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History Match of a Mature Cyclic Steam Stimulation Process at Cold Lake

J.P. Lebel, and R.T. Moriyama, Imperial Oil Limited

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Abstract

The Imperial Oil Limited, Cold Lake commercial bitumen recovery project has been in operation for over ten years. Over 500 pilot area and 1900 commercial area wells have been drilled and produced using a cyclic steam stimulation (CSS) process. The bitumen, with a live in-situ viscosity of 65,000 cp, is essentially immobile before heating with steam. Initial steam injectivity is only achieved with pressures exceeding the formation fracture pressure of 10 MPa. The CSS process is a complex interplay of recovery mechanisms including bitumen viscosity reduction by heating, gas drive, recompaction drive and gravity drainage. Multi-well numerical simulation history matches of several pads in this mature cyclic steam operation have been completed. The current study utilized 9 cycles, or 10 years of performance data in which up to 24% of the original bitumen in place has been recovered. This is almost double the 5 cycles (5 years) and 15% bitumen recovery used in previous Cold Lake CSS history match work. Significant changes from previous Cold Lake modeling work are the inclusion of a match of gas production, pressures and temperatures at six observation well (OB well) locations and process conformance as measured by seismic. Several new simulation modeling techniques were incorporated to achieve the field data matches. One example is that the match of OB well temperatures required that steam injection create an isotropic horizontal fracture near the well perforation depth. Another is that matching of gas production trends required a "foamy oil" phase, or higher critical gas saturation, in the warmer regions of the reservoir as well as a representation of in-situ generation of CO_2 from steam-rock reactions. The resulting modeling techniques are used to assess improvements to operating strategies, future development and CSS follow-up recovery options. The study also identifies several areas that warrant further improvement.

Introduction

Background. Imperial Oil's Cold Lake bitumen recovery project is located 260 km northeast of Edmonton, Alberta. This commercial cyclic steam stimulation (CSS) project has been in operation for over ten years and now involves 1900 wells currently producing 14500 m^3/day of bitumen. Twenty or thirty wells are drilled on a 1.62 ha (4.0 acre) spacing from a single surface location called a "pad".

Throughout the piloting and commercial implementation of CSS at Cold Lake, reservoir simulation has been utilized to guide development and operating practices. The current work is the fourth major history match that has been conducted on Cold Lake CSS. The first work in this area was completed in 1987 and focused on the average behavior of L pad wells in the Cold Lake Lemming pilot area. The single well, 2D radial L pad model demonstrated the need to account for geomechanical effects including matrix dilation and fracturing. These mechanisms were necessary to achieve a steam injection pressure match and an acceptable representation of areal heat distribution. References 1 and 2 discuss these modeling techniques.

In 1989, a multi-well history match[3] was completed which focused on W pad in the Lemming pilot area. W pad is a prototype of the commercial 1.62 ha, 1.7:1 aspect ratio well configuration. The principle objective was matching typical inter-well fluid movements. The study concluded that to match five cycles of CSS, a model containing a minimum of three wells was needed in order to match the middle well in the model. The study also concluded that horizontal fractures were narrow features which, on W pad, were oriented at N43°E.

In 1990, a study[4] was undertaken to match the performance of wells drilled on close spacing of 0.94 ha (2.33 acre). This study concluded that modeling parameters used in the W pad work were not suitable for the closer spacing.

The current study was undertaken to improve confidence in simulation based predictions of CSS and secondary or "follow-up" processes to CSS by extending previous history match work and clarifying the role of solution gas as a drive mechanism.

Available field data spanned more than ten years, double that of the earlier work. Additional data in the form of observation (OB) well pressures and temperatures, 3-D seismic, and seismic travel time tomography were also available. The collection and metering of gas production also became common practice.

The history match was performed simultaneously on groups of wells from four different pads to ensure that modeling techniques were applicable across a variety of situations. Results with two of these pads are reported in this paper.

The first was a match of performance at the Cold Lake Maskwa D03 pad. This pad was selected because it contained six highly instrumented OB wells and because of its 3D and cross-well tomography seismic surveys.

The second case was an extension of the previous Lemming W pad work. This pad was converted to a cyclic steam drive pilot after its fifth CSS cycle. As such it represented a special challenge to simulation in that exactly the same modeling techniques were to be used to match both the CSS and displacement processes. 3D seismic surveys were also available at W pad for evaluation of process conformance.

Reservoir Description. Thermal recovery at Cold Lake is conducted in the Clearwater formation whose regional geology is described in references 5 and 6. The Clearwater formation in the currently developed area has a net pay ranging from 25 to 45 m. It consists of a fine grained unconsolodated sand having a porosity of up to 35% and oil saturations of up to 13 weight percent. The top and base of the reservoir are almost always bounded by an impermeable shale interval. Discontinuous calcite bands (tight streaks) up to three meters in thickness are sometimes present in the reservoir.

Study Approach. The first efforts were to match the pressure and temperature responses at the D03 pad OB wells and the early cycle inter-well communication events at both D03 and W pads. The modeling parameters that improved the match most significantly were: the use of a petrophysical description that accounted for bound water and the utilization of laboratory data for water-oil imbibition relative permeability, an increase in matrix compressibility when in shear failure mode, and the introduction of an isotropic horizontal fracture layer whose transmissibility increased more quickly as a function of pressure than in the previous W pad models.

Having achieved acceptable pressure and temperature matches, focus shifted to bitumen and gas production. An approximate match of bitumen production was achieved by adjusting the water-oil drainage relative permeability.

At this point, the match of gas production had improved significantly as a result of the pressure match. This match was further improved by utilizing a lower critical gas saturation and a new simulator feature that allowed in-situ generation of CO_2 as a function of temperature and its transport in both the water and gas phases.

The bitumen production match degraded with the improved match of gas production and ultimately was restored with the use of a foamy oil feature that is described below.

Simulator Description. The finite-difference thermal simulator[7] used for this study utilizes a fully coupled, fully-implicit formulation that incorporates a volume balance approach. As such it is particularly well suited to model the behavior of the CSS recovery process that involves steam flashing and condensation, hydraulic fracturing, pore volume dilation and recompaction and extreme changes to the gas phase mobility.

D03 CSS History Match

Model Grid Description. The D03 history match concentrated on matching observations at well D03-08 and surrounding OB wells. The history match was conducted using a half symmetry element model containing 1890 grid blocks and incorporating four CSS wells. Figure 1 shows the model grid (solid rectangle) and its relationship to surrounding wells. The model represents an area 662 m long, 48 m wide, and 53 m thick. The well spacing along the major axis of the model averages 167 m, and orthogonal wells by symmetry are located 98 m apart.

Simulator input data for porosity, permeability and bitumen saturation was derived from five cored wells in and around the study area. Tight streak locations and continuity were estimated using well logs from 25 wells within and adjacent to the study area. These are represented in the models as barriers to vertical fluid flow.

Table 1 lists the average properties by layer in the D03 model. The average horizontal permeability is 2190 md. The average vertical permeability is 570 mD. The average porosity is 30.8% with a bitumen saturation of 64% or 9.2 weight percent.

The well steam injection pattern in the study area historically proceeded from southwest to northeast with long rows of adjacent wells receiving steam concurrently. Because of this, the long axis of the model is aligned perpendicular to the rows implying no flow boundaries between adjacent row wells.

As illustrated in Figure 1, well D03-08 is surrounded by six OB wells. Relative to D03-08, two OB wells are located on trend to the northeast, two are directly off trend, one is at the infill location to the northeast and one is partly off trend to the south. OB1 through OB5 provide temperature and pressure measurements through time. OB6 data is not presented here because it is influenced mainly by CSS wells located outside the model boundary.

The model size is based on a requirement to include wells that interact with D03-08 or which influence OB well responses. The main inter-well effects are between D03-08 and D03-13, and between D03-03 and A01-18. D03-08 also had some interaction with A01-18 in the first cycle, and D03-03 has a strong influence on pressures at OB1.

Vertical gridding for the D03 model was developed to conform to geological variations as illustrated in Figure 1. A thin (0.1 meter) horizontal fracture layer was placed at the top of CSS perforations that corresponded to the depth at which peak temperatures are observed at the OB wells.

Results.

Steam Injection and Total Liquid Production. In these models, the steam injection and total liquid production rates for each well were specified according to field data. Small variations in the rates were smoothed. In this respect, each well in the simulation matched the field data exactly. Other field observations including pressure, temperature, bitumen cut, gas production and volumetric conformance were history matched by changing model parameters.

Steam injection rates average 250 to 300 m^3/day with a down hole quality of about 60%. Fluid production is dictated by inflow and a down hole pump capacity of 65 m^3/day. When bottom hole pressures (in the field) exceed the fluid head in the wellbore, about 4 MPa, higher producing rates are possible because the wells will flow without being pumped.

Pressure Match. At high pore pressures, the reservoir matrix dilates in a shear failure mode as the effective stress between sand grains decreases. If injection rates are sufficiently high, the reservoir will develop a fracture that is typically horizontal. This fracture promotes areal distribution of injected steam and water. Both failure modes are represented in the simulation by increases to porosity and permeability as pressures exceeded 10 MPa. The fracture layer is modeled as a thin (0.1 m) feature and, at peak pressures, experiences a much higher (a factor of up to 100) permeability increase than matrix blocks which roughly double in absolute permeability.

CSS Well Bottom Hole Pressure. Figure 2 compares the simulated and measured bottom hole pressure responses at the D03-08 CSS well. Bottom hole pressures in the model during steaming peak at about 10.5 MPa, a pressure equal to that exerted by the overburden.

The simulated bottom hole pressure during production declines to nearly zero (gauge) in most cycles with a profile similar to that observed in the field. The pressure match degrades somewhat in cycle 9 when model injection and producing pressures exceed those observed in the field. This is attributed to increased fluid movements across the model boundary due to connection of depleted regions.

An interesting pressure peak occurs in cycle 2 (mid-1987) during production when D03-08's neighbor to the south (D03-13) receives steam. The pressure spike observed at D03-08 and four OB wells is the result of a fracture extending from D03-13 beyond D03-08 and is an important event for the calibration of the model fracture mechanics.

Observation (OB) Wells. Figure 3 compares the model and field pressure responses at five OB wells which are perforated at the same depth as the nearby CSS wells. The most significant responses coincide with D03-08 steaming. The model pressures are almost always within 2.0 MPa of the field values, and are more typically within 0.3 MPa, particularly in later cycles. In cycle 9, the effect of large scale fluid movements impact OB well pressures in a manner consistent with pressures at the D03-08 CSS well.

OB Well Temperature Match. Figure 4 compares model and field OB well temperatures. In all OB wells, except OB1, the model experiences more heating than is indicated by the field data. This likely results from temperature gradients at the edge of the heated area that are sharper features than can be represented by the coarse gridding in the model. Sensitivity cases should be run to confirm this hypothesis.

Well OB2 is located just on the boundary of the heated zone near D03-08 in the first 6 cycles. While the field data shows temperature increases of about 40 °C, the model temperature increases about 100 °C. It is likely that a heated path between D03-08 and D03-13 allows more heat to distribute to the south and less to the north than the simulation predicts. This is consistent with the seismic image as described below.

Bitumen Match. The model average cumulative bitumen production profile is compared with the field data in Figure 5. The final model average cumulative bitumen is 2% low relative to the field. At the end of the history match period, individual well cumulative bitumen volumes that range from 3% high to 5% low relative to the field as shown in Figure 6.

The quality of this bitumen match is acceptable in that the cumulative bitumen tracks the field value consistently through time. This suggests that there is little bias towards optimistic or pessimistic predictions. Previous Cold Lake history match work typically showed a good match to final cumulative volumes (up to cycle 5), but had a trend that was clearly high in cycles 4 and 5.

Gas Match.

Volumes. The model average cumulative gas production profile is compared with the field in Figure 7. The produced gas is a combination of solution gas and CO_2 from steam-rock reactions. The final model average cumulative gas produced is 30% low relative to the field. Previous D03 models[8] were approximately 80% low relative to the field. The improved gas match is a result of two factors:

First, an improved pressure match at both producing and OB well locations results in generally lower and more uniform pressures during production.

The second factor is the use of a foamy oil formulation that allows a certain amount of evolved gas to exist as a dispersed phase within the oil phase. The creation of this dispersed phase is triggered in each grid block when its temperature exceeds a specified minimum. The oil phase which contains vapor is given a correspondingly higher compressibility and a slightly lower viscosity.

In the history match, the maximum vapor content within the foamy oil phase is set to 14%, and the activation temperature is set to 60 °C. The effect is primarily an increase in gas saturation in the heated region. This retards the flow of gas in this region, increases the pressure gradients and thus increases the flow of bitumen.

In regions of the reservoir which are below 60°C, the critical gas saturation is fixed at 0.5% which is significantly lower than the 5% value used in previous Cold Lake modeling. The 0.5% value is consistent with field observations in other parts of Cold Lake where solution gas in a bitumen zone is depleted due to production of an overlying gas cap. The net effect of the lower critical gas saturation and the foamy oil model combination is to allow greater depletion of solution gas without a significant reduction in bitumen production.

Gas production in the simulation is very sensitive to model pressure. Because of this, in the last cycle, when the model pressures are high relative to the field, the simulated gas production is low.

Composition. Cold Lake produced gas has consistently maintained an average composition with 25 to 30% CO_2, 60 to 65% methane, and about 10% other light hydrocarbons and nitrogen. Because the simulations are not fully compositional they cannot match the 10% light hydrocarbon and nitrogen components. As such, an acceptable volume match is assumed to be 90% of field gas production with about 30% CO_2. The cumulative average CO_2 gas fraction in the D03 history match is slightly high at 35%.

Conformance Versus Seismic. A 3-D seismic delay time map[8] from D03 pad taken in 1990 (cycle 6) is compared in Figure 8 with a corresponding map derived by forward modeling seismic velocities using simulator results. Because the simulation model is a half symmetry element, it has been reflected so as to appear as a full element in the map.

The sizes and shapes of conformance regions, indicated by darker regions, at D03-03 and D03-08 correspond well between 3D seismic and the forward model. The simulator anomaly at D03-13 is somewhat larger and stronger than in the 3D seismic image while the connection between D03-13 and D03-08 appears stronger in the 3D seismic than it does in the simulator.

Figure 9 compares seismic cross-borehole travel time tomography with forward modeled seismic velocities using simulator conditions. The upper image represents the seismic velocity through the Clearwater oil sand. The image corresponds with the simulator image shown below.

The thickness and extent of the simulator anomaly at D03-08 corresponds well with the tomography. The simulator anomaly however has a more uniform shape and intensity than does the field image. The resolution of the tomography is better than the 3D seismic, but will still smear sharp fronts if they exist. Both simulator and tomography indicate some depletion below the perforations.

D03 Model Sensitivities

Impact of Isotropic Horizontal Fracture. Figure 10 shows temperature responses at OB well 1 located on-trend and at OB well 4 located off-trend. Two simulation cases are compared with the field data in this figure. The first, labeled "Isotropic Fracture", is the history match base case which utilizes a fracture layer with isotropic properties. The second, labeled "Narrow Fracture", is a case which allows fracture propagation in only the on-trend direction. Both cases result in acceptable bitumen and gas production matches, but the isotropic case distributes heat in a manner more consistent with the field as measured at OB well 1. The increased model temperature at OB well 4 is an artifact of the relatively coarse gridding.

Effect of Foamy Oil - Gas Drive on Performance. Figure 11 shows model average cumulative bitumen production for the base case and for a case which uses no foamy oil. The base case has foamy oil in hot regions and a fixed 0.5% critical gas saturation in cool regions. The sensitivity case has a fixed critical gas saturation of 5%. The total gas production for the two is almost identical, however the base case yields a superior bitumen match in later cycles.

Effect of CO_2 Generation on Performance. The inclusion of CO_2 generation has little effect on the simulated bitumen production, but does significantly improve the overall match of gas production as its generation adds significantly to the total produced gas volume.

Because bitumen production is relatively unaffected when CO_2 generation is removed, we can infer that the CO_2 provides little, if any, additional gas drive or bitumen viscosity reduction in these models.

W Pad CSS and Cyclic Displacement Process Match

Modeling methods and parameters used for W pad were identical to those used in matching D03 pad. The wells chosen, in and around W pad, had undergone five cycles of CSS followed by four cycles of cyclic steam displacement process referred to as the Injector Only Infill (IOI) follow up process.

Reservoir Description. A brief description of the Clearwater formation is provided above in the D03 pad section, and a description of the W pad area is provided in reference 3.

Reservoir properties for the W pad model were evaluated in a manner similar to that for the D03 model. The net pay thickness is 46 m with an average horizontal permeability of 1450 md, vertical permeability of 660 md, porosity of 29.5% and a bitumen saturation of 68% or 9.3 weight percent. Tight streaks are identical to those used in previous W pad work.

Simulator Model Grid Description. The W Pad cases were run using a half symmetry element model containing 1998 grid blocks. Figure 12 shows the model area and its relationship to surrounding wells. The model represents an area 762 m long, 49 m wide, and 46 m thick.

The model incorporates six CSS wells and three IOI wells. The three FF pad 0.94 ha spacing CSS wells to the north were included because over the history match period they developed a strong connection with, and are believed to have had an impact on the performance of W pad wells.

History Match Results. The following discussion of the history match includes only W Pad wells because the three FF pad wells were intended only to account for model boundary effects.

W Pad Cyclic Steam Stimulation Bitumen Match -- 1983 through 1988. The model average cumulative bitumen production profile is compared with the field estimate in Figure 13. The cumulative bitumen at the end of the match period is 4% low relative to the field values.

The model average bitumen profile tracks low relative to the field beginning in late 1984 almost entirely due to low model bitumen at W-08 in its second CSS cycle. During this cycle, measured bitumen cuts exceed 80% which may indicate a measurement problem. Following cycle 2, the bitumen rate at W-08 matches the field values closely.

Individual well cumulative bitumen volumes at the end of the history match period range from 8% low to 1% high relative to field data as shown in Figure 14. With the exception of W-08 cycle 2, the model bitumen production tracks the field closely until the beginning of IOI in 1988. Thereafter, both W-08 and W-13 continue to track the field bitumen.

W Pad Cyclic Displacement Bitumen Match -- 1989 through 1995. From 1989 onward, infill wells were steamed in a cyclic mode while the previous CSS wells were operated as producers only. This is an enhanced recovery technique we refer to as "Injector-Only-Infill" (IOI). During this time, the simulation results for both W-08 and W-13 closely track the field bitumen and reach a recovery level of 24%.

The simulated performance of W-03 during the first cycle of IOI is low relative to field data. The low simulated bitumen production is due to steam injected into wells to the north flowing as condensate to well W-03 and reducing its oil cut. In reality, steam injected to the north flowed toward wells located to the east, outside the model boundary.

Gas Match. The model average cumulative gas production profile is compared with the field estimate in Figure 15. The model production tracks the estimate of produced gas up to 1988. The estimate of gas production to that point is based on typical Cold Lake gas production trends. After 1988, gas conservation at W pad was installed and therefore gas data is available from that time onward. The gas production match is acceptable during the first IOI cycle (mid 1989 to mid 1990), but falls short of the field values until the last cycle (1994/95). The final cumulative gas production is about 18% low. The model average CO_2 mole fraction in the produced gas is approximately 30%, consistent with field observations.

Areal Conformance Versus 3D Seismic. A 3-D seismic image of W pad in late 1993 (cycle 9) steaming is compared in Figure 16 with corresponding plan view of forward modeled delay time from simulation results. The dark regions indicate unaffected reservoir while the lighter areas indicate conformance. The simulator anomalies at each injector match the magnitude and size of those in the 3D seismic. Two features of interest are:

The lack of any anomaly beyond well W-03 in both images indicating agreement between field and simulator that little or no IOI recovery occurs in the region outside the IOI pattern.

The lack of strong anomalies connecting to the producers in the simulation image as compared with the 3D seismic. The producing wells in the 3D seismic image do however always appear to be on a boundary of the anomaly.

When infill IOI wells were drilled at W pad in 1988, their temperature profiles varied significantly. Their average peak temperature was between 20 and 25 °C and the depth of this peak was either at or above the perforation depth of nearby CSS wells. The current history match shows no such temperature anomaly at the infill location. The previous W pad work aligned a narrow fracture corridor to achieve a match to these observations. The current work leaves open a hypothesis that the heat at the infill location is a result of isotropic fracture flow of steam in early cycles and that the current modeling method underestimates the extent of these fractures when steam injection rates are high.

Conclusions

The history match for thermal processes at Cold Lake has been successfully extended from that of previous work, incorporating new match parameters and modeling techniques. Results match field production and conformance data reasonably well.

Use of a dispersed gas phase or foamy oil model was successful in obtaining a better match to gas production while maintaining an acceptable bitumen match. Its use at this time is strictly empirical, and more work is needed to mechanistically represent the apparently higher gas saturations required within the heated region surrounding the CSS wells.

Improved fracture leak off calculation methods should be pursued to improve the ability to match W pad infill well temperatures and inter-well fluid movements in early cycles.

Field data indicate that fluid movements beyond model boundaries limit their ability to match field data in late cycles. More appropriate, larger models become impractical however, due to memory and computer speed limitations.

Acknowledgments

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Table 1: D03 Model Average Properties

layer	h (m)	Ø	S_w	k_h (md)	k_v (md)
1	14.0	0.312	0.331	2640	620
2	7.0	0.285	0.373	1570	620
3	7.0	0.316	0.340	1880	540
4	5.5	0.288	0.331	1630	390
5	5.1	0.320	0.300	2150	630
6	0.1	0.320	0.300	1560	260
7	3.6	0.310	0.300	1460	340
8	4.0	0.313	0.311	2280	600
9	7.0	0.320	0.248	3040	640
All	53.3	0.308	0.362	2190	570

Note: The vertical permeability in locations corresponding to tight streaks is set to zero.

Table 2: W/FF Pad Model Average Properties

layer	h (m)	Ø	S_w	k_h (md)	k_v (md)
1	6.8	0.320	0.333	1480	520
2	5.9	0.300	0.260	1770	940
3	7.4	0.264	0.313	970	570
4	0.1	0.264	0.313	1390	690
5	3.0	0.312	0.245	1840	830
6	4.0	0.296	0.274	1540	680
7	4.3	0.289	0.206	2460	1440
8	4.0	0.312	0.251	2140	1090
9	10.0	0.291	0.355	750	110
All	45.8	0.295	0.323	1450	660

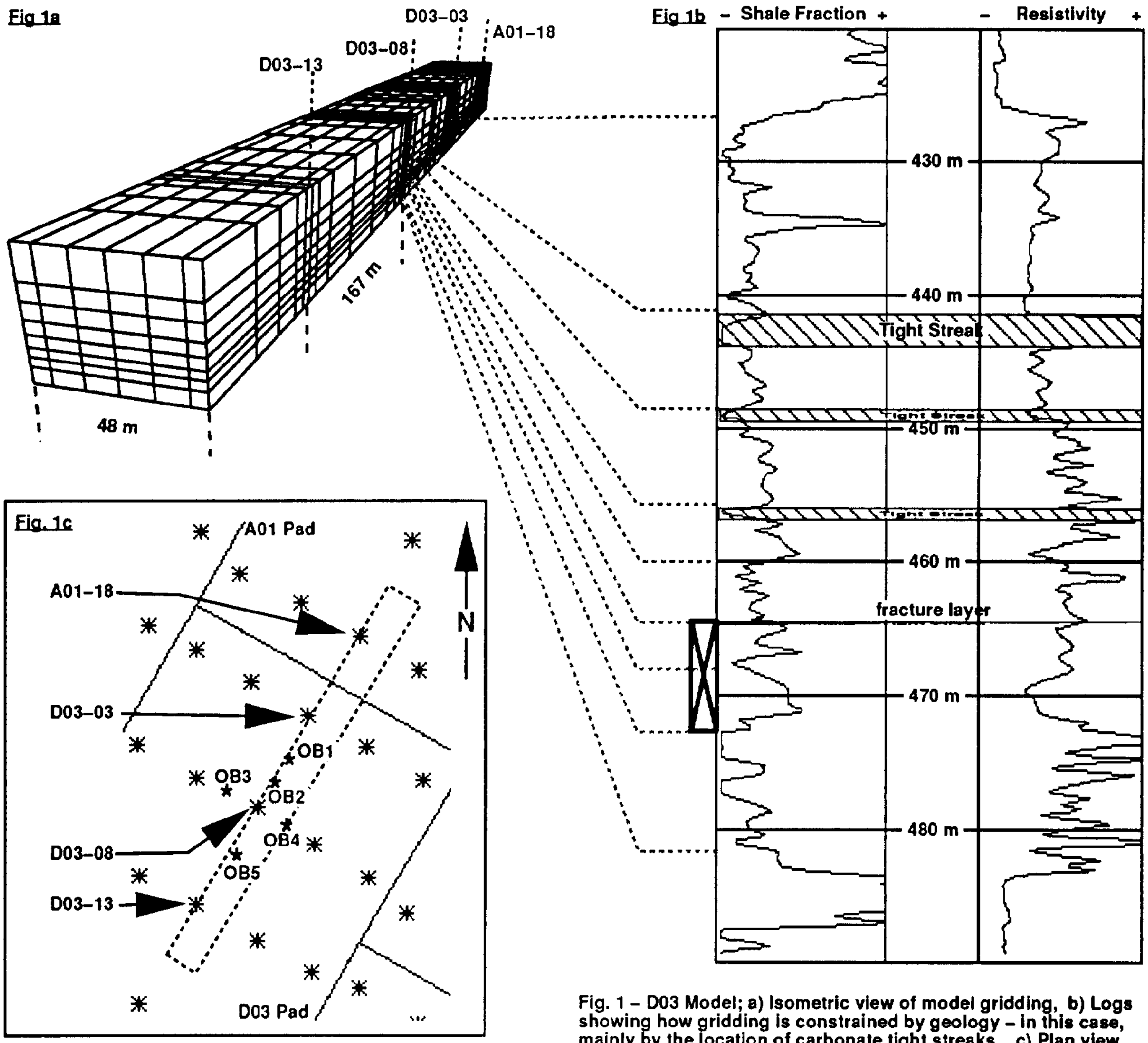

Fig. 1 – D03 Model; a) Isometric view of model gridding, b) Logs showing how gridding is constrained by geology – in this case, mainly by the location of carbonate tight streaks, c) Plan view of well locations

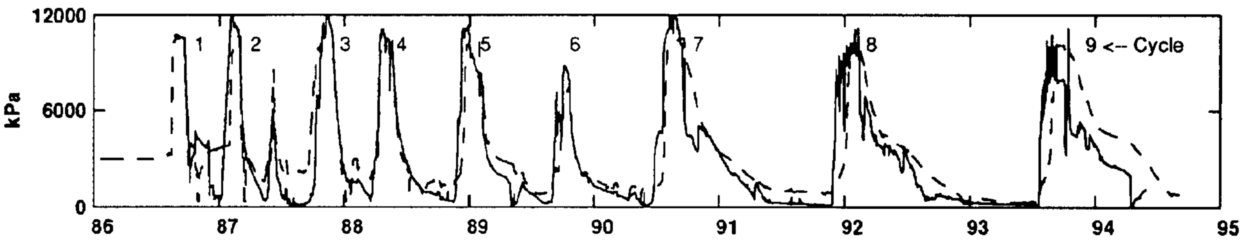

Fig. 2 – Comparison of simulated and measured bottom hole pressures for CSS well D03-08. Solid line is field values and dashed line is simulation. Note that simulator pressure is high relative to the field in cycle 9 (last peak) due to boundary effects. In the field, by cycle 9, fluids are beginning to flow beyond model boundaries.

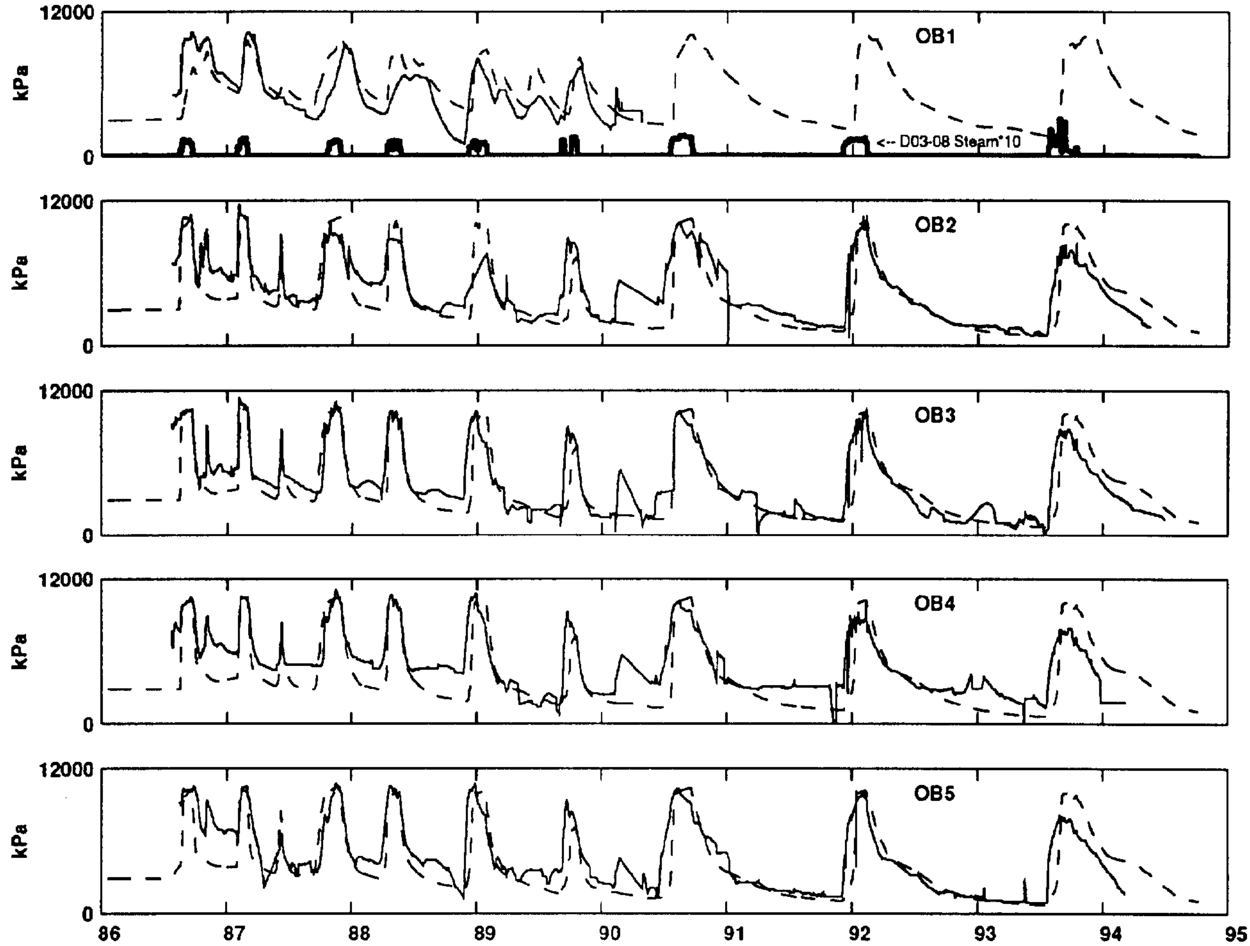

Fig. 3 – Comparison of simulated and measured bottom hole pressures for D03 pad observation wells. Simulation values are the dashed line and field values are the solid line. For reference purposes, the steam injection rate (m^3/day) for D03–08 is shown in the figure containing pressures for OB1.

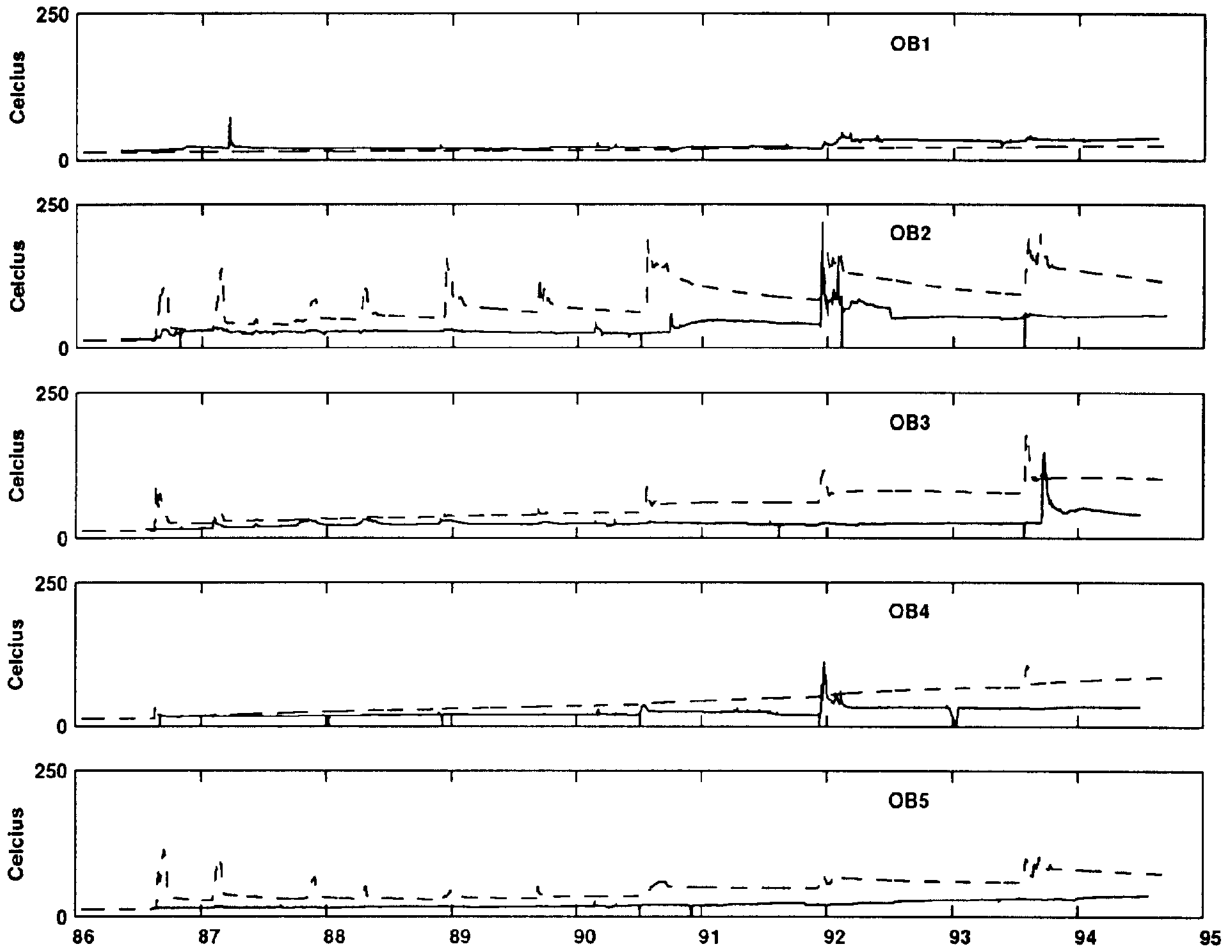

Fig. 4 – Comparison of simulated and measured bottom hole temperatures for D03 pad observation wells. Simulation values are the dashed line and field values are the solid line. Note that relatively large grid block sizes in the simulator result in model temperatures which generally exceed those of the field.

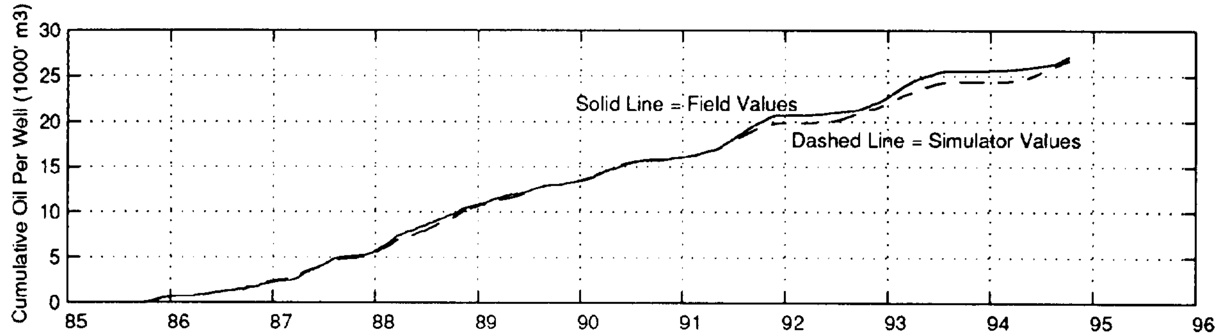

Fig. 5 – D03 model average cumulative oil production compared with field data.

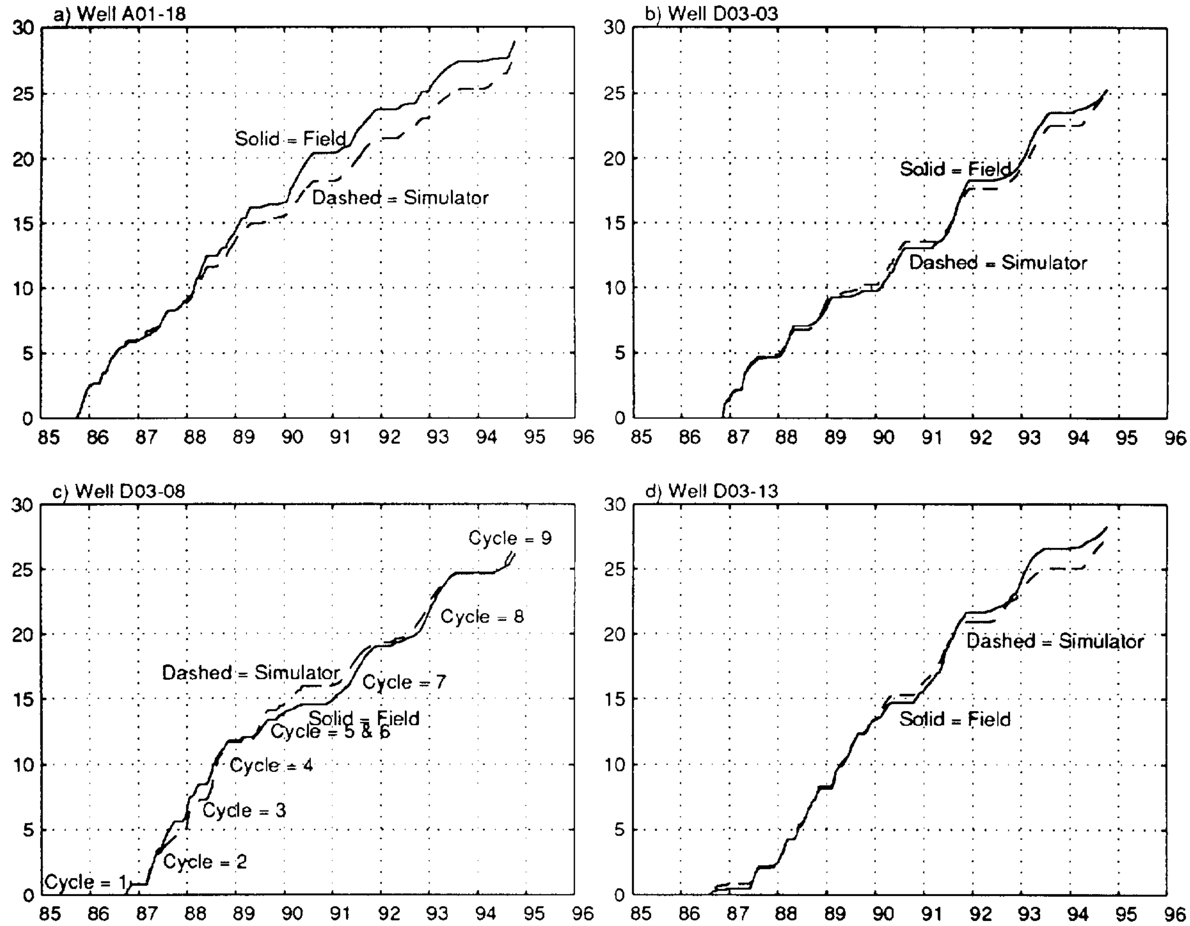

Fig. 6 – D03 individual well cumulative oil production compared with field data.

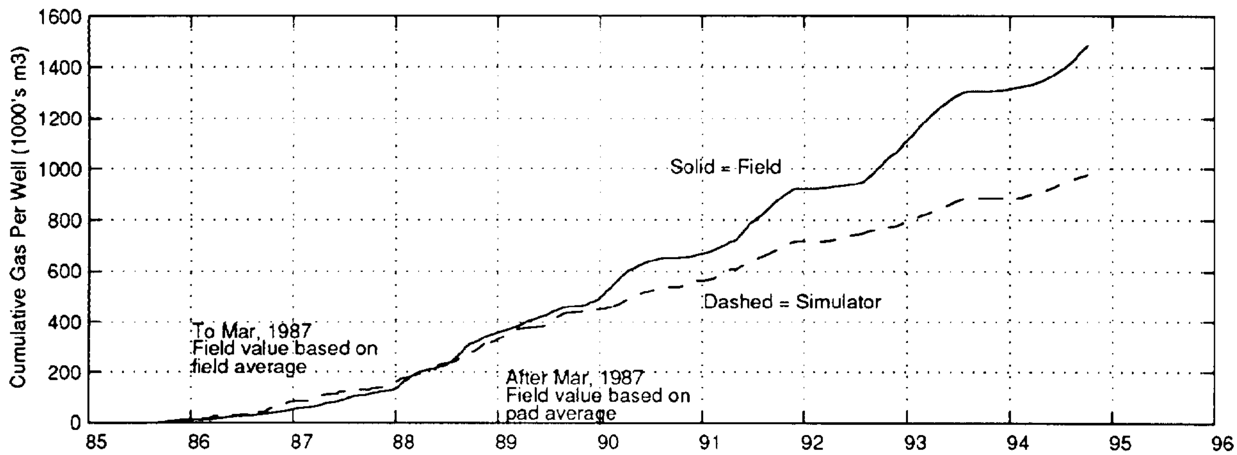

Fig. 7 – D03 model average cumulative gas production compared with field data.

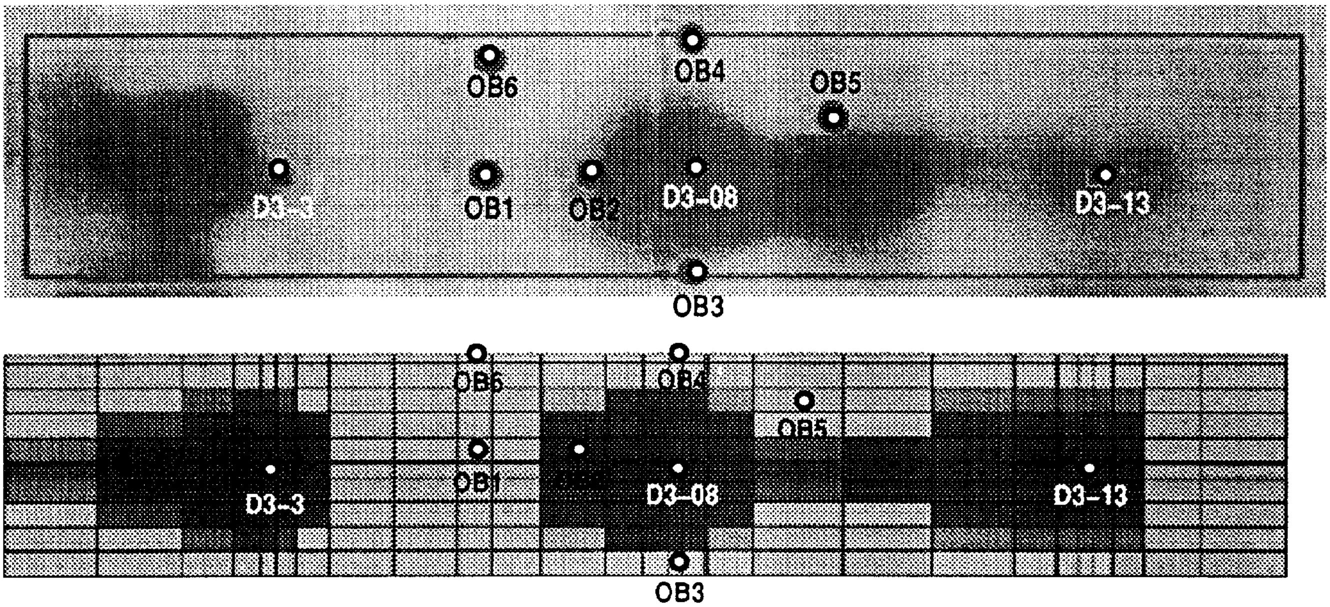

Fig. 8 – Comparison of simulator conformance and field conformance. The field conformance image (upper) is a map of the seismic delay time and the simulator conformance image (lower) is the forward-modelled delay time using grid block properties from the simulation at the same time (April, 1990). Dark areas indicate areas with greater delay time which is interpreted as conformance.

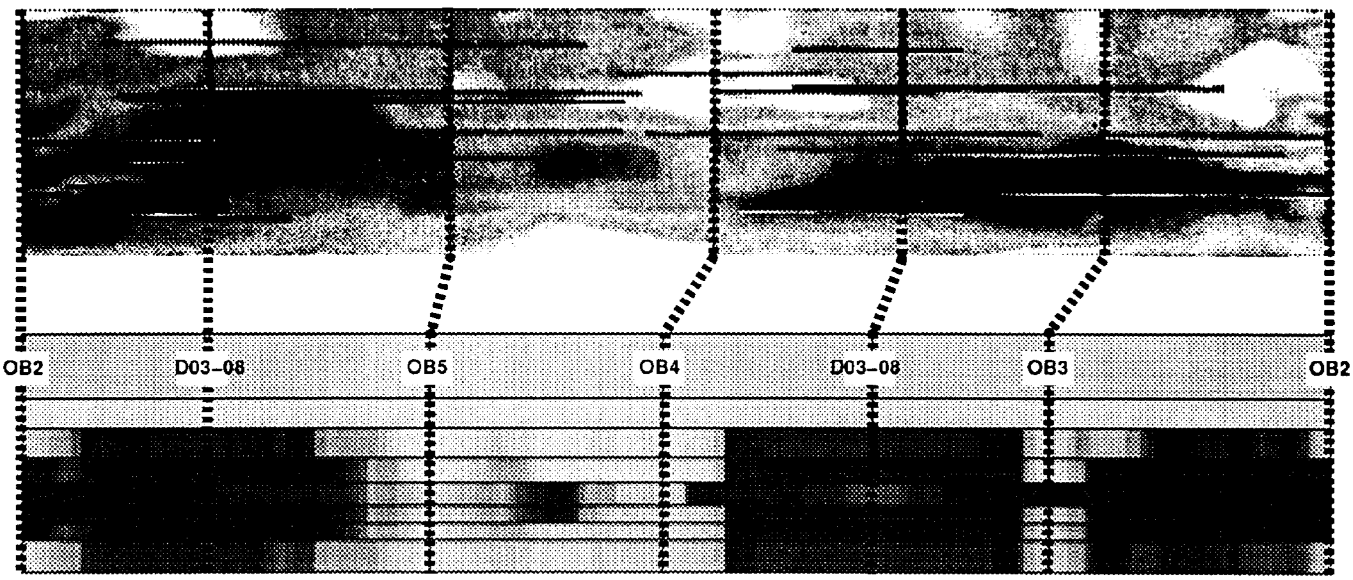

Fig. 9 – Comparison of simulator conformance and field conformance. The field conformance image is a series of travel-time tomography cross-sections between the wells indicated. The cross-sections show the seismic velocity with low velocities indicated as dark areas. The simulator conformance image is the forward-modelled seismic velocity using grid block properties from the simulation on the same date (April, 1990). Dark areas in both images indicate areas with greater delay time which is interpreted as conformance.

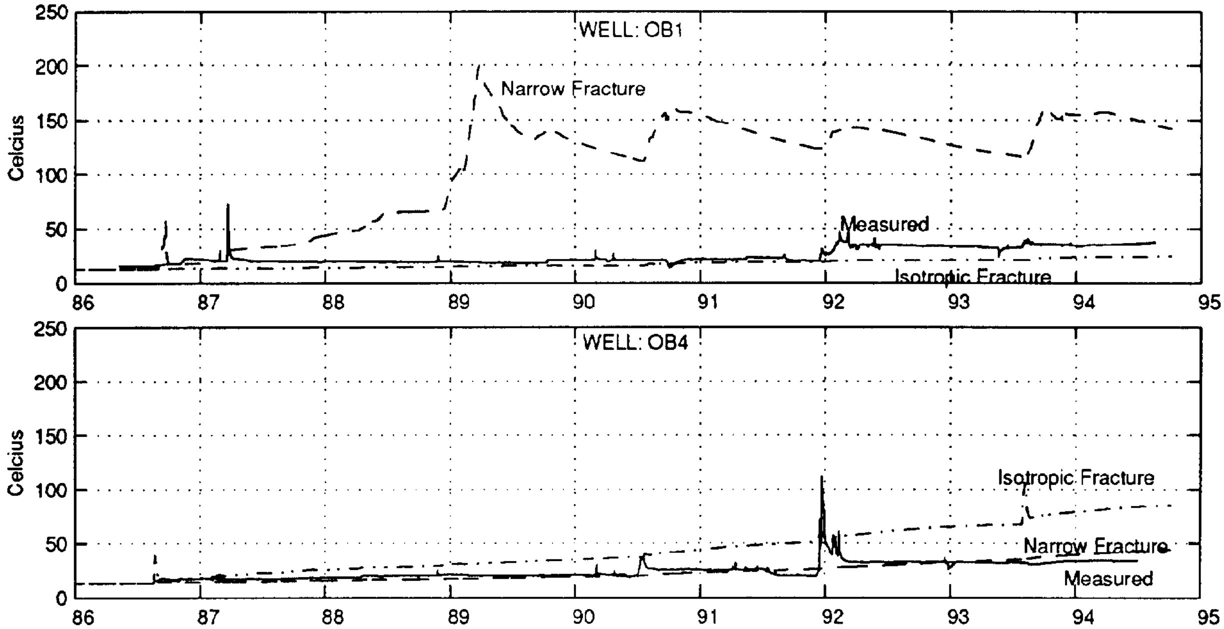

Fig. 10 – Comparison of temperature match for narrow fracture and isotropic fracture simulation cases. Note that the isotropic case matches well OB1 while the narrow fracture case matches temperatures at OB4 well. The overall match is better with the isotropic fracture.

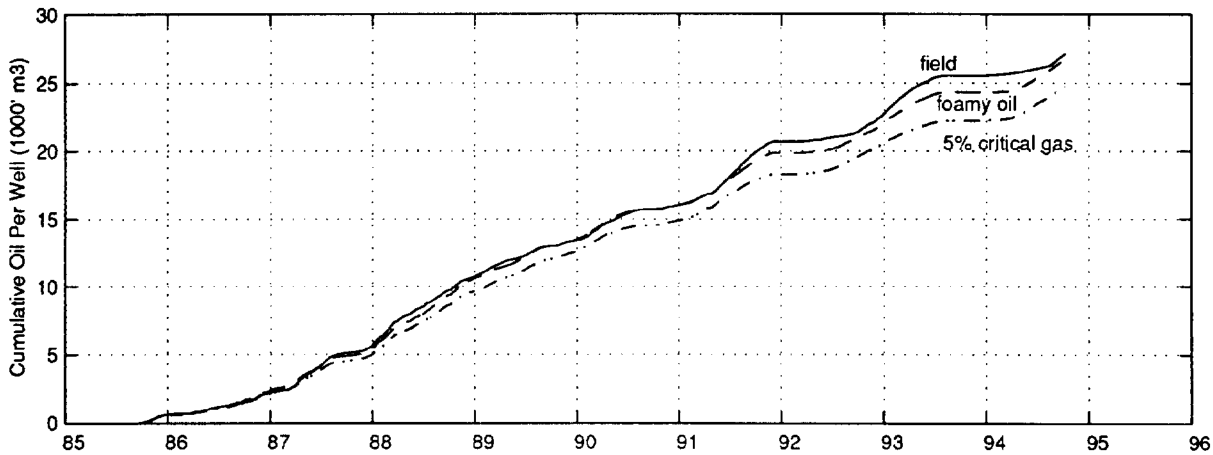

Fig. 11 – Comparison of oil production for the foamy oil base case and a case using a 5 percent fixed critical gas saturation. The oil match is superior with the foamy oil case.

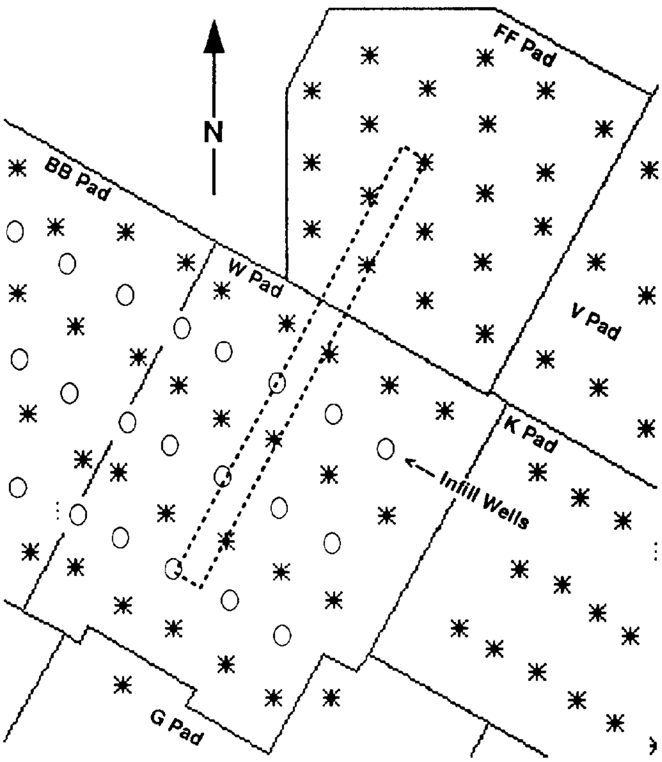

Fig. 12 – Plan view of W pad simulation model area and surrounding wells.

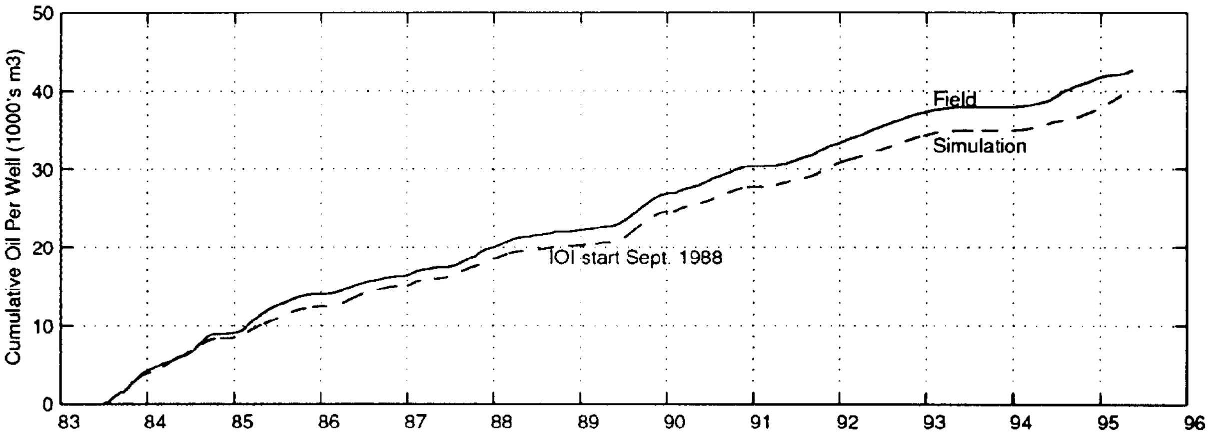

Fig. 13 – W pad model average cumulative oil production compared with field data. The simulated oil production is lower than the field value in early cycles (1983 to 1985). Two factors contribute to the acceptance of the simulated oil; first, the quality of the oil match from 1986 onward is very good, and second, there are suspected measurement errors in the field data prior to 1986.

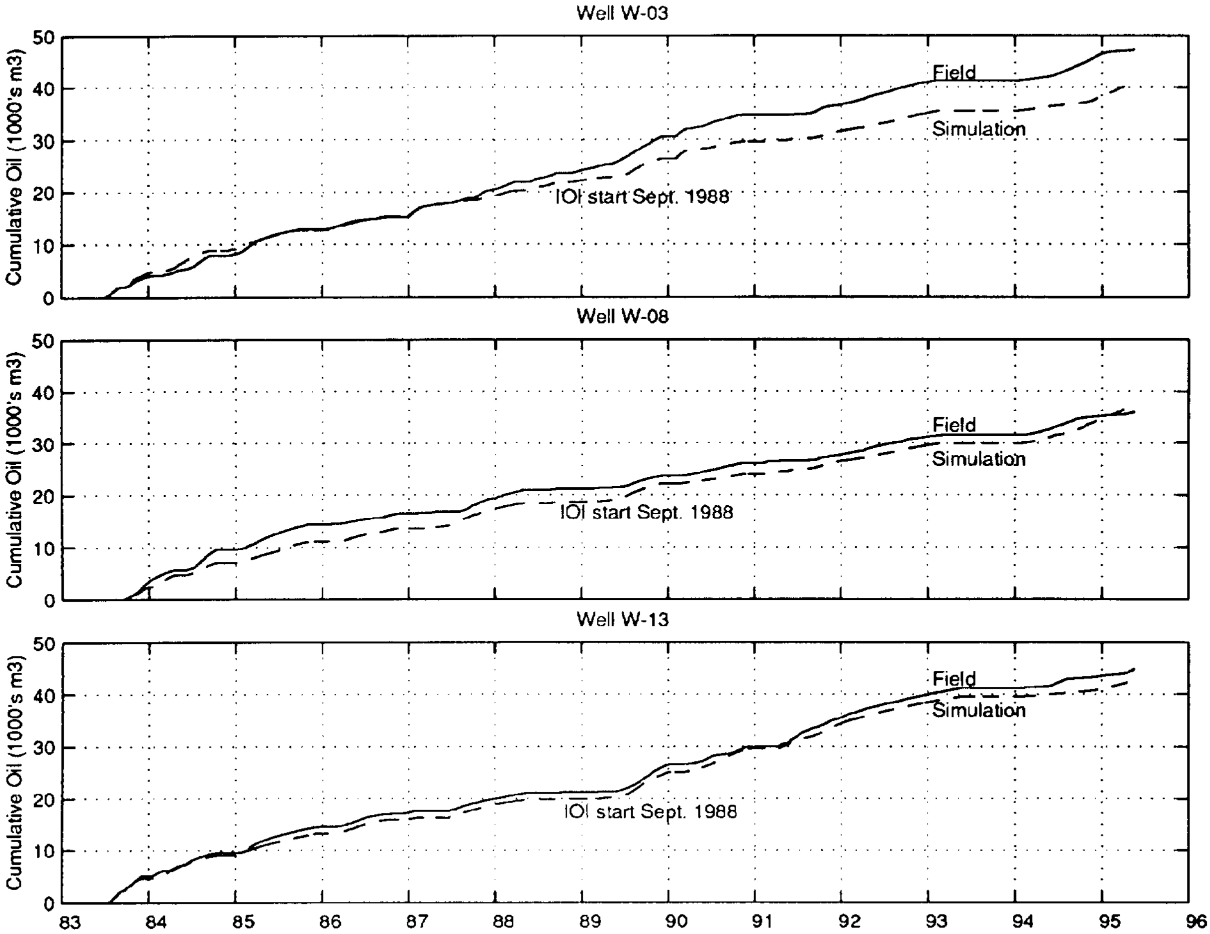

Fig. 14– W pad model individual well cumulative oil production compared with field data. During the CSS period (1983 to 1988), the oil match for all wells is generally acceptable – the difference between the simulation and the field for well W–08 in 1984 is possibly due to measurement errors in th field data. The oil match over the cyclic displacement period (1990 to 1995) is very good for two of the three wells. The W–03 well oil cut in 1989 was influenced by a well to the north. This effect was more severe in the model than it was in the field.

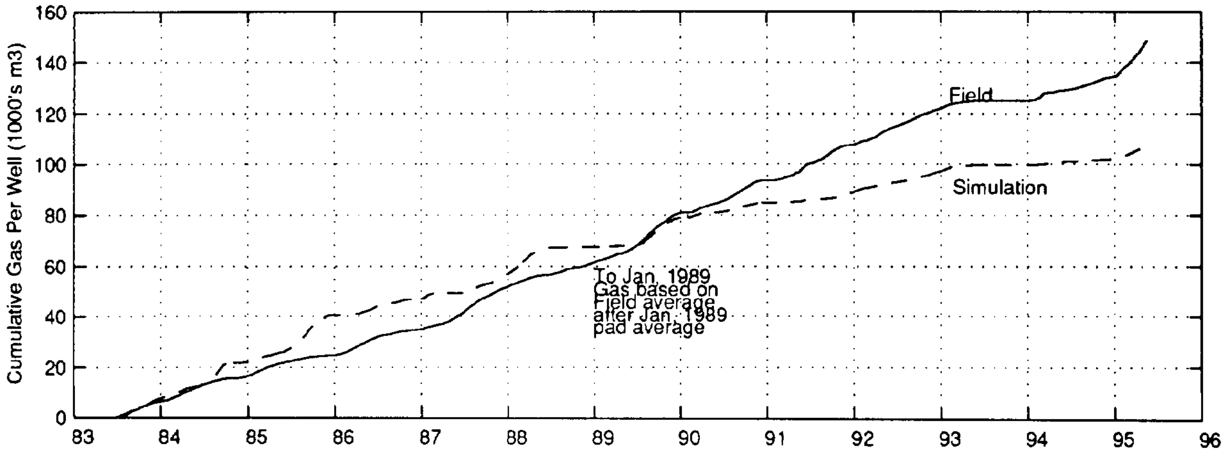

Fig. 15– W pad model average cumulative gas production compared with field data. The simulator gas production up to 1989 is consistent with expectations based on field average data. The simulated gas production is lower than the field after the cyclic displacement process began in late 1988.

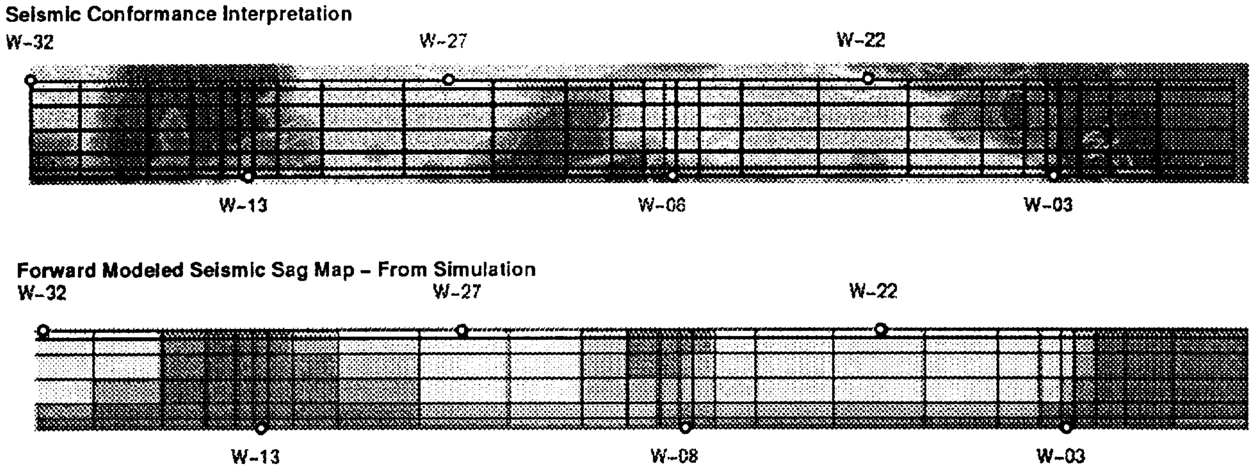

Fig. 16 – Comparison of simulator conformance and field conformance. The field conformance image is from discriminant analysis of 3D seismic and the simulator conformance image is the forward–modelled delay time using grid block properties from the simulation at the same time (1994). Dark areas indicate areas with greater delay time which is interpreted as conformance.