

# Co-production of geothermal heat on petroleum sites: opportunities and challenges

Eric Léoutre & Laurent Ghilardini, VERMILION, France

Geological modelling (les Pins field) by Gilles Fabre, GEOXILIA

MEET Project – Geothermal Winter School – February 2021



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792037

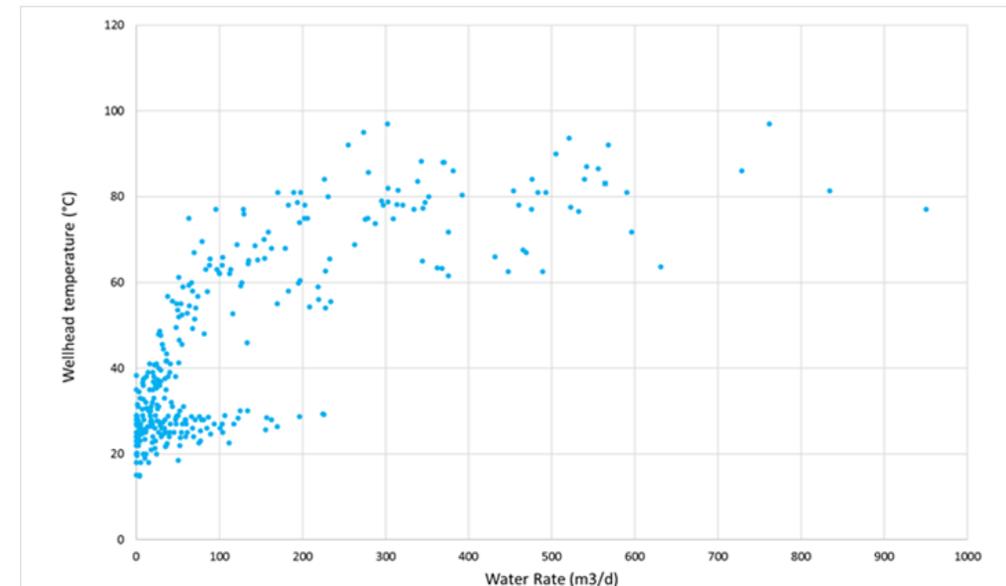
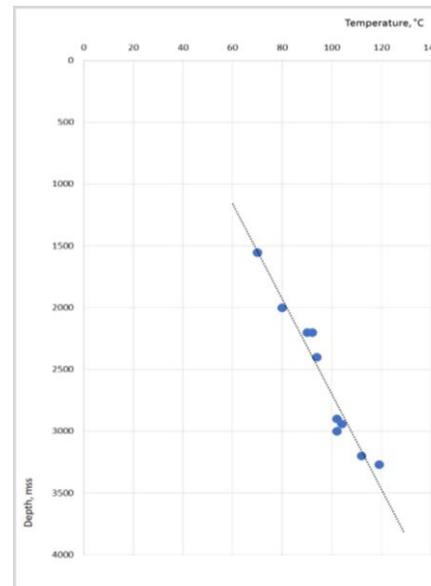
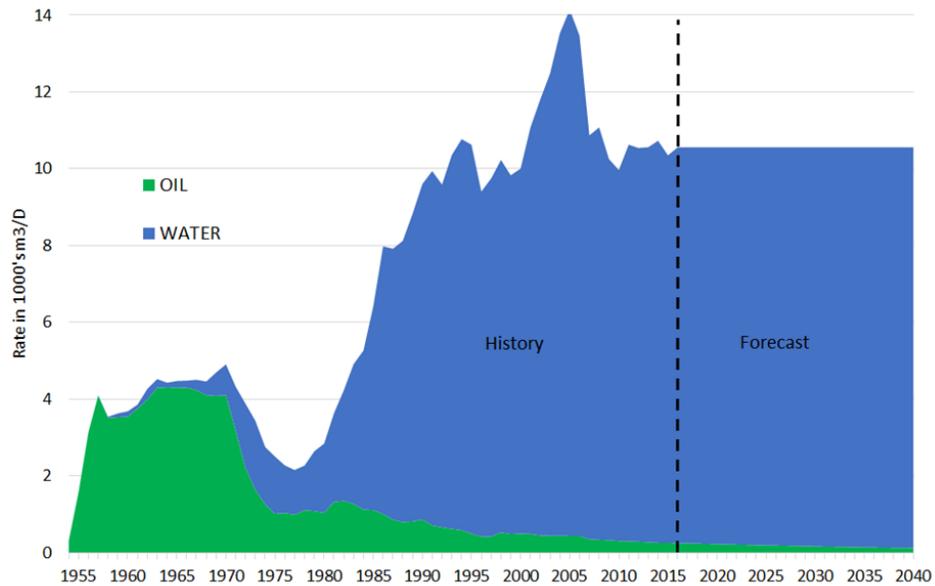
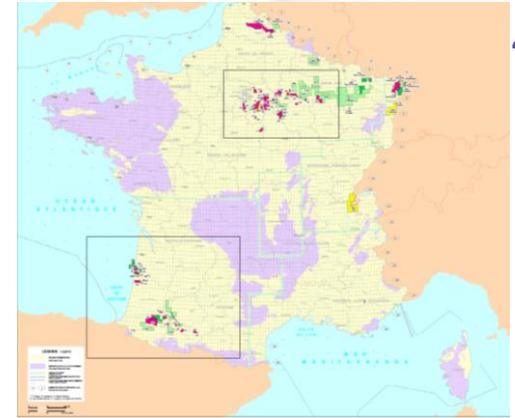
# Key Messages ahead



- Onshore mature oilfields can produce large volumes of hot brine
- Heat can be valorised at reinjection site when a end-user is identified nearby, or brought in
- Vermilion has demonstrated feasibility at very different scales: from 0.5 to 10 MW of heat capacity
- Key uncertainties from the producer perspective : unlike large open aquifer, oil field are small closed structure hence the need to study « cold front » & well interferences
- Existing O&G tools and models can be re-used to predict long-term geothermal resources
- Key risk from the user perspective: geothermal heat long-term availability is dependant on oil price and oil field economics
- Impact on oilfield facilities & exploitation is minimal
- Oil revenues >> heat revenues, conversion to geothermal is hindered by electrical O&M in depleted oilfields (deep submersible pumps)

# An oil producer ?

- Lots of brine: average porfolio at 95 % BSW
- 40 000m<sup>3</sup>/d of hot brine from 26 concessions
- Geothermal gradients: 29 to 30 °C/km
- Surface temperature ranging from 60 to 100 °C at wellhead



# Project location

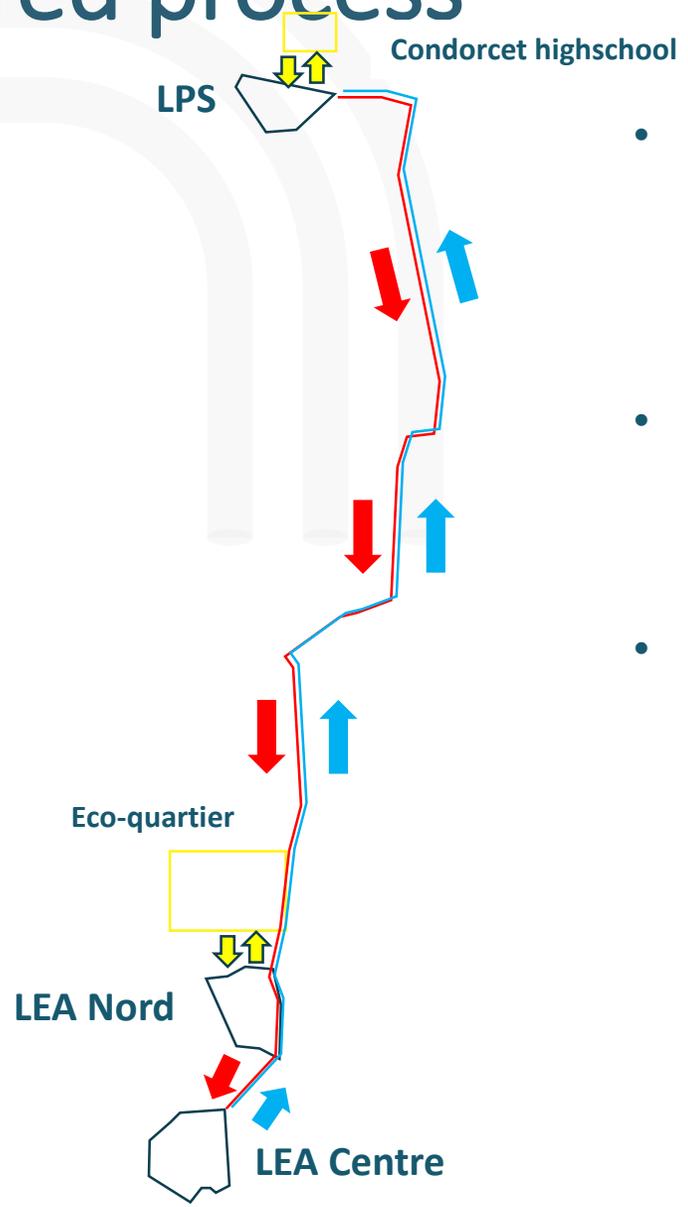
High-school heated by gas  
Heat needs: 850 MWh/y  
CO<sub>2</sub> : 230 t/y



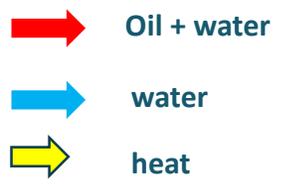
Oil field « **Les Pins** »: 3 producers +2 injector wells  
Injection temperature 61 °C  
350 m<sup>3</sup>/d to 800 m<sup>3</sup>/d



# 2 oil fields with shared process



- The **liquid** produced in LPS (LPS3D, LPS5D), LEA Nord (LEA1D) and LEA Centre (LEA2D) is gathered in LEA Centre and separated
- The produced and **separated water** is sent to LEA Nord (LEA3D) and LPS (LPS1D, LPS2D) to be re-injected
- The **heat exchange is realized on the water before re-injection** in LEA Nord and LPS



# Project uncertainties to be addressed

## Subsurface

- ✓ Long-term brine volume = f (oil reserves ) = f (oil price)
- ✓ Long-term injectivity (plugging risks)
- ✓ Impact of colder reinjection on tubing packer
- ✓
- ✓ **Injector- producer thermal interferences: cold front an thermal breakthrough ?**
- ✓ Impact on oil reservoir (dentisty & viscosity)

## Surface

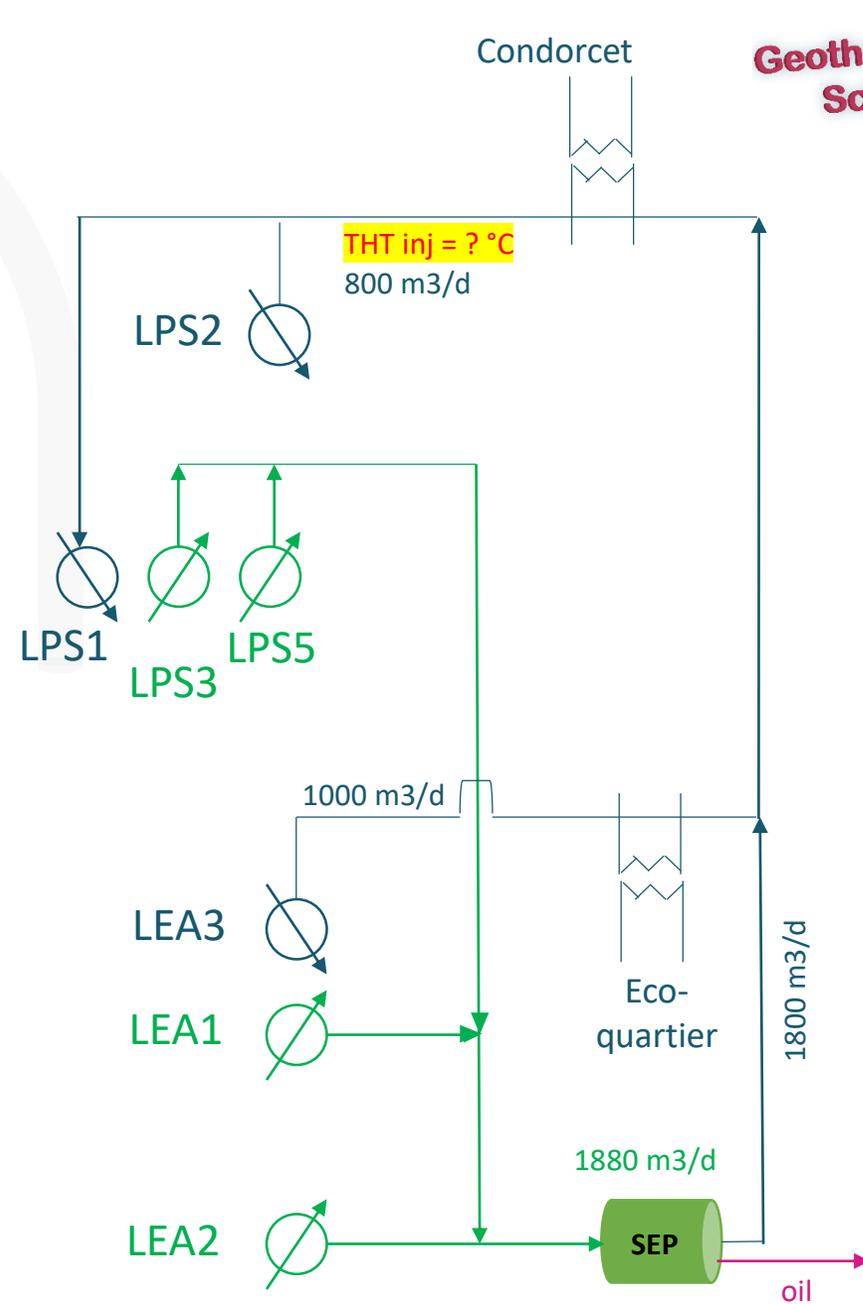
- ✓ Impact of well downtime on heat delivery
- ✓ Impact of injection line on HEX design
- ✓ Optimisation of oil vs. water ?
- ✓ Allocation of injection

# Thermal study objective

	LPS1	LPS3	LPS5	LEA1	LEA2	LPS2 inj	LEA3 inj
Q m3/j	155	80	395	466	380	350	950
THT °C	70	59	83	86	83	62	71
BHT °C	101	102	101	99	101	63	75

measured
estimated Prosper
estimated Tnav
by analogy

- Currently: 1 injector at LPS, T = 62°C
- After heat delivery : 2 injectors , temperature evolution unknown in the long-term (large T losses along the process)

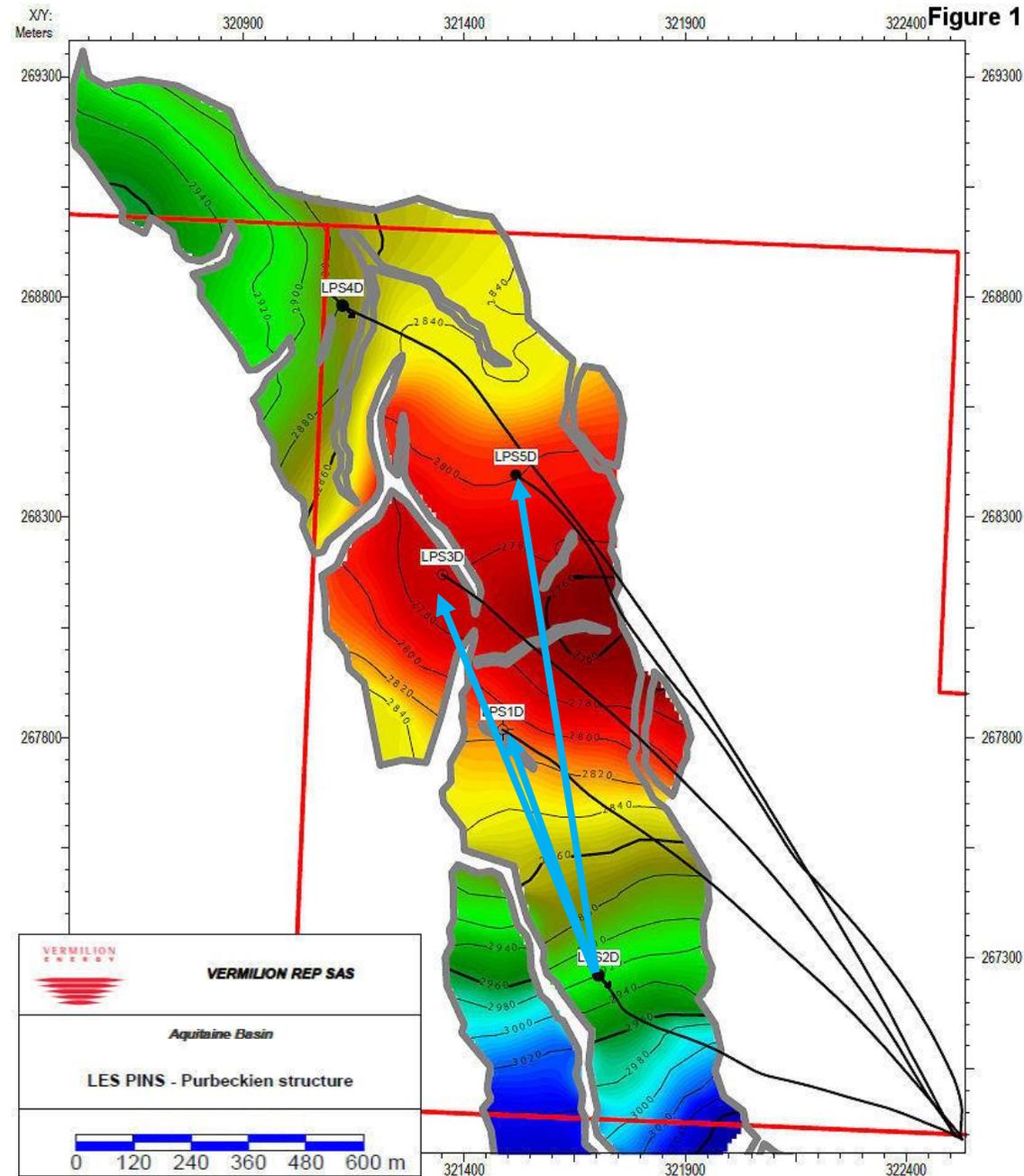


# Thermal study objective

- What is going to drive the cold front in the model is:
  - The temperature of the water injected
  - The speed of the water injected (injection rate **and** permeability of the reservoir)
  - The distance between producer and injector
  - The proportion of aquifer in the produced water (active vs. weak aquifer)
  - The thermal parameters of the rock / fluids
  - The boundary conditions (outside reservoir boundary heat supply)

# Les Pins modeling (static & dynamic)

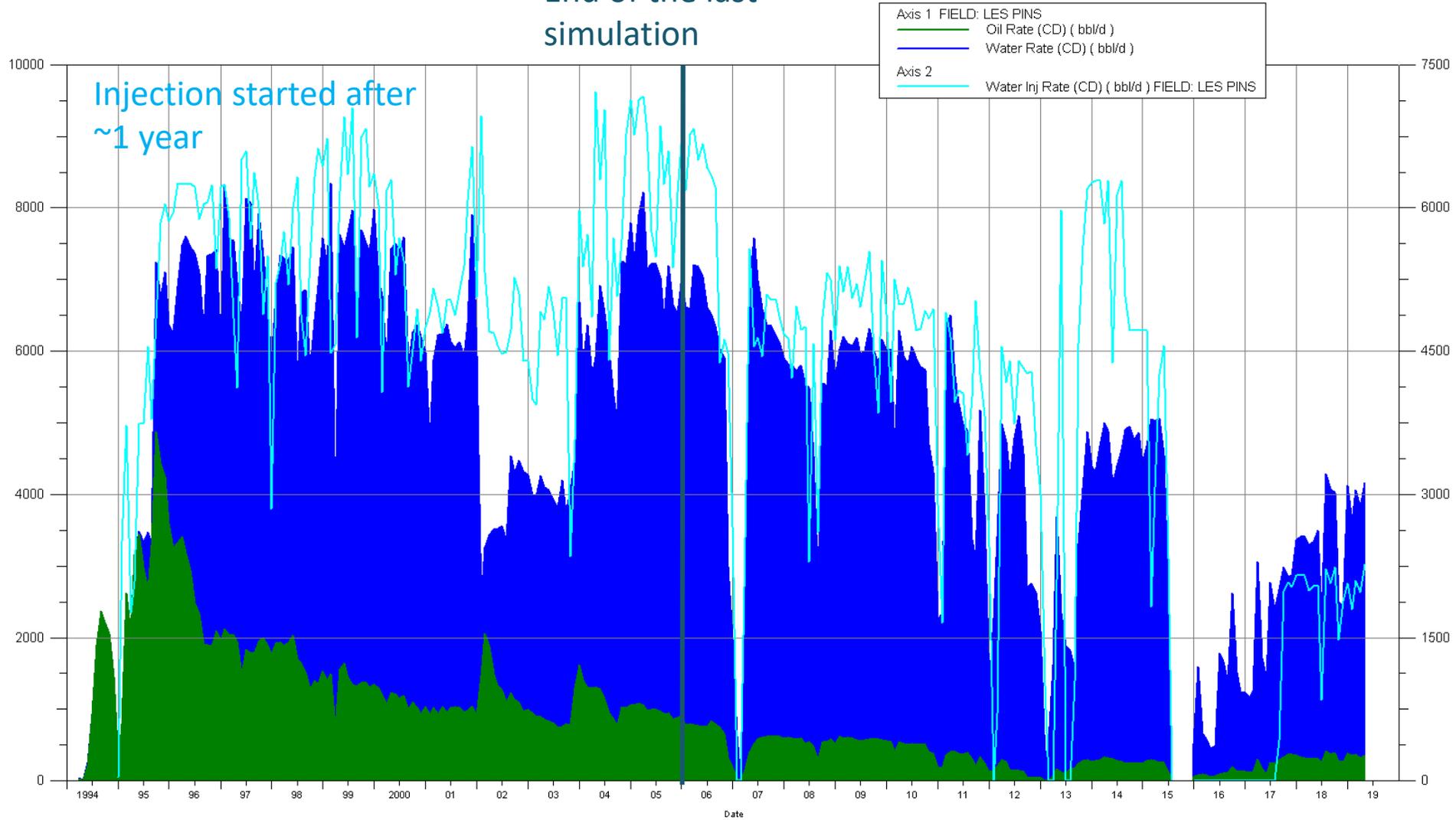
# Top Reservoir Map



LPS1D (580m) is closer to the injector compared to LPS3/LPS5 (900/1180m)

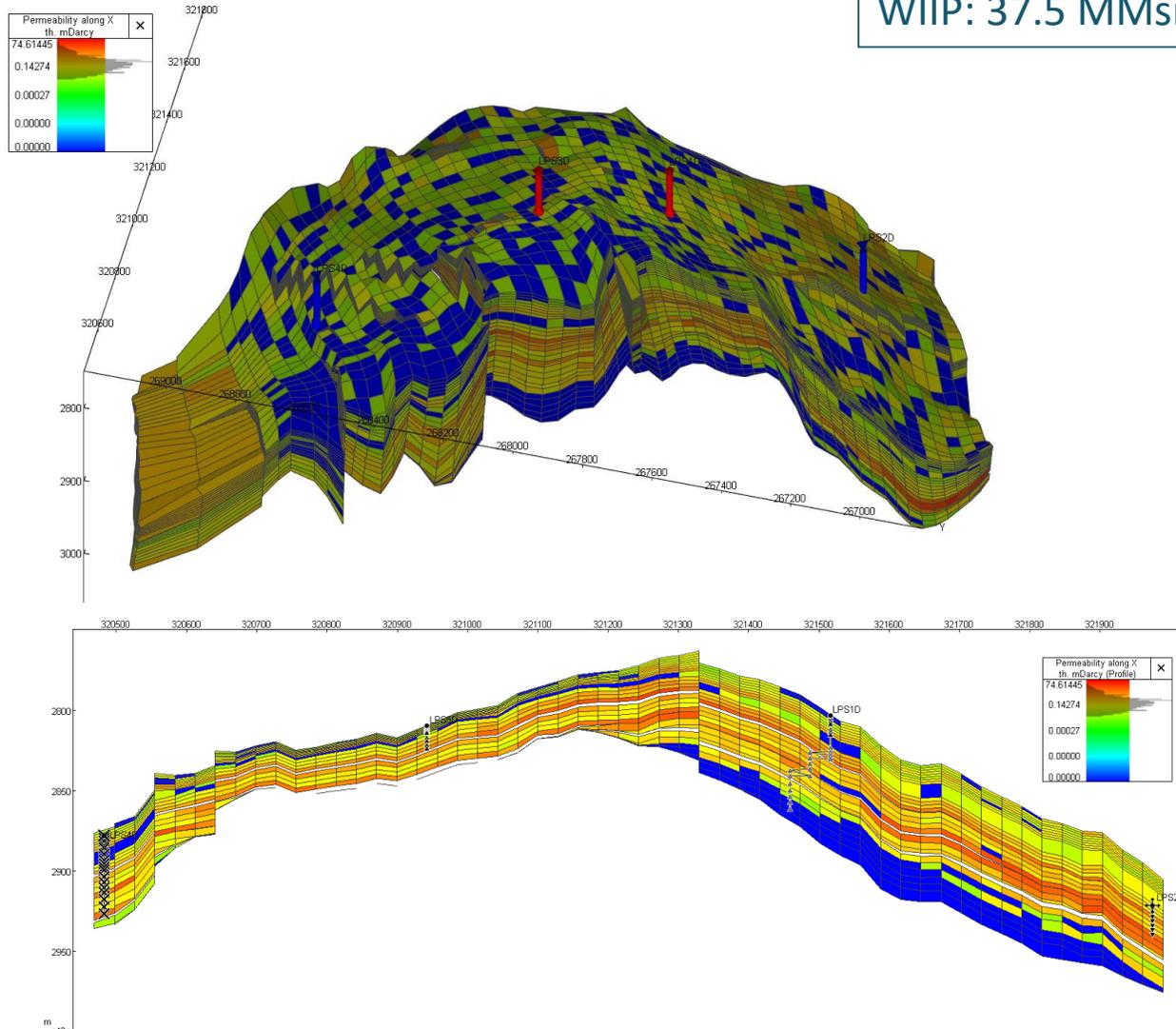
# Prod history

End of the last  
simulation



# Existing model

OOIP: 3 MMsm<sup>3</sup>  
 WIIP: 37.5 MMsm<sup>3</sup>



```
-- Layering
-- unit    top bot n layers upsc.meth
-- G1-2     1  8  8   Proportional
-- G3-4     9  9  1   Proportional
-- G5       10 13  4   Proportional
-- G5 Shale 14 14  1   Proportional
-- G6       15 18  4   Proportional
-- G6 Shale 19 19  1   Proportional
-- G7       20 22  3   Top conforming
-- G7 Shale 23 23  1   Top conforming
-- G8       24 26  3   Top conforming
-- G9       27 29  3   Top conforming
```

Structure from seismic horizons

Grid: 25 x 57 x 29

DX~30m

DY~43m

DZ~2.5m

Reservoir property (Phi) populated using geostatistical methods

K from K/Phi laws (logs)

Water saturation from Pc curves (SCAL)

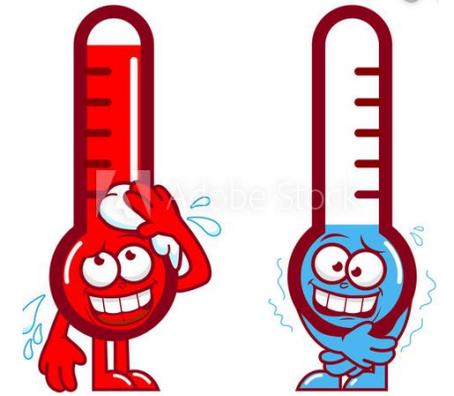
# Existing model history matching



Good field HM in terms of rates and total

# Looking for temperature data!

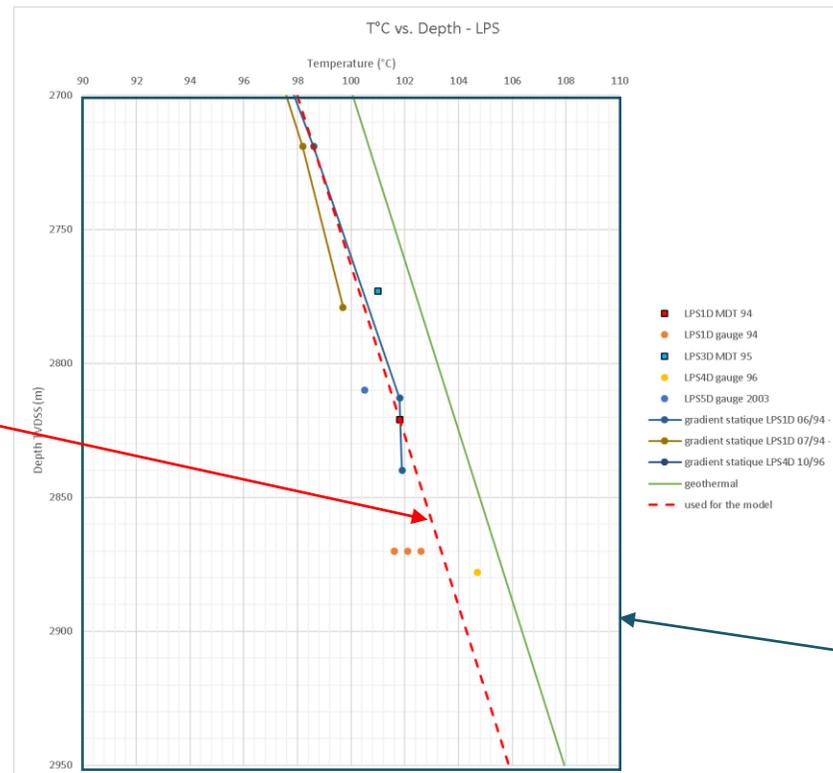
- Temperature data in our O&G industry is not generally acquired with the aim of studying geothermal topics but several data are available associated with the monitoring of the reservoir:
  - Flowmeter logs/Thermometer logs to study the injection contribution of LPS-2D
  - Gauge temperature
    - RFT/MDT: in LPS-1D, 2D, 3D, 4D, for the initial reservoir temperature
    - Permanent gauge in LPS-3D and 5D, for the bottom hole temperature at a given date
    - Gauge for pressure surveys: in LPS-1D, 3D, 4D and 5D



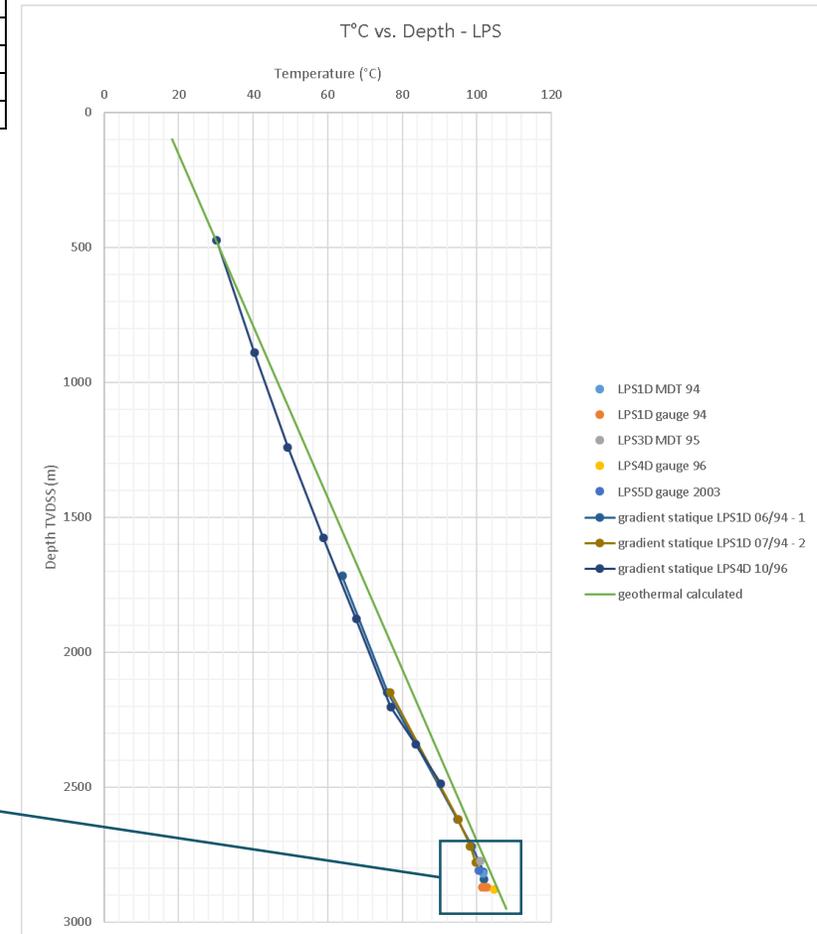
# Initial reservoir temperature

WELL	DATE	TYPE	MID PERF MD m	MID PERF TVDSS m	GAUGE DEPTH MD m	GAUGE DEPTH TVDSS m	TEMPERATURE °C	Comment
LPS1D	22/03/1994	MDT	3208,5	2821	3208,5	2821	101,8	
LPS1D	27/06/1994	Test Gauge	3259	2870	3228	2840	102,6	well flowing
LPS1D	01/07/1994	Test Gauge	3259	2870	3228	2840	101,6	well flowing
LPS1D	13/07/1994	Test Gauge	3259	2870	3228	2840	102,1	well flowing
LPS1D	24/07/1994	Test Gauge	3259	2870	3140	2755	101,6	well flowing
LPS3D	16/05/1995	MDT	3368,2	2773	3368,2	2773	101	
LPS4D	23/04/1996	Test Gauge	3856	2878	2746	2037	104,7	well flowing
LPS5D	23/10/2003	Test Gauge	3440	2810	3377	2750	100,5	well flowing

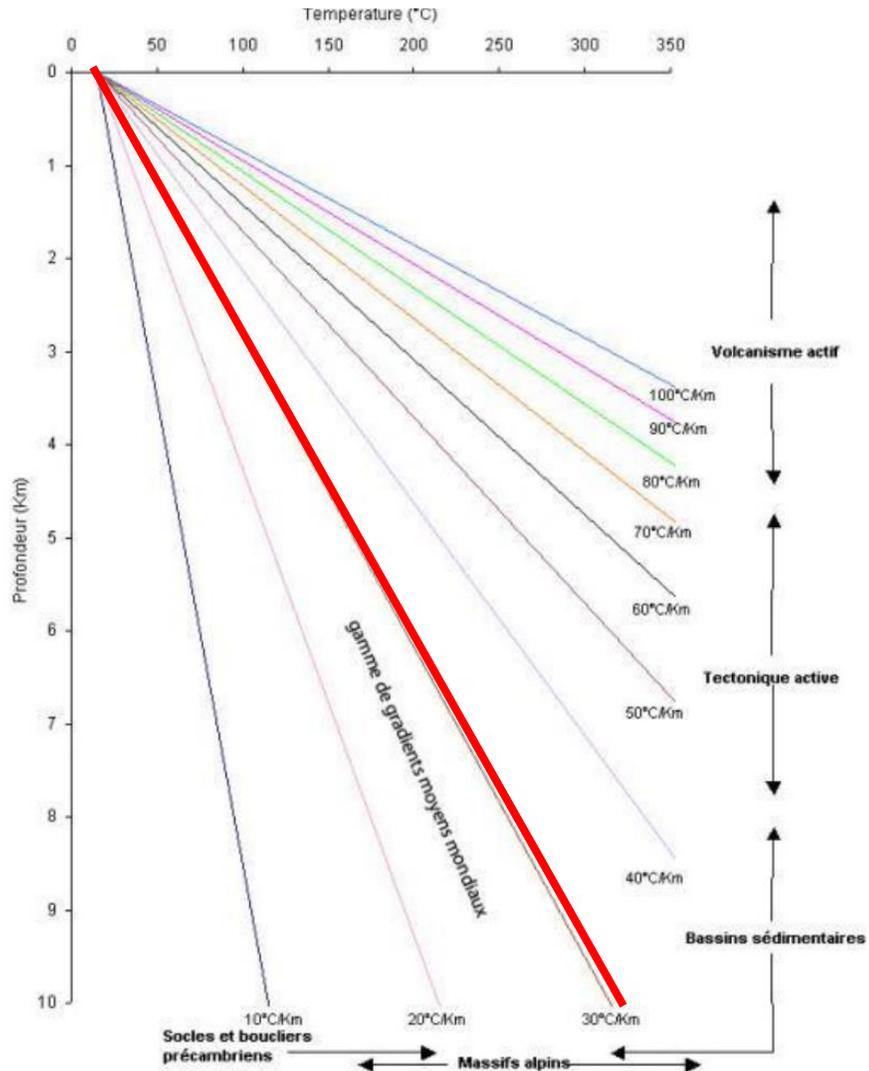
Initial reservoir temperature from MDT and pressure survey data



Initial temperature selected for the reservoir:  
 2700m 98°C  
 2821m 101,8°C  
 2950 m 105,9°C

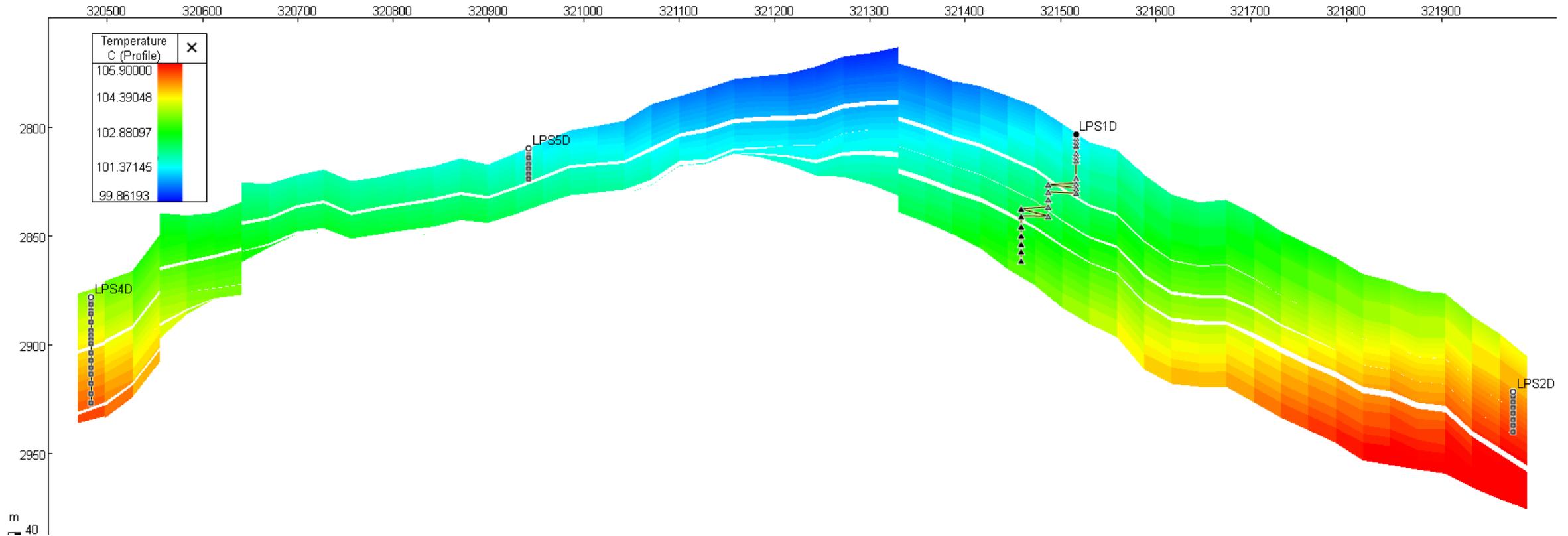


# Initial reservoir temperature



With  $\sim 30,7^{\circ}\text{C}/\text{Km}$ , the geothermal gradient in Les Pins is as expected for a sedimentary basin

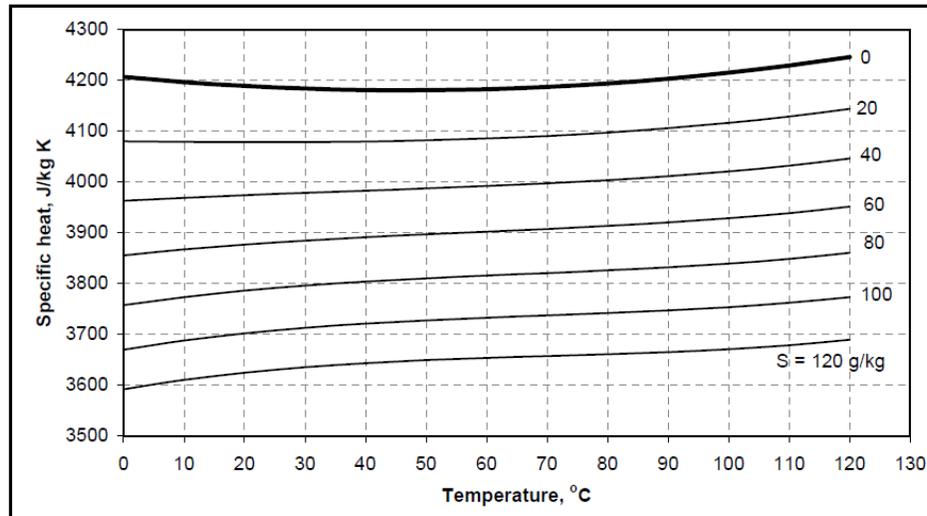
# LPS Initial reservoir temperature (1994)



# Brine specific heat

Specific heat at constant pressure, J/kg K

Temp, °C	Salinity, g/kg												
	0	10	20	30	40	50	60	70	80	90	100	110	120
0	4206.8	4142.1	4079.9	4020.1	3962.7	3907.8	3855.3	3805.2	3757.6	3712.4	3669.7	3629.3	3591.5
10	4196.7	4136.7	4078.8	4022.8	3968.9	3916.9	3867.1	3819.2	3773.3	3729.5	3687.7	3647.9	3610.1
20	4189.1	4132.8	4078.2	4025.3	3974.1	3924.5	3876.6	3830.4	3785.9	3743.0	3701.8	3662.3	3624.5
30	4183.9	4130.5	4078.5	4027.8	3978.6	3930.8	3884.4	3839.4	3795.8	3753.6	3712.7	3673.3	3635.3
40	4181.0	4129.7	4079.6	4030.7	3982.9	3936.4	3891.0	3846.7	3803.7	3761.8	3721.1	3681.6	3643.2
50	4180.6	4130.8	4081.9	4034.1	3987.3	3941.5	3896.6	3852.9	3810.1	3768.3	3727.5	3687.8	3649.0
60	4182.7	4133.7	4085.5	4038.3	3992.0	3946.5	3902.0	3858.3	3815.5	3773.7	3732.7	3692.6	3653.4
70	4187.1	4138.5	4090.6	4043.6	3997.3	3951.9	3907.4	3863.6	3820.6	3778.5	3737.2	3696.7	3657.0
80	4194.0	4145.3	4097.3	4050.1	4003.7	3958.1	3913.3	3869.2	3825.9	3783.5	3741.7	3700.8	3660.7
90	4203.4	4154.2	4105.9	4058.3	4011.5	3965.4	3920.2	3875.7	3832.0	3789.1	3746.9	3705.6	3665.0
100	4215.2	4165.4	4116.4	4068.2	4020.9	3974.3	3928.5	3883.6	3839.4	3796.0	3753.5	3711.7	3670.8
110	4229.4	4178.8	4129.1	4080.2	4032.2	3985.1	3938.7	3893.3	3848.6	3804.9	3761.9	3719.9	3678.6
120	4246.1	4194.7	4144.2	4094.6	4045.9	3998.2	3951.3	3905.4	3860.3	3816.2	3773.0	3730.7	3689.4



Accuracy ±0.28%

Volume specific heat of water vs. Temperature:  
Use of correlations: **3.974 KJ/KG/°C**

Assuming that most of the water in the reservoir is reservoir water. In reality the reservoir will be partially filled with time with less salted (source) water. In the simulator, only one value can be entered...

# Rock specific heat

Matériau	Capacité thermique volumique (en $10^6$ J/m <sup>3</sup> /K)
Eau	4.185
Argile (sèche)	2.1
Argile (humide)	2.3
Granite	2.1
Grès	2.3
Sable sec	1.9
Sable humide	1.9
Sel	2.0

Figure 54 – Ordre de grandeur de capacité thermique volumique.

(Source : G de Marsily : Quantitative Hydrogeology – Hydrology for Engineers. Academic Press London)

Sandstone mass specific heat (literature): 0,710 KJ/kg/K

Density of Les Pins Sandstone: 2650 kg/m<sup>3</sup>

→ Volume specific heat of rock: 1881 KJ/m<sup>3</sup>/K

**A value of 2000 kJ/m<sup>3</sup>/K will be assigned to the reservoir rock** with an uncertainty in the range of 1800-2400 kJ/m<sup>3</sup>/K

# Thermal conductivity rock

Type de roche	$\lambda$ (W m <sup>-1</sup> K <sup>-1</sup> )*
Granite	2.5 - 3.8
Gabbro, basalte	1.7 - 2.5
Péridotite, pyroxénite	4.5 - 5.8
Calcaire	1.7 - 3.3
Dolomite, sel	~ 5.0
<b>Grès</b>	<b>1.2 - 4.2</b>
Sable (sec - saturé en eau)	0.5 - 3.0
Argile (selon la teneur en eau)	0.8 - 2.1
Tufs volcaniques (selon la porosité)	1.2 - 2.1
Sédiments marins profonds (selon la teneur en eau)	0.6 - 0.8
Eau	0.6
Béton	0.9 - 2.0
Air (20 °C)	0.025

\* Valeurs de conductivité thermique à température ambiante (Bowen, 1989)

Type de roche	Conductivité thermique $\lambda$ (W/mK)			Capacité thermique volumétrique $\rho C$ (MJ/m <sup>3</sup> K)
	min	valeur typique	max	
<b>Roches sédimentaires</b>				
Calcaire	2.5	2.8	4.0	2.1 - 2.4
Marne	1.5	2.1	3.5	2.2 - 2.3
Quartzite	3.6	6.0	6.6	2.1 - 2.2
Sel	5.3	5.4	6.4	1.2
<b>Grès</b>	<b>1.3</b>	<b>2.3</b>	<b>5.1</b>	<b>1.6 - 2.8</b>
Roches argileuses limoneuses	1.1	2.2	3.5	2.1 - 2.4
<b>Roches non consolidées</b>				
Gravier sec	0.4	0.4	0.5	1.4 - 1.6
Gravier saturé d'eau	env. 1.8			env. 2.4
Moraine	1.0	2.0	2.5	1.5 - 2.5
Sable sec	0.3	0.4	0.8	1.3 - 1.6
Sable saturé d'eau	1.7	2.4	5.0	2.2 - 2.9
Arg	0.5		1.0	1.5 - 1.6
Arg	1.7		2.3	1.6 - 3.4

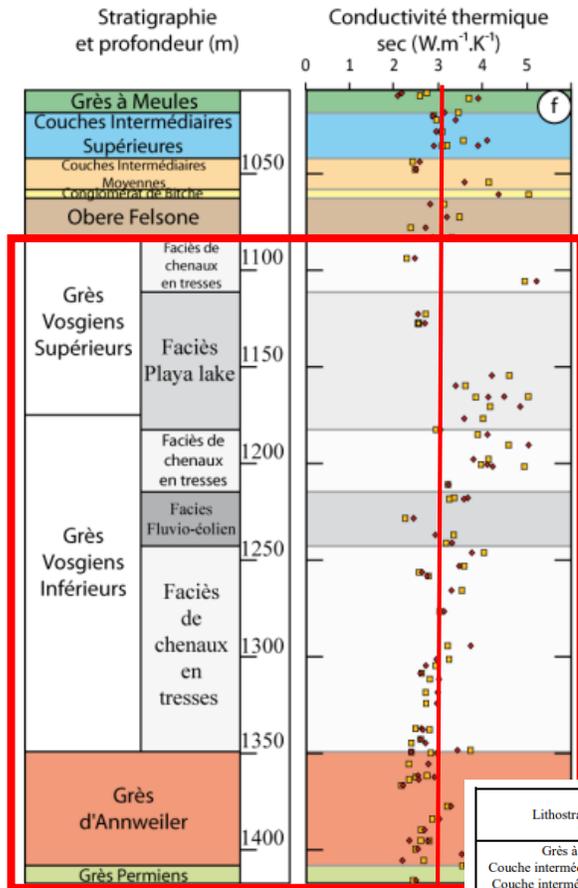
TABLEAU 5.1  
VALEURS COMPARÉES DE LA CONDUCTIVITÉ THERMIQUE  
DU DIAMANT, DES ÉVAPORITES, DES ROCHES DES SOCLÉS,  
DES ROCHES SÉDIMENTAIRES ET DE L'EAU PURE  
(D'après Clark Jr., 1966 et diverses sources)

	Conductivité thermique (W/m <sup>2</sup> C)
Cristal de diamant .....	121 à 163
Roches salines .....	5.33 à 7.19
Anhydrite .....	4.89 à 5.81
Gypse .....	1.29
Granite .....	2.59 à 3.76
Basalte .....	2.38 à 2.92
<b>Grès quartzites .....</b>	<b>3.09 à 8.03</b>
<b>Grès .....</b>	<b>1.46 à 4.26</b>
Dolomites .....	1.96 à 2.97
Calcaires .....	1.96 à 2.97
Argiles <sup>(1)</sup> .....	1.17 à 2.88
Limons .....	0.15 à 0.87
Eau pure .....	0.56

(1) non chloritiques.



# Thermal conductivity rock



Caractéristiques géothermiques du réservoir gréseux du Buntsandstein Alsace, Sébatsien Haffen, 2013

NIVEAU STRATIGRAPHIQUE	CONDUCTIVITE THERMIQUE (W/mK)
Formations superficielles/Altérites	2.3
Campanien (sud)	3.2
Campanien-Santonien (sud)	2.1
Coniacien (sud)	3.2
Turonien (sud)	3.2
Turonien inf. et Cénomanién sup (sud)	2.1
Cénomanién moy. et inf. (sud)	2.3
Cénomanién basal - jurassique sup (sud)	2.1
Crétacé indifférencié (nord)	2.3
Jurassique sup altéré	2.8
Jurassique sup non altéré	1.8
Dogger	3.2
Toarcien	2.1
Infra-Toarcien	2.8

Illustration 20 : Valeurs de conductivité thermique selon la lithologie des terrains en domaine sédimentaire.

Atlas régional des ressources géothermales très basse énergie de Poitou-Charentes, BRGM, 2018

Lithostratigraphie	Nombre de points de mesure	Conductivité thermique (W.m <sup>-1</sup> .K <sup>-1</sup> )			
		Moyenne	Min.	Max.	Ecart-type
Grès à Voltzia	6555	3.04	1.15	4.49	0.44
Couche intermédiaire supérieures	15312	3.36	1.12	4.64	0.37
Couche intermédiaire moyennes	9778	3.81	1.75	5.87	0.63
Conglomérat de Bitche	4062	4.10	1.77	5.92	0.53
Obere Felsone	15499	3.57	0.99	10.10	0.82
Grès Vosgiens Supérieurs	67913	3.14	0.98	9.76	0.68
Grès Vosgiens Inférieurs	128143	3.35	1.09	6.80	0.56
Grès d'Annweiler	41420	2.88	1.41	4.37	0.32
Grès Permien	7000	2.83	0.96	9.72	0.35
Total	295682	3.27	0.96	10.10	0.63
Faciès (Grès Vosgiens)					
Chenaux en tresses (1112-1084m)	19208	3.40	1.42	5.88	0.59
Playa Lake (1183-1112m)	48705	3.09	0.98	9.76	0.78
Chenaux en tresses (1215-1183m)	24702	3.88	1.09	6.53	0.56
Fluvio-éolien (1243-1215m)	21614	3.19	1.93	5.22	0.44
Chenaux en tresses (1349-1243m)	81827	3.17	1.32	6.80	0.43

ROCHES SEDIMENTAIRES	CONDUCTIBILITE THERMIQUE mw/°C/cm	ROCHES IGNEES	CONDUCTIBILITE THERMIQUE mw/°C/cm
Argiles (carbonifères)	12 à 18	Andésite	33
Calcaire	21 à 29	Gneiss	20 à 36
Conglomérat	29 à 33	Granite	24
Craie	91	Rhyolite (altérée)	31 à 36
Dolomite	41	Syénite	26 à 39
Grès (carbonifères)	25 à 32		
Marnes (permiennes)	17 à 27		
Marne, argiles (Iran)	21		
Quartzite	54		
Sel gemme	112		

FIGURE 13 : Conductibilité thermique de quelques roches (extrait du Handbook of Physical Constants)

**A value of 3 W/m/K will be assigned to the reservoir rock (258 kJ/m/C/day) based on values from literature with an uncertainty in the range of 2,3-3,7 W/m/K (198-318 KJ/m/C/day)**

# Boundary conditions

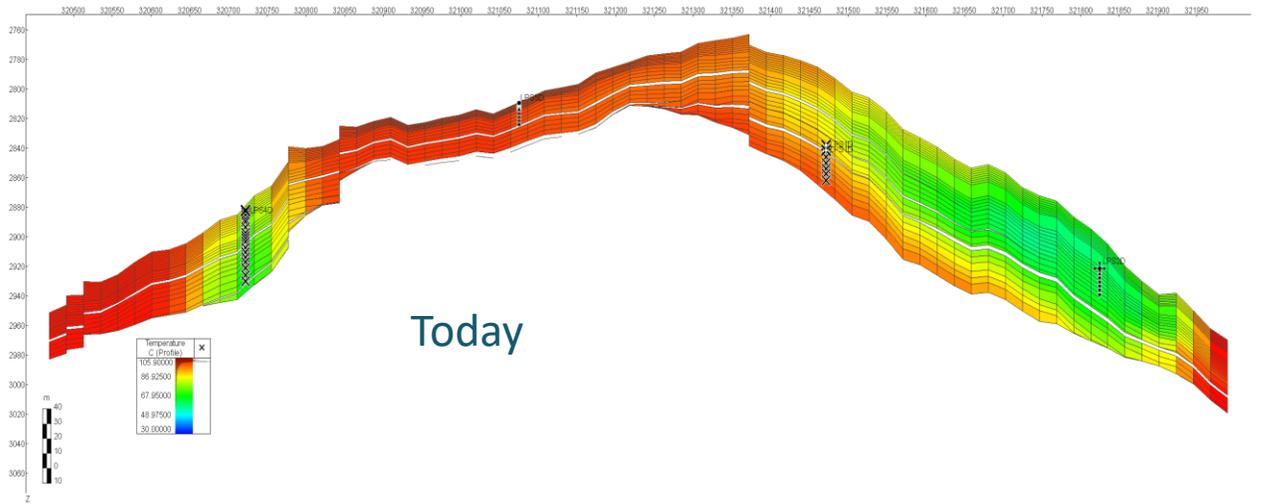
ROCKCONT

```
-- West face  
1 I- 106 2000 258 0 /  
-- East face  
1 I+ 106 2000 258 0 /  
-- North face  
1 J- 106 2000 258 0 /  
-- South face  
1 J+ 106 2000 258 0 /  
-- Top face  
1 K- 102 1700 120 0 /  
-- Bottom face  
1 K+ 108 1700 120 0 /  
/
```



This assumes the reservoir is well isolated from the Jurassic formation of Mano below, known to be fractured and that could bring hotter water if in direct communication

# LPS Base case history match

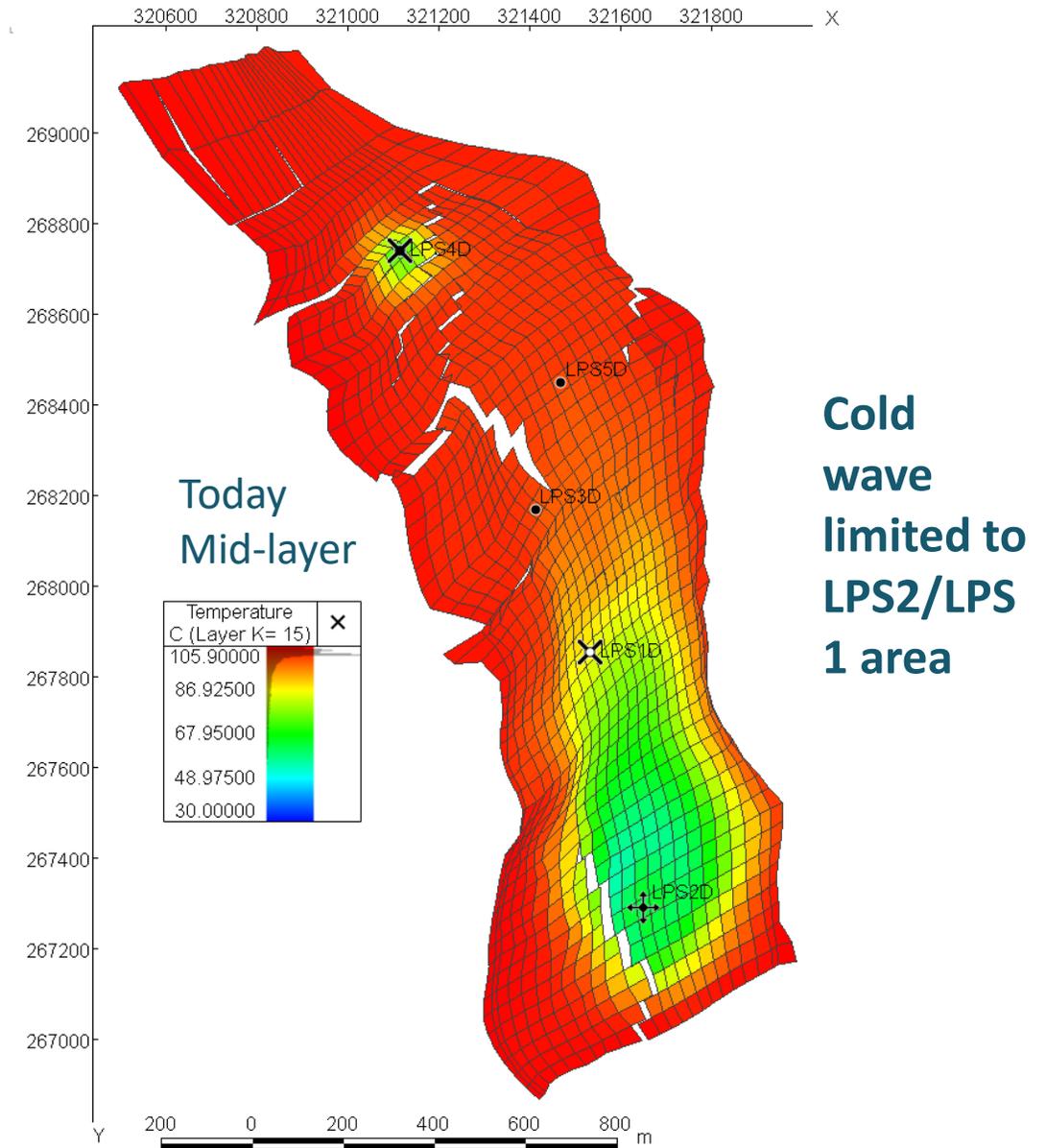


## Parameters:

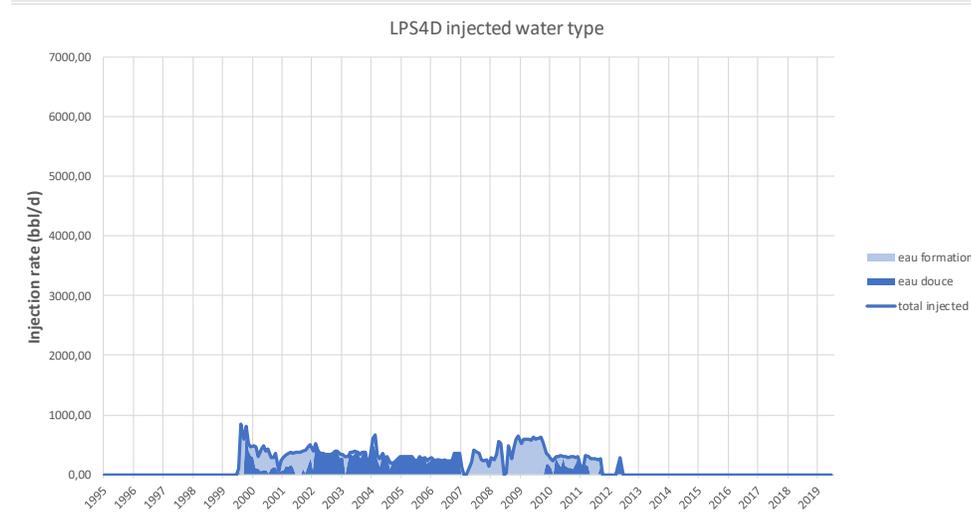
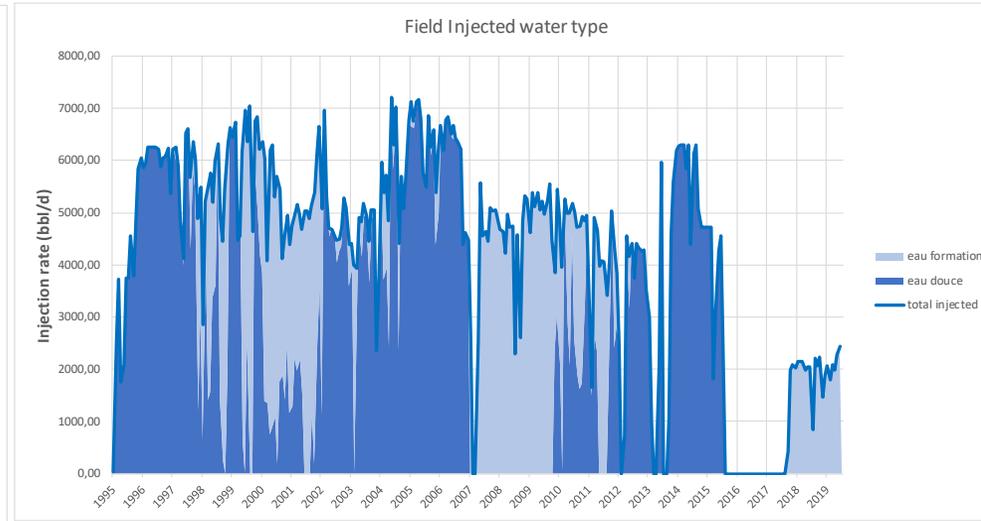
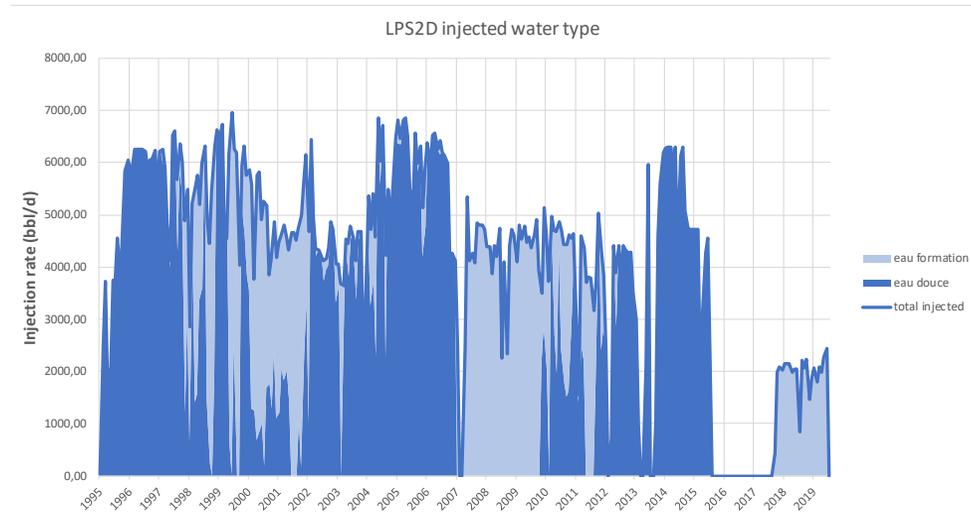
- initial Temperature gradient around 102°C
- Volume specific heat of oil, water, gas: 2,22, 3,97, 2,13 KJ/kg/°C
- Volume specific heat of rock: 2000 KJ/rm3/°C
- Rock thermal conductivity: 258 kJ/m/day/C

## Assumptions:

- Set boundary conditions
- Dead cells participating to heat
- Injected water temperature history from calculation



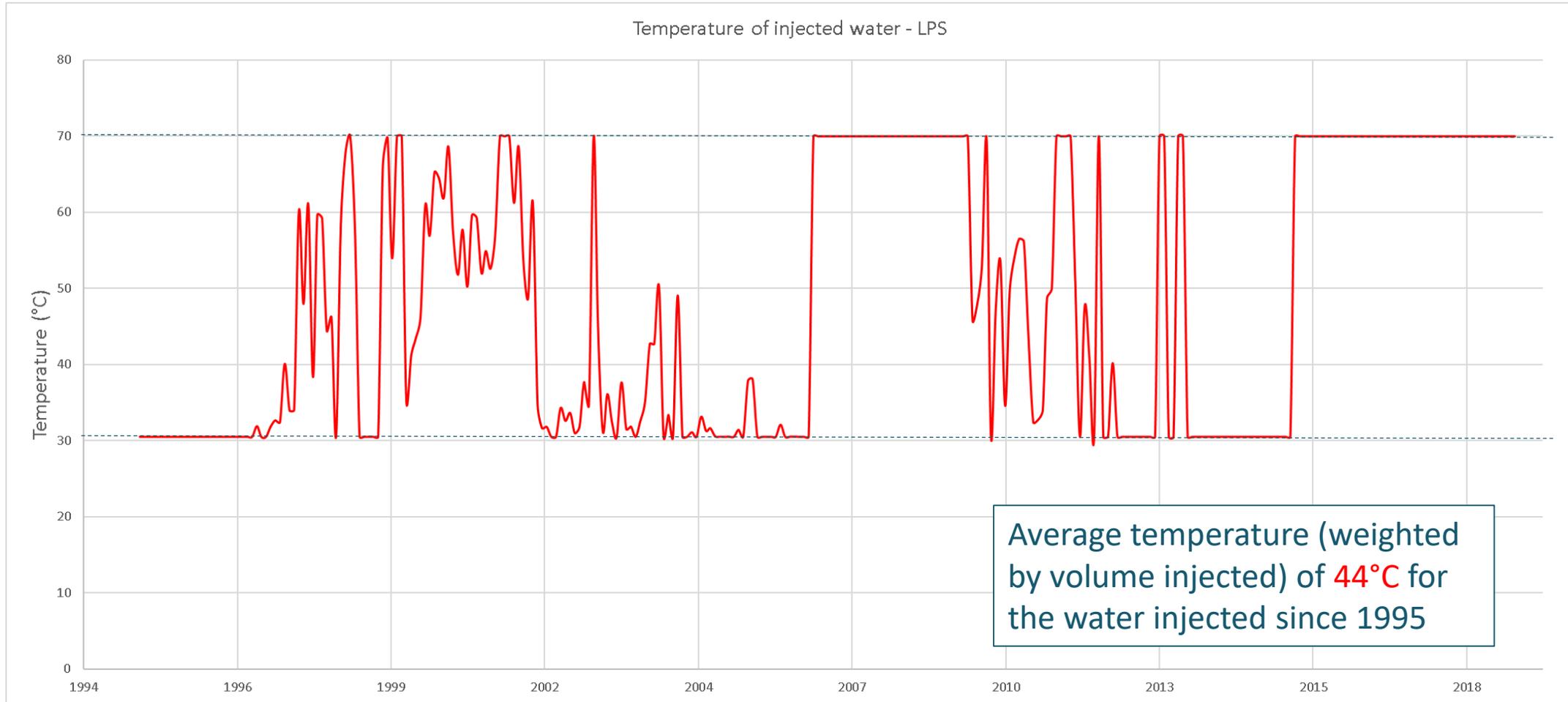
# Past shallow water injection



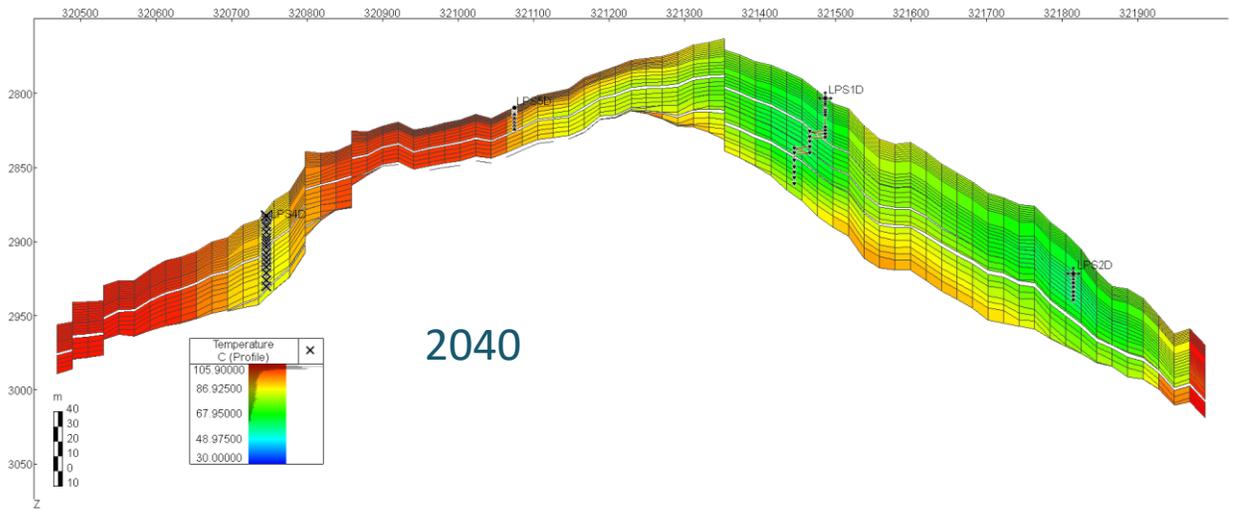
24,5 MMstb of source water injected out of 38 MMstb (**65%**) since 1995

It has been assumed that the same proportion of source water was sent to both LPS2D and LPS4D

# LPS2D injected water temperature / downhole

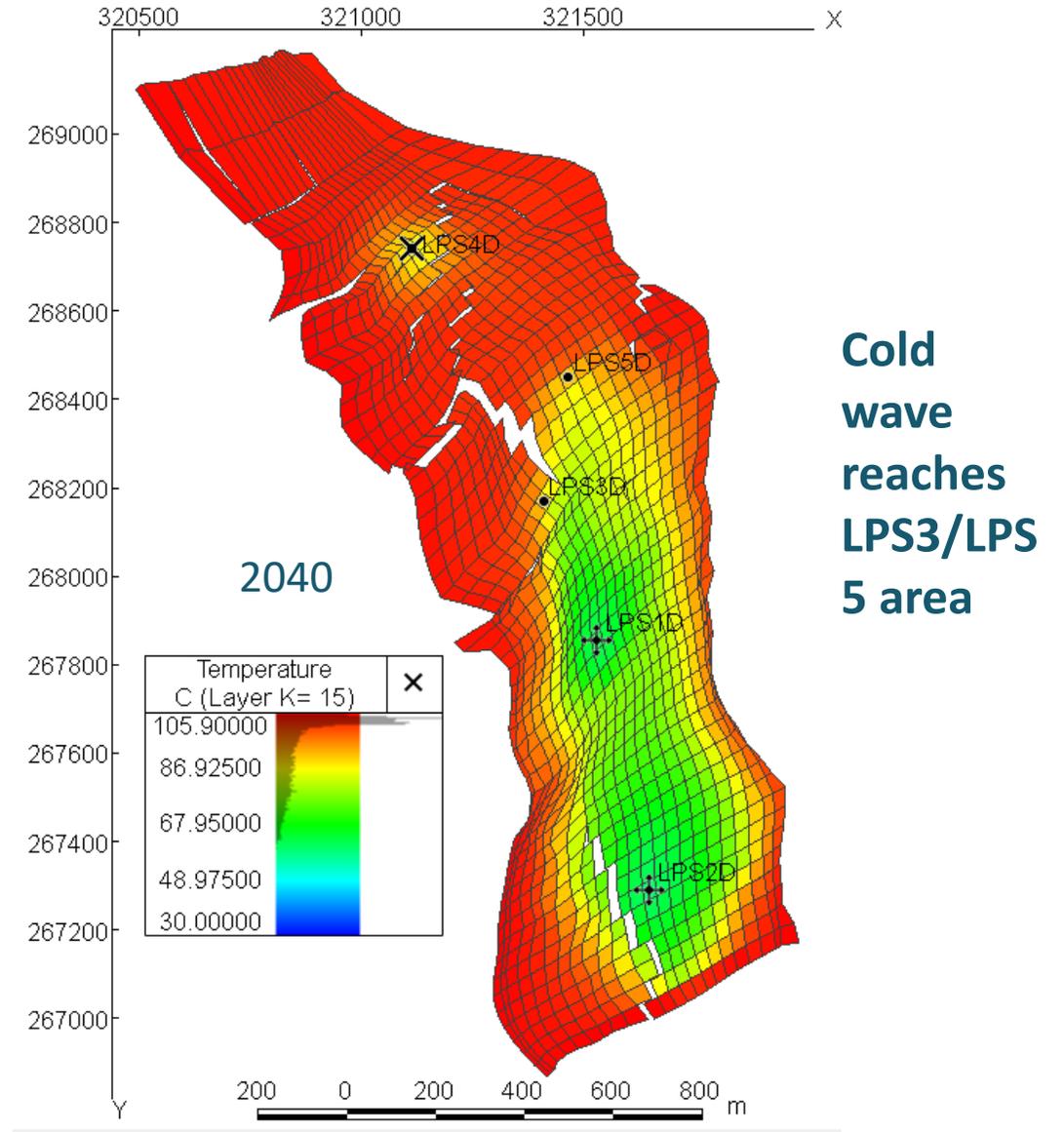


# LPS Base case forecast



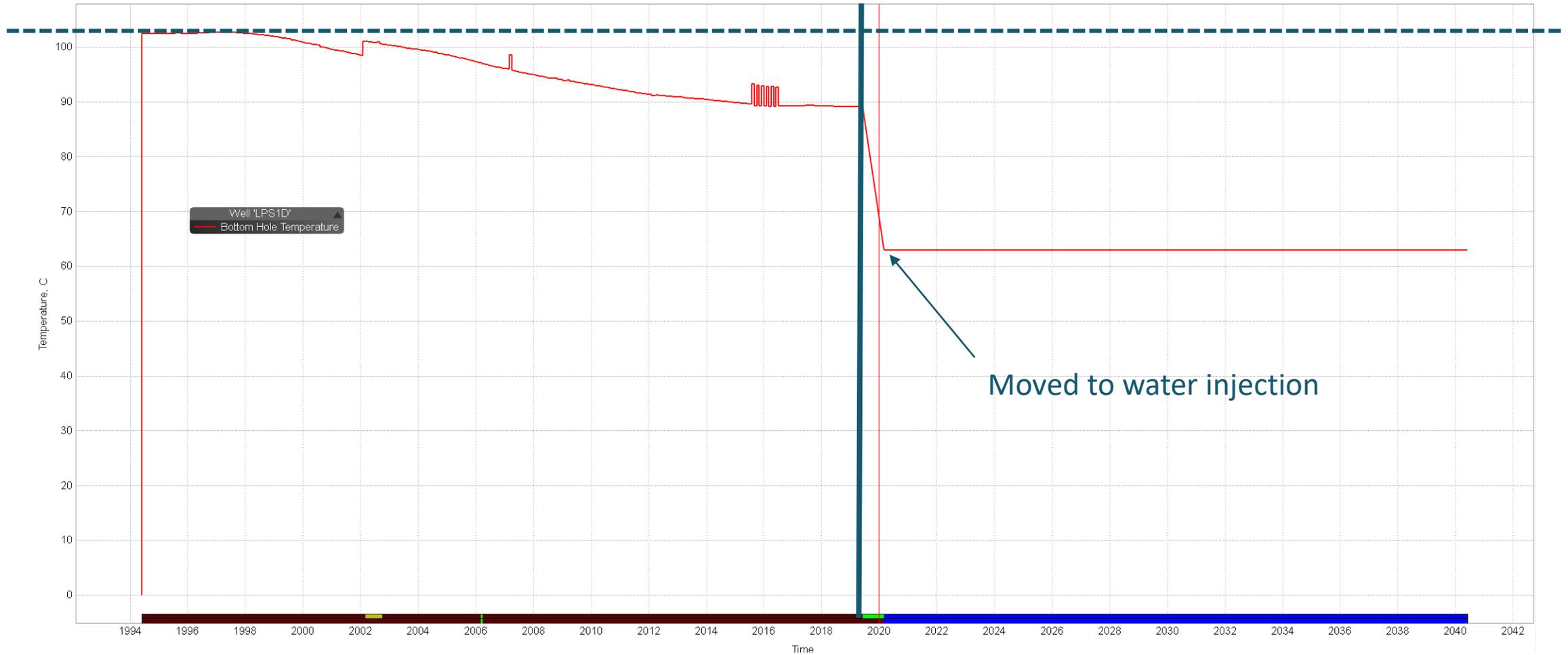
## Forecast:

- Including the LPS1D conversion in 2020
- Wells controlled on BHP
- Optimized Liquid Rates:
  - LPS3D: 79 m<sup>3</sup>/d
  - LPS5D: 600 m<sup>3</sup>/d
- Injected Water Rate:
  - LPS2D: 350 m<sup>3</sup>/d
  - LPS1D: 450 m<sup>3</sup>/d
- Injected temperature linked to Condorcet's project: 63°C (60°C instead of 70°C during 1/3 of the year)



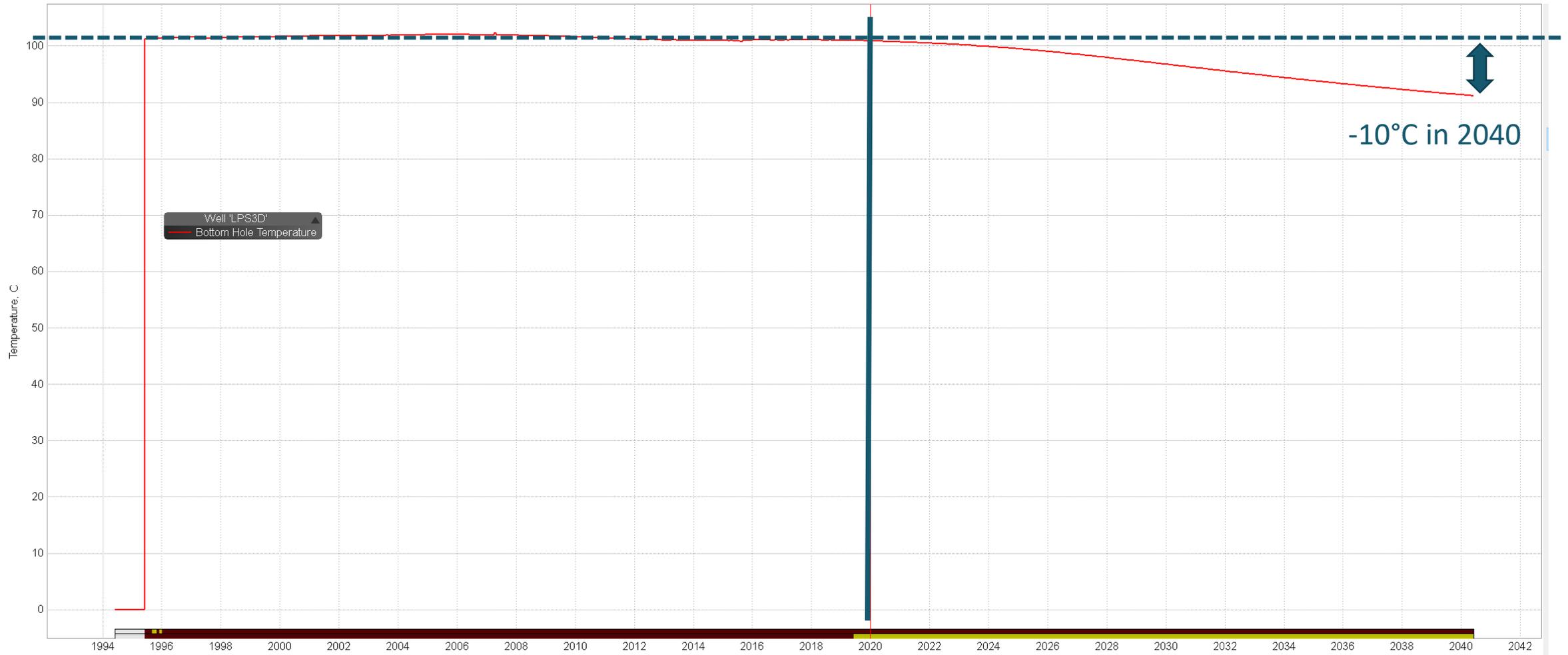
# LPS Base case forecast: LPS1D

## LPS1D



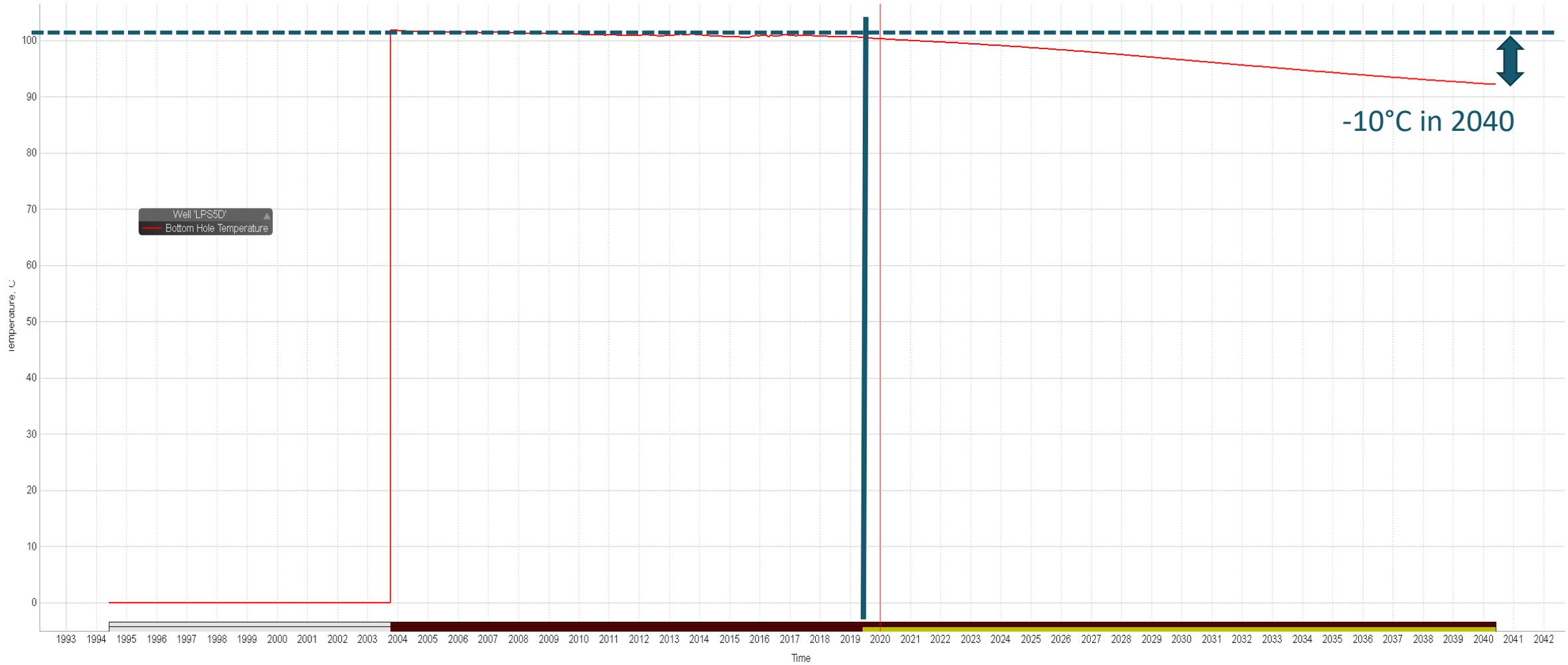
# LPS Base case forecast: LPS3D

## LPS3D

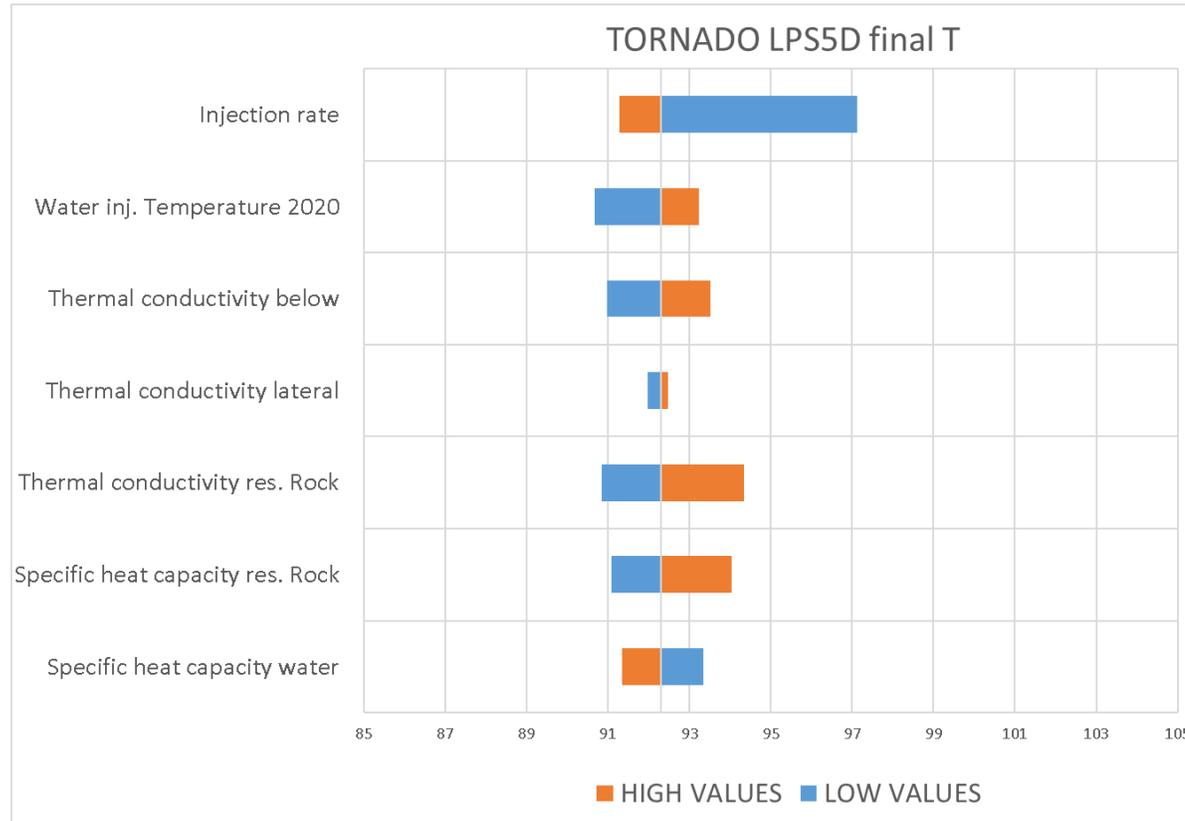


# LPS Base case forecast: LPS5D

## LPS5D



# LPS model uncertainties

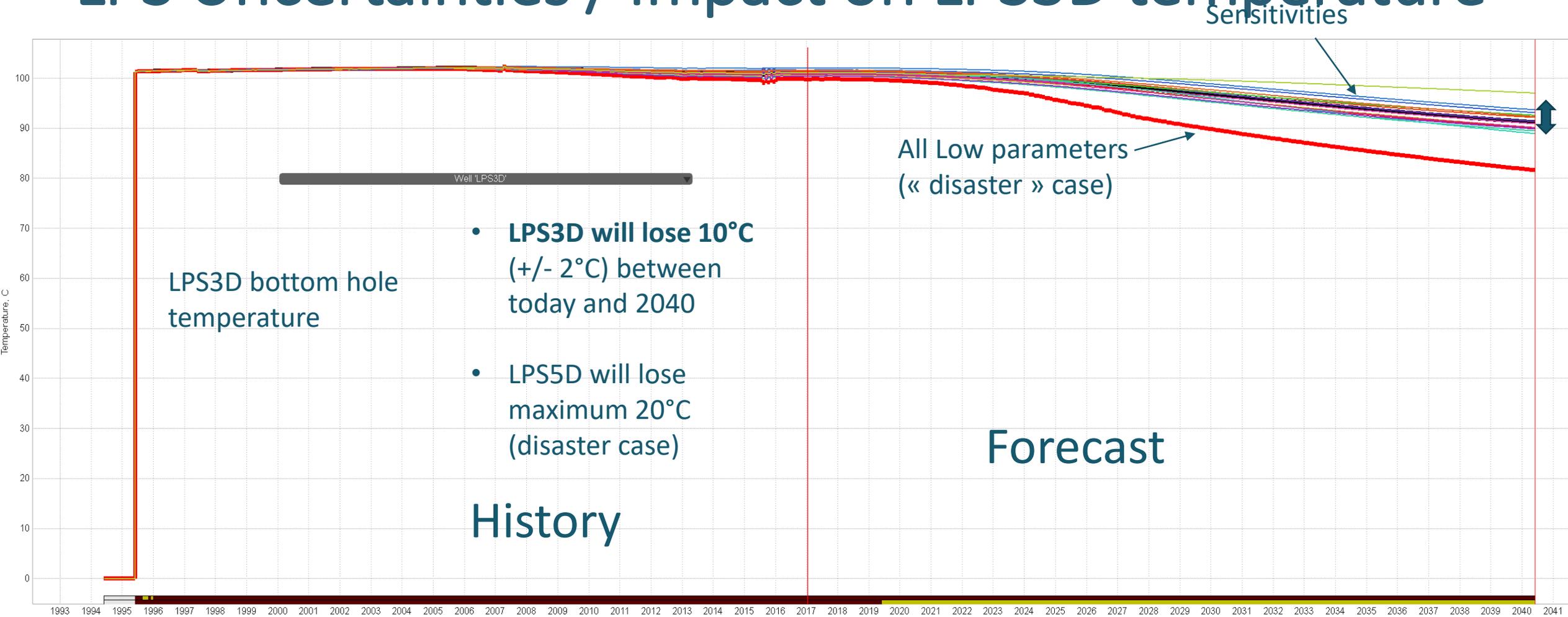


	BASE	LOW	HIGH
<b>INJRATE</b>	800	400	1000
<b>SPECHEATW</b>	3,974	3,7	4,2
<b>SPECROCK</b>	2000	1800	2400
<b>TEMPINIT</b>	63	50	70
<b>THCONBOT</b>	120	50	400
<b>THCONLAT</b>	258	50	400
<b>THCONRES</b>	258	198	318

**Far from the injector**, several things impact negatively the final temperature in 2040 (example of LPS5D): Water injection temperature, Thermal conductivity of the rock, Bottom rock conductivity, specific heat capacity of fluids...  
**BUT the impact is relatively low: -1°C in average of uncertainty**

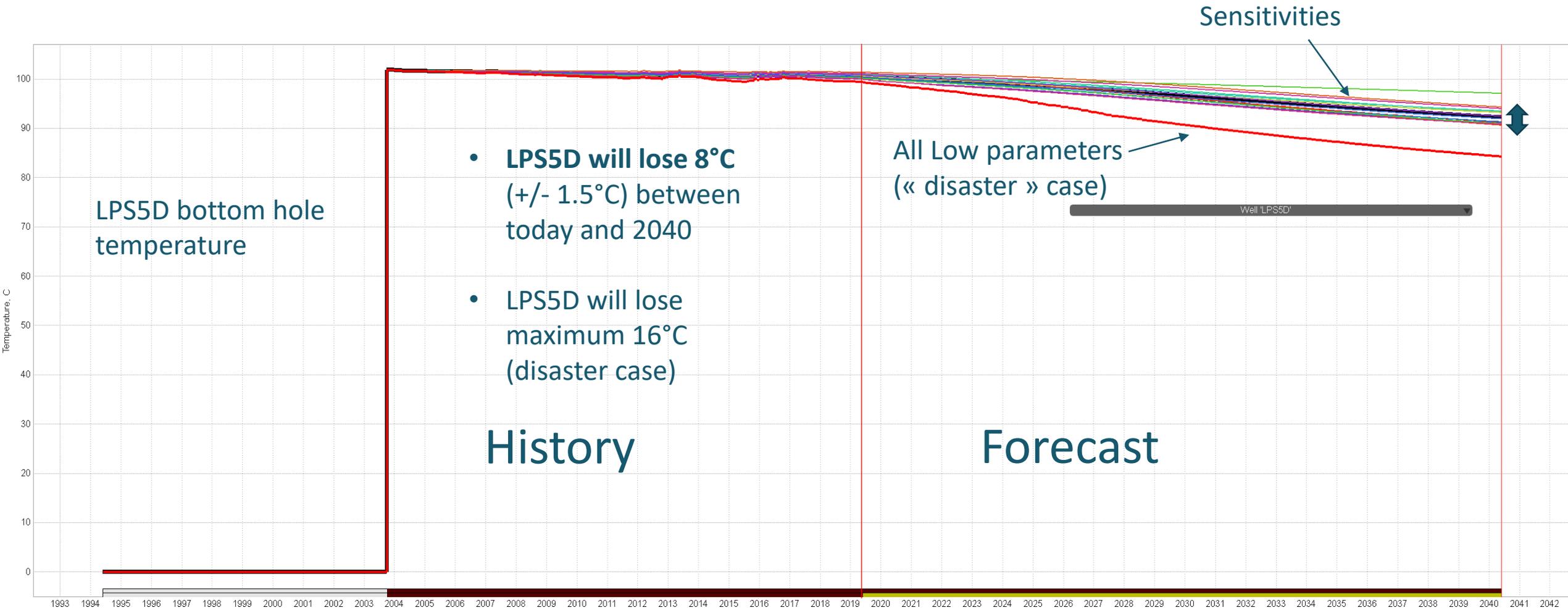
Note the positive impact of massively reducing the injection rate (to 400 m<sup>3</sup>/D in total, which is unlikely)

# LPS Uncertainties / Impact on LPS3D temperature



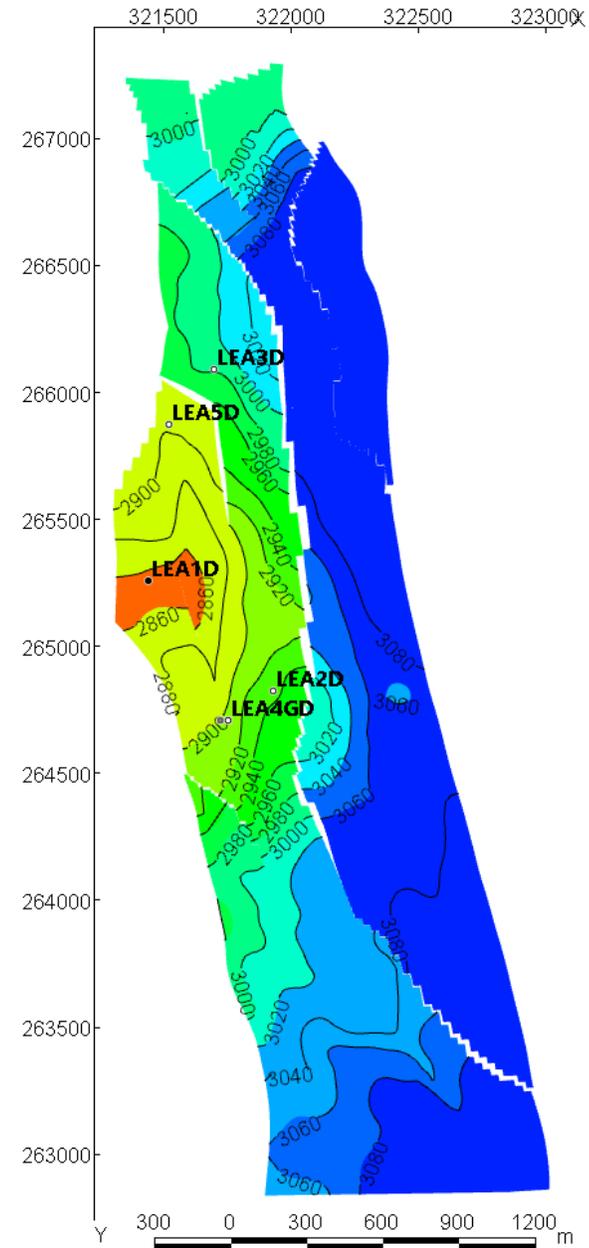
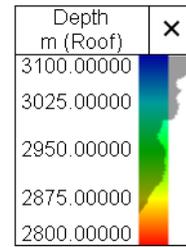
\* Performed without the LPS1D conversion

# LPS Uncertainties / Impact on LPS5D temperature

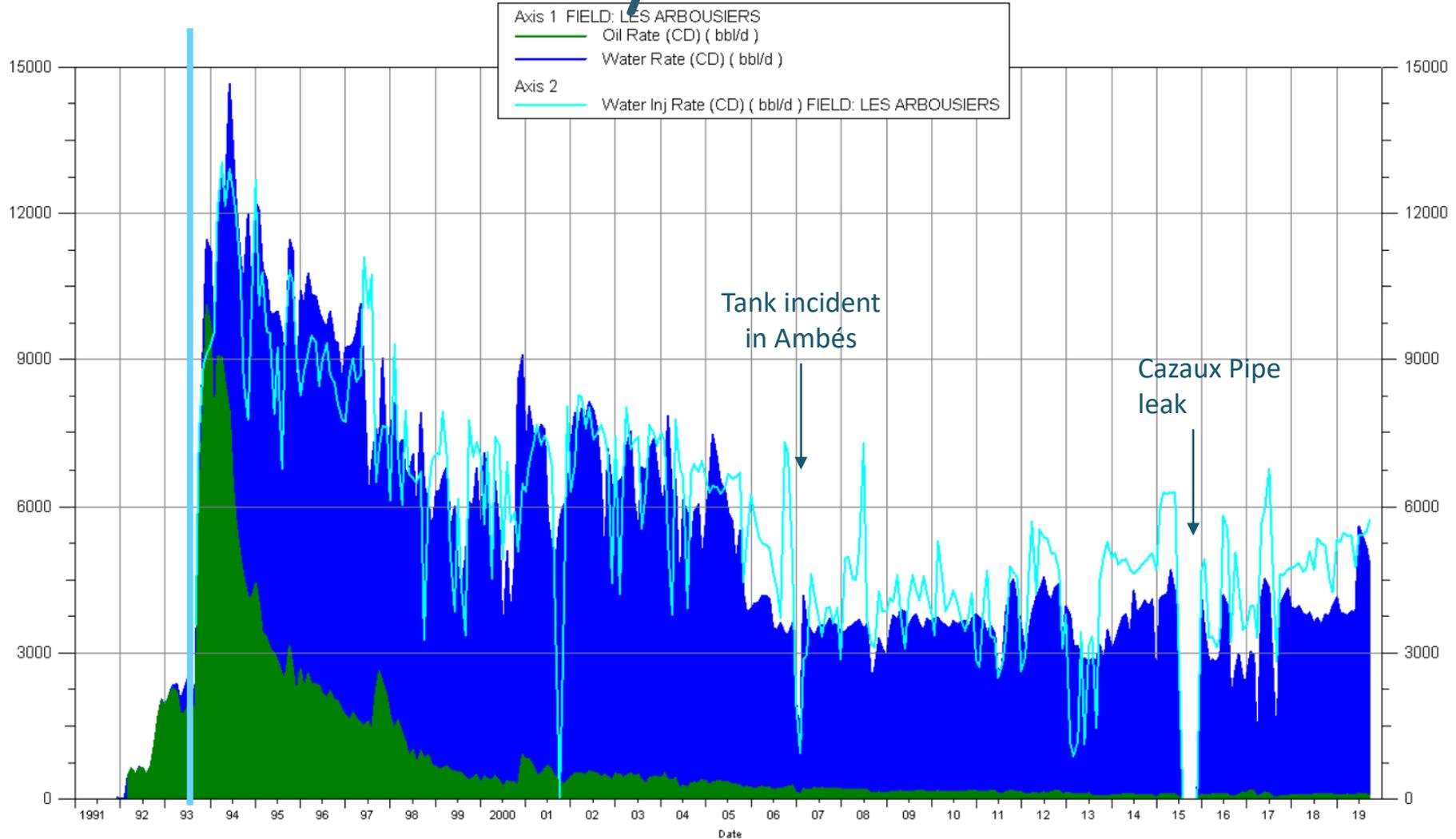


# Les Arbousiers modeling (static & dynamic)

# LEA Top Reservoir Map



# LEA Prod history



Injection started after  
~18 months of prod

# LEA Water injection type

Track records before 2007?



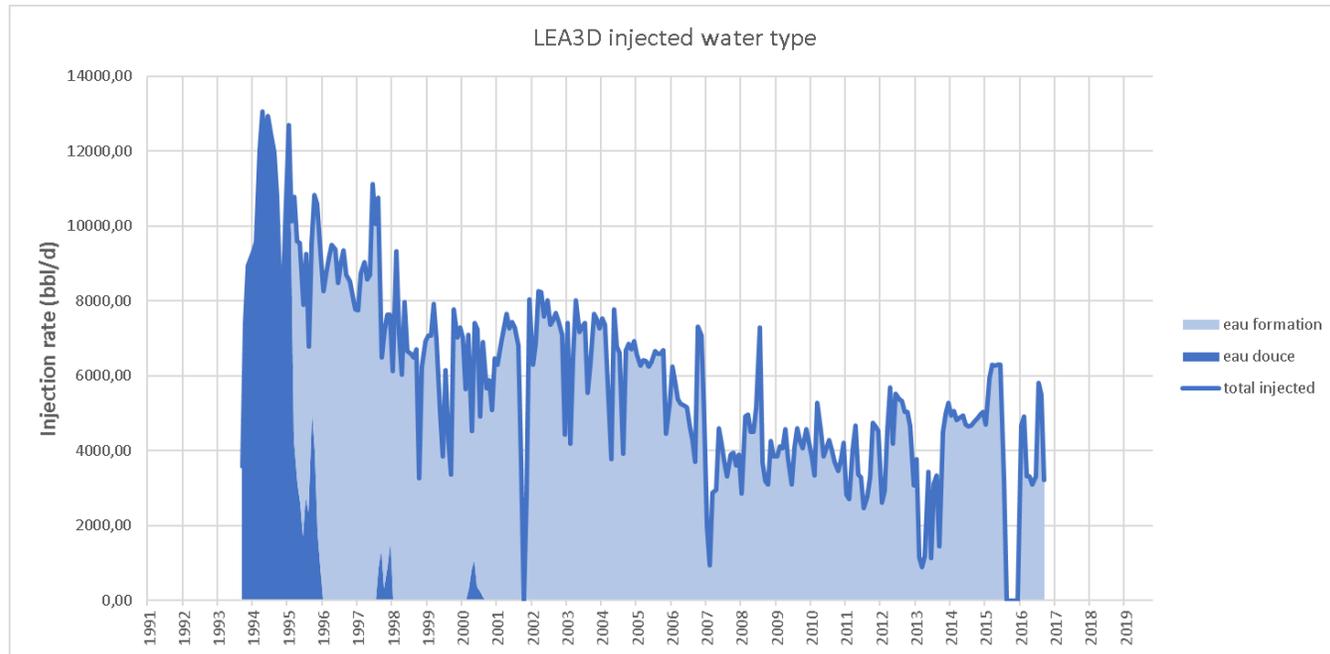
Dig into the old Exxon daily reports to rebuild the split between source water and production water!

EAU DEPOT

CANALISATION DEPOT	DATE	H	VOLUME
FLOOD NORD PARENTIS	30/12-01/01	48	120.0
FLOOD SUD PARENTIS	30/12-01/01	48	0.0
S.W.D. PARENTIS	30/12-01/01	48	19269.0
FLOOD LAC PARENTIS	30/12-01/01	48	2306.0
TOT. DEPART DEPT CX	30/12-01/01	48	7780.0
EAU DCE CX28->DEPOT	30/12-01/01	48	0.0
EAU SALEE LEA SUR CX	30/12-01/01	48	2421.0
SWD CAZAUX	30/12-01/01	48	0.0
DEPOT MTS-->MTS6	29/12-01/01	72	1431.0
DEPOT LGS1-->LGS101	29/12-01/01	72	1922.7
DEPOT LGS6-->LGS29	29/12-01/01	72	0.0
DEPART DEPOT LEA	30/12-01/01	48	2421.0
ED CX28->LEA PROCESS	30/12-01/01	48	6.0

EAU HORS DEPOT

CANALISATION HORS DEPOT	DATE	H	VOLUME
EAU DCE CX28->PUITS	30/12-01/01	48	264.0
EAU DOUCE CX 50	30/12-01/01	48	107.0
EAU DOUCE LEA3	30/12-01/01	48	3661.0



Source water mostly injected at the beginning

6,6 MMstb of source water injected out of 43,6 in total (15%)

# LEA Permeability

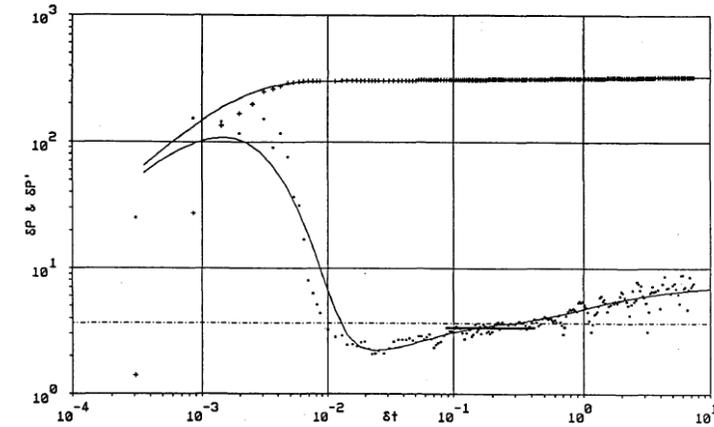
Permeability values from transient pressure tests:

- 12/91: LEA1 3145.2-3150.5 m log, build up de 7h30  
 → **K=1633 mD**

La remontée de pression enregistrée à LEA 1D confirme :

- que le réservoir est de bonne qualité  $k.h = 8500 \text{ mD.m}$  ;
- la présence d'une faille étanche à proximité immédiate du puits (environ 140 m) ;
- suggère que la zone intermédiaire du "Purbeckien" (de 3133 à 3143 m/log) participe à la production ; ceci expliquerait le fort  $k.h$  obtenu ainsi que le skin apparent élevé. Cette hypothèse semble confirmée par les valeurs de perméabilité mesurées sur carottes et par le log de cimentation (CBL - VDL) enregistré suite au test.

Company : ESSO REP                      Test : BUILD UP-SIMULATION  
 Field : LES ARBOUSIERS                Date : 19/12/91  
 Well : 1D                                 Gauge :



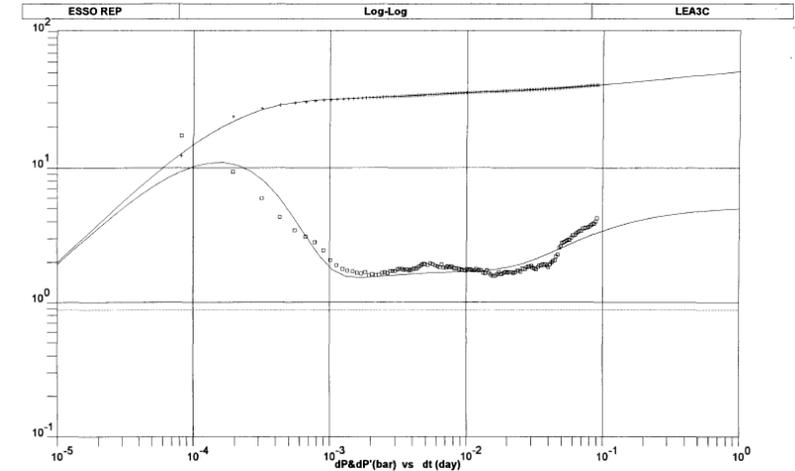
RESERVOIR TYPE	WELL TYPE	BOUNDARY TYPE
2-Permeability	Storage & Skin	1 fault

Flow Period # 10  
 pi 4073.4 psia  
 Smoothing 0  
 Time Match 28000 hr-1  
 Pressure Match .13825 psi-1  
 Storage C .29258E-3 bb/psi  
 kh 27770. md.ft  
 k 1633.6 md  
 Skin Layer1 S1 35.049  
 Skin Layer2 S2 43.907  
 Omega .15  
 Lambda .78854E-5  
 Kappa .9  
 L - Sealing at 447.49 ft

# LEA Permeability

Permeability values from transient pressure tests:

- 12/93: LEA3 3474-3521 m log, fall off test de 54h  
 → **K=190 mD**



	CAS 1 (LEA3C)	CAS 2 (LEA3D)	CAS 3 (LEA3E)	CAS 4 (LEA3F)
Modèle Puits	Storage & Skin	Storage & Skin	Storage & Skin	Storage & Skin
Modèle Réservoir	Homogène	Double Porosité	Homogène	Double Porosité
Configuration Réservoir	2 failles < à 60°	2 failles < à 60°	2 failles < à 45°	2 failles < à 45°
Indice d'injectivité (m3/j/bar)	20.7	21	18.2	18.1
K (mD)	188	196	185	185
Skin	12.8	13.4	12.6	12.2
Distance à la faille 1 (m)	21	16	22	24
Distance à la faille 2 (m)	152	145	154	140

Flow Period #	6	Time match	1.1848E5 (day)-1
Rate	0 m3/day	Pressure Match	0.57801 (bar)-1
Rate Change	1512 m3/day	RESERVOIR	Homogeneous
P @ dt=0	332.67 bar	WELL	Storage & skin
Pi	259.82 bar	BOUNDARY	< faults
Smoothing	0.1	Storage C	0.007669 m3/bar
		CD	235
		Skin factor	12.825
		kh	6785.6 md.m
		K	188.49 md
		Mobility k/mu	471.22
		Angle (Deg)	60
		L1 sealing @	21.056 m
		L2 sealing @	151.95 m

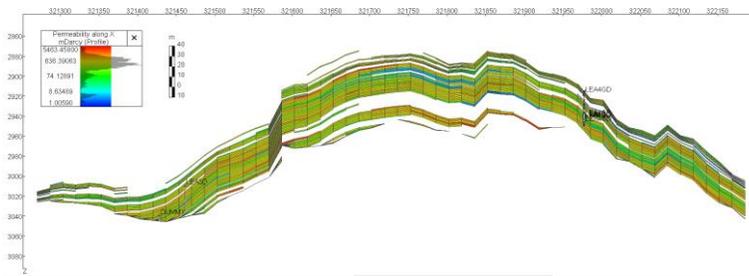
# LEA 2019 dynamic model settings

PETREL

TNAVIGATOR

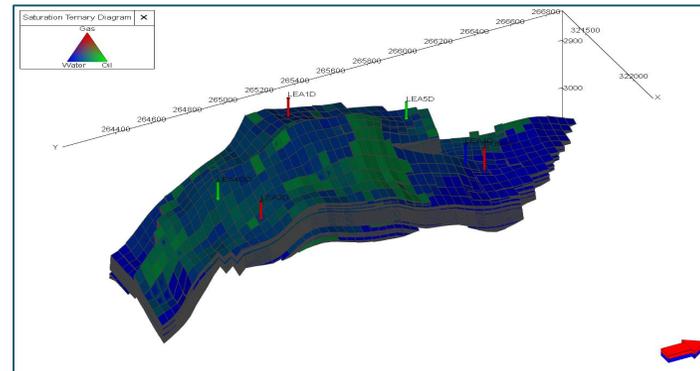
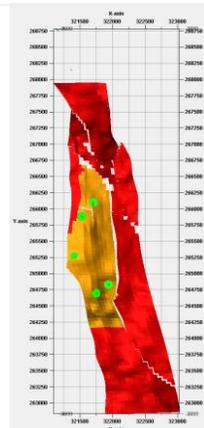
## Structure+Layering

Using available horizons and thicknesses  
Layers parallel to top with erosion from bottom



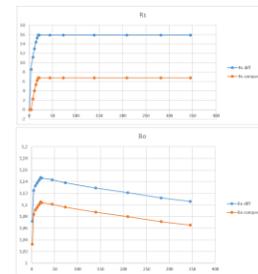
## Property modeling

Geostatistical approach using facies proportion maps, K/Phi laws,  $K_x=K_y=K_z$



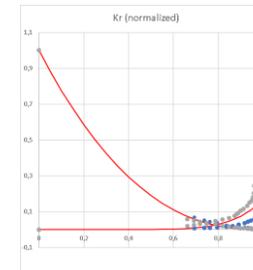
## PVT black oil

Composite BO  
PVT from LEA1  
RFT downhole sample



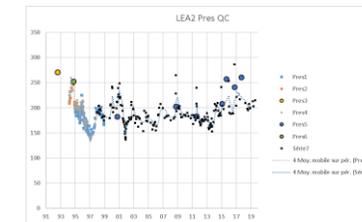
## KrPc

Kr from LEA4 core flood  
Swirr correlated from K  
Sorw using observed  
67% efficiency of displacement  
**No Pc**



## Production/Pressure data

Sporadic pressures at 3000 mTVDSS (RFT, SBHP surveys, static NEA)  
Production data from OFM

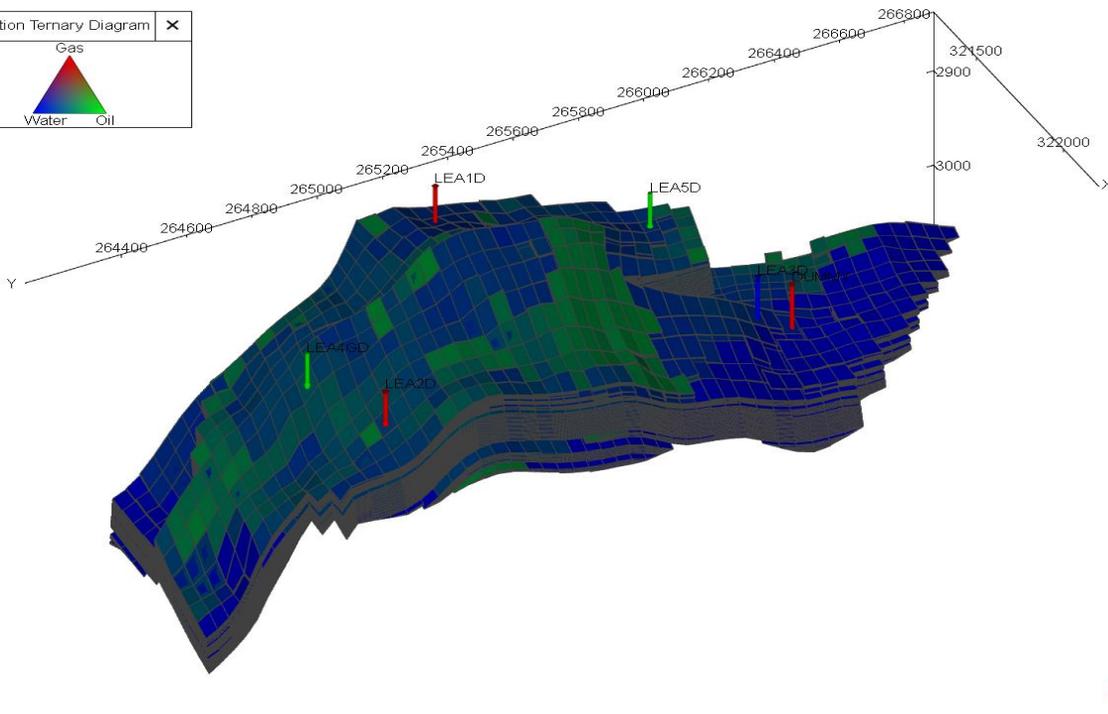
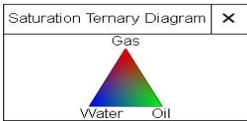
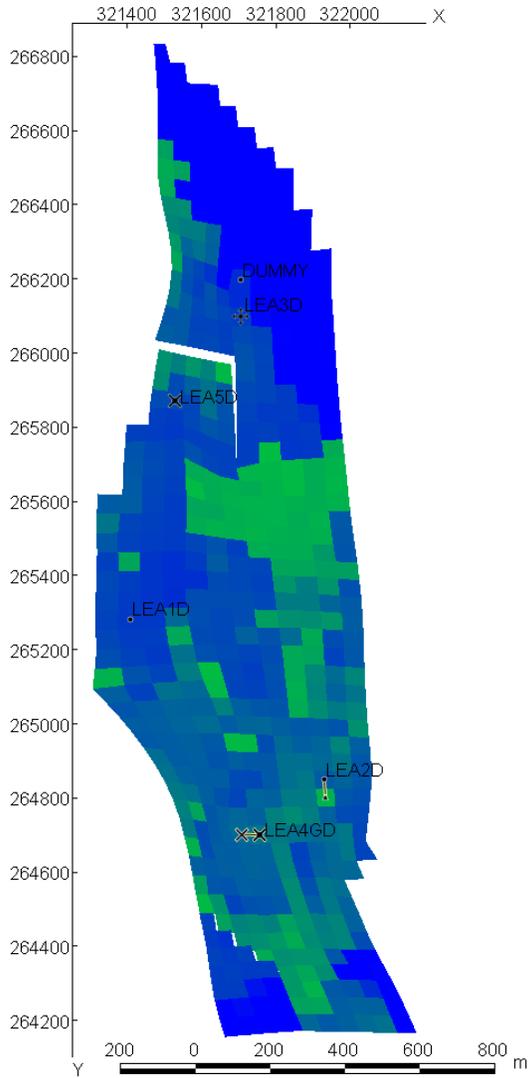


## Aquifer

No additional aquifer (small aquifer)

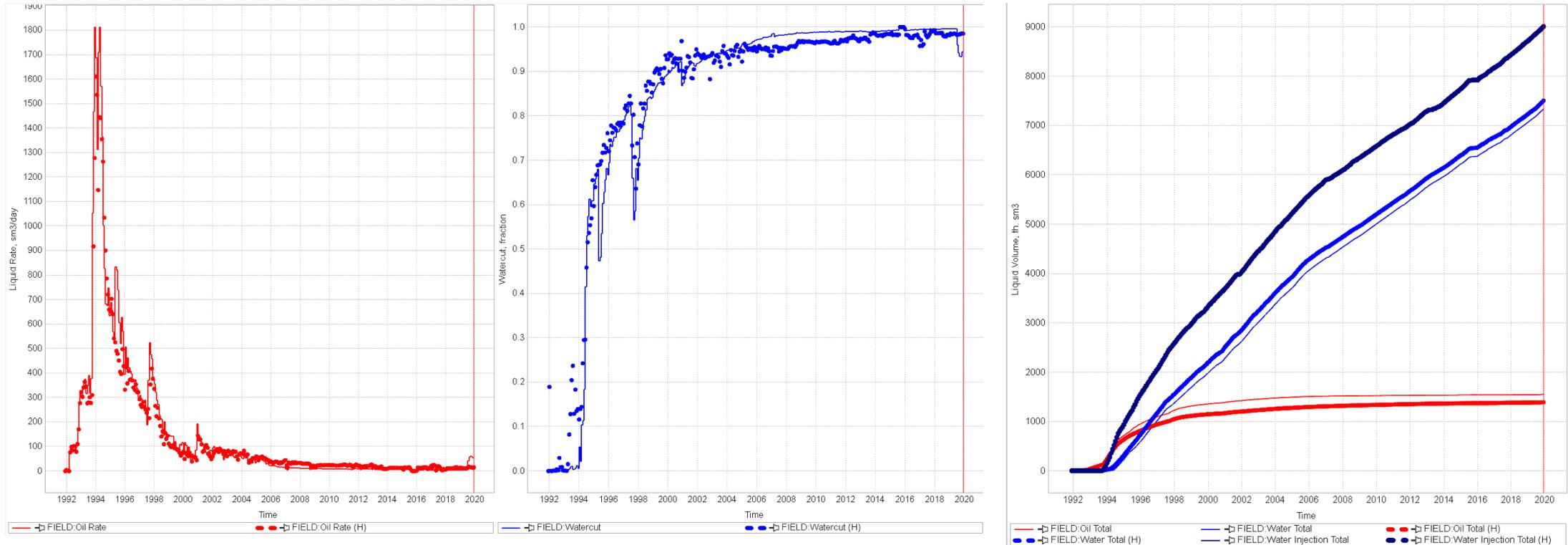
19x104x120=237 120 cells  
Keeping only the « center » of LEA + 0 perm. removed  
➔ 20 668 active cells

# LEA 2019 dynamic model initialization



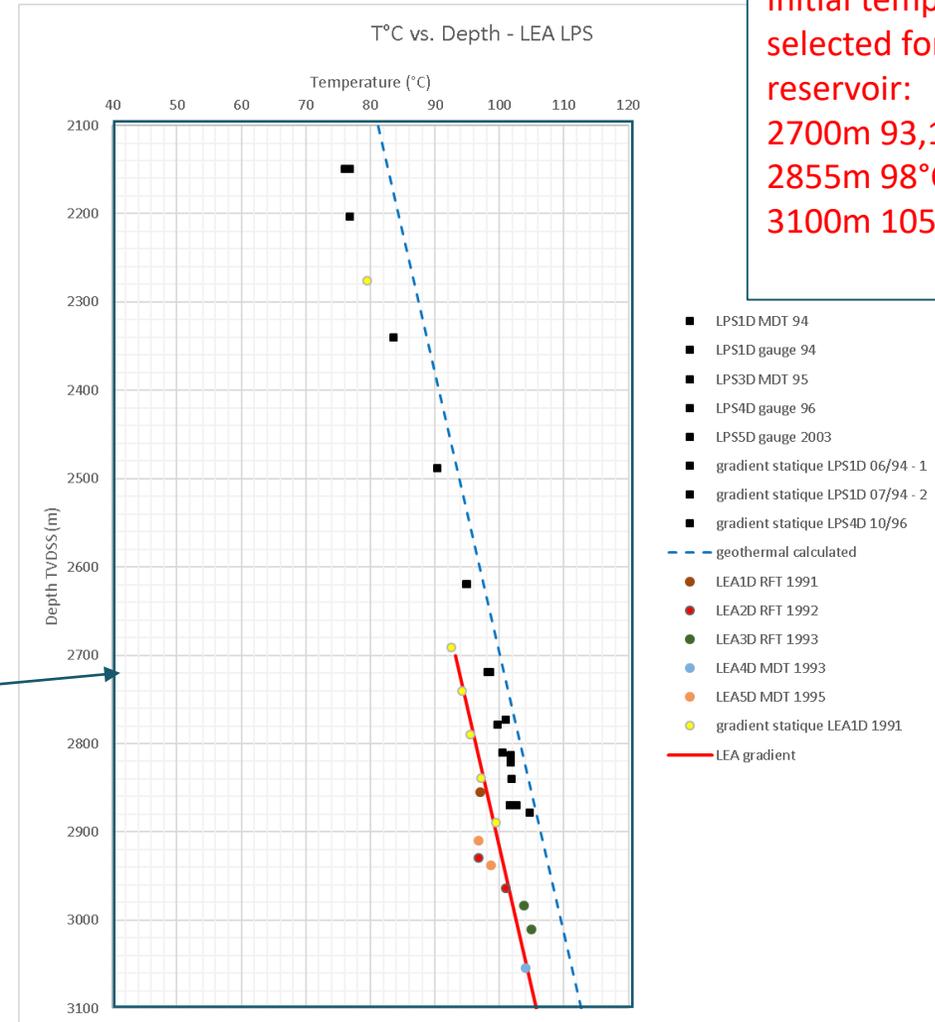
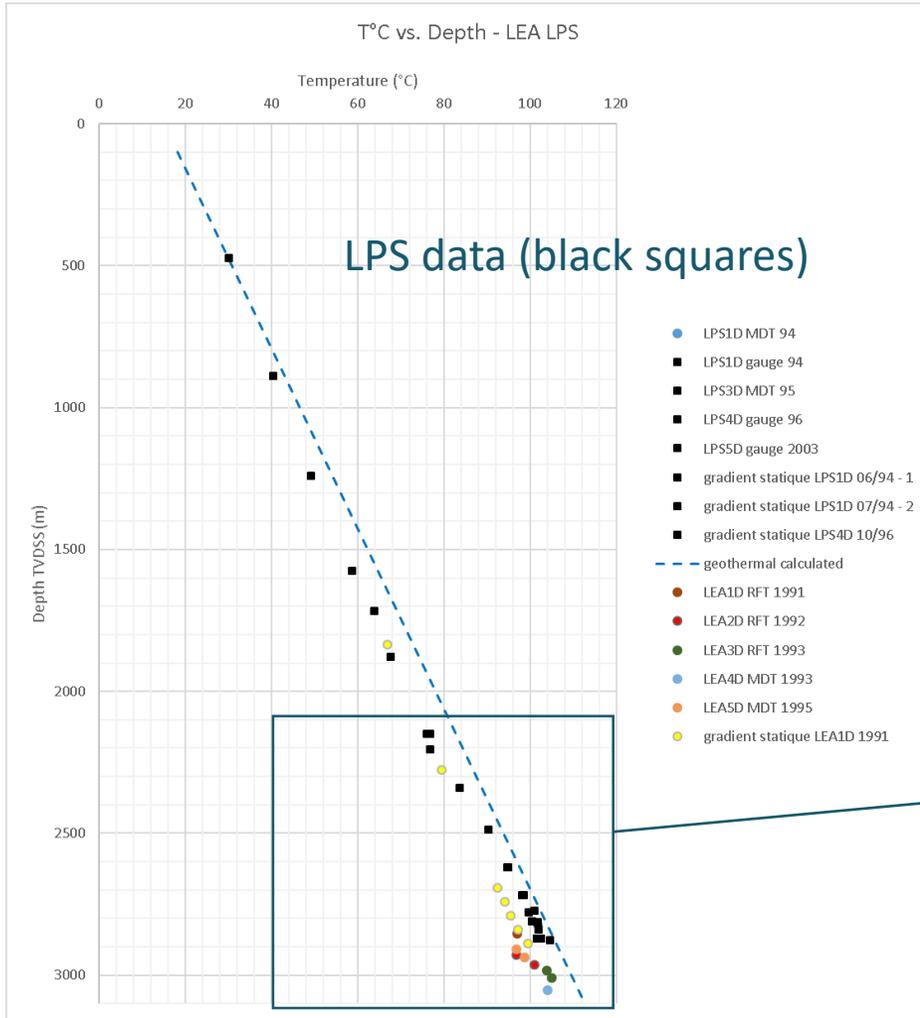
OWC: 3000 mTVDSS  
 GOC: no GOC  
 Pressure at OWC: 293 bars  
**STOIIP: 3003 Msm<sup>3</sup> (18.9 MMstb),**  
 WIIP: 3009 Msm<sup>3</sup> (18.9 MMstb)  
 GIIP (Dissolved): 22 MMsm<sup>3</sup> (777 MMscf)

# LEA Field History Match



Good Field HM

# LEA Initial reservoir temperature

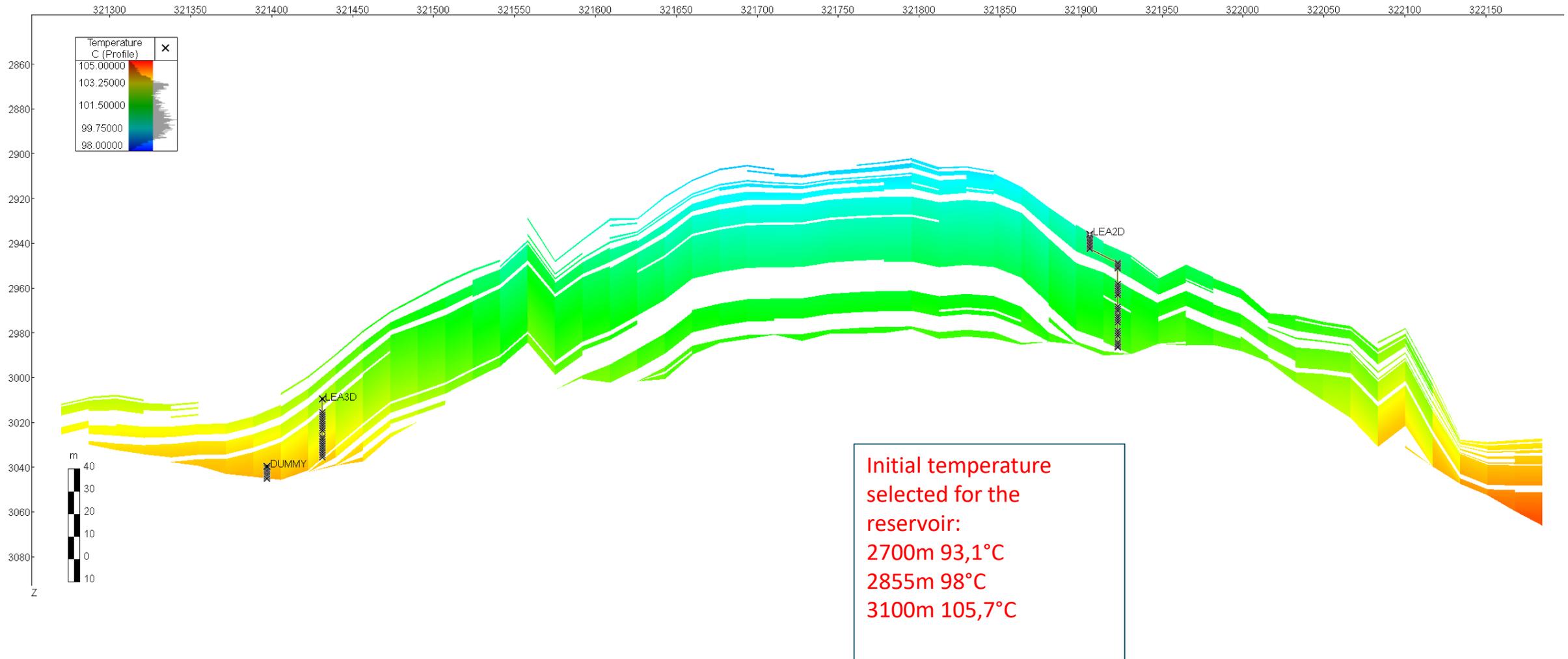


Initial temperature selected for the reservoir:

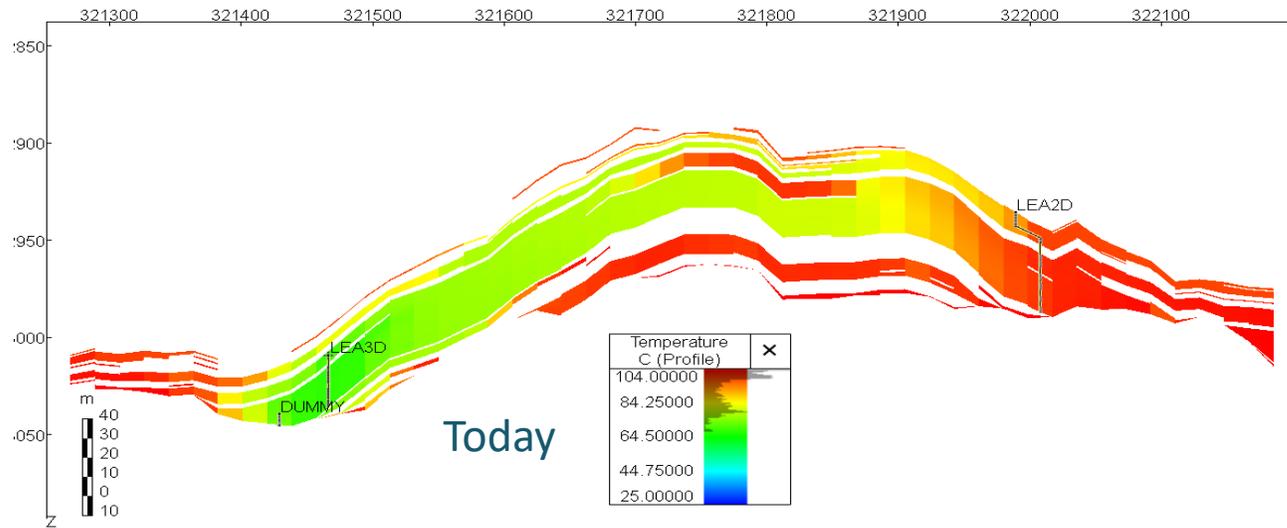
- 2700m 93,1°C
- 2855m 98°C
- 3100m 105,7°C

Temperature slightly below temperature calculated using regional geothermal gradient of 3,15°C/100m and slightly below LPS gradient in Purbeckian

# LEA Initial reservoir temperature



# LEA Base HM thermal simulation

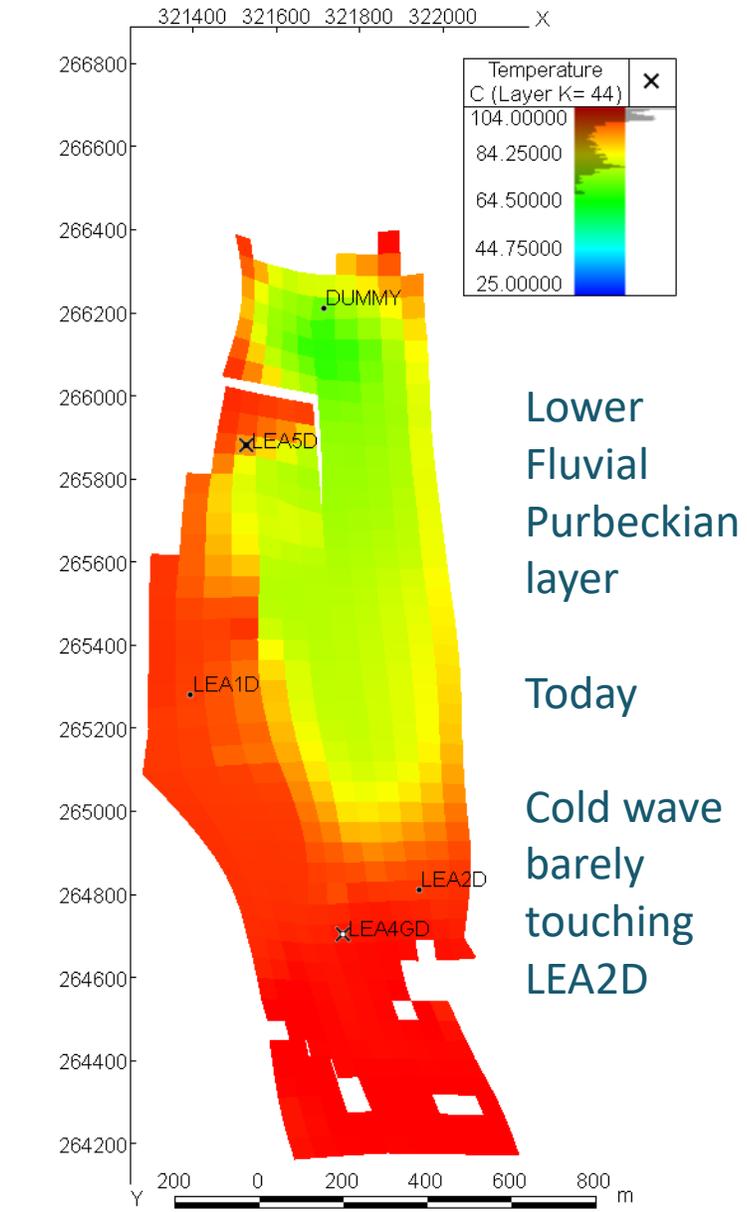


## Parameters:

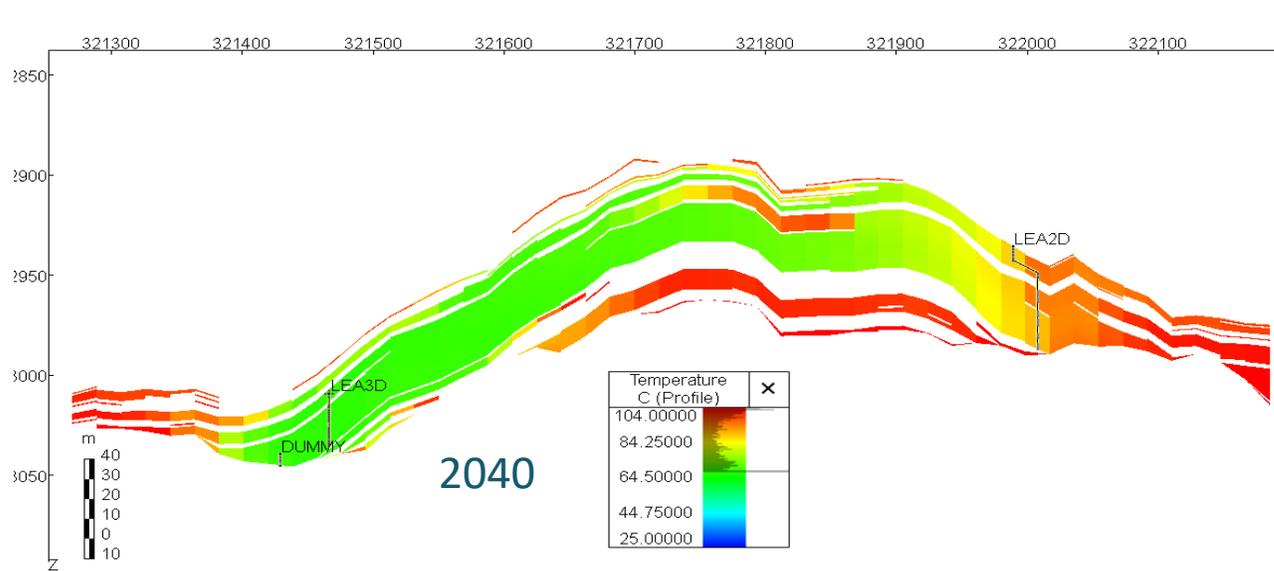
- initial Temperature gradient around 102°C
- Volume specific heat of oil, water, gas: 2,22, 3,97, 2,13 KJ/kg/°C
- Volume specific heat of rock: 2000 KJ/rm3/°C
- Rock thermal conductivity: 258 kJ/m/day/C

## Assumptions:

- Boundary conditions
- Dead cells participating to heat
- Injected temperature based on source water proportion

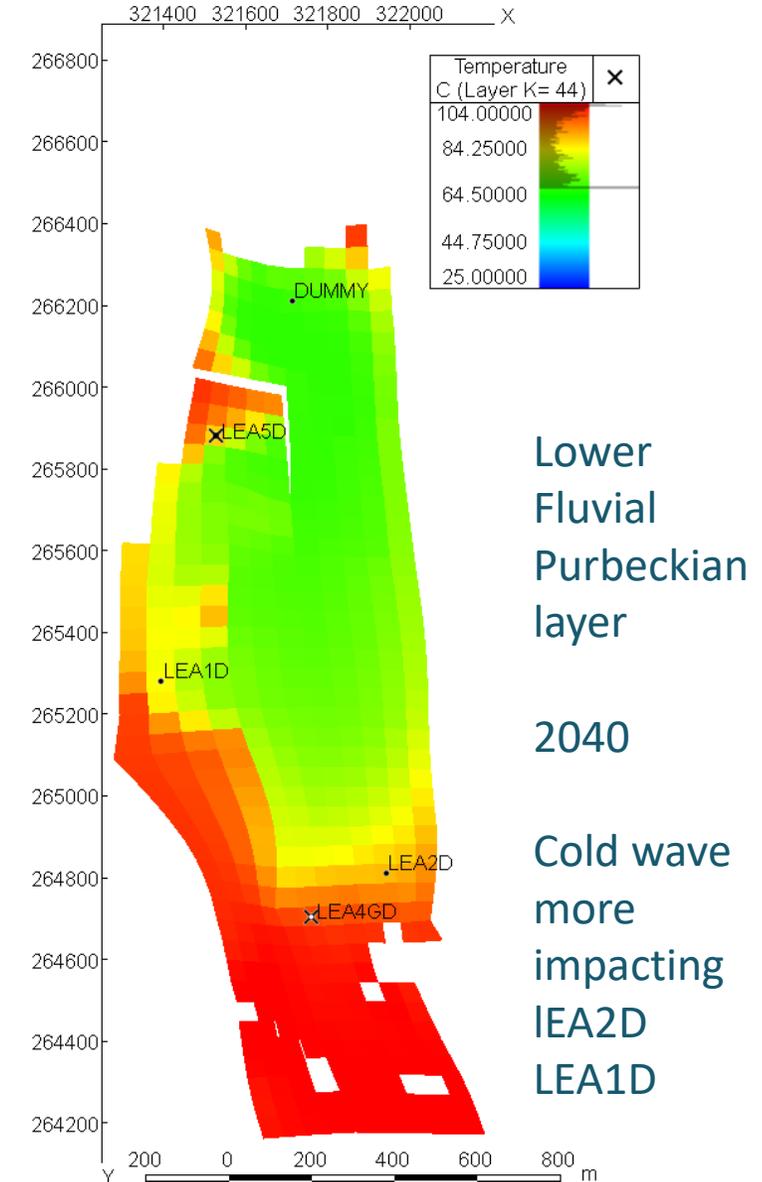


# LEA Base Forecast thermal simulation



## Settings:

- LPS1D converted to injection (increased LPS/LEA water prod capacity)
- Producing wells controlled by Min BHP
  - LEA1D: max liquid rate: 600 m<sup>3</sup>/d
  - LEA2D: max liquid rate: 600 m<sup>3</sup>/d
- LEA3D injection defined by VRR=1 (max rate 1200 m<sup>3</sup>/d)
- Temperature of injected water including HEX project in LEA (68°C instead of 76°C)



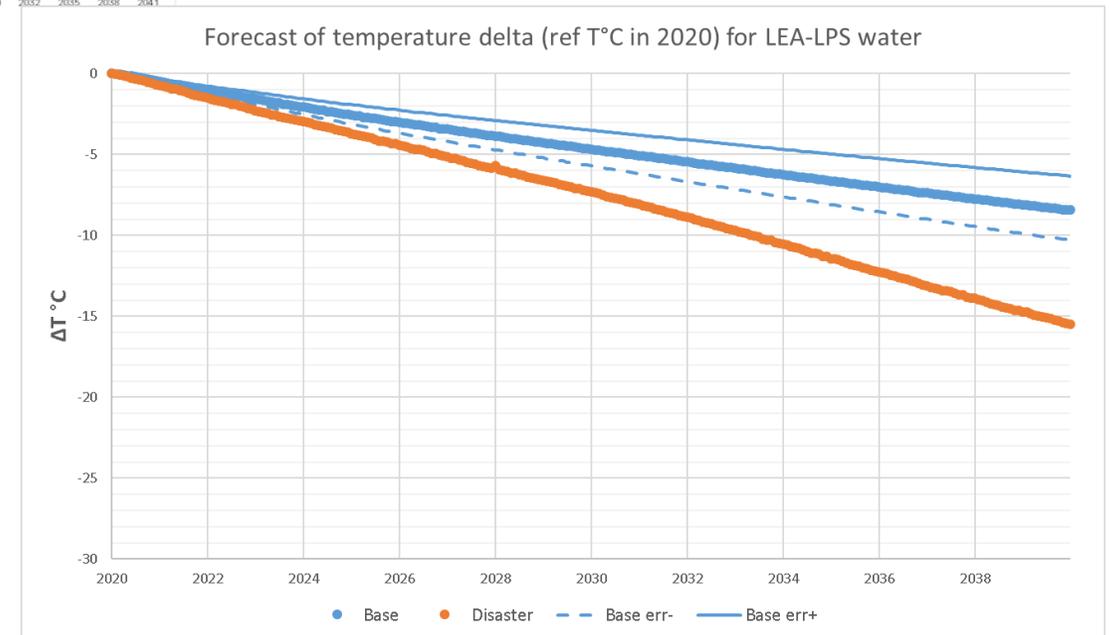
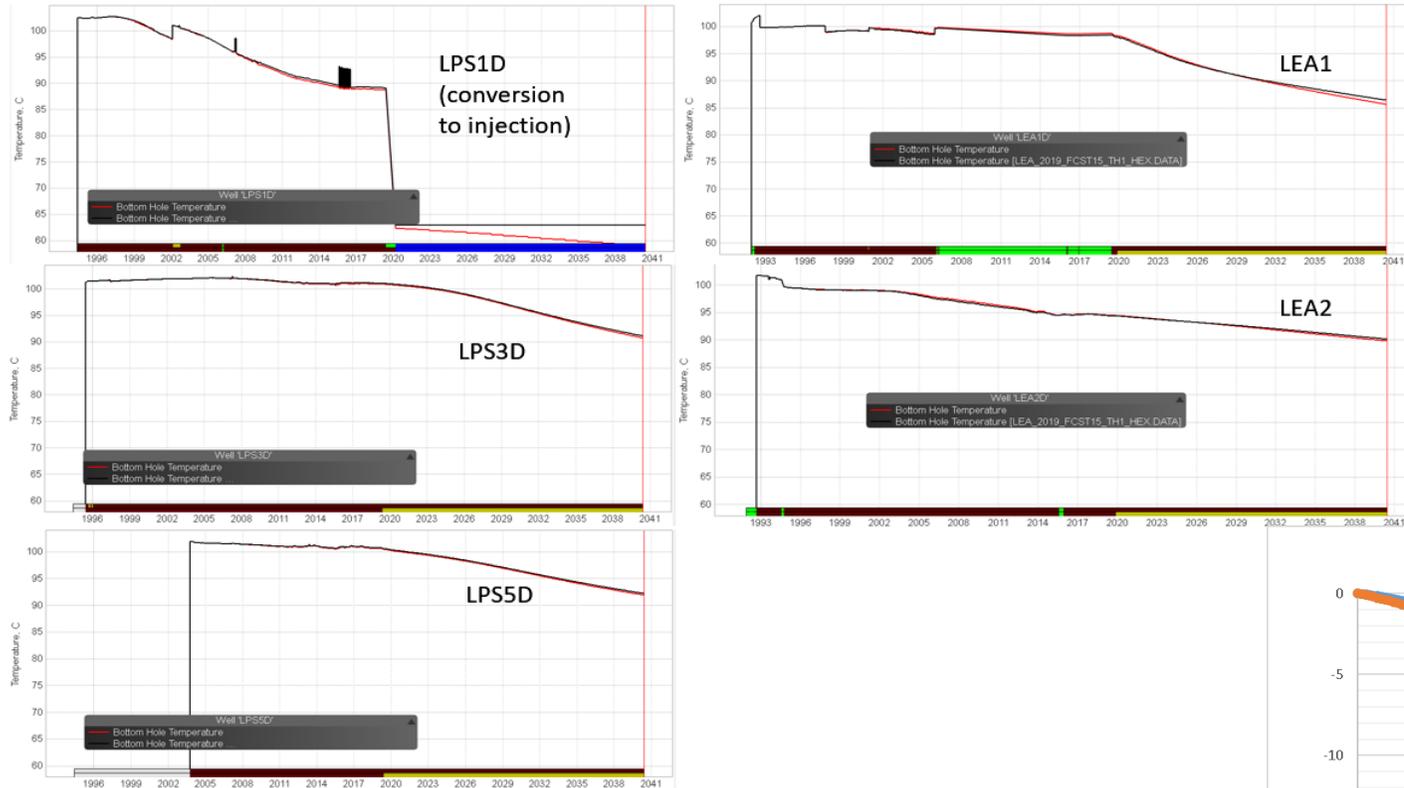
Lower  
Fluvial  
Purbeckian  
layer

2040

Cold wave  
more  
impacting  
LEA2D  
LEA1D

Les Pins / Les  
Arbousiers  
combined results

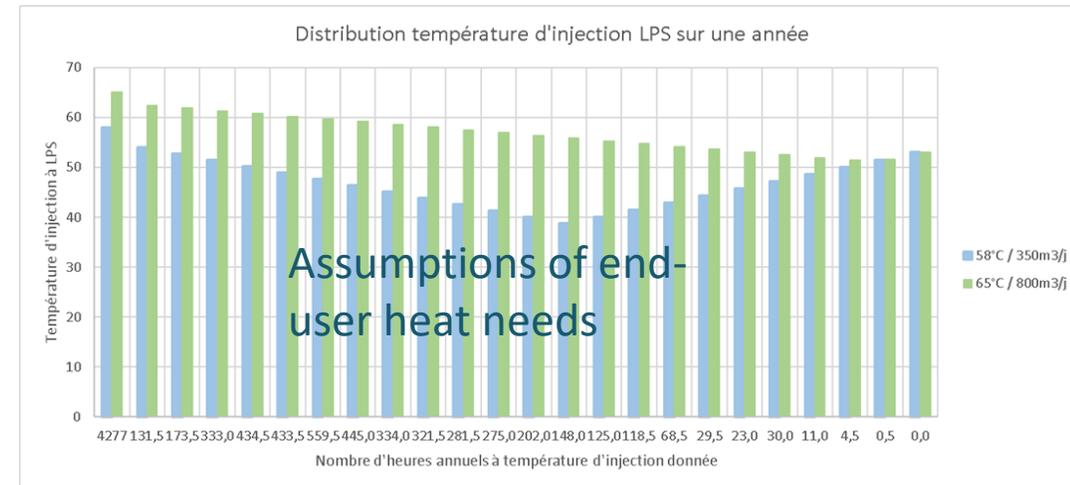
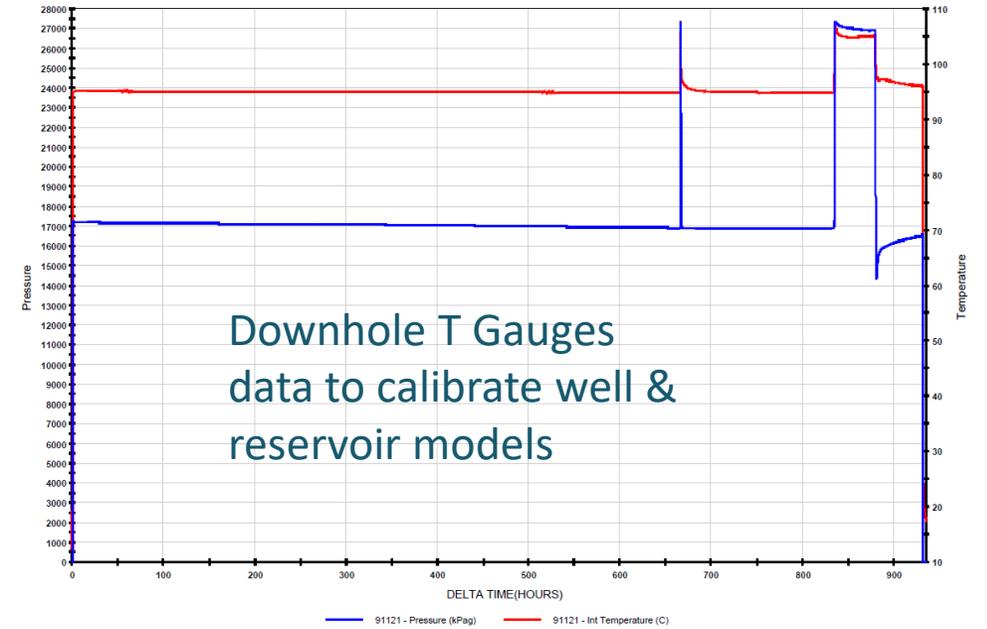
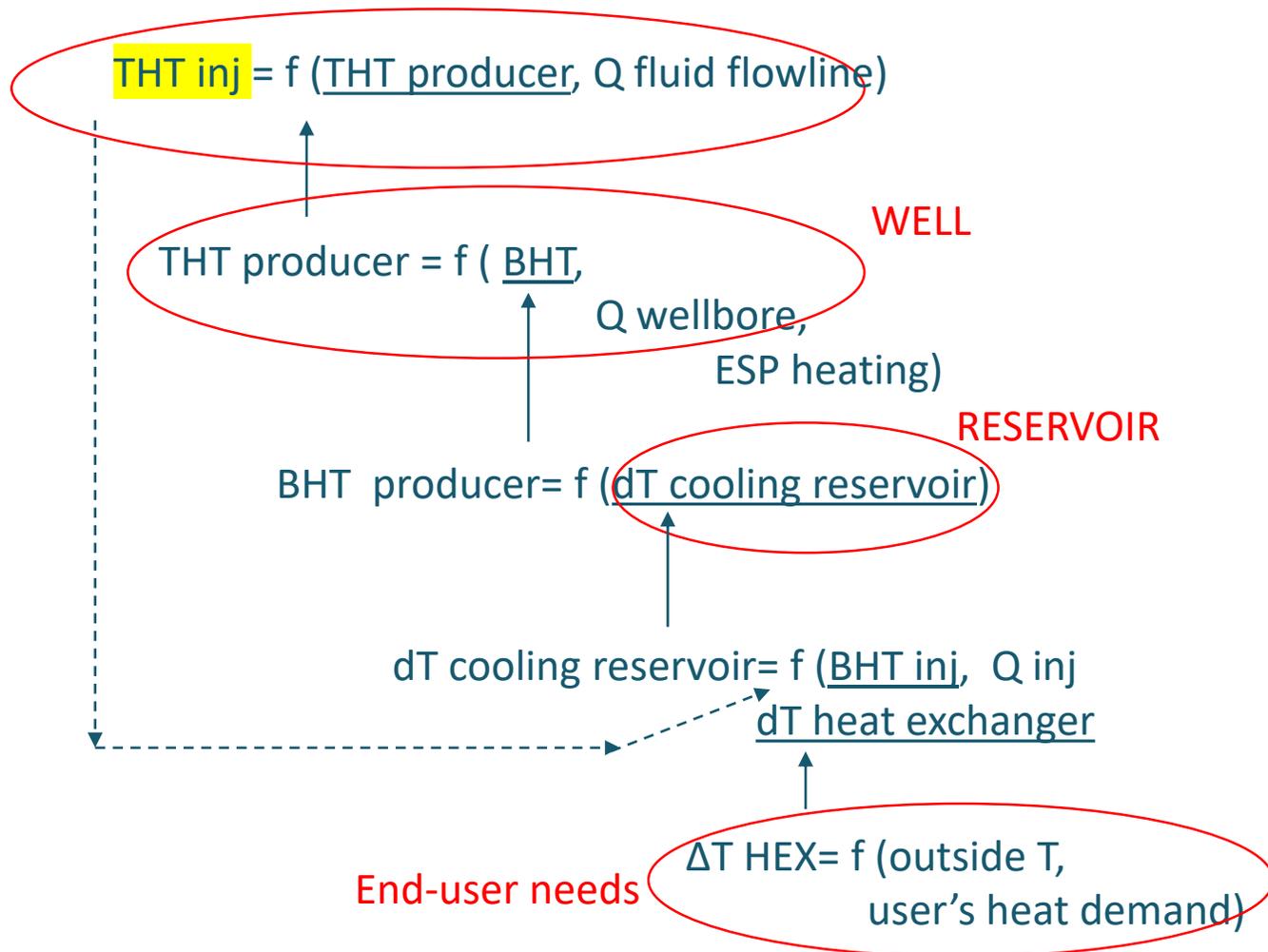
# Downhole T impact for LEA/LPS



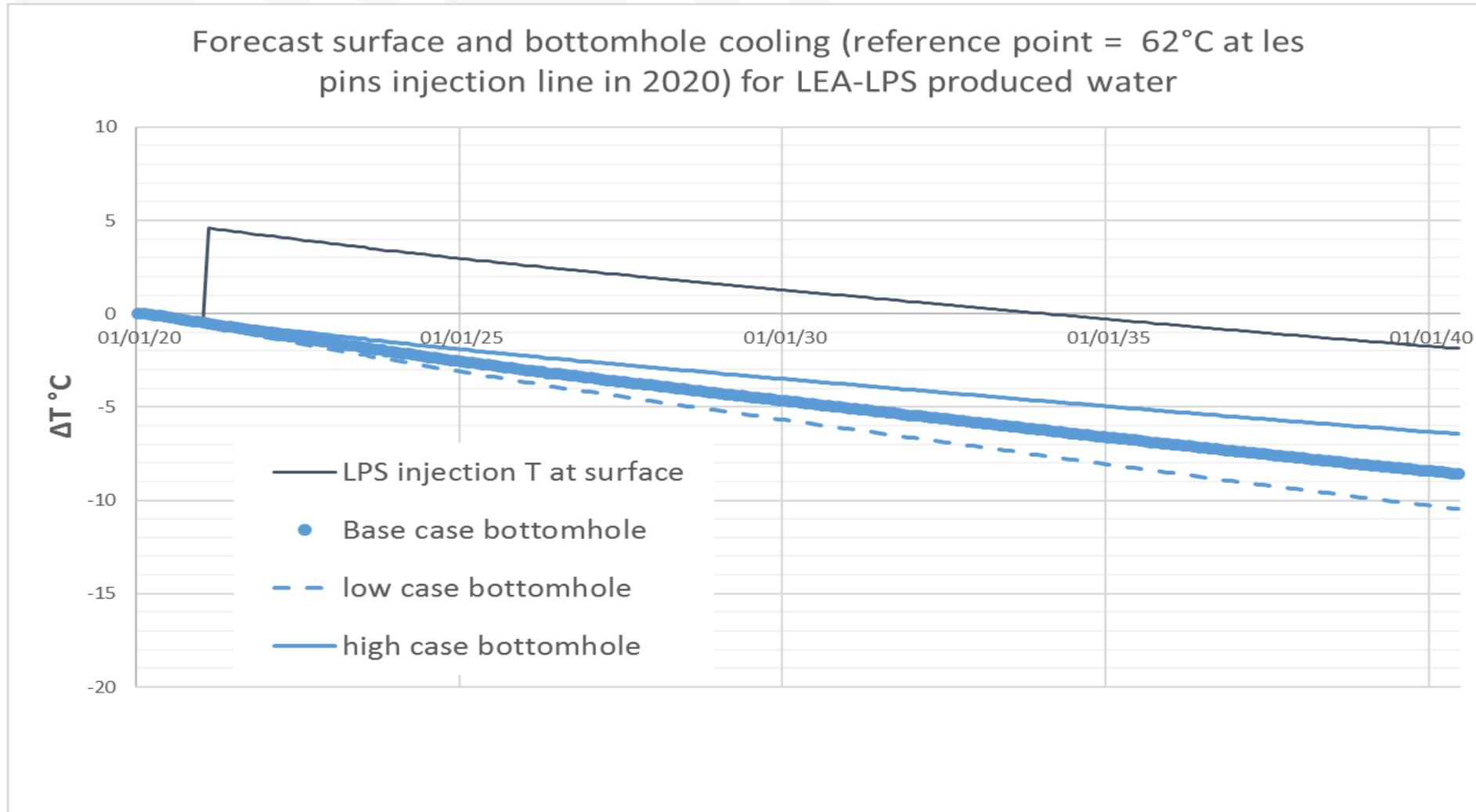
Not included:

- ESP heating
- Reduce surface losses (higher rate = higher velocity)
- Thermal behavior of well (T downhole -> surface)

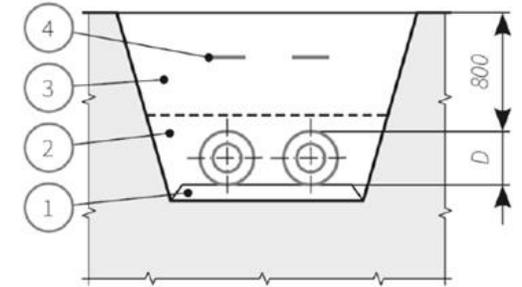
# Downhole to surface loop



# T forecast & impact on project



# Project summary & way forward



- 1/ Lit de sable
- 2/ Sable compacté 0-3/4 mm
- 3/ Terre de remblais
- 4/ Grillage avertisseur



- Field work scheduled June 2021 (awaiting forestry service green light)
- Heat delivered 01/10/2021 for 20 year
- >90% heat covered
- CO2 avoided 200 t/year



# Take-away messages

- Onshore mature oilfields can produce large volumes of hot brine
- Heat can be valorised at reinjection site when a end-user is identified nearby, or brought in **provided you are ready to get involved with local stakeholders**
- Vermilion has demonstrated feasibility at very different scales: from 0.4 to 10 MW of heat capacity
- Key uncertainties from the producer perspective : unlike large open aquifer, oil field are small closed structure hence the need to study « cold front » & well interferences
- Existing O&G tools and models can be re-used to predict long-term geothermal resources
- Key risk from the user perspective: geothermal heat long-term availability is dependant on BRENT price and oil field economics
- Impact on oilfield facilities & exploitation is minimal
- Oil revenues >> heat revenues, conversion to geothermal is hindered by electrical O&M in depleted oilfields (deep submersible pumps)

# Thank you very much for your attention

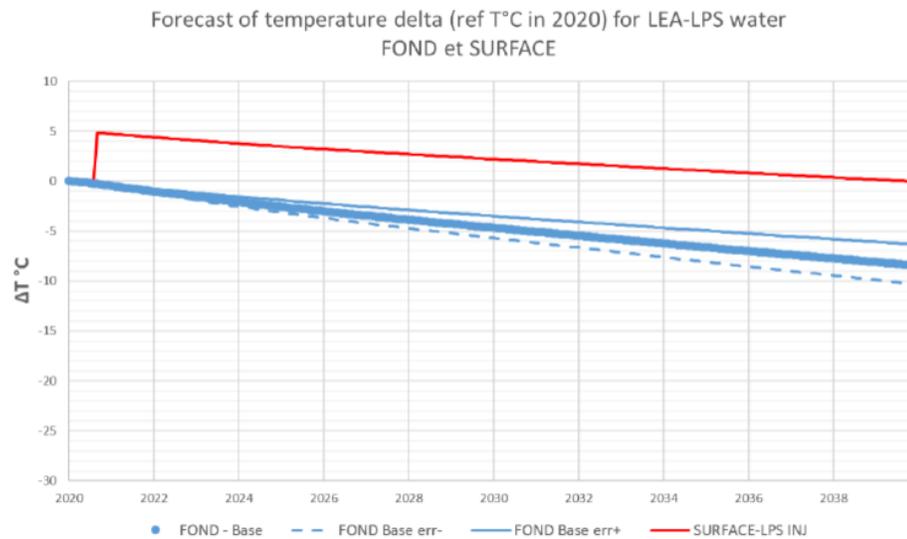


*This work was performed in the framework of the H2020 MEET EU project which has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 792037*

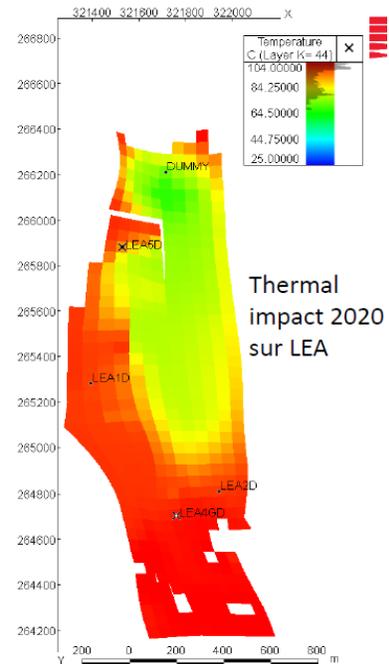


# Etude de faisabilité 2019/2020

- Modélisation de la prévision de température en surface et dans le gisement
- Prise en compte des besoins journaliers du lycée
- Taux de couverture > 93%
- CO<sub>2</sub> évité = 190 t/an



Prédictions de température en surface



Carte de l'impact thermique dans le gisement

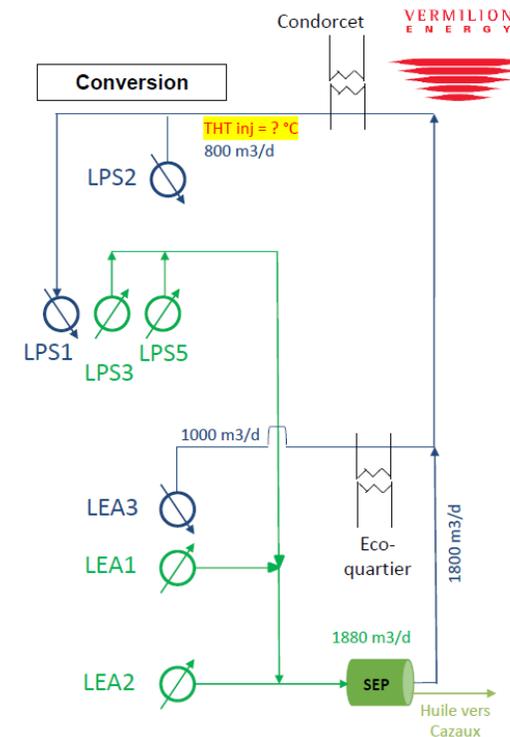
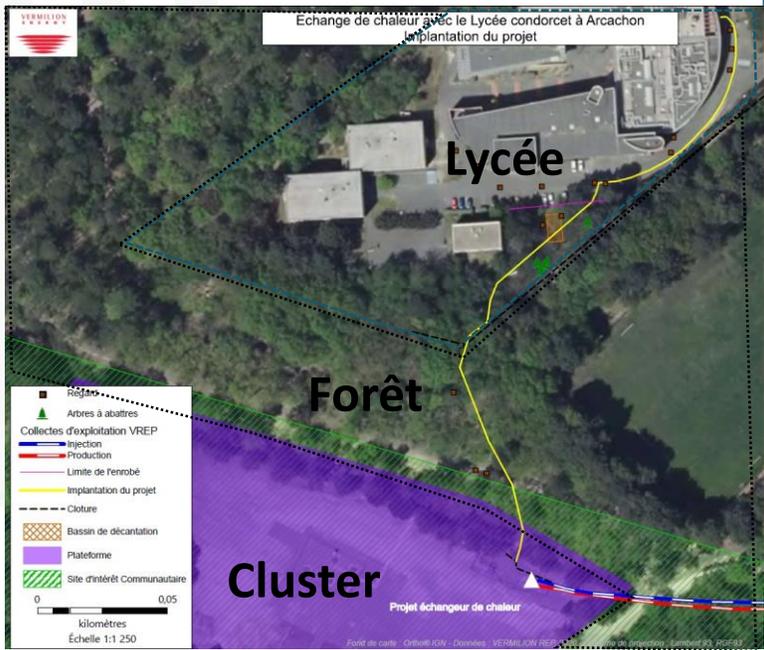


Schéma du process pétrolier en surface

# Non-technical risks (1/2)

## Stakeholder alignment

- 300 m of pipes =
- 2 public field owners
- 2 oil partners
- 1 end-user
- 1 building owner
- 2 regulatory services



	Lycée	Forêt	Cluster
Propriétaire	COBAS	Mairie Arcachon	VET
1) Autorisation travaux	Reçu le 23/07 Vote conseil Communautaire le 17/12	Vote C.M le 22/10/2020	na
2) Contrat de servitude	Vote conseil Communautaire le 17/12		na
3) Accord propriétaire pour déposer dossier DDTM	Reçu 9/09 Vote conseil Communautaire le 17/12		na
4 a) Autorisation défrichement par DDTM forêt	na	Dossier envoyé le 02/11, réponse attendue . <u>Pas officiellement commencé. Réponse attendue pour mi janvier au mieux</u>	na
4 b) Confirmation pas d'impact notable par DDTM natura2000	na		na
5) Lettre d'entente avec IPC	Signée 7/06		
6) vote CA lycée Condorcet	30/11 vote favorable		
7) Contrat de vente avec Région NA	Mandat donné à Président Région par vote en commission le 17/07		

# Non-technical risks (2/2)

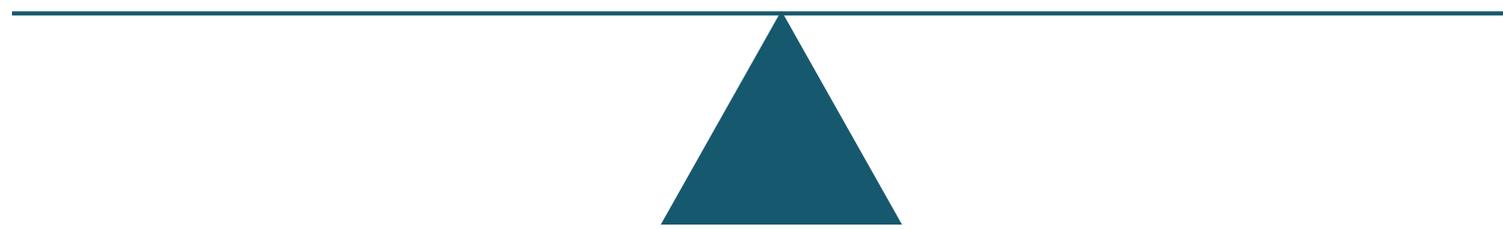
## Risk allocation in contract

### End-user:

- Wants to minimise its CO2 impact
- Wants heat delivery commitments in the long term
- Needs enough geothermal coverage per year to pay back its investment
- Wants a heat price < gas price

### Heat provider:

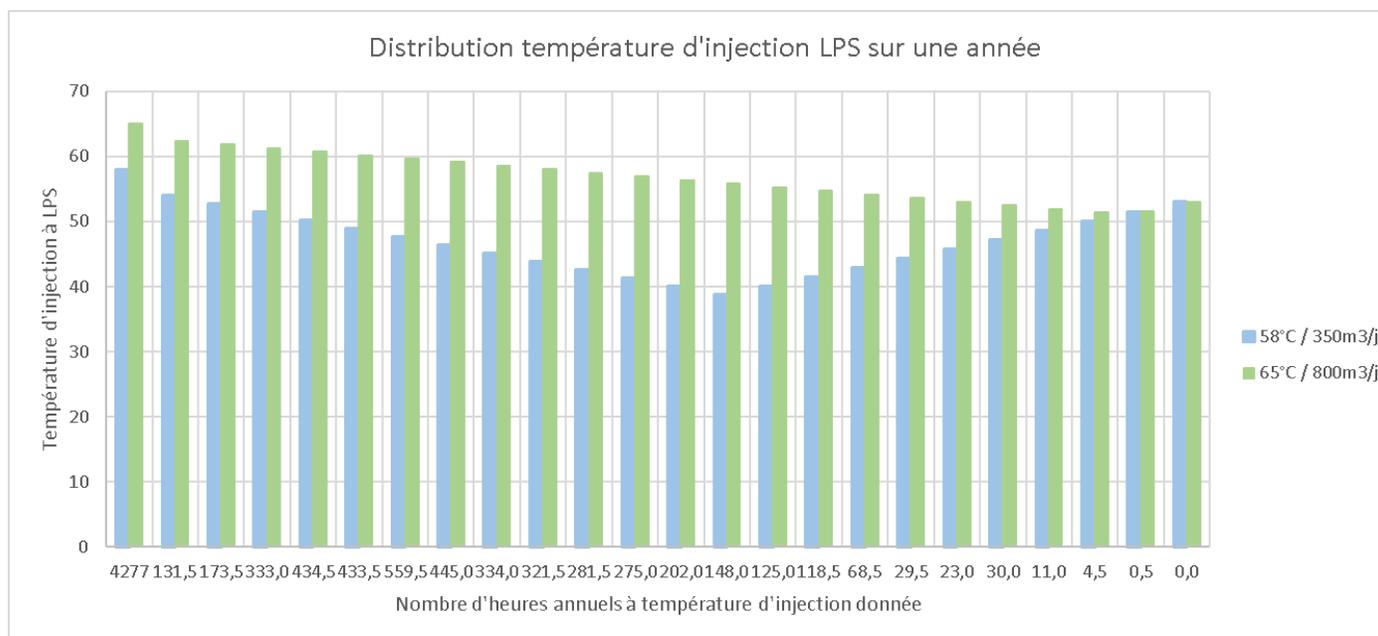
- Do not wants heat delivery commitments (no impact to oil)
- Needs to maximise uptime for oil and water
- Wants heat revenues to cover heat-delivery Capex and O&M
- Cannot guarantee 20 years of concession (renewal processes)
- Cannot predict oil price hence field end of life



# Distribution annuelle de la température d'injection après fourniture chaleur chauffage Condorcet – prédiction

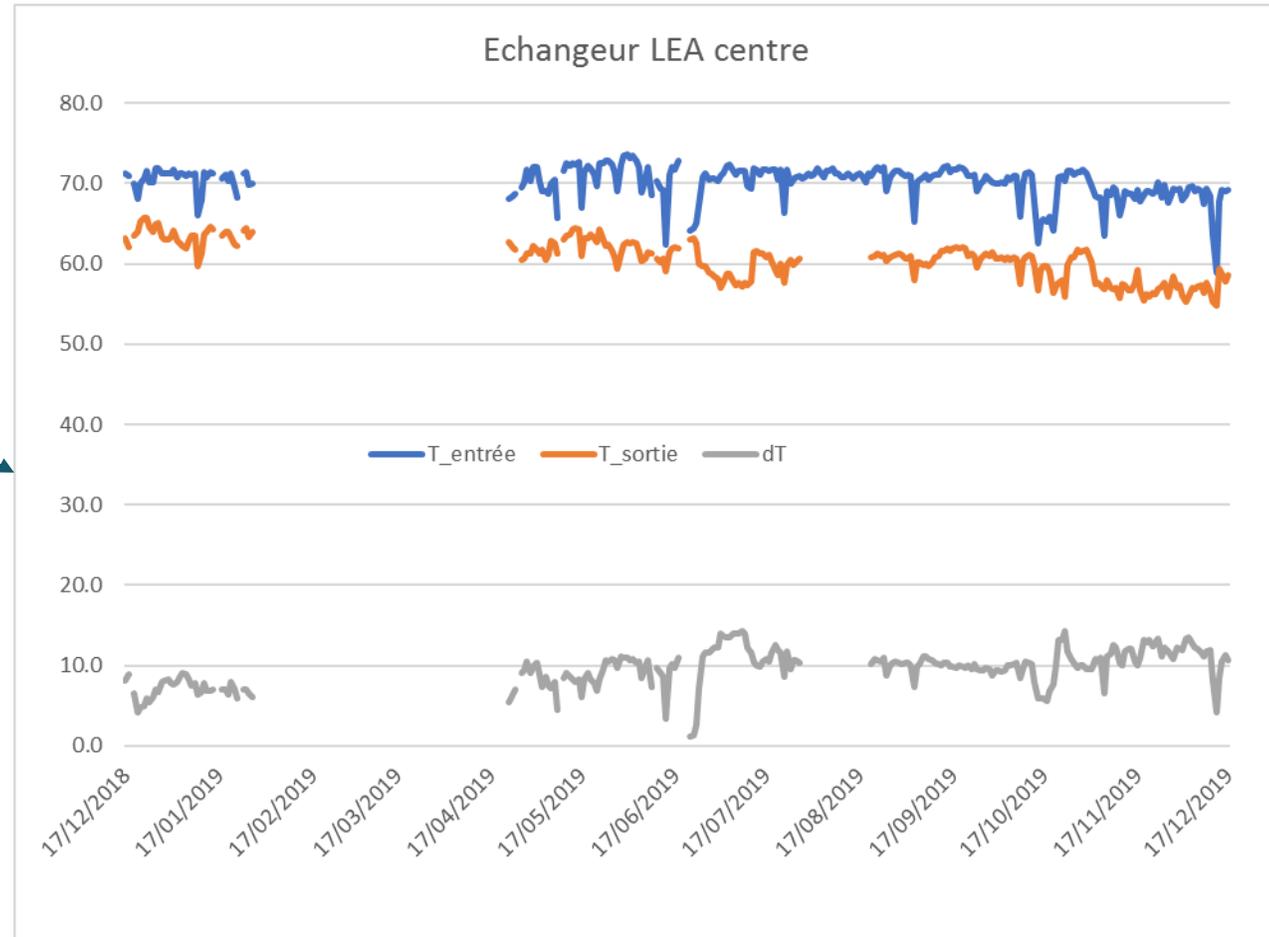
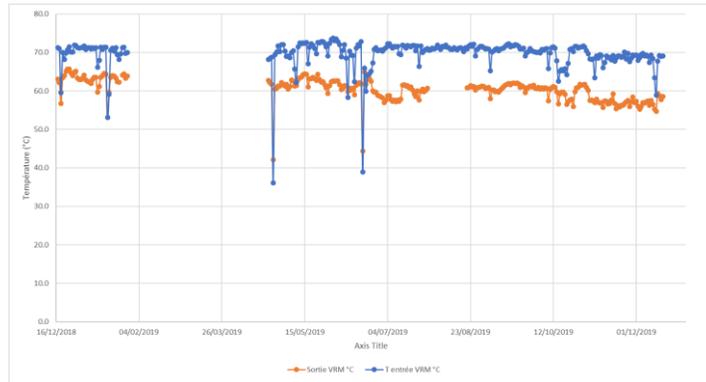
Principe: On chauffe quand  $T^{\circ} \text{ ext} > 17^{\circ}\text{C}$   
 Plus  $T \text{ ext}$  faible, plus on chauffe -> échange thermique plus important à l'échangeur

	T_in_VET	°C	58	65
	Q_in_VET	m3/j	350	800
T_ext	# heures	T_injn=T_o	T_inj=T_o	
°C		°C	°C	
$T_{\text{ext}} > 17^{\circ}\text{C}$	> 17	4277	58	65
$16^{\circ}\text{C} \leq T_{\text{ext}} < 17^{\circ}\text{C}$	17	131,5	54,0	62,4
$15^{\circ}\text{C} \leq T_{\text{ext}} < 16^{\circ}\text{C}$	16	173,5	52,7	61,8
	15	333,0	51,5	61,3
	14	434,5	50,2	60,7
	13	433,5	48,9	60,2
	12	559,5	47,7	59,6
etc	11	445,0	46,4	59,1
	10	334,0	45,1	58,5
	9	321,5	43,9	58,0
	8	281,5	42,6	57,4
	7	275,0	41,4	56,9
	6	202,0	40,1	56,3
	5	148,0	38,8	55,8
	4	125,0	40,1	55,2
	3	118,5	41,5	54,7
	2	68,5	42,9	54,1
	1	29,5	44,3	53,6
	0	23,0	45,7	53,0
	-1	30,0	47,1	52,5
	-2	11,0	48,6	51,9
$-4^{\circ}\text{C} \leq T_{\text{ext}} < -3^{\circ}\text{C}$	-3	4,5	50,0	51,4
$-5^{\circ}\text{C} \leq T_{\text{ext}} < -4^{\circ}\text{C}$	-4	0,5	51,5	51,5
$T_{\text{ext}} < -5^{\circ}\text{C}$	-5	0,0	53,0	53,0



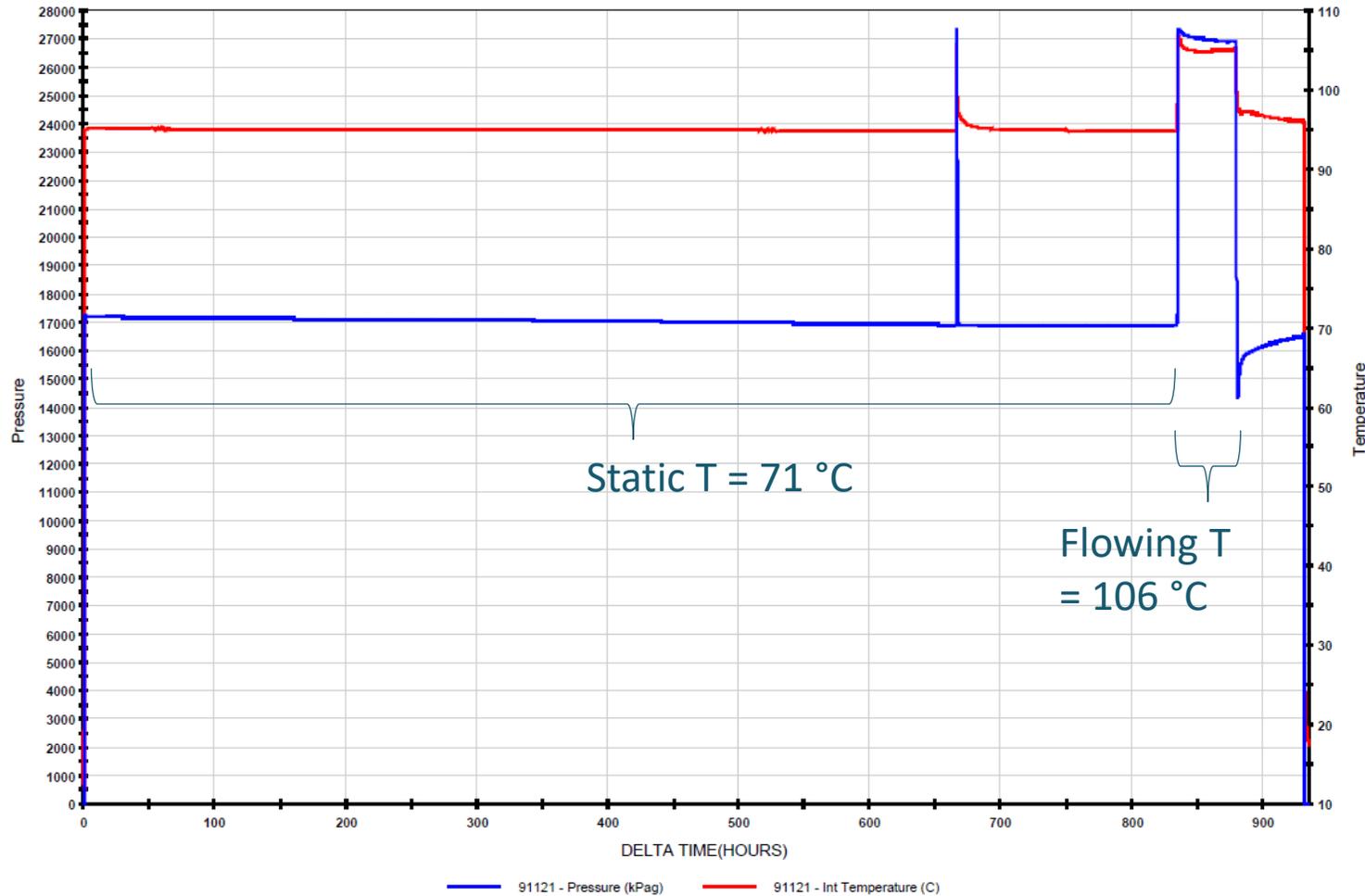
Conclusion:  
 dT moyen de l'échangeur LPS sur une année: **7.3°C à 350 m3/j**  
**3.2 °C à 800 m3/j**

# Distribution annuelle de la température d'injection après fourniture chauffage + Eau Chaude Sanitaire Eco-quartier – données réelles



Conclusion:  
dT moyen de l'échangeur LEA sur une année: **9.6°C**  
~ constant sur l'année cause ECS  
> dT prévu sur LPS car chauffage + ECS

# LPS1 T gauge: conclusion

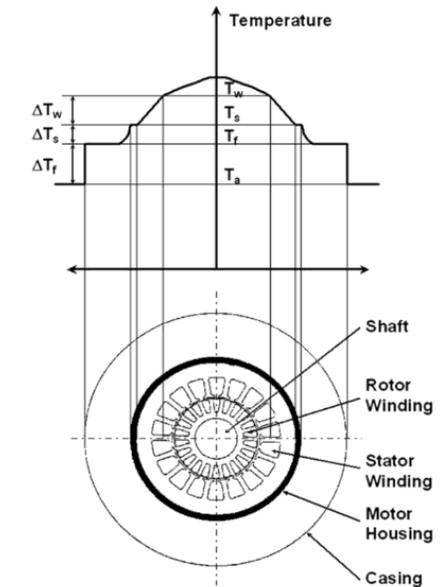


	Depth, msol	Depth, mv
Jauge	2942	2581
PCI intake	2962 (+20m)	2600 (+19m)
Top perf	3190 (+248 m)	2821 (+240m)

- Static T of 71°C is not representative of reservoir fluid
- Static T corrected to top perf gives 79°C but likely lower than actual because of convection effect in well (higher thermal losses)
- Flowing T > initial T of 102°C at top perf : likely impact of motor heating with dT of up to 10 -20 °C (cf. pump design)
- **Model prediction of 89°C is realistic although it cannot be checked accurately**

# LPS1 T gauge: ESP heating

	LPS1	LPS3	LPS5	LEA2	LEA2
ESP depth (md/mv)	2962/260 8	3089 /2533	3320 / 2715	2017/186 9	2220/21 29
Top perf (md/md)	3198/282 9	3367 / 2790	3430 / 2819	3118/287 9	3051/29 49
Distance (md/mv)	260/221	278 / 258	110/104	1101/101 0	831/ 820
Fluid rate (m3/d)	125	80	400	466	380
$\Delta T_s$ design	9°C	7°C		1°C	1°C
$\Delta T_w$ design	20°C	13°C		13°C	27°C



$$T_s = T_a + \Delta T_f + \Delta T_s$$

where

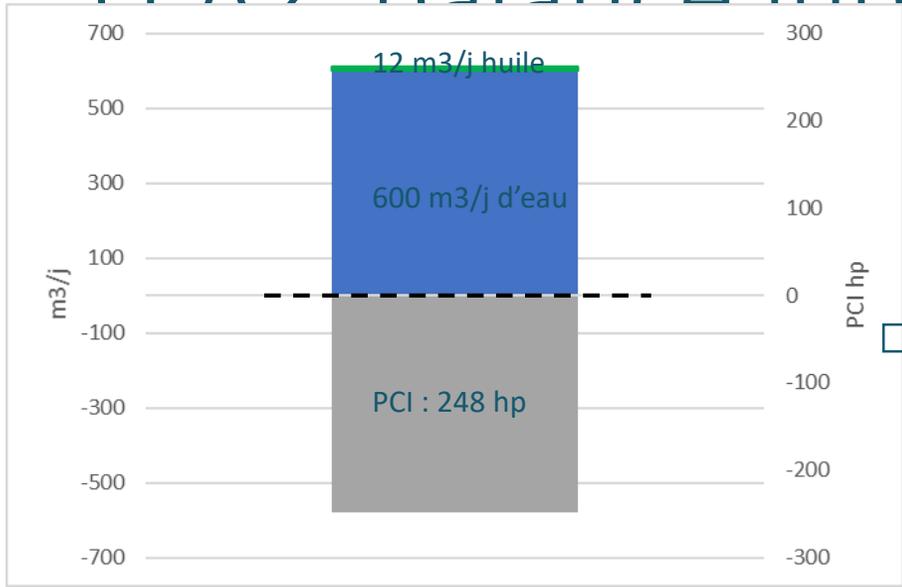
$T_s$  = motor skin temperature, °F

$T_a$  = ambient (geothermal) temperature in the annulus, °F

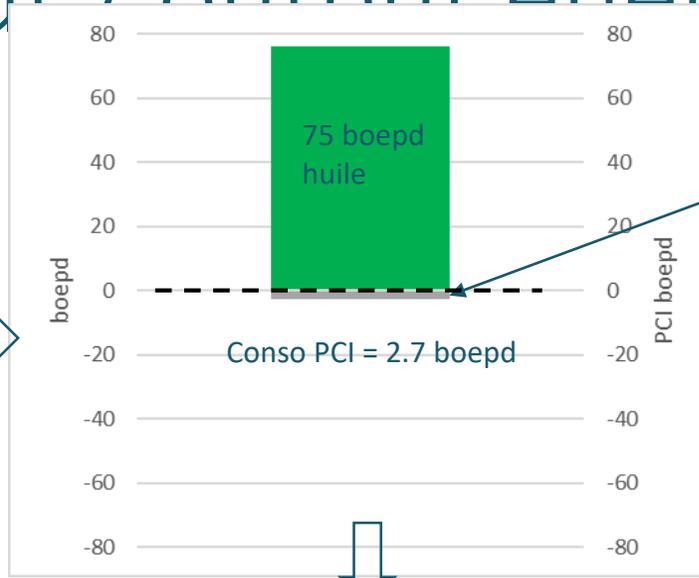
$\Delta T_f$  = temperature rise in the fluid, °F

$\Delta T_s$  = skin temperature rise on motor housing, °F.

# IEA2 balance input / output energie

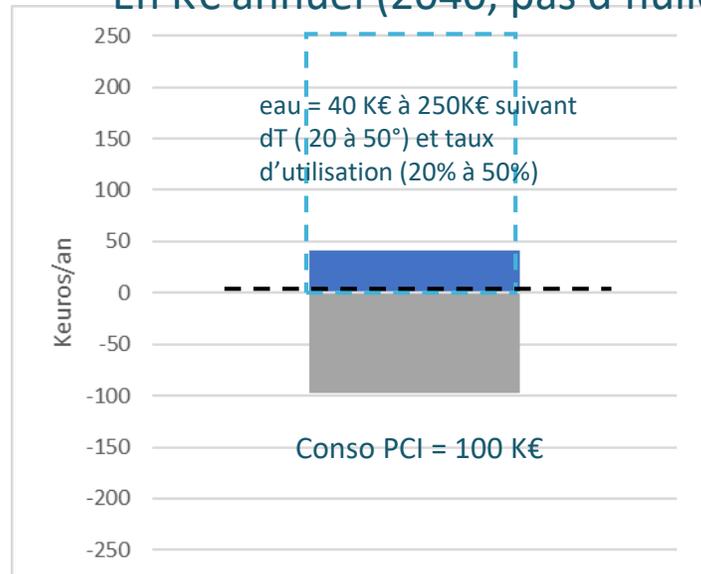


En équivalent barril d'huile

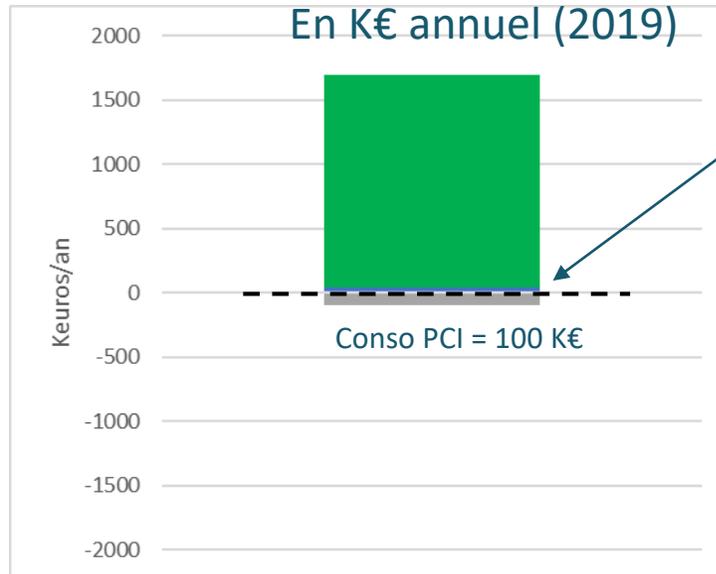


eau = 0.3 à 1 boepd suivant dT

En K€ annuel (2040, pas d'huile)



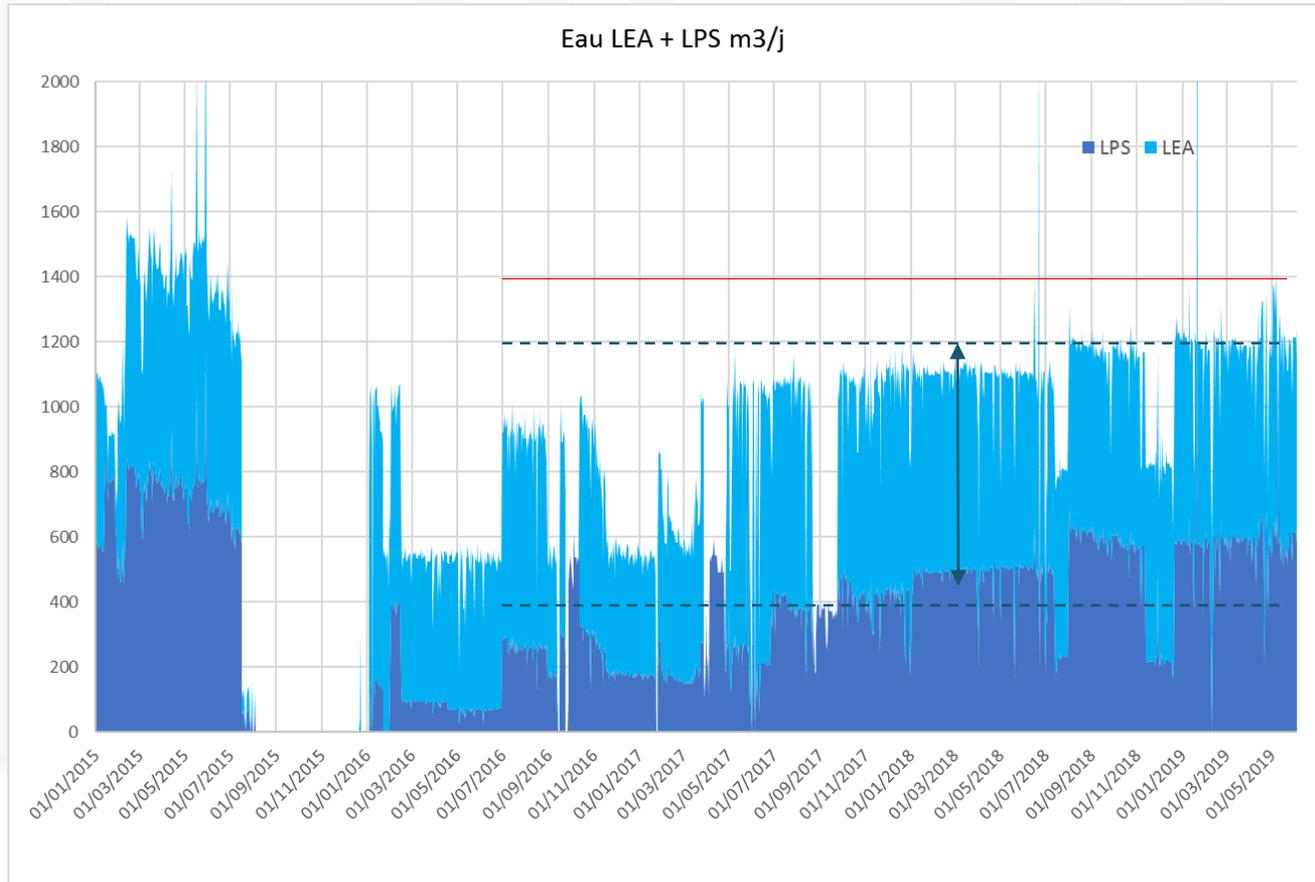
En K€ annuel (2019)



eau = 40 K€ à 250K€ suivant dT et taux d'utilisation

1 barril	1628.2 Kwh	
1 hp	0.75 Kwh	
Mwh	40 euro	chaleur
1 boepd	60 euros	
load	20%	
Mwh	60 euros	elec

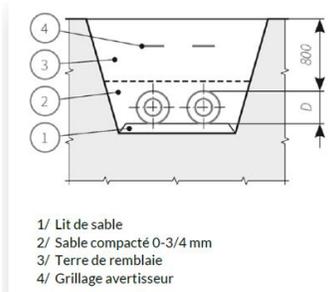
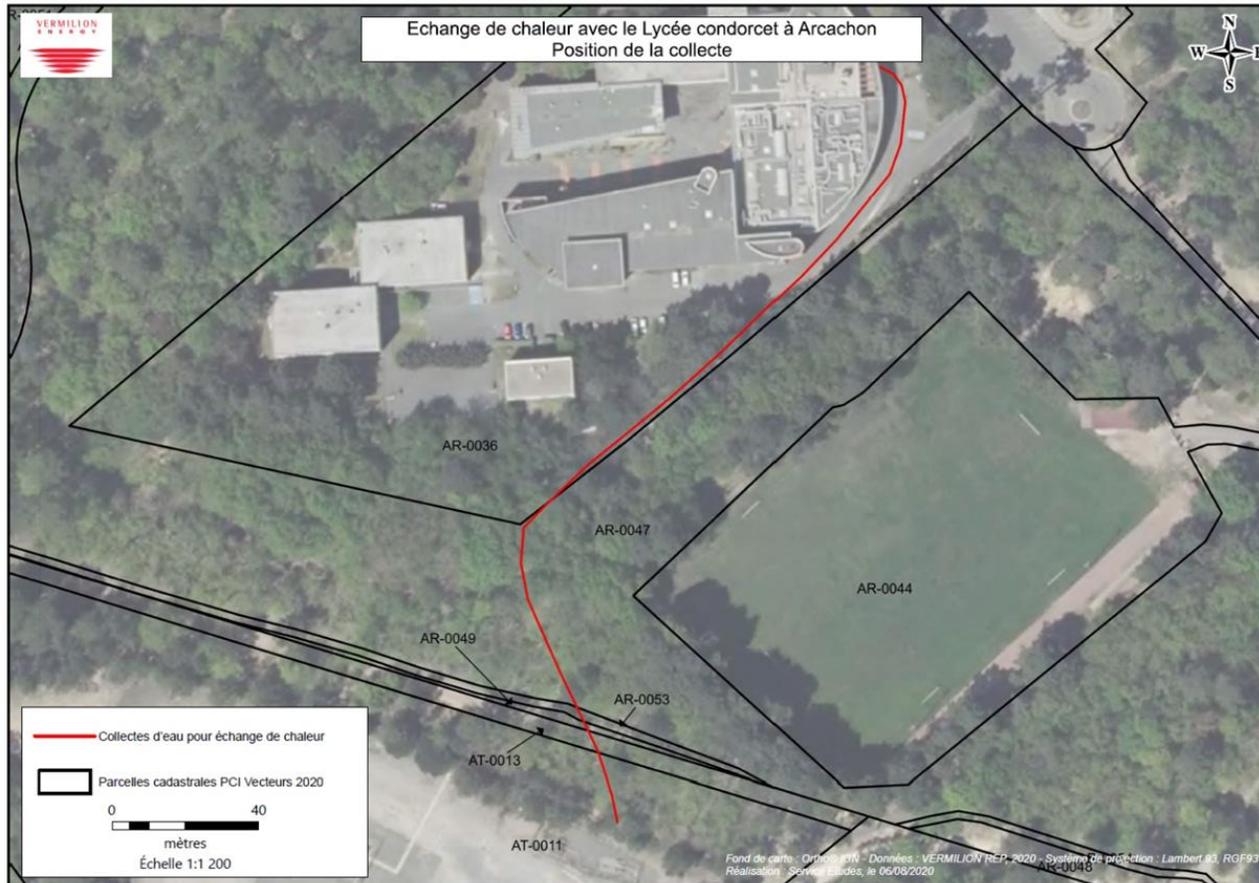
# Downtime LEGE



- Downtime moyen sur 2017/2018 = 6%
- Les casse puits impactent la production huile et eau
- Puits profonds /chauds = durée de vie des pompes de fond plus faible qu'ailleurs
- Fréquence moyenne de pulling sur 10 ans = 2 ans
- Avec LEA1 en production la limite de réinjection sera atteinte (1400 m<sup>3</sup>/j)

# Tracé proposé

- Tracé optimisé : suivi d'une « trouée » en forêt au N de piste cyclable
- Longueur 130 m dans les 5 parcelles de la commune avec servitude de 5 m
- Autorisation à déposer notre dossier de défrichement à la DDTM



- 1/ Lit de sable
- 2/ Sable compacté 0-3/4 mm
- 3/ Terre de remblais
- 4/ Grillage avertisseur

Tranchée ( 1 m profondeur  
\* 1 mètre de largeur)

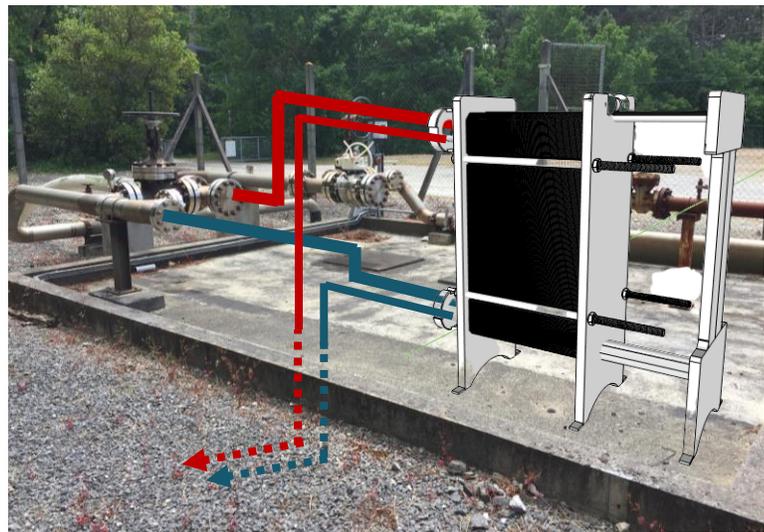
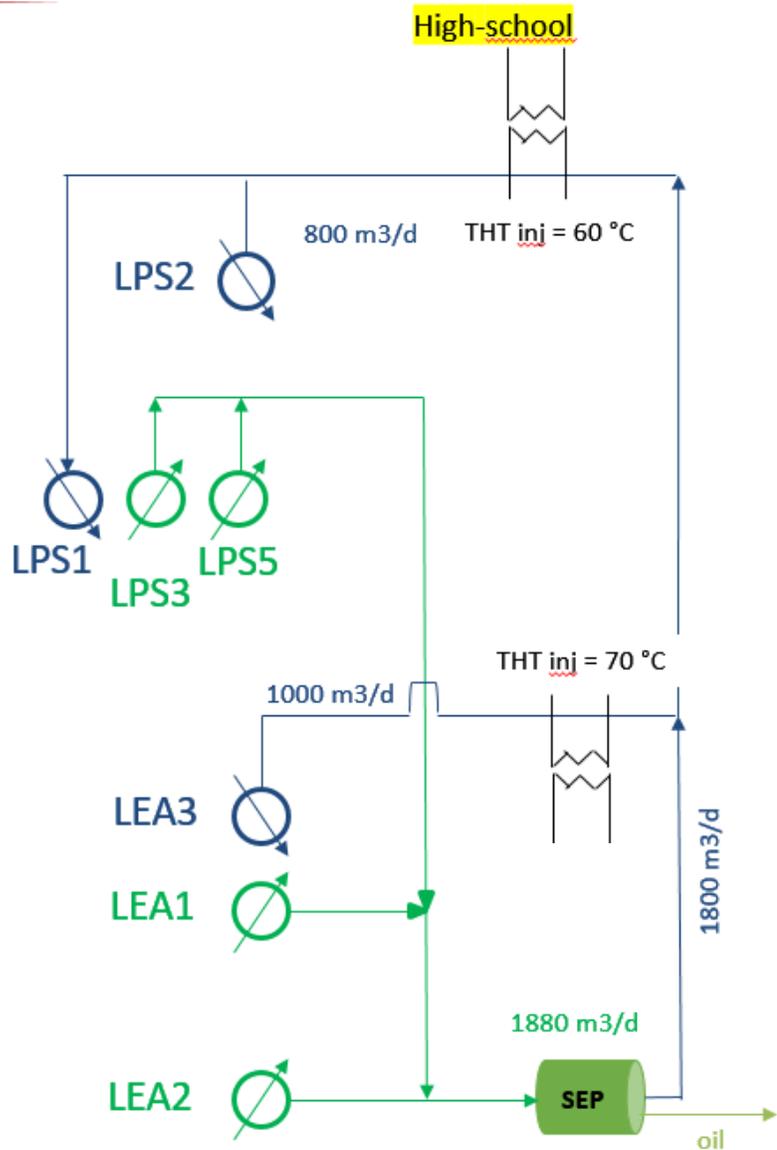


Canalisation à dérouler et enterrer (D = 10 cm)



Vue du passage vers la piste cyclable

# Oil and heat coproduction pilot



## Project Impact (planned Q4 2020)

- ✓ Delivers 820 MWh / year
- ✓ >95% of heat needs are covered
- ✓ CO<sub>2</sub> reduction 220 t/year

## Key challenges

- 1) Thermal interferences in reservoir
- 2) Scaling & injectivity risks
- 3) Long-term thermal resources = f (Brent price)
- 4) Load factor vs. economics
- 5) Heat delivery vs. oil production optimisation
- 6) Regulatory