4 History Match

4.1 Phase 4 model changes

Compared to the previous Phase 2, some changes have been made to the models. The main change was the creation of new static models that did not need a pore volume multiplier ('MULTPV') to attain the correct static volumes, which ranged in the previous phase between 1.15 and 1.19. To achieve this, the seismic uncertainty on the top structure was used to create higher top-ROSLU-maps, see section 2.2. The new static models are called INTERA / INTERB, depending on the distribution of extra volume more to the north or in the middle of the model. A second change was to incorporate the more easterly continuation of the main-bounding fault, also know as 'ALT5'. This fault makes the MAIN compartment smaller relative to the previous models that had the more northerly lying fault 'ALT2'. The BGM-7 compartment logically has a larger pore-volume with the ALT5 fault and as a result of the higher reservoir pressure in block-2 than block-1 (ca 24 bar vs. 12 bar) in June 2008, the remaining Gas-In-Place is also little higher.

	GIIP [Bscm]			GIIP [Bscm] 1 Juni 2008			Pavg_reservoir [bara] 1 Juni 2008	
Run	block I	block II	TOTAL	block I	block II	TOTAL	block I	block II
BGM_InterA_dismid_alt2_bell050	13.158	4.508	17.665	0.703	0.426	1.129	14.0	22.0
BGM_InterB_dismid_alt2_bell050	13.415	4.221	17.636	0.635	0.447	1.082	12.7	23.9
BGM_InterA_dismid_alt2_bell080	13.158	4.508	17.665	0.686	0.425	1.111	13.7	21.6
BGM_InterB_dismid_alt5_bell033	11.743	6.068	17.811	0.619	0.677	1.296	14.3	24.9
BGM_InterA_dismid_alt2_bell050_LowCushion	13.076	4.507	17.583	0.708	0.352	1.060	14.5	24.7
BGM_HighP_alt5_bfls	12.230	5.727	17.956	0.694	0.743	1.437	16.0	26.9

Table 4-1 GIIP and reservoir pressure at beginning and end of history match, phase 4 models. The summer injection test of 2007 and 2008 production is included. The initial reservoir pressure is 227.8 bara at 2100 m tvdss.

Other changes that were made for the Phase 4 models are a.o. a refinement of the top ROSLU section. It was found that where the future horizontal UGS-wells were planned, the permeability increases with 8.6% per m, or a factor 2 per 8 m, see section 5.4. With a reduced cell-thickness the models are more accurate on the expected productivity. A new case was made, the HIGHP case, in which the lower permeabilities in the top ROSLU were not modified with the BELL multipliers, but rather, the porosity trend was put in correctly, after which the permeability was correlated normally, see section 2.3. Later in this chapter, the productivity of BGM-7 is discussed again.

4.2 Realizations

It was tried to create extra models compared to Phase2 that would capture the range of uncertainty for the future (horizontal) wells and the behaviour of the UGS better. The range in productivity created by the BELL-multipliers (BELL033/BELL050/BELL088) has the most effect on the future verticals wells in the MAIN compartment. To also create a low case productivity for the horizontal wells in the top ROSLU, the HIGHP scenario was created, in which the permeability in the top ROSLU was significantly decreased. In order to increase the hysteresis effect during the UGS cycles, extra baffles were included in the BGM-7 block for this realisation. Although the base case was run both with InterB and InterA to compare the difference in the UGS phase, the InterA realisation was chosen as the base case as it was more conservative on hysteresis effects.

		Top	Aqf	Comp	fault	xtra bfls	v-prod	h-prod
Base	BGM_InterA_dismid_alt2_bell050	N uplift	no	base	alt2		base	base/high
BaseProp	BGM_InterB_dismid_alt2_bell050	0.4	no	base	alt2		base	base/high
HighProd	BGM_InterA_dismid_alt2_bell080	N uplift	no	base	alt2		high	high
LowVProd	BGM_InterB_dismid_alt5_bell033	0.4	no	base	alt5		low	base/low
LowCushion	BGM_InterA_dismid_alt2_bell050_LowCushion	N uplift	fet	high+irrevers	alt2		base	base/high
LowHprod	BGM_HighP_alt5_bfls	1.0	no	base	alt5	yes	base	low

Table 4-2 Phase 4 realisations.

Another change to the range of models used in Phase2, was to get a scenario with external aquifer attached to Bergermeer (such a scenario was run in Phase1). Although the P/Z curve, the GWC measurements in BGM-1 and the Groet-Bergermeer pressure history do not indicate there is any aquifer, it was found that the history does leave room for a small aquifer, with the majority of the water influx towards the end of the historical period. This case eventually indicated what the possible amount of water-invasion could be, thus establishing a lower bound estimate for the amount of cushion gas for the UGS. The aquifer modeling is discussed in detail in section 4.4.

4.3 History Match Results

The newly created models were history matched in the same way as for the Phase2 models, with two exceptions. Due to the porosity log corrections & well test matching the permeabilities have decreased somewhat. The resulting tendency of the BGM1 GWC to rise is countered by adding a specific permeability multiplier (< 1) for the water leg gridblocks. In addition, the permeability in the grid-blocks in which BGM7 was completed did not include the BELL-multiplier. This is needed because if the rising water table covers the bottom perforations, the BGM7 gas PI decreases so much that the well cannot make its historic rates. If this gas rate mismatch is significant, a pressure match is no longer achievable. Still, water-production in BGM7 through coning could not be avoided in most realisations. The base case has some 2500 sm3 being produced at the end of HM, accompanied by a small cumulative gas-production mismatch in BGM7. It was found that applying an LGR around this well *in addition* to not applying the bell multiplier, reduced the water-cone to below the perforations (Figure 4-1, Figure 4-2), thus attaining the historical gas production. As prediction of the BGM7 well was not a major aim of the study, and the projected horizontals suffer a lot less from coning, this LGR was not pursued in the normal runs. It does highlight, however, the unsatisfactory character of the bell multiplier, and the need to handle this in a better way (cf. the 'HIGHP' scenario; see section 2.3) if the model is updated in the future.

The pressure matches were less difficult to constrain. In some cases a PV-multiplier a few % from 1 was still needed to match the runs.

Furthermore, the low cushion case was designed to define the minimum amount of cushion gas needed. Apart from a Fetkovich aquifer attached to the north of Block-2, irreversible compaction was also included. The aquifer has a pore-volume of 2e9 rm3 and PI of only 5 sm3/d/bar, a higher PI gave too much water production in BGM-7. The pore-volume was estimated to be available in the blocks surrounded by Bergermeer. It is however doubtful that such an aquifer could exist; as water keeps on invading during the UGS phase, the reservoir pressure in the surrounding blocks has to be higher than that in the UGS (77-133 bar). All the fields surrounding BGM are also depleted with reservoir pressures at ca 10 bar. Also, BGM-7 has seen virtually no water production, but the aquifer case produces some 10,000 m3. Numerical aquifer modeling (without the analytical Fetkovich aquifer attached) was done to investigate the size and productivity of the aquifer, see the section on aquifer sensitivities 4.4.

The compaction that was included for the low-cushion case reduces the pore-volume irreversibly. The maximum compaction possible in the aquifer case was 0.5%, defined at 1 bara with respect to initial conditions. The other runs have a base model with a rock compressibility of 1e-5 bar^{-1}.

	MULTPV	Main FLT	BFLN	BFLS	WL-MULT	XTRA BFLS	COMPAC	AQUIFER
INTERA_ALT2_BELL050	1	0.003	0.1	0.1	0.4			
INTERB_ALT2_BELL050	1.03	0.003	0.1	0.1	?			
INTERA_ALT2_BELL080	1	0.0015	0.03	0.1	0.5			
NTERB_ALT2_BELL033	1.03	0.015	0.2	0.3	0.4			
INTERA_BELL050_ALT2_LOWCUSHION	1	0.03	0.1	0.1	0.4		0.5% (irrevers.)	Fetk.
HIGHP_ALT5_BFLS	1.02	0.01	0.1	0.1	0.25	0.1		

Table 4-3 Phase 4 History Match Parameters per realization.

For the HIGHP_BFLS case, the faults that were interpreted on seismic in the north of Block-2, were given a reduced transmissibility, see Figure 4-3. Previously they were neglected, as they have no throw and their existence can not be proven, ref. Klima & Heinemann [4]. Also the baffle in the north of the MAIN UGS compartment was given a higher transmissibility than in the previous models. This was done to keep the historical pressure difference between BGM3A and BGM6 at maximum 3 bar.

The main scenario's HM QC plots are shown in Figure 4-4 to Figure 4-15. For the scenarios a GWC match is shown (for the computation of this, see ref. [1]) and a pressure match is shown. The pressure match is plotted as a deviation from a straight-line p/z plot. Plotting a 'normal' p/z is less informative because the mismatches (a few bars) are so much less than the pressure decline over the field history (200 bar).

In section 4.4 we specifically discuss the aquifer modeling that was done. Finally, section 4.5 discusses some further aspects of the GWC behavior over the HM period.

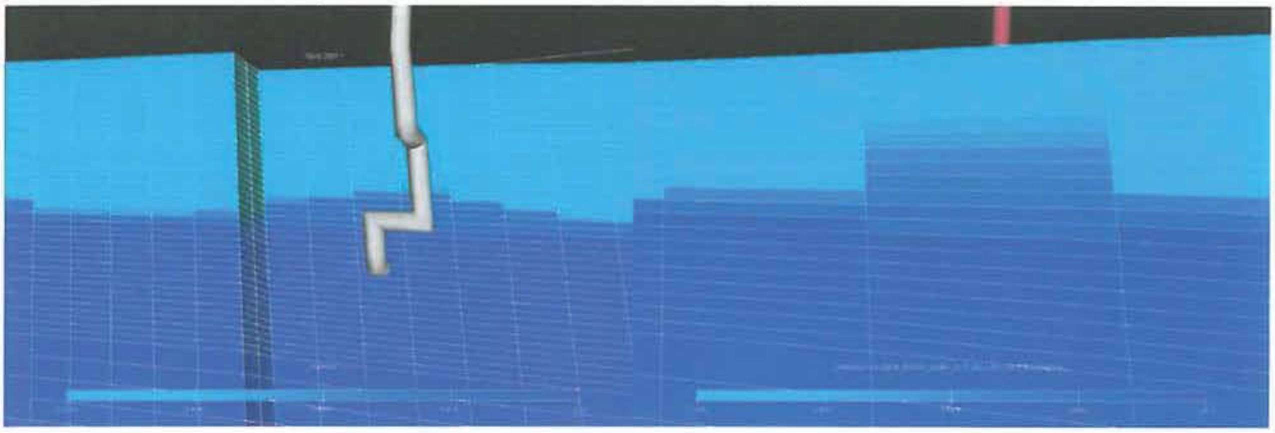

Figure 4-1 Effect of LGR on water coning behaviour. The LGR is in the picture on the left. Without LGR (right), the cone is overestimated.

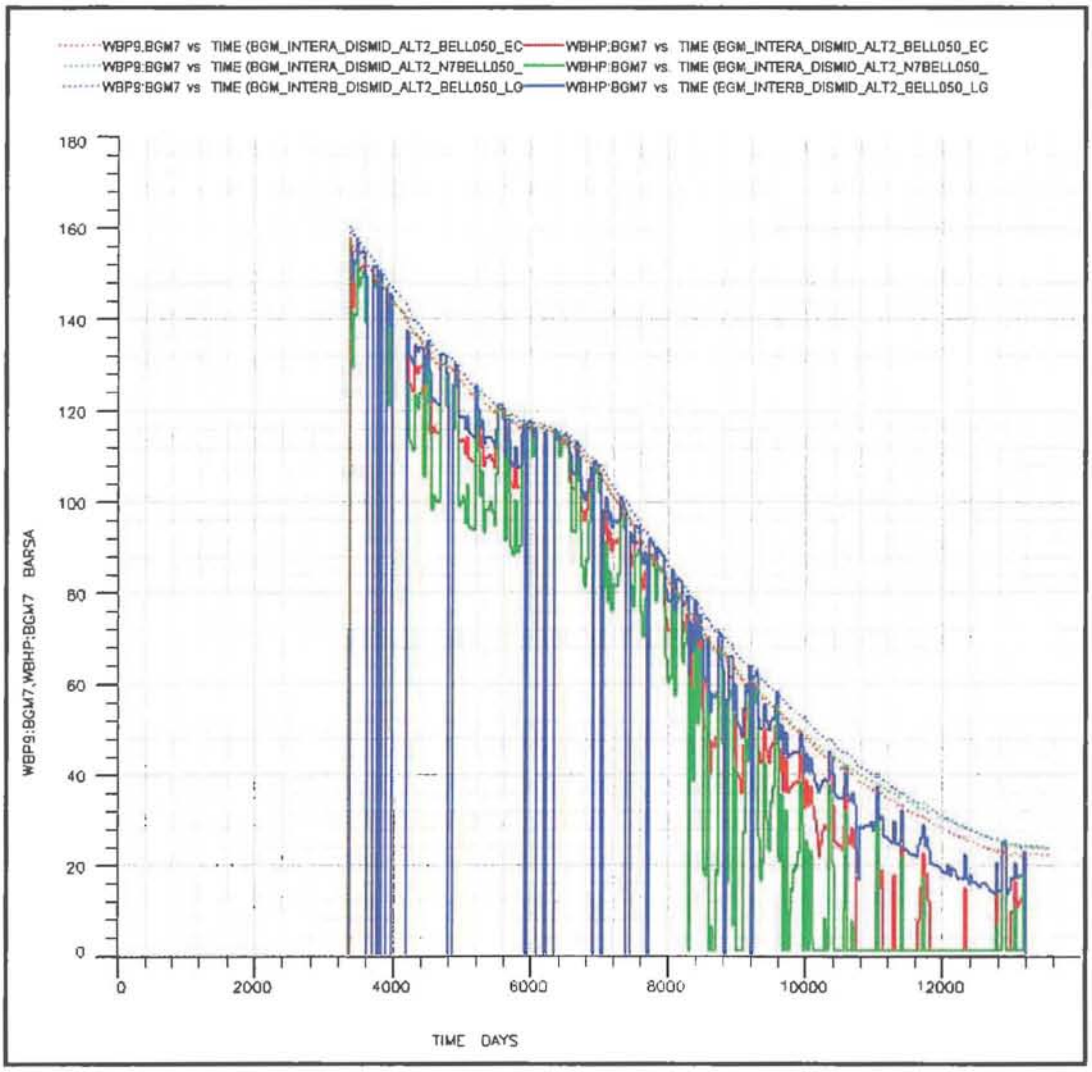

Figure 4-2 **HM comparison of WBHP in the base case (red), BC with LGR (blue) and BC with LGR and BELL multiplier (green). In the base case, without LGR, the water production is overestimated, BHP is 0 bar as water breaks through. The effect of the BELL-multiplier is stronger than the LGR as in this case water breakthrough is earlier than in the base case.**

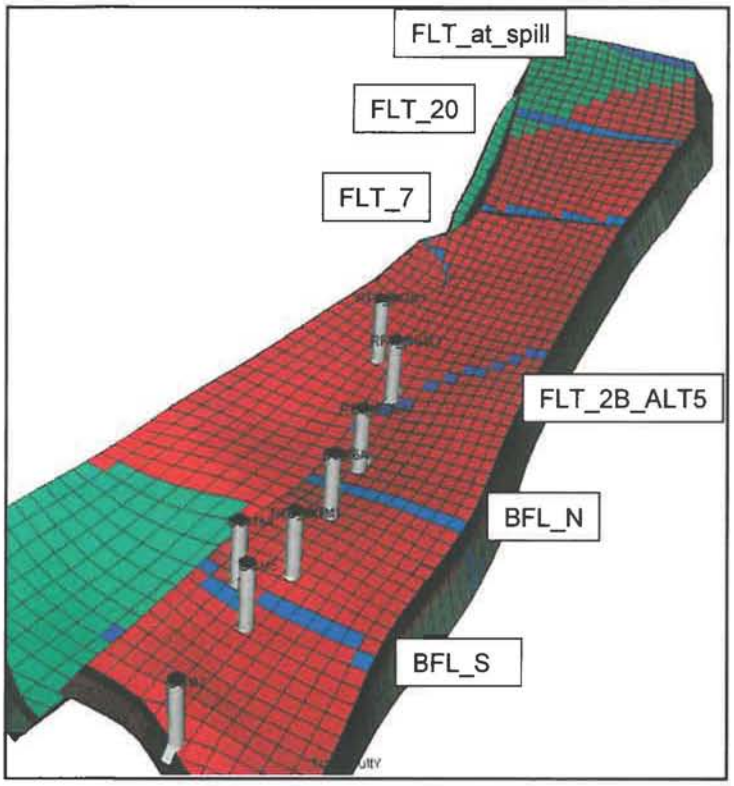

Figure 4-3 Location of baffles in HIGHP-scenario, visualised by 3D model of transmissibilities. Red is the gas-leg, green is the water-leg. The baffle-transmissibility is ca 10* that in the main fault.

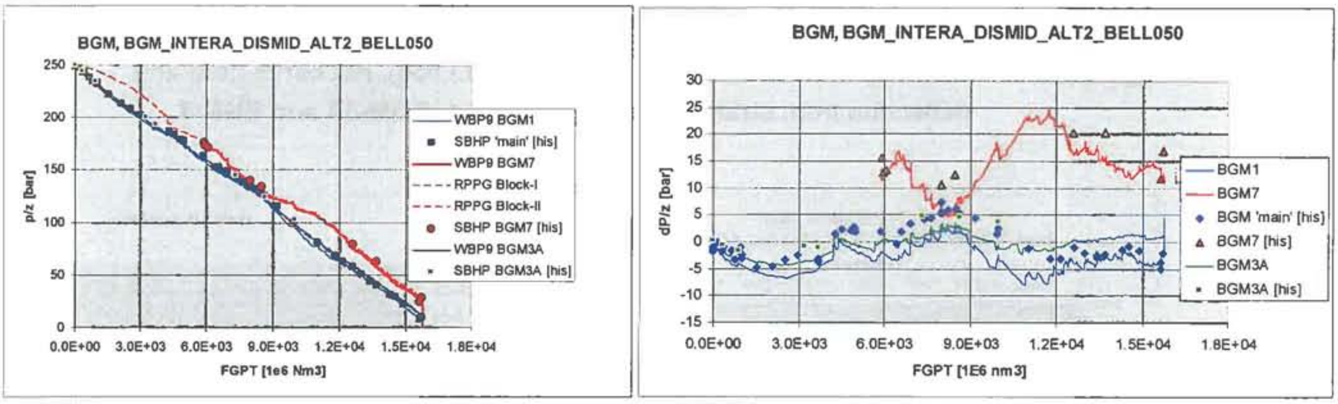

Figure 4-4 Pressure match base case (INTERA_BELL050), P/Z curve (left) and deflection from straight line (right) for BGM-1, BGM-3A and BGM-7.

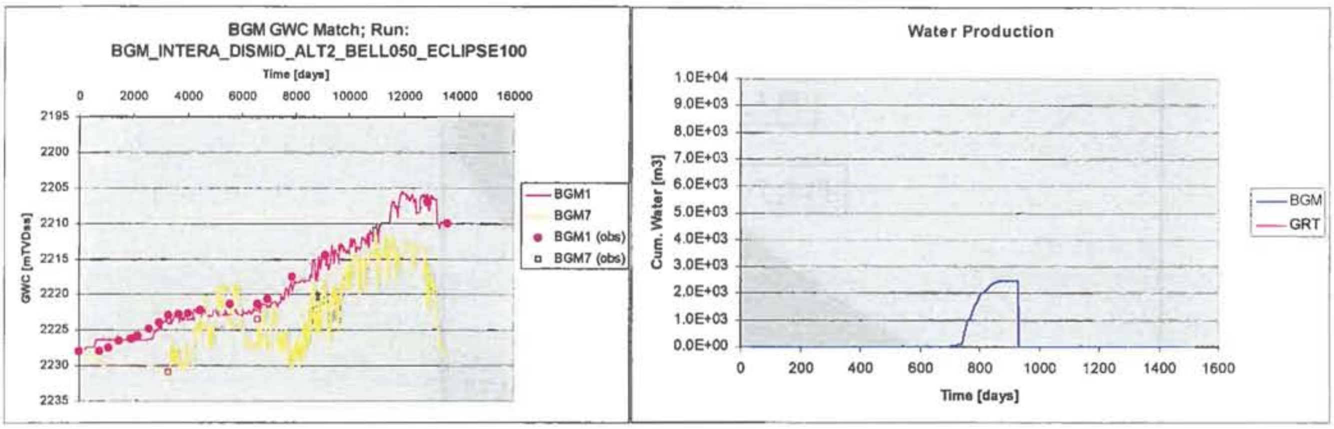

Figure 4-5 GWC-match base case (INTERA_BELL050) of BGM-1 and BGM-7 (left) and water-production BGM-7 (right).

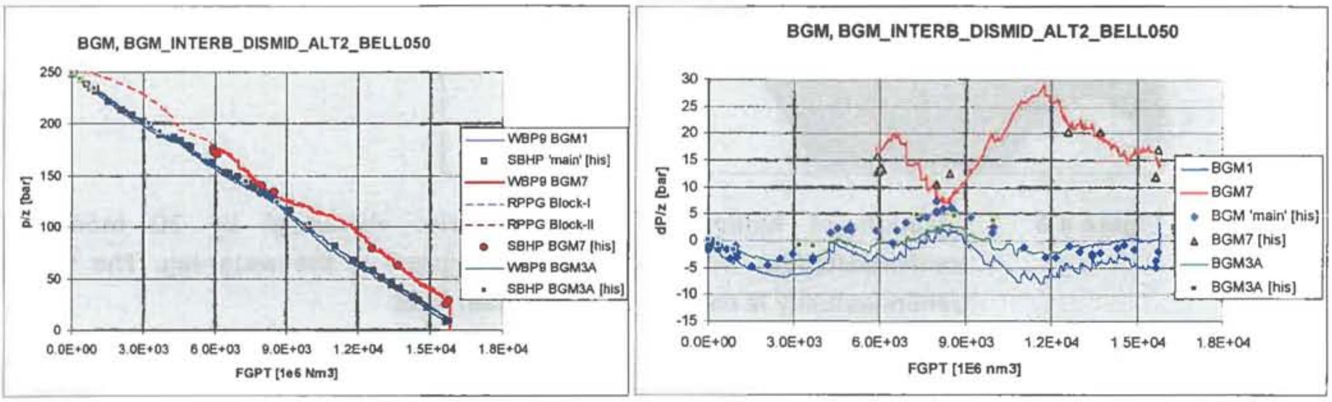

Figure 4-6 Pressure match base case (INTERB_BELL050), P/Z curve (left) and deflection from straight line (right) BGM-1, BGM-3A and BGM-7.

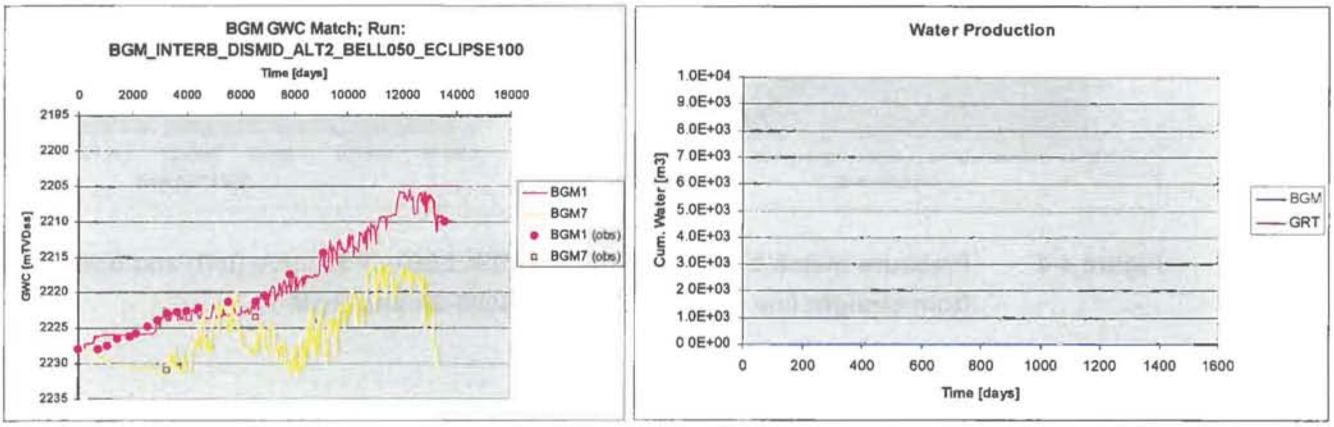

Figure 4-7 GWC-match base case (INTERB_BELL050) of BGM-1 and BGM-7 (left) and water-production BGM-7 (right).

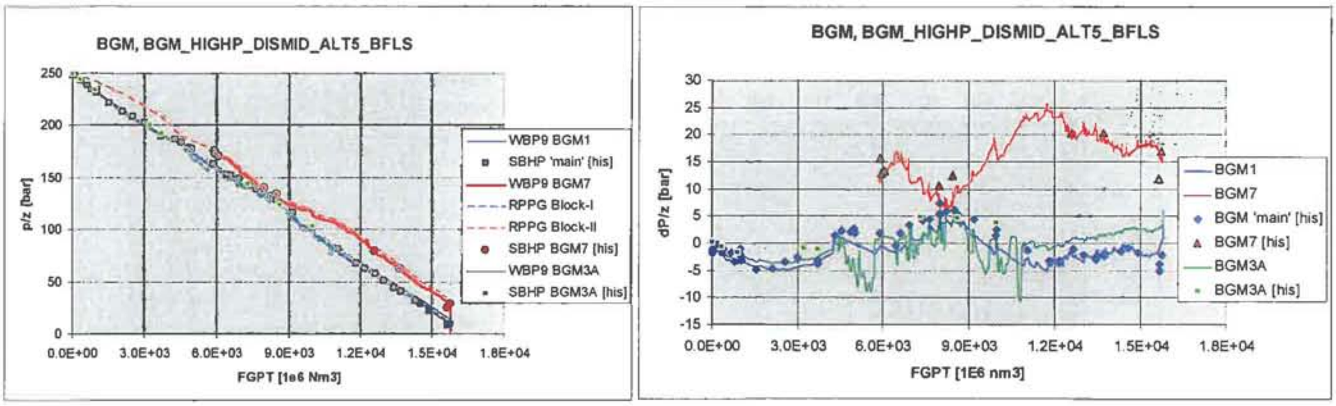

Figure 4-8 Pressure match low case horizontal productivity (HIGHP), P/Z curve (left) and deflection from straight line (right) BGM-1, BGM-3A and BGM-7.

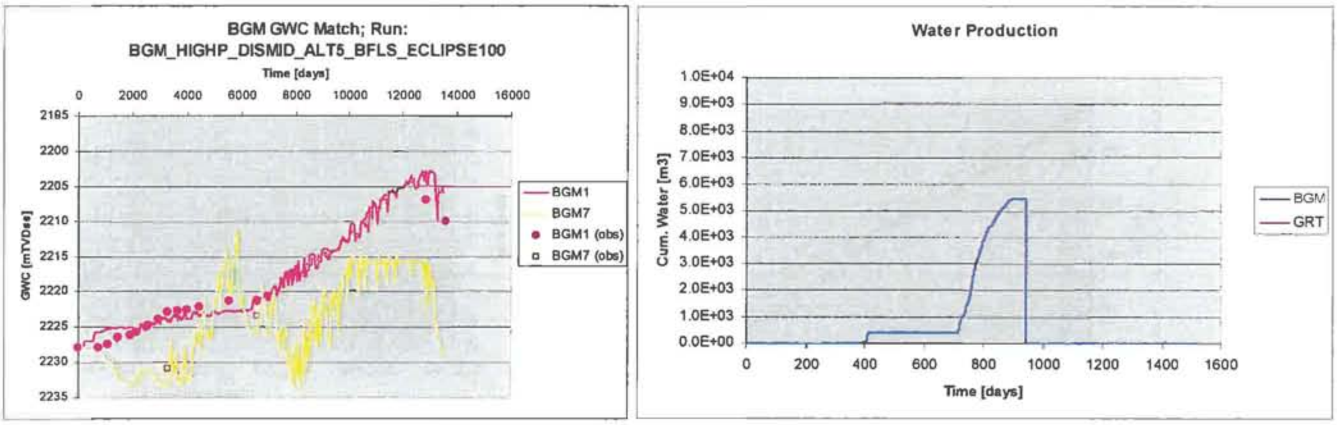

Figure 4-9 GWC-match base case (HIGHP) of BGM-1 and BGM-7 (left) and water-production BGM-7 (right).

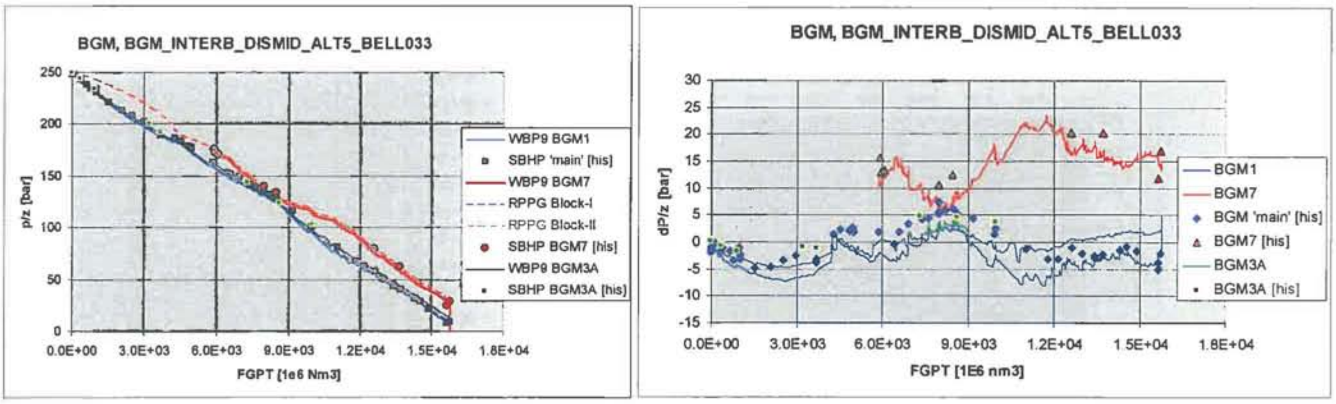

Figure 4-10 Pressure match low vertical productivity case (INTERB_BELL033), P/Z curve (left) and deflection from straight line (right) BGM-1, BGM-3A and BGM-7.

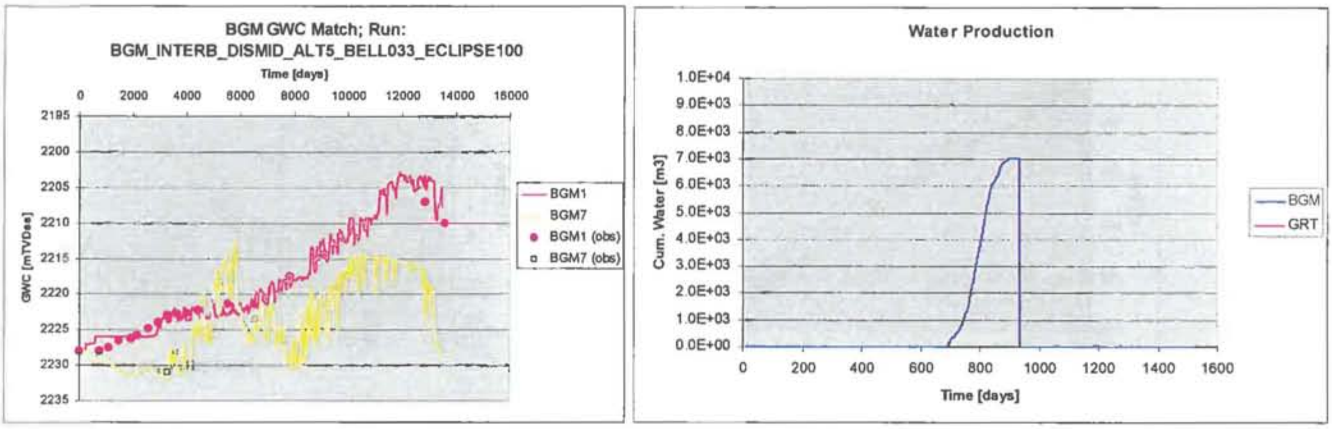

Figure 4-11 GWC-match low productivity case (INTERB_BELL033) of BGM-1 and BGM-7 (left) and water-production BGM-7 (right).

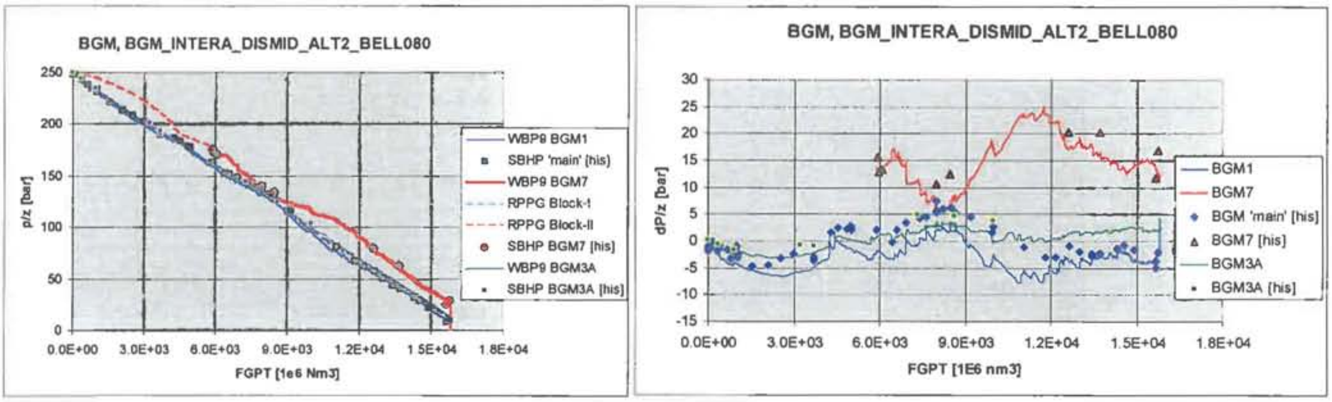

Figure 4-12 Pressure match high productivity (INTERA_BELL080), P/Z curve (left) and deflection from straight line (right) BGM-1, BGM3A and BGM-7.

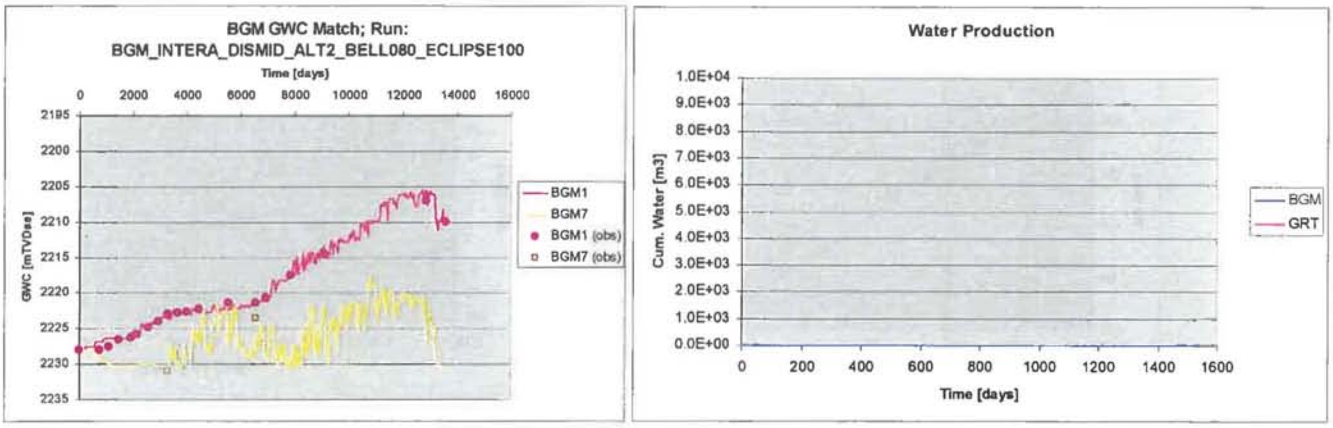

Figure 4-13 GWC-match low productivity case (INTERA_BELL080) of BGM-1 and BGM-7 (left) and water-production BGM-7 (right).

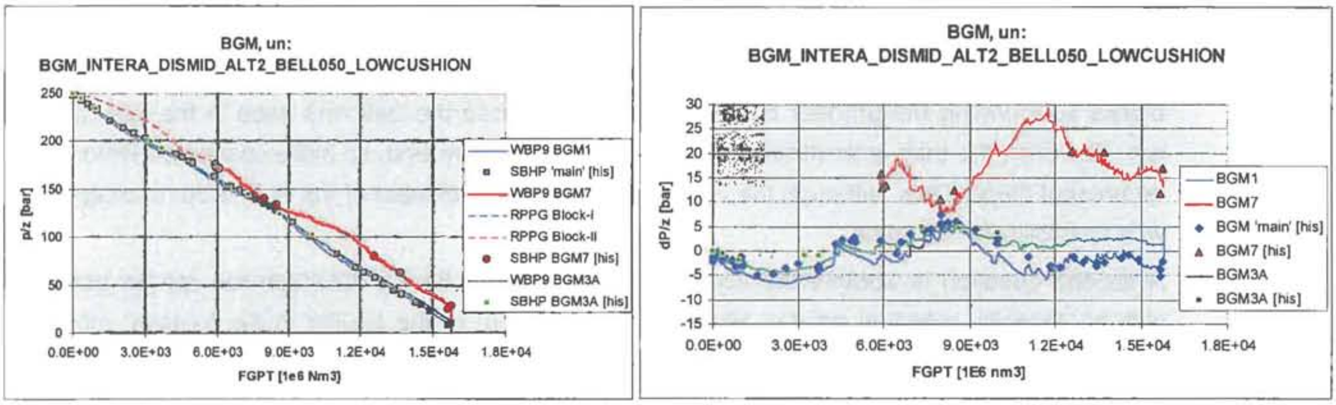

Figure 4-14 Pressure match aquifer case (LOWCUSHION), P/Z curve (left) and deflection from straight line (right) BGM-1, BGM-3A and BGM-7.

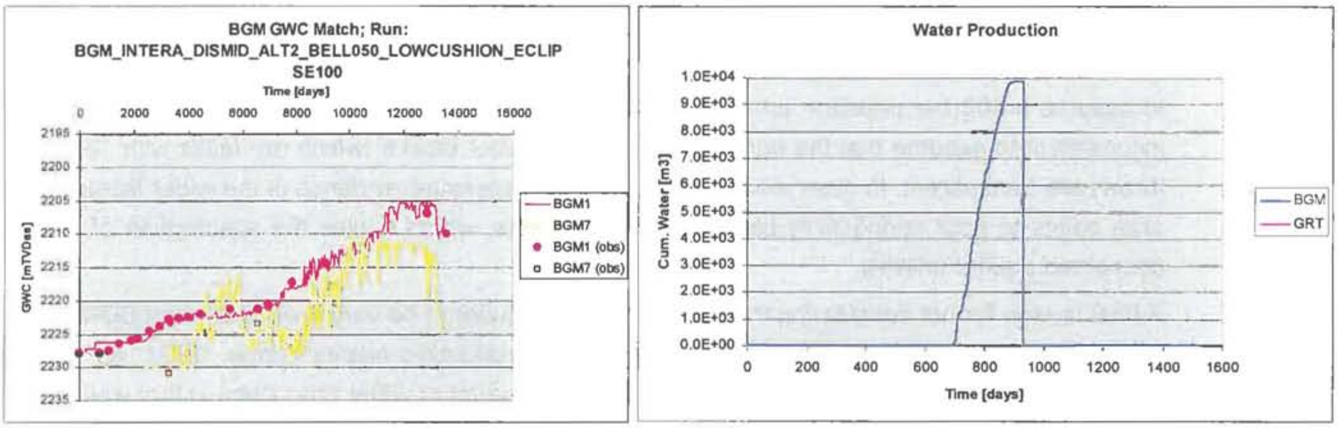

Figure 4-15 GWC-match aquifer case (LOWCUSHION) of BGM-1 and BGM-7 (left) and water-production BGM-7 (right).

4.4 Aquifer sensitivities

Several aquifer sensitivities were carried out, see Table 4-4. The Lowcushion realisation was designed to come up with the minimum amount of cushion gas possibly needed, in line with the project goals to span the range of UGS realization. Not only does it have a Fetkovich aquifer attached to the northwest of Block-2, it also includes compaction and an alternative fault-extension (ALT5). The Fetkovich aquifer has a volume of 2e9 rm3 and PI of 5 sm3/d/bar. The pressure match is very similar to the base case (see Figure 4-14 in the previous section). For a match on the GWC in BGM-1, the permeability in the water-leg was reduced. Additional coning and invasion of water in BGM-7 could not be avoided.

The LowCushion_Revers was created to see the additional effect of compaction on the LowCushion run. Comparing Figure 4-15 with Figure 4-21 it can be seen that with only rock compressibility, no compaction, the water-coning in BGM-7 decreases from 10,000 m3 (LowCushion) to 6,700 m3 (Lowcushion_Revers). Apart from the Fetkovich aquifer, only the reversible rock compressibility and water expansion mechanisms are decreasing the available pore-volume.

The LowCushionX / Y / Z were made to compare the effect of an analytical to an explicit aquifer. A first question is whether the aquifer *size* used in the LowCushion run be achieved with the water physically available in the surrounding blocks? The pore-volume calculated to be present in the blocks surrounding Bergermeer is ca 0.7e9 rm3, less than the 2e9 rm3 used in the LowCushion run. However, the map is terminated artificially at the southern end, so more connected water could be present there. Thus, although the volume is smaller, it is at least of the right order of magnitude, with possibility for increase.

A second question is whether the aquifer *strength* used in the LowCushion run can be achieved with an explicitly modeled aquifer. Studying the behaviour of the aquifer in the forecast mode we see that the aquifer still flows water into the field *after* the cushion gas is injected. This means that the aquifer must have an internal pressure of well over 100 bar. We therefore need a fault transmissibility at the NW end of the field suitable to have a 100 bar pressure differential at the given influx rate, and an aquifer strong enough to keep its pressures at well over 100 bars *after* injecting that amount of water into the BGM field. Figure 4-19 shows the pressure distributions in such a run. Since also the Groet and Bergen fields have reservoir pressures of ca 10 bar, it seems a bit far fetched to assume that the water blocks in between are at 100+ bars. Moreover, the aquifer strength needed requires all the water blocks involved to be well connected. Since we have to assume a 100 bar pressure jump at the NW end of the field over a subseismic fault, it seems inconsistent to assume that the barriers between the water blocks (which are faults with 10's of m throw) are transparent. In other words, all the available pressure evidence in the wider Bergermeer area points to poor connectivity between its fault blocks, which makes the assumption of a well-connected aquifer unlikely.

A final reason for not considering the possibility of an aquifer to be very likely is the fact BGM-7 has produced virtually without any water at the end of production history (since 1999). All aquifer scenarios have a significant tendency to increase the amount of water production in that well.

		Top	Aqf	Comp	fault	xtra bfls	v-prod	h-prod
LowCushion	BGM_InterA_dismid_alt2_bell050_LowCushion	N uplift	fet	high+irrevers	alt2		base	base/high
HighProd	BGM_InterA_dismid_alt2_bell080	N uplift	no	base	alt2		high	high
LowVProd	BGM_InterB_dismid_alt5_bell033	0.4	no	base	alt5		low	base/low
BaseProp	BGM_InterB_dismid_alt2_bell050	0.4	no	base	alt2		base	base/high
Base	BGM_InterA_dismid_alt2_bell050	N uplift	no	base	alt2		base	base/high
LowHprod	BGM_HighP_alt5_bfls	1.0	no	base	alt5	yes	base	low
HighCushion	BGM_InterB_dismid_alt5_bell050	0.4	no	base	alt5		base	base/high
Ubell (LowHProd	BGM_InterA_dismid_alt2_Ubell050	N uplift	no	base	alt2		base	low
LowCushionR	BGM_InterA_dismid_alt2_bell050_LowCushion_Revers	N uplift	fet	base	alt2		base	base/high
LowCushionX	BGM_InterB_dismid_alt2_bell050_LowCushionX	0.4	fet+blocks	high+irrevers	alt2		base	base/high
LowCushionY	BGM_InterB_dismid_alt2_bell050_LowCushionY	0.4	fet+blocks	base	alt2		base	base/high
LowCushionZ	BGM_InterB_dismid_alt2_bell050_LowCushionZ	0.4	blocks	base	alt2		base	base/high

Table 4-4 Realisations table for runs including the aquifer, INTERB and UBELL sensitivies.

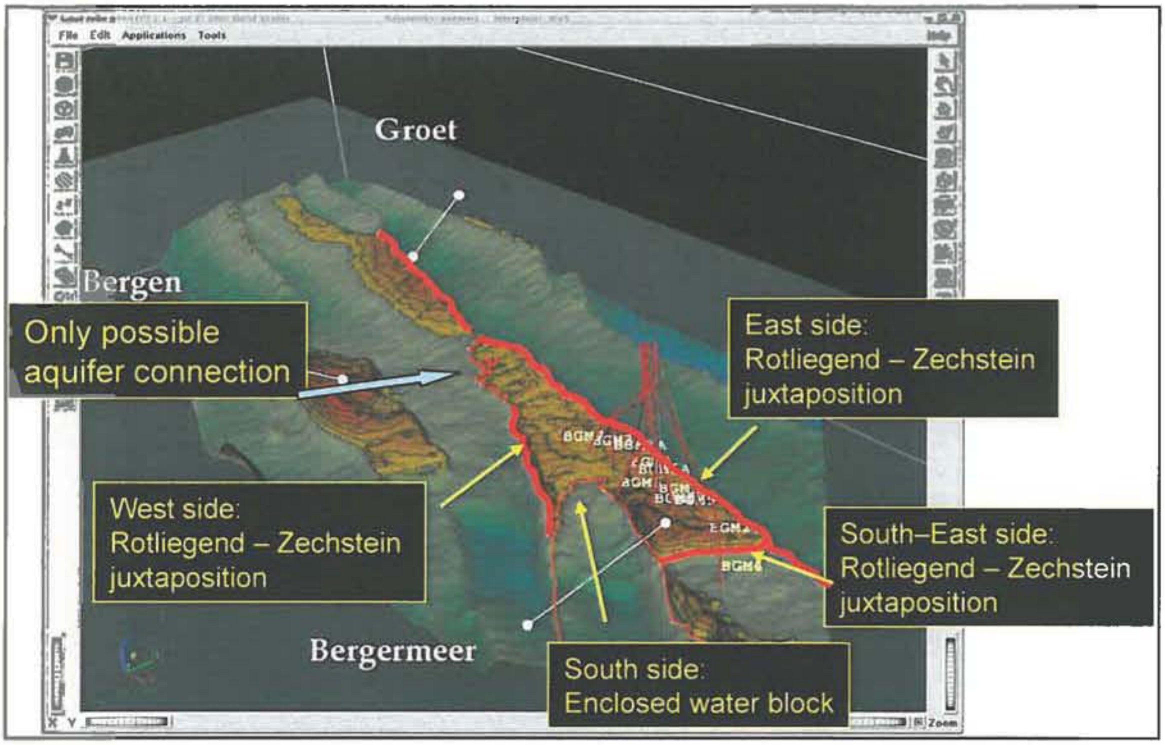

Figure 4-16 **3D model of seismic interpretation of Bergermeer, Groet and Bergen fields showing the only possible location of external aquifer is to the northwest of Bergermeer.**

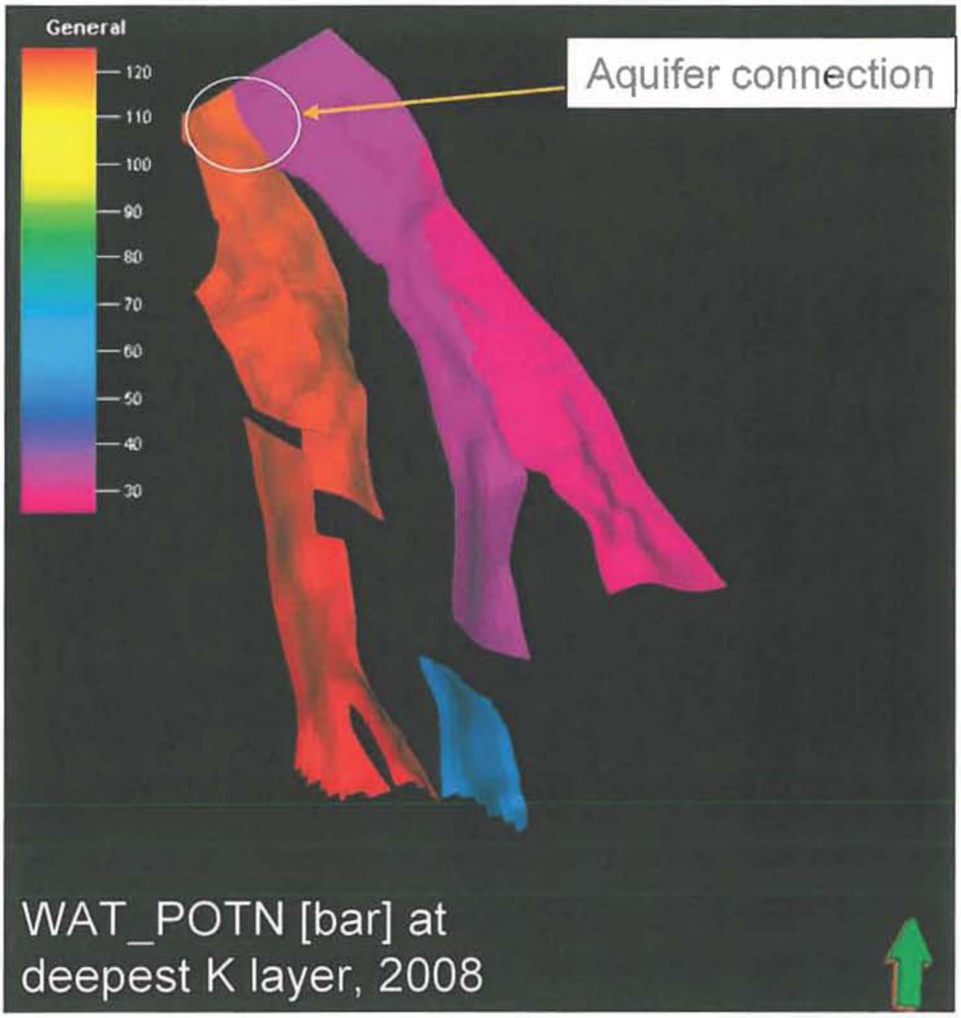

Figure 4-17 **Plot of water potentials [bar] in the blocks surrounding BGM for explicit aquifer scenario. The aquifer's connection with BGM is highlighted. The run shown is similar to the 'LowCushionX' run, but the aquifer strength and fault transmissibility were tuned to reproduce both the 100+ bar aquifer end pressure and the amount of water influx over the historic period, to indicate what the physical implications of the Fetkovich model are. Cf. Figure 4-18. Between the water blocks, all fault transmissibilities are unmultiplied.**

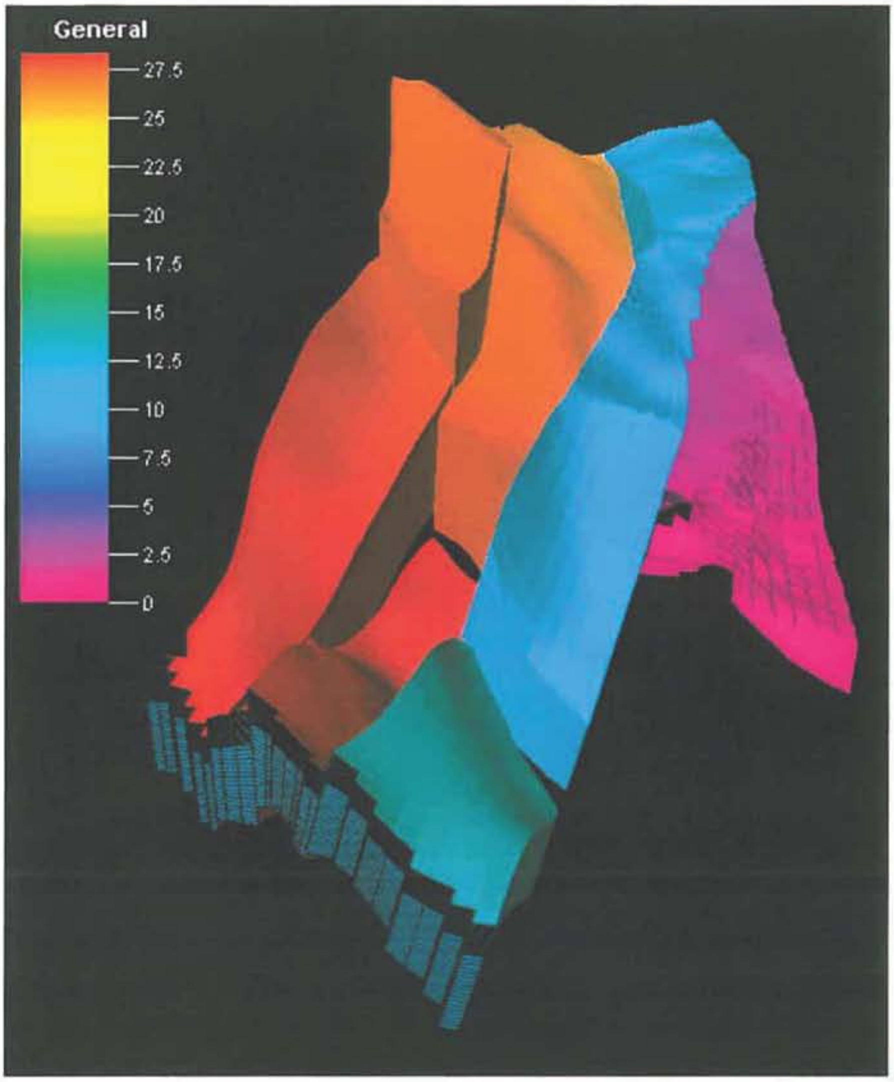

Figure 4-18 Pressure distribution (plotted is the water potential) and additional explicit aquifer attachment in the LowCushionX case. The fault transmissibility multiplier in the NW is set to a similar value as the BGM-7/BGM-main fault. Cf. Figure 4-17. Between the water blocks, all fault transmissibilities are unmultiplied.

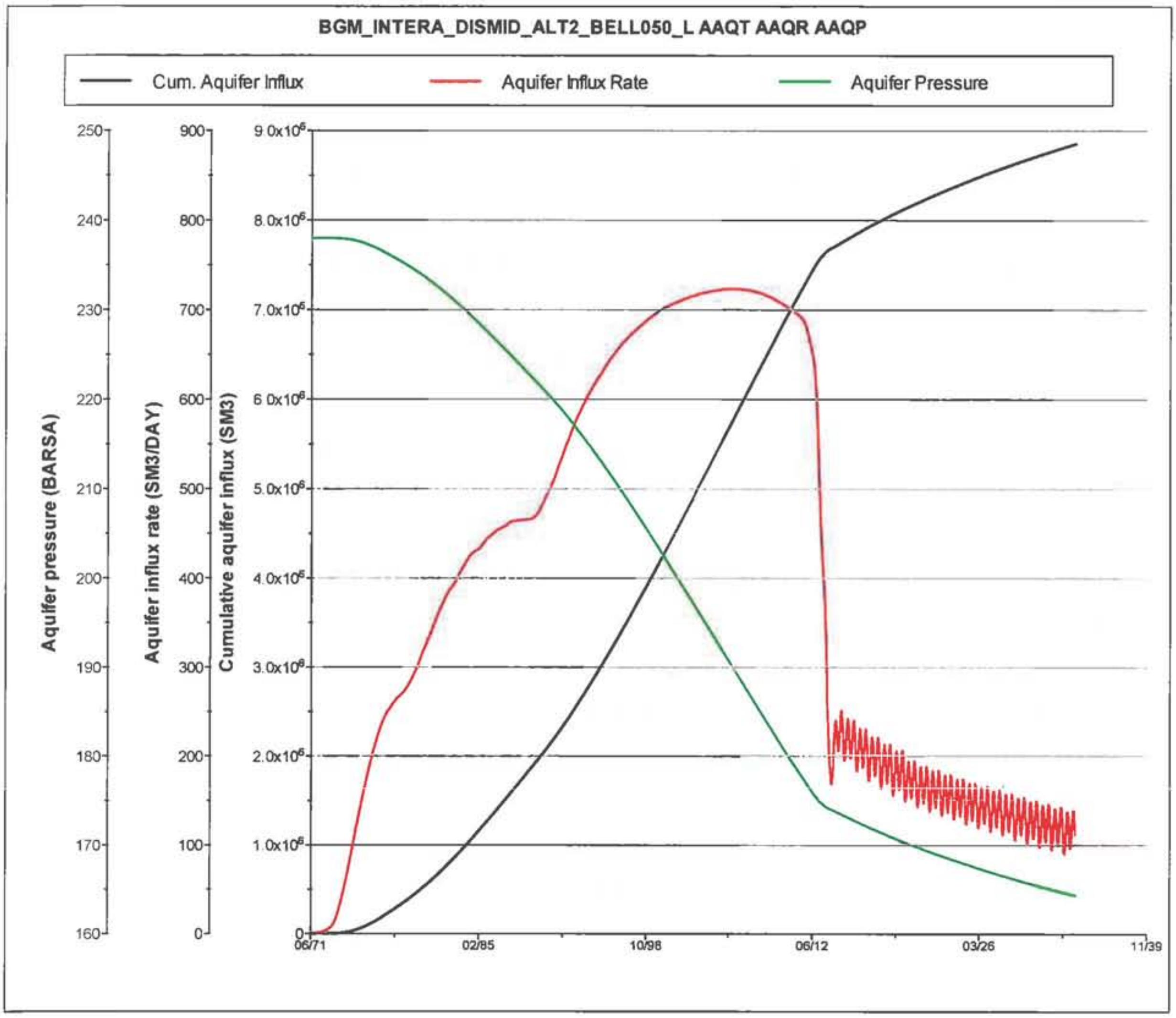

Figure 4-19 **Aquifer inflow plot, LOWCUSHION case. It can be seen that aquifer influx does not reverse with cushion gas injection, which means the aquifer pressure is higher than the BGM reservoir pressure.**

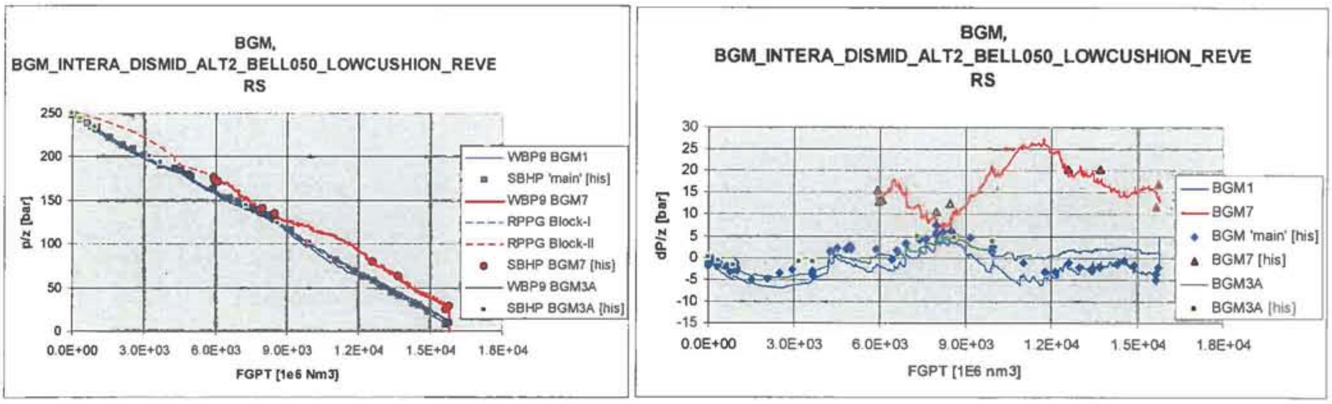

Figure 4-20 **Pressure match aquifer case (LOWCUSHION_REVERS), P/Z curve (left) and deflection from straight line (right) BGM-1, BGM-3A and BGM-7.**

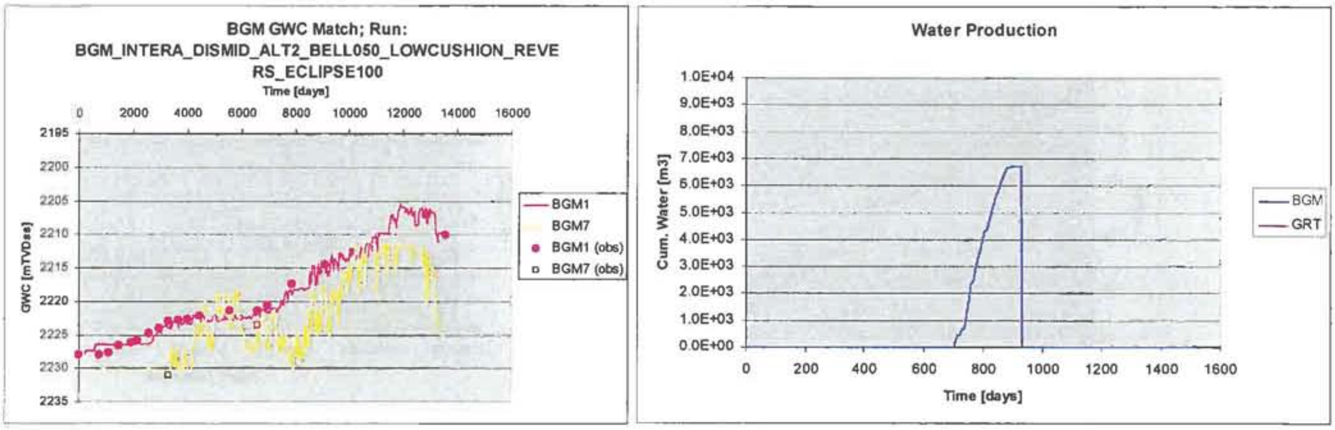

Figure 4-21 GWC-match aquifer case (LOWCUSHION_REVERS) of BGM-1 and BGM-7 (left) and water-production BGM-7 (right).

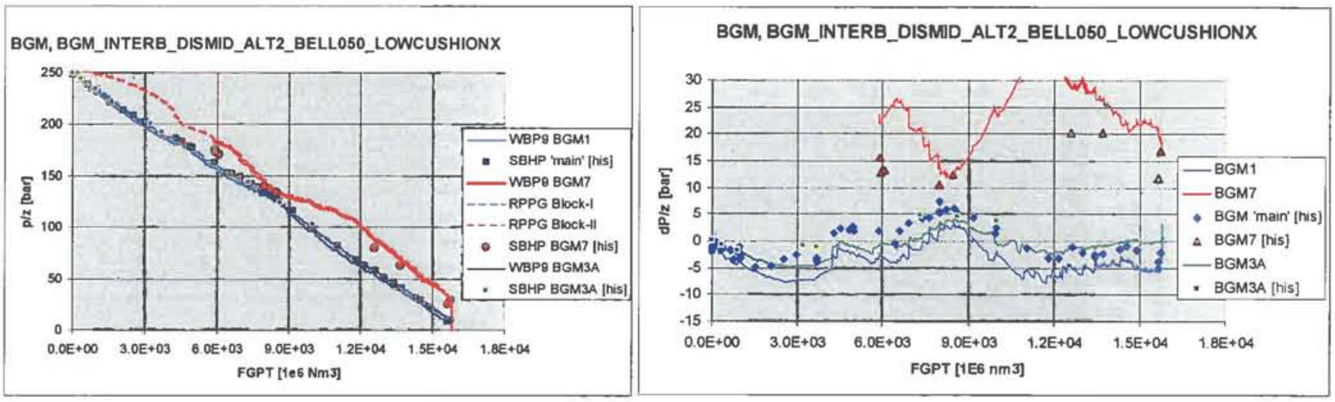

Figure 4-22 Pressure match aquifer case (LOWCUSHIONX), P/Z curve (left) and deflection from straight line (right) BGM-1, BGM-3A and BGM-7.

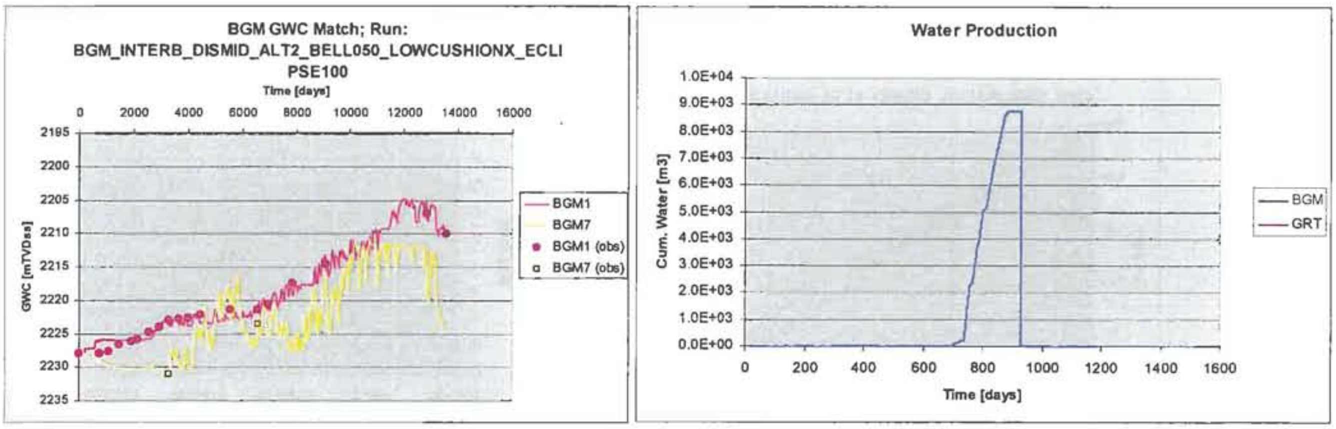

Figure 4-23 GWC-match aquifer case (LOWCUSHIONX) of BGM-1 and BGM-7 (left) and water-production BGM-7 (right).

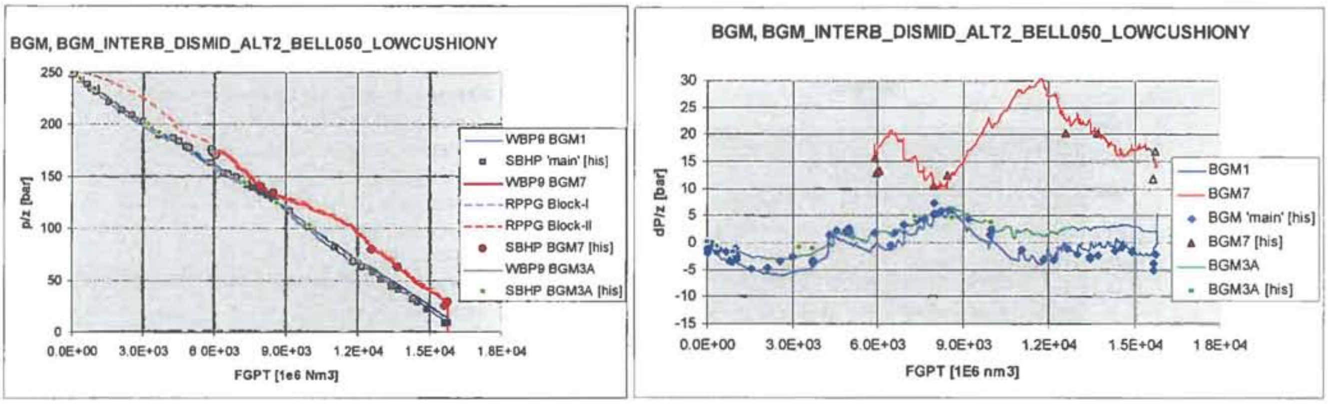

Figure 4-24 Pressure match aquifer case (LOWCUSHIONY), P/Z curve (left) and deflection from straight line (right) BGM-1, BGM-3A and BGM-7.

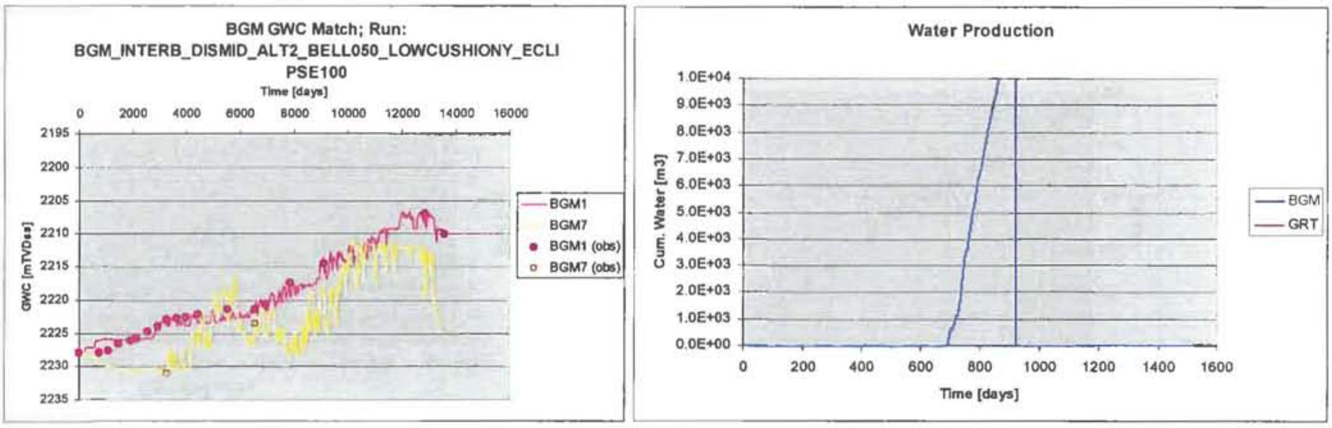

Figure 4-25 GWC-match aquifer case (LOWCUSHIONY) of BGM-1 and BGM-7 (left) and water-production BGM-7 (right).

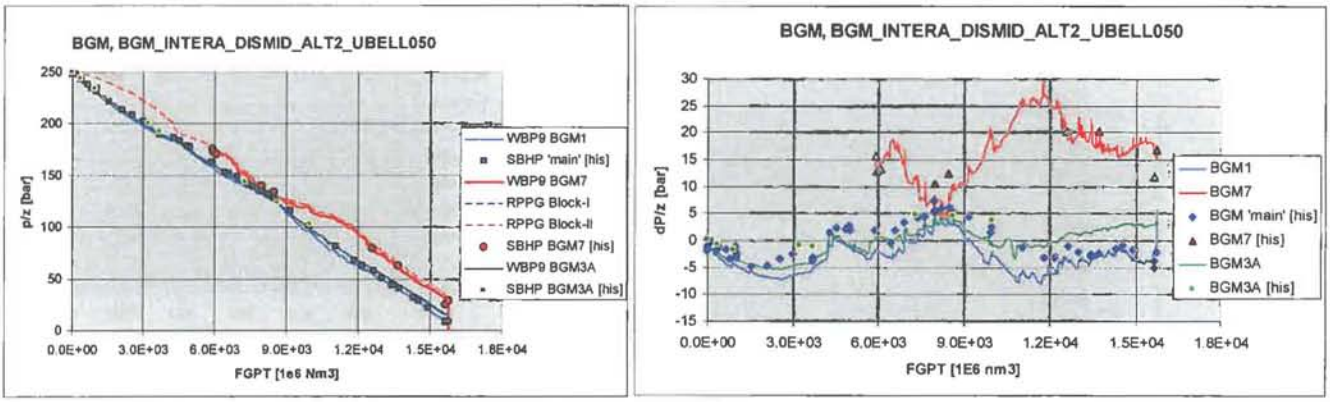

Figure 4-26 Pressure match low productivity case (UBELL050), P/Z curve (left) and deflection from straight line (right) BGM-1, BGM-3A and BGM-7.

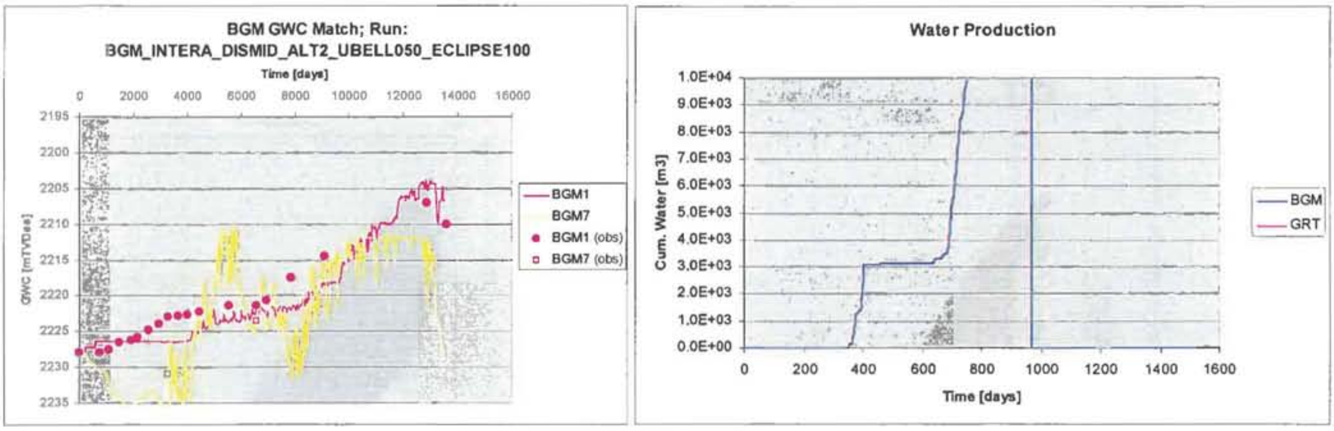

Figure 4-27 **GWC-match low productivity case (UBELL050) of BGM-1 and BGM-7 (left) and water-production BGM-7 (right).**

4.5 GWC behaviour

It was mentioned in the HM-section 4.3 that an extra parameter was introduced in order to limit the flow of water through the main bounding fault. This was done because in the top ROSLU the permeability was reduced (see section 2.3). In all cases, except the INTERA_BELL080, water has reached well BGM-7 at the end of HM. For BGM-7, most of the increase in GWC comes from coning near the wellbore. For BGM-1, the increase is mainly governed by the tilting of water in the produced block. This can be seen in Figure 4-28 (right). Within the main block the highest GWC is in the middle of the main block, where the best producers are located. South of baffle_s (interpreted by the summer injection test in 2007), the rise in GWC is some 20 m less and in the extreme north of the main block, the GWC has actually gone down. Figure 4-28 (left) shows the GWC at end of HM of the LOWCUSHION model. The encroachment of water is in the north of the block-2, the GWC is matched at the position of wells BGM-1 and BGM-7.

Figure 4-29 (left) shows the GWC behaviour of a variation on the base case INTERB_BELL050. Compared to the base case INTERA_BELL050, this model has less volume in the north. As a consequence of its lowered top structure, the fault transmissibility is also lower in the north. This creates a bit more flux and GWC tilting in the main block. Figure 4-29 (right) displays GWC-rise of the HIGHP_ALT5_BFLS model. With the reduced volume in the main block, the GWC rise is equal in the north and middle of the block. Across the extra baffles in block-2, the GWC now also changes. This suggests that the baffles in the Bergermeer field could be detected by making GWC measurements in the other wells than BGM-1. The impact of structure on GWC changes is much smaller than the impact of local heterogeneities.

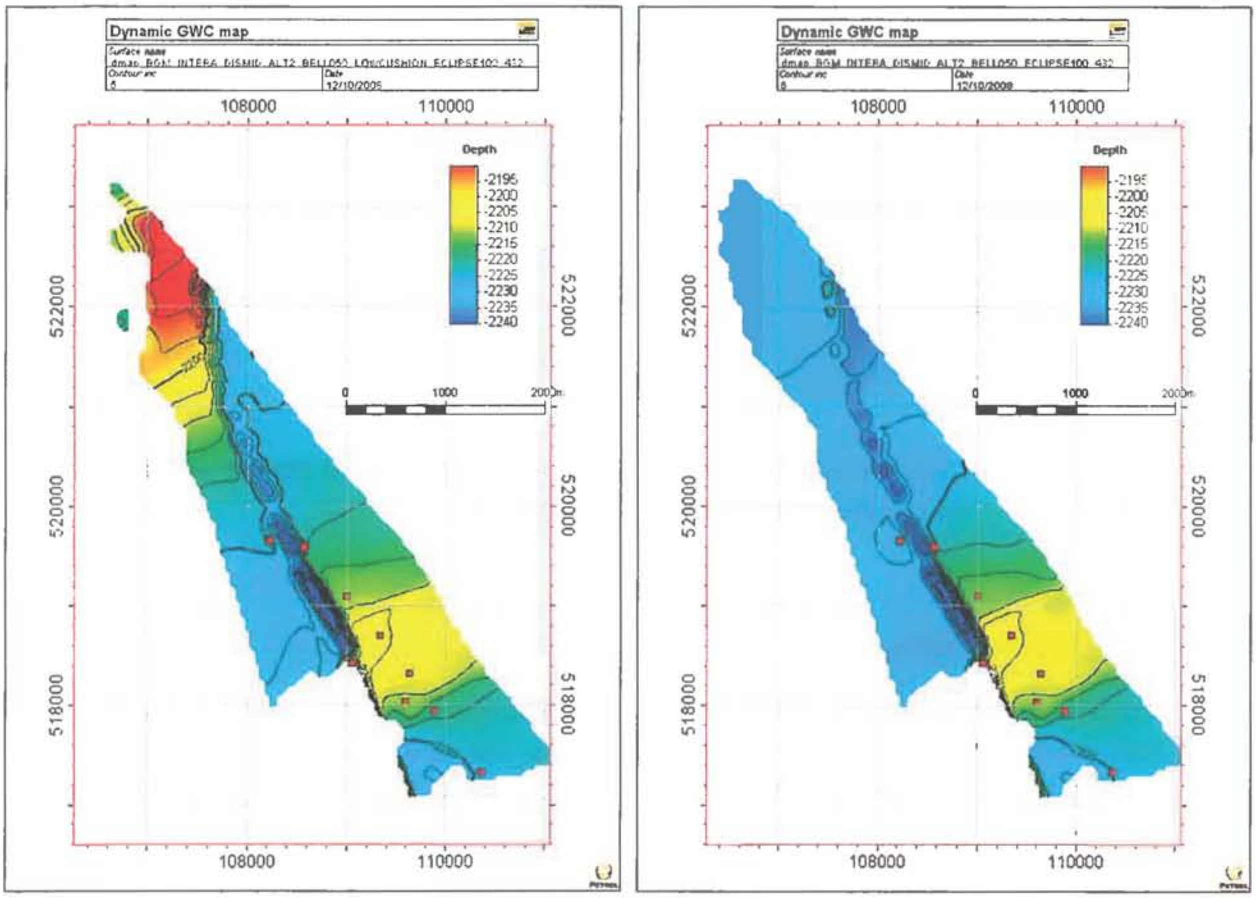

Figure 4-28 **Dynamic GWC maps at June 2007 of LOWCUSHION run (left) and base case, INTERA_BELL050 (right). Interestingly, while the GWC measured near the production wells is identical, aquifer influx has reduced the pore-volume in the north of BLOCK-2.**

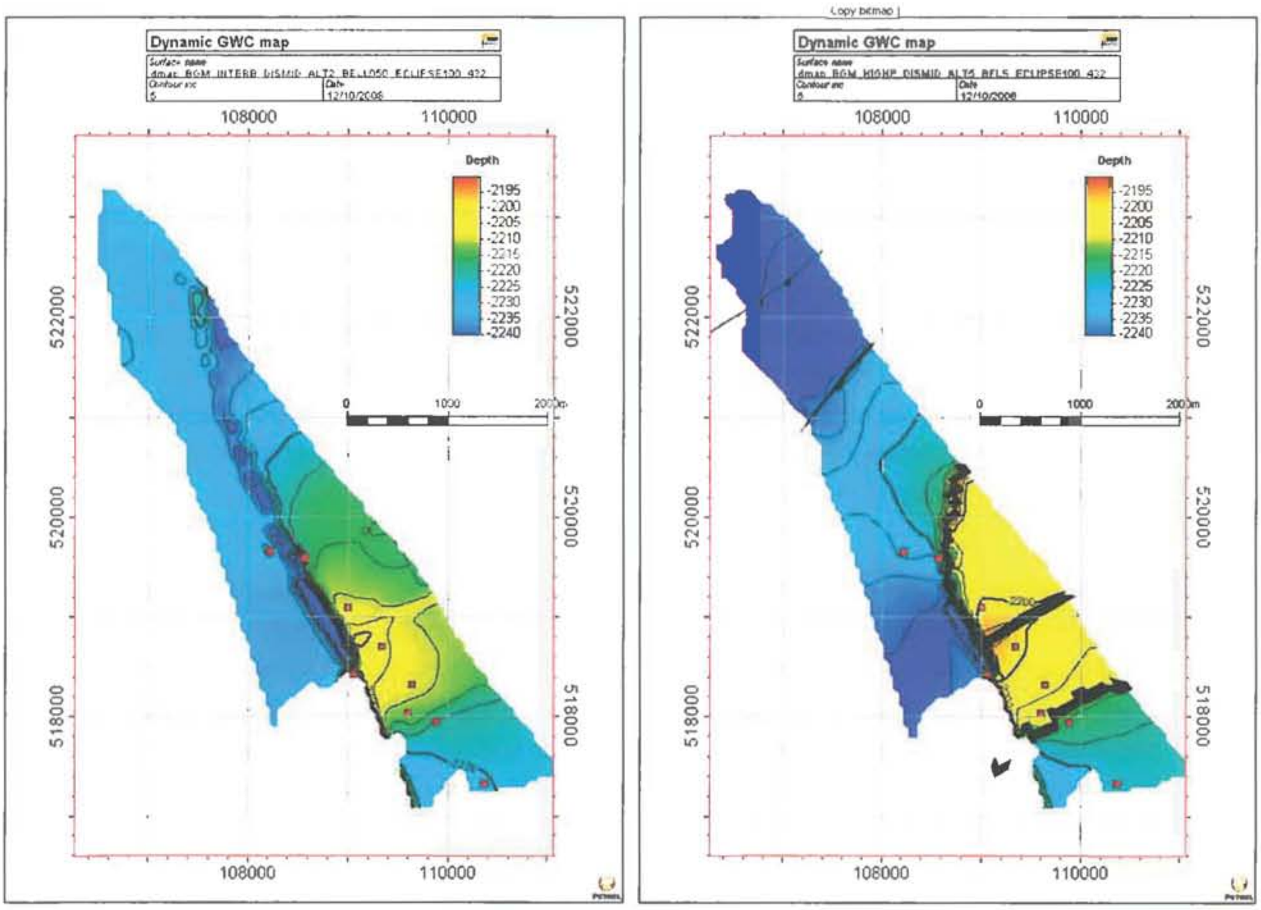

Figure 4-29 Dynamic GWC maps at June 2007 of INTERB_BELL050 run (left) and HIGHP run (right). The INTERA and INTERB maps are very similar, but the HIGHP_ALT5_BFLS run shows increased local uplift of GWC near the best producers. The baffles in the MAIN block have similar transmissibilities.

4.6 Conclusions

A broader range of cases was defined in order to find the cushion gas range and a low productivity estimate for the horizontal wells. It was shown that although the historical pressure, production and GWC-measurement data seemed to exclude the presence of any aquifer, it was still possible to include a small aquifer to the dynamic model. Both the aquifer and non-aquifer cases indicate that the GWC has risen to near the bottom perforations, compare Figure 4-5 with Figure 4-15. The current phase 4 base case has some water production, while in reality, not much water production was seen in BGM-7. With aquifer attached, the influx of water in BGM-7 is much more, which makes it a less likely case. The fact that the BHP in BGM-7 has decreased a little after production was halted in the summer of 2007, also seems to indicate limited water-influx in Block-2, although this effects also occurs in the small aquifer case.

The HIGHP model showed that it was very difficult to create a case with less permeability in the top reservoir that would still produce a reasonable history match on GWC. Water breakthrough in both BGM-1 and BGM-7 is much earlier than in the base case, which makes this case less likely. The case was created however to create a low case horizontal well productivity model. The less transmissibility in the gas-leg, the larger the water-flux and thus contact rise in the MAIN block. The next chapter will show that the effect of heterogeneities will be blown up significantly during the UGS operations.

bname	TOTAL ERROR	TOTAL ERROR	delta_bgm7	p_bgm1_1976	p_bgm7_1981	p_bgm1_1989	p_bgm7_1988	p_bgm1_2001	p_bgm7_1997	p_bgm1_2005	p_bgm7_2005	gwc_bgm1_1980	gwc_bgm1_2005	gwc_bgm7_1980	gwc_bgm7_1989	gwpt_bgm_2005
Weight	BGM		1	1	1	1	1	1	2	1	1	0.25	0.5	0.25	0.125	0.00025
Threshold			1	1	1	1	1	1	1	1	1	2	2	2	2	1000
Best:	0.56	0.43														
BAG25_ALT2_DISMIDHIGHKV_BELL_050	0.73	0.45	2.8	-0.8	-0.7	-2.8	-3.5	-4.2	-1.9	-3.3	3.5	-1.4	-7.0	-4.7	5.9	1180
BGM_INTERA_DISMID_ALT2_BELL050	0.65	38.36	3.8	-1.3	-0.8	-3.2	-4.6	-0.7	-4.1	1.5	1.6	-0.1	1.1	-3.2	3.6	1369
BGM_INTERB_DISMID_ALT5_BELL033	0.73	38.36	2.0	-1.8	-1.6	-2.6	-3.6	-0.6	-3.6	1.9	3.9	-0.7	-1.5	-2.4	1.7	4702
BGM_HIGHP_DISMID_ALT5_BFLS	0.90	38.36	1.9	0.2	-0.7	-1.2	-2.6	1.1	-0.6	4.0	5.4	0.5	-1.0	-0.7	1.8	4001
BGM_INTERA_DISMID_ALT2_BELL050_LOWCU	0.85	38.36	2.5	-0.8	1.3	-0.4	-1.2	1.8	-0.5	3.9	4.7	-0.4	1.3	-3.7	1.8	7371
BGM_INTERA_DISMID_ALT2_BELL080	0.83	38.35	3.9	-1.4	-0.5	-3.2	-4.4	-0.7	-3.1	1.5	1.9	-0.6	0.9	-2.9	4.3	-1000
BGM_INTERA_DISMID_ALT2_UBELL050	1.37	38.37	3.6	-1.6	0.5	-2.0	-3.1	-0.1	-2.1	2.4	6.0	3.5	0.4	-1.4	0.8	18052

Table 4-5 **Overview of HM quality using pressure and GWC points at certain moments in time. For reference, the base case from phase 2 (DISMIDHIGHKV_BELL050 is also given.**