Cedar Hill and Tiffany: Case studies in coalbed methane reservoir simulation

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ABSTRACT

Heterogeneous reservoir descriptions are required to simulate coalbed methane well performance for the Cedar Hill field and the Tiffany area of the Ignacio-Blanco field. Multi-well, three-dimensional simulation studies demonstrate that structural configuration and permeability anisotropy of Fruitland coalbeds influence both the drainage patterns of individual wells and the simulated distribution in free gas saturation resulting from coalbed dewatering. Thus, structure and permeability anisotropy are important considerations in developing strategies for well placement and spacing to optimize field development.

INTRODUCTION

As part of a study performed for the Gas Research Institute and a consortium of coal seam gas operators, Amoco Production Company's Cedar Hill field and Tiffany area of the Ignacio-Blanco field in the San Juan Basin were among five sites selected for reservoir characterization of their Fruitland coalbed methane resources. The study objectives were to use field and laboratory data from areas with established commercial levels of production to characterize reservoir properties, and using reservoir simulation, to develop a better understanding of the relationships between coal seam gas producibility and the variability in the properties. The long production history and amount of available reservoir data made both Cedar Hill and Tiffany excellent candidates for detailed reservoir simulation study; the Cedar Hill area has the longest production history of any coalbed methane field in the San Juan Basin.

GEOLOGIC SETTING

Cedar Hill is located approximately 20 mi northeast of Farmington, New Mexico (Figure 1) and covers approximately 16 mi^2. The Tiffany area, located northeast of Cedar Hill, is approximately 20 mi southeast of Durango, Colorado and covers over 20 mi^2. Both Cedar Hill and Tiffany are located in "Area 1" of the San Juan Basin, one of three areas defined on the basis of geologic and hydrodynamic similarities[1] (Figure 1). Reservoirs in Area 1 are generally overpressured relative to hydrostatic (pressure gradients of 0.50 to 0.60 psi/ft) and fully water saturated at initial reservoir conditions.

Coalbed methane production at both field sites occurs from coal seams within the basal portion of the Upper Cretaceous Fruitland Formation (Campanian) (Figure 2). Within the Cedar Hill area, two coal seams were identified on stratigraphic cross sections as the "Upper" and "Lower" Basal Fruitland. The two coal seams are separated by a silty shale interval which was assumed to restrict vertical communication between the two model layers used to represent them within the area selected for study. For the Cedar Hill model area, the top of the basal Fruitland coal varies between 3,210 and 3,280 ft above mean sea level, representing 70 ft of structural relief (Figure 3). Within the area mapped, the Fruitland coal attains a total thickness of almost 30 ft on the basis of a 1.75 gm/cc bulk density cut-off, where the "Lower" Basal coal represents a comparatively thin "rider" coal averaging 4 ft or less.

Unlike Cedar Hill, the main producing horizon in the Tiffany area consists of a single thick basal Fruitland coal seam which was represented as a single model layer for the simulation work. Within the area selected for study, the top of the Fruitland varies between less than 3,500 ft to over 3,750 ft above mean sea level, representing a structural relief in excess of 250 ft (Figure 4). Net coal thickness in the Tiffany model area is greater than that mapped for Cedar Hill, varying between 25 and 48 ft on the basis of a 1.75 gm/cc bulk density cut-off.

SIMULATION METHODOLOGY

Seven production wells and three pressure monitor wells were modeled using a 19x23x2 simulation grid representing about 7.4 mi^2 of the Cedar Hill field area (Figure 5). The three monitor wells (Cahn 2, Schneider B-1, and Leeper B-1) were non-commercial Pictured Cliffs (sandstone) wells recompleted to the basal Fruitland coal to monitor formation pressure. Structure and isopach maps resulting from the geologic evaluation provided input data for the simulator to accurately represent the seam geometry determined for the "Upper" and "Lower" Fruitland coals. Additional reservoir parameters used in the simulation study are summarized in Table 1. To analyze the relationship between structural configuration and permeability anisotropy, the grid axes were aligned parallel to the coal face (N40E) and butt cleat directions as determined from oriented core analysis from the nearby Mesa Hamilton No. 3 well[2] (Figure 3).

Production and pressure data for the ten wells were simultaneously history matched using COMETPC 3-D, a two-phase, finite-difference coal seam gas reservoir simulator[3] previously benchmarked against black oil and coal seam gas models[4]. The match period was from field discovery in May 1977 until December 1985 (3,167 days). The history match was performed by specifying the observed water production rates and allowing the simulator to calculate the associated gas rates and bottomhole pressures. Observed data are compared with simulated results for the Schneider B-1S gas well in Figures 6 and 7 and its pressure monitor well, the Schneider B-1, in Figure 8. Matches on the other wells were of similar quality[5].

Similar procedures were followed to history match the ten production wells drilled between October 1983 and November 1989 (2,251 days) in the Tiffany area. Representing about 6.8 mi^2, the 13x19x1 simulation grid (Figure 9) was aligned parallel to the face and butt directions. Oriented core analysis from the Mobil Colorado 32-7 # 9 well[6,7] indicates a face cleat direction of approximately N45W at Tiffany (Figure 4). Additional reservoir parameters used in the Tiffany simulation study are also summarized in Table 1.

In contrast to the approach utilized in the Cedar Hill history match, the ten wells within the Tiffany model area were matched by specifying the observed gas production rates and allowing the simulator to calculate the associated water rates and bottomhole pressures. Although there are no pressure monitor wells in the Tiffany area, bottomhole pressures were periodically measured on the gas production wells. This observed pressure data was used to verify the accuracy of the simulated flowing bottomhole pressures. Observed data are compared with simulated results for the Hott 20-2 gas well in Figures 10-12; matches on the other wells were of similar quality.

RESERVOIR CHARACTERIZATION

The least well defined reservoir properties for Cedar Hill and Tiffany were cleat porosity, absolute cleat permeability, and gas-water relative permeability. Estimates for these coal properties were determined which provided simulated results consistent with observed field performance.

Cleat Porosity and Permeability

A homogeneous reservoir description could not be utilized in simulating actual well performance for either Cedar Hill or Tiffany. Table 2 summarizes the cleat porosities and permeabilities as determined from the two simulation studies.

Reflecting the low water storage capacity of coal, simulated cleat porosities varied between 0.05 and 0.80% (averaging 0.25%) for the Cedar Hill model area. The cleat porosities estimated for Tiffany are approximately 2 to 4 times greater than for Cedar Hill, ranging between 0.5 and 1% (averaging 0.6%). These values are lower than previously published values of 2 to 5%[8-10]. However, recent work by Gash[11] suggests that laboratory-measured cleat porosities for northern San Juan Basin coals may be as low as those shown in Table 2.

Simulated (geometric average) cleat permeabilities varied between 0.5 and 10 md (averaging 7 md) for Cedar Hill which are consistent with data previously reported by Mavor and others[2] for the Mesa Hamilton No. 3 well, and by Oldaker[10] for the Cedar Hill field area. The average cleat permeability simulated for the Tiffany model area varied between 1 and 2.2 md (averaging 1.2 md). For both model areas, the face cleat permeability was generally 2 to 4 times greater than the butt cleat permeability (Table 2).

Gas-Water Relative Permeability

The relative permeability curves resulting from the Cedar Hill and Tiffany history matches are shown in Figure 13. Similar to those used to describe fractured reservoir systems[12], these psuedo relative permeabilities do not resemble the laboratory-measured curves reported, for example, from the Mesa Hamilton No. 3 well[2], also shown in Figure 13 (laboratory-measured curves were not available for the Tiffany area). This is because laboratory relative permeability data obtained from conventional core plugs do not adequately reflect the effects of either natural fractures or gas-water gravity segregation. Thus, the relative permeability curves, which result from matching production from the entire coal thickness with a simulator, are steeper than the laboratory curves, particularly for gas (k_{rg}), as shown in Figure 14. The use of the Mesa Hamilton No. 3 measured curves would require much higher absolute permeabilities (k_{abs}) to achieve the effective gas phase permeability ($k_{eff} = k_{rg} \times k_{abs}$) necessary to simulate the observed gas production for the Cedar Hill model area.

INTERFERENCE EFFECTS

Two competing mechanisms are at play during coalbed methane well interference: 1) amplification and reinforcement of pressure drawdown in the interwell distance, and 2) competition for drainage of gas located in the interwell distance. The first mechanism has a direct bearing upon dewatering and the attendant release of gas from the coal matrix via the sorption isotherm[13]. The efficiency with which this process occurs for a given set of coal reservoir characteristics is related to well spacing[14,15]. Reservoir characterization through the application of multi-well, three-dimensional simulation techniques provides a means by which these well interference effects can be examined[5,16].

Cedar Hill Field

The proximity and timing of drilling of the Cahn 1, Schneider B-1S, and State BW-1 wells provided an opportunity to evaluate well interference effects during the initial 8.7 years of Cedar Hill production history. Cahn 1 is located at the approximate center of a 320 acre five-spot pattern with two of the corner locations occupied by State BW-1 and Schneider B-1S (Figure 5). Between May 1977 and November 1981 (1,645 days), Cahn 1 produced without pressure interference from surrounding wells. Low water production rates were observed when production was initiated in the Schneider and State wells in November 1981. These low rates were the result of the preceding 4.5 years of dewatering and production by the Cahn well and structural differences across the model area (Figure 3). The high initial water rates observed at the Cahn well were absent at the structurally equivalent Schneider B-1S location (Figure 15), while water production observed updip at the State BW-1 well was lower than at either the Cahn or Schneider wells (Figure 16).

As a result of this 4.5 year period of Cahn 1 production, a simulated gas saturation of 5 to 7% was generated at the Schneider B-1S and State BW-1 well locations, yielding rapid responses in their initial gas production rates. For a period of about one year after production was initiated in Schneider B-1S and State BW-1 (1645 to 2000 days in Figure 17), Cahn 1 gas production declined, probably in response to competition for free gas located in the interwell distance. Subsequent to this period of decline, however, Cahn 1 gas production improved, apparently in response to the increased availability of free gas associated with more efficient pressure drawdown in the drainage area affected by production from all three wells.

Both structural relief and permeability anisotropy influenced individual well drainage patterns and the development of the simulated distribution in free gas saturation. Coalbed dewatering and pressure drawdown occurred more rapidly in the face cleat direction which parallels the structural trend at Cedar Hill. As a result, free gas developed more rapidly in the face cleat direction and higher gas saturations accumulated in the up-dip locations of the model area.

To further examine well interference effects within the Cedar Hill model area, three additional cases were simulated which isolated the pressure drawdown effects associated with production from the Cahn 1, Schneider B-1S and State BW-1 wells[5]. Case I assumed that Cahn 1 was the only producing well in the model area throughout the simulated period of 3,167 days. Alternatively, Cases II and III assumed that Cahn 1 was shut-in while the remaining six coalbed methane wells were allowed to produce during the same period. Cases II and III differed in the operating conditions assumed for Schneider B-1S and State BW-1. In Case II, the Schneider B-1S and State BW-1 wells were operated with the same water rates specified for the history match. Alternatively, Case III utilized a flowing bottomhole pressure schedule (estimated from the history match) based on the assumption that the observed production from the Schneider B-1S and State BW-1 wells may vary in the absence of Cahn 1 production. The sum of Cases I and II represents 58% of the 5.4 Bcf cumulative gas production determined from the history match results, whereas the sum of Cases I and III represents 83% (Figure 18). Aggregate gas production apparently benefited from the mutual interaction between Cahn 1, Schneider B-1S and State BW-1, at least for the 8.7 years of production history included in this study.

Tiffany Area

The Hott 20-2, Hott 29-2 # 2 and Hott 30-1 # 2 wells are located along the pattern axis of three contiguous 320 acre five-spot patterns (Figure 4). Comparison of the production character for each of these wells suggests that the pattern axis approximates an isopotential surface. The southeastern edge of the simulation grid (right-hand side of Figure 9) coincides with both the pattern axis and a no-flow boundary. Of the three wells drilled along the pattern axis, Hott 20-2 began production in late 1983, whereas Hott 29-2 # 2 and Hott 30-1 # 2 were not produced until May 1989 (only six months prior to the end of the simulated period).

The simulated pressure distribution for November 1989 (Figure 19) shows that six years of production from the Tiffany model area resulted in limited pressure drawdown from an initial average reservoir pressure of about 1600 psia. The greatest drawdown occurred between wells drilled interior to the 320 acre five-spot patterns where reservoir pressure was lowered more than 200 psia. For wells drilled on a closer spacing, coalbed dewatering and pressure drawdown resulted in the development of simulated free gas saturations approaching 10 to 12%.

The difference between the initial adsorbed gas content prior to production ($[Gc]_{83}$ in Figure 20) and the gas content remaining at the end of the simulated historical period ($[Gc]_{89}$) provides an alternate view of well interference effects in the Tiffany model area. As this difference increases (higher "peaks" in Figure 20), higher gas recoveries for the coalbed reservoir are indicated due to the increased availability of desorbed matrix gas. Wells located interior to a 320 acre five-spot pattern, such as Hott 20-4, appear to benefit from the production of surrounding wells as indicated by the greater reduction in matrix gas content (gas content difference exceeds 75 scf/ton in Figure 20). Alternatively, wells that are not as "confined" such as Hott 30-2 or SU Tr G-1 do not show as great a reduction in the initial matrix gas content. Based on this type of analysis, potential well locations can be selected for areas where pressure lowering is minimal and matrix gas content remains relatively high.

PERFORMANCE DIFFERENCES BETWEEN CEDAR HILL AND TIFFANY

Although the initial gas content and coal thickness at Tiffany is greater than that reported for Cedar Hill, resulting in more than twice the gas-in-place per 640 acres at Tiffany than at Cedar Hill, the average gas production rate for the Tiffany wells represents less than 20% of the average rate observed for Cedar Hill. This is because of less effective dewatering and gas desorption associated with the lower cleat permeabilities simulated for Tiffany.

Development of free gas saturations in the Cedar Hill model area was facilitated by both structural relief and permeability anisotropy, where the higher permeability face cleat direction resulted in more rapid coalbed dewatering parallel to structural dip (Figure 3). However, the combination of the lower permeabilities at Tiffany and a structural relief in excess of 250 ft, which is generally coincident with the lower permeability butt cleat direction (Figure 4), minimized the potential for updip gas accumulations similar to those noted for the State BW-1 well in the Cedar Hill field. As a result, coalbed methane reservoirs characterized by higher cleat porosity (water storage capacity) and lower cleat permeability, such as Tiffany, may be considered potential candidates for closer well spacings[14,15].

CONCLUSIONS AND IMPLICATIONS

The Cedar Hill and Tiffany simulation studies provide insight into the reservoir properties and performance characteristics of the basal Fruitland coals in the northern San Juan Basin. The results of these studies have implications that can be utilized in developing the resources in other coalbed methane producing provinces:

1. Basal Fruitland coals appear to be characterized by lower cleat porosities than previously reported. Lower coal cleat porosities will result in less produced water and lower operating and water disposal costs.

2. Due to the impact on field drainage, the degree of permeability anisotropy and its relationship to structural configuration should be considered in the development of a coalbed methane reservoir, particularly with regard to well placement and spacing.

3. Reservoir heterogeneity may facilitate relatively rapid coalbed dewatering and gas accumulations updip from areas of active coalbed production. If the heterogeneous nature of the producing reservoir is adequately characterized, well locations can be selected with the potential for less initial water production and higher gas rates.

4. Optimum field development should consider multi-well interference effects resulting from various well spacing strategies and their impact on total production. In this way, both the coalbed methane and financial resources can be better managed.

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RESERVOIR PARAMETER	CEDAR HILL	TIFFANY
Initial Pressure, psia	1,562 @ +3,259' msl	1,610 @ 3,530' msl
Langmuir Volume, scf/ton	623	823
Langmuir Pressure, psia	331	707
Desorption Pressure, psia	1,562	1,610
Initial Gas Content, scf/ton	514	572
Temperature, °F	114	120
Pore Compressibility, 10^{-6} psi^{-1}	200	
Cleat Spacing, in.	0.25	
Sorption Time, days	10	
Gas Gravity	0.61	
Water Viscosity, cp	0.565	
Water FVF, RB/STB	1.006	

Table 1. Reservoir parameters used for Cedar Hill and Tiffany simulation studies

RESERVOIR PARAMETER	CEDAR HILL	TIFFANY
Cleat Porosity, %	0.25 - 0.8	0.5 - 1.0
Geometric Average Cleat Permeability, md	0.5 - 10	1 - 2.2
Face Cleat Permeability, md	0.5 - 20	1 - 4
Butt Cleat Permeability, md	0.5 - 5	1 - 1.2
Face/Butt Cleat Permeability Ratio	1:1 - 4:1	1:1 - 4:1
Irreducible Water Saturation, %	85	75
Initial Water Saturation, %	100	100

Table 2. Fruitland coal reservoir parameters determined from history matching Cedar Hill and Tiffany

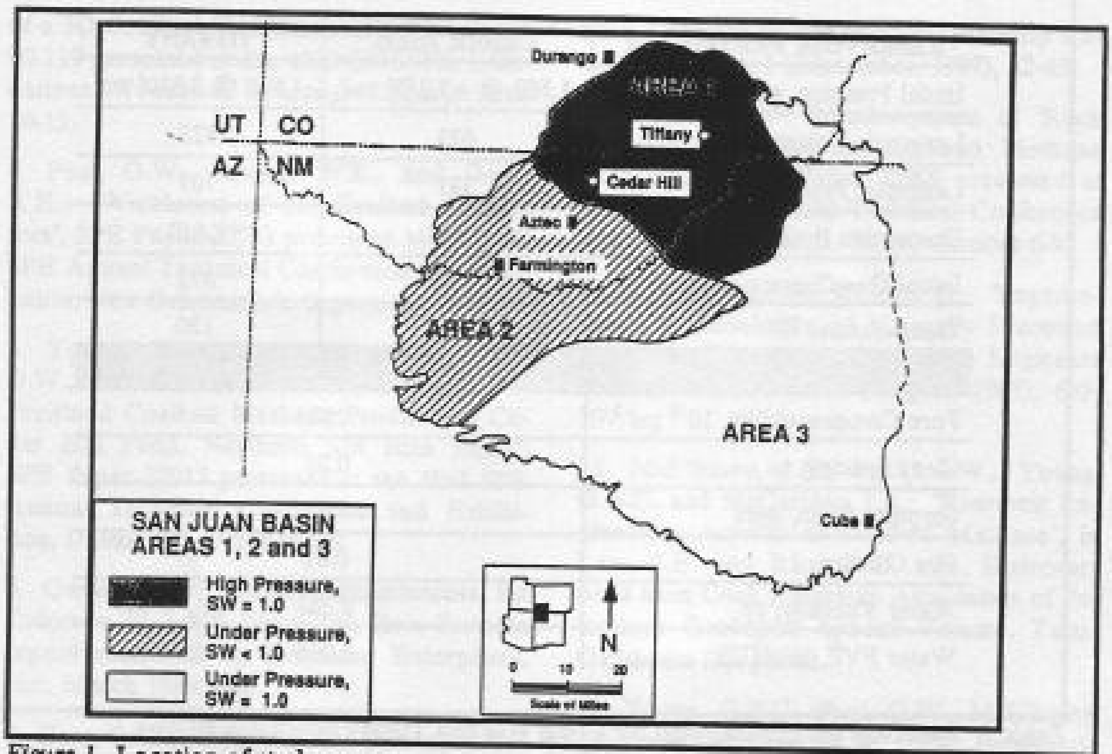

Figure 1. Location of study areas

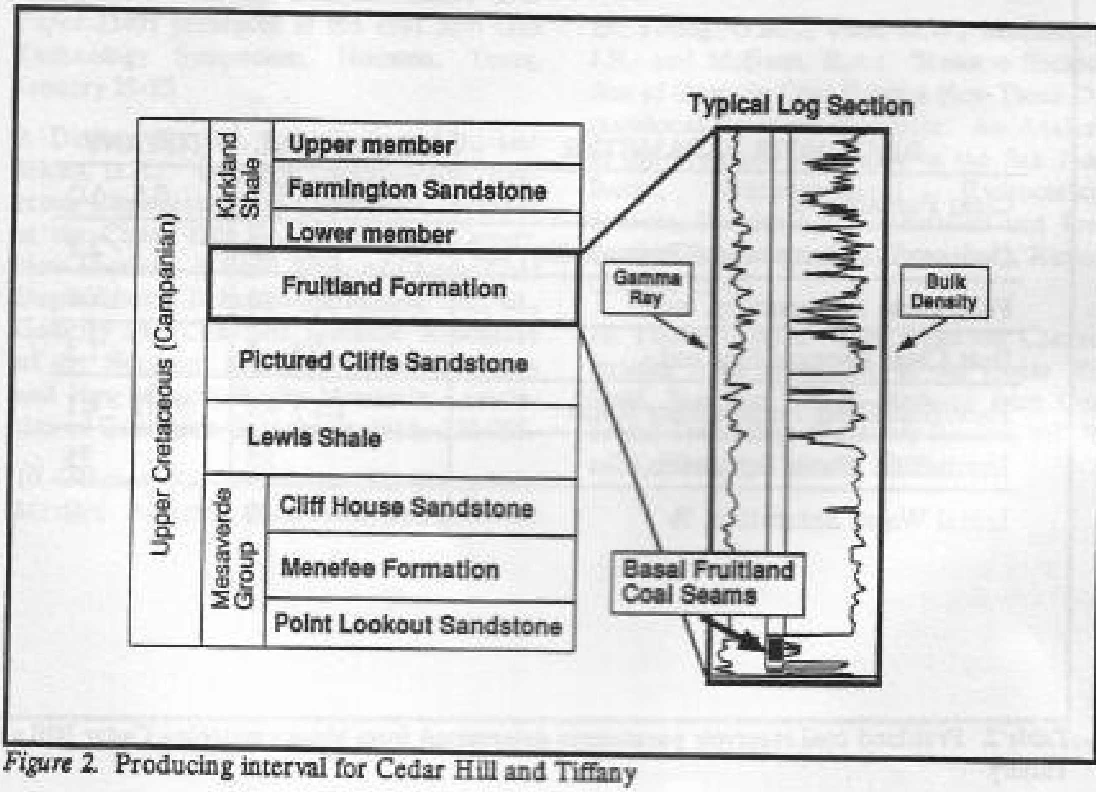

Figure 2. Producing interval for Cedar Hill and Tiffany

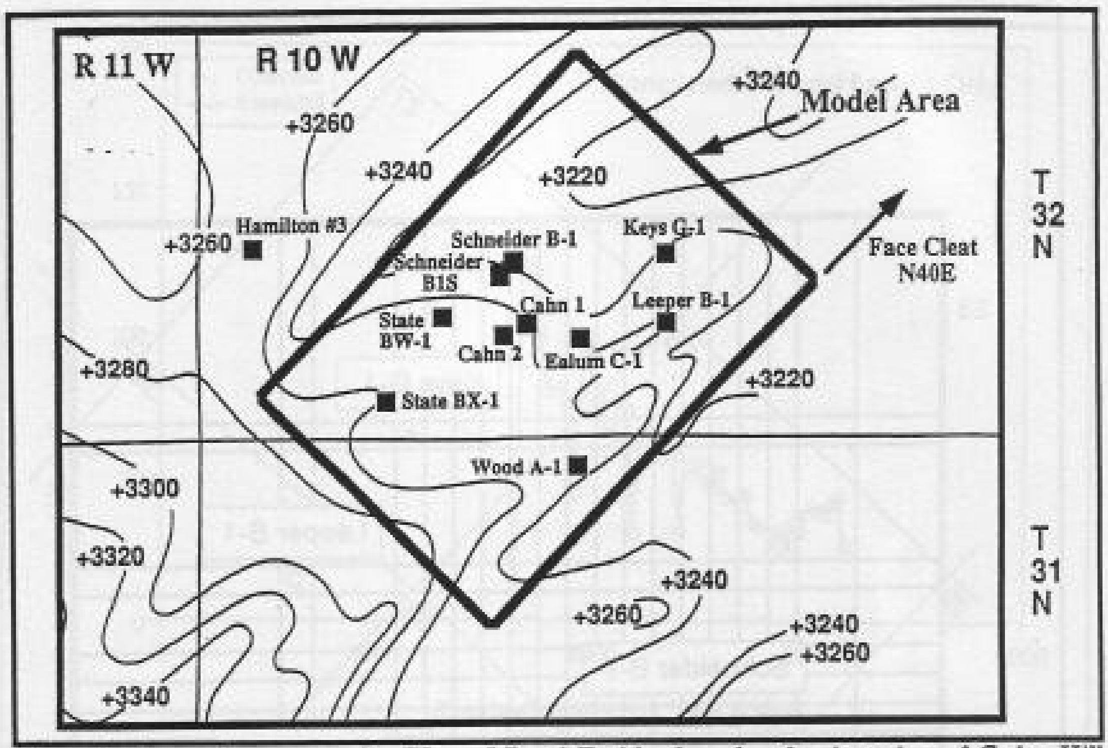

Figure 3. Top of structure for "Upper" Basal Fruitland coal and orientation of Cedar Hill model area relative to coal cleat directions

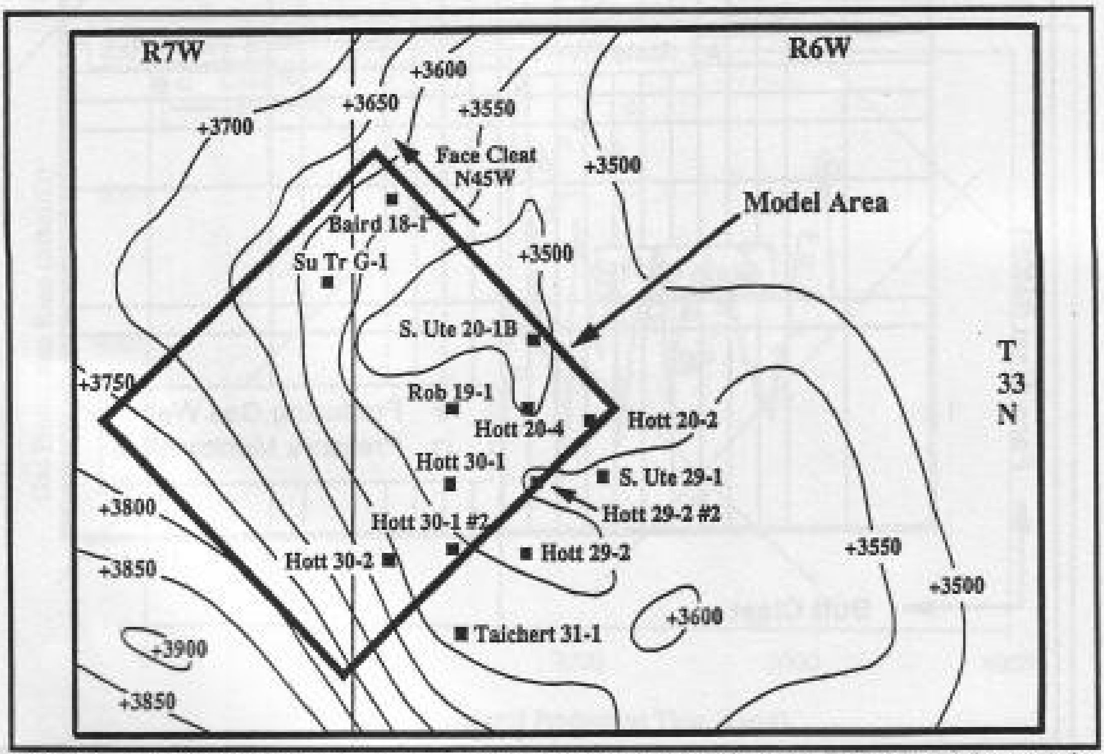

Figure 4. Top of structure for Basal Fruitland coal and orientation of Tiffany model area relative to coal cleat directions

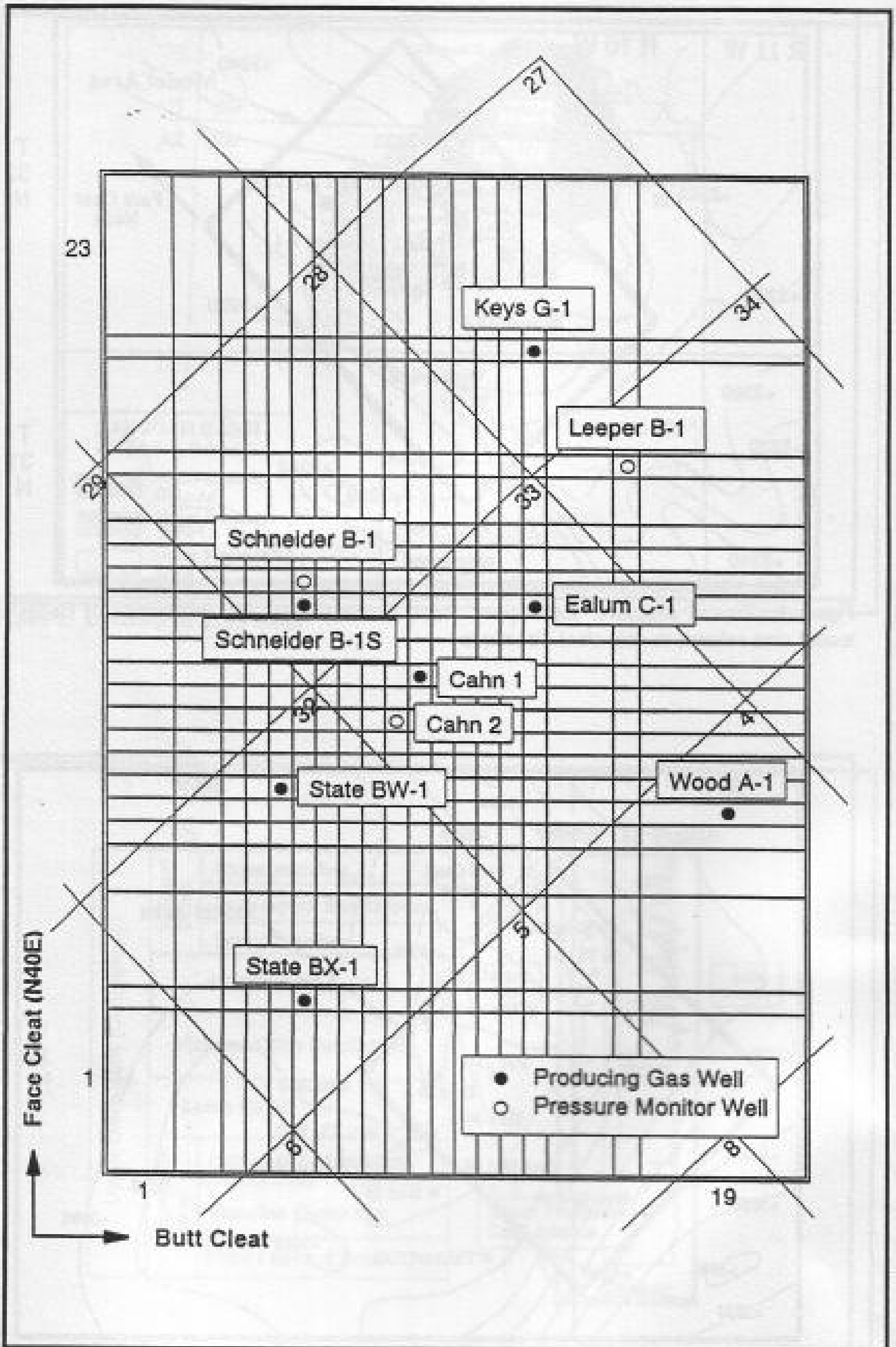

Figure 5. Cedar Hill simulation grid

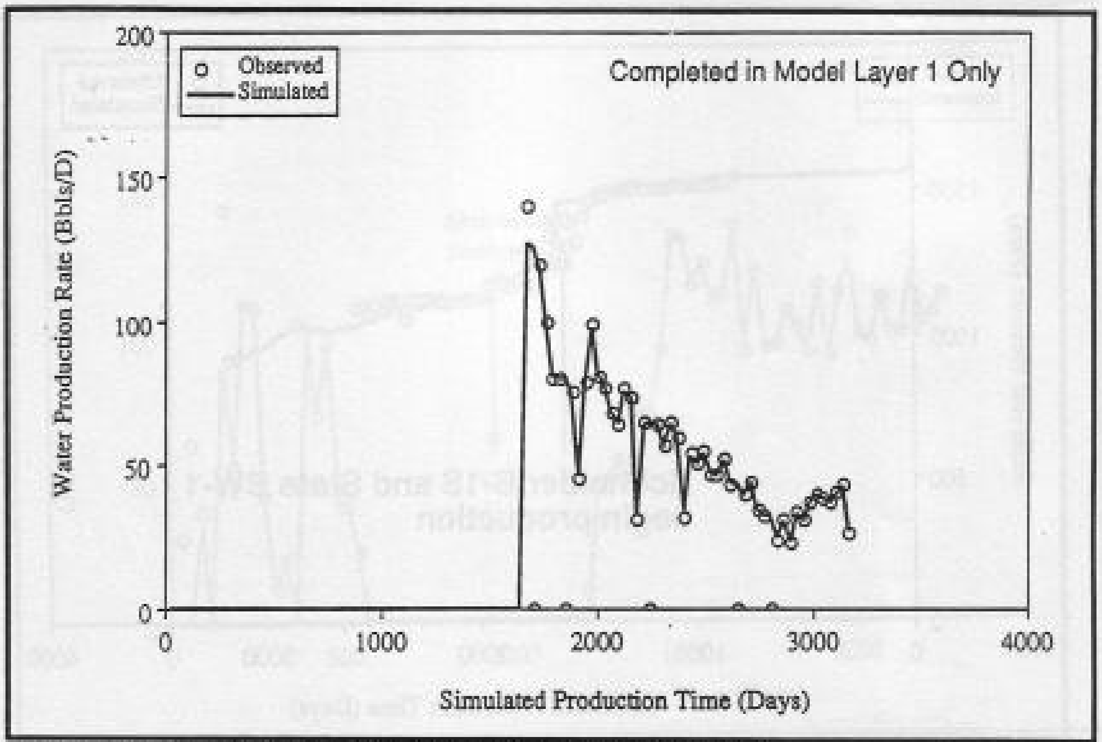

Figure 6. Water rate schedule for Schneider B-1S, Cedar Hill field

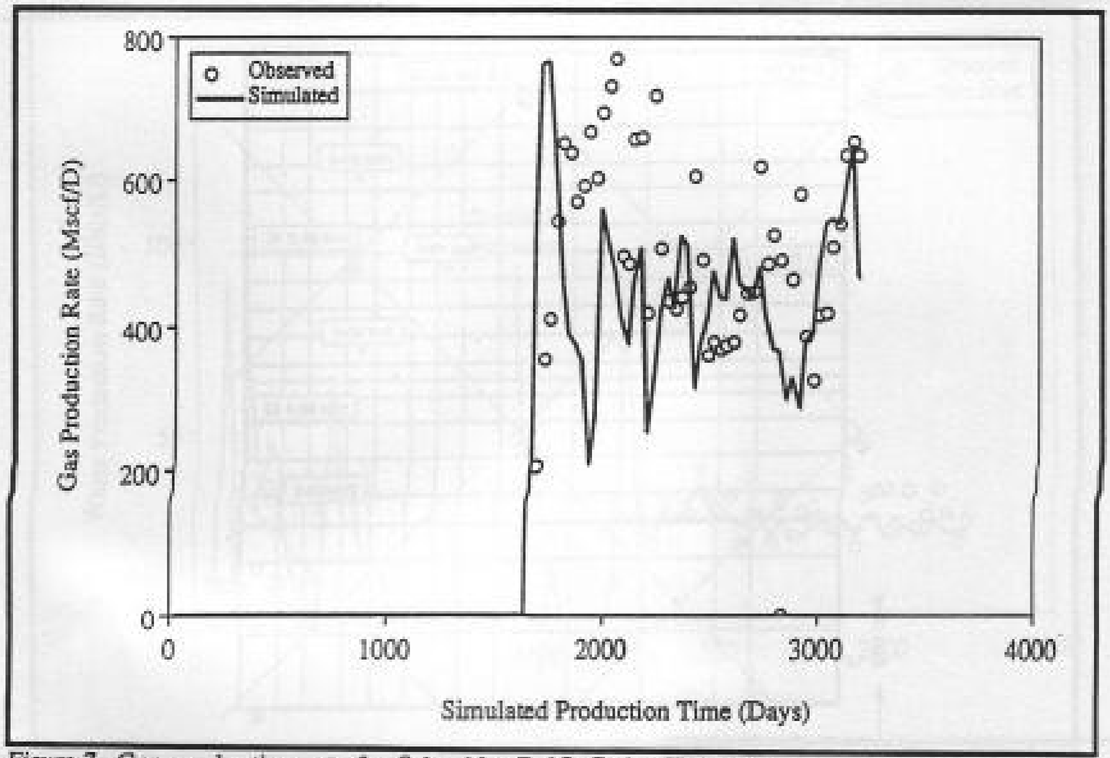

Figure 7. Gas production rate for Schneider B-1S, Cedar Hill field

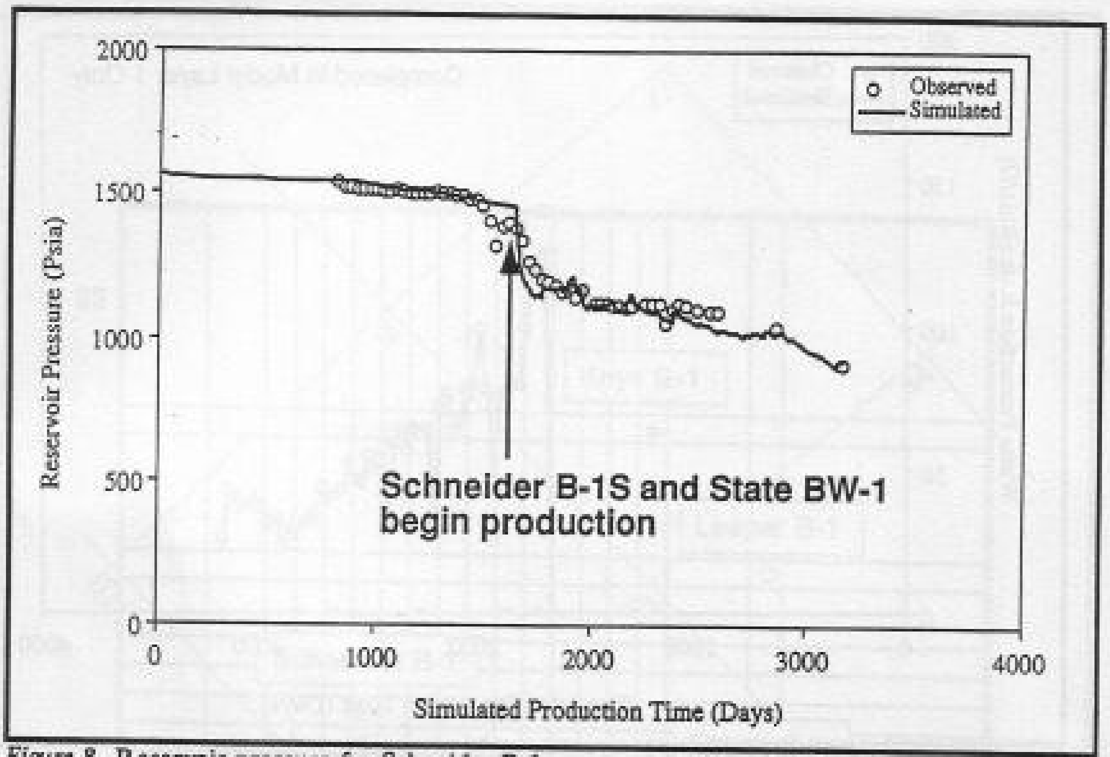

Figure 8. Reservoir pressure for Schneider B-1 pressure monitor well, Cedar Hill field

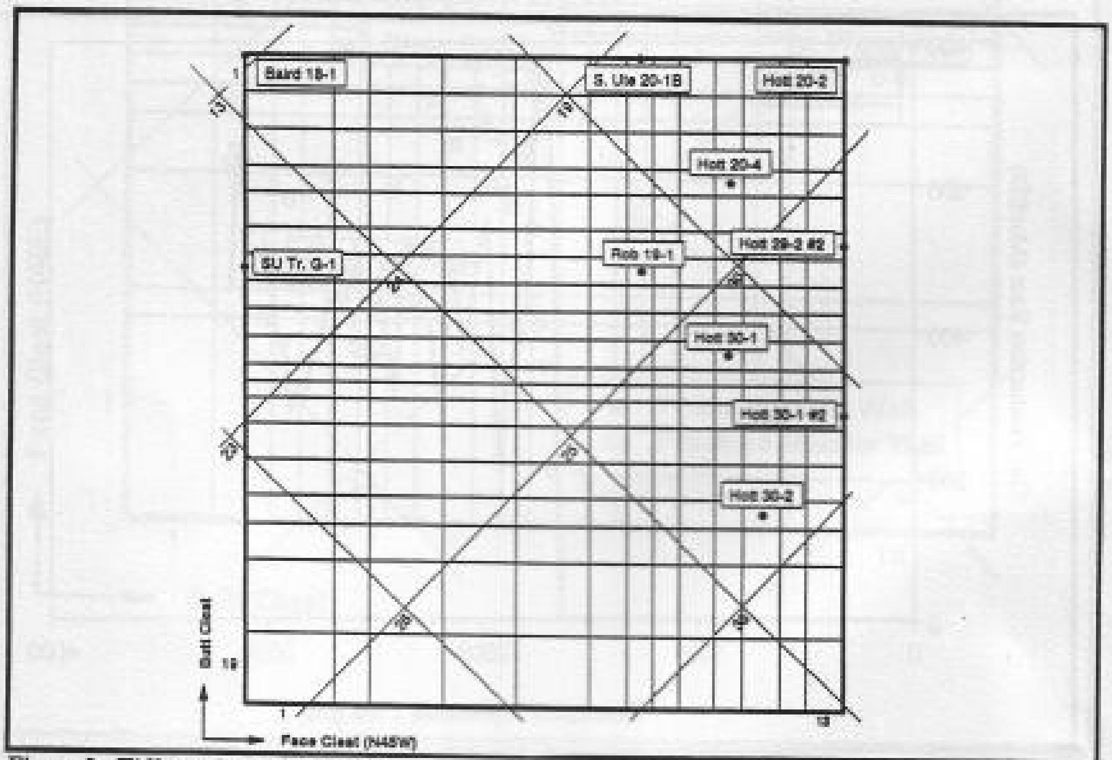

Figure 9. Tiffany simulation grid

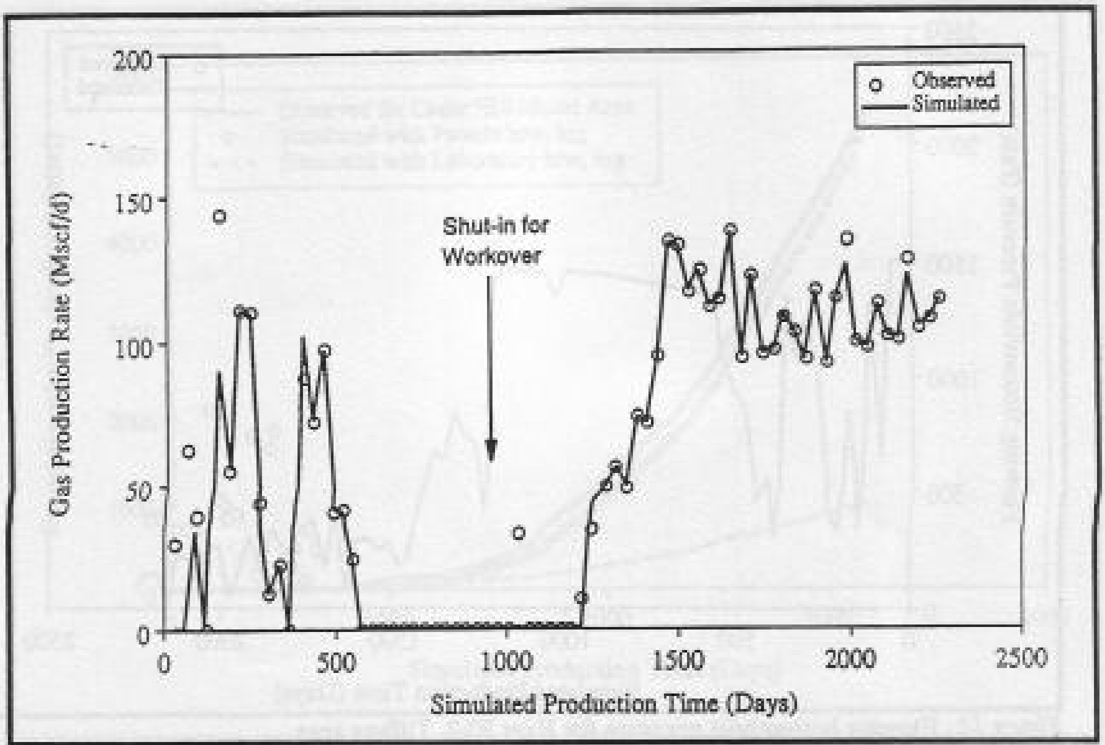

Figure 10. Gas rate schedule for Hott 20-2, Tiffany area

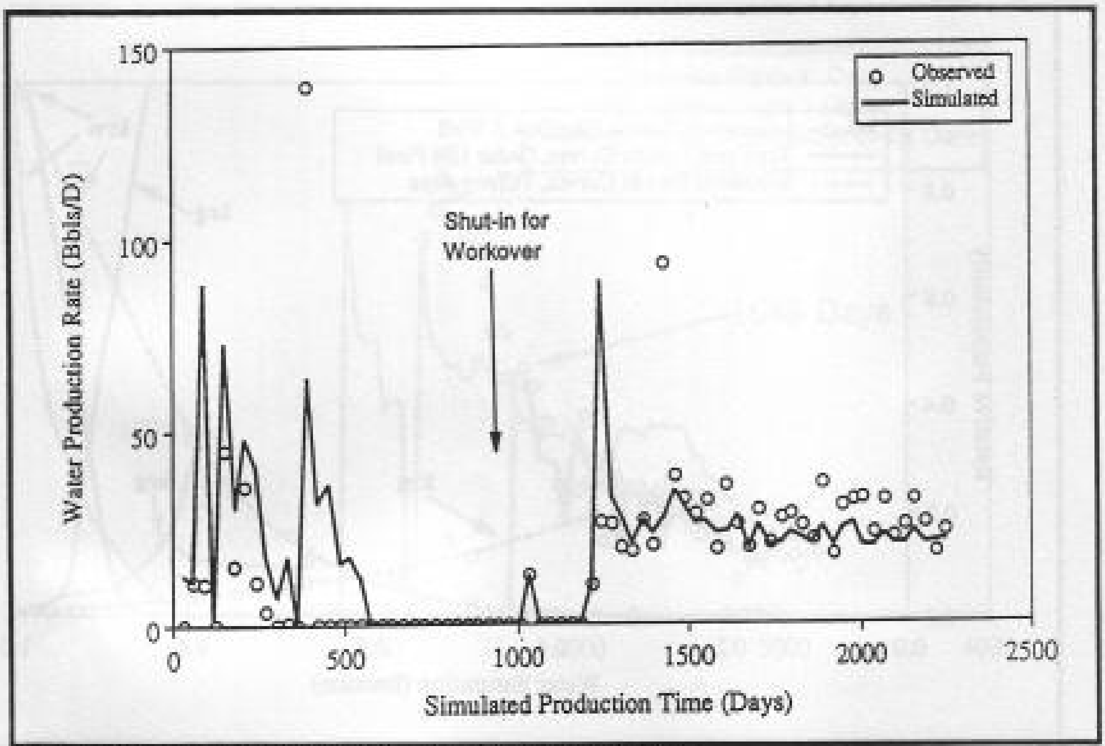

Figure 11. Water production rate for Hott 20-2, Tiffany area

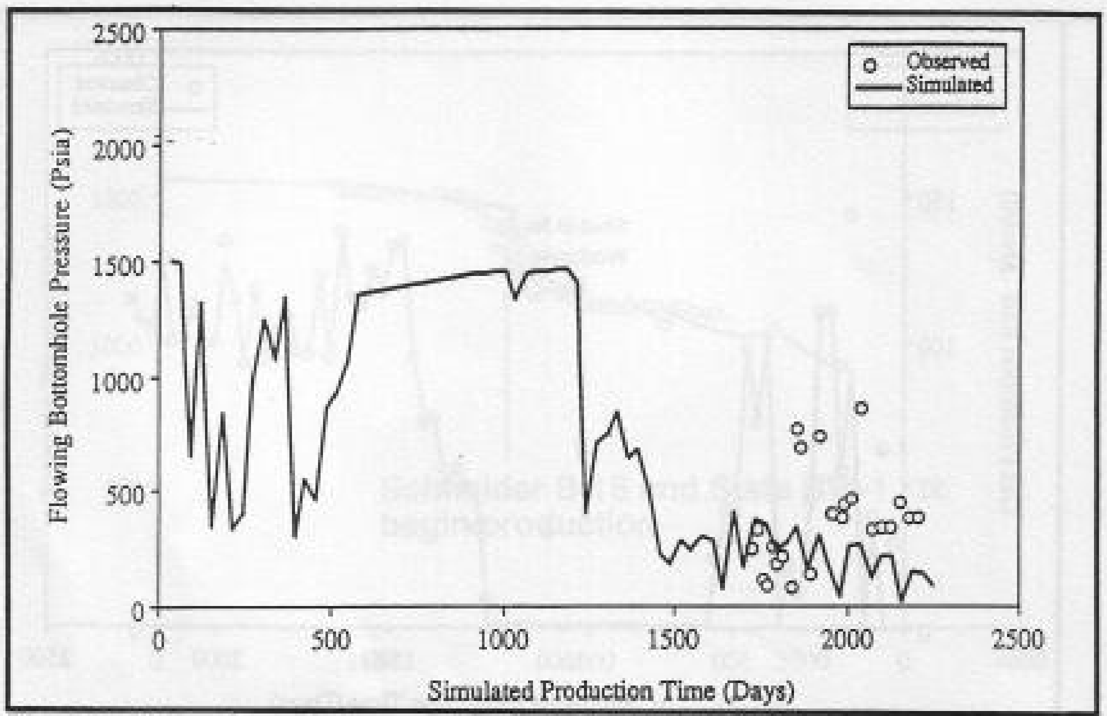

Figure 12. Flowing bottomhole pressure for Hott 20-2, Tiffany area

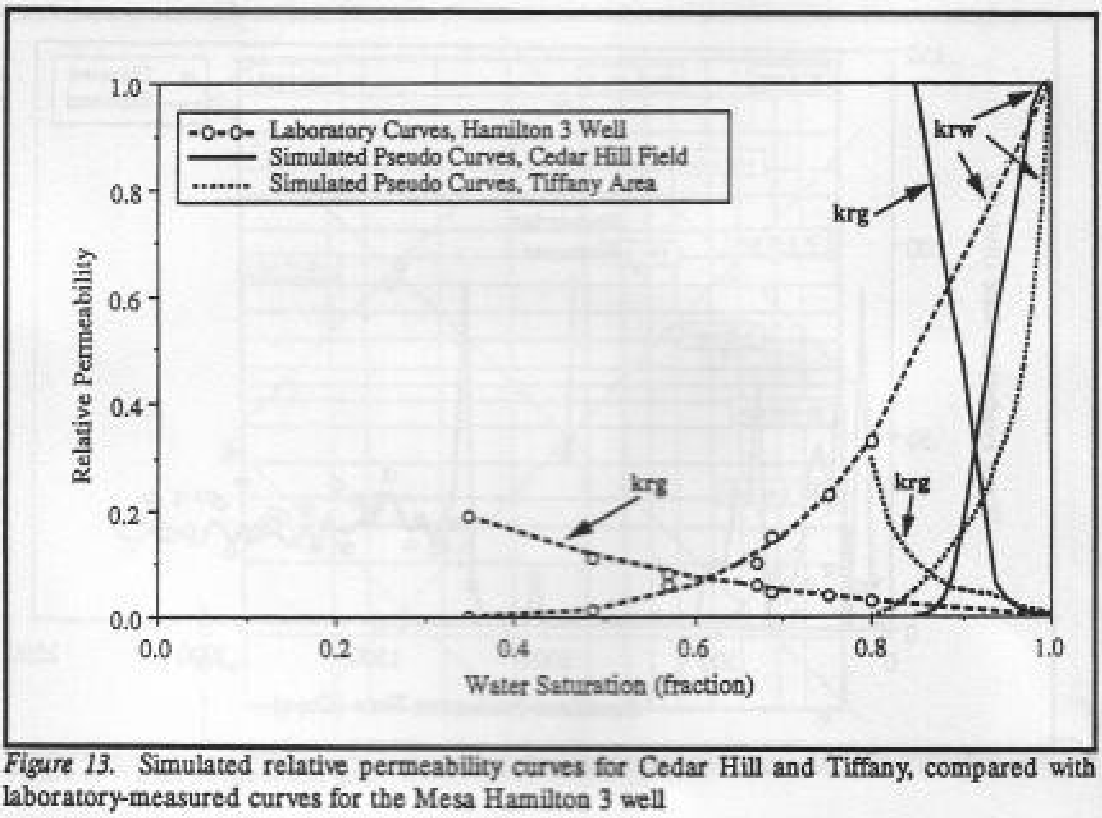

Figure 13. Simulated relative permeability curves for Cedar Hill and Tiffany, compared with laboratory-measured curves for the Mesa Hamilton 3 well

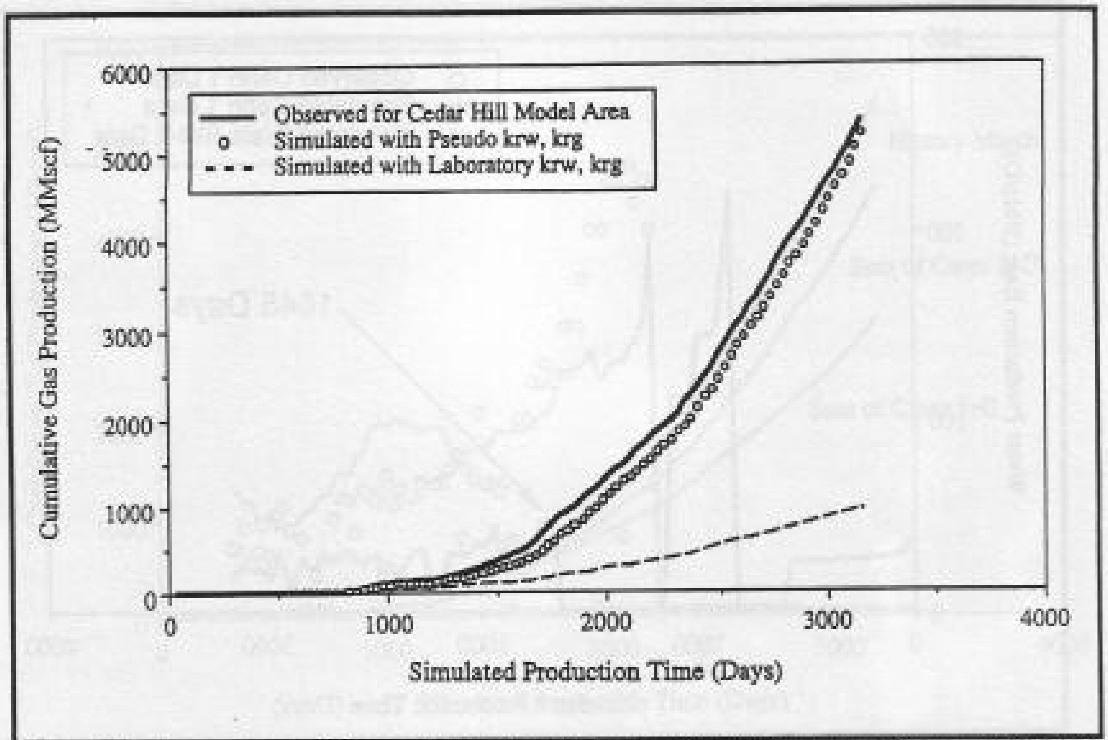

Figure 14. Comparison of observed and simulated cumulative gas production for Cedar Hill using laboratory-measured and pseudo relative permeability curves

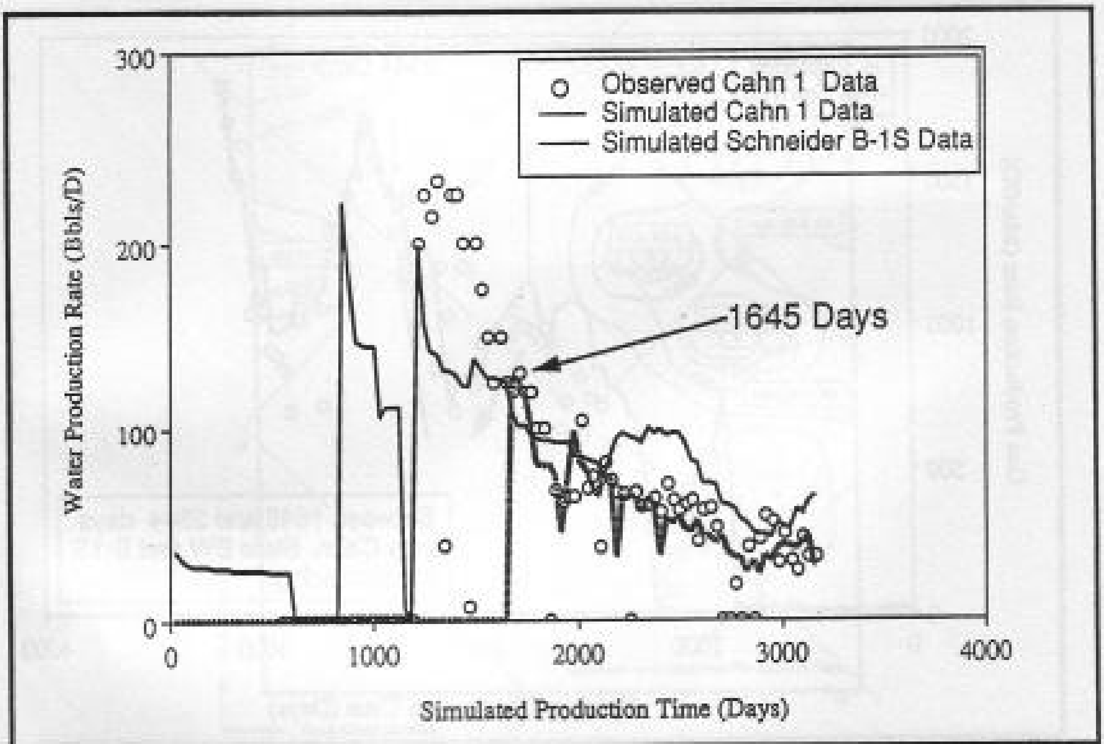

Figure 15. Schneider B-1S has benefited from early dewatering at Cahn 1 where both wells are at the same structural elevation in Cedar Hill area

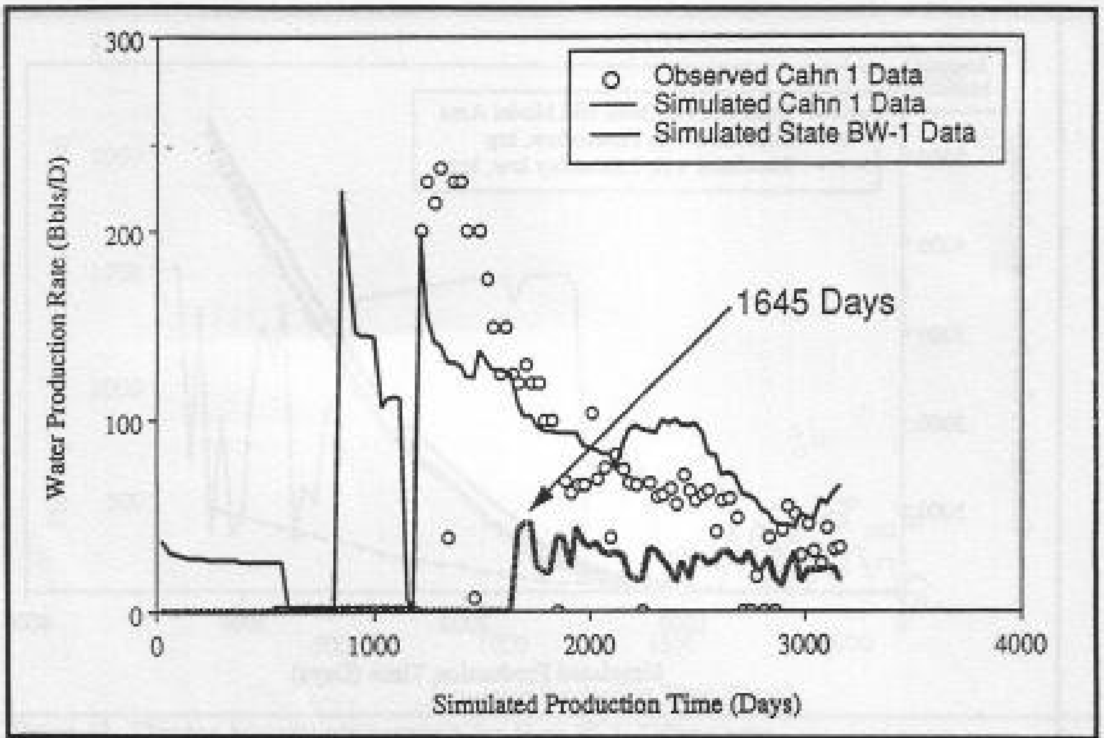

Figure 16. State BW-1 has benefited from both early dewatering and its updip position relative to Cahn 1 at Cedar Hill

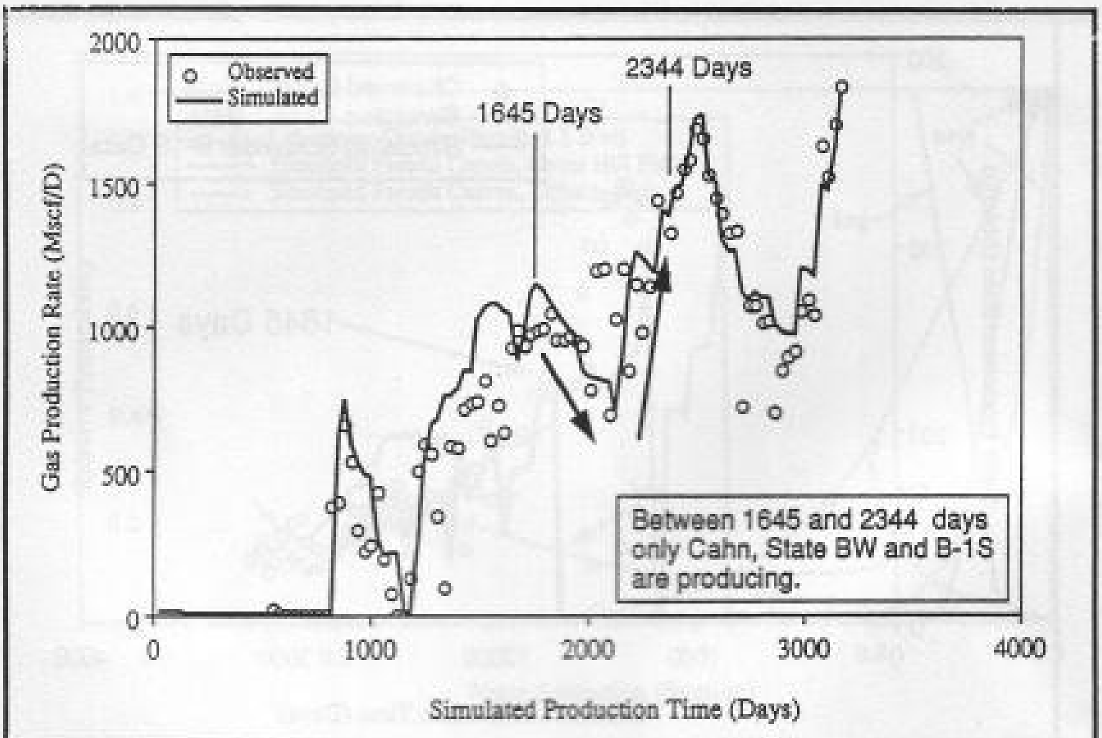

Figure 17. Cahn 1 gas rate was affected by production from Schneider B-1S and State BW-1 in the Cedar Hill model area

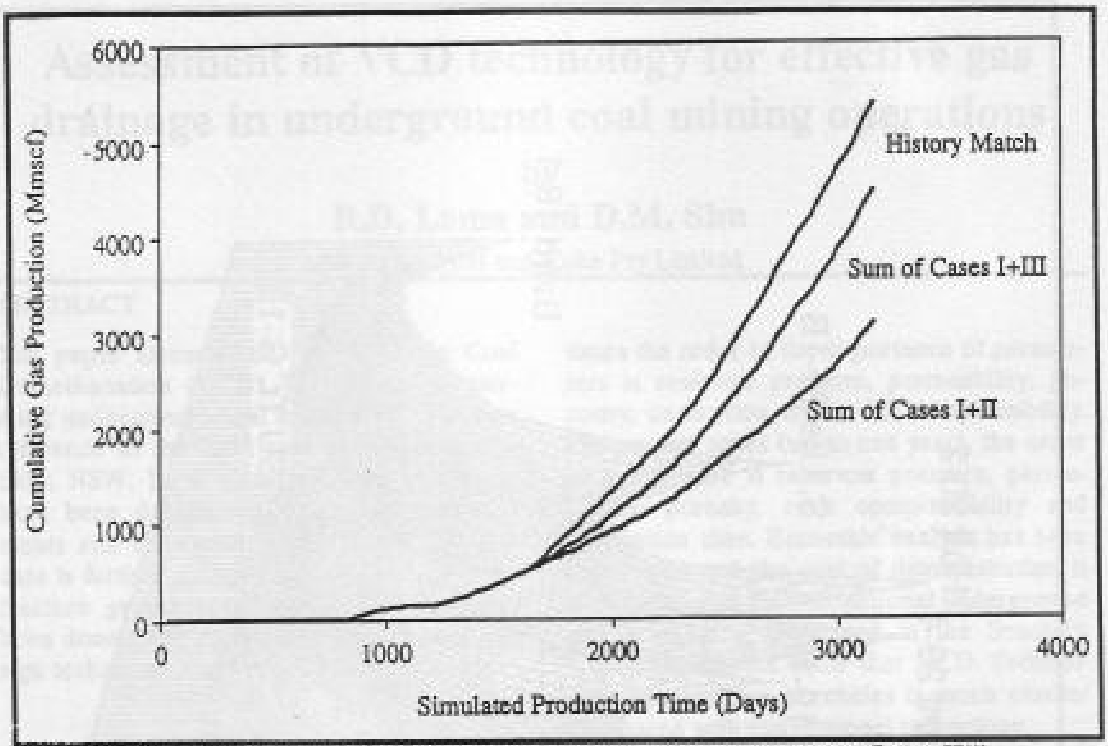

Figure 18. Cumulative gas production for simulated interference effects at Cedar Hill

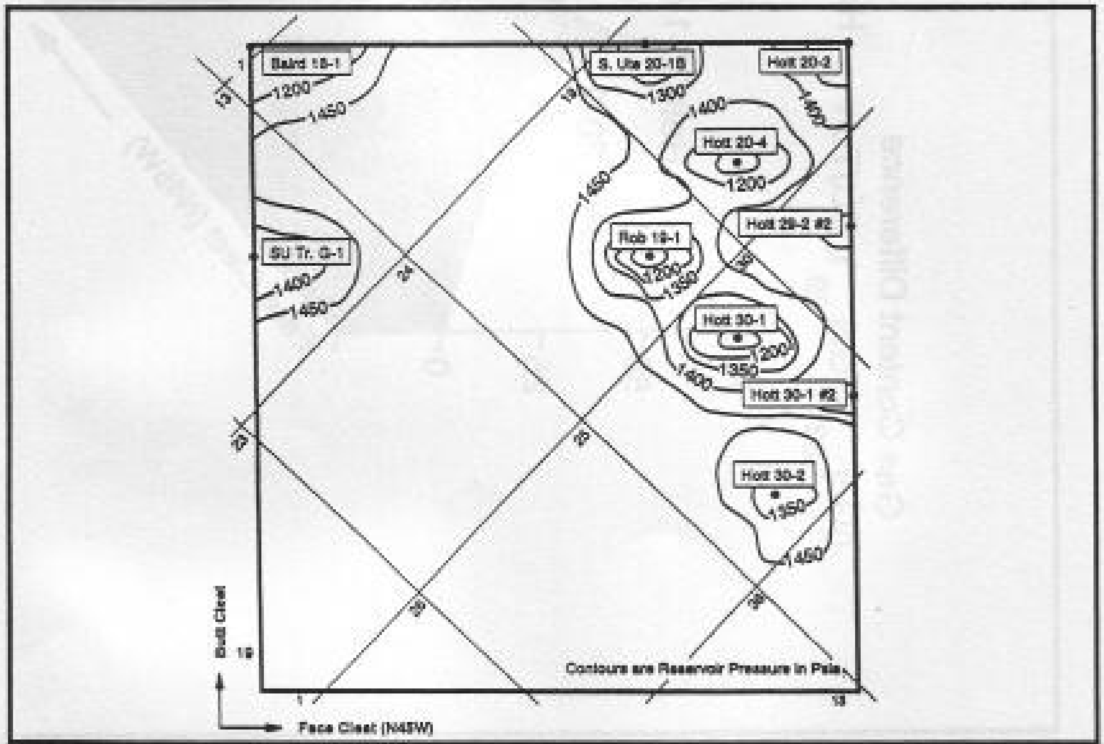

Figure 19. Simulated distribution in reservoir pressure for Tiffany model area, November 1989

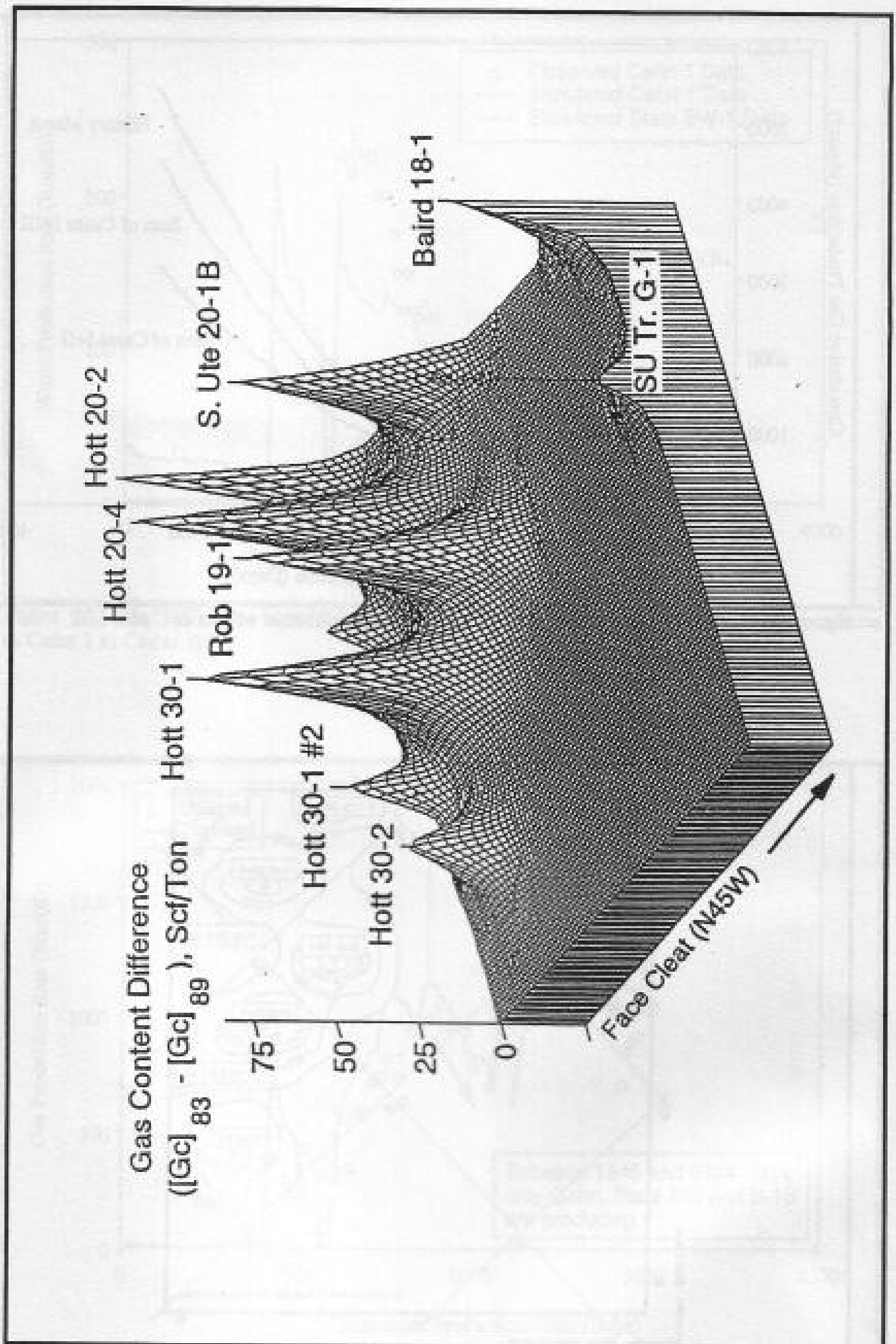

Figure 20. Simulated difference in matrix gas content between October 1983 and November 1989 for the Tiffany model area