

CO2 gas + WAG + water injection into Pf-A-I oil reservoir

Case Study

**/Istvan Uj senior reservoir
eng. MOL Plc
Tibor Fekete geologist MOL
Plc./**

Location of PF-A-I oil field



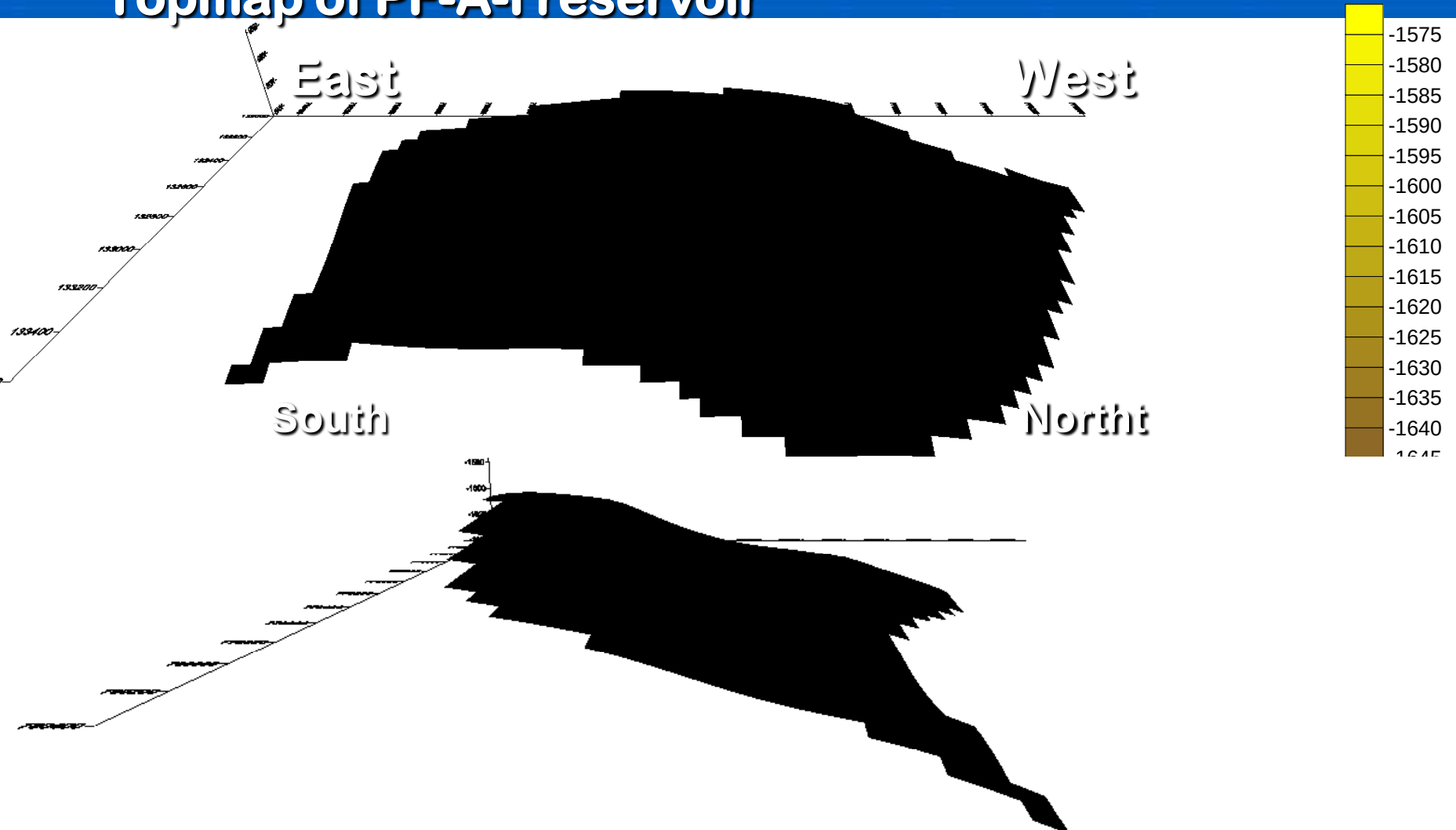
Geology

The reservoir is in a stratigraphic trap – combined with lithological changes. The reservoir rocks are clayey sandstone and aleurite with layers of claymarl interbeds.

Area of reservoirs	3,3 km ² (815,4 acres)
Type of reservoirs	sandstone
OWC	1644 ssm (5392 ft)
Pi	17,45 MPa (2531 psi)
Ti	122 °C (251 °F)
Net pay	3,5 m (11,5 ft)
Porosity	20,6%
Swi	30,0%
Permeability	10 mD

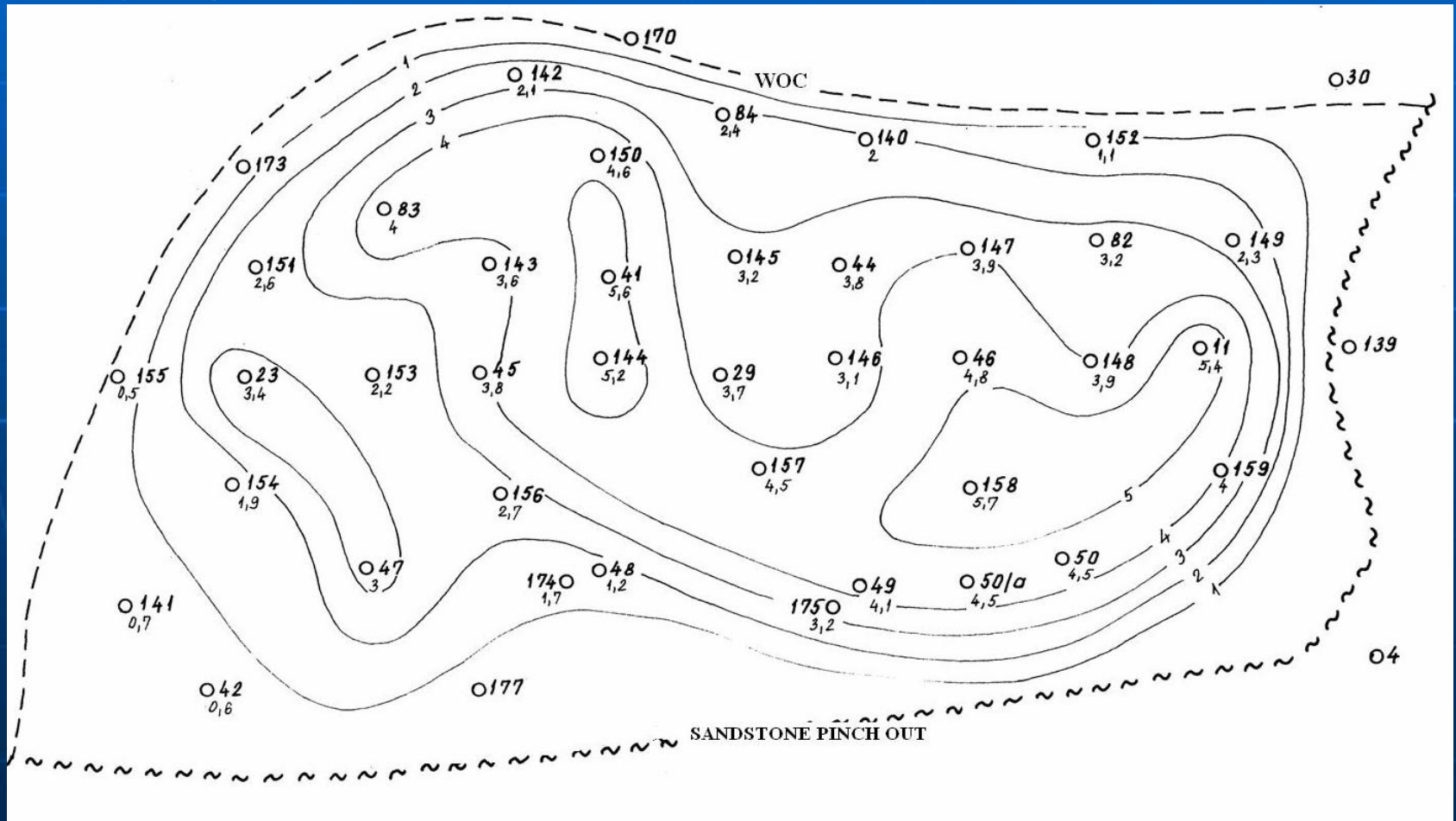
Geology

Topmap of PF-A-I reservoir

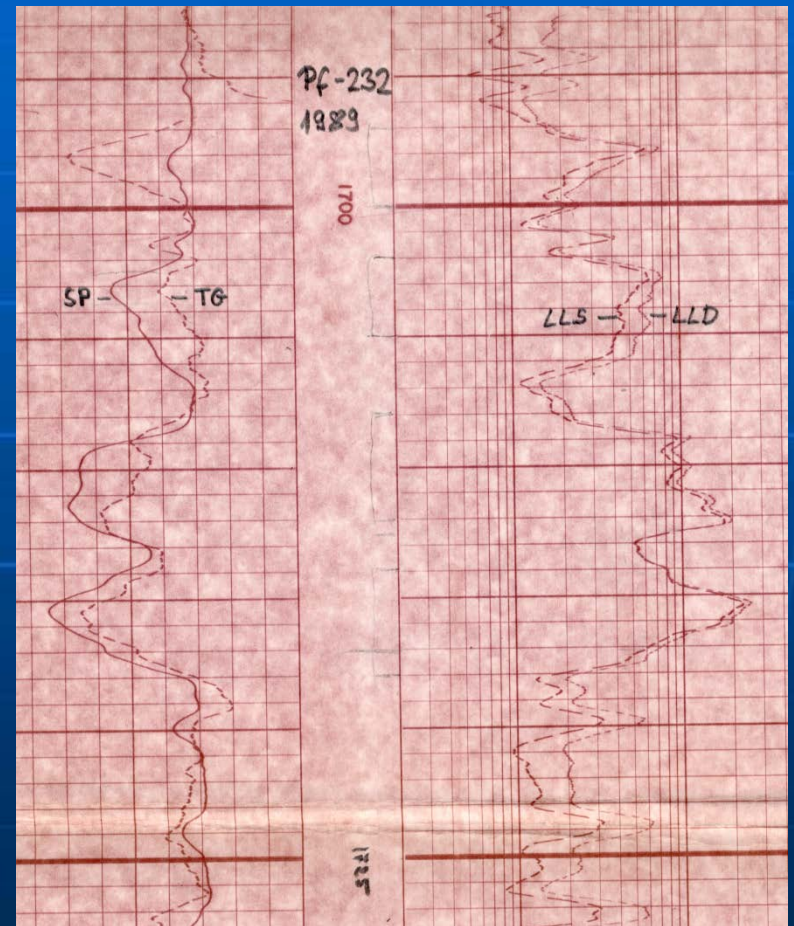
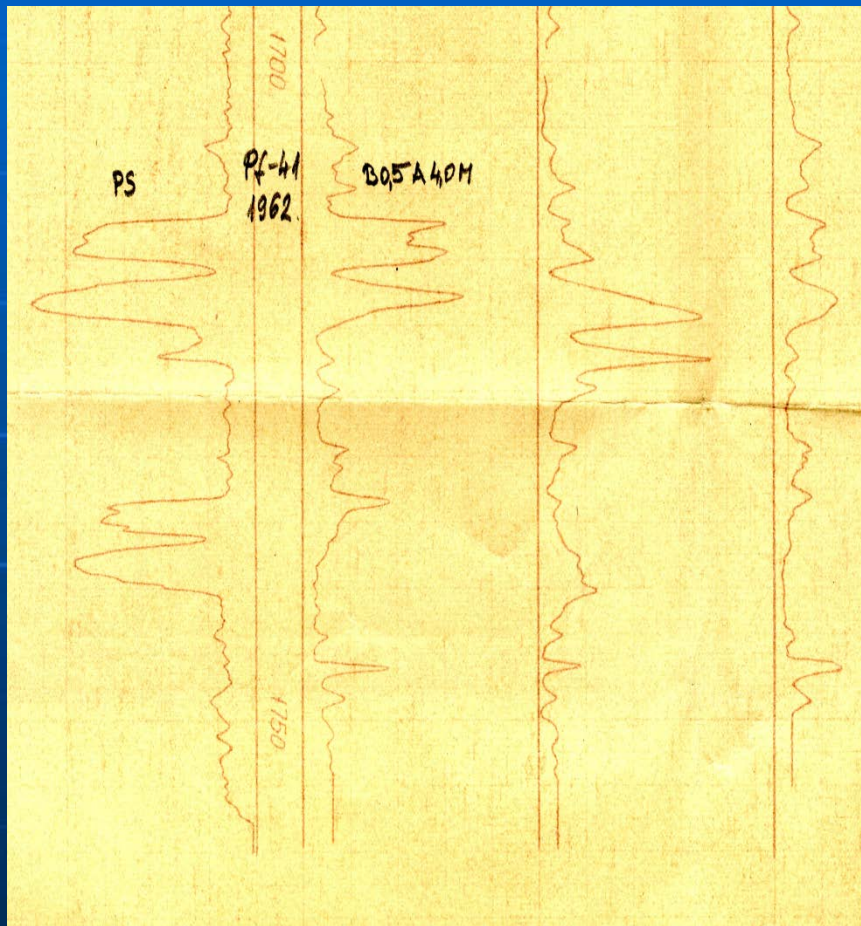


Geology

Net pay of PF-A-I oil reservoir



Geology



Fluid properties and PVT data

oil

intermediate

Gravity (API°) 30,2

Density 875 kg/m³

Pi 17,45 MPa

Ti 122 °C

Boi 1,18 m³/m³

Rsi 41,4 m³/m³

Pb 12,7 MPa

Bob 1,193 m³/m³

μob 0,96x10⁻³ Pas

composition of solution gas

C1 = 80,67 vol%

C2 = 5,50 vol%

C3 = 3,58 vol%

C4 = 1,67 vol%

C5+ = 0,28 vol%

CO2 = 5,60 vol%

N2 = 2,70 vol%

Density = 0,924 kg/m³

Relative density = 0,71

Volumetrics

Year	Bulk Volume	HCPV	OOIP	OGI _P	B _{oi}	R _{si}	Φ	S _{wi}
	10 ⁶ m ³	10 ⁶ m ³	10 ³ m ³	10 ⁶ m ³	m ³ /m ³	m ³ /m ³	%	%
1961	8,185	1,140	967,480	38,1	1,1780	40,0	20,0	30
1965	7,538	1,067	925,216		1,1530		20,0	30
1969	8,431	1,180	1015,789		1,1620		20,0	30
1975	9,304	1,237	1064,915	35,8	1,1622	33,6	19,0	30
1985	8,725	1,258	1065,281	44,1	1,1810	41,4	20,6	30

Production stages

The production stages of PF-A-I reservoir:

- 1960-1972 primary recovery (depletion + water drive)
- 1973-1983 CO₂ gas injection
- 1984-2004 WAG and water injection
 - 1984-1989 planning, construction, pressure increasing
 - 1990-1996 WAG injection
 - 1997-2004 water injection
- 2005- „primary recovery” again

Primary recovery 1960-1972

(All the wells were flowing well)

The first well (Pf-23) was put in production in 10/1960.

Number of new production wells year by year:

1960 – 2 (Pf-11,-23)

1961 – 4 (Pf-29,-45,-46,-47)

1962 – 1 (Pf-41)

1963 – 1 (Pf-44)

1964 – 1 (Pf-40)

1965 – 10 (Pf-83,-84,-141,-142,-143,-144,-145,-146,-147,-154)

1966 – 5 (Pf-148,-149,-151,-158,-159)

1967 – 3 (Pf-150,-157,-170)

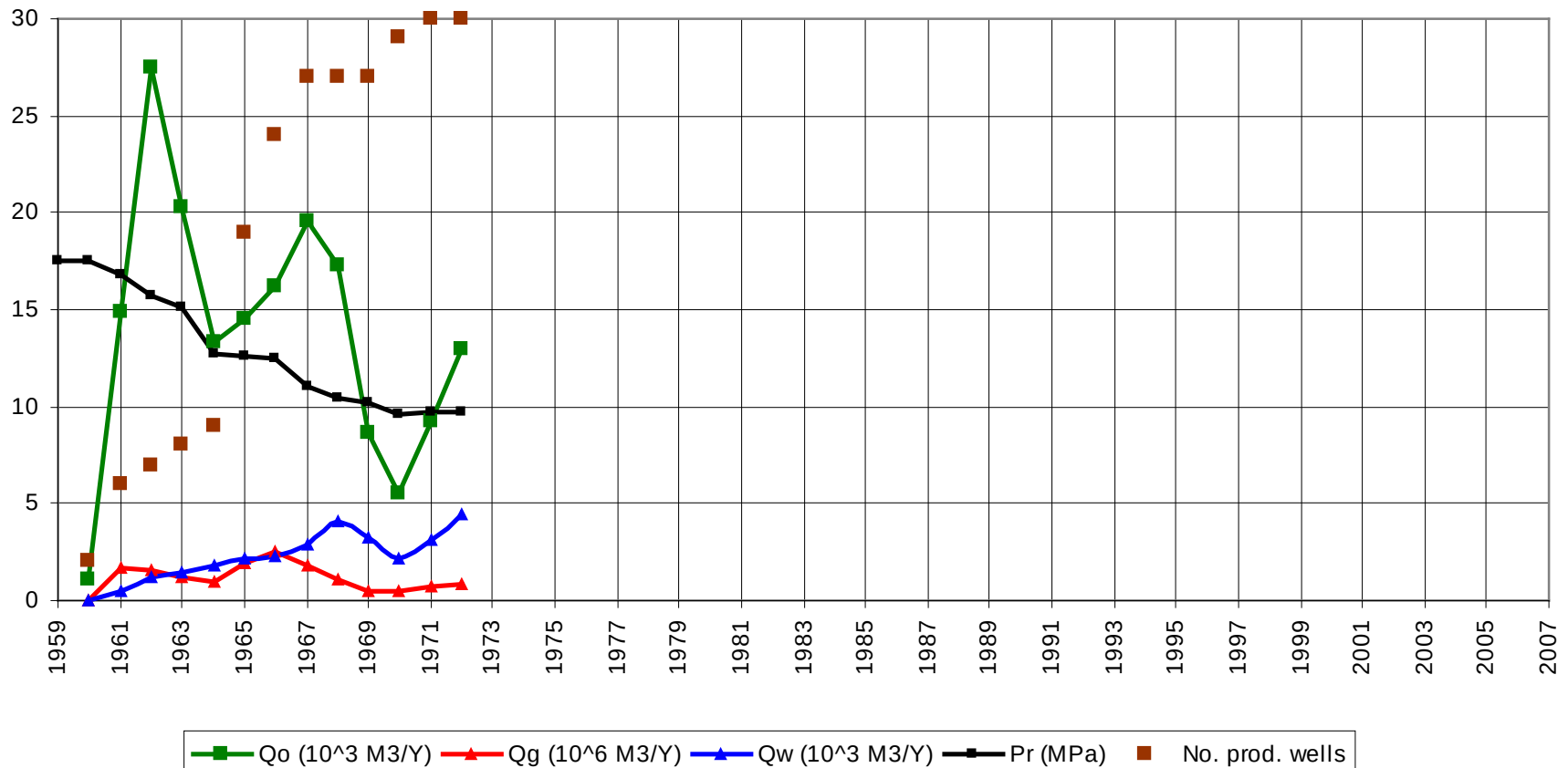
1970 – 2 (Pf-156,-170)

1971 – 1 (Pf-177)

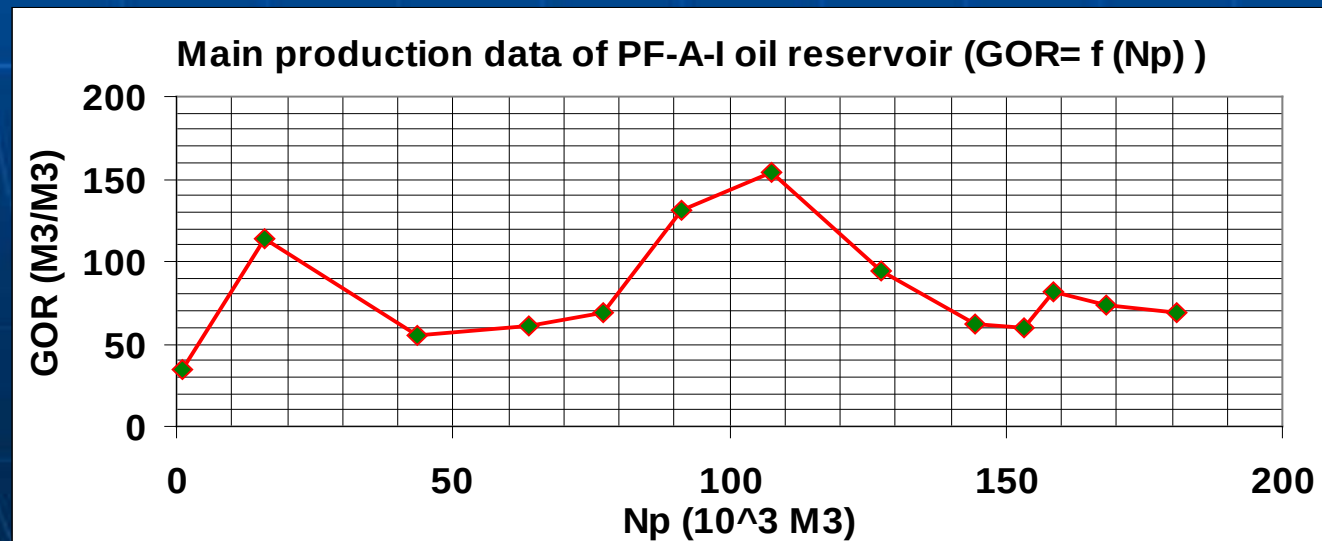
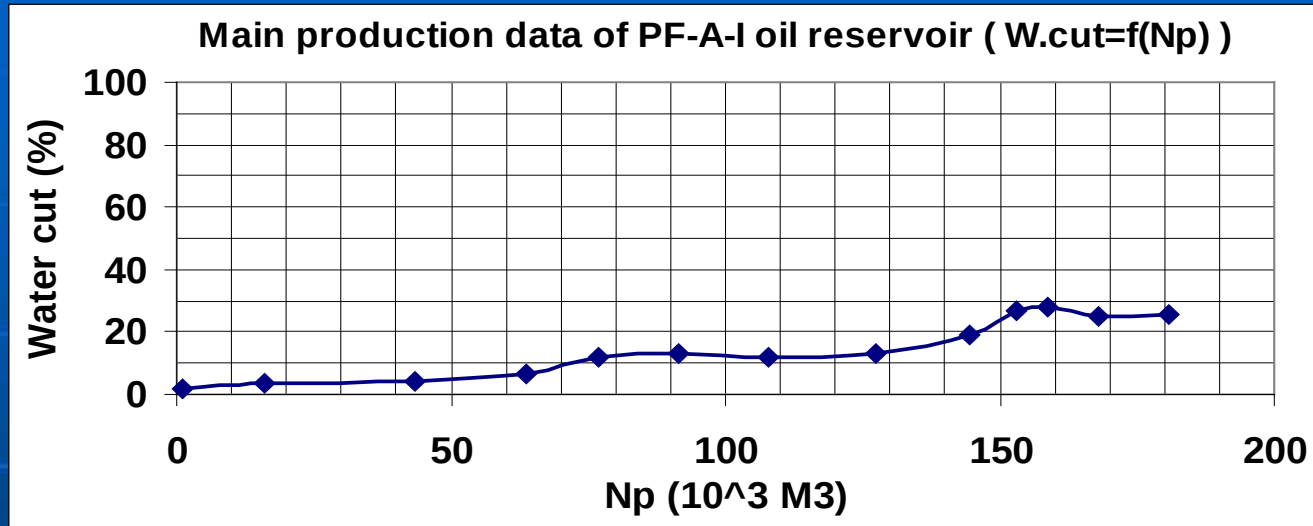
Total number of production wells in depletion stage: 30
(0,11 Km²/well -27 Acre spacing)

Primary recovery 1960-1972

Main production data of PF-A-I oil reservoir

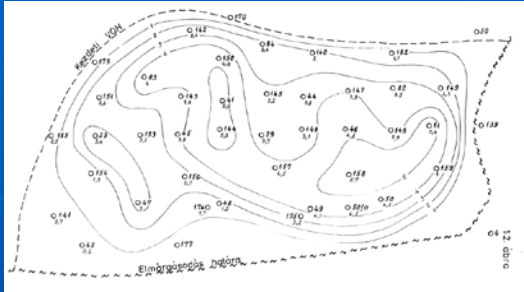


Primary recovery 1960-1972

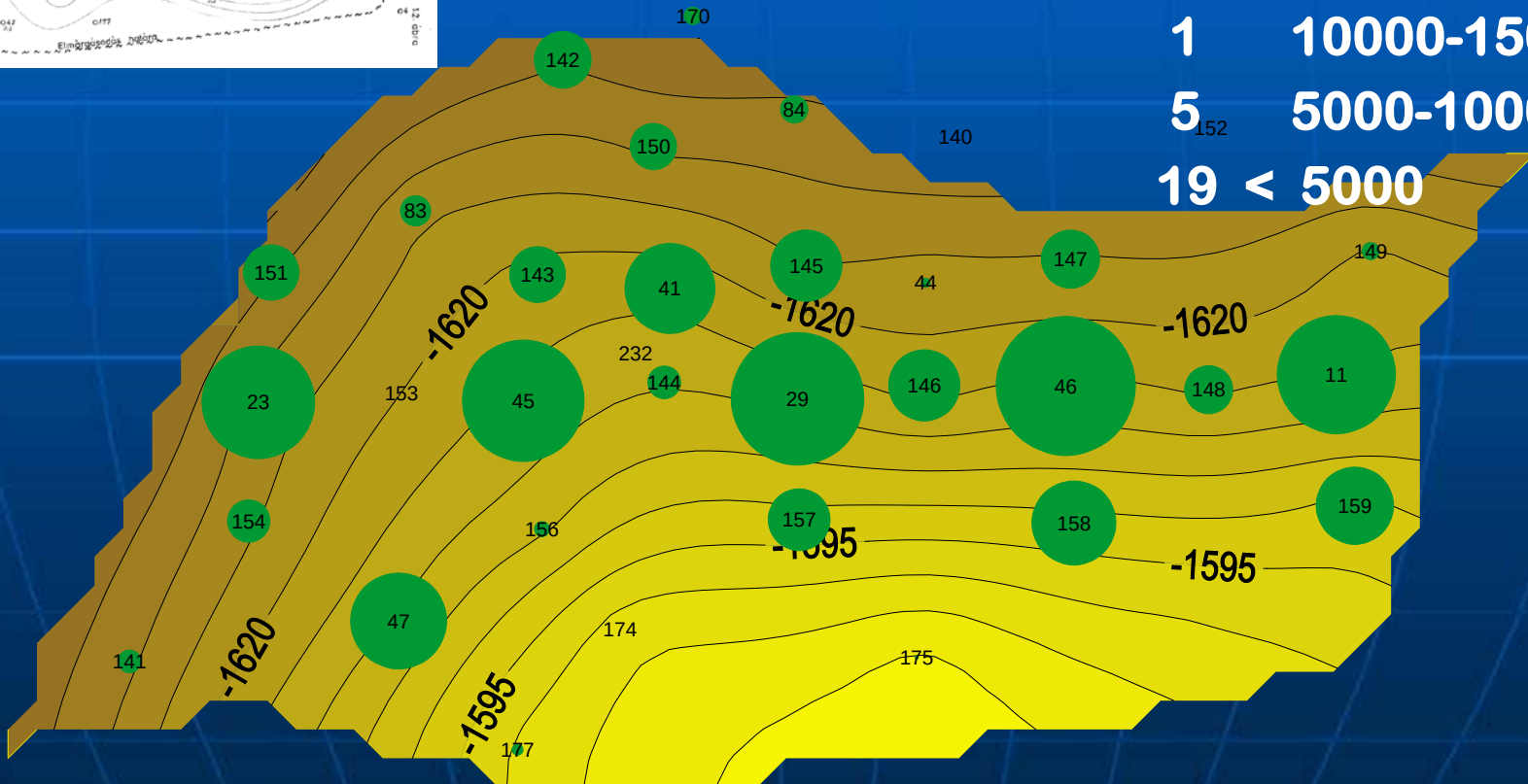


Primary recovery 1960-1972

Cumulative oil production by wells



Wells	Np(m ³)
2	> 20000
3	15000-20000
1	10000-15000
5	5000-10000
19	< 5000



Primary recovery 1960-1972

Summary

$F_{wl} = 2 \Rightarrow 25 \%$

$P_r = 17,46 \Rightarrow 9,71 \text{ MPa}$

$GOR_{AVR} = 84 \text{ m}^3/\text{m}^3$

No. of production wells $30 \Rightarrow 20$

All wells - flowing wells

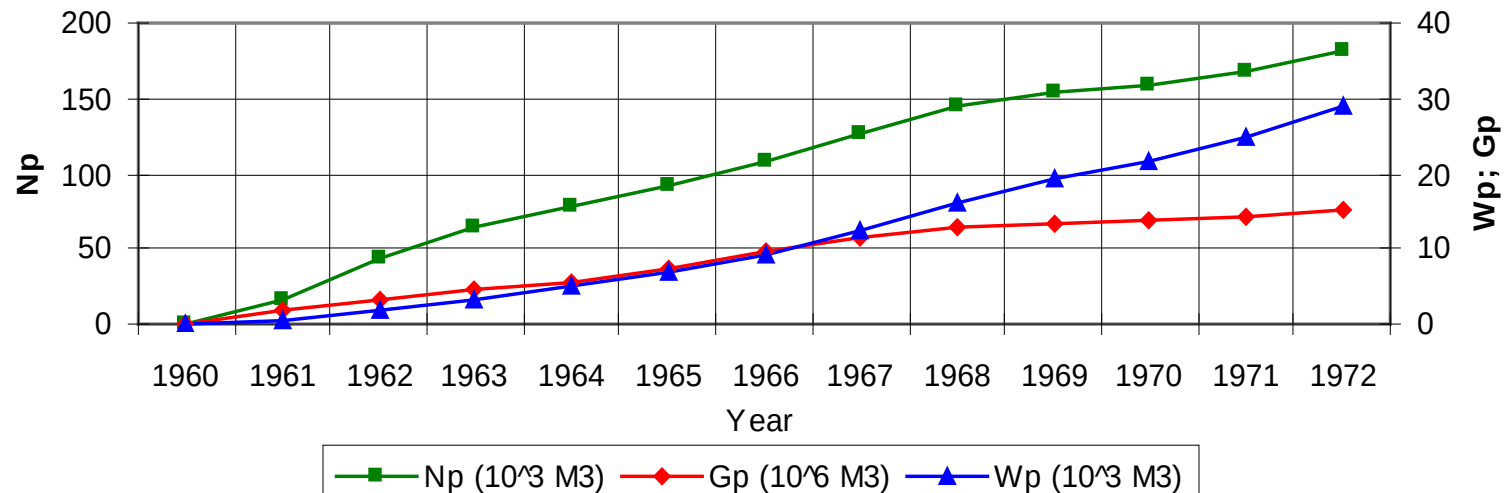
$N_p = 180,9 \cdot 10^3 \text{ m}^3$

$Rec.F = 16,9 \%$

$G_p = 15,2 \cdot 10^6 \text{ m}^3$

$W_p = 29,1 \cdot 10^3 \text{ m}^3$

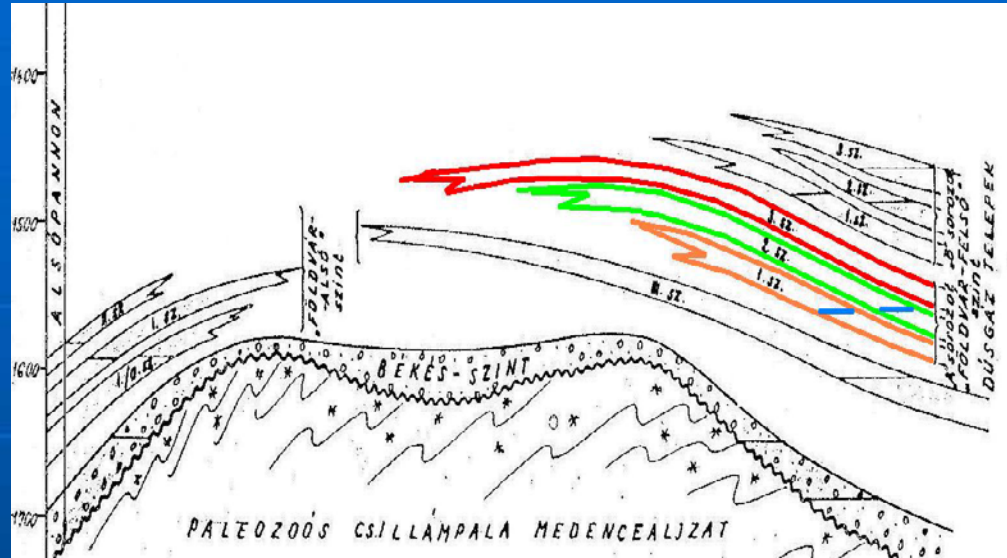
Cumulative productions



CO₂ gas injection 1973-1983

1969 – Planning

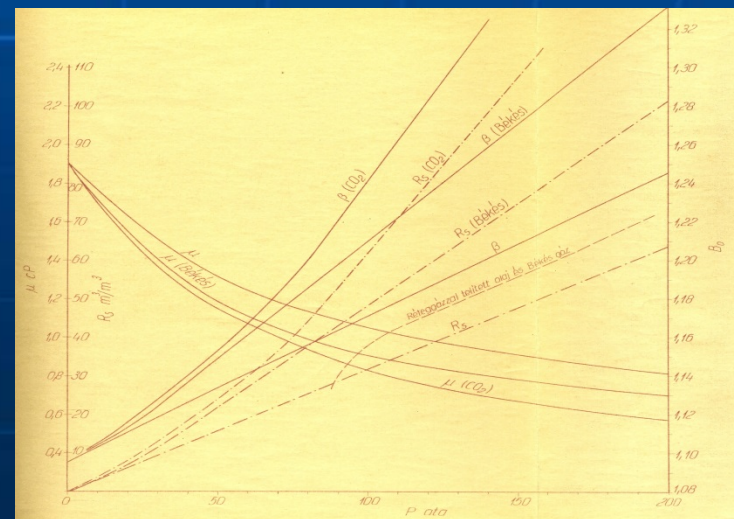
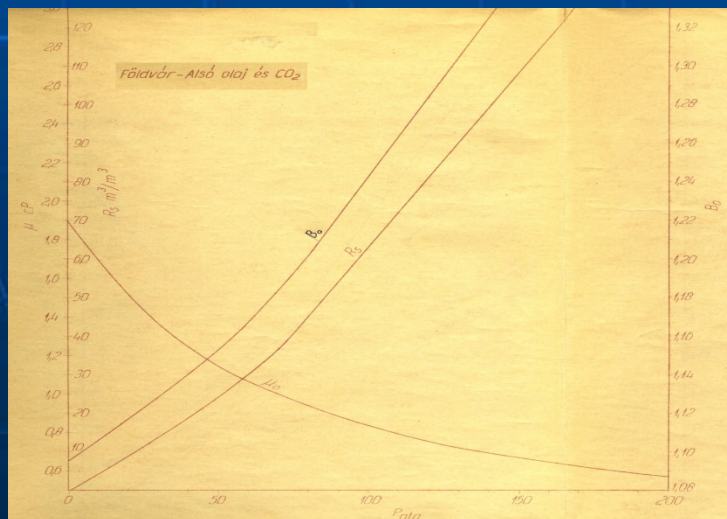
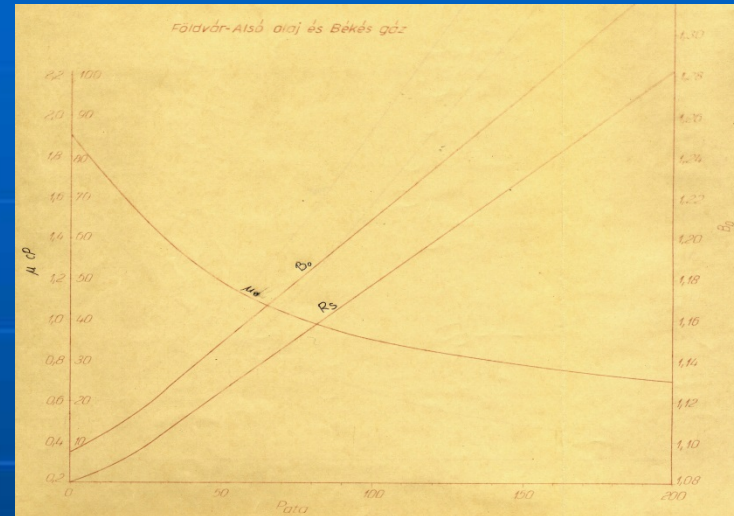
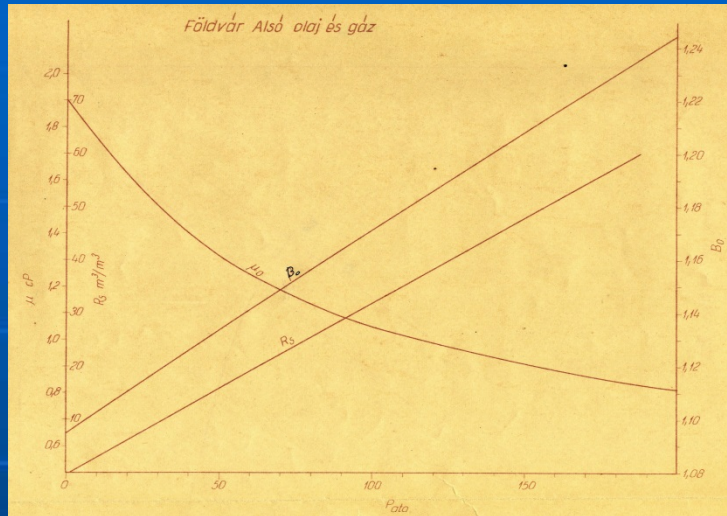
Why CO₂ injection ?



- $5,4 \cdot 10^9 \text{ m}^3$ recoverable CO₂ gas - CO₂=67,5%, N₂=2,6%, CH=29,9% - PF-Bekes reservoir ~ 150 m below PF-A-I reservoir
- Existing surface facilities – gas wells, gas treating plant, pipelines, etc...
- Low costs
- Successful CO₂ injection other Hungarian oil fields

CO₂ gas injection 1973-1983

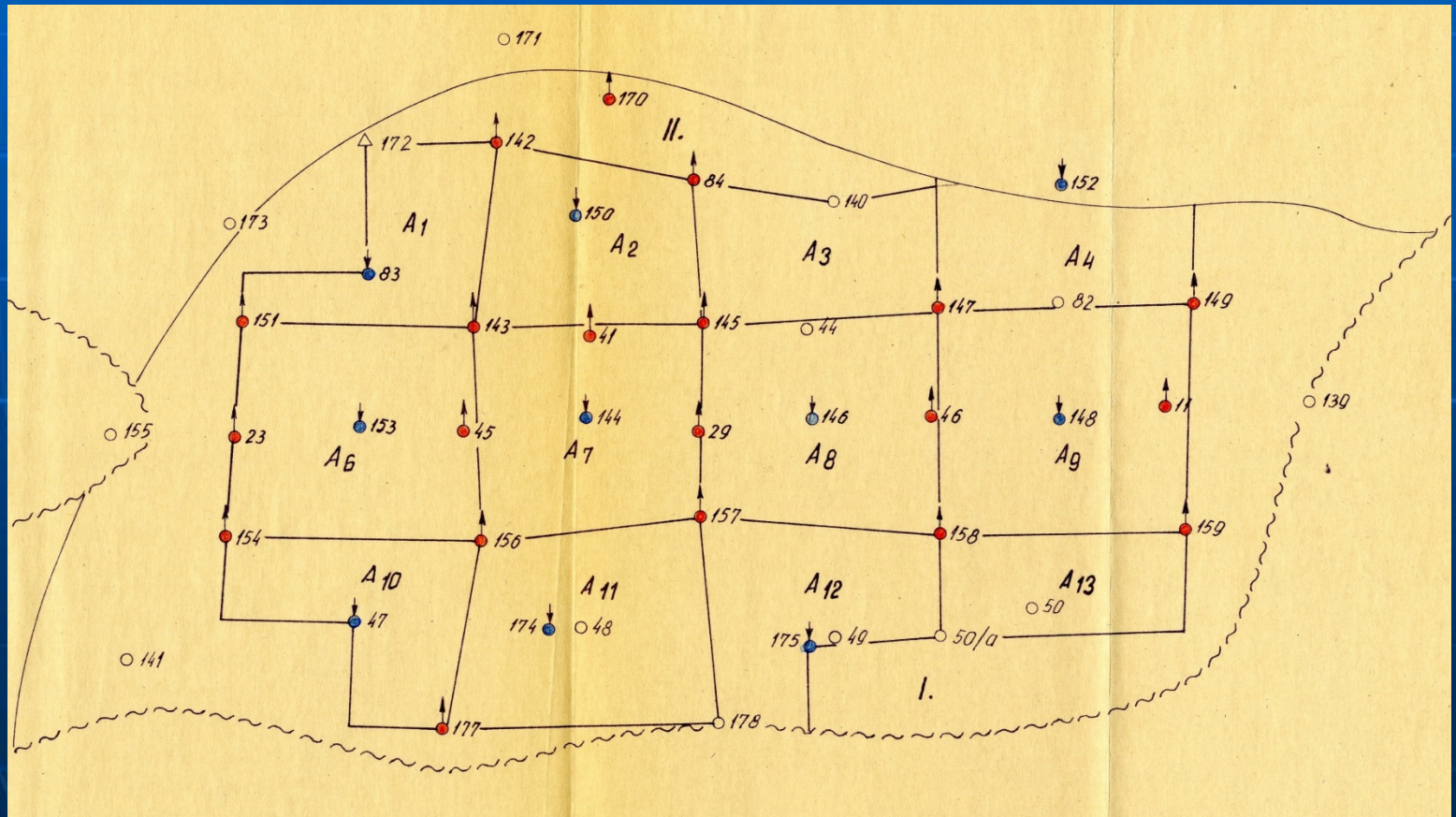
1969 – Planning: *PVT* measurements



CO₂ gas injection 1973-1983

1969 – Planning: *Determination of well pattern*

10 injection wells - recompleted, 20 production wells - existing wells



CO₂ gas injection 1973-1983

1969 – Planning

Calculation of HCPV, gas injection, recoverable oil in every (13) block and total (no PC – slide-rule!)

Conditions:



Pr increasing 10 → 12 Mpa (maintenance)

Vertical sweep efficiency = 0,8

Areal sweep efficiency = 0,7

Gas injection rates (10 ³ m ³ /d)		
Pr increasing	before breakthrough	after breakthrough
54,9	20,1	87,5

Cumulative gas injection (10 ⁶ m ³)			Cumulative oil production (10 ³ m ³)	
Pr increasing	before breakthrough	after breakthrough	before breakthrough	after breakthrough
8,2	14,7	95,7	75,1	31,3
0,5 yr	2 yrs	3 yrs	2 yrs	3 yrs

CO₂ gas injection 1973-1983

Planned and fact

	Gas injection rates (10 ³ m ³ /d)			No. of injection wells
	Pr increasing	before breakthrough	after breakthrough	
planned	54,9	20,1	87,5	10
fact	-	11-33	33-64-20	8

	Cumulative gas injection (10 ⁶ m ³)				Cumulative oil production (10 ³ m ³)		
	Pr increasing	before breakthrough	after breakthrough	total	before breakthrough	after breakthrough	total
planned	8,2	14,7	95,7	118,6	75,1	31,3	106,4
fact	-	20,0	112,3	132,3	59,1	64,1	123,2
planned	0,5 yr	2 yrs	3 yrs	5,5 yrs	2 yrs	3 yrs	5 yrs
fact	-	3,5 yrs	7,5 yrs	11 yrs	3,5 yrs	7,5 yrs	11 yrs

CO₂ gas injection 1973-1983

Planned and fact – by wells

Wells Np(m³)

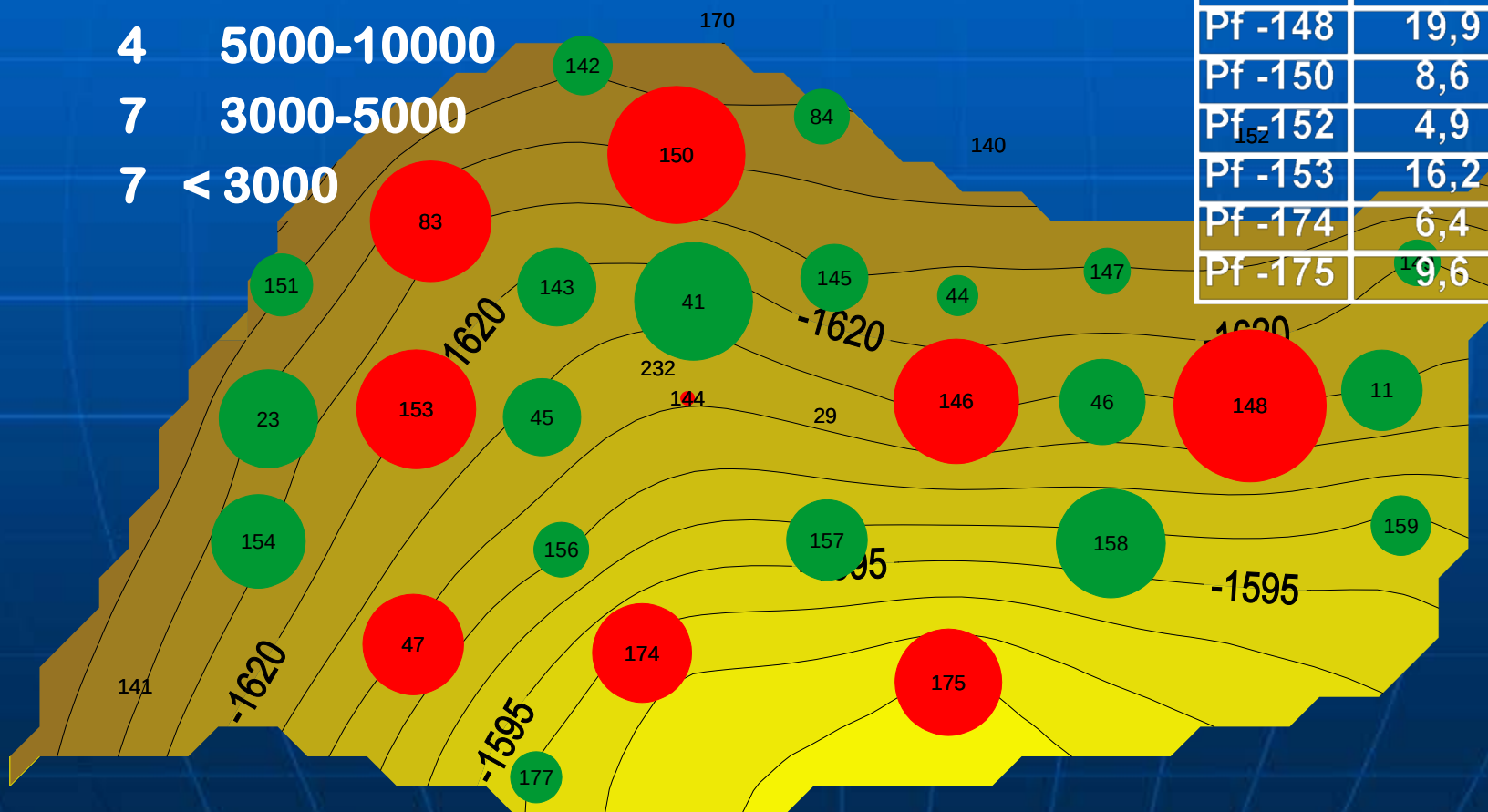
2 10000-15000

4 5000-10000

7 3000-5000

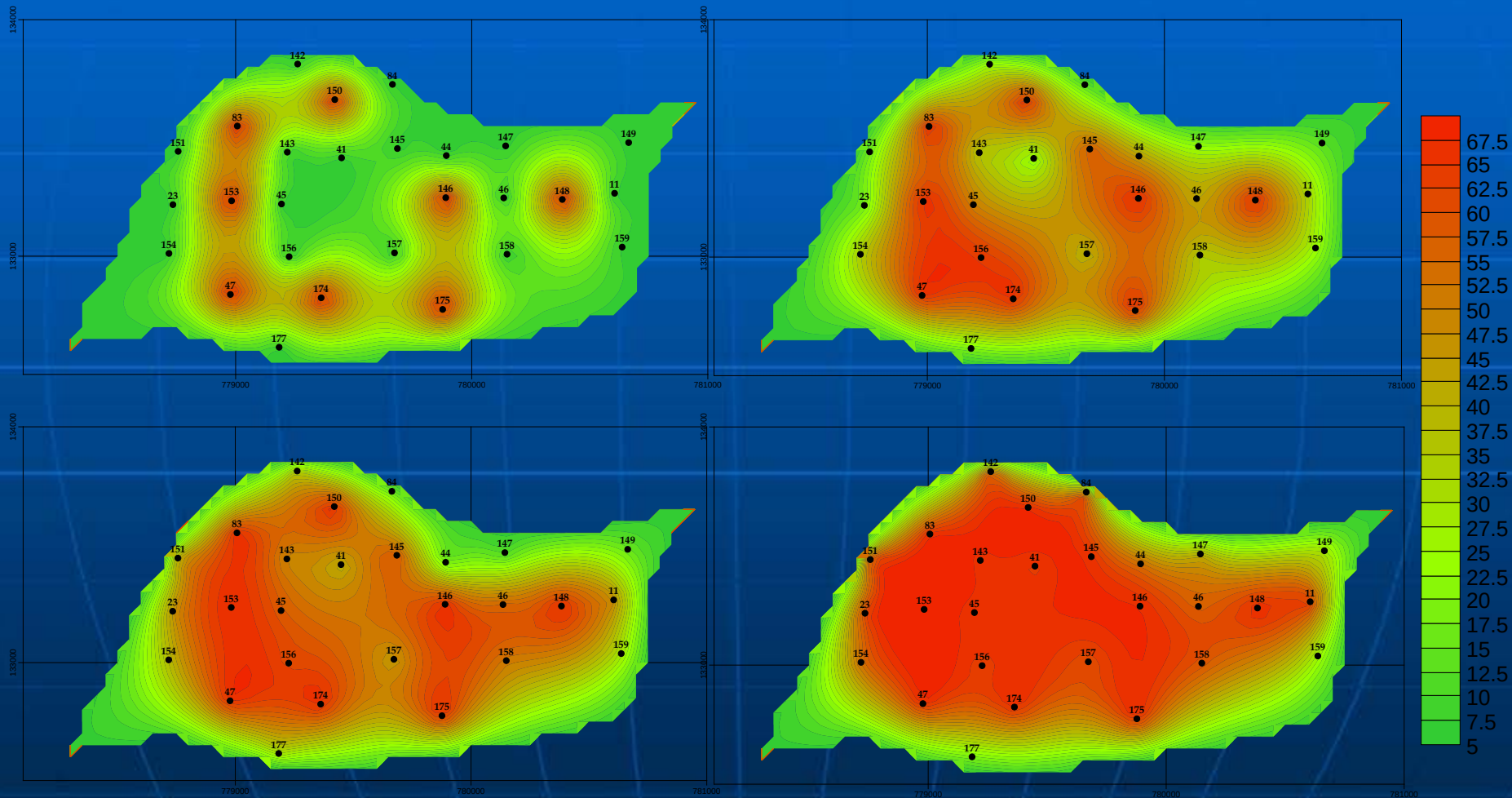
7 < 3000

Wells	Gi (10 ⁶ m ³)	
	planned	fact
Pf -47	7,9	11,7
Pf -83	7,5	16,8
Pf -144	20,2	(casing)
Pf -146	17,4	17,9
Pf -148	19,9	24,6
Pf -150	8,6	20,6
Pf -152	4,9	(cost)
Pf -153	16,2	16,3
Pf -174	6,4	11,3
Pf -175	9,6	13,1



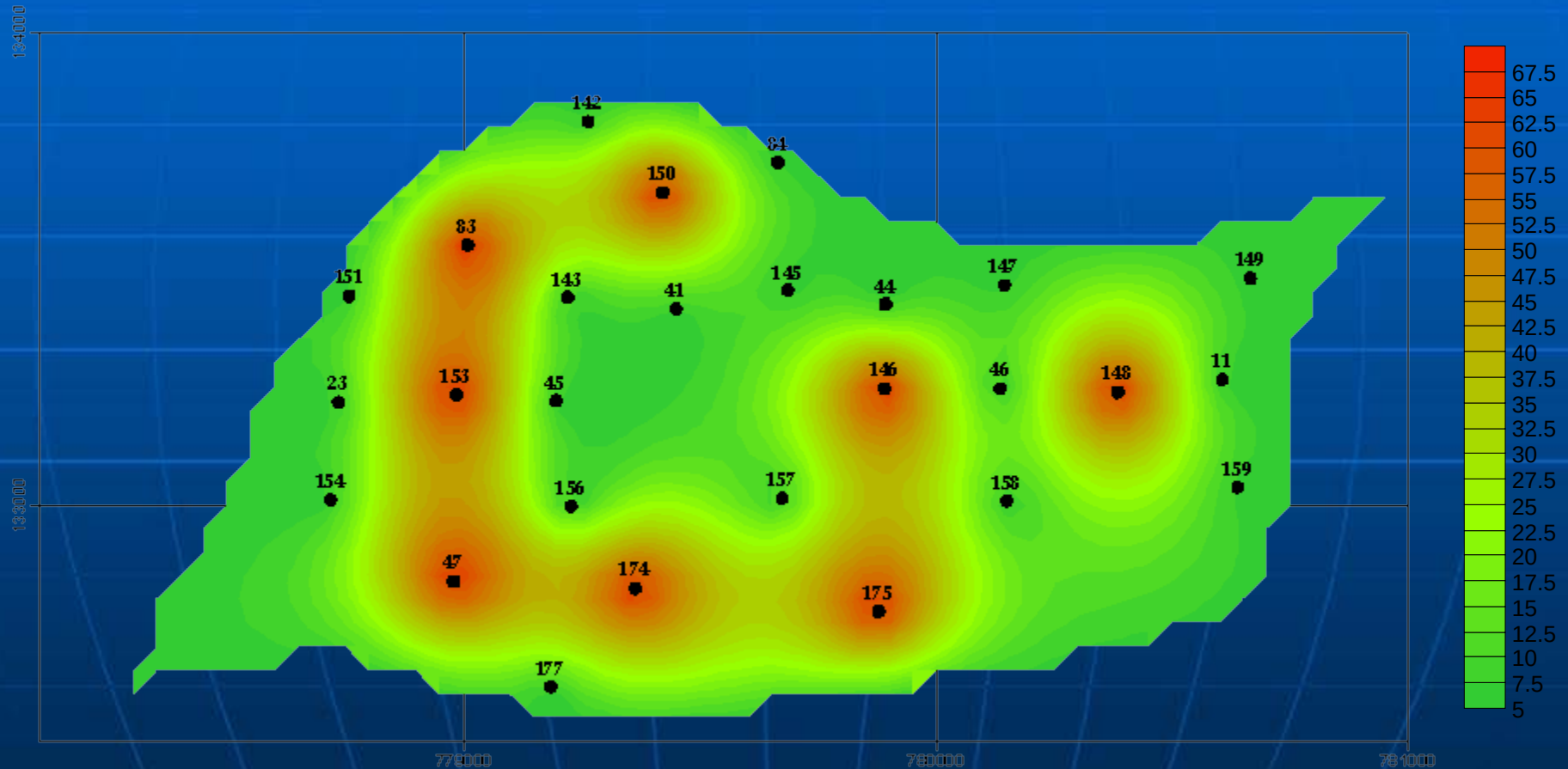
CO₂ gas injection 1973-1983

CO₂ content in 1973, 1975, 1976, 1983



CO₂ gas injection 1973-1983

CO₂ content year by year - 1973-1983



CO₂ gas injection 1973-1983

Summary

Fwl=25⇒50 %

Pr=9,7⇒10,3 MPa

Gi=132,2*10⁶ m³

11 flowing – 9 sucker
rod pump

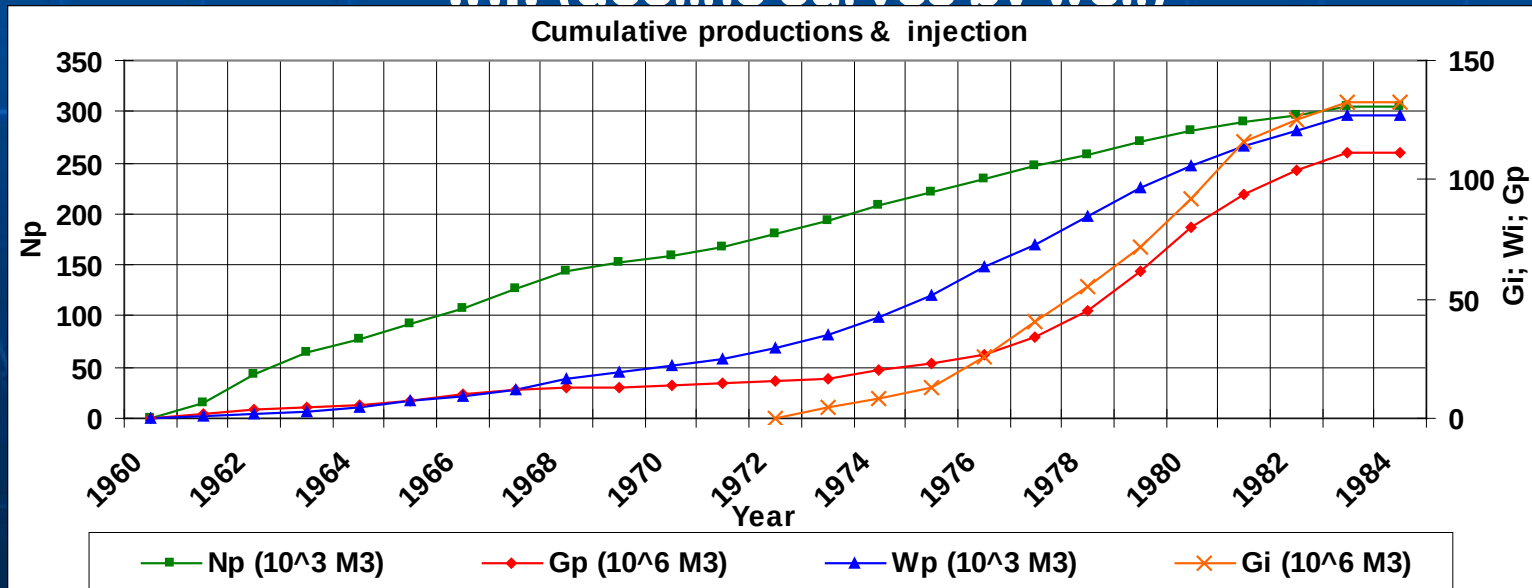
Np=123,2*10³ m³ (180,9⇒304,1)

Gp= 95,7*10⁶ m³ (5,2⇒110,9)

Wp=98,0*10³ m³ (29,1⇒ 127,1)

Rec.F=16,9⇒28,5%

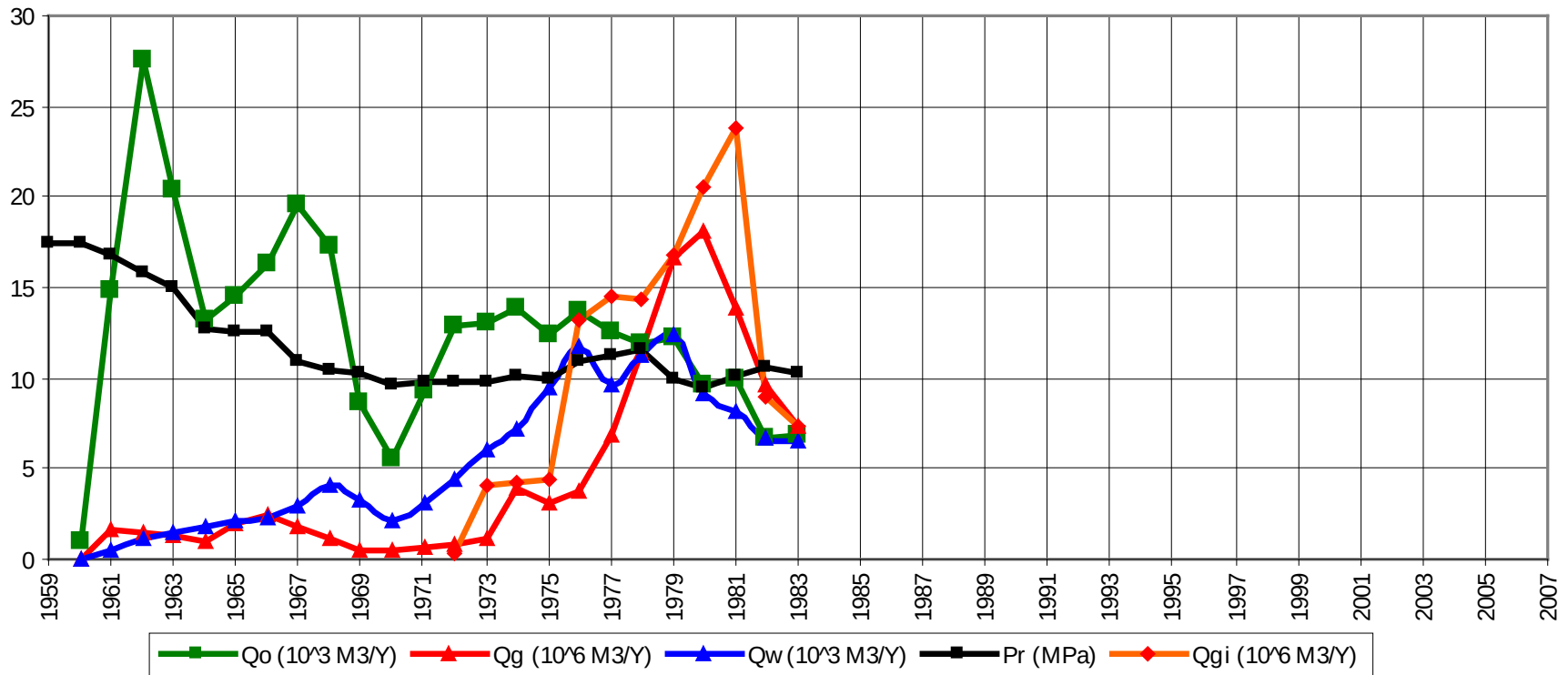
Np=304,1*10³ m³⇒241,9*10³ primary + 62,2*10³ m³ CO₂
ini. (decline curves bv well)



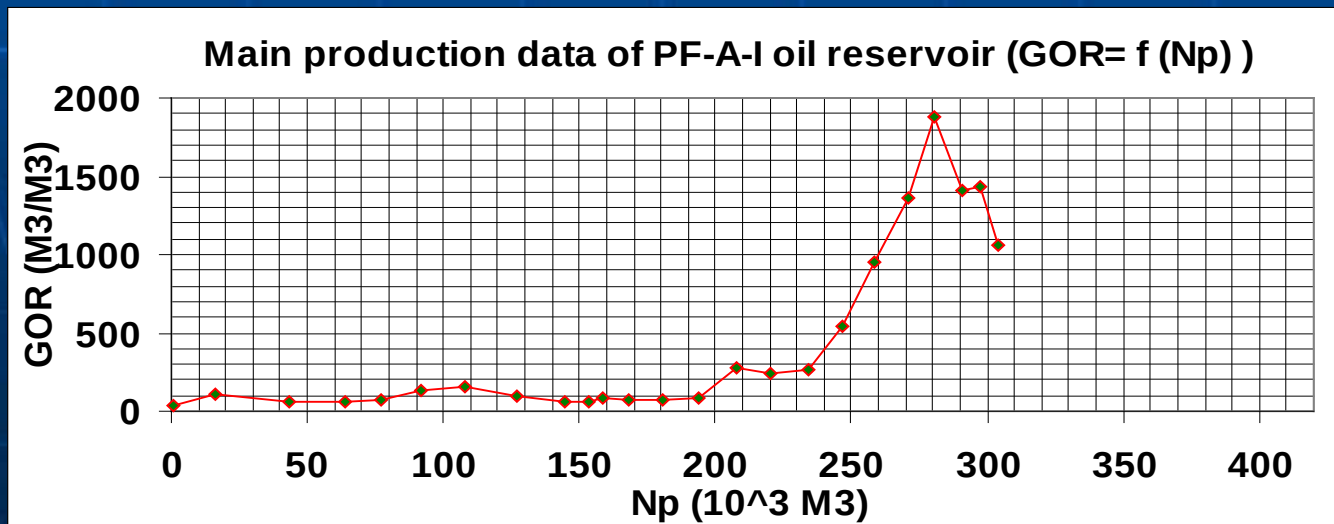
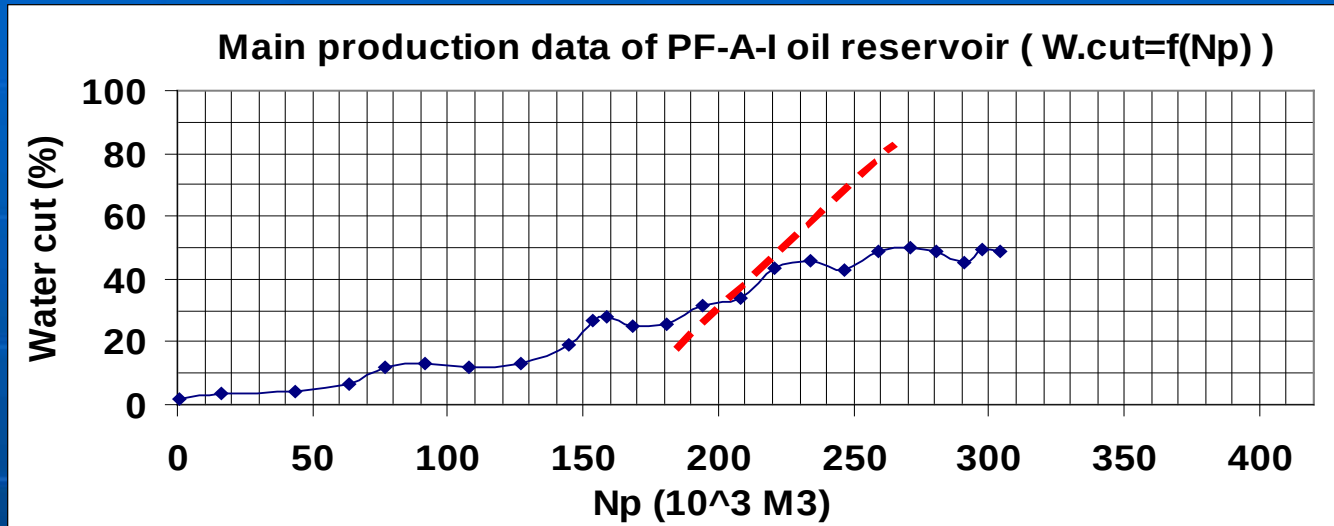
Primary+CO₂ gas injection

1960-1983

Main production data of PF-A-I oil reservoir



Primary+CO₂ gas injection 1960-1983



WAG and water injection 1984-2004

1984-1989 planning, construction

Wells completion, water treatment and injection facilities planning and construction, pressure increasing

Water injection

Version	Pr (Mpa)	dNp (10 ³ m3)	Qwi (m3/d)	Wi (10 ³ m3)	Qgi (10 ³ m3/d)	Gi (10 ⁶ m3)	Prod.Time (years)
1. A	10	91,6	300	1728	0	0	16
1. B	10	91,6	400	1728	0	0	12
2. A	12	101,8	300	1728	50	12	17
2. B	12	101,8	400	1746	50	12	13
3. A	14	112,6	200	1432	50	23	20
3. B	14	112,6	300	1674	50	23	16

WAG + water injection

Version	Pr (Mpa)	dNp (10 ³ m3)	Qwi (m3/d)	Wi (10 ³ m3)	Qgi (10 ³ m3/d)	Gi (10 ⁶ m3)	Prod.Time (years)
1. A	10	102,0	300	1410	64	44,8	15
1. B	10	102,0	400	1449	64	44,6	12
2. A	12	116,0	300	2045	50	66,0	18
2. B	12	116,0	400	1648	50	69,2	15
3. A	14	127,7	200	1306	50	91,0	22
3. B	14	127,7	300	1719	50	89,0	20

WAG and water injection 1984-2004

Plans and facts – Version 2.B.

Pressure increasing: 10⇒12 Mpa - gas injection, rate: 50000 m³/day - 240 days - 12 millions m³

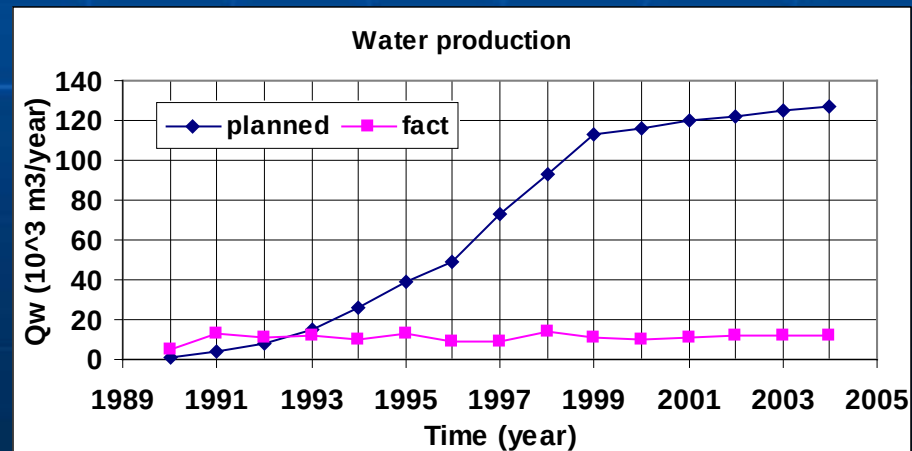
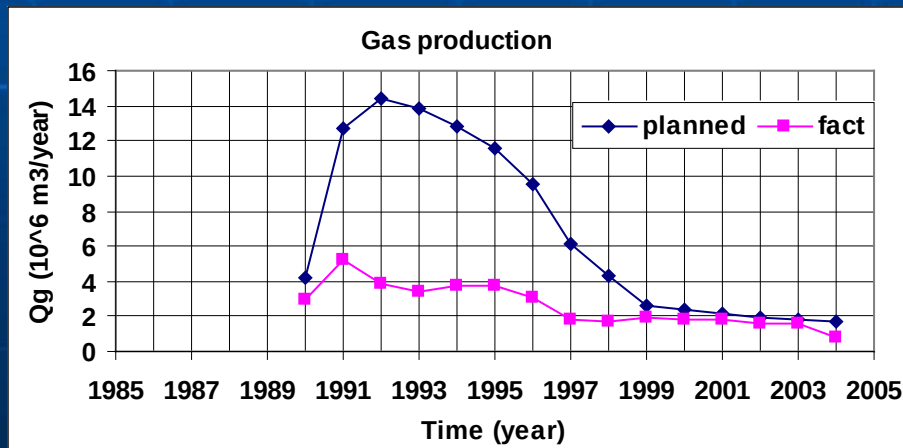
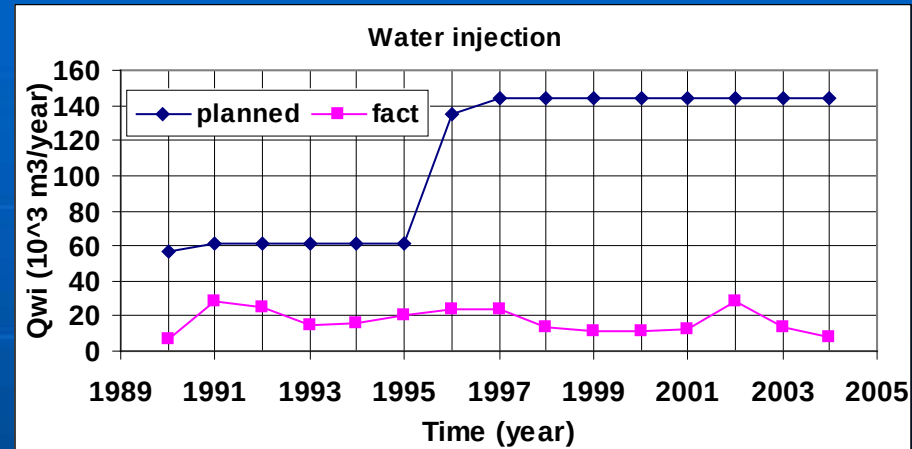
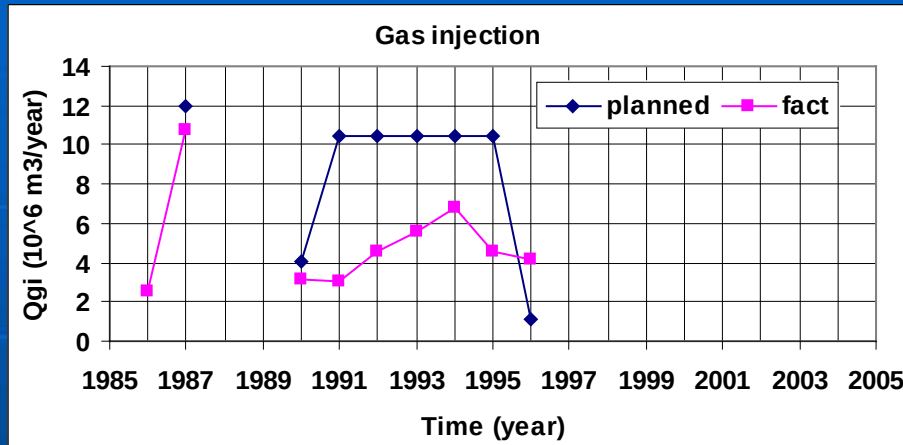
WAG injection (22 cycles): Q_{wi} = 400 m³/day - 38 days (0,0086 Vp) + Q_{gi} = 50000 m³/day - 52 days (0,01337 Vp)

Pressure maintenance : Q_{wi} = 400 m³/day - 144 10³ m³/year

Date	G _{inj} (10 ⁶ m ³ /y)		W _{inj} (10 ³ m ³ /y)		N _p (10 ³ m ³ /y)		G _p (10 ⁶ m ³ /y)		W _p (10 ³ m ³ /y)		Pr (Mpa)
	planned	fact	planned	fact	planned	fact	planned	fact	planned	fact	
1986		2,58									10,88
1987	12,00	10,74									12,56
1988											13,11
1989											13,02
1990	4,10	3,18	57,20	7,22	2,32	3,15	4,24	2,90	1,20	4,52	13,12
1991	10,40	3,05	60,80	27,91	6,95	8,44	12,75	5,22	3,58	13,39	12,48
1992	10,40	4,60	60,80	24,44	10,66	10,80	14,43	3,85	7,53	11,28	13,20
1993	10,40	5,55	60,80	14,72	13,62	9,63	13,84	3,44	14,86	11,62	13,52
1994	10,40	6,75	60,80	16,27	14,71	9,33	12,77	3,71	25,79	10,11	13,79
1995	10,40	4,57	60,80	20,96	13,85	7,18	11,55	3,78	39,27	12,88	14,09
1996	1,10	4,20	135,20	23,94	11,21	6,89	9,55	3,07	49,04	8,91	14,32
1997			144,00	23,31	9,57	6,52	6,15	1,80	72,75	8,81	14,30
1998			144,00	14,08	7,44	6,35	4,34	1,69	92,92	14,11	13,79
1999			144,00	10,83	6,75	6,36	2,56	1,98	112,51	11,17	13,40
2000			144,00	11,11	5,29	4,72	2,35	1,82	116,31	9,57	13,23
2001			144,00	12,06	4,32	4,13	2,15	1,87	119,58	11,47	13,70
2002			144,00	28,44	3,61	3,29	1,98	1,64	122,32	12,11	14,31
2003			144,00	13,97	3,09	3,69	1,81	1,55	124,69	12,48	14,28
2004			144,00	8,24	2,69	2,40	1,67	0,83	126,78	11,81	14,14
Sum:	69,2	45,2 (65%)	1648,4	257,5 (16%)	116,1	92,9 (80%)	102,1	39,1 (38%)	1029,1	164,2 (16%)	

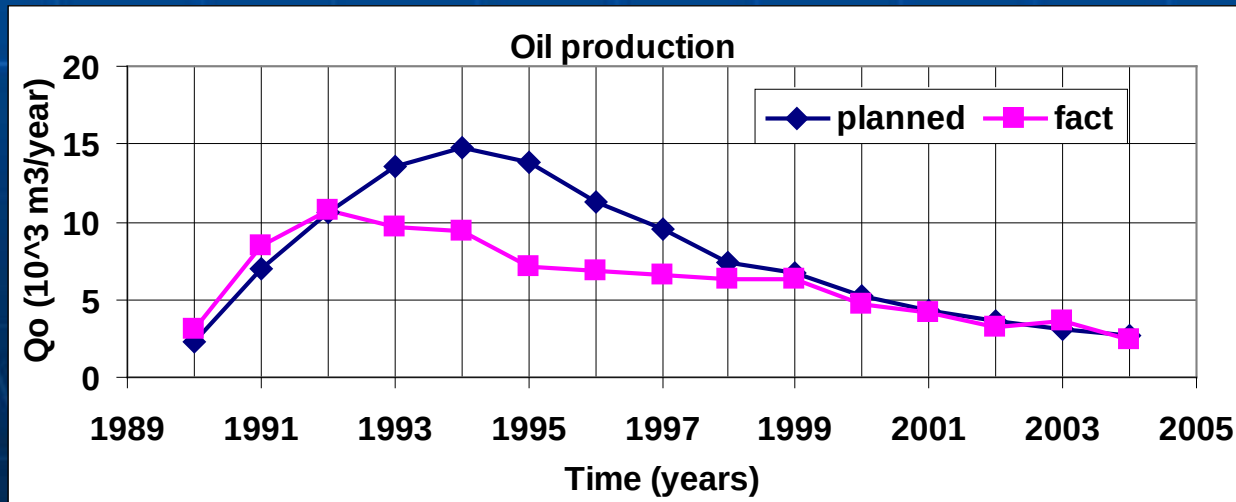
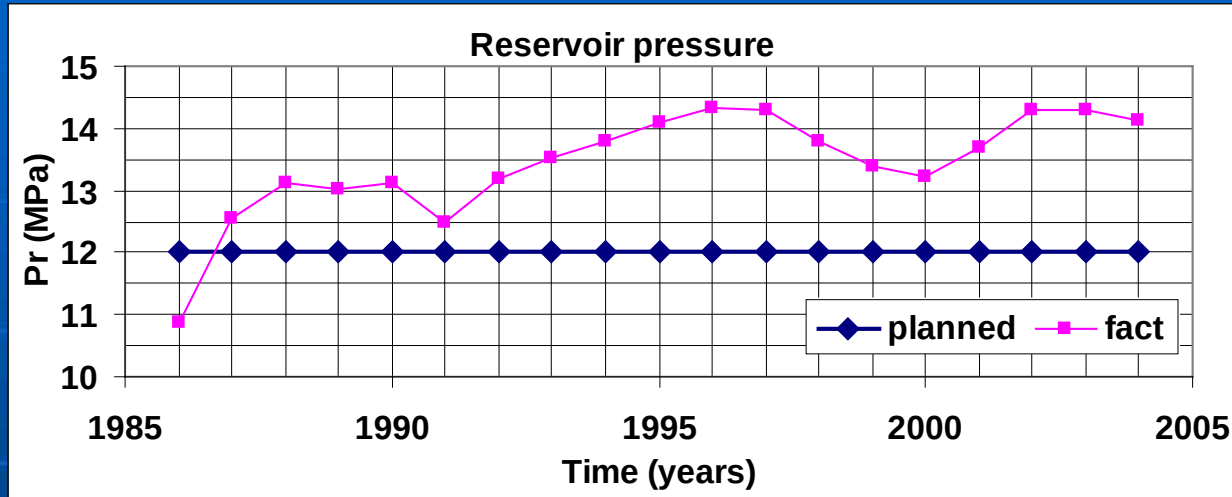
WAG and water injection 1984-2004

Plans and facts – Version 2.B.



WAG and water injection 1984-2004

Plans and facts



WAG Injection 1986-1996

Injection wells	WAG injection	
	Gi(10 ⁶ m3)	Wi(10 ³ m3)
<i>Pf -41</i>	5,8	22,8
Pf -47	4,4	14,2
Pf -83	4,9	7,9
<i>Pf -140</i>		7,0
Pf -146	8,7	24,6
Pf -148	6,3	14,4
<i>Pf -152</i>		4,9
Pf -153	5,1	20,0
<i>Pf -170</i>		7,4
Pf -174	4,4	6,8
Pf -175	5,5	5,3

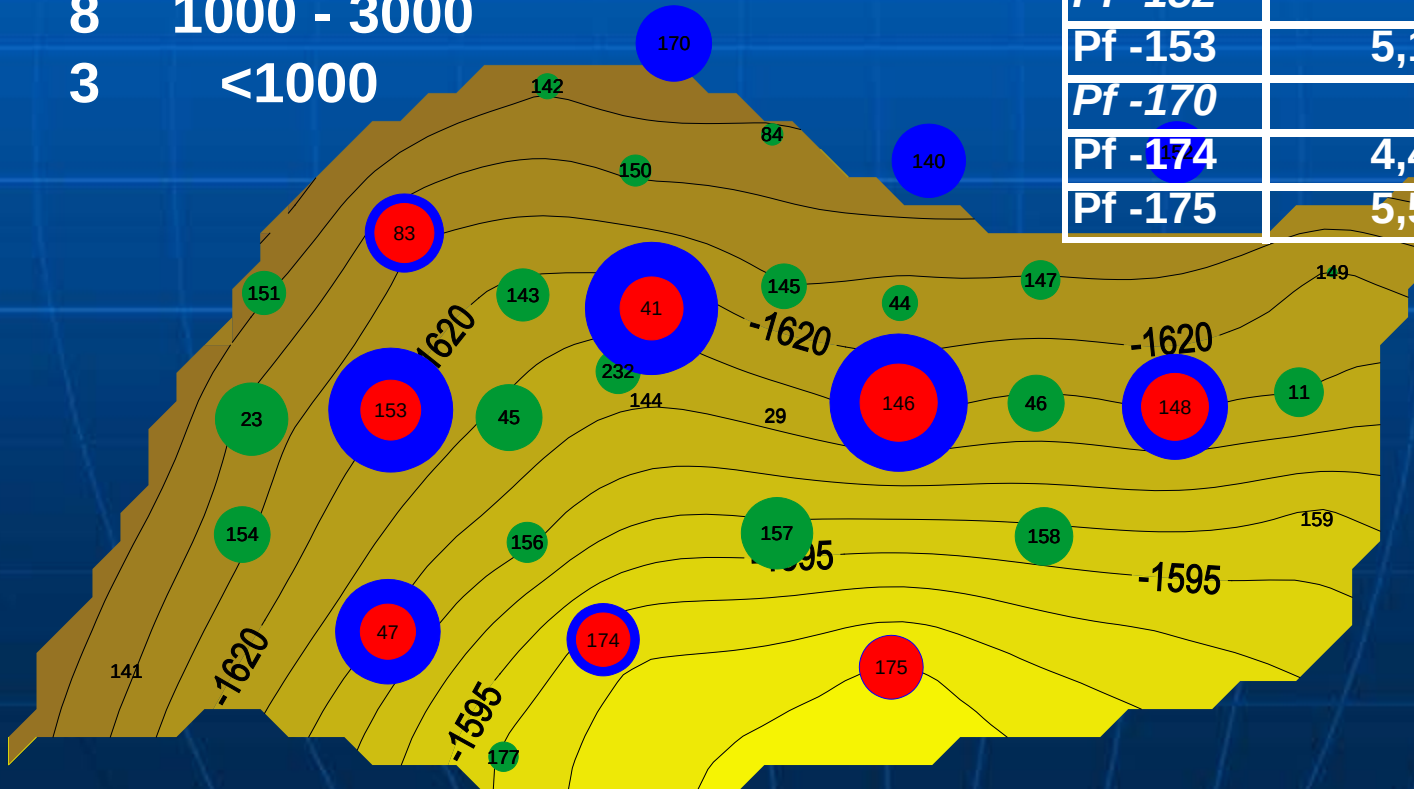
wells	Np (m3)
1	100
2	200
3	300
4	400
5	500
6	600
7	700
8	800
9	900
10	1000
11	1100
12	1200
13	1300
14	1400
15	1500
16	1600
17	1700
18	1800
19	1900
20	2000
21	2100
22	2200
23	2300
24	2400
25	2500
26	2600
27	2700
28	2800
29	2900
30	3000
31	3100
32	3200
33	3300
34	3400
35	3500
36	3600
37	3700
38	3800
39	3900
40	4000
41	4100
42	4200
43	4300
44	4400
45	4500
46	4600
47	4700
48	4800
49	4900
50	5000
51	5100
52	5200
53	5300
54	5400
55	5500
56	5600
57	5700
58	5800
59	5900
60	6000
61	6100
62	6200
63	6300
64	6400
65	6500
66	6600
67	6700
68	6800
69	6900
70	7000
71	7100
72	7200
73	7300
74	7400
75	7500
76	7600
77	7700
78	7800
79	7900
80	8000
81	8100
82	8200
83	8300
84	8400
85	8500
86	8600
87	8700
88	8800
89	8900
90	9000
91	9100
92	9200
93	9300
94	9400
95	9500
96	9600
97	9700
98	9800
99	9900
100	10000

3 5000 - 7000

5 3000 - 5000

8 1000 - 3000

3 <1000



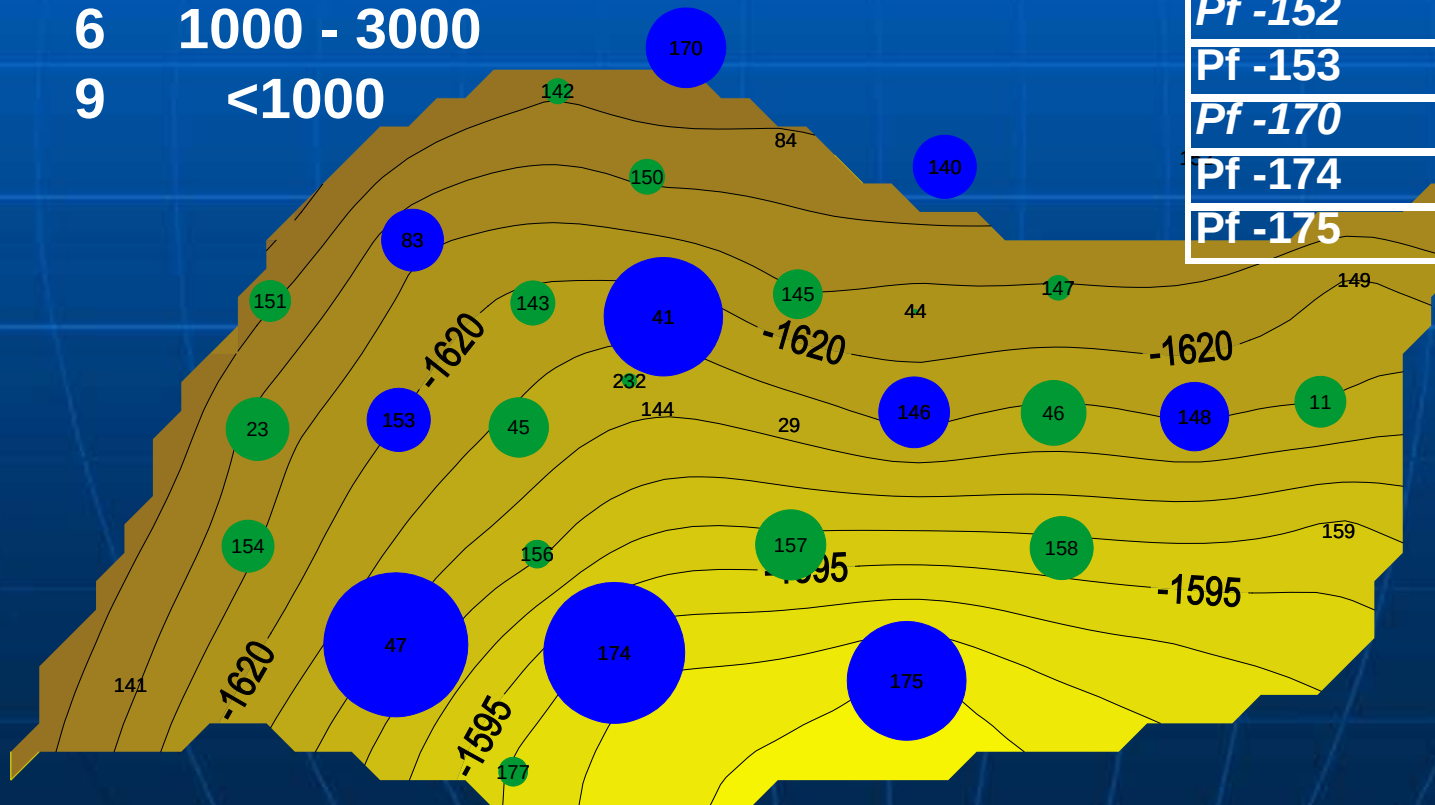
WAG and water injection 1984-2004

Water Injection 1997-2004

wells Np (m3)

1	5000 - 6000
4	3000 - 5000
6	1000 - 3000
9	<1000

Injection wells	Wi (10 ³ m3)
<i>Pf -41</i>	17,7
<i>Pf -47</i>	26,2
<i>Pf -83</i>	4,8
<i>Pf -140</i>	5,1
<i>Pf -146</i>	6,3
<i>Pf -148</i>	5,9
<i>Pf -152</i>	
<i>Pf -153</i>	5,0
<i>Pf -170</i>	8,0
<i>Pf -174</i>	25,1
<i>Pf -175</i>	17,8



WAG and water injection 1984-2004

Summary

$F_{wl}=50 \Rightarrow 83 \%$

$P_r=10,3 \Rightarrow 14,1 \text{ MPa}$

$G_i=45,3 \cdot 10^6 \text{ m}^3$

$W_i=257,5 \cdot 10^3 \text{ m}^3$

All wells sucker rod pump

$N_p = 92,8 \cdot 10^3 \text{ m}^3$

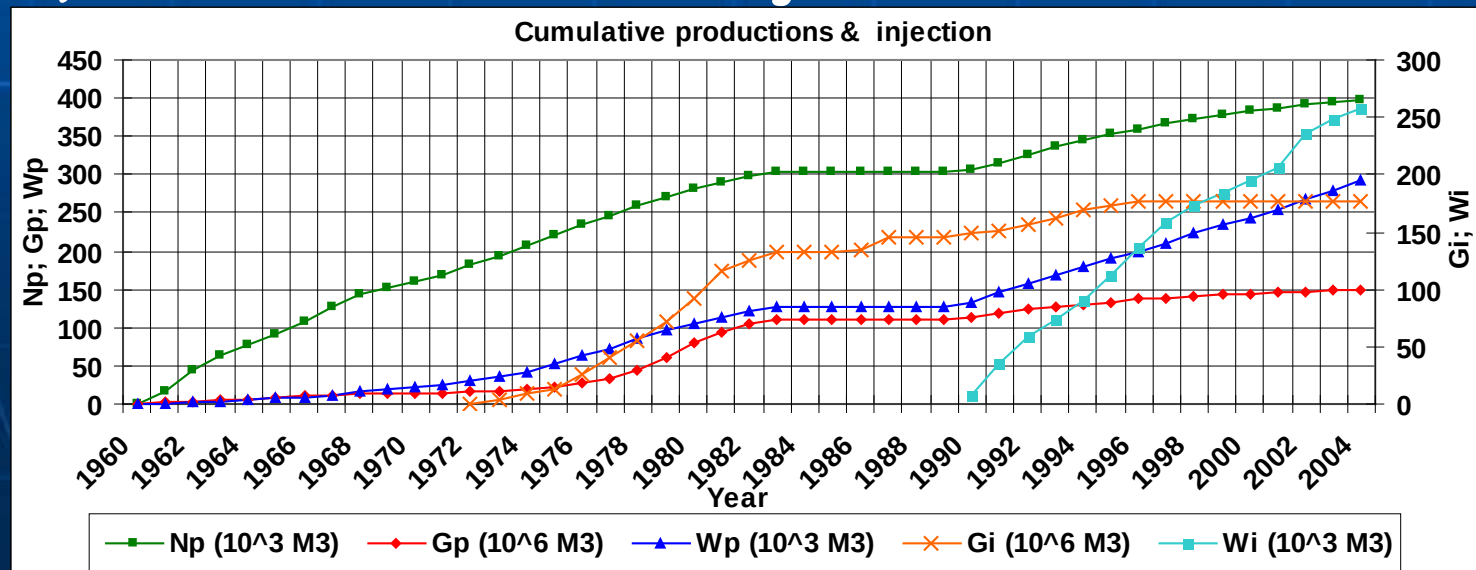
$G_p = 39,2 \cdot 10^6 \text{ m}^3$

$W_p = 164,3 \cdot 10^3 \text{ m}^3$

$\text{Rec.F} = 28,5 \Rightarrow 37,3\%$

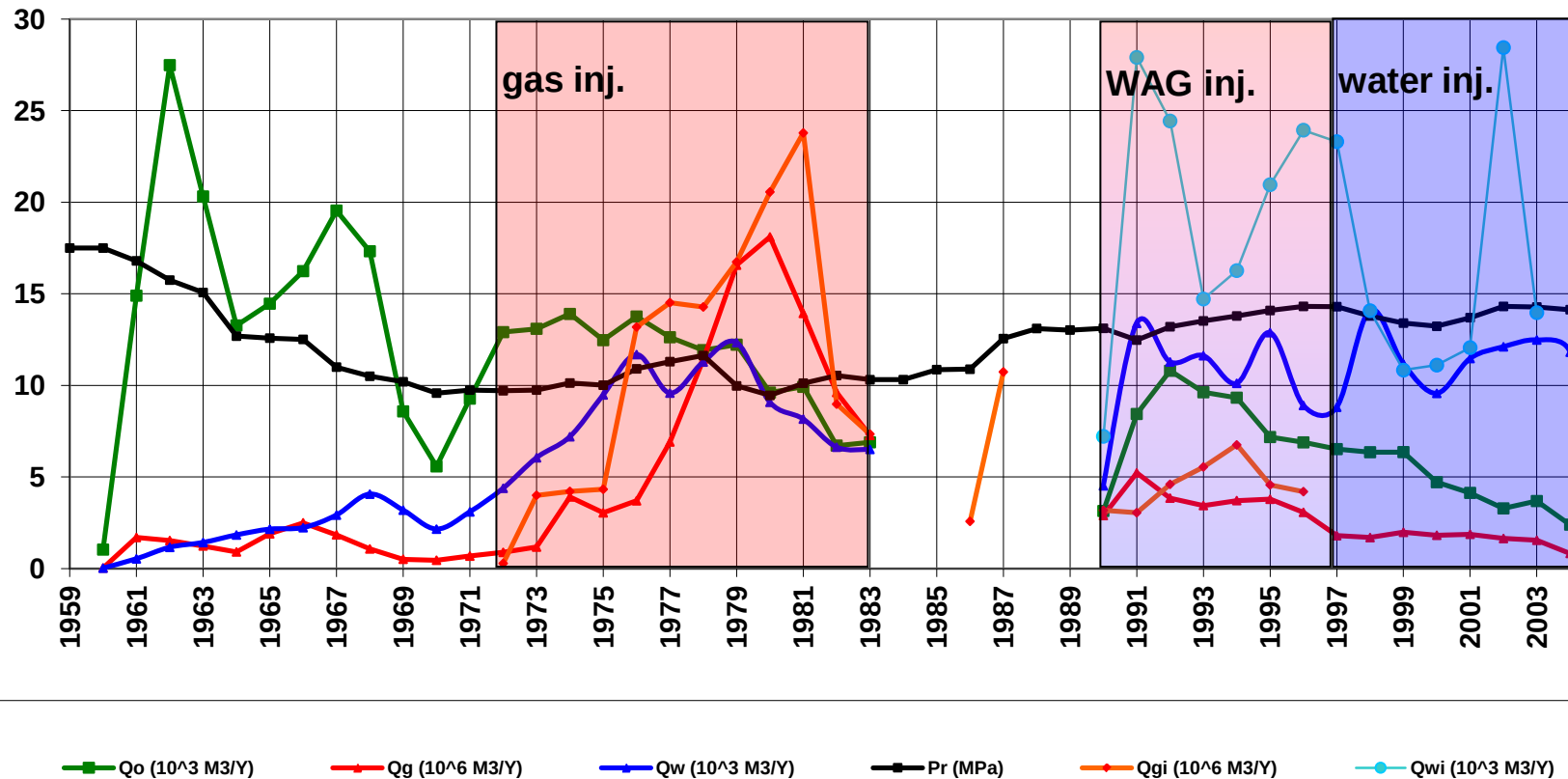
No. of prod. wells 20 $\Rightarrow$ 11

$N_p=396,9 \cdot 10^3 \text{ m}^3 \Rightarrow 293,6 \cdot 10^3 \text{ primary} + 62,2 \cdot 10^3 \text{ CO}_2 \text{ inj.} + 41,1 \cdot 10^3 \text{ m}^3 \text{ WAG+water injection}$

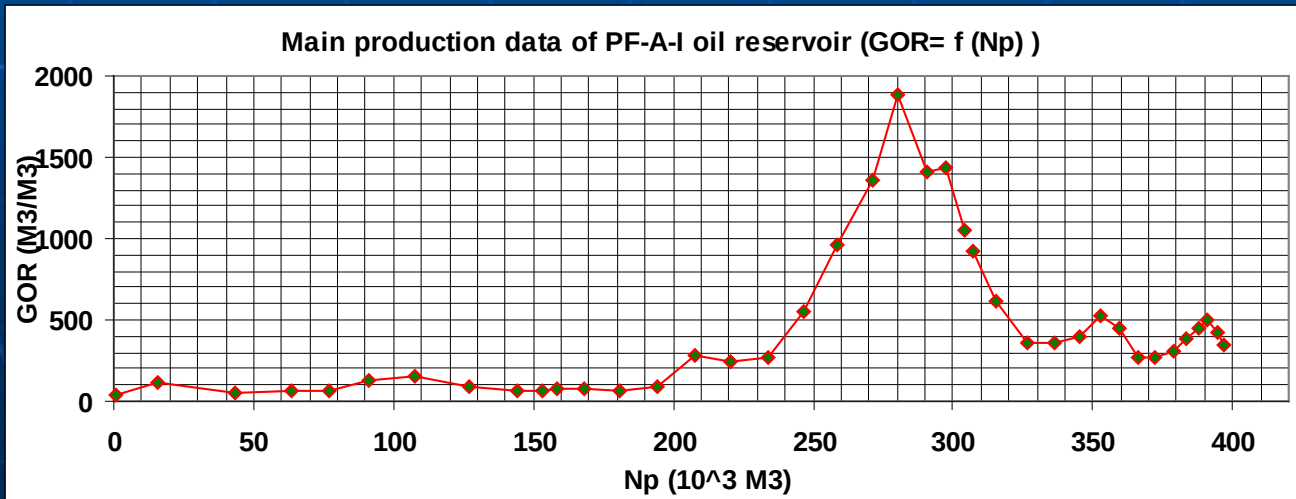
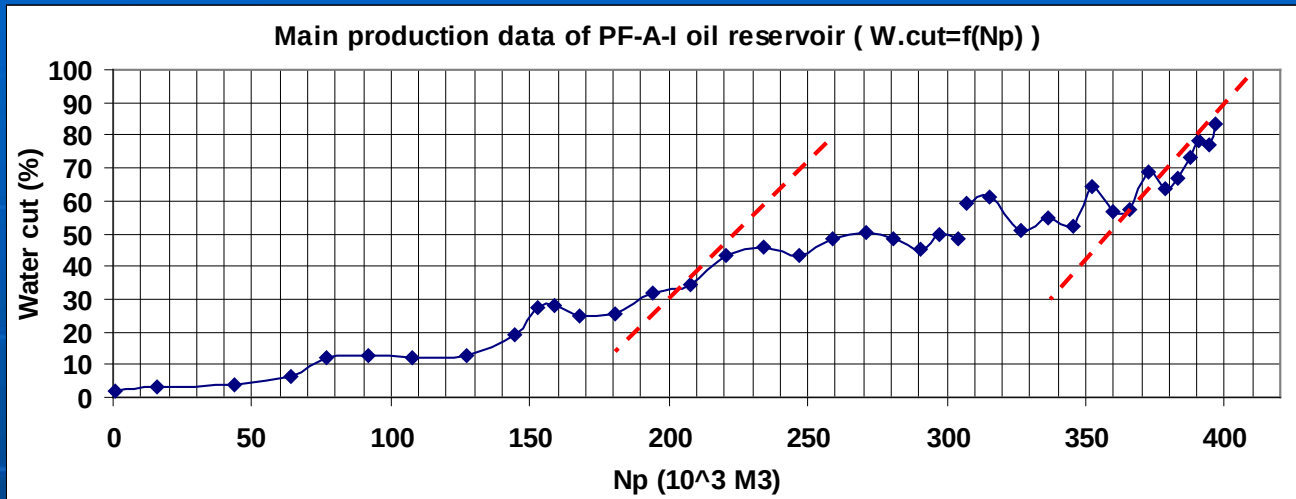


Primary+CO₂+WAG+water injection 1960-2004

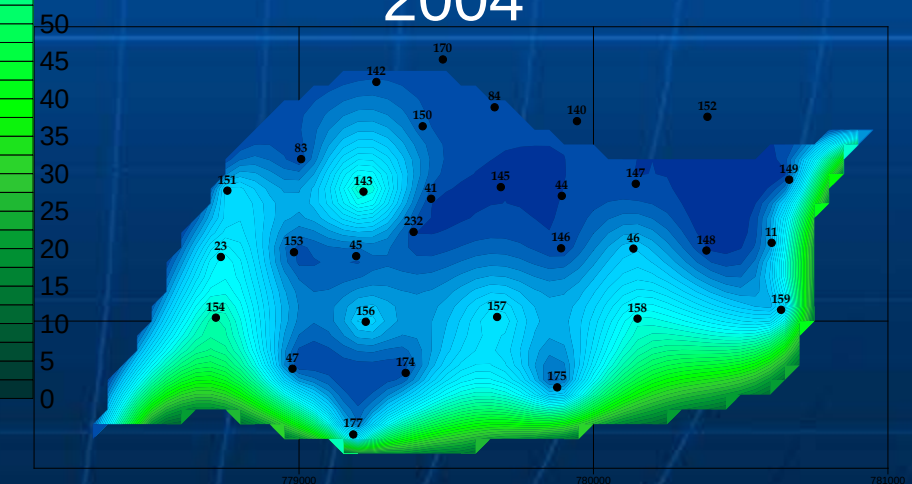
Main production data of PF-A-I oil reservoir



Primary+CO₂+WAG+water injection 1960-2004

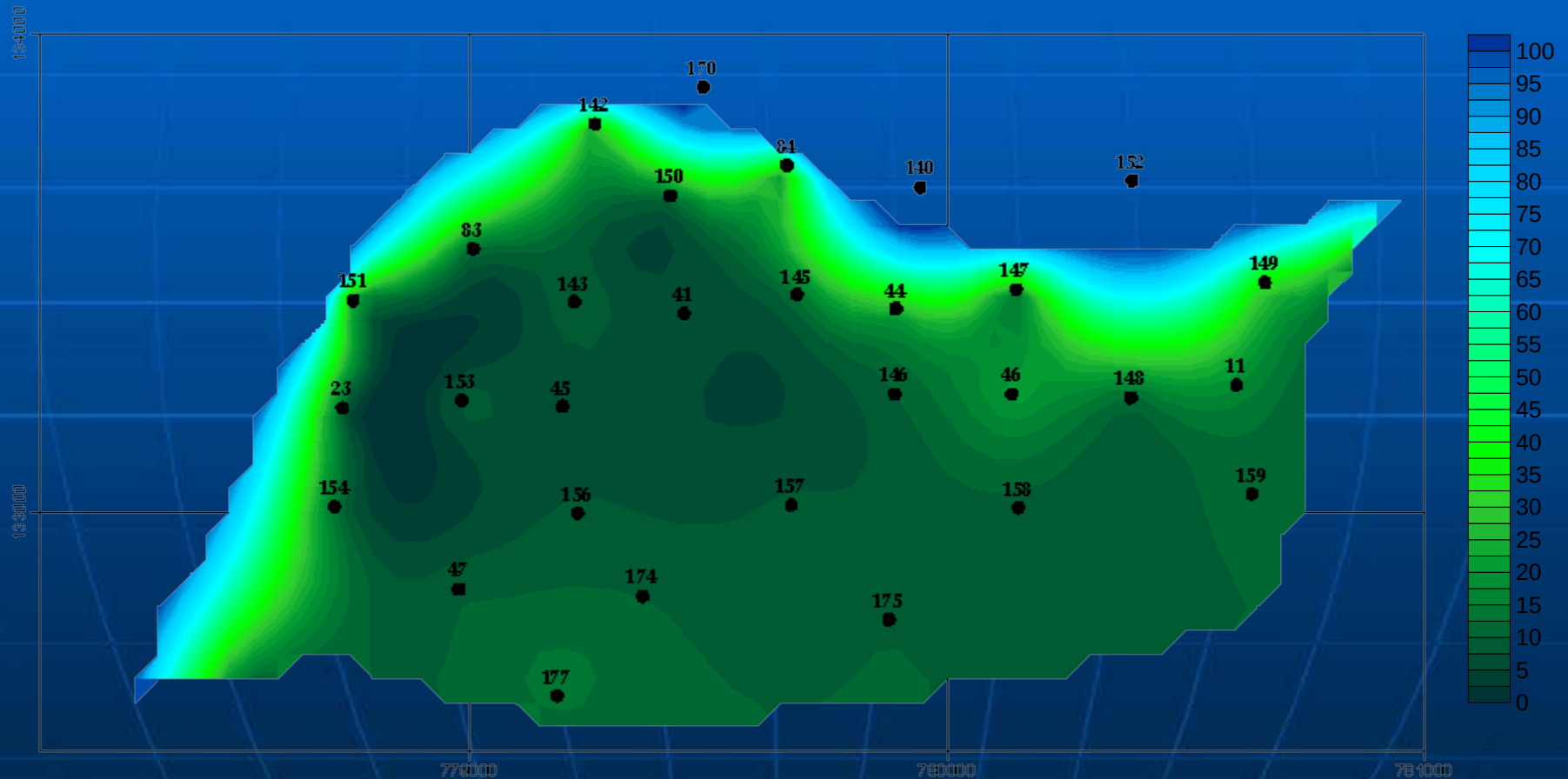


Water cut in:1973



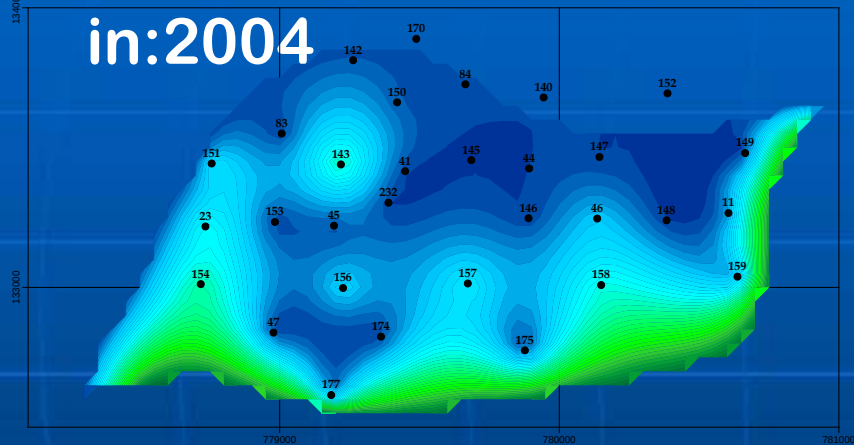
Primary+CO₂+WAG+water injection 1960-2004

Water cut changing 1973-1983 & 1990-2004

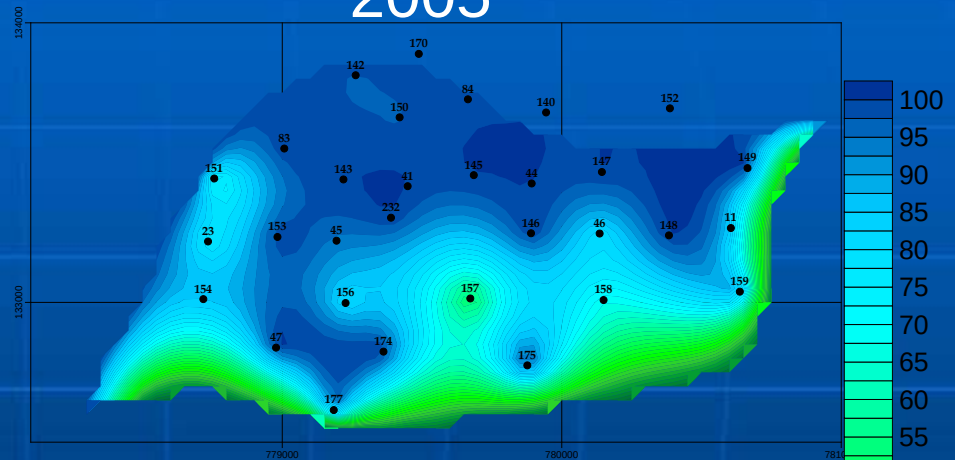


„Primary recovery” 2005- (2013)

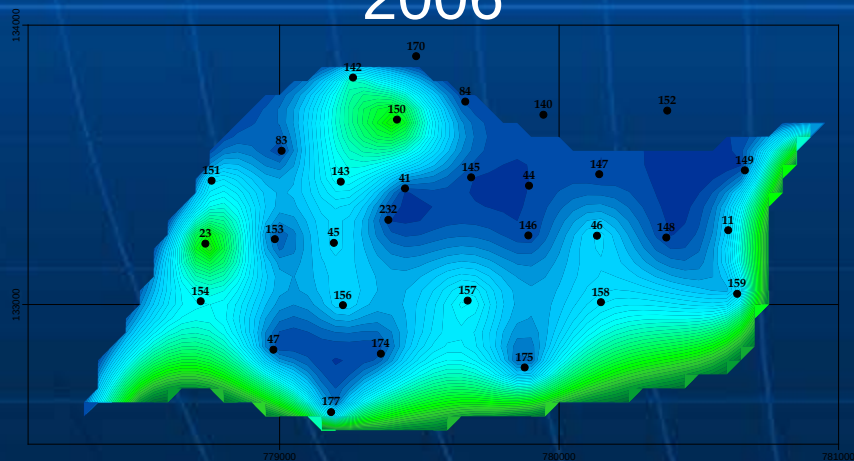
Water cut
in:2004



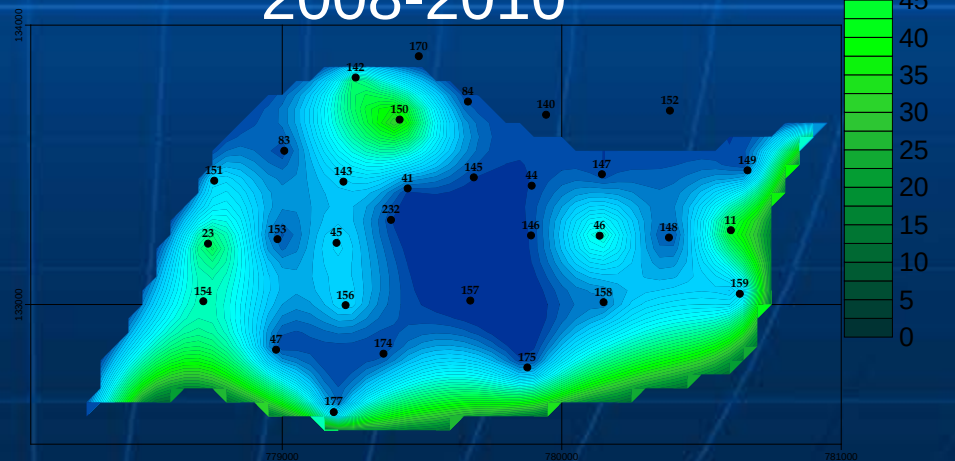
2005



2006



2008-2010



„Primary recovery” 2005- (2013) Summary

Fwl = 83,1 $\Rightarrow$ 80,5 %

Pr = 14,1 $\Rightarrow$ 12,5 MPa

All wells sucker rod pump

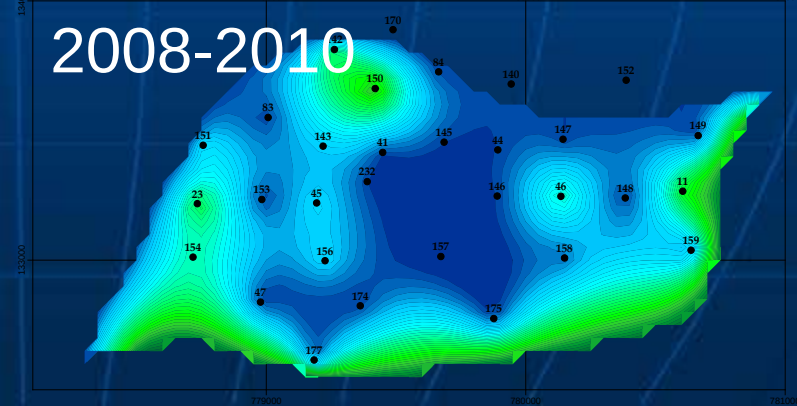
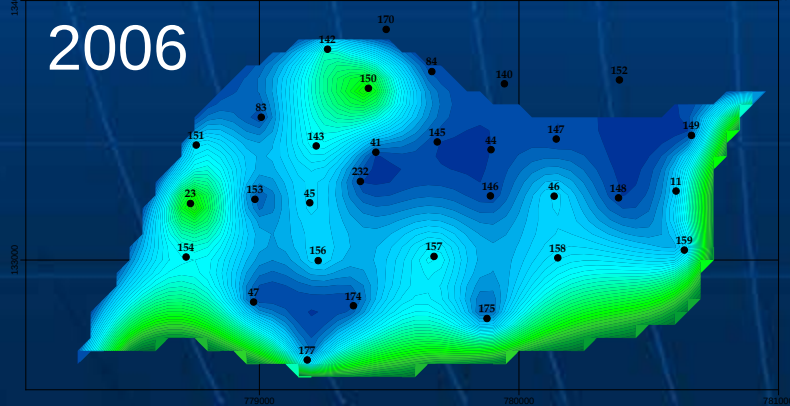
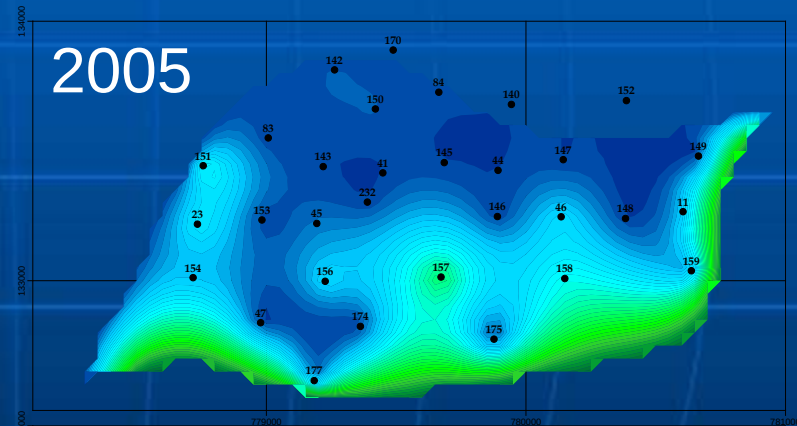
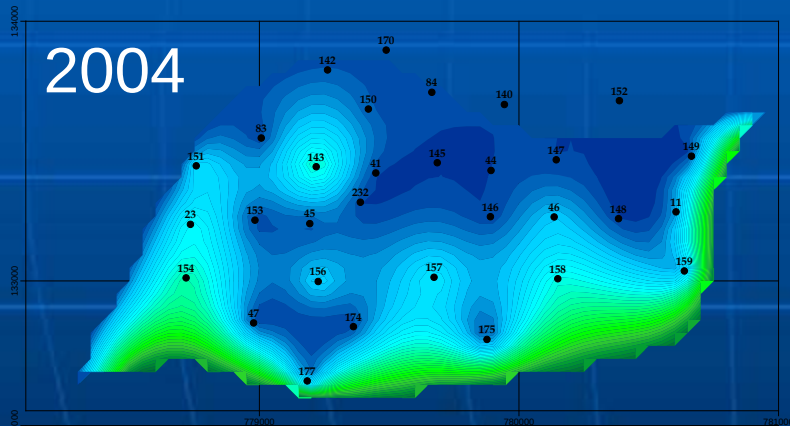
No. of prod. wells: 8

Np = $18,7 \cdot 10^3 \text{ m}^3$

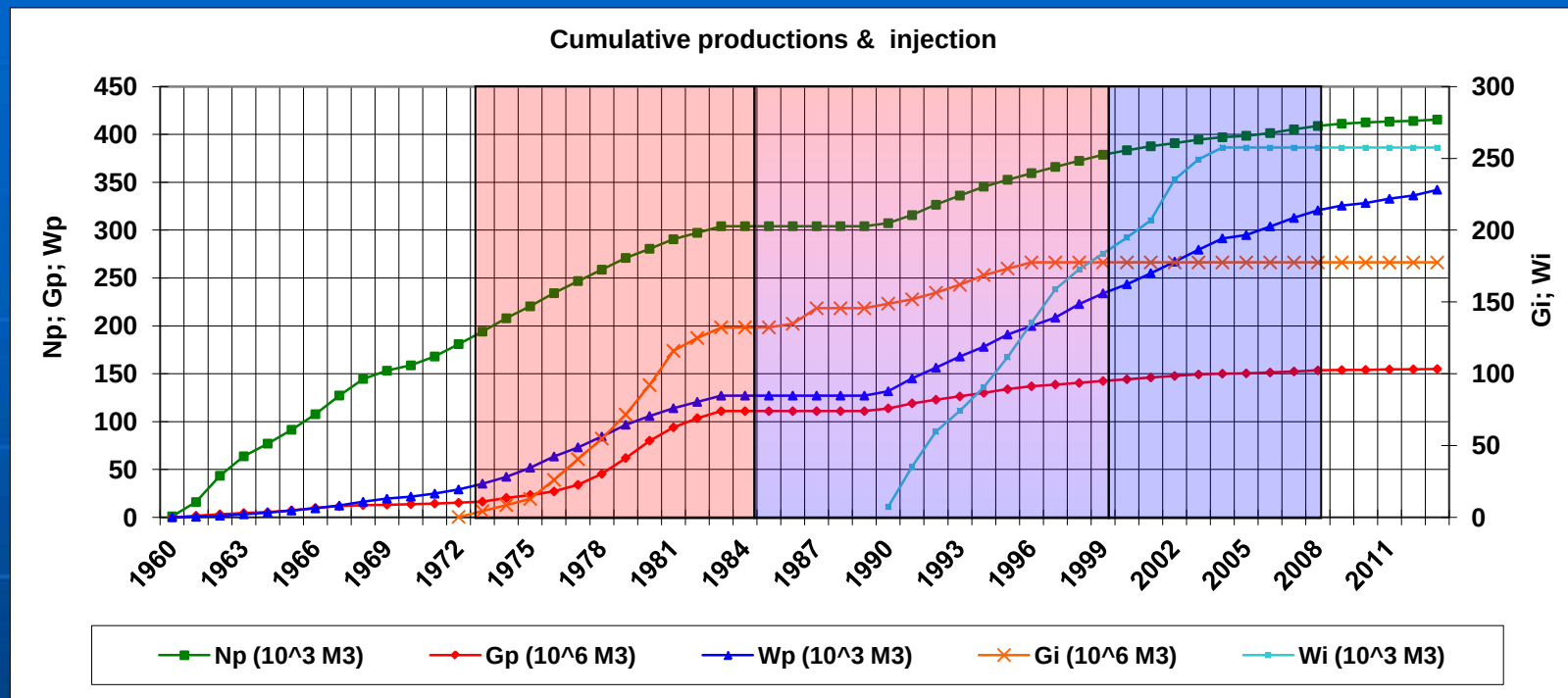
Gp = $4,9 \cdot 10^6 \text{ m}^3$

Wp = $51,1 \cdot 10^3 \text{ m}^3$

Rec.F = 37,3 $\Rightarrow$ 38,97%



SUMMARY



Oil production (10^3 m³)

Primary oil rec. 293,6

CO₂ injection 62,2

WAG+water inj. 59,7

Total 415,5

Rec.F (%)

27,6

5,8

5,6

38,97

Gp= $155,0 \cdot 10^6$ m³

Gi = $177,5 \cdot 10^6$ m³

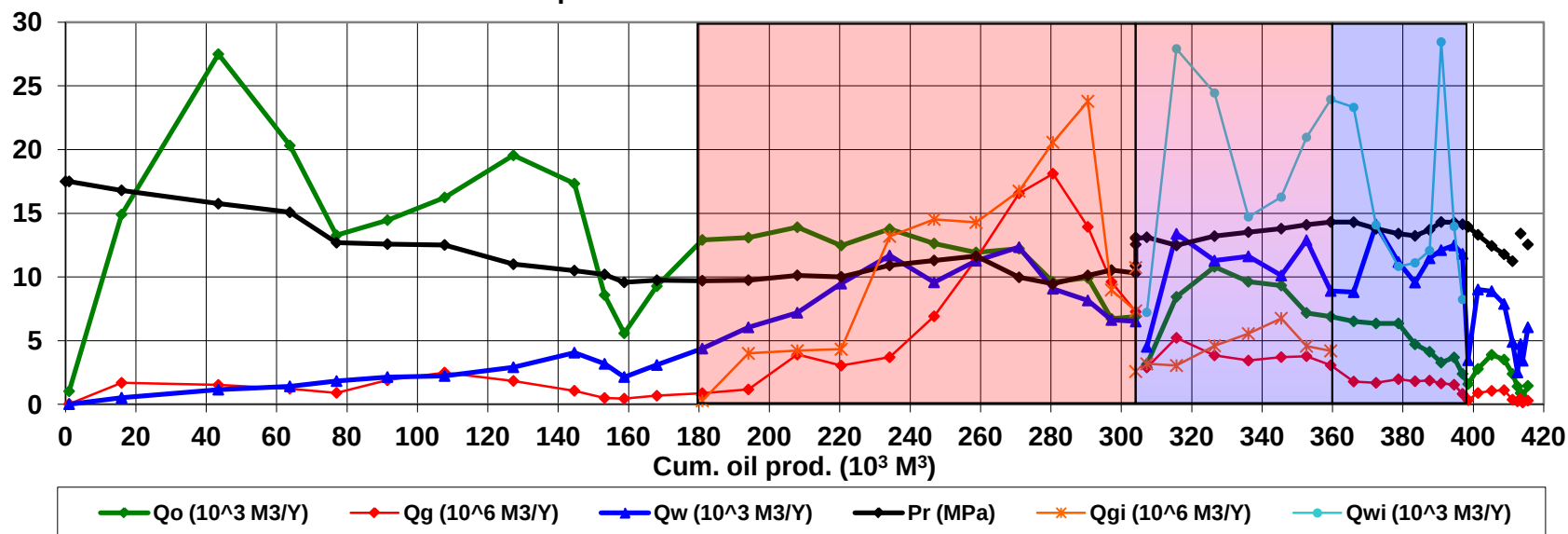
Wp= $342,2 \cdot 10^3$ m³

Wi = $257,5 \cdot 10^3$ m³

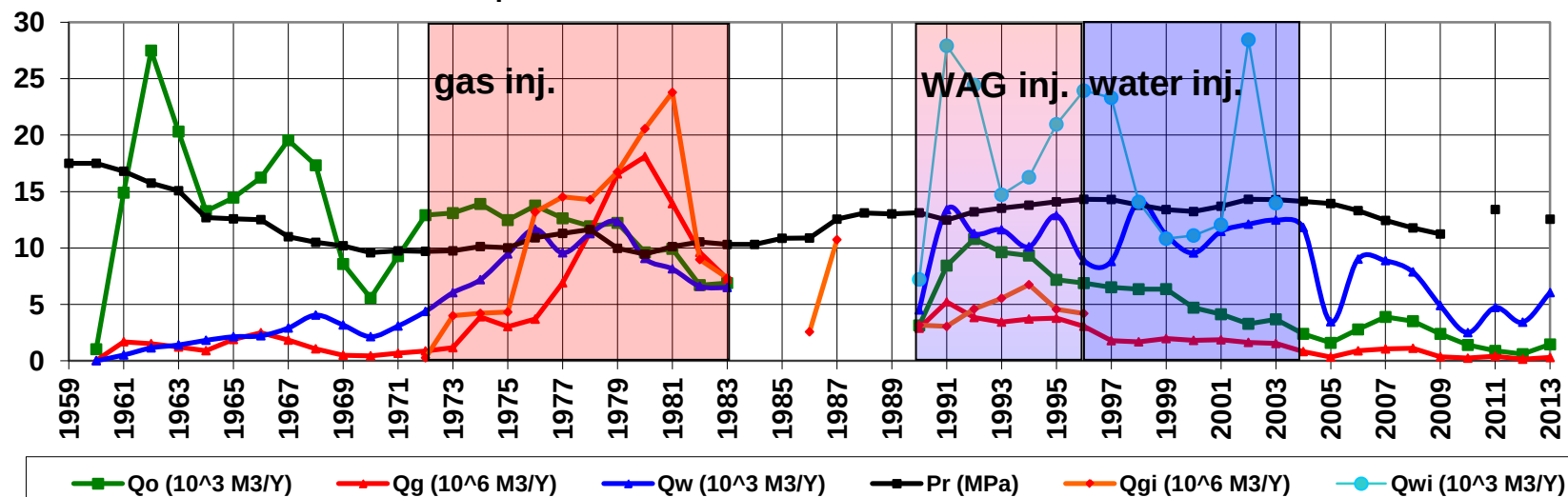
Pr= 17,4 $\Rightarrow$ 12,5 MPa

SUMMARY

Main production data of PF-A-I oil reservoir



Main production data of PF-A-I oil reservoir



**Thank you for your
attention!**