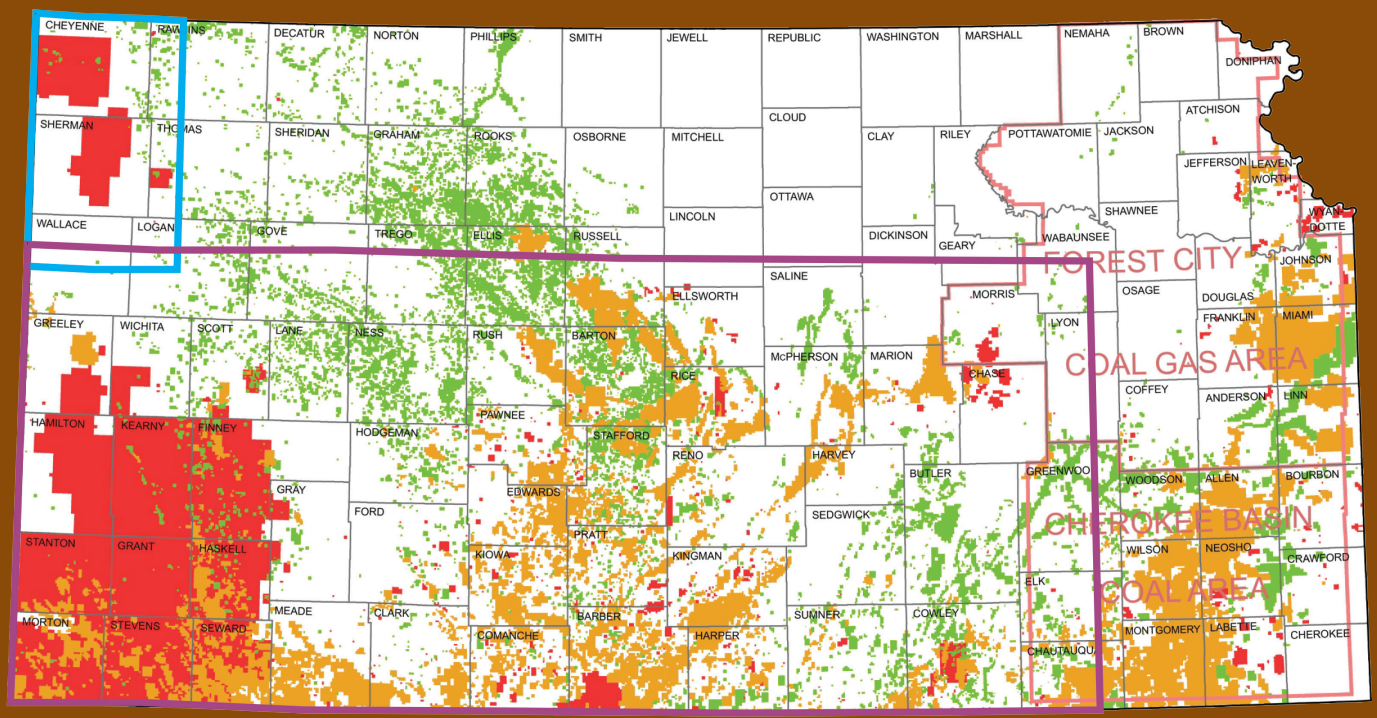
Kansas Geological Survey Bulletin 266



Stratigraphic and Regional Trends in Chemistry and Quality of Natural Gas in Central and Western Kansas, Midcontinent, USA

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KU KANSAS GEOLOGICAL SURVEY
The University of Kansas

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Bulletin 266
2025

ACKNOWLEDGMENTS

I thank John Stover (consulting petroleum engineer, Lawrence, Kansas) for his insights regarding solubility of gases in water. Doug Davis (consulting geologist, Wichita, Kansas), Curtis Breckon (consulting geologist, Tulsa, Oklahoma), Clyde Becker, Jr. (President, Becker Oil Corp., Conifer, Colorado), Dr. Don Whittemore (emeritus scientist, Kansas Geological Survey, Lawrence, Kansas), and Dr. Sal Mazullo (emeritus geology professor, Wichita State University, Wichita, Kansas) are thanked for their effort and time to critique and review earlier versions of this manuscript. Dr. Tim Carr (geology professor, West Virginia University, Morgantown, West Virginia), Dr. Alton A. Brown (consulting geologist, Richardson, Texas), and Dr. Steven Tedesco (President, Running Foxes Petroleum, Englewood, Colorado) are thanked for formally reviewing the final manuscript. Julie Tollefson (editor, Kansas Geological Survey, Lawrence, Kansas) is thanked for all her input and attention to detail. All of the aforementioned individuals brought attention to sloppy grammar, typographical errors, bad spelling, and illogical geologic reasoning that were sorely in need of correction. Any errors that may remain are my fault and entirely my responsibility.

Editor: Julie Tollefson
ISBN: 978-1-58806-341-0

CONTENTS

FIGURES

TABLES

Key Words
low-BTU gas, sour gas, gas migration
gas alteration, hydrocarbon gases, helium

ABSTRACT

Natural gas from many midcontinent geological formations can contain significant quantities of nitrogen and subsidiary amounts of helium. Argon and carbon dioxide also can be present, but they commonly compose less than 0.5% of the total gas. In as many as a third of the fields in Kansas, noncombustible component gases reduce heating values to less than 950 BTU/scf.

Natural gas analyses, when differentiated into histograms according to their heat content (i.e., BTU/scf), array as skewed bell-shaped distributions with a "tail" on the lower-BTU flank of the distribution. There are no separate populations of low-BTU and high-BTU gases. The definition of a low-BTU gas is therefore somewhat arbitrary and artificial and mostly defined by what quality of natural gas will be accepted by pipeline companies. A gas with less than 950 BTU/scf — usually the minimum quality of gas accepted by pipelines without price discounts — is nominally identified as a low-BTU gas. Occurrences of low-BTU gas are geographically extensive in Kansas. Much of this low-BTU gas has either been shut in behind pipe or simply abandoned after discovery if it could not be blended with any readily available higher-BTU gas.

Most gas production in Kansas is from Permian Chase Group strata in the giant Hugoton Gas Field in southwestern Kansas. Elsewhere in the state, other Permian and older strata producing gas are associated with petroleum that was generated in and then migrated out of the Anadarko basin of Oklahoma. Cretaceous gases are present in the northwestern corner of the state. The Cretaceous gases are biogenic in origin and are updip of thermogenic gas occurrences in the Denver-Julesburg basin of Colorado and Wyoming.

Percentages of higher-molecular-weight hydrocarbon component gases (i.e., ethane, propane, butane, pentane, etc.) and helium generally decrease with decreasing age of the reservoir. Helium content is commonly linked to nitrogen content in a relatively constant ratio that generally increases with decreasing age of the reservoir. The median nitrogen/helium ratio for Kansas Cretaceous gases is 45/1. Median ratios for other strata are 31/1 for Permian strata, 25/1 for Pennsylvanian (Virgilian) strata, and 21/1 for Pennsylvanian (Missourian) strata. Gas-bearing zones along the basal Pennsylvanian angular unconformity have a median nitrogen/helium ratio of 11/1.

Some low-BTU regions in the Hugoton Gas Field and along the basal Pennsylvanian unconformity are possibly caused by interaction of the gases with formation water. Formation water could either leach the component gases, such as various hydrocarbon gases, from a natural gas accumulation or it could contribute component gases such as nitrogen and helium to a gas accumulation. Alternately, mixing with a lower-BTU gas also could alter the original composition of a natural gas accumulation.

The natural gas in the Chase Group of the Hugoton Gas Field in southwestern Kansas displays some consistent changes in composition. The perimeter of the field is characterized by low-BTU gas, and the perimeter is particularly wide in the northeastern corner of the field. For reasons unknown, gas analyses in the western (updip) part of the field assay with greater hydrocarbon wetness (i.e., greater percentages of higher-molecular-weight gases relative to methane) than gases in the eastern part of the field.

Helium content in natural gas accumulations increases from south to north and peaks on the southern part of the Central Kansas uplift. Maps of helium percentages and nitrogen/helium ratios define several areas where helium can be extracted to augment the economics of natural gas production in Kansas.

INTRODUCTION

This publication concentrates on mapping and comparing the component gases of natural gas in central and western Kansas. The aim of the mapping and cross-plots presented in this publication is to provide constraints for a better understanding of the origin and migration of the various sources and migration routes of the many natural gas plays in the state. In addition, this publication can provide an introduction and valuable regional overview of energy and non-energy component gases in Kansas, perhaps aiding energy and resource companies and research organizations for more detailed studies and expediting exploration objectives for natural gas and its component gases. Until this Kansas Geological Survey publication, the chemistry and chemical variability of natural gas in central Kansas have not been discussed and summarized in any single publication, particularly with emphasis on the age of the rocks that harbor this gas and with respect to its geographic and geologic location and depth of occurrence.

Natural gas produced in Kansas has been an important source of energy for decades. Much of this natural gas has been directed eastward via several major pipelines to large metropolitan areas in the midwestern United States. In addition to the energy value of the hydrocarbon components of the natural gas, much of the natural gas in Kansas contains helium, a valuable non-combustible component gas. Historically, the main source of helium produced in the United States has been gas fields in Kansas, and in turn, the United States has been the main source of helium produced in the world (Mohr and Ward, 2014). The main source of helium in Kansas is natural gas produced from Permian strata in the giant Hugoton Gas Field and nearby associated fields (i.e., Bradshaw, Byerly, Greenwood, Hugoton North, Leoti Gas Area, Panoma, and several smaller fields) in the southwestern part of the state (Newell and others, 2009). The fields that account for most of the helium production in Kansas were discovered decades ago and are steadily depleting.

Although new sources of energy and helium are being developed worldwide, fossil fuels and helium production are still important in the economy of Kansas, and discovery of new fields and outpost drilling on existing fields will be critical for the continued production of these gases in the state.

An important factor upon which the commerciality of a natural gas deposit depends is the chemical composition of the natural gas. Compositions of natural gas vary widely. To gain an understanding of such compositional variations, chemical analyses and heating values have been analyzed from natural gas samples obtained from individual producing wells for well over a century. These analyses have been published by government, academic, and industry researchers. This Kansas Geological Survey publication combines these numerous and disparate sources of gas analyses and then graphically displays them in the context of their stratigraphic and geographic occurrence. This research approach has not been widely used on a basinal or multi-basinal scale, but the approach yields compositional trends that can be mapped, and in doing so, predictions about gas compositions can be made in undrilled areas and untested strata. The viability of extraction of component gases such as helium also can be assessed. In addition, such compositional maps can be used to plan the trace of future pipelines so that such a pipeline can be placed to access a maximum number of existing and possible new trends of gas fields.

The compositional maps (i.e., heating value, hydrocarbon wetness, helium percentage, and nitrogen-to-helium ratio) presented in this bulletin are the first of their kind to be published for Kansas. No earlier maps exist. The research presented will hopefully serve as a bellwether type of study on which other geologic provinces also can be examined in the same context.

Non-Hugoton natural gas production is dispersed over much of the rest of Kansas and includes all major geological structural features of Kansas except the Salina basin. Hugoton Gas Field natural gas includes a small percentage (commonly less than 0.5%) of helium (Parham and Campbell, 1993). This helium is usually extracted from the production stream by refrigerating the raw natural gas in chambers called "cold boxes" to a low temperature so that the hydrocarbon gases are liquefied and then removed and further processed (Newell and others, 2009). The remaining gaseous fraction consists of mostly helium and nitrogen, which can be subject to additional chemical processes to concentrate the helium.

This publication also summarizes the chemistry and quality of natural gas in southern and western Kansas — essentially those parts of the state not including the Cherokee and Forest City basins. Variations in natural-gas chemistry are illustrated using basic statistical techniques and by mapping gas compositions by stratigraphic occurrence. Although the origin of the component gases that make up natural gas in Kansas is not a focus of this study, this work presents information that can constrain genetic studies of natural gas, its migration, and post-accumulation alteration.

Studies of stable isotopes in hydrocarbon noble gases give insight into the origin of gases in Kansas (Rice and Claypool, 1981; Rice, 1984; Jenden and others, 1988) and of the Hugoton Gas Field and related fields (Pierce and others, 1964; Gold and Held, 1987; Jenden and others, 1988; Jenden and Kaplan, 1989; Ballentine and Sherwood Lollar, 2002; Brown, 2019), but percentages of the component gases within the natural gas and their variations with respect to stratigraphy and geography have not been studied in detail. Gas chemical data have been collected for decades, but it has not been amalgamated into large datasets and analyzed on a regional basis as in this bulletin. This publication hopefully addresses this research gap.

"Subquality gas" may account for as much as 60 trillion cubic feet (TCF) of reserves in the United States (Lokhandwala and Zammerilli, 2006). Although this potential resource has been largely ignored in recent years due to low commodity prices, it can be a future exploration target if natural gas prices rise and justify application of current and new technologies for upgrading it to pipeline quality. After the price crash in late 2008, low-BTU natural gas has either been shut in behind pipe or simply abandoned after discovery if it could not be blended with readily available higher-BTU gas.

A scarce and sought-after component of natural gas — helium — also can augment the price that natural gas receives, thus provoking an exploration strategy to follow trends and the presence of helium in natural gas. Percentages as low as 0.3 mole % helium can be economically produced from marketable natural gas, provided distance to recovery and upgrading facilities is not excessive (National Research Council, 2010). This NRC study also indicated that helium concentrations as low as 0.04 mole % can be economic if gas is chilled and purified to meet specifications as liquefied natural gas. Nitrogen and helium are commonly found together in stratigraphic horizons in relatively constant ratios (Pierce and others, 1964; Gold and Held, 1987; Jenden and others, 1988; Brown, 2010, 2019). This ratio can affect processing costs to vent the nitrogen and retain the helium. Maps of nitrogen/helium ratios are included in this study.

STUDY AREA

Kansas is in the southern midcontinent petroleum province (**fig. 1A**). The cratonic basins and uplifts composing the major ancient and present-day tectonic features in the state (**fig. 1B**) are defined by geologic data obtained from decades of drilling for oil and gas. All of the present-day basins and uplifts produce petroleum, save for the axis of the Salina basin in north-central Kansas. In general, gas production is limited to the southern part of Kansas (**fig. 2**), and fields producing both oil and gas have an increasing component of gas production toward the south into the Anadarko basin (Walters, 1958; Newell and others, 1987). Most oil and gas in Kansas are sourced from the Anadarko basin in central Oklahoma and have migrated long distances northward from thermally mature areas deep in the basin (Rich, 1931; Walters, 1958; Price, 1980; Burruss and Hatch, 1989; Gerhard, 2004).

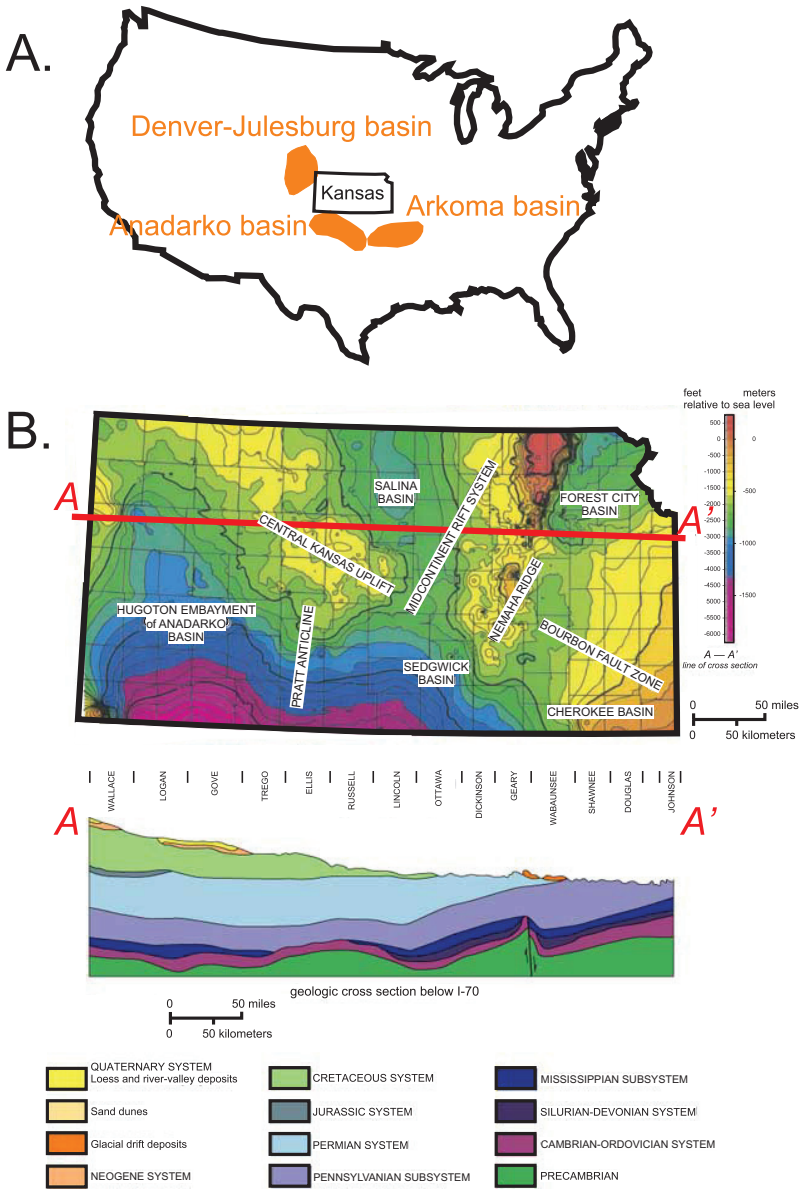


Figure 1. A) Kansas is in the southern midcontinent, on the North American craton, north of the Anadarko basin in Oklahoma and east of the Denver-Julesburg basin in Colorado. B) Tectonic features of Kansas, basement structural contours, and an east-west geologic cross section across the state (from Gerhard, 2004). All the basins and uplifts have producing fields, except for the relatively barren Salina basin in north-central Kansas.

Kansas has a venerable history of oil and gas production (Newell and others, 1987; Merriam, 2002, 2006), with exploratory drilling commencing in the eastern part of the state a few miles south of Kansas City as early as 1860 (Haworth, 1908; Jewett, 1954; Merriam and Newell, 2011). Approximately 42.2 trillion cubic feet (TCF) of natural gas has been produced in Kansas (Kansas Geological Survey, 2025a). The majority of this gas is from Permian strata in the giant Hugoton Gas Field, which underlies several counties in the southwestern part of the state (**fig. 2**). Dubois and others (2007) credited the Hugoton (Kansas), Panoma (Kansas and Oklahoma), and Guymon-Hugoton (Oklahoma) fields as producing 35 TCF since the Hugoton Gas Field was first discovered in 1922. Historical oil production in Kansas as of 2025 approximates 6.9 billion barrels (bbls) and much of this oil has been associated with natural gas production. In 2024 (the latest complete annual production data for Kansas), Kansas produced 26.8 million bbls of oil from 48,342 wells and 126.7 billion cubic feet (BCF) of natural gas from 17,426 wells (Kansas Geological Survey, 2025a).

The major pay zones in the Hugoton Gas Field in Kansas are several porous dolomite units in the Permian (Wolfcampian) Chase Group. This gas field, as it extends into the Oklahoma and Texas panhandles is sometimes called the Hugoton-Panhandle Field. It ranks as one of the largest gas fields in the world (Mason, 1968; Pippin, 1970). The Panoma Gas Field, which underlies the Hugoton Gas

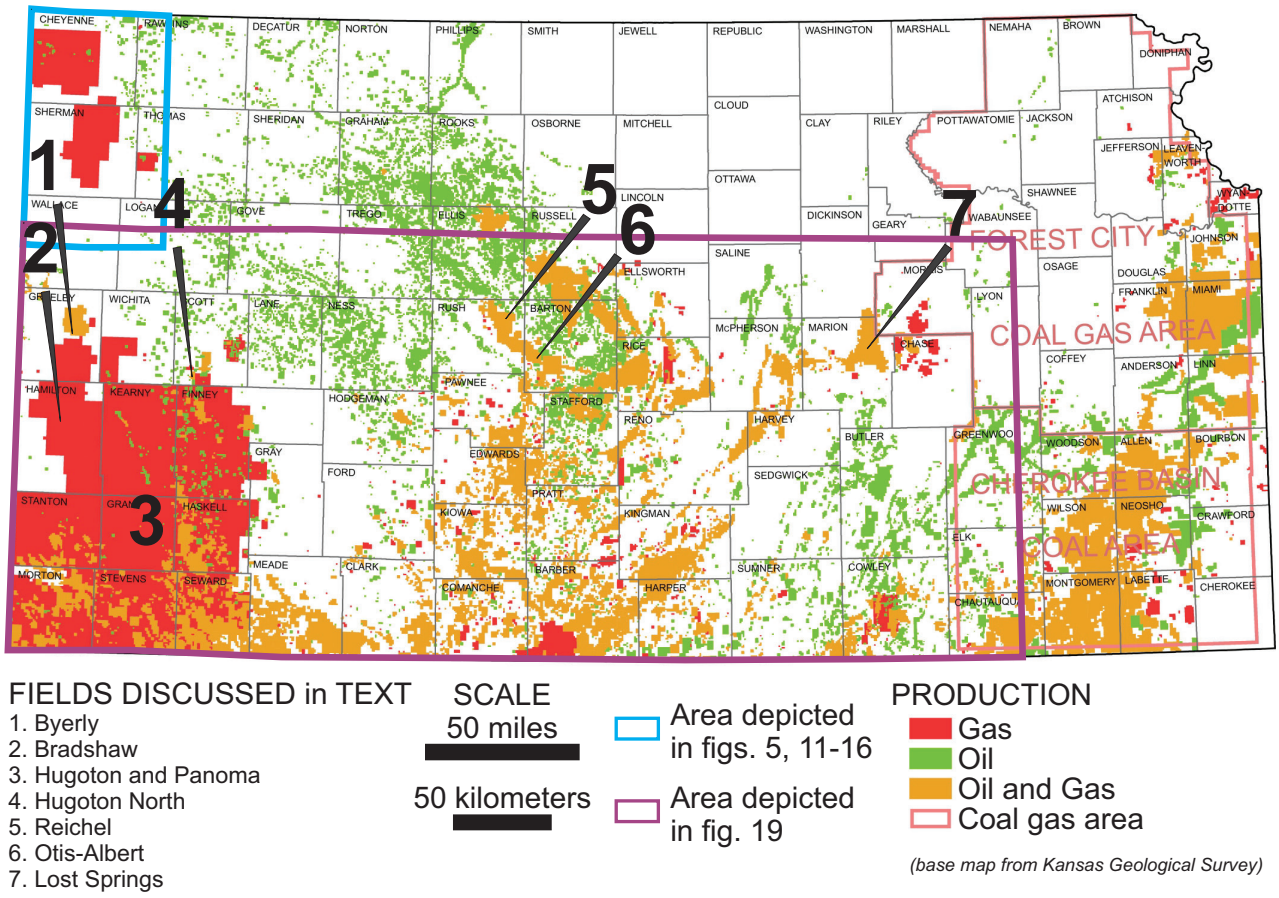


Figure 2. Oil and gas fields in Kansas (from Kansas Geological Survey). Gas production is mostly in the southern half of the state and in its northwestern corner. Gas-producing fields mentioned in the text are shown on the map. Red rectangle outlines mapping area for low-BTU gases (**fig. 5**) and Paleozoic gas accumulations (**figs. 11–16**); blue rectangle outlines mapping area for Cretaceous gas accumulations (**fig. 19**).

Field, produces from carbonate strata in the Permian (Wolfcampian) Council Grove Group beneath the Chase Group (Parham and Campbell, 1993). The producing zones in the Chase and Council Grove Groups are essentially components in a single complex field (Dubois and others, 2006, 2007). The production of the Panoma Gas Field in 2024 was 16.4 BCF, whereas the production from the Hugoton Gas Field was 61.4 BCF. In 2024, the annual production of the Hugoton and Panoma fields in Kansas was 77.8 BCF, which was 61% of the 126.7 BCF of natural gas produced in the entire state of Kansas that year (Kansas Geological Survey, 2025b).

Maturation studies indicate some local oil and gas generation occurs in Kansas, as Paleozoic strata in the central part of the state are in the beginning stages of oil generation (Newell, 1997). Similarly, Ordovician strata (Simpson Group and Viola Limestone) are in initial stages of oil generation in northeastern Kansas (Hatch and Newell, 1999). Maturation measurements in the Cherokee basin in eastern Kansas (Barker and others, 1992) also indicate Pennsylvanian and older strata are capable of generating hydrocarbons locally, although thermal maturity is not yet at peak oil generation. Subsurface temperatures are typical of cratonic geothermal gradients (Stavnes and Steeples, 1982) — about 1.37–1.67 °F/100 ft (25–30 °C/km) — hence subsurface temperatures at about 3,000 ft (915 m), which is a depth where much of the oil and gas are found, are expected to be about 100 °F (38 °C).

Eastern Kansas has both oil and gas production, and in the late 1980s through 2008, this region experienced a surge in drilling for coalbed natural gas (Stoeckinger, 1989, 1990; Newell and Yoakum, 2010). Accurate production records for the older oil and gas fields in eastern Kansas — type of production, volume, well locations, and particularly the chemistry of the natural gas produced — are only spottily archived; hence, the Cherokee basin and Forest City basin will not be discussed in detail in this publication.

Northwestern Kansas has commercial gas production from the Cretaceous Niobrara Chalk. The Cretaceous gases in northwestern Kansas are far removed from other gas-producing regions in Kansas and are isolated to the shallow eastern flank of the Denver-Julesburg basin of Colorado and Wyoming (**figs. 1A, 2**) on closures atop the broad Las Animas arch that extends into northwestern Kansas (see Sonnenburg, 2011). Other gas-producing areas in Kansas are

associated with hydrocarbons generated within the Anadarko and Arkoma basins in Oklahoma. In turn, these hydrocarbons migrated updip and northward into Kansas.

DATA SOURCES

The natural-gas analyses that constitute the basic data used in this publication are accessible in a downloadable open-file report and associated spreadsheet (Newell, 2025) available on the Kansas Geological Survey website (https://kgs.ku.edu/). The data were compiled over several decades, up to early 2020 for this bulletin. At the time of this research, this compilation comprised 5,576 analyses. As of 2025, 5,741 analyses are included in this database and as such, it is the most extensive publicly available compilation of natural-gas analyses for the state of Kansas. A total of 136 sources contributed to this database (see **table 1**), with the earliest being from Allen and Lyder (1918) and some analyses dating back to 1917 from the U.S. Bureau of Mines. More detail on data sources is provided in Newell (2025).

The U.S. Bureau of Mines (USBM) publication series on gas chemistry and helium content for natural gases produced in the United States represents a major source (32%) of data in the Newell (2025) open-file report. These publications are presented in approximately 35 separate and summary issues (cf., Moore, 1982; Hamak and Sigler, 1993; Gage and Driskill, 2005) published between 1917 and 2005. After the USBM closed in 1995, the gas analytical series continued through the Bureau of Land Management in the U.S. Department of the Interior until 2008.

Natural gas analyses included with test results from drill-stem tests (DSTs) and flow tests of natural gas wells compose 11% of the database. These analyses are sometimes included in well completion reports or voluntarily inserted in reports turned over to the Kansas Corporation Commission (KCC) and then, in turn, transmitted to the Kansas Geological Survey for presentation on its website for public access. The analyses are typically included in scans of source documents for individual wells. A special report to the KCC (Wilkonson, 1960) yielded a collection of 2,391 gas heating-value analyses (i.e., British thermal units/standard cubic foot [BTU/scf]) for the Hugoton Gas Field. This report comprises 43% of the wells in the Newell (2025) database. Other data were obtained by the author and by unpublished personal communications from several oil and gas operators. These operators, in the course of their exploration and production operations, contracted to have samples of their natural gas analyzed by various commercial laboratories.

Supplementary information and updates to the well from which the analyses were made (such as field name, API well number, and location information such as section, township, range, county, latitude, and longitude of the well) were added to the database by the author. Missing information and corrections such as the well operator and well number often needed clarifications. Geological information such as producing formation, depth, surface datum, and the stratigraphic hierarchy of the pay zone, wellhead pressure, and flow rate (if available) also was added, as were association or non-association with oil production and subcrop/superposition relationship of the producing formation to the widespread basal Pennsylvanian angular unconformity.

Analyses of natural gases over time and by multiple laboratories could conceivably be a source of variability for the percentages of component gases, but commercial laboratories have an existential motivation to provide accurate analyses. Simply put, these analytical laboratories will not survive if their product is inferior or erroneous. Maps and cross-plots of the analytical data presented in this report, regardless of the analyzing laboratory, are largely consistent, indicating that there is a good level of agreement in analytical results even though the analyses were done by different government, commercial, and academic laboratories.

Data presented in an analysis of a natural gas include heat-content (BTU/scf) and molar percentages of hydrocarbon gases, including methane, ethane, propane, *i*- and *n*-butane, *i*- and *n*-pentane, and all heavier hydrocarbons in the catch-all term "hexane+." The heat-content analyses considered in this report are "dry" analyses in that water vapor is excluded as a component gas in

Table 1. Data sources (see Newell, 2025) for mapping gas compositions. Analysis means chemical compositional analysis or BTU analysis, or both.

Source	Number of Analyses	% of Total Analyses
U.S. Bureau of Mines, Bureau of Land Management	1,794	32%
Drill-stem test (DST) reports	348	6%
Scout cards, well history control system (WHCS) database searches, well completion record	343	6%
Peer reviewed publications and KGS open-file reports	305	5%
One-point or four-point open-flow test	251	5%
Donated unpublished analyses	148	3%
Wilkonson (1960) – Kansas Corporation Commission Docket	2,391[a]	43%

[a]BTU analyses only

the natural gas. Small percentages of water vapor — about 1.5 to 2.5% — are usually present in natural gas, and this water vapor decreases the heating value of the natural gas by about 10 to 30 BTU/scf when it is included in the calculation of the heating value. Aside from the physical or mathematical removal of water vapor, compositions of natural gases in this report are pristine analyses. Wellhead and DST natural gas analyses, rather than analyses of processed gas prior to its injection into a pipeline, are thus the type of analyses that constitute the basic data used in this report. The significant digits presented in each analysis are preserved in the database. In general, most commercial analyses list amounts of component gases to the nearest one-hundredth of a percent (0.23%, for example).

Major non-hydrocarbon gases in an analysis of natural gas in Kansas typically include oxygen (O_2), carbon dioxide (CO_2), nitrogen (N_2), argon (Ar), helium (He), and to a lesser extent hydrogen (H_2). Sour gas (H_2S) is not usually included in an analysis unless it is detected or smelled at the well site; if it is not listed in a chemical analysis, it is probably safe to assume this gas is not present.

Corrections for atmospheric contamination were made to gas compositions and heating values. These corrections are based on oxygen content of the sample, whereby any oxygen in the sample is assumed to be due to atmospheric contamination. In most analyses where any oxygen is present, it composes less than 0.1 to 0.2% of the total gas, so the correction is minor. Where oxygen composes more than 1% of a gas analysis, however, the correction can be substantial. The correction procedure starts by subtracting the oxygen content from the summed percentage of component gases (ideally 100%), as well as other atmospheric gases in their respective ratios to oxygen. The composition of dry air by volume (from which these ratios to oxygen content can be calculated), according to Weaver (1966), is nitrogen (78.00%), oxygen (20.95%), argon (0.93%), carbon dioxide (0.03%), helium (0.0005%), methane (0.0002%), and hydrogen (0.00005%). Neon (0.0018%), krypton (0.0001%), nitrous oxide (0.00005%), xenon (0.000008%), and ozone (0.000001%) also are present in the atmosphere, but these component gases are not included in typical analyses of natural gases because they are usually very miniscule in a natural gas. Once oxygen and the other atmospheric gases are subtracted from the reported gas composition, the remaining percentages of component gases are recalculated to 100%. Air correction will principally reduce nitrogen, argon, and carbon dioxide content in an analysis, since these gases are in the largest ratios to atmospheric oxygen. Air correction will have a net effect of increasing the proportion of hydrocarbon gases in an analysis. In turn, the calculated heating value (i.e., BTU content) of the natural gas will be increased.

For calculation of BTU content, **table 2** lists the BTU content of component hydrocarbon gases.

Hydrogen (H_2) can contribute to the heat content of a natural gas, as it has a heating value of about 325 BTU/scf, but it is not significant (usually less than 0.5%) in central and western Kansas gas fields. Non-combustible components in a natural gas that degrade its heat content include nitrogen, helium, carbon dioxide, argon, and other minor gases that are not usually analyzed in typical oil-field analyses. In Kansas, nitrogen is the major diluent component gas that decreases BTU content. If they are not specifically analyzed, other minor non-combustible component gases are usually included in the nitrogen percentage. In a "dry gas" (i.e., hydrocarbon component composed principally of methane), a non-combustible gas content of about 16% will lower the overall heating value of the gas to 850 BTU/scf (i.e., the commonly accepted upper limit of heating value for a "low-BTU gas").

Table 2. Hydrocarbon component gases and their heating values.

Component	Gross Heating Value
methane (CH_4)	1,012 BTU/scf
ethane (C_2H_6)	1,783 BTU/scf
propane (C_3H_8)	2,557 BTU/scf
i-butane (C_4H_{10})[a]	3,354 BTU/scf
n-butane (C_4H_{10})[a]	3,369 BTU/scf
cyclopentane (C_5H_{10})[b, c]	3,764 BTU/scf
i-pentane (C_5H_{12})[c]	4,001 BTU/scf
n-pentane (C_5H_{12})[c]	4,009 BTU/scf
hexane+ (C_6H_{14} and heavier hydrocarbons)	4,760 BTU/scf)[d]

[a]Butane is sometimes not differentiated into *i*-butane and *n*-butane. In these circumstances, an average heating value is used
[b]Reported in some USBM analyses but usually not elsewhere
[c]Pentane BTU content is usually not differentiated by its isomers; undifferentiated pentane is assigned as 4,009 BTU/scf in most oil-field analytical laboratories
[d]Generalized heating value for hexane+ used by most oil-field analytical laboratories

A survey of the gas compositional database for Kansas (Newell, 2025) yields the maximum and average values for component gases and BTU content shown in **table 3**.

CHARACTERIZATION OF GAS CHEMISTRY BY HISTOGRAMS AND CROSS-PLOTS

Percentages of component gases of natural gases are put into histograms or cross-plots so that the range of compositions and centrality (average, mode, or median) can be assessed. Divisions of the total range of compositions are then determined based on the distribution of compositional data.

The age of the reservoir rock from which a natural gas is produced is differentiated into seven stratigraphic intervals (**fig. 3**) according to Kansas surface and subsurface geology. From youngest to oldest, these stratigraphic intervals are Cretaceous (Niobrara Chalk); Permian (Nippewalla, Sumner, Chase, and Council Grove Groups); Pennsylvanian, Virgilian (Admire, Wabaunsee, Shawnee,

Table 3. Maximum percentages recorded for component gases in Kansas. Average values and the number of analyses used to determine the average values are given under the component gases on the left side of the table.

Gas	Greatest Amount	Well Name, Location (Section, Township, Range), Field Name, County, Geologic Province, Producing Unit of Well Recording Maximum Percentage
Methane *avg. = 74.7%* *n = 2,842*	99.7%	Raymond Mowrey #1 Schlegel, sec. 09, T. 24 S., R. 23 E., Schlegel Field, Bourbon County, Cherokee basin, Pennsylvanian Cherokee Group, Bartlesville Sandstone
Argon *avg. = 0.1%* *n = 1,730*[a]	2.1%	TXO Prod. #2 Antrim 'A', sec. 30, T. 32 S, R. 08 W., Sullivan East Field, Harper County, Sedgwick basin, Pennsylvanian Lansing Group, Stalnaker sandstone
CO_2 *avg. = 0.4%* *n = 2,488*[a]	42.8%	W.T.W. Operating #1 Wilson, sec. 32, T. 01 S., R. 17 E., gas show, Brown County, Forest City basin, Precambrian gneiss and schist
Helium *avg. = 0.69%* *n = 2,539*[b]	10.8%	Murfin Drlg. #6 Glathart, sec. 29, T. 11 S., R. 17 W., Bemis-Shutts Field, Ellis County, Central Kansas uplift, Cambrian-Ordovician Arbuckle Group
Hydrogen *avg. = 0.1%* *n = 2,100*[a]	33.5%	CFA Oil #1 Heins, sec. 27, T. 13 S., R. 06 E., gas show, Geary County, Nemaha uplift, Mississippian Kinderhook sandstone
H_2S[c] *avg. = 0.1%* *n = 36*[a]	1.3%	Berentz Drlg. #1 Aiken, sec. 17, T. 32 S., R. 11 E., Kingston Field, Chautauqua County, Cherokee basin, Mississippian limestone
Nitrogen *avg. = 14.2%* *n = 2,341*[a]	99.5%	Smith Cattle #1 Helm, sec. 35, T. 18 S., R. 40 W., Bradshaw Gas Area, Greeley County, Anadarko embayment, Permian Nippewalla Group, Glorieta Sandstone
BTU content *avg. = 971 BTU/scf* *n = 5,425*	2,934 BTU/scf	Dieter Prod. #1 A. Krch, sec. 15, T. 18 S., R. 04 E., Lost Springs Field, Marion County, Sedgwick basin, Mississippian chat

[a]"Trace" readings considered to be 0.04% for averaging

[b]"Trace" readings considered to be 0.004% for averaging

[c]H_2S is commonly called "sour gas" in the oil fields; 1,600 analyses are listed as 0.0%; 1,200 listed as "not given"; 30 listed as "trace" or "sour"

All averages and maximums are calculated compositional percentages, with atmospheric gases (based on oxygen content) and water vapor eliminated.

and Douglas Groups); Pennsylvanian, Missourian (Lansing-Kansas City and Pleasanton Groups); Pennsylvanian, Desmoinesian and lower (Marmaton and Cherokee Groups, Morrowan- and Atokan-Stage pay zones); basal Pennsylvanian angular unconformity (pay zones subcropping beneath this major angular unconformity — usually Mississippian strata, except on uplifts — and Pennsylvanian reservoirs directly overlying this unconformity); and sub-Mississippian (pay zones significantly below and not in communication with reservoirs associated with the regional basal Pennsylvanian angular unconformity).

Rich (1931) recognized porous zones immediately below and above the regional basal Pennsylvanian angular unconformity as regional carrier beds for movement of hydrocarbons generated in deep basinal areas in Oklahoma. The oldest reservoirs are fractured Precambrian quartzites and granites that are present on local structural and paleotopographic highs on the Central Kansas uplift and Nemaha uplift (Merriam, 1963). Away from these major uplifts, younger Paleozoic strata up to Mississippian age carbonates subcrop beneath the unconformity.

The stratigraphic unit designated as "sub-Mississippian pay zones" is usually composed of lower Paleozoic strata, specifically Ordovician Simpson Sandstone, porous limestone in the Ordovician Viola Limestone, porous dolomite in the Ordovician Maquoketa Shale, and the basal sandstone below the Devonian-Mississippian Chattanooga Shale (sometimes called "Kinderhook" or "Misener" sandstone). Provided these units are not subcropping immediately below the basal Pennsylvanian angular unconformity, they are presumed hydrologically isolated from porous zones associated

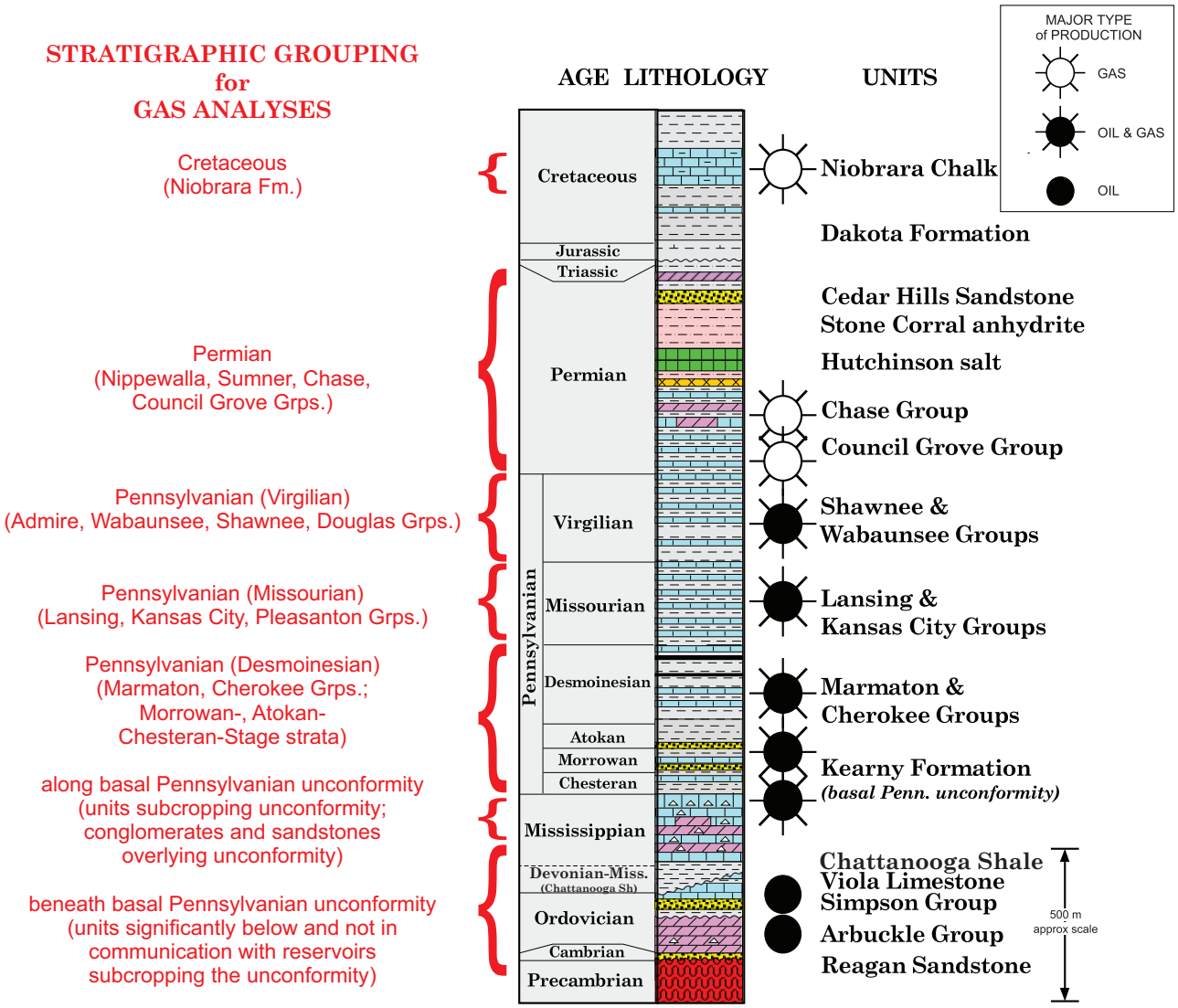


Figure 3. Generalized stratigraphy of Kansas — most petroleum production in Kansas is from Paleozoic strata, with minor gas production from Cretaceous (Niobrara) chalks in the northwestern corner of the state. The most prolific gas reservoirs are several thin carbonate units in the Permian (Wolfcampian) Chase Group, which comprise the main pay zones in the Hugoton Gas Field. This bulletin maps and compares gas chemistry for seven broad stratigraphic units (after Newell and others, 2009).

with the unconformity. A stratigraphic separation of about 50 ft (12.2 m) of non-porous strata or shale below the unconformity was considered sufficient to categorize a pay zone as being in the "sub-Mississippian" classification. Similarly, a stratigraphic separation of about 50 ft (12.2 m) of non-porous strata or shale above the basal Pennsylvanian angular unconformity was considered sufficient to categorize a pay zone into a stratigraphic interval above the unconformity (usually Pennsylvanian [Desmoinesian, Morrowan, and Atokan pay zones] or Pennsylvanian [Missourian] intervals).

For each of the seven major stratigraphic intervals considered, this publication presents four chemical characteristics for construction of histograms, cross-plots, and maps of gas composition: heating value, hydrocarbon wetness, helium percentage, and nitrogen-to-helium ratio (i.e., nitrogen %/helium %). Quantity intervals of these four characteristics were color-coded in many figures for easy recognition, as the colors were applied to data points on maps and histogram bars for each of the seven stratigraphic-unit maps presented in this report. Each stratigraphic unit depicted in this report has at least 75 analyses associated with it. The majority of samples (2,824) are concentrated in the Permian, mostly heating values from the Hugoton Gas Field (2,682 samples) and Panoma Gas Fields (92 samples). The stratigraphic unit comprising pay zones associated with the basal Pennsylvanian angular unconformity has the most chemical analyses (1,069) of all the stratigraphic intervals.

HYDROCARBON GASES

The simplest but most common measure of natural-gas quality is the heating value, or heat content, which is expressed in the American energy industry as BTU/scf. A histogram of natural-gas BTUs (**fig. 4**) summarizing 1,253 Kansas gas analyses as of 2007 (from Newell, 2007; Newell and others, 2009), exclusive of the Hugoton and Panoma fields, indicates that gas quality in Kansas is characterized by a continuum from high- to low-BTU gas. In other words, there is not a bi-modal distribution of high- and low-BTU gas analyses. The distribution of heating values appears as a single, bell-shaped distribution, skewed with a "tail" on the lower-BTU flank of the distribution. Superimposed on these data is another histogram, with narrower class intervals, for the distribution of 2,492 BTU values for the giant Hugoton Gas Field. These data are principally from Wilkonson (1960). The distribution of heating values of the gases produced in the Hugoton Gas Field also has a low-BTU tail, similar to all the other Kansas natural gases (**fig. 4**).

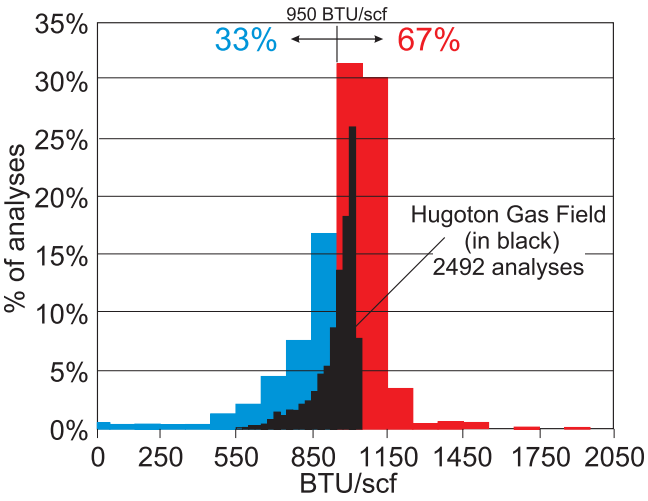


Figure 4. Distribution of natural-gas BTU contents for the Hugoton Gas Field (in black) and for Kansas (excluding the Hugoton and Panoma gas fields) (in red and blue). Both distributions are skewed toward lower-BTU gas (from Newell and others, 2009). The Kansas analyses excluding the Hugoton and Panoma gas fields are separated into blue (less than 950 BTU/scf) and red (more than 950 BTU/scf) distributions.

As there is not a clear division between high-BTU gas and low-BTU gas in **fig. 4**, the definition as to what is low-BTU gas is somewhat arbitrary. The distinction of what is a low-BTU gas is thus based on standards for gas quality set by natural gas pipeline companies. Most pipeline companies set a minimum standard of 950 BTU/scf. Thus, the analyses presented in this publication use a provisional value of 950 BTU/scf as the maximum heating value in a low-BTU gas. As shown in **fig. 4**, 33% of natural gases at the wellhead have heating values less than 950 BTU/scf.

Mapping of gas analyses (**fig. 5**) shows that higher concentrations of low-BTU gas occur on the Central Kansas uplift and the Pratt anticline in south-central Kansas. The occurrence of the low-BTU gas increases northward from the Oklahoma state line to the Central Kansas uplift. Generally, the BTU content of these low-BTU gases also decreases northward. The distribution of low-BTU gas forms a halo around the main portion of the Hugoton Gas Field, with the BTU/scf decreasing outward. Other geologic regions of Kansas, such as Pennsylvanian strata in the Cherokee and Forest City basins in eastern Kansas, also have low-BTU natural gas, but data in these areas are relatively sparse (particularly for gas fields produced and depleted in the first half of the 20th century) and trends are thus difficult to discern. Cretaceous gases in northwestern Kansas are discussed in this report but are presented separately from those areas depicted in **fig. 5**.

Lower-BTU natural gas can supplement natural gas supplies in the future, if prices justify its exploration and upgrading at the surface. In some cases, it is burned at the surface near the wellhead for heat and power. However, there is a lower explosive or flammable limit (i.e., LEL/LFL) for low-BTU gas in air. Inasmuch as methane is usually the principal flammable component of low-BTU gas, gas containing methane less than 4.4% by volume will not ignite (The Engineering Toolbox, 2025). This percentage of methane corresponds to a gas with a heating value of 45 BTU/scf. If any ethane, propane, or butane is present, their LEL/LFLs are respectively 3.0%, 2.1%, and 1.86%.

Hydrocarbon wetness expresses the proportion of higher-molecular-weight hydrocarbons in a natural gas to that of the total hydrocarbons present. The hydrocarbon wetness used in this study follows Jenden and others (1988):

$$\text{Hydrocarbon wetness} = \Sigma(C_2\text{-}C_{6+})/(\Sigma C_1\text{-}C_{6+})*100$$

This is a percentage of the total moles of hydrocarbon components that are ethane and heavier. C_1 = methane, C_2 = ethane, and C_{6+} = hexane and heavier hydrocarbons. $\Sigma(C_2\text{-}C_{6+})$ is the summation of individual component hydrocarbon gases from ethane to hexane and any heavier gaseous hydrocarbons (i.e., ethane, propane, and butane, pentane, and hexane, heavier gaseous hydrocarbons, and any isomers thereof). $\Sigma(C_1\text{-}C_{6+})$ is the summation of individual component hydrocarbon gases from methane to hexane+ (i.e., methane, ethane, propane, and butane, pentane, and hexane and any heavier gaseous hydrocarbons, and any isomers thereof). Inasmuch as all gases behave as ideal gases at surface temperature and pressure, the percentage of each component gas is its molar percentage in a natural gas. Natural gases with large percentages of higher-molecular-weight hydrocarbons are "wetter," whereas natural gases that are largely composed of methane are "drier." "Geochemical" wetness defined by light hydrocarbons should not be confused with gas wetness referring to gas condensate yield.

The major combustible component in natural gas is usually the C_1 component (i.e., methane, CH_4). Since methane has a heating value of 1,012 BTU/scf, any natural gas with a heating value greater than 1,012 BTU/ton has to contain some higher-molecular-weight hydrocarbons (i.e., ethane, propane, butane, etc.; see previous discussion regarding their heating values), and particularly so if a natural gas contains a significant percentage of non-hydrocarbon gases.

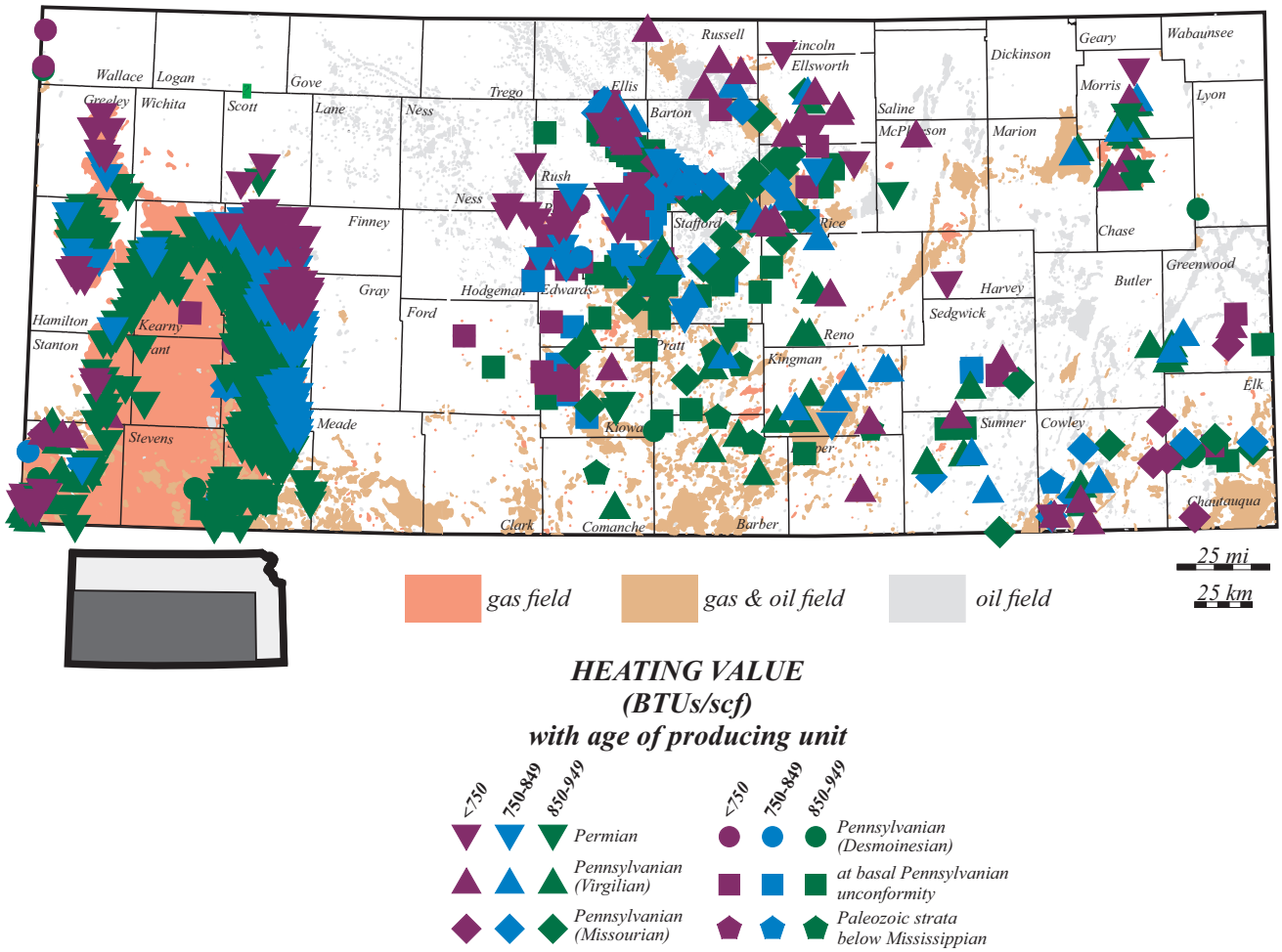


Figure 5. Heating values of low-BTU natural gas analyses (i.e., less than 950 BTU/scf) in southern and western Kansas (after Newell and others, 2009). Almost all Paleozoic accumulations of low-BTU gases are mapped here. Distribution of Cretaceous low-BTU gases are shown in **fig. 19**. The inset on the small Kansas map shows the figure area. The relative dearth of gas analyses from Paleozoic strata in eastern Kansas (principally the Forest City and Cherokee basins and Bourbon arch) precludes mapping any meaningful low-BTU trends in these regions.

Figure 6 shows histograms of BTU content and hydrocarbon wetness for each of the seven stratigraphic units (see **fig. 3**). Colors of the histogram bars (red, orange, yellow, green, blue, and purple) correspond to the same composition ranges that are depicted in maps of BTU content and hydrocarbon wetness presented later in this report. Averages, standard deviations, and ranges of values for BTU content and hydrocarbon wetness are identified at the base of each histogram, and these statistical summaries are presented synoptically for easy comparison of the stratigraphic intervals in **fig. 7**. The BTU histograms are generally skewed distributions with longer "tails" on the low BTU sides of the distributions (**fig. 6**), in a manner similar to collective BTU analyses for all Kansas gases (**fig. 4**). A skewed distribution with a long tail toward wetter gases is evident on several of the hydrocarbon-wetness histograms (**fig. 6B–G**).

Analyses of gases shown in **fig. 6B** are only for gases that are from Permian fields east of the larger Permian fields in the Hugoton embayment. If all the Permian analyses were considered just as one group, the sheer number of analyses from the Hugoton, Panoma, Hugoton North, Bradshaw, and Byerly fields would obfuscate any trends that could be depicted with these smaller fields elsewhere in Kansas. A group of 130 analyses are depicted in **fig. 6B**, with 68% from the Chase Group, 20% from the Council Grove Group, 10% from the Sumner Group, and 2% from the Nippewalla Group.

In general, BTU content and hydrocarbon wetness increase with increasing age of the producing strata (**fig. 7**). Cretaceous gases (**figs. 6A, 7B**) are the driest of all the seven stratigraphic units. The analyses from geologic formations below the basal Pennsylvanian angular unconformity are the wettest (**figs. 6G, 7B**). The percentage of analyses registering more than 950 BTU/scf (the boundary between low- and high-BTU gases; noted on the BTU histograms) generally increases with increasing age of the reservoir (**fig. 7**).

A cross-plot of BTU content vs. total hydrocarbon percentage (i.e., ΣC_1-C_{6+}) not surprisingly shows a generally positive linear

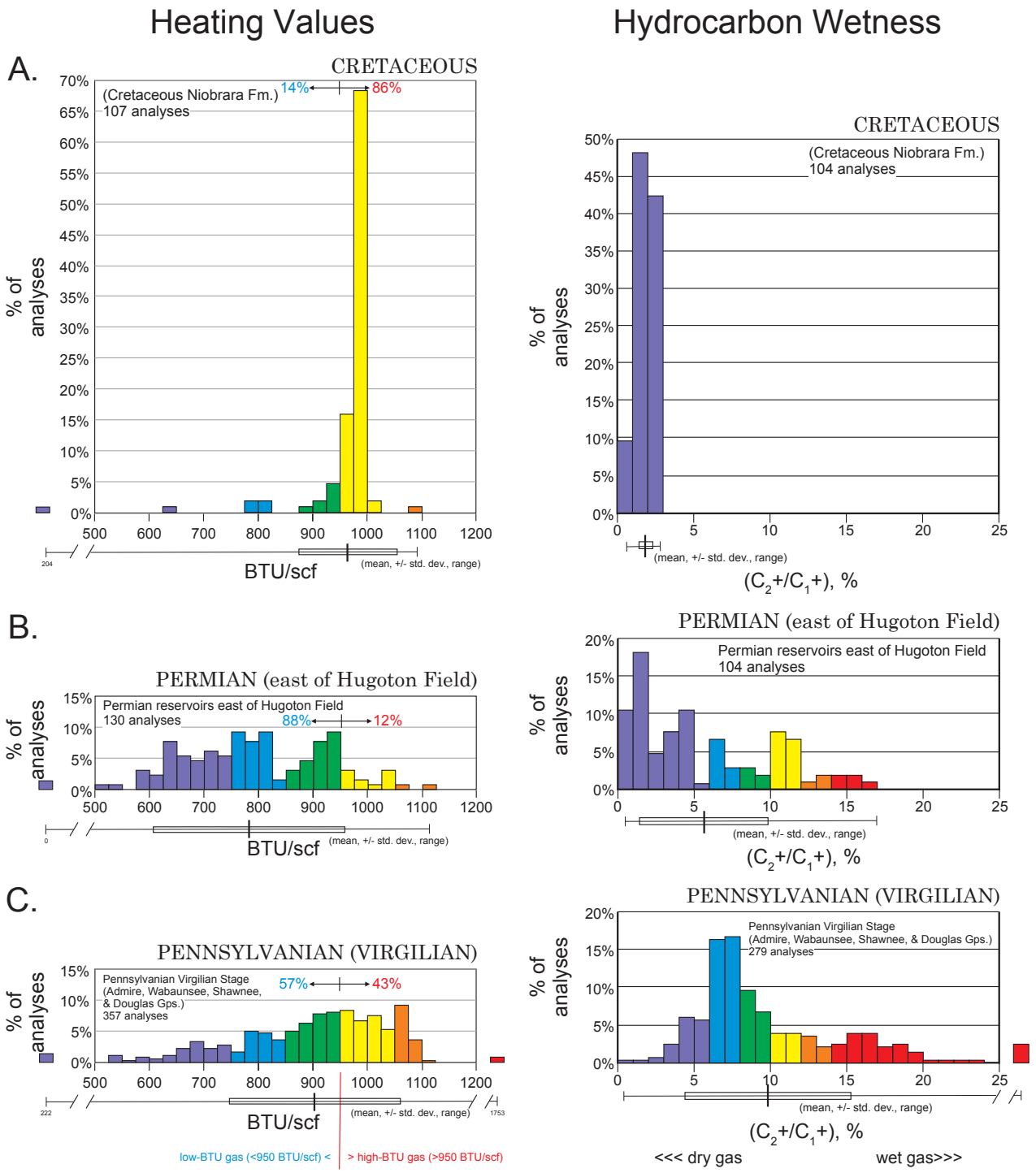


Figure 6. Histograms showing the distribution of analyses for BTU content and hydrocarbon wetness in Kansas natural gases, by stratigraphic units defined in **fig. 3**: A) Cretaceous, B) Permian (exclusive of the large gas fields in Anadarko embayment; i.e., Bradshaw, Byerly, Hugoton, Panoma fields), C) Pennsylvanian (Virgilian). Colors of the histogram bars correspond to colors used in mapping BTU content and hydrocarbon wetness in **figs. 11–16, 19**.

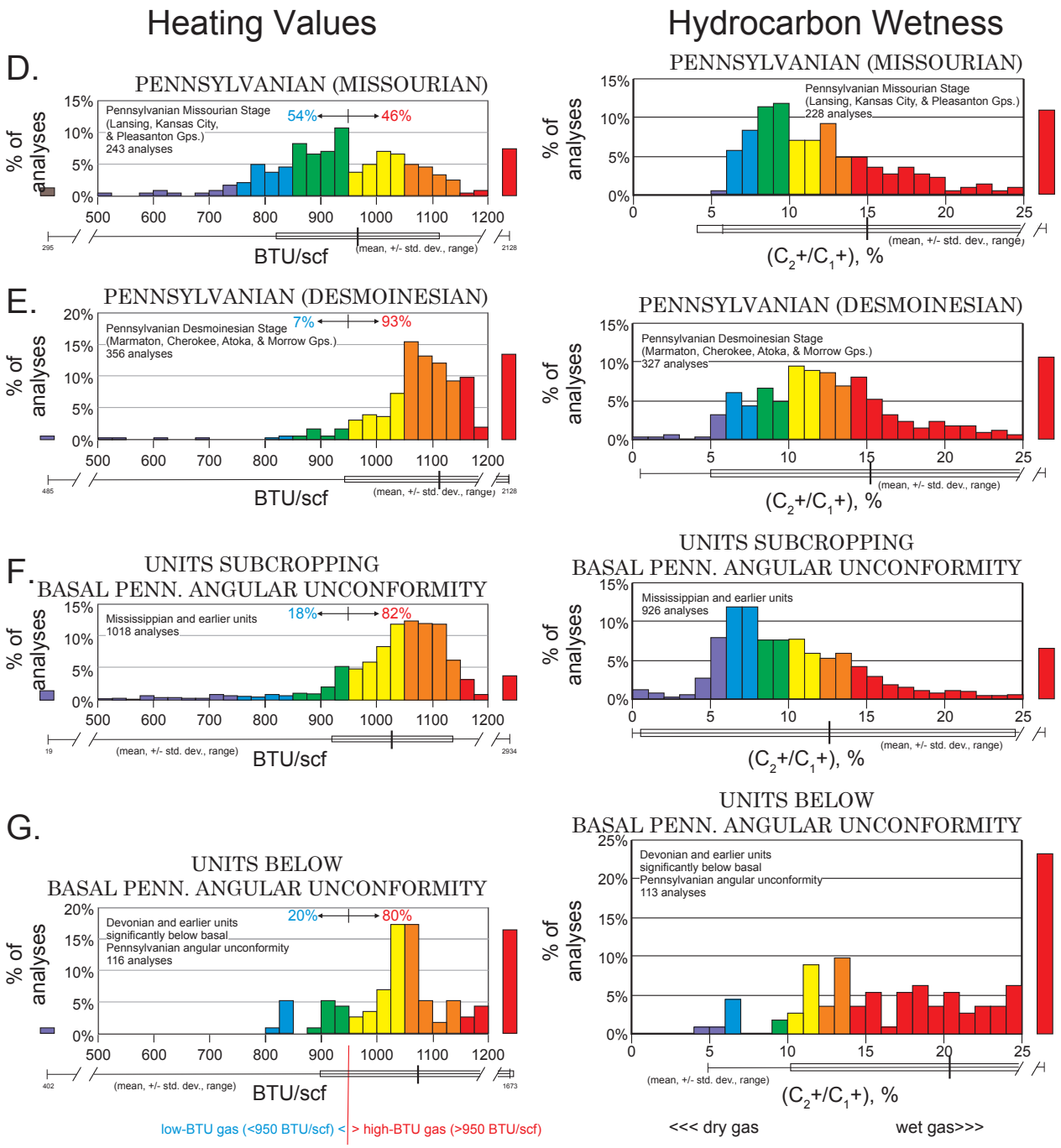


Figure 6 (continued). Histograms showing the distribution of analyses for BTU content and hydrocarbon wetness in Kansas natural gases, by stratigraphic units defined in **fig. 3**: D) Pennsylvanian (Missourian), E) Pennsylvanian (Desmoinesian), F) units along basal Pennsylvanian unconformity, and G) units below and not in communication with the basal Pennsylvanian unconformity. Colors of the histogram bars correspond to colors used in mapping BTU content and hydrocarbon wetness in **figs. 11–16, 19**.

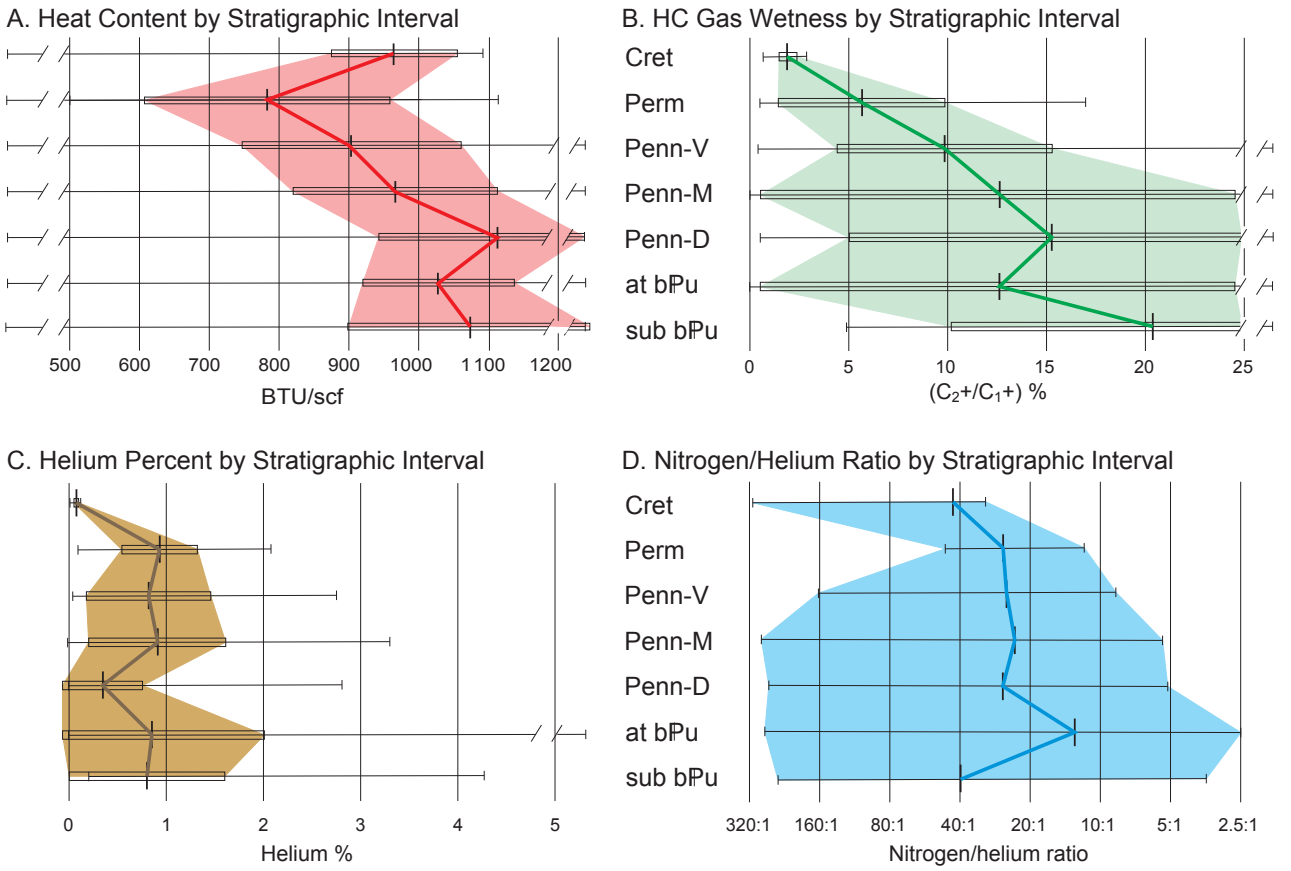


Figure 7. Variations in natural-gas characteristics by stratigraphic unit: A) BTU content, B) hydrocarbon wetness, C) helium percentage, D) nitrogen/helium ratio. These diagrams were constructed using the statistical summaries at the bases of the histograms in **fig. 6**. The dark line between each stratigraphic interval follows changes in the average or median; the lighter areas mark +/- standard deviation for A), B), and C) and upper and lower ranges for D). Data for the Permian do not include the large gas fields in the Anadarko embayment (i.e., Bradshaw, Byerly, Hugoton, and Panoma fields). Cret = Cretaceous; Perm = Permian; Penn-V = Pennsylvanian (Virgilian); Penn-M = Pennsylvanian (Missourian); Penn-D = Pennsylvanian (Desmoinesian); bPu = basal Pennsylvanian unconformity.

correlation for all the seven stratigraphic units (**fig. 8**). Total hydrocarbon percentage could have been used instead of BTU content to depict gas quality, but more BTU analyses are available than are chemical analyses of component gases. The correlation of BTU content with total hydrocarbon percentage closely parallels the line of expected BTU values that would occur with increasing percentages of methane in a sample, if methane was the sole hydrocarbon gas (**fig. 8A**). Increasing scatter in the data depicting heat content is evident in older stratigraphic units (**fig. 8B-E**), particularly at higher BTU values. The scatter of data points to the right of the red methane line (defined in **fig. 8A**) is particularly prevalent when hydrocarbon percentages in a sample are greater than 85%. This also indicates that gases in the older stratigraphic units are generally wetter than in the younger units (**fig. 8**).

NON-HYDROCARBON GASES

The major non-hydrocarbon gases in most natural gases in Kansas are nitrogen and helium. Other commonly measured non-hydrocarbon gases (i.e., argon, carbon dioxide, sour gas, hydrogen) are not specifically addressed in this report because their occurrence is minimal, but patterns of their occurrence may be worth further study. Other than the presence of nitrogen in natural gases in Kansas, other non-hydrocarbon gases may be locally dominant. For example, coalbed methane (CBM) production from Pennsylvanian (Desmoinesian) coal beds in the Cherokee basin in southeastern Kansas can carry significant percentages of carbon dioxide, particularly in long-lived wells (lasting perhaps several years). Natural gas from these wells can be prone to increasing percentages of CO_2 over time (Newell and Yoakum, 2010). Hydrogen can be a substantial component of gas shows in lower Paleozoic rocks immediately overlying the basement of the Forest City basin and Nemaha uplift in northeastern Kansas (Goebel and others, 1984; Guelard and others, 2017).

Helium is one of the foci of this report because it is a strategic resource and can be recovered as a salable gas, with recent prices

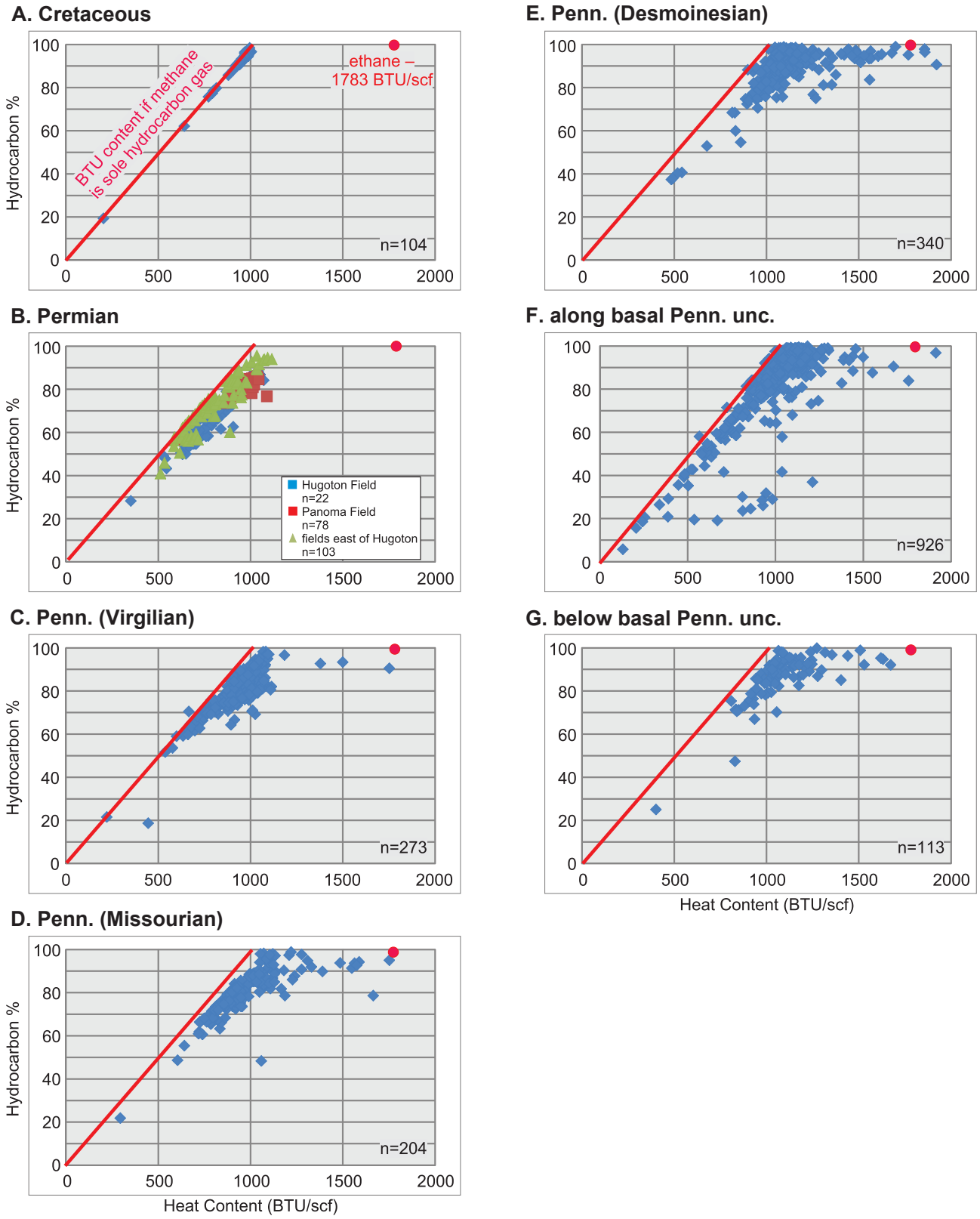


Figure 8. Cross-plots of BTU content vs. total hydrocarbon percentage for gas analyses in the seven stratigraphic units considered in this study. The hydrocarbon component in Cretaceous gases (A) is almost all methane; therefore, its samples lie along the methane line (in red). Points for gases from other stratigraphic units (B–G) are displaced to the right of this methane line due to the increasing presence of higher-molecular-weight hydrocarbons (with generally higher BTU content) with increasing age of the reservoir.

ranging in excess of $90/thousand cubic feet (mcf) and even briefly as high as $400/mcf for refined helium (C. Becker, Jr., Conifer, Colorado, personal communication, 2020). Helium is linked to nitrogen in a relatively constant ratio for a given geologic horizon (Pierce and others, 1964; Gold and Held, 1987; Jenden and others, 1988); therefore, more helium in a natural gas in Kansas also likely means more nitrogen. Hence, the BTU content of gases bearing significant helium and nitrogen is usually low, and often these non-hydrocarbon gases need to be extracted before the hydrocarbon component can be accepted to natural-gas pipelines. However, the cost of upgrading may be offset through the sale of the helium.

Figure 9 displays a geometric progression (i.e., class divisions at 160:1, 80:1, 40:1, 20:1, 10:1, etc.) in histograms of nitrogen/helium ratios for each of the seven stratigraphic units. Nitrogen/helium ratios generally decrease with increasing age of the reservoir (**fig. 9**). The median nitrogen/helium ratio is 45:1 for Cretaceous strata, 31:1 for Permian strata, 25:1 for Virgilian strata, 21:1 for Missourian strata, and 11:1 for pay zones along the basal Pennsylvanian unconformity. In contrast, strata below the basal Pennsylvanian angular unconformity have a median nitrogen/helium ratio of 40:1. The range of nitrogen/helium ratios also spreads with increasing age of the stratigraphic unit (**figs. 7, 9**).

Helium percentage and its changes with time are somewhat enigmatic in that there is not a strong enrichment or depletion with increasing age of the reservoir, aside from the fact that Cretaceous gases in the northwestern part of the state are poor in helium and have relatively high nitrogen/helium ratios. Older stratigraphic units tend to have ranges of helium concentrations that extend to higher values, even though average helium compositions do not show significant enrichment with increasing age of the stratigraphic interval (**figs. 7, 9**). Bimodal distributions are evident in the histograms for Pennsylvanian (Virgilian and Missourian) stratigraphic units for both helium percentages and nitrogen/helium ratios (**fig. 9**).

There is considerable spread in cross-plots of nitrogen and helium percentages for each stratigraphic unit (**fig. 10**). Natural gases found along and significantly below the basal Pennsylvanian unconformity generally have lower nitrogen/helium ratios if they contain higher percentages of nitrogen and helium (**fig. 10F, G**). This pattern of relative enrichment in helium is not as well developed in younger stratigraphic units (**fig. 10A–E**).

MAPPING GAS CHEMISTRY BY STRATIGRAPHIC HORIZON

Mapping of BTU content, hydrocarbon wetness, helium percentage, and the nitrogen/helium ratio for each of the seven stratigraphic intervals reveals geographic trends in these characteristics. Analyses for each stratigraphic unit are color-differentiated into six categories (red, orange, yellow, green, blue, and purple), with each color corresponding to the color ranges of the histogram bars presented in **figs. 6** and **9**.

Most natural gases in the lowest stratigraphic unit (i.e., strata significantly below the basal Pennsylvanian unconformity) are high-BTU gases (more than 950 BTU/scf; **fig. 11A**), but regional trends are difficult to detect due to scarcity of data. Analyses mapped in the younger stratigraphic units (except the Cretaceous) show that BTU content generally increases deeper (i.e., southward) into the Anadarko basin. Although lack of data can obscure such trends, hydrocarbon wetness (**fig. 11B**) also increases with BTU content southward into the Anadarko basin. Conversely, helium content increases northward onto the Central Kansas uplift (**fig. 11C**) along with decreasing nitrogen/helium ratios (**fig. 11D**).

The greatest number and widest spatial distribution of analyses are from the basal Pennsylvanian angular unconformity (**fig. 12**). BTU content (**fig. 12A**) and gas wetness (**fig. 12B**) increase southward into the Anadarko basin. Helium percentage (**fig. 12C**) and nitrogen/helium ratios (**fig. 12D**) increase northward out of the basin. The distal end of the migration route out of the Anadarko basin and up the Pratt anticline appears to be the southern and western flank of the Central Kansas uplift. Another migration route is located to the east, skirting the northern end of the Sedgwick basin. It extends into McPherson County and then turns eastward and terminates on the Nemaha uplift at the Lost Springs Field in northeastern Marion County.

Gas analyses from Pennsylvanian (Desmoinesian) strata (**fig. 13**) are not as numerous as those along the basal Pennsylvanian unconformity (**fig. 12**). These gases are principally located in the deeper areas of the Anadarko basin in two areas: the larger area covers seven counties (Grant, Haskell, Meade, Morton, Seward, Stanton, and Stevens) in southwestern Kansas over the Hugoton embayment, and a smaller area is farther east in south-central Kansas in Comanche, Kiowa, and eastern Clark counties. This latter area has characteristics similar to that of the underlying gas production along the basal Pennsylvanian unconformity (**fig. 12**), thus upward leakage of gas into Desmoinesian strata cannot be ruled out. Helium content (**fig. 13C**) tends to be lower in this eastern area and in the eastern side of the Hugoton embayment. Pennsylvanian (Desmoinesian) helium percentage within the Hugoton embayment gradually increases west-northwestward.

Pennsylvanian (Missourian) (**fig. 14**) and Pennsylvanian (Virgilian) (**fig. 15**) analyses are similar in that they are characterized by low-BTU gases on the Central Kansas uplift and higher BTU gases south of the uplift. Both stratigraphic units display a horseshoe-shaped area along the perimeter of the Central Kansas uplift where low-BTU gas is prevalent, extending from northeastern Rush County, southwestern Barton County, west-central Rice County, southwestern Ellsworth County, and southern Russell County. Natural gas analyses are not available in the interior of this area. Hydrocarbon wetness tends to be higher in Missourian and Virgilian strata in the Hugoton embayment than in other areas, whereas helium content is generally greater in parts of the horseshoe-shaped area than other regions. Both stratigraphic units are cyclothemic (Merriam, 1963) and have several (about 20) separate reservoirs that produce petroleum.

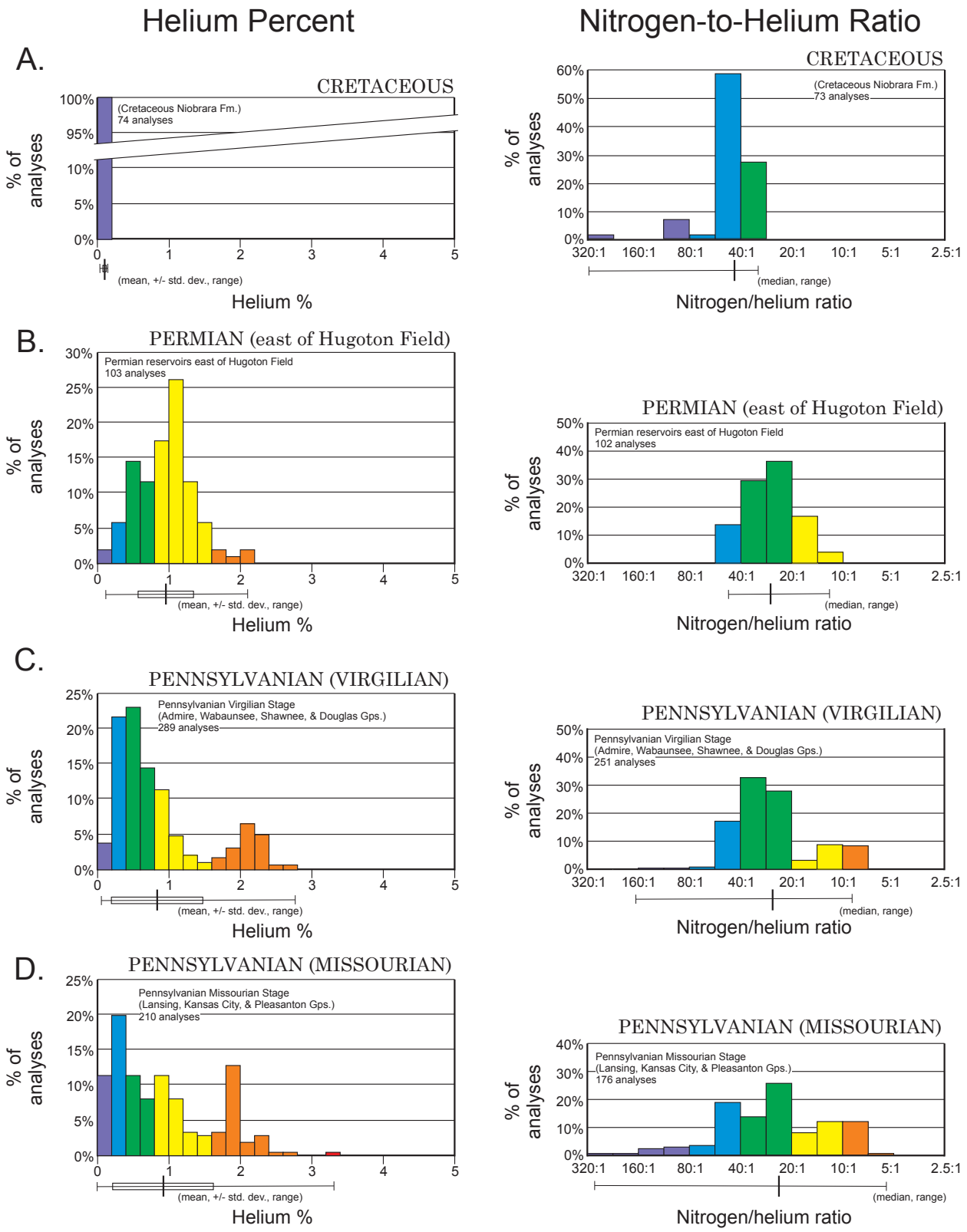


Figure 9. Histograms showing the distribution of analyses for helium percentage (left column) and nitrogen/helium ratio (right column) in Kansas natural gases, by stratigraphic intervals defined in **fig. 3**. Colors of the histogram bars correspond to colors used in mapping helium percentage and nitrogen/helium ratios in **figs. 11–16, 19**.

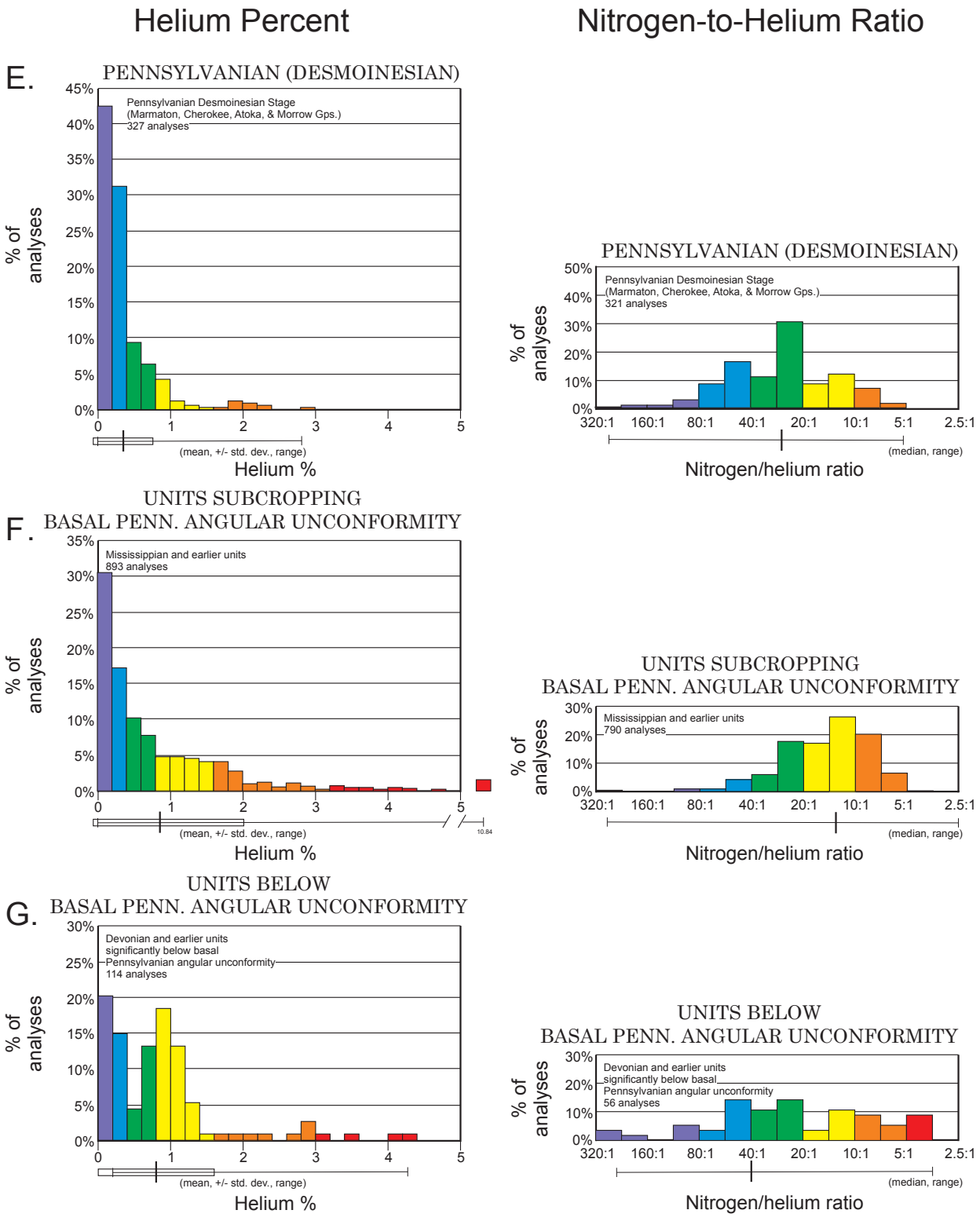


Figure 9 (continued). Histograms showing the distribution of analyses for helium percentage (left column) and nitrogen/helium ratio (right column) in Kansas natural gases, by stratigraphic intervals defined in **fig. 3**. Colors of the histogram bars correspond to colors used in mapping helium percentage and nitrogen/helium ratios in **figs. 11–16, 19**.

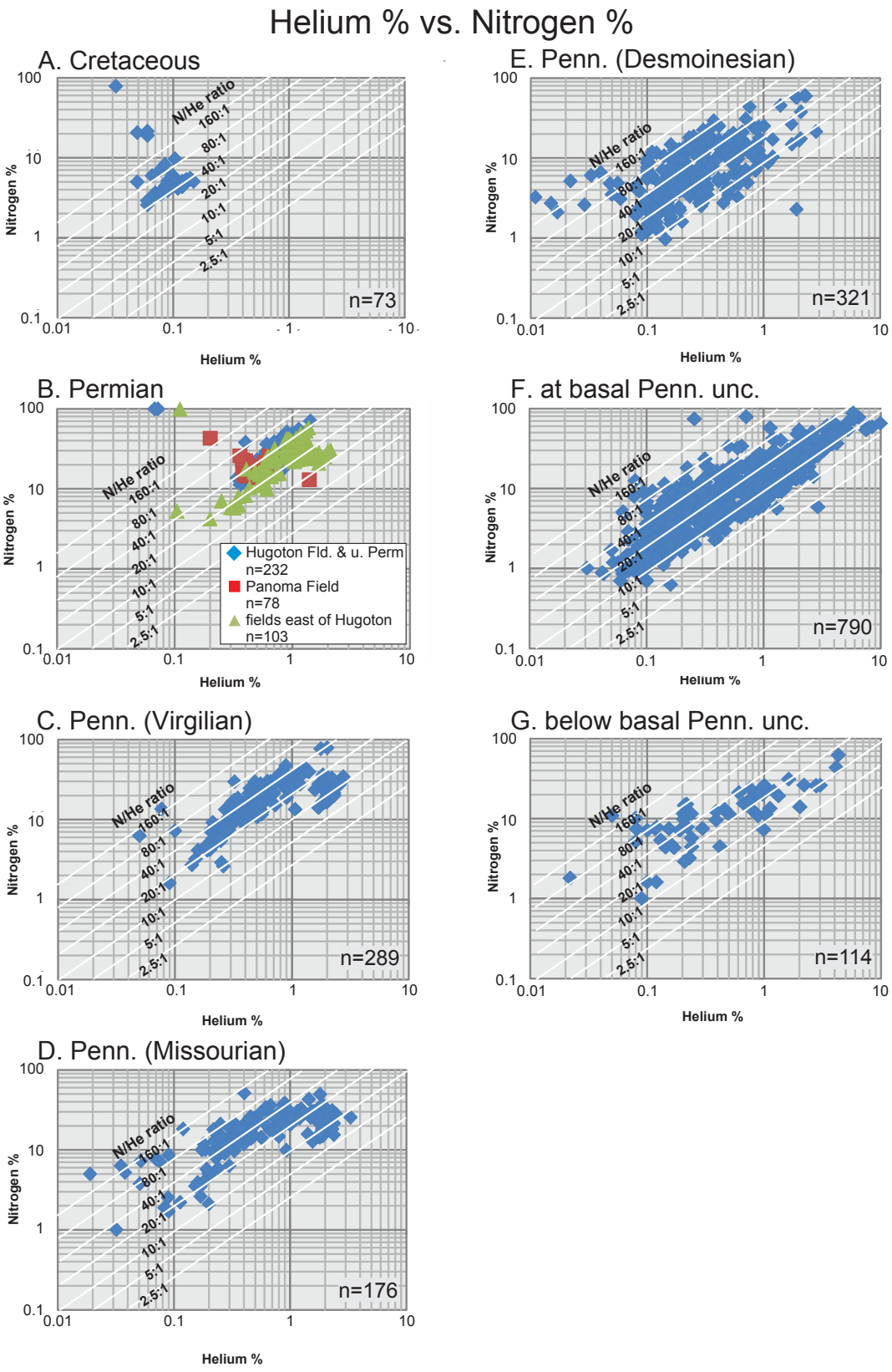


Figure 10. Cross-plot of helium and nitrogen percentages for gases in the seven stratigraphic intervals considered in this study. Levels of nitrogen/helium ratios are superimposed on the cross-plots.

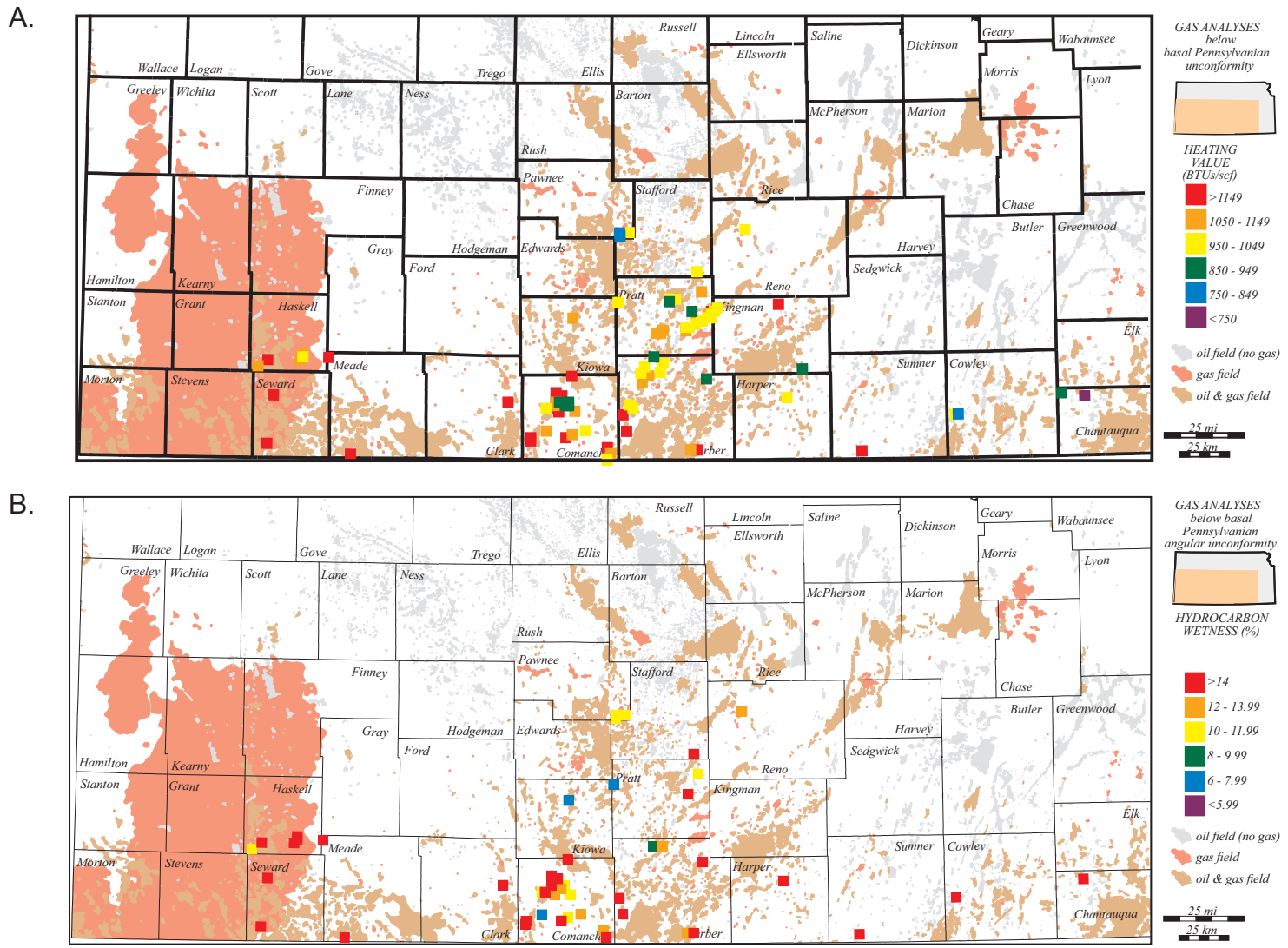
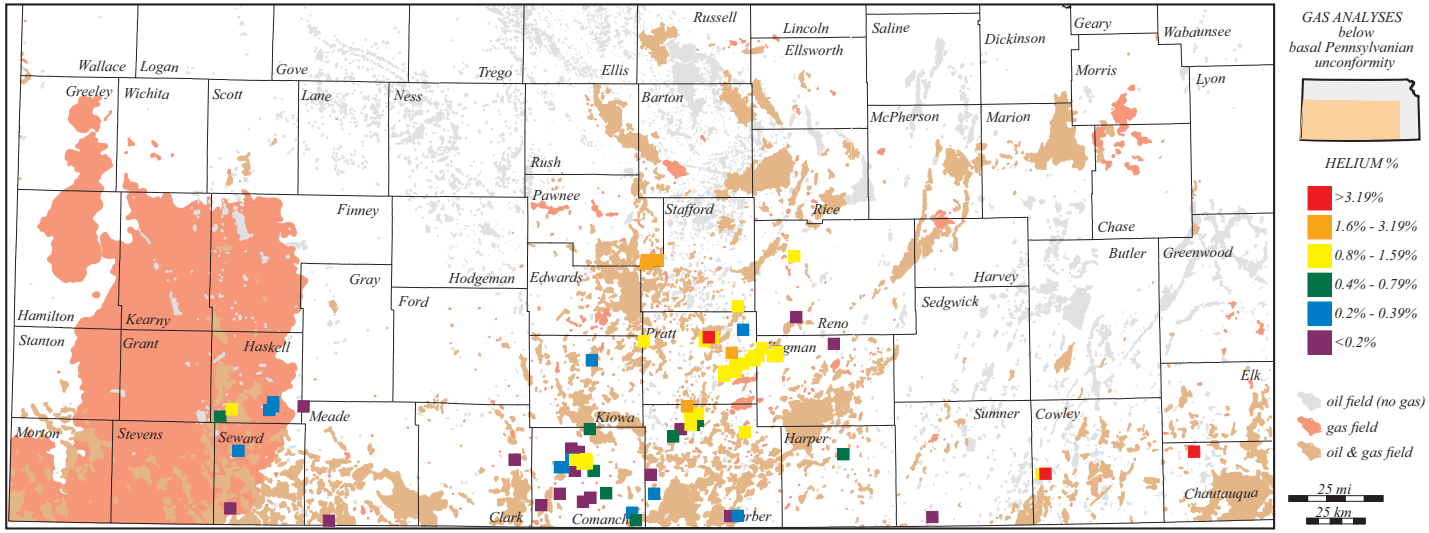


Figure 11. Geographic variation in A) BTU content and B) hydrocarbon wetness for gases produced from the various strata below the basal Pennsylvanian unconformity in central and western Kansas. These strata include various Mississippian-age and older reservoirs subcropping at the basal Pennsylvanian unconformity or reservoirs immediately above the basal Pennsylvanian unconformity. Gas accumulations at least 50 ft (15.2 m) above the basal Pennsylvanian unconformity and stratigraphically separated from the unconformity by sealing strata (usually shale or non-porous limestone) are considered to be separate from the gases associated with the unconformity. Each colored square represents an analysis. At map scale, each symbol is 3 X 3 miles (4.8 X 4.8 km) (i.e., 9 sq. miles; 23.3 sq. km) and is centered over the section where the well sample is located. Each section is one square mile (2.6 square km).

C.



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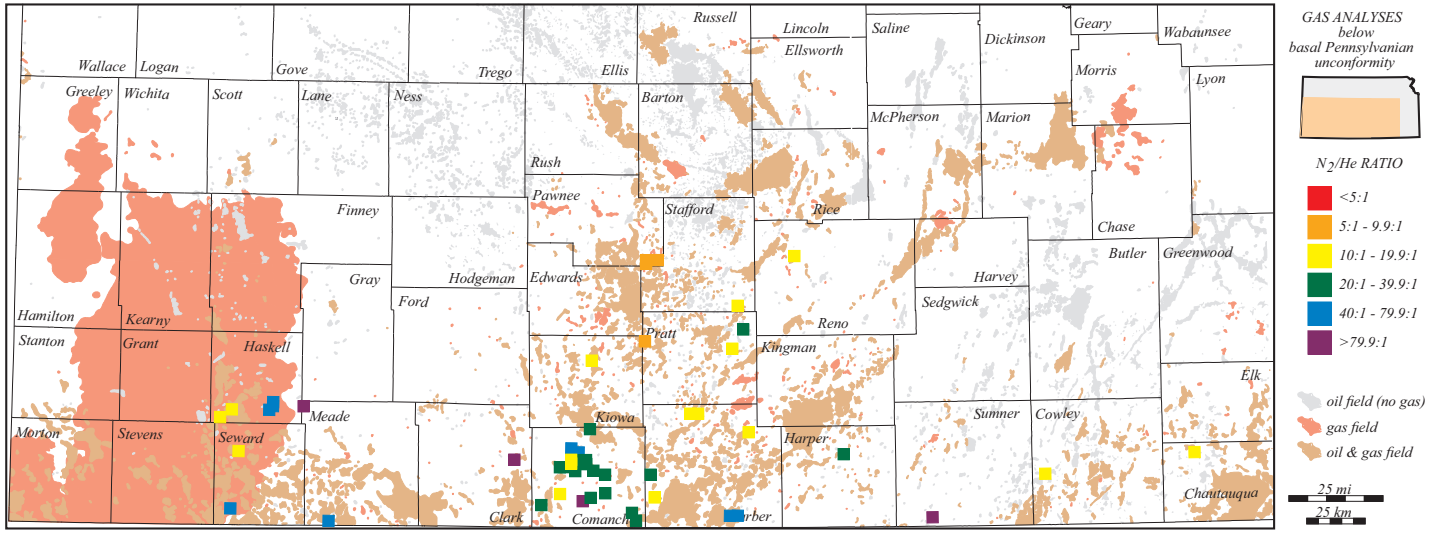


Figure 11 (continued). Geographic variation in C) helium content and D) nitrogen/helium ratio for gases produced from the various strata below the basal Pennsylvanian unconformity in central and western Kansas. These strata include various Mississippian-age and older reservoirs subcropping at the basal Pennsylvanian unconformity or reservoirs immediately above the basal Pennsylvanian unconformity. Gas accumulations at least 50 ft (15.2 m) above the basal Pennsylvanian unconformity and stratigraphically separated from the unconformity by sealing strata (usually shale or non-porous limestone) are considered to be separate from the gases associated with the unconformity. Each colored square represents an analysis. At map scale, each symbol is 3 X 3 miles (4.8 X 4.8 km) (i.e., 9 sq. miles; 23.3 sq. km) and is centered over the section where the well sample is located. Each section is one square mile (2.6 square km).

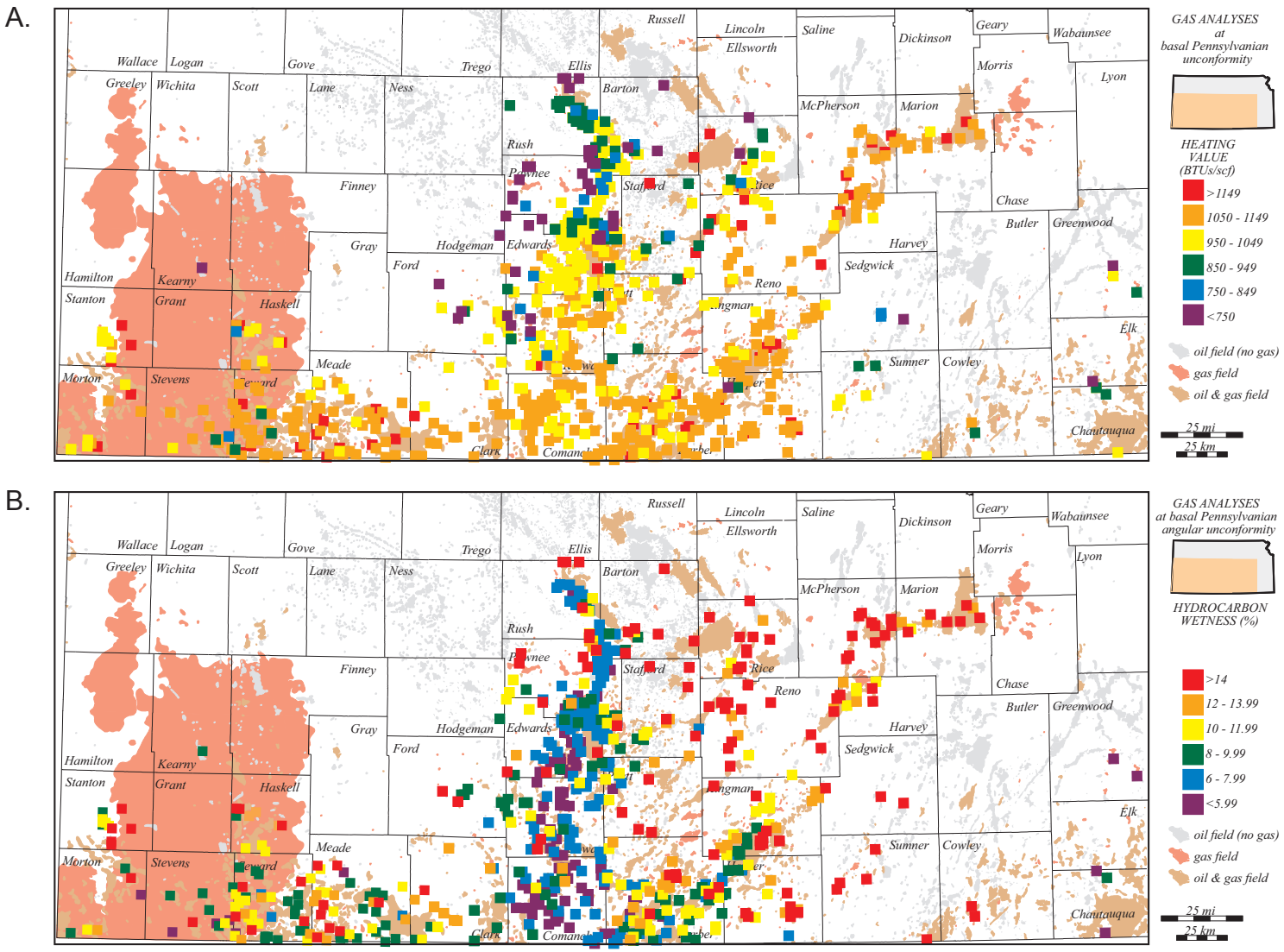
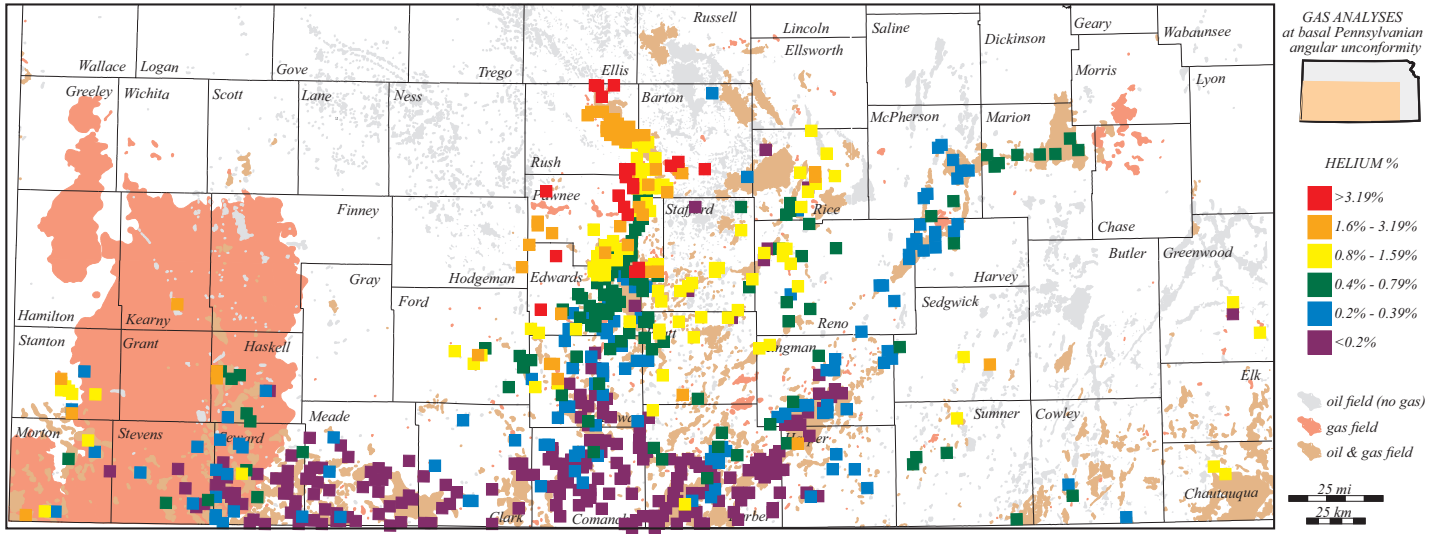


Figure 12. Geographic distribution of A) BTU content and B) hydrocarbon wetness for gases produced from the various strata along the basal Pennsylvanian unconformity in southern and western Kansas. Mississippian and older strata down to fractured Precambrian basement subcrop beneath this regional unconformity. Conglomerates, weathered zones, and basal sandstones are locally present above the unconformity. Symbol size and placement are described in the caption for **fig. 11**.

C.



D.

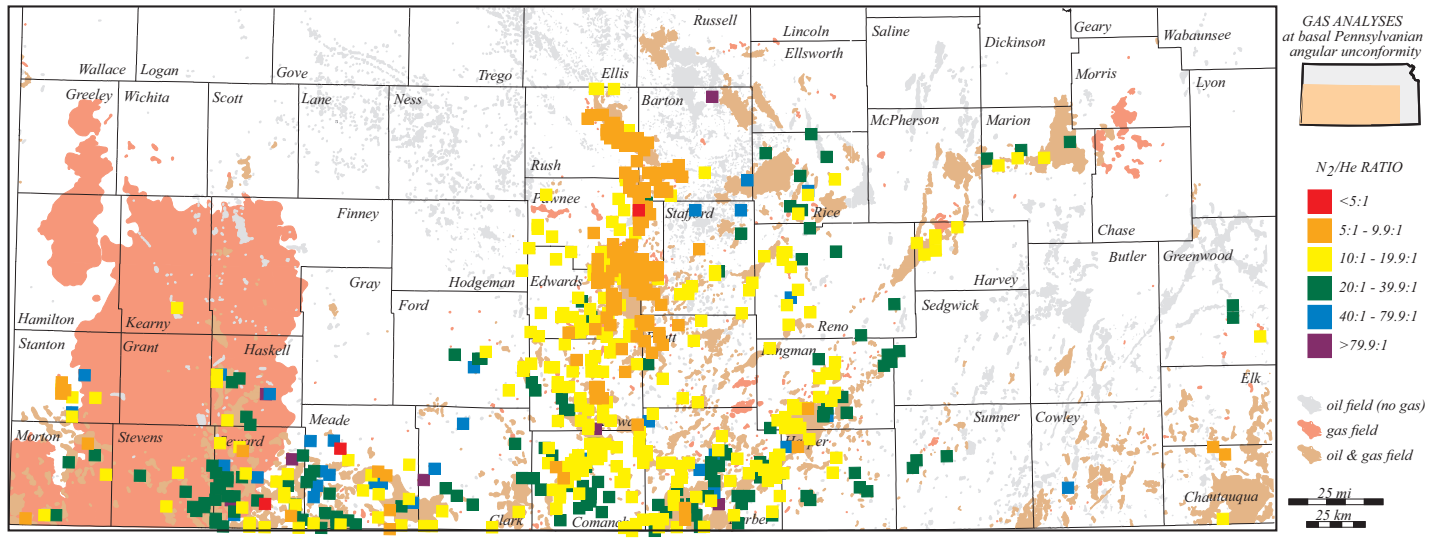


Figure 12 (continued). Geographic distribution of C) helium content and D) nitrogen/helium ratio for gases produced from the various strata along the basal Pennsylvanian unconformity in southern and western Kansas. Mississippian and older strata down to fractured Precambrian basement subcrop beneath this regional unconformity. Conglomerates, weathered zones, and basal sandstones are locally present above the unconformity. Symbol size and placement are described in the caption for **fig. 11**.

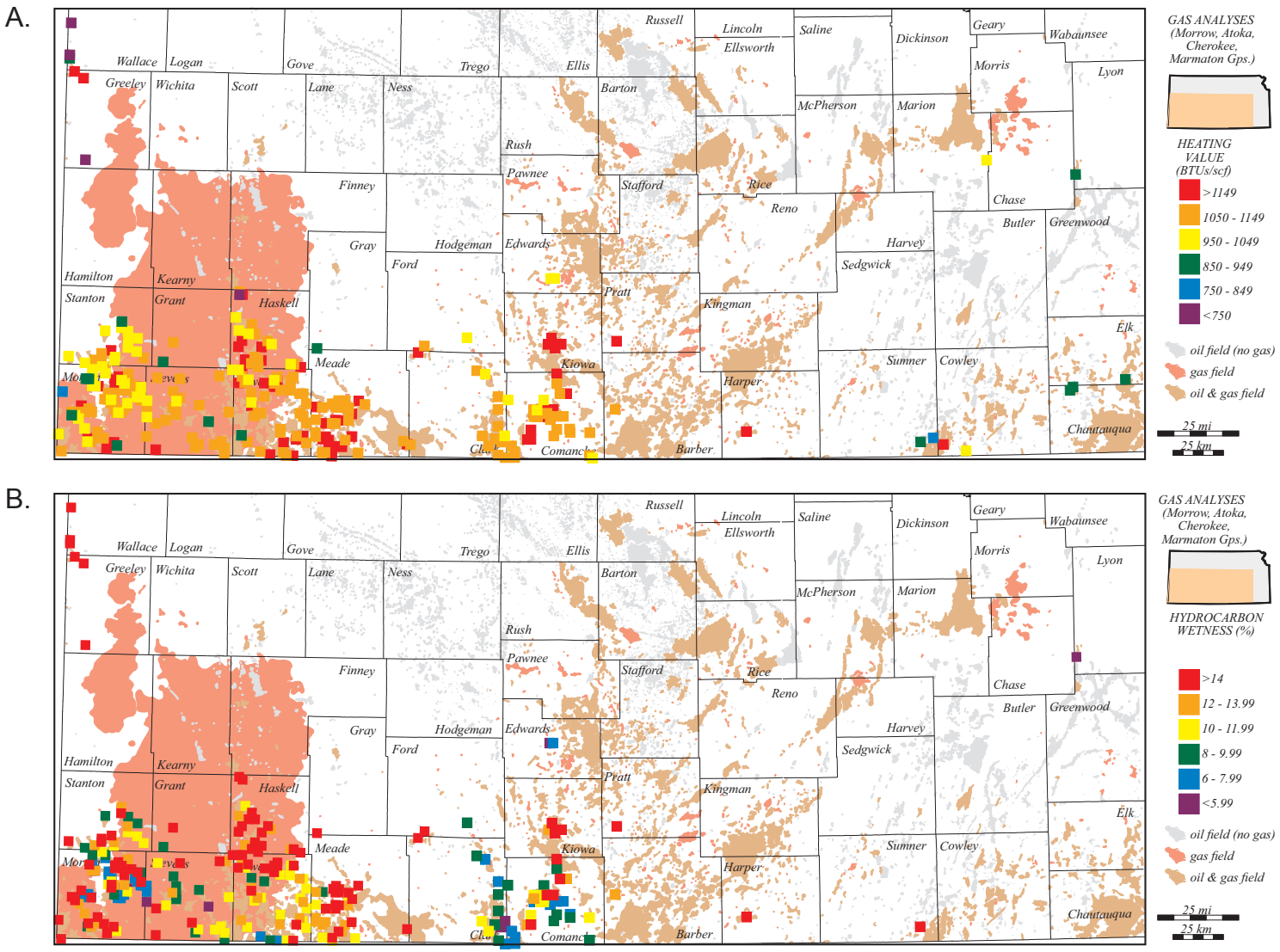
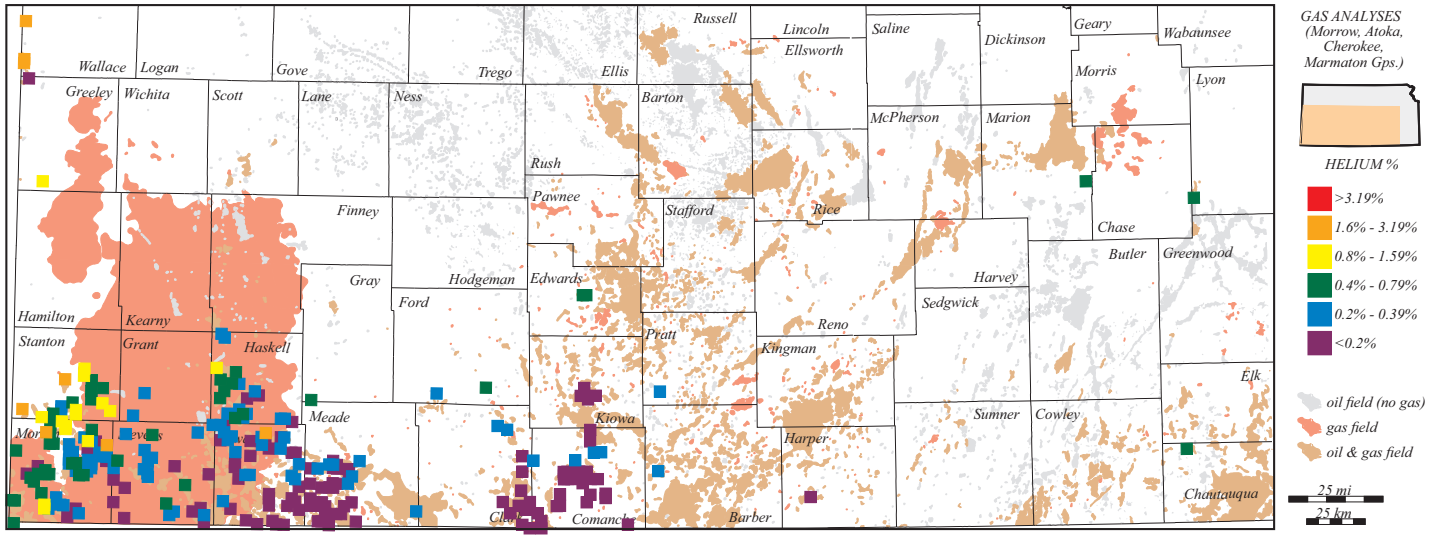


Figure 13. Geographic distribution of A) BTU content and B) hydrocarbon wetness for gases produced from Pennsylvanian (Desmoinesian) strata in southern and western Kansas. Symbol size and placement are described in the caption for **fig. 11**.

C.



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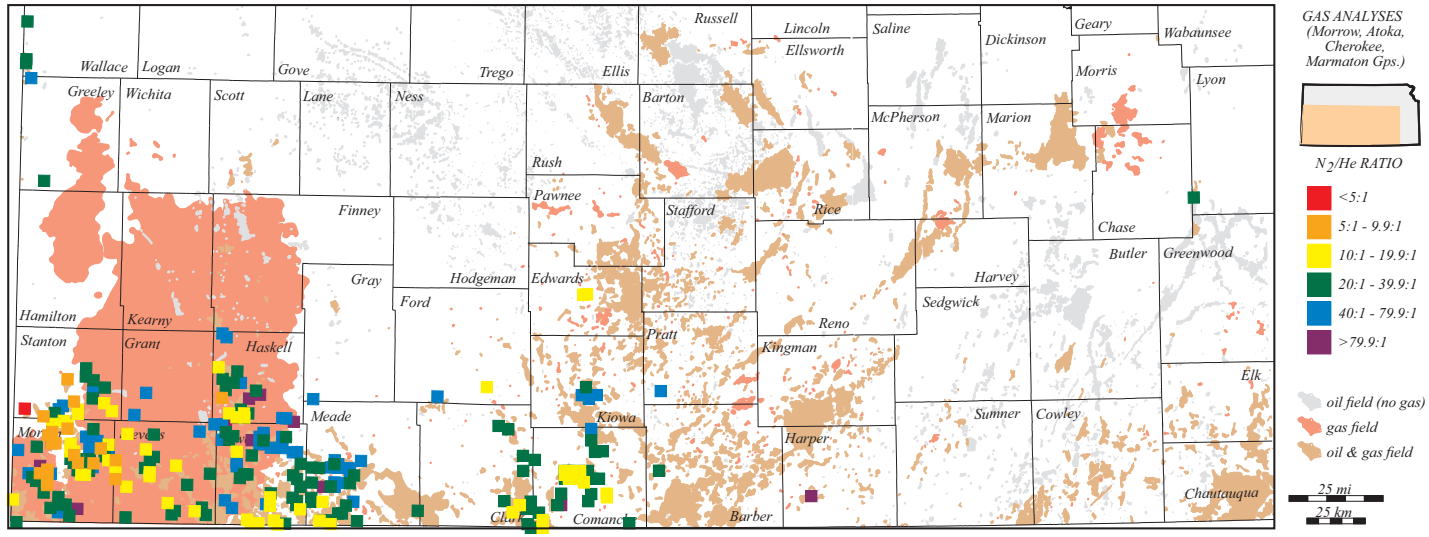


Figure 13 (continued). Geographic distribution of C) helium content and D) nitrogen/helium ratio for gases produced from Pennsylvanian (Desmoinesian) strata in southern and western Kansas. Symbol size and placement are described in the caption for **fig. 11**.

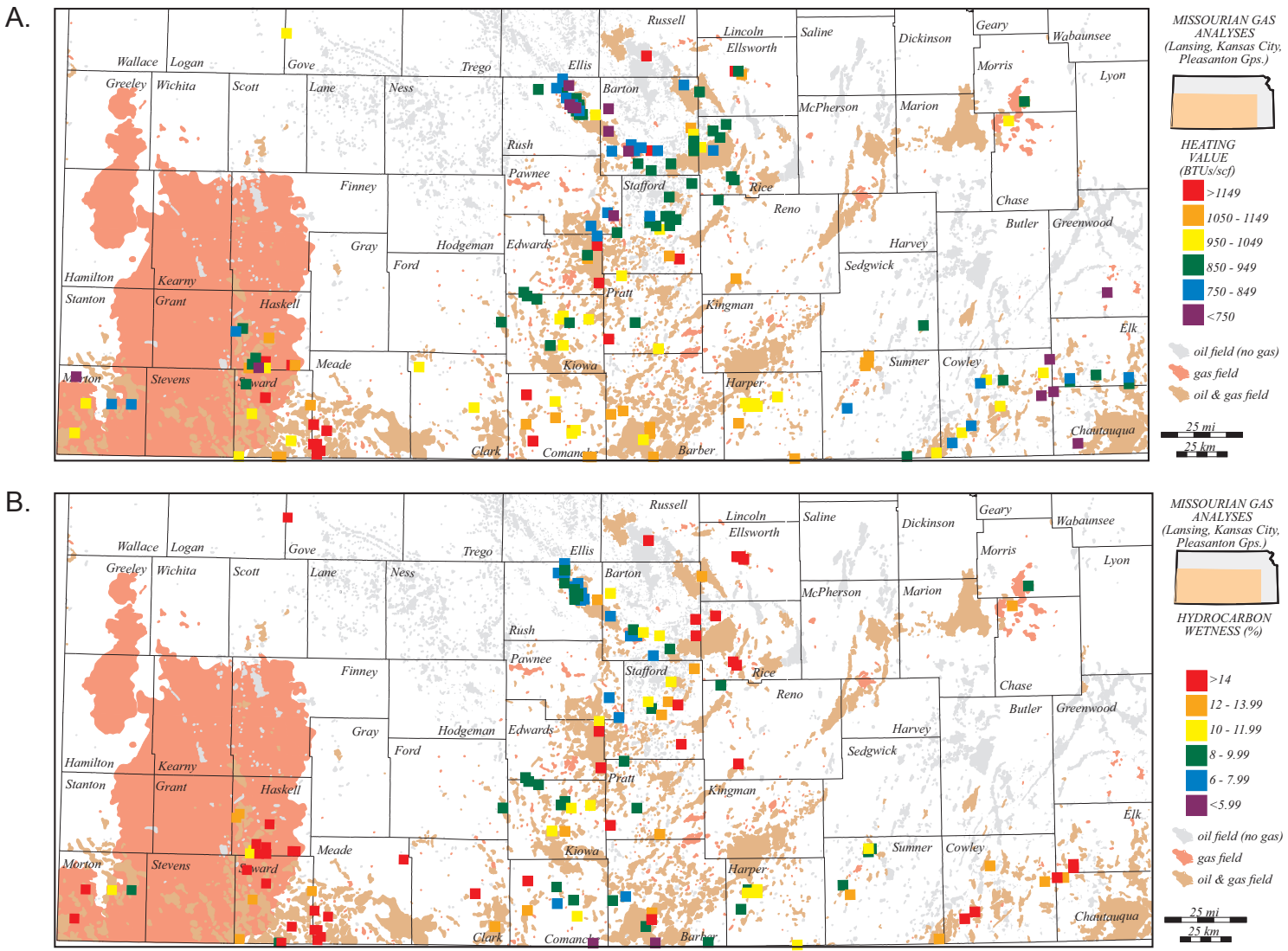
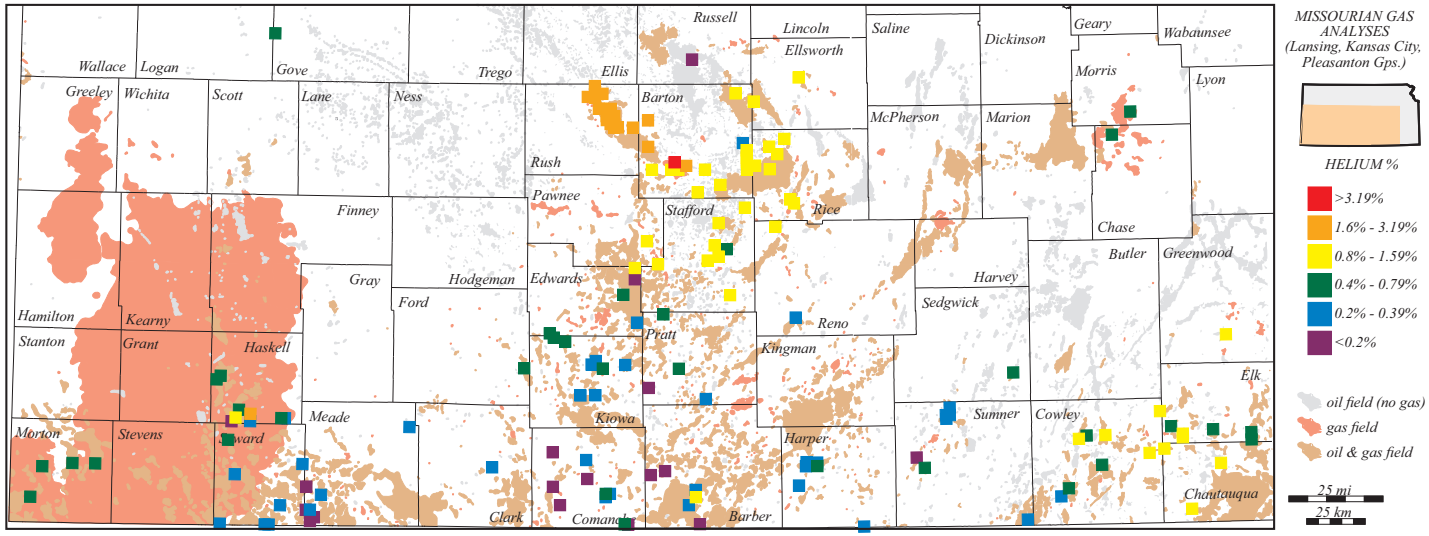


Figure 14. Geographic distribution of A) BTU content and B) hydrocarbon wetness for gases produced from Pennsylvanian (Missourian) strata in southern and western Kansas. Symbol size and placement are described in the caption for **fig. 11**.

C.



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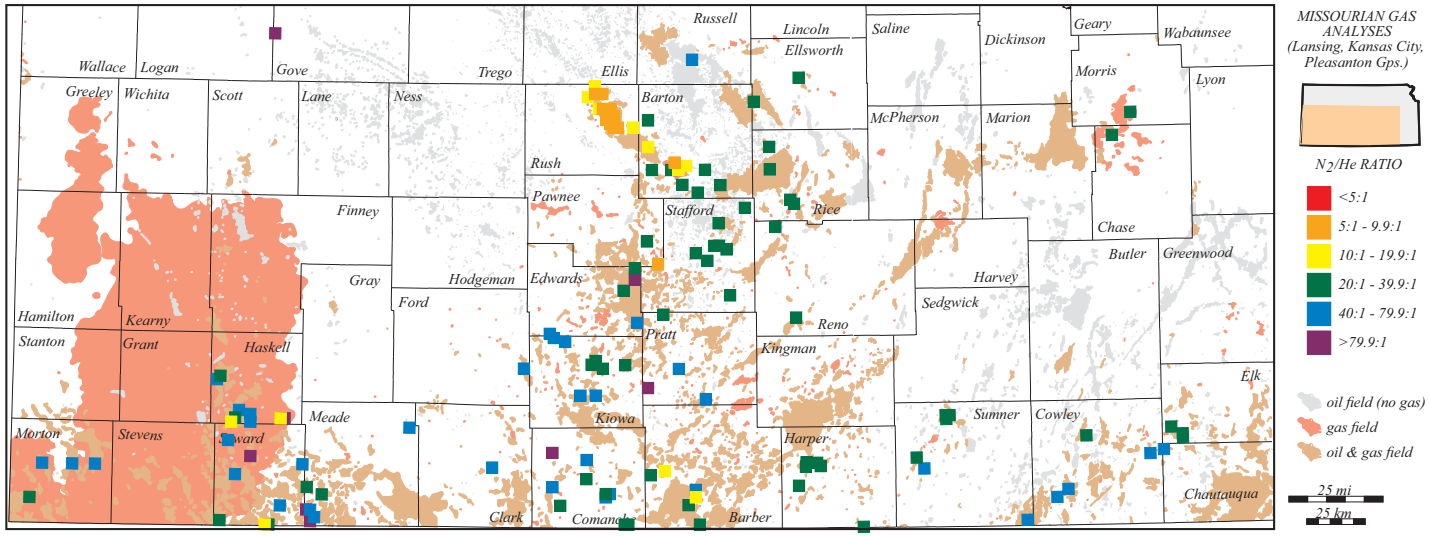


Figure 14 (continued). Geographic distribution of C) helium content and D) nitrogen/helium ratio for gases produced from Pennsylvanian (Missourian) strata in southern and western Kansas. Symbol size and placement are described in the caption for **fig. 11**.

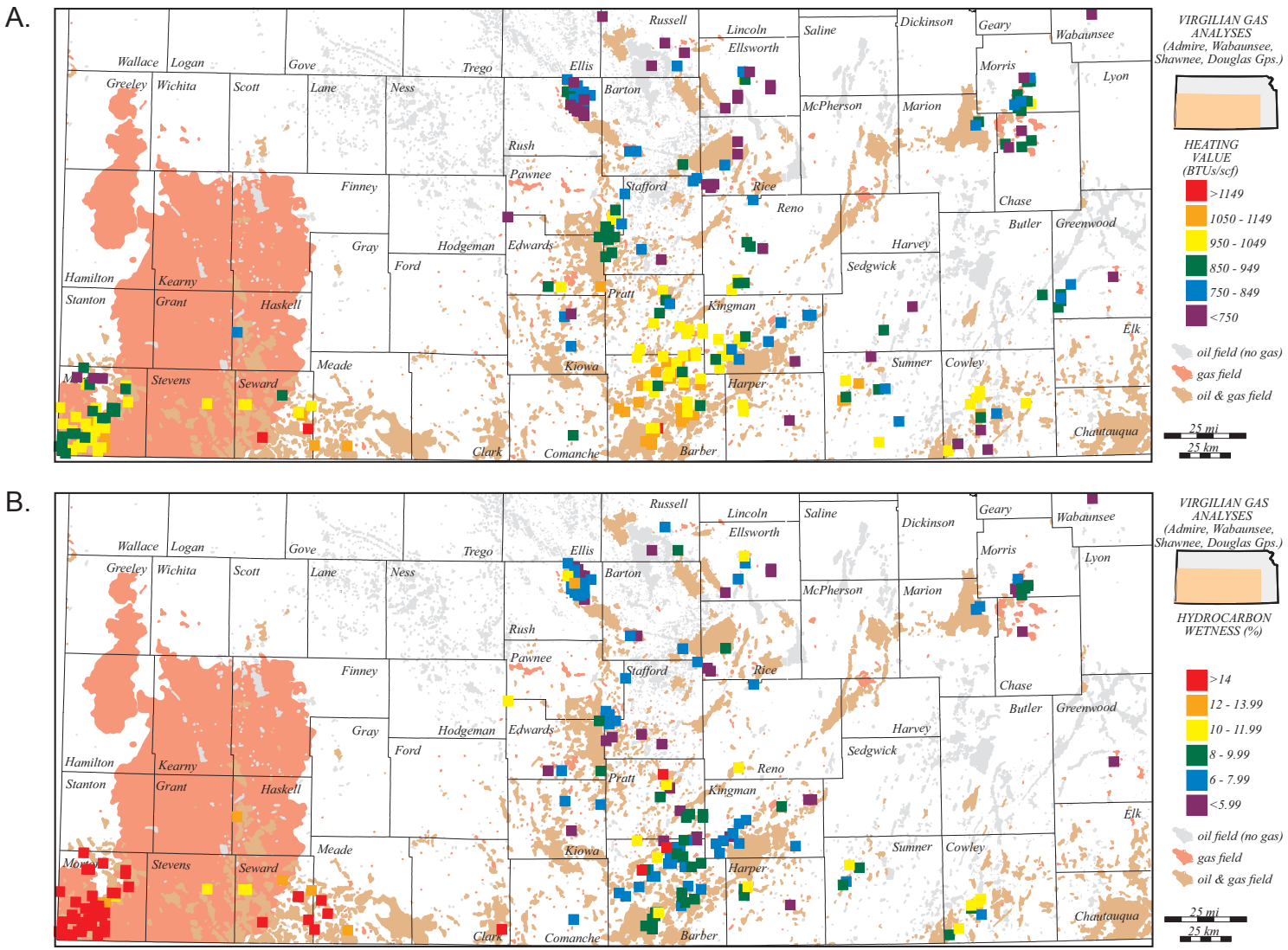
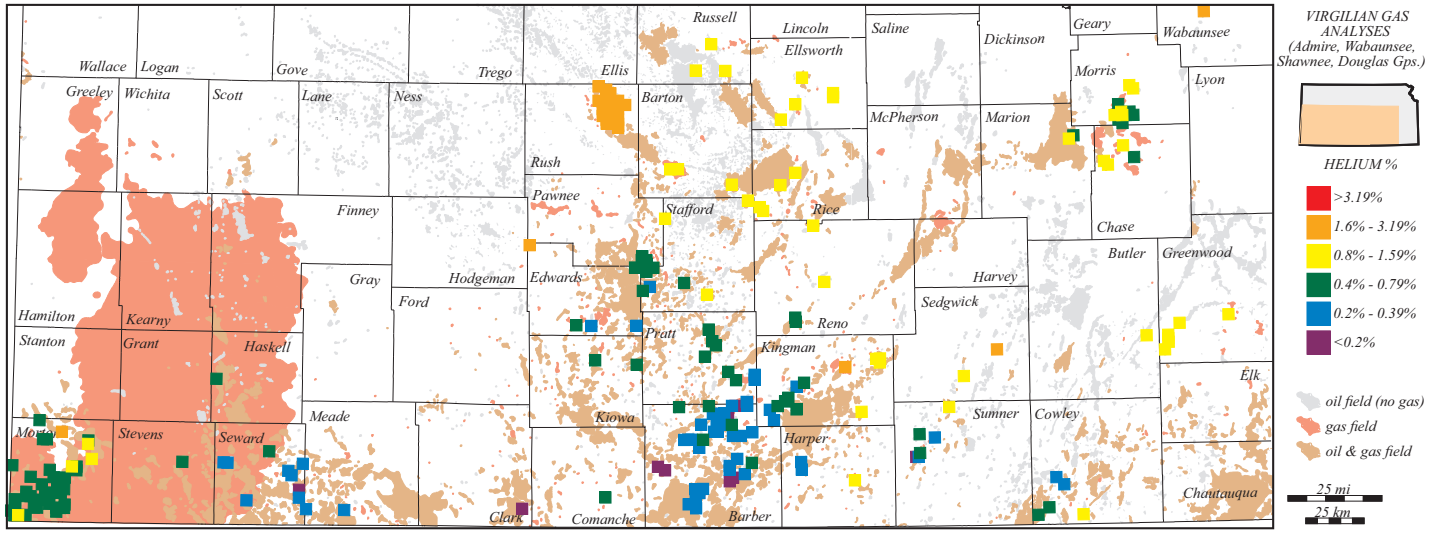


Figure 15. Geographic distribution of A) BTU content and B) hydrocarbon wetness for gases produced from Pennsylvanian (Virgilian) strata in southern and western Kansas. Symbol size and placement are described in the caption for **fig. 11**.

C.



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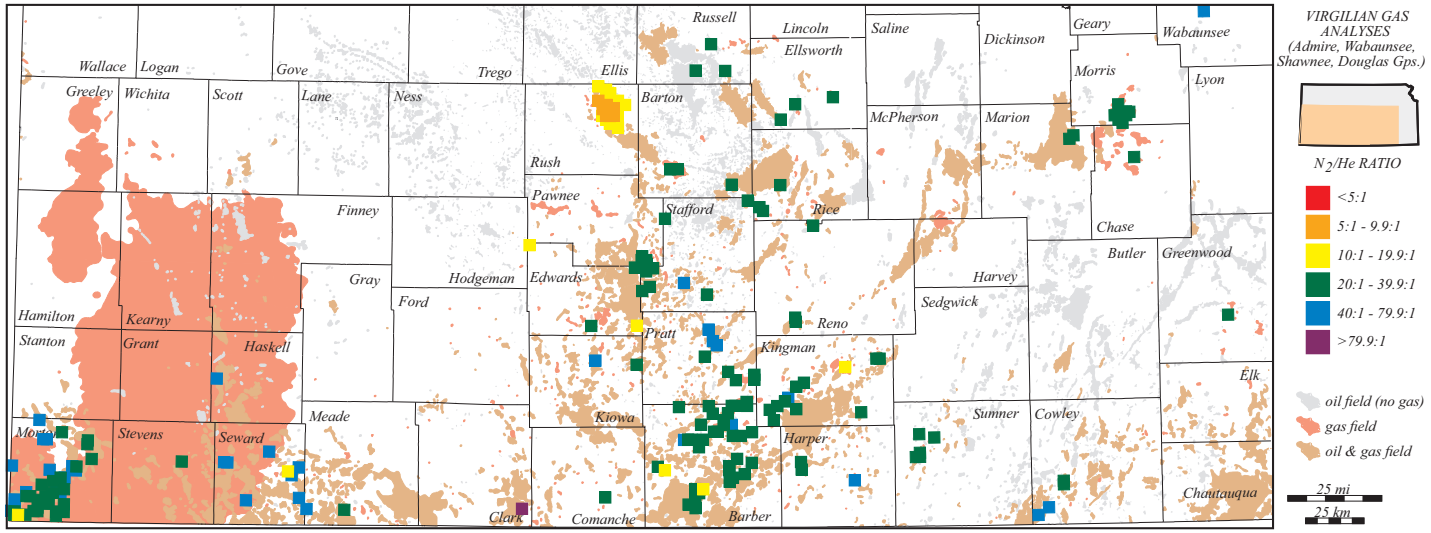


Figure 15 (continued). Geographic distribution of C) helium content and D) nitrogen/helium ratio for gases produced from Pennsylvanian (Virgilian) strata in southern and western Kansas. Symbol size and placement are described in the caption for **fig. 11**.

The pattern of gas quality in Permian strata (**fig. 16**) differs from the underlying geological units in that low-BTU Permian gases in central Kansas are concentrated on the western flank of the Central Kansas uplift and Pratt anticline (i.e., Pawnee, southeastern Ness, eastern Hodgeman, northern Edwards, and southwestern Stafford counties) rather than the Central Kansas uplift as with the older stratigraphic units. The group of Permian fields on the western flank of the Central Kansas uplift are depicted (**figs. 6–10**) as the Permian component of the seven stratigraphic units discussed in this report. These Permian fields increase in BTU content to the southeast (**fig. 16A**). When natural-gas prices were relatively high in the decade before 2008, attempts were made to channel the produced gas in this region to a central processing facility to remove the nitrogen present and thus upgrade the gas to pipeline quality (Newell and others, 2003). Eastern Rush and western Barton counties also stand out as a localized area of Permian production.

Most natural gas in Kansas is produced from the Permian fields in the Hugoton embayment, specifically the giant Hugoton Gas Field in southwestern Kansas, as well as the underlying Panoma Gas Field, the Bradshaw Field in Hamilton and Greeley counties, the Byerly Field in Greeley County, the Hugoton North Field in south-central Scott County, and the Hugoton Northeast Gas Area in eastern Scott County. The distribution of heating values in the Hugoton Gas Field, based on the Wilkonson (1960) compilation, shows a rim of low-BTU natural gas around the field (**fig. 16A**) that is broader on the eastern (downdip) side of the field. This low-BTU rim is widest in the northeastern corner of the field in western Finney County. The low-BTU rim in the northern part of the Hugoton Gas Field is analyzed in more detail later in this bulletin.

The small Permian fields on the Pratt anticline and western flank of the Central Kansas uplift produce drier gas than the Hugoton and Panoma gas fields (**fig. 16B**). These small fields also show a greater spread of BTU content (**fig. 16A**) and hydrocarbon wetness (**fig. 16B**).

The distribution of heating values in the Panoma Gas Field (**fig. 17B**) does not have the broad distribution of low-BTU values shown in the Hugoton Gas Field (**fig. 17A**). Hydrocarbon-wetness histograms of both fields also show that the Hugoton Gas Field includes a greater number of drier gases. The non-hydrocarbon gases in the Permian (**fig. 18)** have spreads that follow those of the hydrocarbon gases (**fig. 17**). The Panoma Gas Field has more uniform compositions than the Hugoton Gas Field, whereas the small fields on the west flank of the Central Kansas uplift show the greatest spread in their helium percentage and nitrogen/helium ratios. The Hugoton Gas Field has a broader distribution on the richer side of its helium histogram (**fig. 18A**), and its nitrogen/helium ratios tend to be slightly greater than those of the Panoma Gas Field (**fig. 18B**). Gases in the Hugoton and Panoma gas fields have considerably lower helium content (less than 0.5%) than the fields on the western flank of the Central Kansas uplift.

Wetter hydrocarbon gases are concentrated in the western (updip) part of the Hugoton Gas Field. These wetter gases appear contiguous with the similarly wet hydrocarbon gases in the Bradshaw Gas Field in Hamilton and southern Greeley counties and in the Byerly Gas Field in northeastern Greeley County (**fig. 16B**). With respect to helium concentration (**fig. 16C**), the center-west part of the Hugoton Gas Field registers a slightly lower helium percentage than the rest of the field (i.e., see zone of analyses in southwestern Kearny, western Grant, and western Stevens counties that register 0.2–0.39% helium [blue squares]). Greater percentages of helium (0.8–1.59% [yellow squares]) characterize the northern part of the Hugoton Gas Field in northwestern Finney County and the northern and southern ends of the Bradshaw and Byerly gas fields in Greeley and Hamilton counties. This same area also is characterized by a grouping of analyses that registers higher nitrogen/helium ratios (i.e., 40–79.9:1 [blue squares]) than the rest of the Hugoton Gas Field, which is mostly characterized by analyses registering nitrogen/helium ratios of 20–39.9:1 (green squares; **fig. 16D**).

Figure 19A displays the distribution of boreholes drilled for hydrocarbons, the location of wells producing Cretaceous natural gas, and the BTU content of Cretaceous gases in northwestern Kansas. These Cretaceous gases are not associated with oil; thus, they are relatively dry (i.e., methane-dominated) with respect to hydrocarbon composition. Regional dip for Cretaceous strata in northwestern Kansas is to the north-northeast according to structural mapping on the base of the Niobrara Chalk presented in Merriam (1963, p. 198); thus, heating values increase downdip (**fig. 19A**). Hydrocarbon wetness (**fig. 19B**) increases, and nitrogen/helium ratios (**fig. 19D**) decrease downdip (north-northeastward). Helium percentage (**fig. 19C**) is uniformly low (less than 0.2%). There is scatter in the analyses, and compositional trends cannot be discerned with any confidence. Analyses presented in Newell (2025) indicate that the major non-combustible components in the Cretaceous gases are nitrogen and, secondarily, carbon dioxide.

Lastly, **fig. 20** maps the presence of sour gas in Kansas oil and gas fields. Hydrogen sulfide (H_2S), also called "sour gas," is generally not a significant component gas in Kansas natural gases, but its presence is important because it is potentially lethal to rig personnel, the public, and animals. In trace concentrations, this gas smells like rotten eggs, but respiratory paralysis and sudden asphyxiation can occur when air is contaminated with as little as 0.1% H_2S by volume (Hunt, 1979, p. 169). It is thus a drilling hazard, and it is usually removed from produced natural gas near the wellhead if the natural gas carrying the H_2S is sold or consumed on site for fuel. Windsocks and warning signs usually mark sour-gas producing well sites.

A group of oil and gas fields containing H_2S in central Kansas extends in a north-south direction, ranging from eastern Rush County to southwestern Stafford County, a distance of approximately 40 miles (65 km; **fig. 20**). Geologically, this group of fields is on the southwestern part of the Central Kansas uplift and where the uplift transitions into the northern part of the Pratt anticline. Elsewhere in the state, sour gas occurrences are apparently isolated and certainly not common.

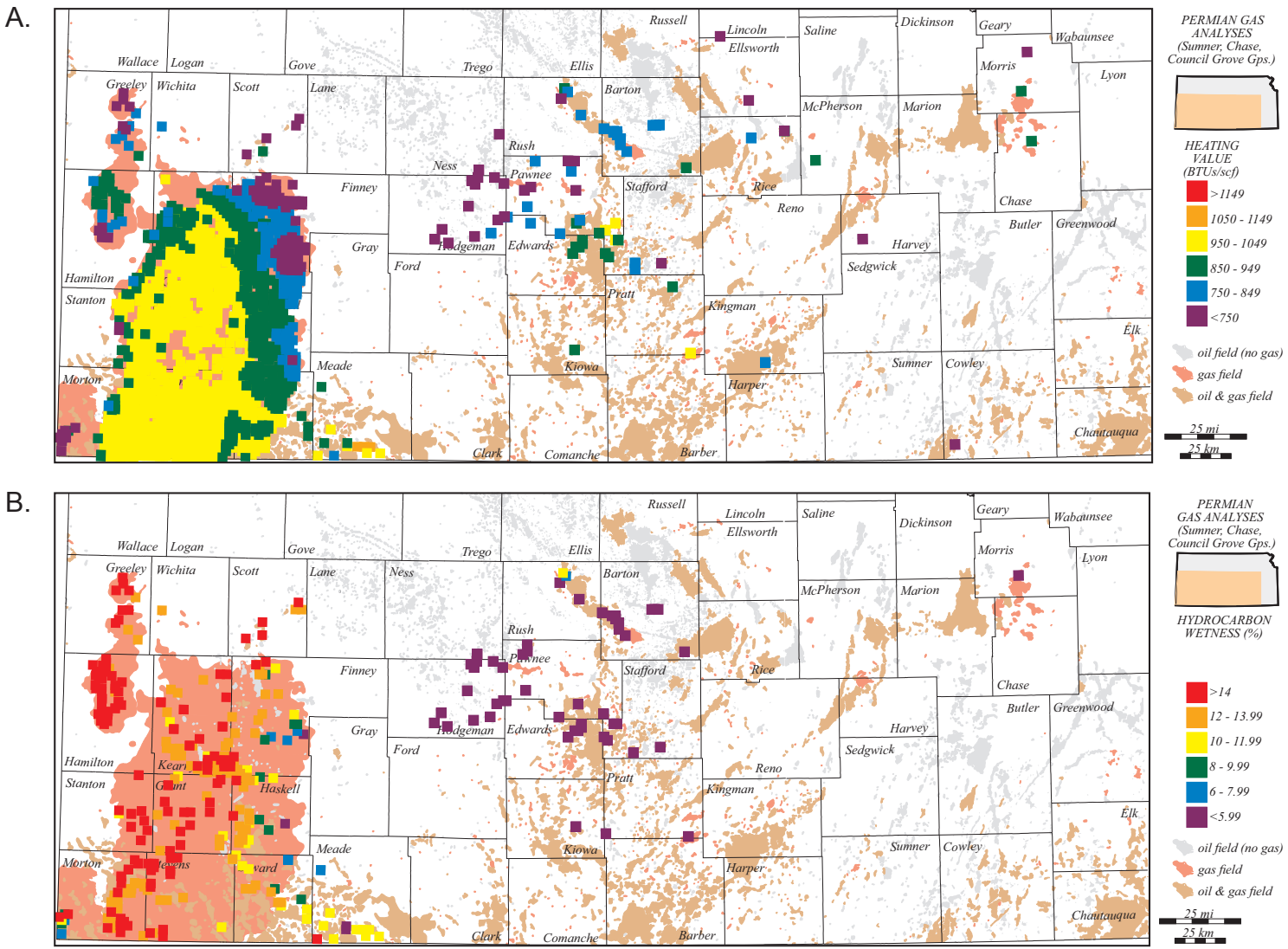
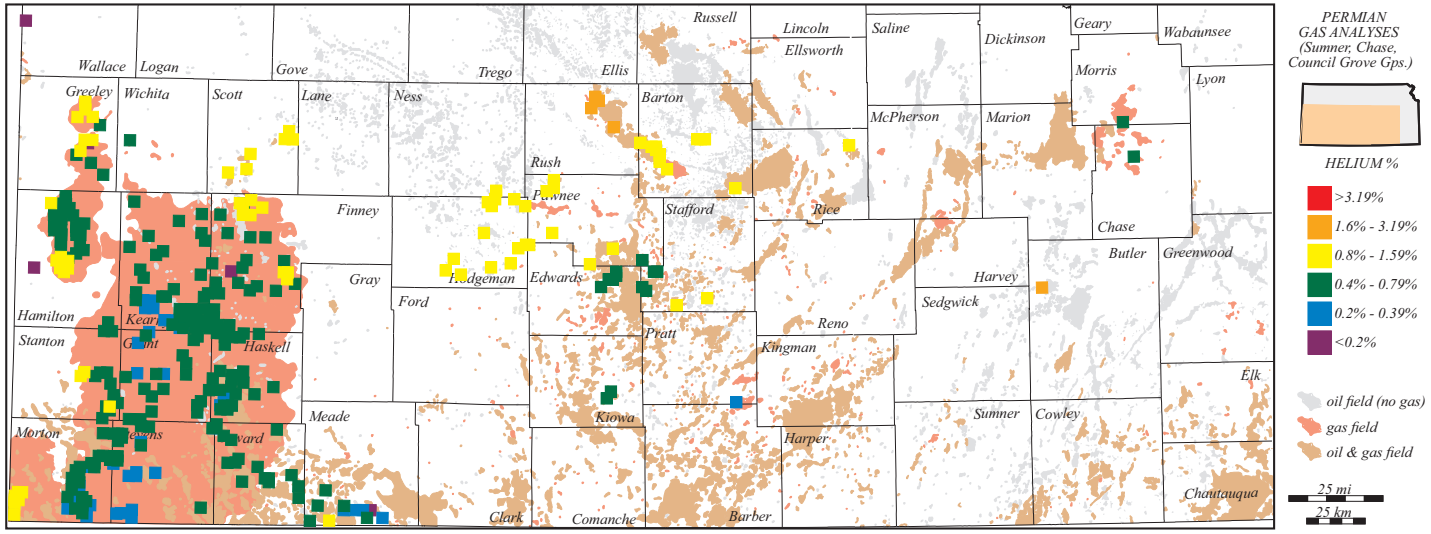


Figure 16. Geographic distribution of A) BTU content and B) hydrocarbon wetness for gases produced from Permian strata in southern and western Kansas. Symbol size and placement are described in the caption for **fig. 11**.

C.



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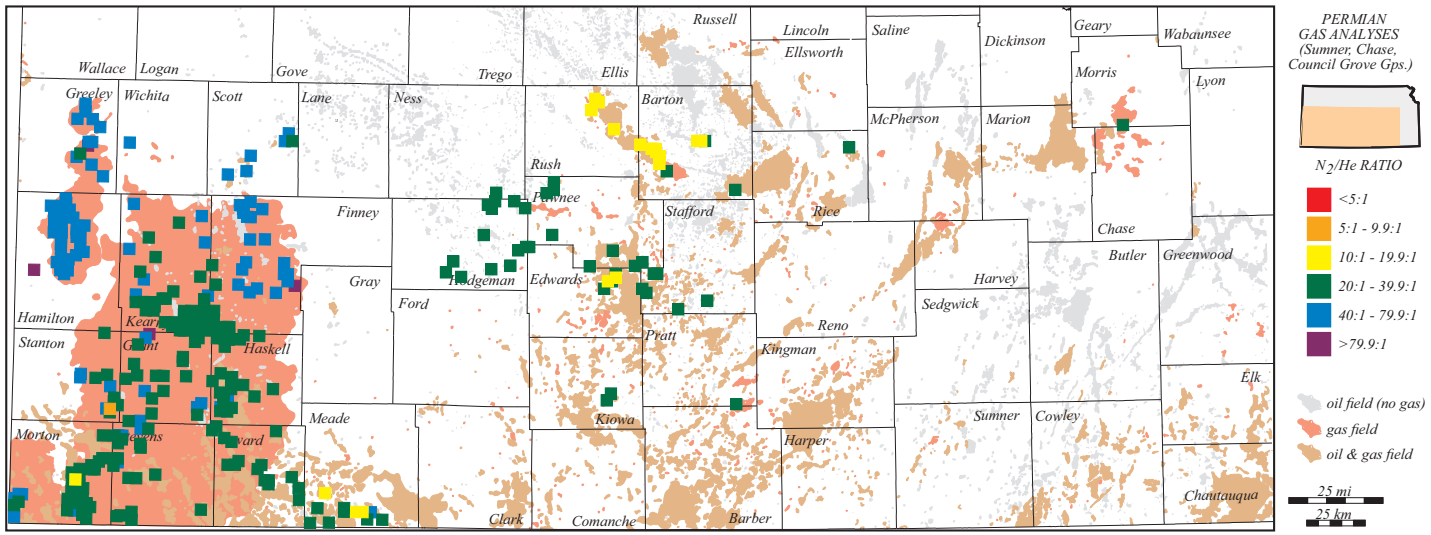


Figure 16 (continued). Geographic distribution of C) helium content and D) nitrogen/helium ratio for gases produced from Permian strata in southern and western Kansas. Symbol size and placement are described in the caption for **fig. 11**.

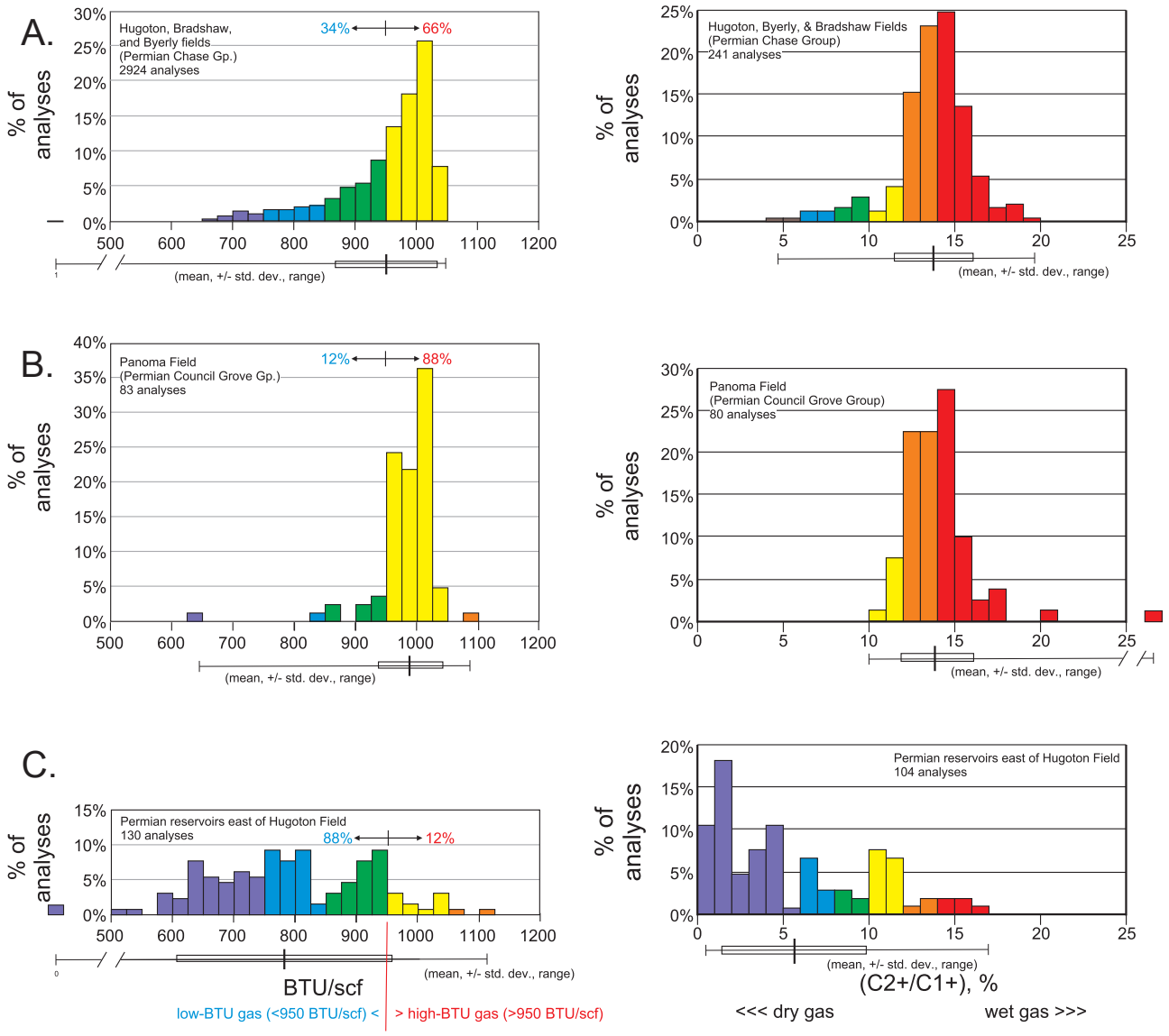


Figure 17. Histograms comparing the BTU content (left column) and hydrocarbon wetness (right column) for the A) Hugoton, Bradshaw, and Byerly gas fields, B) the Panoma Gas Field that underlies the Hugoton Gas Field, and C) the group of Permian gas fields that lie east of the Hugoton Gas Field on the western flank of the Central Kansas uplift. Histograms for C) fields east of the Hugoton Gas Field are also presented in **fig. 6**. Colors of the histogram bars correspond to colors used in mapping BTU content, hydrocarbon wetness, helium percentage, and nitrogen/helium ratios in **figs. 11–16, 19**.

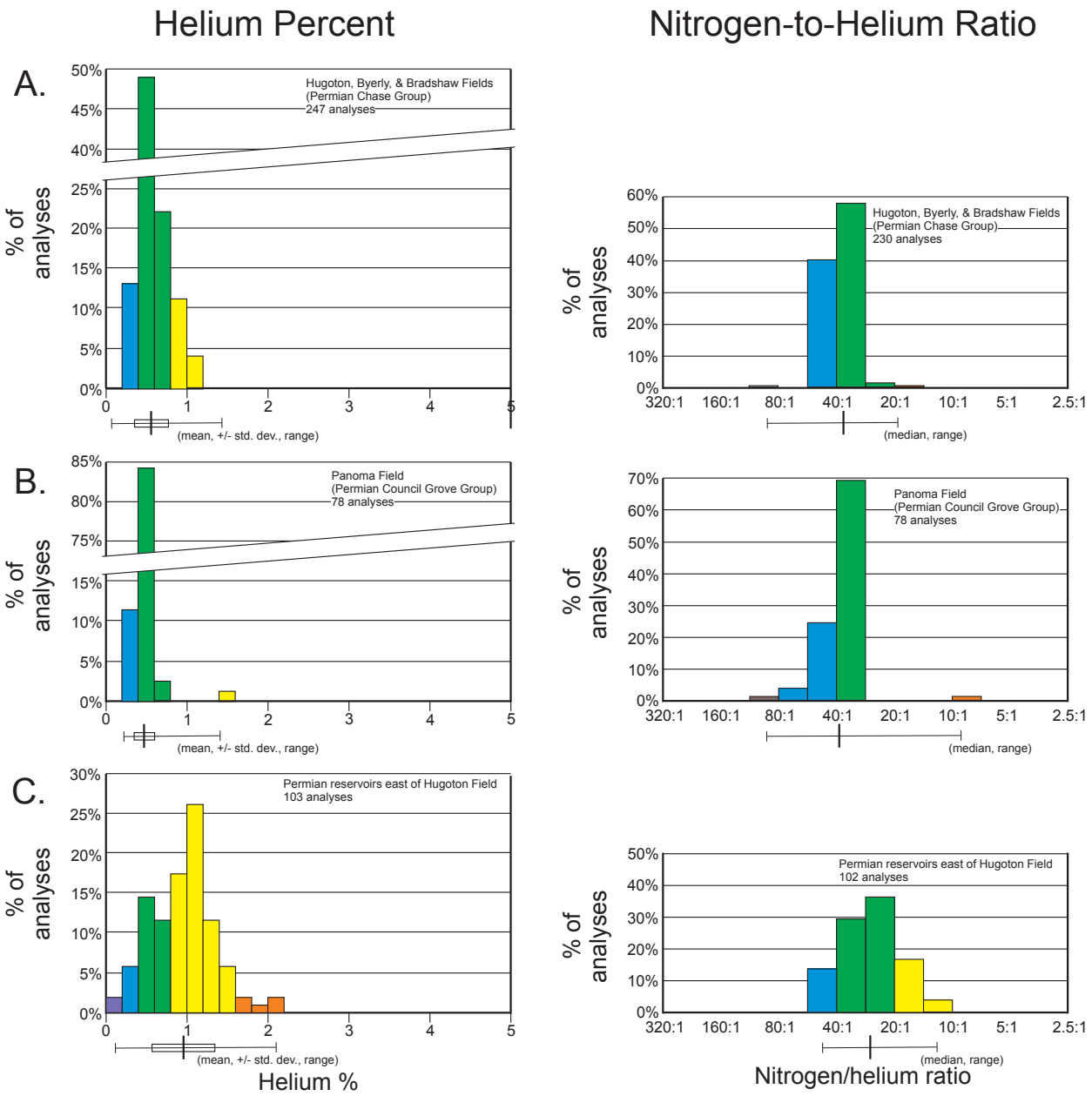
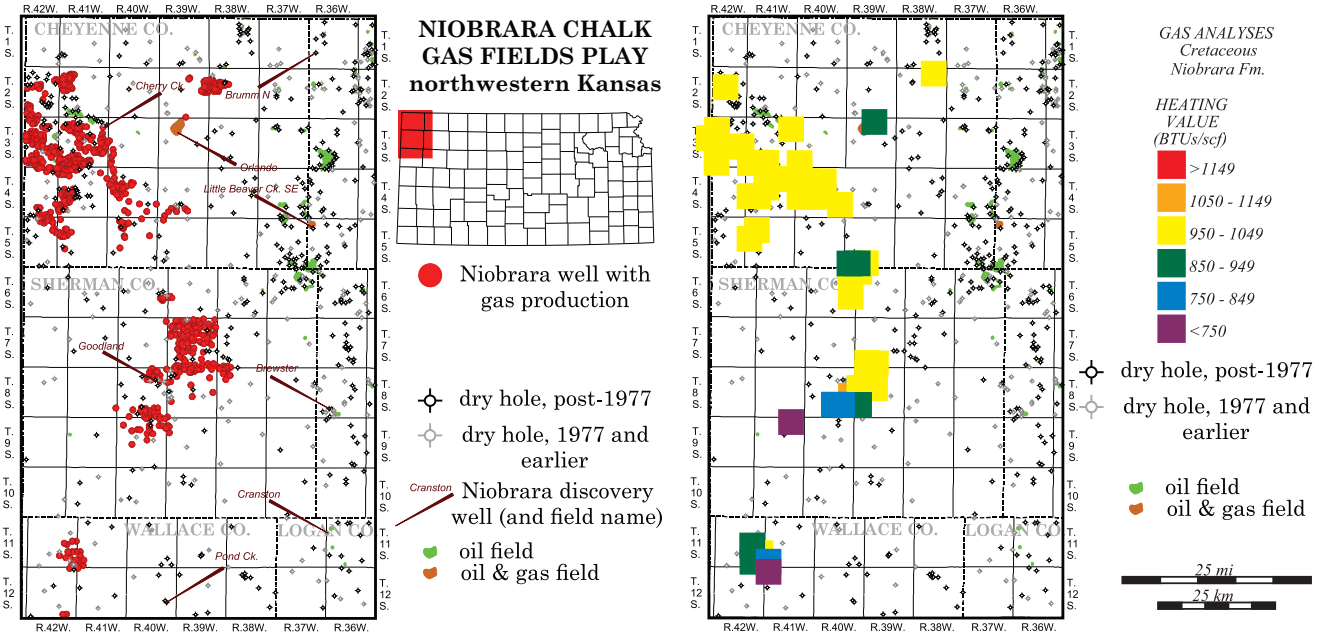


Figure 18. Histograms comparing the helium percentage and nitrogen/helium ratios for the A) Hugoton, Bradshaw, and Byerly gas fields, B) the Panoma Gas Field that underlies the Hugoton Gas Field, and C) the group of Permian gas fields that lie east of the Hugoton Gas Field on the western flank of the Central Kansas uplift. The histogram for the fields east of the Hugoton Gas Field is also presented in **fig. 9**. Colors of the histogram bars correspond to colors used in mapping BTU content, hydrocarbon wetness, helium percentage, and nitrogen/helium ratios in **figs. 11–16, 19**.

A.



B.

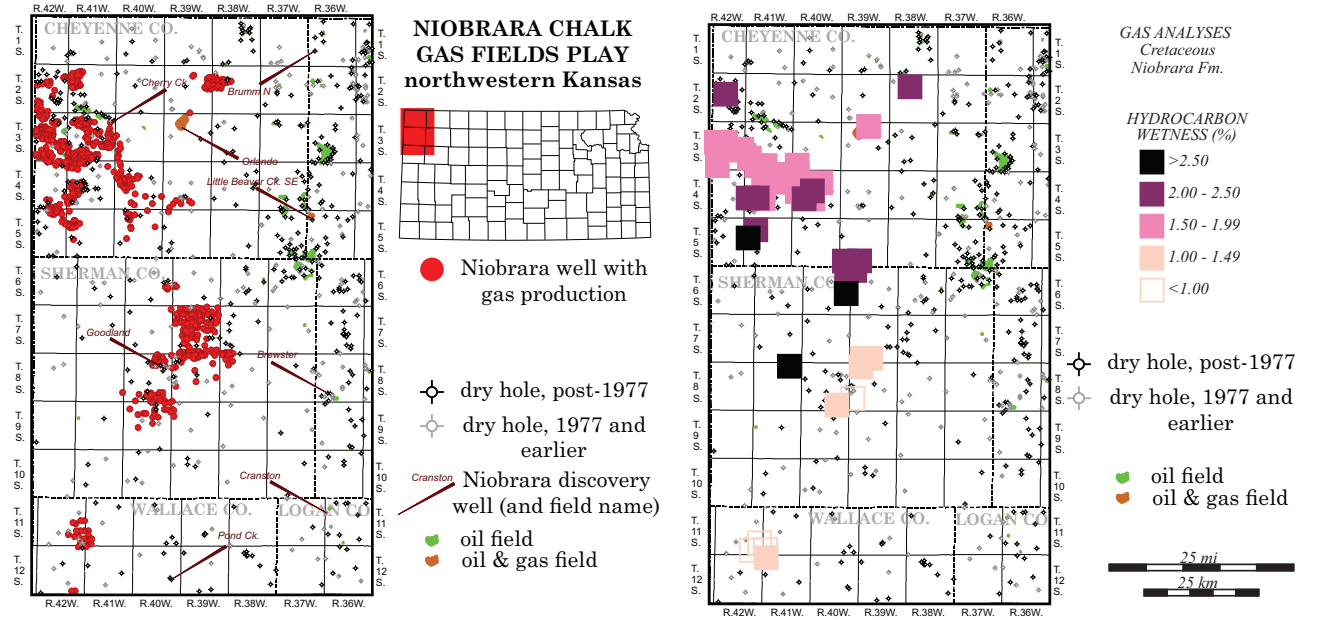
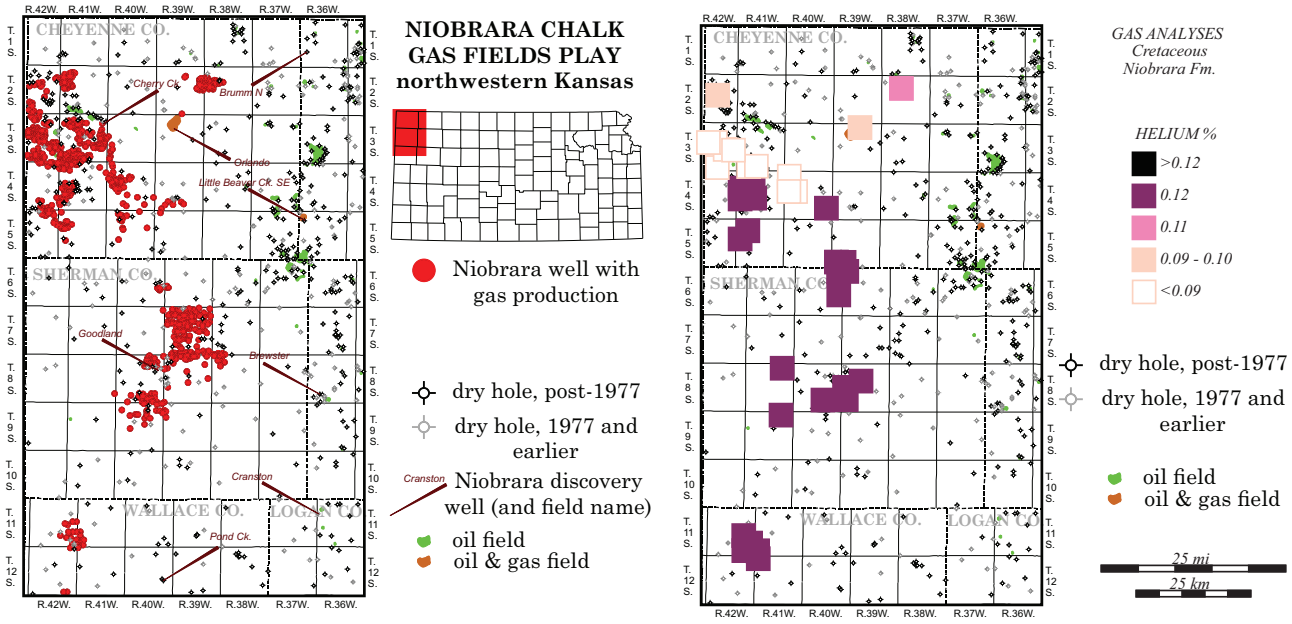


Figure 19. Distribution of boreholes drilled for petroleum, locations of wells producing gas, and geographic distribution of A) BTU content and B) hydrocarbon wetness for gases produced from Cretaceous strata (Niobrara Chalk) in northwestern Kansas. Symbol size and placement are described in the caption for **fig. 11**. Color of symbols for hydrocarbon wetness (B) and helium percentage (C) (next page) are shades of purple, effectively subdividing the category that purple represents in the maps of the other stratigraphic units (i.e., **figs. 11B, C–16B, C**, respectively representing less than 5.99% hydrocarbon wetness and less than 0.2% helium).

C.



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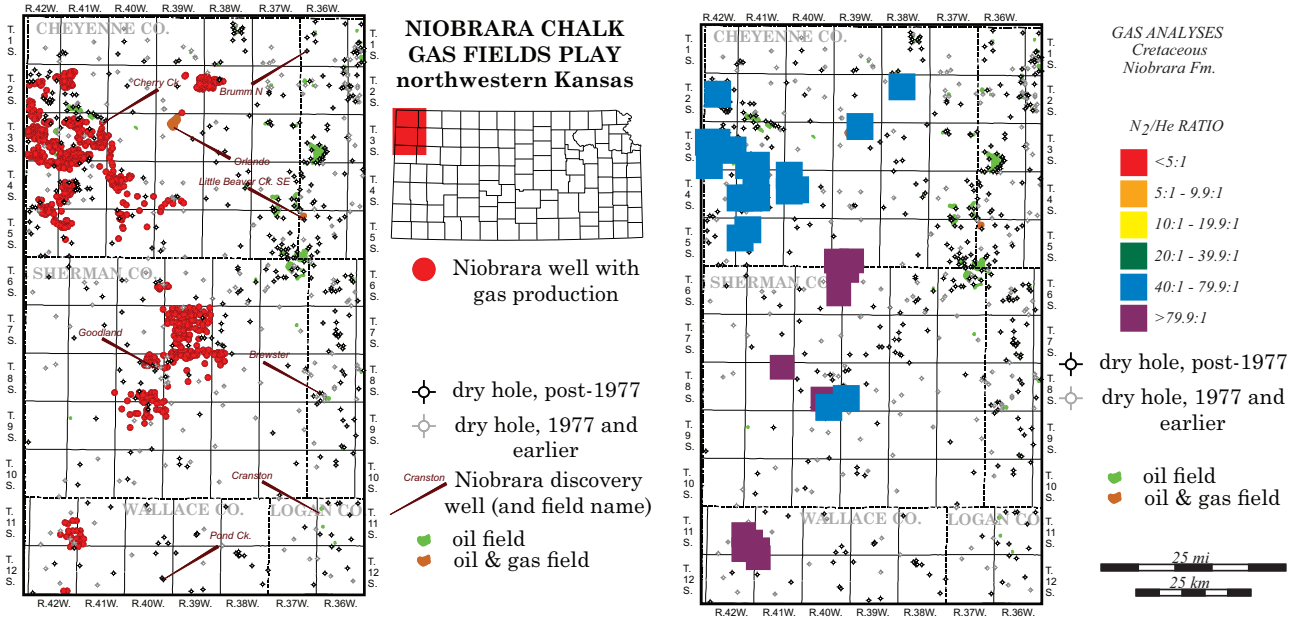

Figure 19 (continued). Distribution of boreholes drilled for petroleum, locations of wells producing gas, and geographic distribution of C) helium content and D) nitrogen/helium ratio for gases produced from Cretaceous strata (Niobrara Chalk) in northwestern Kansas. Symbol size and placement are described in the caption for **fig. 11**. Color of symbols for hydrocarbon wetness (B) (previous page) and helium percentage (C) are shades of purple, effectively subdividing the category that purple represents in the maps of the other stratigraphic units (i.e., **figs. 11B, C–16B, C**, respectively representing less than 5.99% hydrocarbon wetness and less than 0.2% helium).

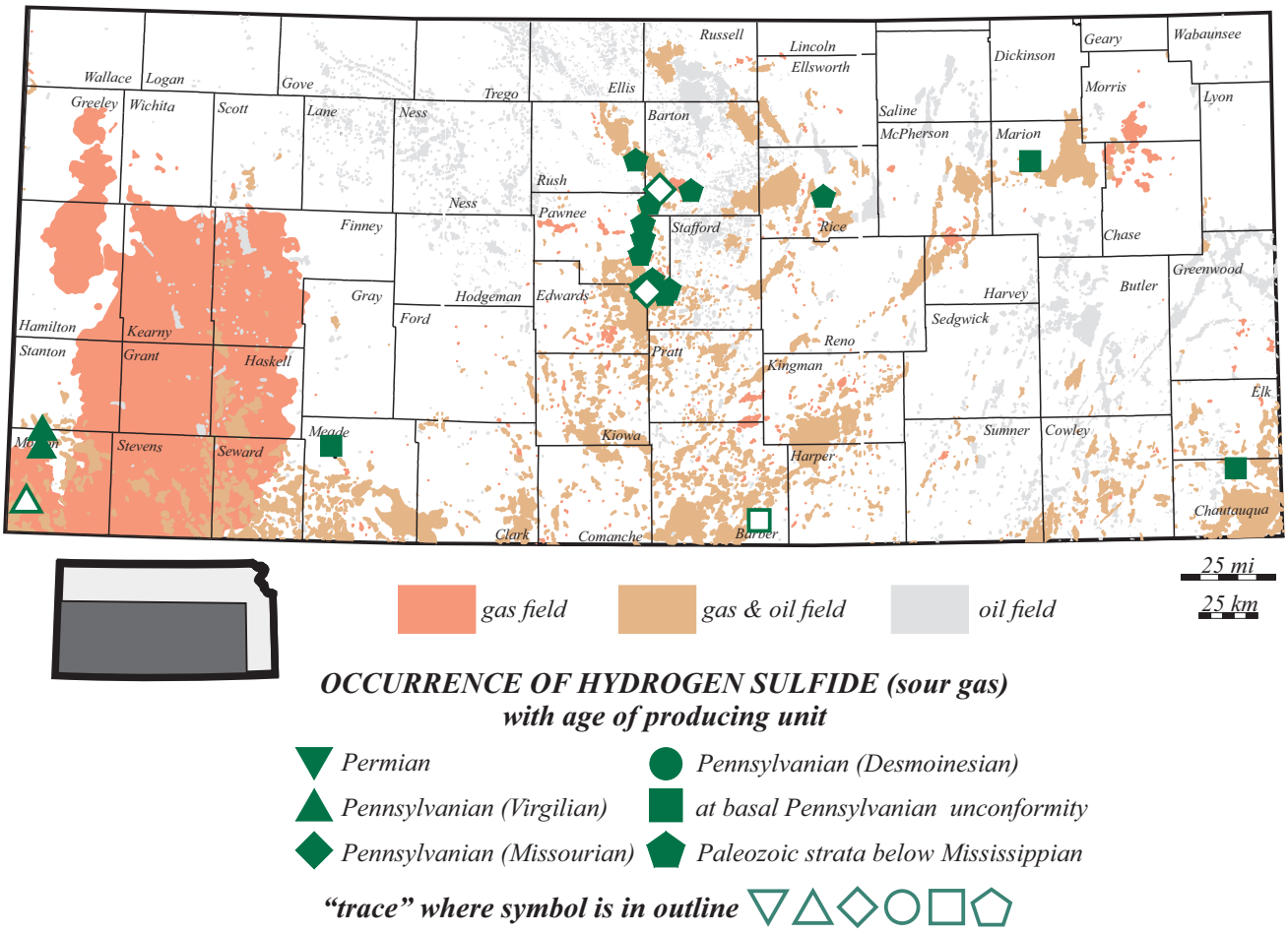

Figure 20. Sour (H_2S) gas in Kansas. This map is the result of a compilation of gas analyses in Kansas (Newell, 2025), and a search of scout cards in the well data library at the Kansas Geological Survey in Lawrence, Kansas (see **Appendix 1**).

Of 5,588 gas analyses, 36 (0.6% of all analyses) note the presence of sour gas in Kansas, either in the gas sample analyzed or in remarks on scout cards that note that sour gas is present in wells drilled in the same field. The maximum amount of H_2S gas recorded from an analyzed natural gas sample in Kansas (1.3%) is from Mississippian strata sampled in the Berentz Drilling #1 Aiken well in sec. 17, T. 32 S., R. 11 E. (Chautauqua County), in the Kingston Field in the Cherokee basin (see **table 3**). For considerations of safety, **Appendix 1** lists in more detail occurrences of sour gas in wells drilled for Kansas petroleum.

DISCUSSION

This work examines stratigraphic and geographic changes in gas compositions and ratios of component gases for each of the seven major stratigraphic units considered in this study (see **fig. 3**). Percentages of individual hydrocarbon gases will be examined in more detail. Percentages of non-hydrocarbon gases, particularly helium and nitrogen, will be compared with each other and with various hydrocarbon gases to better understand processes of migration, accumulation, and post-accumulation alteration.

Gases below the basal Pennsylvanian angular unconformity

Relatively few data points exist for this deepest stratigraphic unit. Most of the gas accumulations in this stratigraphic unit are in Comanche County in south-central Kansas and in a north-northeast–south-southwest trend extending from western Barber County to northeastern Pratt County (**fig. 11**). This may be caused by a focusing of gas onto local structural culminations and stratigraphic traps on the crest and flanks of the Pratt anticline (**figs. 1B, 11**). Overall, the gas zones in this stratigraphic unit have greater hydrocarbon wetness than the overlying stratigraphic units (**fig. 6**). This is likely due to the greater thermal maturity that comes with deeper burial of its contributing source-rock intervals. In a manner that is mimicked in the other stratigraphic intervals, the helium percentage is minimal in deeper areas (**fig. 11C**), but in updip areas toward the Central Kansas uplift the helium percentage increases and the nitrogen/helium ratio decreases (**fig. 11D**). This may be due to the gas reservoirs, which are mostly lower Paleozoic in age, being in closer proximity to the Precambrian basement the closer they are to the Central Kansas uplift. Concomitantly, BTU content (**fig. 11A**) and hydrocarbon

wetness (**fig. 11B**) decrease updip toward the Central Kansas uplift. Perhaps this implies the hydrocarbon gases are mixing with increasing amounts of non-hydrocarbon gases closer to the uplift.

Gases along the basal Pennsylvanian angular unconformity

A common feature of the gas-characteristics maps (**figs. 11–16**) for all stratigraphic units other than the Cretaceous (**fig. 19**) is that BTU content and nitrogen/helium ratios decrease northward (updip) onto the Central Kansas uplift. Conversely, helium content increases updip (**fig. 12C**). The Central Kansas uplift is essentially the distal end of a migration route of petroleum moving out from deeper parts of the Anadarko basin in Oklahoma, where it was generated, to shallower structural and stratigraphic traps on the cratonic shelf, where it accumulated. Porous zones in association with the basal Pennsylvanian angular unconformity collectively constitute a major hydrocarbon carrier bed, as evidenced by the large number and areal extent of the oil and gas fields at this stratigraphic level (see Newell and others, 1987).

A close examination of gas analyses along a relatively narrow hydrocarbon migration route up the south-plunging Pratt anticline reveals several consistent changes in gas chemistry along the migration route. To these ends, gas analyses were selected from a narrow rectangle geographically centered along the plunge of the Pratt anticline (**fig. 21**). This rectangle is three townships wide in the east-west direction (T. 15 W.–T. 17 W.) and 20 townships in length (T. 16 S.–T. 35 S.) in the north-south direction (nominally 18 by 117 mi; 30 by 188 km). Along this area of investigation, dozens of oil and gas fields have been sampled over several decades. Several natural gas characteristics (BTU content, hydrocarbon wetness, reservoir depth, total hydrocarbons, nitrogen/helium ratio, and *n*-butane/*i*-butane ratio) are simultaneously displayed along the 117-mile length of this migration route (see **fig. 21**).

The BTU content for natural gas along the basal Pennsylvanian unconformity generally decreases northward (updip) on this migration route (**fig. 21A, B**). This updip decrease in BTU content corresponds to an updip decrease in total hydrocarbon percentage (**fig. 21C**). Conversely though, hydrocarbon wetness (**fig. 21E**) slightly increases updip, but evidently this relative increase in the heavier (and higher BTU) hydrocarbon compounds is not sufficient to offset the overall updip decrease in BTU content due to decreased percentage of total hydrocarbons.

Other producing zones in addition to the reservoirs along the basal Pennsylvanian unconformity also show decreasing BTU content updip along this migration route (**fig. 21B, D**), even though the BTU content for the Pennsylvanian (Missourian, Virgilian) and Permian gases are generally less than that for gases that are directly associated with the basal Pennsylvanian angular unconformity (**fig. 21B**). At the distal end of the migration route (its northern extreme), gases from Missourian, Virgilian, and basal Pennsylvanian unconformity reservoirs have similar BTU content. This is at the Reichel Field, where hydrocarbons from the basal Pennsylvanian angular unconformity have leaked upward into shallower reservoirs (Jenden and others, 1988).

Helium increases updip relative to nitrogen, as illustrated by the northward decrease of the nitrogen/helium ratio along the migration route (**fig. 21F**). This may be an effect of preferential migration of helium over that of nitrogen, in that helium has a smaller kinetic diameter than the nitrogen molecule. Although gas movement up the anticline may mostly be in a discrete phase driven by buoyancy, some diffusion through the heterogeneously distributed shales and sealing rocks along the basal Pennsylvanian unconformity also may occur (see Ismail and others, 2015, p. 14); thus, helium may experience less of an impediment to its movement when migrating, or perhaps chemical or sorption reactions could gradually remove nitrogen. Nitrogen is also more soluble in water than helium (see below), so nitrogen may be preferentially dissolved in formation water and then removed as that water flows away from any gas accumulation. Alternatively, perhaps natural gas is mixing with a nitrogen-helium gas of separate origin as it migrates northward. If the Precambrian basement is a source of helium, the closer proximity of the gas accumulations to the basement nearer the Central Kansas uplift may also be a factor in the northward decreasing nitrogen/helium ratio.

Miao and others (2012) stated that when natural gas migrates through dense cap rocks, the value of *n*-butane/*i*-butane (n-C_4/i-C_4) decreases, whereas when it migrates laterally along a reservoir, the value of n-C_4/i-C_4 increases. Both of these hydrocarbon molecules have the same molecular weight, but *i*-butane has a shorter length than *n*-butane, thus it may be subject to less resistance as it moves in a relatively impermeable rock. A plot of n-C_4/i-C_4 ratios along the migration route (**fig. 21G**) shows the n-C_4/i-C_4 ratio is relatively constant from T. 35 S. to T. 19 S. (see scale at base of **fig. 21E, G**), and then from T. 19 S. northward it decreases overall (**fig. 21G**). Perhaps this indicates that natural gas migrating northward up the crest of the Pratt anticline is subject to more impermeable strata north of T. 19 S. along the basal Pennsylvanian unconformity and in localities where it may be leaking stratigraphically upward into Permian strata. In some ways, this conclusion is rather speculative because migration of hydrocarbons from Oklahoma up onto the Pratt anticline could be more complex than simple fill-and-spill of successive updip traps composed entirely of laterally contiguous and permeable water-wet reservoir rock. The migration process, instead of entirely being controlled by differential entrapment of hydrocarbons as explained by Gussow (1954), could be subject to relatively impermeable barriers due to the heterogeneity of rocks along the basal Pennsylvanian angular unconformity. In this case — a situation outlined by Schowalter (1979) — natural gas and certain component gases may migrate more easily than oil; thus, gas can be preferentially concentrated in the distal ends of a petroleum migration path. An additional complication that may influence gas composition is that some hydrocarbons may be locally generated by source strata present along the flanks of the Pratt anticline.

Localized, sharp deviations of data occur for most all of the characteristics depicted on the basal Pennsylvanian unconformity migration route northward along the Pratt anticline (**fig. 21A**). For example, in townships 24 S., 20 S., and 16 S. (i.e., 37.9, 38.3, and 38.7 °N latitude; see axis scale at base of **fig. 21E, G**), BTU content (**fig. 21A**)

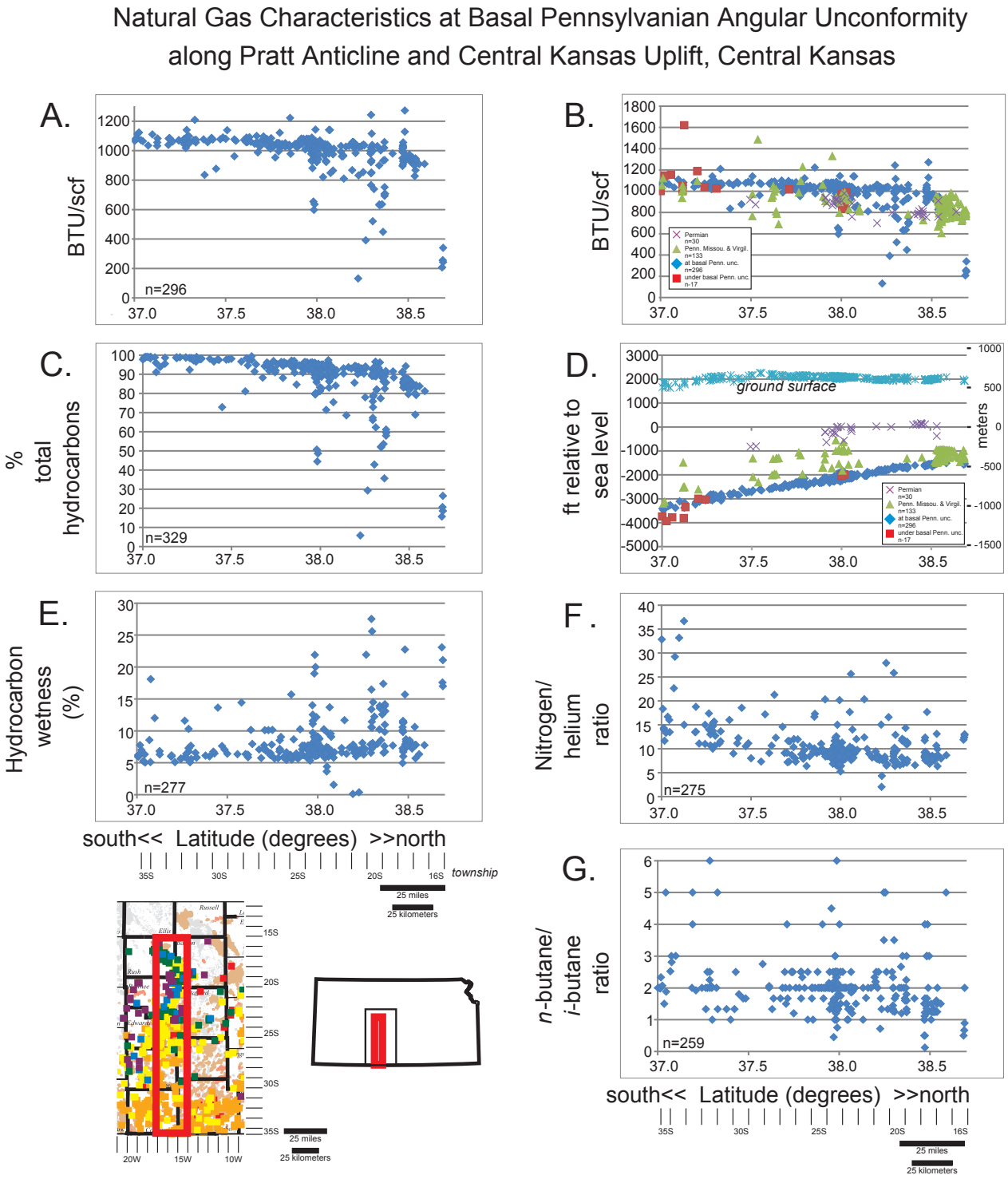

Figure 21. Natural gas compositional variation along the hydrocarbon migration path from the Pratt anticline to the southern part of the Central Kansas uplift. A) BTU content for natural gases along the basal Pennsylvanian unconformity; B) BTU content for natural gases from all stratigraphic intervals — gases along the basal Pennsylvanian unconformity (see **fig. 21A**) are shown as blue diamonds; C) total hydrocarbon percentage for analyses along the basal Pennsylvanian unconformity; D) depths of samples and ground surface elevation relative to sea level; E) hydrocarbon wetness for analyses along the basal Pennsylvanian unconformity; F) nitrogen/helium ratios for analyses along the basal Pennsylvanian unconformity; and G) *n*-butane/*i*-butane ratio for analyses along the basal Pennsylvanian unconformity. The x-axis for the plots is degrees of latitude; corresponding townships south are also indicated at the base of each column of plots. The index map is a segment of **fig. 12A**. With regard to perspective for the graphs, the observer is looking west, with north to the right and south to the left.

and total hydrocarbon percentage (**fig. 21B**) drop steeply for several data points, whereas the hydrocarbon wetness (**fig. 21E**) markedly increases. This indicates that even though a range of hydrocarbon component gases were likely withdrawn from the pristine high-BTU natural gas at these localities, methane was preferentially withdrawn over all the heavier hydrocarbons. Alternatively, heavier hydrocarbon gases could have been preferentially added to the gas accumulation over that of methane, but this is not likely, as methane is generated along with other hydrocarbons in the thermal maturation of source rocks. The addition of a methane-poor hydrocarbon gas would still require a prior step to eliminate methane gas. Also, if addition of heavier hydrocarbons was the operative process, the overall BTU content in these localities would more likely increase rather than decrease.

Conceivably, the drop in BTU content (**fig. 21A**) and total hydrocarbon percentage (**fig. 21C**) could be caused by the addition of nitrogen and helium, perhaps by upward migration of these non-hydrocarbon gases from the Precambrian basement through joints and fractures. However, this process would not account for the localized increases in hydrocarbon wetness (**fig. 21E**), unless the same process that introduces nitrogen and helium to the gas reservoir at the basal Pennsylvanian unconformity simultaneously and preferentially dissolves methane.

Another way to examine the chemistry of natural gases along this migration route is to examine percentages of component gases as a function of BTU content (**fig. 22**). In this analysis, total hydrocarbon percentage decreases with decreasing BTU content (**fig. 22A**) and concomitantly nitrogen percentage and helium percentage increase (**fig. 22C, D**). This does not necessarily imply that nitrogen and helium are being added to the natural gas; it may only mean that these gases are not as easily removed as methane and other hydrocarbons from the original natural gas. The projection of the nitrogen/helium ratio to 0 BTU/scf has the nitrogen/helium ratio approaching 20:1 at that point (**fig. 22B**), whereas the normal nitrogen/helium ratio of natural gas along the basal Pennsylvanian unconformity is approximately 6:1 to 12:1 (as per the nitrogen/helium ratios for the cluster of data points at 1,050 BTU/scf in **fig. 22B**). 20:1 is conceivably the ratio of the nitrogen and helium that could either be mixing with or introduced to the resident natural gas along the basal Pennsylvanian unconformity.

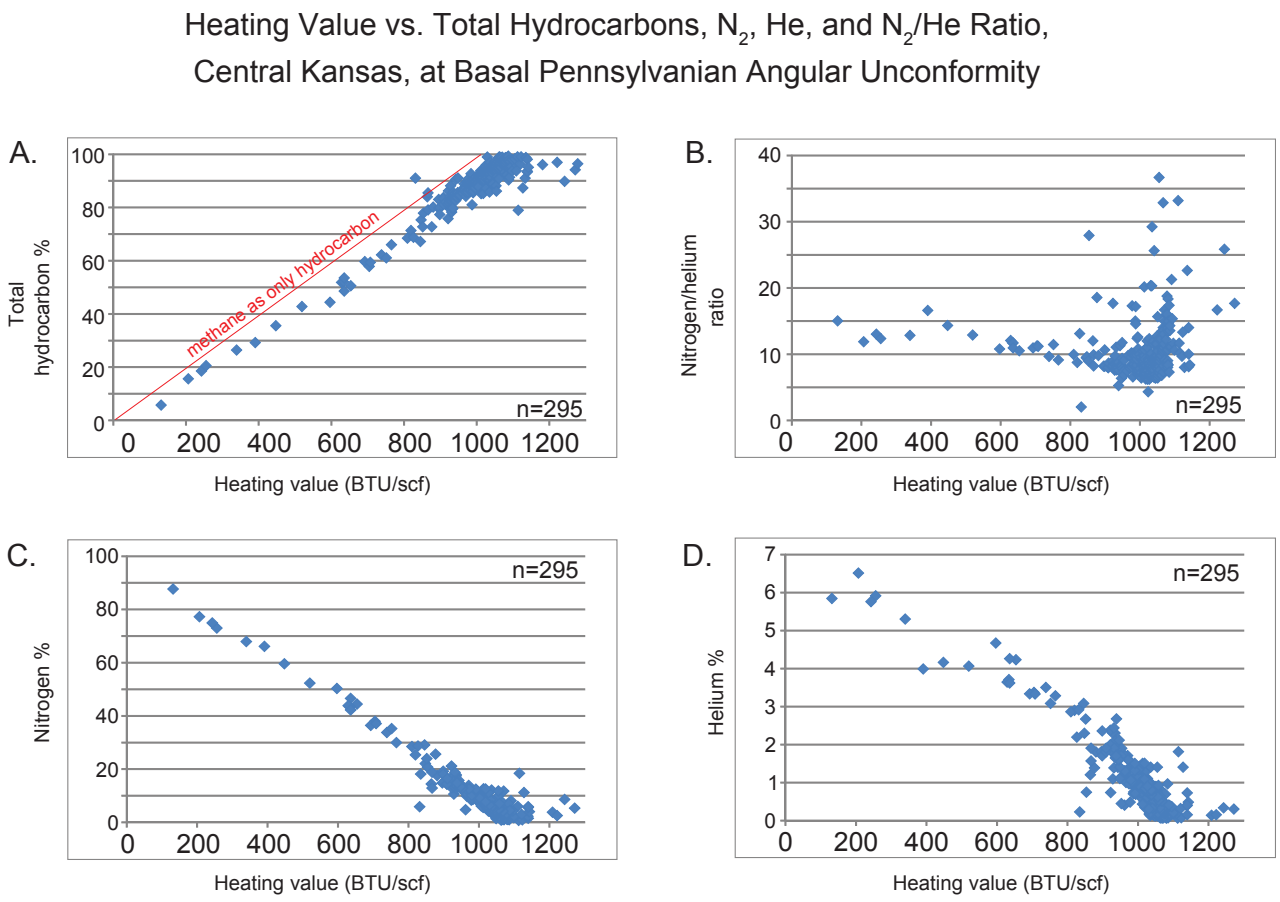

Figure 22. Variation in gas chemistry along the hydrocarbon migration path from the Pratt anticline to the Central Kansas uplift (see **fig. 21** index map) as a function of changes in heating value of the natural gas. A) Total hydrocarbon percentage (this cross-plot is a the same as **fig. 8F**), B) nitrogen/helium ratio, C) nitrogen percentage, and D) helium percentage. Analyses are for natural gases along the basal Pennsylvanian unconformity.

Interaction of the natural gas with formation waters over geologic time is a possible cause for the occurrences of low-BTU, methane-poor, wet gases. This then becomes an issue of gas solubility in formation water that underlies the gas-water contact at the base of the gas accumulation. In turn, the solubility of component gases in a natural gas depends on the temperature and pressure to which the system is subjected. The temperatures and pressures affecting a natural gas accumulation also can change over geologic time with uplift and subsidence and changes in hydrology and hydrostatic gradient. The direction and rate of movement of the formation water over geologic time may be guessed, but the certainty of the guess will be low. The effects of an oil leg residing under a natural gas cap also will probably complicate movement of gas into or out of a natural gas accumulation. The mineral content of formation water also can be a factor in that formation water is a veritable ionic stew with its sum total of dissolved mineral solutes ranging from at least 10,000 ppm total dissolved solids (TDS) to as much as 250,000 ppm TDS. As the salinity of the formation water increases, the ability of water to hold dissolved gas will generally decrease. As pressure rises, solubility of a gas will increase in the formation water. As temperature goes up, the gas will become less soluble.

Component gases in natural gas have different solubilities in water. If the formation water in contact with a natural gas accumulation is undersaturated with respect to the component gas, then the component gas will dissolve into the formation water over time and will be partly or wholly removed from the natural gas accumulation. Conversely, if the formation water is saturated with respect to the dissolved component gas, and the gas accumulation is relatively devoid of that component gas, then the component gas will evolve out of the formation water and into the gas accumulation until that gas accumulation is saturated with respect to the water.

In chemical analyses of natural gas, concentration of a component gas is measured by its volume percent at 1 atmosphere pressure and near room temperature. This volume percentage is equivalent to the molar percentage. However, as discussed above, the concentrations of component gases in formation waters in Kansas are unknown, both for present-day conditions and for the geologic past. This renders any calculation of relative movement of component gases into and out of the gas accumulation as speculative. Nevertheless, a crude approximation of how component gases behave relative to each other as the natural gas is altered to a lower BTU gas is possibly useful. In general, hydrocarbon component gases increasingly heavier than methane (i.e., ethane, propane, butane, pentane, hexane, hexane+, etc.) have successively decreasing solubilities in water. The solubility of ethane marginally exceeds that of methane at these specific temperature and pressure conditions (see **table 4**). For example, **table 4** lists the solubility (mole fraction solubility) of hydrocarbon gases and other non-hydrocarbon component gases in water at 308.15 °K (i.e., 35 °C, 95 °F) (from Gevantman, 1992). Carbon dioxide dissolves most easily of all the major component gases in natural gas (at said conditions) into freshwater. Helium is least soluble.

Table 4. Solubilities (moles/liter) of component gases in water at a temperature of 95 °F (35 °C) (Gevantman, 1992).

Component Gas	Solubility
carbon dioxide (CO_2)	48.0×10^{-5}
ethane (C_2H_6)	2.686×10^{-5}
methane (CH_4)	2.180×10^{-5}
argon (Ar)	2.169×10^{-5}
propane (C_3H_8)	2.088×10^{-5}
n-butane (C_4H_{10})	1.645×10^{-5}
hydrogen (H_2)	1.350×10^{-5}
i-butane (C_4H_{10})	1.278×10^{-5}
nitrogen (N_2)	1.047×10^{-5}
helium (He)	0.699×10^{-5}

Conditions midway along the basal Pennsylvanian unconformity migration route on the Pratt anticline are about 122 °F (50 °C; 323.15 °K) and about 1,500 psig (103 atm). Percentages of the hydrocarbon component gases vs. BTU content all have concentrations of data points in one small area of each of their cross-plots (**figs. 22, 23**). These concentrations of data points are taken to represent the original unaltered composition of the natural gas along the basal Pennsylvanian unconformity migration route. Original percentages of component gases (from **figs. 22, 23**) are inferred to be 90% methane, 4% ethane, 1.5% propane, 0.75% butane, 0.25% pentane, and 0.2% hexane+. Non-hydrocarbon gases (from **figs. 9F, 21**) are about 9.6% nitrogen and about 0.8% helium, in a 12:1 nitrogen/helium ratio (roughly midway along the migration route). Summing all the above gases and recalculating to 100% yields an original gas composition of 84% methane, 3.7% ethane, 1.4% propane, 0.5% *n*-butane, 0.2% *i*-butane, 9.0% nitrogen, and 0.8% helium. Pentane and hexane+, as well as carbon dioxide, argon, and hydrogen, which are present in small percentages, are ignored.

Percentages of hydrocarbon gases with respect to BTU content of the natural gas (**fig. 23**) along the basal Pennsylvanian unconformity on the Pratt anticline all decrease with decreasing BTU content, although the degree of decrease is less pronounced with the heavier hydrocarbon gases (**fig. 23C–F**). Concentrations of data points in each graph at approximately 1,050 BTU/scf probably indicate relatively pristine natural gas before any alteration to low-BTU gas.

Changes in ratios of hydrocarbon gases with changing BTU content along the basal Pennsylvanian unconformity (**fig. 24**) are an additional way to understand the manner in which the low-BTU gases have formed. Such changes possibly are caused by interactions of the pristine natural gas accumulations at the basal Pennsylvanian unconformity with formation water, but as previously discussed, these changes in percentages and component-gas ratios cannot be easily tied to the solubilities and concentrations of these component gases to formation waters. With decreasing BTU content, the methane/ethane ratio decreases (**fig. 24B**). Methane is likely

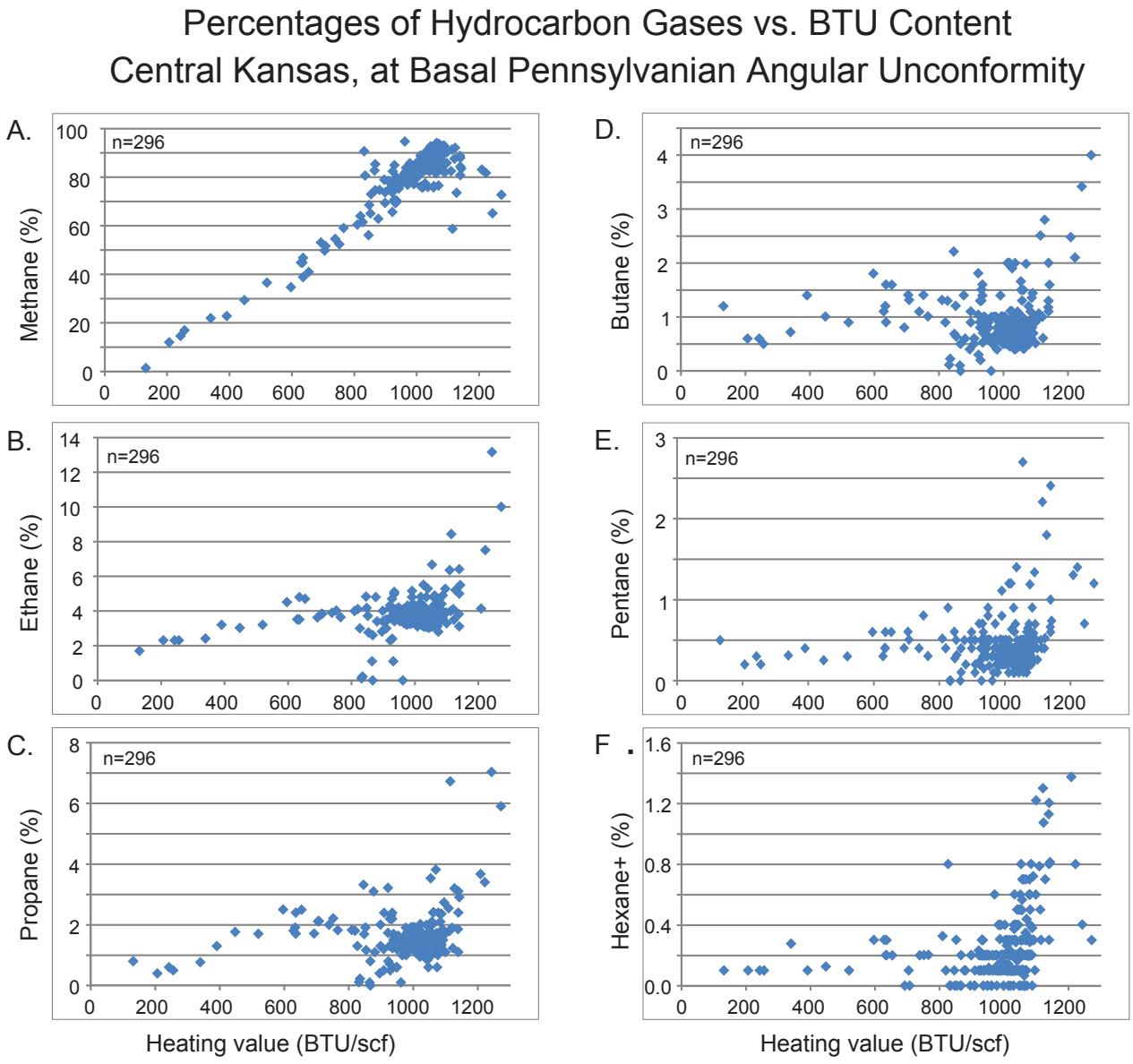

Figure 23. Variation in percentages of the hydrocarbon gases chemistry along the hydrocarbon migration path from the Pratt anticline to the Central Kansas uplift, as a function of changes in heating value of a natural gas. A) Methane percentage, B) ethane percentage, C) propane percentage, D) butane percentage, E) pentane percentage, and F) hexane+ percentage. Analyses are for natural gases along the basal Pennsylvanian unconformity.

preferentially being removed over the heavier hydrocarbons. This may account for the steady increase in hydrocarbon wetness with decreasing BTU content (**fig. 24A**). The effects on hydrocarbon wetness are not as strong with the heavier hydrocarbon gases; with decreasing BTU content, there is no strong change in the ratios of ethane/propane (**fig. 24C**), butane/pentane (**fig. 24E**), and pentane/hexane+ (**fig. 24F**). A weak decrease in the propane/butane ratio is displayed (**fig. 24D**). The concomitant increase in nitrogen with lower BTU content and lower hydrocarbon wetness (**fig. 24G**) is predictable, but the relationship is not strongly linear. No explanation is evident for this.

The behavior of helium mimics that of nitrogen in that the percentage of both of these non-hydrocarbon component gases increase with decreasing BTU content (**fig. 22C, D**). The nitrogen/helium ratio (**fig. 22B**) also increases with decreasing BTU. The similar patterns of nitrogen and helium suggest that both gases remain relative to the hydrocarbons being removed or are possibly being added while the hydrocarbon gases are being depleted in those localized areas on the Pratt anticline where low-BTU gas occurs. The source of the nitrogen and helium is unknown, but since these two gases are usually found in a constant ratio in a given stratigraphic unit (Pierce and others, 1964; Gold and Held, 1987; Jenden and others, 1988), it suggests a

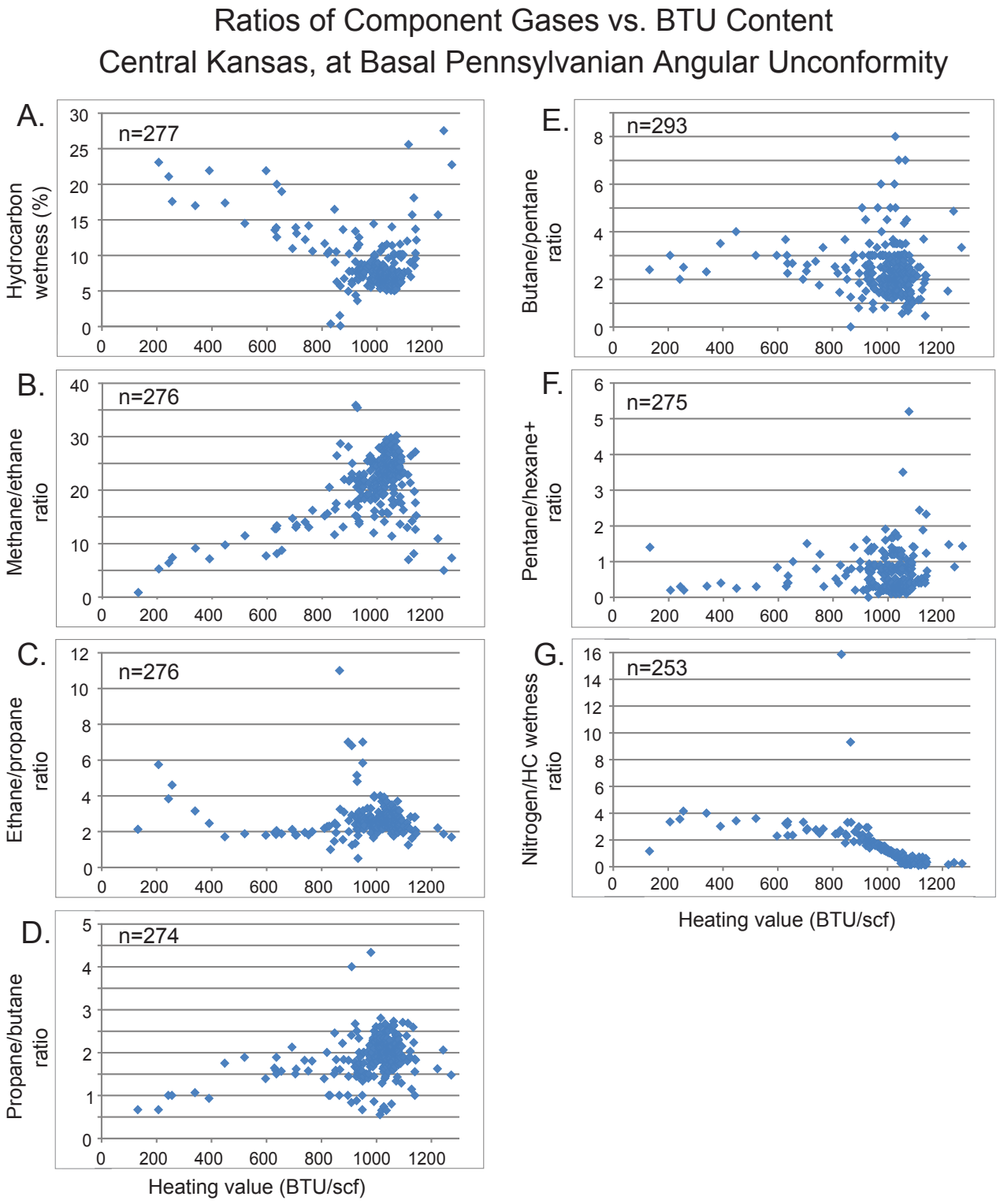

Figure 24. Ratios of component gases compared to BTU content of the gas sample, chemistry along the hydrocarbon migration path from the Pratt anticline to the Central Kansas uplift. A) Hydrocarbon wetness percentage, B) methane/ethane ratio, C) ethane/propane ratio, D) propane/butane ratio, E) butane/pentane ratio, F) pentane/hexane+ ratio, and G) nitrogen/hydrocarbon wetness ratio. Analyses are for natural gases along the basal Pennsylvanian unconformity. The sequence of ratios from A) to G) follows the increasing molecular weight of the component hydrocarbon gases.

common origin or means of transport, or both. The slight increase in the nitrogen/helium ratio with lower BTU content (**fig. 22B**) suggests a more efficient removal of helium than nitrogen, the addition of nitrogen, or a mixing with a gas with a higher nitrogen/helium ratio.

If alteration by formation water is the means by which low-BTU gas accumulations are created along the basal Pennsylvanian unconformity migration route, these fields should have gas-water contacts where their gas columns would be in direct contact with formation water. Although a few of these fields appear to have gas-water contacts, several fields with low-BTU gas have oil-bearing intervals (i.e., "oil legs," in the vernacular of the energy industry) that separate the natural gas from direct contact with formation water. The effect of the oil leg on gas chemistry and its interactions with formation water is unclear, but an oil leg would certainly complicate any processes altering the chemical composition of natural gas. Some fields have no gas cap, so the gas that is present is solution gas that evolves out of the oil as it depressurizes during production. Until more detailed sampling and geologic analysis take place, it can only be inferred that gas-water interactions probably account for some of the low-BTU gas. Considering the scatter of data points in **figs. 22–24**, it is likely that interactions of the formation water and natural gas are more complex than just one episode of simple interactions at a gas-water contact.

Gases in Pennsylvanian strata

Oil and gas reservoirs in the Pennsylvanian (Desmoinesian, Missourian, and Virgilian) stratigraphic units differ from other stratigraphic units in that the three Pennsylvanian units contain multiple reservoirs and beds of potential petroleum source rocks. These three stratigraphic units are the product of cyclothemic sedimentation (see Moore, 1949; Heckel, 1977). The identification of individual producing sections is necessary for a better understanding of these three Pennsylvanian stratigraphic units, but many completion reports and chemical analyses do not include detailed identification of producing zone. Instead, most stratigraphic calls are only at group and series level — for example "Lansing-Kansas City," "Kansas City," "Cherokee," or "Shawnee."

It is also difficult to determine whether individual gas accumulations in Pennsylvanian strata are the product of single or multiple source rocks. Conversely, the petroleum accumulations along the basal Pennsylvanian angular unconformity largely represent movement and entrapment of an initially homogeneous type of petroleum, albeit differentiated and separated in a geologically complex system of porous and sealing strata (Walters, 1958). Similarly, the gas fields in the Permian of the Hugoton embayment also represent the entrapment of a single type of gas (see Jenden and others, 1988) as do the Cretaceous fields in northwestern Kansas (see Rice, 1984). The uniformity may be due to a single source or hydrocarbons from several sources that were homogenized during migration.

Gases in Pennsylvanian (Desmoinesian) strata

The gas-bearing rocks in this stratigraphic unit are primarily limited to the axis of the Hugoton embayment in southwestern Kansas and the western flank of the Pratt anticline in southern Kansas. Eastern Kansas has considerable Desmoinesian gas production, including coal-bed methane, but this production is not considered here because of the lack of compositional data in eastern Kansas. According to structural mapping of the top of Mississippian rocks in Merriam (1963), the deepest part of the Hugoton embayment at this level in Kansas is in the southern parts of Meade and Clark counties in southwestern Kansas. Comanche County, immediately east of Clark County, is characterized by southwestward dips, whereas Seward County, immediately west of Meade County, is characterized by southeastward dips. Although the limited geographic extent of the gas in this stratigraphic unit makes comparisons to other stratigraphic units somewhat unclear, in the updip direction BTU content generally decreases (**fig. 13A**), hydrocarbon wetness slightly increases (**fig. 13B**), and helium percentage increases (**fig. 13C**). Total hydrocarbon percentage decreases with decreasing BTU content less than 1,050 BTU/scf (**fig. 25A**).

Although nitrogen/helium ratios generally decrease updip for gases along the basal Pennsylvanian unconformity (**fig. 12D**), no obvious trends in nitrogen/helium ratios can be discerned along dip direction for the gases in the Pennsylvanian (Desmoinesian) stratigraphic unit (**fig. 13D**). The reason for this is unknown, but perhaps source-to-accumulation migration routes in Desmoinesian strata in southwestern Kansas may be more complex than those along the basal Pennsylvanian unconformity. A cross-plot of nitrogen/helium ratios with BTU content for Desmoinesian natural gases (**fig. 25B**) shows that the nitrogen/helium ratio has no marked trend, but rather there is a clustering of data points centered about 1,050 BTU and 45 nitrogen/helium ratio. A scattering of data points with high nitrogen/helium ratios in the higher BTU region (i.e., greater than 1,250 BTU/scf, to the upper right of the central cluster) may be a mathematical artifact of the division of a small nitrogen percentage by an even smaller helium percentage. At present, there is no apparent cause for the scattering of high nitrogen/helium ratio data points to the right and above the central cluster.

Gases in Pennsylvanian (Missourian) strata

Data points in this stratigraphic unit are geographically widespread but show a concentration in a horseshoe-shaped region in Rush, Barton, Rice, and Ellsworth counties on the Central Kansas uplift (**fig. 14**). The nitrogen/helium ratio does not show strong geographic trends (**fig. 14D**). Several gases with low nitrogen/helium ratios (5:1 to 10:1) and high helium content (1.6% to 3.2%, **fig. 14C**) are located in northeastern Rush County and western Barton County (i.e., in the Reichel and Otis-Albert fields). Discussion of these analyses is deferred to the following section on Virgilian gases.

Overall, the Pennsylvanian (Missourian) gases (**fig. 26**) are chemically similar to Pennsylvanian (Desmoinesian) gases (**fig. 25**). Hydrocarbon gases decrease with heat content decreasing below 1,050 BTU/scf (**figs. 25A, 26A**). Nitrogen increases in a linear fashion with heat content decreasing below 1,050 BTU/scf (**figs. 25C, 26C**), but helium increases in a less linear fashion (**fig. 25D, 26D**). The pattern of the nitrogen/helium ratio is a cluster of data points, with a scattering of higher nitrogen/helium ratios tied to samples with heat content greater than 1,200 BTU/scf (**fig. 25B, 26B**).

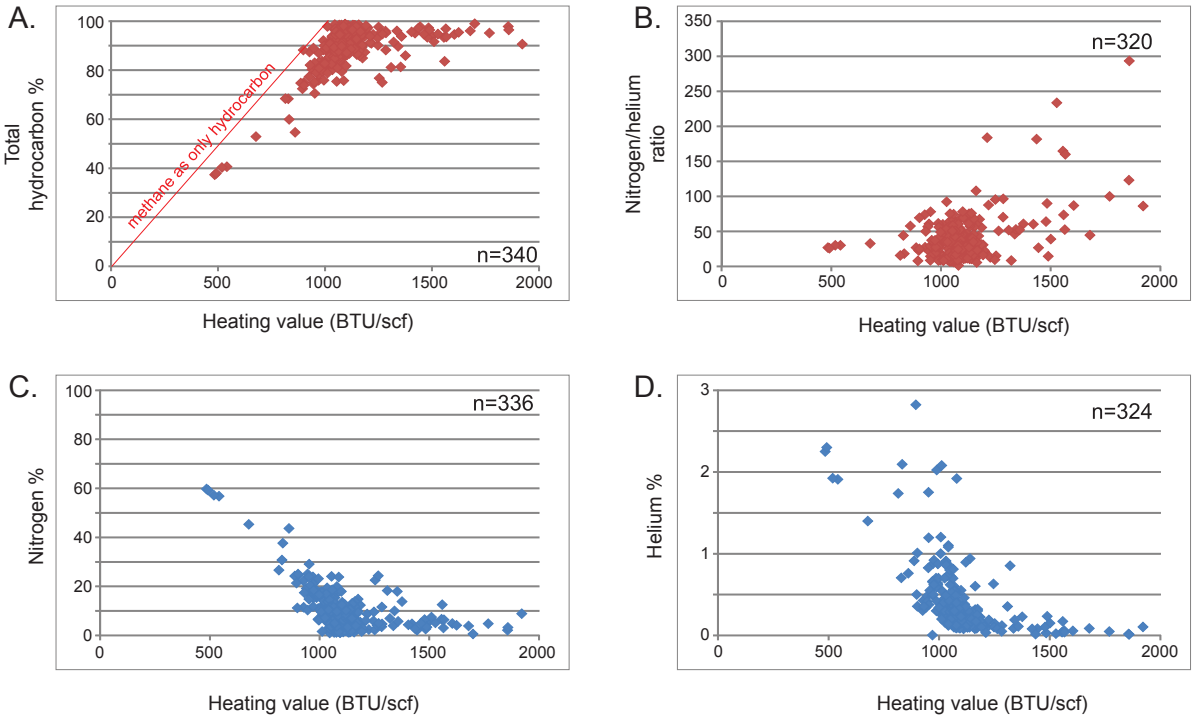

Figure 25. Characterization of gases present in Pennsylvanian (Desmoinesian) strata by A) total hydrocarbon percentage (this cross-plot is the same as **fig. 8E**), B) nitrogen/helium ratio, C) nitrogen percentage, and D) helium percentage, all cross-plotted against heating value (BTU/scf).

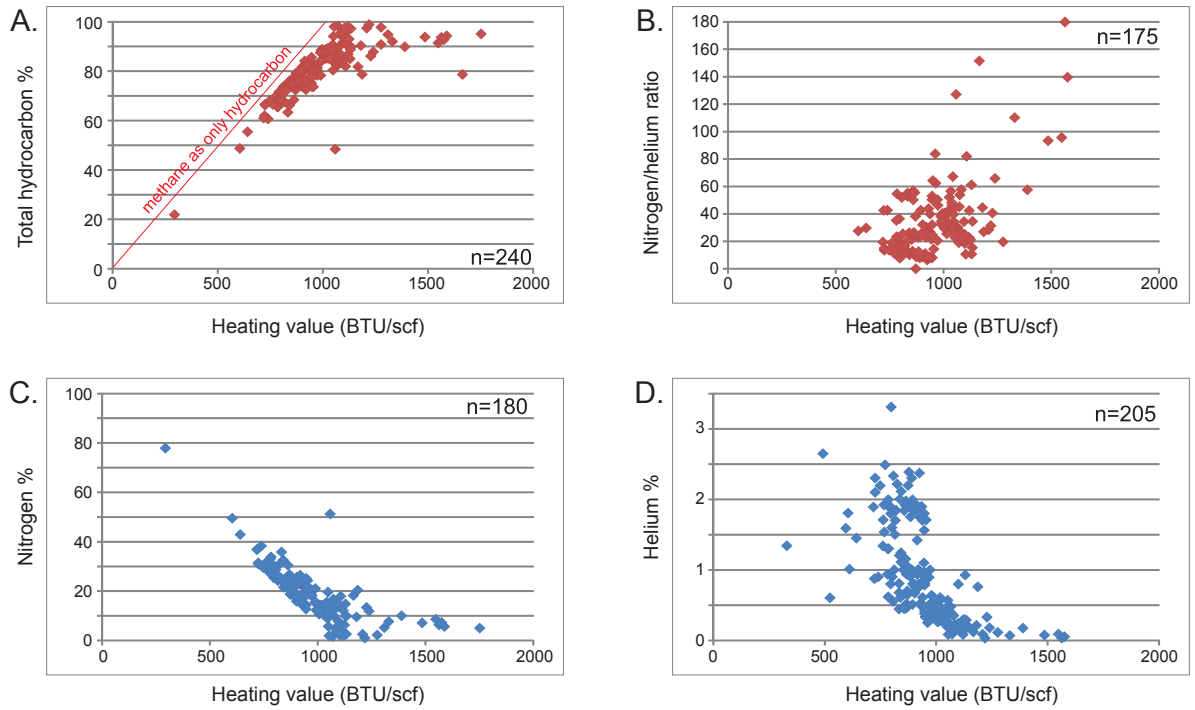

Figure 26. Hydrocarbon percentage and wetness of Pennsylvanian (Missourian) gases cross-plotted against heating value (BTU/scf). The undifferentiated overlay of natural gases produced with oil ("associated" gas production) and those that are not ("non-associated" gas production) indicates that despite their production designation, there is not a significant difference in the chemistry of these two types of gases.

The gas samples from Missourian strata can be used to test whether there is a significant difference in the composition of natural gases present directly above oil accumulations, as compared to gas accumulation present directly above formation water (i.e., natural gas with no oil zone intervening between the gas and underlying formation water). In the energy industry, a gas accumulation is described as "non-associated" and "associated" production (i.e., respectively, from a reservoir producing only gas as opposed to a reservoir producing both oil and gas).

The widespread geographic extent of the Missourian gases and the possibly varied source-to-trap conditions for its numerous separate pay zones make this unit a good study for determining whether there are significant chemical differences between "associated" and "non-associated" gases. Total hydrocarbon percentage and hydrocarbon wetness of "associated" and "non-associated" gases are plotted against their BTU content (**fig. 27**). The trends for each group of gases overlap (see **fig. 27**). This indicates that "associated" and "non-associated" gases are not useful terms for predicting the heating value of Missourian gases or for predicting the presence of an oil leg below the natural gas. This probably applies to other stratigraphic units as well.

If the presence of an oil leg has minimal effects on natural-gas compositions, then this would simplify the puzzle presented in the previous discussion of why some low-BTU gas accumulations on the Pratt anticline have an oil leg whereas some higher-BTU gas accumulations directly contact formation water. The effect of an oil leg in a natural gas accumulation certainly needs more rigorous study.

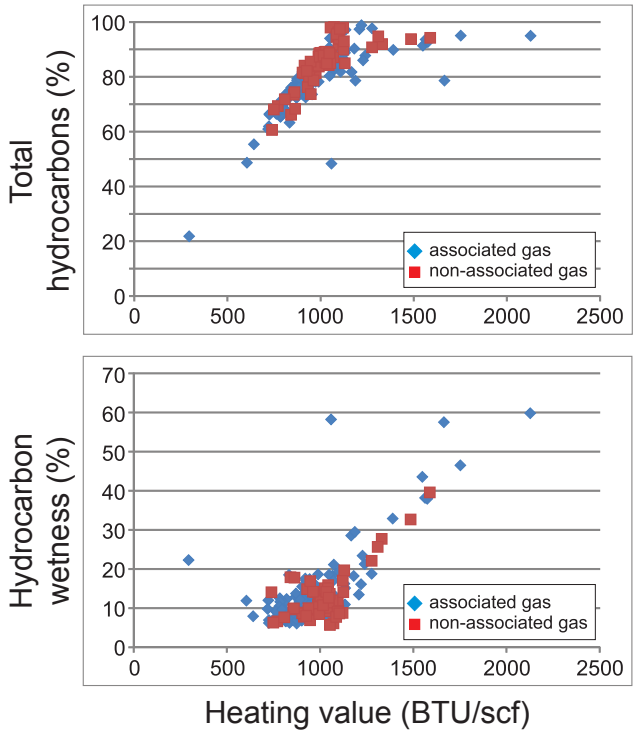

Figure 27. Characterization of natural gases present in Pennsylvanian (Missourian) strata by A) total hydrocarbon percentage (this cross-plot is the same of **fig. 8E**), B) nitrogen/helium ratio, C) nitrogen percentage, and D) helium percentage, all cross-plotted against heating value (BTU/scf).

The "associated" versus "non-associated" designation is not so straightforward either, as differential entrapment and migration as outlined by Gussow (1954) and Walters (1958) can cause a gas field to be "non-associated," but directly updip along the same migration route, the same gas can have an oil zone directly beneath it. In contrast to the "spill and fill" process described by Gussow (1954), Schowalter (1979) explains that differences in ease of movement of oil and natural gas through permeability barriers can enable natural gas to more easily migrate than oil; thus, gas can be preferentially concentrated in the distal ends of a migration path of petroleum.

In a larger sense, even the Hugoton Gas Field may be considered associated gas; the "non-associated" gas zones in the Hugoton Gas Field in Kansas are contiguous with "associated" gas accumulations in Texas and Oklahoma, where the gas-producing zone is found directly above oil (see Brown, 2019). Duration of production also may be a factor in that with continued production and decreasing reservoir pressure, successively heavier hydrocarbon gases could evolve out of an oil leg in a reservoir into the overlying gas accumulation. Alternately, with production, a thin or depleted oil leg would have minimal effect on the chemistry of the overlying gas accumulation.

Gases in Pennsylvanian (Virgilian) strata

As BTU content drops below 1,050 BTU/scf in all three Pennsylvanian stages, hydrocarbon content drops in a linear fashion (**figs. 25A, 26A, 28A**). Conversely, nitrogen content increases in a linear fashion (**figs. 25C, 26C, 28C**). This is not to say that nitrogen is physically being added to these natural gases, thus decreasing BTU content. The nitrogen component and other component gases in a natural gas can be seemingly increased in a series of analyses if a major component gas is consistently being withdrawn from the natural gas. Methane, which usually composes the majority of a natural gas, is quantitatively the only component gas that can cause such a strong rise in the other component gases, if it is being withdrawn. Helium (**figs. 25D, 26D, 28D**), like nitrogen (**figs. 25C, 26C, 28C**), also shows an increase with lower BTU content, but the linearity of its increase is not as pronounced as nitrogen. In addition to the apparent increase in its percentage possibly caused by methane withdrawal, other processes that either add or decrease helium may be operating. Instead of being distributed in a linear fashion, nitrogen/helium ratios for the three Pennsylvanian stages (**figs. 25B, 26B, 28B**) are more clustered with respect to BTU content. A weak scattering to the upper right of the central cluster indicates possible enrichment of nitrogen, depletion of helium, or both. For reasons that are unclear, this scattering is strongest in gas accumulations in the Missourian (**fig. 25B**).

The percentages of hydrocarbons, nitrogen, helium, and nitrogen/helium ratios in relation to BTU content for the three Pennsylvanian

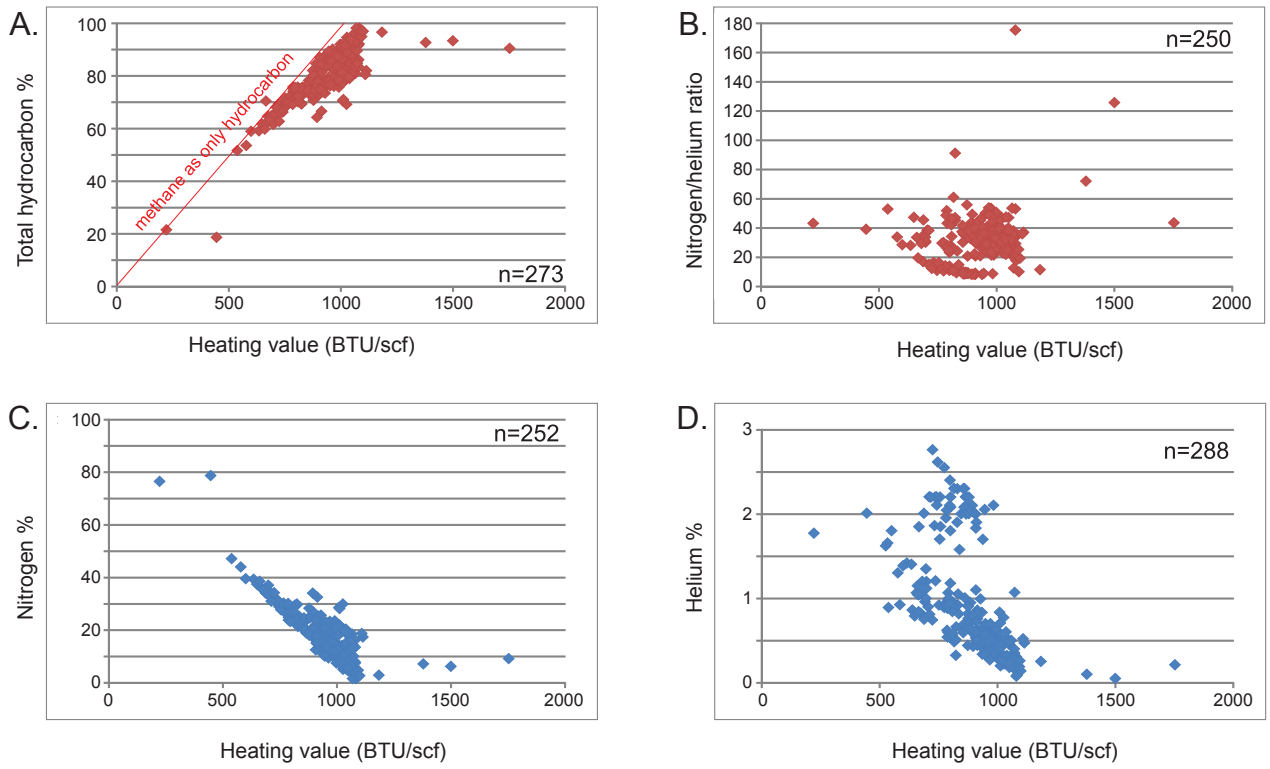

Figure 28. Characterization of gases present in Pennsylvanian (Virgilian) strata by A) total hydrocarbon percentage (this cross-plot is the same as **fig. 8C**), B) nitrogen/helium ratio, C) nitrogen percentage, and D) helium percentage.

stages (**figs. 25, 26, 28**) are comparable, but subtle differences are detectable when cross-plots of Desmoinesian, Missourian, and Virgilian data are plotted on the same graphs (see **figs. 29, 30**). In these two figures, the Missourian analytical data are displayed as black circles overlaying the Desmoinesian data (shown as orange diamonds). Data for the Virgilian stage (shown as blue squares) are superimposed on that of the Missourian stage. A clustering of Desmoinesian data points at 20% hydrocarbon wetness above the clustering of Missourian data points at 10% hydrocarbon wetness (**fig. 29B**) probably reflects incrementally more thermal maturation of the Desmoinesian strata. Similarly, the clustering of Virgilian data points around 8% hydrocarbon wetness, below that of the Missourian cluster, also may be indicative of lesser overall thermal maturation of Virgilian strata as compared to the underlying Missourian strata (**fig. 29B**). The three Pennsylvanian stages have no consistent differences in their hydrocarbon content vs. their heating value (**fig. 29A**).

Nitrogen and helium in the three Pennsylvanian stages (**fig. 30A, B**) generally increase with decreasing BTU content. The increase of nitrogen and helium with lower BTU content is the reverse of the linear pattern of decreasing hydrocarbon content with lower BTU content (see **fig. 29A**). Depletion of methane and other higher-molecular-weight hydrocarbons would account for apparent increase of nitrogen and helium with lower BTU content. Although there is overlap of data for nitrogen/helium ratios, Missourian gas accumulations have slightly lower nitrogen/helium ratios than Desmoinesian strata (**fig. 30C**). Virgilian nitrogen/helium ratios appear similar to that of the Missourian strata (**fig. 30C**). Perhaps the relative abundance of radioactive black shales in the cyclothemic Missourian and Virgilian strata tends to add more helium into gas accumulations than do such strata in the Desmoinesian.

Histograms for helium percentages in Pennsylvanian (Missourian) and Pennsylvanian (Virgilian) gas analyses show a bimodal distribution, with peaks at approximately 0.2% and 2% (**fig. 9C, D**). The Pennsylvanian (Desmoinesian) helium percentage distribution (**fig. 9E**) also shows a similar but weaker bimodality.

Bimodality in the histograms for nitrogen/helium ratios also is expressed in the cross-plots of the natural gas chemistry for the Pennsylvanian stratigraphic intervals as a second cluster of data points for helium concentrated at 800 BTU and 2% helium (**figs. 24D, 25D, 27D, 30B**). This second grouping of data points is evident in the cross-plots for the Missourian and Virgilian stages but not the Desmoinesian stage (**fig. 30B**). These subsidiary clusters of helium data points in Missourian and Virgilian helium-BTU cross-plots also are expressed as subsidiary clusters of data points centered at 800 BTU and 18 nitrogen/helium ratio in the nitrogen/helium ratio-BTU cross-plots (**fig. 30C**). Although there is considerable overlap, the major clusters of data points for the Desmoinesian, Missourian, and Virgilian stages are centered on 35 nitrogen/helium ratio and 1,050 BTU.

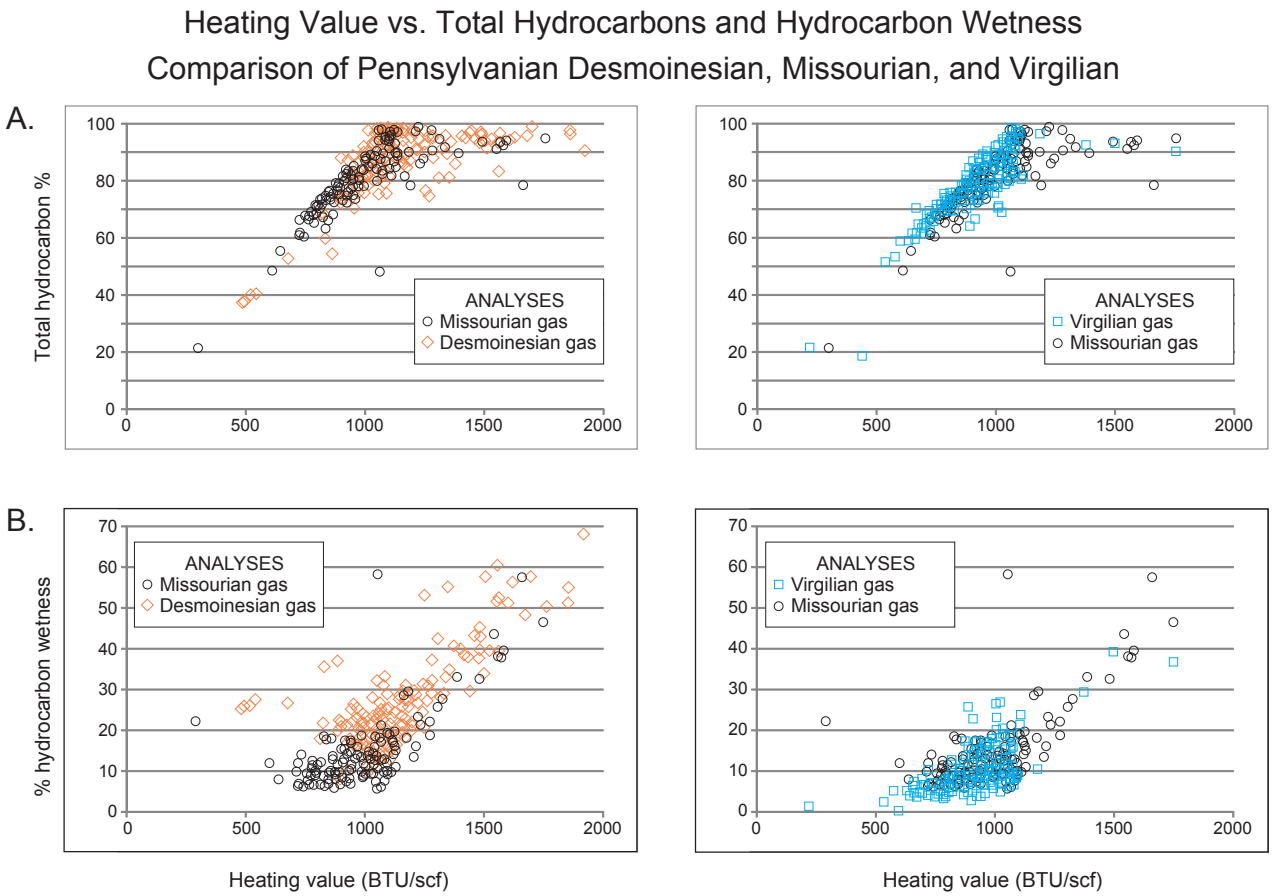

Figure 29. Heating values vs. A) total percentage of hydrocarbons and B) hydrocarbon wetness, for gas analyses from Pennsylvanian Desmoinesian, Missourian, and Virgilian Stages. Desmoinesian analyses are orange diamonds (diagrams at left), Missourian analyses are black circles (all diagrams), and Virgilian analyses are blue squares (diagrams at right). For clarity, some analyses are omitted in areas where data are highly concentrated.

The secondary clusters of data points evident in the helium and nitrogen/helium ratios in **fig. 30B, C** are from the Reichel Field in northeastern Rush County and the Otis-Albert Field in eastern Rush County and western Barton County. Both of these fields are situated on the western flank of the Central Kansas uplift, atop a prominent northwest-southeast trending basement horst (see Miller, 1968; Parham, 1993) called the "Rush Rib" (Merriam, 1963). The Reichel Field is a multi-pay oil and gas field, with producing zones ranging in age from Cambrian granite wash and Lamotte (Reagan) Sandstone to the Permian Chase Group (Kansas Geological Survey, 2025). Lower Paleozoic stratigraphic units are eroded on the crest of the Rush Rib; thus, Pennsylvanian strata lie directly on basement rock. Cambrian Reagan sandstone and Cambrian-Ordovician Arbuckle Group dolomite underlie Pennsylvanian strata toward the flanks of the Rush Rib. The granite wash, Reagan, Arbuckle, and the Pennsylvanian sandstones are all closely associated with the basal Pennsylvanian unconformity. All these units produce oil and gas. Above the basal Pennsylvanian unconformity, the Missourian-age Lansing-Kansas Group and the Virgilian-age Shawnee Group also produce both oil and gas. Only natural gas is produced from the Virgilian-age Wabaunsee Group and the Permian Council Grove and Chase Groups.

The Otis-Albert Field, which is on-trend to the Reichel Field, is also a multi-pay oil and gas field. Its main pay zones are oil and gas produced from Pennsylvanian conglomerates, Cambrian-Ordovician Arbuckle Group, and Cambrian Reagan Formation, all of which are locally associated with the basal Pennsylvanian unconformity (Miller, 1968; Kansas Geological Survey, 2020b). Higher up in the field, oil and gas are produced from the Missourian-age Lansing-Kansas City Group, and only gas is produced from the Virgilian-age Topeka Limestone and the Permian Chase Group.

Isotopic analysis of the hydrocarbon gases produced from both fields indicates that the gases in the zones at the basal Pennsylvanian unconformity, the overlying Pennsylvanian zones, and the Permian are isotopically identical (Jenden and others, 1988). Therefore, hydrocarbon gases at this locality are inferred to leak from reservoirs at the basal Pennsylvanian unconformity into shallower reservoirs, probably along bounding faults of the horst. This leakage appears to be manifest in gas chemistry, for gases present in Missourian strata (**fig. 14C, D**), Virgilian strata (**fig. 15C, D**), and Permian strata (**fig. 16C, D**) on the Rush Rib spatially have markedly

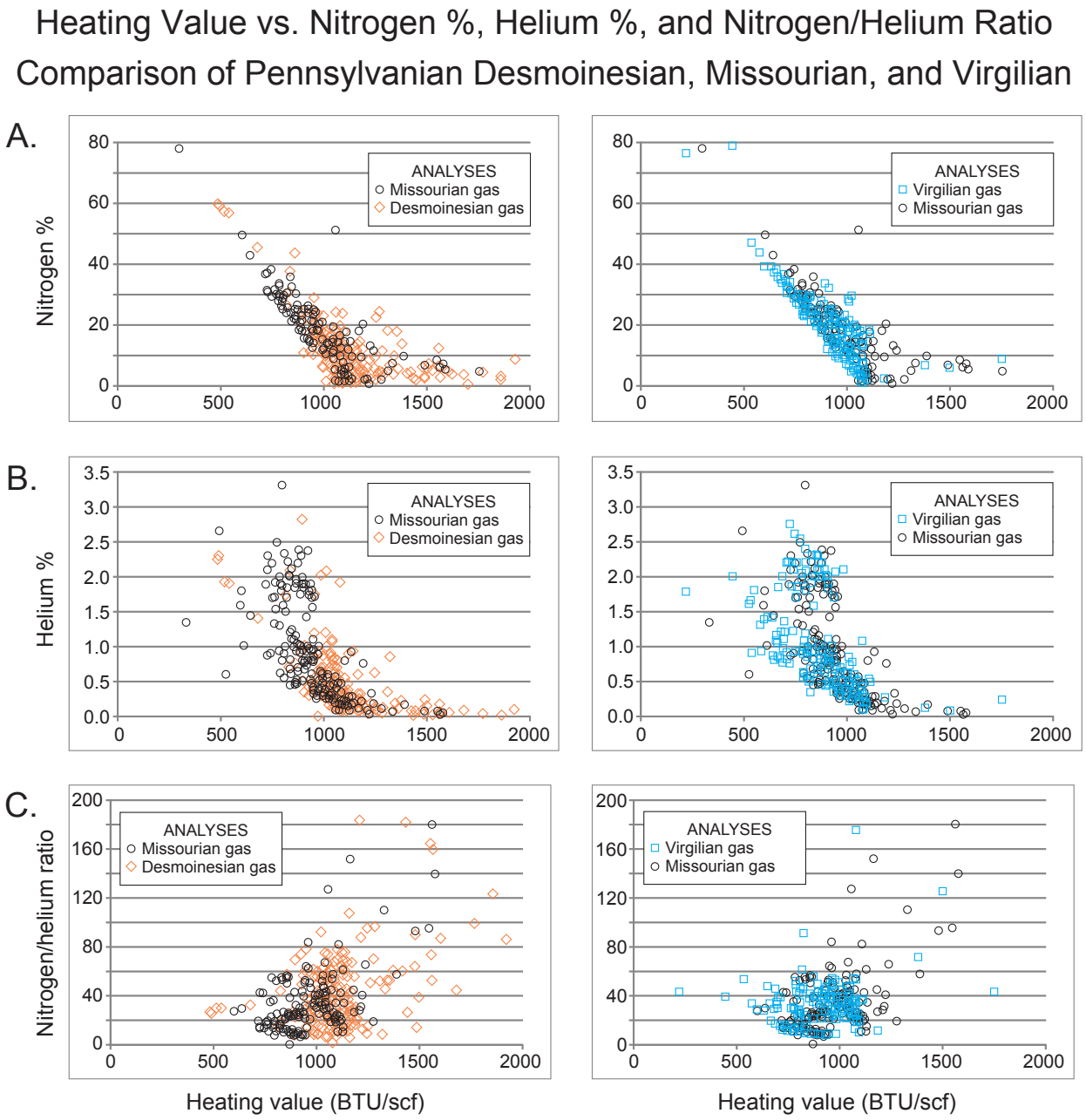

Figure 30. Heating values vs. A) nitrogen percentage, B) helium percentage, and C) nitrogen/helium ratio, for gas analyses from Pennsylvanian Desmoinesian, Missourian, and Virgilian Stages. Desmoinesian analyses are orange diamonds (diagrams at left), Missourian analyses are black circles (all diagrams), and Virgilian analyses are blue squares (diagrams at right). For clarity, some analyses are omitted in areas where data are highly concentrated.

higher helium percentages and lower nitrogen/helium ratios than nearby gases of similar age.

The gas chemistry in the pay zones in the Reichel and Otis-Albert fields all show a wide range in BTU content (**fig. 31A**), methane content (**fig. 31B**), hydrocarbon wetness (**fig. 31C**), nitrogen content (**fig. 32A**), helium content (**fig. 32B**), and nitrogen/helium ratios (**fig. 32C**). The variations in gas chemistry are particularly pronounced (i.e., displaying a wide spread of values) in the Pennsylvanian (Missourian) and Pennsylvanian (Virgilian) gases, whereas gases present in the Permian and associated with the basal Pennsylvanian unconformity and the Permian show less variation. Similar processes of gas alteration appear to be replicated in each reservoir or perhaps in the migration of the gas into shallower strata.

Curiously, four samples from reservoirs associated with the basal Pennsylvanian unconformity are apparently greatly altered compared to other samples (see **figs. 31, 32**). These samples have relatively low BTU content (207–340 BTU/scf; **fig. 31A**), low methane content (12–22%; **fig. 31B**), high nitrogen content (68–77%; **fig. 32A**), and high helium content (5.3–6.5%; **fig. 32C**). Geologically, these four samples were taken from either the northeastern or southwestern edges of the Reichel Field, where the gas column is thin. This may indicate that the altering effects of formation water (or microbes in the formation water?) on the gas column may be very pronounced where the gas column is thin.

Cross-plotting of component gas percentages against methane percentages (**fig. 33**) allows additional insights on gas alteration in the Reichel and Otis-Albert fields. Notwithstanding the four greatly altered basal Pennsylvanian unconformity gas samples, methane content in the Reichel and Otis-Albert gas samples was probably about 78% and then decreased to 58% (**fig. 33A**). Expectedly, methane content varies inversely with nitrogen content, which was probably originally 13% but increases to about 35% in some of the more altered gases (**fig. 33A, B**). With the degree of alteration corresponding to 58% methane, C_2+ hydrocarbons change from 6.7% to about 4.5% (**fig. 33E**), helium changes from 1.7% to about 2.4% (**fig. 33C**), and the nitrogen/helium ratio changes from 7.7 to about 14.6 (**fig. 33D**). The changes in the helium percentage (**fig. 33C**) and the nitrogen/helium ratios (**fig. 33D**) are very approximate; data points in these cross-plots have more scatter than other cross-plots in **fig. 33**. An estimate for the composition of a typical altered gas in the Reichel and Otis-Albert fields is thus 58% methane, 35% nitrogen, 4.5% C_2+ hydrocarbons, 2.4% helium, and 1% "other" gases (i.e., hydrogen, argon, carbon dioxide). This composition is recalculated to 100% in **table 5**.

Most of the samples from the basal Pennsylvanian unconformity cluster more tightly than the other stratigraphic intervals when considering their nitrogen content (**fig. 33B**), helium content (**fig. 33C**), nitrogen/helium ratio (**fig. 33D**), and C_2+ hydrocarbons (**fig. 33E**). This indicates that the gas in the pay zones associated with the basal Pennsylvanian unconformity is the least altered of all the pay zones.

With present compositional data, two general processes can be invoked to account for the alteration of gas in the Reichel and Otis-Albert fields. The first process is "hydrocarbon depletion," in which methane and C_2+ hydrocarbons are removed from the original natural gas. As these hydrocarbons are removed from the reservoir, the relative proportions of nitrogen and helium increase in the reservoir even though they are not actually being added to the reservoir. The second process is "nitrogen and helium addition," where these two gases are essentially added to the reservoir. Concomitantly, as nitrogen and helium are added, methane and other hydrocarbon gases decrease in percentage, even though they are not actually being removed from the reservoir. The main instrument of change in both cases is probably formation water. In the case of "hydrocarbon depletion," the formation water is under-saturated with respect to the hydrocarbon gases, and these hydrocarbon gases are removed from the reservoir by dissolution into formation water. In the case of "nitrogen and helium addition," the formation water is oversaturated with respect to nitrogen and helium. These gases thus exsolve out of the formation water and enter the reservoir in the gas phase. Another means by which "nitrogen and helium addition" can occur is simple mixing of two types of gases.

A mass-balance exercise, summarized in **table 5**, illustrates the amount of gas that has to be removed or added with each process. A pristine or unaltered gas has to be estimated, and inspection of **figs. 31–33** can yield a most likely unaltered natural gas in the Reichel and Otis-Albert fields. This gas is likely 78% methane (i.e., the maximum amount of methane present in any of the four main gas reservoirs and, in particular, the deepest gas reservoir (i.e., the basal Pennsylvanian unconformity). Other gas percentages (nitrogen, helium, C_2+ hydrocarbons) are those percentages associated with 78% methane. In total, this unaltered gas is considered to be composed of 78% methane, 13% nitrogen, 6.7% C_2+ hydrocarbons, and 1.7% helium. Other gases, including carbon dioxide, hydrogen, and argon, compose only a minuscule portion (about 0.5%) of the unaltered gas. This estimation of the original percentages of component gases in the unaltered natural gas in the reservoir appears to be reasonably accurate because the sum total of the component gases is 99.9%. In **table 5**, a slight recalculation adjusts the percentages of the component gases to 100%.

The calculation of how much of a component gas needs to be added or subtracted from the unaltered gas to make an altered gas is relatively simple in that composition of natural gases are given in volume percent, at standard temperature (essentially room temperature) and at one atmosphere pressure. At these conditions, most gases behave as ideal gases. Therefore, a mole of any of these component gases occupies the same volume. The mathematics of adding or subtracting a component gas is thus a simple exercise of adding or subtracting an arbitrary percentage (which is a molar percentage) of a component gas and then recalculating the resultant percentages of all the component gases to 100%. In **table 5**, the calculations of the amount of gas needed to be added or subtracted to the original unaltered gas compositions are given in units of "molar volumes" so that there will be less confusion with the percentages used to describe recalculated gas compositions.

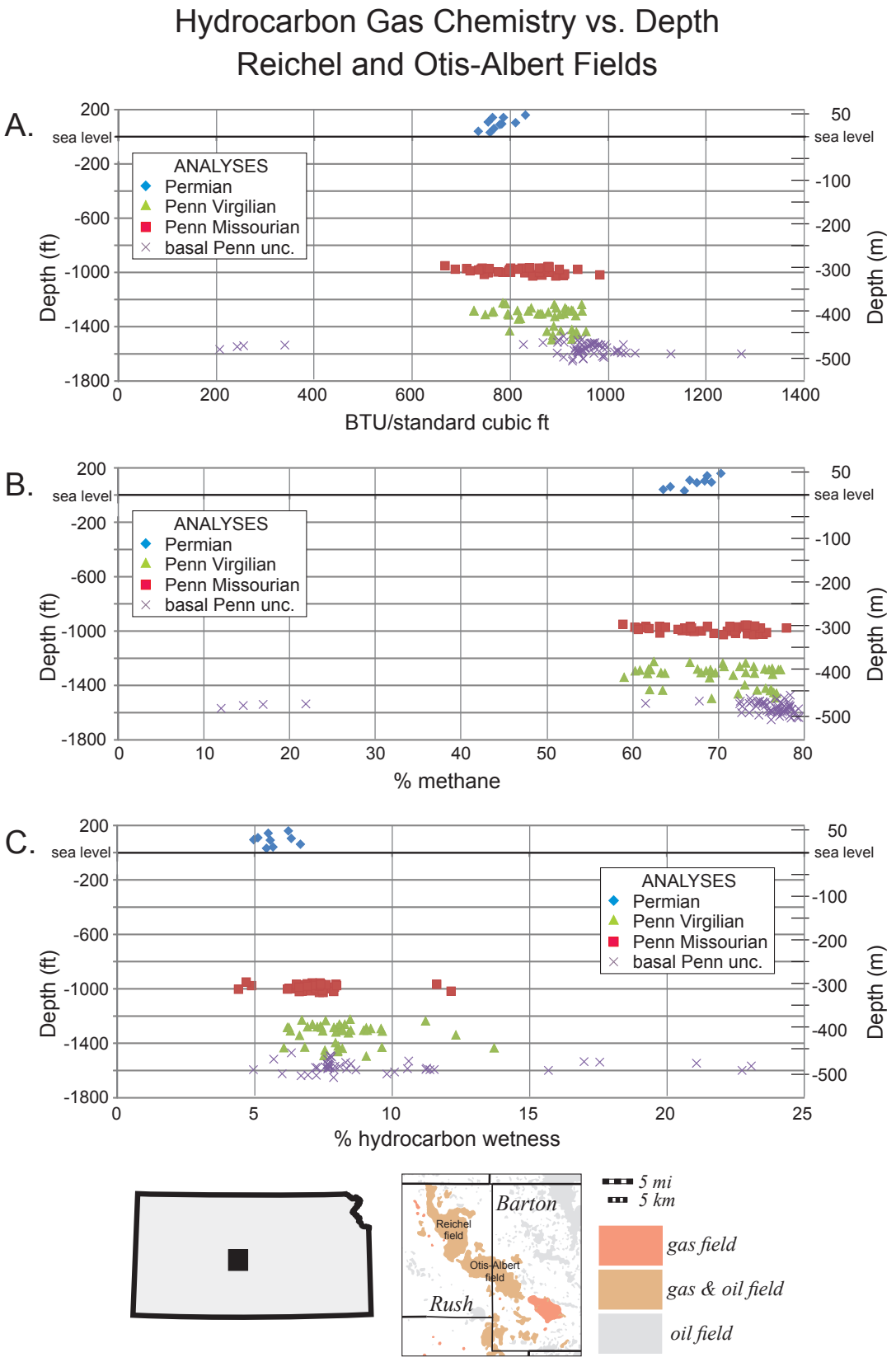

Figure 31. Characteristics of hydrocarbon gases vs. depth in the Reichel and Otis-Albert fields, on the Rush Rib, Central Kansas uplift. A) Heating value (BTU/scf), B) methane percentage, and C) hydrocarbon wetness all show a wide range of values for each stratigraphic interval. Unc = unconformity.

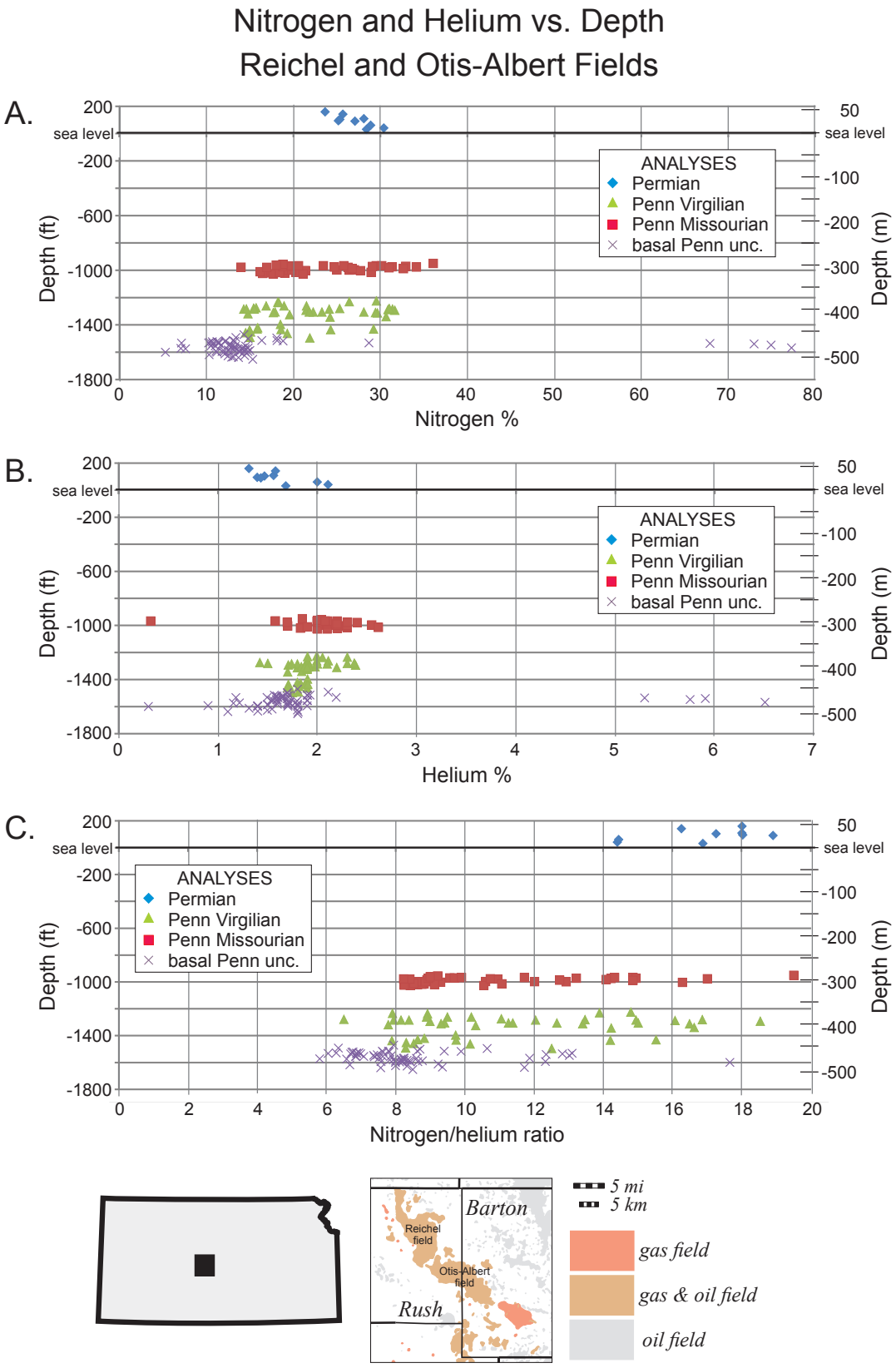

Figure 32. Characteristics of non-hydrocarbon gases vs. depth in the Reichel and Otis-Albert fields, on the Rush Rib, Central Kansas uplift. Like the hydrocarbon gases, A) nitrogen percentage, B) helium percentage, and C) nitrogen/helium ratios all show a wide range of values for each stratigraphic interval. Unc = unconformity.

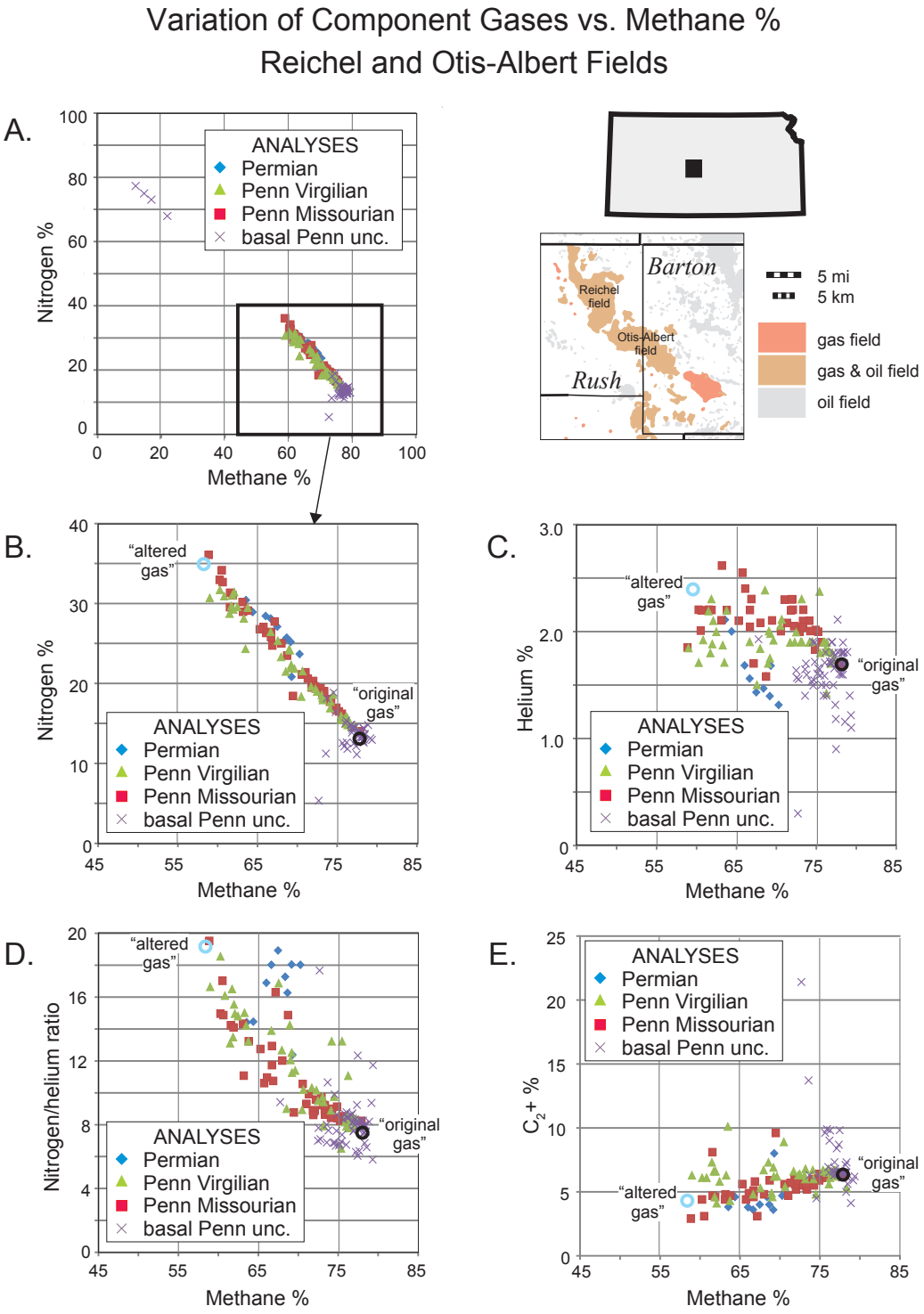

Figure 33. Compositional characteristics of the gases from the Reichel and Otis-Albert fields cross-plotted with methane percentage. A) and B) depict variation of nitrogen percentage with methane percentage at two different scales. With respect to methane percentage, C) depicts the variation of helium content, D) depicts the variation of the nitrogen/helium ratios, and E) depicts the variation of the heavier-molecular-weight hydrocarbons (i.e., C_2+). A black circle indicates the composition of the original gas, and a blue circle indicates an approximate composition of an end-member altered gas. Two processes can account for the alteration of gas chemistry in the Reichel and Otis-Albert fields. One process involves withdrawal of methane and other gases out of the gas reservoirs, possibly due to chemical dissolution and removal by unsaturated formation water. A second process involves the addition of nitrogen and other gases into the reservoirs, possibly due to chemical exsolution of nitrogen and other gases into the reservoirs by saturated formation water. The results of both processes are shown in **table 5**.

Table 5. Composition of the "original" and "altered" gas in the Reichel and Otis-Albert fields and the changes in composition necessary to alter the "original" gas to the "altered gas." Two alteration processes produce nearly similar results. "Hydrocarbon depletion" necessitates removal of methane, C_2+ gases, and a small amount of helium from the "original" gas, whereas "nitrogen and helium addition" adds these two gases.

Compositions of Original and Altered Gas (from Composition Cross-plots)						
	[a]CH_4	[b]C_2+	[c]N_2	[d]He	[e]other	
original gas (%)	78.0	6.7	13.0	1.7	0.5	**<< sum = 99.9**
altered gas (%)	58.0	4.5	35.0	2.4	1.0	**<< sum = 100.9**
Compositions of Original and Altered Gas (Calculated to 100%)						
	[a]CH_4	[b]C_2+	[c]N_2	[d]He	[e]other	N_2/He ratio
original gas (%)	78.1	6.7	13.0	1.7	0.5	7.65
altered gas (%)	57.5	4.5	34.7	2.4	1.0	14.58
Compositional Changes to Original Gas Needed to Produce Altered Gas (Assuming 100 Molar Volumes of Original Gas)						
	[a]CH_4	[b]C_2+	[c]N_2	[d]He	[e]other	N_2/He ratio
By "Hydrocarbon Depletion"						
Molar volumes	21.9	1.7	13.0	0.9	0.5	14.46
Calculation to 100%	57.5	4.5	34.2	2.4	1.3[f]	14.46
# of molar volumes lost	-56.2	-5.0	0.0	-0.8	0.0	**<< sum = -62.0**
By "Nitrogen and Helium Addition"						
Molar volumes	78.1	6.7	47.1	3.3	0.5	14.27
Calculation to 100%	57.6	4.9	34.7	2.4	0.4[f]	14.27
# of molar vols. added	0.0	0.0	34.1	1.6	0.0	**<< sum = 35.1**

[a]Methane

[b]Ethane, propane, butane, pentane, hexane, hexane+

[c]Nitrogen

[d]Helium

[e]Minor components of natural gas – argon, carbon dioxide, hydrogen. Because of their small percentages, these component gases are not considered in calculations

[f]Compare percentages of component gases to altered gas (calculated to 100%)

If "hydrocarbon depletion" is the primary process responsible for changing the composition of the original gas in the reservoir, then the first step is to mathematically remove the methane content so that the percentage of methane decreases from its original 78.0% to 57.5%. (These are the slightly adjusted percentages that result when the quantity of the component gases, as determined from **fig. 33**, is corrected to 100%). When this is done, the gases not being added (i.e., nitrogen, helium, and C_2+ hydrocarbons) calculate to higher percentages. Due to recalculation of compositions to 100%, about 72% of the original methane volume has to be removed so that the composition (recalculated to 100%) equals 57.5%. A check in the viability of the process is to see how close other resultant percentages of component gases are to the cross-plot values in **fig. 33**. For example, with removing methane, the C_2+ percentage increased to 15%, which is the opposite of the apparent decrease in C_2+ hydrocarbon illustrated in **fig. 33**. To compensate for this, some C_2+ hydrocarbons have to be removed in addition to the methane removed. A removal of 5.0 molar volumes of C_2+ achieves the drop in C_2+ illustrated in **fig. 33E**. This amount of C_2+ gases removed constitutes 75% of the volume of the original C_2+ gases in the unaltered gas, which is comparable to the 72% of the original methane that was removed (see **table 5**).

Another adjustment has to be made in the helium in the original gas. If no helium is removed from the original gas, the resultant helium percentage in the altered gas calculates to be in excess of 4%, which is too high for the about 1% increase noted in **fig. 33C**. A decrease to 47% of the original helium volume (see **table 5**) fits the slight increase in helium in **fig. 33C**. This loss of helium also fits the apparent increase in nitrogen/helium ratio as the gas is altered (see **fig. 33D**).

With addition of nitrogen and helium, an extra 34 molar volumes of nitrogen (267% of the original nitrogen volume) and 2.4 molar volumes of helium (another 94% of the original helium volume) have to be added to the original gas to achieve the composition of the average altered gas in the Reichel and Otis-Albert fields (see **table 5**). The results of the "nitrogen and helium addition" closely matches the percentages of methane and C_2+ gases in the altered gas (see **table 5**); thus, two different processes of gas alteration can achieve virtually the same result. "Nitrogen and helium addition" requires approximately half the volume of gases to be moved than with the "hydrocarbon depletion" process (i.e., 36 moles added to the original gas vs. 62 moles removed; see **table 5**). This does not necessarily refute the hydrocarbon depletion process though. In some circumstances, the "hydrocarbon depletion model" is the more efficient model. For example, calculations (not shown) to make the four previously discussed greatly altered gas samples associated with the basal Pennsylvanian unconformity require the addition of about 350 molar volumes of nitrogen and helium to the original gas. The "hydrocarbon depletion" calculation requires only 80 molar volumes of methane, C_2+ hydrocarbons, and helium to be removed.

With present data, it is still difficult to choose which model for gas alteration is more viable for explaining the compositional changes in the gases at the Reichel and Otis-Albert fields. More information, such as detailed field maps, knowledge of original reservoir pressures and their pressure drops with production, or further analyses of trace gases and isotopic analyses of helium and nitrogen in each reservoir may help in ascertaining an answer. Both fields are depleting, though, so the wells available for sampling are dwindling.

Gases in Permian strata

Permian gas compositional characteristics presented in **fig. 9** are for the many Permian fields east of the Hugoton embayment. However, the Permian gas fields in the Hugoton embayment are the "elephants in the room," as they have sourced the majority of annual and historical natural gas production in Kansas. A comparison of hydrocarbon wetness, BTU content, helium percentage, and nitrogen/helium ratios for all the Permian reservoirs in Kansas (**fig. 34**) shows that there are similarities in BTU content and hydrocarbon wetness for gases produced from the Chase Group (Hugoton, Bradshaw, and Byerly fields) and the Council Grove Group in the Panoma Gas Field, which underlies the Hugoton Gas Field. A common origin and migration history for these gases is thus indicated. The histogram data (**fig. 34**) that characterize the smaller Permian fields east of the Hugoton embayment are quite spread out compared to that of the Chase Group and Council Grove Group in the Hugoton embayment. More varied origins and migration histories for these smaller fields are inferred. The leakage from deeper pay zones at the Reichel and Otis-Albert fields accounts for some of the higher hydrocarbon contents (**fig. 34A**) and richer helium percentages (**fig. 34B**) for the Permian fields east of the Hugoton embayment. The large percentages of dry-gas analyses (i.e., those poor in higher-molecular-weight hydrocarbons) in the smaller fields east of the Hugoton embayment indicate that some of these Permian fields may be partly biogenic in origin.

The modal peaks of the Hugoton embayment gases are identical, but the range in composition of the BTUs in the Chase Group gases in the Hugoton Gas Field varies more than the range in composition of the Panoma Gas Field (**fig. 34A**). This may mean gases in the Council Grove Group are not as altered as the gas in the overlying Chase Group.

Most of the low-BTU gases in the Hugoton Gas Field are along the perimeter of the field. This low-BTU perimeter is particularly wide in the northeastern corner of the field (**fig. 16A**). The northeastern corner of the field (i.e., the area north of 37.3° latitude and east of 101.40° longitude) has heating values as low as 528 BTU/scf, whereas the center of the field has heating values ranging from 950 to 1,044 BTU/scf. Eighty-two chemical analyses are available in the northeastern corner of the field. Comparing the BTU content of these gases vs. their depth and location in this region (**fig. 35**) indicates that low-BTU gases in the Hugoton Gas Field are primarily situated at or near the gas-water interface (about 190 ft [58 m] elevation). This zone of low-BTU gas at the edge of the field also apparently extends up section in the Chase Group to higher (updip) elevations along the northern and eastern margin of the field (**fig. 35**). The gas columns in the separate pay zones in the Chase Group all thin to zero thickness at the perimeter of the field.

Percentages of hydrocarbon gases (i.e., methane, ethane, propane, butane, pentane, hexane+) all decrease with decreasing BTU content toward the northeastern perimeter of the Hugoton Gas Field (**fig. 36**). This decrease could be caused by withdrawal of the hydrocarbon gases by their dissolution in formation water, by addition of a nonhydrocarbon gas such as nitrogen by its exsolution from formation water, or both. Mixing of the original Hugoton gas with a low-BTU, high-nitrogen gas is also a possibility.

The composition of the original (or at least relatively unaltered) natural gas in the Hugoton Gas Field is inferred from the component gas percentages that are associated with the gas with the highest heating value. This highest heating value is determined from a concentration of data points at the right end of the BTU analyses cross-plots (see **fig. 36**). Original percentages are projected to be 74.0% methane, 6.5% ethane, 3.5% propane, 1.5% butane, 0.4% pentane, and 0.3% hexane+. Hydrocarbon wetness thus calculates to 14.2% (i.e., 12.2/(12.2+74), where 12.2% is the sum of all hydrocarbons heavier than methane). The *n*-butane/*i*-butane ratio is estimated to be 3:1; therefore, *n*-butane is inferred to be 1.1% and *i*-butane to be 0.4%. Nitrogen and helium are 14% and 0.4%, respectively (see **fig. 37**). This calculates to an original nitrogen/helium ratio of 35.0. As with the gases trapped along the

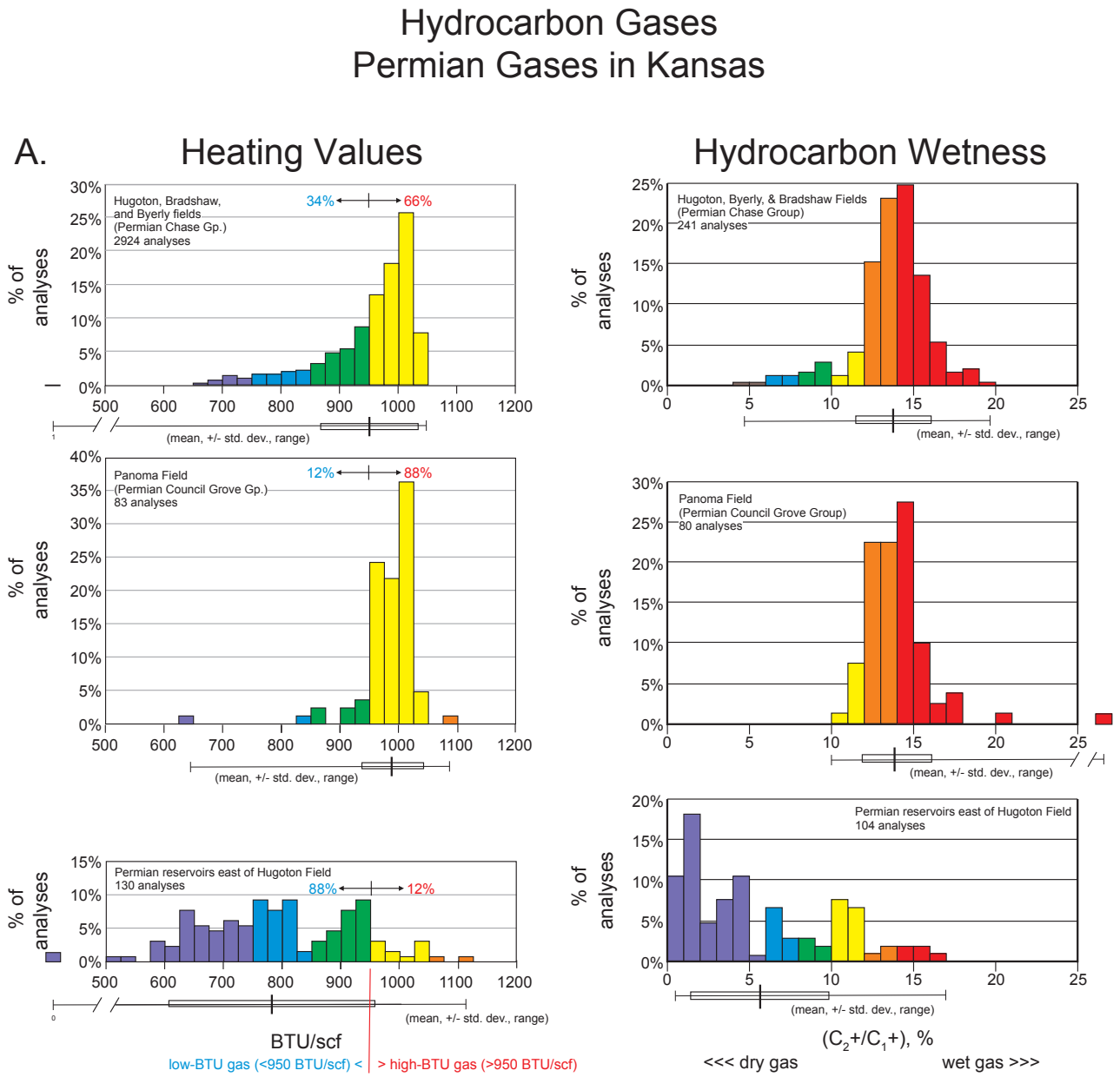

Figure 34. Histograms depicting the compositional characteristics of Permian gases in Kansas: A) heating value and hydrocarbon wetness. Natural gases produced from the Chase Group in the Hugoton embayment from the Hugoton, Bradshaw, and Byerly fields display a relatively narrow range of compositions as compared to the smaller Permian fields east of the Hugoton embayment. This indicates the more varied origin of these smaller Permian gas accumulations. Council Grove production from the Panoma Gas Field (underlying the Hugoton Gas Field) is similar to the Chase Group in the Hugoton, Bradshaw, and Byerly fields. The color scheme and format of this figure follow that of **fig. 9**.

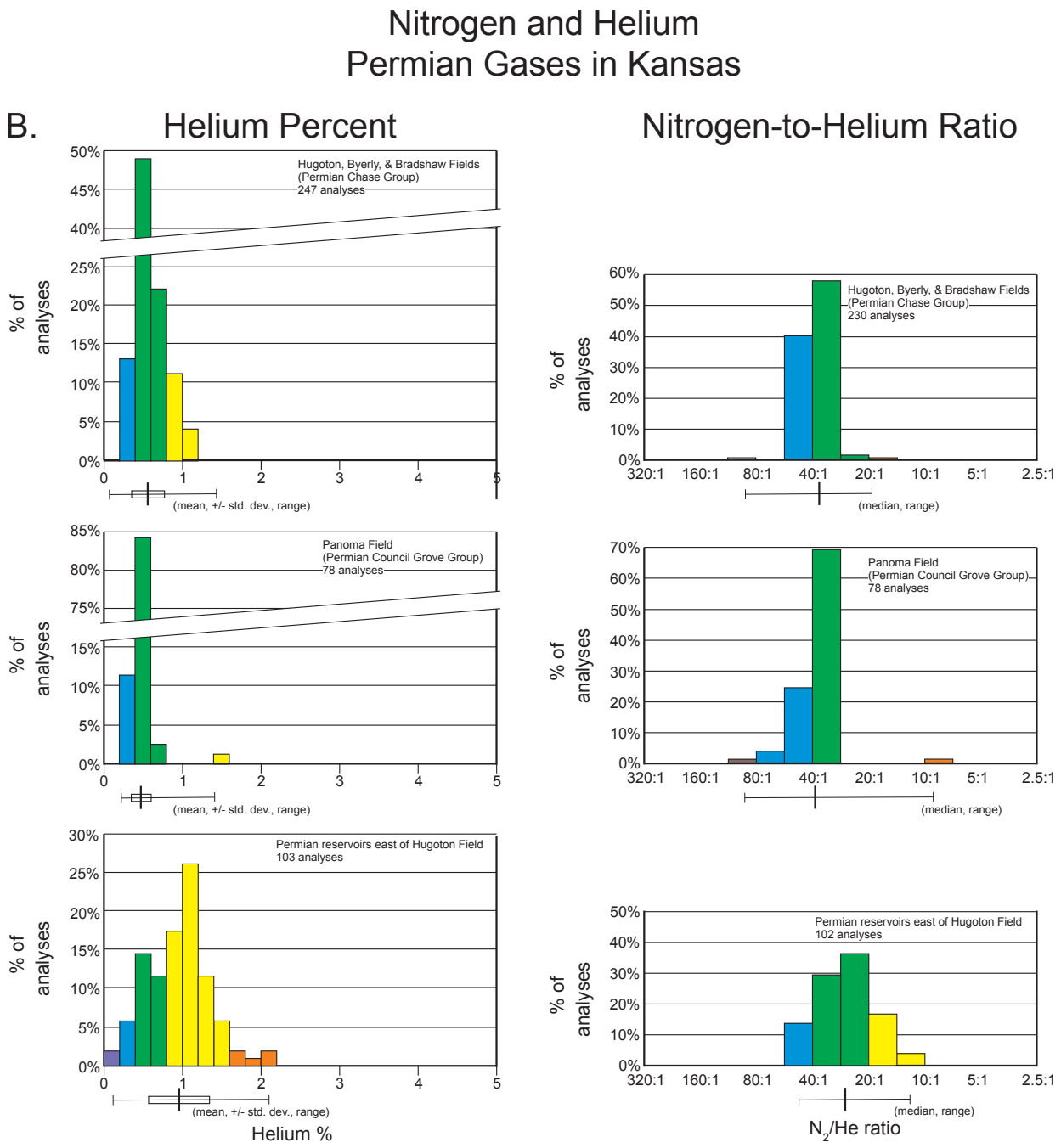

Figure 34 (continued). Histograms depicting the compositional characteristics of Permian gases in Kansas: B) helium percentage and nitrogen-to-helium ratio. Natural gases produced from the Chase Group in the Hugoton embayment from the Hugoton, Bradshaw, and Byerly fields display a relatively narrow range of compositions as compared to the smaller Permian fields east of the Hugoton embayment. This indicates the more varied origin of these smaller Permian gas accumulations. Council Grove production from the Panoma Gas Field (underlying the Hugoton Gas Field) is similar to the Chase Group in the Hugoton, Bradshaw, and Byerly fields. The color scheme and format of this figure follow that of **fig. 9**.

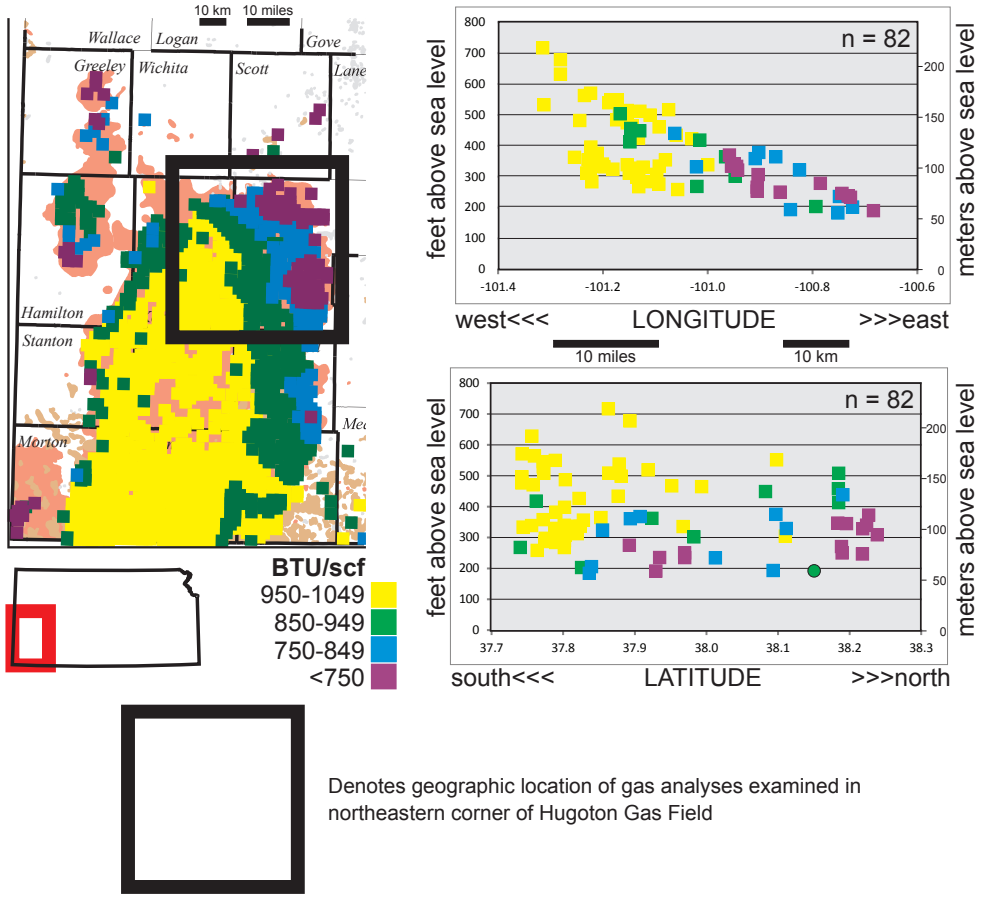

Figure 35. Location of 82 gas analyses of Permian Chase Group gases in the northeastern corner of the Hugoton Gas Field. Depth and BTU contents are displayed in east-west and north-south projections. The northeastern corner of the field is defined as the area north of 37.3° latitude and east of 101.40° longitude. Color of the symbol identifies the BTU content of the analysis. All samples are from the Hugoton Gas Field. Location map is a portion of **fig. 16A**.

basal Pennsylvanian unconformity at the Reichel and Otis-Albert fields, hydrogen, carbon dioxide, and argon are not considered because their percentages are exceedingly low; the estimated sum of their compositions is about 0.2%. The hydrocarbon wetness in the various gas fields on the Pratt anticline (about 7%; see **fig. 21E**) is approximately half that of the Hugoton Gas Field (14.2%, see above), despite the fact that the fields on the Pratt anticline are closely associated with oil accumulations.

The Chase Group (the principal gas-bearing formation in the Hugoton Gas Field) and underlying Council Grove Group (the principal gas-bearing formation in the Panoma Gas Field) have a common gas-water contact (Dubois and others, 2006, 2007), so the basal pay zone of the Panoma Gas Field should contain low-BTU gas if it contacts the gas-water interface and not some impermeable shale. However, it is unclear if this zone of lower-BTU gas would even be significant for production because the volumetric contribution of this hypothetical low-BTU zone may be minimal compared to the total gas contributed by the entire footage of the gas column in a given well. Unfortunately, no compositional data are publicly available for individual gas-producing zones in the Hugoton Gas Field or the Panoma Gas Field.

For purpose of comparison to the behavior of the component gases in the northeastern part of the Hugoton Gas Field, this study examined a group of 68 Chase Group gas analyses from the northwestern part of the Hugoton Gas Field and nearby Bradshaw and Byerly fields (**fig. 38**). These samples are essentially from the updip side of the Hugoton Gas Field, whereas the samples from the northeastern corner of the field are from the downdip side of the field. Spatially, there is a comparable degradation in heating values in the updip (northwestern) part of the Hugoton Gas Field as there is in the downdip (northeastern) portion of the field, if the Bradshaw and Byerly fields are considered with the Hugoton Gas Field. The perimeter of alteration in the Hugoton Gas Field narrows to the south (see **figs. 16A, 35, 38**), and there is not a sufficient number of spatially close gas analyses to ascertain the degree of alteration there.

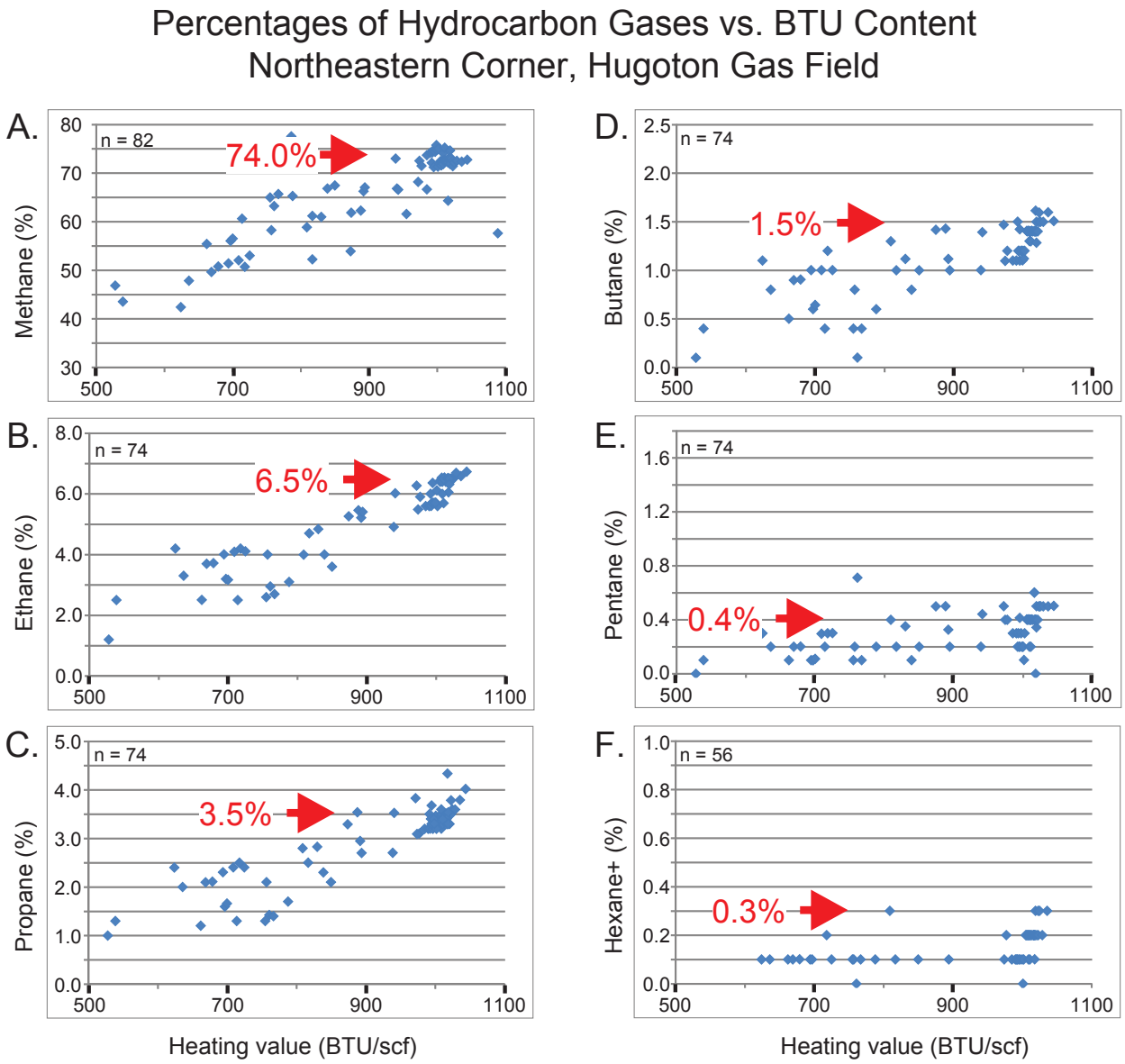

Figure 36. Variation in percentages of the hydrocarbon gases in the northeastern corner of the Hugoton Gas Field as a function of changes in heating value of a natural gas. A) methane percentage, B) ethane percentage, C) propane percentage, D) butane percentage, E) pentane percentage, and F) hexane+ percentage. Red arrows indicate the percentages of component gases that compose the original (or least altered) natural gas in the Hugoton Gas Field.

The alteration of the gas in the Chase Group in the updip portion of the Hugoton Gas Field (**figs. 39, 40**) appears to be comparable to that in the downdip portion of the field (**figs. 36, 37**) but with slight differences. For example, alteration of the original gas in the Chase Group appears to be slightly stronger in the northwestern part of the field than in the northeastern part, as evidenced by a few analyses that contain lesser amounts of methane than in the northeastern part of the field. Furthermore, there is less scatter in the decrease in methane content (**fig. 39A**) and ethane content (**fig. 39B**) with decreasing BTU content for the northwestern corner of the field than in the northeastern corner (cf., **fig. 36A, B**). Consistent drops in the percentages of propane, butane, pentane, and hexane+ with decreasing BTU content in the northeastern part of the field are not as strong and consistent as they are in the northwestern part of the field (cf., **figs. 39C–F, 36C–F**). Conversely, the decrease in hydrocarbon wetness with decreasing BTU content in the northeastern part of the field (**fig. 37B**) compares with an increase in hydrocarbon wetness with decreasing BTU content in the northwestern part of the field (**fig. 40B**). For unknown reasons, heavier-molecular-weight hydrocarbons, particularly butane, pentane, and hexane+ (see **fig. 39D, E**), are better retained in natural gases in the northwestern part of the field.

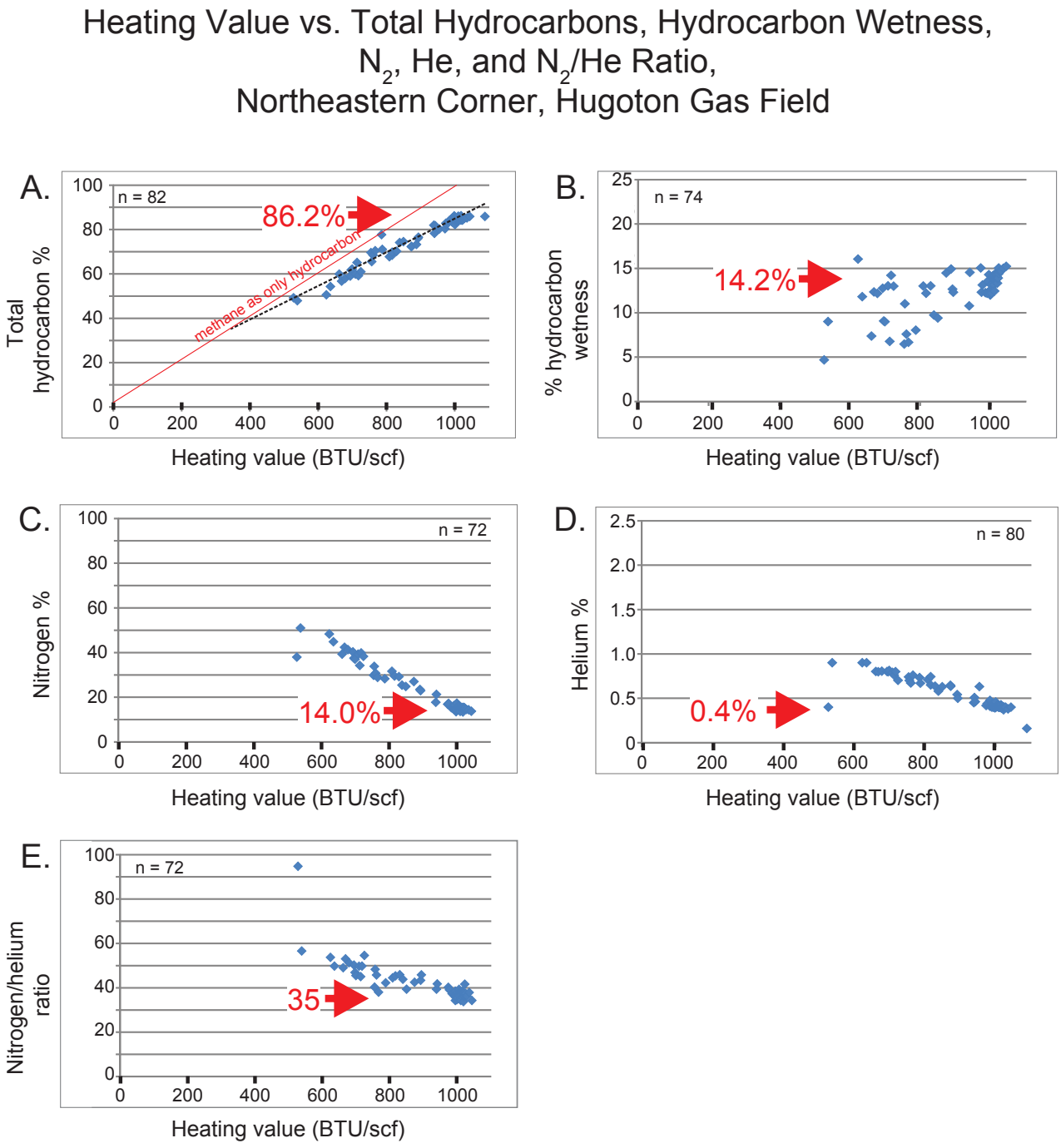

Figure 37. Variation in gas chemistry in the northeastern corner of the Hugoton Gas Field as a function of changes in heating value. A) Total hydrocarbon percentage (this cross-plot is a subset of **fig. 8B**), B) hydrocarbon wetness percentage, C) nitrogen percentage, D) helium percentage, and E) nitrogen/helium ratio. Red arrows indicate the percentages of component gases that compose the original (or least altered) natural gas in the Hugoton Gas Field.

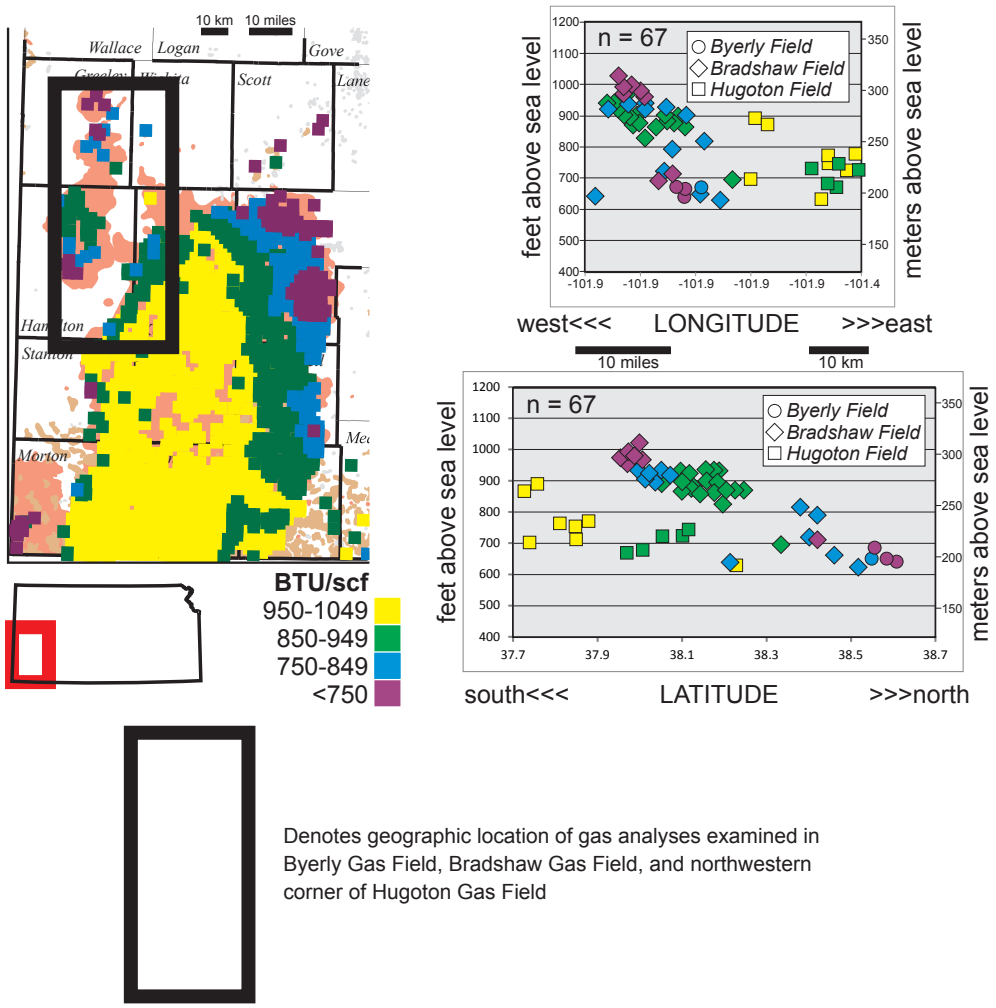

Figure 38. Location of 67 gas analyses of Chase Group gases in the northwestern corner of the Hugoton Gas Field and nearby Bradshaw and Byerly fields. Depth and BTU contents are displayed in east-west and north-south projections. The northwestern corner of the field is defined as the area north of 37.3° latitude and west of 101.40° longitude. Color of the symbol identifies the BTU content of the analysis. The shape of the symbol identifies the gas field from which a sample was taken. Location map is a portion of **fig. 16A**.

A mass-balance exercise similar to the one performed for the gas compositions in the various pay zones for the Reichel and Otis-Albert fields (see **fig. 33** and associated discussion in text) can be performed to determine whether the composition of the altered gas is caused by removal of hydrocarbons or a mixing with a nitrogen-helium gas introduced to the reservoir. Composition of the "original" natural gas in the Hugoton Gas Field has been reasonably established (see above), but the composition of an altered gas for both the northeastern and northwestern parts of the field needs to be determined. Compositional cross-plots (**figs. 36, 37, 39, 40**) help determine what likely typifies the composition of an altered gas.

Cross-plotting of methane content vs. nitrogen, helium, and C_2+ content for both the northeastern and northwestern parts of the field illustrate the slight differences in their alteration patterns (**fig. 41**). Close examination of the nitrogen-methane cross-plot (**fig. 41A, B**) shows that whatever process increases the nitrogen content (or decreases the methane content) of the original Hugoton gas is slightly more active in the northeastern part of the field because the array of data points for the northeastern part of the field plots slightly above that for the northwestern part. Nevertheless, the apparent process of methane depletion (or nitrogen enrichment) in the northwest has played out farther than the northeast; a couple of data points in the northwest have reached almost 35% methane, whereas data points from the northeast extend only to about 45% methane (**fig. 41B**). Helium enrichment appears to be virtually identical for both the northeast and northwest (**fig. 41C**), but again, the process accounting for the helium enrichment is more extensive in the northwest. The nitrogen/helium ratio and the apparent depletion in C_2+ hydrocarbons for both parts of

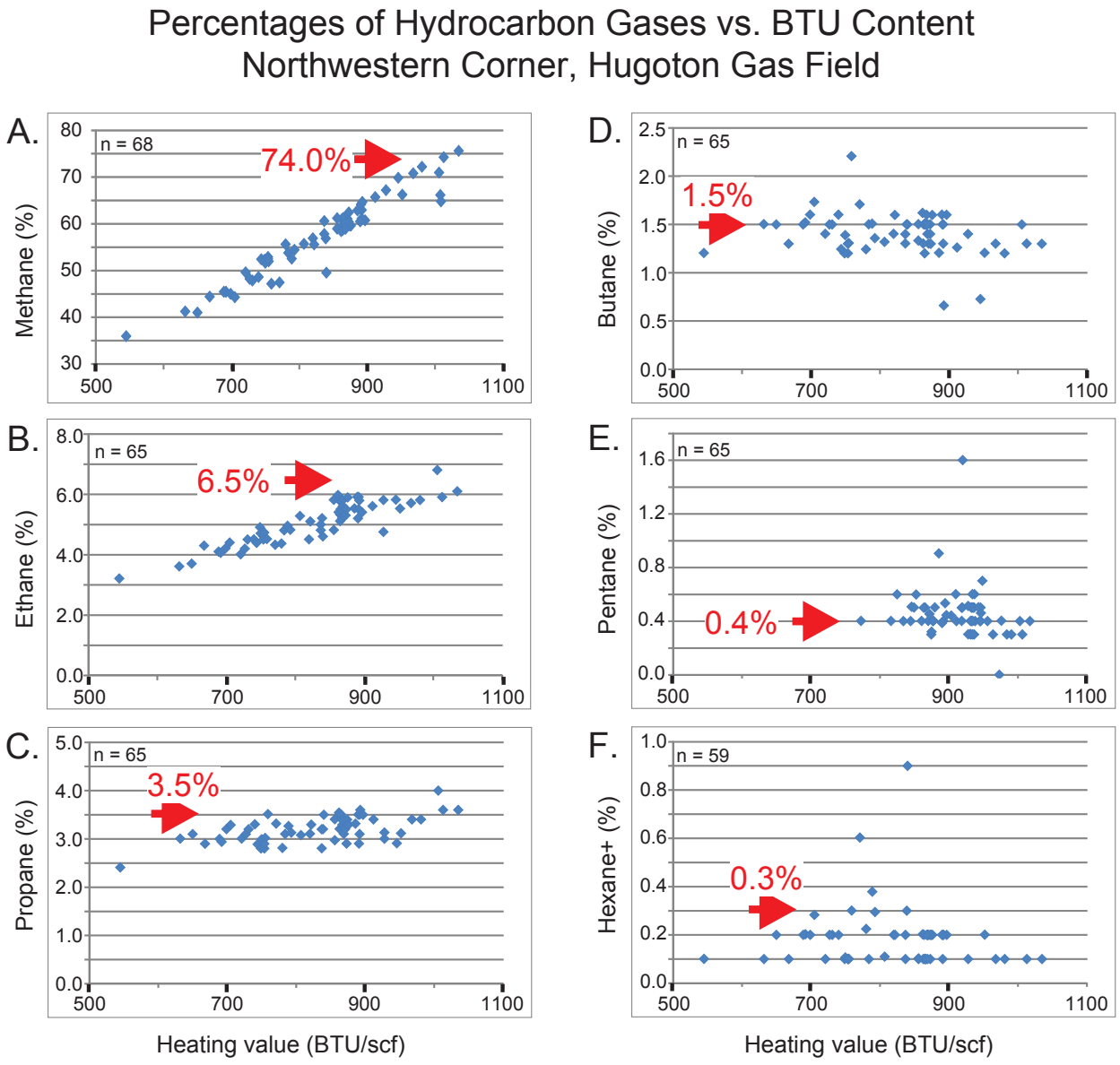

Figure 39. Variation in percentages of the hydrocarbon gases in the northwestern corner of the Hugoton Gas Field and nearby Bradshaw and Byerly fields as a function of changes in heating value of a natural gas. A) Methane percentage, B) ethane percentage, C) propane percentage, D) butane percentage, E) pentane percentage, and F) hexane+ percentage. Red arrows (taken from **fig. 36**) indicate the percentages of component gases that compose the original (or least altered) natural gas in the Hugoton Gas Field. All graphs are at a common scale with the graphs that pertain to the northeastern corner of the field (**fig. 36**).

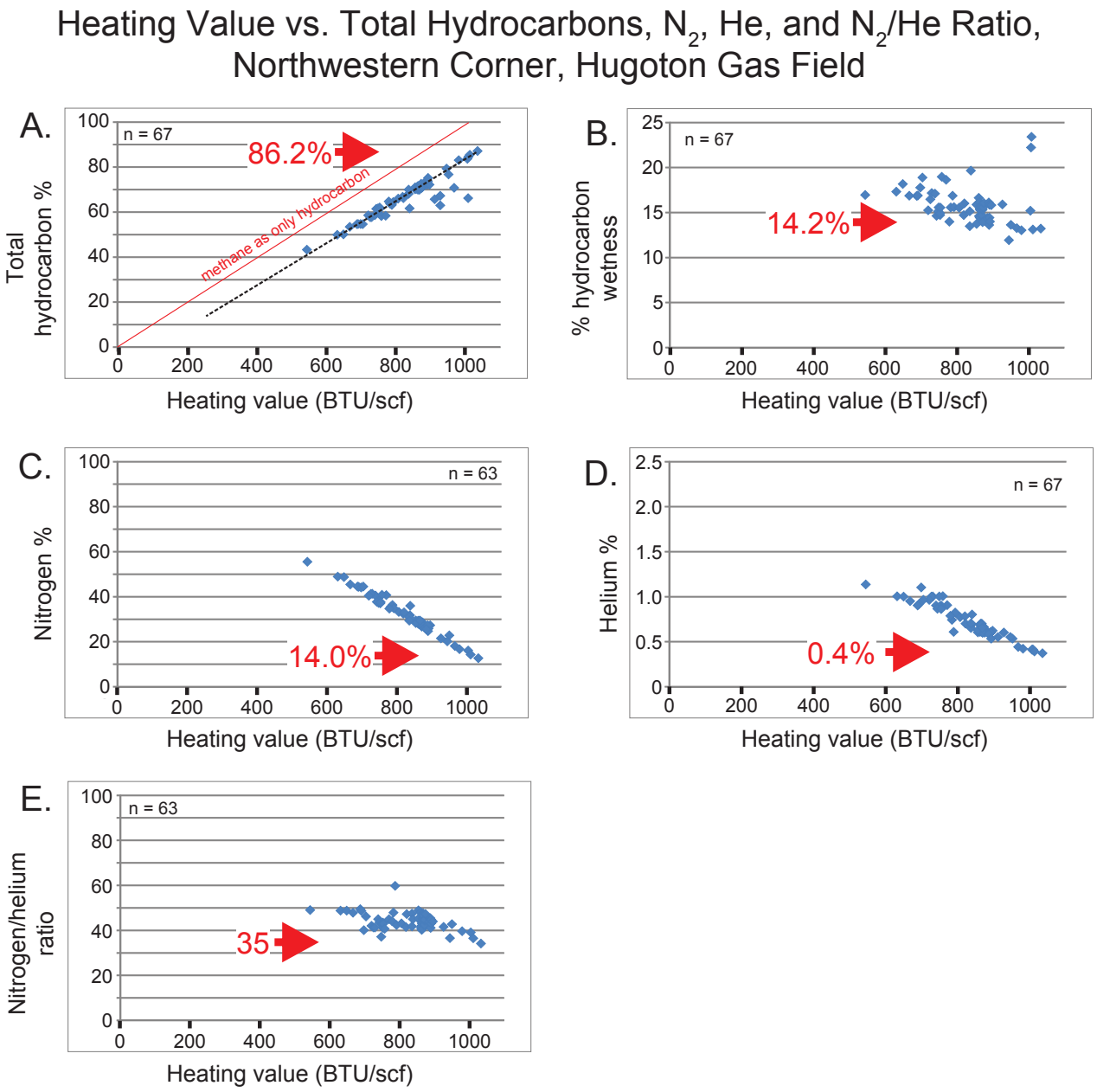

Figure 40. Variation in gas chemistry in the northwestern corner of the Hugoton Gas Field and nearby Bradshaw and Byerly fields as a function of changes in heating value. A) Total hydrocarbon percentage (this cross-plot is a subset of **fig. 8B**), B) hydrocarbon wetness percentage, C) nitrogen percentage, D) helium percentage, E) nitrogen/helium ratio. Red arrows (taken from **fig. 37**) indicate the percentages of component gases that compose the original (or least altered) natural gas in the Hugoton Gas Field. All graphs are at a common scale with the graphs that pertain to the northeastern corner of the field (**fig. 37**).

the Hugoton Gas Field exhibit considerable scatter (**fig. 41D, E**). Compositions of an end-member "altered gas" for the northeastern and northwestern parts of the field are thus slightly different. For the northwest, this "altered gas" is composed of 35% methane, 55% nitrogen, 9% C_2+ hydrocarbons, and 1.2% helium. For the northeast, it is composed of 45% methane, 50% nitrogen, 3% C_2+ hydrocarbons, and 0.9% helium (**fig. 41).** These respective percentages are slightly adjusted with recalculation to 100% in **table 6**.

Calculations employed for the Reichel and Otis-Albert fields can similarly be applied to see whether the "original gas" in the Hugoton Gas Field can be altered to reach the composition of the "altered gas." Again, two processes can be tested — "hydrocarbon removal" from the "original gas" or "nitrogen and helium addition" to the "original gas." Other processes are possible, but these two are the simplest ways to change the composition of the "original gas." The composition of the "original gas" (see above) is recalculated to a composition that sums to 100% in **table 6**. Using the process of "hydrocarbon removal," methane is mathematically removed from the "original gas" until the recalculated composition of resultant gas equals the methane content of the "altered gas." In the case of the Hugoton Gas Field, C_2+ hydrocarbons and helium also need to be removed so that their compositions equal, or nearly equal, that of the "altered gas." Some iteration in the amounts of methane, helium, and C_2+ hydrocarbons that need to be removed may be necessary, but once all these three component gases nearly equal their respective levels in the "altered gas," then a check of the veracity of the process is how much nitrogen is present in the "altered gas" when total composition of the "altered gas" is recalculated to 100%. In the case of the "altered gas" in the northeastern part of the field, 50.0% nitrogen is calculated to be in the "altered gas" (**table 6**). This matches the 50% interpreted in the compositional cross-plots (see **figs. 36, 37, 41**). For the northwestern part of the Hugoton Gas Field, 54.8% nitrogen is present in its "altered gas" determined from the compositional cross-plots (**figs. 39, 40, 41**), and 54.2% was calculated to be present after the requisite amounts of methane, C_6+ hydrocarbons, and helium were removed (**table 6**).

If nitrogen and helium are added to the "original gas," the resultant levels of methane and C_2+ hydrocarbons in the "altered gas" can be used as a test of the additive process. In the case of the northeastern part of the field, the calculated methane percentage is 41.6% when nitrogen is added to make the "altered gas" contain 50.5% nitrogen. The value of 41.6% methane is a few percentage points short of the 45% indicated by the cross-plots (see **figs. 36, 37, 41**). The C_2+ hydrocarbons calculate to 6.9%, which is slightly more than twice the 3% C_2+ hydrocarbons indicated by the cross-plots. For the northwestern part of the Hugoton Gas Field, addition of the amounts of nitrogen and helium needed so the "altered gas" has 55.0% nitrogen and 1.2% helium (indicated in the cross-plots), results in 37.5% methane and 6.2% C_2+ hydrocarbons (**table 6**). The cross-plots suggest the "altered gas" should be composed of 35% methane and 9% C_2+. These slight discrepancies suggest that the "hydrocarbon depletion" process may marginally better fit the compositional data than simply adding nitrogen and helium to the "original gas." Also, less material has to be removed from the "original gas" with "hydrocarbon depletion" (i.e., 72.2 and 74.4 molar volumes, respectively, for the northeastern and the northwestern parts of the Hugoton Gas Field) than need to be added with "nitrogen and helium addition" (i.e., 76.3 and 95.9 molar volumes, respectively, for the northeastern and northwestern parts of the Hugoton Gas Field; see **table 6**). However, "nitrogen and helium addition" better accounts for the presence of higher-molecular-weight hydrocarbons in the altered gases of the Hugoton Gas Field. Brown (2019) and Ballentine and Sherwood Lollar (2002) evaluated changes in gas chemistry by formation water in the Hugoton-Panhandle fields. Both studies determined that the original gas in these giant fields mixed with a high nitrogen source, having a higher nitrogen/helium ratio than the fields themselves. This essentially supports the model for "nitrogen and helium addition."

The simplest scenario accounting for the low-BTU rim around the Hugoton Gas Field is perhaps that the hydrocarbon gases were preferentially removed from the original gas in the field by dissolution into formation water along the gas-water contact and field perimeter. Hubbert (1953, 1967), who referred to the field as a "hydrodynamic trap," hypothesized a west-to-east movement of water in the Hugoton Gas Field. Although this scenario of hydrodynamic trapping is disputed (see Sorensen, 2003, 2005), the effects of water over geologic time in modifying the original gas composition could be substantial. Alternately, the Hugoton Gas Field also has been called a stratigraphic trap. An updip facies change to impermeable shales and nonporous carbonates in the Permian Chase Group to the west of the field may serve as a seal to trap its gas (Parham and Campbell, 1993; Olson and others, 1997). The low-BTU rim around the field may support the hydrodynamic trapping mechanism because dissolution and removal of a large volume of trapped gas would necessitate a large amount of moving formation water over an extended period of geologic time. Additional evidence supporting hydrodynamic trapping is that some wells west of the updip limit of the field test water and gas from the Chase Group (C. Becker, Jr., Conifer, Colorado, personal communication, 2020) whereas they would not likely produce any water if the Chase Group at that locality was composed of an impermeable sealing facies. Inasmuch as the northern end of the Hugoton Gas Field is characterized by the lowest BTU gas in the field (**fig. 16A**), and because the low-BTU perimeter is broadest in this region, perhaps water movement in this part of the field is stronger than farther to the south.

Although methane originally constituted the highest percentage of all the component gases in the Hugoton Gas Field, it was removed to a slightly greater extent in the northwestern corner of the field. Conversely, C_2+ hydrocarbons were more effectively removed in the northeastern part of the field but were better preserved in the northwestern part of the field (**fig 41**). This is puzzling, for presumably the eastward-moving formation water would be more effective in removing component gases in the western part of the field. However, another possibility that may account for the wetter hydrocarbon gases in the western part of the field (see **figs. 16B, 41E**) is that the change in hydrocarbon wetness across the field may

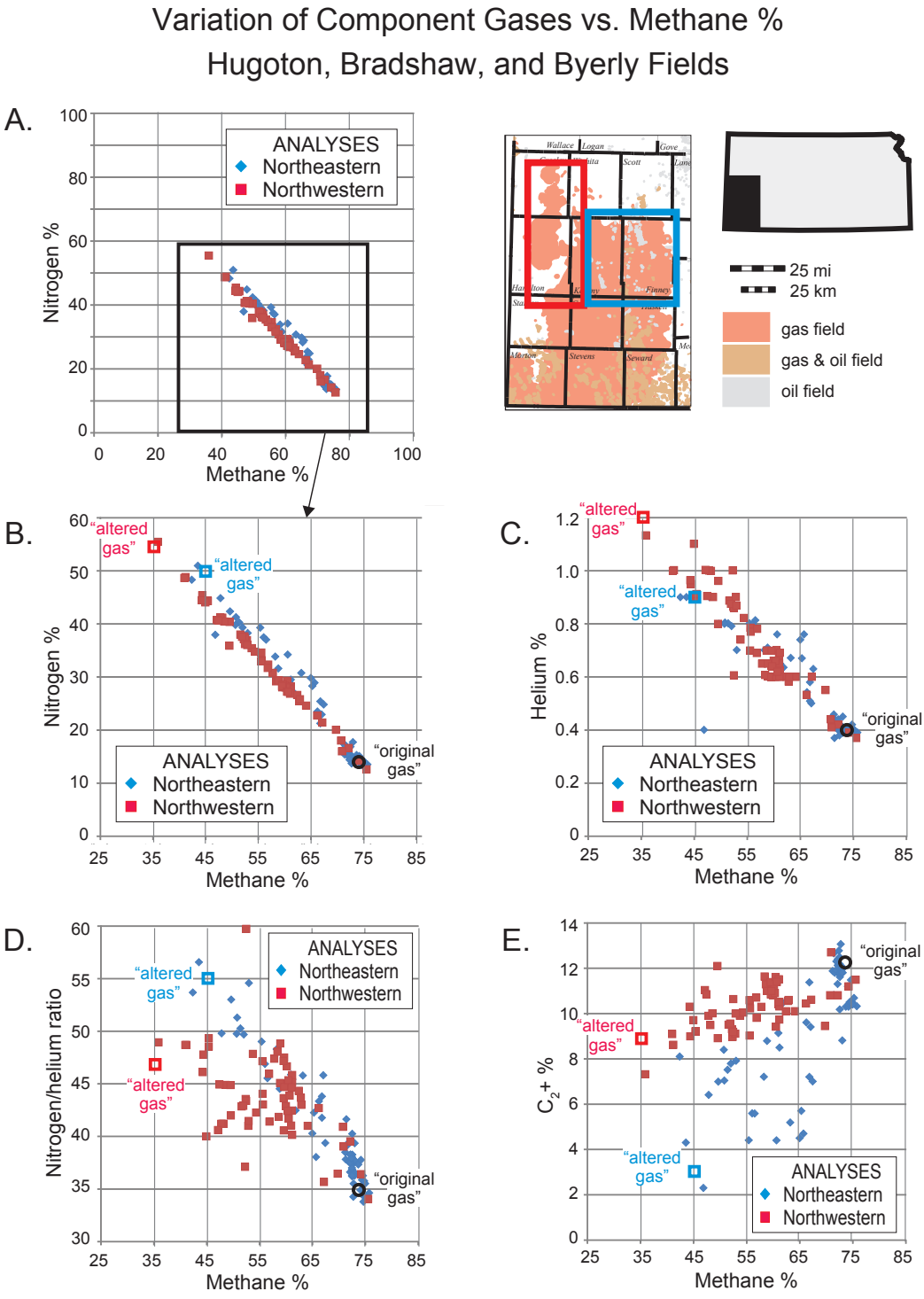

Figure 41. Compositional characteristics of the gases from the northeastern (blue diamonds) and northwestern (red squares) parts of the Hugoton, Bradshaw, and Byerly fields cross-plotted with methane percentage. A) and B) depict variation of nitrogen percentage with methane percentage at two different scales. With respect to methane percentage, C) depicts variation of helium content, D) depicts variation of nitrogen/helium ratios, and E) depicts variation of heavier-molecular-weight hydrocarbons (i.e., C_2+). The compositions of "original gas" (black circle) and "altered gas" (blue and red circles respectively for the northwestern and northeastern corners of the Hugoton Gas Field) are shown. The composition of "altered gas" should be compared to calculated compositions of "altered gas" respectively produced by "hydrocarbon depletion" and "nitrogen and helium addition" processes, shown in **table 6**. This figure is similar in form to **fig. 33**.

Table 6. Composition of the "original gas" and "altered gas" in the Hugoton, Bradshaw, and Byerly fields and the changes in composition necessary to alter the "original gas" to the "altered gas." Two alteration processes produce nearly similar results. "Hydrocarbon depletion" necessitates removal of methane, C_2+ gases, and a small amount of helium from the "original gas," whereas "nitrogen and helium addition" adds these two gases to the "original gas."

Compositions of Original and Altered Gas (from Composition Cross-plots)						
	[a]CH_4	[b]C_2+	[c]N_2	[d]He	[e]other	
original gas (%)	74.0	12.2	14.0	0.4	0.2	**<< sum = 100.8**
altered gas (%) (NE)	45.4	3.0	50.0	0.9	0.2	**<< sum = 99.1**
altered gas (%) (NW)	35.0	9.0	55.0	1.2	0.2	**<< sum = 100.4**
Compositions of Original and Altered Gas (Calculated to 100%)						
	[a]CH_4	[b]C_2+	[c]N_2	[d]He	[e]other	N_2/He ratio
original gas (%)	73.4	12.1	13.9	0.4	0.2	35.0
altered gas (%) (NE)	45.4	3.0	50.5	0.9	0.2	55.6
altered gas (%) (NW)	34.9	9.0	54.8	1.2	0.2	45.8
A. Northeastern Hugoton: Compositional Changes to Original Gas Needed to Produce Altered Gas (Assuming 100 Molar Volumes of Original Gas)						
	[a]CH_4	[b]C_2+	[c]N_2	[d]He	[e]other	N_2/He ratio
By "Hydrocarbon Depletion"						
Molar volumes	12.6	0.82	13.9	0.3	0.2	55.6
Calculation to 100%	45.4	3.0	50.0	0.9	0.7[f]	55.6
Number of molar volumes lost	-60.8	-11.3	0.0	-0.1	0.0	**<< sum = -72.2**
By "Nitrogen & Helium Addition"						
Molar volumes	73.4	12.1	89.0	1.5	0.2	59.3
Calculation to 100%	41.6	6.9	50.5	0.9	0.1[f]	59.3
Number of molar volumes added	0.0	0.0	75.1	1.1	0.0	**<< sum = 76.3**
B. Northwestern Hugoton: Compositional Changes to Original Gas Needed to Produce Altered Gas (Assuming 100 Moles of Original Gas)						
	[a]CH_4	[b]C_2+	[c]N_2	[d]He	[e]other	N_2/He ratio
By "Hydrocarbon Depletion"						
Molar volumes	9.0	2.3	13.9	0.31	0.2	44.8
Calculation to 100%	34.9	9.0	54.2	1.2	0.8[g]	44.8
Number of molar volumes lost	-64.5	-9.8	0.0	-0.1	0.0	**<< sum = -74.4**
By "Nitrogen & Helium Addition"						
Molar volumes	73.4	12.1	107.8	2.4	0.2	44.9
Calculation to 100%	37.5	6.2	55.0	1.2	0.1[g]	44.9
Number of molar volumes added	0.0	0.0	93.9	2.0	0.0	**<< sum = 95.9**

[a]methane

[b]ethane, propane, butane, pentane, hexane, hexane+

[c]nitrogen

[d]helium

[e]minor components of natural gas – argon, carbon dioxide, hydrogen. Because of their small percentages, these component gases are not considered in calculations

[f]compare percentages of component gases to altered gas (%) NE (calculated to 100%)

[g]compare percentages of component gases to altered gas (%) NW (calculated to 100%)

be caused by the early filling history of the field rather than post-accumulation alteration. Modeling of changes in gas compositions with changes in pressure, volume, and temperature may elucidate how this change in hydrocarbon wetness could occur.

If the broad low-BTU rim in the northern and northeastern parts of the Hugoton Gas Field is due to dissolution of the original gas, then the formation water immediately to the east of the broad perimeter could contain dissolved methane and other hydrocarbon gases and perhaps even helium. This begs the question of whether these dissolved gases could be recovered if prices for natural gas and helium were sufficiently high. Could pumping and degassing Permian formation water immediately east of the Hugoton and Panoma gas fields be commercially viable? Some formation-water testing, supplemented by input from petroleum engineers, could be warranted.

A final discussion for Permian gas in the Hugoton embayment focuses on a single chemical analysis of natural gas from the NCRA #1 Tate well in Finney County (sec. 35, T. 24 S., R. 31 W.), in the east-central part of the Hugoton Gas Field (**fig. 42**). The Bureau of Mines reported that natural gas from this well contained 11.6% carbon dioxide (see Munnerlyn and Miller, 1963). This amount of carbon dioxide is way in excess of what is usually reported from the Chase Group and underlying Council Grove Group. The next largest carbon dioxide analysis from these two stratigraphic units in the Hugoton embayment registers only 1.5% carbon dioxide. Furthermore, 174 analyses from the Hugoton Gas Field and the nearby Bradshaw and Byerly gas fields average only 0.16% carbon dioxide; 45 analyses from the Council Grove Group average 0.15% carbon dioxide.

Ordinarily, this 11.6% carbon dioxide measurement could easily be ignored and attributed to spurious calibrations or instrumentation glitches, or even transcription errors, but this gas was collected and analyzed by long-standing national laboratories at the U.S. Bureau of Mines, with the analyses annually released in formal publications. Presumably, these laboratories would be sensitive to data anomalies and would double-check the analytical results, particularly if the anomaly was from a single well.

Interestingly though, a geologic source could also account for this excess carbon dioxide. Igneous activity commonly produces carbon dioxide (Lowenstam, 2001). Twenty miles (32 km) west of the Kansas-Colorado state line (due west of Stanton County at the latitude corresponding to T. 28 S.; approximately 100 miles [160 km] west of the Tate well), near the town of Two Buttes, Colorado, is an exposed laccolith composed of andesite porphyry, emplaced during late Miocene time (Sanders, 1934). It is an open question whether this igneous activity extended into Kansas.

Unfortunately, the veracity of the unusual carbon dioxide measurement from the #1 Tate well is difficult to assess, for the U.S. Bureau of Mines has long quit its gas chemistry program. The NCRA #1 Tate well was plugged in 1962, and thus it cannot be resampled. Operators of nearby wells within the same section and adjacent sections (nominally 1 square mile each [1.61 X 1.61 km]) report no unusual amounts of carbon dioxide. Without any definitive refutation of the analysis, it is conceivable that perhaps a nearby thin igneous dike, sill, or small stock may have sourced the carbon dioxide in the #1 Tate well, if this analysis was indeed not in error. Nevertheless, extraordinary conclusions require extraordinary evidence, and in this case extraordinary evidence is suspect. Although extension of the southeastern Colorado igneous province into southwestern Kansas would be exciting, more geologic data are necessary.

Nitrogen gas in upper Permian strata

The dominant non-hydrocarbon gas in Kansas natural gases is nitrogen. However, in some cases nitrogen is the overwhelmingly dominant gas, as some analyses in western Kansas test as almost 100% nitrogen. High nitrogen gases common in the western United States could be due to nitrogen generation from clays and organic matter that have undergone low thermal maturation (Brown, 2019). The number of analyses of nitrogen-rich gases in Kansas also likely under-represents the total volume of entrapped nitrogen gas in the state, because unless an energy company is interested in the possible presence of helium or is simply curious about testing its non-flammable gas, an analysis of such gas retrieved in a drill-stem test or by another method would be a superfluous expense.

A single analysis of a Permian natural gas having a composition of 99.2% nitrogen and only 0.11% helium is evident in the upper left corner of the nitrogen-helium cross-plot in **figure 10B**. This sample is from the Wellington Formation (Leonardian Series, Sumner Group) from the Monsanto Chemical #1 Tate well in sec. 17, T. 24 S., R. 42 W. in Hamilton County, near the Colorado state line (Anderson and Hinson, 1951; Boone, 1958) (**fig. 42**). A BTU analysis from 65 miles (105 km) north in Wallace County reveals a similar gas (99.9% nitrogen and 0.08% helium) from the Sinclair-Prairie #1 Glad and Brock Trustees well in sec. 19, T. 13 S., R. 42 W. (Anderson and Hinson, 1951; Boone, 1958) (**fig. 42**). This gas show was from the Permian (Leonardian Series) Nippewalla Group at 2,460 ft (750 m) depth, which is stratigraphically above the Wellington Formation. These shows, combined with observations from well-log analyses, may reveal a vast reservoir of nitrogen gas in the upper Permian of western Kansas that covers several counties, where total volume could be as much as 14 TCF (G. Timson, Tulsa, Oklahoma, personal communication, 2014).

The primary stratigraphic unit holding this nitrogen may be the widespread Cedar Hills Sandstone (Leonardian Series, Nippewalla Group; see **fig. 2**) and possibly stratigraphically nearby sandstones down to the underlying Runnymeade Sandstone (Leonardian Series, Sumner Group). This nitrogen has proved to be a drilling hazard, as gas-charged Cedar Hills Sandstone was likely the source for what was probably the longest well blowout in Kansas history, which lasted at least two weeks (Lawrence Journal-World, 1984). The well was the Smith Cattle, Inc. #1 Helm (sec. 35, T. 18 S., R. 40 W., at 2,216 ft [675.5 m] depth), near the town of Tribune in Greeley County (**fig. 42**). The drill rig never burned up, because nitrogen is not flammable.

Nitrogen, being the major gas in our atmosphere, is not inherently economic to produce from wells, but perhaps such an extensive reservoir of it could be used as compressed-air energy storage for other variable power sources, such as solar cells or wind turbines. The non-combustible nature of 100% nitrogen in a subsurface reservoir would allow simply adding compressed atmospheric air to the reservoir to re-pressurize it. Any oxygen would be no problem because no hydrocarbon gases are present in the upper Permian sandstones to explosively react with it. Placement of infrastructure and compressors for downhole injection could accommodate the likely selective logistics (e.g., hilltops and ridges for wind turbines, proximity of transmission lines) of a power-generating facility inasmuch as the nitrogen reservoir appears to be so widespread. Pressure of the Permian reservoirs in western Kansas is below hydrostatic and on-trend with the pressure gradient, accounting for the pristine pressure of the Hugoton Gas Field (about 435 psig), as per data gleaned from drill-stem test shut-in pressures (**fig. 43**).

Gases in Cretaceous strata

The Cretaceous gas fields in northwestern Kansas are associated with the Denver-Julesburg basin and not with the Anadarko basin. Regional dip is to the north-northeast and the trapping mechanisms are structural closures in porous Niobrara Chalk caused by differential solution of underlying Permian salt beds (Rice, 1984; Newell and Watney, 2010).

Isotopic studies indicate that the Cretaceous gases in Kansas are of biogenic origin and are thus dry gases (Rice and Claypool, 1981; Rice, 1984) and very uniform in hydrocarbon content (**fig. 6A**). What hydrocarbon wetness there is, nevertheless, decreases in the updip direction. This may be an expression of a slight component of thermal maturation where the Niobrara is more deeply buried.

Nitrogen is the chief non-hydrocarbon gas that serves to lower the BTU content of the Cretaceous gases (**figs. 10A, 19A, B**). It appears to be more abundant in updip fields toward the south-southwest (**fig. 19B**). This may be due to leakage upward from high nitrogen accumulations in the Permian in west-central Kansas (see discussion in previous section). The nitrogen/helium ratio increases updip (**fig. 19D**) as it generally does with older stratigraphic intervals in southern Kansas. This may be due to the mixing with nitrogen in the shallower parts of the Denver-Julesburg Basin near the outcrop, but more analysis is necessary to support this speculation.

H_2S (sour gas) in Kansas

The north-south trend of H_2S-bearing fields on the southwestern flank of the Central Kansas uplift and northwestern Pratt anticline (see **fig. 20**) implies a regional and common origin for its sour gas, but a detailed geologic analysis is necessary to determine the natural habitat of this gas and, in turn, its possible origin. This exercise should concentrate on isolating the geologic horizon or horizons that carry H_2S and on figuring out which nearby oil and gas fields do not produce significant amounts of this lethal component gas. Dolomites in the Cambrian-Ordovician Arbuckle Group are the dominant reservoir in this H_2S trend. Hunt (1979, p. 171) states that thermal maturation of organic matter at temperatures well in excess

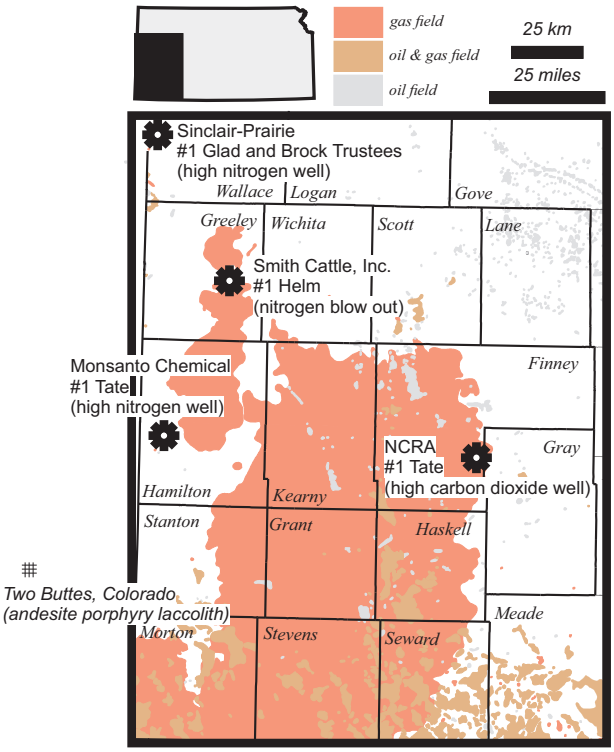

Figure 42. High nitrogen wells in the upper Permian in western Kansas. The locality of the NCRA #1 Tate well, with the anomalous showing of carbon dioxide in the Permian Chase Group, is also shown. Two Buttes, Colorado, where a laccolith of andesite porphyry is exposed, is also placed relative to the Kansas state line. See text for discussion.

of 248 °F (120 °C) are necessary for generation of H_2S in the deep subsurface. Present-day temperatures, however, at Arbuckle level in the vicinity of the H_2S trend are only about 110 °F (45 °C). Other geologic processes are likely responsible for the H_2S.

For the sake of safety, the isolated presence of significant sour gas, such as at the Berentz Drilling #1 Aiken well (see **table 3**), is rather unsettling because its presence is unpredictable. It is possible that this sour gas and other isolated localities recording H_2S are not natural occurrences, but instead they may be caused by injected water contaminated by bacteria that produce H_2S by reduction of sulfates (see Hunt, 1979, p. 169). Information about water floods and water chemistry are, of course, necessary to infer such an origin for the sour gas. As a supplement to safety concerns regarding sour gas in Kansas, sour gas shows are discussed in more detail in **Appendix 1**.

CONCLUSIONS

Aside from its use in locally determining BTU or helium content for pipeline gas-quality requirements or on-site processing at oil and gas leases, chemical analyses of natural gases, in sufficient numbers, reveal regional and stratigraphic changes in natural gases. Assembling natural gas chemical analyses and analyzing the lateral and stratigraphic changes in the component gases of natural gas reveal

that natural gas in central and western Kansas shows consistent spatial and stratigraphic changes. In general, the BTU content of natural gases increases with age of the reservoir and decreases toward the distal end of hydrocarbon migration routes out of basins. Similarly, hydrocarbon wetness decreases with age of the reservoir and toward the terminus of migration routes.

Localized areas of low-BTU gas in accumulations present along the basal Pennsylvanian unconformity and along the perimeter of the Hugoton Gas Field may be caused by interaction of an original high-BTU natural gas with formation water or by mixing with a separate accumulation of high nitrogen gas. Loss of hydrocarbons and helium or a gain (or mixing) of nitrogen and helium can produce the same lower-BTU gas. Additional data are needed to select which process may be more likely.

The distinction of what is a low-BTU natural gas is largely arbitrary as there is not a strong compositional separation between high- and low-BTU natural gases. Instead, the transition is gradual, and thus this publication considers 950 BTU/scf, a level suggested by pipeline standards, as the boundary between high- and low-BTU gas.

Lower-grade natural gas can supplement natural gas supplies in the future, if prices (governed principally by supply and demand) justify exploration and development of these potential resources. In Kansas, low-BTU natural gas is generally found at the distal ends of migration pathways and in shallower and younger strata higher in the stratigraphic column. Pennsylvanian reservoirs on the Central Kansas uplift may be prospective for low-BTU gas, and reservoirs principally in the Permian Chase Group hold promise for low-BTU reserves west of the Central Kansas uplift and east of the Hugoton Gas Field. Wellsite extraction technologies can focus on removing helium from low-BTU gas fields in western and central Kansas if economics allow.

The volume of low-BTU gas present in Kansas is still to be determined, but its presence appears to be widespread over south-central and western parts of the state. Mapping of the occurrences of low-BTU gas can be effective as a first step in any exploration program for the low-BTU gas itself or for the helium it commonly contains.

Nitrogen is the major non-combustible component gas in Kansas. Its presence increases with decreasing age of the reservoir. Vast stores of nitrogen in upper Permian sandstone reservoirs in western Kansas are suggested by a few widespread natural gas analyses. Although the nitrogen itself is probably not commercial, the potential vastness of the nitrogen reservoirs and its pressure may be amenable to compressed-air energy storage for wind or solar energy projects.

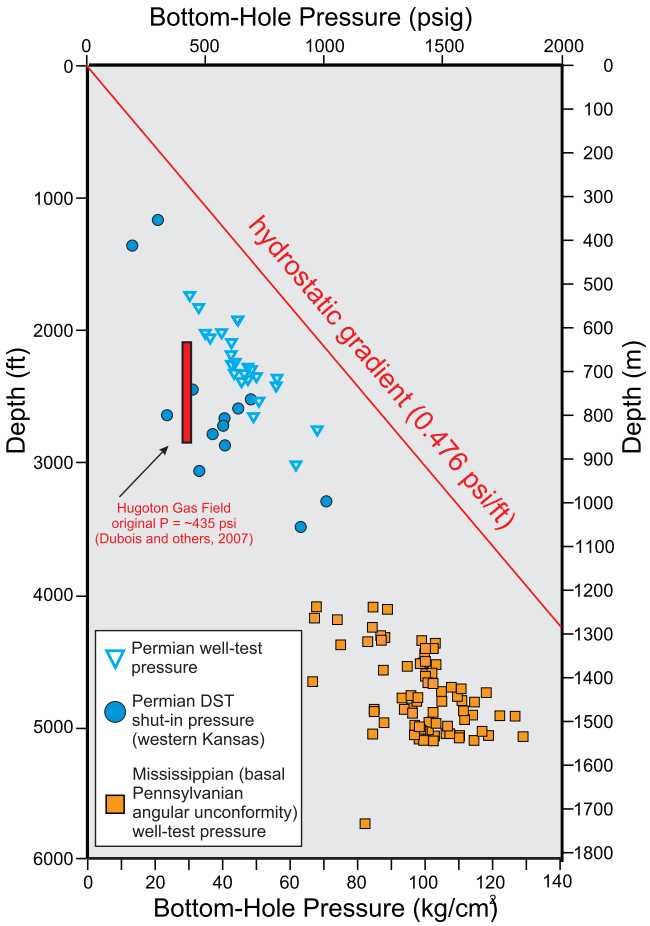

Figure 43. Depth-pressure relationships of fluids from Permian strata (mostly from western Kansas) and Mississippian strata (mostly from central Kansas), from static well pressures and drill-stem tests (DSTs). Both stratigraphic units are under-pressured with respect to a hypothetical hydrostatic gradient with the top of the water column close to the local land surface. The hydrostatic gradient shows water pressure expected for subsurface brine with a density of about 1.1 g/cc, or about 155,000 ppm total dissolved solids.

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APPENDIX 1: SOUR GAS (H_2S) IN KANSAS OIL AND GAS FIELDS

Shows of sour gas (H_2S) are listed alphabetically by county, then by township and range.

Barton County

Chaffee Field
Sec. 31, T. 19 S., R. 13 W., sec. 36, T. 19 S., R. 14 W.; sour gas noted in field in Cambrian-Ordovician Arbuckle Group at 3,480 ft; reference: scout cards

Clarence Field
Western Petroleum #1 Suchy; sec. 27, T. 19 S., R. 15 W.; trace sour gas noted in Pennsylvanian Kansas City Group at 3,164 ft; reference: Miller and Norrell (1964a)

Converse Field
Sec. 7–9, 16–20, 29, T. 20 S., R. 15 W.; sour gas noted in field in Cambrian-Ordovician Arbuckle Group at 3,800 ft; reference: scout cards

Chautauqua County

Kingston Field
Berentz Drilling Aiken #1; sec. 17, T. 32 S., R. 11 E.; sour gas (1.3%) noted in Mississippian at 1,809 ft; reference: Jenden and others (1988)

Edwards County

Bradbridge Field
Barnett Oil Neidig #1; sec. 1, T. 24 S., R. 16 W.; sour gas noted in Cambrian-Ordovician Arbuckle Group at 4,053 ft; reference: Moore and Shrewsbury (1967), scout cards

Marion County

Durham East Field
Rounds & Stewart Scully-Hanson #1; sec. 35, T. 18 S., R. 2 E.; trace sour gas noted in Mississippian limestones at 2,533 ft; reference: Cardwell and Benton (1970b), scout cards

Meade County

Hockett SE Field
Cobra O&G Harris 34 #1; sec. 34, T. 31 S., R. 29 W.; sour gas (0.1%) noted in Mississippian Chester Fm. at 5,564 ft; reference: Hamak and Sigler (1991)

Morton County

Sparks Field
Sec. 17, 18, 20, 21, 26–29, 32–36, T. 30 S., R. 40 W., sec. 8, 18–20, T. 31 S., R. 41 W., sec. 1–5, 10–15, 22–24, T. 31 S., R. 42 W.; sour gas noted in Topeka Limestone of Pennsylvanian Shawnee Group at 3,170 ft; reference: scout cards

Greenwood Gas Area
Superior Oil Boyd #1; sec. 33, T. 31 S., R. 42 W.; sour gas (0.1%) noted in Elmont Member of Emporia Limestone of the Permian Wabaunsee Group at 2,800 ft; reference: Moore (1982)

Pawnee County

Sweeney West Field
Sec. 13, 14, T. 21 S., R. 16 W.; sour gas noted in field in Cambrian-Ordovician Arbuckle Group at 3,810 ft; reference: scout cards

Evers Field
Carmen Schmidt, Inc. Prosser #1; sec. 36, T. 21 S., R. 16 W.; sour gas from Ordovician Simpson Group at 3,846 ft and Cambrian-Ordovician Arbuckle Group at 3,894 ft, with sour gas removal equipment at wellsite; reference: letter attached to DST report (Kansas Geological Survey, 2025)

Zook Field
Sec. 3, 4, 9, 10, 13, 16, 23–27, 32–36, T. 22 S., R. 16 W.; sour gas noted in field in Cambrian-Ordovician Arbuckle Group at 4,010 ft; reference: scout cards

Benson Field
Dunne-Gardner Petro#1; sec. 29, T. 23 S., R. 15 W.; sour gas noted in Cambrian-Ordovician Arbuckle Group at 4,027 ft, possibly also in the Zeandale Limestone of the Permian Wabaunsee Group at 3,010 ft; reference: Miller and Norrell (1964b), Cardwell and Benton (1970a), scout cards

Rice County

Lyon Field
Sec. 35, T. 19 S., R. 8 W., sec. 2, 11, 14, T. 20 S., R. 8 W.; sour gas noted in field in Ordovician Simpson Group at 3,230 ft; reference: scout cards

Rush County

Otis-Albert Field
Skelly Oil Dyer #2; sec. 21, T. 18 S., R. 16 W.; sour gas (0.9%) noted in Cambrian Reagan Fm. at 3,544 ft; reference: Munnerlyn and Miller (1963)

Stafford County

Macksville Field
Sec. 33, 34, T. 23 S., R. 15 W., sec. 2–4, 10, 11, T. 24 S., R. 15 W.; sour gas noted in Ordovician Simpson Group at 4,070 ft; reference: scout cards

O'Connor Field
Rex & Morris Petro #2; sec. 9, T. 24 S., R. 15 W.; trace sour gas noted in basal Pennsylvanian sandstone at 4,053 ft; reference: Miller and Norrell (1964b)

Macksville Townsite Field
F.G. Holl Doran #2-14; sec. 14, T. 24 S., R. 15 W.; sour gas (0.6%) noted in Cambrian-Ordovician Arbuckle Group at 4,108 ft; reference: Jenden and others (1988)

Farmington Field
Cities Service Westgate #1; sec. 6, T. 25 S., R. 15 W.; trace sour gas noted in Cambrian-Ordovician Arbuckle Group at 4,169 ft; reference: Boone (1958)

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ISBN: 978-1-58806-341-0