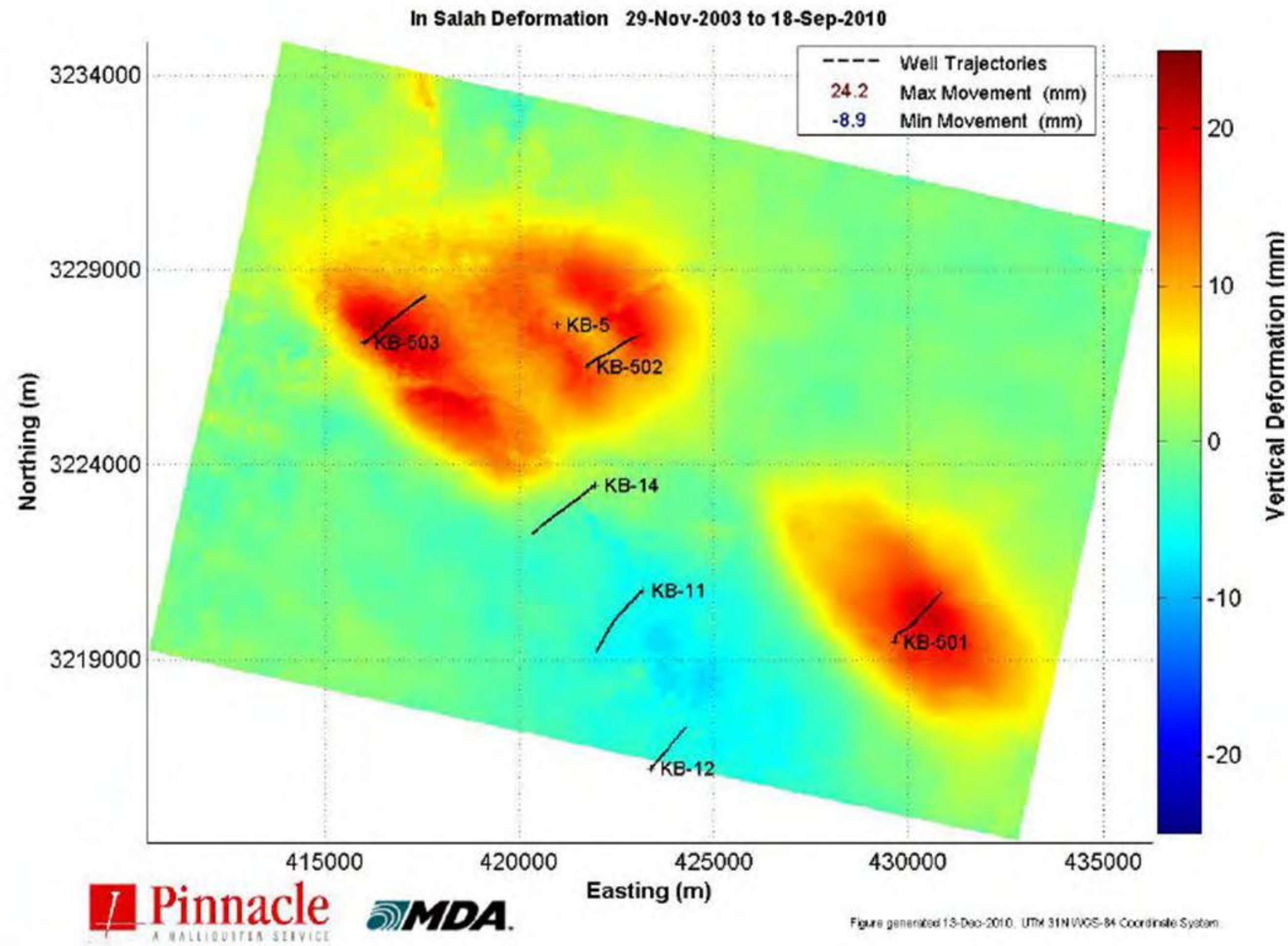


Figure II.3: Actual technologies applied at Krechba

We are also interested in the surface distribution of Methane (CH4) and Ethane (C2H6). If these hydrocarbons are found in the proximity of wellheads they may be indicative of Well Integrity problems and leakage from wellbores or wellheads. That these gases have been detected at surface would indicate a pathway from shallow to deep that may also be used by CO2.

. Mi c r o –s e i s mi c

The CO2 at Krechba was injected at high pressure into a well consolidated reservoir known to contain fractures. This implies micro-seismic monitoring could have considerable potential as a tool to assess the integrity of the cap-rock and provide assurance of secure storage of the injected CO2. However, as the area is located in a stable craton, induced events are likely to be small (M<0) and may be detectable only using downhole sensors close to the reservoir. This is too expensive and in Krechba a single pilot well was drilled to assess the technology and collect basic micro-seismic passive monitoring data.

Feasibility modelling carried out by Micro-seismic Inc. in May 2006 suggested that a 25 station array of sensors at ~50m depth would be capable of mapping activity down to M=-2 using beam-steering, though conventional first arrival methods must still be applied to the larger (M~0) events to validate the approach. Due to cost, a simple pilot based on sensors in a single shallow (~500m) borehole was recommended to establish the dependence of ambient noise with depth and the approximate level of micro-seismic activity so that the array design could be optimised.

The injection of CO2 at high pressure into the well consolidated low permeability C10.2 reservoir at Krechba was almost certain to induce fracturing. Typical behaviour of fracture opening was observed in the injector response for injection pressures over 3100 psi. Re-interpretation of the 1997 3D seismic revealed the presence of a number of faults including some near the injectors Kb-502 and Kb-503 which may be re-activated by the high pressure injection and could act as high permeability conduits for CO2 both laterally and vertically, although there is no evidence of through-going faults or fractures above the reservoir (C10.2) in the 1997 3D seismic. Fracturing the mudstone caprock could also affect the long-term viability of CO2 storage at Krechba – although with such a thick shale section overlying the reservoir, leakage to the major aquifers above the Hercynian unconformity is only likely through pre-existing fracture zones. Information on fracturing is fundamental to future CO2 sequestration operations and claims of safe geologic storage at Krechba

The micro-seismic well, KB-601 was drilled immediately above the central part of the KB-502 injection well to a depth of 500m. Forty-eight 3 component geophones were cemented into the well (figure II.4) and three Reftek 6 channel recording system supplied by Lawrence Berkeley National Laboratories installed to record information from the array. While the 48 level array is more than is strictly required for micro-seismic monitoring, it provides better definition of noise changes with depth, allows the efficacy of a variety of depth combinations to be tested and also has the potential to be used for acquiring (time-lapse) VSP data. Plans to operate the array during the 2009 3D, providing simultaneous downhole and surface recording of the shots, fell through because of delays in installation.

The array started recording in July 2009, about one month after the completion of the 3D seismic survey in the area.

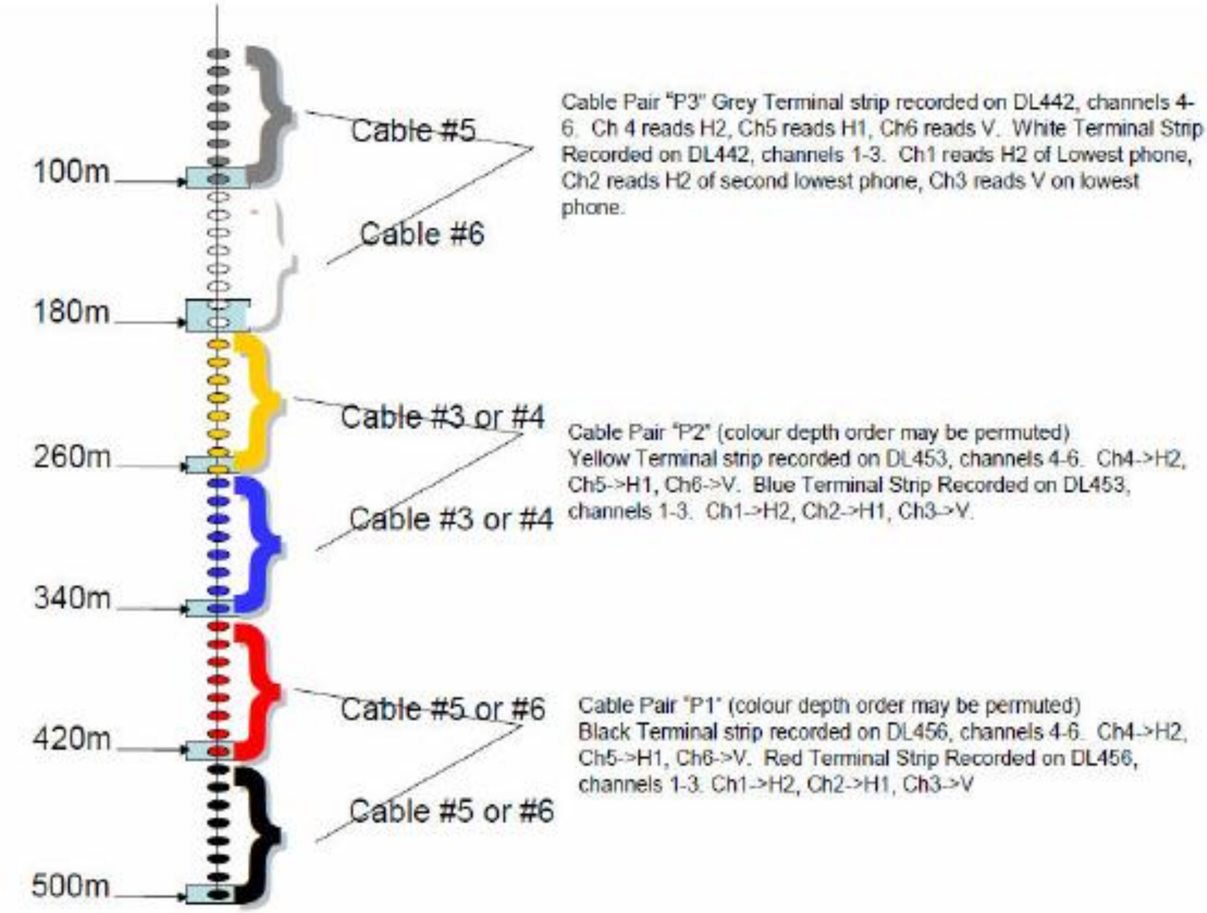


Figure II.4: Arrangement of installed geophone array in KB-601

The micro-seismic operations had two phases. The initial phase was the drilling of the well, installation of geophone cables and use of Lawrence Berkeley National Laboratory (LBNL) Reftek™ equipment. The second phase was the disconnection of the LBNL Reftek™ recorders due to problems with GPS signal timekeeping and replacement with a Dolomit™ recording system designed and installed by the Norwegian Geotechnical Institute (NGI).

Results from the Lawrence Berkeley National Laboratory (LBNL) equipment were mixed. The data recorded did not represent enough channels to adequately reflect the signals that could be recorded. Also, the system recorded ALL data and did not have a trigger to start recording when a particular event size was reached. This made it time consuming for analyses of data recorded and led to ambiguity as to what events had been recorded. Initial reports suggested the events were not real because they did not display a time offset across the array. However, a very detailed analysis by Pinnacle strongly suggested that real events are being recorded and that a better recording system should help clarify uncertainties for the current data set. The Pinnacle analysis revealed significant problems with the time signals on the 3 Reftek recorders.

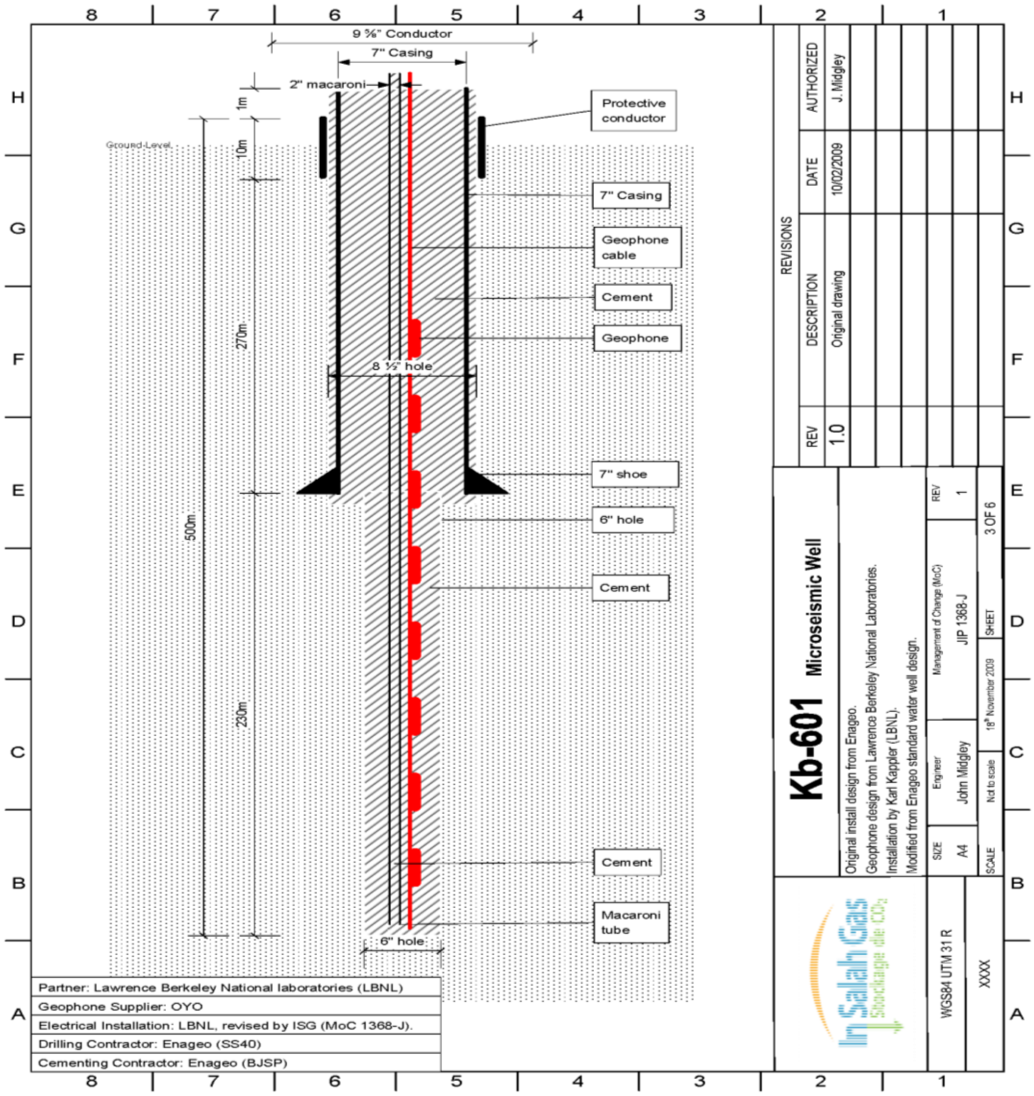


Figure II.5: well completion design in KB-601

. Tracer Injection

In Krechba two kinds of CO2 can be identified, the ancient CO2 taken from the Carboniferous and Devonian production wells and biogenic CO2, created by microbial action in the shallow geology. These variants can be differentiated by isotopic analysis in a laboratory, to make this differentiation easier; a specific tracer was introduced to each of the injector wells to enable identification of the source of the re- injected CO2.

Perfluorocarbon tracers were injected in the CO2 injection wells in 2007 by the Institute for Energy Technology2 (IFE) of Norway on the 1st of June 2007.

7.5kg of perfluoromethylcyclohexane (PMCH) was injected in Kb- 501.

8.5kg of perfluoroethylcyclohexane (PECH) was injected in Kb- 502.

9.5kg of n- propylperfluorocyclohexane (n- PPCH) was injected in Kb- 503.

The working hypothesis is that where the perfluorocarbon tracers are detected the combining CO2 is from the associated injector.

In the organigram below are the main methods use for CO2 surveillance in ISG after the stop of reinjection:

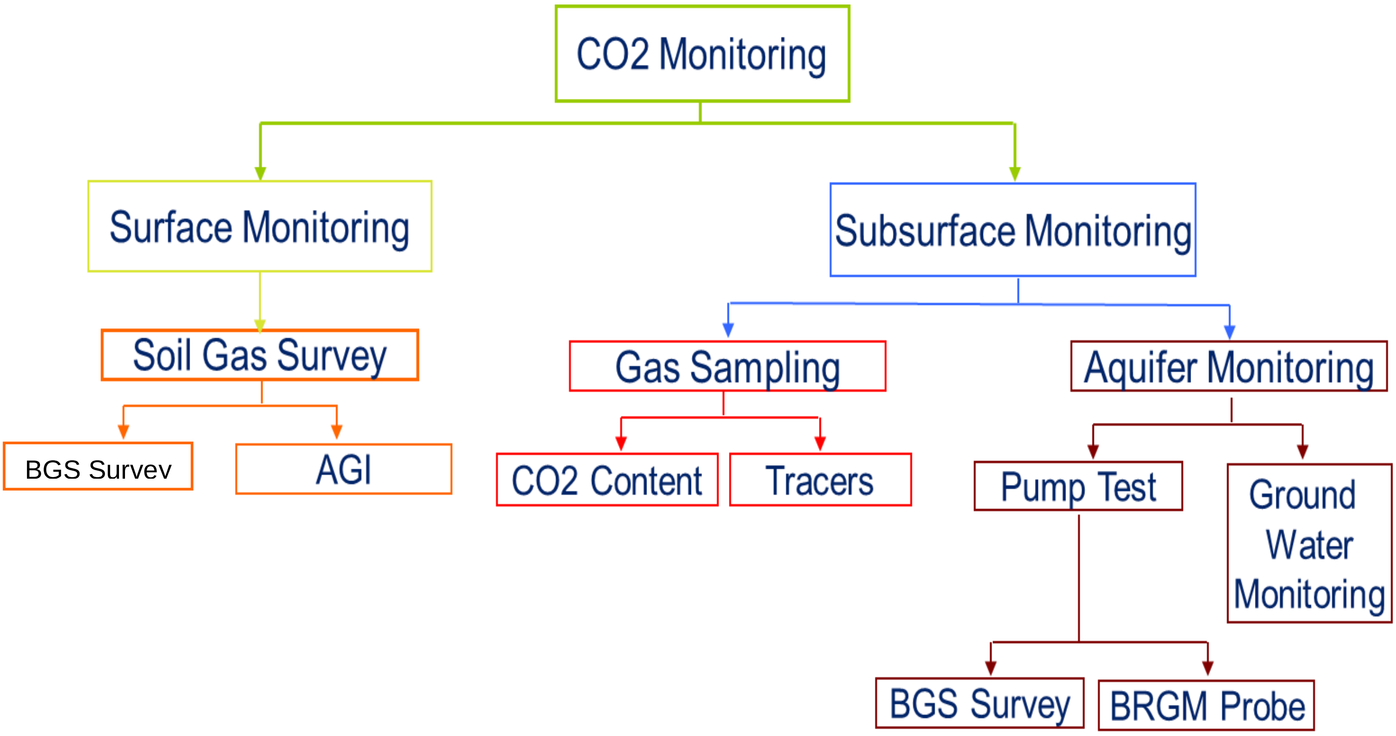


Figure II.6: Actual technologies applied at Krechba

Surface Surveillance Methods (Soil –Gas survey):

Soil Gas studies represent a profitable method with regard to CO2surveillancefor the shallow parts of the subsoil, they also make it possible to have basic measurements of the CO2 concentration in order to detect any CO2 leakage at the surface level.

In comparison with Aquifer Monitoring, this method seems less effective, because in the event of CO2 infiltration towards the surface, the first contaminated zone will be the shallow aquifer. However, it remains a necessary tool to understand the CO2 migration paths through major faults or wells of questionable mechanical integrity. It also makes it possible to have early warning signs of an increase in the level of CO2 at the surface.

While the Gore method (newly called AGI) aims to measure the concentration of perfluo-carbon tracers initially associated with the CO2 injected in June 2007. Soil Gas monitoring is generally implemented during the cool periods of the year because of the detection limits of equipment.

. BGS Survey method :

The objective of this method, which is based on the experiences already acquired with its implementation during the period from 2009 to 2012, will include the following points:

A mobile laser tool for measuring the concentration of CO2 and CH4 around the three injectors, kb-501, 502 and 503 while covering the raised area of a few centimetres based on data from InSAR (satellite), at the turn Kb-5 (site already affected by a CO2 leak), Kb-4 (well near kb-502) and in an area to the west close to the area of producing wells. Other areas may be affected by this laser scanning depending on future needs. Static laser measurements near wellheads to detect high concentrations of CO2 Mobile laser measurements in the direction of winds and torch gas at the CPF (Central Processing Facility). Additional or alternative elements can be considered at the request of ISG, however this could affect the cost, for example:

Continuous monitoring of specific sites, such as KB-5 areas near injectors or the CPF area. This can be implemented using Eddy's Covariance, flow chambers or monitoring probes (measurement of gas concentration).

Vertical profile and deep sampling in shallow wells to reduce the impact of the elements included in the atmosphere on soil and gas measurements.

Soil and Gas sampling for laboratory analyses should include a wide range of components (example: CO_2, O_2, N_2, CH_4 etc.), which may help to understand the origin of the CO_2 detected while including tracer analysis.

Some of these options have already been discussed in our 2012 study report (Jones and Lister, 2012). These options can be used to finalize the origin and rate of gas emission at the Kb-05 level, with a better quantification of the quantities of gas emitted, or for a temporal evaluation near the surface around the CPF, which can be subject to variations due to weather and wind conditions.

Figure.II.7. Open-path laser CO2 and CH4 detectors were mounted on Toyota car

Figure.II.8. Soil probe and solid state analyser at use in the field

Figure.II.9. West Systems portable flux meter with a LICOR LI-820 IR detector

. AGI survey method:

This method has a potential to provide data in order to assess possible CO2 leakage paths over large areas through the detection of tracers initially mixed with the injected CO2. This method makes it possible to target very specific areas by taking into account the detection of tracers injected into well determined wells.

The objective of the AGI modules consists of:

- Take measurements around the injection wells to detect surface leaks of CO2.
- Take CO2 concentration measurements near old wells to ensure their integrity.

- Understand the distribution and quantify the quantities of CO2 flared near the CPF zone.

The objective of AGI modules is to acquire Soil data and Gas using a different method than that used by BGS. The AGI method does not make it possible to detect the CO2 leak directly, but it is the textile modules that will be tested for the presence of perfluo-carbon tracers already injected with the CO2 in 2006.

The AGI method is the only method that we have identified as being able to give direct measurements of perfluo-carbon tracers. As in 2012, the AGI modules were not implemented on the KBA site, they will soon be implemented under the responsibility and supervision of ISG Overview of the monitoring method The objective of the AGI modules will be to determine and delineate the presence of tracers at the surface. This will also provide a second method in the event of a surface CO2 leak. The service provided by AGI to ISG will consist of:

- Discussion with the joint venture for the preparation and implementation of a Soil program gas for monitoring perfluo-carbon tracers near injectors and other areas of interest.
- Provision of a specialist for the installation of equipment and demobilization of these on site Provide monitoring equipment (AGI modules).
- Analyses the data collected on site in their laboratory in Europe or the USA.
- Provide the JV with a detailed report of the monitoring results with the necessary interpretations.

Due to certain HSE obligations, transport policy at ISG and military escort requirements, the first person in charge of setting up the equipment on site and demobilizing it will be OPS geological intervention who will have received adequate training for this type of task on the part of AGI, GMBH in Munich or in another site within the national territory.

The import and export of the material necessary for the on-site operation will be the responsibility of the JV.

. . Advantage:

- This method directly detects perfluo-carbon tracers.

- Large areas can be covered quickly in desert areas with fairly high wind speeds.
- A large dataset can provide generic models of how gases move in an environmental monitoring of the arid environment.

. . Disadvantages :

- This monitoring system does not directly detect the injected CO2.

It requires special equipment and training only available from one supplier.

- The equipment used is very sensitive to sources of contamination.
- AGI modules can only be analysed by AGI in the United States.

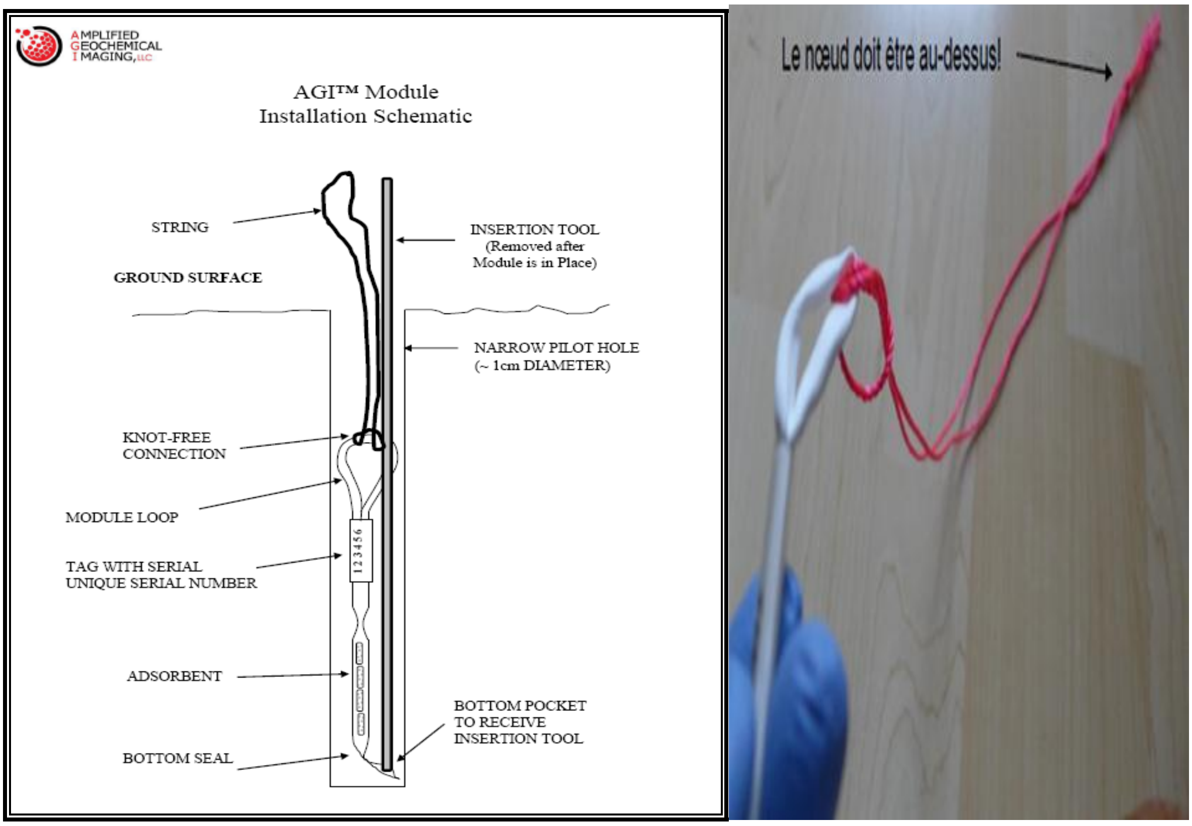


Figure. II.10. The schematic installation module

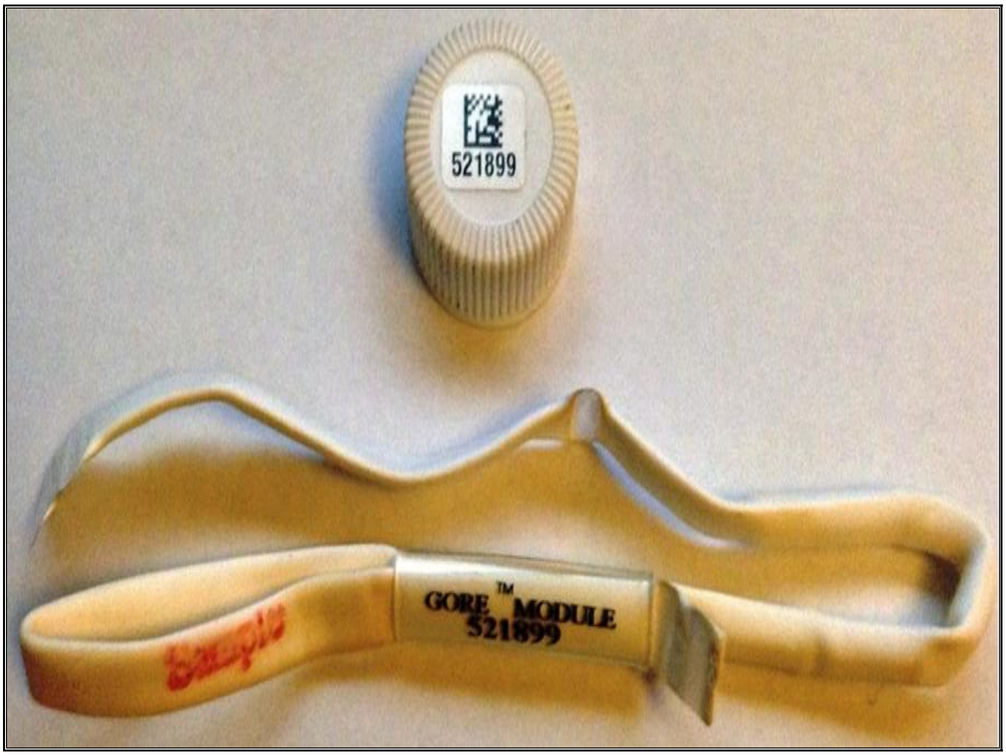


Figure. II.11. AGI's schematic installation module

Sub-Surface Monitoring Methods (Gas sampling):

Sampling of wellhead fluids from the Krechba well production column is carried out on a regular basis by the ISG.

Furthermore, sampling bimonthly is also carried out on the annulus A and B of all the wells with sufficient pressure to allow sampling.

These data are very important in the detection of sweep of H_2O by CO_2(CO_2 intrusion) in controlled wells and must be checked regularly.

Currently, all wells must be sampled every two months except for Kb-14 which should be

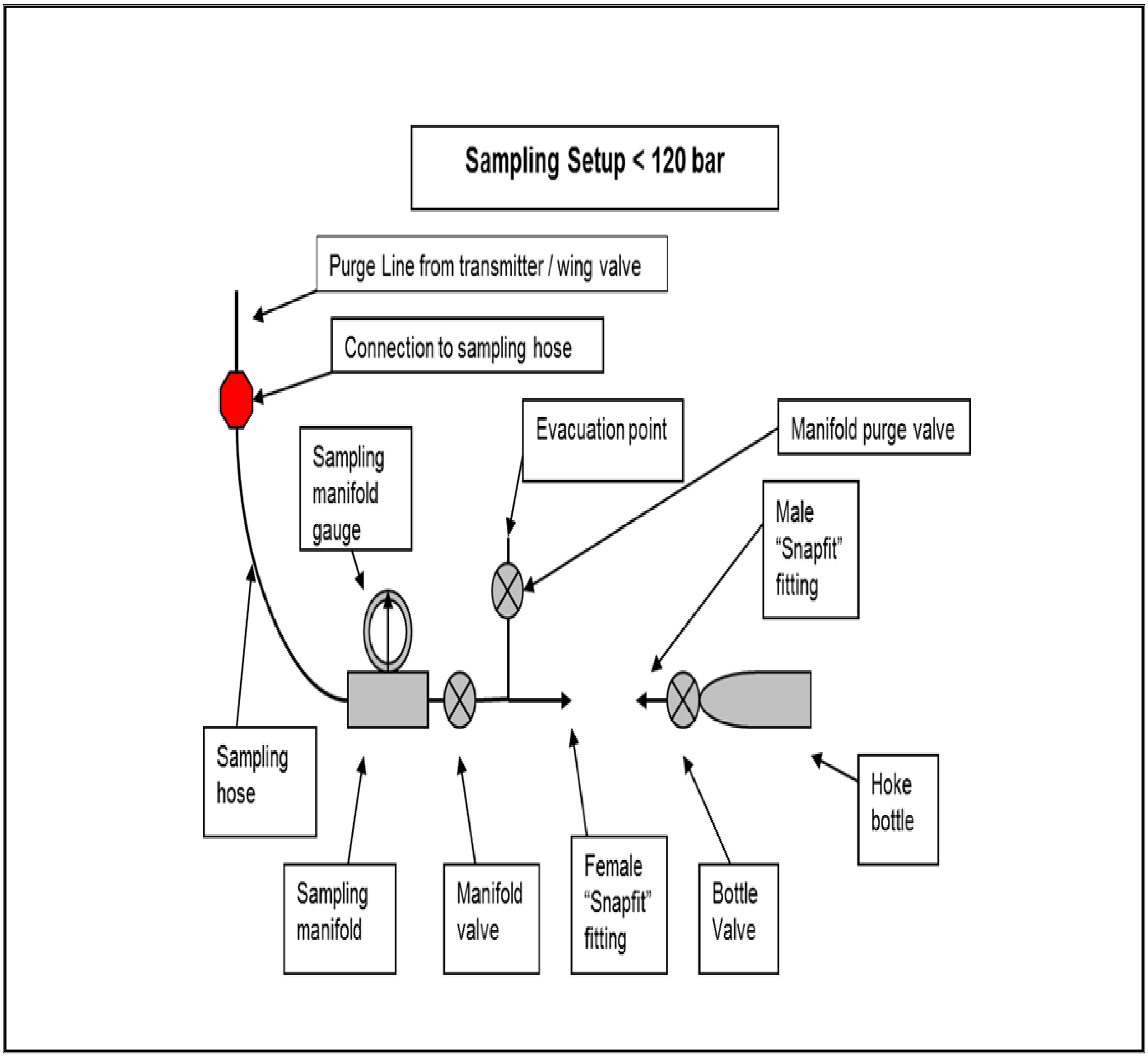


Figure. II.12. Schematic Explains Gas Sampling method

. Raw Gas Sampling for Tracer Detection:

Fluid sampling for chemical composition measurement and tracer analysis has been an integral part of the Association's monitoring procedures since the start of the project. Samples are collected regularly from Kb-14 and Kb-12 (producing wells) as well as in the old Sonatrach wells (Kb-4, Kb-6 and Kb-9). The objective of this sampling in the Krechba wells is to detect any change in the composition of the fluids, linked to the injection of CO2.

The sampling operation for the study of gas composition and analysis of the tracers has already been incorporated into the routine activities of the JV as part of the annual monitoring program since the start of the injection. The objective of this sampling consists mainly in monitoring the composition of the gas as well as analysing the tracers at the level of the wellheads and annular spaces as a function of time.

Samples are collected every two months from KB-4, KB-6z and KB-9. The frequency of taking samples on Kb-14 has been revised upwards since the detection of tracers at the level of this well. KB-11 and KB 12 have been added to the list of wells to be sampled since 2012

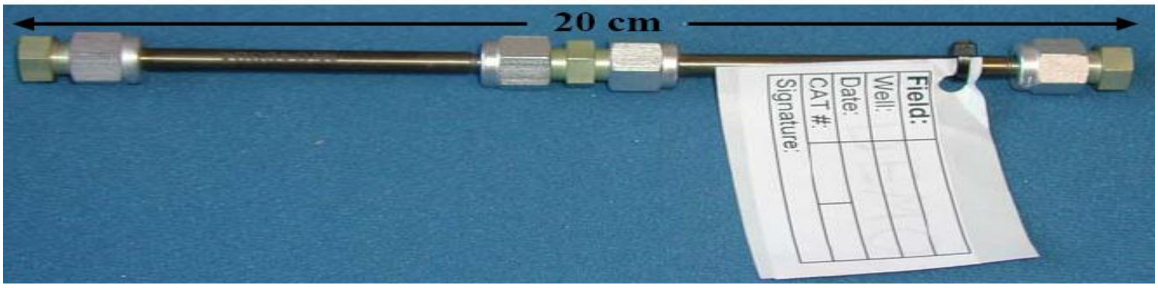


Figure II. 13. Tracer sampling wadding

Table. II.1: list of wells concerned by the sampling campaign for Tracer analysis

Puits	Point d'échantillonnage	Fréquence
Kb-14	Tête de Puits & Annulaire A	Monsuelle
Kb-4	Annulaire A	Bi-mensuelle
Kb-8	Annulaire A	Bi-mensuelle
Kb-6	Tête de Puits	Bi-mensuelle
Kb-9z	Tête de Puits	Bi-mensuelle
Kb-11	Tête de Puits	Bi-mensuelle
Kb-12	Tête de Puits	Bi-mensuelle

6.2 Raw gas sampling to monitor the CO2 content

The raw gas is sampled at the level of the producing well heads and the annular of the old Sonatrach wells. The operation is carried out regularly to follow the evolution of the CO2 content in the gas in order to detect the passage of CO2 in the area where the well is installed. Currently all wells are sampled from the wellhead and / or A&B annuli every two months with the exception of KB-14 which must be sampled monthly due to its proximity to KB-502.

Table II .2- Lists of wells concerned by the CO2 sampling campaign

	Point d'échantillonnage	Fréquence
Kb-14	Tête de puits & Annulaire A-B	Mensuelle
Kb-4	Annulaire A-B	Bi-mensuelle
Kb-8	Annulaire A-B	Bi-mensuelle
Kb-6	Tête de puits & Annulaire A-B	Bi-mensuelle
Kb-9z	Tête de puits & Annulaire A	Bi-mensuelle
Kb-11	Tête de puits	Bi-mensuelle
Kb-12	Tête de puits	Bi-mensuelle
Kb-501	Tête de puits	Bi-mensuelle
Kb-502	Tête de puits	Bi-mensuelle
Kb--503	Tête de puits	Bi-mensuelle

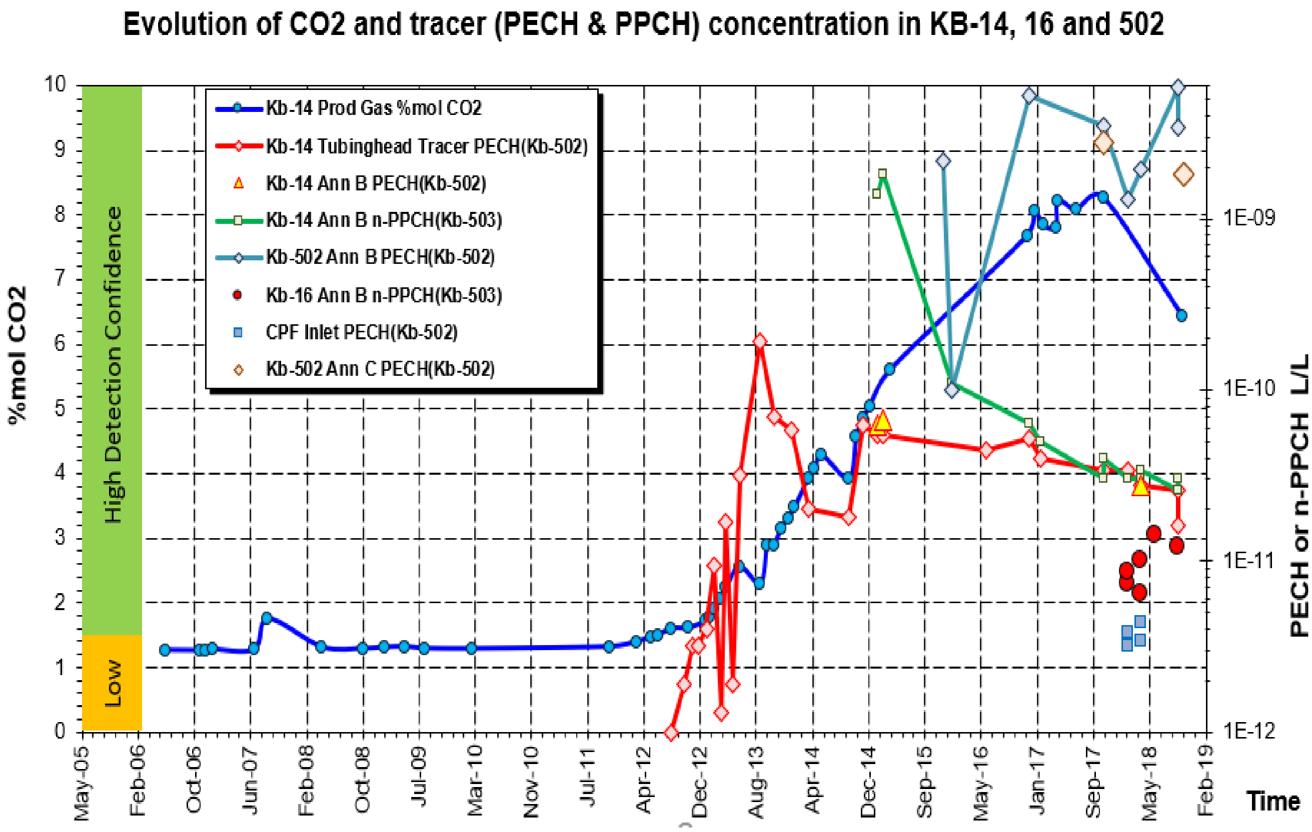


Figure II. 14. Evaluation of CO2 and tracers (PECH, PPCH) Concentration KB-14, Kb-16 and Kb-502

C o n c l u s i o n

The surveillance The surveillance plan applied in Krechaba was started even before the CO2 reinjected such as the satellite imaging (InSAR) and microcosmic (applied on Kb-601). For the surveillance after stop the CO2 reinjection is divided on two parts as the organigram on figure II.2, surface and subsurface; the surface is based on the gas surface survey (BGS and AGI methods).

The main subsurface surveillance is directly related to the risk of CO2 leakage into the aquifer, which is the continental intercalare in the case of Krechba field. This is our subject in the third chapter below;

CHAPTER III

CONTINENTAL INTERCALARE AQUIFER MONITORING

Introduction :

Aquifer monitoring is an important study not only as an indicator of CO_2 movement in the subsurface but also to monitor water quality. The Continental Intercalaire (CI) is the major source of potable water for the majority of North Africa and monitoring its quality is a primary objective of ISG. The purpose of the hydrogeology fieldwork is to acquire data to populate the local and regional hydrogeological model. A robust model of the local and regional hydrogeology will enable modelling of potential aquifer contaminants within the Krechba field Continental Intercalaire sequence.

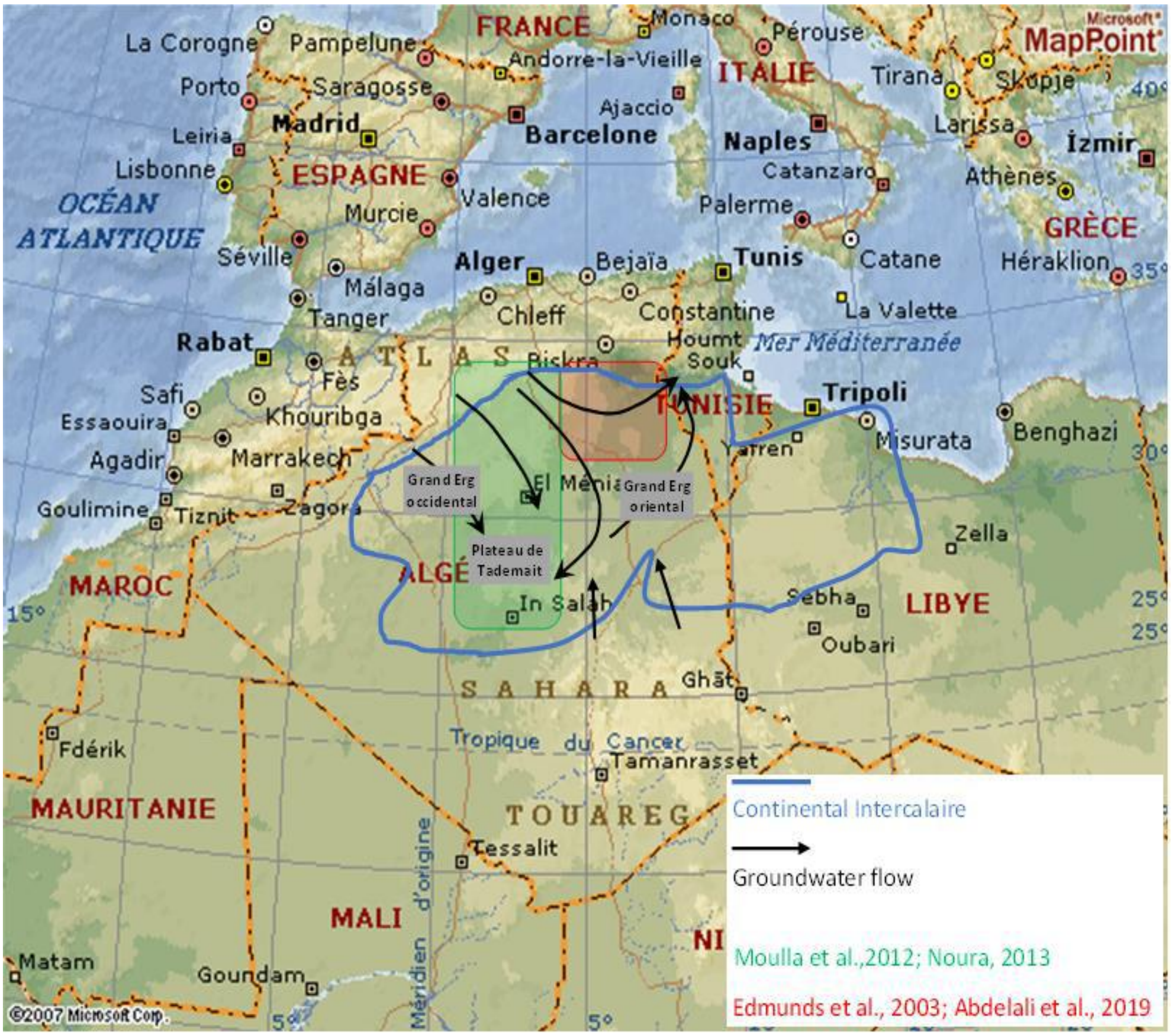


Figure III. 1. Map of the Maghreb with the limits of the CI area and the directions of the groundwater flow

The aquifer monitoring and modelling is done in partnership between In Salah Gas (ISG), the Joint Industry Project (JIP) partners and the British Geological Survey (BGS) in Wallingford, UK till 2012 and the Bureau de Recherché Géologiques et Minières (BRGM) of Orléans, France till today. The monitoring work has three major parts; groundwater flow modelling, pump testing & field sampling, and the construction of a robust hydrogeological field model.

In order the continues five (05) shallow aquifer wells have been drilled, one beside each injector, one in a remote control location and one between the KB5 and KB502 wells in the north of the field, their names (KB 602, KB 603, KB 604, KB 605 and KB 606). Three water supply boreholes are also present at the site for industrial use and for sampling programs (KB 101, KB 102 and KB 103).

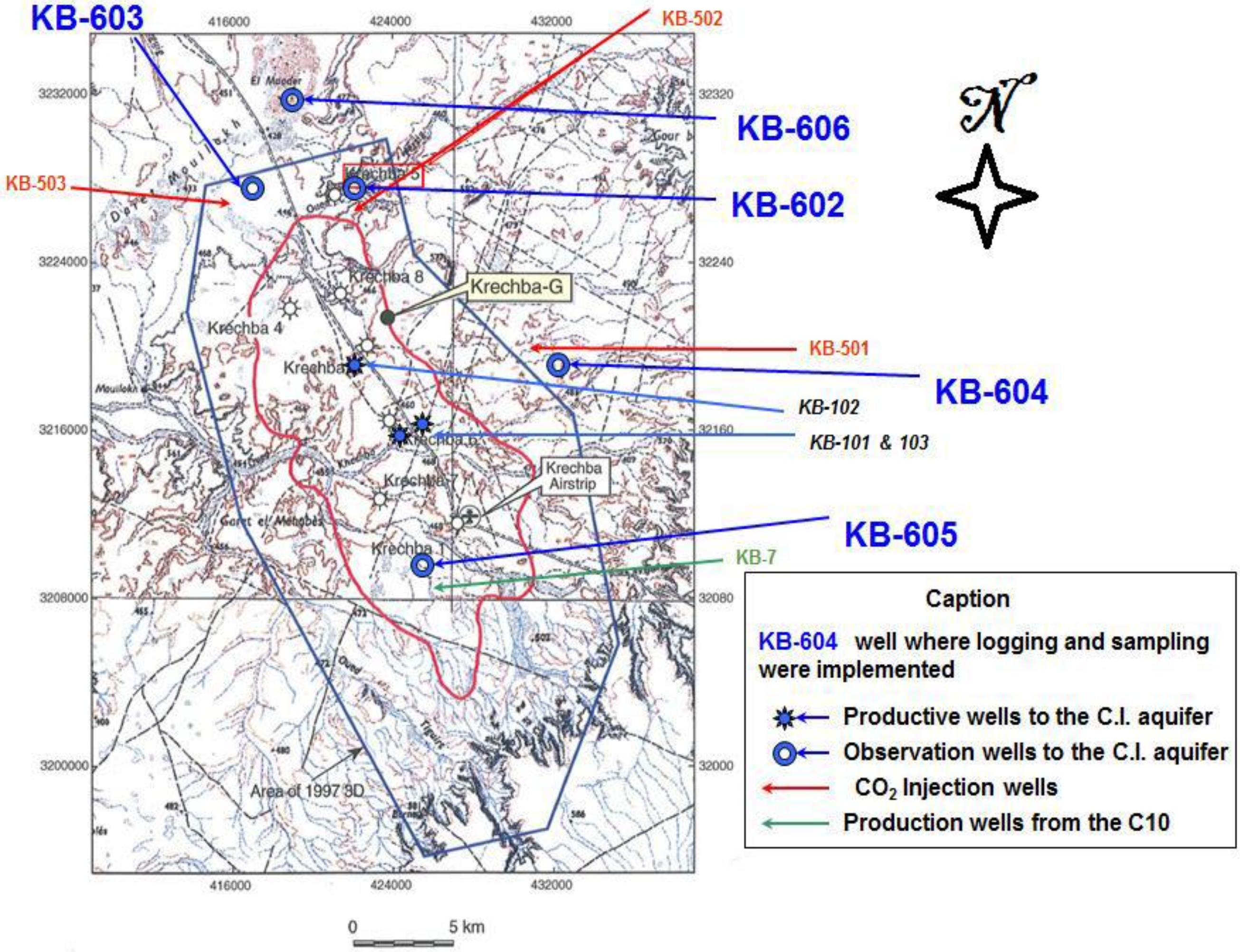


Figure III. 2. Location of the shallow aquifer wells

2 The Continental Intercalaire (Ci) Aquifer :

2.1 Hydrogeological Background:

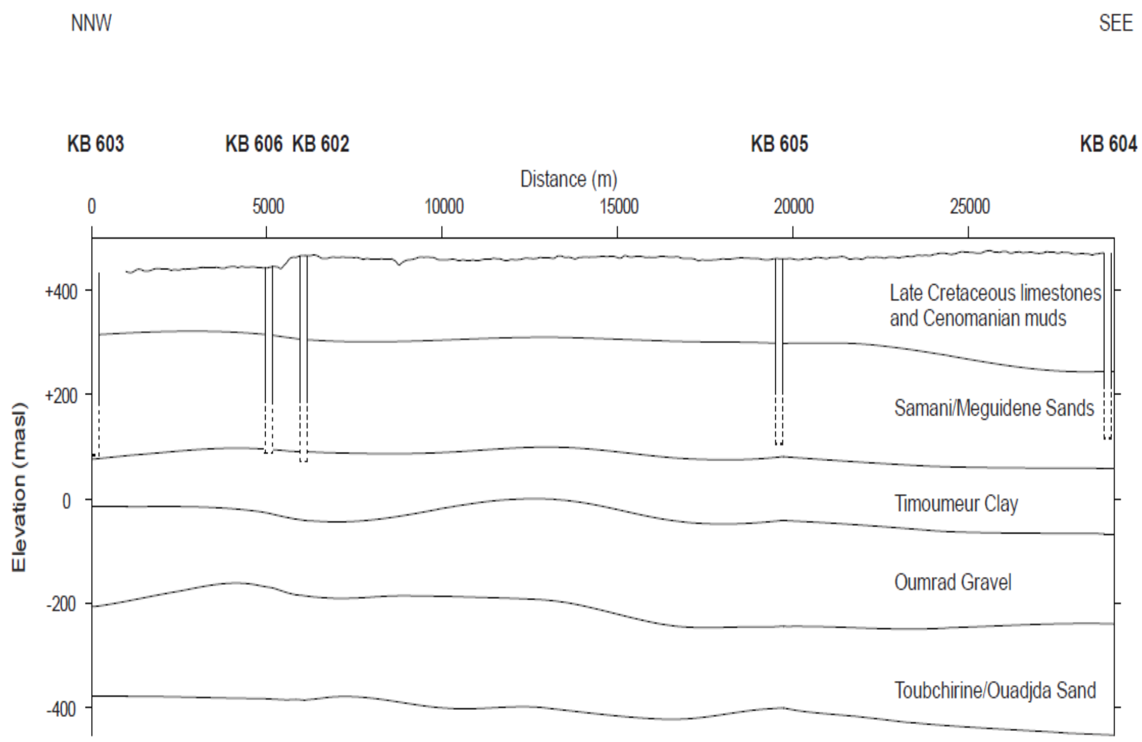
The Continental Intercalaire (C.I.) is one of the world's largest groundwater systems extending (Figure 1) across Algeria, Tunisia and Libya in the northern Sahara Desert (Edmunds et al., 2003). The C.I. is a heterogeneous geological formation, made by a pile of clastic continental deposits formed between the Namurian and the Cenomanian marine transgressions.

The Continental Intercalaire (CI) aquifer at Krechba is on average 700 m thick and consists of the following layers, with thicknesses approximated at KB 502 (Newell and Kirby, 2011):

- Toubchirine/Ouadjda Sand (c. 200 m thick) - although termed sand, appears to be represented by a relatively mud-rich interval at the Krechba site.
- Oumrad Gravel (c. 150 m thick) - coarse sand and gravel with occasional interbedded mudstones.
- Timoumeur Clay (c. 125 m thick) - muddy intervals can be up to 50 m thick with cuttings indicating a predominance of red-brown mud. Laterally muds are replaced by thick sands in some wells (e.g. KB-501).
- Samani/Meguidene Sands (c. 225 m thick) - medium-coarse sand with occasional interbedded thin mudstones. Location of aquifer monitoring boreholes.

The aquifer is confined by late Cretaceous limestones and Cenomanian muds which are up to approximately 150 m thick.

The aquifer is confined by the overlying Complex Terminal (CT) which is up to approximately 150 m thick and encompasses late Cretaceous limestones and Cenomanian muds.



Note: elevation data in NS-59; geological section based on Newell and Kirby (2011) model.

Figure III. 3. Estimated location of screened sections of monitoring boreholes within the CI

2.2 HYDROGEOCHEMICAL BACKGROUND

Edmunds et al. (2003) performed a hydro-geochemical overview of the C.I. aquifer relying on data collected over a section covering the northern Saharan region of Algeria and Tunisia, i.e. at the north the Krechba area (Figure III.1). It led to the following conclusions:

- the studied area can be considered as a hydraulically continuous flow (> 800 km) from a recharge area in the Atlas Mountains to a discharge area in the Chotts of Tunisia; some other flow contributions (e.g. from the Tinrhet plateau) may also converge to the discharge area;
- the water-rock interaction is dominated by a non-carbonate mineralogy; however, the calcium concentration in the groundwater remains controlled by calcite dissolution;
- all C.I. groundwaters are very close to Quartz saturation governed by formation temperature and residence time;

- there is no evidence (in temperature or salinity) of any upward leakage to the C.I. aquifer from deeper formations; conversely, the C.I. aquifer may locally supply other overlying aquifers (e.g. the Complexe Terminal -CT) strengthening the risk of contamination in case of significant abstraction from the CT toward the CI aquifer;
- several sources of mineralisation and rainfall recharge can be interpreted;
- the source of salinity is mainly derived from a non-marine evaporate or syn-depositional clay minerals (except in the NE, Tunisian area);
- the presence of oxidising conditions, including saturated dissolved oxygen, and high NO3 concentrations are recognised over 350 km from outcrop suggesting the absence of organic material in the C.I. (although present below it); this lead to the accumulation of some trace elements (e.g. Cr, mentioned which may be of concern for drinking water and other uses); concentrations in some other trace metals (Ni, Cu, Zn, Pb) are generally low;
- the recharge mainly occurred in cooler, humid periods during last Pleistocene (i.e. 25-30,000 up to 100,000 years BP from groundwater age data) consequently the C.I. water resource must be regarded as non-renewable;
- the C.I. aquifer is bounded by more saline waters both above and below and especially in the discharge areas where they could be entrained during abstraction.

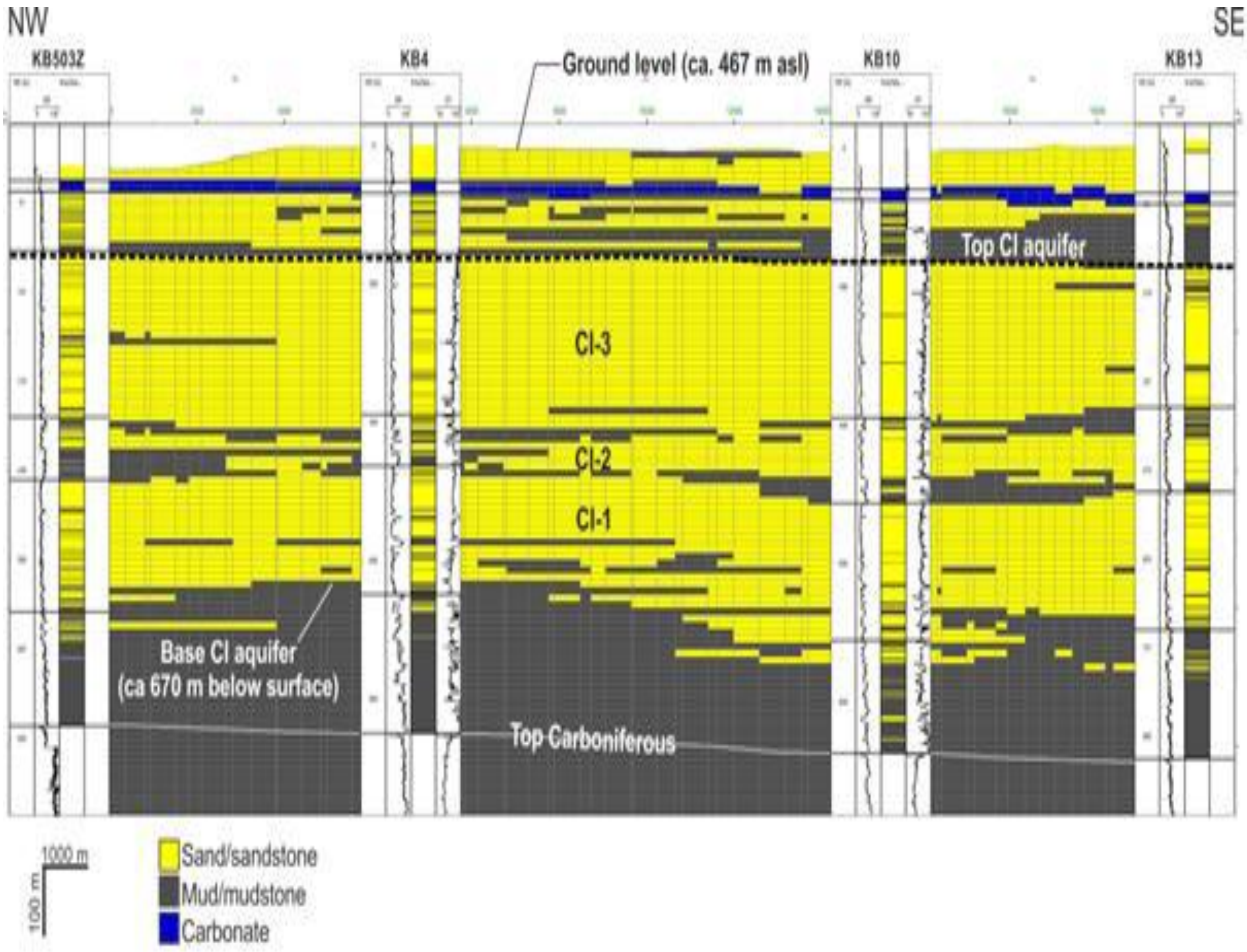


Figure III. 4. Northwest to southeast cross-section across the Krechba site showing four wells. Tracks for gamma-ray log, facies and sonic velocity (where available) plotted against the cellular geological model. (Asfirane et al 2012).

Edmunds et al. (2003) also suggest that measuring the pH at the well heads, “might have led to some increase in the pH from in situ values as the carbonate equilibria respond to new PT conditions”. This overestimation could be explained mainly by the CO2 release into the atmosphere during the water ascent as pressure decreases, according to the reaction:

$CO_2 + H_2O \leftrightarrow HCO_3^- + H^+$,

A decrease of pressure, leading to a release of CO2 moves the chemical equilibrium towards the left side and leads in the same time to a lowering of H+, i.e. to an increase of the pH (= -log(H+)).

In the case of a total leakage, changes in the quality of the IC could be expected because:

- as the host-rock formation is a sandy-clayey one, the hosted water could be more impacted by a possible acidification due to CO2 input, contrary to carbonate bearing rocks that could buffer such acidification;
- as the deposits are possibly linked by channels, when an aquifer is contaminated, very often the other ones follow;
- the present recharge is negligible and once a part of the C.I. aquifer is spoilt, a larger one of this fossil Saharan aquifer would need treatment.

Nevertheless, this assumption suggests a more detailed study confirming:

- With a high level of certainty, the composition of the aquifer sands, their compositional heterogeneity, and their buffering potential across the AOI
- Ensure the relevance of the geological and hydrogeological models by conducting a sensitivity study of the hydrodynamic model parameters.
- Knowledge and network measurements (piezometers, sampling measurements etc.....) more robust on the whole aquifer.

3 Aquifer Monitoring At Krechba Field:

The aquifer monitoring and modelling is done in partnership between In Salah Gas (ISG), the Joint Industry Project (JIP) partners and the British Geological Survey (BGS) in Wallingford, UK till 2012 and the Bureau de Recherché Géologiques et Minières (BRGM) of Orléans, France till today. The monitoring work has three major parts; groundwater flow modelling, pump testing & field sampling, and the construction of a robust hydrogeological field model.

the BGS (British Geological Survey) based their surveillance on the static and pumping study, for BRGM (Bureau de Recherche Géologique et Minière) the study is more based on the logging and the downhole sampling.

3.1 British Geological Survey (BGS) method:

The purpose of the hydrogeology fieldwork with BGS is to acquire data to populate the local and regional hydrogeological model. A robust model of the local and regional hydrogeology will enable modelling of potential aquifer contaminants within the Krechba field Continental Intercalaire sequence.

The objectives of the study are:

- To acquire aquifer pressure and piezometric level data while pumping.
- Collect co-mingled flowed water samples in the five aquifer monitoring wells in Krechba to analyse for physical and chemical parameters.
- Work with local agencies in obtaining data about the Continental Intercalaire at Krechba.
- The monitoring plan was designed to:
- Pump test the Continental Intercalaire to collect volume and pressure data to evaluate recharge capacity.
- Measure changing piezometric levels (head of water) in the observed well and adjacent wells.
- Collect samples of flowed water at regular intervals.
- Analyse sampled water for changes in physical and chemical properties through the duration of the flow.

3.1.1 Methodology

3.1.1.1 Well Pumping

3.1.1.1.1 Fieldwork

Based on input from the BGS, the well will be flowed, first at varying rates for a step test, then continuously for approximately 24 / 48 hours whichever is most practical, or until the pressure sensor shows a steady state has been reached, whichever is soonest. All wells are 'dipped' to record hydrostatic head at the start, end and during operations.

1. Pump should be set to allow sufficient drawdown – circa. 20 - 60m below

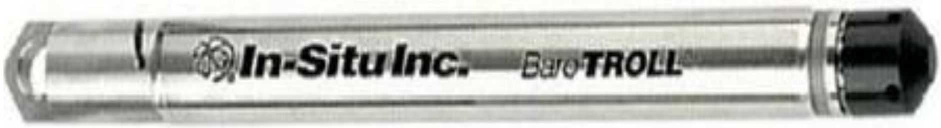
resting water level (RWL).

2. 1 hour steps at rates of about 10, 15, 20, 25 Litre/second (36, 54, 72, 90 m3/hour)
3. Recover for 8 hours (or overnight)
4. 8 hour pumping at constant rate depending on response to step test – circa. 20 Litre/second.
5. Monitor recovery for 8 hours (or overnight)
6. Measure flow rate using in- line flow meter set in by- pass so initial flow which may contain sediment does not pass through meter.
7. Duplicate/check flow measurement by timing filling of 200 Litre drum or tank of known volume.
8. Monitor pH, conductivity and redox status throughout the constant rate test via a flow cell fed from 3- port sampling manifold set upstream of flow meter, to procedure as specified. Collect water and dissolved gas samples from the manifold at 0.5 hour 4 and 7 hours, to specified procedure of sample collection and on- site analysis of alkalinity.
9. Monitor water level throughout the test using down hole pressure transducer, backed up with periodic dipper measurements.
10. Analyse pumping test results to determine Well efficiency, Q/s and transmissivity. These results will guide selection of aquifer properties used in regional and local groundwater models.

Ideally each test should be achievable in 48 hours but local conditions may preclude a test of this length due to weather, logistics failure or availability of escorts.

All water levels were monitored every second using vented 20 m range In-Situ® Inc. Level TROLL® 500 pressure transducers during abstraction and water level recovery. Additionally, water levels were monitored for around 12 hours prior to testing to ensure the level was static. These instruments are accurate to ± 0.02 m according to the manufacturer specification.Atmospheric pressure was also measured every minute throughout all testing using In-Situ® Inc. BaroTROLLs®, which were installed around 5 m below ground level in the borehole to minimise air temperature fluctuations. Therefore, all pumping test data can theoretically be corrected for the effects of the earth tides in the future: once the barometric efficiency of the aquifer has been estimated through longer-term monitoring of air and potentiometric pressures. (details in Appendix 1)

For water level measurement, install the static level valve



To measure the water pressure installed 3m below the static level

Figure. III.5. transmitted to BGS

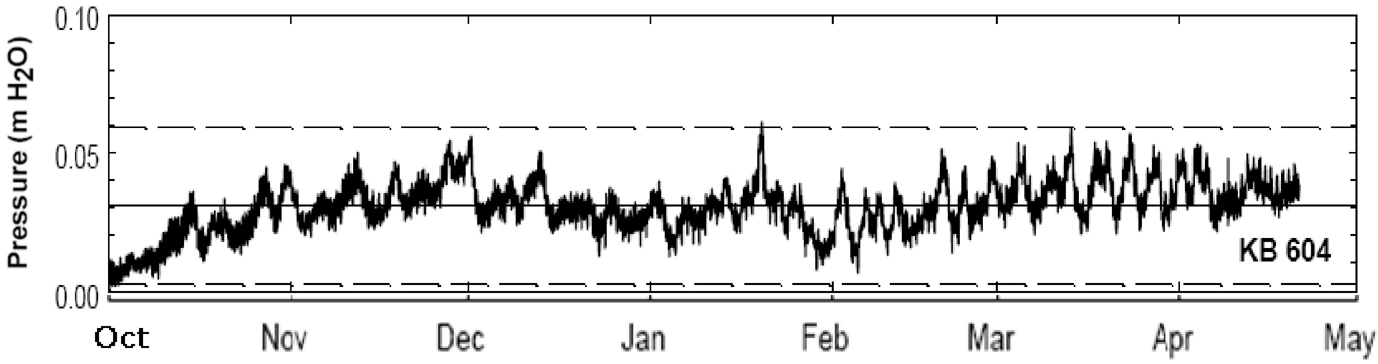


Figure III.6. Annual measurements of the bottom pressure of the aquifer

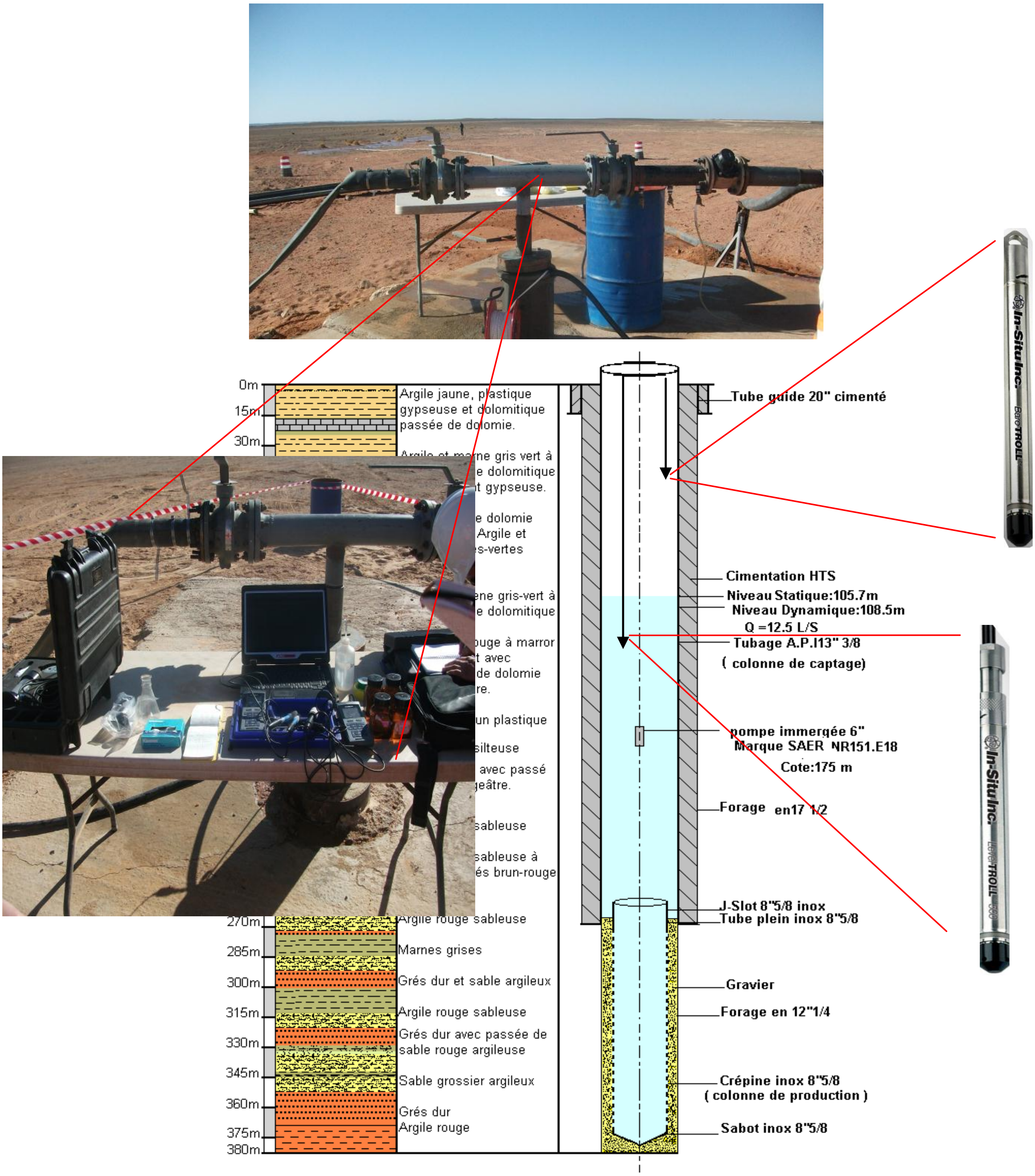


Figure III.7. Schematic showing layout and equipment for pump testing aquifer monitoring wells

Figure III.8. Piezometer and physico-chimes measurements

3.1.1.1.2 Analysis

All pumping tests were initially analysed using Theis curve-fitting and Theis recovery for unsteady-state flow in a confined aquifer. A key assumption of these methodologies is that the borehole fully penetrates the aquifer and hence flow to the borehole is horizontal. However, bedding within the sedimentary CI aquifer is considered to be relatively flat and interbedded mudstones are present so the aquifer is likely to have significant vertical anisotropy. Moreover, all tests were of relatively short duration and induced small drawdowns. Therefore, it is considered justifiable to assume that flow would be predominantly horizontal.

3.1.1.2 Sampling:

3.1.1.2.1 Fieldwork:

Groundwater samples were obtained from each monitoring borehole using a submersible pump, installed at least 10 m below the rest water level, and taps on a borehole manifold (Figure III.4). The intention was to exclude any contact between sampled groundwater and the atmosphere. Samples were collected after 1-2 hours of pumping and, hence, sufficient borehole purging, then after a total of 7-8 hours. Samples were collected twice to investigate any potential changes in hydrochemistry with pumping; equivalent to obtaining samples from varying distances from the borehole.

Figure III. 9. Surface equipment setup showing borehole manifold, flow meter and sampling taps.

On-site measurements of pH, Specific Electrical Conductivity (SEC) and dissolved oxygen (DO) were conducted at the wellhead using a series of Mettler Toledo® instruments. Duplicate parameters were also monitoring with WTW® multi-parameter instruments for quality control purposes. Alkalinity was also determined on site by micro-titration.

Samples for hydrochemistry were passed through a 0.45 µm filter. Separate 30 mL samples were collected in HDPE plastic bottles for cations and anions, with the anion sample remaining untreated. The cation sample was acidified by the addition of 1% and 0.5% by volume of concentrated AristaR grade HNO3 and HCl acids, respectively. Samples for stable C isotope ($\delta^{13}C$) and radiocarbon (^{14}C) were collected unfiltered in 60 mL and 1 litre HDPE bottles, respectively. Dissolved gas samples were collected in stainless steel cylinders of ~50 cm3 capacity using clamped gas-tight connections for the tubing from the wellhead.

Table III.1. Water Analyses parameters

Type	Determinand	Application
Field Measurement	Eh, DO, pH, SEC, alkalinity	In- situ redox and carbonate systemproperties
Major inorganic species	Na, K, Ca, Mg, alkalinity, Cl, SO_4,S, NO_3- N, Si	General water quality/ evolution, redox state
Minor inorganic species	Ba, B, Br, Fe, Li, Mn, NH_4- N, Sr	Redox state, water/rock interaction/evolution
Isotopes	$\delta^{18}O$, $\delta^{2}H$, $\delta^{13}C$- DIC, ^{14}C	Residence time, water/rock interaction
Gases	N_2, CO_2, O_2, CH_4, C_2–C_6, benzene	Reservoir gas leakage, redoxconditions

3.1.1.2.2 Analysis:

Hydrochemical analysis was conducted at BGS Keyworth by ICP-OES for cations, and ion chromatography for anions, except for alkalinity which was measured in the field as mentioned above. Carbon stable isotope analysis was carried out at BGS Keyworth by mass spectrometry after conversion of the dissolved inorganic carbon to CO2 by acidification with phosphoric acid. Radiocarbon analysis was conducted by AMS at the Centre for Isotope

Research, Groningen, Netherlands following preparation at RadioCarbon Dating Ltd in the UK. Dissolved gas analysis was carried out at BGS Wallingford by outgassing the samples into ~120 cm3 glass tubes and measuring the headspace gases using a gas chromatograph with molecular sieve and porous polymer packed columns, and TC and FID detectors.

3.1.1.3 Results:

3.1.1.3.1 Pumping Tests:

Pumping tests were conducted at all water monitoring boreholes for between 7.5 and 20.25 hours and flow rates of between 9.4 and 10.4 L/sec (Table III.2). The calculated specific capacities are all very similar to those calculated from pumping tests undertaken in 2011

Borehole	**Pump depth** (m bd)	**Av. pumping rate** (L/sec)		**Duration** (hrs:mins)	**Drawdown** (m)	**Specific capacity*** (L/sec/m)
		Flowmeter	*Drum*$^{+}$			
KB 602	140	-	9.9	08:00	2.85	3.5
KB 603	102	9.9	9.4	20:14	1.97	5.0
KB 604	132	10.0	-	07:40	0.69	14.5
KB 605	140	-	9.7	08:40	1.27	7.6
KB 606	102	10.4	-	19:09	2.10	5.0

Note: * calculated using flowmeter discharges where available; + based estimated drum volume of 207 L.

Table III.2. Details of pumping tests

Time-drawdown curves for all pumping tests are shown in figure III.5 concurrently with the pumping tests from 2011. The results from the recent tests indicate:

- Boreholes KB 604 and KB 605 both show rapid initial drawdown within the first 100 seconds - the majority probably a result of well storage - and then minimal subsequent drawdown. Considering the total potential instrument error and the effects of earth tides, it is not therefore possible to analyse these pumping tests with any degree of confidence.

- Greater initial drawdown, and thus total drawdown, in KB 602 is likely to be a result of more significant well losses, as the cross-sectional area of the casing is only half that of the other boreholes.

- The reduction in drawdown near the start of the tests in borehole KB 604 (10 secs) is likely to represent a delayed response in the aquifer to pumping within the well.

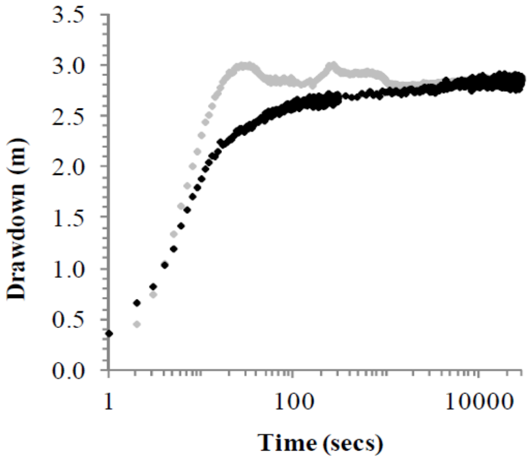
- Drawdown within boreholes KB 602, KB 603 and KB 606 is much more progressive over time and allows analysis.
- There are no obvious indications of hydraulic boundaries or secondary porosity in possible fractures within more cemented horizons over the test period.

The recent test results are also very similar to those undertaken in 2011. The only exception is at borehole KB 602 where the initial 20 minutes are significantly different. This may be because of a varying pumping rate over this period during 2011, resulting in several small adjustments in drawdown. Nevertheless, the data are alike following this period.

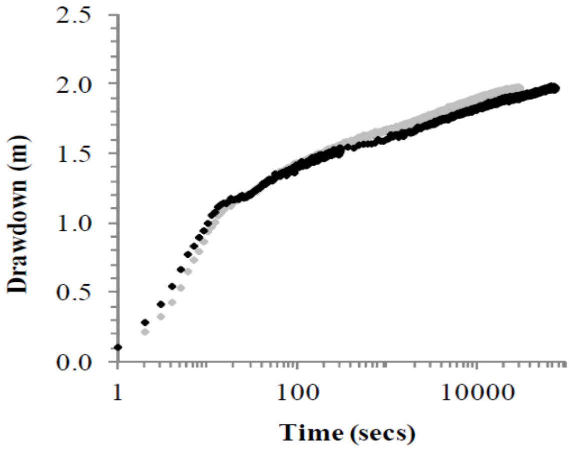
Similar behaviour within all boreholes is also displayed in the recovery curves (Figure III.6), although there is a greater change in residual drawdown following the initial 100 seconds compared with the drawdown phase.

Observations at KB 606 indicated there was no response to the pumping test at KB 603 roughly 5 km away. Nevertheless, around 0.05 m of drawdown was induced by the test at KB 602 approximately 900 m away.

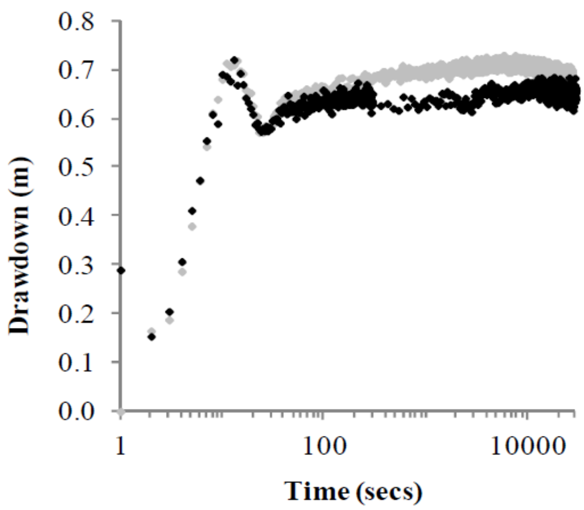
KB 602



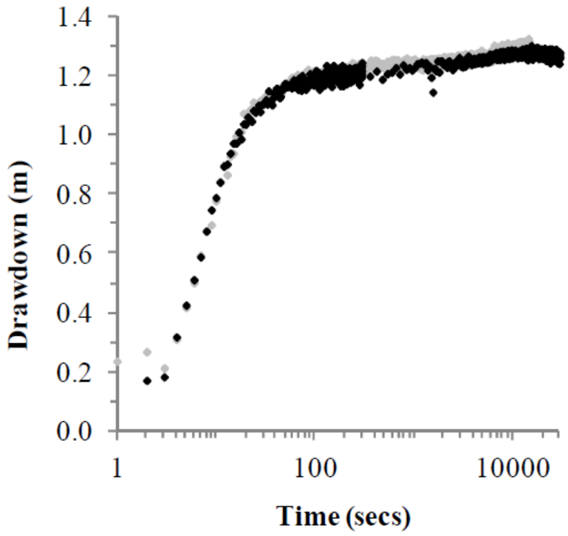
KB 603



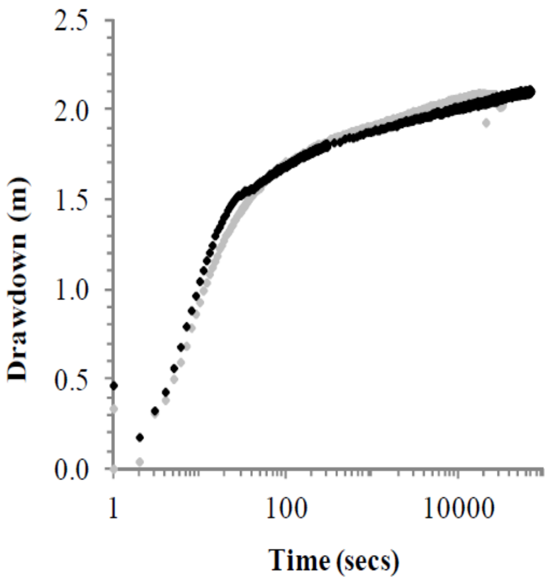
KB 604



KB 605



KB 606



KB 602 as an observation well during test on KB 606

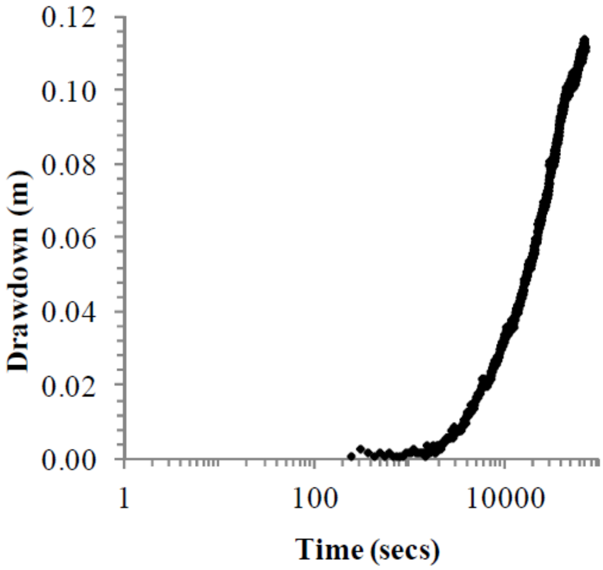
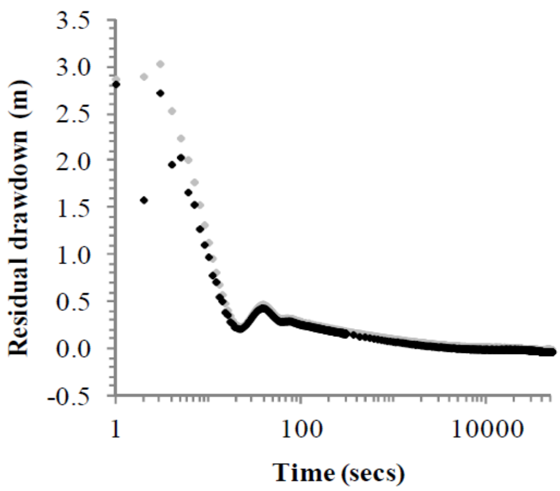
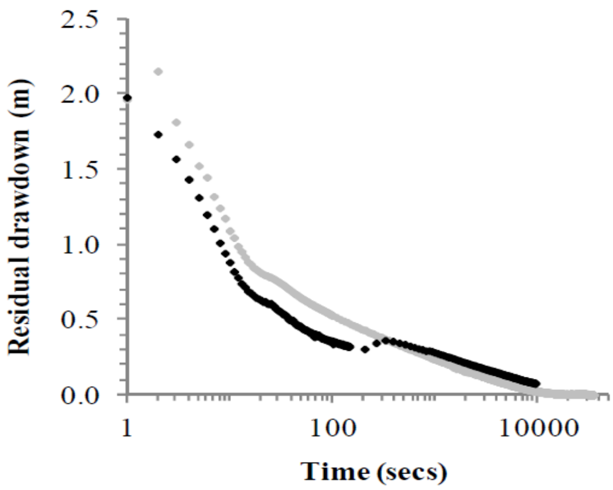


Figure III.10 Time-drawdown curves for borehole

KB 602



KB 603



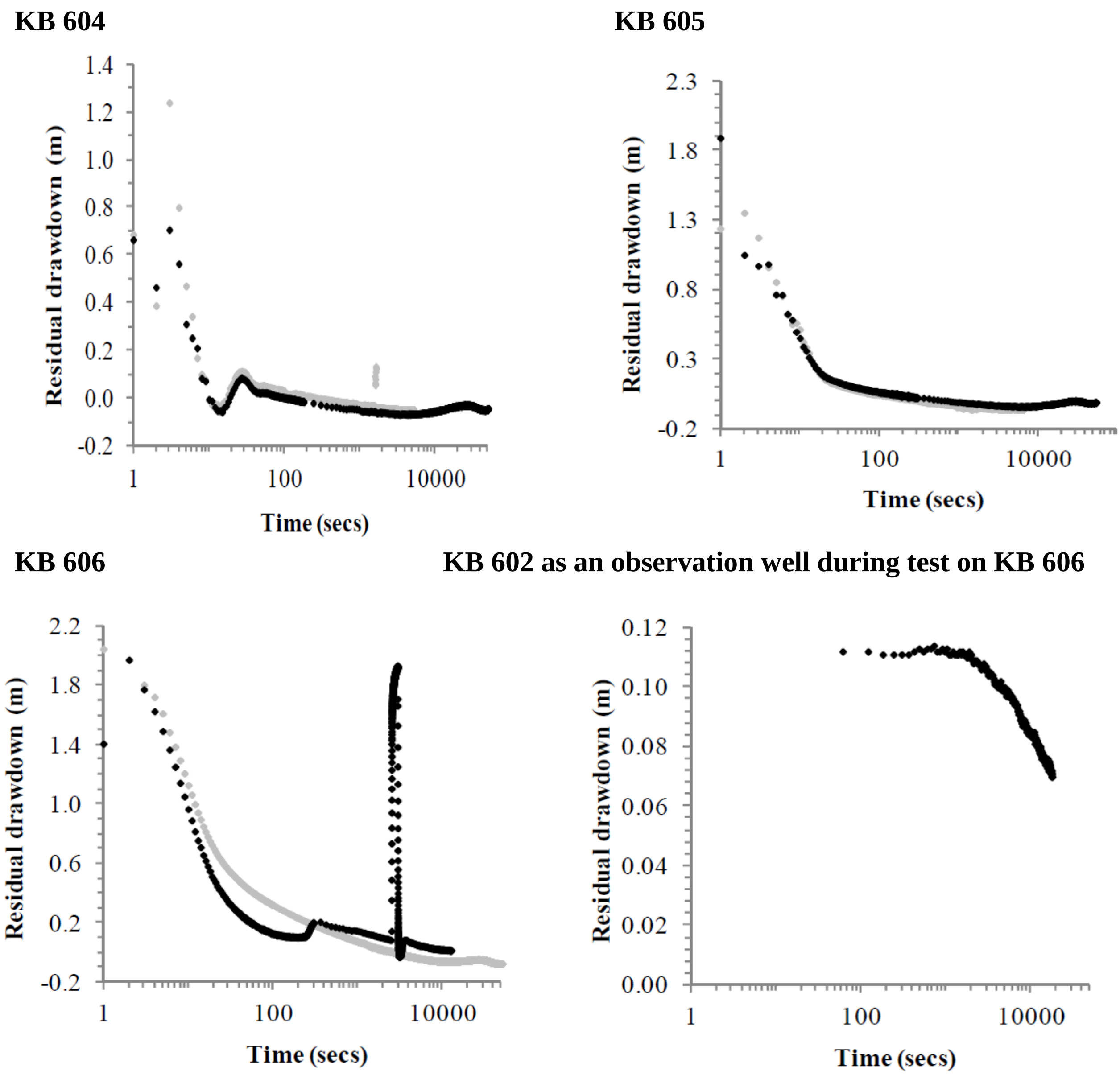


Figure III.11 Time-recovery curves for boreholes

3.1.1.3.2 Analytical Analysis:

All pumping tests were analysed using Theis curve-fitting and Theis recovery for unsteady state flow in a confined aquifer. A key assumption of these methodologies is that the borehole fully penetrates the aquifer and hence flow to the borehole is horizontal. However, bedding within the sedimentary CI aquifer is considered to be relatively flat and interbedded mudstones are present so the aquifer is likely to have significant vertical anisotropy. Moreover, all tests were of relatively short duration and induced small drawdowns. Therefore, it is considered justifiable to assume that flow would be predominantly horizontal.

Theis analysis of boreholes KB 603 and KB 606 are shown in Figure III.7. These both show good agreement, after initial well losses, with the type curve. Curve-fitting for boreholes KB 602, KB 604 and KB 605 was not undertaken due to minor drawdown beyond 100 seconds resulting in considerable uncertainty in the process.

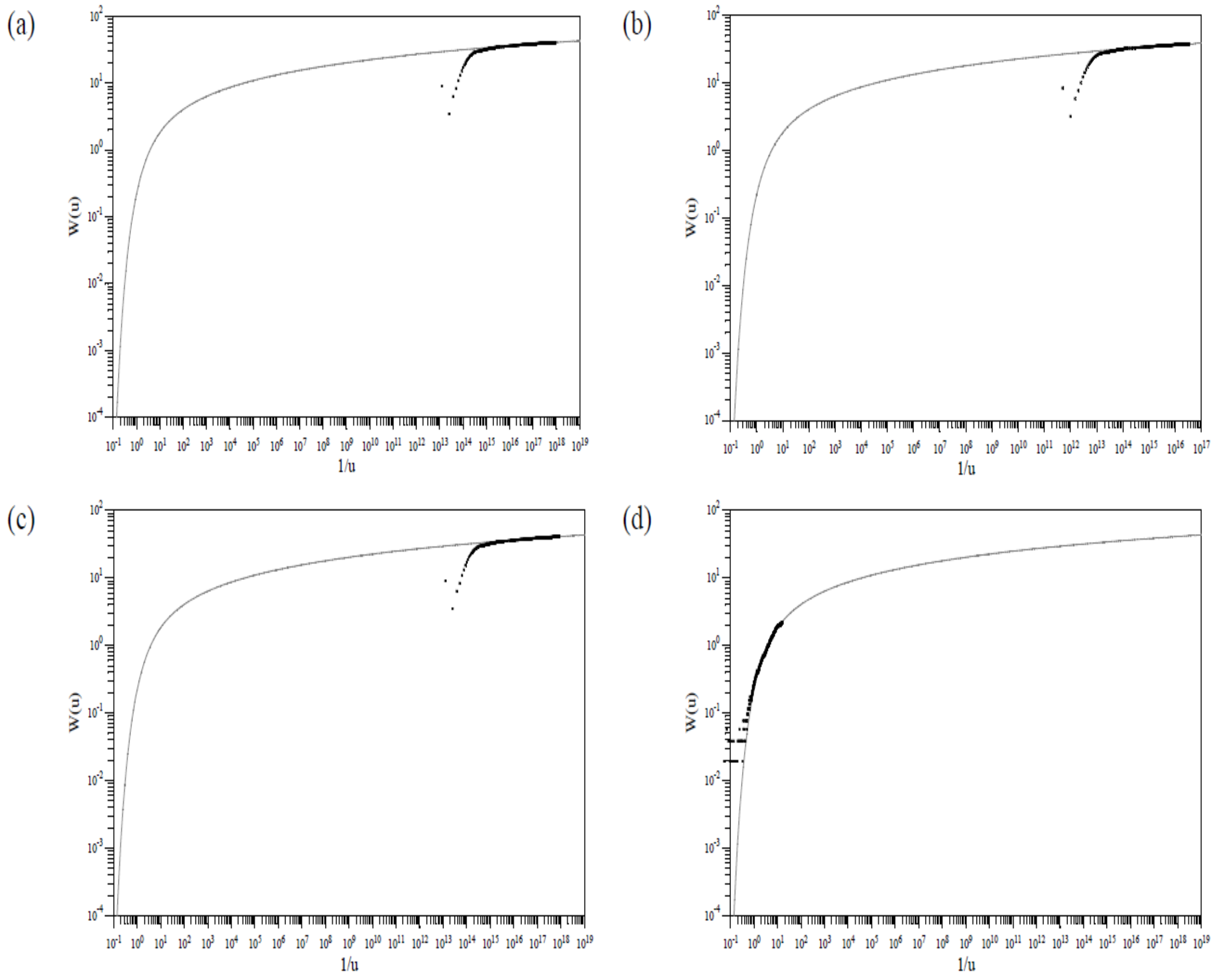


Figure III.12. Theis analysis of pumping tests at boreholes (a) KB 602, (b) KB 603, (c) KB 606 and (d) KB 602 as an observation well during test on KB 606.

Theis recovery analysis was performed successfully on all single borehole pumping tests (Figure III.8). Nevertheless, the change in residual drawdown over the section which fits the Theis recovery line for boreholes KB 604 and KB 605 is only around 0.1 m and therefore there is low confidence in these results. However, it is still possible to state that the section of the aquifer tested appears to be more transmissivity than that in boreholes KB 602, KB 603 and KB 606. Unfortunately, the pump appears to have been restarted in borehole KB 606 during recovery (at 05:00), limiting the available data to analyse and hence reducing the confidence in the analysis.

Estimated transmissivity values indicate a range between 690 and 2820 m2/d over the section of the aquifer tested (Table III.3). Following the assumptions stated in Section 2.1.2, it is possible to suggest that hydraulic conductivity varies between 7 and 27 m/d based upon the more reliable Theis recovery data. This is consistent with the 6–24 m/d range calculated in 2011 (Sorensen et al., 2011).

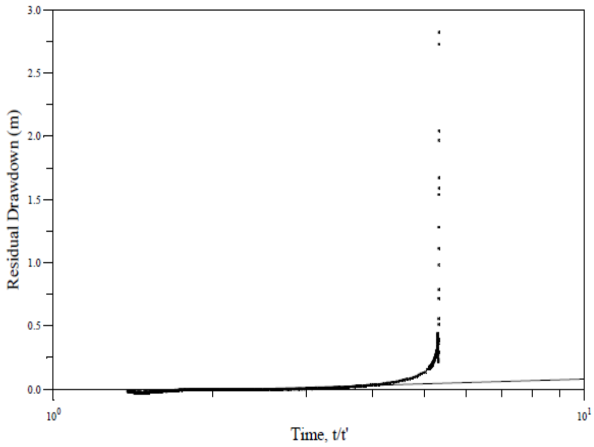
The longer duration pumping tests undertaken on boreholes KB 603 and KB 606, sing similar abstraction rates to the previous tests, do not significantly refine estimates of ydraulic conductivity. There is minimal difference between the calculated transmissivity performed on the data from pumping well and observation well in the KB 606 pumping test. However, analysis of the observation well data also provides an estimate of storativity of 3.4 × 10-4.

Table III.3. Analytical estimates of transmissivity and hydraulic conductivity

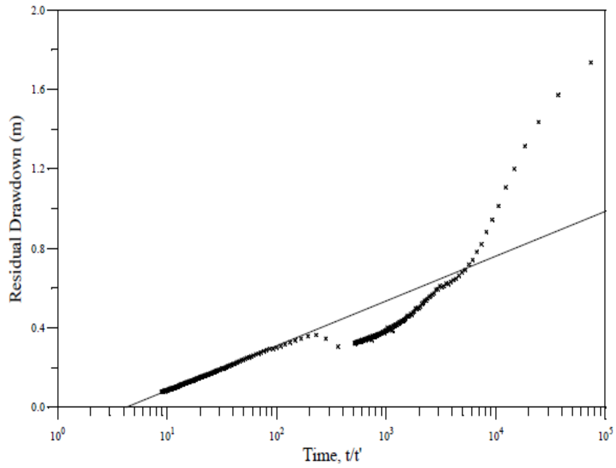
Borehole	Theis (m^2/d)	Theis Recovery (m^2/d)	Hydraulic Conductivity (m/d)
KB 602	1310	980	8.8
KB 603	1210	690	6.7
KB 604	-	2820	27.4
KB 605	-	1970	19.1
KB 606	PW 1380+	1280	12.4
	OW 1370*	-	12.4

Notes: + pumping well; * KB 602 observation well

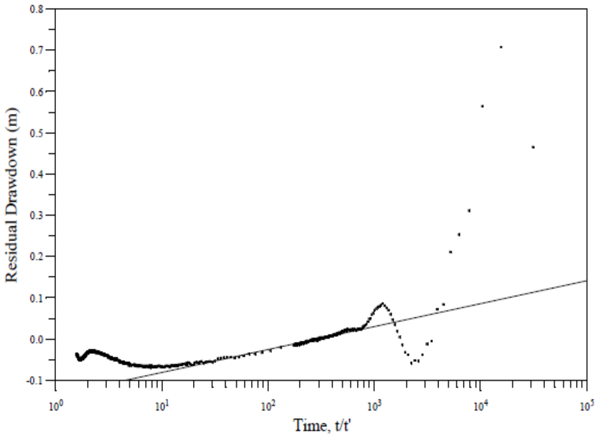
Kb602



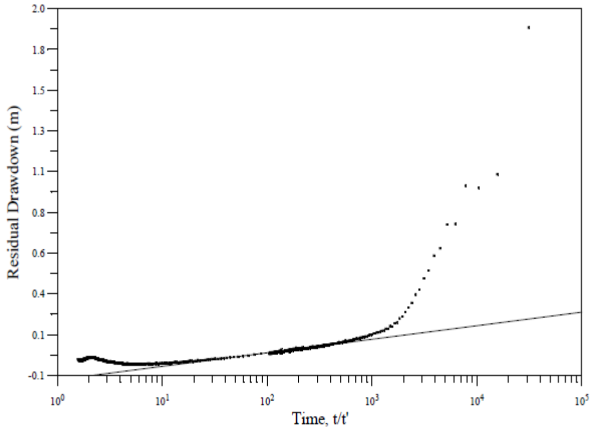
Kb603



Kb604



Kb605



KB606

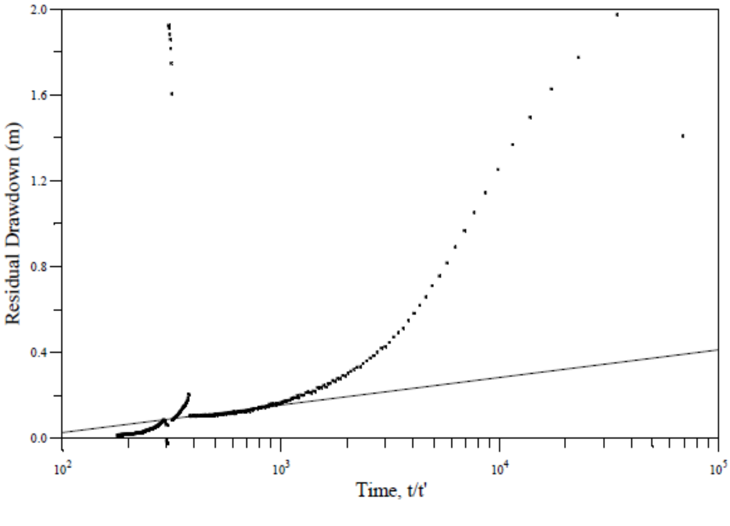


Figure III.13 Theis recovery analysis of boreholes

3.1.1.3.3 Numerical Analysis:

A finite difference cylindrical grid numerical model (Mansour et al., 2011) was used to analyse the pumping test results. This numerical model can simulate many flow processes including well storage, well losses, effect of casing and the effects of partly penetrating boreholes which are all prevalent in the data. Radial symmetry is assumed to be a valid assumption in these analyses. Therefore, groundwater flows are simulated in only two dimensions – radial and vertical. It is also assumed that the pumping tests were uninfluenced by boundary effects.

Drawdown at the abstraction borehole KB 606 could be acceptably reproduced using the previously derived hydraulic parameters in Sorensen et al. (2011), but these did not produce a good match at the observation borehole. Therefore, the KB 606 model was re-parameterised by calibration against data from the observation well (Table 3.3). This involved reducing the specific storage by tenfold to 2 × 10-6 m-1, the vertical hydraulic conductivity from 1 to 0.04 m/d and the horizontal conductivity from 8.2 to 8 m/d to produce an acceptable fit (Table III.4 and Figure III.10). These hydraulic parameters also replicate the response in the abstraction well reasonably well during pumping (Figure III.9). The recovery observation data are limited as discussed in Section 3.1.1. Nevertheless the model matches the general rate of recovery.

The analysis of the observation well data estimated the specific storage as 2 × 10-6 m-1 (i.e. a storativity of 4.1 × 10-4). This value is used in the analysis of the KB 603 single borehole pumping test to refine the values of horizontal and vertical hydraulic conductivity.

Table III.4. Hydraulic parameters for models

Parameter	KB 603	KB 606
Horizontal hydraulic conductivity (m/d)	8	8
Vertical hydraulic conductivity (m/d)	0.01	0.04
Specific storage (m^{-1})	0.000002	0.000002
Well losses	0.18	0.08
Thickness of aquifer in contact with borehole (m)	206	197

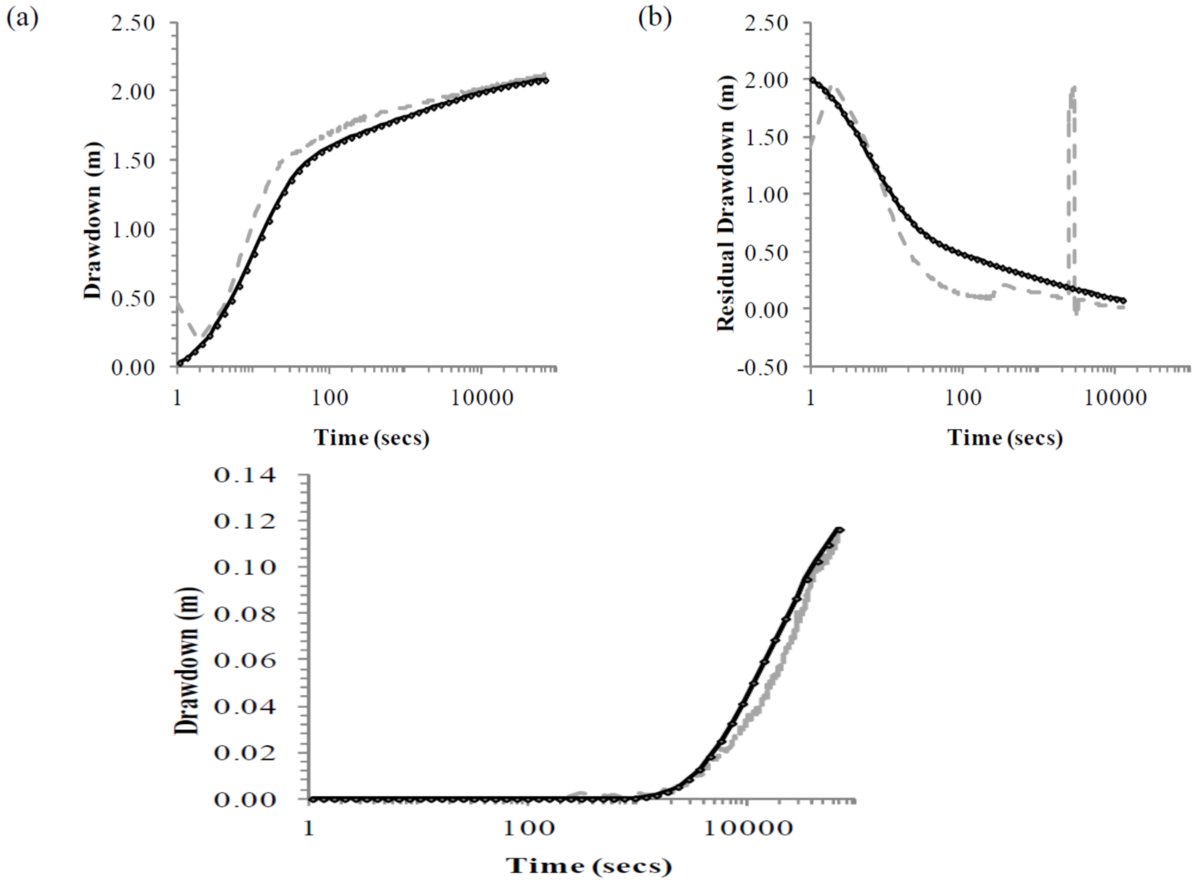


Figure III.14. Observed (grey) and simulated (black) (a) time-drawdown recovery curves for observation well for KB 606 test

Results from both analytical and numerical analysis are reasonably comparable indicating a hydraulic conductivity of 7–27 m/d and storativity of 3–4 × 10-4. Furthermore, the estimates of hydraulic conductivity concur with previous estimates in Sorensen et al. (2011). The results again indicate that boreholes in the north of the site appear to be screened against a less permeable section of the aquifer compared with the other monitoring boreholes.

There is still considerable uncertainty in the upper limit in the range of hydraulic conductivity given how quickly boreholes KB 604 and KB 605 approach steady state at the pumping rate. Nonetheless, the estimated hydraulic conductivity values at Krechba are concurrent with analysis of over 80 pumping tests in the Adrar region which produced a range of 3–27 m/d (BGS/BRGM, 2012). There is minimal information concerning aquifer properties in the lower section of the aquifer.

3.1.1.4 Hydrogeochemistry:

3.1.1.4.1 field measurements:

Temperature, pH, dissolved oxygen, redox potential, specific electrical conductivity and alkalinity were measured at the wellhead concurrently with hydrochemical sampling. The following results were obtained.

Table III.5. Values of parameters measured at the wellhead during the pumping tests

Sample ID	Elapsed time hr	Date	Temp °C	pH	DO[1] mg/L	Eh mV	SEC[2] µS/cm	Alkalinity mg/L
KB-602	1	16-Feb-12	32.4	7.73	6.00	166	525	86
KB-602	7	16-Feb-12	32.7	7.73	6.50	221	526	85
KB-603	1.5	12-Feb-12	32.2	7.67	6.40	174	586	87
KB-603	7.5	12-Feb-12	32.4	7.62	7.20	141	594	91
KB-604	1	19-Feb-12	34.7	7.34	6.40	172	438	87
KB-604	8	19-Feb-12	35.0	7.39	6.60	224	443	92
KB-605	1	21-Feb-12	34.0	7.63	6.70	175	461	90
KB-605	8	21-Feb-12	34.0	7.64	6.90	153	462	89
KB-606	2	14-Feb-12	32.5	7.90	6.70	173	528	84
KB-606	8.5	14-Feb-12	32.9	7.64	6.30	160	529	82

[1]Dissolved oxygen
[2]Specific electrical conductivity

Measured values changed little between the first and second samplings, indicating that water quality remained similar throughout each test. However, there were some differences between the individual monitoring wells, mainly in SEC which was lower in wells KB 604 and KB 605. Dissolved O2 was found at similar concentrations in all the well waters.

3.1.1.4.2 Hydrochemistry:

The same determinants as measured in Sorensen and Darling (2011) were analysed on the pumping test waters, with results as shown in Table 2. As with the wellhead parameters, there were no significant changes in concentration between the first and second samplings.

Table III.6. Analyses of major and selected minor ions in waters from the monitoring wells during the pumping tests of February 2012.

Sample ID	Ca mg/L	Mg mg/L	Na mg/L	K mg/L	HCO_3 mg/L	Cl mg/L	SO_4 mg/L	NO_3-N mg/L	NO_2-N mg/L	NH_4-N mg/L	Si mg/L	Mn µg/L	Fe_{tot} µg/L	Cr µg/L	Cu µg/L	Ni µg/L	Pb µg/L	Zn µg/L
KB-602 i	39.3	12.8	35.1	5.7	86	66.0	61.3	4.84	<0.015	<0.20	6.54	10	30	9.4	1.0	0.1	0.03	2.9
KB-602 ii	40.1	13.3	35.6	5.8	85	68.4	64.3	4.23	<0.015	<0.20	6.62	8.1	40	10.8	1.2	0.1	0.05	3.8
KB-603 i	39.5	15.9	45.1	6.0	87	81.9	67.7	4.53	<0.015	<0.20	6.66	7.3	16	12.5	1.2	0.8	<0.02	2.0
KB-603 ii	40.6	16.0	45.2	6.1	91	85.0	69.1	4.74	<0.015	<0.20	6.82	7.4	25	13.0	2.5	0.5	0.03	2.9
KB-604 i	38.0	11.7	27.9	5.5	87	47.9	54.4	3.63	<0.015	<0.20	7.50	12	8.0	9.0	1.0	0.5	0.04	10.4
KB-604 ii	37.0	11.6	27.4	5.6	92	46.3	52.1	3.69	<0.015	<0.20	7.42	10	27	10.7	2.0	0.3	0.05	5.9
KB-605 i	37.8	12.2	28.6	5.5	90	51.3	56.7	3.55	<0.015	<0.20	7.49	6.4	9.0	14	1.5	0.1	0.02	4.2
KB-605 ii	38.6	12.2	29.1	5.8	89	50.7	56.2	3.61	<0.015	<0.20	7.56	5.1	17	14.9	3.3	0.2	0.12	8.1
KB-606 i	39.7	13.8	37.9	6.0	84	68.2	63.4	4.13	<0.015	<0.20	7.71	20	16	8.8	<0.4	0.3	<0.02	2.6
KB-606 ii	39.1	13.7	37.7	6.0	82	67.5	62.7	4.25	<0.015	<0.20	7.24	14	25	9.9	1.0	0.2	<0.02	3.1

(i) and (ii) refer respectively to the initial and final samples from the pumping tests

However, as suggested by the SEC results, total dissolved solids were again lower in KB 604 and KB 605, due mainly to lower Na and Cl values.

3.1.1.4.3 Dissolved gases:

Samples for dissolved N2, O2 and CO2 analysis were not collected during the 2012 sampling round since O2 is already known from the wellhead electrode measurement, and CO2 is calculable from temperature, pH and alkalinity measurements (Table III.5). However, the opportunity was taken to acquire samples to analyse for the presence of CFCs to determine whether or not the dissolved O2 found in the sampled waters was the result of the introduction of modern air during the pumping tests. The results are given in Table III.6

Table III.7. Values of pCO2 and the equivalent dissolved CO2 concentrations calculated from wellhead data from the February 2012 pumping tests.

Sample ID	pH	Alkalinity mg/L	Temp °C	log $p\,CO_{2\ calc}$ bar	diss $CO_{2\ calc}$ mg/L
KB-602 i	7.73	86	32.4	-2.72	2.4
KB-602 ii	7.73	85	32.7	-2.72	2.3
KB-603 i	7.67	87	32.2	-2.65	2.8
KB-603 ii	7.62	91	32.4	-2.58	3.3
KB-604 i	7.34	87	34.7	-2.30	5.9
KB-604 ii	7.39	92	35.0	-2.33	5.5
KB-605 i	7.63	90	34.0	-2.58	3.1
KB-605 ii	7.64	89	34.0	-2.60	3.0
KB-606 i	7.90	84	32.5	-2.90	1.6
KB-606 ii	7.64	82	32.9	-2.64	2.8

(i) and (ii) refer respectively to the initial and final samples from the pumping tests

3.2.1 Methodology:

3.2.1.1 Physico-Chemical Logging:

The use of a multi-parameter probe (Idronaut Ocean Seven 303) to measure physico-chemical parameters within the water column is applicable wherever a water body presents variations or is stratified. The probe is lifted by a housing to enable downhole usage on wireline (Figure III.15A & B).

The manufacture of the cuff-support (housing) was by SCODIP® company. The cuff-support was manufactured in 2015 using a 3.6 mm-thick stainless steel tube with an outer diameter of 60.3 mm. A foam pipe was provided to wedge the probe in the housing. Grooves of triangular section were put along the whole length of the hose to let as much water flow into the cuff-support and so on to the probe sensors. In order to lock the probe, a valve was set at the base and at the top of the probe with an open pipe for the probe cable. As the housing was distorted during the 2015 field campaign, a new thicker one (7 mm-thick) was ordered and used during the 2017 field campaign.

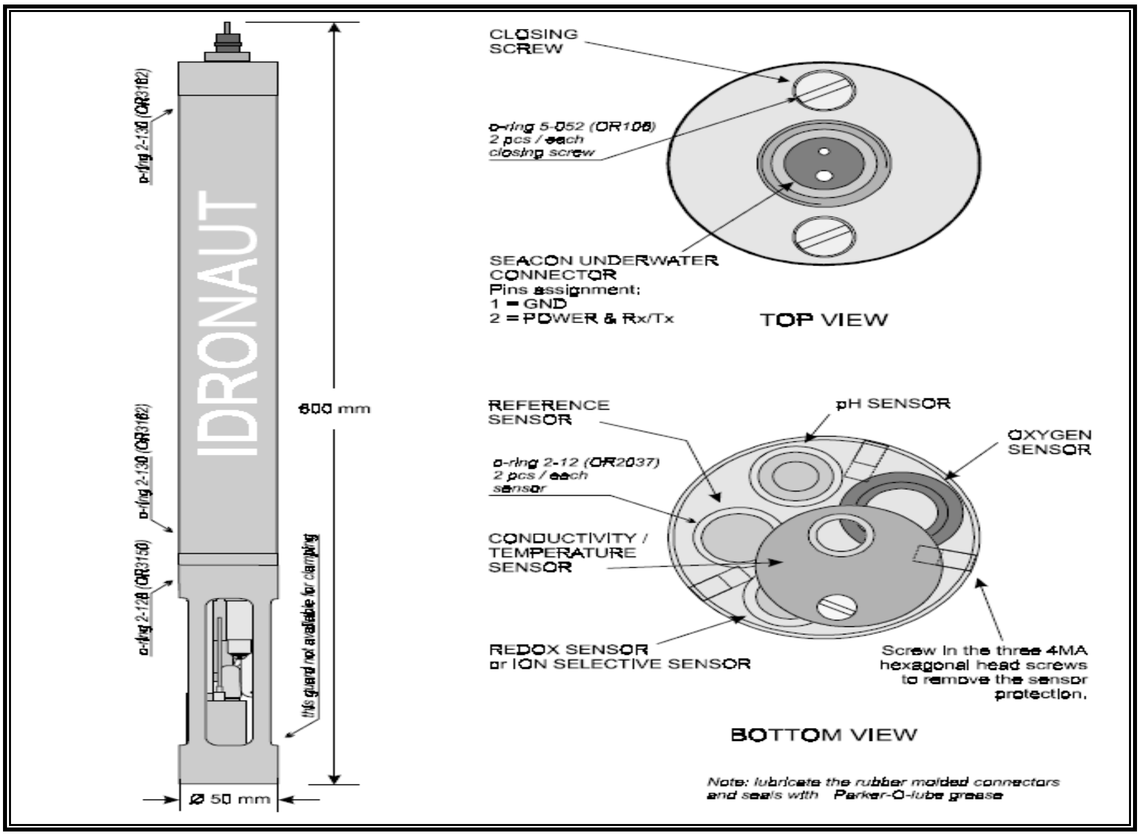


Figure III.15.A. schematic of BRGM Probe

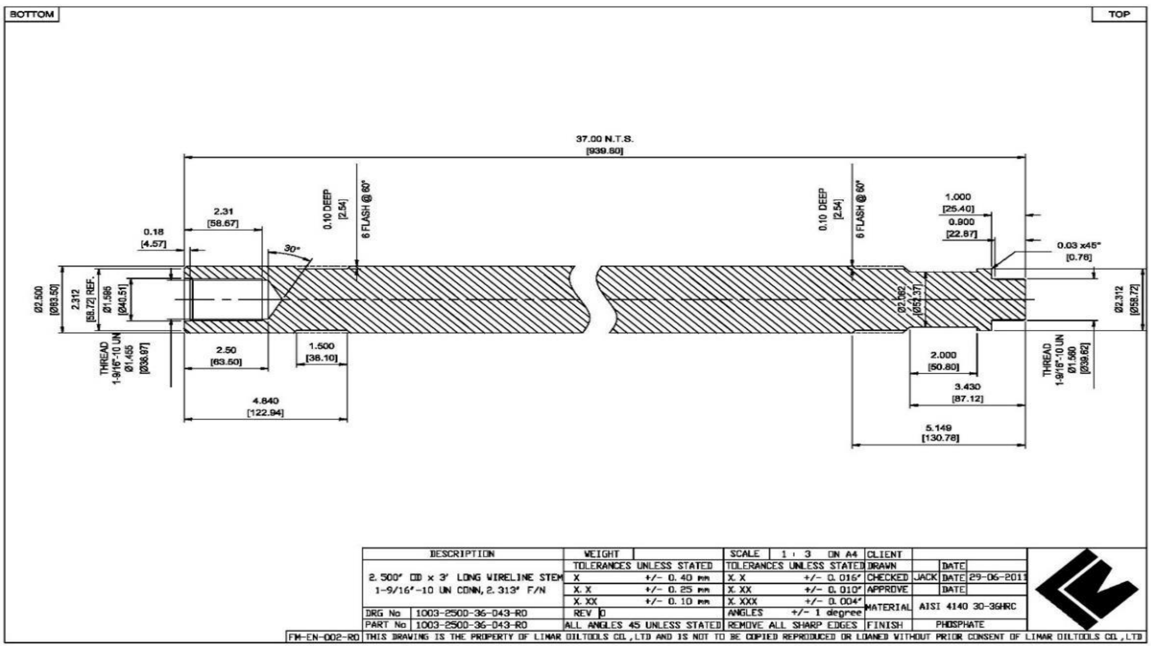


Figure III.15. B. Probe housing design

The measured parameters are the pressure (or depth), temperature (T), pH, electric conductivity (Cond.), redox potential (Eh) and dissolved oxygen (O2). The profiles of T, pH, Cond., Eh and O2 can be drawn as functions of depth and provide information about the possible heterogeneities of the water body. In the case of the C.I. aquifer, consistent parameter discontinuities may reveal differences in the aquifer formation and even different productive levels. The logging operation must be carefully performed with regard to the lifting speed: the response time of each parameter must be taken in consideration (Appendix 2). The response time of pH, Eh and O2 sensors is much longer (3 s) than the one of T, P and Cond. (50 ms at a lift speed of 1 m/s). The average lift speed was fixed at 5 m/min (8 cm/s); the depth uncertainty of measured pH, Eh and O2 values will thus be approximately 30 cm.

The five observation wells (Figure III. 2) were investigated starting from the NW ones (KB-603 and KB-606), followed by the southern wells (KB-604 and KB-605) and ending with the KB-602 which in the past had displayed more difficulties for the probe penetration. In particular, KB-602 casing diameter passes from 95/8” to 41/2” instead of 13 3/8” to 85/8” on the other wells (Figure III. 2).
On each well, the Expro team implemented a slick-line unit helping to operate up- and down-lifting of the probe and sampler, to keep on a relatively constant lifting speed and to pass when obstacles were met (using centralizer, joints, etc.) (Figure III.16).

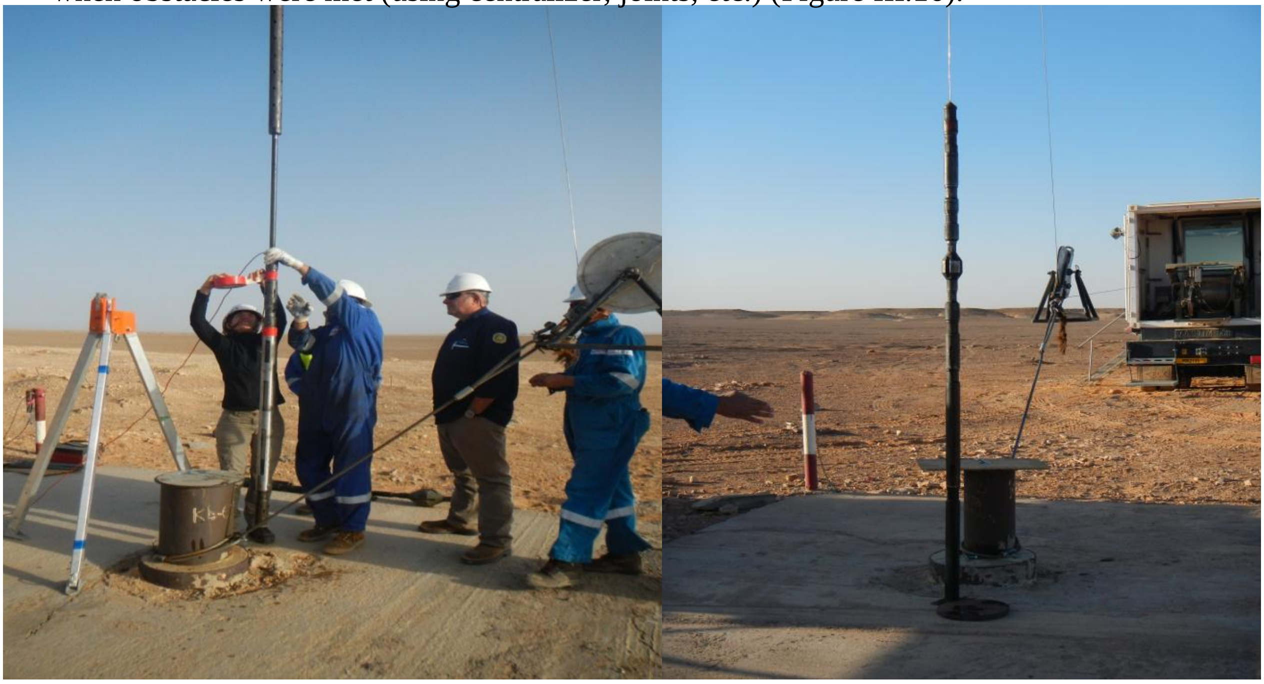


Figure III.16. Field operation BRGM and Expro Team

3.2.1.2 In-Situ Sampling:

The aims of this method of deep sampling (Figure III.17) were to sample at a precise depth avoiding a mixing into the water column in the case of different productive layers,

better preserve the gas phase within the fluid during its ascent in the sampling tube and implement a light and quick operation of sampling. The principle of this method relies on gas-driven sampling. The carrier gas must be inert with respect to the sampled fluid.

Helium or nitrogen is delivered from a bottle equipped with a pressure regulator through a plastic pipe, part of a bi-tube device. A check valve is set between the upper bi-tube and a lower single tube. A water sample is obtained after a sequence of pressurizing adjusted to the desired depth of sampling and stopping the pressurization when the deep fluid can flow up. The first volume of the pipe immersed in the borehole before pressurizing which corresponds to the initially stagnant water of the drill-hole, must be discarded. Then, the water driven from the productive layer, flows out. Caution must be paid to dissolved gas sampling where enough water can buffer the pressurized carrier gas (helium or nitrogen).

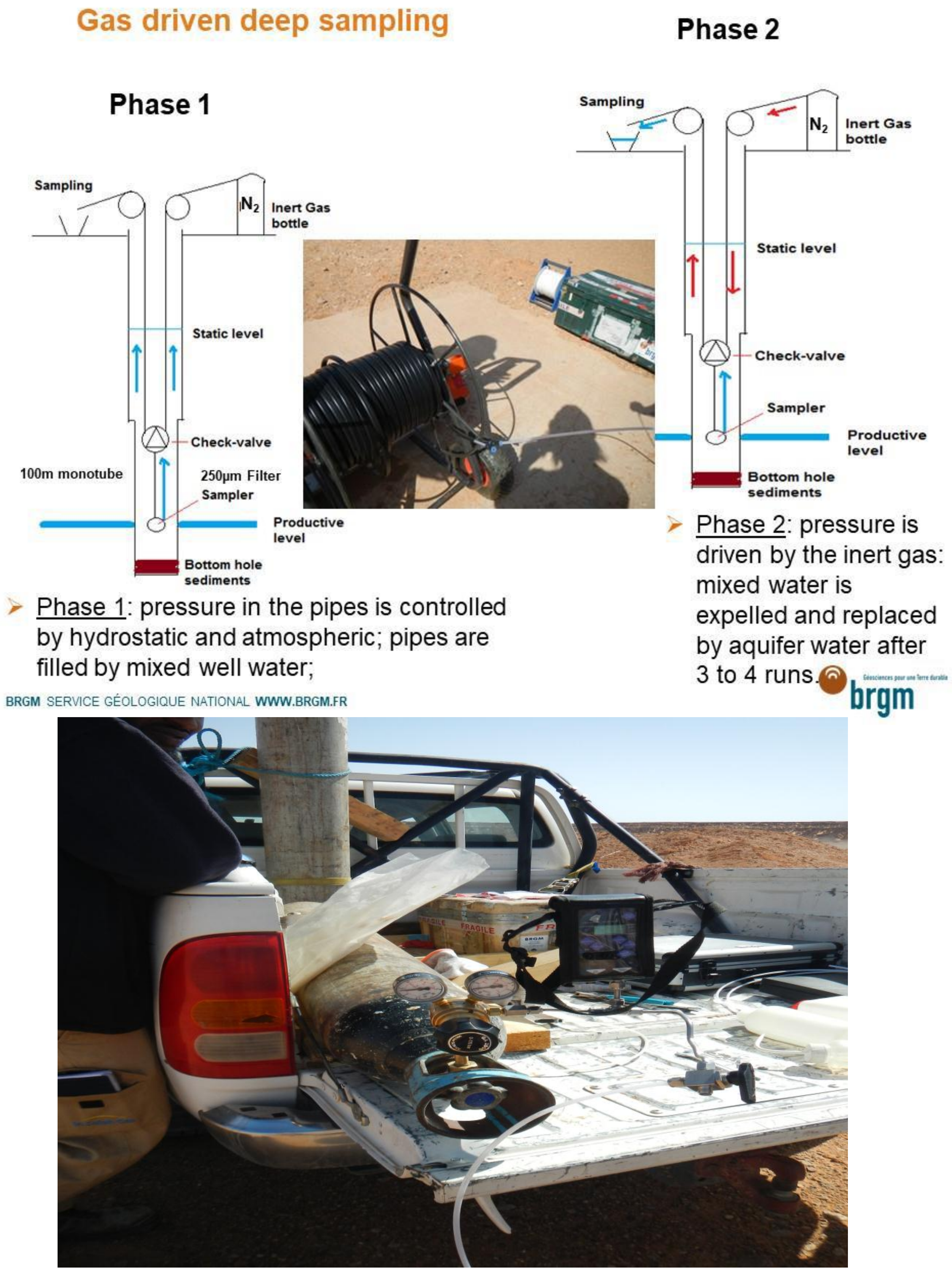


Figure III.17. Deep in-situ sampling

The water was being sampled according to some special criteria and to the different species to be analysed. Filtration at 0.45 µm was carried out for some species in order to prevent the suspended matter affecting the analysis.

Table III.8. Sampled wells and investigations done.

Date	Borehole	Sampling depth (m bgl)	Water column logging	Samples taken	AGI modules (search of PFC)
12/13/2019 15:15	KB-603	280	Yes	For all the boreholes: cations, anions, dissolved gas, isotopes: ^{14}C, $\delta O_{NO3} - \delta N_{NO3}$, $\delta O_{H2O} - \delta H_{H2O}$, $\delta O_{SO4} - \delta S_{SO4}$, $\delta^{13}C_{DIC}$, $^{87}Sr/^{86}Sr$	Yes
12/14/2019 11:15	KB-606	280	Yes		Yes
12/15/2019 12:00	KB-604	300	Yes		Yes
12/16/2019 11:45	KB-602	310	Yes		Yes
12/17/2019 11:15	KB-605	300	Yes		Yes
12/18/2019 09:25	KB-101	Surface	Not feasible		–
12/18/2019 10:15	KB-102	Surface	Not feasible		–
12/18/2019 09:45	KB-103	Surface	Not feasible		–

3.2.2 Results and Interpretation:

3.2.2.1 Physico-chemical parameters measured during aquifer sampling:

the evolution through time of the aquifer water composition comes from the measurement of physico-chemical parameters during the sampling step. This information is reported in Table III.8. It is reminded that deep sampling systems such as the ball-check valve system used carry water from the desired sampling depth up to the surface in pipes of small inner diameter. It takes some times to draw the water from depth to the surface and water may cool during this phase. Physico-chemical parameters are not conservative ones, and they are mostly sensitive to temperature changes (with the exception of electrical conductivity that is normalized at 25°C). Additionally, the pipe used to collect the water is not entirely lowered in the borehole and some parts are exposed to the outside temperature (there may be some heating influence of sunshine radiations depending on the period of the day the sampling is done). The outcome is that temperature measured during sampling at KB-60X wells is likely lower than the in-situ temperature. At the opposite, temperatures measured at KB-10X wells, where the water is pumped, are likely to be representative of the temperature conditions several hundred meters below the surface.

Table III.9. Physico-chemical parameters measured during water sampling;(EC: electrical conductivity; DO: dissolved oxygen; ORP: redox potential; ORP values are given in reference to Standard Hydrogen Electrode).

Borehole	Temperature (°C)			EC (µS.cm^{-1} @25°C)			pH			DO (% sat. / mg.L^{-1})			ORP (mV SHE)		
	2017	2018	2019	2017	2018	2019	2017	2018	2019	2017	2018	2019	2017	2018	2019
KB-602 (310)	31	28	27.5	525	523	534	8.1	7.9	8	62 / 4.32	69.7 / 5.07	83.6 / 6.3	340	390	400
KB-603 (280)	29.6	27.3	24.9	583	585	586	8.1	8.07	8.28	71 / 5.11	75.8 / 5.86	19 / -	310	390	250
KB-604 (300)	32.5	28.7	25.3	443	455	460	8.42	8.29	8	47 / 3.19	67.3 / 4.92	73 / 5.7	280	380	390
KB-605 (300)	29.3	24.5	27.4	473	458	470	8.09	8.15	8	61.5 / 4.56	65.3 / 5.14	66.2 / 4.03	410	400	430
KB-606 (280)	30.2	28.7	25.7	523	527	533	8.18	8	7.9	72.5 / 5.17	82.7 / 6.06	77 / 5.9	310	330	390
KB-101	33.3	36	34.9	476	470	482	7.76	7.68	7.76	102.9 / 7.41	105.3 / 6.83	122 / 8.05	400	430	420
KB-102	31.2	33	31.4	458	466	498	7.59	7.75	7.9	99.4 / 7.08	109.9 / 7.48	100 / 7.01	370	410	390
KB-103	31.3	32	33	494	456	470	7.9	7.87	7.86	105.2 / 7.28	104.6 / 7.28	106.8 / 7.27	370	410	400

This explains that the temperatures reported in December 2019 are lower than previous ones (acquisitions were done in late October). The temperature change is nevertheless reduced (a few degrees) so that its influence onto temperature-dependent parameters, such as pH or dissolved oxygen (expressed in mg.L-1) are low. pH values are given at ±0.1 unit and there is generally no change from one year to the other; only KB-604 may have a value lower than those measured before but this pH value is still in line with values measured in other boreholes. Electrical conductivity values experience minor variability, often lesser than 2%. The EC at KB-604 increases by less than 4% between 2017 and 2019: this may be related to the slightly more acidic pH, but this likely the result of natural variability in a large aquifer (e.g. Jenkins, 2020)1. The largest increase in EC is reported for KB-102 (+8%) but this increase is not related to a pH decrease (the pH increased), supporting an origin of EC variations from intrinsic variability in the aquifer. Dissolved oxygen concentrations in samples from KB-60X wells are not considered because they are measured on a fluid that is intentionally collected when some nitrogen, used as pressuring gas for deep sampling system functioning, is present in the water, thus artificially lowering the oxygen content. Real estimates of the oxygen concentrations come from KB-10X samples, all characterized by oxygen saturation, as previously reported e.g. by Darling et al. (2018) as a characteristic of the CI aquifer at Krechba. The existence of elevated oxygen concentrations in the water is corroborated by the redox values, close to +400 mV, a value typically occurring under oxidizing conditions.

3.2.2.2 Physico-Chemical Parameters Measured by Wellbore Logging:

Chemical logging of the wells offers the possibility to get the values of the physico-chemical parameters in-situ, at reservoir conditions. Consequently, these data are more accurate and representative than the above-discussed ones, and they constitute the reference data. These data are presented for each physico-chemical parameter and their evolution through time is discussed. All the data are first plotted in a synthetic figure that is further split into separate figures (one for each borehole) for the ease of reading.

3.2.2.2.1 Temperature:

The temperature measurements carried out in 2019 are very consistent with previous ones (Figure.III.18 and Figure. III.19). As underlined above, there may be some differences on the temperature profiles when they are considered in the cased section, but these variations are not linked to changes occurring in the CI aquifer at the depths it is tapped. These variations may be related to the influence of the geothermal gradient (mean gradient is +3°C/100 m), the thermal influence of water circulations occurring in shallower aquifers (not tapped but circulating outside the borehole), or to the influence of weather conditions on the casing (heating or cooling of metal pipes depending on the season).

The geographical distinction established earlier between northern boreholes (KB-602, 603 and 606) and southeaster ones (KB-604 and 605), based on their respective thermal gradients, is still well described. The northern group is set in a region where the local gradient (approx. +2.3°C/100 m) is lower than further south, where the gradient is equal to the mean geothermal gradient on earth. This demonstrates that large aquifers are intrinsically not homogeneous, their properties varying vertically and laterally, possibly in relation with porosity/permeability variations in a large aquifer and subsequent differences in the existence of vertical/lateral heat transfers.

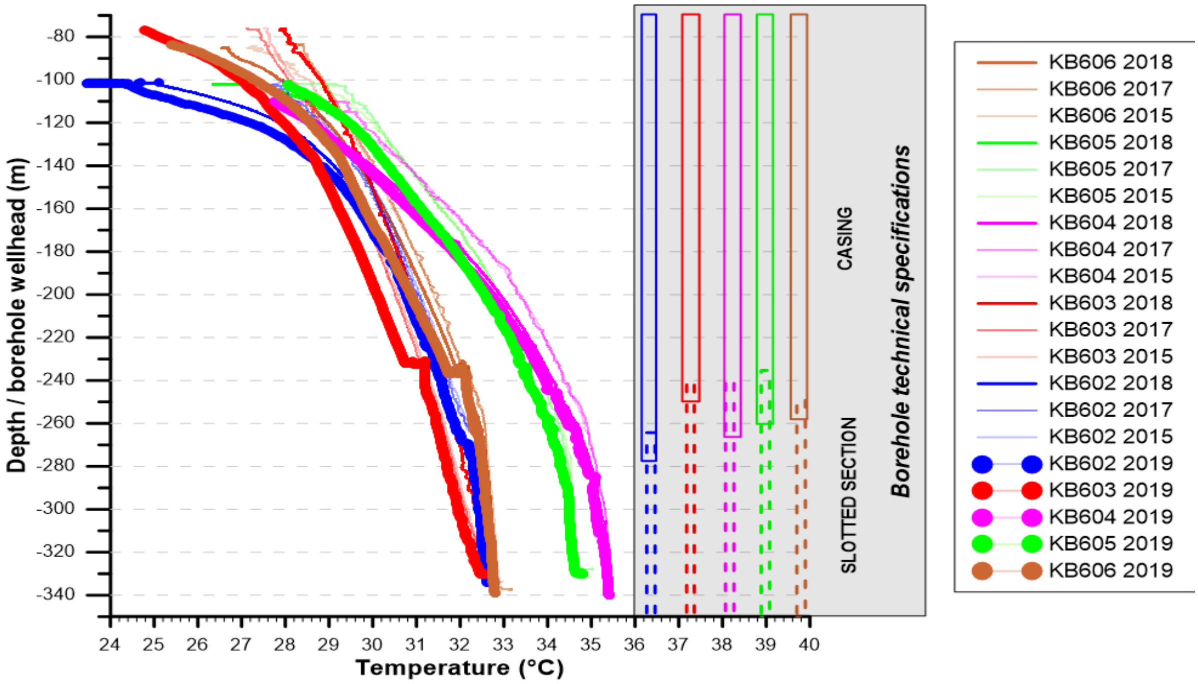


Figure III.18. Temperature as a function of depth

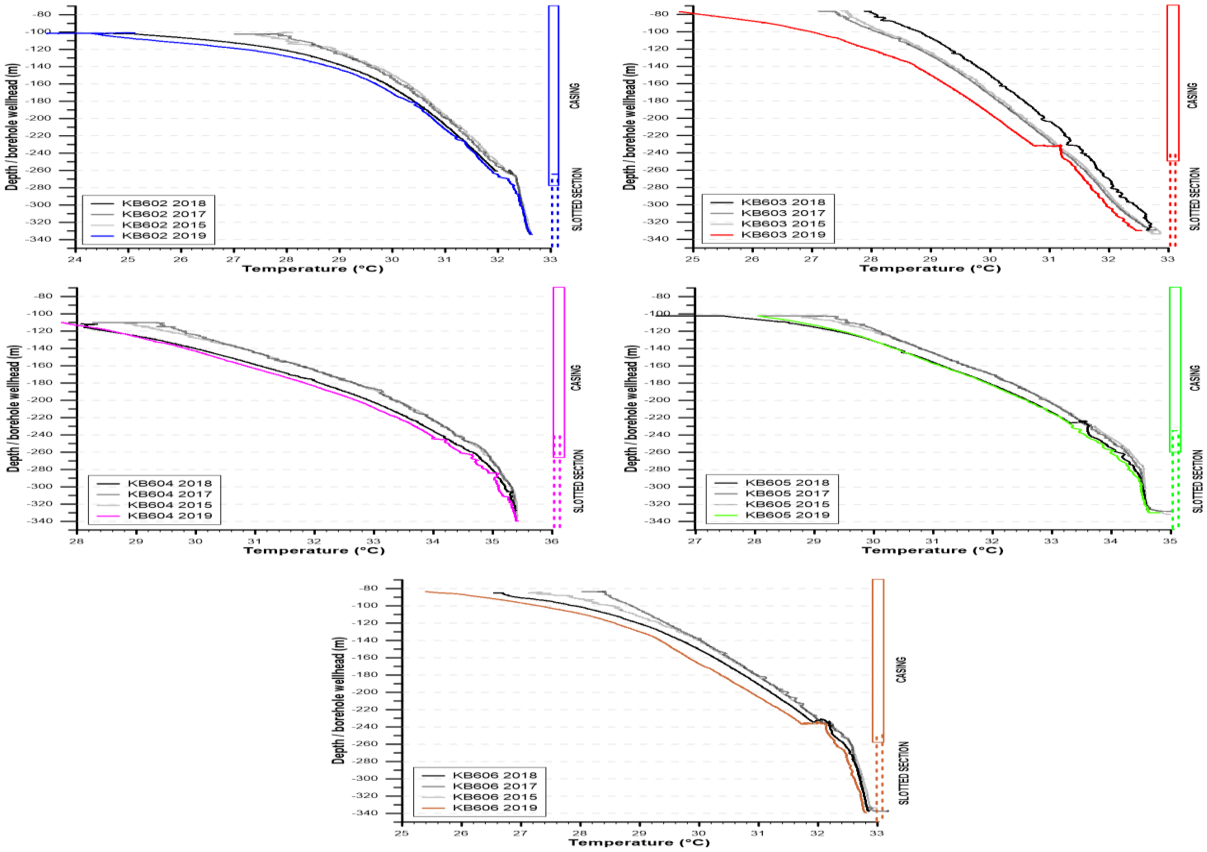


Figure III.19. detail for each KB-60X borehole Temperature as a function of depth

3.2.2.2.2 Electrical conductivity:

Like temperature measurements, electrical conductivity measurements do not show large variations from one year to the other in the slotted section (Figure. III.20 and Figure.III.21). The variation of the conductivity through time does not exceed 4%, a value very close to the uncertainty of the measurement of this parameter, which is usually close to 2%. There is one exception at KB-606 in 2017 as previously reported (Asfirane et al., 2019). In 2017, a transient increase of the conductivity was reported in the slotted section (increase of +20% compared to 2015 and 2018-2019 data). This was not supported by measurements made at the surface during sampling that were in agreement with 2015 data (and also in agreement with more recent acquisitions; Table. III.7). This increase remains unexplained, and can be hardly attributed to a malfunctioning of the sensor, otherwise loggings performed in other boreholes should be biased too. This is also difficult to explain that electrical conductivity evolves so sharply in few minutes when comparing bottom and surface measurements. The only explanation is the occurrence of an electronic bias during this specific acquisition (poor transcription of the signal into conductivity values), which is not related to any chemical change in the aquifer (no indication of the presence of CO_2).

there is a difference in electrical conductivity between southern and northern wells. This is not linked to any temperature effect because electrical conductivity data are normalized at 25°C precisely to avoid this bias. Southern wells have lower conductivities (less than 500 µS/cm) whereas northern wells always have higher conductivities (greater than 500 µS/cm). This was already noticed in previous surveys, including that of Darling et al. (2018), and this is also apparent when sampling (Table. III.7). As for temperature data, this is likely related to relative heterogeneity of the aquifer at a kilometric scale.

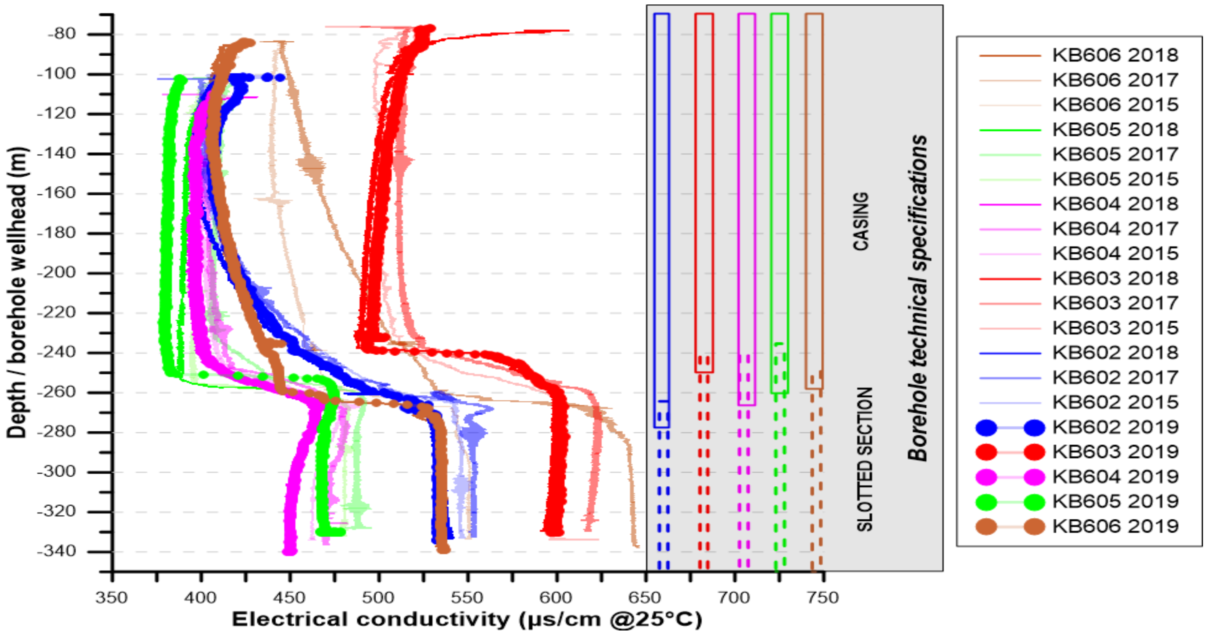


Figure. III.20. Electrical conductivity as a function of depth: synthetic figure showing the 2015, 2017,

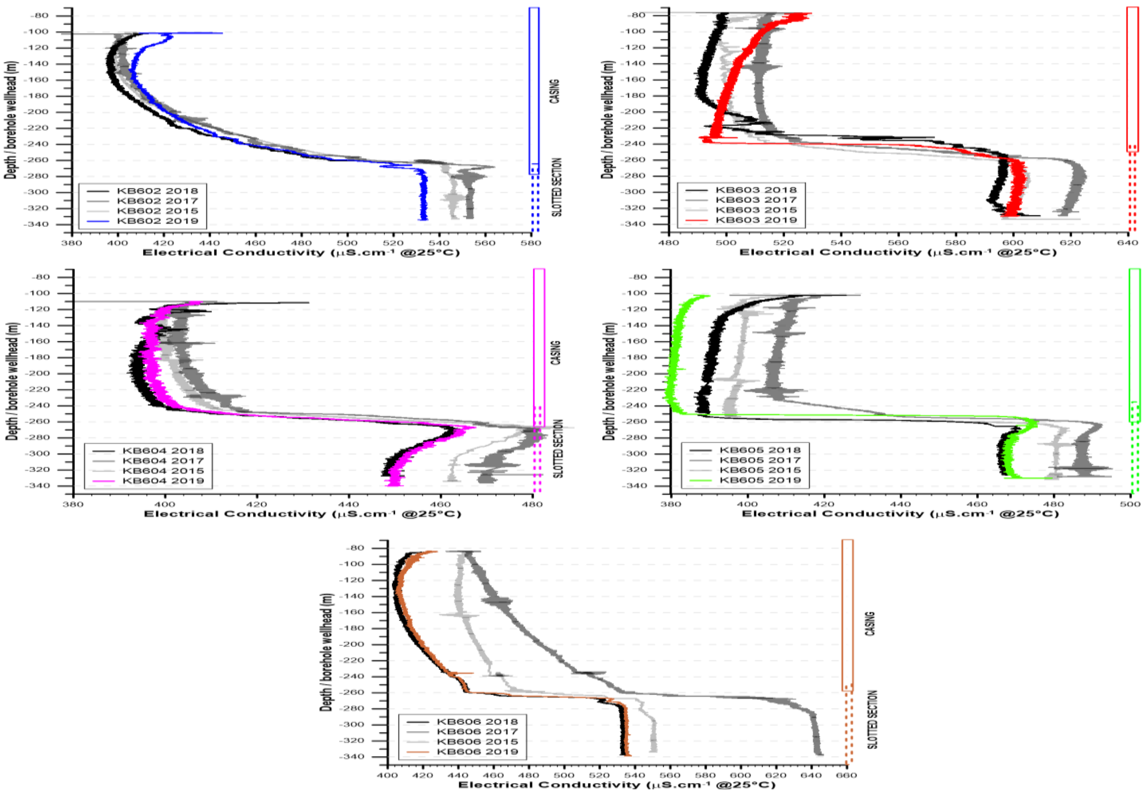


Figure. III.21. Electrical conductivity as a function of depth (2015, 2017, 2018 and 2019 acquisitions): detail for each KB-60X borehole,

3.2.2.2.3 PH:

The pH data are presented in Figure.III.22 and Figure.III.23. As for other parameters, there is little to no variability in the time for a selected borehole, and the profiles always show a higher pH in the cased section as a result of stagnant water interacting with metal tube. Only KB-602 has slightly higher pH values in 2019 compared to previous years (mean value close to 8.1, compared to 7.9), but this increase remains in the uncertainty range of pH measurements (±0.1 unit) and further interpretation would only be speculative. On the opposite, pH values measured in KB-605 are slightly lower but again in the accuracy range of the method. The equilibrium pH value in the aquifer is homogeneous throughout the boreholes and is close to 8.0. This is in good agreement with measurement done at the surface (Table.III.7) considering 1) the uncertainty of the measurement and the temperature effect on pH (Asfirane et al., 2019).
There is no variability of the pH value once in the slotted section (the profile is vertical). Only KB-605 shows a slight increase close to the bottom of the well, probably because sediments are present downhole2 as suggested by the increase of electrical conductivity (Figure.III.23). Like for electrical conductivity, the absence of noticeable changes, or the existence of only subtle changes, is likely the result of the natural evolution of the water in a large aquifer.

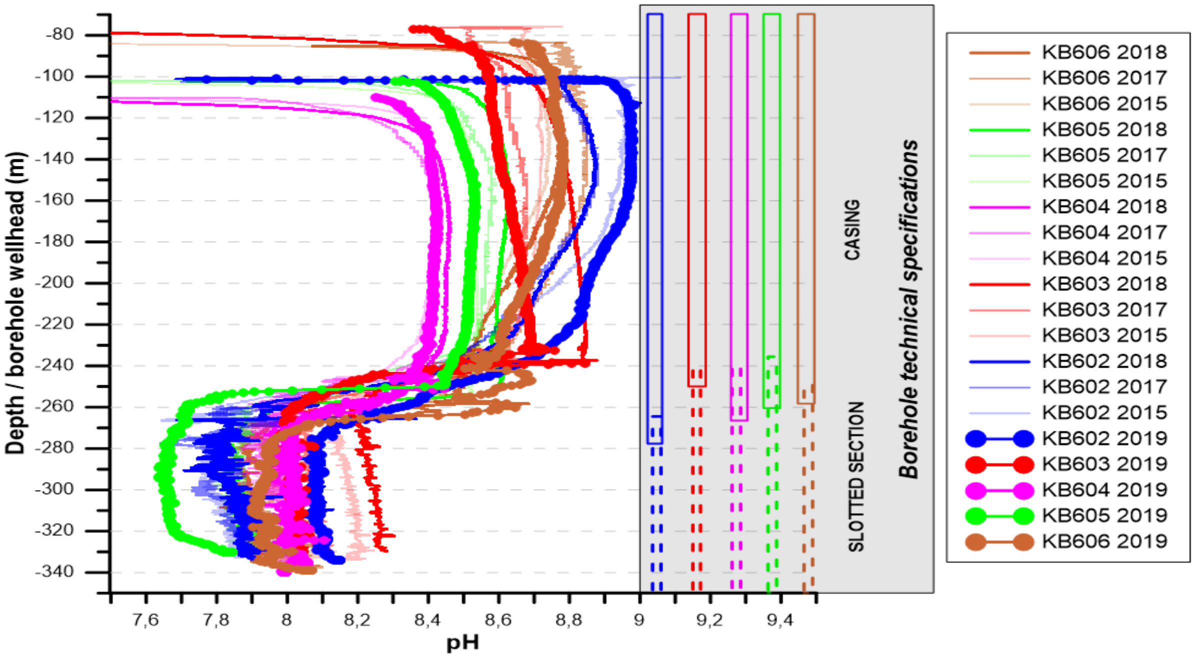


Figure.III.22. pH as a function of depth: synthetic figure showing the 2015, 2017, 2018 and 2019 acquisitions.

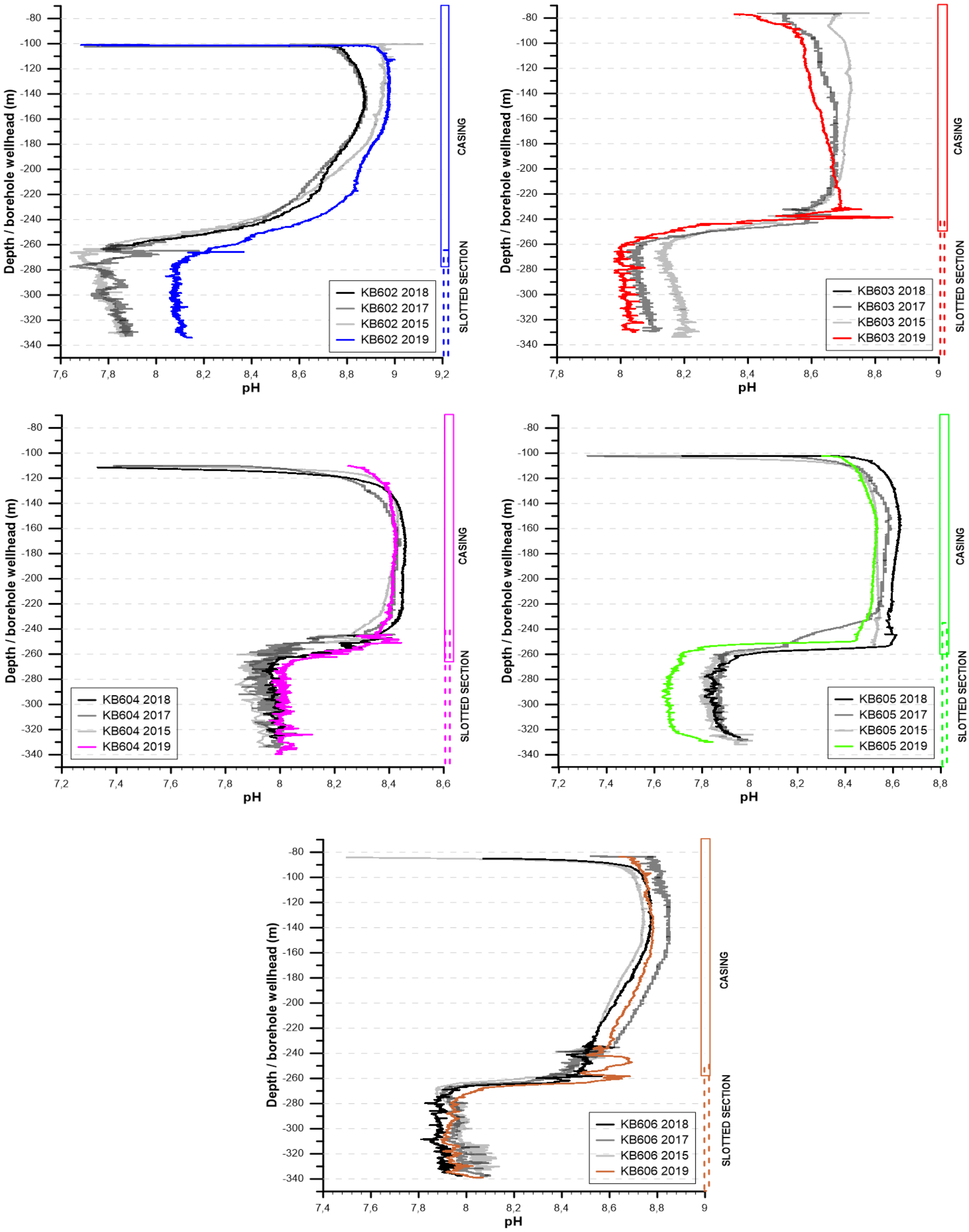


Figure.III.23. pH as a function of depth (2015, 2017, 2018 and 2019 acquisitions): detail for each KB-60X borehole (compared to Figure.III.14, the X-axis scales have been adjusted for each borehole).

3.2.2.2.4 Redox potential:

The uncertainty on the measurement of the redox potential is by far larger than the uncertainties on other parameters. Some authors report that redox of most natural waters cannot be detected more accurately than ±50 mV (Kölling, 2000), mainly because several redox couples govern the redox potential of the water, and their relative influence can change even on short time scale. Consequently, having some differences in between years for a selected borehole is not surprising (Figure.III.24 and Figure.III.25), however the agreement with surface measurements is quite good (Table.III.7). Despite this intrinsically poor constraining of the redox value, it should be mentioned that there is a good sensitivity of the measurements: data acquired in the cased section are negative, thus indicating reducing conditions, and the data acquired in the slotted section are positive, thus indicating oxidizing conditions. This matches the understanding we have of the processes inside the borehole: interaction of the water with the casing in the cased section, and water flow from the aquifer in the slotted section. As described in section 3.1, the water is oxygen-rich thus measuring redox values characteristic of oxidizing conditions is normal.

There are some variations in a selected redox profile, in the screened section, for KB-602 (2018, 2019). Because this was not observed in other wells at the same time, this may possibly be related to some heterogeneity in the aquifer.

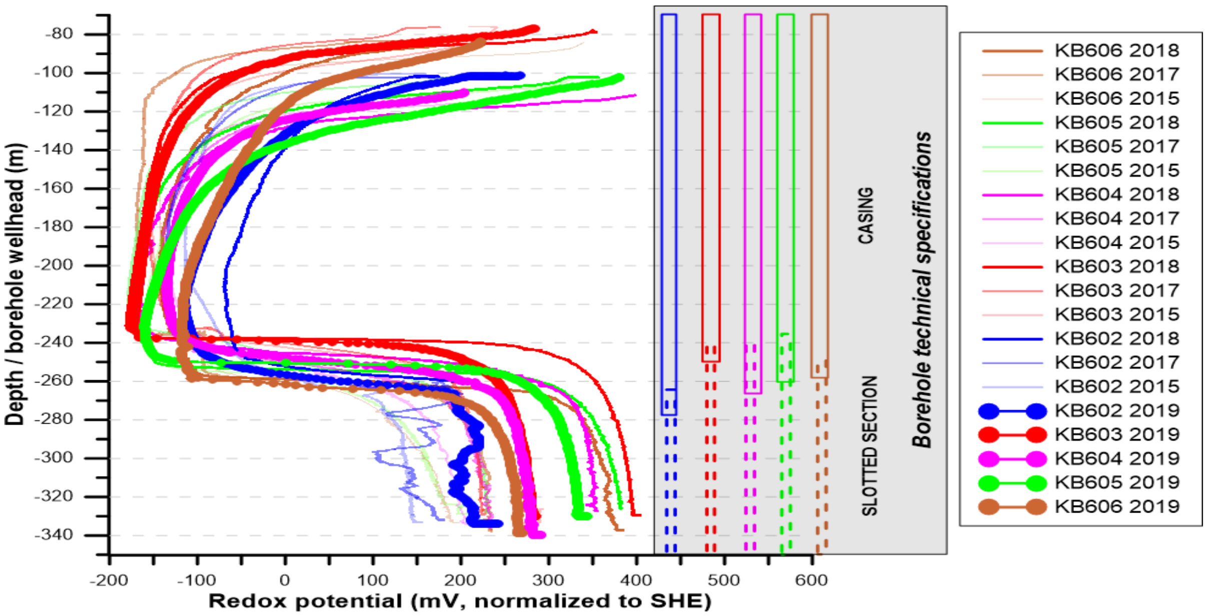


Figure III.24. Redox potential (in reference to the Standard Hydrogen Electrode) as a function of depth

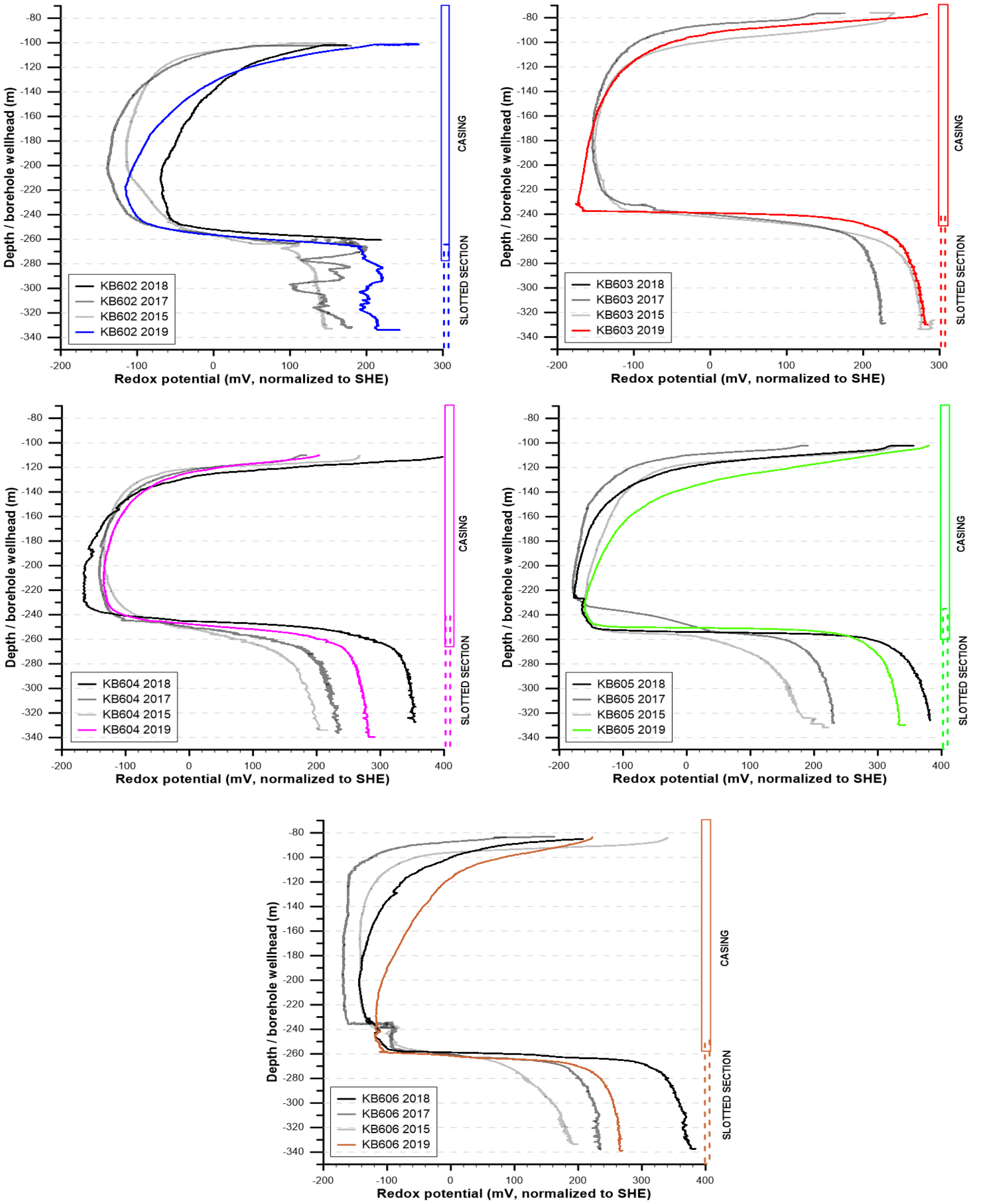


Figure. III.25: Redox potential (in reference to the Standard Hydrogen Electrode) as a function of depth (2015, 2017, 2018 and 2019 acquisitions): detail for each KB-60X borehole (compared to Figure 9, the X-axis scales have been adjusted for each borehole).

3.2.2.2.5 Dissolved oxygen:

the CI aquifer has the specificity to have dissolved oxygen concentrations reaching saturation (in the slotted section). Albeit the dissolved oxygen profiles are very noisy in the cased section, they reach saturation once the sensors penetrate in the screened section (Figure III.26 and Figure III.27). The evolution of dissolved oxygen mimics that of the redox potential: low values in the cased section (the interaction with the tube causes a loss of oxygen) and values reaching the saturation in the slotted section, especially where water circulation is likely to be significant.

The comparison of in-situ data and surface data (Table III.7) shows one of the drawback of the deep sampling system: like for temperature, there is often an under-evaluation of the oxygen content of water. In the present case, some oxygen is lost when measuring at surface because the volume of water is not sufficient to allow measuring in flowing water; the presence of residual nitrogen from the sampling system can also lower the oxygen content. This drawback does not exist when sampling water from boreholes equipped with pumps (KB-10X wells).

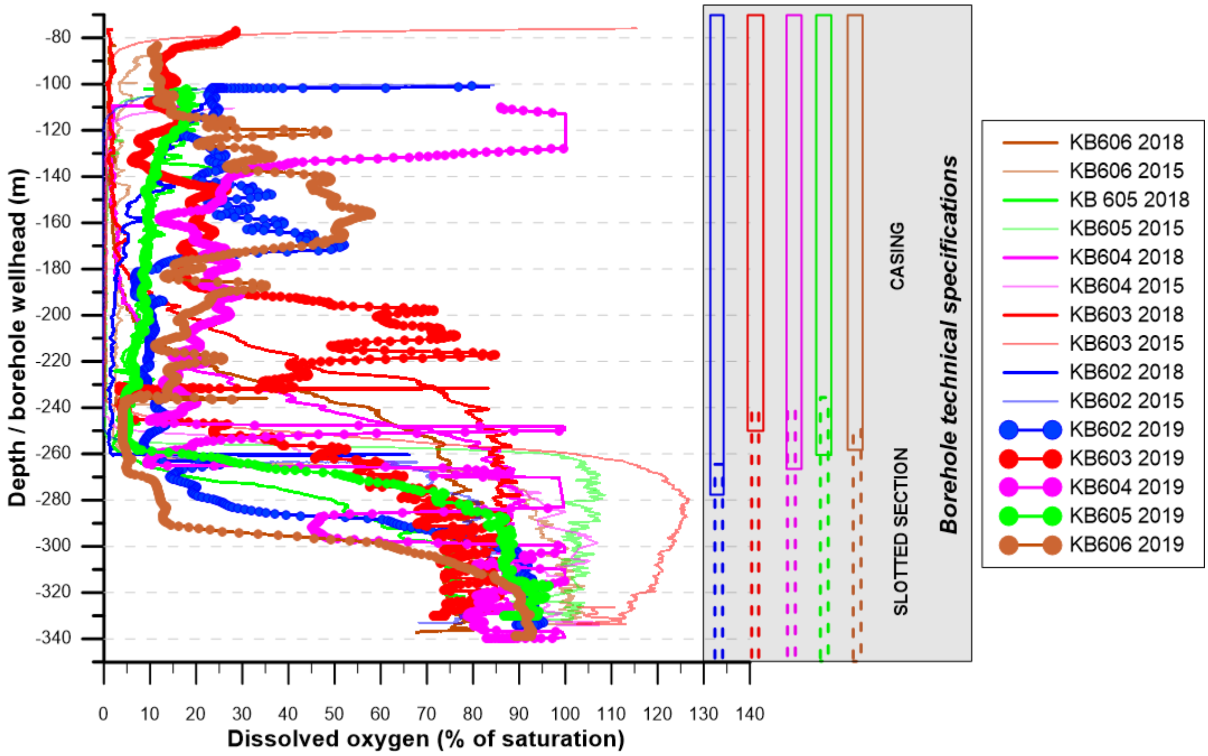


Figure.III.26. Dissolved oxygen as a function of depth: synthetic figure showing the 2015, 2018 and 2019 acquisitions – 2017 data not reported due to sensor malfunctioning.

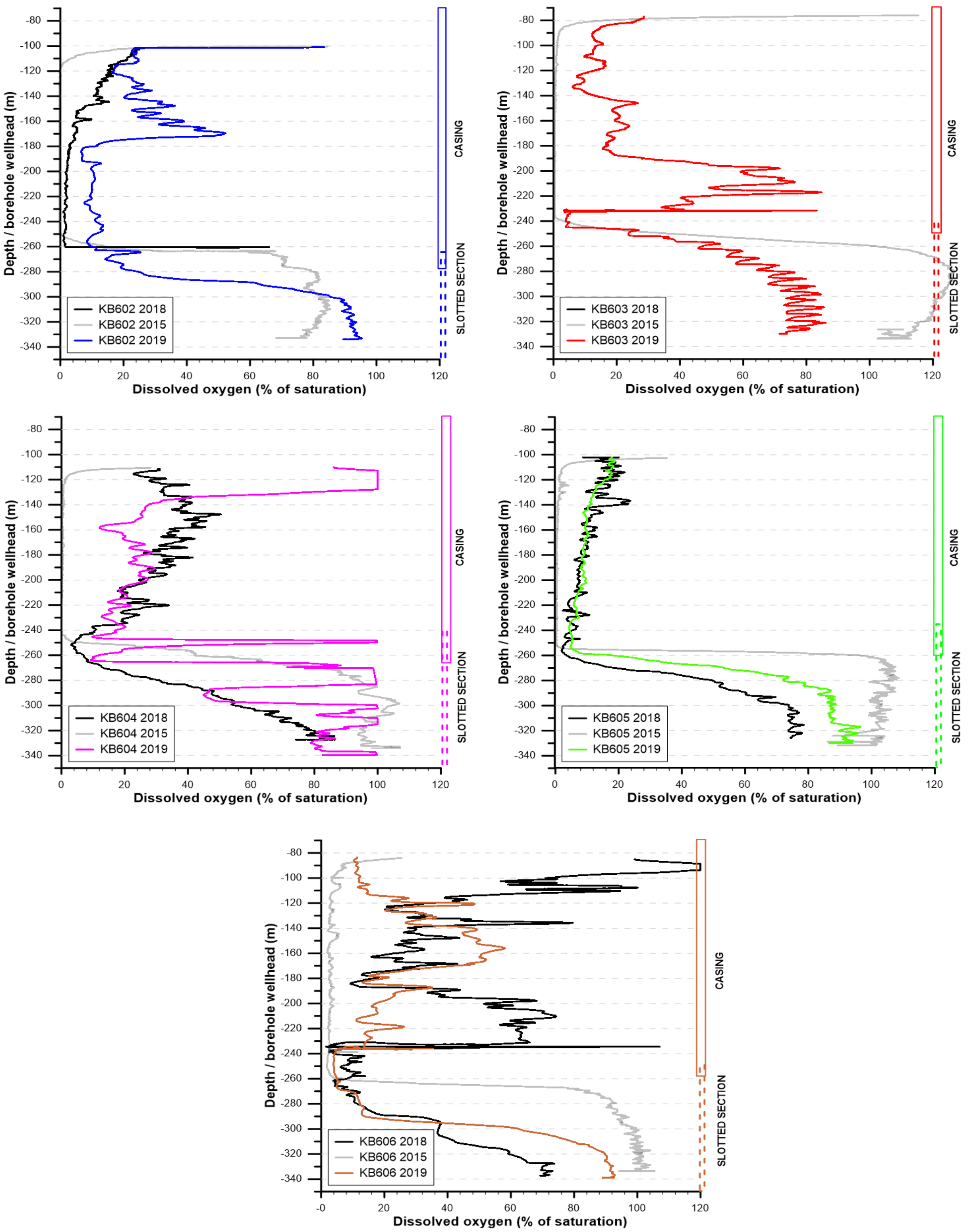


Figure.III.27: Dissolved oxygen as a function of depth (2015, 2018 and 2019 acquisitions): detail for each KB-60X borehole.

3.2.2.3 Chemical Composition of the Krechba Upper Continental intercalare Fluids:

Considerations about the quality control of the chemical determinations and the subsequent representativeness of the samples can be found in Asfirane et al. (2018, 2019). The data acquired in late 2019 follow the same QA/QC protocol. Analyses were done at BRGM labs in Orléans following procedures described in the previous reports.

3.2.2.3.1 Major elements geochemistry:

Results are reported in Table.III.8. The 2019 dataset will be further compared to those derived previously from older analyses, in order to depict as possible for each well any evolution of groundwater geochemistry through time.

Table.III.10. Major elements data for the groundwater sampled in December 2019; LQ: limit of quantification.

Sample	Na	K	Ca	Mg	Cl	F	HCO_3	CO_3	SO_4	NO_3	NO_2	NH_4	Fe	SiO_2	DIC
KB-101	30.3	5.4	36.3	12.5	51.7	0.24	98	<LQ	55.2	17.6	<LQ	<LQ	<LQ	15.7	19.8
KB-102	33	5.7	35.3	12.4	54.7	0.25	97	<LQ	55.9	17.5	<LQ	<LQ	<LQ	15.4	19.7
KB-103	29.2	5.5	35.5	12	50	0.24	95	<LQ	54.9	16.9	<LQ	<LQ	<LQ	16	19.3
KB-602 (310 m)	36.5	6.2	38.7	13	66.1	0.27	91	<LQ	65.9	18.5	0.01	<LQ	<LQ	13.5	18.5
KB-603 (280 m)	43.6	6.1	39.3	15	84	0.26	94	<LQ	69.1	20.4	<LQ	<LQ	0.021	13.4	19.5
KB-604 (300 m)	27.5	5.7	35.8	11.6	53.1	0.26	93	<LQ	55.5	16.5	<LQ	<LQ	<LQ	15.4	18.8
KB-605 (300 m)	28.5	5.7	36.6	11.9	50.2	0.23	94	<LQ	57.6	16.6	<LQ	<LQ	<LQ	15.6	19.2
KB-606 (280 m)	36.5	6.3	38.2	12.8	66.6	0.26	89	<LQ	60.4	18.3	<LQ	0.13	<LQ	13.4	18.9
LQ	*0.5*	*0.5*	*0.5*	*0.5*	*0.5*	*0.1*	*10*	*10*	*0.5*	*0.5*	*0.01*	*0.05*	*0.02*	*0.5*	*0.5*

3.2.2.3.2 Regional background:

The geochemical facies of the groundwater, derived from the major anions and cations, may be emphasized in the so-called Piper diagram (Figure III.28). Groundwater of the CI aquifer have low bicarbonate concentrations, especially in the eastern part (GEE; Edmunds et al., 2003; Abdelali et al., 2019). The dominant anions are chlorides and sulfates. In contrast, no clear dominant cation can be emphasized in the Piper diagram (Figure III.28), both for groundwater for the GEE and for the western part of the CI (GWE and Tademait Plateau; Moulla et al., 2012; Noura, 2013).

The Krechba waters do not show any clear geochemical facies: there is no dominant cation or anion. In contrast to the other waters from the western part of the CI, those from Krechba do not show any sulfate – chloride geochemical facies in the Piper diagram (Figure.III.28).

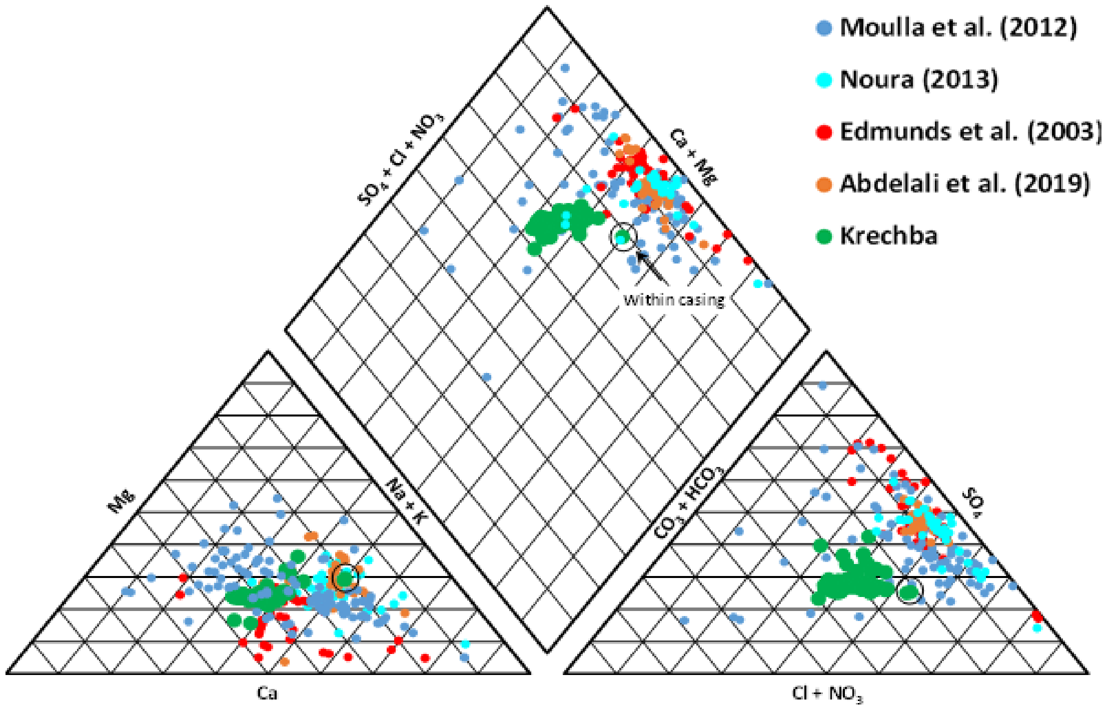


Figure. III.28. Piper diagram for the groundwaters of the Continental Intercalaire (references are given in the text) and for the groundwaters of Krechba.

Major element data, as well as pH and TDS values obtained for the groundwater of the CI, show that the Krechba waters are typically much more dilute compared to the average characteristics of the CI, with TDS clearly lower than 500 mg/l (Figure.III.29). Their pH is also higher than 7 and may reach values close to 9 for the two waters of well KB-606 recovered at a depth of 150 m, at the upper limit of the CI. It is recalled that the sample taken at 150 m comes from the cased section and is therefore not representative of the chemistry of the aquifer because of evolution of the non-renewed water in this cased section.

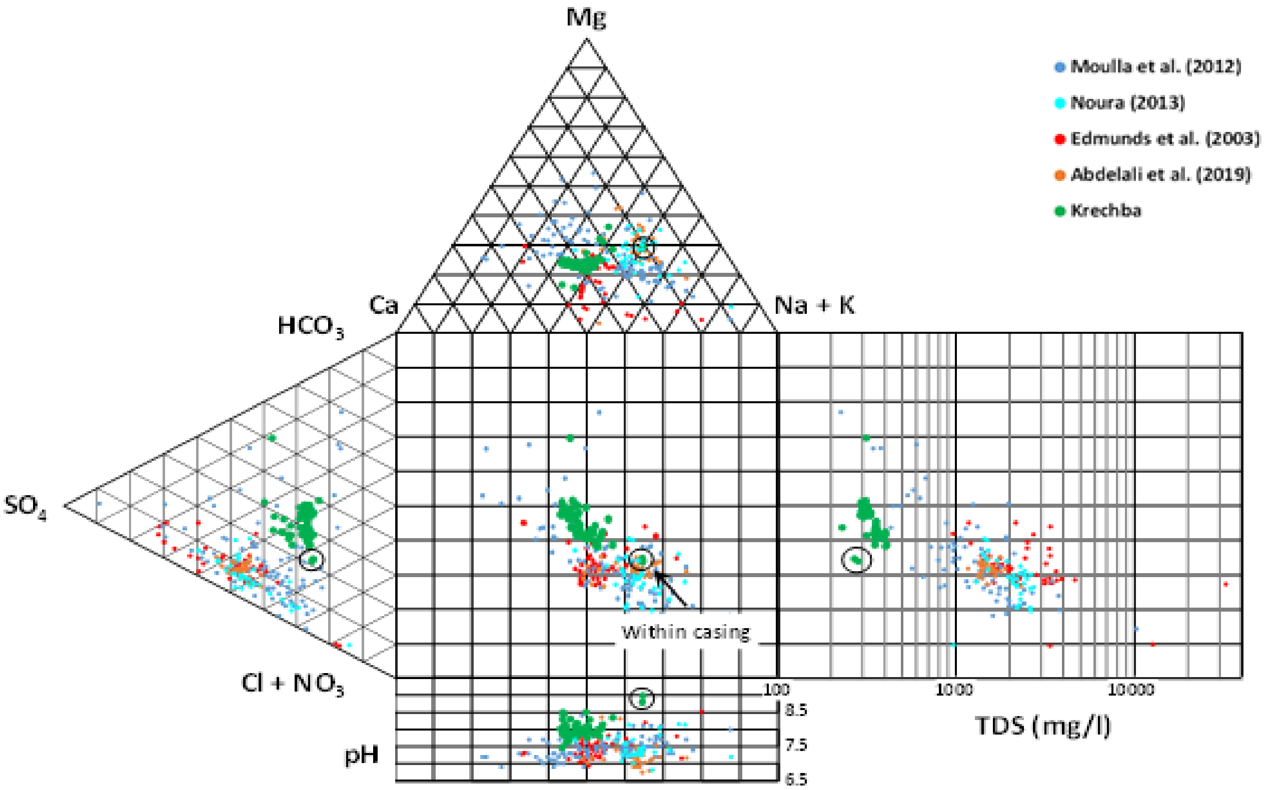


Figure. III.29: Durov diagram for the groundwaters of the Continental Intercalaire (references are given in the text) and for the groundwaters from Krechba.

3.2.2.3.3 Krechba waters:

Only slight variations in the geochemical faces of the groundwater are emphasized in the Piper diagram, both from a well to the other, and also considering the evolution through time of waters from a single well (Figure. III.30). The most significant variations relate to waters recovered from well KB-606 at a depth of 150 m, in 2017 and 2018, because of non-representativeness of the aquifer chemistry as this sample is collected in the cased section.

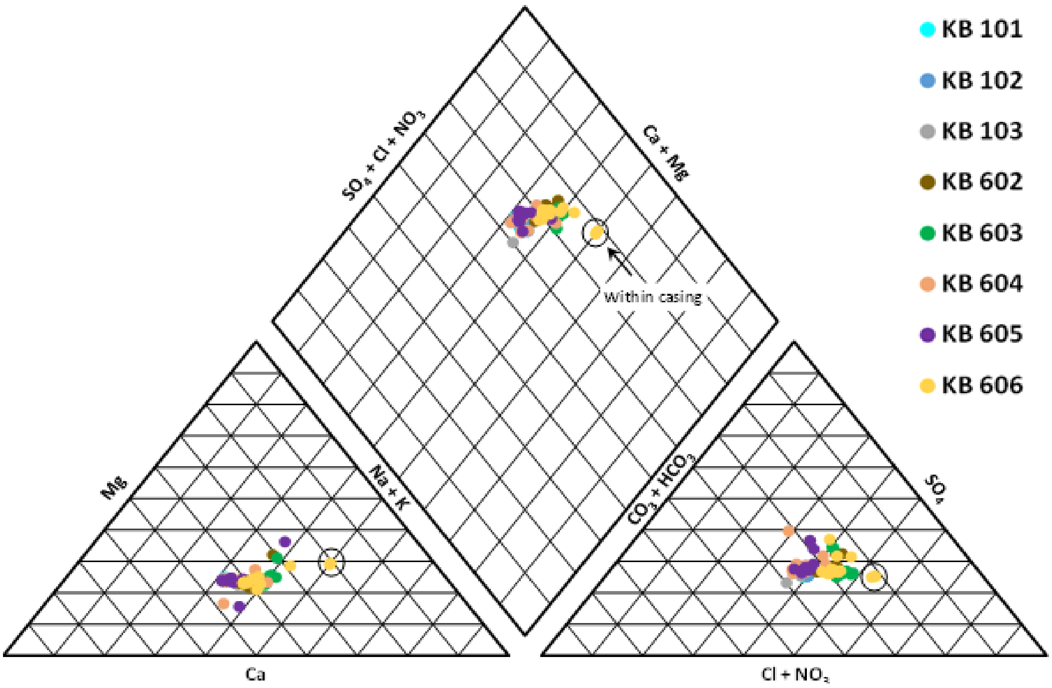


Figure. III.30: Piper diagram for the groundwaters of the Krechba wells. Analyses were done at either ANRH, BGS (Darling et al., 2018) or BRGM.

Further information can be derived from the Durov diagram. Groundwater from well KB-603 display the highest TDS (Figure. III.30), around 400 mg/l. In addition, groundwater from wells KB-602 and KB-606 have TDS close to 350 mg/l, whereas waters from the other wells are more dilute (around 300 mg/l, Figure. III.30). The three wells having higher TDS come from the northern part of the Krechba area. Such a (slight) discrepancy between the northern and the southern wells has been evidenced earlier (Asfirane et al., 2019). However, it is noteworthy that no evolution through time can be emphasized for a single well (Figure III.31). The pH values are in any case slightly higher than 7 (except for the two groundwater recovered from well KB-606 at a depth of 150 m, see above).

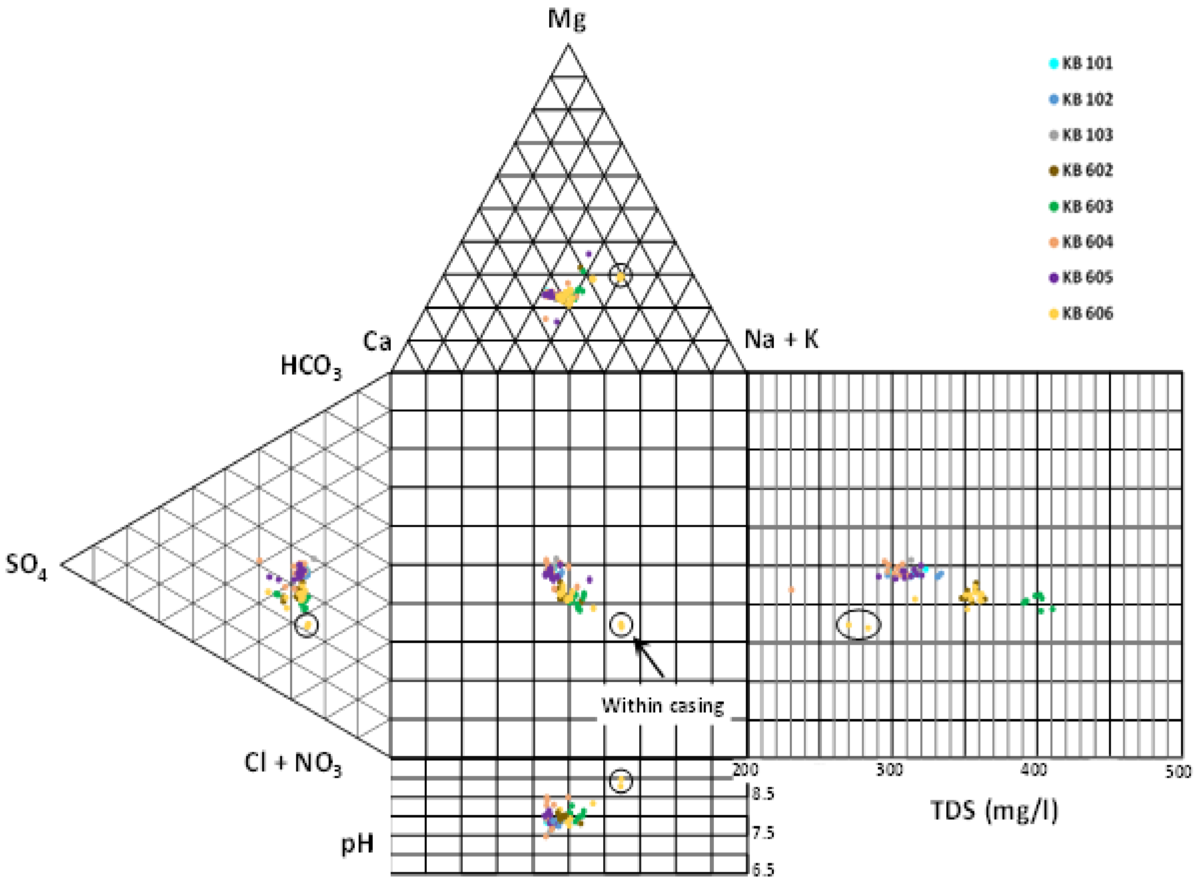


Figure. III.31: Durov diagram for the groundwater of the Krechba wells. Same legend than in Figure. III.30

Conclusions:

The subsurface monitoring of CO2 regarding the aquifer continental intercalare part on Krechba is based on tow impotent methods BGS and BRGM; the BGS is based on the pumping tests and sampling results. for the BRGM methods is also base on the downhole sampling and borehole logging the variation of physico-chemical parameters such as the temperature, PH, the oxygen disout, redox and the electric conductivity.

Bothe methods results and even the comparison of the aquifer waters with other near sites show no evidence of CO2 leakage on the top of aqufer.

Conclusions

The suite of technologies that can be deployed to a CO_2 storage site for monitoring and verification purposes are readily available and utilize primarily standard oilfield and environmental monitoring techniques and existing practices. However, each site will require a site specific suite of cost effective and targeted technologies to provide the maximum benefit - there is no "simplistic" approach when it comes to designing a monitoring and verification program. Main findings to date are as follows:

- Each storage site is unique. Monitoring and verification programs should be designed specifically for the risks at each site.
- Cost-effective technologies such as wellhead and annulus monitoring have proven to be very useful in verifying long-term storage.
- CO_2 plume development is far from homogeneous and requires data to High resolution for reservoir characterization and modelling.
- InSAR data has proven to be very useful for monitoring millimetre dimensional surface deformation in relation to changes in subsoil pressure caused by injection and production. This resulted in significant changes to the originally planned monitoring program.
- Eight years of CO_2 storage at this site demonstrate successful storage of 3.8 million tonnes of CO_2. Long-term storage continues to be guided by an efficient storage monitoring program fit for the overall purpose, cost.
- Old (legacy) wellbore integrity is a key leakage risk that must be managed effectively (permanent abandonment, Appendix 3).
- Understanding the geomechanical properties of the reservoir and the cover rock is vital.
- Injection strategies must be linked to the geomechanical modeling of the reservoir and the overburden.

- Quantified risk assessment (QRA) has proven to be a valuable aid in understanding and manage the storage operation and should be repeated during the life of the storage project by a careful operator.

- Monitoring of the shallow aquifer is more important than the surface flow due to the limited nature of the shallow aquifer at Krechba and the presence of the water table at -105m below the ground surface.

The consequences of dissolution of CO2 into CI groundwater are:

- decrease of pH (even in presence of carbonate: limited effect of the buffering);
- dissolution of carbonates (calcite and dolomite) buffers the acidity;
- dissolution of potassic feldspar participates also but in a minor extent to the buffering of acidity;
- increase of cation (Ca, Mg, K), and carbonate (HCO3) concentrations.

Many methods have been implemented in Krechba since the beginning of injection for CO2 monitoring. The results show no infiltration or migration of CO2 through the cover layer.

With taking the recommendation below is big possible to have the Modelling CO2 leakage and good thermodynamic equilibrium for CI water- rock interactions, allows a description of freshwater quality evolution.

Recommendations

In the case of CO_2 leakage into CI groundwater, rapid and systematic increase of major and trace elements concentrations is calculated with the decrease of pH value. These processes can be moderated or increased as a function of the mineralogical composition of the rock: presence of carbonates (buffering effect), clays (CEC values), iron oxy- hydroxides (sorption sites). Coupled geochemical- multiphase flow model could estimate further reactions because of the density- driven- flow mixing water on the whole heterogeneous aquifer thickness. However, the modelling approach by scenario study of leakage is very limited because of:

- the weak constraints on the relative permeability, porosity, capillary function, etc. of sand and shale constituting the aquifer;
- the unknown leakage geometry (point, line, area), localization, rate, period, composition (CO_2 gas, impurities, mixed gas- water, …).

The Continental Intercalaire is a heterogeneous terrestrial deposit of sand/sandstone and mudstone. In such a geological formation it is possible to find water bodies with different compositions and flow paths. This can only be confirmed by geochemical logging and in situ sampling at specific depths. This could identify the depths of water bodies which may be more reactive to CO_2 leakage (e.g. pH variation, trace element mobilization). A new borehole which reached the base of the aquifer would allow logging (including geochemical logging) and in situ sampling for laboratory analyses and would greatly improve our understanding of water and rock heterogeneity across the full thickness of the Continental Intercalaire.

Resistivity logs suggest variations in water quality within the aquifer, with significantly higher mineralization at the base. Variations in water chemistry throughout the aquifer could not be taken into account in this study because there was no analytical data.

Direct sampling of the lower part of the CI aquifer is required because it could modify the results of geochemical and hydrodynamic modelling. Resistivity log data needs to be calibrated and normalized with respect to the existing direct conductivity measurements and compared to the porosity data in order to determine the distribution of different aquifer layers.

Appendix

Appendix

Level Troll 500 & Baro Troll specifications.

Versatile Design

The titanium Level TROLL® 500 Instrument is used for confidence in all applications, including salt water.

Applications

- Dewatering—mining and construction
- Flood and storm surge monitoring
- Landfill monitoring
- Long-term monitoring in fresh, brackish, or salt water
- Municipal and industrial monitoring
- Real-time monitoring via telemetry
- River, lake, and reservoir monitoring
- Stormwater monitoring
- Wetlands/estuaries monitoring

Features

- Integrated Modbus/RS485, SDI-12, and 4-20 mA simplifies connection to SCADA and telemetry systems
- Linear, fast linear, and event logging modes
- 2 MB memory
- Fastest logging rate and Modbus rate of 2 per second
- Fastest SDI-12 and 4-20 mA output rate of 1 per second
- Sensor accuracy of 0.1% full scale
- Vented (gauged) and non-vented (absolute) instruments
- Narrow diameter body (0.72" OD)
- Uses Win-Situ® Software for simplified setup and fast data downloads

Key Specifications

The BaroTROLL® Instrument is designed to collect barometric pressure and temperature data.

This data is used to correct Level TROLL® 300, 500, or 700 data by compensating for barometric pressure effects during the course of a log.

Range of deployment options: 0.72-in (1.83-cm) diameter titanium housing is designed for harsh environments.

Accurate readings Barometric sensor: 0.1% full scale **Temperature:** 0.1°C **Extended battery life:** Typical battery life is 10 years or 2 million readings (1 reading = time and date plus all available parameters polled or logged from the device). **Flexible communications:** Modbus/RS485, SDI-12, and 4-20 mA

A p p e n d i x

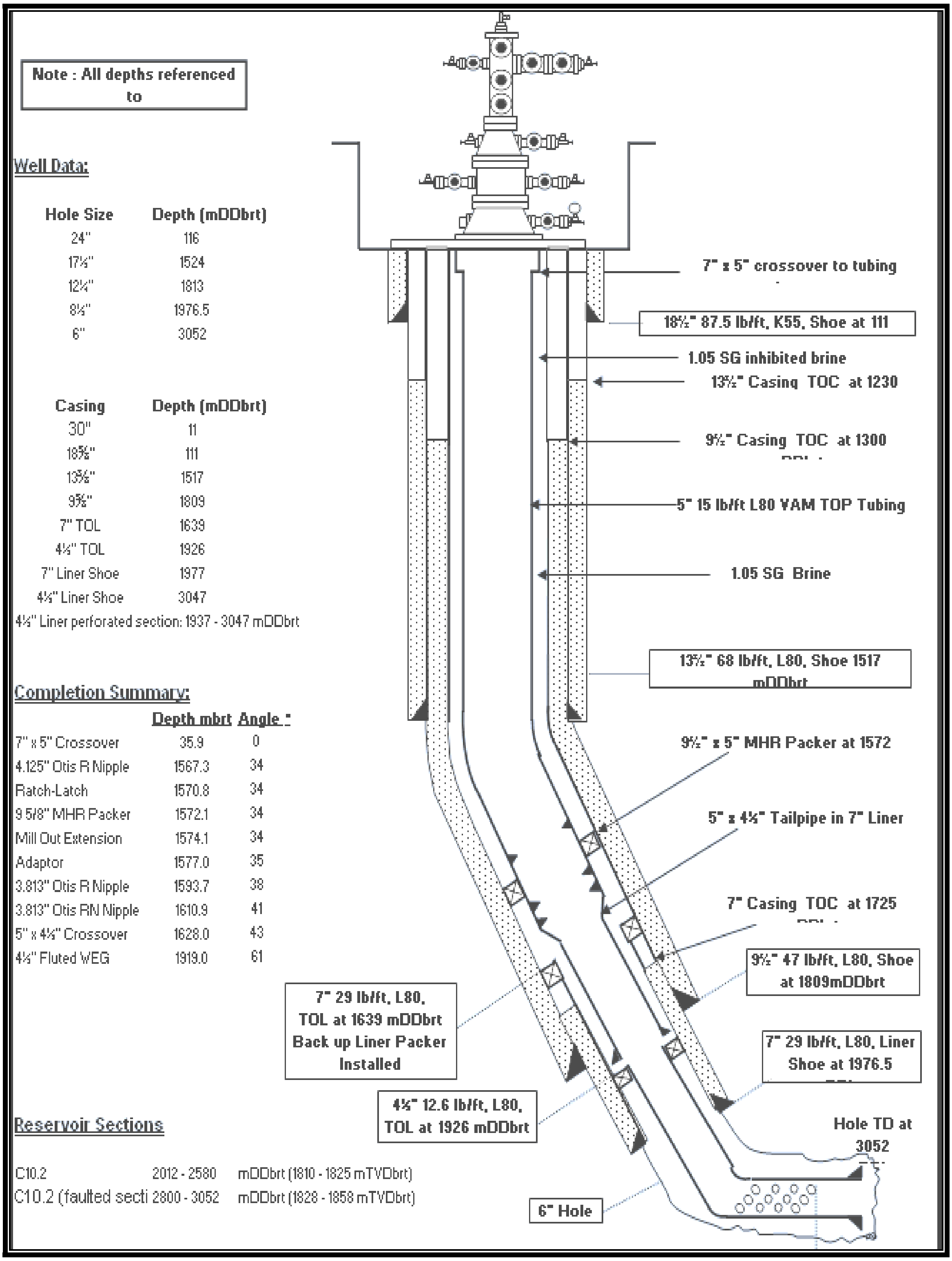


Figure.6.1 Well completion design of injector well

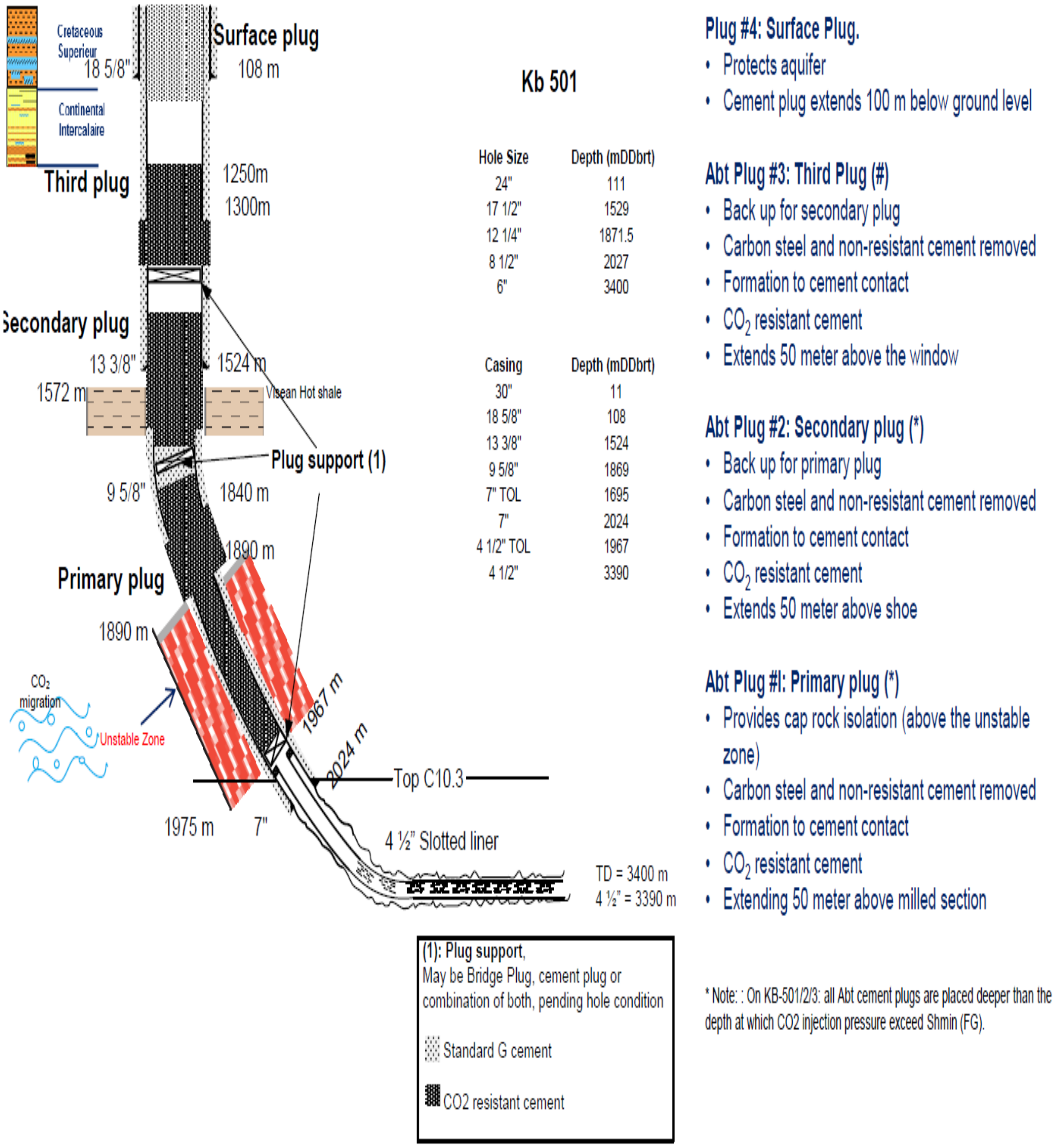


Figure.6.2. P r o g r a mme o f P e r ma n e n t e A b a n d o n me n t S c h e ma t i c a n d Pl u g Ob j e c t i v e s

Bibliographer

- 1. P. Meyer, Summary of carbon dioxide enhanced oil recovery (CO2EOR) injection well technology, American Petroleum Institute (2007).
- 2. A. Mathieson, I. Wright, D. Roberts & P. Ringrose. Satellite Imaging to Monitor CO2 Movement at Krechba, Algeria. GHGT-9; (2008)
- 3. RA Chadwick, D. Noy, R. Arts, O. Eiken, Quantification issues from the latest time-lapse seismic data at the Sleipner CO2 injection operation, GHGT-9, (2008)
- 4. Daniel J. Talley, Thomas L. Davis, Robert D. Benson, and Steven L. Roche, Dynamic reservoir characterization of Vacuum Field, The Leading Edge; v. 17; no. 10; (1998).
- 5. JL Brady, JL Hare, JF Ferguson, JE, Seibert ,, FJ Klopping, T. Chen ,, and T Niebauer, T., Results of the world's first 4D microgravity surveillance of a waterflood-Prudhoe Bay, Alaska: SPE Annual Technical Conference & Exhibition, San Antonio, September (2006), Expanded Abstracts, SPE 101762.
- Enhanced Hydrocarbon Recovery by CO2 Flooding. Technical and Economic Aspects
- ISG CO2 Monitoring Program For ARH Issued Abdelkrim / Sofiane) July 2014)
- Report of the Krechba Field CO2 Monitoring Program
  Issued Abdelkrim / Sofiane) July 2014)
- Capture and sequestration of CO2 Krechba / In Salah Gas

- JPMeyer, Summary of carbon dioxide enhanced oil recovery (CO2EOR) injection well technology, American Petroleum Institute (2007) 54p.
  - Geochemical
  - BRGM Report; monitoring of the Continental Intercalaire aquifer at Krechba – In Salah, Algeria (December 2019 field campaign)

- A. Mathieson, I. Wright, D. Roberts & P. Ringrose. Satellite Imaging to Monitor CO2 Movement at Krechba, Algeria. Paper (307) GHGT-9; (2008)

- Capture, transport and geological storage of CO_2 Pierre LE THIEZ, Alexandre ROJEY (French Petroleum Institute)
- Documentation of BGS.
- AGI Documentation file: // H: \ settings \ profile \ desktop \ Short services contrac \ UK - WL Gore Short Service Contract Draft _07.11.12 .doc
- Capture and geological storage of CO_2 "TOTAL" 2007.
- Enhanced Hydrocarbon Recovery by CO_2 Flooding. Technical and Economic Aspects.
- http: // www. ieaghg.org/ccs-resources/monitoring-selection-tool1.
- file: // H: \ settings \ profile \ desktop \ Short services cont WL Gore Short Service Contract Draft _07.11.12 .doc .
- http://www.pedosphere.ca/resources/bulkdensity/triangle_us.cfm?57,307 .
- http://www.esri.com/software/arcgis/arcgis-for-desktop
- http://environment.uwe.ac.uk:geocal/SoilMech/classification/default.htm
- http://www.safetydirectory.com/hazardous_substances/hydrogen_sulfide/fact_sheet.hm
- http://www.sciencedirect.com/science/article/B984K-4W0SFYG/