PRESSURE ARCHITECTURE OF THE PERMIAN AND PENNSYLVANIAN SECTION IN CARSON, MOORE, HUTCHINSON, AND POTTER COUNTIES, TEXAS PANHANDLE

By

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PREFACE

This study was undertaken in an attempt to improve current understanding of the hydrodynamics and pressure architecture of a specific region within the Texas portion of the Panhandle-Hugoton gas field, the largest gas field in the coterminous United States. Data suggest that certain reservoir units within the area of study are underpressured with respect to a normal hydrostatic gradient, and might serve as possible disposal (injection) zones for oilfield brines and other types of liquid waste (municipal, industrial, etc.). Specific objectives of this research were to a) construct stratigraphic cross sections in order to better understand the geologic sequencing of formations within the study area, and b) construct contour maps displaying equipotential surfaces (hydraulic head elevation) over the study area. Both a) and b) were accomplished using Rockworks 99™ software developed by Rockware, Inc.

I sincerely thank my masters committee—Drs. Jim Puckette (Chair), Zuhair Al-Shaieb, and Richard A. Marston—for guidance, support, and advice in the completion of this research.

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CHAPTER 1

Introduction

The Panhandle-Hugoton gas field, the largest in the coterminous United States, covers portions of 19 counties in the states of Texas, Oklahoma, and Kansas. The field is approximately 275 mi long, and its width varies from 8 to 57 mi (Fig. 1). Understanding and evaluating the hydrodynamics of the field, particularly the Texas portions, is an important first-step in the process of selecting potential locations for deep subsurface disposal wells. Ideally, such wells would penetrate reservoirs with sufficient porosity and permeability to accommodate large volumes of fluid, maintain adequately low pore pressures as to not create additional stresses on the reservoir from pressure buildup during the injection process, and be vertically isolated from other formations by

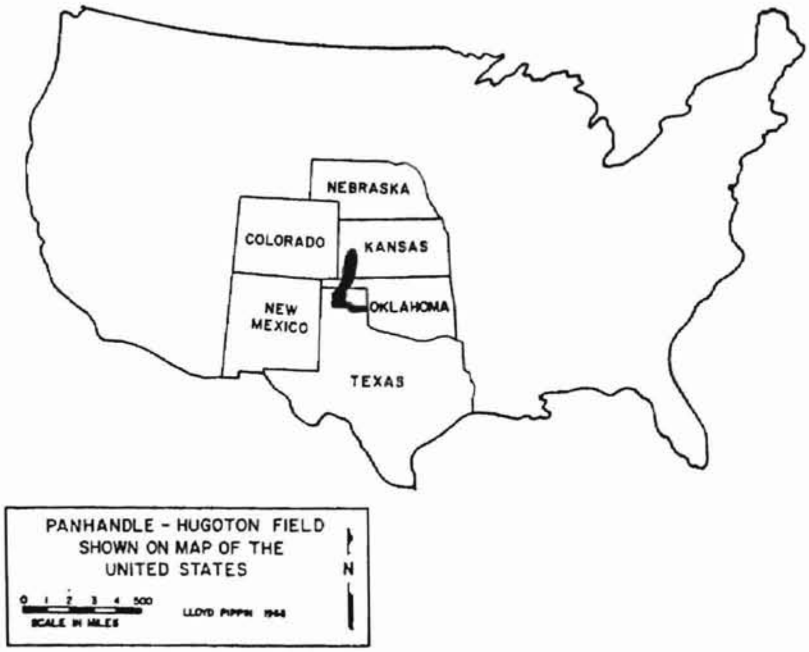


Figure 1. Map of the United States showing location of Panhandle-Hugoton field (Pippin, 1970).

confining layers on both the top and bottom of the reservoir.

The primary purposes of this study are to establish the pressure architecture of the Panhandle-Hugoton field in the central part of the Texas Panhandle and evaluate the continuity of confining units. Reservoirs with sub-normal pressures have a much greater capacity to accommodate introduced fluids than reservoirs with normal or abnormally high pressures. Low injection pressures at the surface may reduce the possibility of fracturing confining beds, thereby limiting the risk of fluids migrating vertically out of the reservoir. Sub-normal pressure (underpressure) may be associated with a depleted reservoir that once contained oil or gas, and minimal or no pressure at the surface would be required to inject fluid into the reservoir. Such reservoirs normally maintain high volumes of storage space (available porosity) due to the removal of the original in-place fluids (gas, oil, water).

The area considered for this study lies in the central panhandle region of the state of Texas, and includes a significant portion of the Panhandle West field, a sub-unit of the larger Panhandle-Hugoton field (Fig. 2). Four counties, adjacent to and including the city of Amarillo, were selected as the focus of this study: Carson, Hutchinson, Moore, and Potter. This area was selected for the following reasons: 1) proximity to an urban-industrial area that is a potential liquid waste source, 2) relative geographic isolation in relation to the more densely populated regions of the United States, 3) reservoirs that have relatively good porosity and permeability, 4) low pressure, and 5) abundant pressure and fluid data accumulated during the development of the field over the last seven decades.

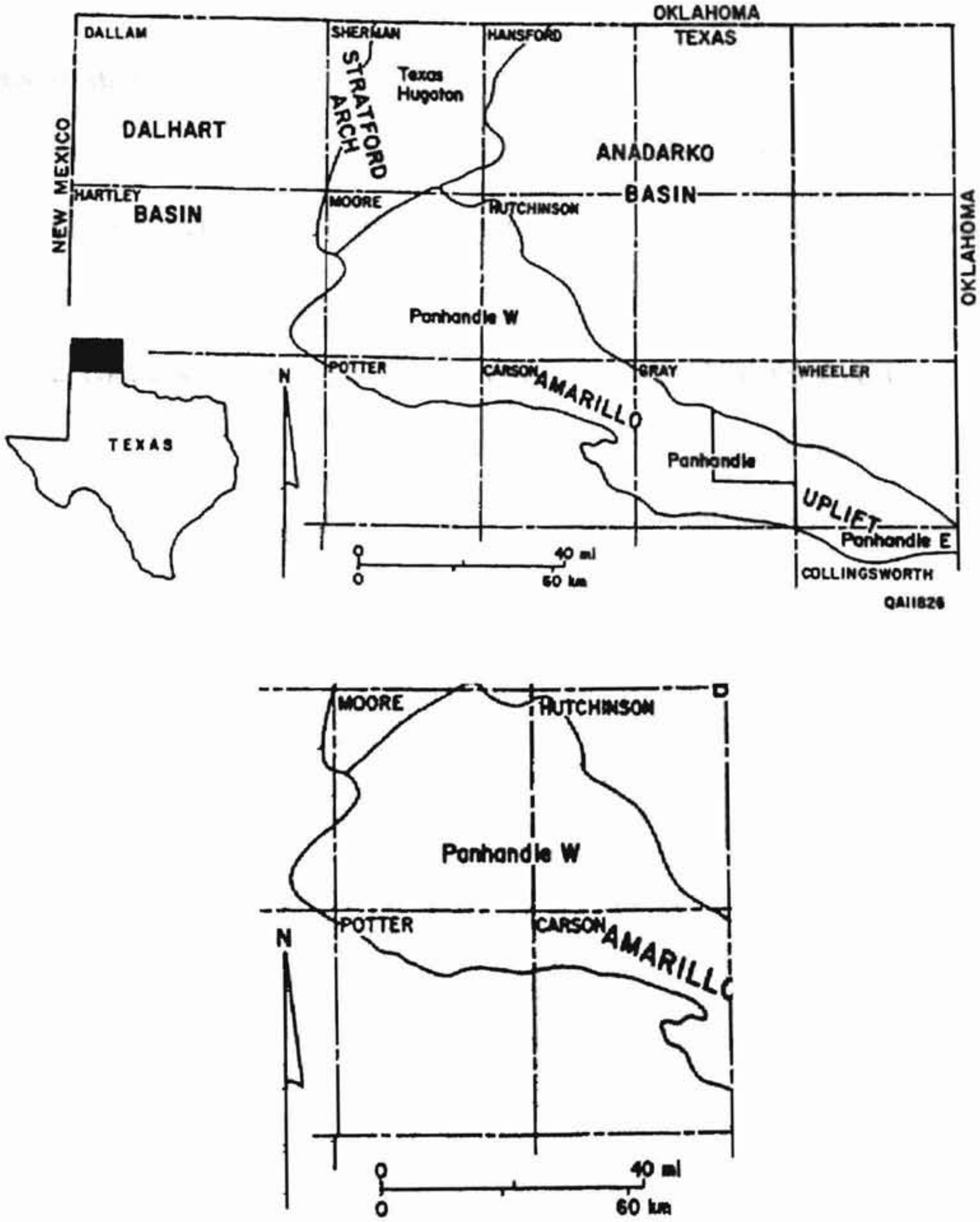


Figure 2. Location of Panhandle West field and counties included in the study area (Ruppel and Garret, Jr., 1989).

CHAPTER 2

Literature Review

Previous Studies

Published information on the Panhandle-Hugoton field is somewhat rare considering its geographic size and the quantities of oil and gas it has produced over the past 70 years. Relatively little is known of the basic architecture of the reservoirs or the fundamental controls on the migration, trapping, and production of reservoir fluids. Pippin (1970) published a widely accepted general study of the field, including information on the lithology of the major late Paleozoic producing reservoirs and their general structural trends and stratigraphy. Ruppel and Garret, Jr. (1989) published a broad overview of the field, including geologic and engineering production parameters such as porosity and permeability values for late Paleozoic reservoir units. Recent studies conducted by Al-Shaieb et al. (1994) on the pressure characteristics of older (pre-Permian) Paleozoic reservoirs in the deep Anadarko Basin of western Oklahoma and the eastern portion of the Texas Panhandle emphasized the development and identification of reservoir compartmentalization. Very little published information exists on the pressure characteristics of shallower Permian and Pennsylvanian reservoirs in the Panhandle (Texas) field. As a result, a need exists for preliminary studies to be undertaken in order to provide information regarding pressure characteristics of the area and establish a data foundation for future studies.

Geologic Setting, History, and Regional Stratigraphy

The Panhandle (Texas) field is a complex structural trap overlying the Amarillo Uplift. It generally occupies a broad anticline formed by drape over the primary axis, a horst-like structure formed by the uplift's granite core (Fig. 3). The presence of numerous fault blocks, coupled with the irregularity of the uplift's surface, has resulted in a complex fold-and-fault controlled closure across the field. The Panhandle-Hugoton field occupies a structural feature known as the Hugoton Embayment that is widely interpreted as a broad, flat, shelf-like extension of the deeper Anadarko Basin. The ancestral Anadarko Basin was bounded on the south by the Texas peninsula and on the north by a broad, flat cratonic shelf until post-Mississippian time. Hunton Group and older rocks

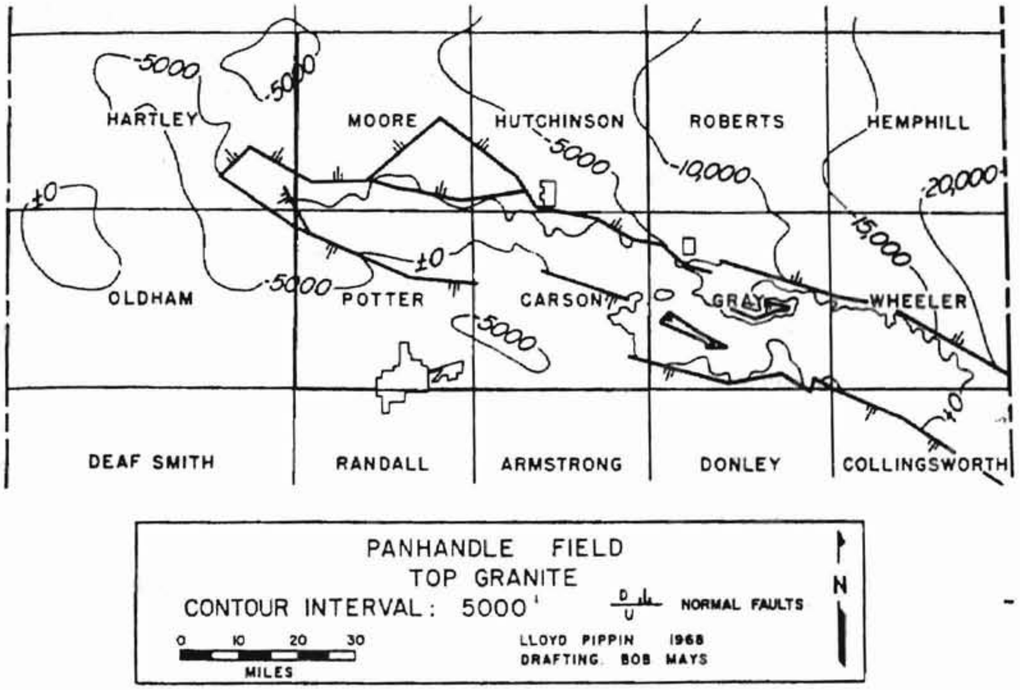


Figure 3. Structure map of the Panhandle (Texas) field area. Datum is top of granite. (Pippin, 1970).

were truncated in the Texas and Oklahoma Panhandles as a result of regional uplift in northeastern New Mexico and southeastern Colorado at the end of Devonian time. Post-Mississippian diastrophism formed the Amarillo Mountains and two major faults just north of them. This uplift shifted the southern edge of the ancestral Anadarko Basin northward from the Texas Peninsula to the Amarillo Mountains, the present boundary of the Anadarko Basin (Pippin, 1970). Pre-Pennsylvanian sediments were later eroded from the Amarillo Mountains. Maximum uplift occurred during Atokan (Pennsylvanian) time, when erosion removed all sedimentary rocks from the mountain axis, exposing the granite core. Erosion of granite resulted in basinward deposition of Granite Wash over the Atoka unconformity. Granite Wash interbedded with marine mud and carbonate as the basin filled, and the Amarillo Mountains were covered by Wolfcampian time (Fig. 4). The Leonardian (Permian) Wichita Formation, which is composed of anhydrite and dense anhydritic dolomite, was deposited and formed a seal over the Wolfcampian reservoir beds (Pippin, 1970). The Leonardian Red Cave, the highest reservoir unit of interest in this study, was deposited on the Wichita Formation. The Red Cave consists primarily of red siltstone and shale, with interbeds of fine-grained sandstone along the west and southwest margins of the Panhandle field. The Red Cave has been interpreted as representing braided ephemeral streams along and emergent coastline (Ruppel and Garret, Jr., 1989). Figure 5 shows a widely accepted stratigraphic column of the Panhandle-Hugoton field. This column illustrates the local subsurface nomenclature of lower Permian and upper Pennsylvanian reservoir units.

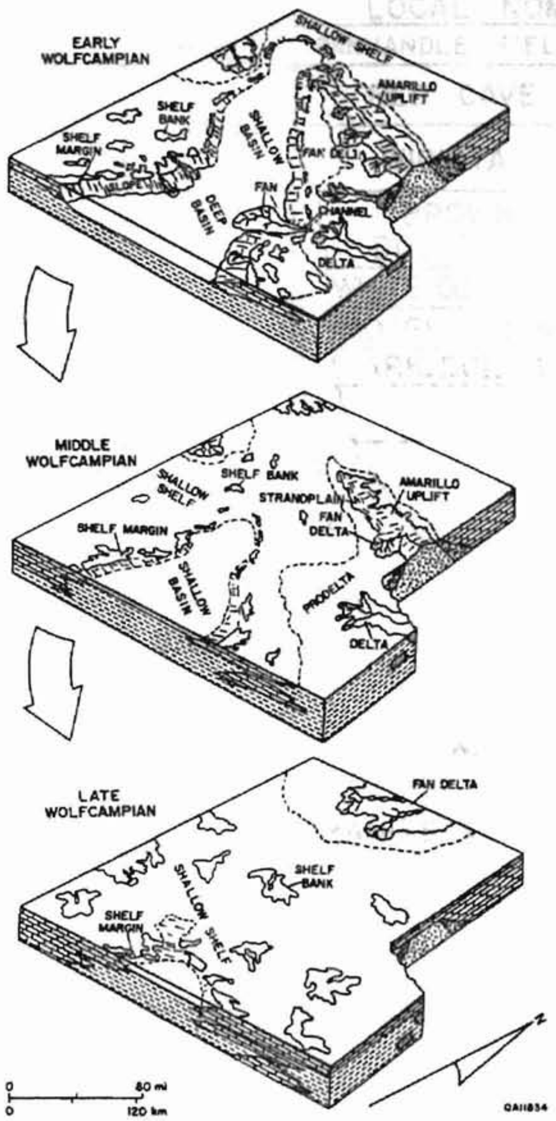


Figure 4. Block diagrams showing paleoenvironmental evolution of Texas Panhandle during the early Permian (Ruppel and Garret, Jr., 1989).

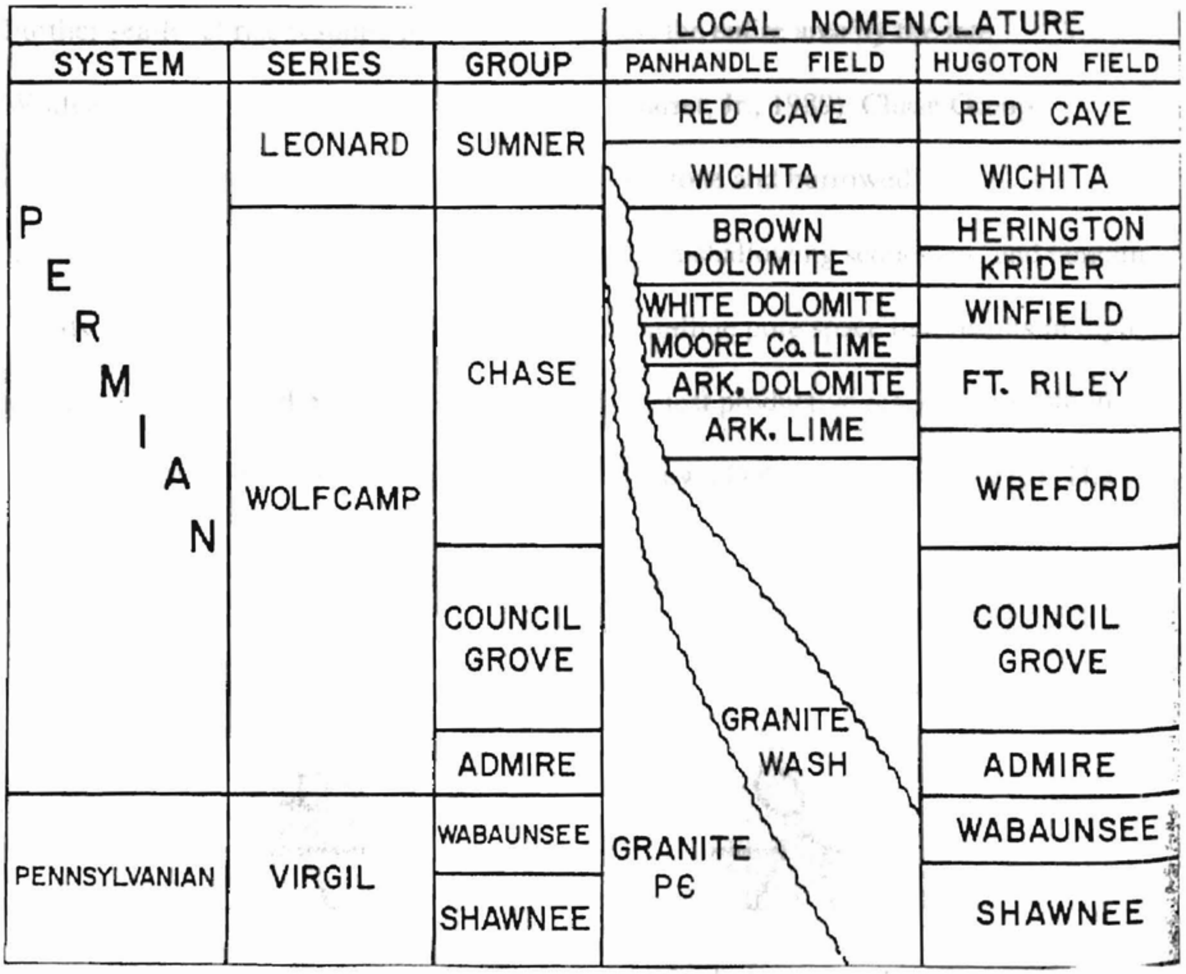


Figure 5. Stratigraphic column of the Panhandle-Hugoton field (Pippin, 1970).

Regional Lithology

Reservoir units of primary interest to this study include the Wolfcampian Chase Group (Brown Dolomite, White Dolomite, Moore County Lime, Arkosic Dolomite, Arkosic Lime) and the Permo/Pennsylvanian Granite Wash. Most gas production in the Texas portion of the Panhandle-Hugoton field comes from Chase Group dolostone and limestone. These rocks are believed to represent deposition on a shallow marine carbonate platform along the margins of the Amarillo Uplift during the earliest Permian.

Further sea-level rise resulted in deposition across the entire area by the late Wolfcampian or early Leonardian (Ruppel and Garret, Jr., 1989). Chase Group carbonates consist primarily of skeletal/ooid grainstone and burrowed mudstone/wackestone deposited in repeated upward-shallowing sequences, and contain locally well-developed intergranular and intercrystalline pore space that results in high values of porosity and permeability (Fig. 6). The most productive reservoir to date in the Panhandle field has been the oolitic zone in the Brown Dolomite (Pippin, 1970). The

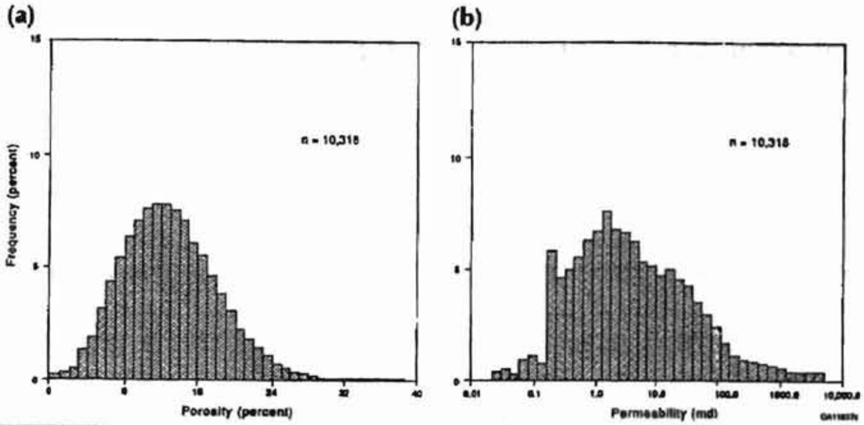


Figure 6. Histogram of (a) porosity and (b) permeability from core measurements in Chase Group (Brown Dolomite) in Panhandle Field (Ruppel and Garret, Jr., 1989).

Granite Wash represents a variety of rock types, ranging from loose, unconsolidated gravel to fine-grained arkosic red shale (Pippin, 1970). The wash, along with fractured crystalline basement rocks, are productive in the Panhandle field. The Granite Wash commonly contains well-developed intergranular porosity and possesses excellent permeability (Fig. 7). The Leonardian (Permian) Wichita Formation (also referred to as the Panhandle Lime) consists of anhydrite and dense anhydritic dolomite and overlies the Chase Group in the Panhandle Field. The Wichita forms a seal that is a barrier to upward fluid migration, although localized fracturing might breach this confining unit. The

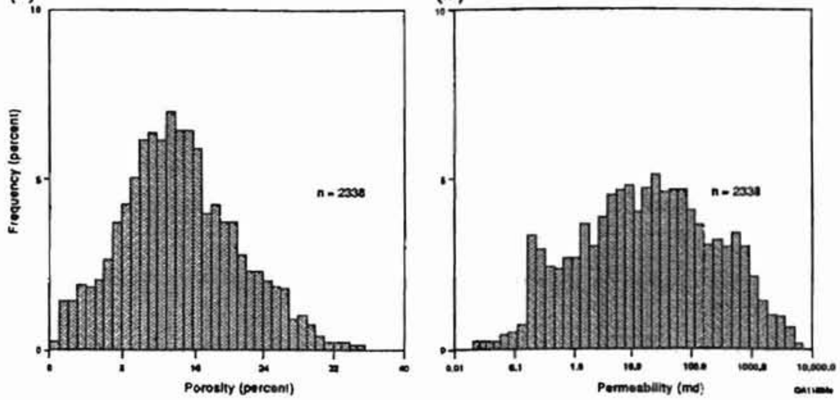


Figure 7. Histograms of (a) porosity and (b) permeability from core measurements in Pennsylvanian/Permian arkose (Granite Wash) in Panhandle field (Ruppel and Garret, Jr., 1989).

Wichita Formation was most likely deposited when carbonate depositional systems migrated southward from the Panhandle into the Midland Basin during the early Permian, gradually transforming the Panhandle region into a vast, low-relief evaporite basin, where salt-bearing strata were deposited through the middle and late Permian (Presley, 1981). The Leonardian (Permian) Red Cave Formation overlies the Wichita Formation. The Red Cave consists primarily of siltstone and shale, with interbeds of fine-grained sandstone common along the western and southwestern margins of the Panhandle field. The sandstone is generally weakly cemented and exhibits well-developed porosity and permeability. The top seal for these sandstone reservoir units is the interbedded redbed shale. The Red Cave is locally productive in the southwest part of the Panhandle field, and is considered a separate reservoir from the Chase Group and Granite Wash (Ruppel and Garret, Jr., 1989).

Regional Structure

Pressure and production data suggest that all reservoir units in Panhandle field are in vertical communication and effectively constitute a single reservoir (Ruppel and Garret, Jr., 1989), although heterogeneities observed in the Chase Group in the Hugoton field in Kansas are likely present in Panhandle field as well. These include marked lateral and vertical variations in porosity that result in considerable reservoir compartmentalization (Ruppel and Garret, Jr., 1989). Table 1 lists various geologic, engineering, and production parameters of reservoirs in the Panhandle field. Data indicate that a combination of fault closure and faulted anticlines provides the predominant trapping mechanism in Panhandle field. Cross-section E-E' in Figure 8 is a generalized cross section that roughly parallels a cross section constructed for this study. These cross sections show structural closure and the relative positions of the oil, gas, and water columns to reservoirs in Panhandle field. More reservoir beds are present in this area than in any other part of the field (Pippin, 1970). The angle of dip is low, so the intersection of the oil column with these reservoir beds produces a wide band of oil pay. Migration of oil was limited southward by intersection of the oil column with granite (Pippin, 1970). Figure 9 shows the areal extent of the gas-water, gas-oil, and oil-water contacts within the study area. Oil accumulation is almost exclusively limited to the northern flank of the uplift, while the gas column is present on both the north and south flanks of the uplift. Most development of the shallower Red Cave (Leonardian) reservoirs occurred from 1960 to 1965 and Red Cave development continues to the present. The sandstones are porous and permeable in the productive area, but pore spaces are commonly filled with salt and anhydrite around the perimeter of the field, suggesting that gas did not migrate

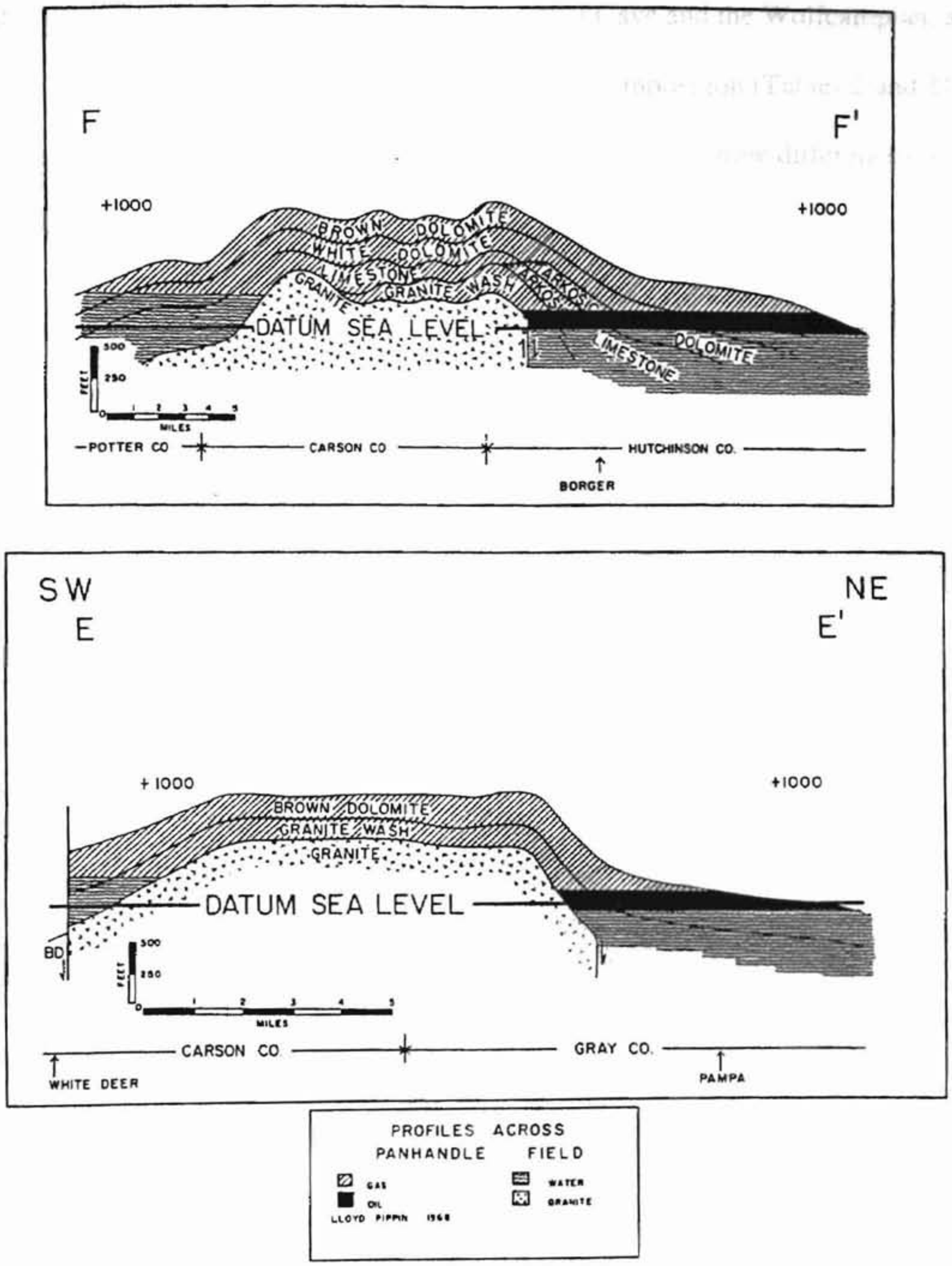


Figure 8. NW-SE cross sections showing relations of oil, gas, and water in Panhandle field (Pippin, 1970).

laterally into the field, but probably migrated vertically through fractures from the Wolfcamp below. This hypothesis is partially supported by evidence that formation pressures were originally similar in both the Red Cave and the Wolfcampian, although chemical analysis shows some differences in the composition (Tables 2 and 3) of Red Cave and Wolfcamp gases (Pippin, 1970). Tables 4 and 5 show differences in gas

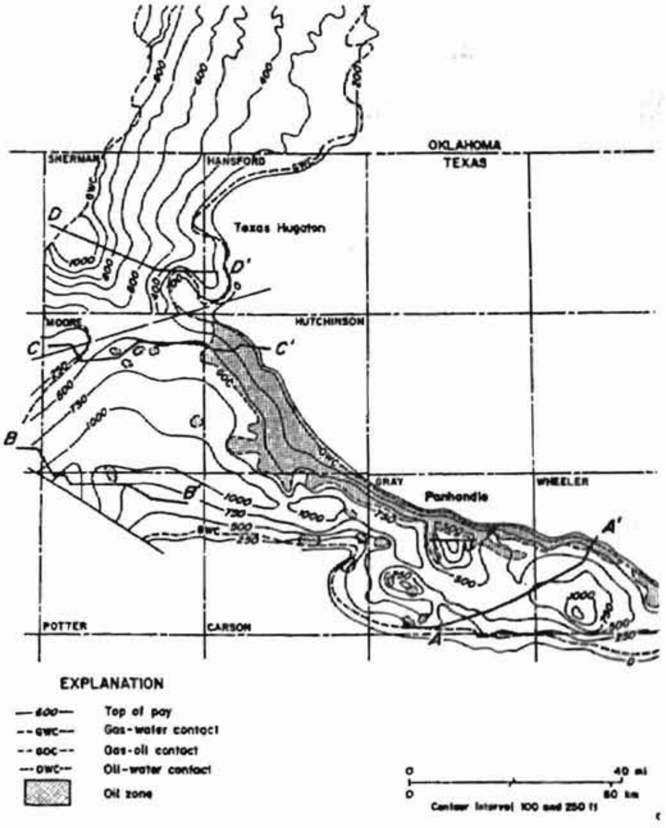
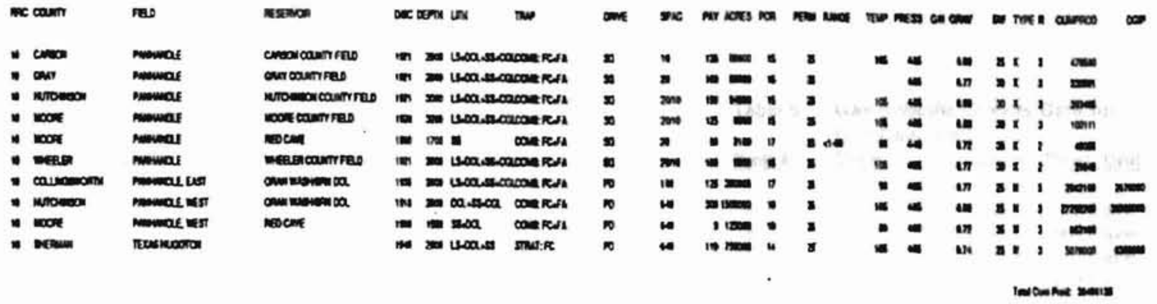


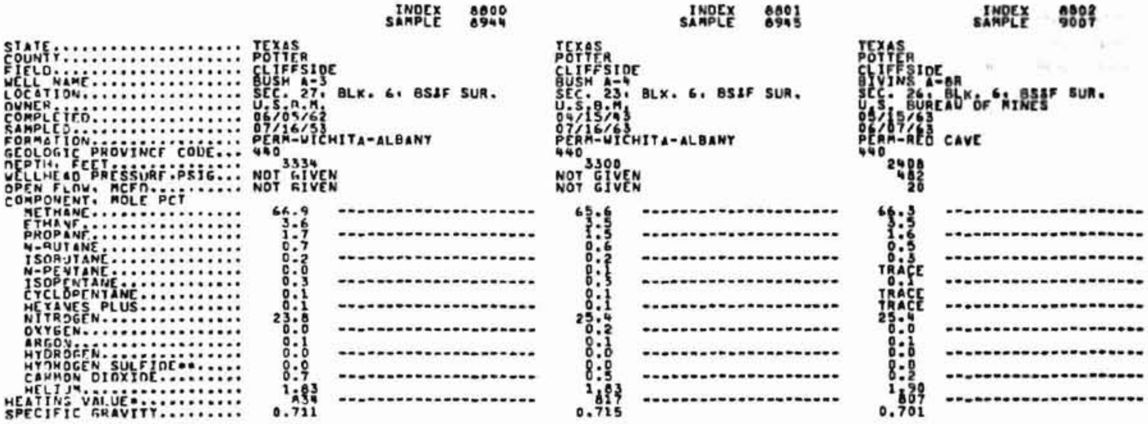
Figure 9. Map showing gas-oil-water contact boundaries within Panhandle field (Ruppel and Garret, Jr., 1989).



RRC	COUNTY	FIELD	RESERVOIR	DISC	DEPTH	LITH	TRAP	DRIVE	SPAC	PAY	ACRES	POR	PERM	RANGE	TEMP	PRESS	GR GRAV	DIF	TYPE	R	CUMPROD	DCP
10	CARSON	PANHANDLE	CARSON COUNTY FIELD	[illegible]	[illegible]	LS-DOL-SS-CGL	COMB: FC-FA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
10	GRAY	PANHANDLE	GRAY COUNTY FIELD	[illegible]	[illegible]	LS-DOL-SS-CGL	COMB: FC-FA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	0.77	[illegible]	[illegible]	[illegible]	[illegible]	
10	HUTCHINSON	PANHANDLE	HUTCHINSON COUNTY FIELD	[illegible]	[illegible]	LS-DOL-SS-CGL	COMB: FC-FA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
10	MOORE	PANHANDLE	MOORE COUNTY FIELD	[illegible]	[illegible]	LS-DOL-SS-CGL	COMB: FC-FA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
10	MOORE	PANHANDLE	RED CAVE	[illegible]	[illegible]	[illegible]	COMB: FC-FA	[illegible]	[illegible]	[illegible]	[illegible]	17	[illegible]	[illegible]	[illegible]	[illegible]	0.72	[illegible]	[illegible]	[illegible]	[illegible]	
10	WHEELER	PANHANDLE	WHEELER COUNTY FIELD	[illegible]	[illegible]	LS-DOL-SS-CGL	COMB: FC-FA	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	0.77	[illegible]	[illegible]	[illegible]	[illegible]	
10	COLLINGSWORTH	PANHANDLE, EAST	GRAN WASH [illegible] DOL	[illegible]	[illegible]	LS-DOL-SS-CGL	COMB: FC-FA	PD	[illegible]	[illegible]	[illegible]	17	[illegible]		[illegible]	[illegible]	0.77	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	HUTCHINSON	PANHANDLE, WEST	GRAN WASH [illegible] DOL	[illegible]	[illegible]	DOL-SS-CGL	COMB: FC-FA	PD	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10	MOORE	PANHANDLE, WEST	RED CAVE	[illegible]	[illegible]	SS-DOL	COMB: FC-FA	PD	[illegible]	[illegible]	12000	[illegible]	[illegible]		[illegible]	[illegible]	0.72	[illegible]	[illegible]	[illegible]	[illegible]	
10	SHERMAN	TEXAS HUGOTON		[illegible]	[illegible]	LS-DOL-SS	STRAT: FC	PD	[illegible]	119	[illegible]	14	[illegible]		[illegible]	[illegible]	0.74	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

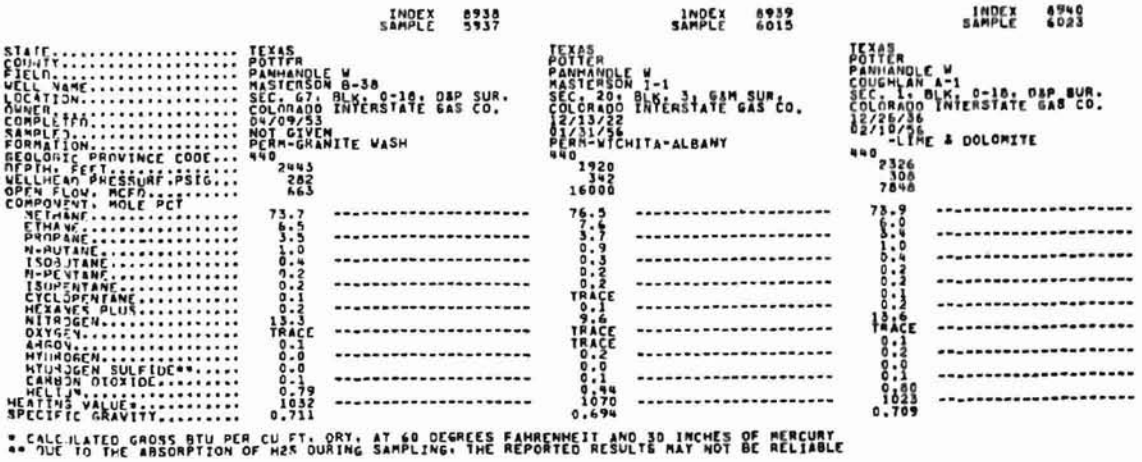
Total Cum Prod: [illegible]

Table 1. Geologic and engineering production parameters for Texas-Hugoton field (Ruppel and Garret, Jr., 1989).



	INDEX 8800 SAMPLE 8944	INDEX 8801 SAMPLE 8945	INDEX 8802 SAMPLE 9007
STATE	TEXAS	TEXAS	TEXAS
COUNTY	POTTER	POTTER	POTTER
FIELD	CLIFFSIDE	CLIFFSIDE	CLIFFSIDE
WELL NAME	BUSH A-3	BUSH A-4	BIVINS A-8R
LOCATION	SEC. 27, BLK. 6, BS&F SUR.	SEC. 23, BLK. 6, BS&F SUR.	SEC. 26, BLK. 6, BS&F SUR.
OWNER	U.S.B.M.	U.S.B.M.	U.S. BUREAU OF MINES
COMPLETED	06/05/62	04/15/43	05/15/63
SAMPLED	07/16/53	07/16/63	06/07/63
FORMATION	PERM-WICHITA-ALBANY	PERM-WICHITA-ALBANY	PERM-RED CAVE
GEOLOGIC PROVINCE CODE	440	440	440
DEPTH, FEET	3334	3300	2408
WELLHEAD PRESSURE, PSIG	NOT GIVEN	NOT GIVEN	482
OPEN FLOW, MCFD	NOT GIVEN	NOT GIVEN	20
COMPONENT, MOLE PCT			
METHANE	66.9	65.6	66.3
ETHANE	3.6	3.5	3.5
PROPANE	1.7	1.5	1.6
N-BUTANE	0.7	0.6	0.5
ISOBUTANE	0.2	0.2	0.3
N-PENTANE	0.0	0.1	TRACE
ISOPENTANE	0.3	0.5	0.1
CYCLOPENTANE	0.1	0.1	TRACE
HEXANES PLUS	0.1	0.1	TRACE
NITROGEN	23.8	25.4	25.4
OXYGEN	0.0	0.2	0.0
ARGON	0.1	0.1	0.1
HYDROGEN	0.0	0.0	0.0
HYDROGEN SULFIDE**	0.0	0.0	0.0
CARBON DIOXIDE	0.7	0.5	0.2
HELIUM	1.83	1.83	1.90
HEATING VALUE*	834	817	807
SPECIFIC GRAVITY	0.711	0.715	0.701

Table 2. Gas chemical composition analysis data for Red Cave unit (Moore, 1982).



	INDEX 8938 SAMPLE 5937	INDEX 8939 SAMPLE 6015	INDEX 8940 SAMPLE 6023
STATE	TEXAS	TEXAS	TEXAS
COUNTY	POTTER	POTTER	POTTER
FIELD	PANHANDLE W	PANHANDLE W	PANHANDLE W
WELL NAME	MASTERSON B-38	MASTERSON I-1	COUGHLAN A-1
LOCATION	SEC. 67, BLK. 0-18, D&P SUR.	SEC. 20, BLK. 3, G&M SUR.	SEC. 1, BLK. 0-18, D&P SUR.
OWNER	COLORADO INTERSTATE GAS CO.	COLORADO INTERSTATE GAS CO.	COLORADO INTERSTATE GAS CO.
COMPLETED	04/09/53	12/13/22	12/26/36
SAMPLED	NOT GIVEN	01/31/56	02/10/56
FORMATION	PERM-GRANITE WASH	PERM-WICHITA-ALBANY	-LIME & DOLOMITE
GEOLOGIC PROVINCE CODE	440	440	440
DEPTH, FEET	2443	1920	2326
WELLHEAD PRESSURE, PSIG	282	342	308
OPEN FLOW, MCFD	663	16000	7848
COMPONENT, MOLE PCT			
METHANE	73.7	76.5	73.9
ETHANE	6.5	7.6	6.0
PROPANE	3.5	3.7	3.4
N-BUTANE	1.0	0.9	1.0
ISOBUTANE	0.4	0.3	0.4
N-PENTANE	0.2	0.2	0.2
ISOPENTANE	0.2	0.2	0.2
CYCLOPENTANE	0.1	TRACE	0.1
HEXANES PLUS	0.2	0.1	0.2
NITROGEN	13.3	9.6	13.6
OXYGEN	TRACE	TRACE	TRACE
ARGON	0.1	TRACE	0.1
HYDROGEN	0.0	0.2	0.2
HYDROGEN SULFIDE**	0.0	0.0	0.0
CARBON DIOXIDE	0.1	0.1	0.1
HELIUM	0.79	0.44	0.80
HEATING VALUE*	1032	1070	1023
SPECIFIC GRAVITY	0.711	0.694	0.709

* CALCULATED GROSS BTU PER CU FT, DRY, AT 60 DEGREES FAHRENHEIT AND 30 INCHES OF MERCURY
** DUE TO THE ABSORPTION OF H2S DURING SAMPLING, THE REPORTED RESULTS MAY NOT BE RELIABLE

Table 3. Gas chemical composition analysis data for Wolfcampian unit (Moore, 1982).

Table 4. Gas Specific Gravity Data for Wolfcampian/GW Units

Well #	Type	SG	Prod. Unit
2A**	GAS	0.87	Wolfcampian
3A	GAS	0.83	Wolfcampian
4A	GAS	0.85	Wolfcampian
6A*	GAS	0.83	Wolfcampian/GW
7A*	GAS	0.89	Wolfcampian
8A*	GAS	0.85	Wolfcampian
12A	GAS	0.85	Wolfcampian/GW
6B	GAS	0.79	Granite
8B*	GAS	0.83	Wolfcampian
9B	GAS	0.96	Wolfcampian
14B	GAS	1	Wolfcampian
15B**	GAS	0.65	Wolfcampian
16B	GAS	0.66	Wolfcampian
1P*	GAS	0.84	Wolfcampian
3P	GAS	0.88	Wolfcampian/GW
4P	GAS	0.92	Wolfcampian
8P	GAS	1.02	Wolfcampian
9P	GAS	0.89	Wolfcampian
11P	GAS	0.67	Wolfcampian
14P	GAS	0.87	Wolfcampian
15P*	GAS	0.83	Wolfcampian
16P	GAS	0.85	Wolfcampian
17P	GAS	0.79	Wolfcampian/GW
18P	GAS	0.8	Wolfcampian
19P	GAS	0.72	Wolfcampian
20P**	GAS	0.79	Wolfcampian
21P	GAS	0.87	Wolfcampian
22P	GAS	0.95	Wolfcampian
24P	GAS	0.82	Wolfcampian
25P**	GAS		Wolfcampian
26P	GAS	0.81	Wolfcampian
27P**	GAS	0.75	Panhan./Wolfcamp
28P	GAS	0.79	Wolfcampian
29P	GAS	0.88	Wolfcampian
30P**	GAS	0.7	Wolfcampian
31P	GAS	0.75	Wolfcampian
37P	GAS	1.01	Wolfcampian
38P	GAS	0.93	Wolfcampian/GW
39P	GAS	0.81	Wolfcampian
40P	GAS	0.74	Wolfcampian
41P	GAS	0.84	Wolfcampian
42P	GAS	0.73	GW
43P	GAS	0.99	Wolfcampian
44P	GAS	0.8	Wolfcampian
45P	GAS	0.95	Wolfcampian
46P*	GAS	0.9	Wolfcampian/GW
47P	GAS	0.81	Wolfcampian
48P	GAS	0.95	Wolfcampian
49P	GAS	0.85	Wolfcampian
50P	GAS	0.84	Wolfcampian
	Mean:	0.840816 N=49	

Table 5. Gas Specific Gravity Data for Red Cave Units

Well #	Type	SG	Prod. Unit
5B	GAS	0.69	Red Cave
7B	GAS	0.75	Red Cave
2P	GAS	0.74	Red Cave
5P	GAS	0.74	Red Cave
6P	GAS	0.77	Red Cave
7P	GAS	0.73	Red Cave
10P	GAS	1.03	Red Cave
12P	GAS	0.69	Red Cave
13P	GAS	0.89	Red Cave
23P	GAS	0.77	Red Cave
32P	GAS	0.68	Red Cave
33P	GAS	0.75	Red Cave
34P	GAS	0.77	Red Cave
35P	GAS		Red Cave
36P	GAS	0.96	Red Cave
	Mean:	0.782857 N=14	

specific gravity for Red Cave and Wolfcampian samples. Ruppel and Garret, Jr. (1989) considered the Red Cave a separate reservoir, and this study utilizes their conclusions that the Wichita Formation provides a barrier between the Wolfcampian and Red Cave throughout the study area.

Post-Permian Stratigraphy

The stratigraphic position and lithology of units overlying the Permian section in the study area are of interest, considering the potential for vertical migration of fluids injected into Permo/Pennsylvanian reservoir units. Overlying Permian rocks in the Panhandle area are terrestrial clastic facies of the Triassic Dockum Group and alluvial facies of the Miocene-Pliocene Ogallala Formation (Presley, 1981). Figure 10 is a stratigraphic chart of Middle and Upper Permian salt bearing strata and associated formations in the Texas Panhandle. Multiple layers of evaporites are present throughout the Middle and Upper Permian section between the Leonardian Red Cave and Triassic Dockum Group. Most of these formations form effective confining layers, though exceptions may exist in areas of localized fracturing or salt dissolution. The Glorietta Sandstone is considered an aquifer, although waters from the Glorietta are high in total dissolved solids (TDS) and non-potable (salaquifer). Middle and Upper Permian evaporite units range from 1000 to 1500 ft in thickness, with member formations typically ranging from 50 to 500 ft in thickness (Presley, 1981). These units often outcrop in the Panhandle region. Overlying the Permian section are sandstone, siltstone, and mudstones of the Triassic Dockum Group (Collins, 1990). Figure 11 shows the general surface stratigraphy for each physiographic subdivision of the Texas Panhandle and adjacent areas of the Oklahoma Panhandle and eastern New Mexico. The portion of the Panhandle-Hugoton field occupying the study area lies within the Canadian Breaks

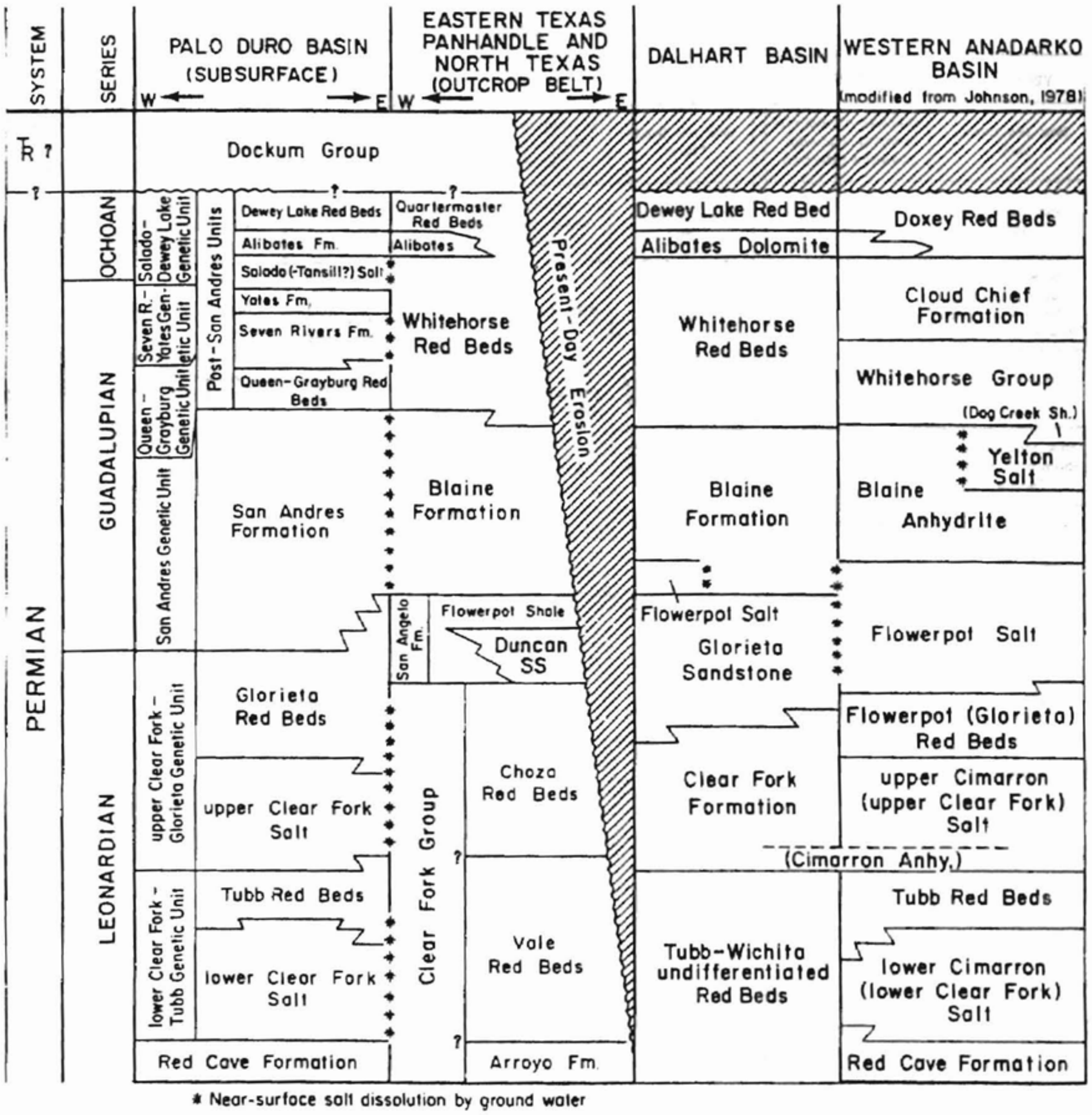


Figure 10. Stratigraphic chart of Middle and Upper Permian salt-bearing strata and associated formations in the Texas Panhandle. Asterisk indicates salt dissolution has occurred between units; outcropping units lack salt (Presley, 1981).

physiographic subdivision. The Cretaceous section is absent in this area, and the Tertiary (Mio-Pliocene) Ogallala Formation overlies the Triassic Dockum Group. The Ogallala contains sand, silt, mud, gravel, caliche, and some sandstone and mudstone. The Ogallala serves as the region's principal aquifer and outcrops at the surface over significant portions of the four-county study area. The Ogallala is considered a terrace alluvium type aquifer, and ranges in thickness from 50-600 ft, with an average depth to water of 50-300 ft. Hydraulic conductivity varies from 10-700 ft/day, and typical well yields range from 50-1000 gal/min (Todd, 1983). Pressure evaluation of Permo/Pennsylvanian reservoirs should examine possible routes or mechanisms for fluid migration from these deeper units upward into the Ogallala aquifer.

	North Plains		Southern High Plains		Canadian Breaks	
	Unit	Lithology	Unit	Lithology	Unit	Lithology
Recent to Pleistocene	Windblown deposits, alluvium, and lake deposits	Sand, silt, and mud*	Windblown deposits, alluvium, and lake deposits	Sand, silt, and mud*	Windblown deposits, alluvium, terrace and lake deposits	Sand, silt, and mud
Pleistocene	Lake deposits, Blackwater Draw Formation	Sand, silt, and mud*	Lake deposits, Blackwater Draw Formation	Sand, silt, and mud*	Lake deposits	Silt, mud, and sand
Tertiary	Ogallala Formation	Sand, silt, mud, gravel, caliche, and some sandstone to mudstone	Ogallala Formation	Sand, silt, mud, gravel, caliche, and some sandstone to mudstone	Ogallala Formation	Sand, silt, mud, gravel, caliche, and some sandstone to mudstone*
Cretaceous	Dakota and Purgatoire Formations	Sandstone and shale	Duck Creek and Klamichi Formations, and Edwards Group	Shale, limestone, some sandstone		
Triassic	Dockum Group	Sandstone, siltstone, and mudstone	Dockum Group	Sandstone, siltstone, and mudstone	Dockum Group	Sandstone, siltstone, and mudstone*
Permian					Quartermaster, Alibates, and Cloud Chief formations, and Whitehorse Group	Sandstone, siltstone, dolomite beds, and gypsum beds*

Figure 11. General surface stratigraphy for various physiographic subdivisions of the Texas Panhandle and adjacent areas of the Oklahoma Panhandle and eastern New Mexico (Collins, 1990).

Injection Well Parameters

Injection wells are commonly used for the permanent underground storage of industrial wastes (Warner, 1968). Deep-well injection may become an increasingly important alternative to conventional surface and near-surface waste disposal methods.

Large urban areas producing voluminous amounts of municipal and industrial waste might consider deep-well disposal as a means to better protect surface environmental resources such as soil and water. Suitable locations for deep-well injection would include areas with oil and gas production, as existing wells might be used for waste injection and subsurface data would be available for well planning. Such locations are commonly found in the Mid-Continent, Great Plains, Rocky Mountains, and Gulf Coast (Collins, 1975). In the case of deep injection wells, the term "deep" refers to rock (not soil) that is below and completely isolated from all freshwater aquifers (Keller, 2000). A more conventional definition might be an injection well with a storage horizon that is greater than 305 m (1000 ft) deep. Figure 12 is a schematic cross section of a hypothetical deep-well injection system. The figure shows the position of the disposal reservoir with respect to confining layers and fresh water aquifers. Acceptable geologic areas for deep injection wells include most synclinal basins with porous sedimentary rocks available as reservoirs. Such strata are found under approximately 50% of the land area in the United

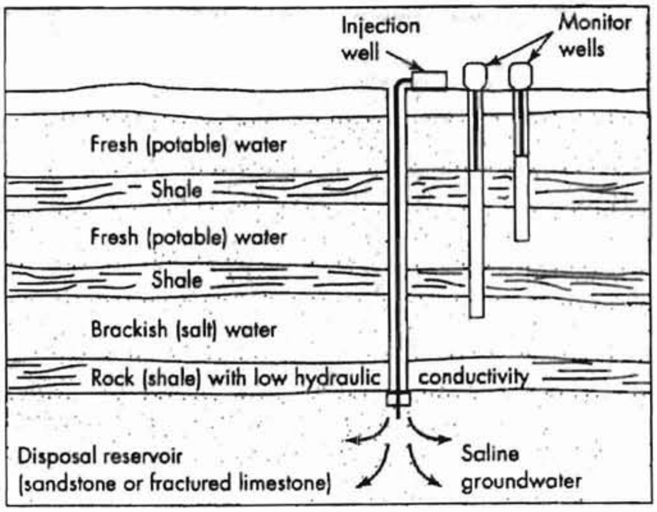


Figure 12. A deep-well injection system (Keller, 2000).

States, including the Mid-Continent and Great Plains (Collins, 1975). Reservoir characteristics of suitable disposal zones include; large porosity, permeability, and thickness, large areal extent, uniform and not too heterogeneous reservoir units, salaquifer, injection zone laterally and vertically separated from freshwater zones, and no unplugged or improperly plugged wells penetrating the zone in the vicinity of the disposal well (Collins, 1975). Figure 13 illustrates how liquid waste might enter a freshwater aquifer through abandoned wells, implying that careful geologic and hydrodynamic planning is essential when considering possible sites for deep-well waste injection.

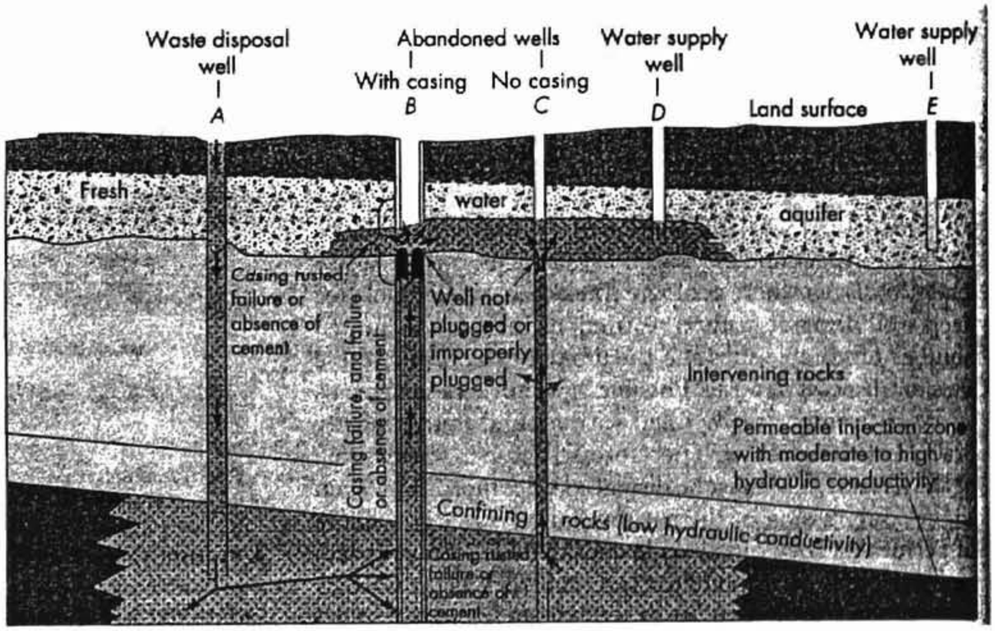


Figure 13. Diagram illustrating importance of knowing locations of abandoned wells in relation to disposal and water supply wells (Keller, 2000).

Basic Hydrodynamic Principles

Hydrodynamic evaluation of the Panhandle field requires the acceptance of certain fundamental principles of fluid behavior with depth. Any body of fluid has, with respect to pressure, the following attributes (Dahlberg, 1995):

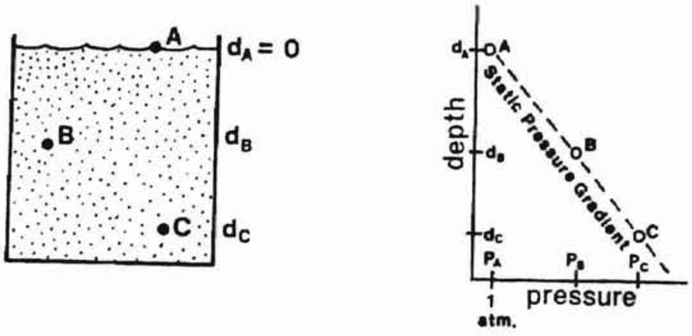
1) The internal pressure increases with depth in the body

2) The rate at which the pressure increases is called the *static pressure gradient* and it depends only on the density of the particular fluid concerned

3) The two- or three-dimensional orientation of the vector representing the direction of maximum rate of pressure increase is vertical if the fluid concerned is static

4) Pressure-depth relationships are completely independent of the shape of the fluid's container (or formation)

Figure 14 illustrates pressure-density and gradient relationships in a static body of fluid. Pressures at all points within a confined fluid body (or system) plot graphically on a single straight line which represents the pressure gradient (Fig. 14). At any point on the line, pressure is dependent on three factors (Dahlberg, 1995):



$$P_B = P_A + \text{grad}\,P(d_B - d_A)$$

$$P_C = P_B + \text{grad}\,P(d_C - d_B)$$

$$\text{grad}\,P = \text{normal pressure gradient} = \frac{(P_C - P_B)}{(d_C - d_B)} = \frac{\Delta P}{\Delta d}$$

Figure 14. Pressure-density and gradient relationships in a static body of fluid (Dahlberg, 1995).

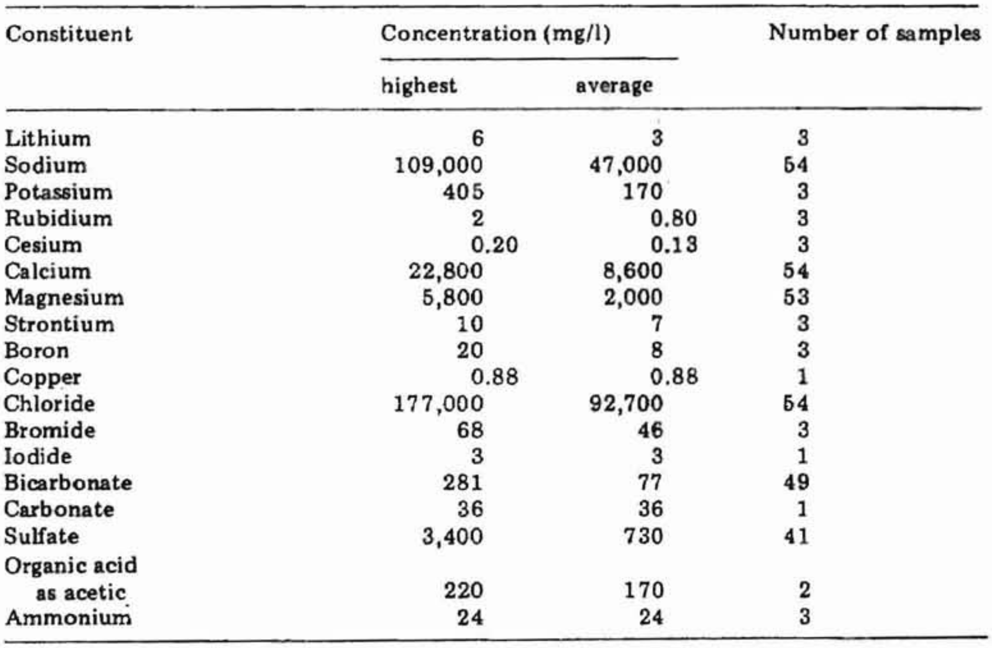
1) The density of the fluid itself

2) The depth of the point below the top of the fluid column

3) The pressure at the top of the fluid column

The pressure build-up with depth is attributable to the increasing weight of the fluid column above the particular point concerned and the rate at which the pressure increases downward with depth (Dahlberg, 1995). Fluids in the reservoir units examined are assumed to be in continuous contact through the pore network. The graphical slope of the pressure gradient, dP/dZ, is numerically equal to D x g, where D is fluid density (lb/ft3) and g is the acceleration of gravity (ft/sec2). The pressure gradient (grad P = dP/dZ) can be calculated for practical purposes using the specific gravity and the following equation (Dahlberg, 1995):

$$gradP = \frac{specificgravity \times 62.4}{144} = \frac{dP}{dZ} \quad (2.1)$$



Constituent	Concentration (mg/l)		Number of samples
	highest	average	
Lithium	6	3	3
Sodium	109,000	47,000	54
Potassium	405	170	3
Rubidium	2	0.80	3
Cesium	0.20	0.13	3
Calcium	22,800	8,600	54
Magnesium	5,800	2,000	53
Strontium	10	7	3
Boron	20	8	3
Copper	0.88	0.88	1
Chloride	177,000	92,700	54
Bromide	68	46	3
Iodide	3	3	1
Bicarbonate	281	77	49
Carbonate	36	36	1
Sulfate	3,400	730	41
Organic acid as acetic	220	170	2
Ammonium	24	24	3

Figure 15. Highest concentration of a constituent found, average concentration, and number of samples analyzed for Permian system formation waters throughout the United States (Collins, 1975).

Formation waters of Permo/Pennsylvanian reservoirs in the study area are estimated to have an average chloride concentration of 92,700mg/l (Fig. 15). This value results in a specific gravity of 1.074 and a pressure gradient of 0.465 psi/ft, a commonly accepted brine gradient value for Oklahoma, Texas, and the Gulf Coast (EG & G Continental Laboratories, 1982). As stated earlier, reservoir units in this study are assumed to be in a hydrostatic environment, where there is no internal motion or movement of the fluid. The maximum internal pressure gradient is vertical and attributable to the weight of overlying fluids. All internal forces are oriented vertically with buoyancy as the major one (Dahlberg, 1995). Figure 16 is a mechanical "tank" model of a hydrostatic subsurface reservoir. It shows the essential internal and external components and the dimensional

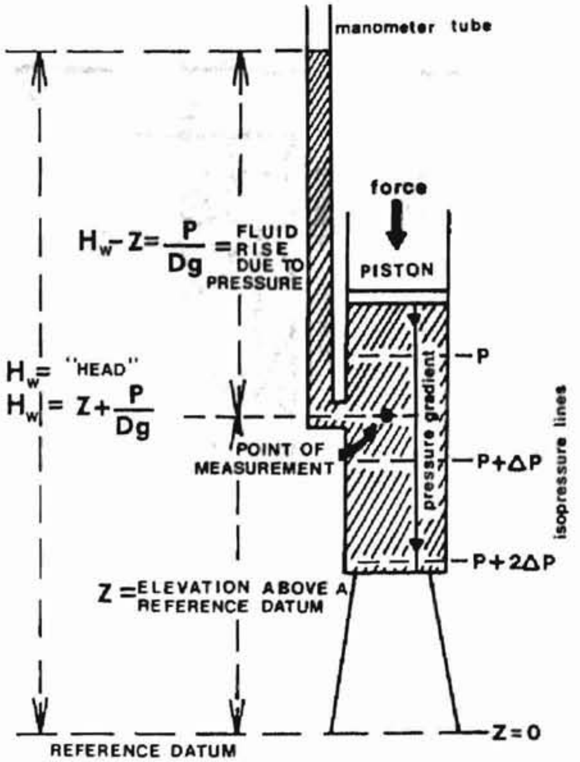


Figure 16. A "tank" model of a hydrostatic reservoir illustrating the relationships between internal fluid pressure at a point in the fluid body and the corresponding hydraulic "head" of the fluid at that point reflected by the height of the fluid column in a manometer tube (Dahlberg, 1995).

variables from which the hydrologic parameters can be calculated (Dahlberg, 1995). The Permo/Pennsylvanian units within the study area are underpressured with respect to a normal hydrostatic gradient. This may be the result of reservoir compartmentalization (isolation of certain reservoir units by impermeable or semi-permeable barriers). Figure 17 shows a hypothetical rock-water system with an internal, completely impermeable seal that is supported by the underlying grains or its own mechanical rigidity. The seal transmits little of the weight of the overburden and fluids above the seal to the fluids below the seal. This mechanism, combined with the relatively shallow depths of reservoir units within the study area, may explain their underpressured nature. Barker (1974) states that if a normally pressured zone becomes effectively isolated from its surroundings (i.e., the Wichita Formation seal on the Wolfcamp), and if this zone is cooled by uplift or removal of overburden during erosion, the pressure in the isolated volume will fall below the normal hydrostatic gradient (the pressure must decrease in order to maintain a

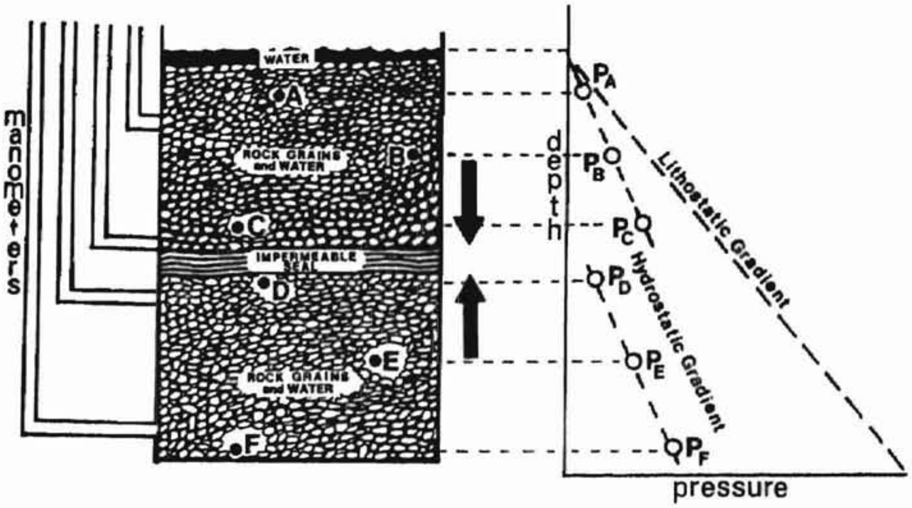


Figure 17. A model rock-water system with an internal, completely impermeable seal. The rock framework in the compartment underneath the seal supports the weight of the rocks *and* the water overlying the seal (Dahlberg, 1995).

constant fluid density). The Panhandle (Texas) field discovery well, drilled in 1918 to a depth of 2395 ft, recorded an initial shut-in pressure of 420 psi. This value falls well below the normal hydrostatic gradient for that particular depth, suggesting Permo/Pennsylvanian reservoirs in Panhandle field were underpressured before large-scale production of the area began. Other North American basins that are naturally underpressured or display characteristic zones of underpressure include the Alberta Basin of western Canada (Dahlberg, 1995), portions of the Denver Basin, and the Salina and Forest City Basins of northeastern Kansas (Warner, 1968). Underpressured intervals in normally or abnormally pressured basins, produced by hydrocarbon depletion, might serve as suitable zones for deep-well injection, provided adequate confining layers exist above and below the interval.

CHAPTER 3

Methodology

Stratigraphic Cross Section Generation

Evaluating the areal extent, continuity, and thickness of reservoir and confining units within the area of study is an important first step in characterizing the hydrodynamics of Panhandle field. The study area includes parts of Carson, Hutchinson, Moore, and Potter Counties, Texas (Fig. 2), and lies between latitudes 35°15' and 36°00' N and longitudes 101°15' and 102°00' W. Two stratigraphic cross sections were constructed for this study using wells that were selected from 1"=1 mile scale Herndon geologic maps of the representative counties.

Cross section A-A' (Fig. 24, Chapter 4) trends NW-SE and extends approximately 55 miles. Thirteen wells were used as control points, resulting in an average spacing of 4.2 miles. Cross section B-B' (Fig. 23, Chapter 4) trends SW-NE and extends approximately 59 miles. Seventeen wells were used as control points, resulting in an average spacing of 3.5 miles. No specific standards exist for determining stratigraphic cross section control well spacing. Miall (1999) suggests that spacing should conform to the scale and type of cross section under consideration. Spacings of 6.2-12.5 mi per well have yielded statistically acceptable formation correlation results in certain basinwide studies. Formation tops of interest, ground elevation, total well depth, production depth, and well type were determined using wireline electric logs and production and completion data available in the Oklahoma City Geological Society Well Log Library. Table 6 lists the counties, names, locations, well types, and data availability for all wells

Table 6. Well Locations and Availability of Data for Panhandle Study-Cross Sections AA', BB'

Well #	Well Name	County	Location	Strip Log	Wireline	Scout Card	Production Decline Plot	Type
10B	Cities Service #12 Deahl "B"	Carson	H & GN Sec. 4	N	Y	Y	N	OIL
9A	Cities Service Deahl "B" #5	Carson	AB & M BLK 3 Sec. 8	N	Y	Y	N	OIL
10A	A. C. Bruce Burnett #1-81	Carson	I & GN BLK 5 Sec. 81	N	Y	Y	N	D & A
11A	Cities Service Oil Co. #1-C-50 Burnett Ranch	Carson	I & GN BLK 5 Sec. 50	N	Y	Y	Y	D & A
12A	Cities Service Gas Co Burnett 101 A	Carson	I & GN BLK 5 Sec. 2	N	Y	Y	Y	GAS
13A	Cities Service Pet. #3-8 Empire GW Unit	Carson	I & GN BLK 7 Sec. 12	N	N	Y	N	OIL
11B	Phillips Petroleum J. M. Sanford #3	Hutchinson	B & B BLK 1 Sec. 1	N	Y	Y	N	OIL
12B	J. M. Huber #4 Johnson "B"	Hutchinson	A & B BLK Y Sec. 37	N	Y	Y	Y	OIL
13B	Gulf Oil Corp. #3 K. Reimer	Hutchinson	H & TC BLK 47 Sec. 29	N	Y	Y	N	OIL
8A	Phillips Pet. Co. #3 Kermicle	Hutchinson	H & TC BLK 46 Sec. 89	N	N	Y	Y	GAS
15B	Pathfinder Pet. 19-1 Wisdom	Hutchinson	TC RR BLK M23 Sec. 19	N	N	Y	Y	GAS
16B	Pathfinder Pet. #1-4 Wisdom	Hutchinson	FREDERICK Sec. 1	N	Y	Y	Y	GAS
17B	Ladd Pet. #1 Dent	Hutchinson	D & P BLK 17 Sec. 1	N	Y	Y	N	D & A
14B	J. M. Huber #1 Hazel	Hutchinson	H & OB BLK XO2 Sec. 4	N	N	Y	Y	GAS

Well #	Well Name	County	Location	Strip Log	Wireline	Scout Card	Production Decline Plot	Type
1A	Texas Co. #1 R. L. Beard	Moore	H & TC BLK 44 Sec. 369	Y	Y	Y	N	D & A
2A	Shamrock #2 Harrington	Moore	H & TC BLK 44 Sec. 307	N	N	Y	Y	GAS
3A	Nat. Gas P. G1 R Powell LB	Moore	H & TC BLK 44 Sec. 227	N	N	Y	Y	GAS
4A	Nat. Gas P. #33 R. S. Coon	Moore	H & TC BLK 44 Sec. 189	N	Y	Y	Y	GAS
5A	Kerr-McGee #1-31-A Sneed	Moore	T & NO BLK 6T Sec. 31	N	Y	Y	N	D & A
6A	Colo. Int. Gas D-2 Sneed	Moore	T & NO BLK 6T Sec. 42	Y	Y	Y	Y	GAS
7A	Colo. Inter. #6-A Fee	Moore	G & M BLK 3 Sec. 79	Y	Y	Y	Y	GAS
1B	Plains Res. 1-156 O'Brien Trust	Potter	BS & F BLK 9 Sec. 156	N	N	Y	N	D & A
2B	U.S. Bureau of Mines Bush #A-8	Potter	BS & F BLK 6 Sec. 26	N	Y	Y	N	HELIUM
3B	U.S. Bureau of Mines Fuqua A-1	Potter	BS & F BLK 6 Sec. 18	N	Y	N	N	HELIUM
4B	Baker & Taylor Emeny #1	Potter	G & M BLK M19 Sec. 29	N	N	Y	Y	OIL
5B	Eason Oil Bivins Ranch #1-3	Potter	ACH&B BLK 4 Sec. 3	N	Y	Y	Y	GAS
6B	Colo. Interstate Gas B-99 Masterson	Potter	H & TC BLK 47 Sec. 67	N	N	Y	Y	GAS
7B	Colo. Inst. B 55R Masterson	Potter	G&M BLK 3 Sec. 26	N	N	Y	Y	GAS
9B	Pioneer Nat. Res. A-208 Bivins	Potter	G & M BLK 5 Sec. 11	N	Y	Y	Y	GAS
8B	Col. Inter. Gas #163-A Bivins	Potter	H&TC BLK 46 Sec. 103	N	Y	Y	Y	GAS

used in cross section construction. The physical locations of wells were converted to X and Y coordinates (northings and eastings in ft) using the southwest corner boundary of Potter County as the origin (0,0). Depths to various rock units, including the Red Cave, Panhandle Lime (Wichita Formation), Wolfcampian, Pennsylvanian and older Paleozoic units, Granite Wash and Granite, as well as total depth were determined from scout cards and wireline electric logs. Well coordinates, rock unit data, and well collar elevations were entered into spreadsheets (Tables 7 and 8) and used to create stratigraphic cross sections using Rockworks 99™ software. These cross sections are presented in Chapter 4.

Pressure Data Analysis

Pressure data for control wells used in this study were obtained from PI/Dwights PLUS on CD database. Wellhead shut-in pressure (WHSIP) and bottomhole pressure (BHP) values for both active and inactive gas wells were obtained from detailed well test reports. Pressure values and all other engineering units used in this study are U.S. Customary (Hammer and MacKichan, 1981). Wells were identified on Herndon geologic maps (Herndon Map Service, 2001) of the four-county study area and their positions reported as northings and eastings in ft. Figure 18 is a simplified schematic of a producing oil well (the same diagram could apply to a producing gas well). Instrumentation at the wellhead records static shut-in pressure (WHSIP) that can be used to calculate bottomhole pressure (BHP) if certain variables are known. "Bottomhole" pressure is reservoir pressure at the point of the lowest (deepest) perforation in the production casing (Fig. 18) and not the actual bottom (total depth) of the drilled hole, though the two are sometimes the same.

Table 7. Cross Section A-A' , NW-SE
Northing and Eastings from southwest corner boundary of Potter Co. (0,0)
Formation tops in feet above/below datum (mean sea level)

Well #	Easting (ft)	Northing (ft)	Red Cave	Panhandle	Wolfcamp Dol	Granite Wash *	MDSO **	TD
1A	26822	274560	1062	562	312	-288		-388
2A	42768	258202	1585	824	555			322
3A	61248	240250	1729	963	715			200
4A	81312	225994	1494	1075	762	-162	-1802	-2622
5A	104016	198010	1756	1366	1072	476		-214
6A	124608	190882	1627	1307	983	583		203
7A	134112	172930	1678	1288	1023	713		201
8A	166056	179424	1508	1158	728			-252
9A	184642	147797	1391	1143	723	191		26
10A	215900	139613	1616	1403	795	493		-144
11A	218540	119021	1626	1407	991	701		-65
12A	242458	101861	1419	1184	799	430		380
13A	253018	92093		1018	606	220		-12

* Granite Wash may be Permo/Pennsylvanian

** Mississippian, Devonian, Silurian, Ordovician

Table 8. Cross Section B-B' , SW-NE
Northing and Eastings from southwest corner boundary of Potter Co. (0,0)
Formation tops in feet above/below datum (mean sea level)

Well #	Easting (ft)	Northing (ft)	Red Cave	Panhandle	Wolfcamp Dol	Pennsylvanian *	Granite Wash **	Granite ***	MDSO ****	TD
1B	33792	38016		-191	-676	-1436	-2711			-4747
2B	50160	52272	737	313	-25					-270
3B	57552	65472	851	373	-53					-251
4B	73392	82368	808	271	-149	-1476	-2410	-2571		-2723
5B	95568	89760	616	322	-200					-419
6B	103435	111936	1579	1357	1221		1126	1050		267
7B	106392	127248	1706	1506	1336		1216			-109
8B	129096	133848	1645	1859	1111		881			309
9B	140712	144778	1694	1446	1316		836			406
10B	181474	151536	1361	1114	699		207			132
11B	198898	173712	1531	1361	926		259			-140
12B	199109	186120	1462	1207	824					-150
13B	199980	203438	1216	961	477		106			-22
14B	194172	223396	1195	921	419					-10
15B	211596	246100	1135	785	235					-104
16B	212916	252436	1149	802	227					-92
17B	228756	279628	1171	811	91	-1771			-3611	-4999

* Pennsylvanian sedimentary units
** Granite Wash may be Permo/Pennsylvanian or older Pennsylvanian
*** Granite most likely Cambrian-Pre Cambrian
**** Mississippian, Devonian, Silurian, Ordovician

Most BHP values used in this study were taken directly from Dwights/PI detailed well test reports. In some cases, only the WHSIP was listed for a particular well. Echometer Acoustic Bottomhole Pressure Survey (version 2.1), a DOS based program, was used to calculate a BHP value, provided the well's maximum production depth, gas specific gravity, and basic gas chemical composition (if available) were known. BHP values were obtained and tabulated for producing gas wells in both the Wolfcampian and Red Cave. Initial BHP values were tabulated separately from the most recent BHP

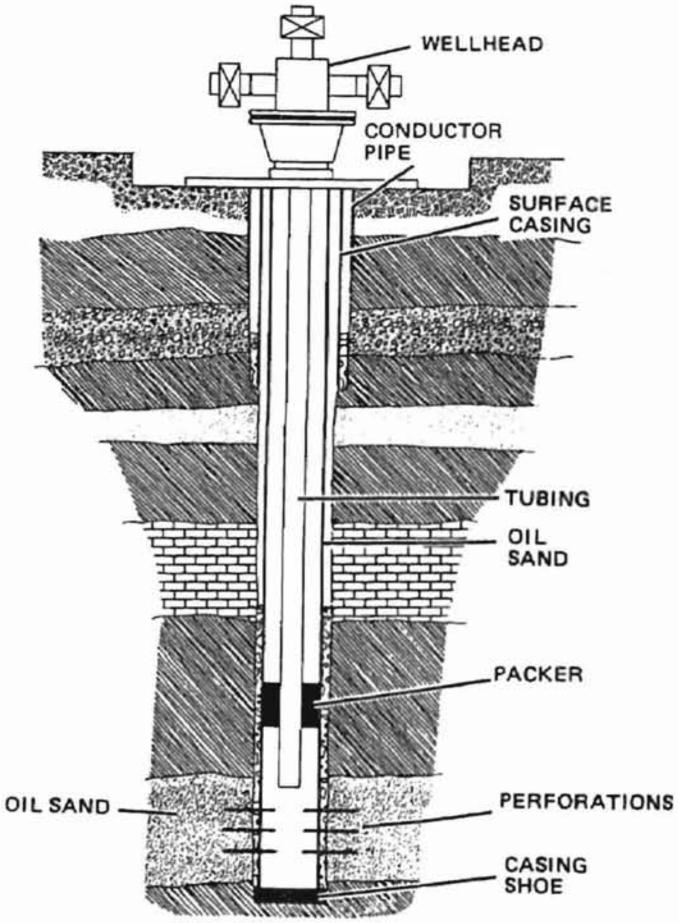


Figure 18. Casing, tubing, and packer arrangement in a flowing well (Petroleum Extension Service, 1979).

values. Pressure-depth (P-D) plots were constructed using Excel 2000 for initial and recent BHP values from both Wolfcampian and Red Cave data. A sample pressure-depth plot from Hutchinson County, Texas is shown by Figure 19. Depth is plotted on the y-axis, decreasing upward, and pressure plotted on the x-axis, increasing to the right. A hydrostatic gradient line using 0.465 psi/ft brine density is then plotted on the graph to provide a reference for the individual data points (points suggesting normal, subnormal, or abnormal reservoir pressures). Wolfcampian and Red Cave P-D plots are presented in Chapter 4.

Potentiometric Surface Map Generation

Potentiometric surface maps were selected as the primary form of graphical representation of pressure conditions present in Wolfcampian and Leonardian reservoirs examined in this study. A potentiometric surface represents a calculated imaginary surface, the topography of which reflects geographic variation in the fluid potential of the formation water within a particular aquifer or subsurface reservoir (Dahlberg, 1995). The elevation of the surface at any point reflects (but does not exactly equal) the height to which a column of water would rise above a reference datum within a vertical tube (ignoring capillarity). This is an approximation of the hydraulic "head" (H_w), which reflects the level of potential energy of the water in the reservoir/aquifer. The height of the column mirrors the pressure within the aquifer (or reservoir) at that point (Dahlberg, 1995). Hydraulic head is normally calculated from pore pressure (BHP) measurements in fluid-saturated rock as follows (Dahlberg, 1995):

$$H_w = Z + \frac{P}{D_w g} \qquad (3.1)$$

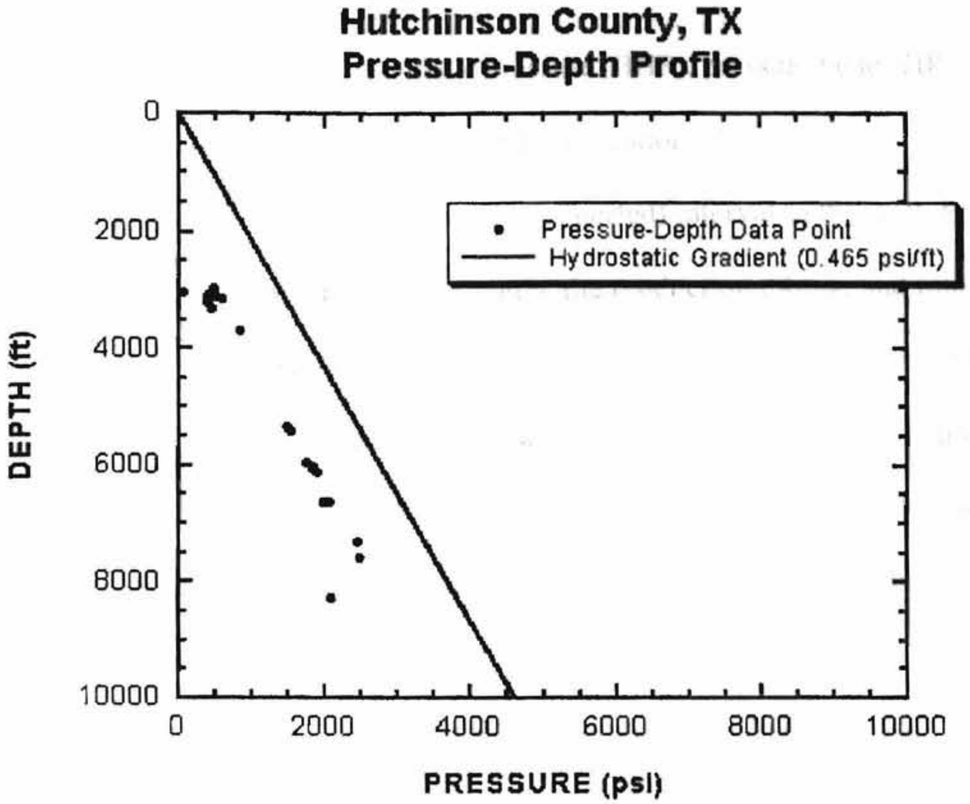


Figure 19. Hutchinson County, Texas P-D profile (Oklahoma State University, 2000).

where Z = reference datum in feet above or below a constant datum (mean sea level for this study); P = bottomhole pressure in psi; D_w = density of the water throughout the fluid column above the point of measurement (lb/ft3); and g = acceleration of gravity (ft/sec2). Substituting *grad P* for D_wg in (3.1) yields:

$$H_w = Z + \frac{P}{gradP} \qquad (3.2)$$

For the purposes of this study, grad P maintains a constant value of 0.465 psi/ft. Therefore, hydraulic head values for control wells may be calculated using the relationship:

$$H_w = Z + \frac{P}{0.465} \qquad (3.3)$$

Table 9 lists elevation (Z), bottomhole pressure (BHP), pressure head (HP), and total head (HT) for control wells used in this study. Elevation (Z) is the height above mean sea level (MSL) in ft of the lowest producing (perfed) interval in the well. Pressure head (HP) is the height in ft of the water column in the production tubing, and total head (HT) is the sum of the elevation and the pressure head in ft. Calculations were performed in a standard Excel 2000 spreadsheet. Only gas wells that were active during or up to the years1996-2000 were used as control points. This screening minimized reservoir pressure differences between wells that were the result of drawdown and provided a more accurate "snapshot" of current reservoir pressure conditions.

Once positions and total head values were determined for control wells, Rockworks 99™ software was used to generate two and three-dimensional equipotential surface contour maps for both Wolfcampian and Leonardian (Red Cave) reservoir units. An inverse distance method, one of the more common gridding methods, was selected to produce the contour maps presented in Chapter 4. This modeling method was selected over seven other modeling methods offered by Rockworks 99™ based upon perceived accuracy of interpretation of the existing geologic and pressure data. Appendices D-J offer examples of 2-D contour maps constructed with other Rockworks 99™ modeling methods using the same data set. Most of the maps generated a pattern of concentric contours ("bulls-eyes"), a result of the particular gridding algorithm. Figure 20 shows an example of a potentiometric surface map (with flow direction arrows) of part of the San Juan Basin. Wolfcamp and Red Cave potentiometric surface maps are presented in Chapter 4.

Table 9. Production data used for determining pressure head and total head for control wells.

* Echometer program used for BHP values

** Data not used for contour maps

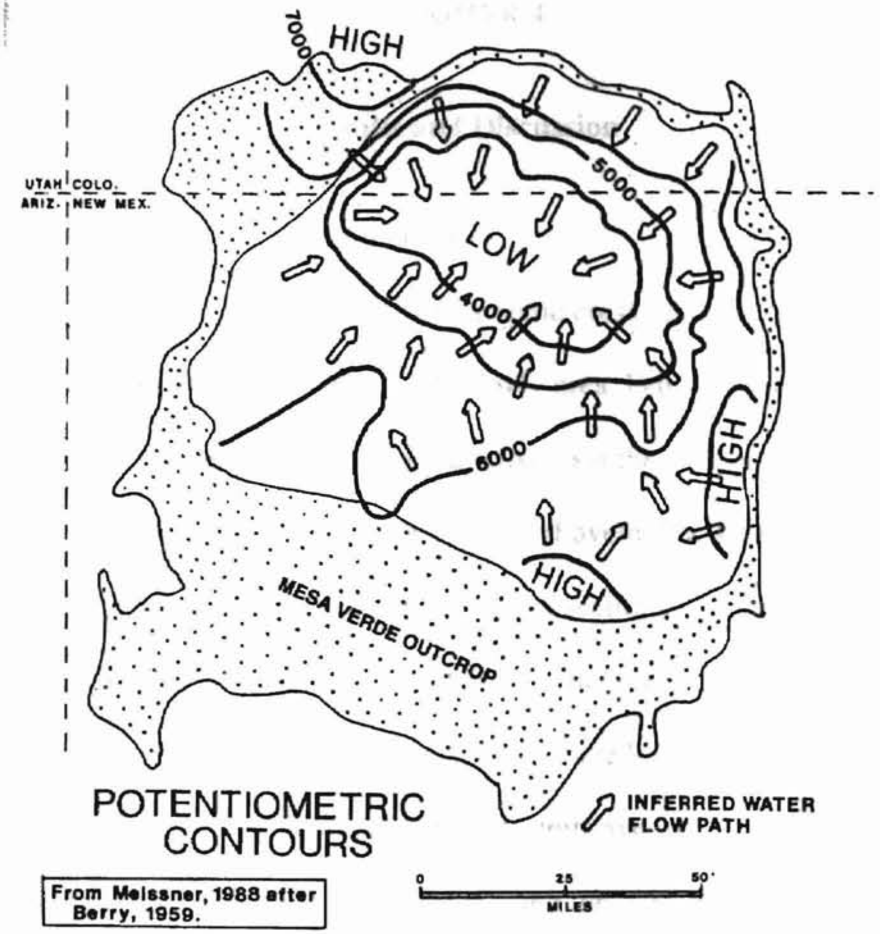
Well #	Easting (ft)	Northing (ft)	Type	SG	Prod. Unit	Prod. Depth (ft)	Elev. KB (ft)	KB-PD (ft)	BHP (psi)	Date	Pressure Head (ft)	Total Head (ft)
2A**	42768	258202	GAS	0.87	Wolfcampian	3322	3667	345	22	6/28/1989	47.31183	392.3118
3A	61248	240250	GAS	0.83	Wolfcampian	3140	3643	503	23	6/8/2000	49.46237	552.4624
4A	81312	225994	GAS	0.85	Wolfcampian	3031	3358	327	25	6/8/2000	53.76344	380.7634
6A*	124608	190882	GAS	0.83	Wolfcampian/GW	2957	3283	326	53	5/18/1998	113.9785	439.9785
7A*	134112	172930	GAS	0.89	Wolfcampian	2844	3138	294	36	5/27/2000	77.41935	371.4194
8A*	166056	179424	GAS	0.85	Wolfcampian	3040	3078	38	35	5/4/2000	75.26882	113.2688
12A	242458	101861	GAS	0.85	Wolfcampian/GW	2921	3304	383	1	5/1/2000	2.150538	385.1505
5B	95568	89760	GAS	0.69	Red Cave	2929	3270	341	375	10/25/1996	806.4516	1147.452
6B	103435	111938	GAS	0.79	Granite	2545	3269	724	1	5/1/2000	2.150538	726.1505
7B	106392	127248	GAS	0.75	Red Cave	1629	3126	1497	50	5/18/1987	107.5269	1604.527
8B*	129096	133848	GAS	0.83	Wolfcampian	2670	3259	589	30	7/29/1996	64.51613	653.5161
9B	140712	144778	GAS	0.96	Wolfcampian	2610	3016	406	17	5/12/2000	36.55914	442.5591
14B	194172	223396	GAS	1	Wolfcampian	2885	3104	219	1	5/1/2000	2.150538	221.1505
15B**	211596	246100	GAS	0.65	Wolfcampian	3135	3196	61	239	4/3/1987	513.9785	574.9785
16B	212916	252436	GAS	0.66	Wolfcampian	3238	3208	-30	1	5/1/2000	2.150538	-27.84946
1P*	74646	183744	GAS	0.84	Wolfcampian	2900	3500	600	2	5/1/2000	4.301075	604.3011
2P	78144	178728	GAS	0.74	Red Cave	2300	3500	1200	153	7/22/1992	329.0323	1529.032
3P	64112	183744	GAS	0.88	Wolfcampian/GW	2900	3665	765	1	5/1/2000	2.150538	767.1505
4P	61776	192192	GAS	0.92	Wolfcampian	3265	3500	235	1	5/1/2000	2.150538	237.1505
5P	74712	190080	GAS	0.74	Red Cave	2272	3546	1274	163	5/24/1999	350.5376	1624.538
6P	74976	205392	GAS	0.77	Red Cave	2282	3550	1268	140	5/25/1999	301.0753	1569.075
7P	84374	200904	GAS	0.73	Red Cave	2110	3452	1342	124	9/14/2000	266.6667	1608.667
8P	167059	213048	GAS	1.02	Wolfcampian	3140	3149	9	14	4/25/1997	30.10753	39.10753
9P	185539	216216	GAS	0.89	Wolfcampian	2850	3122	272	23	5/20/2000	49.46237	321.4624
10P	181051	209880	GAS	1.03	Red Cave	1891	3110	1219	65	5/6/1996	139.7849	1358.785
11P	181051	198264	GAS	0.67	Wolfcampian	2867	2973	106	1	5/1/2000	2.150538	108.1505
12P	175771	197736	GAS	0.69	Red Cave	1748	3036	1288	22	9/11/1997	47.31183	1335.312
13P	172867	205761	GAS	0.89	Red Cave	1885	3050	1165	55	8/21/1997	118.2796	1283.28
14P	229416	139392	GAS	0.87	Wolfcampian	2475	3167	692	15	5/24/1999	32.25806	724.2581
15P*	252120	156499	GAS	0.83	Wolfcampian	2700	3258	558	2	5/1/2000	4.301075	562.3011
16P	223080	156024	GAS	0.85	Wolfcampian	2740	3192	452	29	8/6/1997	62.36559	514.3656
17P	232848	148368	GAS	0.79	Wolfcampian/GW	3020	3124	104	1	5/1/2000	2.150538	106.1505
18P	177936	117744	GAS	0.8	Wolfcampian	3022	3424	402	1	5/1/2000	2.150538	404.1505
19P	177461	110088	GAS	0.72	Wolfcampian	3120	3456	336	1	5/1/2000	2.150538	338.1505
20P**	168696	135538	GAS	0.79	Wolfcampian	2690	3420	730	44	5/21/1989	94.62366	824.6237
21P	147576	259512	GAS	0.87	Wolfcampian	3110	3397	287	16	7/8/2000	34.4086	321.4086
22P	115051	225720	GAS	0.95	Wolfcampian	2714	3245	531	12	6/8/2000	25.80645	556.8065
23P	87490	141768	GAS	0.77	Red Cave	1699	3320	1621	31	6/11/1993	66.66667	1687.667
24P	41870	225456	GAS	0.82	Wolfcampian	3463	3675	212	22	10/17/1999	47.31183	259.3118

Table 9. Production data used for determining pressure head and total head for control wells.

* Echometer program used for BHP values

** Data not used for contour maps

Well #	Easting (ft)	Northing (ft)	Type	SG	Prod. Unit	Prod. Depth (ft)	Elev. KB (ft)	KB-PD (ft)	BHP (psi)	Date	Pressure Head (ft)	Total Head (ft)
25P**	235488	157872	GAS		Wolfcampian	3065	3106	41	16	5/3/1994	34.4086	75.4086
26P	244992	142666	GAS	0.81	Wolfcampian	2800	3143	343	14	6/9/2000	30.10753	373.1075
27P**	244200	166056	GAS	0.75	Panhan./Wolfcamp	2770	3033	263	18	1/15/1989	38.70968	301.7097
28P	50424	197525	GAS	0.79	Wolfcampian	3309	3597	288	16	6/28/2000	34.4086	322.4086
29P	188760	132634	GAS	0.88	Wolfcampian	2828	3250	422	15	5/26/2000	32.25806	454.2581
30P**	190450	110088	GAS	0.7	Wolfcampian	3086	3376	290	155	6/7/1989	333.3333	623.3333
31P	190344	124714	GAS	0.75	Wolfcampian	2868	3320	452	1	5/1/2000	2.150538	454.1505
32P	166795	190344	GAS	0.68	Red Cave	1574	3072	1498	27	6/28/1998	58.06452	1556.065
33P	99792	112992	GAS	0.75	Red Cave	1787	3287	1500	96	9/3/1999	206.4516	1706.452
34P	111144	124608	GAS	0.77	Red Cave	1829	3295	1466	54	5/9/1989	116.129	1582.129
35P	194172	220228	GAS		Red Cave	2000	3138	1138	122	7/20/1998	262.3656	1400.366
36P	155232	146256	GAS	0.96	Red Cave	1580	3188	1608	42	8/7/1992	90.32258	1698.323
37P	161332	148108	GAS	1.01	Wolfcampian	2585	3294	709	11	8/15/1999	23.65591	732.6559
38P	46675	143510	GAS	0.93	Wolfcampian/GW	2833	3497	664	12	5/1/2000	25.80645	689.8065
39P	31680	164208	GAS	0.81	Wolfcampian	3387	3687	300	18	5/16/2000	38.70968	338.7097
40P	97152	89232	GAS	0.74	Wolfcampian	3560	3275	-285	127	12/7/1998	273.1183	-11.88172
41P	114840	135168	GAS	0.84	Wolfcampian	2660	3050	390	1	5/1/2000	2.150538	392.1505
42P	129835	114576	GAS	0.73	GW	2908	3170	262	25	5/22/2000	53.76344	315.7634
43P	111144	152592	GAS	0.99	Wolfcampian	2885	3186	301	13	5/22/2000	27.95699	328.957
44P	115051	252120	GAS	0.8	Wolfcampian	3100	3505	405	28	7/27/1999	60.21505	465.2151
45P	60139	149582	GAS	0.95	Wolfcampian	3334	3634	300	21	6/19/2000	45.16129	345.1613
46P*	78514	141768	GAS	0.9	Wolfcampian/GW	3025	3494	469	34	6/9/2000	73.11828	542.1183
47P	122496	188506	GAS	0.81	Wolfcampian	3097	3302	205	23	5/27/2000	49.46237	254.4624
48P	69960	273514	GAS	0.95	Wolfcampian	3070	3585	515	1	5/1/2000	2.150538	517.1505
49P	135485	272712	GAS	0.85	Wolfcampian	3090	3411	321	24	5/1/2000	51.6129	372.6129
50P	141979	224400	GAS	0.84	Wolfcampian	2686	3300	614	1	5/1/2000	2.150538	616.1505



From Meissner, 1988 after Berry, 1959.

Figure 20. Example of a potentiometric surface map (Dahlberg, 1995).

CHAPTER 4

Results and Discussion

Stratigraphic Cross Section Interpretation

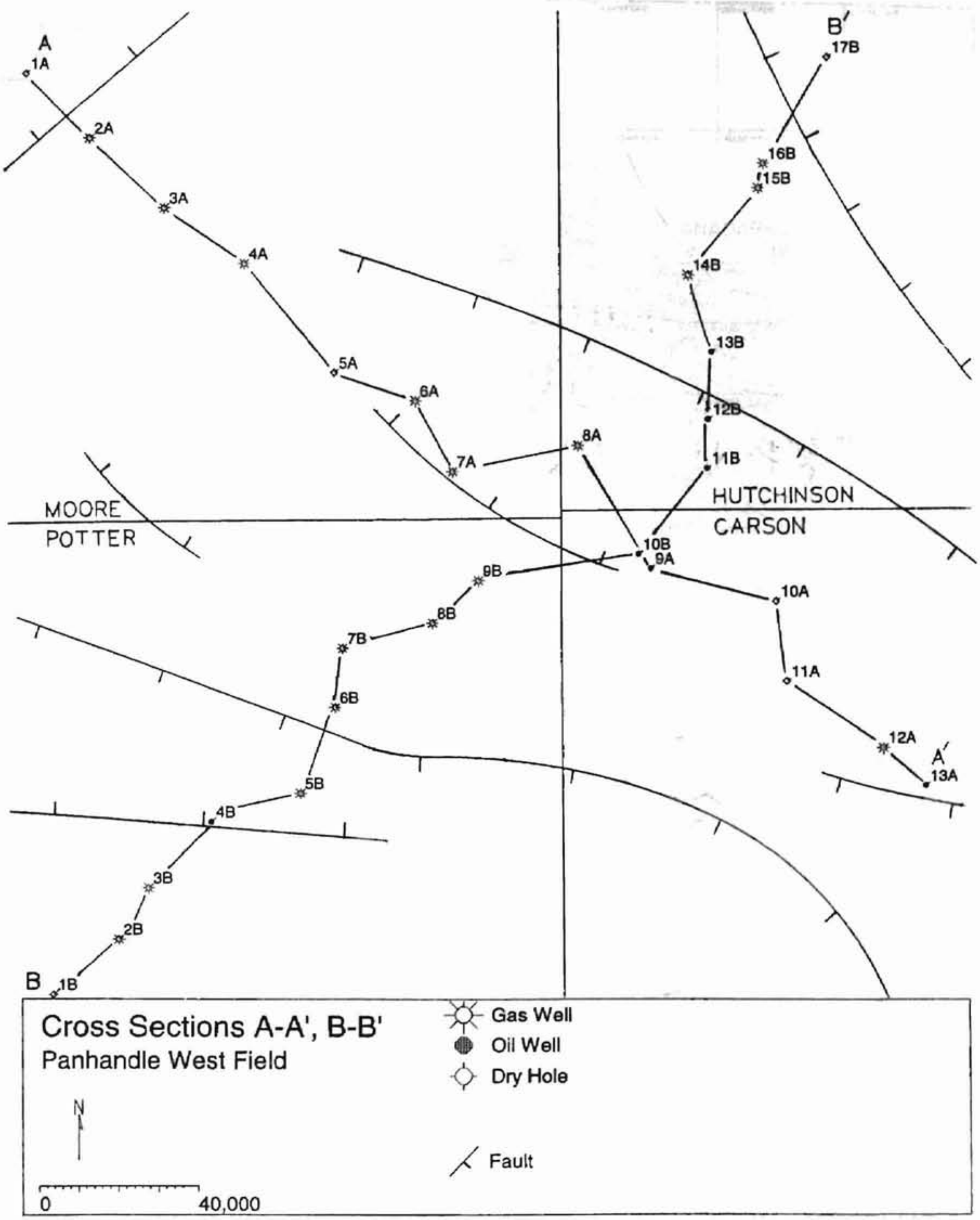
Figure 21 shows the transects of stratigraphic cross sections A-A' and B-B', along with interpreted subsurface fault trends in the study area. Fault positions were obtained from a structure contour map of the top of basement, southern Texas Panhandle (Fig. 22). Tables 7 and 8 list formation top elevations in feet above/below a datum (mean sea level) and well locations (northings and eastings) for cross sections A-A' and B-B'. Table 10 lists thickness values for units of primary interest to this study at specific well locations in the cross sections. Leonardian Red Cave units averaged 347 ft in thickness, with Leonardian Panhandle Lime (Wichita Formation) units averaging 386 ft in thickness. Wolfcampian units averaged 521 ft in thickness, and the Permo/Pennsylvanian Granite Wash averaged 544 ft in thickness. Assuming that Wolfcampian and Granite Wash units are in vertical communication (Pippin, 1970), a total average Lower Permian reservoir thickness of approximately 1000 ft exists within the study area. The Wichita Formation's mean thickness of approximately 386 ft provides an adequate confining layer over Wolfcampian reservoir units. A minimum confining layer thickness of only 20 ft is sufficient for some deep disposal wells (Warner, 1968). Well surface elevations averaged 3308 ft above mean sea level in the study area.

Cross section B-B' (shown with vertical exaggeration) traverses southwest-northeast and crosses the axis of the Amarillo Uplift in a direction normal to the primary trend of the axis. Cross section B-B' crosses at least five mapped subsurface faults (Fig.

21). Wells at both the southwest and northeast ends of the cross section are located off the uplift's axis and were drilled deeper than other wells used in the cross section (Fig. 23). Well 1B does not include the Red Cave in its column due to limited wireline log data. Well 1B, located off the southwest flank of the uplift, penetrates a thick section of Pennsylvanian rocks directly underlying the Wolfcampian section. The well penetrates approximately 2,000 ft of older Pennsylvanian Granite Wash without encountering granite basement. Wells 2B and 3B were drilled on the local structural high of the Bush Dome (Fig. 22), and both penetrate fairly thick sections of the Red Cave and Wichita, while the Wolfcampian section is much thinner here than in well 1B. Both wells 2B and 3B produce helium. Wells 4B and 5B were drilled in a small graben (Fig. 21). Well 4B penetrates a thick Wolfcampian section (1326 ft), approximately 1,200 ft of Pennsylvanian section including 200 ft of older Pennsylvanian granite wash, and approximately 160 ft of granite basement. The Wolfcampian and Red Cave sections thin dramatically in well 5B (deepest penetration), though the Wichita thickens between wells 4B and 5B. Red Cave, Wichita, and Wolfcampian units all thin to the northeast between wells 5B and 6B, and appear to truncate against uplifted granite basement (Fig. 23) along the flank of the Potter County Fault (Fig. 21). Wells 6B, 7B, 8B, and 9B all sit atop a local structural high known as the John Ray Dome (Fig. 22). Red Cave, Wichita, and Wolfcampian units are locally thin on the structural high, but thicken to the northeast. Well 6B penetrates approximately 800 ft of fractured granite basement and produces gas from the granite (the only granite production identified in the study). Well 7B penetrates a thick section (1325 ft) of Permo/Pennsylvanian granite wash that directly underlies a relatively thin Wolfcampian section (Fig. 23). The Granite Wash thins progressively to

Table 10. Unit Thickness (ft) at Specific Well Location in Cross Section

Well ID	Red Cave	Panhandle	Wolfcampian	Granite Wash
1A	500	250	600	100
2A	761	269	233	
3A	766	248	515	
4A	419	313	954	1610
5A	390	294	596	690
6A	320	324	400	380
7A	390	265	310	512
8A	350	430	980	
9A	248	420	532	165
10A	213	608	302	637
11A	219	416	290	766
12A	235	385	369	50
13A		412	386	232
1B		485	760	2,036
2B	424	338	245	
3B	478	426	198	
4B	537	420	1326	161
5B	294	522	219	
6B	222	136	95	76
7B	200	140	150	1,325
8B	245	289	230	572
9B	248	130	480	430
10B	247	415	492	75
11B	170	435	667	399
12B	255	383	974	
13B	255	484	371	128
14B	274	502	429	
15B	350	550	339	
16B	347	575	319	
17B	360	720	1862	
Mean Thickness (ft):	347.0357	386.1333	520.7667	544.4211



A
1A
2A
3A
4A
5A
6A
7A
8A
9A
10A
11A
12A
A'
13A
B
1B
2B
3B
4B
5B
6B
7B
8B
9B
10B
11B
12B
13B
14B
15B
16B
17B
B'
MOORE
POTTER
HUTCHINSON
CARSON
Cross Sections A-A', B-B'
Panhandle West Field
N
0
40,000
Gas Well
Oil Well
Dry Hole
Fault

Figure 21.

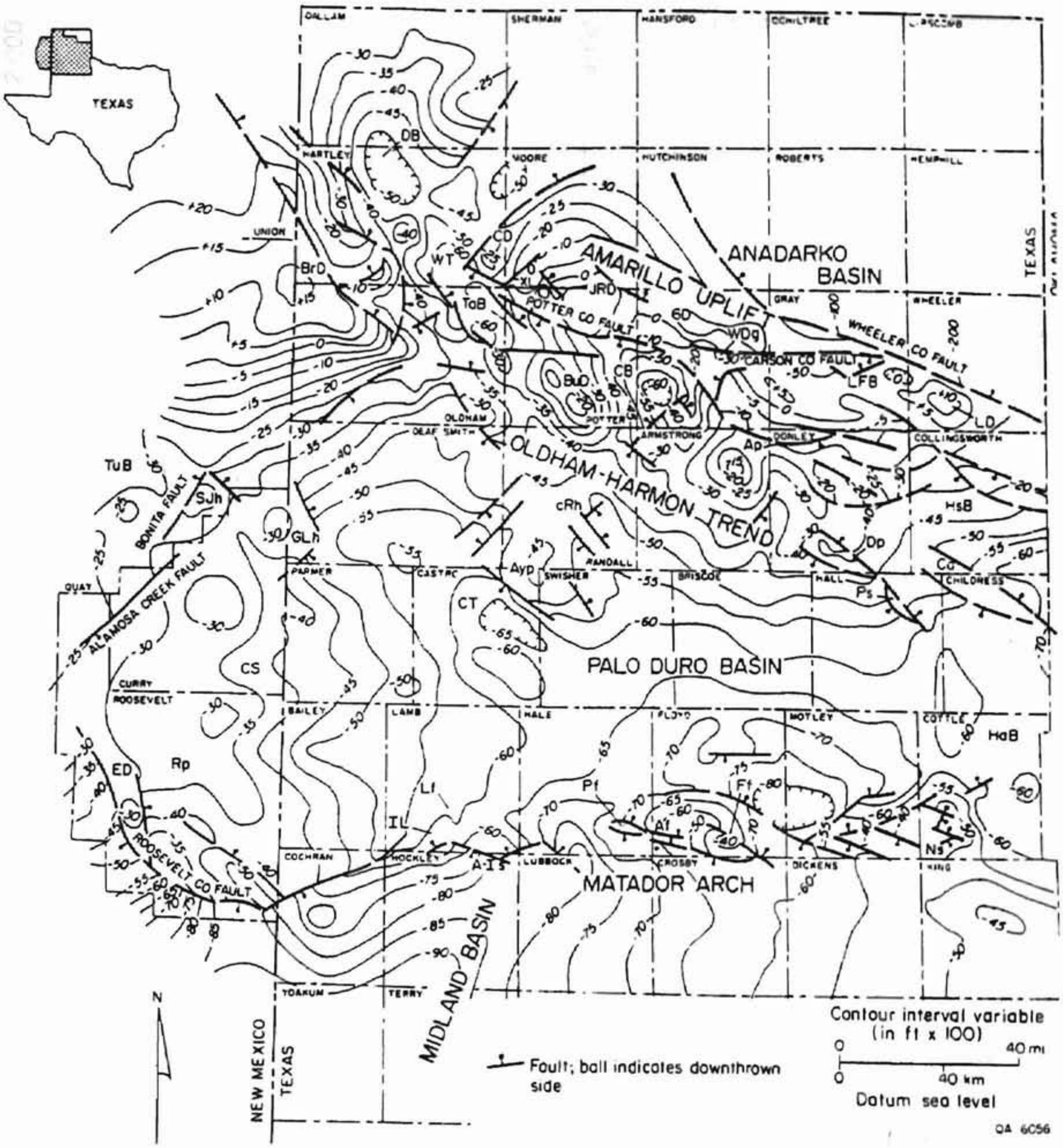


Figure 22. Structure map of top of granite basement in study area (Collins, 1990).

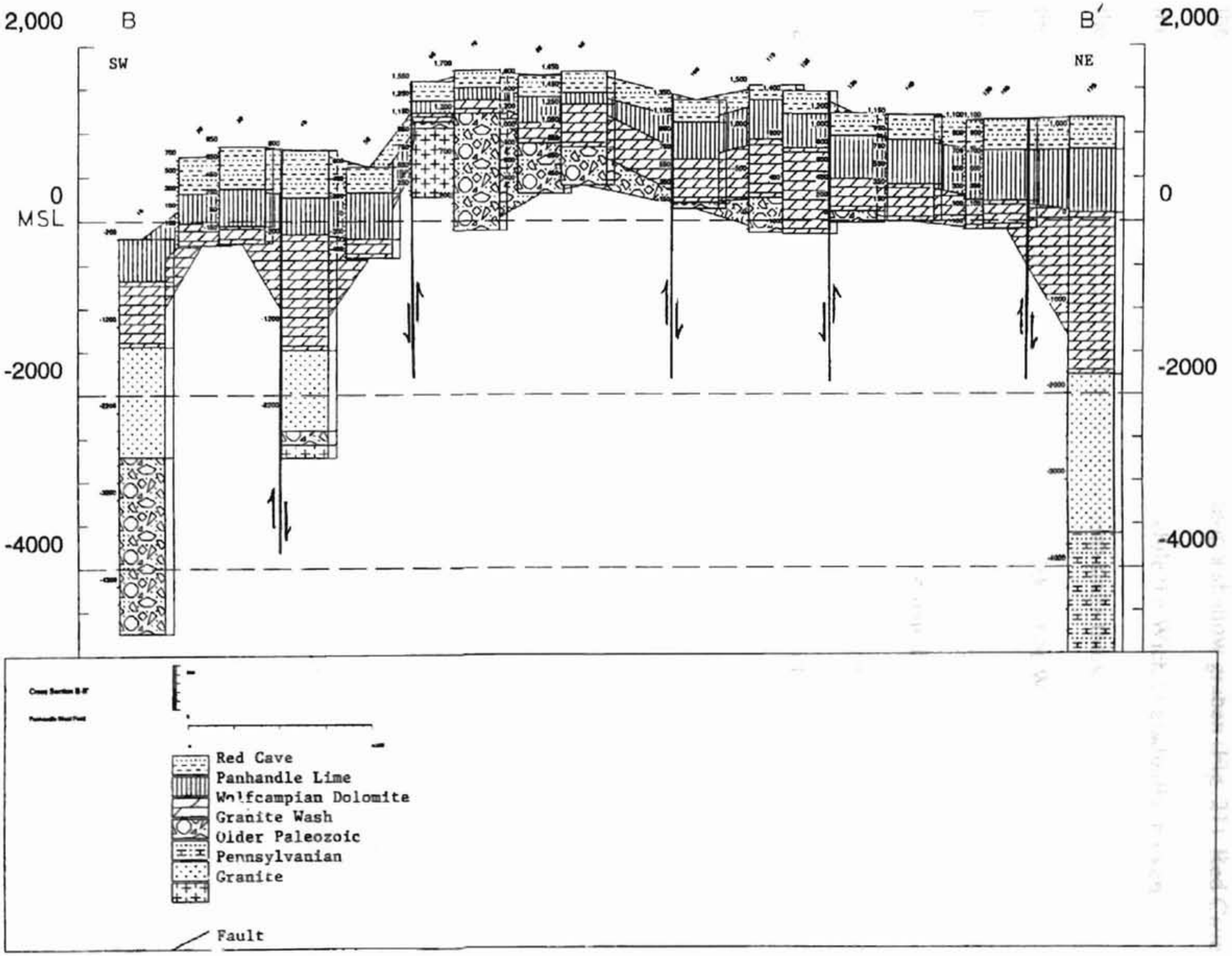


Figure 23. Cross section B-B'.

the northeast. Wells 10B. 11B, and 12B all sit atop a shallow graben (Fig. 21). Red Cave units remain fairly thin (approximately 300 ft), while the Wichita gradually thickens to the northeast to approximately 500 ft. Wolfcampian units thicken to the northeast across the graben, and well 12B penetrates approximately 1000 ft of Wolfcamp. A wedge of Permo/Pennsylvanian granite wash thickens to the northeast, but is not penetrated by well 12B. Red Cave, Wichita, and Wolfcampian units all remain fairly constant in thickness across wells 13B, 14B, 15B, and 16B. Only well 13B penetrates a thin (128 ft) section of granite wash. Well 17B sits off the northeast flank of the uplift's axis and penetrates a thick (1862 ft) section of Wolfcampian which overlies approximately 2000 ft of Pennsylvanian rock. The Pennsylvanian section directly overlies a thick section (1500 ft) of Mississippian and Devonian sedimentary units. Well 17B does not penetrate either granite wash or granite (Fig. 23).

Cross section A-A' (with vertical exaggerations) roughly parallels the Amarillo Uplift's primary axis (Fig. 21). Well 1A sits atop a graben and penetrates a relatively thick section of Red Cave (500 ft). The well penetrates a moderately thick (250 ft) section of the Wichita Formation and approximately 500 ft of Wolfcampian before encountering approximately 100 ft of Permo/Pennsylvanian granite wash (Fig. 24). Red Cave units thicken markedly to the southeast, as seen in wells 2A and 3A. The Wichita maintains a fairly constant thickness, while the Wolfcampian varies from approximately 250 to 500 ft in thickness. Well 4A, the deepest in the cross section, penetrates a thick section of Granite Wash (1610) ft that directly overlies Mississippian and Ordovician (Simpson and Ellenburger) units (Fig. 24). Pennsylvanian sedimentary units may have been eroded off the older Paleozoic units before younger Permo/Pennsylvanian Granite Wash was

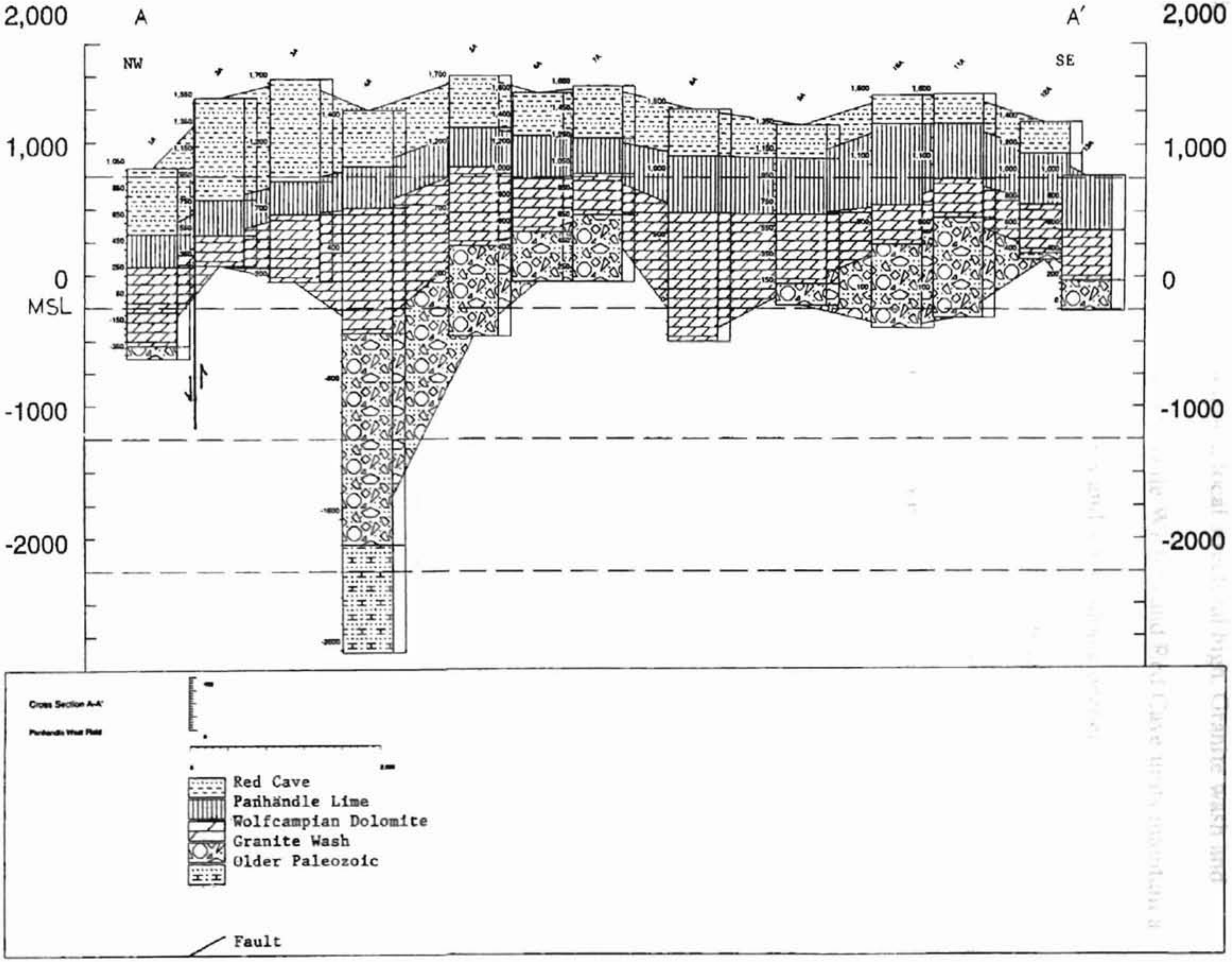


Figure 24. Cross Section A-A'

deposited. Wells 5A, 6A, and 7A sit atop a local structural high. Granite wash and Wolfcampian units thin to the southeast, while Wichita and Red Cave units maintain a fairly constant thickness (Fig. 24). Wells 8A and 9A sit atop a deeper portion of the graben (Fig. 21). Red Cave units thin gradually to the southeast, while Wichita units thicken to approximately 400 ft. Well 8A penetrates a thick section of Wolfcampian (980 ft) without encountering granite wash. Wolfcampian units thin toward well 9A, which penetrates approximately 165 ft of granite wash. Red Cave units maintain a fairly constant thickness in wells 10A and 11A, which sit atop a local structural high (Fig. 24). Wichita units thicken to approximately 600 ft, and approximately 700 ft of granite wash is encountered in wells 10A and 11A. Red Cave, Wichita, and Wolfcampian units maintain fairly constant thicknesses progressing to the southeast from well 11A to well 12A, although only 50 ft of granite wash is penetrated at well 12A. Well 13A does not include a Red Cave section due to limited data availability. Wichita and Wolfcampian units maintain a fairly constant thickness progressing to the southeast from well 12A to well 13A. Well 13A penetrates approximately 230 ft of granite wash.

Pressure-Depth Data Interpretation

Tables 11 and 12 represent pressure-depth relationship data for Red Cave unit wells included in this study. Initial and recent BHP values for fifteen producing gas wells were compared, and the data plotted on two separate P-D graphs (Figures 25 and 26). Production depth for the fifteen wells averaged 1968 ft below surface (mean surface elevation of 3308 ft for study area). Recent BHP values averaged 101 psi, while initial BHP values averaged 380 psi. Both initial and recent BHP values lie well within (to the left of) the normal hydrostatic gradient of 0.465 psi/ft for this region, suggesting

Table 11. Production Depth and Most Recent BHP Values for Gas Wells Used in Study: Red Cave Unit

Well #	Prod. Unit	Year	BHP (psi)	Prod. Depth (ft)
5B	Red Cave	1996	375	2929
7B	Red Cave	1987	50	1629
2P	Red Cave	1992	153	2300
5P	Red Cave	1999	163	2272
6P	Red Cave	1999	140	2282
7P	Red Cave	2000	124	2110
10P	Red Cave	1996	65	1891
12P	Red Cave	1997	22	1748
13P	Red Cave	1997	55	1885
23P	Red Cave	1993	31	1699
32P	Red Cave	1998	27	1574
33P	Red Cave	1999	96	1787
34P	Red Cave	1989	54	1829
35P	Red Cave	1998	122	2000
36P	Red Cave	1992	42	1580
		Mean:	101.2667 N=15	1967.667 N=15

Table 12. Production Depth and Initial BHP Values for Gas Wells Used in Study: Red Cave Unit

Well #	Prod. Unit	Year	BHP (psi)	Prod. Depth (ft)
5B	Red Cave	1972	589	2929
7B	Red Cave	1960	384	1629
2P	Red Cave	1989	399	2300
5P	Red Cave	1996	547	2272
6P	Red Cave	1997	494	2282
7P	Red Cave	1999	383	2110
10P	Red Cave	1963	428	1891
12P	Red Cave	1960	373	1748
13P	Red Cave	1961	402	1885
23P	Red Cave	1962	315	1699
32P	Red Cave	1960	396	1574
33P	Red Cave	1962	304	1787
34P	Red Cave	1968	234	1829
35P	Red Cave	1996	342	2000
36P	Red Cave	1987	118	1580
		Mean:	380.5333 N=15	1967.667 N=15

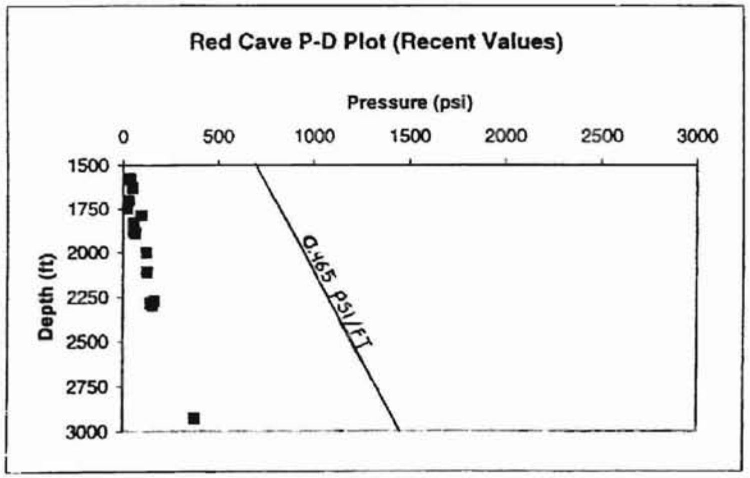


Figure 25.

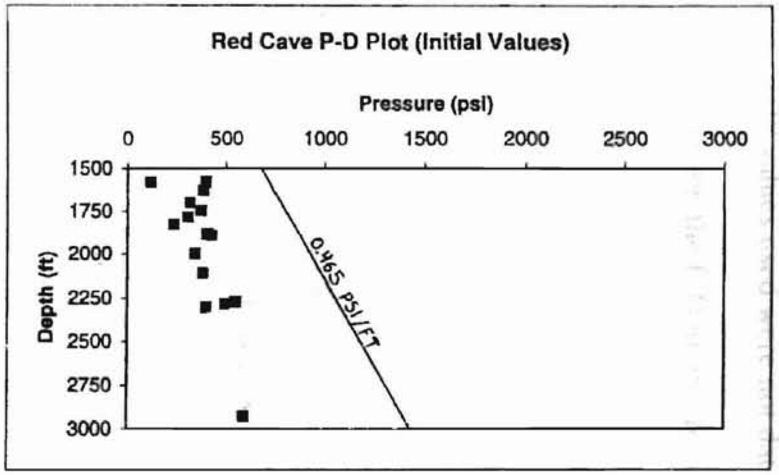


Figure 26.

underpressured reservoir conditions. Initial and recent BHP values used were not date selective, resulting in some scatter amongst the values plotted on the P-D graph. Initial (maximum) pressure conditions associated with early production dates may still be observed as individual points on the plot (Table 9 lists the dates of recent BHP values for both the Wolfcampian and Red Cave).

Tables 13 and 14 represent pressure-depth relationship data for Wolfcampian/Granite Wash unit wells included in this study. As with the Red Cave data, initial and recent BHP values for producing gas wells were compared and the data plotted on two separate P-D graphs (Figures 27 and 28). Production depth for the Wolfcampian/GW wells averaged 2965 ft below surface (mean surface elevation of 3308 ft). Recent BHP values averaged 24 psi, while initial BHP values averaged 160 psi. Both initial and recent BHP values lie well within (to the left of) the normal hydrostatic gradient of 0.465 psi/ft, also suggesting underpressured reservoir conditions.

Figure 29 illustrates a hypothetical system containing abnormally low, high, and normal (hydrostatic) plotted formation pressure measurements. Dahlberg (1995) defines abnormal formation pressure as an accurately measured formation pressure value that differs significantly from the pertinent hydrostatic pressure for a fluid column from the surface down to the depth of measurement. Factors such as rapid burial and addition of overburden, pore space reduction by crystalline overgrowths, heating of reservoir rock, or infusion of gases into rocks with limited pore space may lead to abnormally high formation pressures. Underpressured reservoirs may be produced by such factors as osmosis of fresher waters in a reservoir out of the reservoir and into a more saline unit through a semipermeable membrane (shale), overburden weight being

Table 13. Production Depth and Most Recent BHP Values for Gas Wells Used in Study: Wolfcamp Unit

Well #	Prod. Unit	BHP (psi)	Prod. Depth (ft)	Year
2A	Wolfcampian	22	3322	1989
3A	Wolfcampian	23	3140	2000
4A	Wolfcampian	25	3031	2000
6A	Wolfcampian/GW	26	2957	1998
7A	Wolfcampian	38	2844	2000
8A	Wolfcampian	35	3040	2000
12A	Wolfcampian/GW	1	2921	2000
6B	Granite	1	2545	2000
8B	Wolfcampian	30	2670	1996
9B	Wolfcampian	17	2610	2000
14B	Wolfcampian	1	2885	2000
15B	Wolfcampian	239	3135	1987
16B	Wolfcampian	1	3238	2000
1P	Wolfcampian	2	2900	2000
3P	Wolfcampian/GW	1	2900	2000
4P	Wolfcampian	1	3265	2000
8P	Wolfcampian	14	3140	1997
9P	Wolfcampian	23	2850	2000
11P	Wolfcampian	1	2867	2000
14P	Wolfcampian	15	2475	1999
15P	Wolfcampian	2	2700	2000
16P	Wolfcampian	29	2740	1997
17P	Wolfcampian/GW	1	3020	2000
18P	Wolfcampian	1	3022	2000
19P	Wolfcampian	1	3120	2000
20P	Wolfcampian	44	2690	1989
21P	Wolfcampian	16	3110	2000
22P	Wolfcampian	12	2714	2000
24P	Wolfcampian	22	3463	1999
25P	Wolfcampian	16	3065	1994
26P	Wolfcampian	14	2800	2000
27P	Panhan./Wolfcamp	18	2770	1989
28P	Wolfcampian	16	3309	2000
29P	Wolfcampian	15	2828	2000
30P	Wolfcampian	155	3086	1989
31P	Wolfcampian	1	2868	2000
37P	Wolfcampian	11	2585	1999
38P	Wolfcampian/GW	12	2833	2000
39P	Wolfcampian	18	3387	2000
40P	Wolfcampian	127	3560	1998
41P	Wolfcampian	1	2660	2000
42P	GW	25	2908	2000
43P	Wolfcampian	13	2885	2000
44P	Wolfcampian	28	3100	1999
45P	Wolfcampian	21	3334	2000
46P	Wolfcampian/GW	34	3025	2000
47P	Wolfcampian	23	3097	2000
48P	Wolfcampian	1	3070	2000
49P	Wolfcampian	24	3090	2000
50P	Wolfcampian	1	2686	2000
	Mean:	24.32 N=50	2965.2 N=50	

Table 14. Production Depth and Initial BHP Values for Gas Wells Used in Study: Wolfcamp Unit

Well #	Prod. Unit	BHP (psi)	Prod. Depth (ft)	Year
2A	Wolfcampian	140	3322	1965
3A	Wolfcampian	41	3140	1993
4A	Wolfcampian	242	3031	1961
6A	Wolfcampian/GW		2957	
7A	Wolfcampian		2844	
8A	Wolfcampian		3040	
12A	Wolfcampian/GW	240	2921	1956
6B	Granite	129	2545	1973
8B	Wolfcampian		2670	
9B	Wolfcampian	18	2610	1998
14B	Wolfcampian	462	2885	1930
15B	Wolfcampian	316	3135	1984
16B	Wolfcampian	373	3238	1983
1P	Wolfcampian		2900	
3P	Wolfcampian/GW	36	2900	1980
4P	Wolfcampian	16	3265	1997
8P	Wolfcampian	17	3140	1990
9P	Wolfcampian	46	2850	1980
11P	Wolfcampian	15	2867	1994
14P	Wolfcampian	387	2475	1926
15P	Wolfcampian		2700	
16P	Wolfcampian	467	2740	1926
17P	Wolfcampian/GW	70	3020	1971
18P	Wolfcampian	35	3022	1996
19P	Wolfcampian	94	3120	1983
20P	Wolfcampian	466	2690	1930
21P	Wolfcampian	79	3110	1977
22P	Wolfcampian	23	2714	1995
24P	Wolfcampian	84	3463	1976
25P	Wolfcampian	16	3065	1994
26P	Wolfcampian		2800	
27P	Panhan./Wolfcamp	17	2770	1989
28P	Wolfcampian	374	3309	1947
29P	Wolfcampian	471	2828	1929
30P	Wolfcampian	194	3086	1970
31P	Wolfcampian	148	2868	1971
37P	Wolfcampian	149	2585	1971
38P	Wolfcampian/GW	99	2833	1976
39P	Wolfcampian	47	3387	1994
40P	Wolfcampian	781	3560	1998
41P	Wolfcampian	82	2660	1962
42P	GW	84	2908	1993
43P	Wolfcampian	18	2885	1998
44P	Wolfcampian	28	3100	1999
45P	Wolfcampian	37	3334	1996
46P	Wolfcampian/GW	290	3025	1959
47P	Wolfcampian	46	3097	1998
48P	Wolfcampian	138	3070	1966
49P	Wolfcampian	40	3090	1989
50P	Wolfcampian	48	2686	1989
	Mean:	160.5349 N=43	2965.2 N=50	

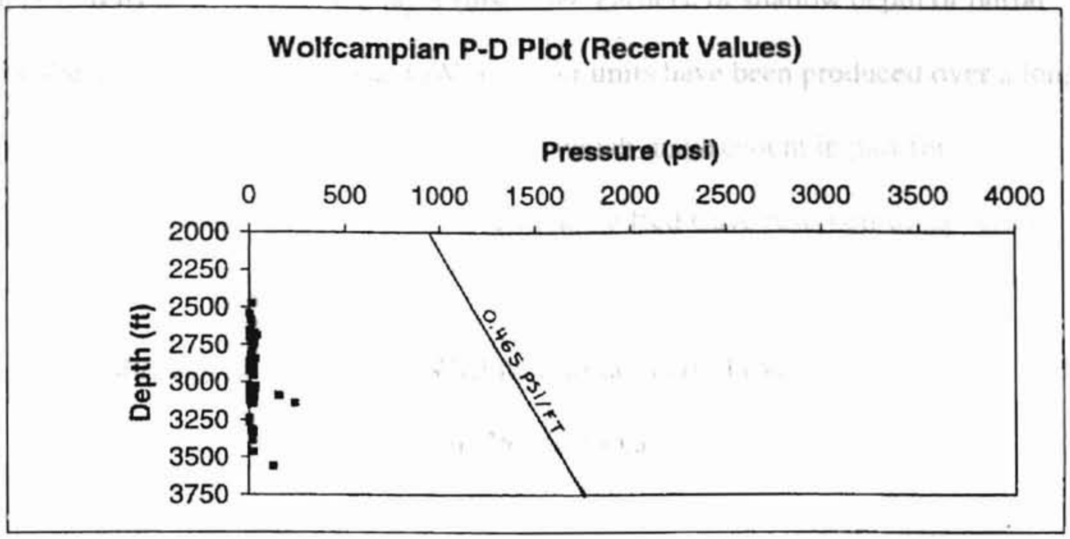


Figure 27. N=50, <BHP>=24.3 psi (Table 13).

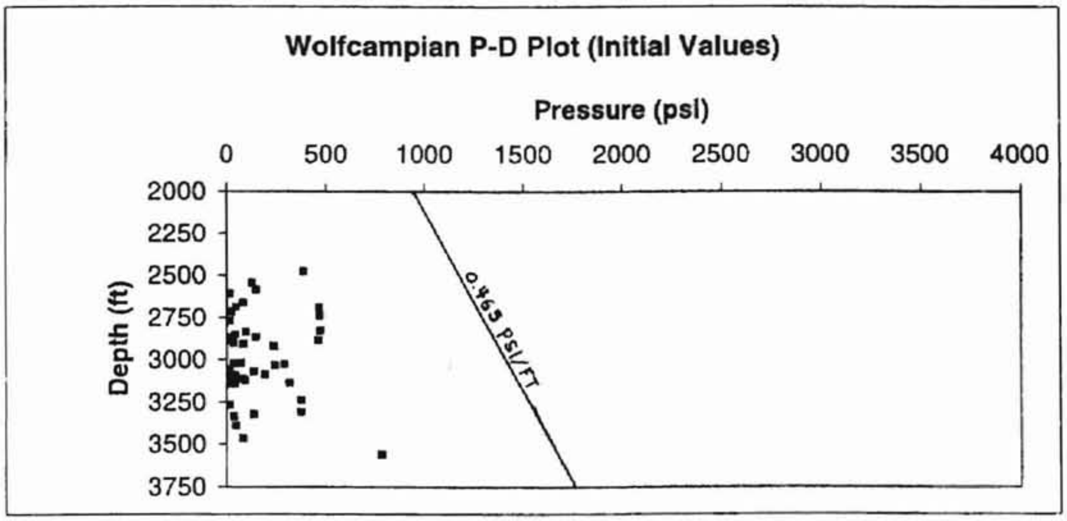


Figure 28. N=43, <BHP>=160.5 psi (Table 14).

supported by a rigid confining layer (discussed earlier), or shallow depth of burial (Dahlberg, 1995). Wolfcampian/GW reservoir units have been produced over a longer time interval than Red Cave reservoir units, which may account in part for their significantly lower pressures. These data indicate Red Cave reservoir units currently maintain higher pressures than Wolfcampian/GW reservoir units, implying that any fluid migration through fractures in the Wichita Formation or through faulty wells would be downward from the Red Cave into the Wolfcampian.

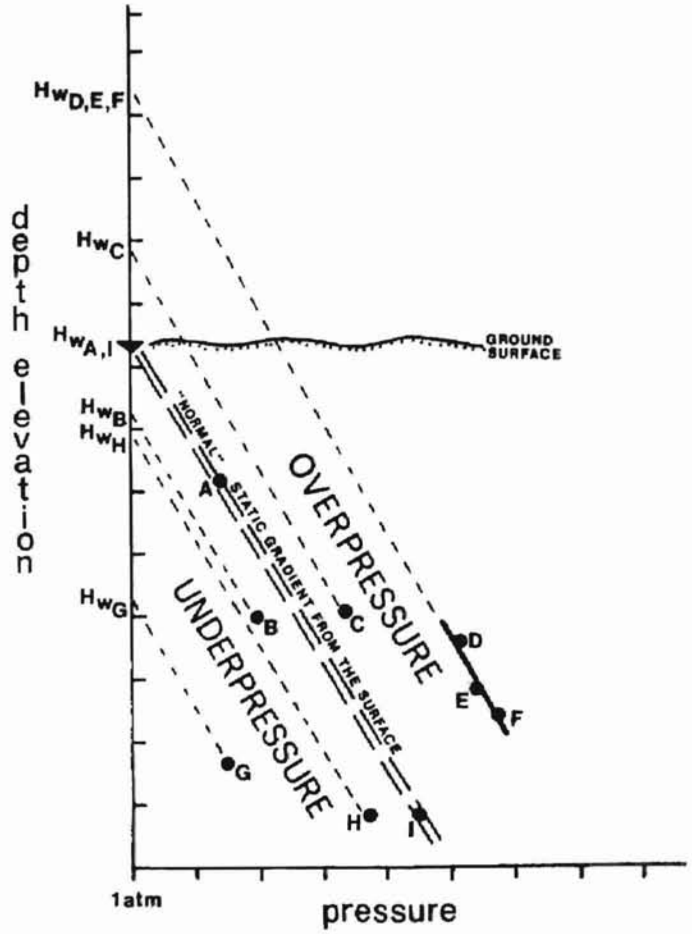


Figure 29. Pressure-depth gradient diagram illustrating locations of positions of plotted formation pressure measurements and corresponding hydraulic head values for abnormally low, high, and normally (hydrostatic) pressured systems (Dahlberg, 1995).

Potentiometric Surface Map Interpretation

Figures 30 and 31 show 2-D and 3-D potentiometric surface maps of the Red Cave generated with Rockworks 99™. Contours (2-D map) represent lines of equal hydraulic head elevation (above a datum). Inferred water flow paths are represented by arrows oriented normal to the contours. The Potter County Fault (trending NW-SE) is represented at the bottom of Figure 30. It extends to the underlying granite basement and is evident in the overlying Leonardian (Permian) Tubb interval (Fig. 32). Such a fault could serve as a possible migration route for fluids between reservoir units located at different stratigraphic levels. Theoretical flow paths are directed primarily to the northeastern and eastern part of the map area, away from pressure highs associated with wells 36P, 33P, and 23P. All computed hydraulic head elevations for the Red Cave are higher than Wolfcampian/GW hydraulic head elevations, suggesting any vertical communication between the reservoirs would result in downward flow from the Red Cave toward the Wolfcamp. Pressure data used for the Red Cave potentiometric surface map are not date selective. Red Cave reservoirs are not the primary focus of the study, and all Red Cave pressure data was presented in order to obtain a general idea of pressure conditions above the Wolfcampian and Wichita units.

Figures 33 and 34 show 2-D and 3-D potentiometric surface maps of the Wolfcampian/Granite Wash generated with Rockworks 99™. As with the Red Cave map, inferred water flow paths are represented by arrows oriented normal to the contours. The Potter County Fault (trending NW-SE) is represented at the bottom of Figure 33. Water flow appears to be directed toward a low pressure "sink" located at the northeast corner of the map. The areal extent of the Wolfcampian/GW pressure study area is

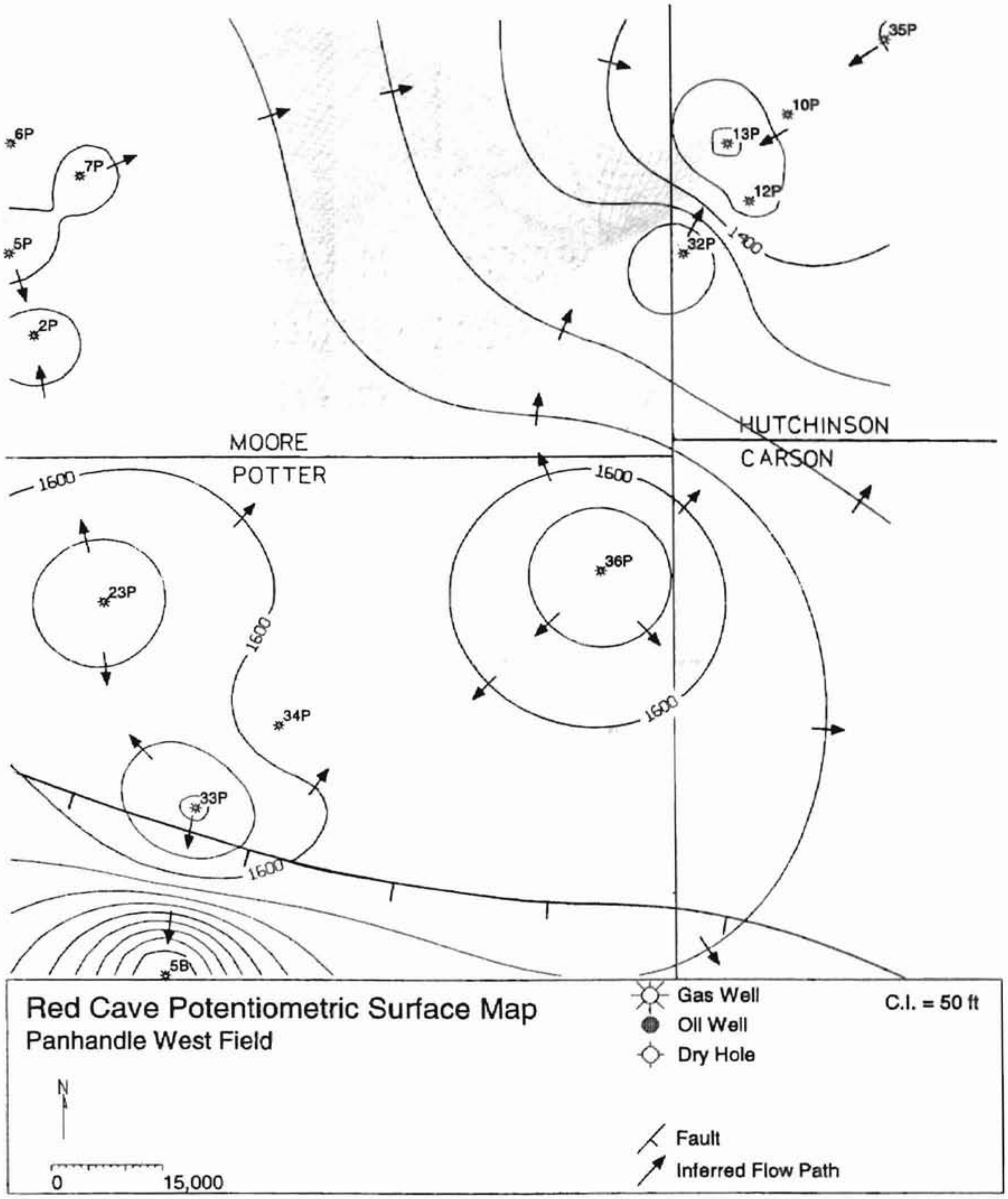

35P
10P
13P
12P
6P
7P
5P
2P
32P
1400
MOORE
POTTER
HUTCHINSON
CARSON
1600
1600
1600
1600
1600
23P
36P
34P
33P
5B
Red Cave Potentiometric Surface Map
Panhandle West Field
Gas Well
Oil Well
Dry Hole
C.I. = 50 ft
N
Fault
Inferred Flow Path
0
15,000

Figure 30.

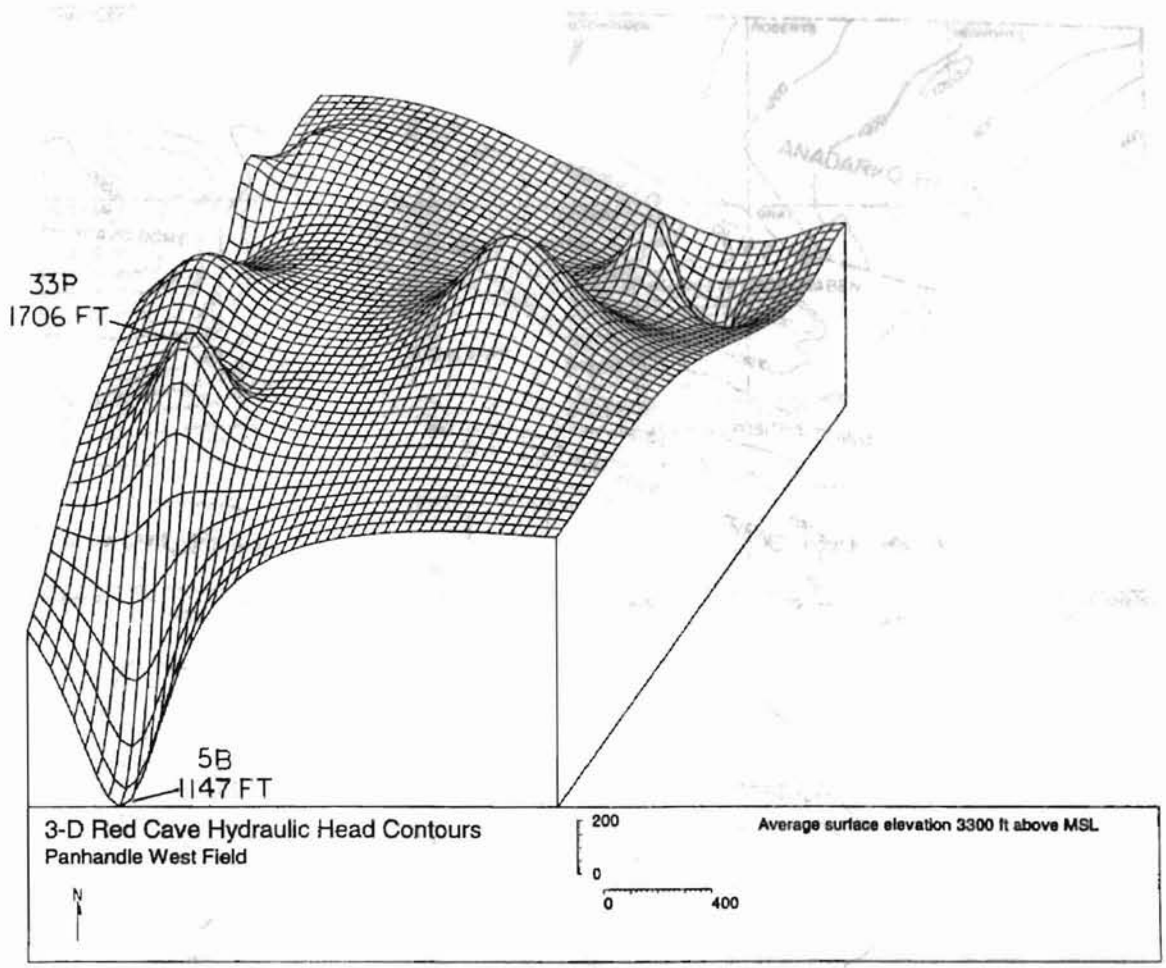

33P
1706 FT
5B
1147 FT
3-D Red Cave Hydraulic Head Contours
Panhandle West Field
N
200
0
0
400
Average surface elevation 3300 ft above MSL

Figure 31.

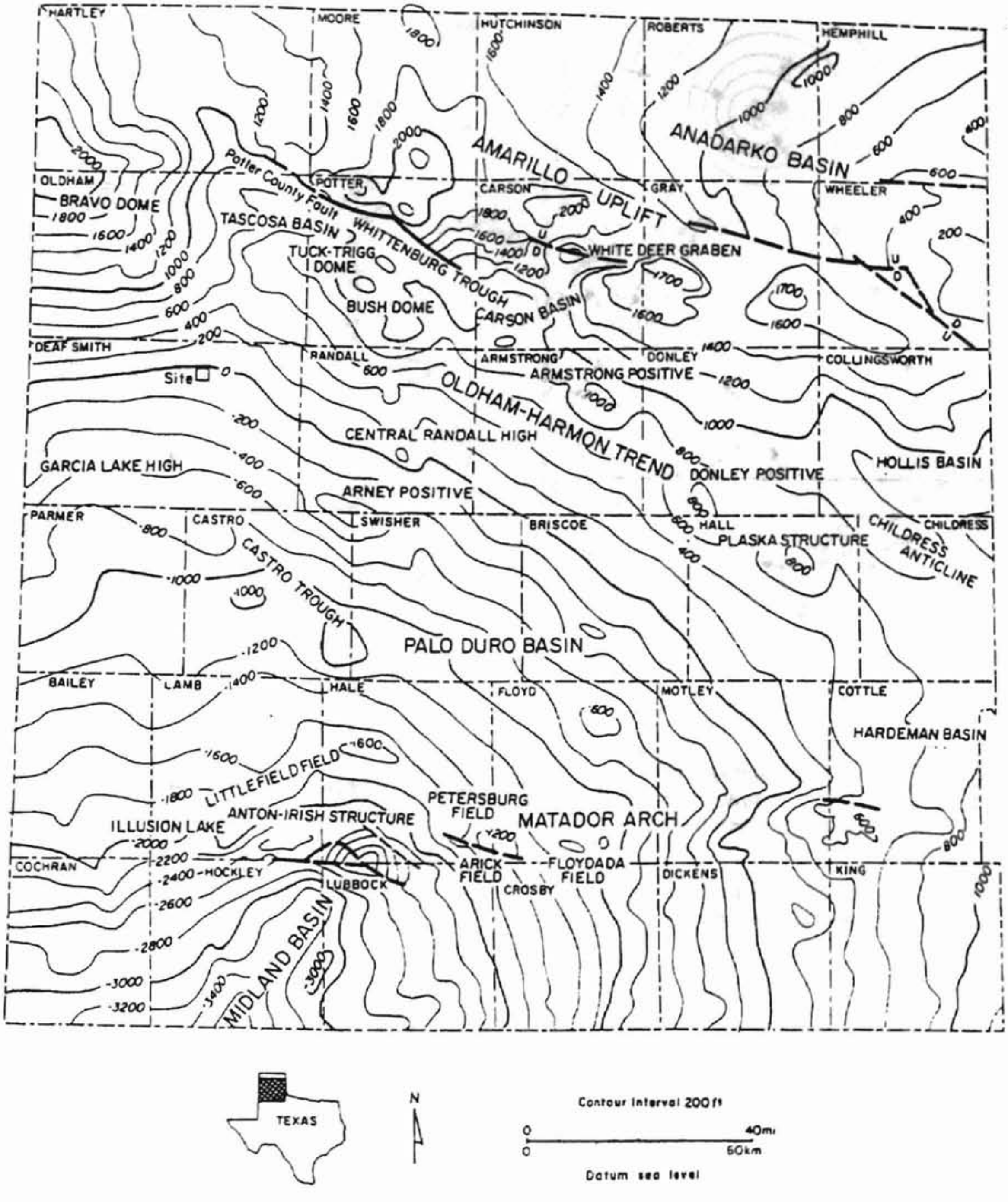


Figure 32. Structure contours on top of Tubb interval (Collins, 1990).

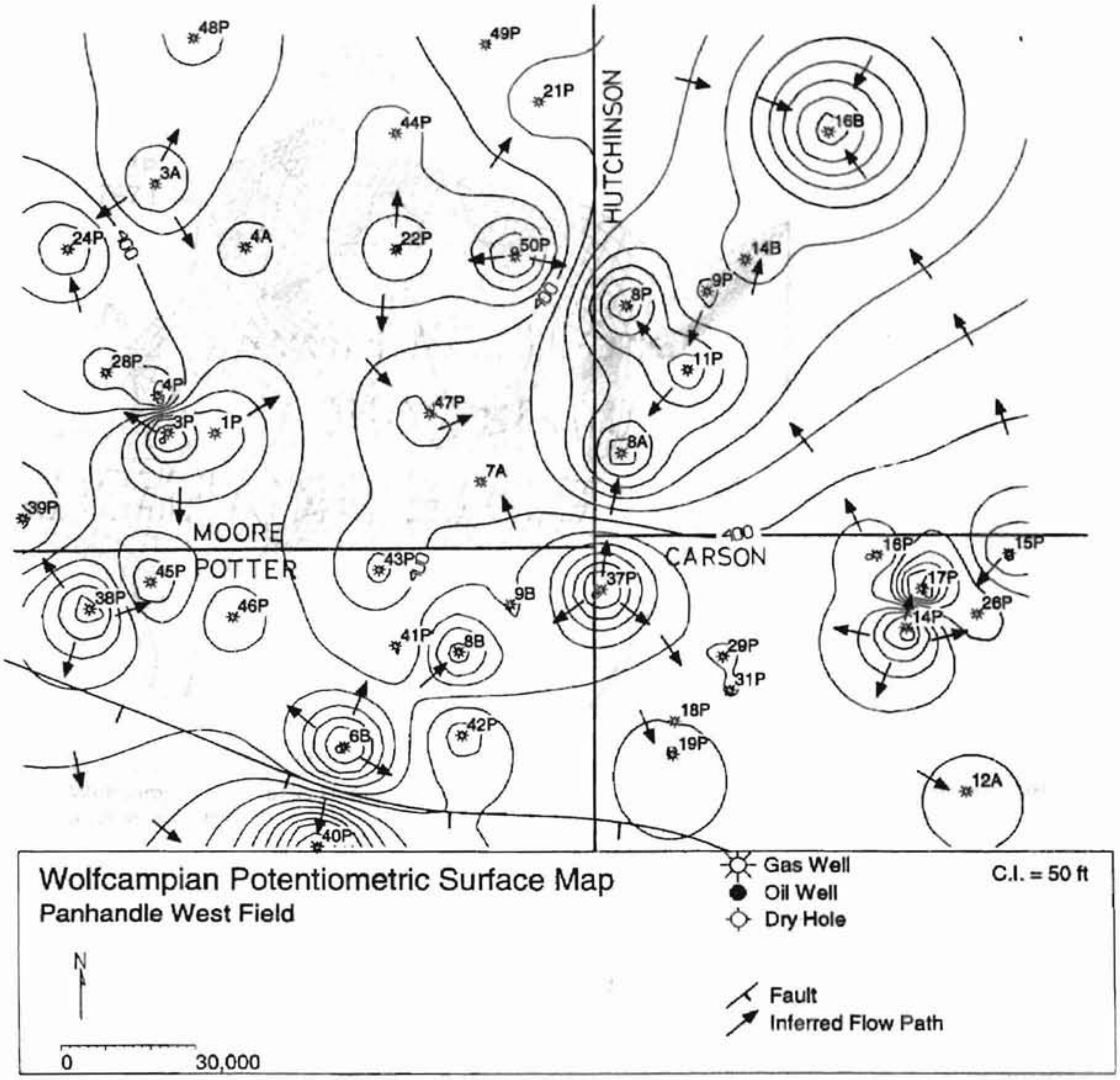

Wolfcampian Potentiometric Surface Map
Panhandle West Field
Gas Well
Oil Well
Dry Hole
C.I. = 50 ft
Fault
Inferred Flow Path
N
0
30,000
MOORE
POTTER
HUTCHINSON
CARSON
400
48P
49P
21P
44P
3A
24P
4A
22P
50P
16B
14B
9P
8P
11P
28P
4P
3P
1P
47P
8A
7A
39P
45P
38P
46P
43P
9B
37P
41P
8B
16P
17P
15P
14P
26P
29P
31P
18P
19P
6B
42P
12A
40P

Figure 33.

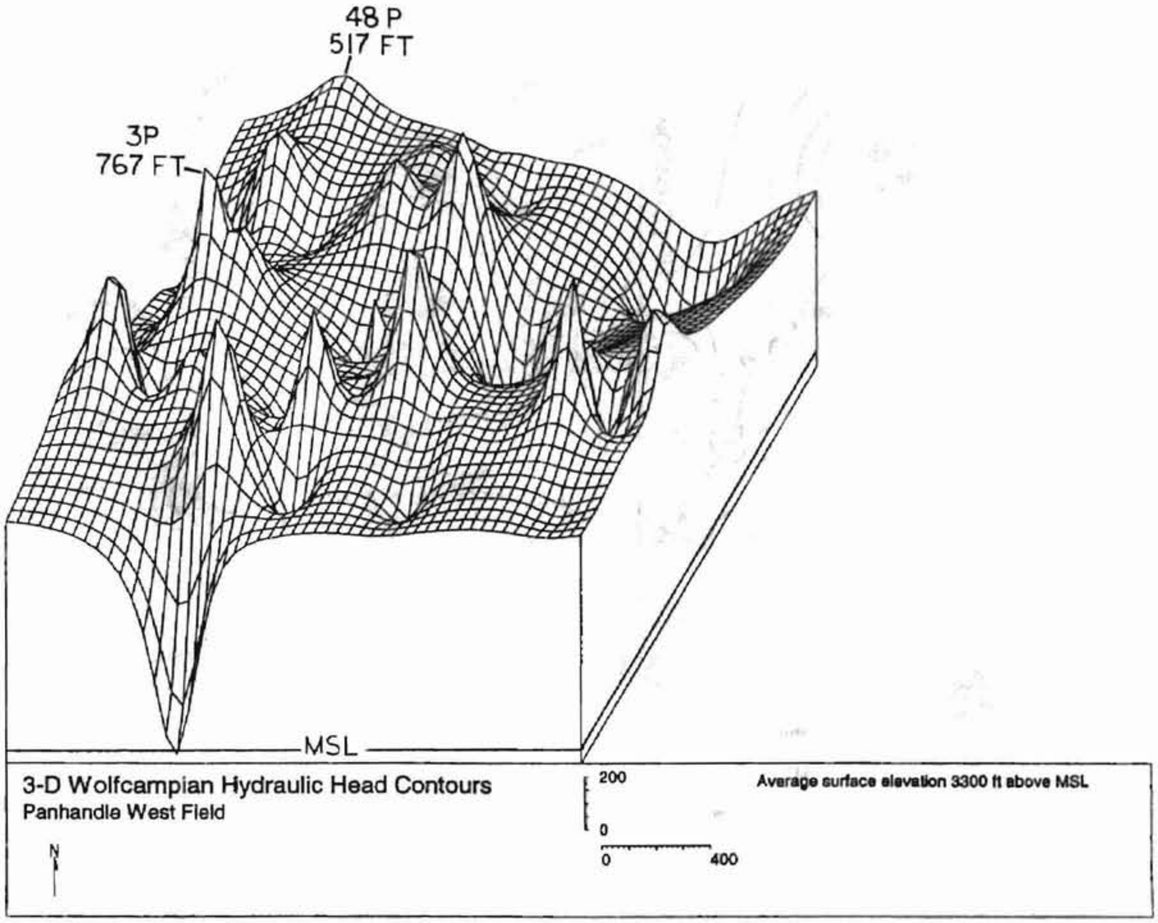

48 P
517 FT
3P
767 FT
MSL
3-D Wolfcampian Hydraulic Head Contours
Panhandle West Field
N
200
0
Average surface elevation 3300 ft above MSL
0
400

Figure 34.

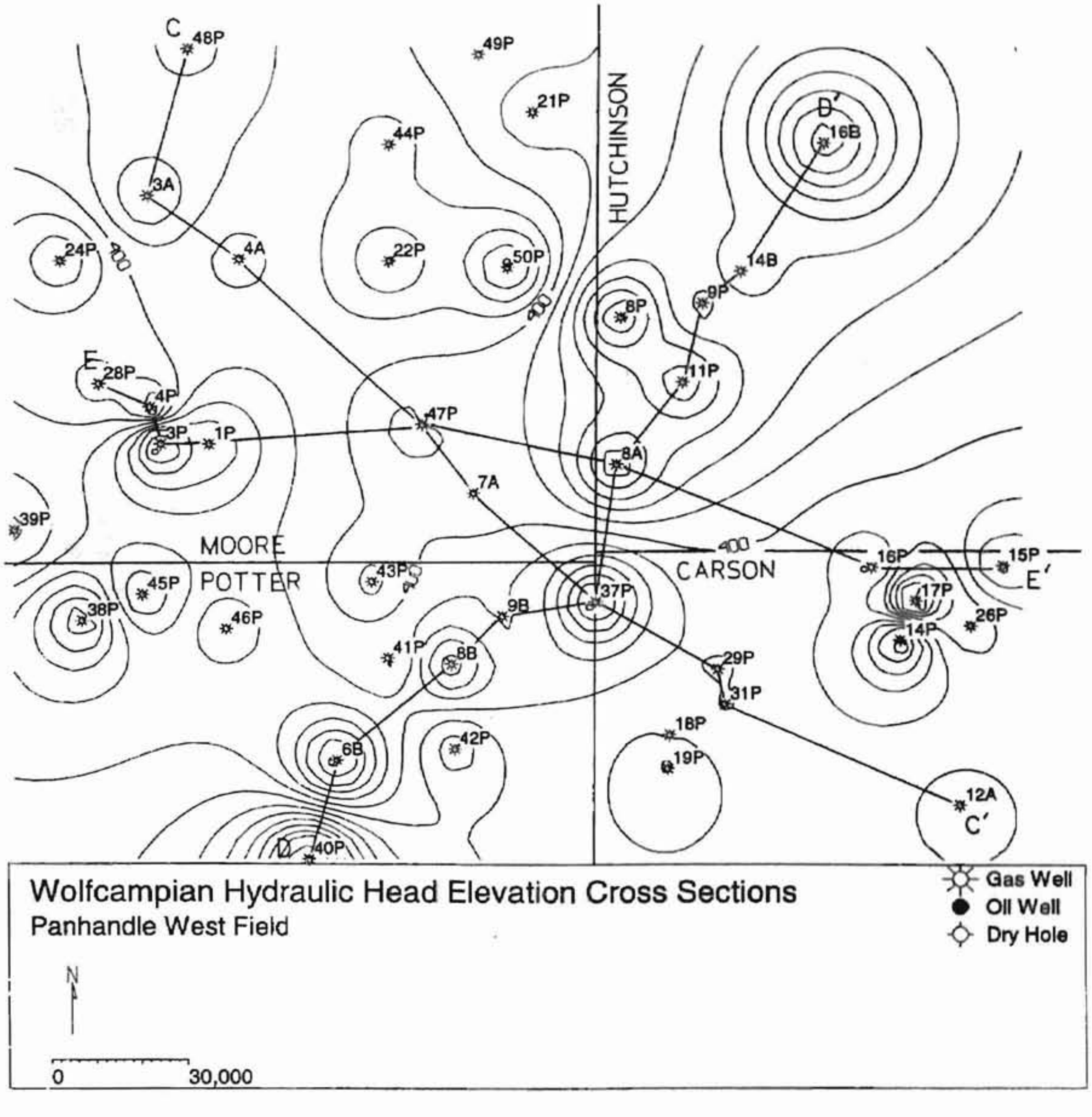

C
48P
49P
21P
HUTCHINSON
D'
16B
44P
3A
4A
22P
50P
24P
400
400
14B
9P
8P
E
28P
4P
11P
47P
3P
1P
8A
7A
39P
MOORE
POTTER
400
CARSON
16P
15P
E'
45P
43P
37P
17P
38P
46P
9B
26P
14P
41P
8B
29P
31P
18P
42P
19P
6B
12A
C'
D
40P
Wolfcampian Hydraulic Head Elevation Cross Sections
Panhandle West Field
Gas Well
Oil Well
Dry Hole
N
0
30,000

Figure 35.

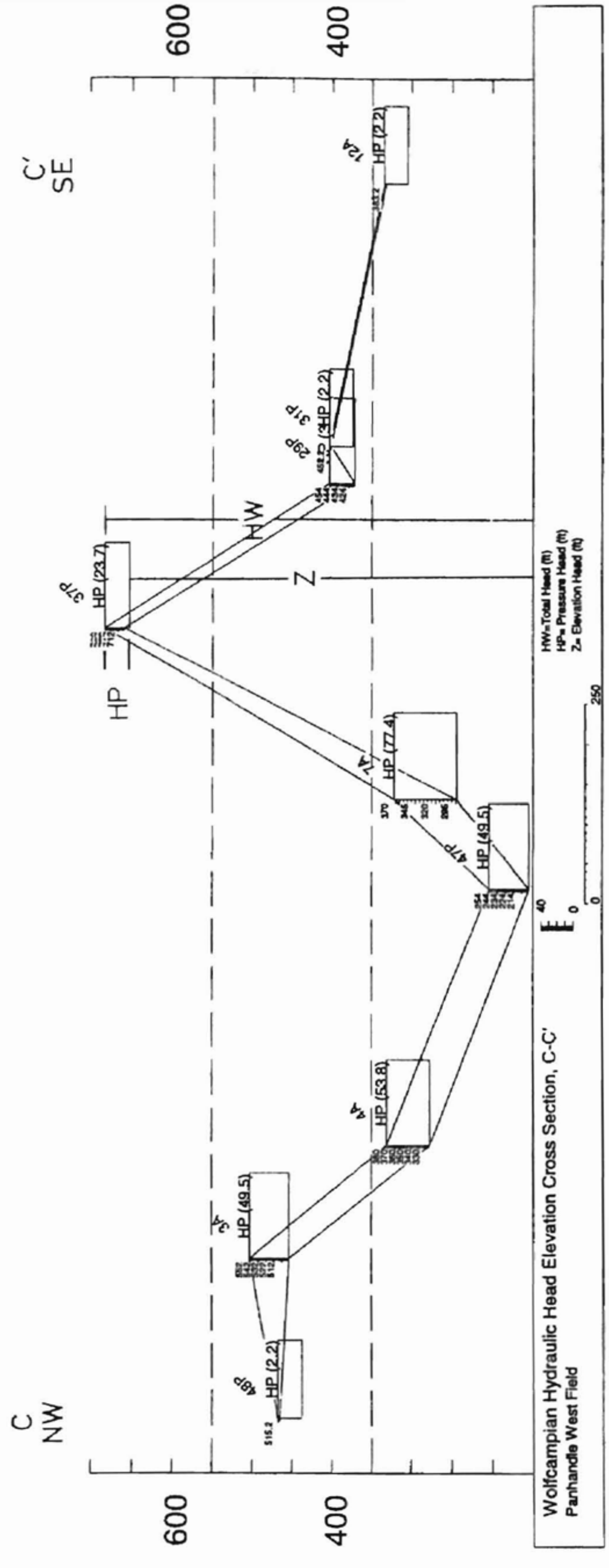

Wolfcampian Hydraulic Head Elevation Cross Section, C-C'
Panhandle West Field
C
NW
C'
SE
600
400
48P
HP (2.2)
515.2
3A
HP (49.5)
4A
HP (53.8)
47P
HP (49.5)
7A
HP (77.4)
370
345
320
295
37P
HP (23.7)
HP
Z
HW
29P
31P
HP (2.2)
12A
HP (2.2)
HW=Total Head (ft)
HP= Pressure Head (ft)
Z= Elevation Head (ft)
40
0
0
250

Figure 36.

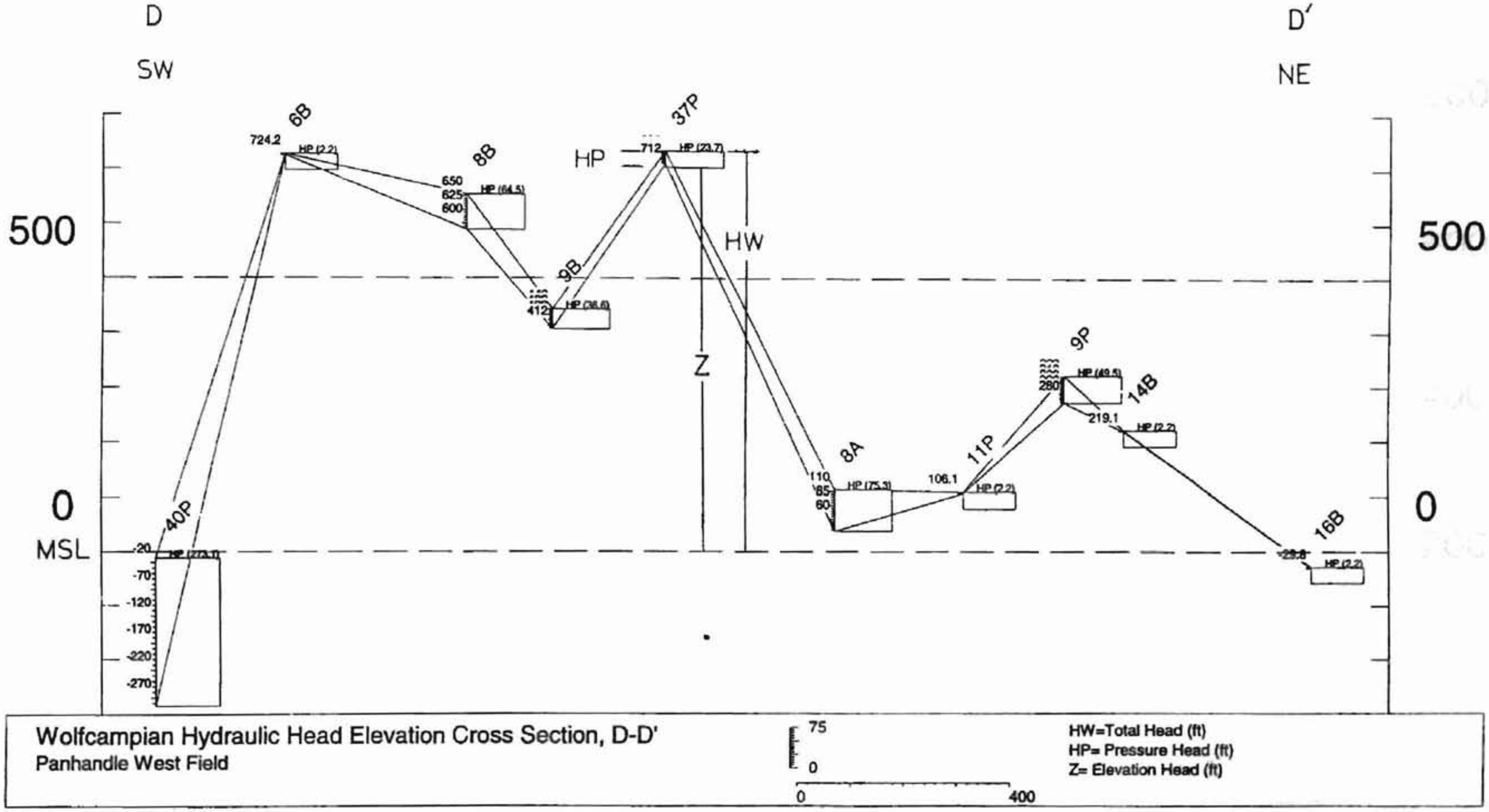
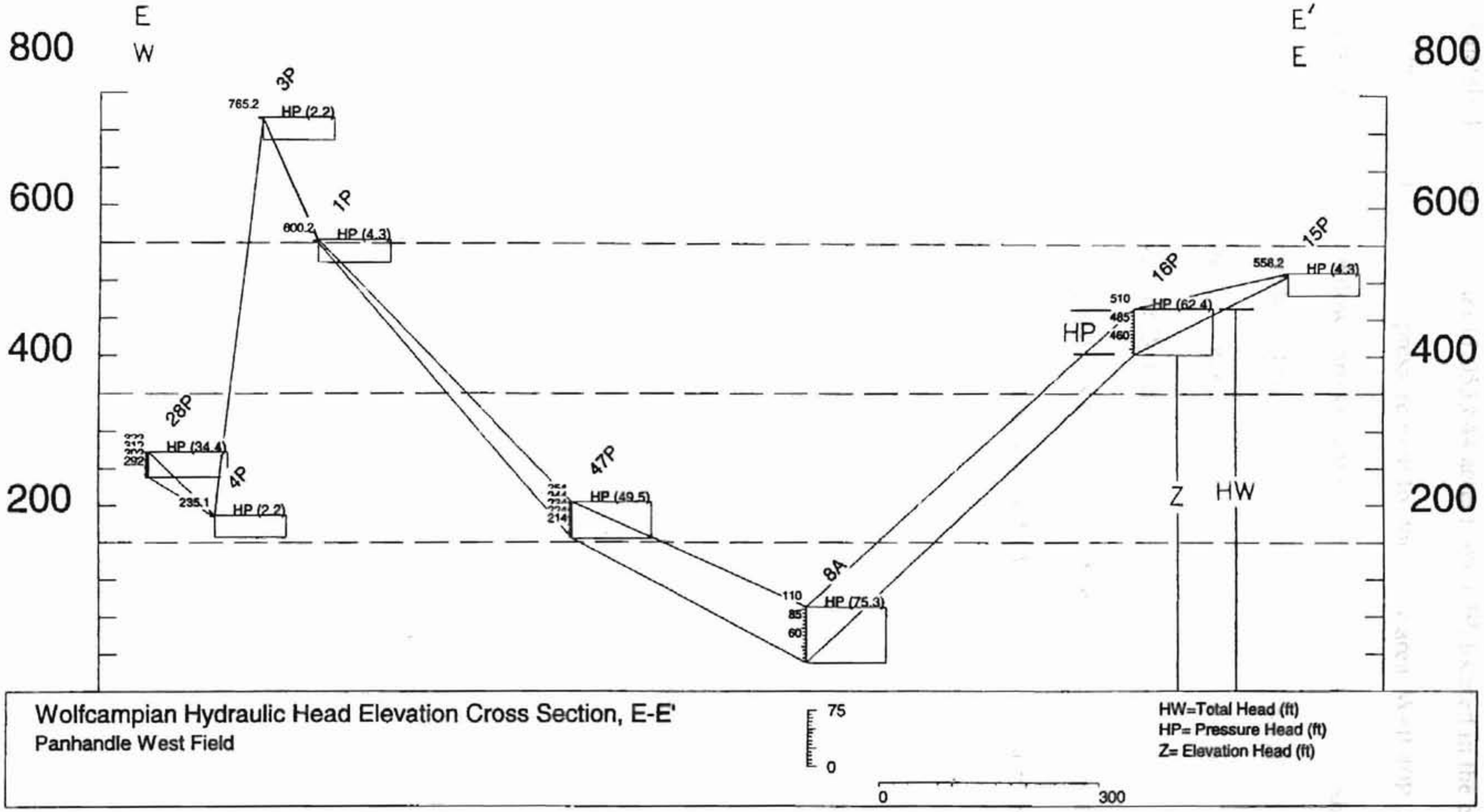

D
SW
D′
NE
500
0
MSL
500
0
6B
724.2
HP (2.2)
8B
650
625
600
HP (64.5)
9B
412
HP (36.6)
37P
HP
712
HP (23.7)
HW
Z
8A
110
85
60
HP (75.3)
106.1
11P
HP (2.2)
9P
280
HP (49.5)
14B
219.1
HP (2.2)
16B
-29.8
HP (2.2)
40P
-20
HP (273.1)
-70
-120
-170
-220
-270
Wolfcampian Hydraulic Head Elevation Cross Section, D-D'
Panhandle West Field
75
0
0
400
HW=Total Head (ft)
HP= Pressure Head (ft)
Z= Elevation Head (ft)

Figure 37.



Wolfcampian Hydraulic Head Elevation Cross Section, E-E'

Panhandle West Field

Figure 38.

approximately 1646 square miles (1,053,644 acres). Well 3P, located in the east-central region of the map, represents the pressure high for the study area. Well 40P, located at the bottom of the map on the downthrown side of the Potter County Fault, showed anomalously high initial WHSIP and BHP values (705 psi and 781 psi) for the Wolfcampian at a total depth of 3800 ft when first produced in February of 1997. Wells in the immediate vicinity were drilled into deeper Pennsylvanian and Mississippian units with higher reservoir pressures, and it is possible that Wolfcampian units in the area are in vertical communication with older Paleozoic units. Bottomhole pressure in this well decreased to 127 psi after only two years of production, and the well's total head value is one of the lowest encountered in the study area.

Hydraulic Head Cross Section Significance

Figure 35 shows the locations of three hydraulic head elevation cross sections for the Wolfcampian/GW units constructed using Rockworks 99™. The cross sections show total head (HW), pressure head (HP), and elevation head (Z) for each well in the cross section. Z represents the elevation above/below a datum (mean sea level) at the well's lowest perforated (production) interval. HP represents the height of the water column in the well above the lowest perforation in the well, and HW represents the sum of Z and HP. Figures 36, 37, and 38 show hydraulic head elevation cross sections in three different directions across the study area. The cross sections were constructed in order to obtain a more comprehensive view of potential water flow directions in the Wolfcampian/GW reservoir units.

Possible explanations for the large number of concentric contours around individual wells include lateral and/or vertical changes in reservoir permeability (compartmentalization), fluid migration barriers such as faults (Fig. 21), or effects produced by the particular computer gridding and contouring algorithm. Figure 39 represents a hypothetical cross section illustrating a potentiometric "step" that reflects a water flow constriction resulting from a zone of reduced permeability (Dahlberg, 1995). According to Pippin (1970) and Ruppel and Garret, Jr. (1989), such zones of reduced permeability are present throughout Permo/Pennsylvanian reservoir units in both the Panhandle and Hugoton portions of the field. Later initial production dates for particular wells might also produce this effect. A well that began production twenty or thirty years after a particular well (or wells) in a less developed portion of the field might not have created as much reservoir drawdown, reflected by a higher current BHP.

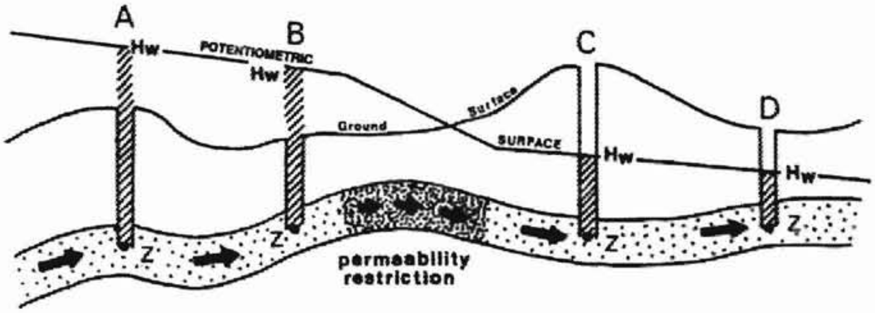


Figure 39. Potentiometric "step" cross section (Dahlberg, 1995).

CHAPTER 5

Conclusions

Stratigraphic cross sections of the four-county study area show thick (up to 1000 ft total) Permo/Pennsylvanian reservoir units (Granite Wash and Wolfcampian carbonates) overlain by a relatively thick Leonardian (Permian) confining layer, the Wichita Formation. The Wichita consists primarily of anhydrite and dense anhydritic dolomite and generally forms a seal over the Permo/Pennsylvanian reservoir units. Some limited Wichita production may occur in areas of localized fracturing. The Leonardian Red Cave, a fairly thick sequence of shale and siltstone and gas producing unit, overlies the Wichita and appears to maintain higher reservoir pressures than Permo/Pennsylvanian units. Wells penetrating older Paleozoic sedimentary units in the study area are not producing gas from those units, and do not appear to be pressurizing the overlying Permo/Pennsylvanian reservoirs. Several exceptions may exist in the southeast part of the study area near the Potter County Fault. Granite basement may act as a lower confining layer for Permo/Pennsylvanian reservoir units, although limited gas production from fractured basement does occur in the study area.

Local anticlinal highs are evident on the cross sections, and the dominant fluid trapping mechanism appears structural in nature. Both Red Cave and Permo/Pennsylvanian reservoirs are underpressured with respect to a hydrostatic gradient of 0.465 psi/ft standard for the region. Such conditions are the result of reservoir compartmentalization and/or depletion after decades of production. Red Cave and Permo/Pennsylvanian potentiometric surface maps both indicate a general flow trend toward low pressure "sinks" in the east-northeast portion of the study area. Possible explanations for observed concentric, closed contouring effects present in the Wolfcampian/GW potentiometric surface maps include lateral variations in reservoir permeability and/or processes in the mapping algorithm.

Pressure data presented in this study indicate that Permo/Pennsylvanian Granite Wash and Wolfcampian carbonate reservoir units have the potential to accommodate large quantities of injected fluids. Red Cave pressure data infer that liquids injected into Wolfcamp/Granite Wash reservoirs would remain confined at lower elevations. Any fluid migration between Red Cave and Permo/Pennsylvanian reservoirs would be in a downward direction. This downward flow eliminates the risk of potentially hazardous liquids migrating upward from Permo/Pennsylvanian disposal wells, either through fractures in the Wichita, existing boreholes, or through poorly designed disposal wells, and contaminating surface or near-surface aquifers. Further detailed reservoir characterization studies are needed to examine suitability of Wolfcamp/Granite Wash units as deep subsurface disposal zones. Reservoir heterogeneity, mineralogy, and temperature must be considered. Additionally, the injectibility of a particular waste depends on the physical and chemical characteristics of the waste, the aquifer (reservoir), and the reservoir fluids. Physical or chemical interactions between the waste and the aquifer minerals or fluids could cause plugging of aquifer pores and a consequent loss of intake capacity. The observed pressure architecture and dynamics of the Permo/Pennsylvanian section in this study appear favorable for continued deep well waste injection feasibility analysis.

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APPENDIX A

Example of scout card and wireline log data for wells 1A thru 13A and wells 1B thru 17B used for construction of stratigraphic cross sections A-A' and B-B'. Data obtained from Oklahoma City Geological Society Well Log Library, Oklahoma City, Oklahoma.

A

130
MAP NO.

ELEV. 3283DF, 3274GL

STATE Texas COUNTY Moore SEC. 42 Blk 6-T Sur T&NO

OPERATOR Colorado Interstate Gas Co. LOC.

WELL NO. D-2 FARM NAME Sneed Estate 2640 FT. FROM S LINE

POOL W. Panhandle (PD 3076) 2640 FT. FROM W LINE

FR. 4-14-61 SPUD 4-28-61 COMP. 8-21-61

CONT./GEOL. Panhandle Drilling

COMPLETION RECORD

	NAME PRODUCING INTERVAL	FROM — TO	PERF. W/HOLES	TREATMENT RECORD
a	Brown Dolomite &	2300-2957	Slotted	6000Ac.F/6X12
b	Granite Wash			
c				
d				

	I. P. OIL/DIST.	WTR.	GAS	M.C.F.P.D.	CHK.	HRS.
a		COF	8600		4 pt	
b	"	"	"	"	"	"
c	"	"	"	"	"	"
d						

D & A ( )

SIP# 185 FI TP # FI CP# SIBHP

GOR. GR. PBTD TD 3080

CASING - CEMENT RECORD

SIZE	DEPTH	W/SAX.	SIZE	DEPTH	W/SAX.
10-3/4"	240	150	Set 696' of 4½" slotted liner @		
7"	2300	250		2957 w/50 sx.	

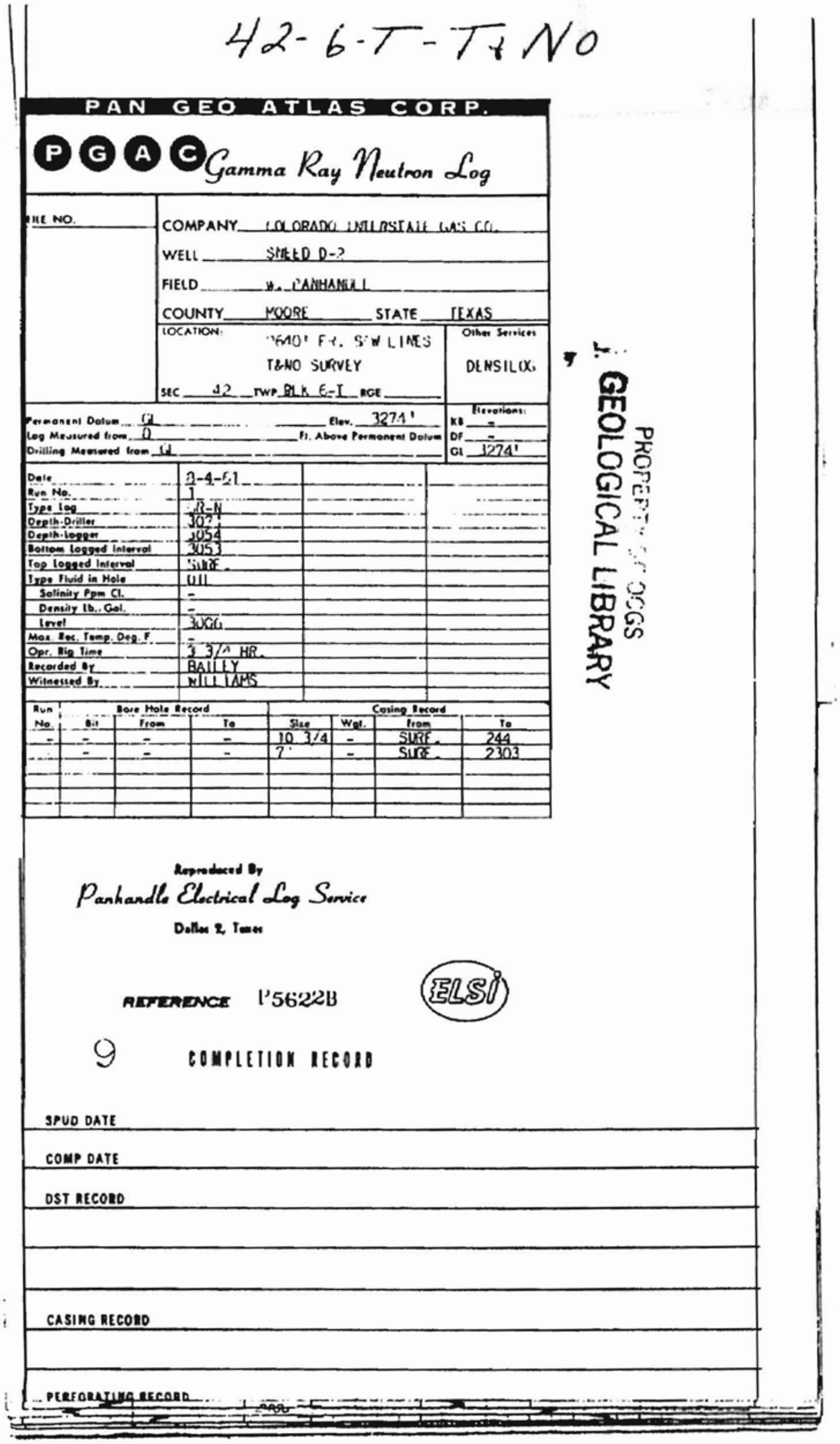
OPERATOR Colorado Interstate ~~Gas~~ WELL NO. #D-2 Sneed Estate ELEV. 3283 DF

SAMPLE TOPS	DEPTH	SUB SEA	ELEC. TOPS	DEPTH	SUB SEA
			Tubb	1367	
			Red Cave	1656	
			Panhandle Lime	1976	
			Brown Dolomite	2300	
			Granite Wash	2700	

13½ mi. NE Masterson.
Spud 4-28-61. 10-3/4" @ 240 w/150 sx. 7" @ 2300 w/250 sx.
TD 3080, logs (Lane Wells- GR-Den) to 2982. MICT.
Set 696' of 4½" slotted liner @ 2957 w/50 sx. Slotted from 2300-2957, 2000-15% Ac, Frac 6000-15% Ac X 12,000 sd. 4000-15% Ac. Swb all ld.

IP 4 pt COF 8,600 MCF, SIP 185, from Dolomite & Granite Wash (2300-2957).

COMPLETE 8-21-61.



42-6-T-T&NO

PAN GEO ATLAS CORP.

PGAC Gamma Ray Neutron Log

FILE NO.

COMPANY COLORADO INTERSTATE GAS CO.
WELL SNEED D-2
FIELD W. PANHANDLE
COUNTY MOORE STATE TEXAS
LOCATION: 2640' FR. S&W LINES
T&NO SURVEY
SEC 42 TWP BLK 6-T RGE

Other Services
DENSILOG

Permanent Datum GL Elev. 3274'
Log Measured from 0 Ft. Above Permanent Datum
Drilling Measured from GL

Elevations:
KB -
DF -
GL 3274'

Date	8-4-61		
Run No.	1		
Type Log	GR-N		
Depth-Driller	3071		
Depth-Logger	3054		
Bottom Logged Interval	3053		
Top Logged Interval	SURF.		
Type Fluid in Hole	OIL		
Salinity Ppm Cl.	-		
Density lb., Gal.	-		
Level	3066		
Max. Rec. Temp. Deg. F	-		
Opr. Rig Time	3 3/4 HR.		
Recorded By	BAILEY		
Witnessed By	WILLIAMS		

Run No.	Bore Hole Record			Casing Record			
	Bit	From	To	Size	Wgt.	From	To
-	-	-	-	10 3/4	-	SURF.	244
	-	-	-	7"	-	SURF.	2303

Reproduced By
Panhandle Electrical Log Service
Dallas 2, Texas

REFERENCE P5622B

ELSI

9

COMPLETION RECORD

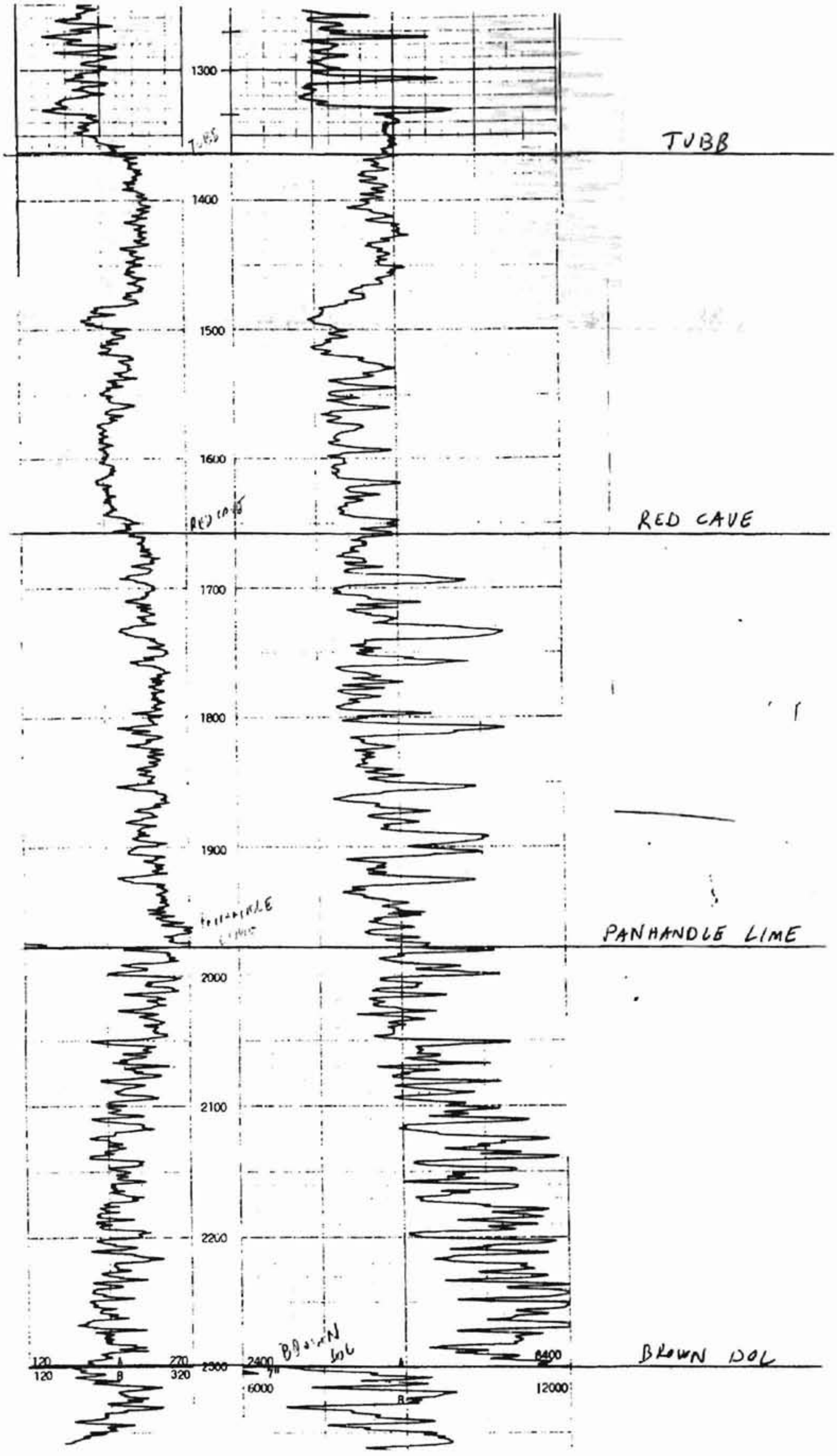
SPUD DATE

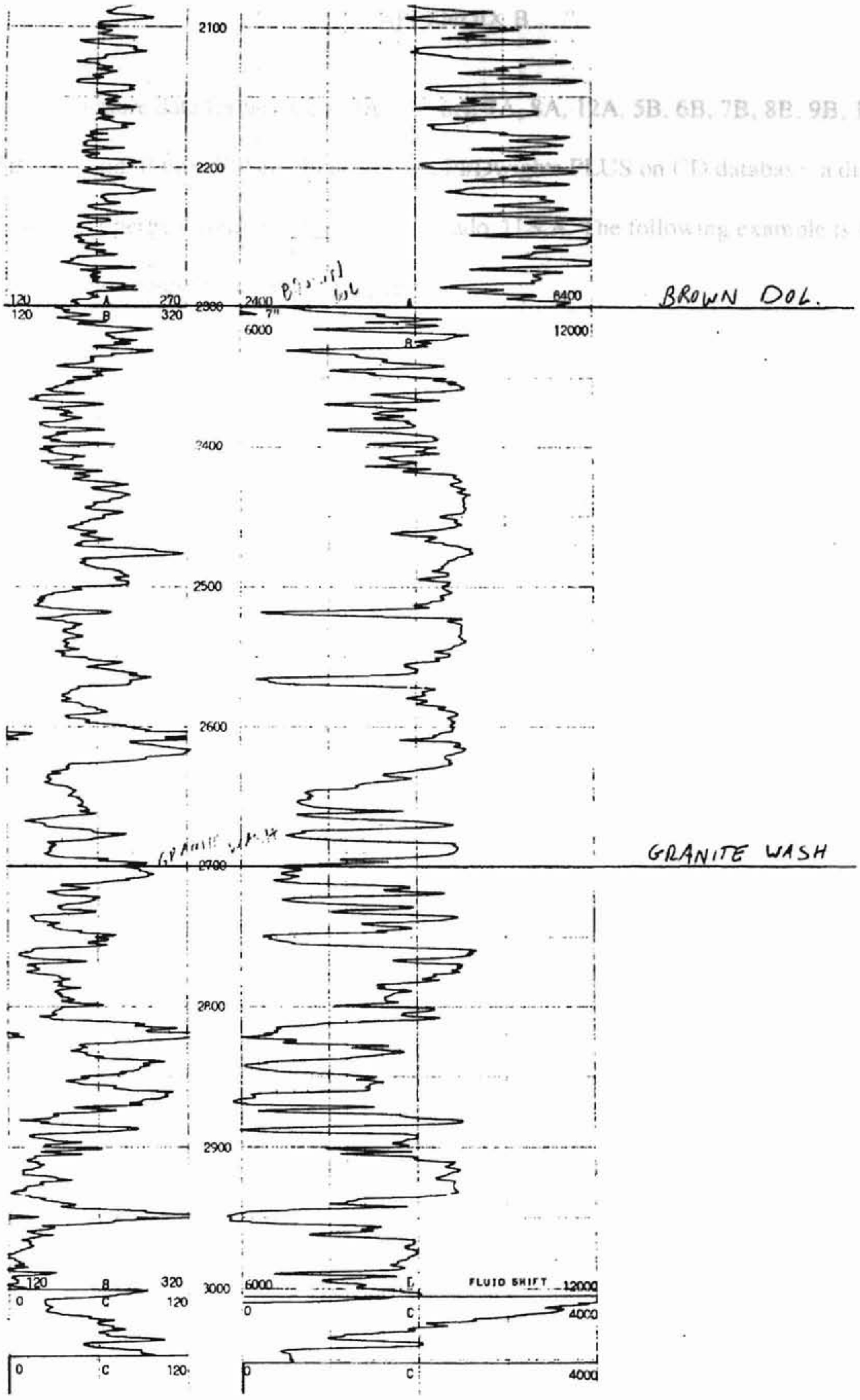
COMP DATE

DST RECORD

CASING RECORD

PERFORATING RECORD


TUBB
1300
TUBB
1400
1500
1600
RED CAVE
RED CAVE
1700
1800
1900
PANHANDLE LIME
PANHANDLE LIME
2000
2100
2200
BROWN DOL
BROWN DOL
120
120
A
B
270
320
2300
2400
6000
7"
A
B
8400
12000


2100
2200
120
120
A
B
270
320
2300
2400
7"
6000
6400
12000
Brown Dol
BROWN DOL.
2400
2500
2600
Granite Wash
GRANITE WASH
2700
2800
2900
120
B
320
0
C
120
3000
6000
D
C
FLUID SHIFT
12000
4000
0
C
120
0
C
4000

APPENDIX B

Pressure data for wells 2A, 3A, 4A, 6A, 7A, 8A, 12A, 5B, 6B, 7B, 8B, 9B, 14B, 15B, 16B and1P thru 50P all obtained from PI/Dwights PLUS on CD database, a division of the IHS Energy Group, Englewood, Colorado, U.S.A. The following example is for one well and represents a well test report.

PI/Dwights PLUS on CD Detailed Well Test Report

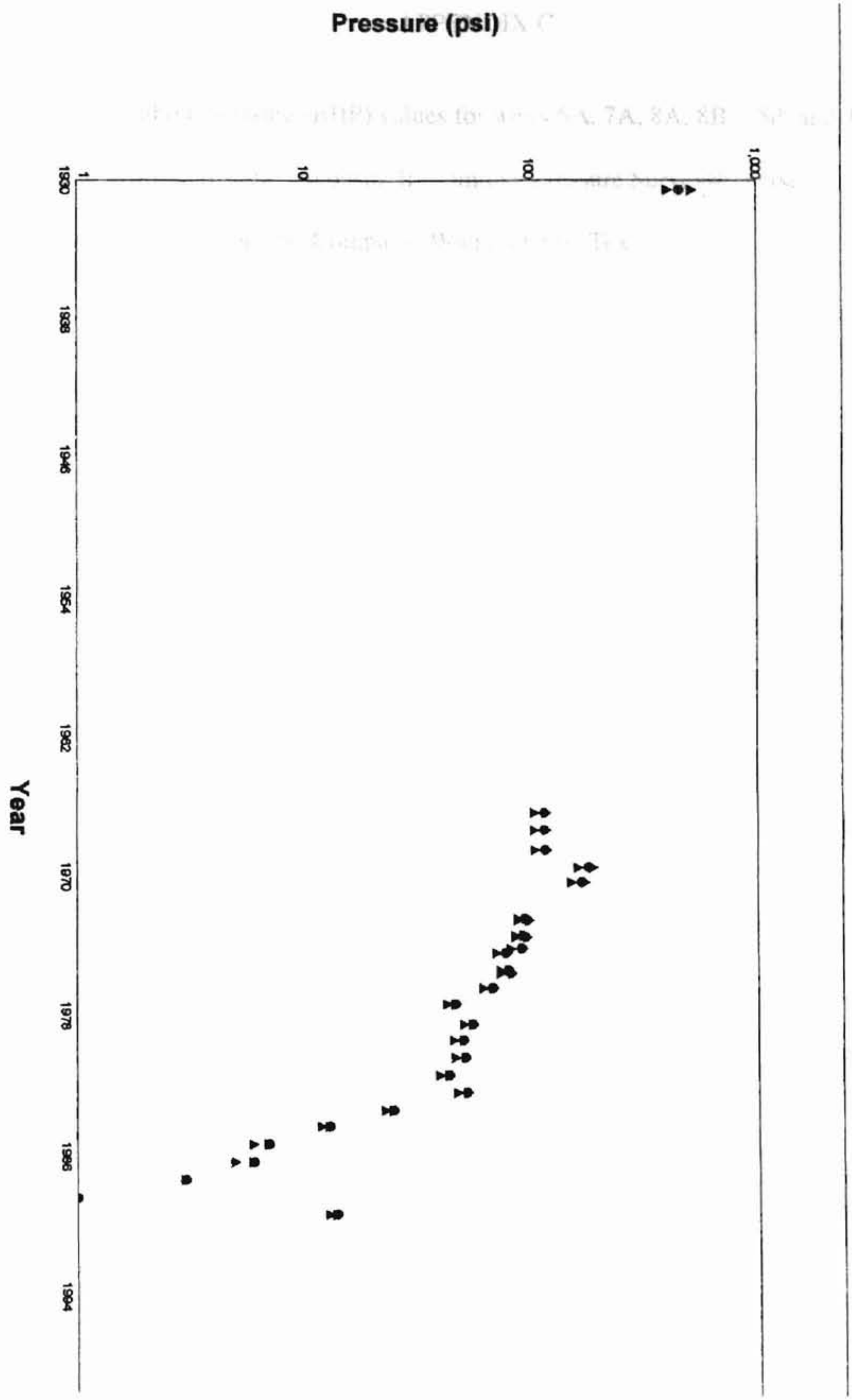
Lease Name:	**HAZEL**	**Well Number:**	**1**
Lease Number:	24896	Cum Oil:	
Operator Name:	HUBER J M CORPORATION	Cum Gas:	1,966,725
State:	TEXAS	Cum Water:	
County:	HUTCHINSON	First Production Date:	JUL 1930
Field:	PANHANDLE WEST	Last Production Date:	SEP 2000
TX Railroad Dist	TEXAS DISTRICT 10	Spot	
Survey Name	H&OB	Abstract Number	615
Block	X02	Section	4
League, Spot code		Labor	
Township		Lot	
Latitude/Longitude:		Lat/Long Source:	
Regulatory #:	24896	Completion Date:	JUL 01, 1930
API:	42233131360000	Total Depth:	
Production ID:	242100024896	Upper Perforation:	2833
Reservoir Name:	UNKNOWN	Lower Perforation:	2885
Prod Zone:	UNKNOWN	Gas Gravity:	1.00
Prod Zone Code:	000UNKWN	Oil Gravity:	
Basin Name:	ANADARKO BASIN	Temp Gradient:	1.1
Gas Gatherer:	DUKEL	N Factor:	0.713
Liquid Gatherer:		GOR:	
Status:	ACTIVE GAS		

Gas Tests **Total count: 30**

API Number	Well Number	Test Type	Test Date	Upper Perf.	Lower Perf.	Cum Prod To Test	WHSIP	WHFP	BHP	BHP/Z	BHP Type	Water B/D	Cond B/D	Gas MCFD	AOF MCFD
First Test															
42233131360000	1	IP	19300715				413		462	528	C				3500
42233131360000	1	CAP	19660515			1298631	105		116	119	C				150
42233131360000	1	CAP	19670503			1311391	105		116	119	C				
42233131360000	1	CAP	19680715			1326580	106		117	120	C				
42233131360000	1	CAP	19690715			1341508	164		182	191	C				
42233131360000	1	CAP	19700518			1356396	153		169	176	C				316
42233131360000	1	CAP	19720601			1390404	88	13	95	96	C			105	
42233131360000	1	CAP	19720718			1393054	88		97	99	C				105
42233131360000	1	CAP	19730601			1400538	86	13	93	94	C			100	
42233131360000	1	CAP	19730703			1401158	86		95	97	C				100

PI/Dwights PLUS on CD Detailed Well Test Report

42233131360000	1	IP	19740313	1407998	82		91	93	C		792
42233131360000	1	CAP	19740601	1424475	71	13	77	78	C	640	
42233131360000	1	CAP	19740625	1429583	71		78	79	C		640
42233131360000	1	CAP	19750601	1491053	74	13	80	81	C	679	
42233131360000	1	CAP	19750804	1503933	74		82	83	C		679
42233131360000	1	CAP	19760603	1557484	62		68	69	C		528
42233131360000	1	CAP	19770526	1608236	43		47	47	C	89	
42233131360000	1	CAP	19780703	1653900	51	47	56	56	C	196	
42233131360000	1	CAP	19790604	1699674	46	38	51	51	C	192	
42233131360000	1	CAP	19800617	1745132	47	45	52	52	C	190	
42233131360000	1	CAP	19810611	1795243	40	28	44	44	C	190	
42233131360000	1	CAP	19820603	1829880	48	45	53	53	C	134	
42233131360000	1	CAP	19830610	1869470	23	14	25	25	C	137	
42233131360000	1	CAP	19840518	1894223	12	4	13	13	C	113	
42233131360000	1	CAP	19850516	1906420	6	1	7	7	C	63	
42233131360000	1	CAP	19860501	1916287	5	2	6	6	C	42	
42233131360000	1	CAP	19870508	1924275	3	1	3	3	C	27	
42233131360000	1	CAP	19880510	1930038	1	1	1	1	C	21	
42233131360000	1	CAP	19890515	1935457	13	10	14	14	C	16	
42233131360000	1	CAP	20000501	1966272	1		1	1	C		


Pressure (psi)
1
10
100
1,000
Year
1930
1938
1946
1954
1962
1970
1978
1986
1994
Lease Name: HAZEL
County, State: HUTCHNSN, TX
Operator: HUBER J M CORPORATION
Field: PANHANDLE WEST
Reservoir: UNKNOWN
Location: XD2 4 615

APPENDIX C

Bottomhole pressure (BHP) values for wells 6A, 7A, 8A, 8B, 15P, and 46P calculated using Echometer Acoustic Bottomhole Pressure Survey© (version 2.1) developed by the Echometer Company, Wichita Falls, Texas, U.S.A.

```
                                             RETURN TO CONTINUE?

WELL: 6A                                                    ****************************
DATE:03-29-2001                                             * ACOUSTIC STATIC          *
                                                            * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 2957                        * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  23                          *                          *
C) SURFACE TEMP.        (F)=    60                          *  BY ECHOMETER            *
E) BOTTOM HOLE TEMP     (F)=    90                          ****************************
G) DEPTH TO LIQUID=   OF JOINTS 29
   AT  100.00 FT/JT=(FT)        2900
H) GAS SPECIFIC GRAVITY=        .83                          CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=   26 PSIG @  2900 FT.

*   BHP=   53 PSIG  @ 2957 FT   *
*********************************     TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                      RETURN TO CONTINUE?

WELL: 6A                                                    ****************************
DATE:03-29-2001                                             * ACOUSTIC STATIC          *
                                                            * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 2957                        * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  23                          *                          *
C) SURFACE TEMP.        (F)=    60                          *  BY ECHOMETER            *
E) BOTTOM HOLE TEMP     (F)=    90                          ****************************
G) DEPTH TO LIQUID=   OF JOINTS 29
   AT  100.00 FT/JT=(FT)        2900
H) GAS SPECIFIC GRAVITY=        .83                          CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=   26 PSIG @  2900 FT.

*   BHP=   53 PSIG  @ 2957 FT   *
*********************************     TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                      RETURN TO CONTINUE?

WELL: 6A                                                    ****************************
DATE:03-29-2001                                             * ACOUSTIC STATIC          *
                                                            * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 2957                        * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  23                          *                          *
```

```
C) SURFACE TEMP.        (F)=    60              *  BY ECHOMETER             *
E) BOTTOM HOLE TEMP     (F)=    90              ****************************
G) DEPTH TO LIQUID=   OF JOINTS 29
   AT  100.00 FT/JT=(FT)        2900
H) GAS SPECIFIC GRAVITY=        .83              CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=   26 PSIG @  2900 FT.

*   BHP=   53 PSIG  @ 2957 FT   *
*********************************      TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                       RETURN TO CONTINUE?


WELL: 7A                                        ****************************
DATE:03-29-2001                                 * ACOUSTIC STATIC          *
                                                * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 2844            * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  13              *                          *
C) SURFACE TEMP.        (F)=    60              *  BY ECHOMETER            *
E) BOTTOM HOLE TEMP     (F)=    90              ****************************
G) DEPTH TO LIQUID=   OF JOINTS 28
   AT  100.00 FT/JT=(FT)        2800
H) GAS SPECIFIC GRAVITY=        .89              CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=   16 PSIG @  2800 FT.

*   BHP=   36 PSIG  @ 2844 FT   *
*********************************      TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                       RETURN TO CONTINUE?


WELL: 7A                                        ****************************
DATE:03-29-2001                                 * ACOUSTIC STATIC          *
                                                * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 2844            * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  13              *                          *
C) SURFACE TEMP.        (F)=    60              *  BY ECHOMETER            *
E) BOTTOM HOLE TEMP     (F)=    90              ****************************
G) DEPTH TO LIQUID=   OF JOINTS 28
   AT  100.00 FT/JT=(FT)        2800
H) GAS SPECIFIC GRAVITY=        .89              CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
```

```
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=   16 PSIG @  2800 FT.

*   BHP=  36 PSIG  @ 2844 FT    *
**********************************       TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                         RETURN TO CONTINUE?


WELL: 8A                                                 ****************************
DATE:03-29-2001                                          * ACOUSTIC STATIC          *
                                                         * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 3040                     * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  14                       *                          *
C) SURFACE TEMP.        (F)=    60                       *  BY ECHOMETER            *
E) BOTTOM HOLE TEMP     (F)=    90                       ****************************
G) DEPTH TO LIQUID=   OF JOINTS 30
   AT  100.00 FT/JT=(FT)        3000
H) GAS SPECIFIC GRAVITY=        .85                       CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=   17 PSIG @  3000 FT.

*   BHP=  35 PSIG  @ 3040 FT    *
**********************************       TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                         RETURN TO CONTINUE?


WELL: 8A                                                 ****************************
DATE:03-29-2001                                          * ACOUSTIC STATIC          *
                                                         * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 3040                     * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  14                       *                          *
C) SURFACE TEMP.        (F)=    60                       *  BY ECHOMETER            *
E) BOTTOM HOLE TEMP     (F)=    90                       ****************************
G) DEPTH TO LIQUID=   OF JOINTS 30
   AT  100.00 FT/JT=(FT)        3000
H) GAS SPECIFIC GRAVITY=        .85                       CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=   17 PSIG @  3000 FT.
```

```
*   BHP=   35 PSIG  @ 3040 FT    *
**********************************          TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                            RETURN TO CONTINUE?


WELL: 8B                                             ***************************
DATE:03-29-2001                                      * ACOUSTIC STATIC         *
                                                     * BOTTOMHOLE PRESSURE     *
A) DEPTH TO PRESSURE DATUM(FT)= 2670                 * SURVEY                  *
B) WELLHEAD PRESSURE    (PSI)=  27                   *                         *
C) SURFACE TEMP.         (F)=   60                   *  BY ECHOMETER           *
E) BOTTOM HOLE TEMP     (F)=    90                   ***************************
G) DEPTH TO LIQUID=   OF JOINTS 26
   AT  100.00 FT/JT=(FT)        2600
H) GAS SPECIFIC GRAVITY=        .83                   CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=   30 PSIG @  2600 FT.

*   BHP=   63 PSIG  @ 2670 FT    *
**********************************          TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                            RETURN TO CONTINUE?


WELL: 8B                                             ***************************
DATE:03-29-2001                                      * ACOUSTIC STATIC         *
                                                     * BOTTOMHOLE PRESSURE     *
A) DEPTH TO PRESSURE DATUM(FT)= 2670                 * SURVEY                  *
B) WELLHEAD PRESSURE    (PSI)=  27                   *                         *
C) SURFACE TEMP.         (F)=   60                   *  BY ECHOMETER           *
E) BOTTOM HOLE TEMP     (F)=    90                   ***************************
G) DEPTH TO LIQUID=   OF JOINTS 26
   AT  100.00 FT/JT=(FT)        2600
H) GAS SPECIFIC GRAVITY=        .83                   CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=   30 PSIG @  2600 FT.

*   BHP=   63 PSIG  @ 2670 FT    *
**********************************          TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                            RETURN TO CONTINUE?


WELL: 8B                                             ***************************
DATE:03-29-2001                                      * ACOUSTIC STATIC         *
                                                     * BOTTOMHOLE PRESSURE     *
```

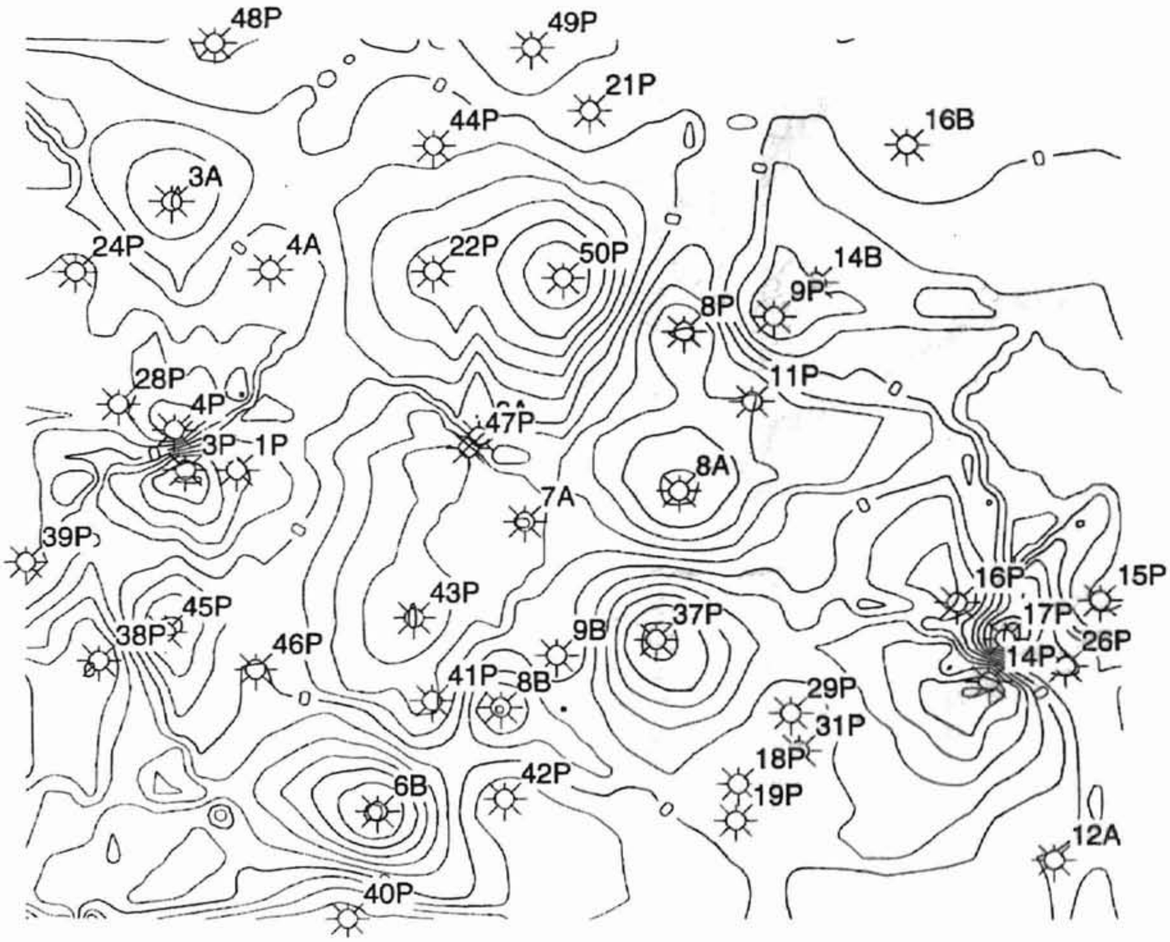
```
WELL:                                                  ****************************
DATE:03-29-2001                                        * ACOUSTIC STATIC          *
                                                       * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 2900                   * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  1                      *                          *
C) SURFACE TEMP.        (F)=    60                     *  BY ECHOMETER            *
E) BOTTOM HOLE TEMP     (F)=    90                     ****************************
G) DEPTH TO LIQUID=   OF JOINTS 29
   AT  100.00 FT/JT=(FT)        2900
H) GAS SPECIFIC GRAVITY=        .84                     CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=    2 PSIG @  2900 FT.

*   BHP=    2 PSIG  @ 2900 FT    *
*********************************     TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                      RETURN TO CONTINUE?


WELL: IP                                               ****************************
DATE:03-29-2001                                        * ACOUSTIC STATIC          *
                                                       * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 2900                   * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  1                      *                          *
C) SURFACE TEMP.        (F)=    60                     *  BY ECHOMETER            *
E) BOTTOM HOLE TEMP     (F)=    90                     ****************************
G) DEPTH TO LIQUID=   OF JOINTS 29
   AT  100.00 FT/JT=(FT)        2900
H) GAS SPECIFIC GRAVITY=        .84                     CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=    2 PSIG @  2900 FT.

*   BHP=    2 PSIG  @ 2900 FT    *
*********************************     TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                      RETURN TO CONTINUE?


WELL:                                                  ****************************
DATE:03-29-2001                                        * ACOUSTIC STATIC          *
                                                       * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 2900                   * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  1                      *                          *
C) SURFACE TEMP.        (F)=    60                     *  BY ECHOMETER            *
E) BOTTOM HOLE TEMP     (F)=    90                     ****************************
```

```
G) DEPTH TO LIQUID=   OF JOINTS 29
   AT  100.00 FT/JT=(FT)        2900
H) GAS SPECIFIC GRAVITY=        .84               CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=    2 PSIG @  2900 FT.

*   BHP=    2 PSIG  @ 2900 FT    *
*********************************     TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                      RETURN TO CONTINUE?


WELL: 15P                                         ****************************
DATE:03-29-2001                                   * ACOUSTIC STATIC          *
                                                  * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 2700              * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  1                 *                          *
C) SURFACE TEMP.        (F)=    60                *  BY ECHOMETER            *
E) BOTTOM HOLE TEMP     (F)=    90                ****************************
G) DEPTH TO LIQUID=   OF JOINTS 27
   AT  100.00 FT/JT=(FT)        2700
H) GAS SPECIFIC GRAVITY=        .87               CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=    2 PSIG @  2700 FT.

*   BHP=    2 PSIG  @ 2700 FT    *
*********************************     TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                      RETURN TO CONTINUE?


WELL:                                             ****************************
DATE:03-29-2001                                   * ACOUSTIC STATIC          *
                                                  * BOTTOMHOLE PRESSURE      *
A) DEPTH TO PRESSURE DATUM(FT)= 2700              * SURVEY                   *
B) WELLHEAD PRESSURE    (PSI)=  1                 *                          *
C) SURFACE TEMP.        (F)=    60                *  BY ECHOMETER            *
E) BOTTOM HOLE TEMP     (F)=    90                ****************************
G) DEPTH TO LIQUID=   OF JOINTS 27
   AT  100.00 FT/JT=(FT)        2700
H) GAS SPECIFIC GRAVITY=        .87               CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
```

```
N) WATER SPECIFIC GRAVITY=       1.1


PRESSURE AT GAS/OIL INTERFACE=    2 PSIG @  2700 FT.

*   BHP=    2 PSIG  @ 2700 FT    *
**********************************      TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                        RETURN TO CONTINUE?


WELL: 46p                                           *****************************
DATE:03-29-2001                                     * ACOUSTIC STATIC           *
                                                    * BOTTOMHOLE PRESSURE       *
A) DEPTH TO PRESSURE DATUM(FT)= 3025                * SURVEY                    *
B) WELLHEAD PRESSURE    (PSI)=  19                  *                           *
C) SURFACE TEMP.        (F)=    60                  *  BY ECHOMETER             *
E) BOTTOM HOLE TEMP     (F)=    90                  *****************************
G) DEPTH TO LIQUID=   OF JOINTS 30
   AT  100.00 FT/JT=(FT)        3000
H) GAS SPECIFIC GRAVITY=        .9                   CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=   22 PSIG @  3000 FT.

*   BHP=   34 PSIG  @ 3025 FT    *
**********************************      TO PRINT RESULTS, TYPE SHIFT+PrtSc
                                        RETURN TO CONTINUE?


WELL: 46p                                           *****************************
DATE:03-29-2001                                     * ACOUSTIC STATIC           *
                                                    * BOTTOMHOLE PRESSURE       *
A) DEPTH TO PRESSURE DATUM(FT)= 3025                * SURVEY                    *
B) WELLHEAD PRESSURE    (PSI)=  19                  *                           *
C) SURFACE TEMP.        (F)=    60                  *  BY ECHOMETER             *
E) BOTTOM HOLE TEMP     (F)=    90                  *****************************
G) DEPTH TO LIQUID=   OF JOINTS 30
   AT  100.00 FT/JT=(FT)        3000
H) GAS SPECIFIC GRAVITY=        .9                   CALCULATING
I) H2S%=                        0
J) CO2%=                        .1
K) N2%=                         13.6
L) WATER % IN LIQUID=           0
M) LIQUID HYDROCARBON API=      0
N) WATER SPECIFIC GRAVITY=      1.1


PRESSURE AT GAS/OIL INTERFACE=   22 PSIG @  3000 FT.

*   BHP=   34 PSIG  @ 3025 FT    *
**********************************      TO PRINT RESULTS, TYPE SHIFT+PrtSc
```

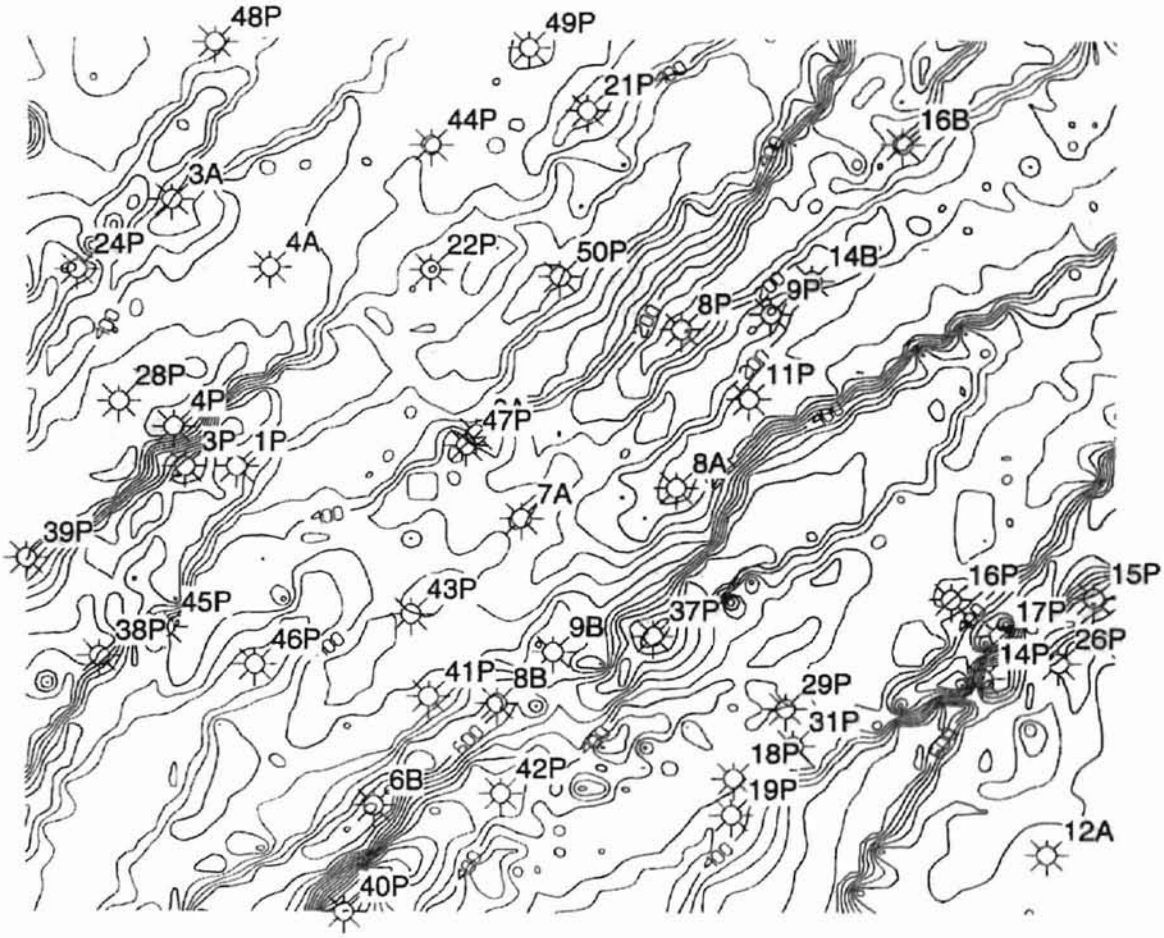
APPENDIX D

Example of contour map constructed with Rockworks 99™ Trend Surface Weighted Residuals method.



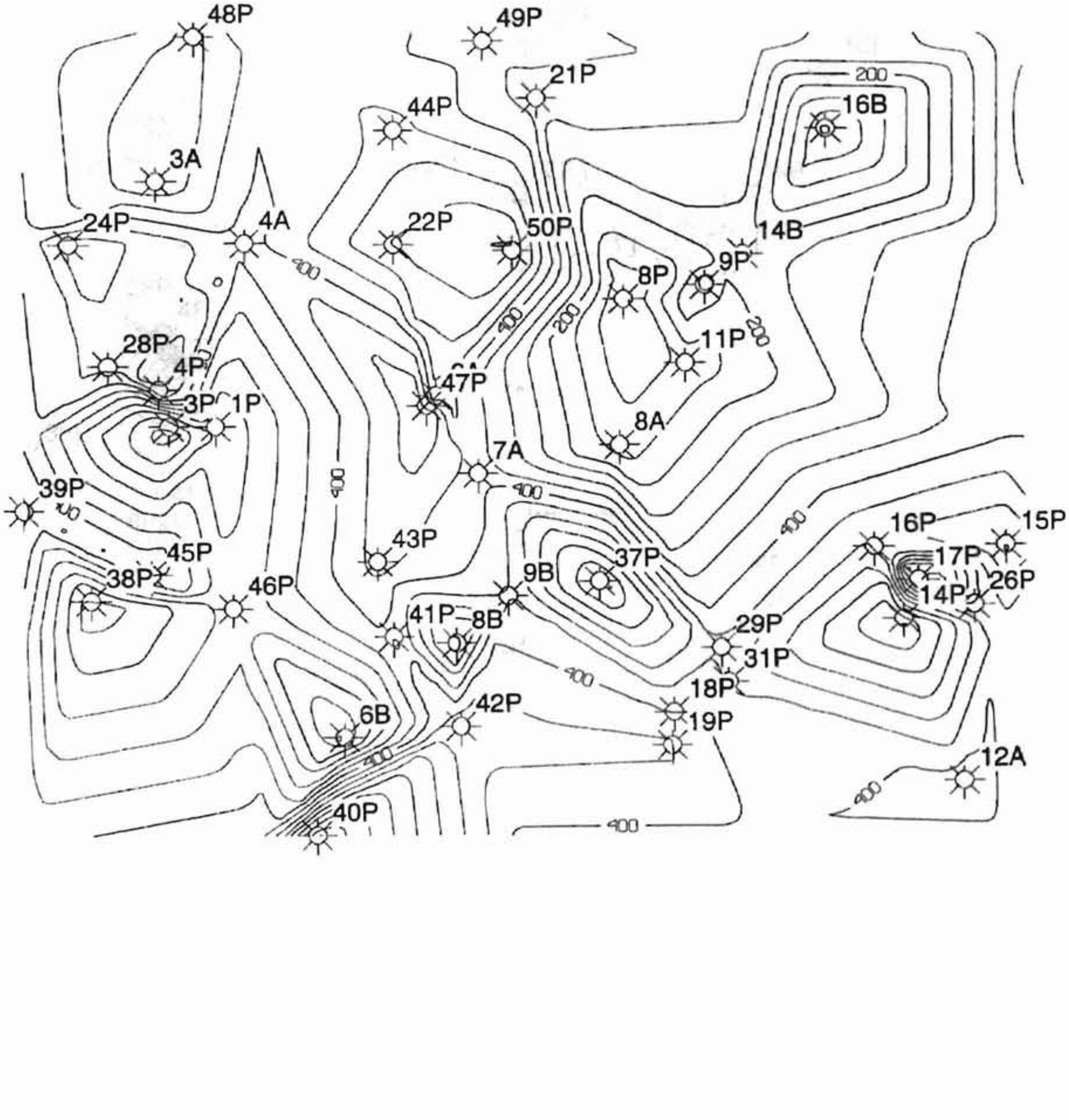
APPENDIX E

Example of contour map constructed with Rockworks 99™ Directional Weighting method.



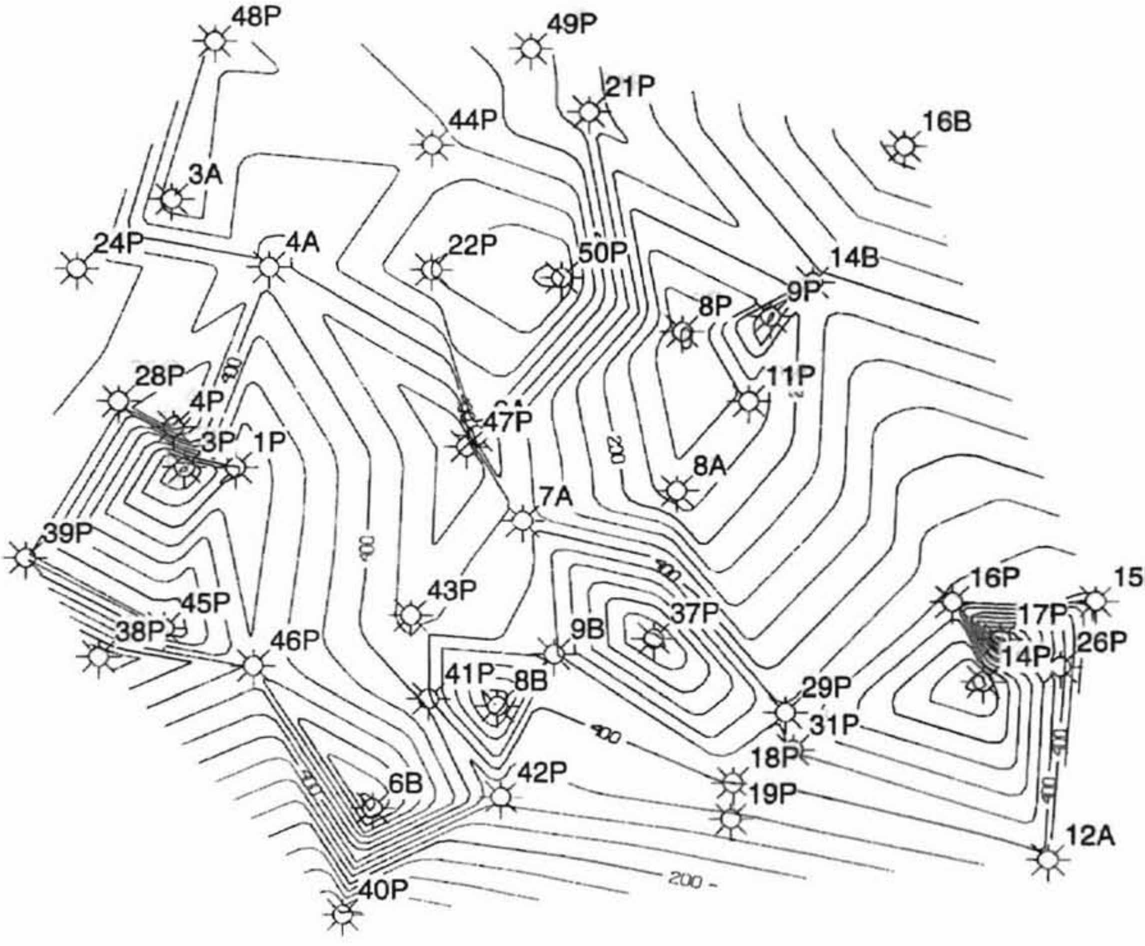
APPENDIX F

Example of contour map constructed with Rockworks 99™ Triangulation Gridding method.



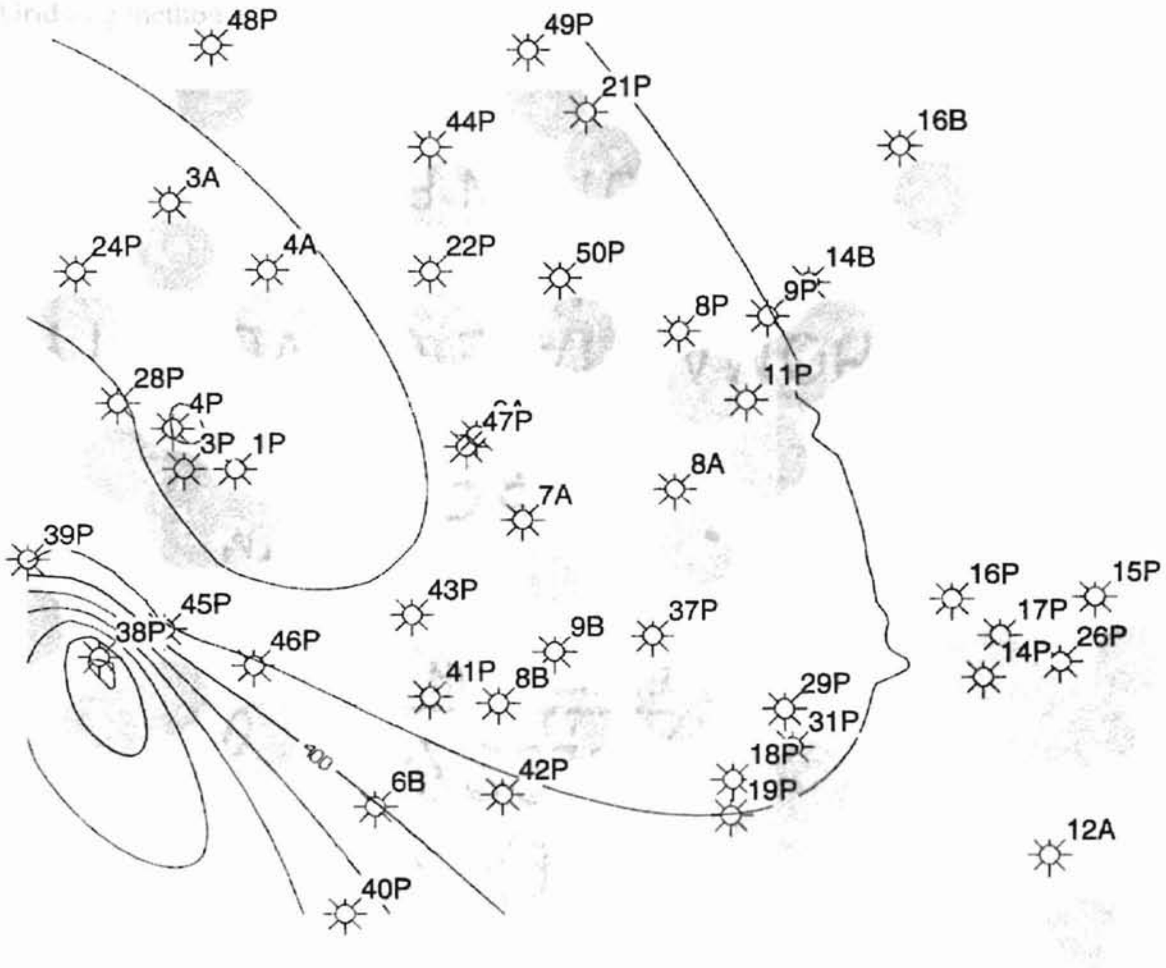
APPENDIX G

Example of contour map constructed with Rockworks 99™ E-Z Map 2-D method.



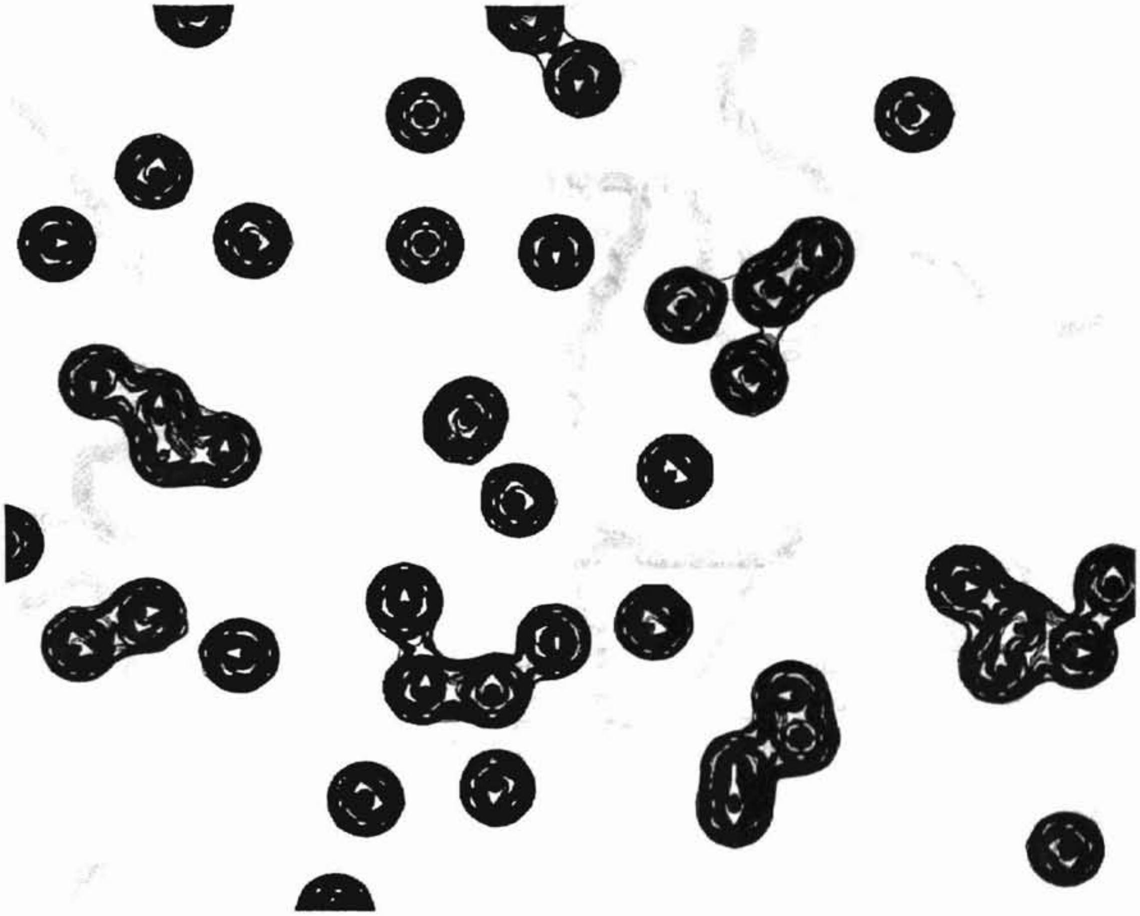
APPENDIX H

Example of contour map constructed with Rockworks 99™ Kriging method.



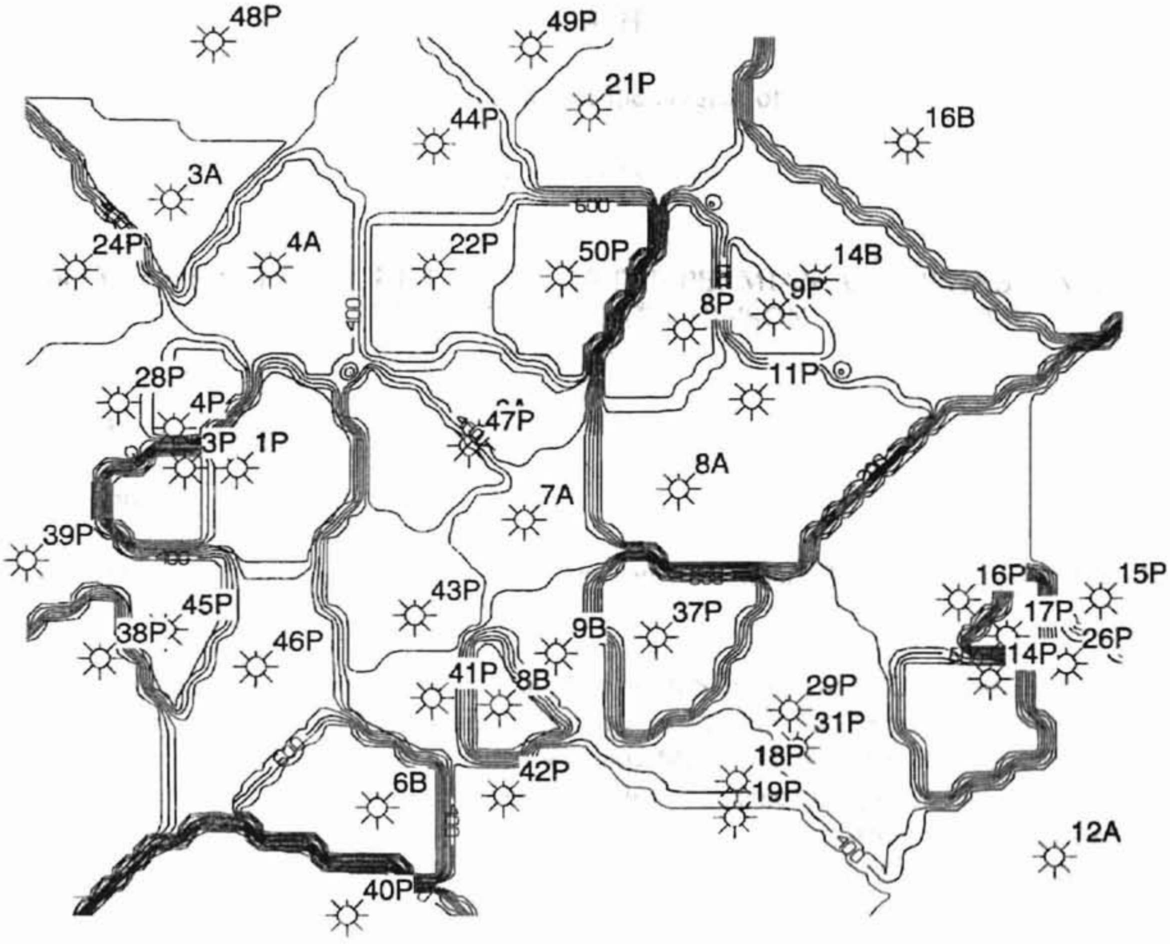
APPENDIX I

Example of contour map constructed with Rockworks 99™ Distance to Point Gridding method.



APPENDIX J

Example of contour map constructed with Rockworks 99™ Closest Point Gridding method.



VITA

Daniel A. Hannah

Candidate for the Degree of

Master of Science

Thesis: PRESSURE ARCHITECTURE OF THE PERMIAN AND PENNSYLVANIAN SECTION IN CARSON, MOORE, HUTCHINSON, AND POTTER COUNTIES, TEXAS PANHANDLE

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Experience: Employed in the petroleum services sector as a hydrocarbon well logger (1994-95), core analysis technician (1995-96), and drilling fluids engineer (1996-98). Employed in the environmental services sector as a geotechnician, 1999 to present.