

**HOW TO DESIGN AN EXPLORATION SURFACE SOIL  
GAS GEOCHEMICAL SURVEY: ILLUSTRATED BY  
APPLICATION EXAMPLES FROM THE HUGOTON  
EMBAYMENT OF SOUTHEAST COLORADO AND  
SOUTHWEST KANSAS**

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Exploration Technologies, Inc.

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Aerial Photograph of a modern-day incised valley in the Lower Jurassic Navajo Sandstone of east-central Utah. This is an excellent analog for the Morrow incised valley-fill sandstones of the Stateline Trend of eastern Colorado and western Kansas.  
Image: Cover photograph of September 2002 AAPG Bulletin

# HOW TO DESIGN AN EXPLORATION SURFACE SOIL GAS GEOCHEMICAL SURVEY: ILLUSTRATED BY APPLICATION EXAMPLES FROM THE HUGOTON EMBAYMENT OF SOUTHEAST COLORADO AND SOUTHWEST KANSAS

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## ABSTRACT

Three regional surface geochemical soil gas surveys covering areas of 150, 53, and 209 square miles were conducted in the Hugoton Embayment of southeast Colorado and southwest Kansas. The three surveys exhibit different sampling densities and comprise both reconnaissance and detailed grids. The surveys were conducted over the prolific Pennsylvanian Morrow Stateline Trend and the Permian Chase Carbonate Gas Trend.

The stratigraphic entrapment of oil and gas in these two plays, relatively shallow depth, and highly variable porosity and permeability of the reservoirs are factors which favor the application of surface soil gas surveys as an important exploration method to reduce risk in exploration, exploitation, or development efforts in these two plays. Examples of actual reconnaissance and detailed surface soil gas surveys in this petroleum province are discussed.

The surveys were conducted from 1987 to 1992 before there was the widespread development drilling as witnessed today. Both the benefits and limitations of a reconnaissance survey over the Stateline Trend from Frontera to Second Wind Fields are discussed. A detailed survey in the Moore-Johnson Field area illustrates the benefits of surface geochemistry in risk reduction in this stratigraphically complex area. An example of a detailed soil gas survey over Byerly Field in Greeley County, Kansas is presented which depicts the complex porosity and permeability variations in the Chase Carbonate.

The paper is a retrospective analysis of soil gas surveys conducted in this complex area in light of new geologic knowledge of the area that has been revealed in the past decade.

## INTRODUCTION

The hypothesis that natural soil gas microseeps detected at the surface from underlying hydrocarbon deposits could continue to be useful as an exploration method is a natural extension of the mapping of macroseeps, which led to the very early discovery of many oil and gas fields in petroleum basins all over the world (Link, 1952). A history of the development of surface soil gas geochemistry may be found in Jones et al. (2000).

Twenty years ago, in 1983, Jones and Drozd published a paper in the AAPG, which improved our understanding of two important basic concepts of surface soil gas geochemistry – magnitude and composition as relating to subsurface reservoirs, significantly improving the viability of surface geochemical prospecting as a viable exploration method.

One of the primary reasons for past failures in the application of surface geochemical surveys is a lack of a proper design of the sampling grid. Few explorationists have adequate knowledge on how to design a surface soil gas survey, and as a result do not accrue nor appreciate the benefits that can be expected

from a properly designed survey. The factors listed in Table 1 are critical for the successful design, employment, and interpretation of a soil gas survey. Another reason for past failures may have been in the sample technique used in the collection of the soil gas samples (Jones, 2004, in review).

The considerations for sample spacing presented in this paper are not only the result of the authors work with exploration surveys in the area over a 16-year period, but also the result of having concurrently employed surface soil gas geochemistry in environmental assessments of petroleum contaminated sites. Reservoir heterogeneities in shallow sedimentary rock units of shallow vadose zones and aquifers are very readily apparent from the surface microseep anomalies observed from the extremely high-density soil gas grids used in these applications. An example of such an application is provided in Agostino, LeBlanc, and Jones (2002).

Exploration soil gas surveys may be designed so that they are very inexpensive and regional in nature, with very few soil gas samples, or they may be designed so that they are more detailed, with dense spacing of soil gas sample sites. As will be demonstrated with application examples, there is a critical balance in the design of surface geochemical surveys that must be met if useful results are to be attained.

Measuring natural gas microseepage, like any scientific analytical method dealing with nature is not perfect. Interpretations of soil gas geochemistry should always be used in conjunction with subsurface geology and geophysics. Another important concept to remember is that there is no direct relationship between the magnitude of a surface microseep and the resultant volumetric hydrocarbon production or economics of a corresponding well or field. Soil gas microseepage, measured at the surface, is the result of light hydrocarbon gases in a reservoir being pressure-driven upward to the surface along natural fractures in the subsurface.

A general rule-of-thumb concerning soil gas surveys is that more soil gas sites per unit area are required in stratigraphic fairways than in structural fairways. However, some caution should be taken in this generalization, as there are few structural hydrocarbon accumulations that do not also have some stratigraphic variations in the reservoir.

Three regional surface geochemical soil gas surveys covering areas of 150, 53, and 209 square miles were conducted in the Hugoton Embayment of southeast Colorado and southwest Kansas. The surveys were conducted from 1987 to 1992 before there was the widespread development drilling as witnessed today. This paper describes various configurations for soil gas surveys that may be designed and discusses the type of exploration information that can be expected from each survey design from reconnaissance to detailed soil gas surveys. Examples will be drawn from the actual soil gas surveys in these areas.

The Hugoton Embayment provides an excellent petroleum basin with which to illustrate these methods for the following reasons: (1) simple tectonics with little faulting, (2) the gas microseepage is vertical, (3) shallow to intermediate depth productive horizons, (4) wide range of types of soil gas surveys, (5) the area contains both oil and gas trends, each having different unit spacing, (6) the resultant oil and gas production in these trends is in the “giant field” category, (7) the actual concentrations of the free soil gas microseepage in these areas has very low magnitudes so that the background concentrations approach zero, and (8) the oil and gas accumulations are predominantly stratigraphic, providing an additional impetus to use geochemical data in this type of high-risk exploration play.

## BASICS OF SURFACE SOIL GAS SURVEYS

In its simplest mode, soil gas samples can be collected from a depth of four feet by means of a hand-held collection probe into a small volume (125 ml) glass sample bottle. These simple collection techniques do not require elaborate logistics, in addition to providing low collection costs, enabling rapid collection, and being generally unobtrusive to the environment.

The general objective of soil gas surveys is to collect and measure microscopic concentrations (microseeps) of methane, ethane, propane, and butane found in the void spaces of near-surface soils that overlie subsurface petroleum reservoirs. These gases are the lightest and most volatile constituents in crude oil, condensate, and natural gas reservoirs and because of this characteristic are the most important components to quantify and map.

A most important requirement for mapping these natural seeps is that the laboratory analytical instruments must have the capability to detect very low concentrations, in the parts per billion (ppb) range, for methane, ethane, propane, and butanes.

gas surveys have been employed in the exploitation or development stages of a play or field. Soil gas surveys have also been documented to be beneficial during the secondary recovery efforts in a particular field much like the current employment of 3-D and 4-D seismic surveys for these purposes.

Soil gas sample density per unit area determines whether a regional soil gas survey is a reconnaissance survey or a detailed survey. In a detailed survey the sample density should be commensurate with the expected prospect areal extent or well spacing of a particular play. Special high-density soil gas spacing has been used in surveys conducted for the development drilling of fields and later in secondary recovery efforts.

Reconnaissance surveys are typically employed in the frontier or semi-mature exploration stages of a concession or basin. There is less justification for a reconnaissance survey in a mature basin. Because reconnaissance soil gas surveys are the least costly exploration technique, they should be applied in series fashion with the more costly exploration techniques (gravity, magnetics, reconnaissance 2-D seismic) following later. However, exceptions do occur. A reconnaissance survey conducted across the Powder River basin in 1976 resulted in the discovery of the Hartzog Draw field (second largest field in this mature basin).

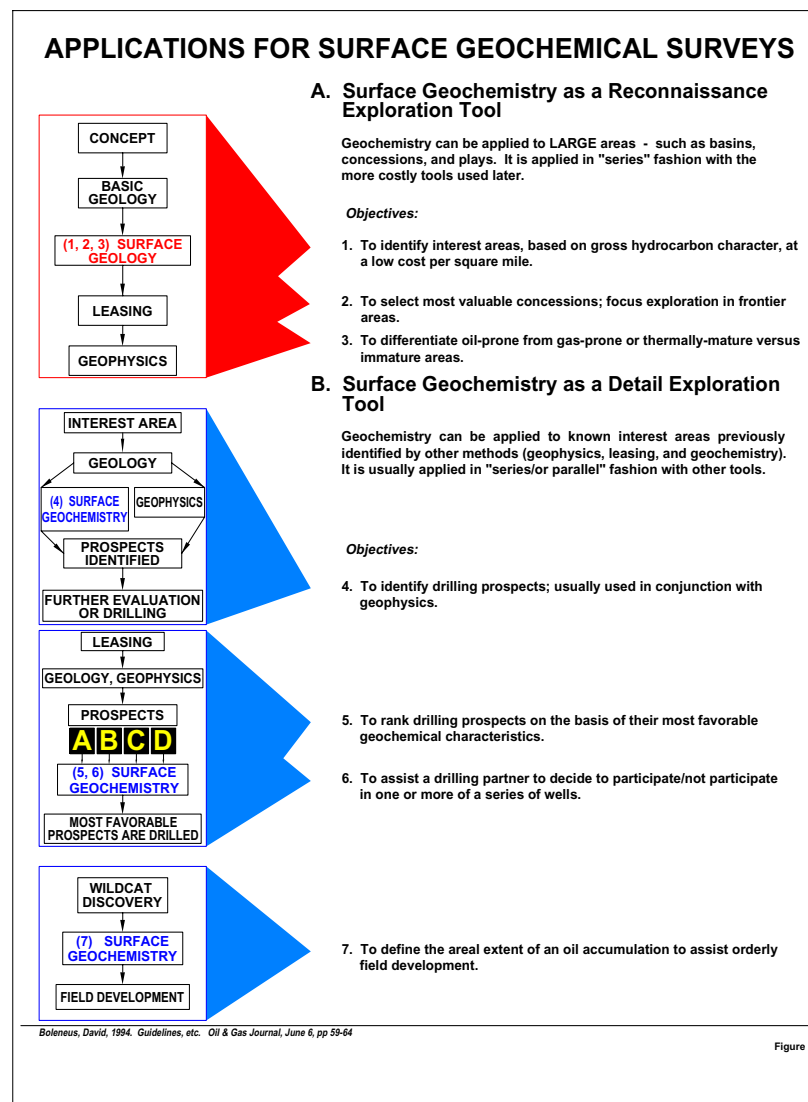
Detailed soil gas surveys are used in later exploration stages to acquire additional exploration information in areas of interest delineated by a reconnaissance survey. Detailed soil gas surveys are typically applied in a parallel fashion with other exploration methods (wildcat wells, detailed 2-D seismic grids, 3-D seismic).

An additional benefit of soil gas surveys is the capability to differentiate (using compositional ratios) between oil-prone or gas-prone fairways in a particular concession or basin or whether certain areas are thermally over-mature or immature. The concept and application of compositional ratios has been discussed in detail by Jones and Drozd (1983) and Jones et al. (2000).

Interpretation of soil gas data involves presenting the geochemical dataset within the most current and detailed geological and geophysical framework available. The magnitudes of the four light gases may be presented many different ways for interpretational presentations:

- (1) Presenting the microseep magnitudes in a profile graphic.
- (2) Presenting the microseep profile in conjunction with a subsurface geologic cross-section or a seismic line.
- (3) Presenting a group of microseep profiles as a fence-diagram graphic.
- (4) Presenting the microseep magnitudes in the form of an interpretative contour map.
- (5) Presenting the microseep magnitudes in the form of a dot map where the diameter of the dots (at each soil gas site) is directly related to the light gas magnitudes. This presentation gives an unbiased interpretation as opposed to a contour map.
- (6) If compositional ratios of the microseeps are used, then the predicted hydrocarbon (oil, condensate, gas) is indicated by color-coding within the magnitude dot maps mentioned above.
- (7) Presenting the microseep magnitudes in the form of a Pixler Plot.

Anomalous concentrations of methane, ethane, propane, and butanes detected at the surface are always real seeps, since active flux is necessary to overcome near surface interfering effects.



Soil gas surveys may be used at any stage of exploration in a petroleum basin – whether in the frontier stage of an unexplored basin or in the development stage of a mature basin. An excellent summary that illustrates the variety of different stages in the application of soil gas geochemistry has been discussed by Boleneus (Figure 1). If employed very early in basin exploration, soil gas surveys can provide justification for purchasing "trend acreage", or if geophysical data is lacking, can be used as further criteria for strengthening a subsurface lead.

Soil gas surveys may be classified as reconnaissance, detailed, regional, or local. The particular survey conducted must be tailored to the exploration objectives.

Regional surface geochemical soil gas surveys may be conducted at any stage in basin exploration – frontier, semi-mature, or mature. Local soil

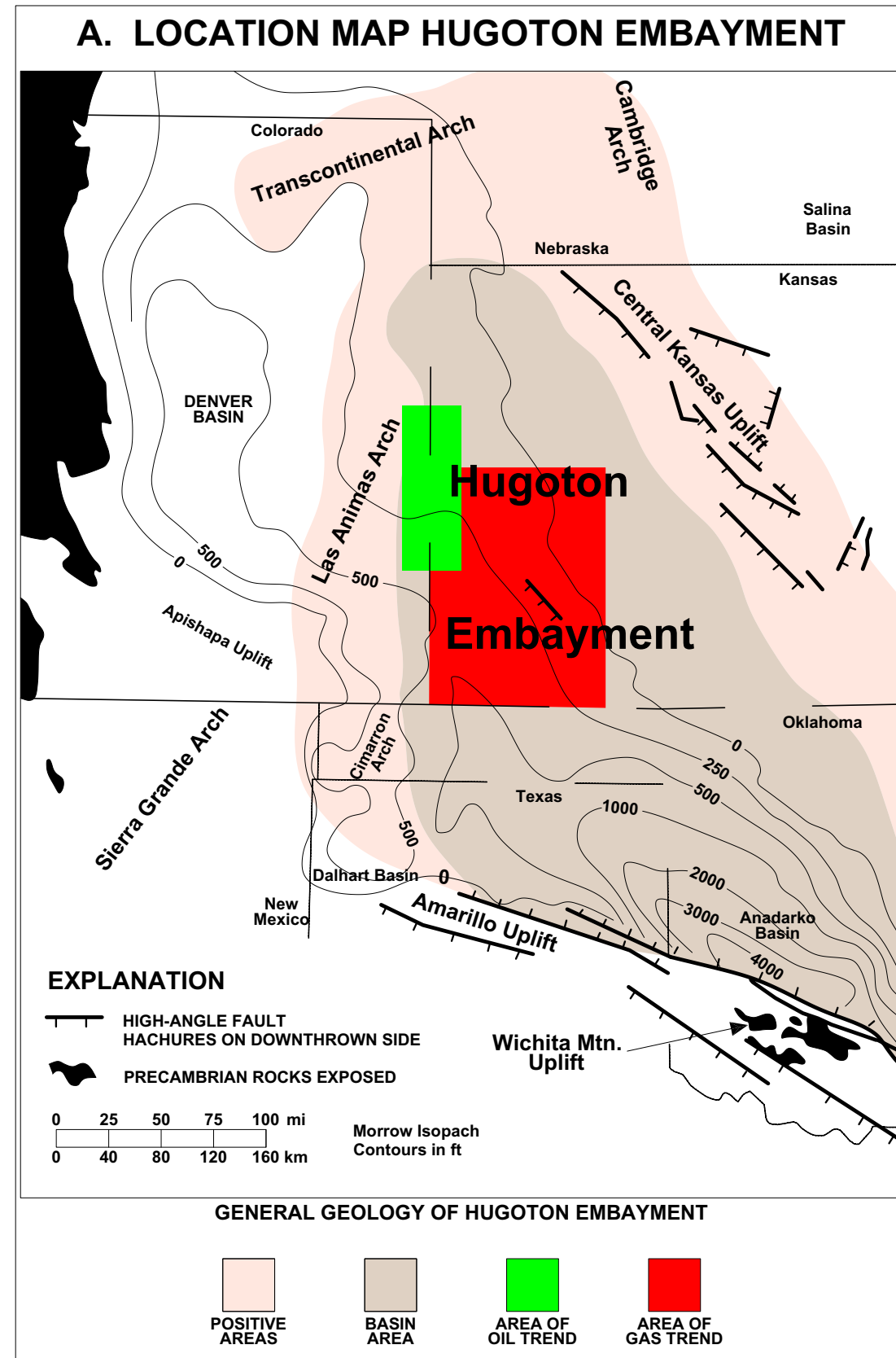


Figure 2

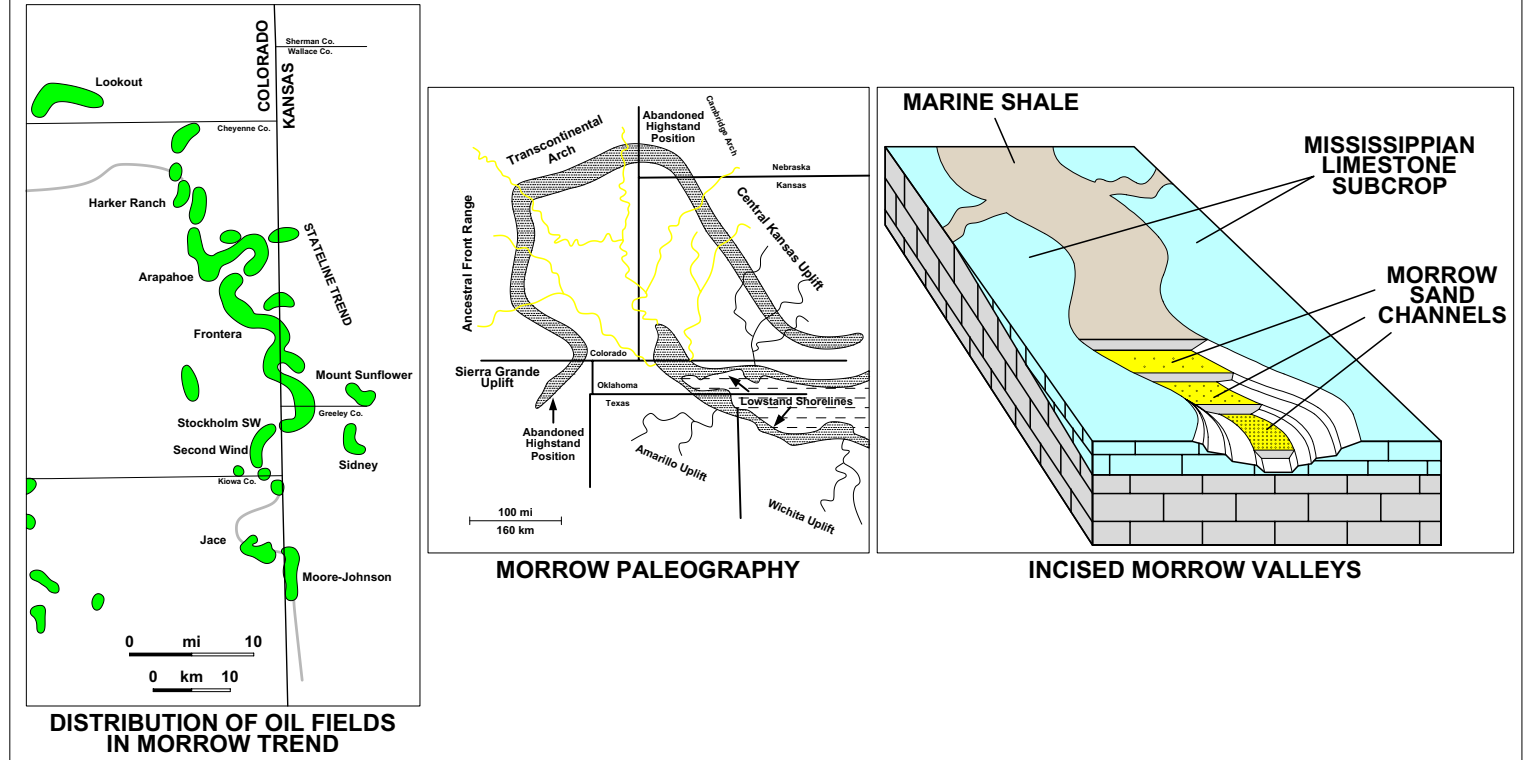
### GENERAL GEOLOGY OF THE HUGOTON EMBAYMENT

The Hugoton Embayment of southwest Kansas and southeast Colorado, shown in Figure 2A, is a wide, southward-plunging Paleozoic syncline of about 12,000 square miles that is bounded on the west, north, and east by uplifted areas. The Hugoton Embayment is the shallower, northward extension of the deeper Anadarko Basin of western Oklahoma and the Texas Panhandle. The Hugoton Embayment is bounded on the west by the Las Animas Arch, on the north by the Transcontinental Arch, and on the east by the Central Kansas Uplift. Sedimentary rocks thicken towards the center of the basin and southward to about 9000 feet near the Kansas-Oklahoma border.

The USGS has recognized 25 different petroleum plays in the Hugoton Embayment and Anadarko Basin (USGS, 1995). Every Paleozoic system that is represented in both these basins has produced some hydrocarbons. The province overall produces primarily gas. According to recent production data, compiled by the USGS, the province has produced more than 2.3 BBO and 65.5 TCFG since the early 1900's. Stratigraphic trapping mechanisms are the most common, combination types less common, and structural types the least common. Pennsylvanian and Permian reservoirs have produced the largest volumes of hydrocarbons to date.

The two petroleum plays discussed in this paper are the Pennsylvanian Morrow Sand Oil Trend and the Permian Chase Carbonate Gas Trend illustrated in Figures 2B and 2C, respectively.

## B. PENNSYLVANIAN MORROW SAND OIL TREND



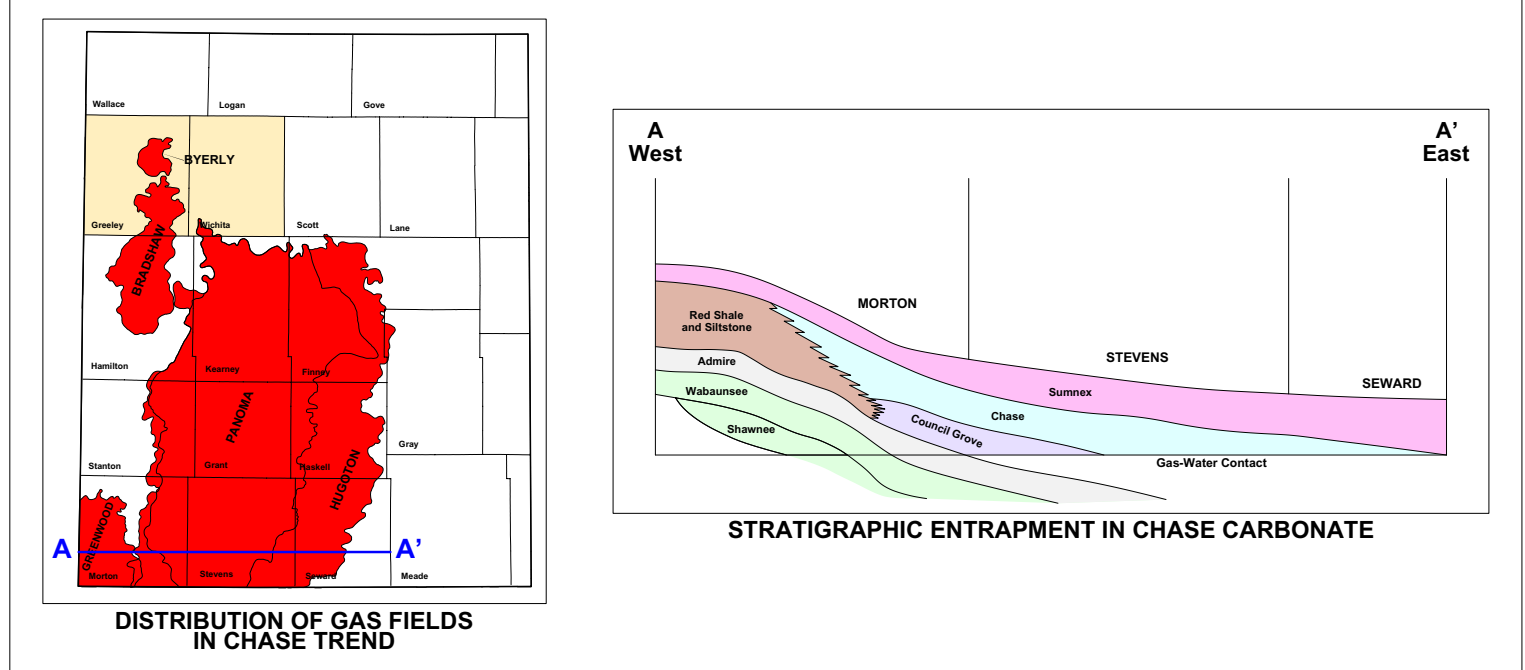
## Pennsylvanian Morrow Sand Oil Trend

Pennsylvanian Morrow fluvial sand channels developed both within and along the margins of the Morrow paleobasin during major regressive events in Early Pennsylvanian time (Figure 2B). There are five recognized regressive-transgressive cycles within the Upper Morrow Formation (Bowen and Weimer, 2003). River valleys were incised into either underlying Lower Morrow or Upper Mississippian limestones and were subsequently progressively filled with fluvial sands, estuarine sands, and finally, marine muds. The distribution of Morrow Sand channels within the incised valleys is commonly very complex, sometimes involving cross-cutting relationships. Later channel stages are frequently incised into earlier ones. The portion of the Morrow Trend mentioned in this paper is commonly referred to as the Stateline Trend and the complex of fields extends for about 60 miles in a north-south direction along the Colorado and Kansas state boundary (Figure 2B). The collection of fields in this complex will have an ultimate recovery of more than 100 MMBO and 500 BCFG.

Regional dip at the top of the Morrow is to the east-southeast. Drill depths to the Morrow reservoirs ranges from 5000 to 5500 feet. Average cumulative production from wells in this trend has ranged from 40,000 to 155,000 BO per well.

A comprehensive compilation of 23 papers on the fields within the Morrow oil trend over the Las Animas Arch and Hugoton Embayment was published by the RMAG (Sonnenberg et al., 1990). Further details of the area may be found in Bowen, 2001. Recently, an excellent summary of the Morrow sequence stratigraphic framework and the relational aspects to reservoir geometry and geology and reservoir performance was presented by Bowen and Weimer (2003).

## C. PERMIAN CHASE CARBONATE TREND



## Permian Chase and Council Grove Carbonate Gas Trend

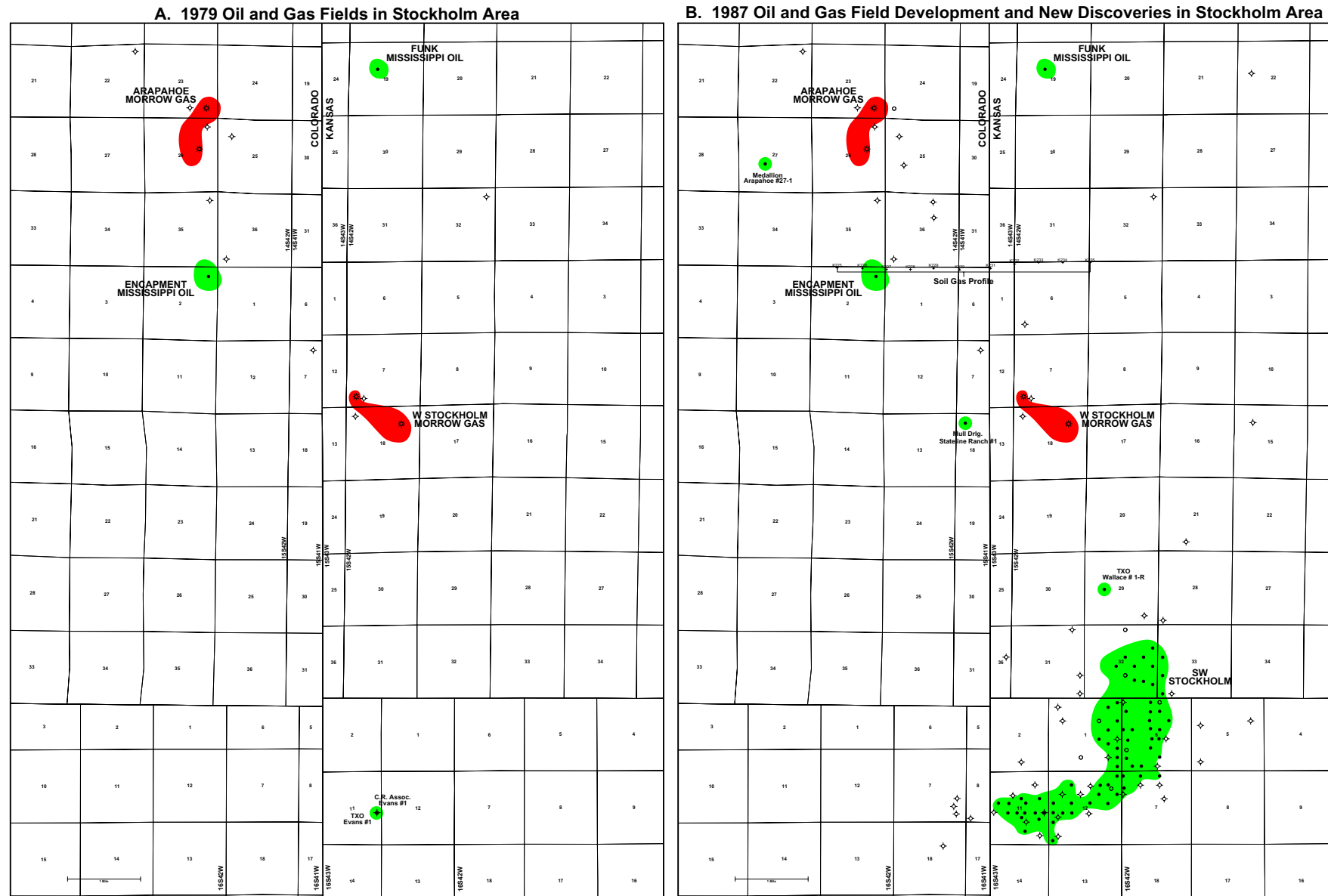
The Permian Carbonate Gas Trend (Chase and Council Grove Groups) in the Hugoton Embayment is the most prolific and important hydrocarbon play in this petroleum province. The major gas fields of this area – Hugoton, Panoma, Greenwood, Bradshaw, and Byerly have produced a total cumulative of 27 TCFG. The natural gas accumulations in these fields are due to stratigraphic entrapment caused by a facies change in the Permian Chase and Council Grove Carbonate reservoirs where they grade from limestones and dolomites in the east to nonmarine red beds in the west (Figure 2C). The upper seal for the gas reservoirs are provided by anhydrites and shales of the overlying Sumner Group.

Regional dip of the Permian Carbonates is to the east-southeast. Average drill depths of the gas reservoir at Byerly Field, in the extreme north of the Hugoton Embayment, range from about 2750 to 2900 feet. Cumulative gas production from individual wells in Byerly Field has ranged from 30 MMCFG to 3,572 MMCFG.

The stratigraphic entrapment of oil and gas in these two plays, relatively shallow depth, and highly variable porosity and permeability of the reservoirs are factors which favor the application of surface soil gas surveys as an important exploration method to reduce risk in exploration, exploitation, or development efforts in these two plays. Examples of actual reconnaissance and detailed surface soil gas surveys in this petroleum province are discussed below.

Figure 2

Additional information on the Chase Carbonate may be obtained from the Kansas Geological Survey website and Bebout et al. (1993).



These four fields were discovered as a result of various exploration plays on low-relief structures.

By the end of 1986, SW Stockholm Field had been developed to the extent shown on Figure 3B. The field contained 53 wells and extended for four miles along the arcuate axis of the field. A history of field development was discussed by Shumard (1991). During 1987 there were three significant developments in the area: (1) TXO completed a one-half mile field-extension in March with the Wallace # 1-R. (2) In April 1987, Medallion drilled a Morrow oil new field discovery with the Arapahoe # 27-1 eight miles to the north of SW Stockholm Field. (3) In July 1987, Mull Drilling established a Morrow oil new field discovery with the Stateline Ranch # 1 well four miles north of SW Stockholm Field. These three wells, along with the wells of SW Stockholm Field had, in general terms, defined a Morrow sand oil fairway for a distance of 10 miles in a north-south direction (Figure 3B). A decision was made to conduct a reconnaissance surface soil gas survey in the area using 11 samples per section. A profile line of samples taken from this low-density grid will be used to illustrate the differences between profile versus surveys conducted on a grid pattern.

**Profile Line**

Eleven soil gas sites collected in a single east-west profile, 3.5 miles long, along a highway that was north of the well established Morrow oil production at SW Stockholm Field and about half way between the two new field discoveries is shown in Figure 3B. Typically, such a soil gas profile would have been placed along the trace of a geophysical seismic line if one was available. The ethane magnitudes shown on this profile indicate a possibility that the Morrow oil production fairway also extended between the two Morrow oil new field discoveries.

On the soil gas profile (Figure 3C) the ethane concentrations range from nine to forty parts per billion (ppb). Background concentrations of ethane occur at sites 225, 227, 228, and 235. The anomalous ethane magnitude at site 226 on the profile appears to be the result of gas microseepage from the one-well abandoned Encampment Oil Field (Mississippian). Anomalous ethane magnitudes at site 229 through site 234 (six sites) represent gas microseepage that appears to be from the subsurface Morrow oil reservoir. The anomalous ethane concentrations extend for a distance of 8800 feet (1.7 miles). This width is consistent with the maximum width of SW Stockholm field.

At this stage, an exploration well could have been drilled within the anomalous area, provided that the geochemical anomaly was supported by geology and/or geophysics, or a reconnaissance soil gas survey could be conducted on a uniform grid pattern in order to more rigidly define the suggested Morrow oil trend trend. Based on this encouraging data, a reconnaissance soil gas survey conducted over this area is discussed below.

**RECONNAISSANCE SOIL GAS SURVEYS**

Reconnaissance soil gas surveys typically are conducted over a large area with wide spacing between soil gas sample sites. The soil gas samples may either be collected along single line profiles or in a regular grid pattern. Examples of surveys conducted over oil fields in the Stateline Trend of the Morrow oil fairway will be used to demonstrate these concepts.

In 1979, TXO drilled the discovery well for SW Stockholm Field (and the Stateline Trend) at the location shown on Figure 3A. At this time, there were only four fields in the immediate area (Figure 3A). There were two one-well abandoned Mississippian oil Fields (Funk and Encampment Fields) and two Morrow gas fields (Arapahoe and W Stockholm Fields).

Figure 3

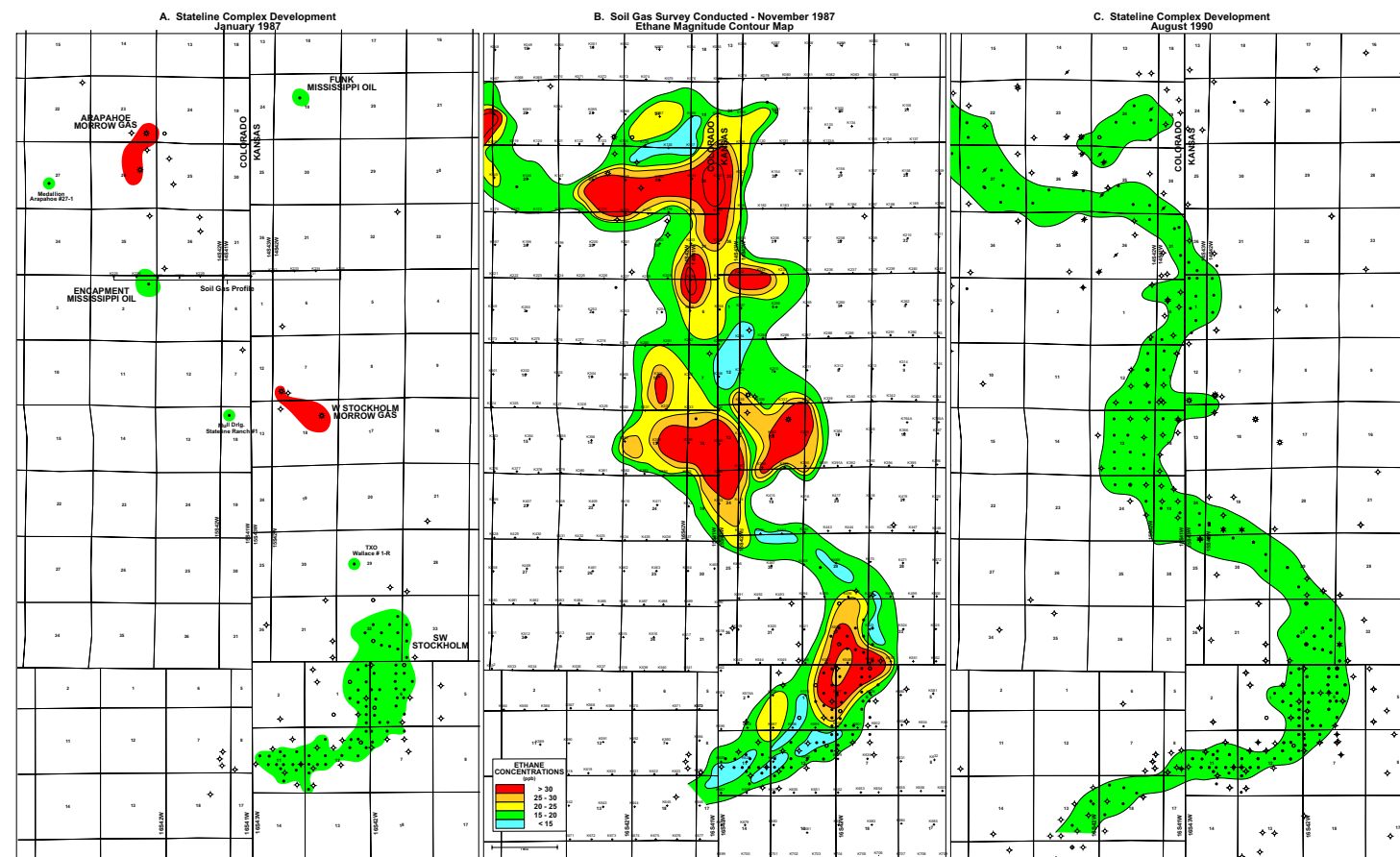


Figure 4

### Reconnaissance Soil Gas Survey on a Uniform Grid

A reconnaissance soil gas survey was conducted in November 1987 over an area of 150 square miles as shown in Figure 4A. The soil gas sample grid used (11 sites per section or square mile) was selected, both to make sample collection rapid by using the existing road network, and to limit the number of sites over such a large area. Because the well spacing of 80 acres per well had been established at SW Stockholm Field, the particular sample density used for this survey requires defining this survey as a reconnaissance survey. The area of the survey was also chosen to include other recent Morrow discoveries to the north of SW Stockholm Field, so that the soil gas data could be calibrated to the oil production with respect to magnitude and composition. A total of 798 soil gas sites were collected over this 150 square mile area. The interpreted soil gas data over the productive trend is illustrated by the ethane magnitude contour map shown in Figure 4B. It can be clearly seen that as early as 1987 (and prior to), the soil gas survey had accurately defined the general areal extent of the productive Morrow incised valley as would be confirmed by development drilling three years later in 1990 (Figure 4C). It can also be discerned that, at this sample density, that the soil gas data is inadequate for use in determining 80-acre drilling sites. Thus, the selected density for this survey conducted in 1987 was at the minimum threshold required to provide useful exploration information. This portion of the Morrow Stateline Trend, to date, has produced a total of 34 MMBO from 299 development wells. A retrospective analysis of this soil gas survey was previously discussed by Dickinson et al. (1994)

A number of untested soil gas anomalies still exist in the remainder of the survey area to the east of the Stateline Trend. These untested soil gas anomalies exhibit similar magnitudes and areal extents as the anomalies mapped within the Stateline Trend. Substantiation that these untested soil gas anomalies do indeed outline areas of additional Morrow oil potential may be seen in the recent development of the Mount Sunflower and Sidney Morrow oil fields in Wallace and Greeley Counties, Kansas. As shown in Figure 5, these two Morrow oil fields now contain a total of 40 oil wells and have produced a total of 2.85 MMBO. Development drilling in these two new fields progressed from 1990 through 1999 and has been conducted by 13 different independent oil companies. The significance of this new Morrow oil production is that, together, the two fields have defined a new Morrow oil productive fairway that is about two miles wide and extends for seven miles in a north-south direction (Figure 5).

The new fairway is four miles east of the older Stateline Trend Morrow oil production. Although the productive area of these two fields is predominantly outside of the area of the 1987 reconnaissance soil gas survey, there are soil gas anomalies that border the current production at these two fields and suggest the possibility of even further extension of this newly established production in the Morrow oil trend. This is an excellent example of an area where a later detailed soil gas survey could be conducted and combined with an earlier reconnaissance survey. A detailed soil gas survey in this area would greatly enhance the exploitation/development efforts in this new Morrow oil trend.

Other important factors for consideration in dealing with soil gas surveys can also be shown and discussed from this data: (1) Calibration with established production, (2) Width of productive fairway in relation to sample density of the reconnaissance survey, and (3) Delineation of Morrow gas fairways.

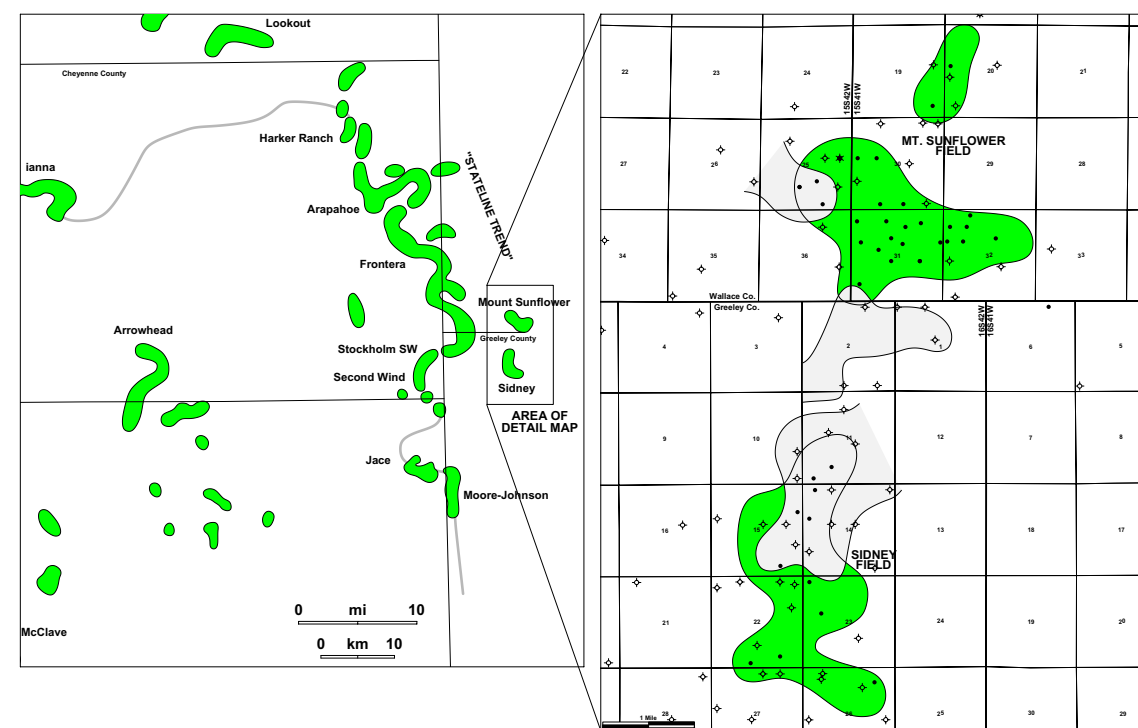


Figure 5

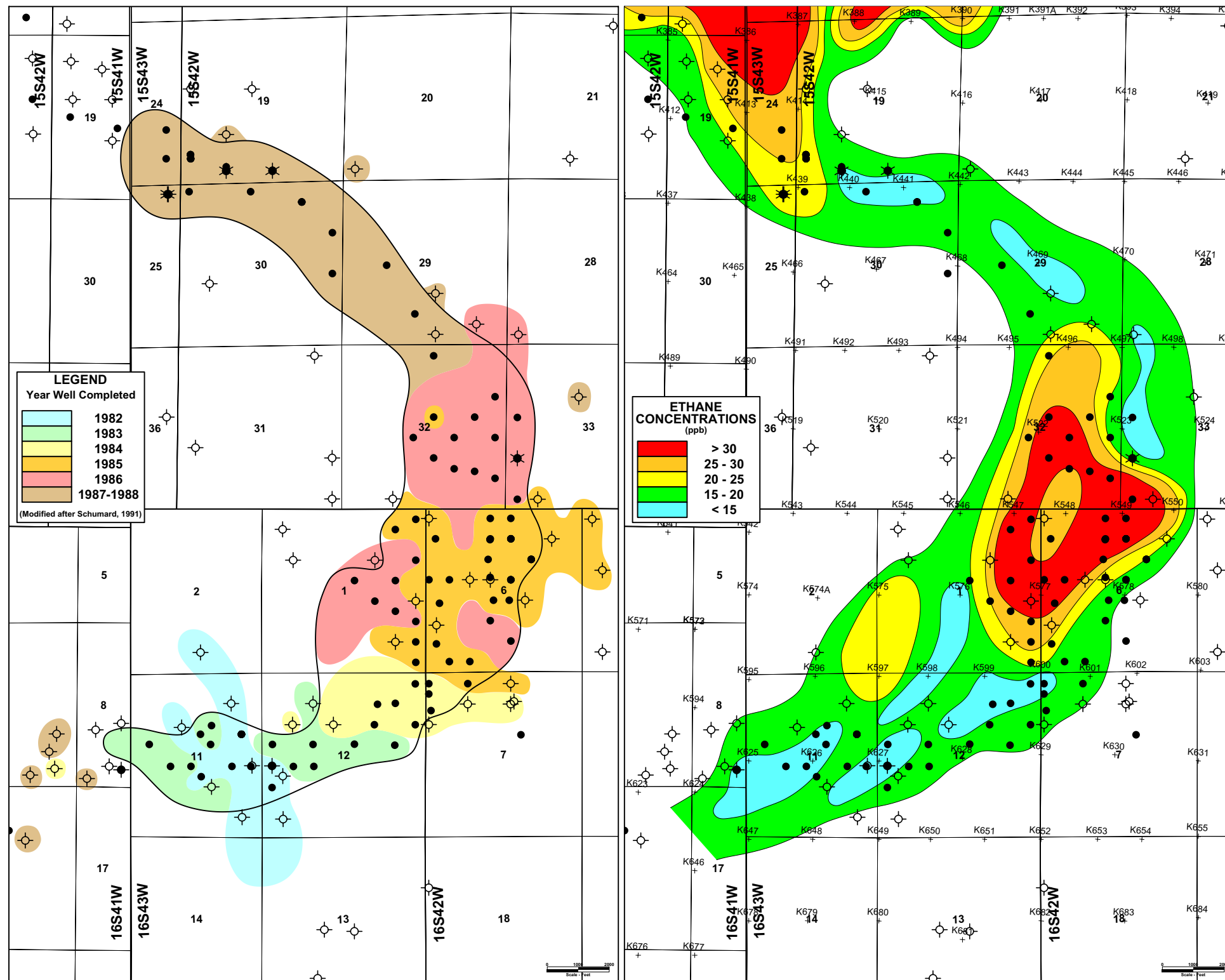


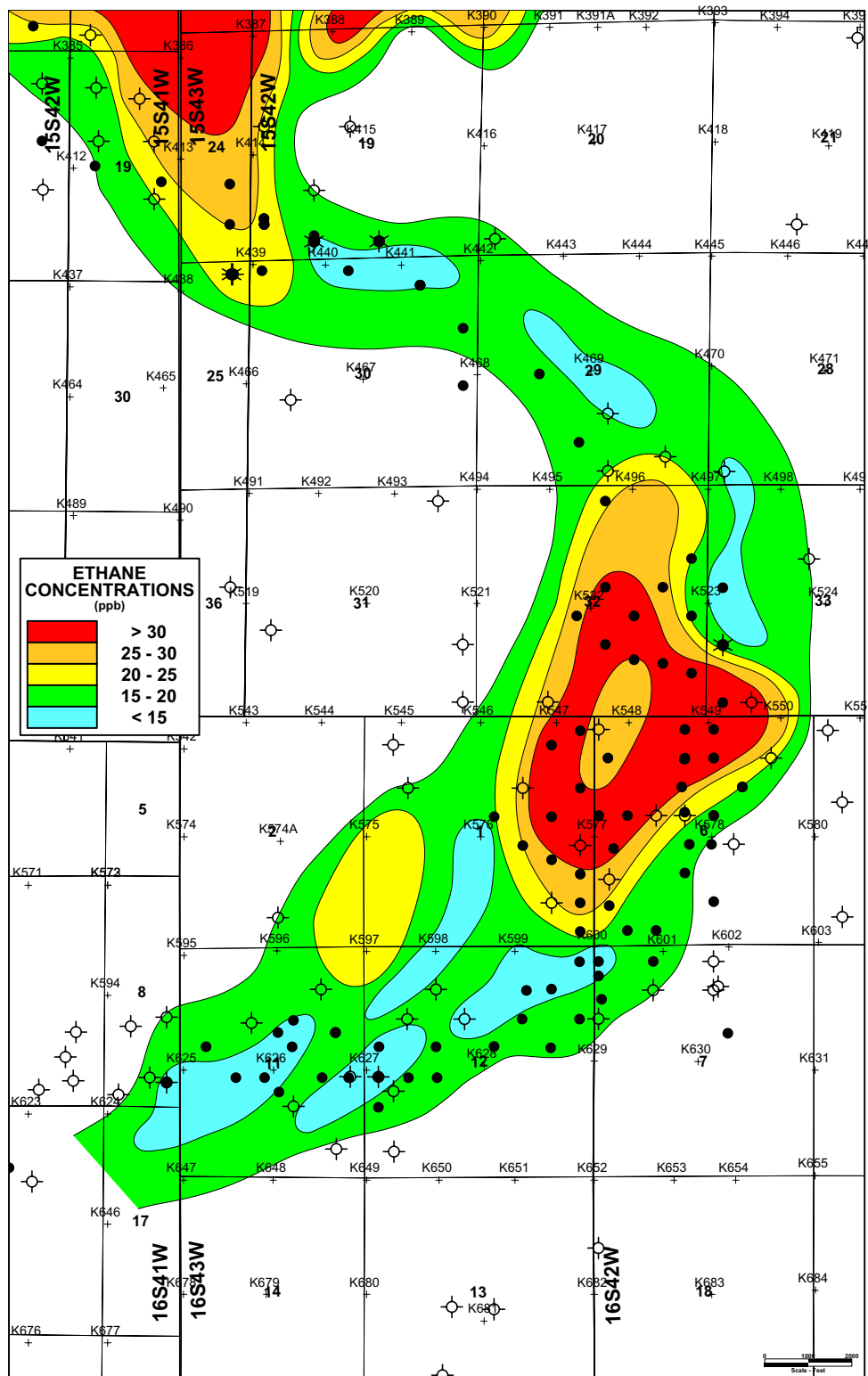
Figure 6

### Calibration With Established Production

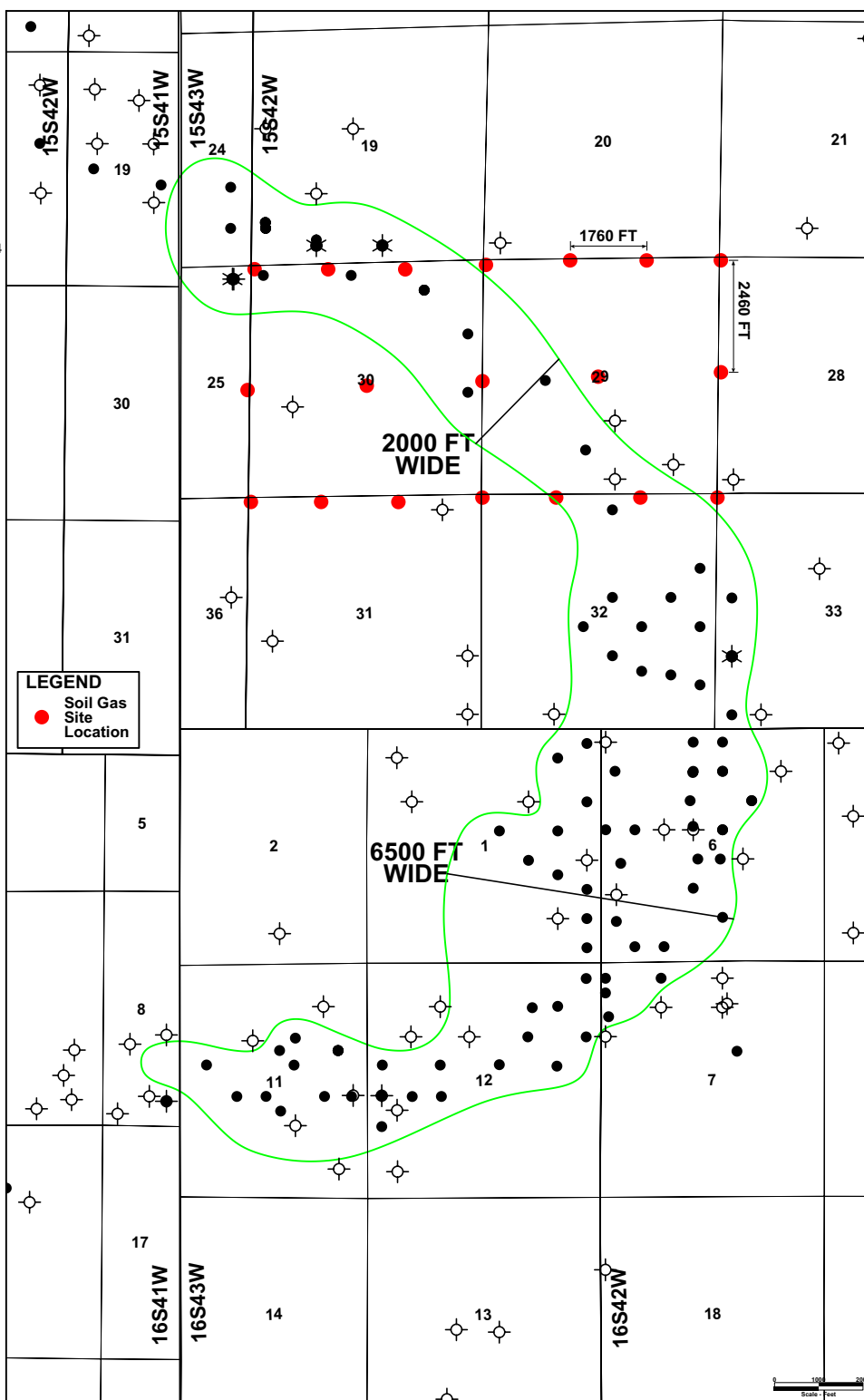
Figure 6 illustrates ethane soil gas concentrations over SW Stockholm Field and shows why caution should be used when selecting productive areas for calibration purposes. The production at SW Stockholm Field, as shown in Figure 6A, was first established in the southern portion of the field where wells were completed between 1982 and 1984 (Shumard, 1991). The area had reached the end of primary recovery and was in initial stages of waterflood when the soil gas survey was conducted in 1987. This means that the original reservoir pressures had been greatly reduced (from 1038 psi to 300 psi) in the southern area and the light gases that did reach the surface in this area were very low magnitude. In contrast, the wells in the central part of the field were completed during 1985 and 1986. Compare the soil gas magnitudes (Figure 6B) in the southern portion of the field with those in the central part of SW Stockholm Field where the wells had been producing a much shorter period of time. The low ethane magnitudes observed over the north part of the field are discussed in the following section.



**A. Contour Map of Ethane Concentrations (ppb)**



**B. SW Stockholm Field Width of Incised Valley**



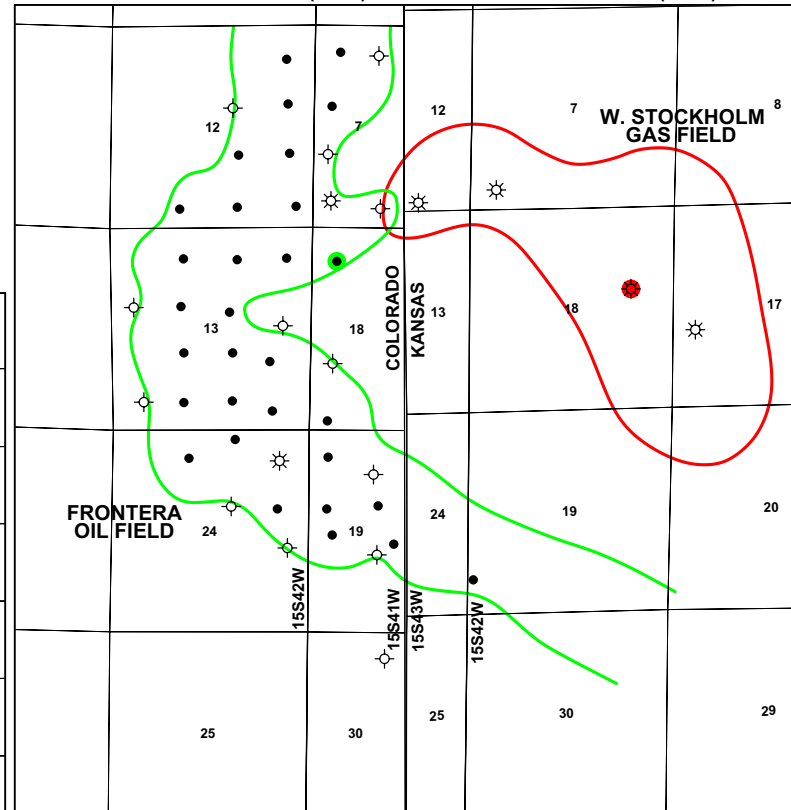
**Width of Productive Fairway in Relation to Sample Density of a Reconnaissance Survey**

As discussed in the previous section, low soil gas magnitudes were observed over the north part of SW Stockholm Field, however, this was not due to depleted reservoir pressures. The wells in this part of the field were completed in 1987 and 1988 (Figure 6A) which was during and after the time the soil gas survey was conducted. Figure 7 illustrates one way that a reconnaissance survey, with widely spaced soil gas sites, can fail to detect gas microseepage from a subsurface petroleum accumulation. The width of the incised Morrow valley at the extreme north end of SW Stockholm Field is only about 2000 feet (0.38 miles) wide compared to 6500 feet (1.23 miles) wide in the central part of the field. The spacing between the soil gas sites in this area is 1760 feet in an east-west direction and 2640 feet apart in north-south directions. Additionally, the orientation of the north end of the field is northwest-southeast which caused the field to transect the survey grid at the point of widest spacing between sample sites.

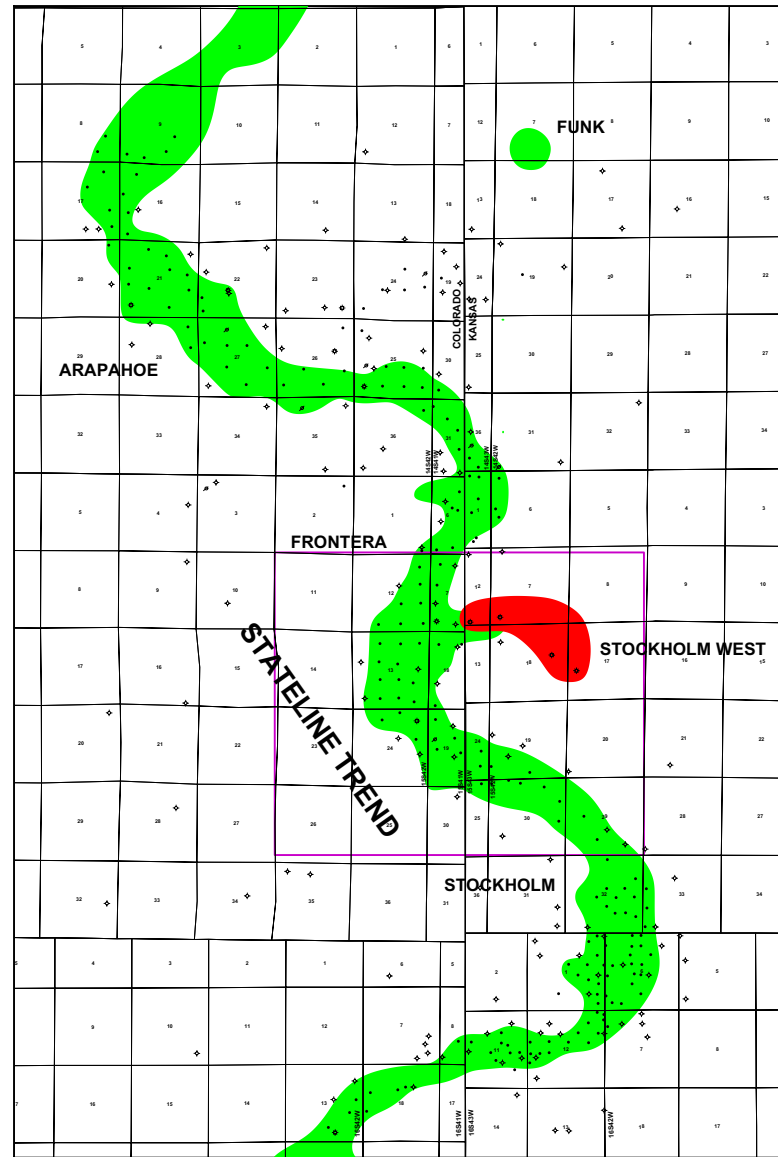
Because of both the width and the orientation of the north end of SW Stockholm Field, compared to the sample spacing of the reconnaissance soil gas survey, there were only low to moderate soil gas concentrations detected at sample sites over the field in the north area. These same circumstances also occurred at Second Wind Field to the southwest of SW Stockholm Field.

Figure 7

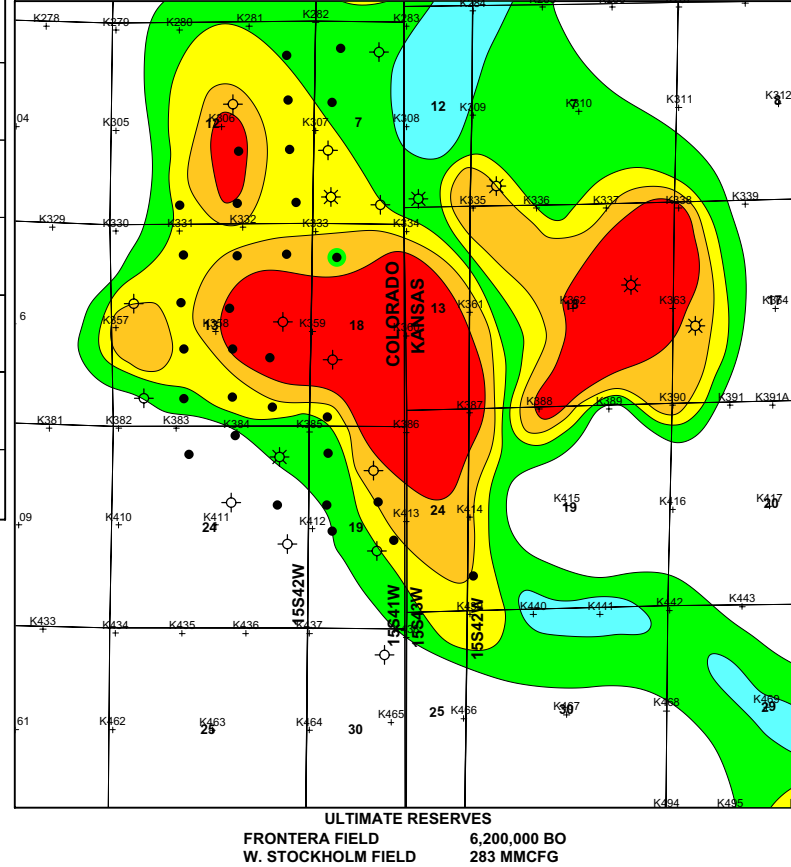
B. Frontera Oil Field (1987) and W. Stockholm Gas Field (1979)



A. Location Map



C. Ethane Concentrations (ppb) Contour Map



### Delineation of Morrow Gas Fairways

About a decade before the discovery and development of the Morrow Stateline Trend, TXO had conducted an exploration effort which targeted Morrow gas on low-relief Morrow structures in the general vicinity of the Las Animas Arch. One of the subsequent TXO Morrow gas discoveries in 1979 was the W. Stockholm (Morrow) gas field shown in Figures 3A and 8A.

TXO completed the discovery well for the field in April 1979. The Morrow gas reservoir was encountered at 5042 feet with 16 feet of net pay. The four-well gas field was developed on 640-acre spacing (Figure 8B). It appears that four dry holes were also drilled to delineate the limits of the field. Cumulative production, since 1979, from the four wells in this field has only been 283 MMCFG. The last reported production was in 1998. This gas field, considering the marginal cumulative gas production over a 21-year period and the eight wells drilled to define the field, would be considered as a non-commercial venture by most oil company economic guidelines.

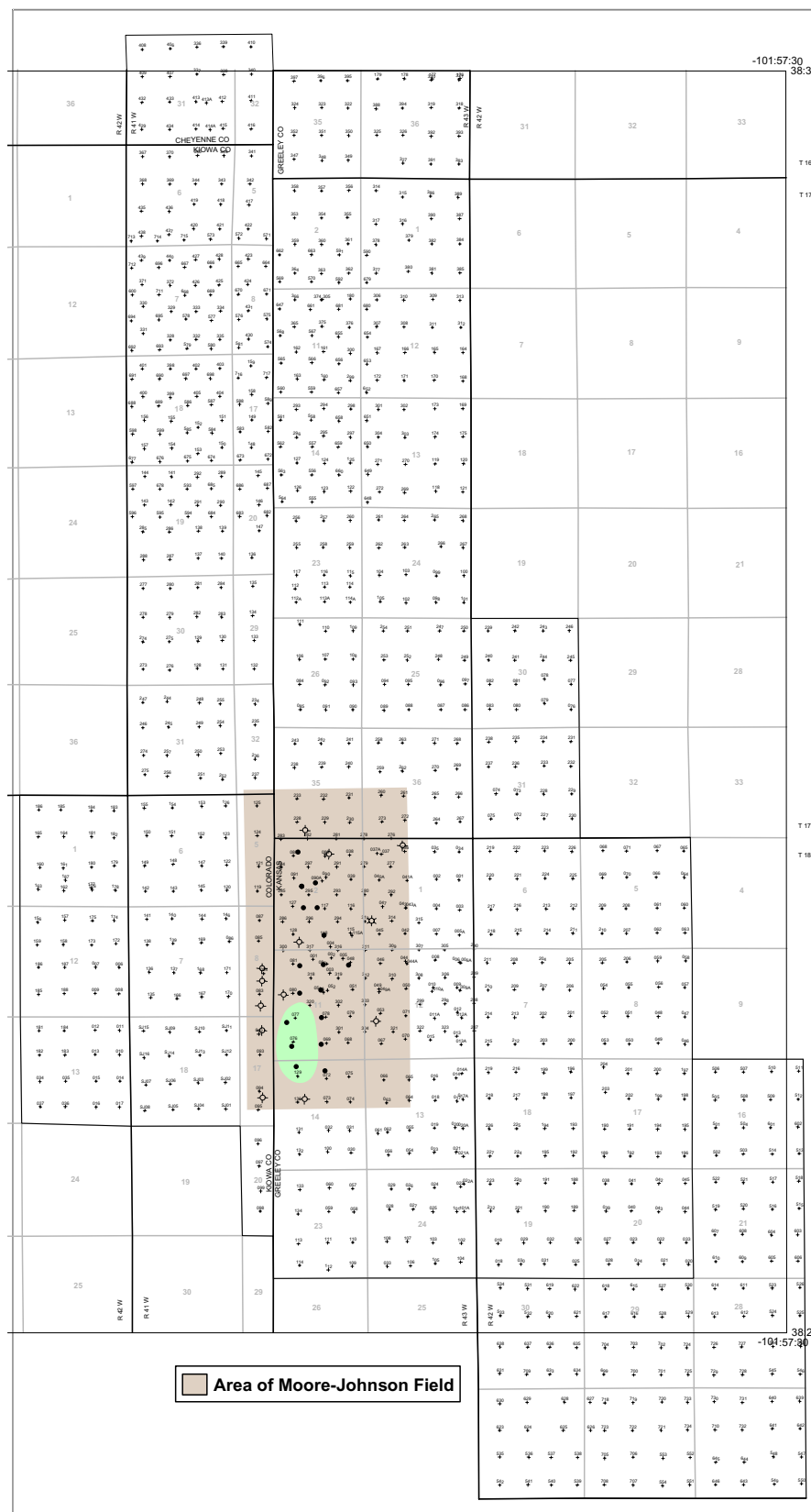
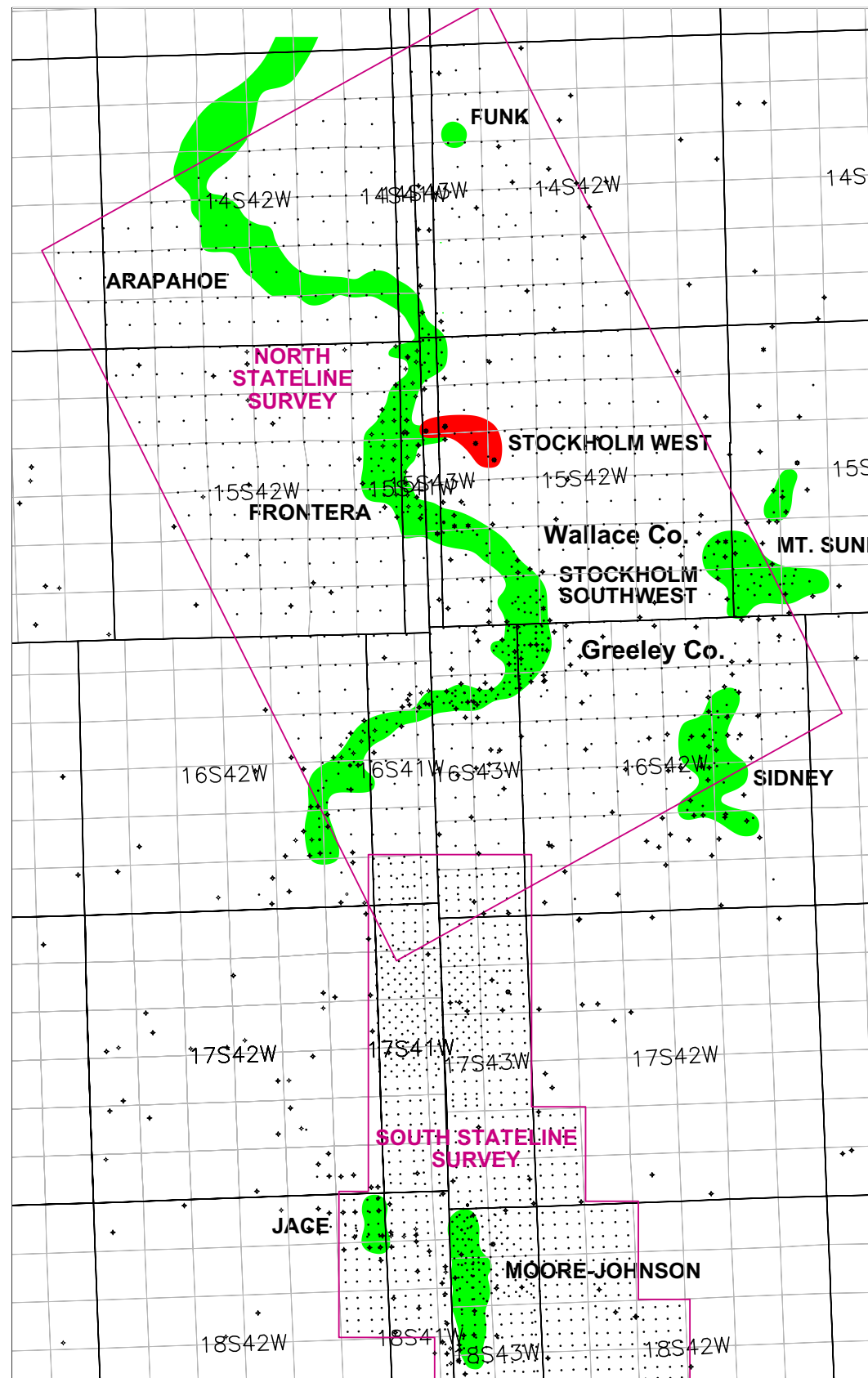
Figure 8C shows a contour map of the ethane soil gas magnitudes over the field area. The anomalous ethane microseeps very clearly defined the limits of the subsurface gas accumulation. Although this is not very significant production, it is interesting to note that the 1987 reconnaissance soil gas survey (designed for Morrow oil exploration) also clearly detected gas microseepage from this structural accumulation, even eight years after production had commenced. It is intriguing to postulate that if TXO had conducted this reconnaissance soil gas survey in 1979, not only would they have detected the W Stockholm gas field, but, also would have had an indication of Morrow oil potential (from the Stateline Trend soil gas anomalies) a full eight years before actual discovery and development of SW Stockholm Field.

This example illustrates two important points: (1) The spacing of the soil gas survey was considered a reconnaissance grid for targeting Morrow oil fairways, however, in a gas fairway with 640-acre gas units, this particular spacing would be considered a detail grid. (2) There is no direct relationship between the magnitude of a surface seep and the resultant volumetric hydrocarbon production or economics of a corresponding well or field. Compare the soil gas anomaly over W Stockholm Field to the soil gas anomaly over Fronterra Field one mile to the west. Both soil gas anomalies exhibit similar ethane magnitudes and areal extent (Figure 8C), however, the resultant hydrocarbon production from the two subsurface reservoirs is very different. W. Stockholm Field has a cumulative production of only 283 MMCFG and is a depleted field. The average per well gas recovery was only 71 MMCFG. Fronterra Field, on the other hand, has a cumulative production of 3.7 MMBO. To date, the average per well oil recovery is 107,000 BO. Secondary recovery efforts are still underway at Fronterra Field.

### Critique of Soil Gas Survey

As early as 1987, the soil gas survey accurately defined the general areal extent of the productive Morrow incised valley fairway, as would be confirmed by development drilling three years later in 1990. It can also be discerned that, at the particular sample density, the soil gas data could not have been used to determine 80-acre drilling sites. Additionally, because of the selected sample density, the very narrow portions of the incised valley (north part SW Stockholm and Second Wing) were not readily discernable. Therefore, the selected sample density was at the minimum threshold required to provide useful exploration information. The soil gas survey also appears to have detected microseepage from the Morrow gas and Mississippian oil fields in the area.

Figure 8



## DETAILED SOIL GAS SURVEYS OVER THE SOUTH STATELINE OIL TREND

Detailed soil gas surveys typically are conducted over a large area with a much denser spacing between soil gas sample sites than in a reconnaissance survey. The soil gas samples in a detailed survey may either be collected as infill in an area with previous sampling collected on a reconnaissance grid spacing or they may be collected in a new area with no previous sampling. Soil gas data collected years apart in the same area have been documented to be fully compatible with one another (Jones et al., 1985, Dickinson and Matthews, 1993). The example discussed in this case was conducted over the southern portion of the Morrow Stateline Trend in 1992.

### Surface Soil Gas Geochemistry

A Denver-based independent oil company decided to explore for Morrow oil in the Stateline Trend on a regional level and attempt to increase the drilling success rate by using surface soil gas geochemistry. The company first purchased a reconnaissance soil gas data set in the north part of the trend and later conducted a new detailed soil gas survey in the south area as shown in Figure 9A. At the time of the new survey (April 1992), the development drilling had been completed at Second Wind field and there were only three development wells at Moore-Johnson field in the south. The two combined soil gas surveys provided soil gas microseep data consisting of 1817 samples covering a total area in the Morrow Trend of 203 square miles.

The detailed soil gas survey in the south part of the trend, consisting of 1034 sites, was conducted over a very large area (53 square miles) from just southeast of Second Wind field in Cheyenne County, Colorado to two miles south and five miles southeast of Moore-Johnson field in Greeley County, Kansas (Figures 9A and 9B).

Realizing the limitations of the northern reconnaissance survey spacing (11 sites per section), this company increased the basic sample density in the southern survey to 16 sites per section (40-acre spacing). In addition as shown in Figure 9B, the company already had several prospects in the survey area and elected to increase the sample density in these areas over the standard spacing of 16 sites per section.

The high-density soil gas survey in the vicinity of Moore-Johnson field (Figure 9B) consisted of 106 sample sites over a four square mile area (24-acre spacing). It is this area which will be the focus of this paper.

The purpose of the regional detailed soil gas survey was threefold: (1) calibration of the soil gas survey to the production at Moore-Johnson field, (2) to aid in further exploitation and development drilling at Moore-Johnson field, and (3) to determine other areas along trend that exhibited similar anomalous soil gas microseepage and therefore would have Morrow exploration potential.

Figure 9

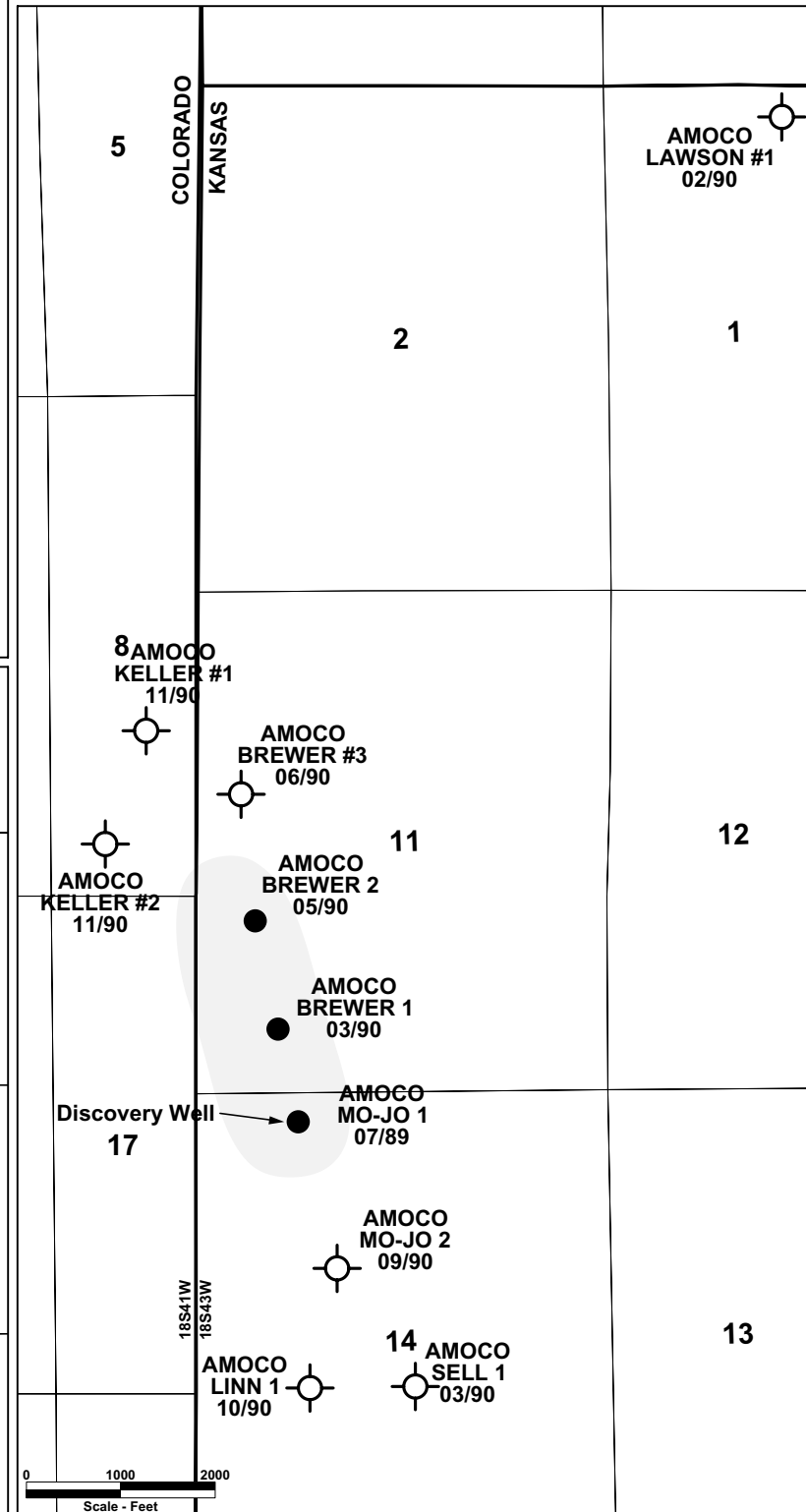
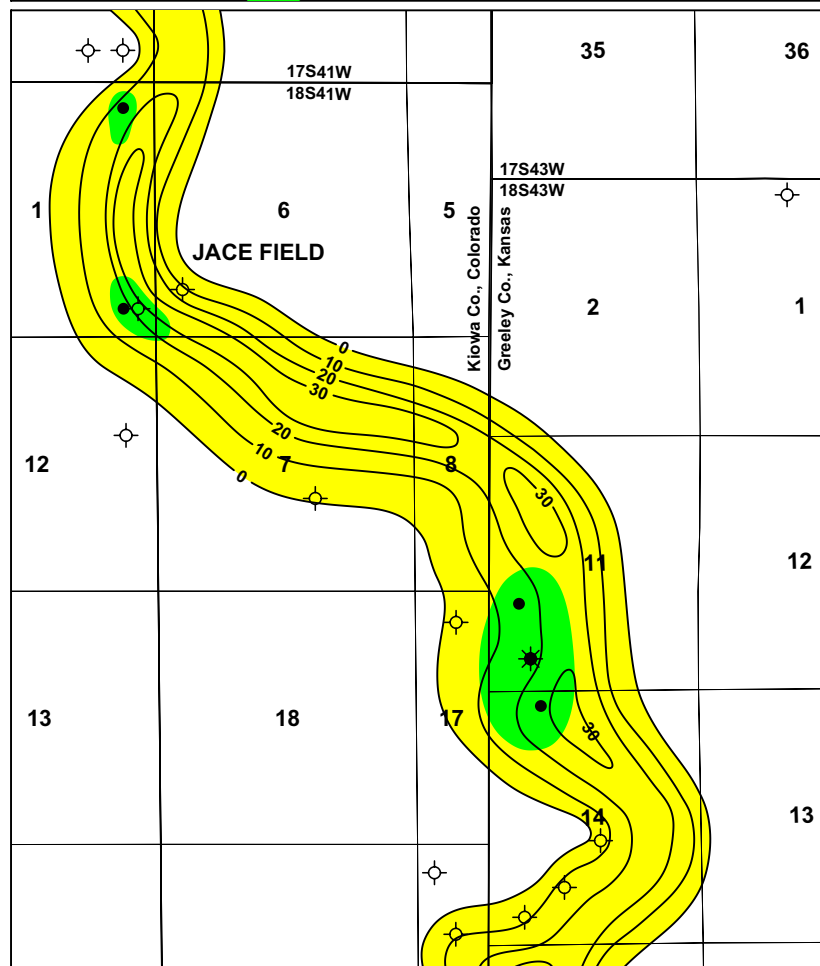
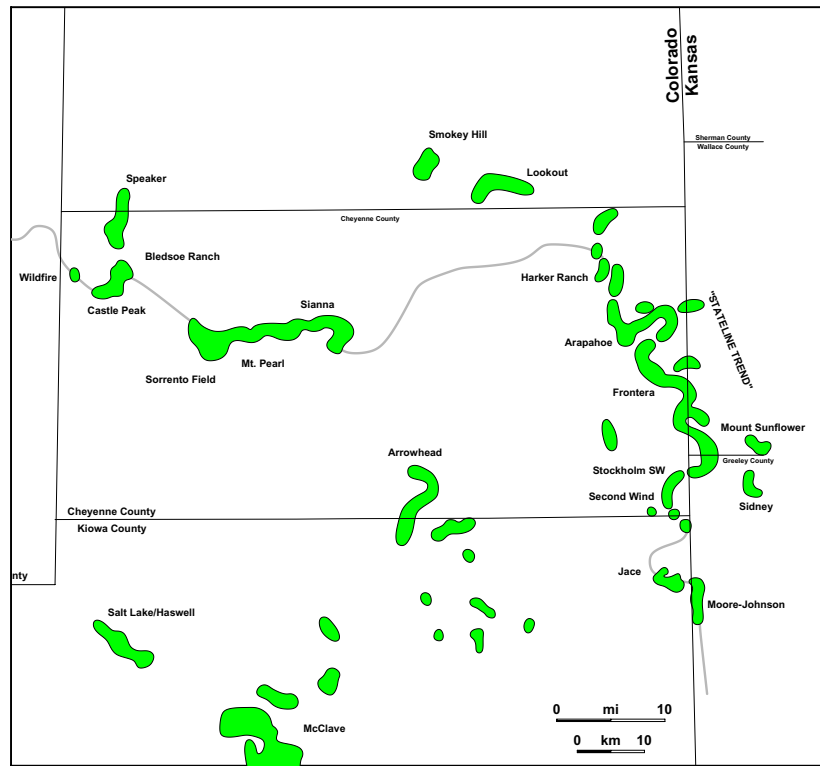


Figure 10

### Discovery of Moore-Johnson Field and Early Development Drilling in 1990

Moore-Johnson field in Greeley Co., Kansas was discovered by Amoco in October 1989 (Adams, 1990). At the time of the discovery, the Stateline Trend had been developed to the extent shown in (Figure 10A). The Amoco Moore-Johnson #1 was the discovery well for the field and was completed for 522 BOPD (Figures 10B and 10C). The well was completed in the sands of the V-7 valley fill sequence of the Morrow Formation. This equivalent interval in the Morrow Formation was initially named the Stockholm Sand during development of SW Stockholm field to the north. The sequence stratigraphy of the Morrow in relation to reservoir geology in the vicinity of Moore-Johnson field has been more recently discussed by Bowen and Weimer (1997, 2003).

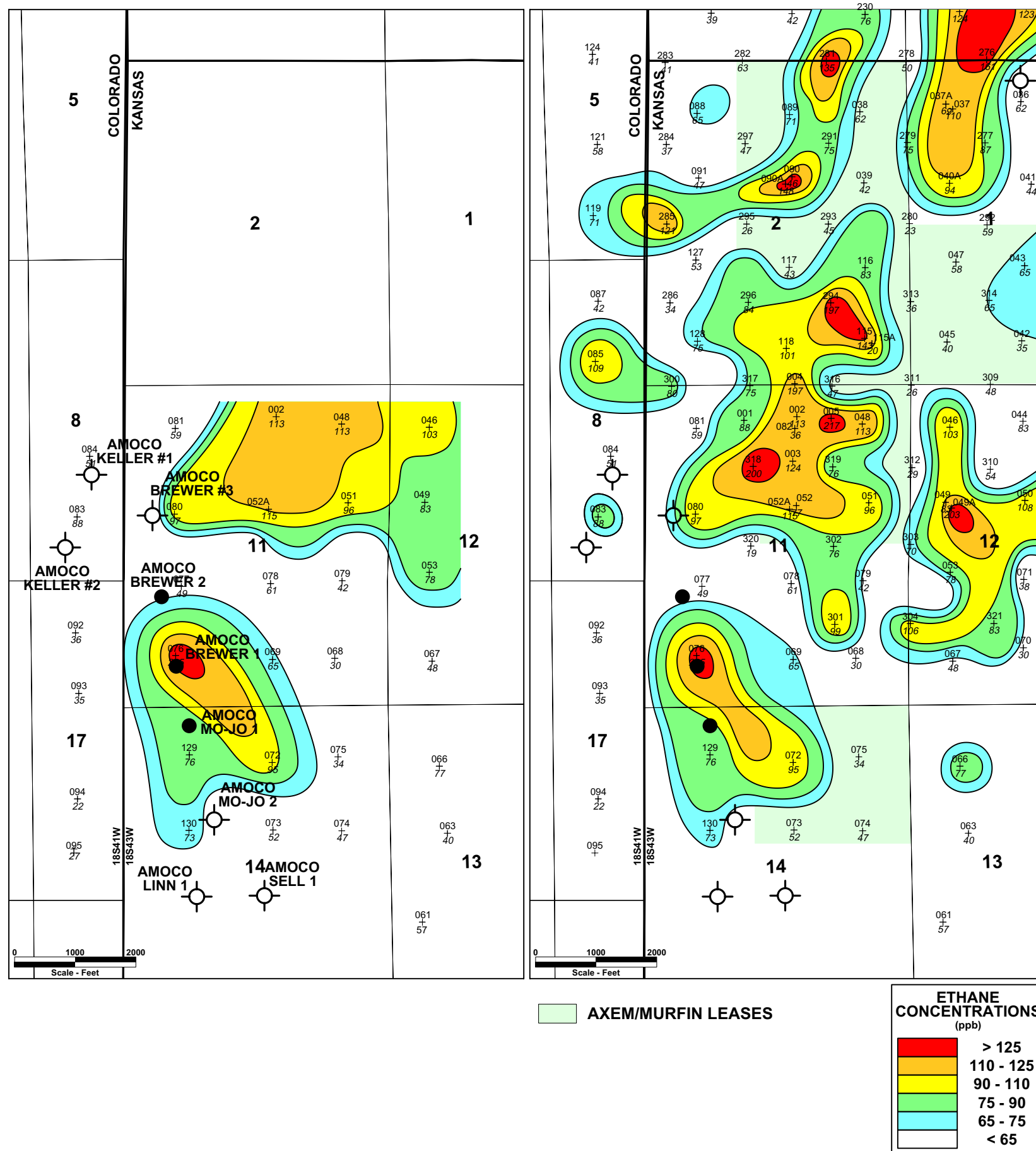
The Amoco combined geological and seismic conceptual model was that of a northwest-southeast oriented Morrow sand body (Figure 10B). The location for the discovery well was determined by identification of the basal upper Morrow fluvial incised valley on 2-D seismic lines supplemented by data from available well control (Adams, 1990). By May 1990, Amoco had extended the field to include three wells (Figure 10C). The Brewer #1 and Brewer #2 flowed at rates of 670 and 350 BOPD, respectively. In the first four months, the Moore-Johnson #1 produced 30,000 BO.

This was a very significant Morrow discovery in that it extended Morrow production for a distance of 10 miles to the south from Second Wind field of the Stateline Trend. Amoco attempts at further development drilling was another story, however.

As shown in Figure 10C, attempts to extend the field to the south by Amoco in 1990 resulted in three dry holes (Moore-Johnson #2, Linn #1, Sell #1). Two successful Morrow development wells were completed by Amoco to the northwest of the discovery well in March and May of 1990 (Brewer #1, Brewer #2). Attempts by Amoco to extend the field farther to the northwest resulted in three more dry holes (Keller #1, Keller #2, Brewer #3). Amoco also drilled another dry hole to the northeast in February 1990 with the Lawson #1.

The overall success rate, at the end of 1990, for development drilling in the Moore-Johnson field area was a disappointing 33%. This was considerably below previous industry standards in the Morrow Trend. Success rates for development of Frontera, SW Stockholm and Second Wind fields of the Stateline Trend were 73%, 68%, and 56%, respectively. There was no further drilling in the field area during all of 1991.

As will be shown later in the paper, had Amoco used soil gas geochemistry, in conjunction to seismic and subsurface geology, the six dry holes could have been avoided.



### Soil Gas Calibration Survey and Detailed Survey in Moore-Johnson Field Area

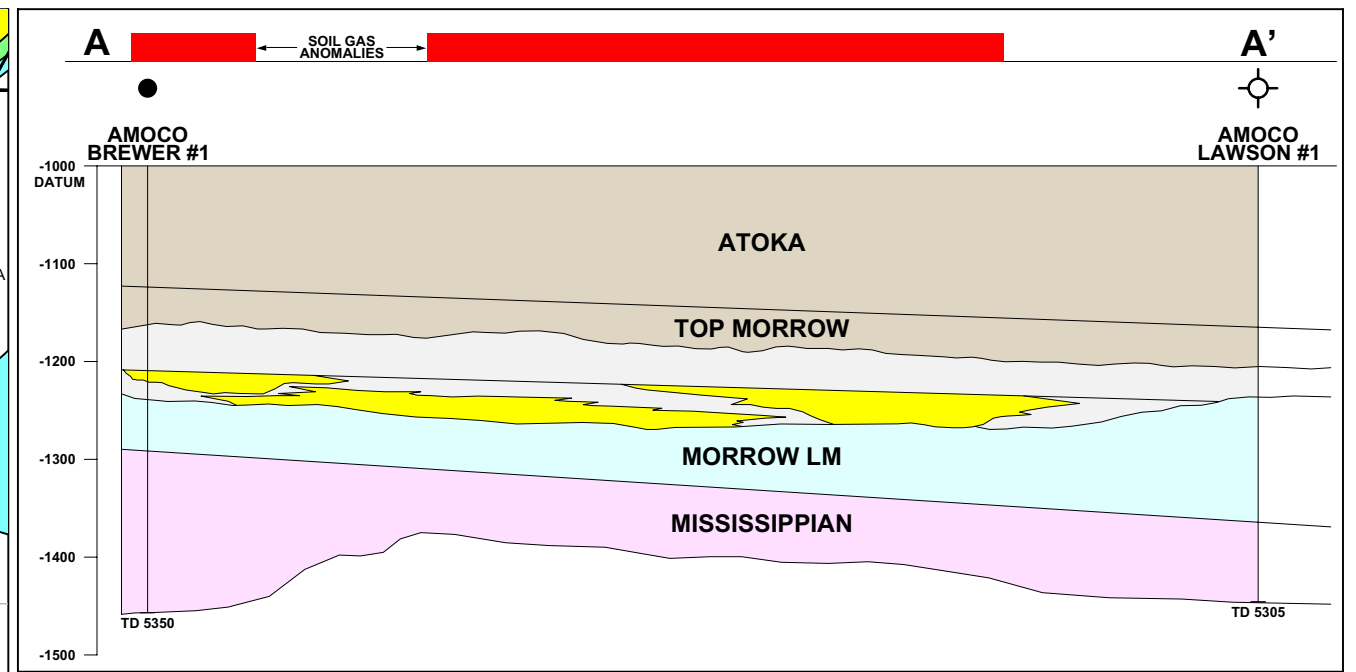
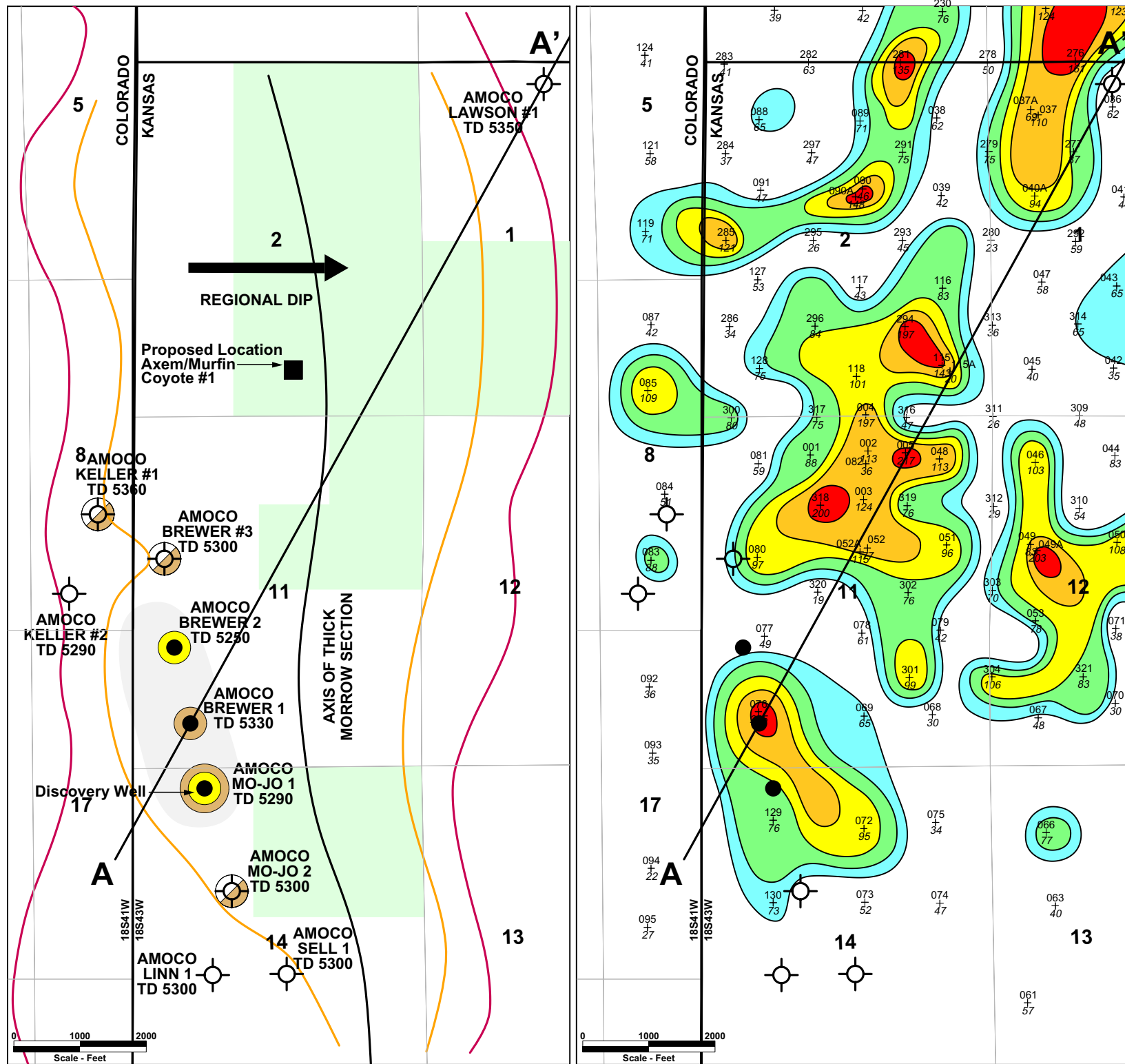
A soil gas calibration survey was first conducted over the three-well field and in the area of the 6 dry holes in April 1992 (Figure 11A). Because the field was being developed in 40-acre units, a sample density of 16 sites per section was selected. An ethane magnitude contour map of the soil gas data in the calibration area is shown in Figure 11A. As shown on the ethane magnitude contour map, low ethane magnitudes were observed in areas where the dry holes were drilled and the anomalous ethane values corresponded to the area of the three Morrow oil wells. There was no problem with reservoir pressure depletion at the time of the survey because of the limited production at that time.

The soil gas contour map for the calibration survey also indicated other areas of anomalous microseepage to the east and northeast of the three productive wells. The more detailed soil gas survey was extended into those areas to aid in further development drilling at Moore-Johnson field.

The initial sample grid of 16 sample sites per section was increased with infill soil gas sites as shown in Figure 11B. A total of 106 soil gas sites were sampled within the map area. The infill sample data significantly increased the detail of the microseepage anomaly pattern from that of the original calibration survey, as evidenced by comparing the two contour maps. Ethane magnitudes ranged from 22 ppb to 205 ppb within this area. The ethane magnitude contour map indicated anomalous microseepage over the Axem Resources and Murfin Drilling (Axem/Murfin) lease block in sections 2, 11, and 14.

The surface soil gas geochemical data was next integrated with the combined subsurface geology and seismic interpretations.

Figure 11



**Integration of Subsurface Geology, Seismic, and Surface Soil Gas Geochemistry**

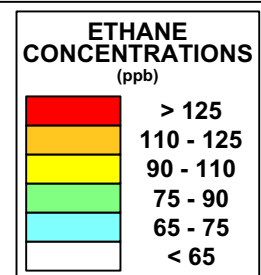
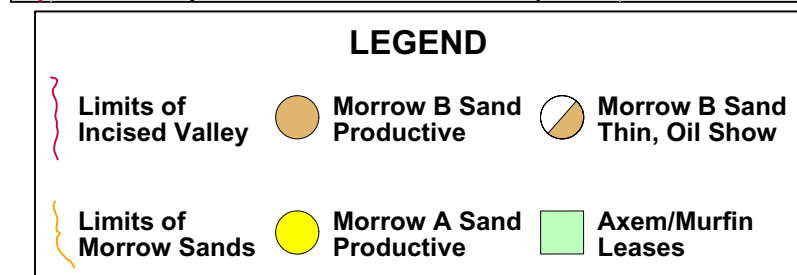
During the first half of 1992, Axem/Murfin integrated the combined subsurface geology and seismic interpretation with the surface soil gas data. The conceptual model for the Morrow trend, derived from the all the development of the northern Stateline Trend fields, was that the Morrow section (base of Atoka to top Morrow Limestone) was observed to thicken in the areas of maximum Morrow sand development and productive wells. In contrast, the Morrow section was much thinner, with non-deposition of Morrow sands, on the east and west flanks of the Morrow fields. This was the Axem/Murfin conceptual model at the Moore-Johnson area interpreted from the available well control and seismic data. The well control available at that time is shown in Figure 12A.

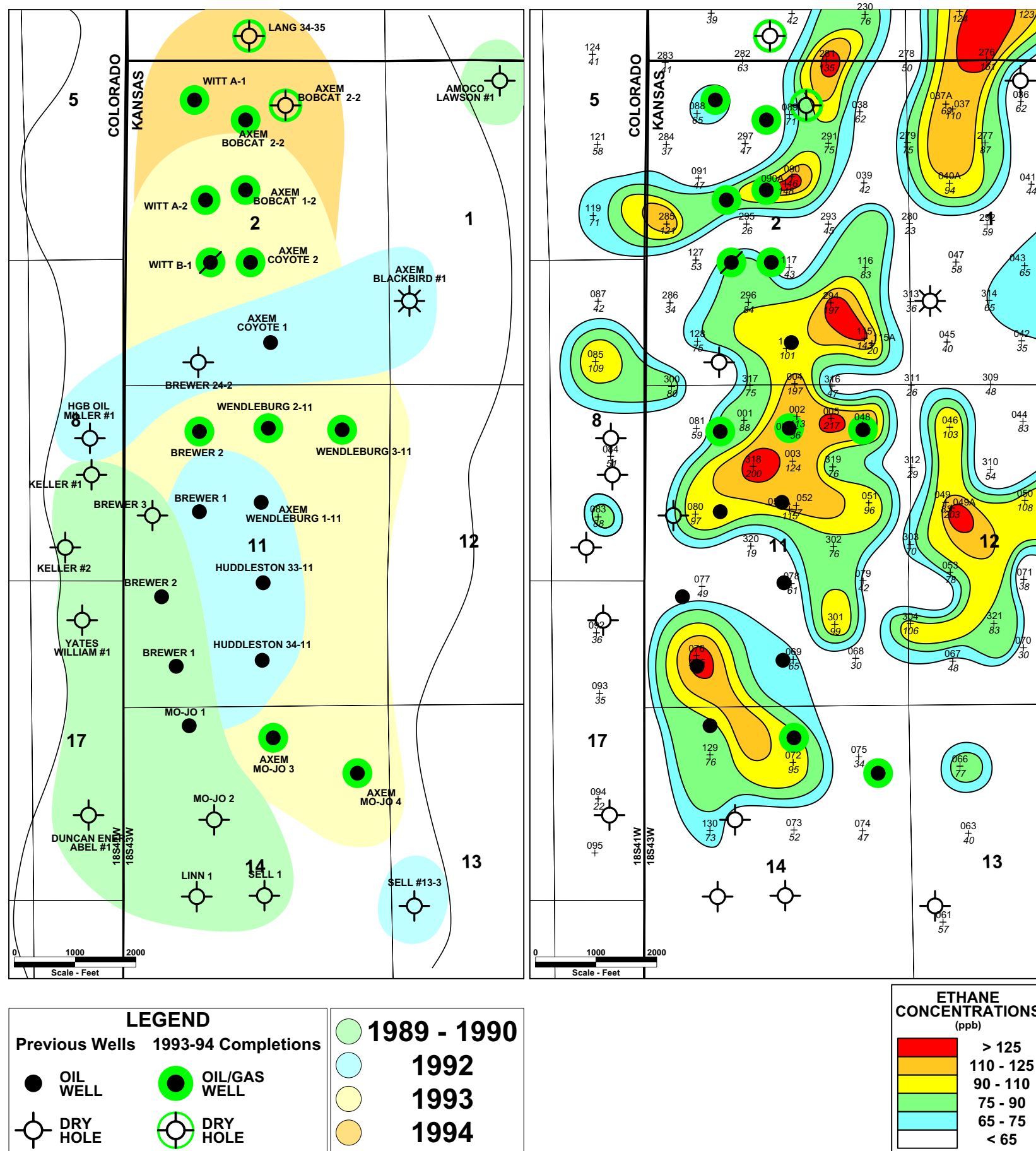
Subsurface data from the 10 Amoco wells in the area and seismic interpretation provided the Axem/Murfin concept of the Morrow incised valley boundaries, regional dip, and general axis of the depocenter of the Morrow valley as indicated on Figure 12A. Amoco had established production from 2 different Morrow sands (named "A sand" and "B sand") in their three wells. The Morrow completion zones in the three wells are as indicated on Figure 12A. Additionally, the Morrow "B sand" was encountered in three other Amoco wells with oil shows, however, the porosity/permeability and thickness of the sand precluded completion attempts in those wells. The Morrow sands were not present in the other four Amoco wells. The expected areal distribution of Morrow sands was interpreted as shown on the map. Axem/Murfin had interpreted the Morrow sands to be oriented north-south in the area as opposed to the previous Amoco concept of a northwest-southeast alignment. In the new interpretation, the Amoco productive wells were interpreted to be at the west, updip limits of a Morrow stratigraphic trap (Figures 12A and 12C).

The interpretation of the soil gas survey data is shown on Figure 12B. The ethane magnitude contour map indicated that the maximum gas microseeps were observed in the central portion of the expected Morrow incised valley and within the expected Morrow sand fairway (Figures 12A and 12B). The geochemical, geological, and geophysical data were all compatible with the conceptual model for a Morrow stratigraphic trap.

The Axem/Murfin acreage position was excellent. A location was staked for the Axem/Murfin Coyote #1 in section 2. The well was spudded July, 25, 1992

Figure 12





### 1992 DRILLING - MOORE-JOHNSON FIELD

Eleven wells were drilled in 1992 by 5 oil companies (Figure 13A). Only Axem/Murfin used the integrated approach of soil gas geochemistry with geology and seismic to select well locations. The locations of the wells drilled in 1992 are shown on Figure 13A. An ethane magnitude contour map (Figure 13B) illustrates the geochemical basis of Axem/Murfin decisions in selecting well sites. The following is the order in which the 1992 wells were drilled:

- 1 In April and May 1992, MW Pet. drilled two Morrow dry holes with the Brewer #24-2 and Sell #13-31 wells. Both wells were 4000-foot step-outs. Both well locations are in areas of background soil gas concentrations. No further wells were drilled by this company in this area
- 2 In August 1992, Axem/Murfin drilled their first well and completed the Coyote #1 as a Morrow oil well (Figures 13A and 13B). This was a very significant well in that it was a 4700-foot step-out extension for Moore-Johnson field. The well location was supported by a strong soil gas anomaly. The well confirmed the conceptual model established by integrating geochemistry with geology and geophysics.
- 3 Duncan Energy completed two direct offsets in October and November to the Amoco Brewer #1 and #2 producing Morrow wells. These two wells were only 1500-foot offset locations.
- 4 In November 1992, Axem/Murfin completed two Morrow wells with the Wendleburg #1-11 and Blackbird #1 wells. The Wendleburg #1-11 location was supported by a strong soil gas anomaly.
- 5 In December 1992, HGB Oil completed the Brewer #1 as a Morrow oil well. This location had been proven by the preceding surrounding wells to the west, east, and south.
- 6 HGB Oil, Yates, and Duncan Energy each drilled a Morrow dry hole in Colorado attempting to extend field production updip and to the west. There were now five dry holes in Colorado to the west of the field. All five well locations are in areas of low magnitude soil gas data.

By the end of 1992, Moore-Johnson field had produced 512,714 BO.

Figure 13

### 1993 and 1994 DRILLING - MOORE-JOHNSON FIELD

The locations of all the wells previously drilled through 1992 are shown on Figure 13A. An ethane magnitude contour map (Figure 7B) illustrates the basis of Axem/Murfin decisions in selecting well sites. The following are the 1993 wells that were drilled:

- 1 Marathon completed the Wendleburg #2-11 as a Morrow oil well in February 1993. This well was a direct offset to the Axem/Murfin Wendleburg #1-11 drilled three months previously in November 1992. This was the only lease Marathon held in the field area.
- 2 HGB Oil drilled three Morrow oil completions from March through July 1993 (Witt #A2, Witt #B1, Brewer #2). The wells were on the updip, west side of the field. The Witt #B1 only produced 1745 BO and is considered to be a dry hole.
- 3 Axem/Murfin drilled three Morrow oil wells in the north area with the Bobcat #1-2, Coyote #2, and Wendleburg #3-11. The Bobcat and Wendleburg well locations were in areas of anomalous microseeps.
- 4 Axem/Murfin drilled two Morrow oil wells in the south area with the Moore-Johnson #3 and Moore-Johnson #4 wells. The Moore-Johnson #3 well was completed in August 1993 and was located in an area of anomalous ethane concentrations.

By the end of 1993, Moore-Johnson field contained 17 Morrow oil wells and extended for 11,000 feet in a north-south direction and 3000 feet in width. Axem/Murfin had completed seven successful Morrow wells without a dry hole. At the end of 1993, cumulative production at the field was 780,549 BO.

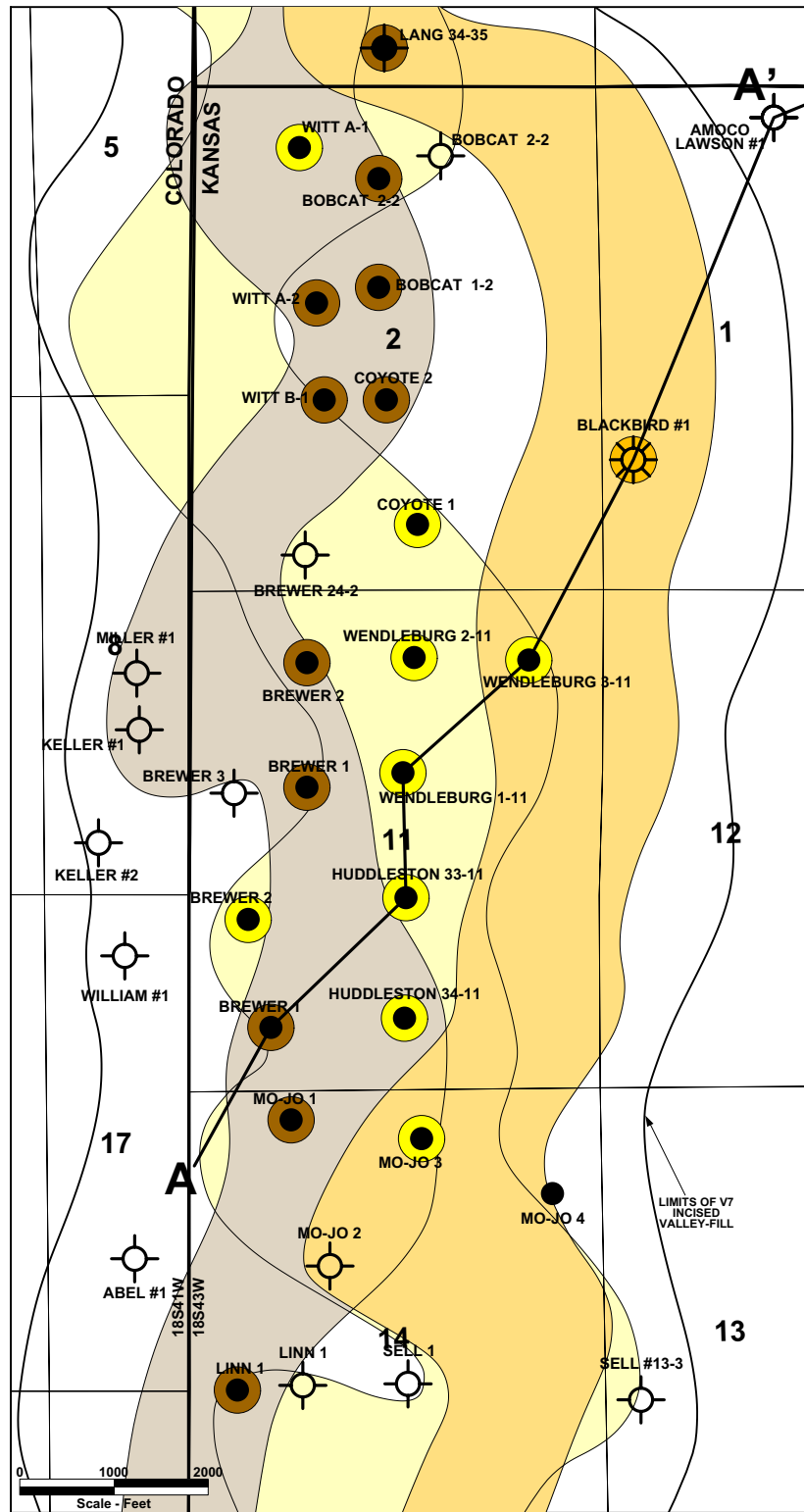
In 1994, four wells were drilled by three oil companies in the north area of the field. The following are the 1994 wells that were drilled:

- 5 HGB Oil drilled the Witt #A1 as a Morrow oil well in January 1994. The well location was on trend and 1500 feet from their Witt #A2 completion 6 months earlier.
- 6 Axem/Murfin drilled their first dry hole in the Bobcat #2-2 in January 1994. A 700-foot offset to the southwest, however, resulted in a Morrow oil completion. The Bobcat lease, to date, has produced a total cumulative of 170,646 BO from two wells.
- 7 Duncan Energy completed a marginal Morrow well with the Lang #34-35 in March 1994. After only producing 477 BO, the well was converted to an injection well.

Moore-Johnson field was fully defined by 34 wells. The major extension of the field only took 24 months. This is one of the shortest development periods for a comparative size field in the whole Morrow trend.

By the end of 1994, the cumulative production from the 19 Morrow wells in Moore-Johnson field was 980,152 BO.





Limits and Dimensions of Morrow V7 Sands		
Areal Extent	Thickness	Width
V7d	0 - 30 ft.	1800 - 2700 ft.
V7c	0 - 18 ft.	1300 - 2300 ft.
V7b	0 - 24 ft.	2300 - 3200 ft.

Morrow Well Completion Zones	
	V7d
	V7c
	V7b

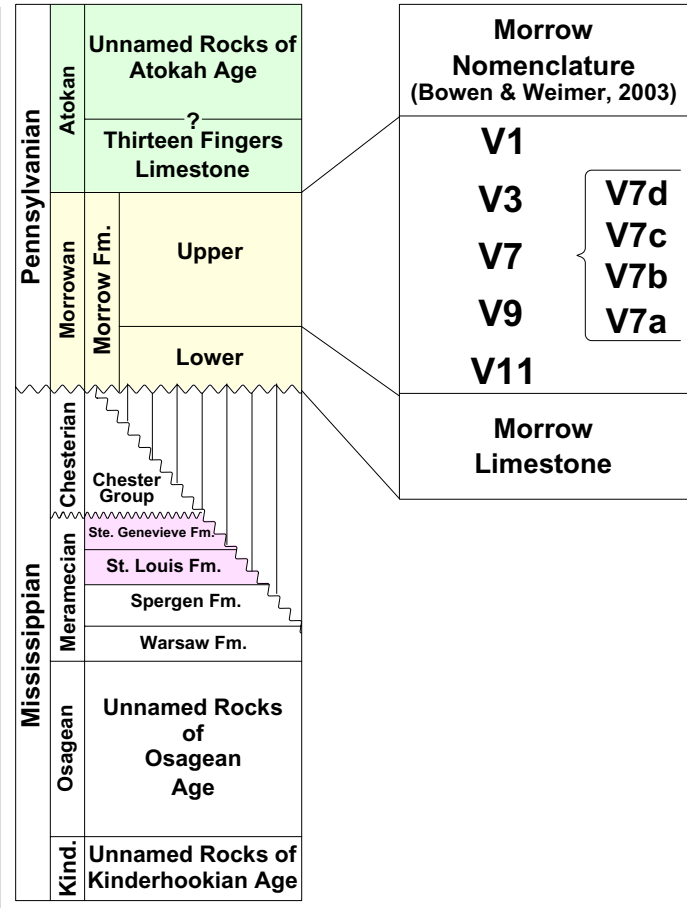
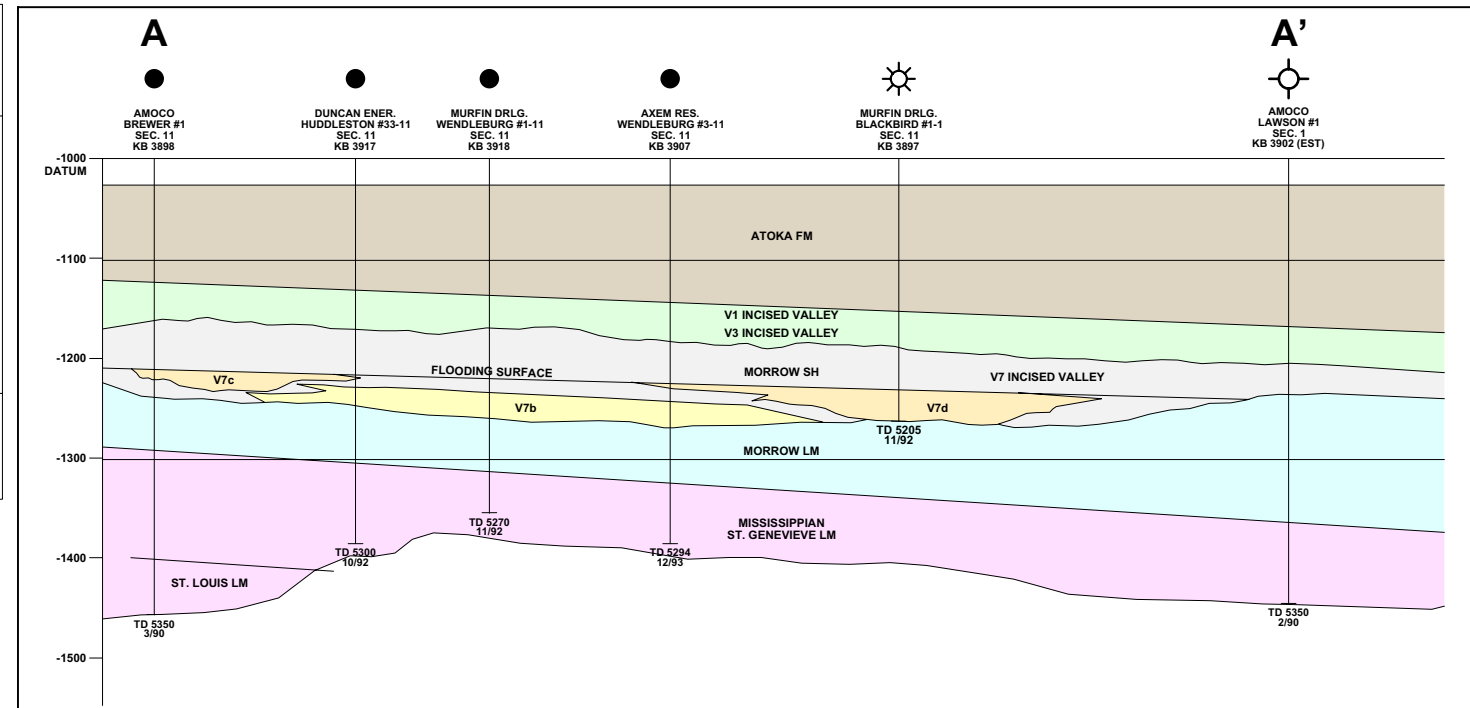


Table 1

**Moore-Johnson Field Parameters**  
(Revised after Adams, 1990)

Reservoir:	Morrow V7 Sandstone
Lithology:	Stratigraphic/structural
Type Trap:	Oct. 1989
Discovery:	5100-5200 ft.
Depth:	40 ac.
Spacing:	1290 ac.
Field Size:	16 ft.
Avg. Net Pay:	14 to 28%
Porosity:	22 to 9,990 md
Permeability:	13 to 47%
Water Sat.:	1040 psi
Pressure:	Gas cap expansion/
Reserv. Drive:	solution gas drive
GOR:	107:1 cu ft / bbl
Cum. Prod:	1,729,000 BO
Ultimate Prod.:	2,000,000 BO



**Subsurface Geology and Reservoir Performance**

Moore-Johnson field (Figures 14A, 14B, and 14C) has been discussed by Adams (1990) and more recently by Bowen and Weimer (1997, 2003). These last two papers document the Morrow sequence stratigraphic framework throughout the trend and relate it to the subsurface geology, reservoir geometry, and reservoir performance at Moore-Johnson field.

The reservoir sands at Moore-Johnson field were deposited as fluvial valley-fill deposits in a valley incised into the Morrow Limestone (Figure 14C). These Morrow sands have been correlated regionally to the Morrow V7 valley sequence (Figure 14B). The areal distribution of the three reservoir sands deposited within the incised valley is shown in Figure 14A. From oldest to youngest, the order of deposition was V7b, V7c, V7d valley fill-sequences.

Structural cross section A-A' (Figure 14C) depicts the positions of the three valley-fill sequences with respect to depth. Regional dip is to the east-southeast. The various Morrow reservoirs were encountered at depths ranging from 5100 to 5150 feet. Initial reservoir pressure was 1040 psi. Other reservoir parameters are shown in Table 1.

The three reservoir sand bodies are predominantly lateral to each other and are rarely incised into one another as is the case in the northern fields. Generally, the three sand bodies are completely encased in estuarine shales (Figure 14C). Porosities range from 14% to 28% with permeabilities from 22 to 9,990 md (Adams, 1990). The GOR was 107:1 (cu ft/bbl). Other field parameters are listed in Table 1.

Compared to the V7 valley fill reservoirs in northern fields, the reservoirs at Moore-Johnson are narrower in cross section (see legend, Figure 14A) and of smaller extent and more compartmentalized due to the dominant shale facies. Because of these conditions, oil columns are thinner and production values are somewhat lower, however, drainage efficiency is high (Bowen and Weimer, 2003). Recovery factors are variable due to, in some cases, problems with pressure maintenance.

Oil volumes produced to date from individual wells range from 32,000 BO to over 230,000 BO. The field-wide average, to date, for the 19 wells is 91,000 BO per well. These per well averages are better than the average values at Castle Peak, Harker Ranch, SW Stockholm, and Jace fields reported by Bowen and Weimer (2003).

Figure 14

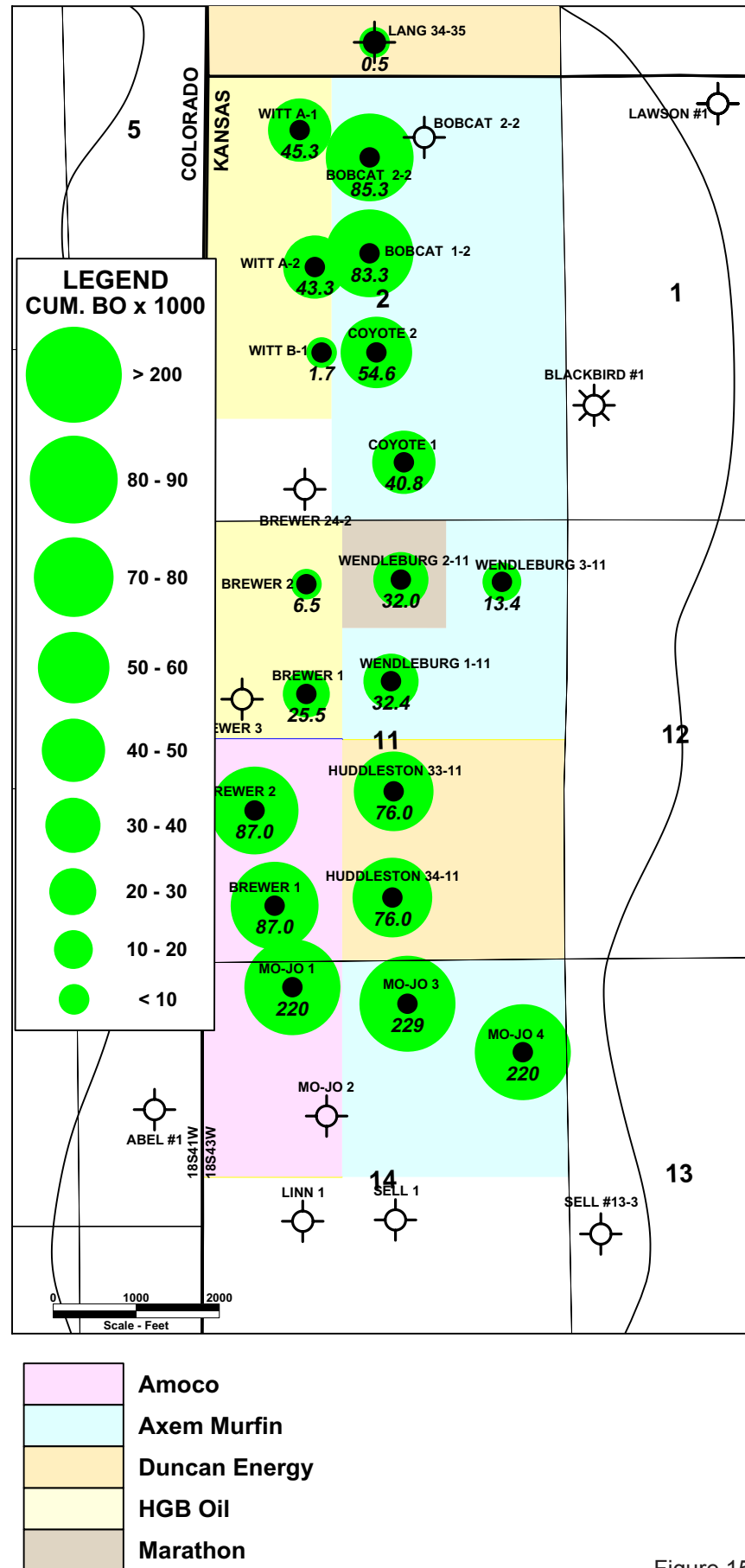
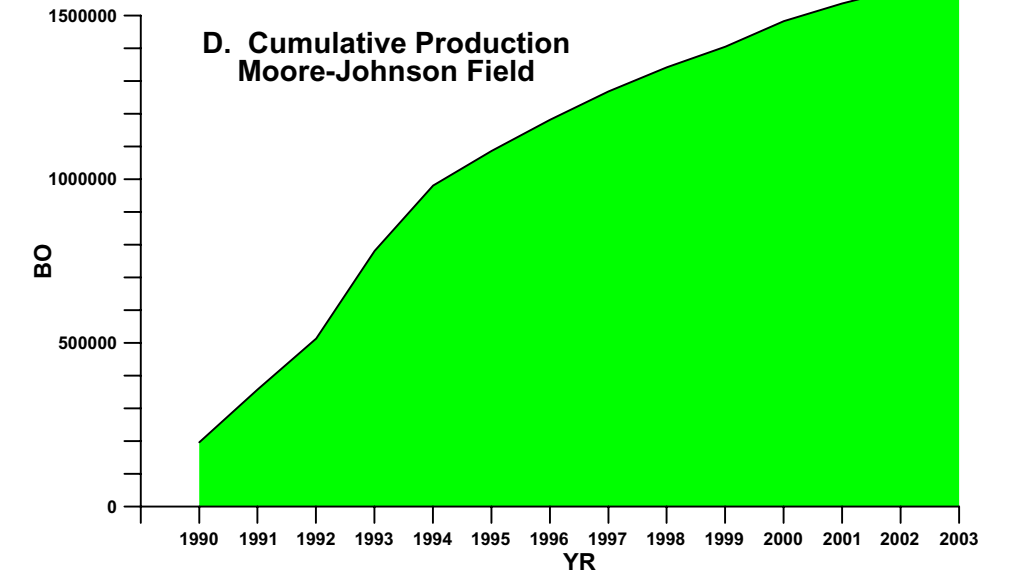
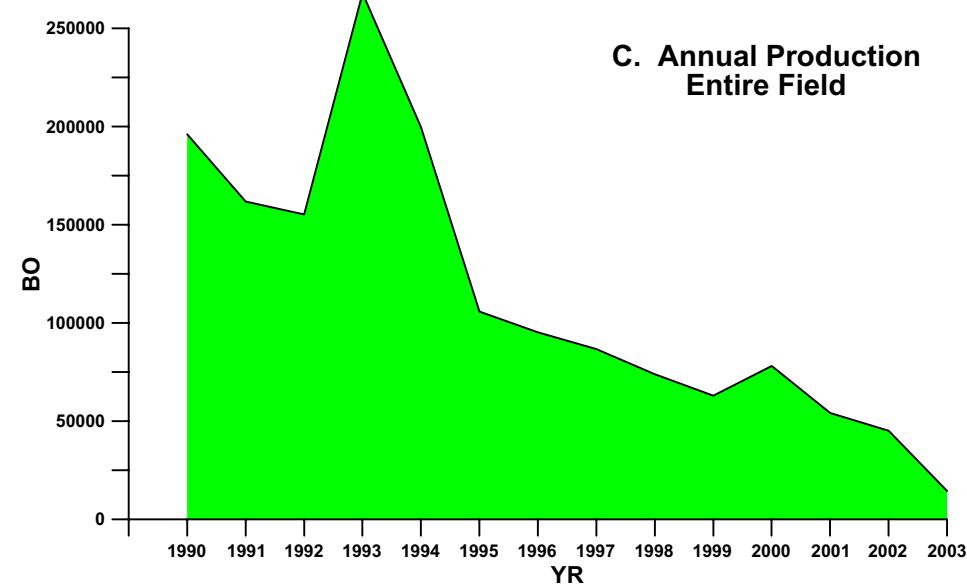
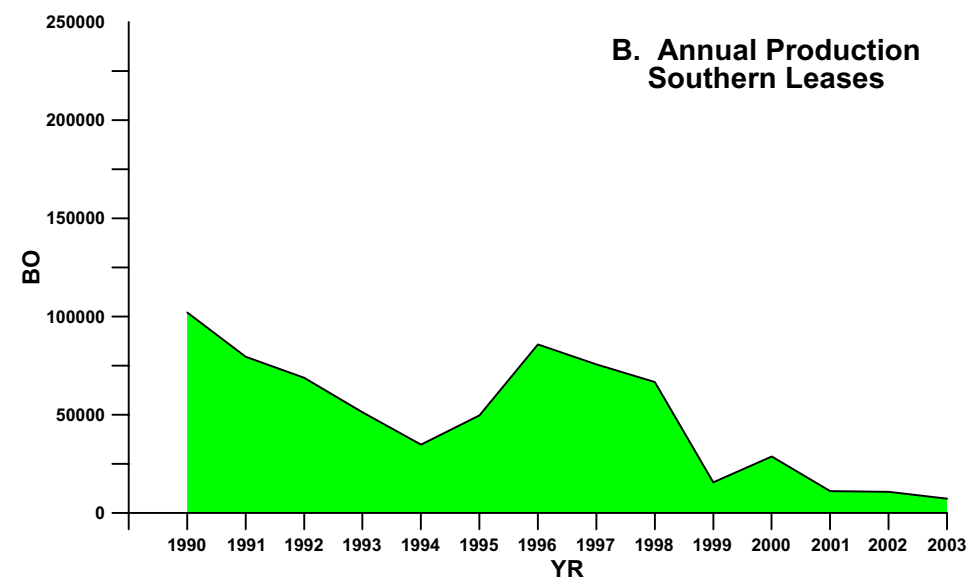
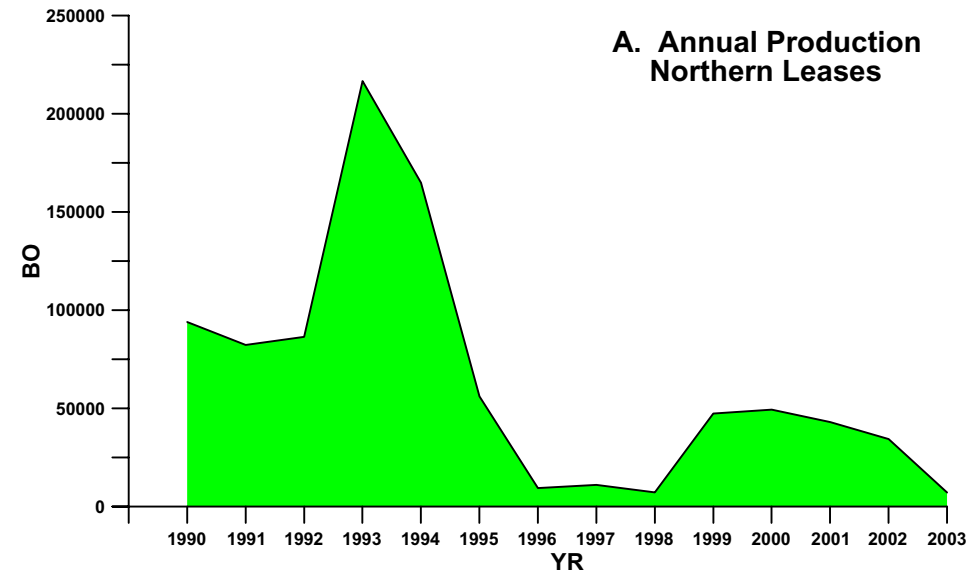


Figure 15



Oil Production at Moore-Johnson Field

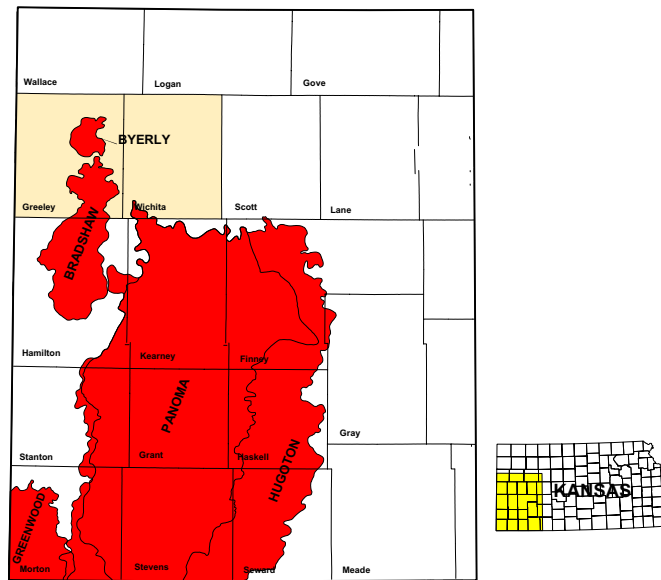
Production for Moore-Johnson field is reported by the Kansas Geological Survey (KGS). Cumulative production is reported by lease and not individual wells. To attempt to show variation in production in the individual wells, the lease production totals were divided by the appropriate number of wells in each lease. Figure 15A illustrates the variation in production among all the wells. Note the differences in cumulative production between the Witt "A" and Bobcat leases in the north part of the field.

Annual production for the northern leases (Witt, Bobcat, Coyote, Brewer, Wendleburg and Huddleston) is shown in Figure 15B. The peak in production from 1992 to 1995 reflects the addition of the new development wells. Annual production volumes for the Moore-Johnson lease are shown on Figure 15C. The peak in production from 1994 to 1998 reflects the addition of the Axem/Murfin Moore-Johnson #3 and #4 wells. Annual production volumes for the entire field are shown in Figure 15D. Total production for the field in 2002 was 45,000 BO. Since 1997, annual production volumes have been declining at a rate of about 15% per year.

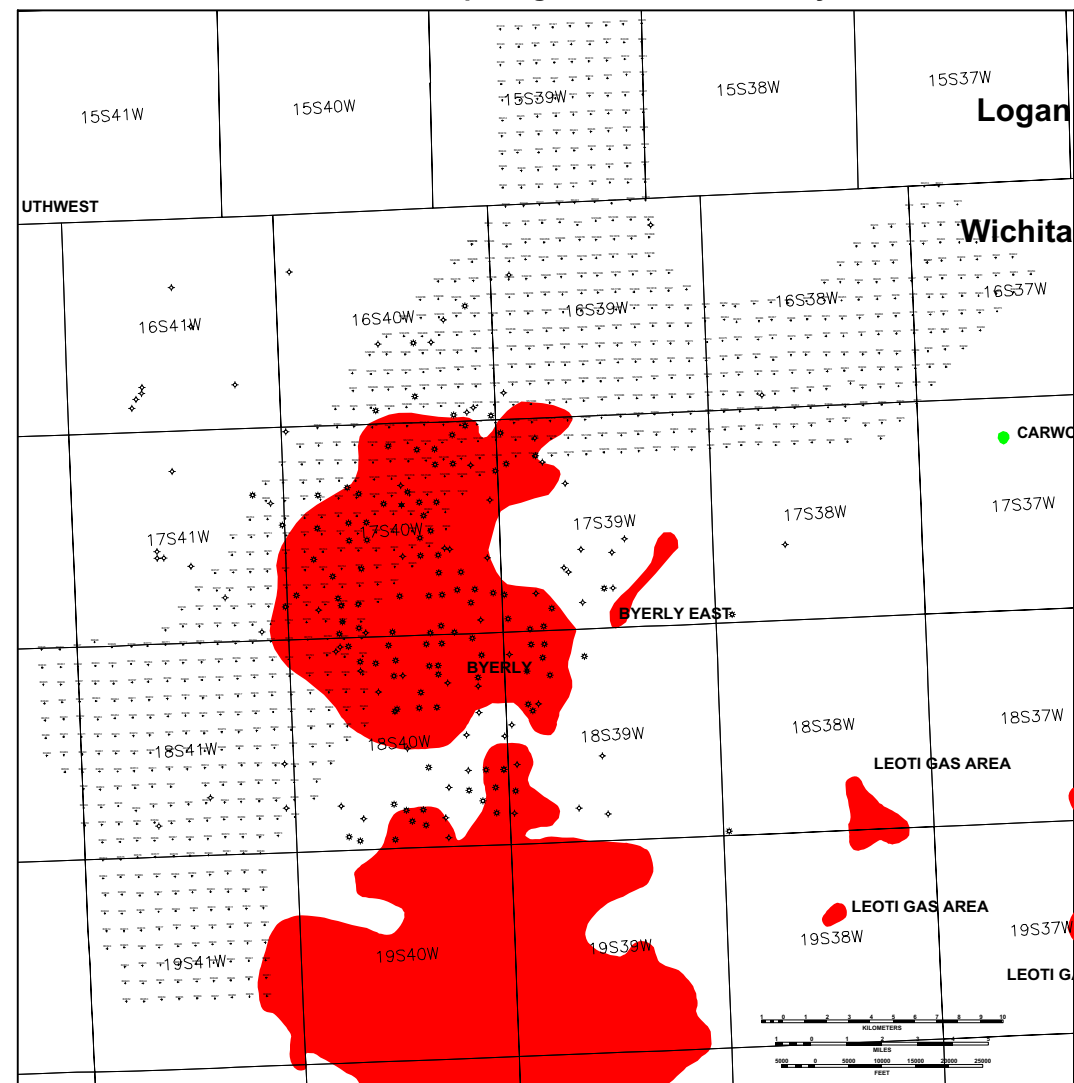
The field was unitized in 1995 for pressure maintenance by gas and water re-injection. Effects of secondary recovery operations in the north leases can be seen, beginning in 1998, in Figure 15B and for the south lease in 1999 on Figure 15C.

Cumulative production for the field is shown on Figure 15E. The year to date total production for the field is 1,729,000 BO. Average per well production for the 19 wells in the field is 91,000 BO. Average per well production for the eight Axem/Murfin wells is 93,750 BO.

The KGS reported seven wells still producing in 2003. Ultimate recoverable reserves for the field will be about 2,000,000 BO



**B. Location Map, Regional Soil Gas Survey**



**B. Location Map, Regional Soil Gas Survey**

### DETAILED SOIL GAS SURVEYS OVER A GAS TREND

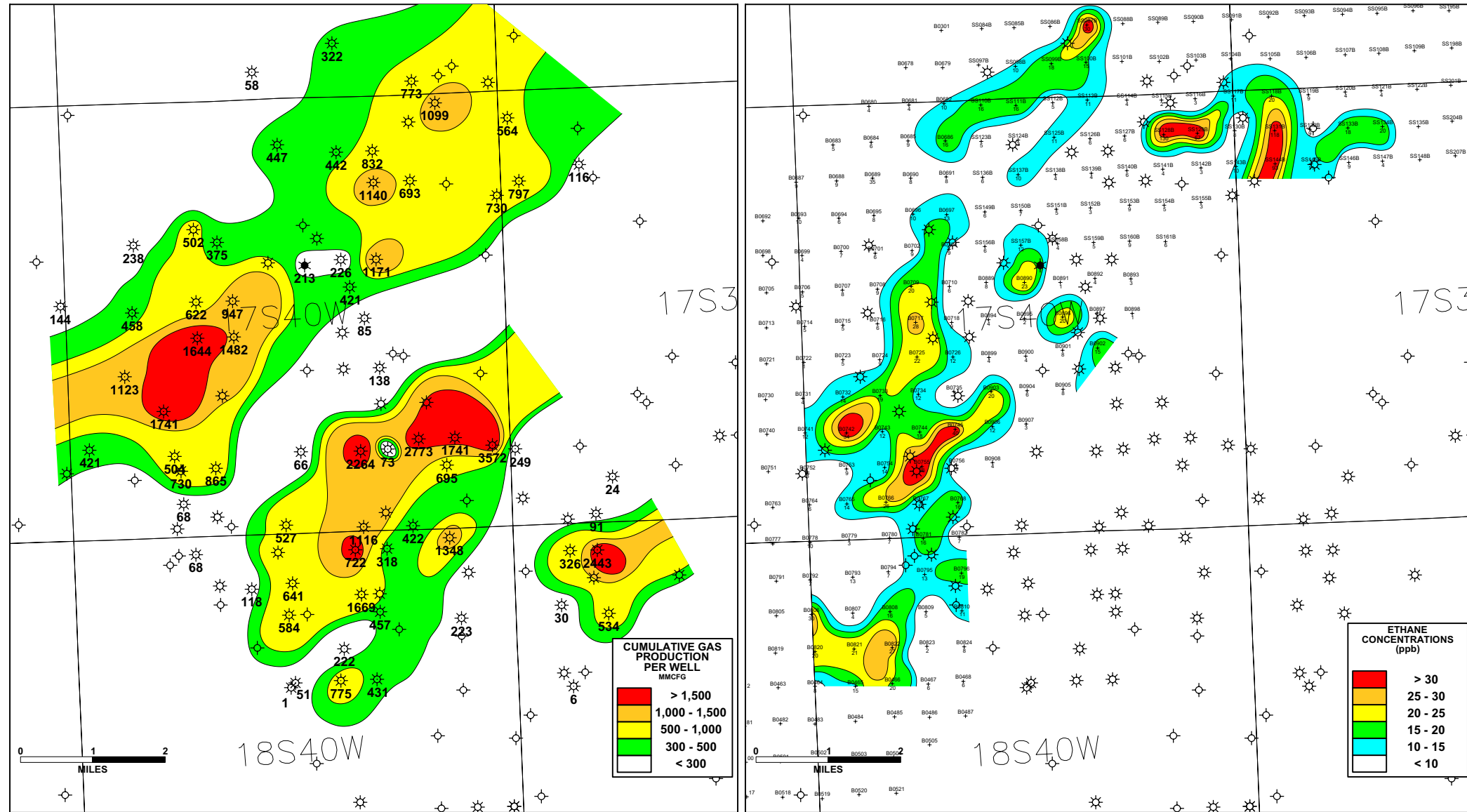
A large detailed regional soil gas survey was conducted by a major oil company in the prolific Permian Chase Carbonate Gas Trend of the Hugoton Embayment of southwest Kansas. As shown in Figure 16, the seven-foot soil gas survey covers an area of about 210 square miles and consists of 923 soil gas sites. The soil gas survey was sampled on a box grid pattern with a one-half mile distance between samples. An average section (640 acres) contains nine soil gas sample sites. Because the established well spacing in this gas trend was 640-acres, this survey, based on sample density, would constitute a detailed soil gas survey. It is noteworthy to mention, at this point, that the previously discussed soil gas survey in the north part of the Morrow Sand Trend with 11 sites per section was considered a reconnaissance survey because the unit spacing in that trend for oil wells is 80-acres.

This detailed regional soil gas survey is located in Greeley and Wichita Counties, Kansas to the west and north of Byerly (47.3 BCFG) and Bradshaw (334 BCFG) Gas Fields. A portion of the soil gas survey was conducted over the northwest half of Byerly Field for calibration purposes. The Permian Carbonate Gas Play (Chase and Council Grove Groups) in the Hugoton Embayment is the most prolific and important hydrocarbon play in this petroleum province. This area of SW Kansas is also referred to as the Hugoton gas area. The major gas fields of this area – Hugoton, Panoma, Greenwood, Bradshaw, and Byerly (Figure 16) have produced a total cumulative of 27 TCFG.

Byerly and Bradshaw Gas Fields, together, have a total cumulative production of 381 BCFG from the Chase Carbonate reservoir. Byerly Field was discovered in 1968. Development drilling at Byerly Field (Figure 17) progressed rapidly through the 1970's up to 1985 when the field reached a maximum development of 55 wells. There was a hiatus in development drilling from 1986 until 1990. Since 1990 there have been 14 Chase Carbonate completions at Byerly Field. There are currently 46 producing gas wells in the field of which 20% have been completed since 1995. Interpretation of the analytical data from the soil gas survey within the northwest part of Byerly Field indicates that there are some additional areas that can be recommended for further development drilling within the field area.

The natural gas accumulations at Byerly Field are due to stratigraphic entrapment caused by a facies change in the Permian Chase Carbonate reservoir where it grades from limestones and dolomites in the east to nonmarine red beds in the west. The generalized geology of the gas trend is illustrated in Figure 2. Regional dip of the Chase Carbonate is to the east-southeast. The upper seal for the gas reservoirs are provided by anhydrites and shales of the overlying Sumner Group. Average drill depths of the gas reservoir at Byerly Field range from about 2750 to 2900 feet. Porosity and permeability in the Chase Carbonate are highly variable as evidenced by the cumulative gas production from individual wells as shown in Figure 17A. Cumulative gas production from wells in Byerly Field range from 30 MMCFG to 3,572 MMCFG.

Figure 16



A. Contour Map of cumulative gas production from wells in northwest part of Byerly Field

B. Ethane magnitude contour map in northwest part of Byerly Field

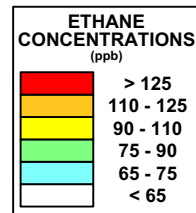
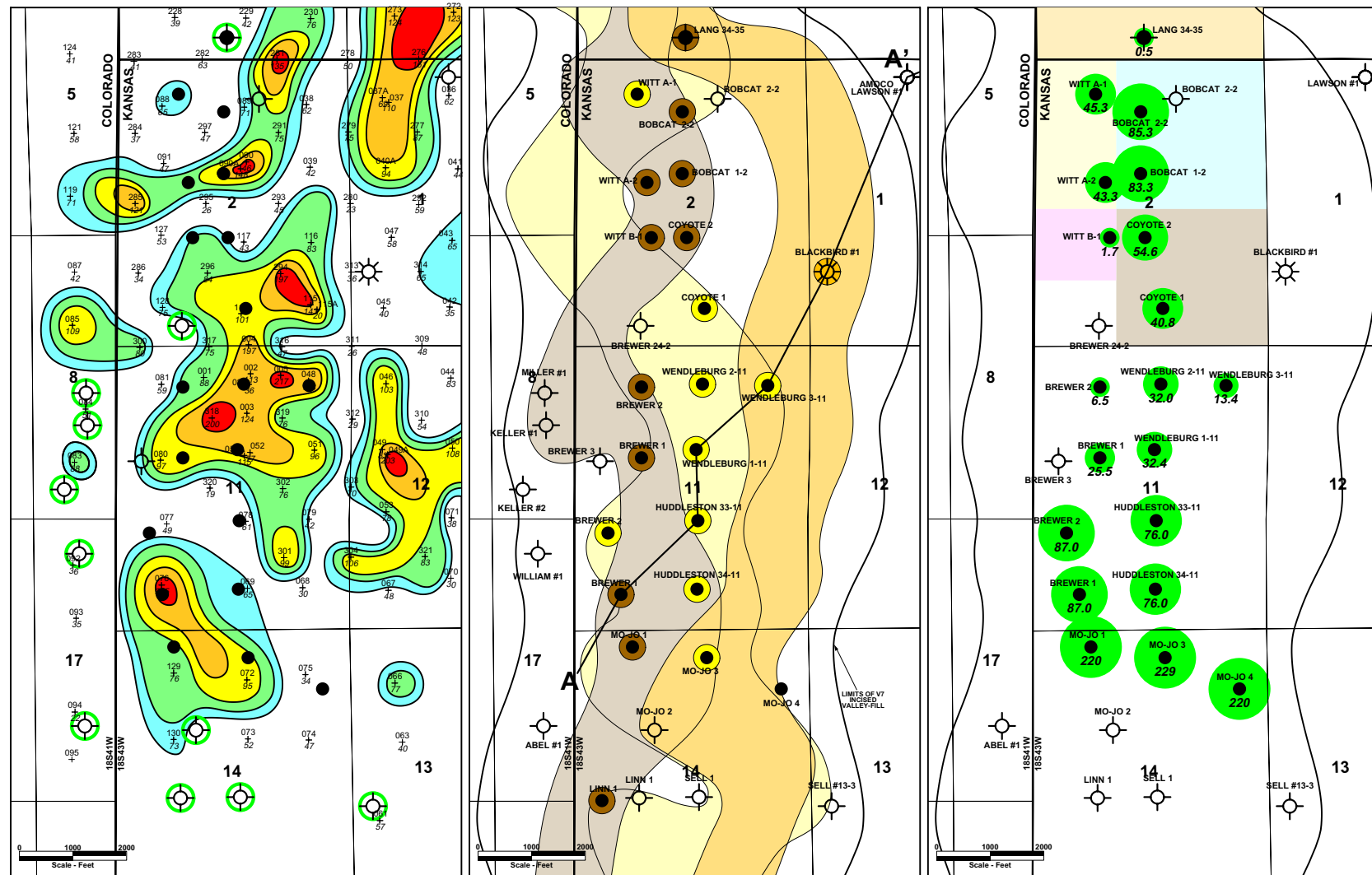
Figure 17

The stratigraphic entrapment of the gas, relatively shallow depth, and highly variable porosity and permeability of the reservoir are factors which favor the application of surface soil gas surveys as an important exploration method to reduce risk in this play.

The purpose of the regional detailed soil gas survey was threefold: (1) calibration of the survey to the gas production at Byerly Field, (2) to aid in possible further exploitation/development drilling at Byerly Field, and (3) to determine other areas along trend that exhibited similar anomalous soil gas microseepage and would therefore indicate areas of exploration potential.

The variability of the cumulative gas production from individual wells in the northwest part of Byerly Field is illustrated in Figure 17A. There is a pronounced northeast-southwest orientation of porosity and permeability development in the Chase Carbonate at Byerly Field. As evidenced by the cumulative gas production contour map, there are three porosity/permeability fairways at Byerly Field. An ethane concentration contour map, constructed from soil gas magnitude analytical data in northwest half of Byerly Field, is shown in Figure 17B. There is very good correlation between areas of maximum cumulative gas production (Figure 17A) and anomalous ethane soil gas concentrations (Figure 17B) in Byerly Field. The trends of microseep anomalies, indicated by the contour map of ethane magnitudes, exhibits the same northeast-southwest orientations as seen in the contour map of cumulative gas production. Since there are many more soil gas data points than development wells at Byerly Field, the soil gas anomalies, indicated by the contour map, probably provides a more realistic depiction of the subsurface porosity/permeability trends in the Chase Carbonate at Byerly Field.

A number of untested soil gas anomalies exist in the remainder of the soil gas survey to the west and north of Byerly Field. These anomalous gas microseeps are not random, isolated points, but rather tend to cluster in groups of gas microseep points that are on trend with established Chase Carbonate gas production at Byerly and Bradshaw Fields. These untested soil gas anomalies exhibit similar soil gas magnitudes and areal extents as the soil gas anomalies mapped within Byerly Field.

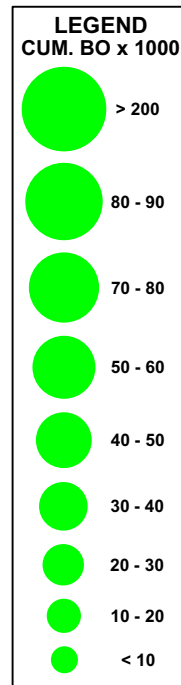


Limits and Dimensions of Morrow V7 Sands	Areal Extent	Thickness	Width
V7d	0 - 30 ft.	1800 - 2700 ft.	
V7c	0 - 18 ft.	1300 - 2300 ft.	
V7b	0 - 24 ft.	2300 - 3200 ft.	

BOBCAT LEASE
WITT "A" LEASE
WITT "B" LEASE
LANG LEASE
COYOTE

DRY HOLE LOCATED IN AREAS OF BACKGROUND ETHANE MAGNITUDES

Morrow Well Completion Zones
V7d
V7c
V7b



### Advantages and Limitations of Soil Gas Surveys

As previously discussed, the major advantage of soil gas surveys in the Morrow oil trend is that of risk reduction and potentially improving the success ratio. As shown on the Figure 18A, had the survey been available to all companies, then probably, 11 of the dry holes on the west side and the north and south end of the field would not have been drilled. This alone would have increased the overall success rate for the field from 56% to 82%. Had the data been available to Amoco in 1990, at least five of the dry holes could have been avoided, increasing Amoco's success rate from 30% to 60%.

Another major advantage of soil gas surveys is the relatively low cost. Considering sample collection, laboratory analyses, and interpretation and reporting costs, the present day cost of the 106 site soil gas survey conducted at Moore-Johnson field would be about \$16,000. This is only about 15% of the dry hole cost of a single Morrow well.

In this portion of the Morrow trend, the sample density of 16 sites per section is only adequate for defining a lead or prospect area and possibly acquiring acreage. This sample density is not adequate for exploitation or development drilling. A sample density of at least 30 sites per section is needed as demonstrated at the Moore-Johnson field (LeBlanc and Jones, 2004a).

Surface soil gas geochemistry will not eliminate all dry holes being drilled within a field. The example previously discussed of the Bobcat #2-2 wells is a good example to illustrate this point. As pointed out by Bowen and Weimer (2003), the V7 sands in this part of the Morrow trend are of smaller areal extent, smaller in cross section, and more compartmentalized than in the Morrow fields to the north. At the sample density of this survey, microseep anomaly patterns could not distinguish the individual trends of the V7b, V7c, and V7d reservoirs. This is because the widths only range from 1800 to 3000 feet (see legend, Figure 18B). Perhaps a denser soil gas grid could have provided the necessary resolution.

Soil gas anomaly data can not distinguish between oil reservoirs of different geologic ages. In this part of the Morrow trend, in most wells the Mississippian has been a secondary (or primary) objective. Although not productive at Moore-Johnson field, anomalous microseeps in the surrounding area could indicate Mississippian potential in addition to Morrow. Additionally, shows were reported in some wells in the Pennsylvanian Lansing-Kansas City interval.

There is no direct relationship between the magnitudes of microseeps and either the rate or total volume of hydrocarbons a well will produce, except in a very general sense. This is particularly true when comparing reservoirs having different entrapment mechanisms, such as the Stateline Morro oil and W. Stockholm gas fields. However, as can be seen comparing the ethane contour map (Figure 18A) to the production map on Figure 18C, this concept may at least potentially work when comparisons are made over the same reservoir. For example, the Bobcat lease (170,646 BO) has been more productive than the Witt "A" lease (90,575 BO) and the Lang lease (477 BO). Similarly, the Coyote lease (95,362 BO) has been more productive than the Witt "B" lease (1745 BO). The ethane magnitudes suggest differences that may be related to these production volumes. This suggests that the amount of reserves on a prospect could likely be improved by a company getting a competitive edge in early lease acquisitions based on soil gas data. One of the reasons that Axem/Murfin had such sizeable reserves at Moore-Johnson field was their excellent lease position.

Figure 18

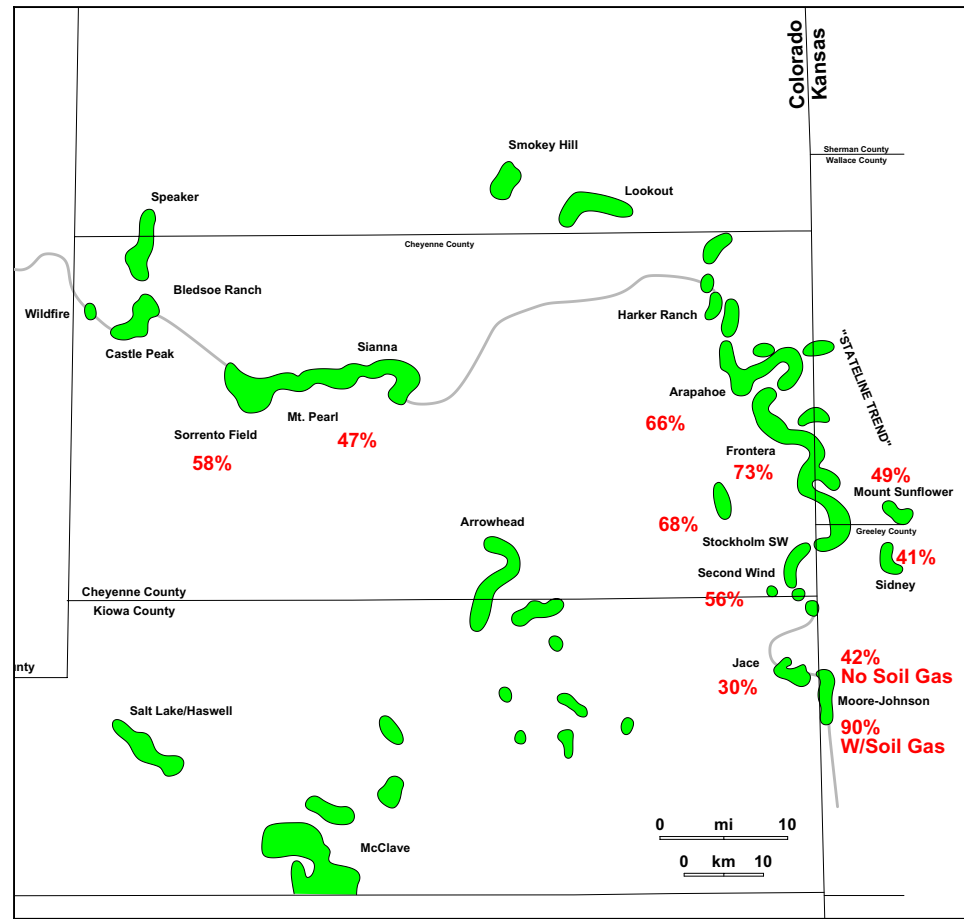


Figure 19

### Recommendations

Figure 19 and Table 2 list success rates for development drilling in representative fields in the Morrow oil trend and other factors (years to develop, per well reserves) affecting the rate of return in the Morrow trend. The fields are grouped according to the facies tracts as defined by Bowen and Weimer (2003). It is apparent that the newer fields most recently developed (Jace, Sunflower, Sidney) have the lowest success rates. As shown at Moore-Johnson field, high-density soil gas surveys could improve drilling success in these areas. Employment of soil gas surveys could also have accelerated the development drilling schedule at Sorrento and SW Stockholm fields from the 10-year period that was required for full field development. As discussed by Bowen et al. (1993) initially (1979 to 1984), an incorrect depositional model was the main reason for the rather lengthy development time frame for these two fields.

Success rates for Morrow exploration wells were reported by Bowen et al. (1993) to have been 5% in the Sorrento-Mt. Pearl-Sianna area and reported by Moriarty (1990) to have been 10% in the Stateline area. There still remain areas of untested Morrow exploration potential in the transitional and updip facies tracts where soil gas surveys could be employed to improve the exploratory success rates over those previously reported. Regional isopach maps of the upper Morrow section have been used to define other areas where Morrow V1, V3, and V7 incised valleys might exist (Bowen and Weimer, 2003, Figure 10). Regional soil gas surveys could be very useful in exploration ventures when used in conjunction with this method, especially in areas with sparse well control (LeBlanc and Jones, 2004a).

As shown in this paper, surface soil gas geochemistry has been successfully used in developing oil reserves in the Morrow V7 incised valley trend. This method would also be applicable in other Morrow incised valley trends of southeast Colorado and southwest Kansas such as the V1 and V3 Valley systems. As reported by Bowen and Weimer (1997, 2003) these two incised valley systems are transparent on 2-D or 3-D seismic due to their close proximity to the base of Atoka/top of Morrow interface. Additionally, other Morrow incised valley fill systems were outlined by Wheeler et al. (1990) in Wallace County, Kansas and farther south in Kiowa, Brent, and Powers Counties, Colorado.

A high degree of compartmentalization has been observed in the V7 reservoirs in the downdip facies tract. Future soil gas surveys in this area, for development drilling purposes, should have a higher density of samples than the grid of 30 sites per section used in the 1992 survey at Moore-Johnson field. For regional exploration activities in the Morrow trend, a soil gas grid of 16 sites per section appears satisfactory only for delineating regional microseep anomalies.

Soil gas geochemistry would also be applicable in other younger Pennsylvanian incised valley systems that have been identified in central and southern Kansas and northern Oklahoma (KGS, 2003). Likewise, Cretaceous age incised valley-fill systems exist in Rocky Mountain areas such as the Denver, Powder River, and Williston basins. The generalized paleodrainage network for the Muddy Formation was illustrated by Weimer (1992, Fig. 3) over the north Colorado, Wyoming, and eastern Montana areas. A more detailed picture of paleovalleys in the Denver basin which were filled with Muddy valley-fill sandstones was also presented.

The advantages of using each of the disciplines of geology, geophysics, and soil gas geochemistry in Morrow exploration and development are well known, however the three disciplines have seldom been used in tandem. A somewhat lesser discussed topic is that of the limitations of these three sciences.

The limitations of using soil gas surveys in the Morrow oil trend have been discussed, to some extent, in this paper. Bowen et al. (1993) discussed limitations of subsurface geology and 2-D seismic in locating reservoir quality sandstones in the Sorrento-Mt. Pearl-Sianna area. Germinario et al. (1995) likewise discussed the limitations of 2-D and 3-D seismic surveys in locating both the incised valleys and reservoir sandstones in the southern Stateline Trend.

The integrated, multidisciplinary approach of using geology, geophysics, and soil gas geochemistry in Morrow exploration (LeBlanc and Jones, 2004b) is a superior method whereby the advantages in one of the three disciplines complement and overcome the limitations or shortcomings of another.

Factors Affecting the Rate of Return in the Morrow Trend

FACIES TRACT	FIELD	RESERVOIRS	SUCCESS RATIO	YRS. TO DEVELOP	AVG. PER WELL RESERVES BO
UPDIP	Sorrento	V7	58%	10 YRS. 1979-1988	358,333
	Mt. Pearl-Sianna	V7	47%	6 YRS. 1984-1990	321,429
TRANSITIONAL	Arapahoe	V3 V7	66%	3 YRS. 1988-1990	154,419
	Frontera	V7	73%	3 YRS. 1988-1990	106,429
	SW Stockholm	V7	68%	9 YRS. 1979-1988	69,892
	Second Wind	V3 V7	54%	4 YRS. 1988-1991	139,474
	Sunflower	V1 V3 V7	49%	4 YRS. 1993-1998	83,500
	Sidney-Kriss	V1 V3 V7	41%	9 YRS. 1990-1999	42,950
DOWNDIP	Jace	V1 V7	31%	5 YRS. 1989-1993	63,846
	Moore-Johnson	V7	42% W/O SOILGAS SURVEY 90% W/ SOIL GAS SURVEY	2 YRS. 1992-1994	91,000

Table 2

## Summary

A high-density soil gas survey was conducted in the vicinity of Moore-Johnson field in 1992. The survey was conducted after the discovery of the field and initial development attempts, all by the same major oil company, which resulted in a total of 10 wells (3 oil wells, 7 D&A). A second attempt to extend the field, starting in 1992, was conducted by six independent oil companies. One of the companies used an integrated approach of combining subsurface geology and seismic with a detailed geochemical soil gas survey. The remainder of the companies used industry-standard Morrow exploration techniques acquired from 1978 to 1990 during development of Morrow oil fields to the north.

A high-density soil gas survey, consisting of 106 sites, was conducted over a four square mile area of interest. Integration of geochemistry, geology, and geophysics resulted in a compatible, unified interpretation that the field could be extended to the north.

The company utilizing the soil gas survey completed the first well to extend the field with a 4700-foot stepout. This company completed eight consecutive successful Morrow wells in the field before drilling a dry hole. After drilling 10 wells, the company had a 90% success rate. A total of 34 wells were drilled to both define the limits of the field and develop the Morrow reserves. By only drilling 29% of the total wells, the company utilizing soil gas geochemistry acquired 47% of the reserves produced to date. Success rates for the remainder of the other field operators were 0%, 30%, 50% and 67%

There are still areas of untested potential in the Morrow oil trend. Fields discovered to date have produced 66.5 MMBO with ultimate recoverable reserves estimated at about 110 MMBO. Fields in the southern portion of the trend are in the downdip facies tract as characterized by Bowen and Weimer (2003). The Morrow sands in these wider incised valleys are of smaller areal extent, smaller in cross section, and more compartmentalized. Correspondingly, the average reserves per well are smaller than the northern fields. Although reserves are lower in the downdip facies, employing soil gas geochemistry can improve the relatively low success rates now being encountered in this area. This could vastly improve the rate of return.

This documentation of a successful application of a detailed soil gas survey demonstrates how the method could be used to delineate other areas of Morrow incised valley-fill systems in areas of untested potential. Additionally, the method would also be applicable in incised valley-fill systems of other geologic ages in Midcontinent and Rocky Mountain basins.

Soil gas geochemistry is not a panacea for Morrow exploration, exploitation, or development drilling, but is an integral part of a thorough exploration program. Applying the recently related concepts of Morrow sequence stratigraphy will undoubtedly be a tremendous advantage in future Morrow exploration and development drilling ventures, reservoir maintenance, and in secondary recovery operations. Using soil gas geochemistry in tandem with this concept would provide a very powerful synergistic effect to Morrow exploration and development projects.

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