INFLUENCE OF ZONES OF CRUSTAL WEAKNESS ON 3-D DISTRIBUTION OF GAS ACROSS THE WATTENBERG FIELD, DENVER BASIN, COLORADO, U.S.A.

Debra Higley, U.S. Geological Survey, Dave Cox, Questa Engineering Corporation , and Robert J. Weimer , Colorado School of Mines , Department of Geology and Geological Engineering

More than 779 billion cubic feet of gas (BCFG) has been produced from the Upper Cretaceous D and Lower Cretaceous Muddy (J) Sandstones in the Wattenberg Field, Denver Basin, Colorado; cumulative gas production from all formations in the field is 839 BCFG (Petroleum Information Production Data on CD-ROM through 1997). Estimated ultimate recovery (EUR) from current D and Muddy (J) Sandstone wells is 1.27 trillion cubic feet of gas (TCFG). Computer-generated 2-D maps and 3-D models of gas production across the field show heterogeneous distribution of produced and estimated ultimate recoverable gas.

Wattenberg Field is a low-porosity and low-permeability basin-center gas accumulation. Figure 1 shows elevation on the top of the Muddy (J) Sandstone, axis of the basin, and wrench fault zones (WFZ). Wrench faults are near vertical to vertical and are basement controlled (Weimer, 1996). Movement through time along these faults influenced environments of deposition, thermal history, and the sealing behavior of fault systems. It has also shifted the local basin and the field axes to the northeast (Weimer, 1996). The basin axis north and south of the field is oriented approximately north south in a line connecting Denver, Colorado, and Cheyenne, Wyoming. Greatest gas production is located along a broad band that is oriented approximately north 45^{o} east. This band is parallel and proximal to the axis of the basin syncline, and is on trend with five right-lateral wrench fault systems (Figures 2, 3).

Figure 2 shows 3-D distribution of initial gas production across the field. Upper surface of the model is elevation at the top of the Muddy (J) Sandstone. Shown are 1) concentration of production along the synclinal axis of the basin, 2) irregular distribution of gas, and 3) vertical and lateral offsets of the Muddy (J) Sandstone, including producing intervals, due to movement along the faults. These factors are also visible on figure 3, distribution of the best-12-months of gas production.

Best-month-, best-12-months, total cumulative, and estimated-ultimate gas production in the maps and model are closely associated with locations of both fault and fracture networks and the area of source rocks that are thermally mature for gas generation. The Wattenberg Field is approximately outlined by a vitrinite reflectance contour of 0.9% R_o (Figure 4). Anomalous levels of thermal maturity within the Wattenberg "hot spot" were probably influenced by increased heat flow, greater efficiency of lateral- and upward-moving fluids through open fracture and fault networks (Higley et al., 1992; Meyer and McGee, 1985), and by a batholith located under the field area (Weimer, 1996). A batholith that is high in ultramafic minerals is indicated by NURE residual magnetic mapping data. Hydrocarbon source rocks bound the Muddy (J) Sandstone and are thermally mature for gas generation (vitrinite reflectance contours range from 0.9% to 1.5% Ro). Vitrinite reflectance values along the outcrop west of Wattenberg are anomalously high compared to outcrop values north and south of the field (Higley et al., 1992).

The main reservoir facies in Wattenberg are low-porosity, low-permeability, thin-bedded very-fine to fine-grained sandstones of delta-front and nearshore marine depositional environments. These are interbedded with thin-bedded marine shales. The primary reservoir is the Fort Collins Member of the Muddy (J) Sandstone; gas is also produced from the unconformably overlying Horsetooth Member of the Muddy, near the southeastern, eastern, and northeastern boundaries of the field. The Horsetooth Member is mostly fine- to medium-grained sandstones of valley-fill depositional environments. Weimer et al. (1986) concluded that movement along the basement faults following deposition of the Fort Collins Member resulted in a northeast-trending structural high that bounded the Wattenberg Field on the north and south. Non-deposition of the Horsetooth Member over most of the field resulted from this structure.

While average sandstone porosity is 10.2% and median permeability is 0.3 mD in the core samples of 8 Wattenberg Field wells, median permeability based on analysis of production data for 1,790 wells is much lower: 0.0035 mD. Petroleum engineering studies also indicate the current average drill spacing of 160 acres may be infill drilled to as close as 40 acres to recover more of the original gas in place; this is currently 25 to 33% of the 2 to 2.5 BCFG in place per 160 acres. Variation in production suggests some faults were sealing, whereas others were open to fluid flow. Vertical offset of faults is minor with the exception of some segments of the wrench fault systems that border and cut the field. Figure 2 shows elevation on the top of the Muddy (J) Sandstone. Contours are offset relative to wrench fault systems. Displacement is commonly less than 6 m (20 ft) but can be 60 m (200 ft) or more along the Windsor and

Johnstown faults near the western margin of the basin. Vertical displacement commonly decreases eastward.

Extreme heterogeneity of production in the Wattenberg Field results from numerous processes, including vertical and lateral movement along fault zones. The Longmont and Lafayette wrench fault zones bracket the region of greatest gas production. Gas production in the western half of the field extends north and south of these fault zones. The eastern half of the field has limited gas production outside these wrench faults. This may result from sealing behavior that limits lateral migration of gas, leakage of gas along open sections of the faults, and lower permeability of some reservoir intervals. Density of drilling also affects distribution of production, an example is the moratorium on drilling in Greeley, north of the Longmont wrench fault zone. The western seal of the field was largely erosional truncation of the primary reservoir interval combined probably with mountain front faulting (Weimer, 1996).

Heterogeneity also results from variation in depositional environments of producing intervals. Increased gas production in the southeast corner of the field results largely from greater porosity and permeability associated with fine-to-medium grained sandstones deposited in a northwest-trending distributary channel system. This is also a primary conduit for gas migration outside the area of source rocks that are thermally mature for gas generation. The Cherry Gulch wrench fault zone, located in this area, did not appear to limit lateral migration of hydrocarbons.

REFERENCES

Higley, D.K., Gautier, D.L., and Pawlewicz, M.J., 1992, Influence of regional heat flow variation on thermal maturity of the Lower Cretaceous Muddy ("J") Sandstone, Denver Basin, Colorado, *in* Leslie Magoon, ed., The Petroleum System- Status of Research and Methods, 1992: U.S. Geological Survey Bulletin 2007, p. 66-69.

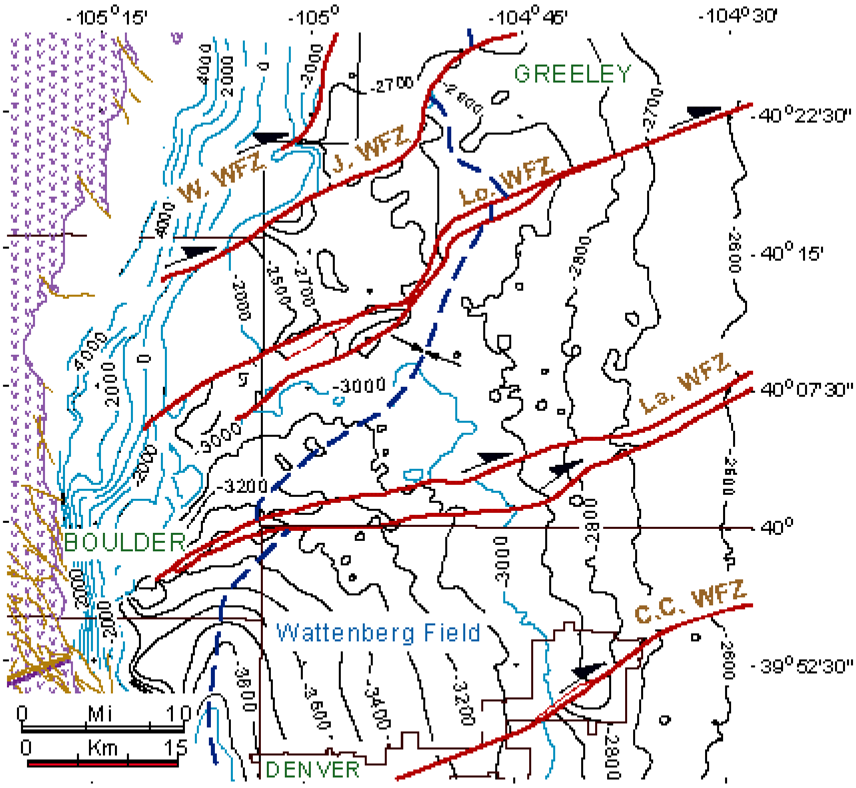
Meyer, H.J., and McGee, H.W., 1985, Oil and gas fields accompanied by geothermal anomalies in the Rocky Mountain Region: American Association of Petroleum Geologists Bulletin, v. 69, no. 6, p. 933-945.

Petroleum Information Corp., 1997, Well History Control System database, available from Petroleum Information Corp., 4100 Dry Creek Road, Littleton, CO 80122.

Petroleum Information Corp., 1998, petroROM Production Data on CD-ROM, available from Petroleum Information Corp., 4100 Dry Creek Road, Littleton, CO 80122.

Weimer, R.J., Sonnenberg, S.A., and Young, G.B.C., 1986, Wattenberg Field, Denver Basin, Colorado: American Association of Petroleum Geologists Studies in Geology, no. 24, p. 143-164.

Weimer, R.J., 1996, Guide to the Petroleum Geology and Laramide Orogeny, Denver Basin and Front Range, Colorado: Colorado Geological Survey Bulletin 51, 127 p.



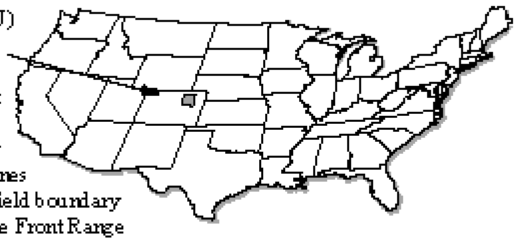


Figure 1. Elevation on the top of the Muddy (J) Sandstone, Denver Basin, Colorado. Index map shows location in the U.S.A. of the study area. Deepest area of the basin is located west of Denver. The north-south trending axis (dashed line) was deflected to the northeast by recurrent movement along the wrench fault zones (Weimer, 1996). Contour interval within the field boundary is 100 ft (30 m); spacing is variable close to the Front Range uplift (V pattern). Thick lines delineate wrench fault zones (WFZ). Thin lines within the Front Range uplift are faults that cut Precambrian and younger rocks.

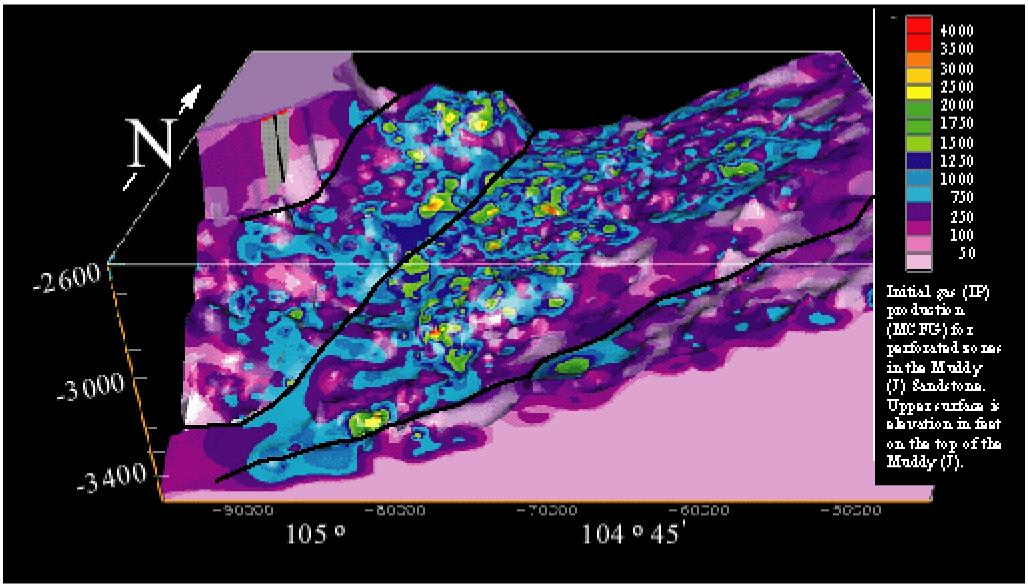


Figure 2. Distribution of initial gas production (MCFG) for the Muddy (J) Sandstone, Wattenberg field, Denver Basin, Colorado. View along the basin syncline is to the northeast. Upper surface is elevation relative to sea level of the Muddy (J) Sandstone. Surface is offset near the north arrow by northeasterly trending Johnstown and Longmont wrench fault zones (black lines). The Lafayette wrench fault zone is located along the bottom of the model. Color bar labels are in MCFG. Shown on the figure are concentration of most production along the local basin syncline, and structural offsets of production and the top of the Muddy (J).

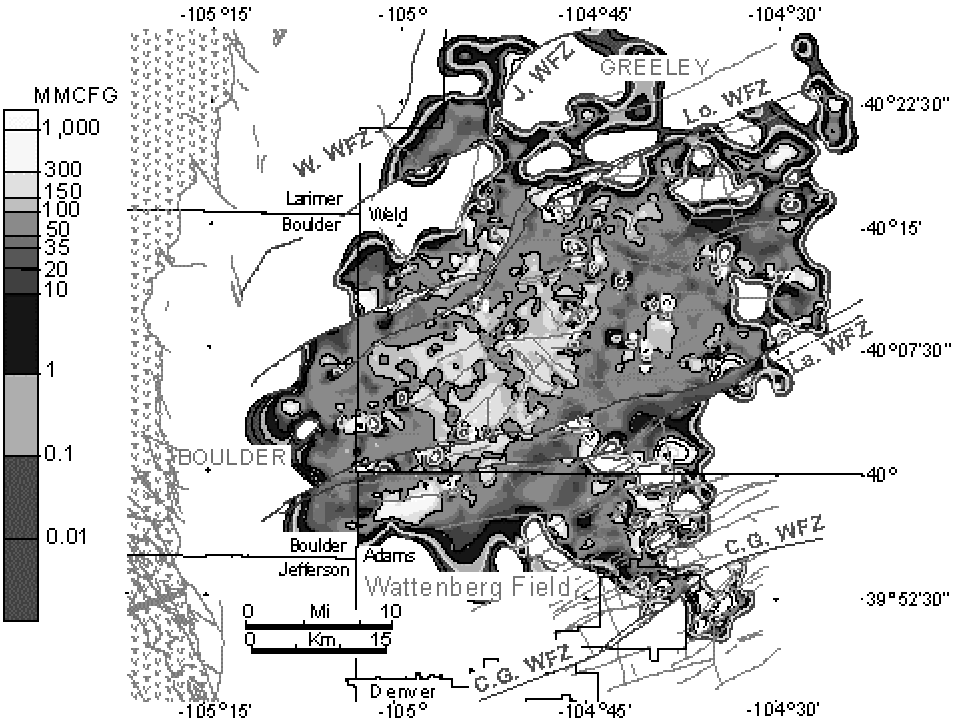


Figure 3. Distribution of the best-12-months of gas production for about 1,800 wells across the Wattenberg field. Greatest production is along a northeast-trending belt proximal to the field and basin syncline. Major wrench fault zones from Weimer (1996) are Windsor (W. WFZ), Johnstown (J. WFZ), Longmont (Lo. WFZ), Lafayette (La. WFZ), and Cherry Gulch (C.G. WFZ). Faults along the Front Range (V pattern) and hypothetical faults within the field (Weimer, 1996) are shown as thin lines.

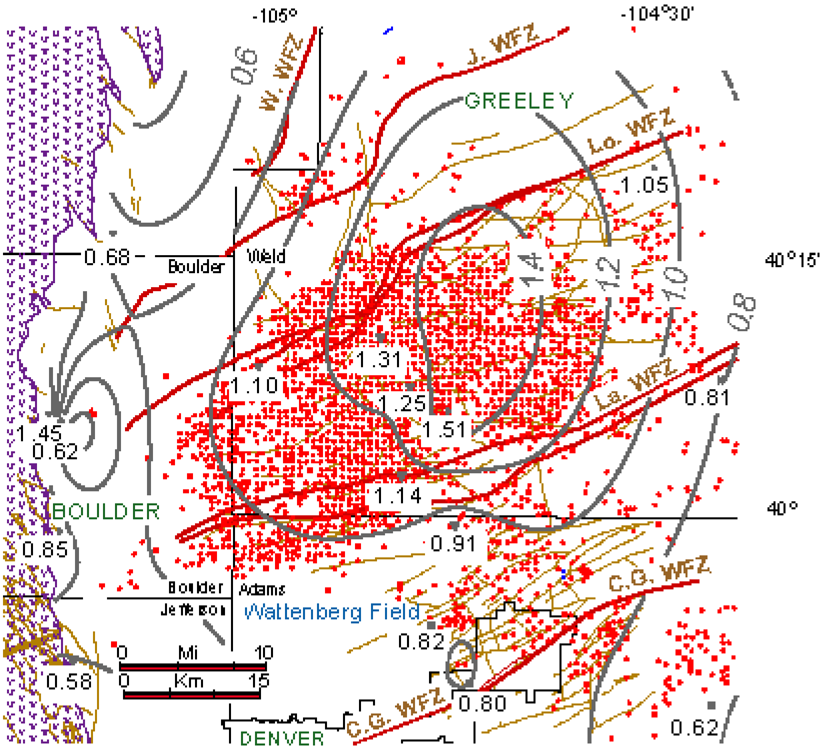


Figure 4. Distribution of gas wells in the Wattenberg field area, Denver Basin, Colorado. The field is approximately outlined by a vitrinite reflectance contour of 0.9% Ro. Ro contour interval is 0.2%; sample locations are shown as black dots and labeled. Wrench fault zones (WFZ) (Weimer, 1996) are thick lines. Fault zones are Windsor (W. WFZ), Johnstown (J. WFZ), Longmont (Lo. WFZ), Lafayette (La. WFZ) and Cherry Gulch (C.G. WFZ). Greatest gas production is concentrated between the Longmont WFZ and the Lafayette WFZ. Thin lines delineate faults along the Front Range uplift (V pattern) and hypothetical faults of Weimer (1996) in the field area.