INFLUENCE OF PERMIAN SALT DISSOLUTION ON CRETACEOUS OIL AND GAS ENTRAPMENT, DENVER BASIN

VOLUME I

DISSERTATION

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ABSTRACT

Subsurface study of Permian evaporites and related strata in the Denver basin reveals that the present distribution of salt has been influenced by a number of depositional and post-depositional controls. Correlations across the basin have identified 13 stratigraphic intervals that, in places, are salt-bearing. Upper Wolfcampian and lower Leonardian salts accumulated in paleolows (Alliance and Sterling evaporite basins and the "Garden County low") which were bounded by low-relief positive features associated with the Transcontinental arch, the Ancestral Chadron arch, and the Ancestral Las Animas arch. Sand (Lyons-Cedar Hills Sandstone) accumulated in eolian and shallow-water environments along paleohighs coeval with deposition of red silts and mud (Salt Plain Formation) and precipitation of halite (salts 9 and 10) in evaporite basins. Paleotectonic elements apparently had little influence on the distribution of younger (upper Leonardian and Guadalupian) salts.

Salt has been locally removed by dissolution at various times. Pre-Late Jurassic truncation partially removed Leonardian strata and completely removed Guadalupian and Triassic strata in the eastern part of the basin. Eastern limits of Guadalupian and upper Leonardian salts parallel

pre-Jurassic subcrop belts, reflecting the stepwise removal of salt by pre-Late Jurassic erosion or near-surface dissolution. Jurassic and Early Cretaceous removal of upper Leonardian and Guadalupian salt may be related to compaction-driven (centrifugal) groundwater flow from the Lyons Sandstone. Post-Cretaceous (Laramide) dissolution, which locally removed salts and influenced Cretaceous-level structure, is probably related to the introduction of groundwater by gravity-driven (centripetal) flow along a regional Lyons-salt facies change.

Timing of salt removal has influenced the distribution and trapping mechanism of oil and gas fields on the eastern flank of the basin. In the western part of the D-J fairway, dissolution (and resultant collapse) pre-dated deposition of D and J Sandstone reservoirs. Here, reservoir-level structure is relatively simple and stratigraphic traps predominate. In the eastern part of the D-J fairway and in the D Sandstone and Niobrara Chalk gas areas, where dissolution post-dated deposition of Cretaceous reservoirs, structure is more complex and structural or structural-stratigraphic traps predominate.

Discovery of oil in the subsalt Paleozoic section in 1980 sparked an exploration effort in the northern Denver basin that has greatly increased the amount of subsurface control with which to examine the stratigraphy of Permian salt-bearing units. A subsurface nomenclature is proposed for the salt-bearing interval in the Denver basin subsurface which uses Mid-Continent terminology for the Leonardian and Rocky Mountain terminology for the Guadalupian.

PREFACE

This report presents the results of a subsurface study of Permian salts in the Denver basin and the relationship of salt removal by dissolution to hydrocarbon trap development at the level of Cretaceous reservoirs. A number of papers and abstracts published during the course of this study present portions of the research.

Overviews of the regional relationships between salt dissolution margins and hydrocarbon production across the basin are summarized in Oldham (1994, 1995, 1996). Regional stratigraphic correlations of salts and related rocks and a proposed subsurface nomenclature are presented in Oldham (1996). Results of a subregional study within the Nebraska panhandle, including an interpretation of the origin of the Sidney trough are presented in Oldham and Smosna (1996a,b) and Oldham and Smosna (1996b). Part of the Nebraska panhandle subregional study is presented in Oldham (1996). Oldham and Smosna (1996c,d) present results of a subregional study in the area of the eastern Colorado Niobrara gas play, including the Eckley gas field study area. Where applicable, this report supercedes the above-referenced publications.

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CHAPTER 1
INTRODUCTION AND OVERVIEW

PURPOSE OF STUDY

The Denver basin (Figure 1-1), also referred to as the Denver-Julesburg or D-J basin, is the largest basin in the U.S. Rocky Mountain foreland. Over the past 50 years the basin has yielded significant volumes of oil and natural gas, predominantly from Cretaceous-age reservoirs. Discovery of oil in Pennsylvanian and Lower Permian reservoirs in the 1980s led to renewed economic interest in the Paleozoic rocks of the basin subsurface and prompted a flurry of deep drilling activity and geophysical study over the past 15 years.

Sandwiched between important Cretaceous reservoir rocks and more recently exploited Paleozoic targets in the Denver basin subsurface (Figures 1-2, 1-3) is a Permian (Wolfcampian, Leonardian, and Guadalupian) evaporite-bearing interval. This interval is comprised of thin anhydrite beds and anhydritic carbonates, red shales and siltstones, and thick salts (predominantly halite). Only one reservoir-quality unit, the Lyons (Cedar Hills) Sandstone, occurs discontinuously within this interval.

As a whole, Leonardian and Guadalupian strata show

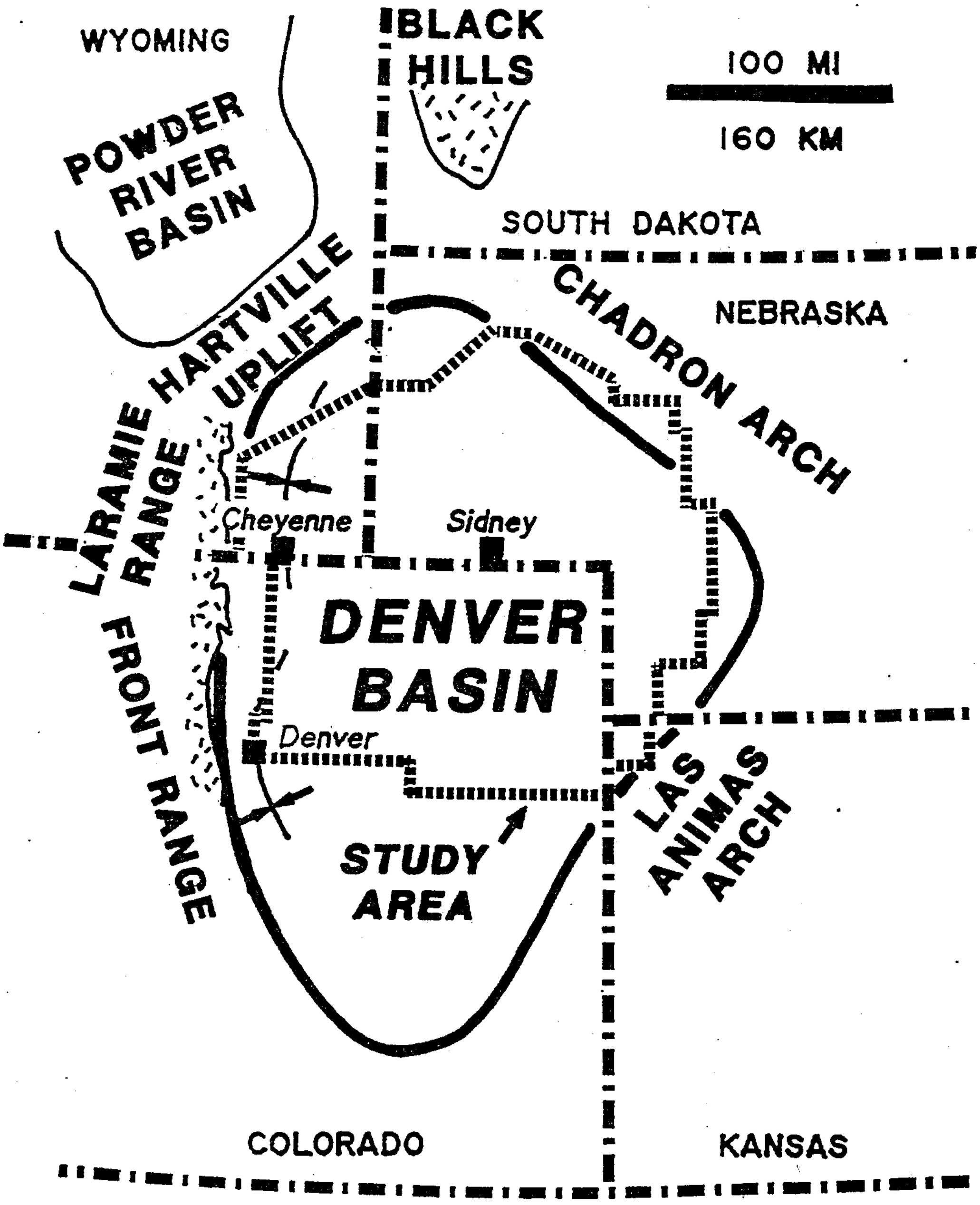


Figure 1-1. Index map of Denver basin and adjacent uplifts showing location of study area.

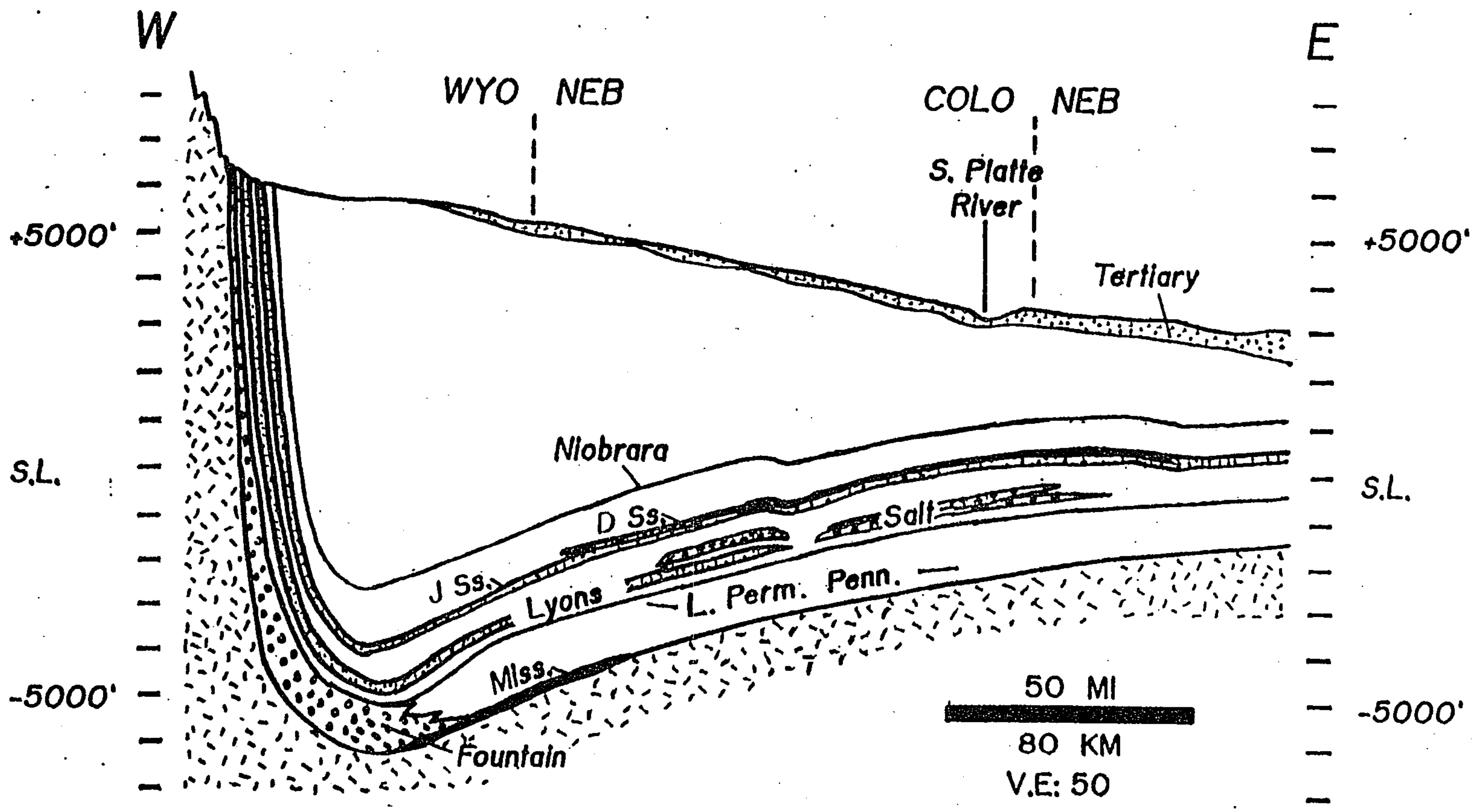


Figure 1-2. Regional cross section along 41st parallel (northern border of Colorado) from Front Range of Colorado to high plains of Nebraska. Permian salts are situated between Cretaceous oil and gas reservoirs (Niobrara chalk and D and J Sandstones) and recently discovered Lower Permian and Pennsylvanian oil reservoirs. Modified from Martin (1965).

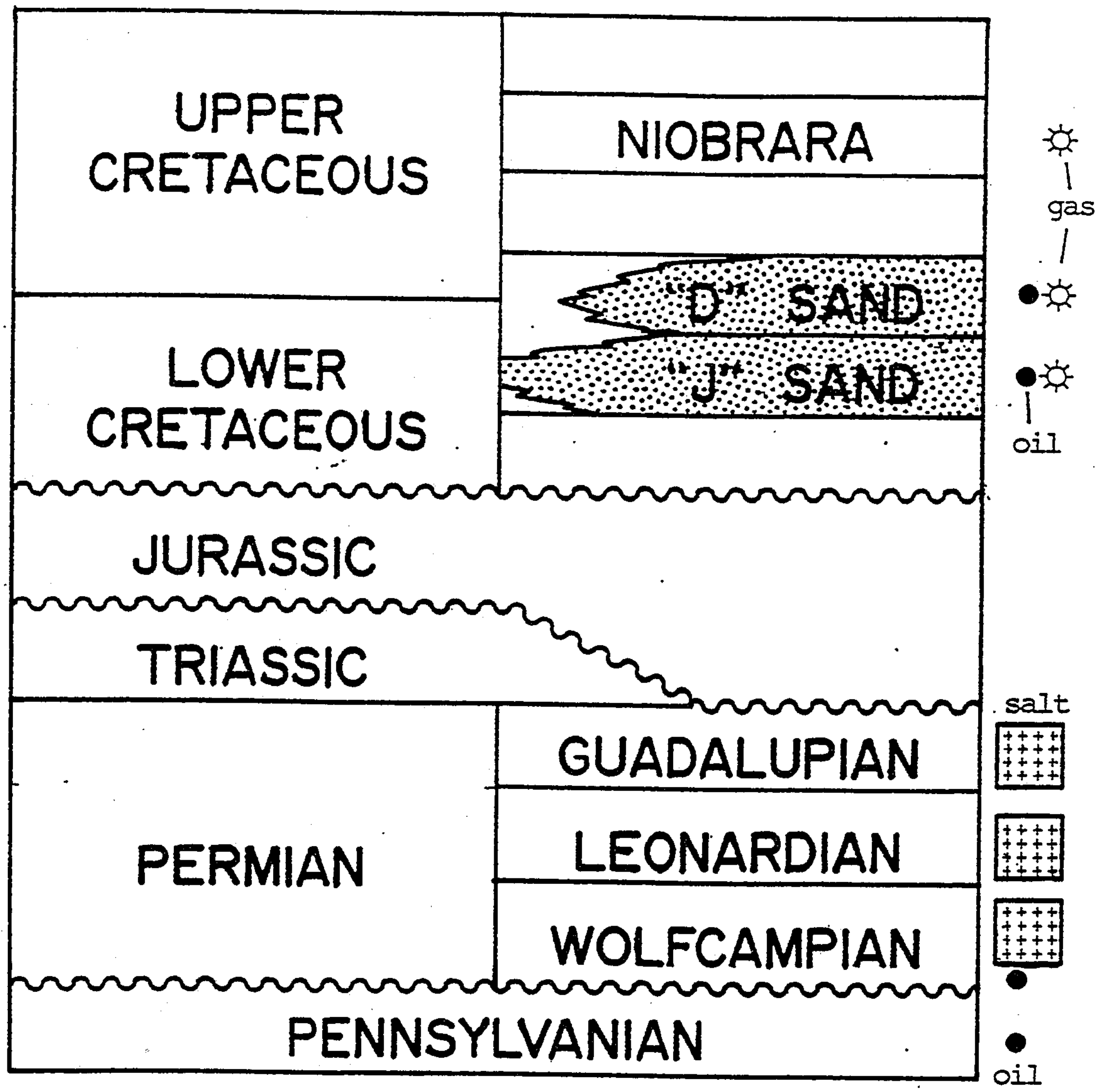


Figure 1-3. Simplified chart for the eastern Denver basin subsurface showing stratigraphic positions of major oil and gas reservoirs relative to Permian salts.

little promise as prospective oil and gas reservoirs. Thus, published studies of Paleozoic rocks in the Denver basin subsurface have focused on deeper Wolfcampian and Pennsylvanian strata, due to their potential as both oil source rocks and reservoirs, but these studies have virtually ignored the post-Wolfcampian (Leonardian and Guadalupian) evaporite-bearing interval.

So, if the Permian salt interval appears to lack oil and gas potential, and if salt has never been exploited as a mineral resource, why study the salts? Because, study of the occurrence and distribution of thick, discontinuous salts will aid explorationists, engineers, and drillers who are exploring for oil and gas in rocks above and below the salt interval in a number of ways, as explained in the following sections.

Salt-related Traps in Cretaceous Reservoirs

Isopach mapping of Leonardian and Guadalupian intervals reveals many localized salt-related thickness variations that correspond with hydrocarbon-productive closed structural highs at the Cretaceous level. Background work (Chapter 2) reveals a relationship between salt dissolution and structural entrapment of oil and gas at a number of fields, including several along the shallow Niobrara gas trend in eastern Colorado and within the D and J Sandstone fairway of Colorado and Nebraska. Study of the distribution of individual salts, controls on their distribution, and predicted areas of abrupt thinning is critical to predicting additional structurally-influenced prospective trends in Cretaceous reservoirs.

Salt-related Velocity Anomalies at the Level of Subsalt Reflectors

Salt outliers which remain as dissolution remnants can cause acoustic anomalies on seismic data. Salt can create false seismic structures at the level of subsalt Permian and Pennsylvanian reflectors, particularly if salt dissolution and removal is relatively late, and accommodation space created by solution collapse is filled with low-velocity Cenozoic sediments. This situation, which causes an apparent velocity pullup below the salt, is likely a reason for many early deep exploratory failures. Study of the location and timing of salt dissolution features will aid in structural and stratigraphic interpretation of seismic data used in the search for additional subsalt oil accumulations in Wolfcampian and Pennsylvanian strata.

Salt-related Drilling Problems in Deep Tests

Operators drilling to Paleozoic targets in certain parts of the basin have encountered serious drilling and completion problems caused by the presence of salts. The major problem involves the so-called "bubble-gum shale" (Montgomery, 1987; Sahl et al., 1993) which is a driller's term for hydrated shale sandwiched between salt beds. The enclosing salts act as effective seals, having prevented fine-grained sediments from dewatering during compaction. The undercompacted, relatively overpressured shales exhibit plastic flow into the wellbore, causing seizing of the drill string and casing collapse if sufficiently high mud weight is not maintained. Increasing mud weight, however, can result in invasion of deeper prospective reservoirs, causing formation damage and log-evaluation problems. Study of the combined occurrence of salt beds which are interbedded with shales will aid in the prediction of potential problem areas.

Paleogeographic Reconstruction

Original extent of bedded salts was largely controlled by the configuration of restricted basins during evaporite precipitation. Thus, subsurface mapping of salts and related strata will provide insight into the tectonic and paleogeographic framework of the area during latest Wolfcampian, Leonardian, and Guadalupian time.

SCOPE OF STUDY

The primary focus of this study is the relationship between subsurface salt dissolution and the formation of hydrocarbon traps in Cretaceous-age reservoirs. The study is a subsurface investigation of a 40,000 sq mi (100,000 sq km) portion of the Denver basin which is both hydrocarbon-productive and salt-bearing. The study area (Figure 1-1) includes parts of northeastern Colorado, northwestern Kansas, southwestern Nebraska, and southeastern Wyoming.

The investigation includes a number of studies at different scales across the basin (Figure 1-4). A regional study covering the northern two-thirds of the basin examines the Permian evaporite interval to determine the stratigraphic position of salt beds, facies relationships between the salts and associated strata, thickness and areal distribution of individual salt beds, depositional and post-depositional controls on the distribution of salts, and the relationship of salt removal by dissolution to trap formation or localization of hydrocarbons within existing traps. Limits of this regional study area were defined on the basis of (a) early work by McKee, Oriel, et al. (1967a,b) who delineated salt-bearing areas across the

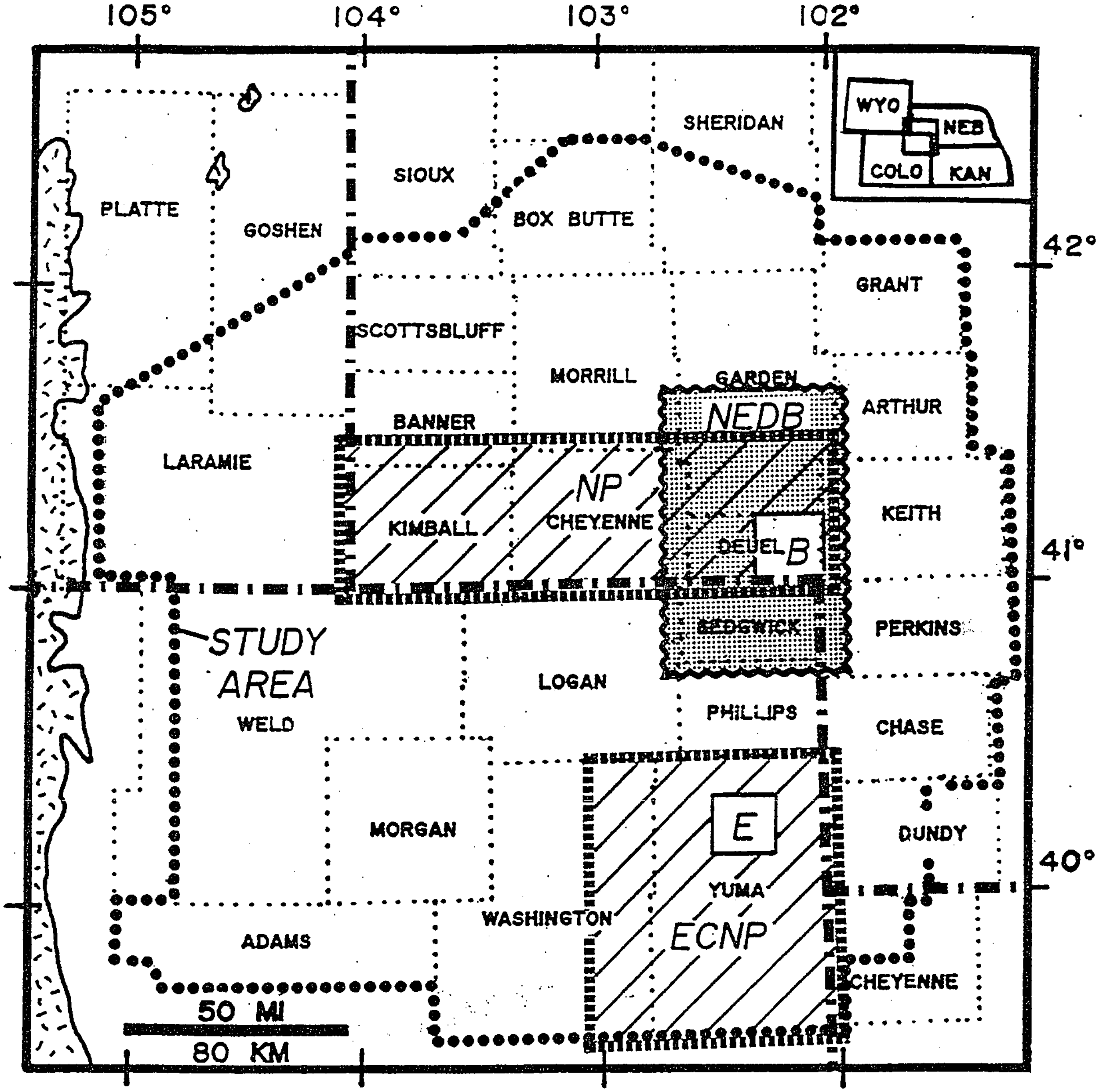


Figure 1-4. Study area location map: NP - Nebraska panhandle subregional area; B - Big Springs gas field area; ECNP - Eastern Colorado Niobrara play subregional area; E - Eckley gas field area. Northeastern Denver basin preliminary study area (NEDB) is discussed in Chapter 2 of this report.

region based on limited subsurface control (Figure 1-5), and (b) general limits of oil and gas production across the basin (Figure 1-6).

Two subregional studies focus on the relationship of oil and gas entrapment to salt dissolution. One subregional area, a 3600 sq mi (9200 sq km) part of the Nebraska panhandle (NP, Figure 1-4), is examined in detail to determine the influence of salt removal on the distribution of oil and gas fields in this part of the D-J fairway. The Big Springs gas field (B), situated near the eastern margin of the Nebraska panhandle area, is examined in more detail using seismic data.

The second subregional study area is a 2900 sq mi (7400 sq km) part of eastern Colorado (ECNP, Figure 1-4). Study of this area focuses on the relationship of salt dissolution to the distribution of gas-productive faulted anticlines within the eastern Colorado Niobrara play. A more detailed study of the Eckley gas field area (E) includes seismic data.

GEOLOGIC SETTING

The generalized Phanerozoic history of the Rocky Mountain foreland, which includes the area now occupied by the Denver basin, can be divided into four phases (Gries et al., 1992):

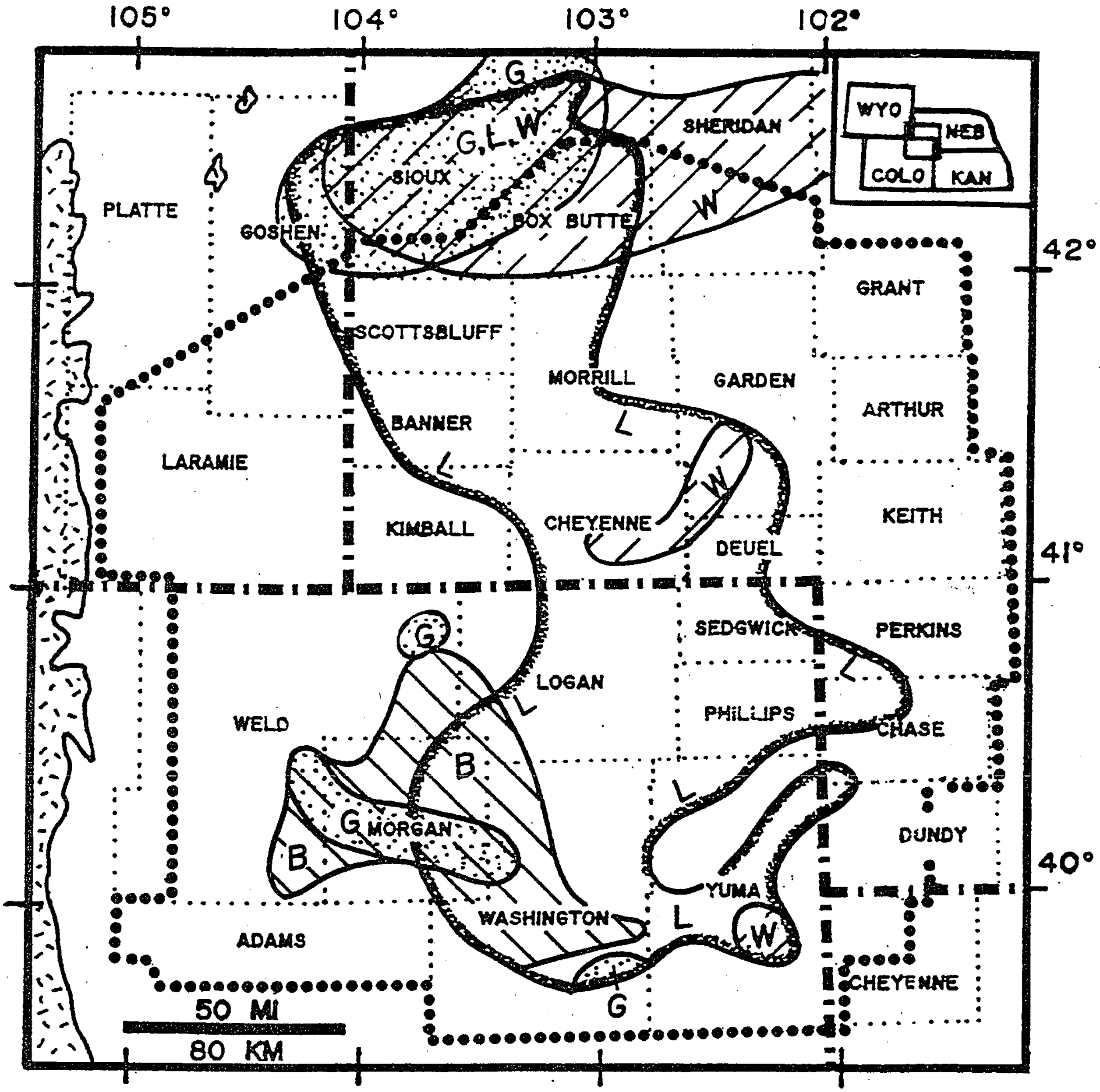


Figure 1-5. Regional distribution of Permian salts, as mapped by McKee, Oriel, et al. (1967b): G - Guadalupian salts; B - Leonardian salts above the Blaine Formation; L - Leonardian salts below the Blaine Formation; W - Wolfcampian salts.

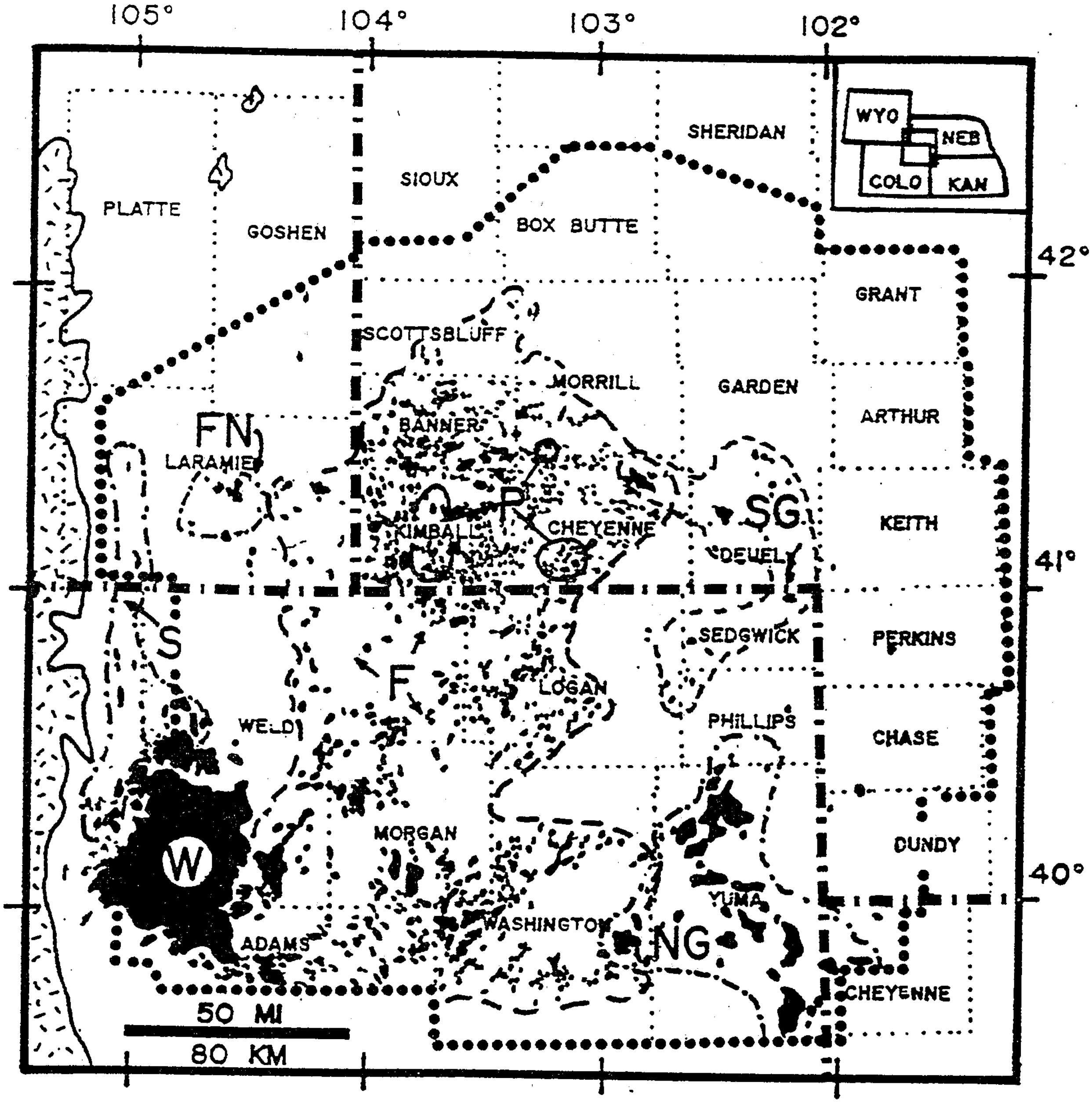


Figure 1-6. Oil and gas fields and generalized plays: S - Structural traps immediately east of the Front and Laramie Range uplifts; W - deep basin gas accumulations in the Wattenberg field area; FN - fractured Niobrara oil production in the Silo field area; F - D and J Sandstone oil and gas fairway; P - recently-discovered subsalt Paleozoic production; SG - shallow gas production from the Niobrara, and D and J Sandstones; NG - shallow Niobrara Gas play.

1. a relatively stable passive margin setting through most of the Paleozoic and early Mesozoic, interrupted briefly by a Middle Pennsylvanian tectonic event which produced the Ancestral Rockies;

2. a foreland basin setting during Jurassic and Cretaceous time (Western Interior Cretaceous seaway), formed by the evolution of the western North American craton from a passive margin to an active subduction/ collision margin;

3. breakup of the region into deep intermontaine basins and uplifts in response to Laramide (Late Cretaceous-Eocene) orogeny, a period of flat-plate subduction; and

4. late Tertiary and Quaternary epeirogenic uplift and erosion.

Permian salts studied in this report formed in the phase 1 passive margin setting. Important Cretaceous reservoir rocks in the basin (D and J Sandstones and Niobrara Chalk) accumulated in the phase 2 foreland basin setting. The Denver basin took its present shape in response to phase 3 Laramide tectonics. Phase 4 uplift and erosion created the present-day landscape.

The asymmetrical Denver basin is bounded by the Front Range and Laramie Range uplifts to the west, the Hartville uplift to the northwest, the Chadron arch to the northeast, and the Las Animas arch to the southeast (Figure 1-1). Within the study area, depth to Precambrian basement ranges from about 4000 ft (1200 m) in the northeast along the Chadron arch to over 12,000 ft (3700 m) along the basin axis (Figure 1-7). Because the basin axis is situated just east of and parallel to the Front Range and Laramie uplifts

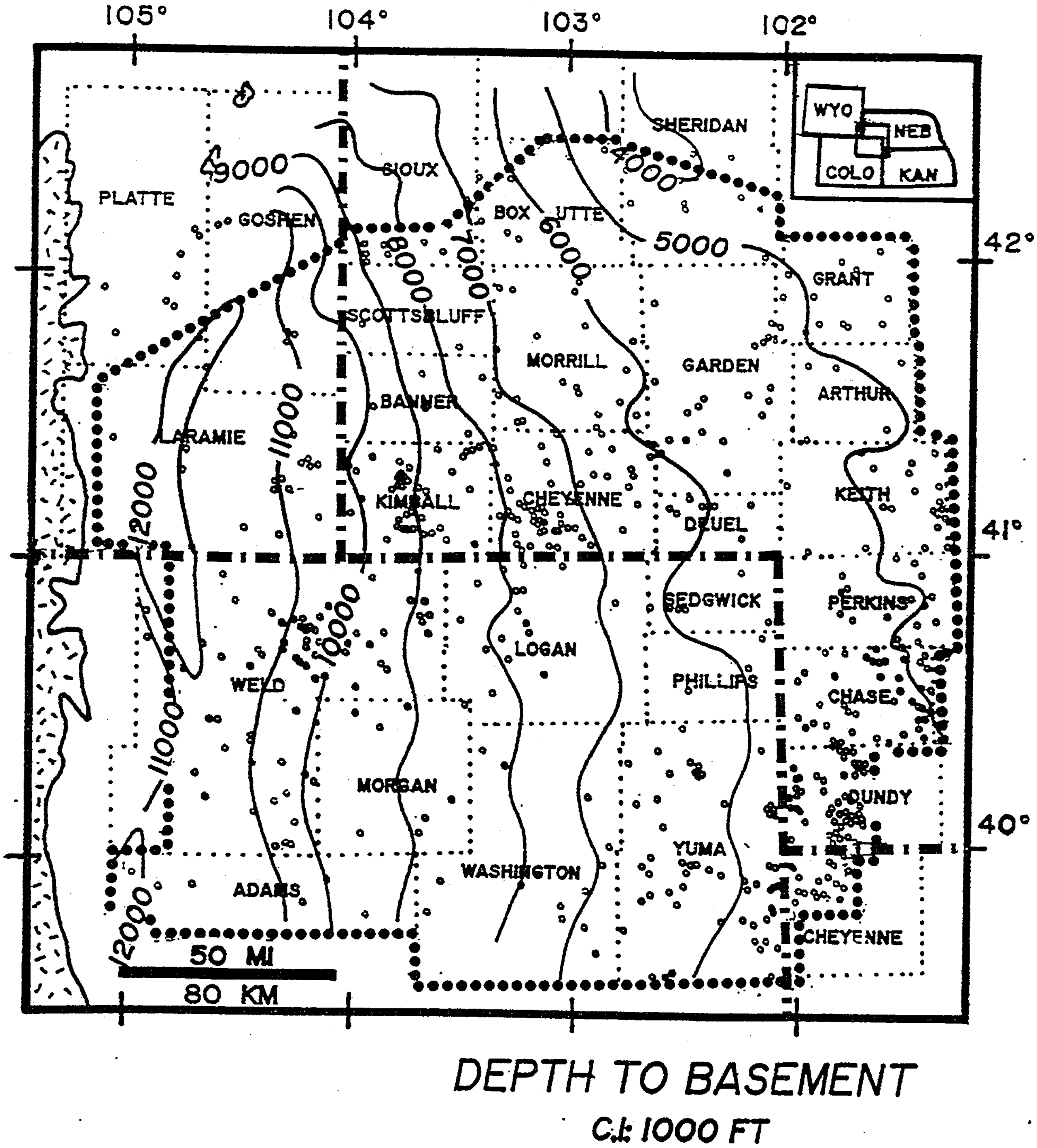


Figure 1-7. Depth to Precambrian basement. Contour interval 1000 ft (300 m). Precambrian rocks are exposed along the Front Range, Laramie Range, and Hartville uplift (western margin of map).

(Figure 1-8), the eastern flank, with regional dips of less than one degree, comprises most of the basin. This study focuses on the gently-dipping eastern flank of the basin.

Salts, where present, range in depth from less than 4000 ft (1200 m) near the eastern margin of the study area in Chase County, Nebraska, to nearly 11,000 ft (3300 m) near the basin axis in Laramie County, Wyoming. The salt-bearing interval lies about 800 to 1000 ft (200 to 300 m) below the D and J Sandstone reservoirs and about 2000 ft (600 m) below the Niobrara Chalk Figure 1-2). Precambrian basement is encountered about 800 to 2000 ft (200 to 600 m) below the salt interval.

METHODS

Geophysical well logs from over 750 Paleozoic tests, including sample descriptions and mud logs where available, were used to pick over 40 formation tops, ranging from the Cretaceous D Sandstone to Precambrian basement, and to measure salt thickness values for a regional subsurface study. Using well logs from selected deep tests, 55 stratigraphic cross sections through the Permian salt interval were tied, forming a regional correlation network (Figure 1-9). Most well logs were acquired during visits to the Denver Earth Resources Library and the Geological Information Center in Denver. Additional well logs were provided by the Nebraska Oil and Gas Conservation

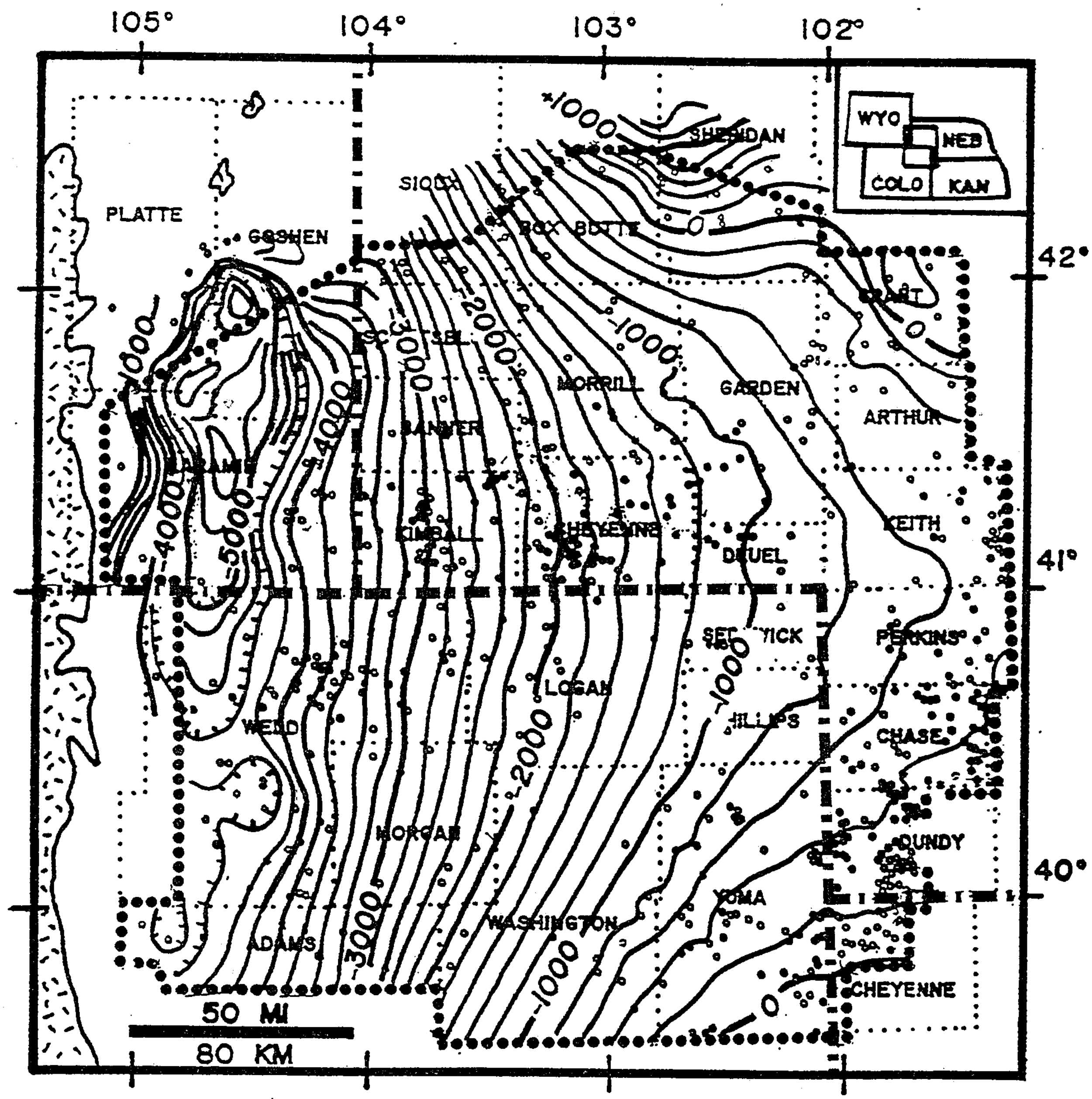


Figure 1-8. Structure drawn on top of Wolfcampian Chase Group, situated at base of salt-bearing interval. Contour interval 200 ft (60 m) except near the basin axis.

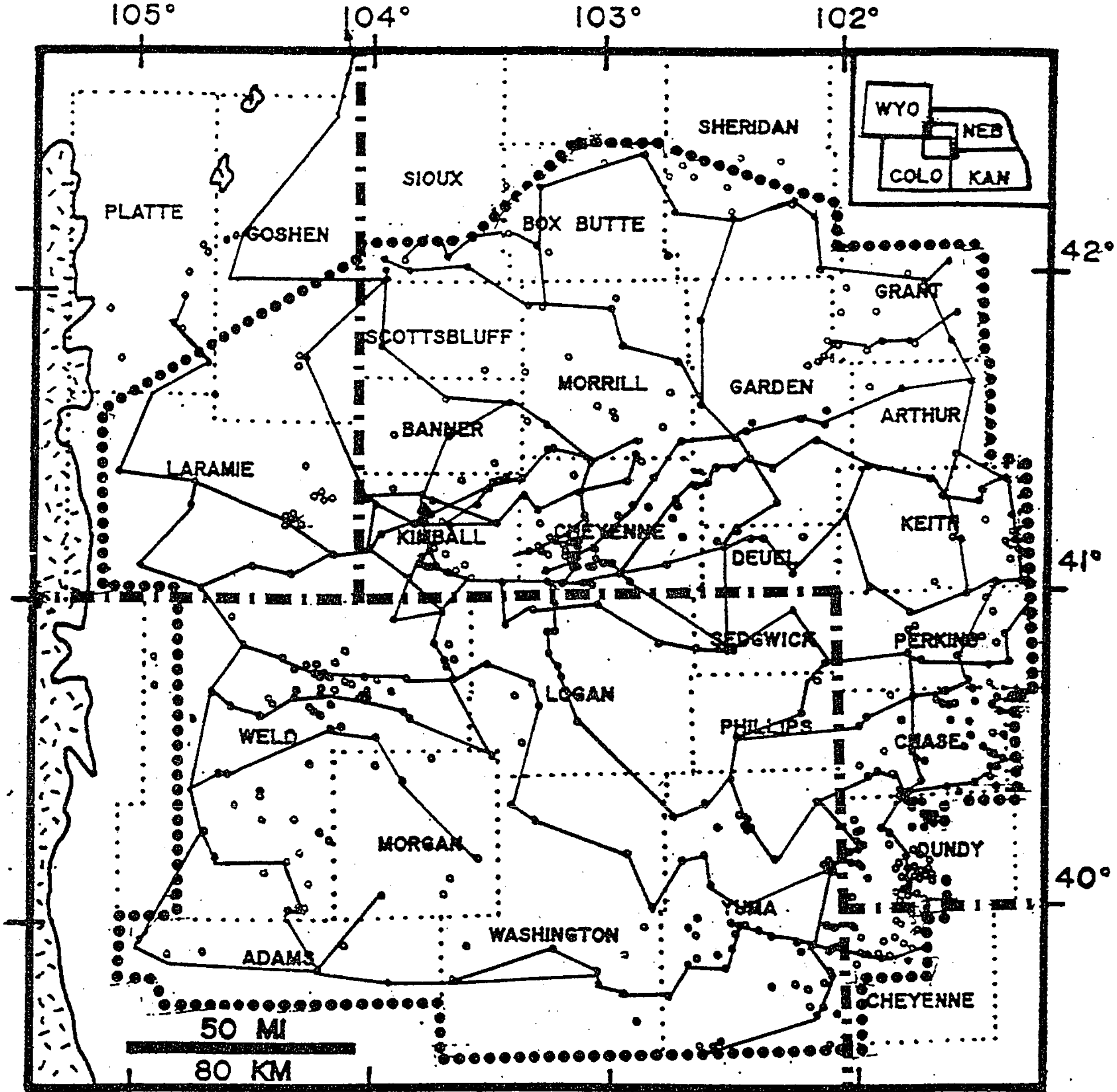


Figure 1-9. Paleozoic subsurface control and regional correlation network.

Commission, M-J Systems, and several oil and gas operators and individuals listed in the acknowledgments of this report. Well completion reports for most Paleozoic tests were provided by Petroleum Information Corporation.

Permian formation tops were initially identified independently of those reported by operators or shown on published cross sections, to reduce the possibility of bias and to ensure accurate internal correlations. Formation tops were subsequently correlated with those of previous workers in adjacent areas, in order to compare subsurface nomenclature.

Formation tops for the D Sandstone from over 9000 Cretaceous tests were used in more detailed studies that related oil- and gas-productive structures to the occurrence of deeper salts in the Nebraska panhandle and northeastern Colorado. Data from approximately 8000 of these tests were provided by Petroleum Information Corporation, and the remaining 1000 tops were derived from well logs.

Niobrara Formation tops, derived from 200 wells in the eastern Colorado Niobrara area, were used in a study of Eckley field and adjoining areas. Niobrara tops from 100 wells in Nebraska, just east of the eastern Colorado Niobrara play, were picked to study the application of a salt dissolution model to assigning exploration priorities.

Several additional types of data were analysed in subregional or field studies. These include: (1) cumulative oil and gas production data for over 400 fields in western Nebraska; (2) formation water salinity values for over 700 samples; and (3) gas production data and seismic reflection data for Big Springs and Eckley fields.

ORGANIZATION OF THIS REPORT

Most chapters of this report are organized into a series of papers which describe the occurrence of Permian salt and emphasize its influence on Cretaceous oil and gas entrapment at various scales across parts of the basin. Following an introduction and overview of the study in this chapter, Chapter 2 provides a brief overview of tectonics in the Denver basin area, a review of previous studies of the Permian in the region, a review of previous work relating subsurface salt dissolution to the entrapment of hydrocarbons, and a description of background work in the Denver basin. Chapter 3 focuses on the stratigraphy and subsurface correlations of the Permian salt-bearing interval and proposes a nomenclature for Leonardian and Guadalupian strata for use in the Denver basin subsurface.

Chapter 4 focuses on a subregional study area of a portion of the Nebraska panhandle (NP) which produces oil and gas from the Cretaceous D and J Sandstones. Chapter 5 is a study of Big Springs gas field (B), a D Sandstone producer situated near the eastern edge of the Nebraska panhandle study area.

Chapter 6 focuses on a subregional study area in eastern Colorado which produces gas from the Niobrara Formation. Chapter 7 is a study of Eckley gas field, a Niobrara producer situated within the eastern Colorado subregional study area.

Chapter 8 refocuses on the regional study area and presents the distribution of Permian salts and syndepositional and post-depositional controls on their occurrence. Regional relationships between salt occurrence and oil and gas entrapment are addressed in Chapter 9, along with a discussion of potential drilling problems associated with salts. Chapter 10 summarizes the results of this study and recommends further studies related to Permian salts in the basin.

CHAPTER 2
PREVIOUS WORK AND BACKGROUND FOR STUDY

This chapter includes: (1) a brief tectonic overview of the Denver basin area; (2) a review of previous regional studies dealing with the Permian System in the Rocky Mountain region and Denver basin area; (3) a review of previous work related to the occurrence, recognition, and origin of salt dissolution features in the subsurface, emphasizing their relationship to hydrocarbon entrapment; (4) a review of previous work related to salt dissolution in the Denver basin; (5) a summary of background work which led to the present study; and (6) a summary of the approach used in this study to identify salt dissolution features in the subsurface.

OVERVIEW OF TECTONIC ELEMENTS IN THE DENVER BASIN AREA

Montgomery (1987) perhaps most accurately described the Denver basin as a transitional depression between the Mid-Continent region to the east and the Rocky Mountain foreland to the west. The gently-dipping eastern flank of the basin gives way to a more steeply dipping and structurally complex western flank, which has been more influenced by tectonism at various times throughout the Phanerozoic.

The Denver basin acquired its present shape predominantly as a result of Laramide (Late Cretaceous - Eocene) orogeny. However, the area was strongly influenced by tectonic elements which existed as early as the Precambrian. Many north-northwest-trending Precambrian faults exist within the Colorado Front Range. These faults parallel the grain of present-day Rocky Mountain ranges as well as the Late Paleozoic Ancestral Rockies (Sonnenberg and Weimer, 1981). A number of northeast-trending Precambrian features also exist in the area. The largest of these comprise part of the Colorado lineament (Warner, 1978, 1980), a 100 mile-(160 km-) wide northeast-trending "San Andreas-type" Precambrian fault system which extends from the Grand Canyon region through the Colorado Rocky Mountains and Denver basin and as far northeast as Minnesota. Warner related the Colorado lineament to Precambrian fault zones along the Front Range and Hartville uplift areas (Figure 2-1), including the Colorado mineral belt (Idaho Springs - Ralston Creek shear zone)(1), the Moose Mountain shear zone (2), the Skin Gulch shear zone (3), the Mullen Creek - Nash Fork shear zone (4), and the Hartville or Whalen Creek fault (5). Warner suggested a relationship between the southeast margin of the Colorado lineament and the subsurface boundary between predominantly granitic (to the southeast) and metamorphic (to the northwest) terranes in Colorado (6,

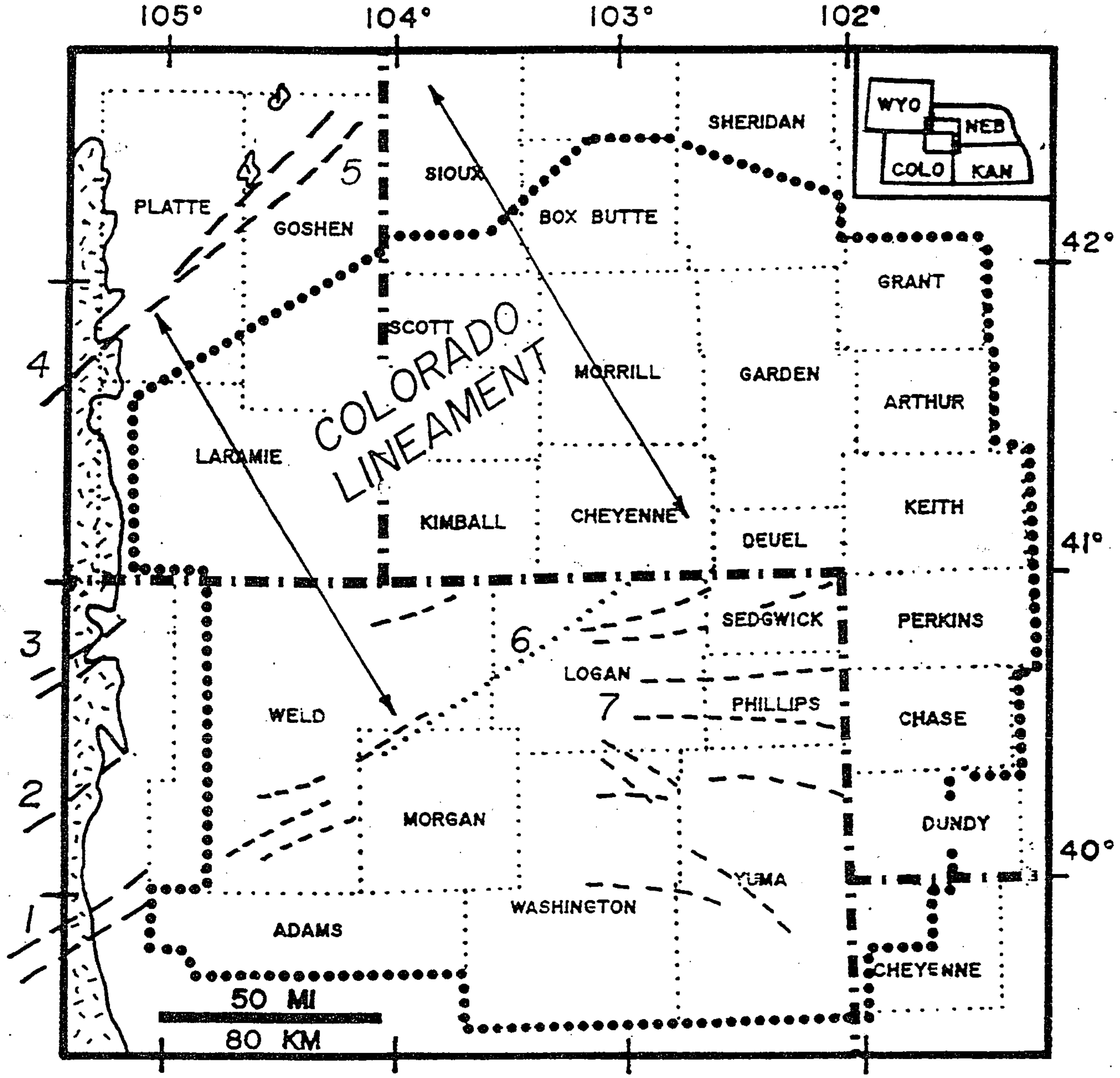


Figure 2-1. Location of Precambrian shear zones (1-5) and Colorado lineament (Warner, 1978, 1980), boundary between granitic and metamorphic terranes (6)(Edwards, 1963), and basement faults (7)(Tweto, 1980). Shear zones include the Colorado mineral belt (Idaho Springs - Ralston Creek shear zone)(1), the Moose Mountain shear zone (2), the Skin Gulch shear zone (3), the Mullen Creek - Nash Fork shear zone (4), and the Hartville or Whalen Creek fault (5).

Figure 2-1). Basement faults in northeast Colorado (7, Figure 2-1) are from Tweto (1980).

Certain Precambrian tectonic features influenced the location of paleotectonic elements which, in turn, controlled deposition and preservation of Paleozoic rocks (including Permian evaporites). One of the most important of these features is the Transcontinental arch (Figure 2-2), a northeast-trending structure, which is centered along the Colorado lineament. The Transcontinental arch was a broad positive area which was likely related to differential movement of basement blocks. Paleozoic thickness patterns in the Denver basin area (Figure 2-2) reflect the influence of the Transcontinental arch on deposition and preservation of sediments (Foster, 1972; Lochman-Balk, 1972; DeVoto, 1980a,b; Sonnenberg and Weimer, 1981; Billo, 1985). Cambrian and Ordovician rocks are confined to areas northwest and southeast of the Transcontinental arch. Mississippian rocks exist in the same areas and in the northwest-trending "Morgan County low" (Sonnenberg and Weimer, 1981), which also influenced accumulation of Pennsylvanian sediments. Permian paleotectonics are discussed in a following section of this chapter. The Transcontinental arch continued to influence deposition during the Late Cretaceous (Weimer, 1978).

Vertical and horizontal movement along faults can be identified or inferred from surface structural and

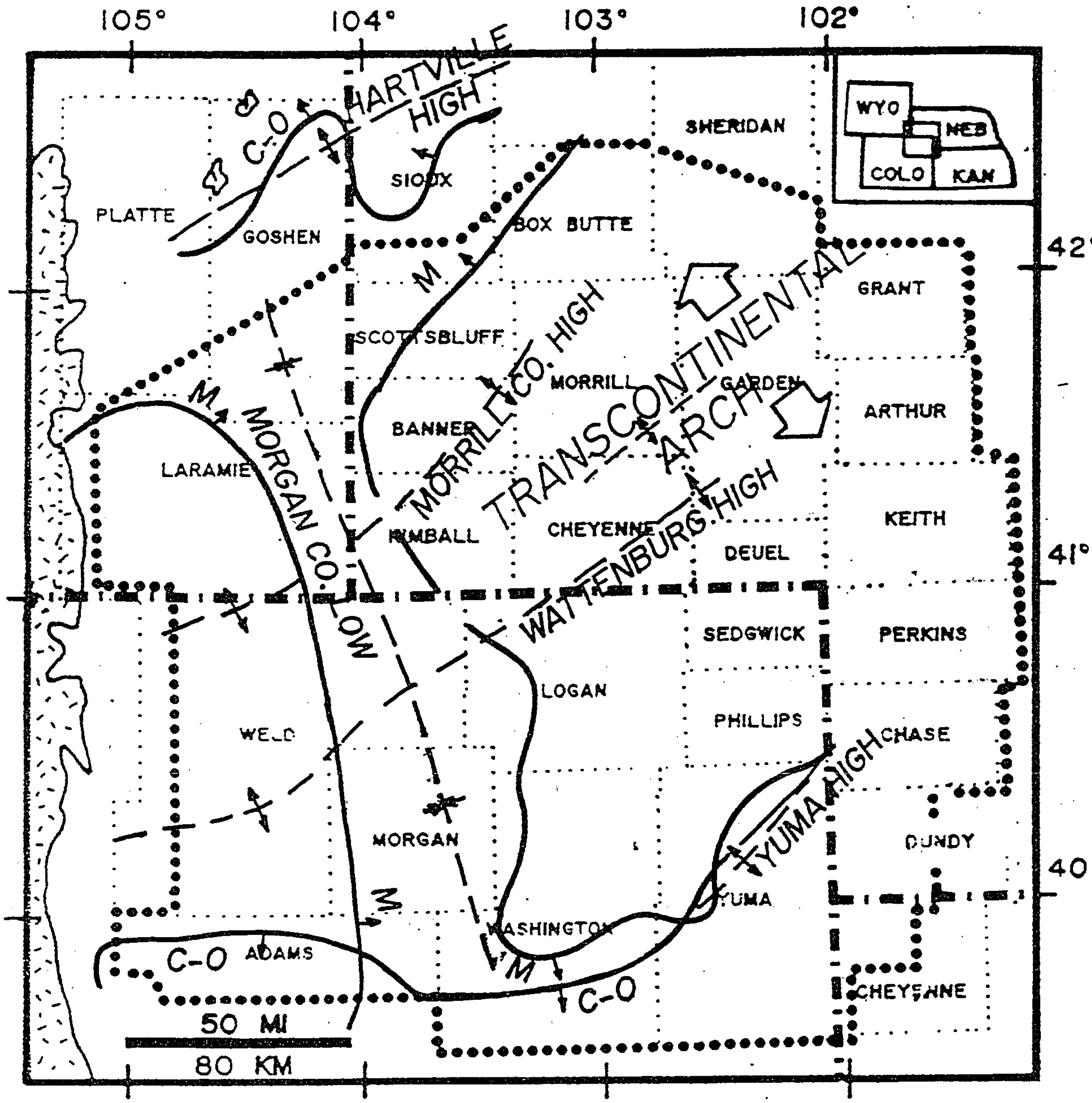


Figure 2-2. Location of limits of Lower Paleozoic rocks and Paleozoic paleotectonic elements (from Sonnenberg and Weimer, 1981). Ancestral Rockies (Late Paleozoic) were situated just west of the figure.

topographic features. Maughan and Perry (1986) identified a number of orthogonal lineaments which are related to structural and depositional patterns of Phanerozoic rocks across the Rocky Mountain region. Several of these (dashed lines on Figure 2-3) are reflected on the surface, including the Fanny Peak, Horn, Chadron, Sybille, Front Range Mineral Belt, and Canon City lineaments. The Front Range Mineral Belt lineament coincides with the Idaho Springs - Ralston Creek shear zone (southeast limit of the Colorado lineament, Figure 2-1) and Sonnenberg and Weimer's (1981) Wattenberg high (Figure 2-2). The Canon City lineament coincides with the Yuma high (Figure 2-2). The Chadron lineament parallels the present-day Chadron arch. The Sybille lineament coincides with the Mullen Creek - Nash Fork shear zone, the Whalen or Hartville fault (Figure 2-1), and the Hartville high (Figure 2-2).

Perry (1985) used Landsat imagery to identify 24 northwest- and northeast-trending lineaments in the northern Denver basin (solid lines on Figure 2-3). Perry related eight lineaments along the mountain flank to mapped basement structures and related 13 lineaments in the basin interior to basement structures inferred from subsurface mapping. Perry interpreted parallelism between mountain-flank and basin-interior lineaments as reflecting a similarity in structural fabric between basement rocks which are exposed along uplifts and those which are buried in the basin.

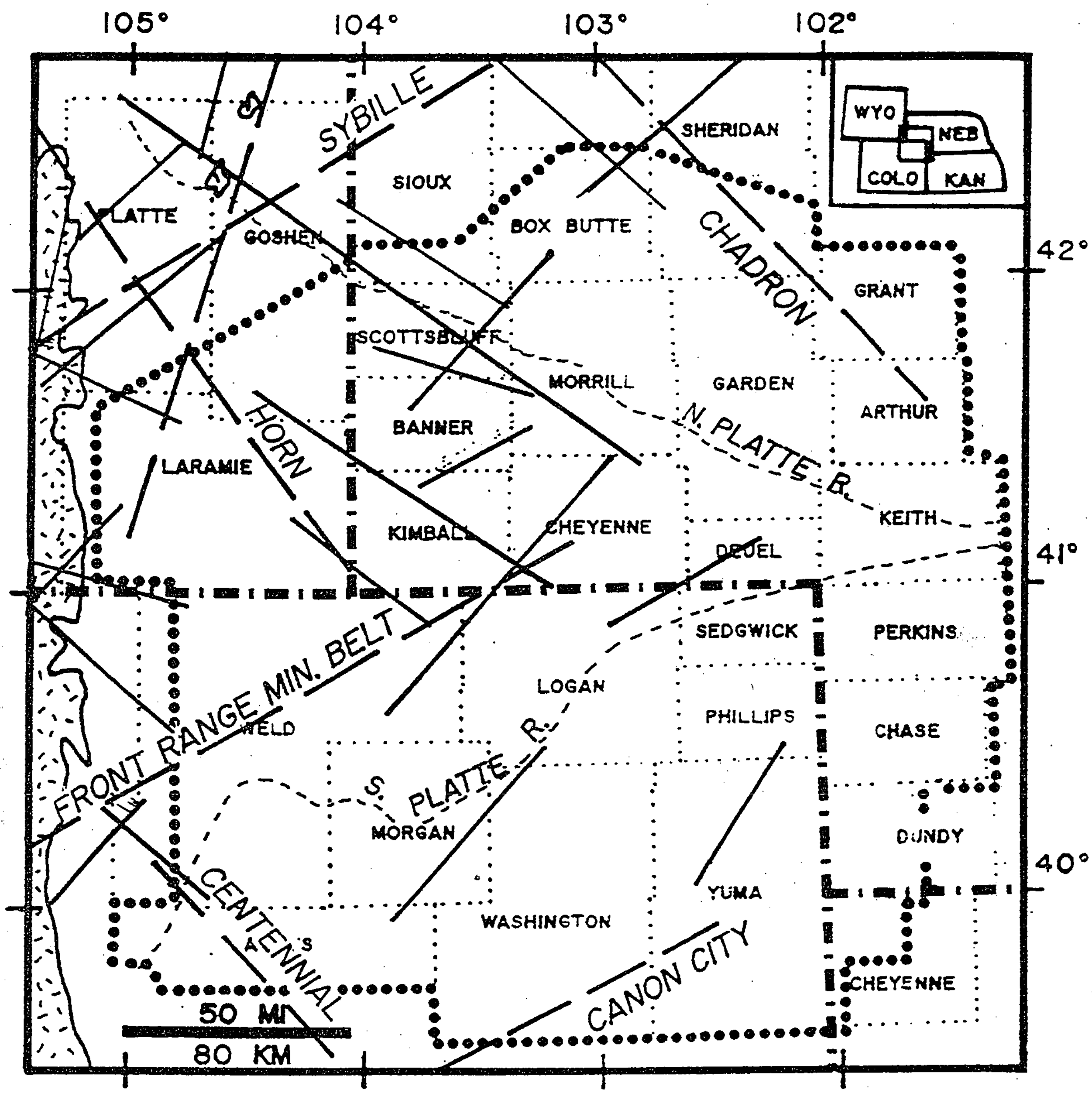


Figure 2-3. Location of lineaments of Maughan and Perry (1986) (dashed lines) and Perry (1985) (solid lines).

Perry related several lineaments to hydrocarbon production trends or limits of production. Merin and Moore (1986) conducted more detailed fracture analysis in the area surrounding Silo field in southeastern Wyoming.

Sonnenberg and Weimer (1981) noted that many workers considered northeast- and northwest-trending fracture systems to represent conjugate shear fractures which developed contemporaneously. They point out, however, that there is disagreement as to the sense of horizontal movement along shear zones: some workers suggest right-lateral movement on northwest fault systems and left-lateral movement on northeast faults, whereas others suggest left lateral movement on northwest faults and right lateral movement on northeast faults. Opposing views as to the sense of movement may be explained by recurrent (reversing) movement (Sonnenberg and Weimer, 1981).

Many basement faults were reactivated during the Cretaceous and in response to Laramide orogeny (Weimer, 1980, Tweto, 1980; Sonnenberg and Weimer, 1981). The principal horizontal stress in the Denver basin area changed from an east-northeast orientation during early Laramide (Late Cretaceous to Paleocene) to a northeast orientation during late Laramide (Eocene) (Chapin and Cather, 1983; Gries, 1983). Moore and Merin (1986) discussed changes in movement along pre-existing fractures in response to changes in orientation of maximum compressive stress.

Location, orientation, and timing and sense of movement along basement faults on uplifts and within the Denver basin is of interest to this study for the following reasons: (1) Basement faulting during the Late Paleozoic would have influenced the configuration of Permian evaporite basins. This would have affected the geometry, depth, and circulation patterns during evaporite precipitation, and thus the thickness and original distribution of Permian salt and related strata; and (2) Basement faults may have controlled subsequent movement of fluids in the subsurface which have acted to dissolve salt at various times since their formation.

REGIONAL PERMIAN STUDIES IN THE WESTERN UNITED STATES

The Permian System in the Rocky Mountain and Mid-Continent regions ranges in thickness from zero (due to truncation in some areas, non-deposition in others) to over 7000 ft (2000 m) in the Paradox basin of western Colorado and eastern Utah (McKee, Oriel, et al., 1967a,b). The interval increases in thickness to the south, where over 17,000 ft (5000 m) of Permian-age rocks are present in the Permian basin of west Texas and southeastern New Mexico. An abrupt thickening of the section occurs in the western Rocky

Mountain region, where observed or inferred thicknesses exceed 9000 ft (3000 m).

The Permian System in the United States is divided into four series, in ascending order: Wolfcampian, Leonardian, Guadalupian, and Ochoan. European equivalents to the North American series are Asselian-Sakmarian, Artinskian, Kungurian-Ufimian-Kazanian-Lower Tatarian, and Upper Tatarian Stages, respectively (Baars, 1990). Extensive investigations of the Permian system in the conterminous United States by U.S. Geological Survey geologists were compiled and reported in McKee, Oriel, et al. (1967a,b) in which a three-fold subdivision of the Permian System was adopted: Interval A, Interval B, and Interval C-D, which generally correspond to Wolfcampian, Leonardian, and Guadalupian-Ochoan Series, respectively. Interval C-D was given a two-letter designation because of uncertainties regarding precise ages of uppermost Permian units. The Ochoan is not represented in the Rocky Mountain region, and Rascoe and Baars (1972) noted that rocks of Ochoan age can be identified with certainty only in west Texas.

Classic work on the Permian within and surrounding the Denver basin study area was published in the early 1900s by Darton (1904) and Schuchert (1910). Later, Heaton (1933) (followed by minor revisions in 1937 and 1950) related the development of the "Ancestral Rockies" to Late Paleozoic and Mesozoic stratigraphy of the Rocky Mountain region. Using outcrop sections from seven western states, Heaton constructed a series of stratigraphic cross sections which correlated the Upper Paleozoic and Mezozoic formations. On the basis of the cross sections, he developed a series of paleogeographic maps. His paleogeographic interpretation for Permian time shows the existence of a marine basin in parts of Wyoming, Idaho, Utah, Nevada, and Arizona, and salt, gypsum, and red bed deposition in the northeastern portion of his study area. Although Heaton did not attempt to subdivide the Permian, his work served as a remarkably accurate basis for later studies, particularly considering that at the time little or no subsurface data were available.

Bartram (1939) presented a summary of Rocky Mountain geology, from Precambrian to Recent, emphasizing stratigraphy over structure. In his discussion of the Permian, he noted the existence of evaporite basins in parts of Colorado and Nebraska, and the occurrence of thick limestone accumulations to the west in the Cordilleran geosyncline.

Regional stratigraphy of the Mid-Continent from Precambrian through Cretaceous was outlined by Dott (1941), who discussed the subdivision and correlation of Wolfcampian, Leonardian, and Guadalupian rocks exposed in parts of north Texas, central and northern Oklahoma, Kansas, Nebraska, and Iowa. By this time, hundreds of oil and gas wells had been drilled in the Mid-Continent. Dott utilized log and sample data, in conjunction with surface exposures, to demonstrate a southward transition from redbeds to evaporites to a deep marine basin (Permian basin of west Texas) and a decrease in age of principal salt beds southward from Kansas to Texas.

Eardley (1949) presented a series of paleotectonic and paleogeologic maps of central and western North America from Early Paleozoic to Late Mezozoic time. The paleotectonic maps were intended to show the extent of tectonically-active areas at selected time intervals. His Permian paleotectonic map shows the development of the Permian and Anadarko Basins and deep troughs to the west along with a broad platform area over much of the northern Mid-Continent and Rocky Mountain regions.

The tectonic history of the Denver basin from Cambrian through Tertiary was reviewed by McCoy (1953). During the Permian, the "Ancestral Rocky Mountains" were represented by two positive elements, termed "North Park positive" and "Uncompahgre positive", located in northcentral and southwestern Colorado, respectively. Another area of uplift, the Siouxia positive, was centered in northcentral Nebraska. McCoy noted that the Permian was a period of almost continuous deposition in the Denver basin area. Red beds and evaporites were deposited in shallow oscillating seas advancing into and retreating from restricted or landlocked basins and salt flats. McCoy extended the axis of the Anadarko basin northwestward from Kansas through the northeastern corner of Colorado into the northwestern corner of Nebraska.

Juilfs (1953) prepared an electric log cross section across southcentral and southwestern Nebraska as part of a subsurface study of Pennsylvanian and Permian rocks. He noted a general thinning of the Pennsylvanian-Permian section across the Cambridge arch, with a westward thickening in the Denver basin accompanied by a marked increase in evaporites. Juilfs attributed difficulties in correlation of parts of the section to a westward decrease in fossil content, which resulted from more restricted marine conditions in this area.

Agatston (1954) concluded that an evaporite basin formed in southeastern Wyoming and adjacent parts of South Dakota and Nebraska during early Wolfcampian time. Carbonates and sandstones were deposited along the fringes of the basin. He observed abundant bryozoan and crinoid remains, along with fusilinids and brachiopods, in time-equivalent carbonates exposed to the west.

A series of Pennsylvanian and Early Permian isopach and lithofacies maps of the northern Denver Basin prepared by Hoyt (1962) indicates decreasing clastic ratios in progressively younger strata. Hoyt concluded that the Hartville uplift area was a positive during late Wolfcampian time. During the same year, Rascoe (1962) published a series of Pennsylvanian and Lower Permian lithofacies and isopach maps, which covered a portion of the western Mid-Continent area of northern Texas, northern Oklahoma, southeastern Colorado, and southwestern Kansas. His interpretations show deposition of shelf carbonates and shales during Wolfcampian time, while an evaporite basin was forming to the north in Hoyt's (1962) study area.

Tenney (1963) included a discussion of the Lower Permian in his paper on Pennsylvanian and Permian deposition in Wyoming and adjacent areas. At the close of Wolfcampian deposition, in addition to marine sandstone, shale, carbonates, and evaporites, massive, high-angle cross-bedded eolian sandstone was deposited. During this time subsidence occurred over a large portion of eastern Wyoming and adjacent areas of Nebraska and Colorado. This marked the transgression of the cold-water "Phosphoria sea", and resulted in the deposition of the phosphate-rich Phosphoria Formation concurrent with the formation of evaporites and associated rocks of the Goose Egg Formation in eastern Wyoming and adjacent areas. With continued subsidence, the Phosphoria sea eventually onlapped the shallow shelf area, resulting in deposition of widespread limestone tongues.

By the 1960s exploratory activity in the Denver basin and surrounding areas had provided adequate deep subsurface information to begin to relate Paleozoic thickness and lithofacies variations to paleotectonics. Momper (1963) related a Permian isopach maximum centered along the Wyoming-Nebraska border to the presence of Wolfcampian, Leonardian, and Guadalupian salt. A second Permian isopach maximum in northeastern Colorado was associated with Leonardian salt. A northeast-trending isopach minimum, centered in western Nebraska, separated the two areas of salt accumulation.

MacLachlan and Bieber (1963) used the term "Morrill County high" for the northeast-trending barrier which separated the two areas of thick Permian rocks and salt accumulation. The authors also applied the name "Alliance basin" to the northern depression situated between the Hartville uplift, Chadron arch, and Morrill County high. The Morrill County high was believed to be the last expression of the Transcontinental arch (or Siouxia), a broad positive feature which influenced sedimentation throughout the Paleozoic.

Martin (1965) was apparently the first to use the term "Sterling basin" for the area of thick Permian strata and halite accumulation in northeastern Colorado. Martin believed the salts of the Sterling basin to be of Wolfcampian age.

Meissner (1967) summarized regional thickness and lithofacies variations of Leonardian and Guadalupian strata, relating variations to major tectonic elements which were present during the Permian. Relatively thick deposits of dark phosphatic shale, chert, and cherty carbonates (basinal Phosphoria Formation) were deposited in the Cordilleran geosyncline of eastern Idaho and western Wyoming. The basinal facies intertongue with, and laterally grade into, a shelf-margin carbonate facies (Park City Formation) in western and central Wyoming. Farther east, the Goose Egg Formation, composed primarily of redbeds (sandstone and shale), replaces the Park City Formation carbonates. The presence of evaporites (anhydrite and halite) increases eastward, in southeastern Wyoming, western Nebraska, and northeastern Colorado (the present study area).

Southeast of the present study area, Meissner demonstrated thinning Leonardian and Guadalupian rocks across the Las Animas arch in eastern Colorado and western Kansas. South of this area, the interval increases in thickness in the Anadarko basin, reaching its maximum thickness in the Permian basin of west Texas and southeastern New Mexico, where the Permian is represented by carbonates, evaporites, and thick basinal sandstone.

Comprehensive discussions of the Permian System in the United States were presented as a series of region-by-region reports and interpretive maps in McKee, Oriel, et al. (1967a), and, as a supplementary volume, in McKee, Oriel, et al. (1967b). These two volumes represent the third in a series of paleotectonic investigations, each covering a geologic system in the conterminous United States. Work on the Permian System involved 15 U.S. Geological Survey geologists, covering 18 regions. Their work resulted in the first effort to map the distribution of salts across the region which includes the present study area (Figure 1-4).

While McKee, Oriel, et al. (1967a,b) were in press, Maughan (1966), one of the 15 USGS geologists, presented a number of preliminary conclusions regarding deposition of Permian salt in the northern Mid-Continent. Maughan's primary focus was on the deposition of halite and related evaporites of Leonardian (Interval B) and Guadalupian (Interval C-D) age in the Williston basin of western North Dakota and the Alliance basin of western Nebraska. He concluded that prevailing winds from the north resulted in upwelling currents in the Phosphoria sea, which was occupying a basin (an eastern extension of the Cordilleran geosyncline) in western Wyoming and eastern Idaho. Little evaporation of the cold water occurred; any moisture that was evaporated was removed southward by prevailing winds, rather than eastward across the craton. The Williston and Alliance intracratonic basins were connected to the Phosphoria sea to the west by a narrow trough in Wyoming, which served as an inlet for seawater influx. Maughan (1966) presented a diagrammatic cross-section of Permian rocks across parts of Wyoming and Nebraska. Phosphate, chert, and organic-rich shale of the Phosphoria Formation formed in the Phosphoria sea of eastern Idaho and western Wyoming. Along the cratonic shelf edge, carbonates of the Park City Formation were deposited. Shale and anhydrite of the Goose Egg Formation were deposited on a more or less stable shelf in central and eastern Wyoming. Two widespread carbonate units, the Minnekahta and Forelle Limestone Members, occur within the Goose Egg Formation, and represent periodic transgressions of the Phosphoria sea, and, possibly variations in the direction and strength of currents in the shelf lagoon (Maughan, 1966).

Maughan (1966) used late Leonardian and Guadalupian lithofacies interpretations to relate the distribution of evaporites in the Alliance and Williston basins to the occurrence of phosphorite and chert in western Wyoming. Channels, which connected these two restricted basins to the Phosphoria sea, were associated with the presence of narrow carbonate bands in eastern Wyoming.

Sonnenberg and Weimer (1981) took advantage of additional subsurface control provided in the 1970s to conduct a subsurface stratigraphic analysis of the northern Denver basin. The authors attributed thickness variations of Paleozoic and Mesozoic strata to the development of paleostructure.

Figure 2-4 is adapted from Sonnenberg and Weimer's "Upper Permian" (intervals B-D, or Leonardian and Guadalupian) isopach interpretation. Over 800 ft (200 m) of

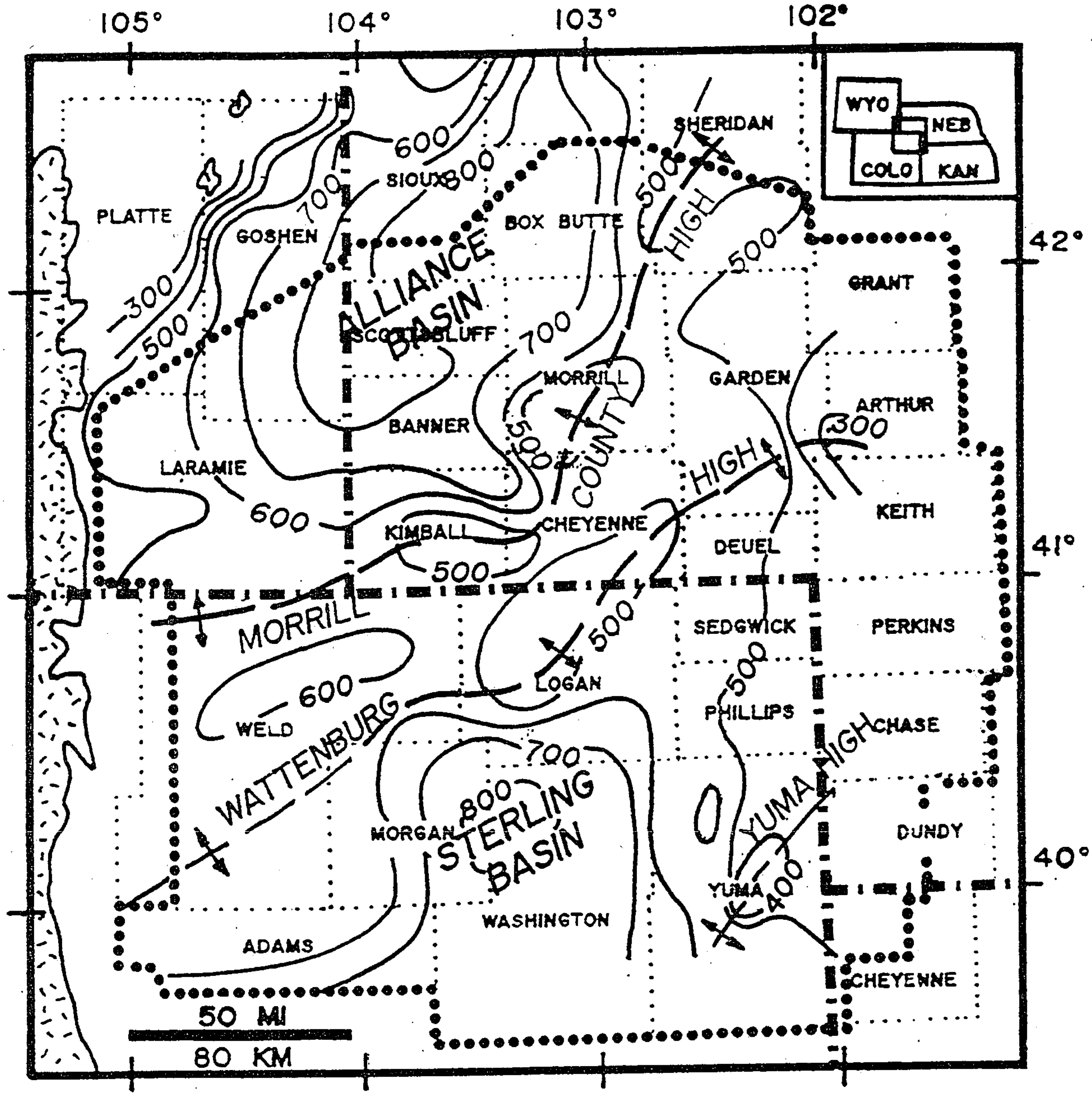


Figure 2-4. Isopach map of "Upper Permian" (adapted from Sonnenberg and Weimer, 1981). Sonnenberg and Weimer's "Upper Permian" interval is roughly equivalent to the combined Leonardian and Guadalupian of this study.

Leonardian and Guadalupian strata were observed in the Alliance and Sterling basins, including a large volume of salt and anhydrite. Thinning of the interval along the northeast-trending Morrill County and "Wattenberg" highs, as well as along the "Yuma" high, was attributed to convergence over paleostructural elements. Sonnenberg and Weimer observed that the thickest accumulations of Lyons Sandstone (Leonardian) were coincident with thinning of the Leonardian-Guadalupian interval along the Morrill County and Wattenberg highs.

Discovery of oil in Wolfcampian and deeper reservoirs in western Nebraska during the 1980s prompted more recent regional stratigraphic studies (Garfield et al., 1988; Rall and Loeffler, 1994; Rall, 1996). These studies focus on the subsalt interval rather than the Leonardian and Guadalupian.

INFLUENCE OF SALT DISSOLUTION ON HYDROCARBON ENTRAPMENT

Dissolution of salt and related evaporites in the subsurface has been the focus of a number of studies, covering a wide range of geologic settings. Depending on the geologic conditions that exist within a given area, salt dissolution and resultant surface and subsurface collapse can cause local and regional modifications that have implication to petroleum generation, migration, reservoir distribution, porosity and permeability enhancement or reduction, and trap and seal development. Many of the papers reviewed in this section deal with a direct relationship of salt removal by dissolution to entrapment of oil and gas. Other papers, which may not directly relate to hydrocarbon accumulation, are included because they address the mechanism of salt dissolution at depth or the recognition of salt-dissolution features.

Much of the early work which dealt with subsurface salt dissolution focused on the Permian basin area. Adams (1944), in a study of the Ochoan of the west Texas Delaware basin, noted extensive salt dissolution at the contact between the Castile and Salado Formations. A north-south trough extending along the center of the salt basin was recognized in the subsurface. The trough was formed by pre-Salado solution of near-surface Castile salts. An anomalously thick section of Salado salt and anhydrite filled the trough. Additional dissolution took place during post-Salado time, in response to uplift along the west edge of the Delaware basin. A series of parallel solution valleys, separated by resistant gypsum ridges, were formed by surface dissolution of outcropping salt beds. The irregular surface was covered by basal sediments of the Rustler Formation. The origin of these solution-subsidence troughs was the subject of a study by Olive (1957). A period of salt dissolution occurred during the Triassic, as evidenced by an 800- to 900-ft (200- to 300-m) deep Triassic sediment-filled trough along the east edge of the Delaware basin.

Adams (1944) called upon slight warping along the Capitan reef to open fractures through which circulating ground waters could enter. Significant salt dissolution occurred during the Tertiary. Adams noted a synclinal solution trough exceeding 1300 ft (400 m) in depth filled with Tertiary sediments. He discounted salt flowage as a cause of solution troughs and cited the uniformity of salt and related sediment thickness up to the very edges of the solution valleys as evidence in favor of subsurface dissolution.

Maley and Huffington (1953) were in agreement with Adams (1944) that the most significant subsurface dissolution of salt took place during the Tertiary, noting that increased thickness of Cenozoic fill coincides with a decrease in combined salt thickness in the Castile and Salado Formations. Maley and Huffington believed that saturated subsurface fluids were recirculated near enough to the surface to enter the Pecos River drainage system. They noted the formation of salt crystals along the banks of the Pecos River and salt springs as evidence of salt dissolution at depth. Localized salinity increases in Pecos River water had been observed earlier by Adams (1944).

Vine (1960) observed several domal features on the surface in southeastern New Mexico. Although he offerred several explanations for arching that caused the localized domes, he proposed differential solution of the Upper Permian salt-bearing section as one mechanism. Initial solution caused a central collapse area, infilled by breccia, and localized sediment fill. Continued dissolution along the margins of the collapse area caused an inversion of structure, with the former collapse area changing to a positive structural feature.

Anderson et al. (1978) recognized persistent dissolution breccias in the western part of the Delaware basin, and found that the breccias are stratigraphically equivalent to halite beds in the eastern part of the basin. They concluded that all of the western salt-bed margins were caused by dissolution rather than depositional thinning. Dissolution of salt along the western basin margin proceeded downdip, in places removing salt over distances in excess of 20 mi (30 km). Localized extensive dissolution caused significant collapse features such as the Big Sinks depression, where 300 ft (90 m) of lower Salado salt has been removed; a matching structural depression occurs on top of the overlying Rustler Formation.

Anderson and Kirkland (1980) invoked brine density flow as a mechanism for dissolution of salt deposits. Dense brines that form from salt dissolution flow downward along separate pathways within the same fracture system or permeable zone as rising fresh water that is being supplied by an artesian source. They proposed that undersaturated water within the Delaware Mountain Group, which underlies the salt deposits in the western part of the Delaware basin, moved upward under artesian pressure through fractures, where it contacted the salt. The resulting brine, because of its higher density, flows downward and eastward, where it is removed through the San Andres Limestone.

Mercer and Hiss (1978) attributed the development of fractures and joints through which fluids flowed to differential compaction and regional tectonism. The activity of bacteria (introduced by meteoric waters) caused biogenic replacement of anhydrite by calcite, resulting in a 10 percent increase in fracture permeability (Anderson and Kirkland, 1980).

In a study of a portion of the Texas panhandle, Gustavson and Budnik (1985) called upon regional stress conditions to explain a preferential northeast trend of salt-solution features. Northeast-directed maximum compressive stress is believed to keep northwest-trending fractures closed, while northeast-trending fractures remain open. Accelerated salt dissolution took place within northeast-trending faults and fractures resulting from differential basement movement. Gustavson and Budnik concluded that dissolution has occurred from as early as the Miocene to as recently as the Quaternary.

Reeves and Temple (1986), in a study of salt dissolution in the Texas panhandle, noted an association of alkaline lake basins and underlying salt solution. They were unable to conclude, however, whether surface lake basin formation was due to salt subsidence or whether subsurface salt dissolution was caused by infiltration of lake waters from the surface.

Though not related directly to deeper oil production, salt solution was recognized in the subsurface at Yates field, a giant oil producer in west Texas (Adams, 1940). In his interpretation, a surface anticline (mapped on the Cretaceous) resulted, in part, from salt dissolution. The surface structure was believed to be caused by a salt outlier flanked by a solution syncline. Recent work (Wessel, 1988; Wessel, 1993) discussed the influence of salt dissolution on surface structure at Yates field.

Lohman (1972) discussed the distinction between subsurface karst formation and salt leaching. He noted that karst processes result in fissures, caverns, and collapse features, while salt dissolution can completely remove halite and potassium salts, leaving only residual carbonate and anhydrite sediment and insoluble residue. The karst process assumes a linear pattern along fractures or more soluble parts of the formation, whereas salt leaching is more of a "frontal attack." If depth is sufficient to allow for plastic flowage of salt, the relative rates of flowage and dissolution can combine to produce three different results: (1) a collapse structure, if dissolution is faster than upward flow of salt; (2) little evidence of leaching, if the two rates are equal; and (3) development of a salt stock if salt flowage exceeds the rate of dissolution.

The term "subrosion" has been used in German literature as early as 1930 for subsurface features related to dissolution of Permian and Triassic salt (Lohmann, 1972). If dissolution progresses to produce a wide zone of salt removal, a "salzspeigel" - salt mirror, forms, which, according to Lohmann, is difficult to recognize by geophysical methods unless the overlying strata are faulted. As dissolution proceeds laterally, the margin of remaining salt (the locus of continued leaching) is termed the "salt slope".

Lohman (1972) offerred several implications for petroleum prospecting in his discussion of salt dissolution:

1. primary collapse-fill materials (dissolution residues and collapsed sediments) may possess enhanced reservoir quality;

2. secondary-fill materials, deposited within salt dissolution-induced lows, may promote stratigraphic entrapment of petroleum; and

3. salt solution features may be an indication of fresh water circulation which acted to destroy petroleum accumulations.

Salt dissolution may affect the distribution of energy minerals other than petroleum. The distribution of Tertiary lignite deposits in Germany is related to solution-induced subsidence basins caused by Permian salt dissolution (Lohmann, 1972). Late Cretaceous - Tertiary removal of salt from the Elk Point evaporite basin (Devonian) in southern Saskatchewan influenced the distribution of thick Paleocene coal seams (Broughton, 1977). Groundwater responsible for salt dissolution is believed to have been introduced from the emerging Rocky Mountains along reactivated basement faults. Heavy oil of the Athabasca tar sands area of Alberta accumulated in traps associated with dissolution of Devonian salts (Vigrass, 1968).

Jenyon and Taylor (1985) presented a summary of salt-solution features associated with North Sea Zechstein salt, noting several important characteristics:

1. salt-solution structures can be both positive and negative;
2. single-stage dissolution will produce a basinward rollover structure; and
3. two-stage dissolution will produce a structural inversion, wherein a thick sediment wedge which was deposited during the first stage becomes a localized high with continued lateral dissolution of salt (a "sombrero" structure).

"Two-stage" dissolution of the Prairie salt (Devonian) was originally invoked by Swenson (1967) to explain oil production from the Devonian Nisku Formation in the Williston basin. During the first solution stage, Souris River Formation carbonates were deposited in the solution sink. A second, more widespread solution event occurred, resulting in removal of salt from the area surrounding the buried sinks. A positive structure is generated at the site of early solution, due to the additional Souris River carbonate interval which had been deposited. Swenson listed steep sides and flat tops as characteristics of salt solution-related structures.

The Williston basin has been the site of the majority of salt dissolution studies in western North America. Anderson and Hunt (1964), suspecting that gravity anomalies in northcentral North Dakota may be due to Prairie salt dissolution, constructed a series of subsurface maps in an effort to delineate the salt edge. Anomalous thickening of Mississippian formations (below which Prairie salt is absent) was interpreted to be due to compensatory thickening which resulted from collapse of underlying beds. Langstroth (1971) used seismic data to refine Anderson and Hunt's (1964) Prairie salt solution edge. Surjik and Hobson (1964) were able to use seismic data to delimit the edge of the Prairie salt in Saskatchewan.

Parker (1967) presented additional examples of salt dissolution within Anderson and Hunt's (1964) study area, and in several other areas of the Williston basin of North Dakota and Montana. Parker and Hess (1980) attributed the increased fracturing of Mississippian reservoir rocks at MonDak field to removal of Devonian salt by dissolution.

Ogelsby (1988) concluded that the Prairie salt in the Williston basin underwent dissolution from two directions: (1) dissolution of salt from the top downward, caused by tectonic fracturing which allowed the introduction of fluids from overlying aquifers, and (2) upward-directed flow of water localized by the presence of pinnacle reefs in the Winnepegosis Formation. McTavish and Vigrass (1987) also observed that, in addition to fracture-related dissolution features, salt removal is localized above Winnipegosis reefs, and that formation-water salinity anomalies can be mapped in the vicinity of the dissolution front. Gerhard and Anderson (1990) noted that dissolution has taken place wherever Prairie salts have been juxtaposed with major fault systems.

Other examples of oil accumulations associated with salt solution in the Williston basin and western Canada include Fryburg field (Anderson, 1966; Parker, 1967). Hummingbird field (Bishop, 1974; Smith and Pullen, 1967; Bishop, 1976), Rainbow field area (Barss, et al. (1970), Poplar Dome (Orchard, 1987), Outlook field (Sandberg, 1961; Parker, 1967;), McCabe field (Rogers and Mattox, 1985), and Westhazel GP pool (Anderson and Cedarwall, 1993).

Rogers and Mattox (1985) cited ten clues to the recognition of salt solution on seismic data:

1. abrupt terminations of all or part of the salt reflector;

2. apparent structural anomalies adjacent to deep-seated faults;

3. abrupt offset of reflectors above salt (indicating collapse);

4. structures above salt that show no paleogrowth;

5. local draping of reflectors above flat, non-continuous salt reflectors;

6. regional sagging of reflectors above salt in areas where no deeper syncline is apparent;

7. sagging of reflectors above and near teminations of salt reflections (indicating velocity problems);

8. onlap of reflectors above and near terminations of salt reflectors (indicating compensational thickening);

9. waveform changes in reflectors above salt section; and

10. any structure below the salt (a possible sign of velocity problems).

Simpson (1978), in a study of salt dissolution in the northern Williston basin, listed six mappable stratigraphic and geomorphologic features arising from solution-influenced collapse of strata:

1. evaporite sequence anomalously thin or absent; also forms isolated prominences;

2. collapse breccias with upward decrease in matrix;

3. fracture-bounded, subcircular or elongate sinks as anomalies on overlying structure maps;

4. anomalous anticlinal features (pseudo-anticlines);

5. anomalous, isopachous high values in post-evaporite strata; and

6. dependence of ancient and modern drainage patterns on antecedent trends in post-evaporite strata.

In a summary of large-scale mechanisms of Prairie salt dissolution in western Canada, Anderson and Knapp (1993) concluded one or more of the following processes initiated or enhanced salt removal:

1. centrifugal flow of water (vertically and laterally), in response to burial and compaction;

2. near-surface exposure, due to the chemical instability of salt at or near the surface;

3. centripetal flow of water into the basin from surrounding highland areas;

4. local or regional faults and/or fractures which act as lateral or vertical fluid conduits;

5. glacial loading, which induces subsidence and expulsion of formation water, thereby increasing the rate of centrifugal flow, or glacial unloading, which can increase porosity and permeability of subsurface strata, enhancing centripetal flow;

6. dissolution of underlying salt, creating fracture permeability in overlying rocks, allowing for introduction of fluids to younger salts; and

7. salt creep, causing faulting and fracture development, allowing for fluid introduction.

LeFever and LeFever (1995) summarized models for the the removal of Prairie salt in the Williston basin:

1. facies-controlled fluid movement through permeable beds that are adjacent to salt;

2. fluid derived from compaction and dewatering of surrounding sediments (centrifugal flow); and

3. basinward flow provided by surface water recharge at the outcrop (centripetal flow).

Although not directly related to hydrocarbon production, additional examples of salt dissolution features in the Williston basin and adjacent areas are given in DeMille et al. (1964), Christiansen (1967), Christiansen (1971), Gendswill and Hajnal (1971), and Oliver and Cowper (1983).

In studies of the Holbrook basin (Supai salt basin) of Arizona, Neal (1994) invoked regional removal of Permian Supai salt for the formation of the Holbrook anticline. Neal, noting that flexure is absent at depth, discounted a tectonic origin for the structure.

Subsurface removal of salt by dissolution is not limited to the western United States and Canada. Landes (1962) attributed abrupt thinning of Salina salt in Michigan to dissolution. Solution-collapse structures in the Michigan basin were observed by Ells (1967), Johnson and Gonzales (1976), and Catacosinos (1990). Kelley and McGlade (1969) related dissolution of salt in the Salina Series to the formation of structural traps at the Oriskany sandstone level in northwestern Pennsylvania.

Grieve (1955) concluded that the introduction of normal marine waters through fractures resulted in removal of Salina salt from as early as late Salina time, continuing intermittently through the Devonian in southwestern Ontario. Sanford et al.(1985) demonstrated that dissolution of Salina salt resulted in formation of hydrocarbon-productive collapse structures in southwestern Ontario, attributing periods of accelerated dissolution to plate movements. In fact, North (1985) noted that the earliest oil field discovered by drilling in North America (located in southwestern Ontario) produced from a salt-solution trap.

Closer to the Denver basin, Rasmussen and Bean (1984) related solution collapse of Permian salt to Mesozoic depositional trends in the Powder River basin of Wyoming. Using both subsurface well logs and seismic data, the authors demonstrated that numerous Cretaceous stratigraphic traps (whose productive reservoir is the Muddy Sandstone, which is correlative with the J Sandstone of the Denver basin) formed as a result of syndepositional dissolution of underlying salt. Rasmussen and Bean concluded that complete removal of salt was prevented by deposition of Upper Cretaceous marine shales, which acted to seal the groundwater circulation system. Salt-collapse structures were previously observed in the Powder River basin by Parker (1967). Moore (1985) presented seismic examples of salt dissolution features in the Powder River basin.

To the southeast of the Denver basin study area in Kansas, salt-dissolution features were observed by Landes (1962), who related a line of swamp- and lake-filled depressions located just east of Hutchinson to the truncated edge of underlying Permian salt. Other salt solution-induced surface depressions in Kansas were described by Frye

(1950) and Merriam (1963). Holdoway (1978) and McQuire and Miller (1989) included subsurface examples of salt dissolution in western Kansas. Sorenson (1995) mapped a salt-dissolution zone in southwestern Kansas and concluded that the overlying Harper and Cedar Hills (Lyons equivalent) sandstones are the source of groundwater responsible for salt removal.

Figures 2-5 through 2-9 summarize factors which influence subsurface removal of salt by dissolution, dissolution-induced structural and stratigraphic features that are potential sites for hydrocarbon accumulation, shallow geologic conditions caused by salt removal at depth, and dissolution-induced situations which can adversely affect hydrocarbon accumulation. Location and timing of salt dissolution in a basin may be influenced by a number of factors (Figure 2-5), including the following:

A. basement faulting, resulting in fluid introduction from the surface or from aquifers which come into contact with salt zone as a result of faulting;

B. aquifer in vicinity of salt zone, which introduces fluid to salt zone by centripetal or centrifugal flow;

C. orogenic event, causing basinward (centripetal) flow of fluid from outcrop due to hydraulic gradient;

D. erosion or near-surface dissolution below an unconformity;

E. lowstand, allowing for introduction of meteoric water from nearby exposed areas;

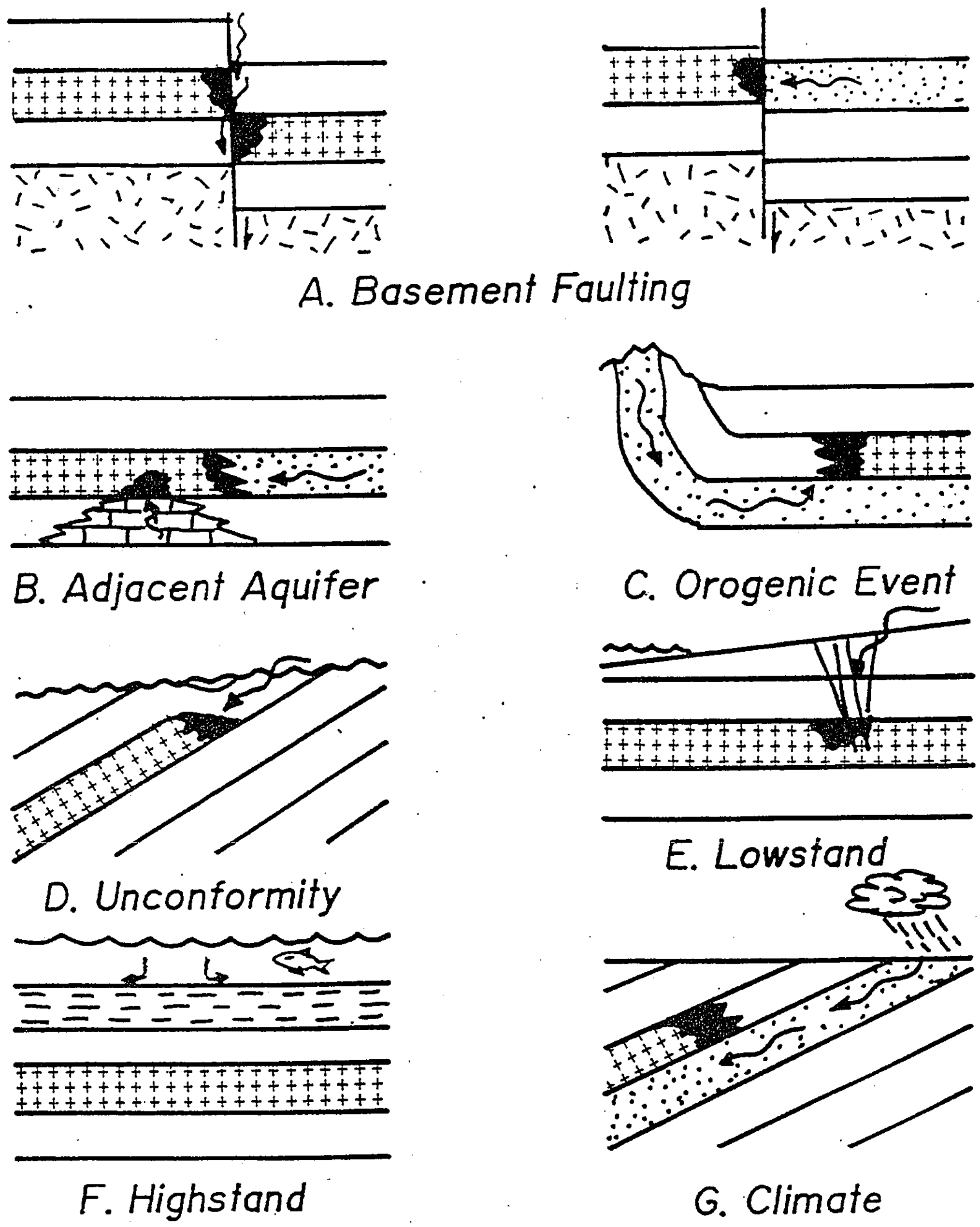


Figure 2-5. Diagram of factors which influence location and timing of salt dissolution.

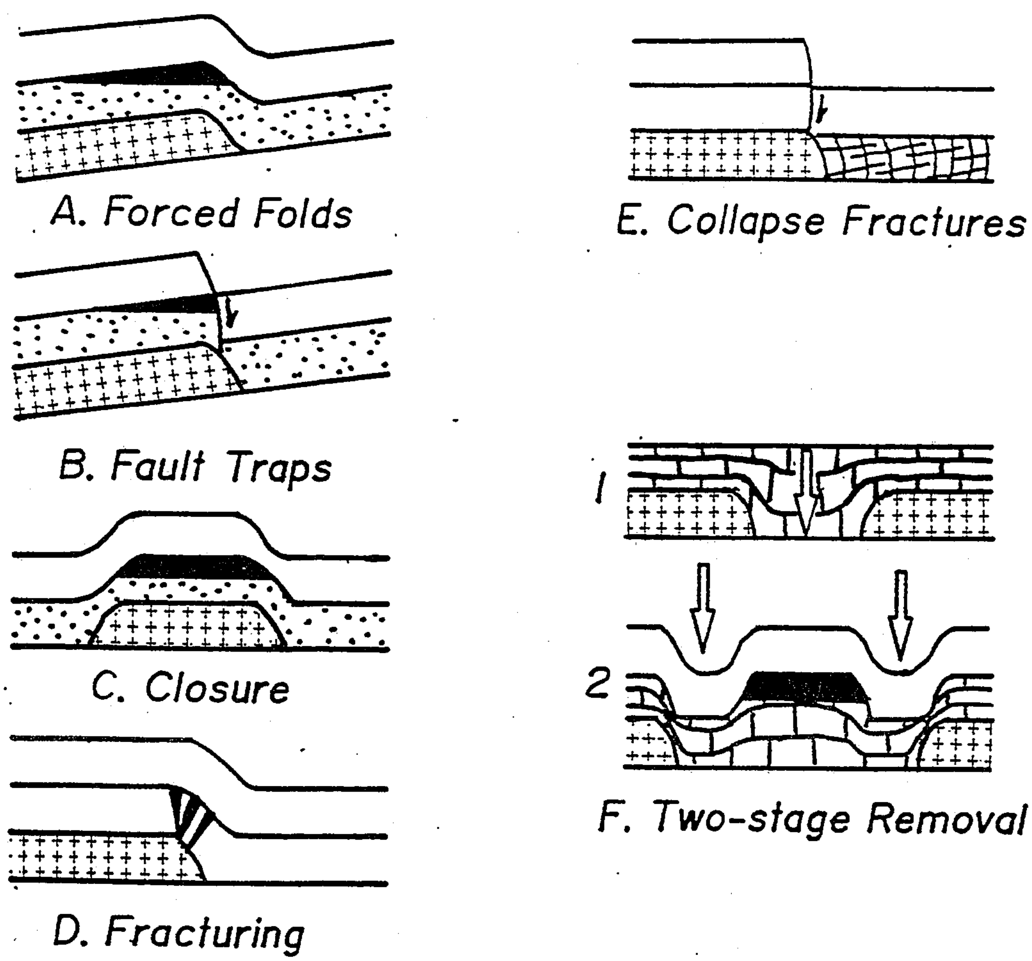


Figure 2-6. Diagram of potentially hydrocarbon-productive structural features resulting from salt dissolution.

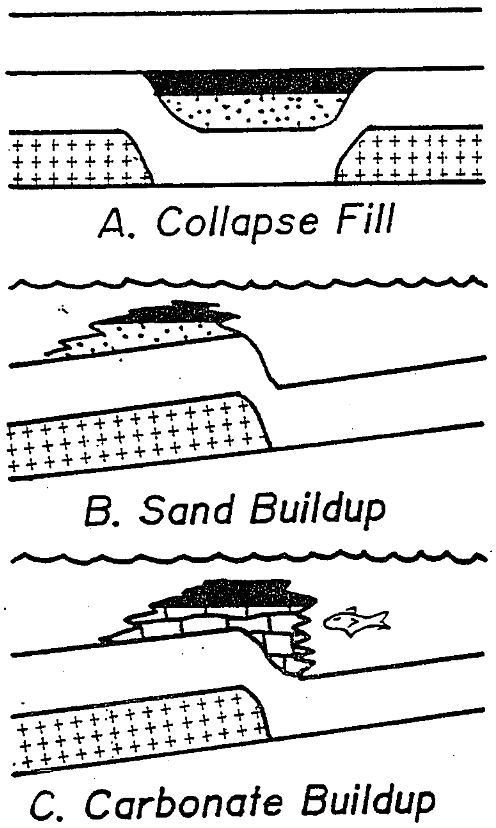
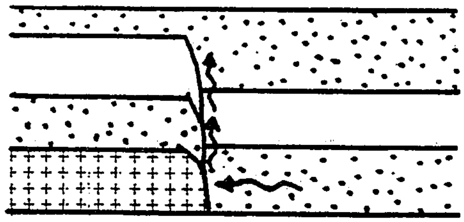
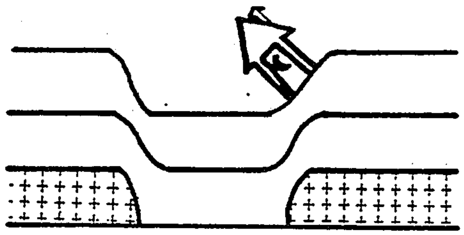


Figure 2-7. Diagram of potentially hydrocarbon-productive stratigraphic features resulting from salt dissolution.



A. Water-salinity Anomaly



B. Surface Depression

Figure 2-8. Diagram of shallow geologic conditions caused by salt dissolution.

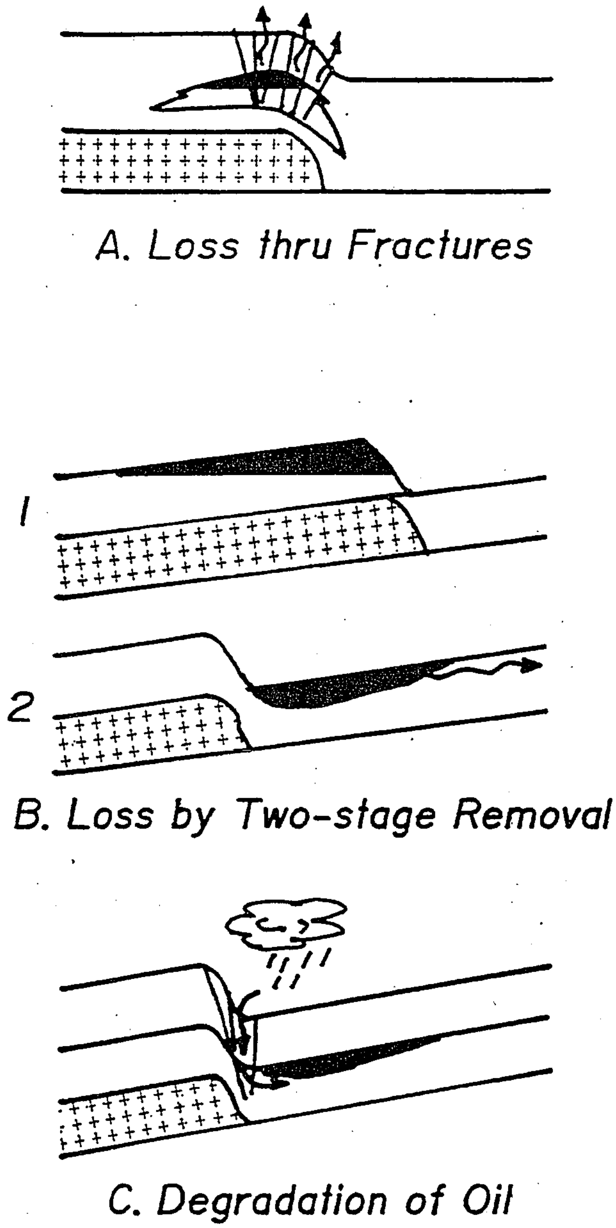


Figure 2-9. Diagram of salt dissolution-related situations which are detrimental to hydrocarbon entrapment.

F. highstand, resulting in deposition of marine shale seal, preventing fluid introduction to salt zone; and

G. climatic variations, which influence recharge of regional aquifers.

Figure 2-6 summarizes a number of structural features resulting from dissolution of salt and collapse of overlying strata which may be favorable to the entrapment of hydrocarbons:

A. forced folds associated with collapse-induced monoclinal flexure above a salt edge;

B. collapse fault traps in more brittle strata above a salt edge;

C. closure over a salt outlier;

D. enhanced porosity and permeability due to extensional fracturing above a salt edge;

E. fracture enhancement in a collapse area; and

F. structural inversion (sombrero structure) caused by two-stage dissolution.

Figure 2-7 summarizes salt dissolution-induced stratigraphic features in the subsurface which may be favorable to hydrocarbon entrapment:

A. accumulation of potential reservoir in syndepositional collapse low;

B. localization of potential sandstone reservoir due to shoaling along syndepositional collapse-induced flexure or high.

C. localization of potential carbonate reservoir in shallow water along syndepositional collapse-induced flexure or high.

Figure 2-8 summarizes shallow geologic conditions which can be caused by salt removal at depth (and may indicate the potential for hydrocarbon entrapment):

A. water-salinity anomaly in shallow formation water or at surface; and

B. surface depressions, resulting from relatively recent collapse.

Figure 2-9 illustrates geologic situations in which salt removal and collapse may be detrimental to the entrapment of hydrocarbons:

A. loss of previously trapped hydrocarbons through collapse-induced fractures;

B. loss of previously trapped hydrocarbons by two-stage dissolution; and

C. degradation of hydrocarbons due to introduction of fresh groundwater.

SALT DISSOLUTION IN THE DENVER BASIN

Compared to other salt-bearing areas, relatively little has been published regarding salt dissolution in the Denver basin. This is not surprising considering that, until recently, the Paleozoic interval was sparsely drilled. Adequate subsurface control with which to identify salt dissolution features has existed only in the past decade or so.

Momper (1963) attributed Permian isopach maxima to the presence of halite, but did not attempt to differentiate between thickness patterns which may be due to paleotectonics and those which were caused by subsequent removal of salt. Momper noted that most of the salt preserved in the basin is found west of the Triassic and upper Guadalupian subcrops (below Jurassic strata), and that Leonardian salts are only present west of the lower Guadalupian subcrop. This suggests that salt removal had been completed by the time Jurassic sediments were deposited across this unconformity. Momper, however, concluded that dissolution continued during Cretaceous time. Although Guadalupian and Triassic shales may have acted to retard movement of dissolving fluids, Momper suggested widespread salt removal during the Cretaceous, along with active present-day dissolution. Thinning of the upper Leonardian and lower Guadalupian was believed to be at least partially due to salt removal.

Specific areas in which studies addressed the presence of salts are shown on Figure 2-10. Fish (1982) reported that subsurface structure in the Juelfs-Gaylord field area (Figure 2-10), where oil production is from the Lower Cretaceous J Sandstone, is generally believed to be related to collapse of the Permian salt section. According to Fish, collapse took place during and prior to deposition of the D and J sandstones; although he did not state it, this implies that Fish believed that salt solution collapse may have influenced the distribution of J Sandstone reservoirs. Sahl et al.(1993) reported that Leonardian salt has been removed

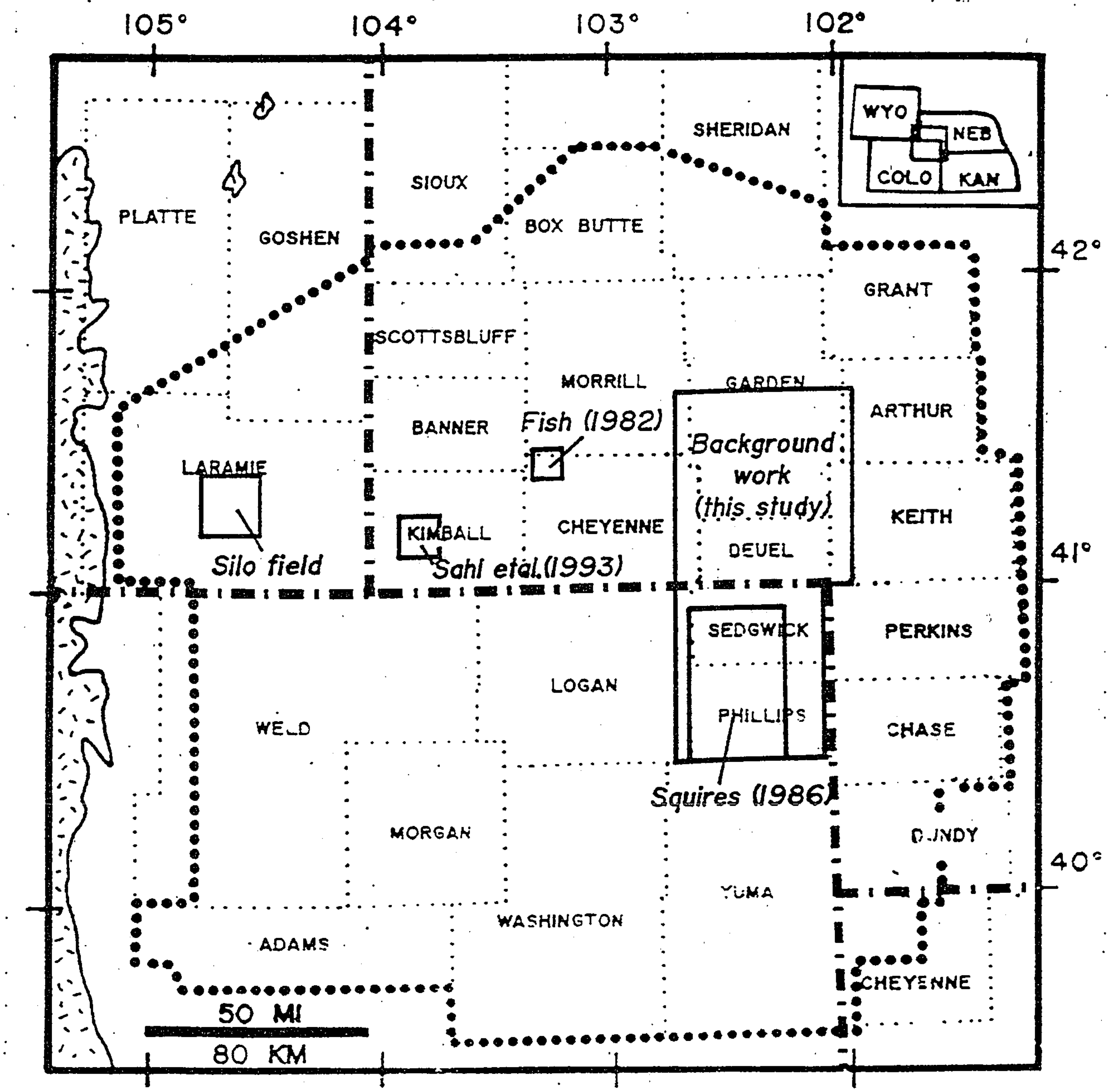


Figure 2-10. Locations of Denver basin studies which mention or address salt dissolution. Area of background work for the present study is shown in northeastern part of basin.

in the Kleinholz field area of western Nebraska (Figure 2-10).

Using seismic data along with limited deep well control, Squires (1986) created a series of seismic models as part of a study of salt dissolution features in northeastern Colorado. The models were integrated with seismic data to construct Permian isochron maps in his study area (Figure 2-10). Squires' work suggests that dissolution of Permian salt may have commenced during the Jurassic, and continued intermittently during the Cretaceous. Spasmodic dissolution, Squires concluded, may have been due to recurrent movement along basement faults, with significant dissolution taking place in response to the Late Cretaceous-Early Tertiary Laramide orogeny.

Seismic data have been used to define a Permian salt dissolution edge south and east of Silo field in southeastern Wyoming (Figure 2-10). Production of oil at Silo field is from fractured Niobrara Formation. Recent successful horizontal-drilling efforts at Silo field have prompted a number of studies (Lewis, 1989; Davis and Lewis, 1990; Campbell and Saint, 1991; Montgomery, 1991a,b; Coates and Torn, 1993; Sonnenberg and Weimer, 1993; Svoboda, 1995). Timing of salt removal and the relationship of the salt edge to fracture development at Silo field remain the subject of considerable debate (Svoboda, 1995).

BACKGROUND WORK RELATED TO THE PRESENT STUDY

Preliminary mapping in the northeastern part of the Denver basin (Figure 2-10) identified a number of areas in which a suspected relationship between salt dissolution, Cretaceous-level structure, and hydrocarbon production existed. This background work served as the basis for the present study.

Subsurface structure at the D Sandstone level was mapped, utilizing well logs from over 600 Cretaceous tests in a 3000 sq mi (8000 sq km) area (Figures 2-10 and 2-11). This mapping reveals an anomalous north-south-trending structural flexure, extending from Garden County, Nebraska, southward through Phillips County, Colorado. Location of a regional syncline associated with this flexure is shown on Figure 2-11).

In Garden County, Nebraska, where regional dip is to the southwest, structural relief within the syncline exceeds 150 ft (50 m) (Figure 2-12). The depression is situated just east of an area of D Sandstone production at McCord, Richards, Jackson, and Oshkosh fields, and a one-well unnamed field in T16N, R42W.

To the south near the Nebraska-Colorado line (Figure 2-13), regional dip is to the west. Relief within the regional syncline in this area also exceeds 150 ft (50 m). The depression is situated just east of Big Springs field, a

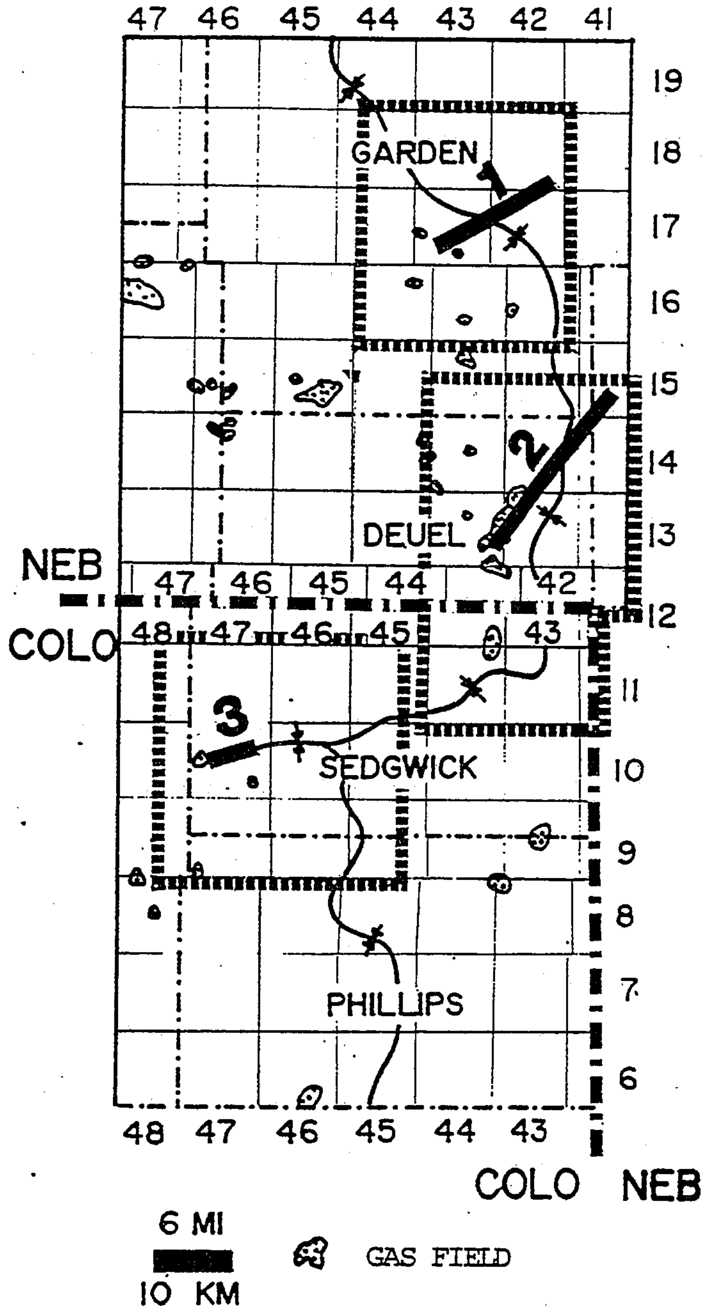


Figure 2-11. Location of synclinal axis associated with regional flexure. Location of D Sandstone structure maps (Figures 2-12 through 2-14) and cross sections (Figure 2-15) are shown.

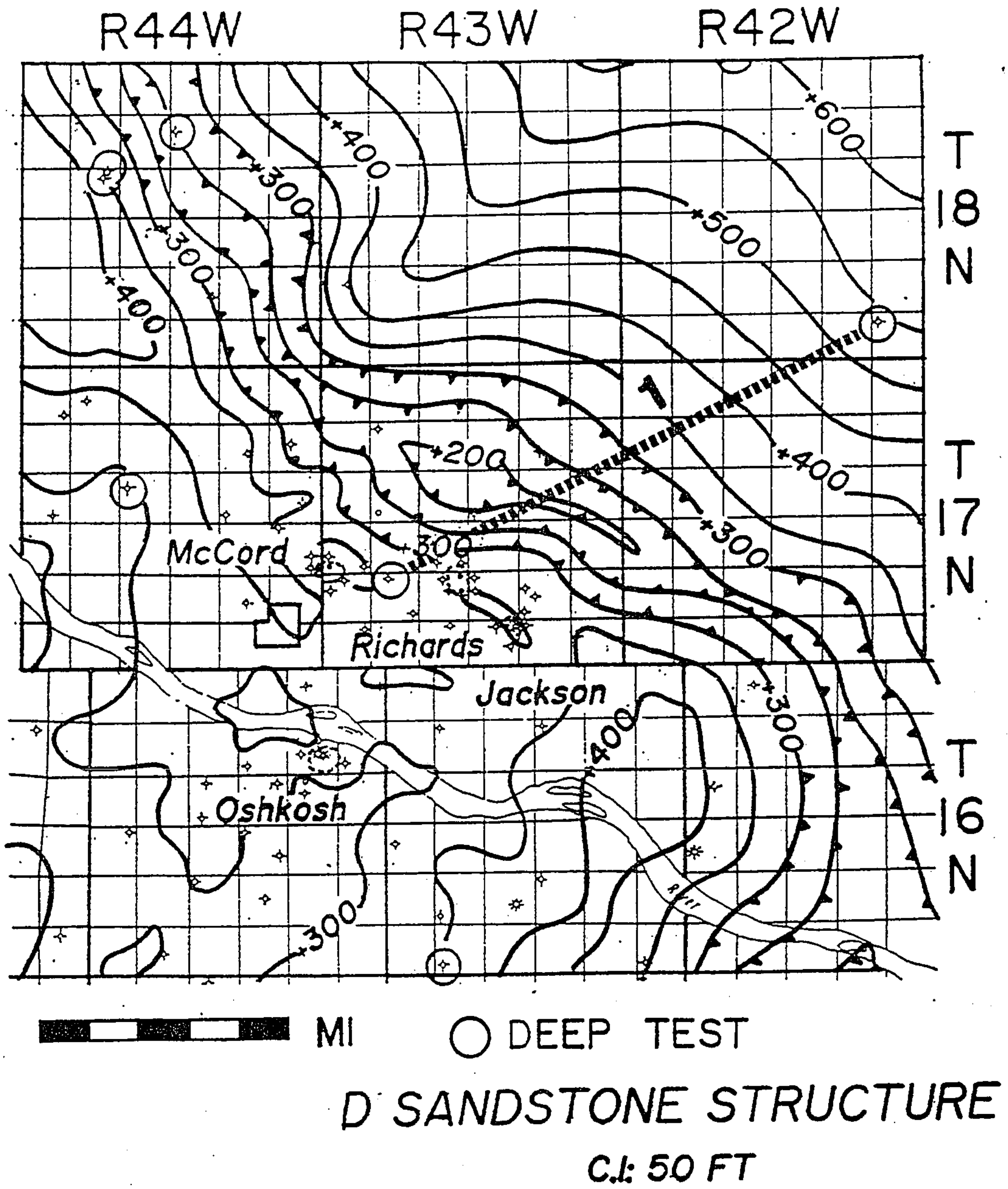


Figure 2-12. D Sandstone structure in McCord-Richards field area, Garden County, Nebraska. Contour interval 50 ft (15 m).

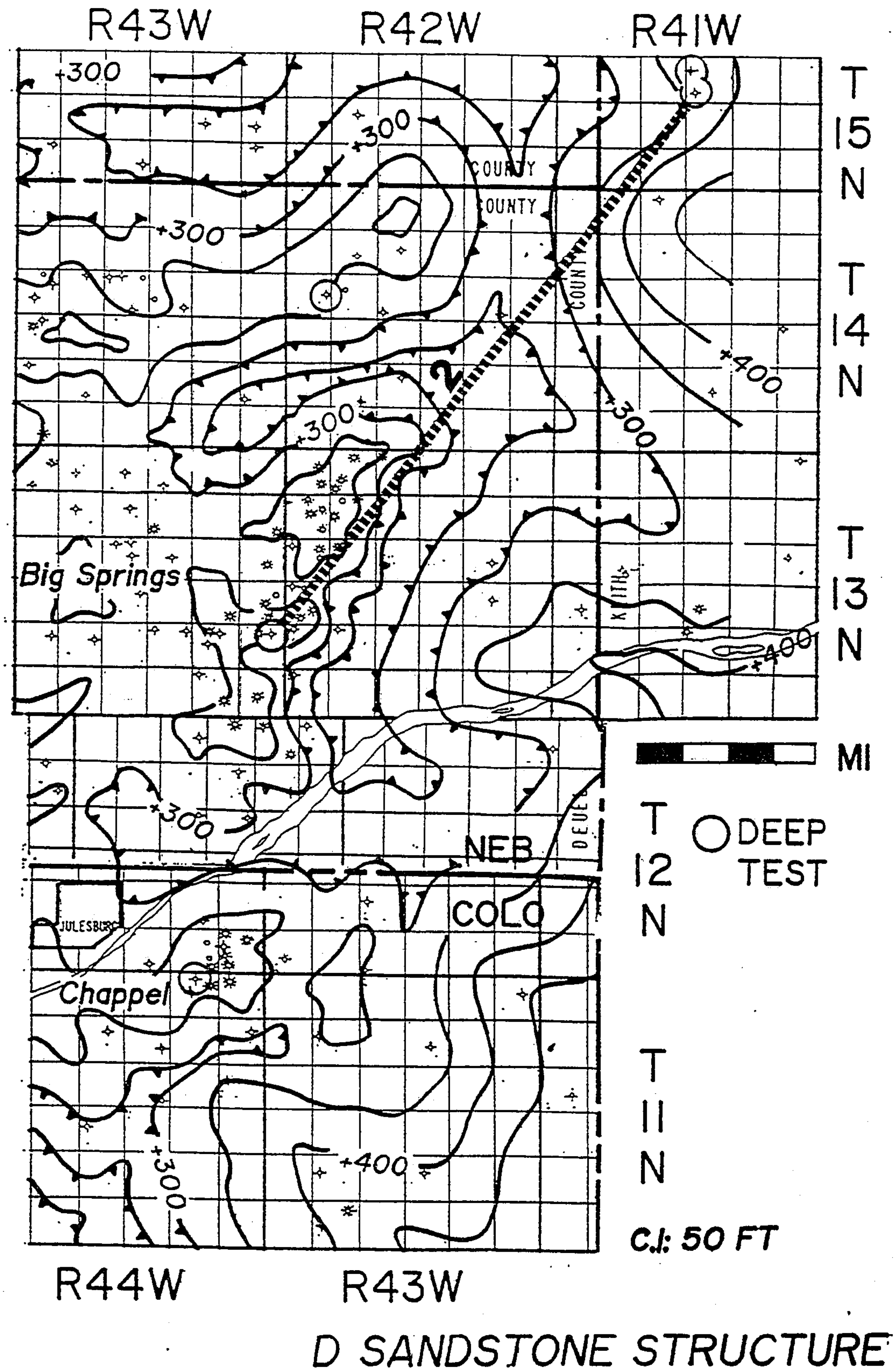


Figure 2-13. D Sandstone structure in Big Springs-Chappell field area, Nebraska and Colorado. Contour interval 50 ft (15 m).

large gas field which produced from the D Sandstone prior to conversion to a gas storage field. The syncline extends to the southwest into Colorado, just southeast of Chappell field, which is another D Sandstone gas field.

Further southwest (Figure 2-14) structural relief is nearly 200 ft (60 m) in a depression located just east of D Sandstone production at Red Lion field. This structural low surrounds marginal oil production at North Marks Butte field, discovered in 1982. Production is from a thin sandstone within the lower Leonardian Sumner Group. Montgomery (1987) reported that production at North Marks Butte is related to an "unexplained, enigmatic circular feature with raised margins, seismically mapped at the top of the Wolfcamp," and that entrapment is associated with the raised margins of an "apparent impact-type feature," about 1.5 mi (2.4 km) in diameter.

A general relationship can be observed between the location of the above fields and the eastern limit of Leonardian salts, as mapped by McKee, Oriel, et al. (1967b) (Figure 1-5). Based on the hypothesis that the regional D Sandstone structural anomaly (and associated production) are at least partially influenced by solution collapse of Leonardian salt, the locus of structural reversal (synclinal axis on Figure 2-11) represents the "best guess" as to the eastern (regionally updip) limit of Leonardian salt in the

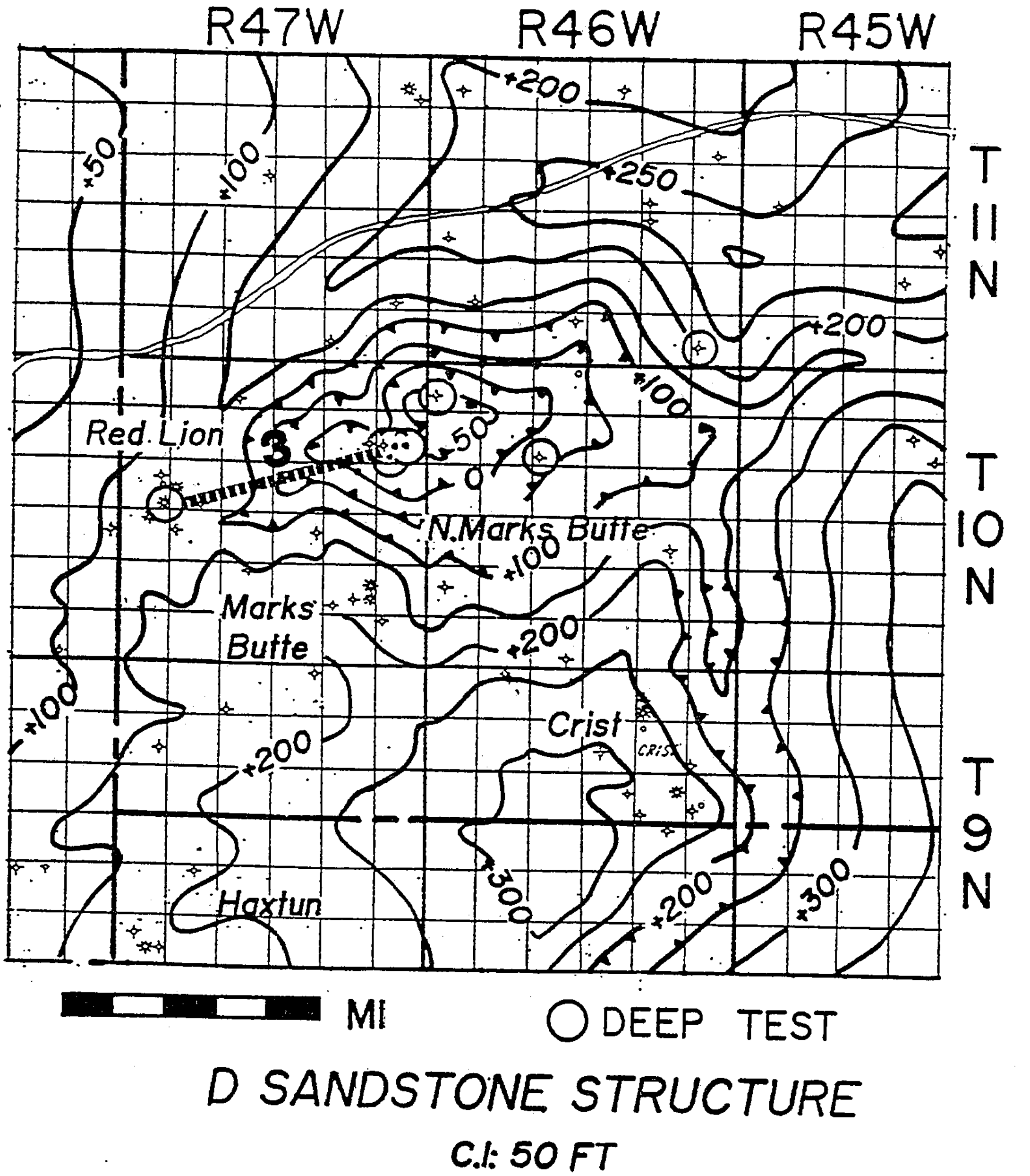


Figure 2-14. D Sandstone structure in Red Lion field area, Sedgwick County, Colorado. Contour interval 50 ft (15 m).

subsurface. Local areas where the line splits off to the west represent possible re-entrants of the salt edge.

The presence of a salt edge and its possible influence on D Sandstone production is supported by three structural cross sections (Figure 2-15) which were constructed using well logs from basement tests near each of the mapped anomalies. Each cross section includes one regionally downdip well in a producing area (McCord-Richards, Big Springs, and Red Lion fields) and a well to the northeast (regionally updip) in an area with no D Sandstone production. In all three cases, salt is present under the D Sandstone pool and is absent in the regionally-updip well.

Maximum structural reversal along the proposed salt edge occurs at Red Lion field, where the D Sandstone, at an elevation of at least 178 ft (54 m) above sea level at the field, was encountered at an elevation of 55 ft (17 m) below sea level 4 mi (6 km) to the east (regionally updip). The pronounced structural low at the Cretaceous level which exists immediately to the east of Red Lion field more likely reflects an area of salt solution collapse at depth than an apparent impact feature, as reported by Montgomery (1987).

APPROACH TO THIS STUDY

A primary objective of the present study is the identification of salt dissolution features in the Denver basin subsurface and the explanation of their origin and

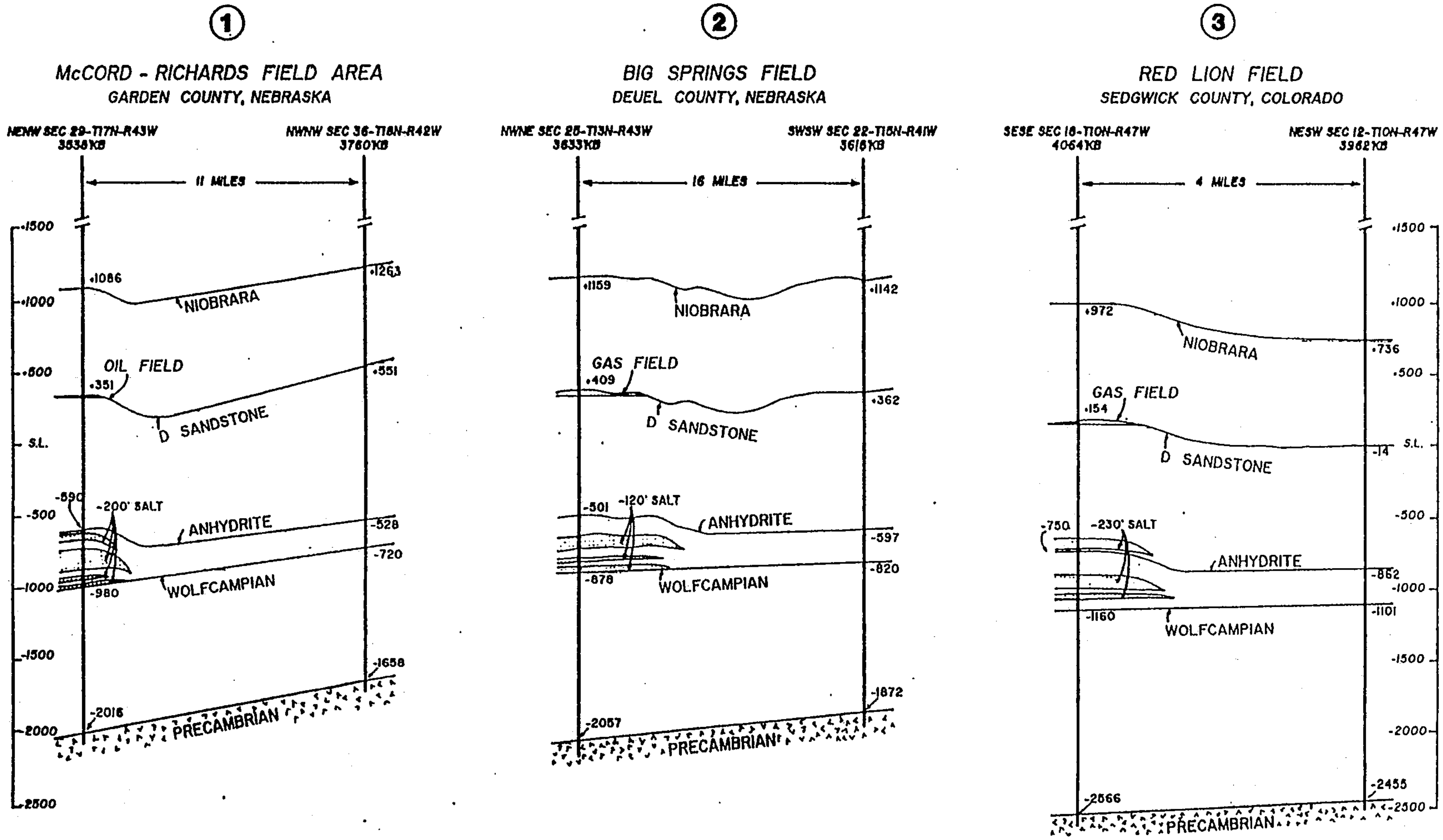


Figure 2-15. Structural cross sections in McCord-Richards, Big Springs, and Red Lion field areas.

relationship to hydrocarbon accumulation. Salt removal by dissolution results in abrupt removal of salt, rather than gradual thinning. Thus, the search for areas in which salt has been removed focuses on recognition of abrupt thinning or disappearance of one or more salt zones from one well to another. (A critical assumption is that subsurface stratigraphic correlations of individual salt zones are free of errors.)

Figure 2-16 is a hypothetical cross section, illustrating a number of possible syndepositional and post-depositional influences on salt occurrence. Each situation is a possible explanation for abrupt lateral thinning or absence of salt in the subsurface, illustrating that, in addition to dissolution (E), a number of other processes can account for salt discontinuity.

Syndepositional causes for abrupt changes in salt thickness include paleotectonic influence on evaporite basin configuration (A) and abrupt facies change (B). Post-depositional causes for absence of salt include faulting (C), salt flowage (D), and truncation or near-surface dissolution below an unconformity (F).

The following chapter describes the use of persistent carbonate, anhydrite, and red shale marker beds to construct a stratigraphic framework with which to identify salt zones. This approach reduces the potential for erroneous physical

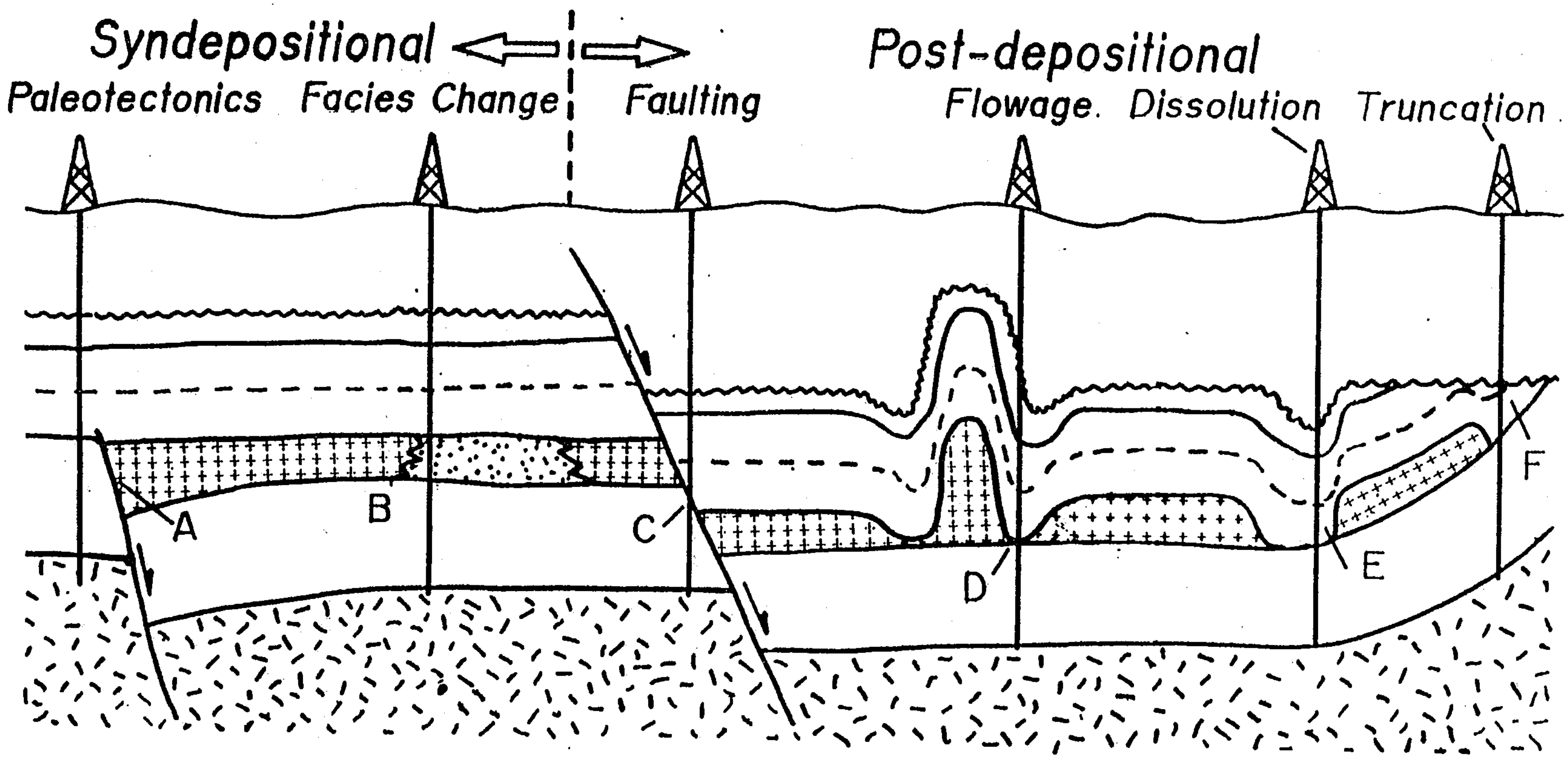


Figure 2-16. Diagram of syndepositional and post-depositional causes for salt discontinuity.

correlations of laterally discontinuous salts in the Denver basin.

CHAPTER 3
STRATIGRAPHY

NOMENCLATURE

As interest in the petroleum potential of Upper Paleozoic rocks converged on the Denver basin from adjacent Rocky Mountain and Midcontinent areas, formation names were introduced for Permian strata which were derived from nearby basins and exposures on adjacent uplifts. As a result, subsurface nomenclature for the Permian of the Denver basin is a confusing mix of terms. Momper (1963), who observed that the nomenclature is "replete with duplicating and overlapping terms," attributed the confusion to the absence of a fossil record, lack of subsurface control, loss of section from salt solution, undiscerned truncation, facies changes, and scattered poor exposures. Garfield et al. (1988) labeled the northern Denver basin an "area of mixed terminology" and offered lack of communication between workers and great distances between exposures as reasons for confusing Permian and Pennsylvanian nomenclature.

Despite noting that low-angle intraseries unconformities and lack of fossils in Upper Permian clastics and evaporites complicate Rocky Mountain and Mid-Continent Permian correlations, Rascoe and Baars (1972) maintained that carbonate and anhydrite formations can be traced over wide areas and can be used to subdivide the Permian into approximately isochronous units. This approach of using recognizable lithostratigraphic units was employed in the present study to subdivide Leonardian and Guadalupian strata in an effort to identify, correlate, and map the regional distribution of individual salt zones in the Denver basin.

In order to simplify and standardize terminology a nomenclature is proposed for the northern Denver basin subsurface (Figure 3-1) which generally uses Mid-Continent unit names for Leonardian strata and Rocky Mountain nomenclature for the Guadalupian and Lower Triassic. A similar approach was suggested by Momper (1963). Momper noted that Mid-Continent nomenclature is more appropriate because the Nippewalla and Sumner Groups are more complete, more persistent, and better understood from the standpoint of chronostratigraphy to the east. Mid-Continent nomenclature is more appropriate than formation names derived from the Rocky Mountain region, where Leonardian-age rocks are poorly preserved. Rocks of Leonardian age are generally absent to the northwest of the Denver basin on the Hartville uplift and in the Powder River basin due to truncation below an intra-Leonardian unconformity and to thinning due to onlap of upper Leonardian units onto the truncation surface (Rascoe and Baars, 1972). In these areas, the Opeche Shale (lowermost Guadalupian) unconformably overlies the partially truncated Minnelusa Formation (Wolfcampian), the upper part of which is

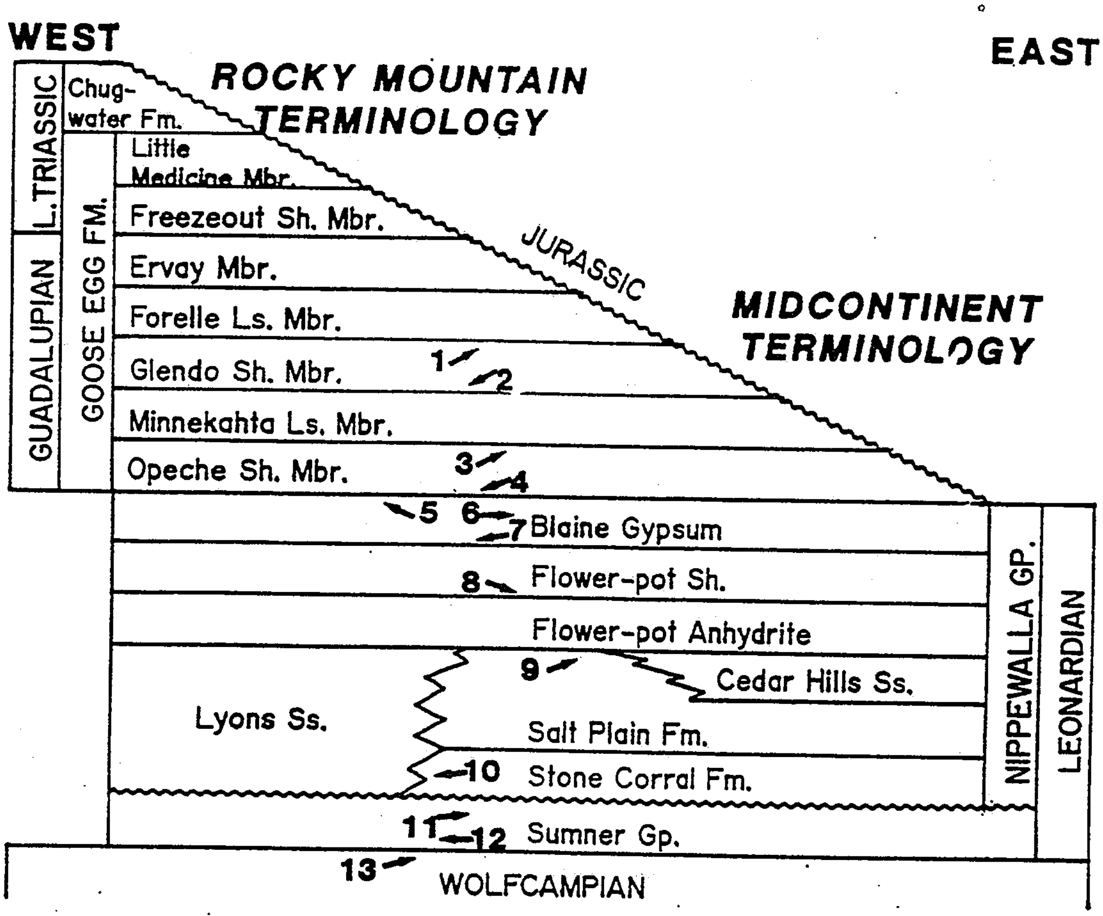


Figure 3-1. Proposed nomenclature for Leonardian, Guadalupian, and Lower Triassic rocks in the Denver basin subsurface. Stratigraphic positions of salt zones identified in this study are indicated by numbers.

equivalent to the Chase Group in the Denver basin and Mid-Continent areas. Because Leonardian strata are poorly represented or absent in areas to the northwest of the Denver basin, it is more appropriate to extend Mid-Continent terminology from the east into the basin for Leonardian-age rocks.

In the eastern Denver basin successively older Lower Triassic and Guadalupian strata (Chugwater and Goose Egg Formations) are truncated to the east beneath a pre-Late Jurassic unconformity (Figures 3-2 and 3-3). Because rocks of Guadalupian age are absent along the eastern margin of the Denver basin (an approximate boundary between the Rocky Mountain and Mid_Continent regions), it is logical to adopt formation names derived from the Rocky Mountain region for Guadalupian-age strata, as these units persist in the subsurface from the Powder River Basin and margins of the Black Hills to the south and east into the Denver basin. Momper (1963) likewise suggested using Rocky Mountain terminology for Guadalupian-age units in the northern Denver basin subsurface.

CORRELATIONS

Study of the distribution of salt and its influence on trap development, velocity anomalies, and well-site operations requires accurate correlations of individual salt

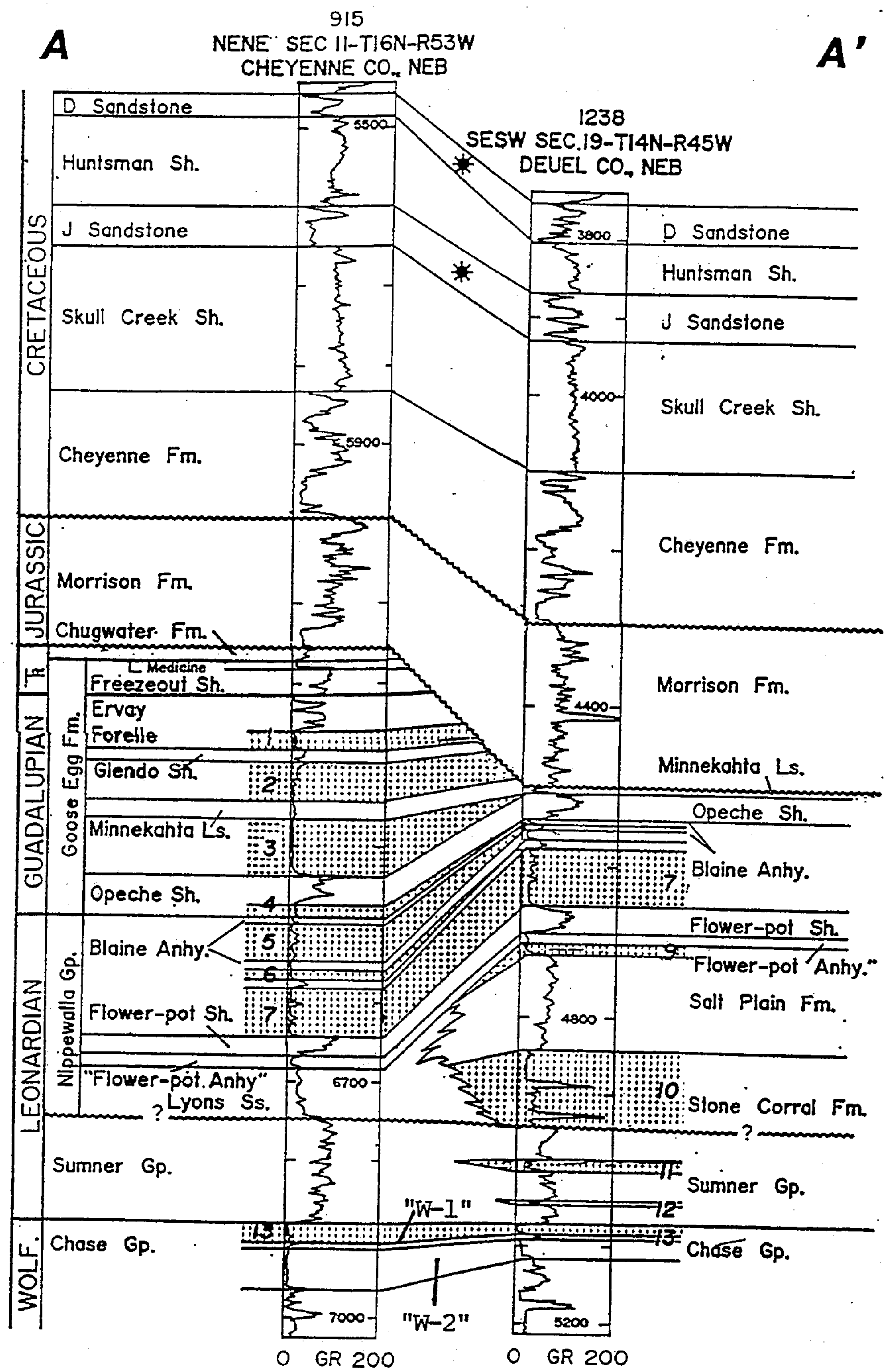


Figure 3-2. Stratigraphic cross section showing formation tops and stratigraphic position of Permian salts, identified by numbers, and Cretaceous D and J Sandstones. Well depths are in feet. Distance between wells is 50 mi (80 km).

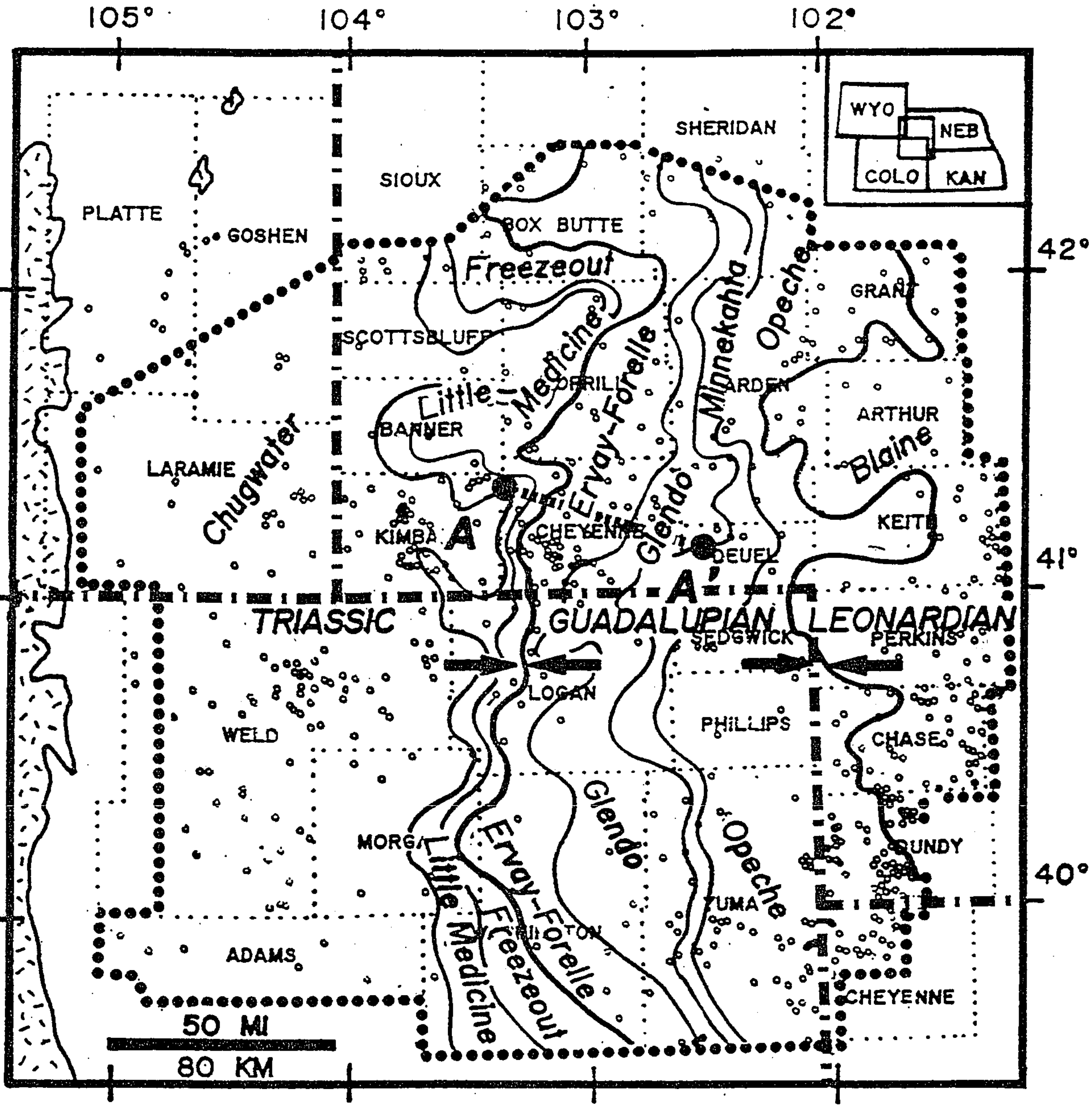


Figure 3-3. Pre-Late Jurassic subcrop map. Cross section A-A' shown on Figure 3-2.

beds. Because salt has been removed in places by dissolution, correlations across the basin (which form the basis for regional salt isopachs) can be problematic. Recognition of persistent non-salt markers (units that are not removed by dissolution) is critical to the subdivision of Leonardian and Guadalupian strata and the accurate correlation of salt beds.

Important marker beds which prove useful in regional correlations are shown on Figure 3-2, a two-well cross section in which all but one of 13 identified salt zones are present. The Leonardian Series is represented by rocks which occur between the top of the Blaine Gypsum and the top of the Chase Group. Persistent markers of Leonardian age which occur across the study area in fairly uniform thickness (except to the east where they are truncated below the pre-late Jurassic unconformity) include, in ascending order: an anhydrite bed, termed the "Flower-pot Anhydrite" in this study, the Flower-pot Shale, and two thin anhydrite beds which correlate with the Blaine Gypsum to the east. The Lyons (Cedar Hills) Sandstone which, where present, occurs below the "Flower-pot Anhydrite", is replaced locally by a red shale and evaporite interval believed to be equivalent to the Salt Plain Formation. In places the lower part of the Lyons Sandstone appears to correlate with the Stone Corral Formation (anhydrite and/or halite) which is present in the eastern half of the study area, whereas farther to the east and southeast, the Stone Corral is separated from the overlying Cedar Hills Sandstone (which is equivalent to the upper Lyons Sandstone) by red shales and siltstones of the Salt Plain Formation.

Persistent markers of Guadalupian and Early Triassic age which occur within the study area (where they have not been truncated by pre-Late Jurassic erosion) include, in ascending order: the Opeche Shale, Minnekahta Limestone, Glendo Shale, Forelle Limestone, Ervay Limestone, Freezeout Shale, and Little Medicine Members of the Goose Egg Formation.

Formation tops reported by operators occasionally include the depth to the "first salt". Figure 3-2 illustrates the potential for correlation problems associated with Permian salts and related strata. The first salt encountered in well 915 is 803 ft (245 m) below the top of the D Sandstone. In well 1238, 45 mi (72 km) to the southeast, the first salt occurs at a comparable depth (827 ft or 252 m) below the top of the D Sandstone. Correlations of persistent anhydrite and shale markers reveal that the "first salts" in the two wells are not equivalent. The youngest salt in well 915 is a Guadalupian-age salt, identified in this study as salt 1, whereas the youngest salt in well 1238 is salt 7, of Leonardian age. Truncation or near paleosurface dissolution below the pre-Late Jurassic unconformity (Figure 3-3) is responsible for removal of younger salts to the east.

A fence diagram (Figure 3-4) shows Lower Triassic, Guadalupian, Leonardian, and uppermost Wolfcampian lithostratigraphic units mapped in the northern Denver basin, their relationship to correlative strata in western Kansas and the Colorado Front Range, Powder River basin, and Chadron arch areas, and their relationship to pre-Late Leonardian and pre-late Jurassic unconformities. Formation names suggested for use in the Denver basin subsurface are given in the center of the diagram and equivalent formation names are shown for surrounding areas.

In the Chadron arch area the Leonardian Series is represented by rocks of the Nippewalla and Sumner groups. However, the Guadalupian Series is represented by only the Opeche Shale, the basal member of the Goose Egg Formation, due to pre-Late Jurassic erosion. In the western Kansas portion of the study area, the Opeche Shale may be equivalent to the Dog Creek Shale of the western Mid-Continent.

Rocks of Leonardian age are absent in the Powder River basin of Wyoming, where pre-late Leonardian erosion has removed lower Leonardian and upper Wolfcampian strata and upper Leonardian rocks pinch out due to onlap to the northwest. Important unconformity traps occur in the Minnelusa Formation where it is overlain by the Opeche

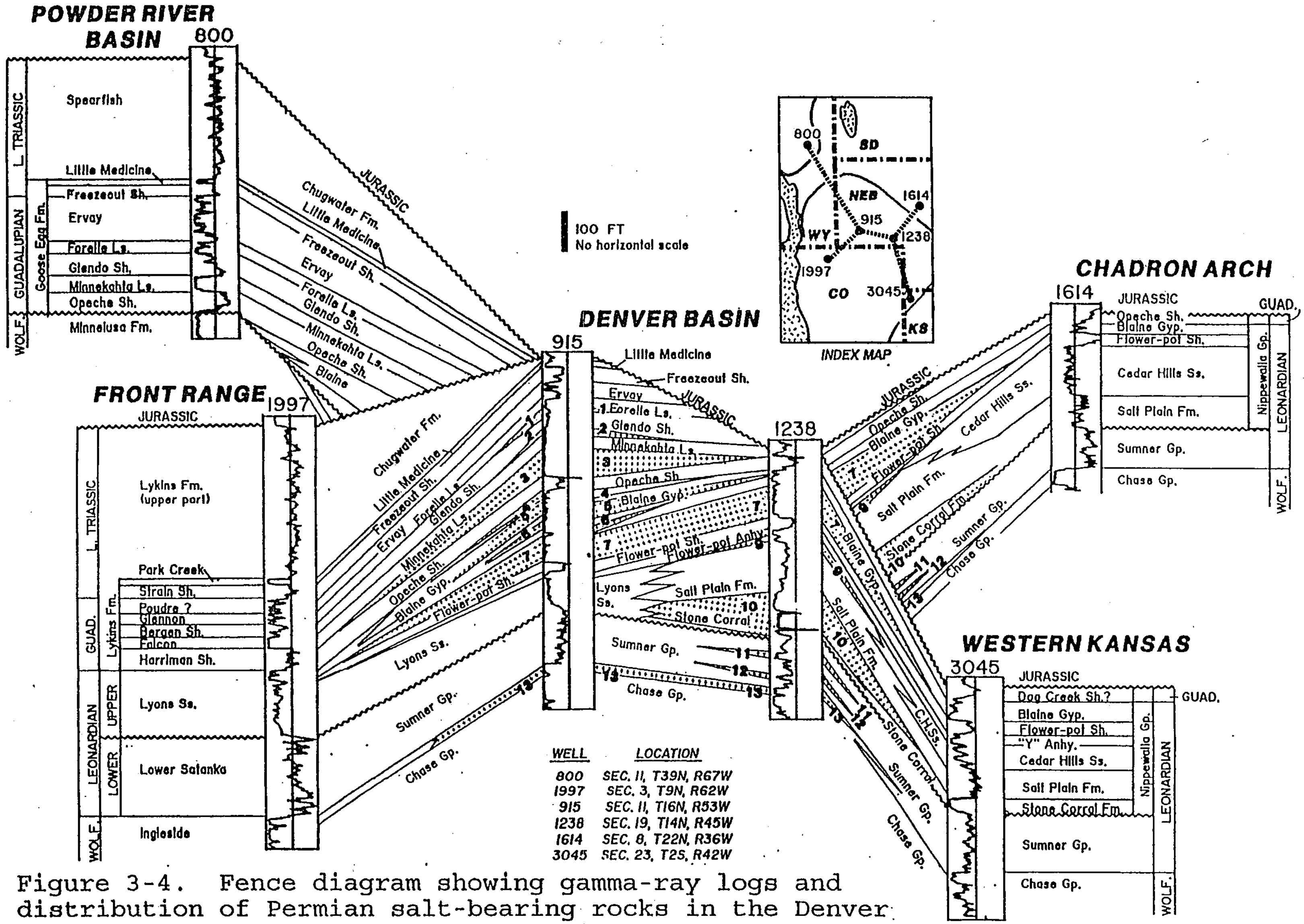


Figure 3-4. Fence diagram showing gamma-ray logs and distribution of Permian salt-bearing rocks in the Denver basin and adjacent areas, relationship to pre-late Leonardian and pre-Late Jurassic unconformities, and equivalent formation names in adjacent areas.

Shale. Permian salt in the Powder River basin ("Ervay salts" of Rasmussen and Bean, 1984) appear to be younger than salt 1 of this study.

Upper Wolfcampian

Study of Wolfcampian-age rocks was limited to those which occur at the top of the Chase Group. A thin anhydrite bed which marks the top of the Chase Group is replaced locally by a thin halite bed, identified in this study as salt 13 (Figure 3-2). This uppermost evaporite interval is named the "W-1 evaporite" in this study. An underlying thick anhydrite unit is named the "W-2 evaporite." Salt occurs lower in the Wolfcampian section at the extreme northern limit of the study area (Alliance basin area). Study of this deeper salt interval is beyond the scope of this report.

Leonardian

Sumner Group

The lower Leonardian is represented by the Sumner Group which conformably overlies upper Wolfcampian anhydrite or salt (W-1 evaporite). The Sumner Group includes red siltstones and shales which Momper (1963) correlated with the Ninnescah Shale, a unit which is well developed in Kansas. Rascoe and Baars (1972, Figure 10), however, show the Ninnescah to be truncated below the pre-late Leonardian unconformity in the eastern part of the Denver basin. They include the fine-grained rocks immediately above the Chase Group in the Wellington Formation, which contains important salt beds farther east in Kansas. In this study all rocks which occur between the base of the Stone Corral Formation or its stratigraphic equivalent and the top of the Chase Group are included in the Sumner Group.

Rocks of the Sumner Group are equivalent to the lower part of the Satanka Shale of Darton (1908), the lower Satanka of Hoyt (1963) and the Owl Canyon of Condra et al. (1940). The upper limit is generally considered to be at an intraseries unconformity (Rascoe and Baars, 1972) below the Stone Corral Formation, although this unconformity is difficult to trace in the subsurface where the Stone Corral is absent due to onlap. In places the top of the Sumner Group may be at the base of the Lyons Sandstone, particularly where the sandstone is thicker. Where the Stone Corral and Lyons are both absent, the contact between the Sumner Group and the overlying Salt Plain Formation cannot be determined with certainty in the subsurface due to similarity in their lithologies and well log responses, and for this reason it is difficult to determine thickness variation of the Sumner across the basin.

In places the Sumner Group contains two salt zones, identified as salts 11 and 12 (Figure 3-2).

Nippewalla Group

The upper Leonardian is represented by the Nippewalla Group (Norton, 1939) which, in the Denver basin, includes rocks between the top of the Blaine Gypsum and the base of the Stone Corral Formation.

Stone Corral Formation

The Stone Corral Formation is comprised of white, light brown, and pink anhydrite, pink and light brown, dolomite, and, locally, halite. The Stone Corral, which occurs above a pre-late Leonardian unconformity (Rascoe and Baars, 1972) is absent in the northwestern half of the study area because of facies change to red shale and siltstone or to onlap above the truncation surface. Salt 10 (Figure 3-2) is present at the level of the Stone Corral in the eastern part of the study area and appears to be equivalent to salt associated with the Stone Corral anhydrite in southwestern Kansas. Generally, where the salt is greater than 100 ft (30 m) thick, two thin, highly radioactive zones are recognized on gamma-ray logs (Figure 3-2). Analysis of a Spectralog across this interval from the Texaco and Halbouty Wright 14-1 deep test, Sec. 14, T14N, R44W, Deuel County, Nebraska (well 1239), indicates that potassium, most likely in sylvite, is the primary source of gamma radiation from the zones. If so, this is the only salt zone within the basin known to contain bittern salt, recording highly evaporative conditions during precipitation as well as conditions which allowed for preservation of the highly soluble salt.

Lyons - Cedar Hills Sandstone

The Lyons - Cedar Hills Sandstone is the thickest, most widespread coarse clastic unit within the study interval. The Lyons was named by Fenneman (1905) for a pure quartz sandstone exposed in the town of Lyons, Colorado. The Cedar Hills is a Mid-Continent term (Cragin, 1896) for a fine-grained bright red sandstone exposed in the Cedar Hills, Barber County, southcentral Kansas. The two units appear to be equivalent at their top, just below the "Flower-Pot Anhydrite". Where the sandstone is over 200 feet (60 m) thick, the base of the sandstone appears to be equivalent to the Stone Corral Formation and the lower part of the Salt Plain Formation. To the southeast, however, the sandstone (Cedar Hills) occurs at a stratigraphic position well above the Stone Corral.

The Lyons was deposited in eolian and shallow-water environments (Walker and Harms, 1976; Weimer and Erickson, 1976). Along the Front Range, eolian sandstones, derived from the north and east, intertongue with arkoses which were derived from the Ancestral Rockies to the west (Sonnenberg and Weimer, 1981).

Holdoway (1978) interpreted the Cedar Hills Sandstone in western Kansas as having accumulated as eolian sediments which may have also been transported by water. Well rounded quartz grains may have been derived from Cambro-Ordovician orthoquartzites exposed during the Permian on isolated uplifts, whereas more angular arkosic sand and silt may have been transported from the Ancestral Rockies.

In contrast to thin but persistent shale, anhydrite, and carbonate beds, the Lyons-Cedar Hills Sandstone represents one of the more significant facies changes within the Permian study interval in the Denver basin, reflecting significant paleotectonic influence which not only provided a source of coarse clastics from both east and west, but also influenced its accumulation.

Salt Plain Formation

The Salt Plain Formation (Cragin, 1896) lies between the Stone Corral Formation and the overlying Lyons (Cedar Hills) Sandstone. Where the Lyons is thickest the Salt Plain is absent. Where no sandstone is present at the Lyons - Cedar Hills level, the Salt Plain occurs directly below the "Flower-Pot Anhydrite". The Salt Plain is comprised of orange to red-brown shale, silty in places, with orange very fine- to fine-grained sandstone.

The Harper Sandstone (Cragin, 1896) is found at the base of the Salt Plain in Kansas, but is not recognized with certainty in the study area. Holdoway (1978) did not attempt to differentiate the Harper Sandstone from the Salt Plain Formation in the subsurface of western Kansas.

The red shale of the Salt Plain, which is often impregnated with salt, is generally thicker where it overlies the Stone Corral salt (salt 10) and where the Lyons-Cedar Hills Sandstone is thin or absent. This suggests that red clays and silts accumulated in the same restricted basin as the Stone Corral, with deposition of eolian and shallow water sand on subtle paleohighs along the basin margins. Salt is locally present (salt 9, Figure 3-2) just below the "Flower-pot Anhydrite", at the same stratigraphic level as the top of the Lyons-Cedar Hills Sandstone.

Flower-pot Shale

The Flower-pot Shale (Cragin, 1896), one of the more conspicuous markers on the geophysical logs, is present in all but the extreme western and northwestern parts of the study area, where it appears to thin due to onlap above the pre-late Leonardian truncation surface. The shale, uniformly about 30 feet (10 m) thick elsewhere within the study area, is recognized in the subsurface as a bright red-orange to light red-brown shale with anhydrite and halite inclusions.

"Flower-pot Anhydrite"

A white anhydrite named the "Flower-Pot Anhydrite" in this study, which occurs at the base of the shale (and at the top of the Lyons - Cedar Hills Sandstone, where present) also serves as an excellent regional marker (Figure 3-2). This unit correlates with an unnamed anhydrite included in the Flower-Pot Shale by Rascoe and Baars (1972). It was placed in the Cedar Hills by Holdoway (1978) and is equivalent to the "Y" anhydrite of Shumaker, 1966). Rascoe and Baars (1972, Figure 12) placed this anhydrite in the Flower-pot Shale in the Syracuse basin of western Kansas.

Although this marker is present across most of the Denver basin, no consistent name has been used to identify it in the suburface. It has been called "Blaine" or "Day Creek" by operators in the eastern part of the basin where it is the first anhydrite encountered below the pre-Late Jurassic unconformity. Farther west, where it is the lowermost anhydrite present within the Leonardian, it has been named "Stone Corral" by many, including Sahl et al. (1993).

Salt is locally present above and below the persistent "Flower-pot Anhydrite" (salts 8 and 9, respectively). Salt 8 has been identified only in a restricted area of eastern Colorado, whereas salt 9 occurs in the same general area as salts 11, 12, and 13, and to a certain extent, salt 10.

Blaine Gypsum

The Blaine Gypsum (Gould, 1902), the youngest unit in the Nippewalla Group in the basin, occurs immediately above the Flower-Pot Shale and directly below the Opeche Shale. The Blaine is a persistent subsurface marker on geophysical logs except in the westernmost and northwesternmost parts of the area where it becomes thinner due to onlap above the pre-late Leonardian unconformity (Figure 3-4) and to the east where it has been truncated below the pre-Late Jurassic unconformity (Figures 3-2 and 3-3). Where no salts are associated with the Blaine interval, it is comprised of two thin white or light pink anhydrite beds, informally called "upper" and "lower" Blaine in the present study, which are separated by a thin shale. No attempt has been made to correlate these two units with those identified in Kansas by Fay (1964).

Three salt intervals (salts 5, 6, and 7) associated with the Blaine have been identified in various places within the Denver Basin (Figure 3-2). Salt 7 , where present, occurs between a thin shale marker at the base of the lower Blaine and the Flower-Pot Shale. Salt 6 is found immediately below the lower Blaine, and salt 5 occurs between the upper and lower Blaine. Salt 4 is situated immediately above the upper Blaine, at the base of the Opeche Shale.

Guadalupian and Lower Triassic

Goose Egg Formation

The Goose Egg Formation (Burk and Thomas, 1956; Maughan, 1964) is a term used in this study for rocks of Guadalupian and Early Triassic age which occur above the Blaine Formation and includes the interval from the top of the Little Medicine Member to the base of the Opeche Shale. The Goose Egg is equivalent to the Lykins Formation of Fenneman (1905) (Figure 3-4). Four Goose Egg salt intervals (salts 1, 2, 3, and 4, Figure 3-2) have been identified in the Denver basin subsurface. These salts occur at a stratigraphic position which is lower than that of the "Ervay salt" of Rasmussen and Bean (1984) in the Powder River Basin. The Freezeout Shale Member (restricted usage of Maughan (1964)) and the Little Medicine Member are Triassic in age, but they are included in the Goose Egg Formation because they represent a continuation of red bed and evaporite accumulation that took place during Late Permian time (Maughan, 1964).

The Goose Egg is absent in the eastern part of the study area where it has been removed by pre-Late Jurassic erosion (Figure 3-3).

Opeche Shale Member

The Opeche Shale Member (Darton, 1901) is a widespread, easily recognizable marker in the subsurface, generally 30 to 50 ft (9 to 15 m) thick. It is comprised of orange-red or brick red to purple shale with minor siltstone, sandstone, and anhydrite. Where interbedded with salt, the Opeche has been described as greasy or gummy in samples and is one of the units informally termed "bubble-gum shale", which can cause costly drilling and completion problems.

The Opeche Shale is equivalent to the Harriman Shale Member (LeRoy, 1946) of the Lykins Formation (Figure 3-4). The Opeche rests unconformably on top of the Minnelusa Formation (Wolfcampian and Pennsylvanian) in the Powder River Basin where pre-late Leonardian erosion has removed lower Leonardian (Sumner Group equivalent) and upper Wolfcampian rocks, and where upper Leonardian rocks are absent due to onlap on the truncation surface.

Minnekahta Limestone Member

The Minnekahta Limestone (Darton, 1901), a prominent unit exposed in the Black Hills, is widely recognized in the Powder River basin and can be traced as a persistent marker into the Denver Basin subsurface. It is equivalent to the Falcon Limestone Member (LeRoy, 1946) of the Lykins Formation, which is exposed along the Colorado Front Range (Figure 3-4). A thin-bedded gray limestone in outcrop, the Minnekahta is generally recognized as white or light pink dolomite and anhydrite in cuttings. The unit, about 20 to 30 feet (6 to 9 m) thick, is absent to the east below the pre-Late Jurassic unconformity (Figures 3-3 and 3-4).

Locally, salts are present immediately above and below the Minnekahta (salts 2 and 3, Figure 3-2). The eastern limits of these salts are controlled by erosion or near-surface dissolution below the pre-late Jurassic unconformity. As with salt 7, these salts may have originally extended much farther to the east of their present limits.

Glendo Shale Member

The Glendo Shale (Condra et al., 1940), which lies above the Minnekahta Limestone, is generally an orange or red-brown shale, 15 to 20 feet (5 to 6 m) thick. It is equivalent to the Bergen Shale Member (LeRoy, 1946) of the Lykins Formation along the Colorado Front Range (Figure 3-4). Sample descriptions of the Glendo include mention of green and gray coloration, which may be related to yellowish-gray to light greenish-gray spots that Maughan (1964) used as a characteristic for identification at exposures in southeastern Wyoming.

Salt 2 (Figure 3-2), where present, occurs in the lower part of the shale. Locally, the Glendo lies between thick salts 1 and 2; where the two salts are present, the potential exists for drilling problems associated with "bubble-gum shale".

Forelle Limestone

The Forelle Limestone (Darton, 1908) is described in the Denver basin subsurface as tan dolomite and anhydrite. A thin shale generally separates the Forelle into two carbonate units on well logs. These two carbonate units may be equivalent to upper and lower dolomitic limestones separated by argillaceous limestone, which have been observed in outcrop by Maughan (1964). The Forelle is equivalent to the Glennon Limestone Member (LeRoy, 1946) of the Lykins Formation which crops out along the Colorado Front Range (Figure 3-4) and is probably equivalent to the Day Creek Dolomite in the western Mid-Continent (Rascoe and

Baars, 1972). Salt 1, the uppermost halite identified within the study area, is associated with the Forelle Limestone (Figure 3-2).

Ervay Member

The Ervay Member of the Goose Egg Formation is defined in this study to include strata from the base of the Freezeout Shale to the top of the Forelle Limestone. Although the name Ervay was originally used for a thin carbonate unit (Burk and Thomas, 1956), several thin carbonate, shale and anhydrite beds were included in the Ervay by Maughan (1964), whose convention is followed in this study (Figure 3-2). No attempt was made to identify the Difficulty Shale Member of Maughan (1964), which is likely included in the basal portion of the Ervay of the present study. The Ervay is equivalent to the Poudre Member of Broin (1957) (Figure 3-4).

Freezeout Shale Member (restricted)

Freezeout is a term first used by Thomas (1934) for two shale tongues of the Chugwater Formation which occur above and below the Ervay Member. Terminology of Maughan (1964), who restricted the usage of the name Freezeout to the upper unit between the Ervay and Little Medicine Members of the

Goose Egg Formation, is used in the present study. The Freezeout shale is probably equivalent to the Strain Shale Member (LeRoy, 1946) of the Lykins Formation along the Colorado Front Range (Figure 3-4).

The Freezeout Shale is present only in the western part of the study area, where it is preserved below the pre-Late Jurassic unconformity. It is generally about 30 feet (10 m) thick and is a distinctive marker on well logs (Figure 3-2). In samples, it is described as orange to red-brown shale and siltstone. The Freezeout Member and the overlying Little Medicine Member, although included in the Goose Egg Formation, are of Early Triassic age (Maughan, 1964).

Little Medicine Member

Little Medicine is a name used by Thomas (1934) for a thin tongue of the Dinwoody Formation (Lower Triassic). Burk and Thomas (1956) included the Little Medicine as a member of the Goose Egg Formation. In the western part of the study area, where it is preserved below the pre-Late Jurassic unconformity, the Little Medicine is a thin, widespread marker on well logs and is generally recognized as clear to white anhydrite in samples.

The Little Medicine is commonly the first persistent anhydrite encountered below Jurassic or Triassic (Chugwater Formation) interval. Formation-top reports for this unit include the names "Day Creek", "Goose Egg", and "top of Permian".

SUMMARY

Subsurface correlations of persistent carbonate, anhydrite, and red shale markers across the Denver basin provide a stratigraphic framework with which to identify 13 salt-bearing intervals. Guadalupian-age salt occurs at four stratigraphic levels, Leonardian salt is present at eight levels, and one salt was identified at the top of the Wolfcampian.

In order to reduce confusion regarding formation names for salt-bearing rocks in the Denver basin subsurface, a nomenclature is used that adopts Mid-Continent terminology for Leonardian lithostratigraphic units and Rocky Mountain terminology for the Guadalupian and Lower Triassic. Lower Triassic, Guadalupian, and uppermost Leonardian strata are truncated to the east below a pre-Late Jurassic unconformity.

The most significant facies change within the Permian salt interval involves the Lyons-Cedar Hills Sandstone. Thick Lyons Sandstone replaces red shales and siltstones of the Salt Plain Formation and salts 9 and 10 in the center of the study area. Where sandstone is present to the southeast (Cedar Hills Sandstone), only salt 9 is replaced and salt 10 and/or the Stone Corral Anhydrite are present at a lower stratigraphic level.

CHAPTER 4
INFLUENCE OF SALT DISSOLUTION ON HYDROCARBON ENTRAPMENT, SOUTHERN NEBRASKA PANHANDLE

INTRODUCTION

The purpose of this chapter is to examine the relationship of Permian salt dissolution to hydrocarbon entrapment in a portion of the D and J Sandstone oil- and gas-producing area (D-J fairway) of western Nebraska. The study area (Figure 4-1) covers 3600 sq mi (9400 sq km) of the southern Nebraska panhandle, including townships 12N to 17N, ranges 41W to 58W, in Kimball, Cheyenne, and Deuel Counties, and parts of Banner, Morrill, Garden, and Keith Counties.

The southern Nebraska panhandle of the Denver basin study area was chosen for more detailed study for the following reasons:

1. *Abundant deep subsurface control* - Discovery of oil from Paleozoic reservoirs led to a wave of deep drilling activity in the southern Nebraska panhandle during the 1980s and 1990s. The area's 196 Permian tests account for over 25 percent of the deep well control in the Denver basin study area. Because most deep tests were drilled in the last 15 years, a dense concentration of high-quality well logs is available with which to study the Permian salt-bearing interval.

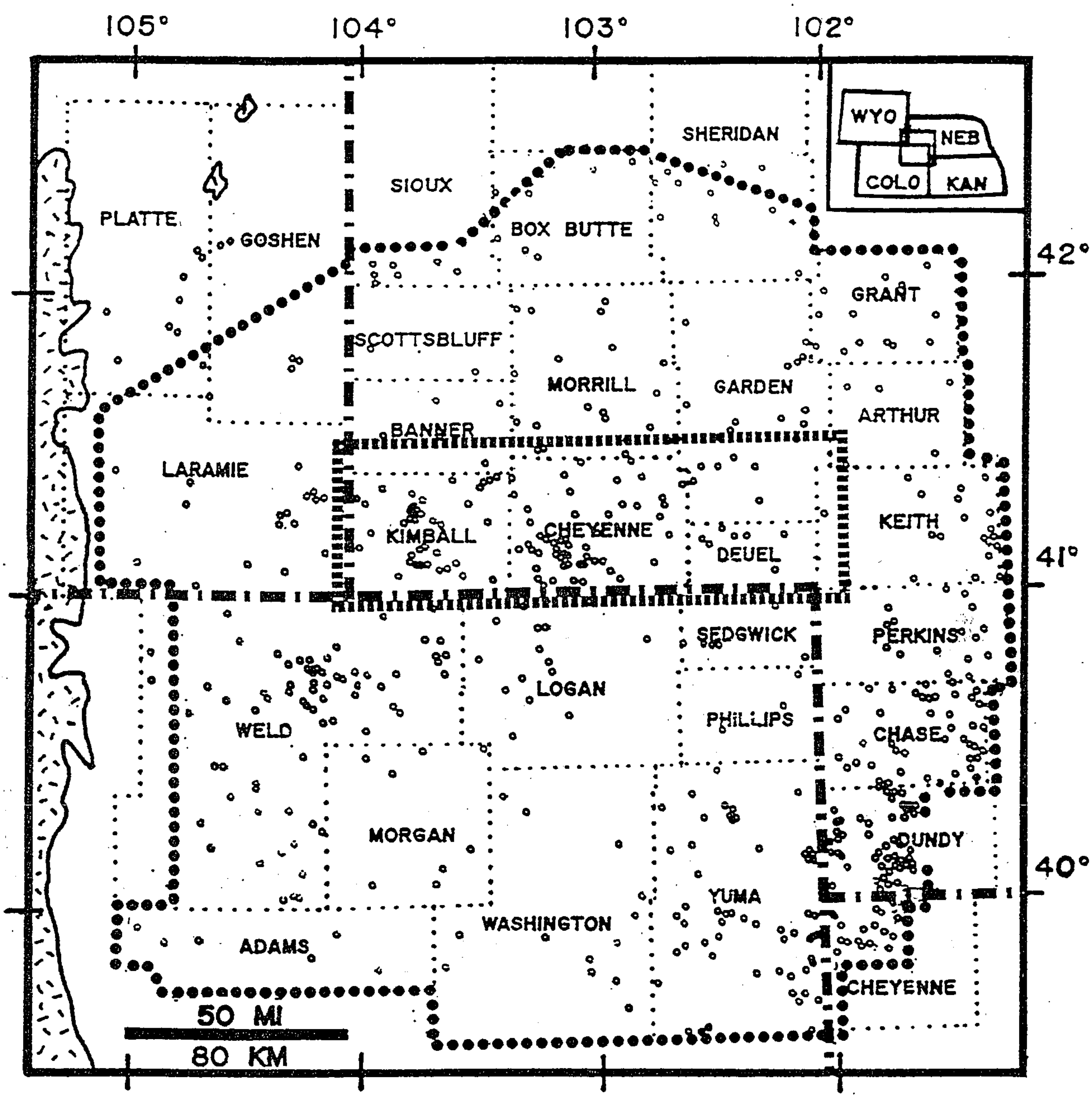


Figure 4-1. Index map showing southern Nebraska panhandle study area.

2. *Occurrence of Permian salts* - Regional mapping indicates that 12 of 13 salt-bearing zones identified in the Denver basin study area occur in the Nebraska panhandle subsurface. Available deep control allow for study of the controls on salt distribution and its relationship to Cretaceous structure.

3. *Dense Cretaceous subsurface control* - Nearly 9000 Cretaceous oil and gas tests have been drilled in the area, making it one of the more densely drilled parts of the Denver basin. This allows for accurate structural interpretations at the level of Cretaceous reservoirs, including the D Sandstone, which can then be related to salt distribution.

4) *Oil- and gas-production* - Since 1949, when oil was discovered at Gurley field, the area has yielded significant volumes of oil and gas from Cretaceous reservoirs, mainly the D and J Sandstones. More than 400 oil and gas fields are situated within the area, accounting for over 60 percent of Nebraska's total oil production and over 90 percent of the state's gas production. The area can be subdivided into two general plays, based on the type of hydrocarbons produced (Figure 4-2). The D-J fairway exists to the west, where oil, associated gas, and nonassociated gas are produced from the D and J Sandstones. Moreover, the Niobrara Chalk is currently being developed as a gas

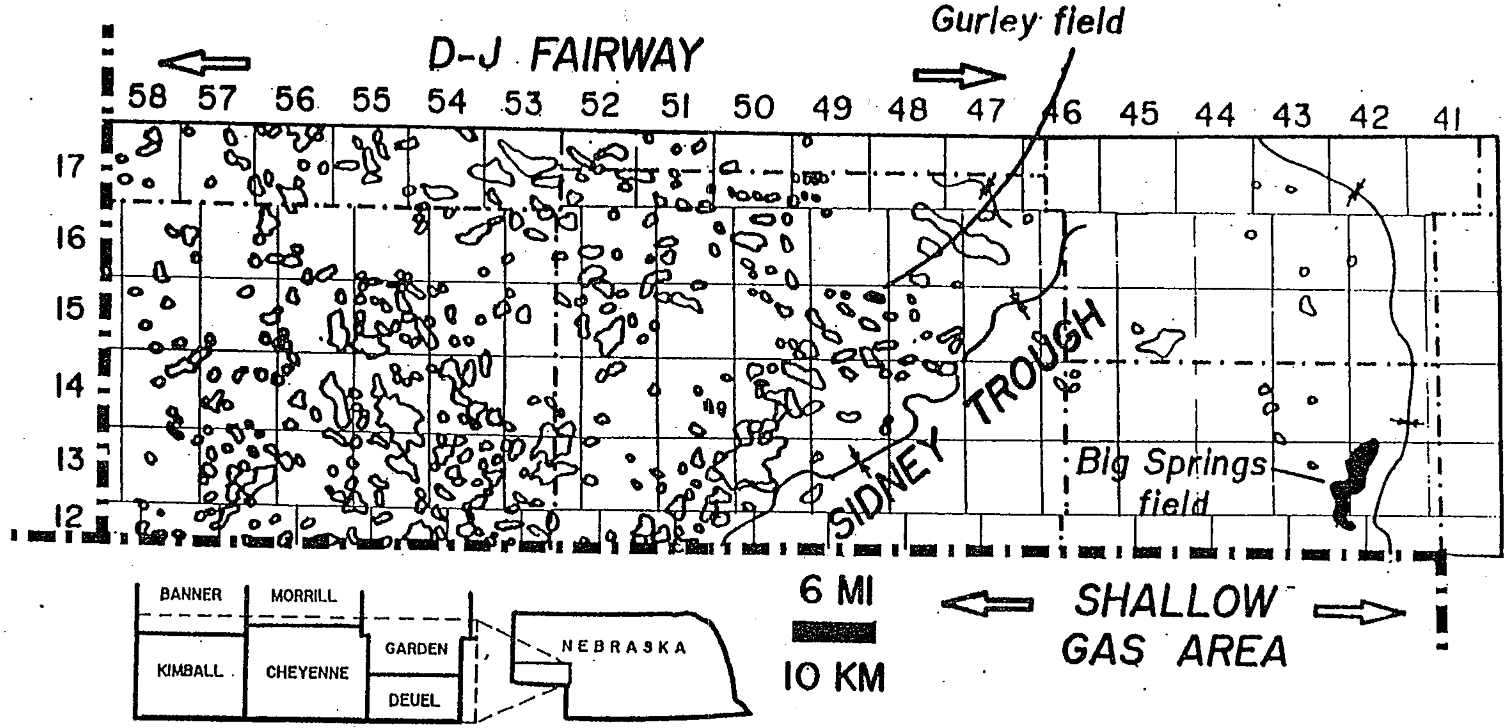


Figure 4-2. Oil and gas fields and major structural features, southern Nebraska panhandle study area.

reservoir in this area. A shallow gas area extends to the east, where biogenic gas is produced from the D Sandstone and the Niobrara Chalk.

OIL AND GAS DEVELOPMENT IN THE NEBRASKA PANHANDLE

The first commercial oil discovery on the eastern flank of the Denver basin was Gurley field in eastern Cheyenne County (Figure 4-2). The Gurley structure was identified by seismic surveys conducted as early as the 1930s (Spence, 1962), but was not drilled until 1949. The Gurley discovery resulted in a seismic survey and drilling boom in western Nebraska and adjacent areas of the Denver basin, leading eventually to the discovery of more than 200 new fields in Nebraska alone during the 1950s.

Exploratory success encouraged drilling of additional Cretaceous prospects in the deeper part of the basin to the west. Although a few wells were drilled to the Precambrian, no production was established from the Paleozoic interval. Discovery of oil in Upper Paleozoic carbonates at Amazon field in 1980 led to a wave of deep drilling activity during the 1980s and 1990s and additional production from Lower Permian and Pennsylvanian carbonates and clastics.

DEEP STRUCTURE

The Nebraska panhandle lies along the gently-dipping eastern flank of the Denver basin. Structure at the level of the subsalt Wolfcampian Chase Group (Figure 4-3) shows regional dip to the west of less than 1/2 degree. Although a few structural noses have been delineated where deep control is denser, no deep structural closures are apparent at the subsalt level.

The top of the Wolfcampian occurs about 1200 to 1500 ft (370 to 460 m) below the top of the D Sandstone. Depth to the top of the Wolfcampian ranges from about 4200 ft (1300 m) at the eastern edge of the study area to about 8500 ft (2600 m) at the Wyoming line. D Sandstone structure is discussed later in this chapter.

DISTRIBUTION OF SALTS

Regional correlations of Permian salts (Chapter 3) identify 13 stratigraphic levels at which Guadalupian, Leonardian, and upper Wolfcampian salts occur. All but one of these salt zones (salt 8) are represented within the southern Nebraska panhandle area.

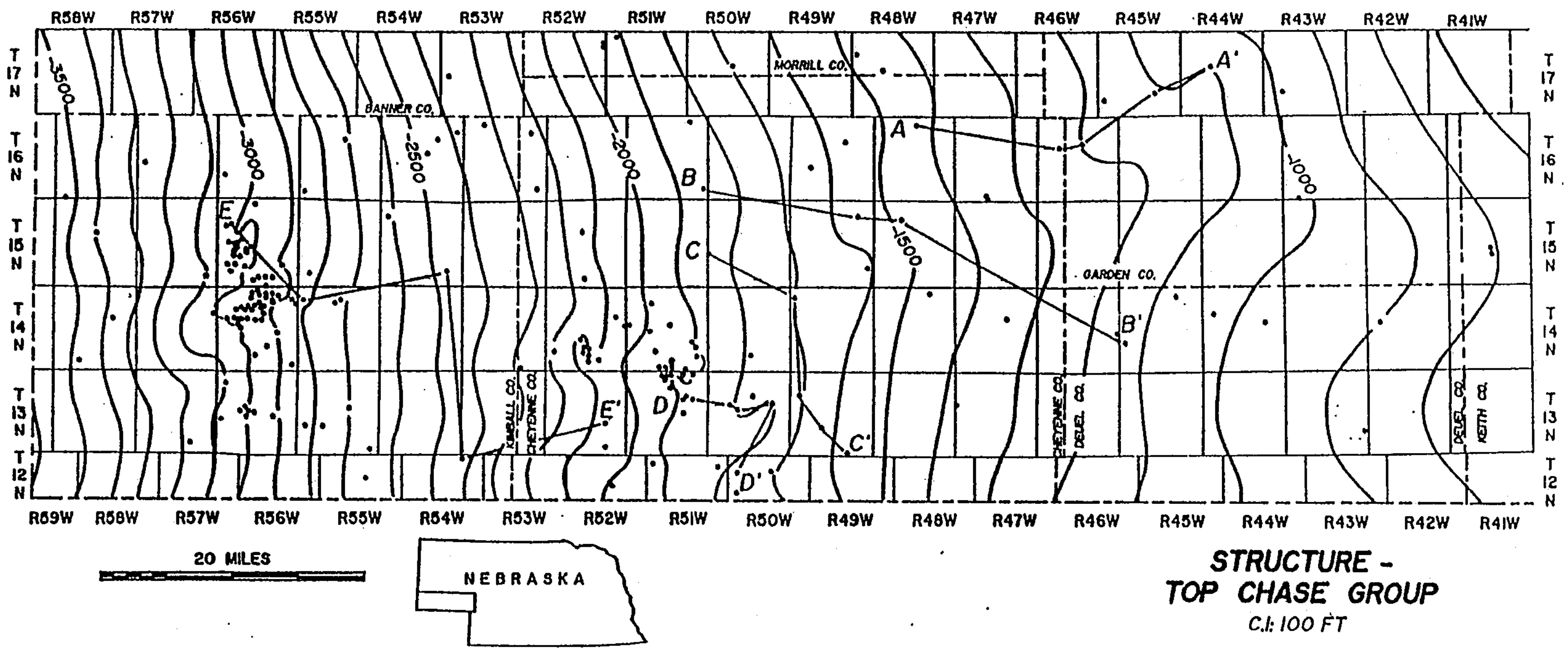


Figure 4-3. Subsalt structure in southern Nebraska panhandle study area, drawn on top of Wolfcampian Chase Group. Contour interval 100 ft (30 m).

Lower Leonardian and Upper Wolfcampian Salts

Distribution of salts 9, 10, 11/12, and 13, of Leonardian and late Wolfcampian age, is shown on Figure 4-4. Salt 13, averages only about 15 ft (5 m) thick, but is the most widespread of these lowermost salts. Salt 13 primarily occurs in the southern Morrill and northern Cheyenne Counties (southern limit of Alliance evaporite basin), in Deuel and southeastern Cheyenne Counties (northern limit of Sterling evaporite basin, where it is 30 ft or 9 m thick), and in southern Garden County ("Garden County low" area; Chapter 8; Oldham, 1996). Salt 13 is absent in the western part of the area and in an northeast-trending area across Cheyenne County.

Although not as widespread, salts 11 and 12 occur in the same general areas as salt 13. Salts 11 and 12 have a combined maximum thickness of 24 ft (7 m) in eastern Deuel County.

Salt 10, the thickest salt encountered in the southern Nebraska panhandle, occurs in the Sterling basin and Garden County low areas, where it is over 130 ft (40 m) thick. This salt has not been encountered in the southern Alliance basin area.

Salt 9 occurs in the Sterling basin and Garden County low areas and in the southern Alliance basin area of

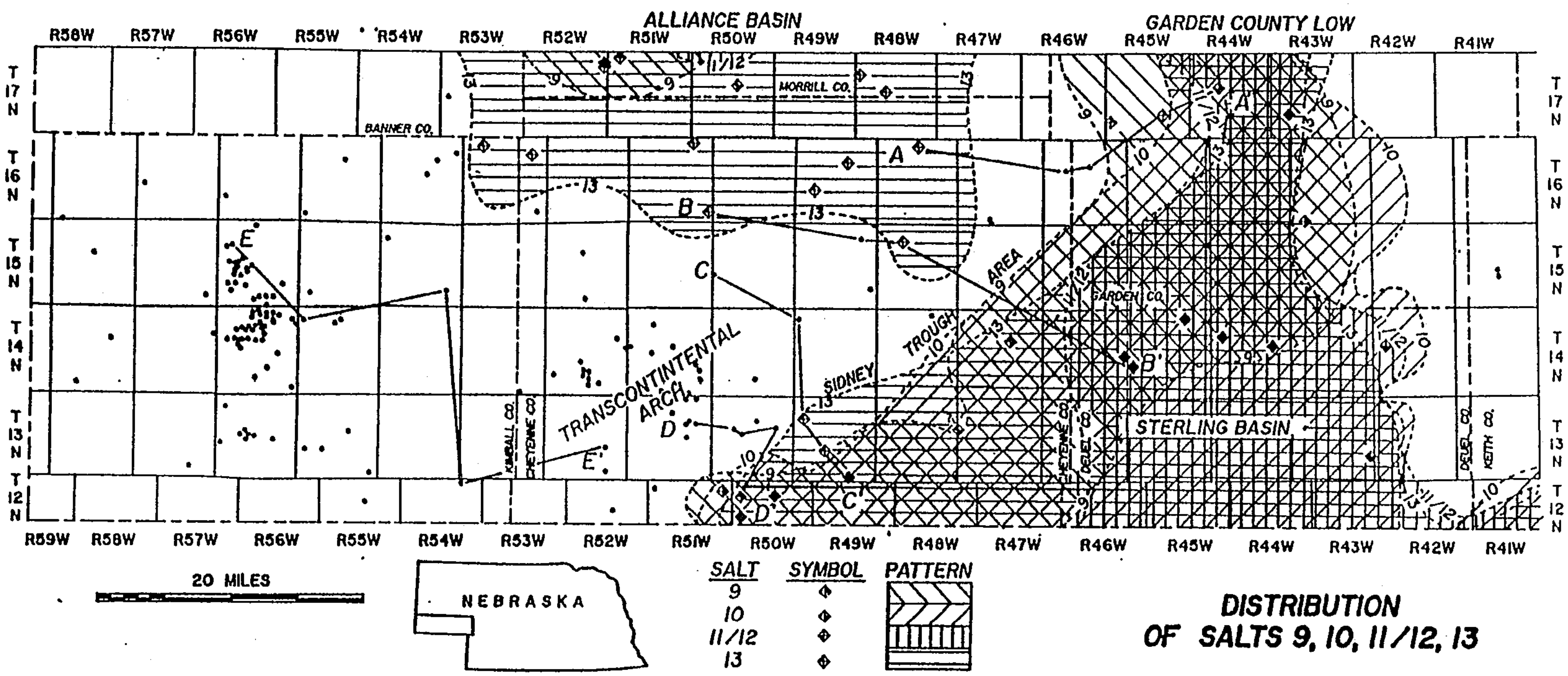


Figure 4-4. Distribution of salts 9, 10, 11/12, and 13 in southern Nebraska panhandle study area.

southern Morrill County. The salt is up to 90 ft (27 m) thick in both areas.

Distribution of these lowermost salts, particularly salts 9 and 10, is related to the distribution and thickness of the Lyons Sandstone (Figure 4-5). Thick Lyons Sandstone is present along a northeasterly trend in southern Kimball County and central Cheyenne County. The sandstone pinches out abruptly to the southeast in the same area as the northwest limit of salts 9 and 10. The Lyons is thin or absent in parts of Morrill and Banner Counties, along the southern margin of the Alliance evaporite basin. It is absent in the northern part of the Sterling evaporite basin in Deuel, southeastern Cheyenne, and in southern Garden Counties, and it is also absent in the Garden County low area. To the northeast of the Sterling basin and Garden County low areas, the sandstone thickens toward the Chadron arch, where it is referred to as the Cedar Hills Sandstone.

Salt 10 (Figure 4-6) is over 100 ft (30 m) thick in the Sterling basin and thins abruptly in all directions away from the evaporite basin. Gamma-ray logs indicate that thin potassium-rich salt zones, probably composed of sylvite, occur with the thick halite zone (two thin highly-radioactive zones within salt 10 on Figure 3-2). The eastern margin of salt 10 coincides with a north-south-trending Cretaceous structural flexure just east of the Oshkosh-Lewellen and Big Springs anticlines (Figure 4-2).

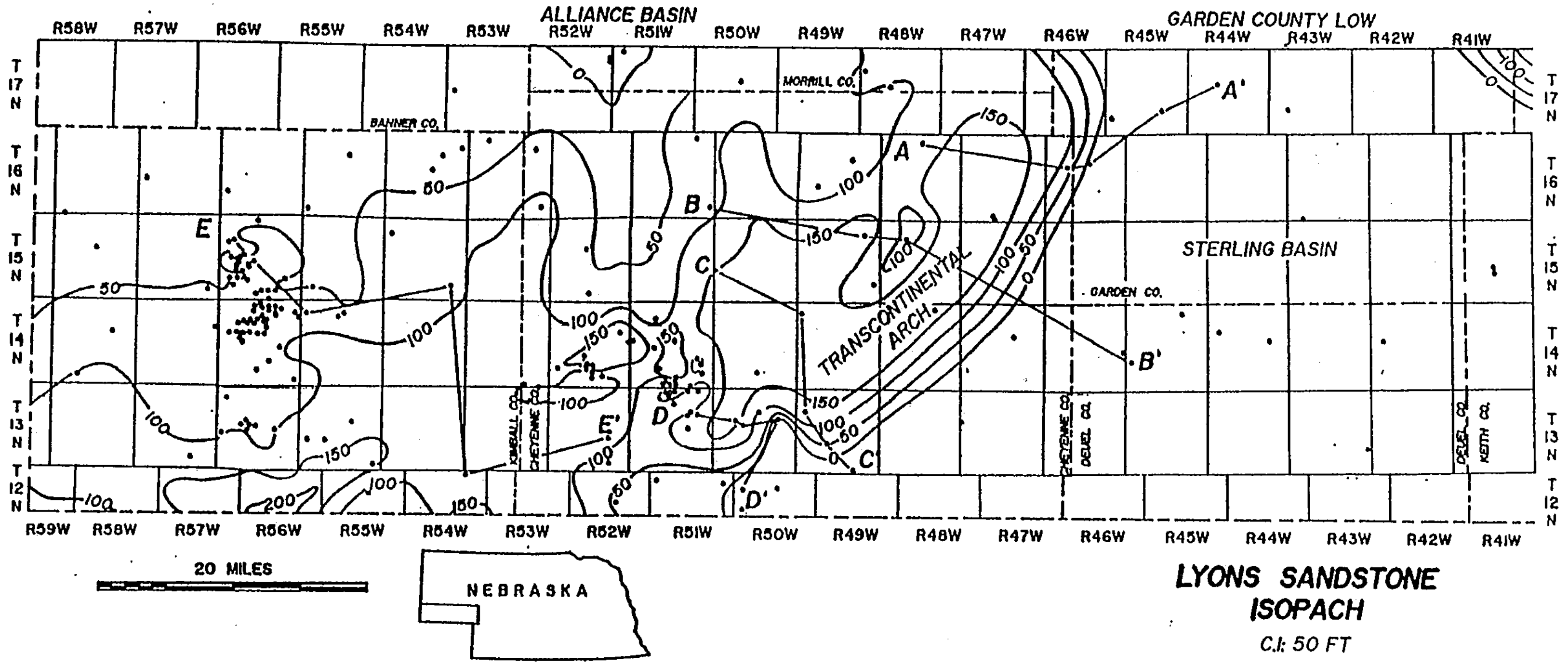


Figure 4-5. Lyons Sandstone isopach, southern Nebraska panhandle study area. Contour interval 50 ft (15 m). Cross sections A-A' through E-E' , whose lines of traverse are shown on this and subsequent maps, are presented on Figures 4-17 through 4-21.

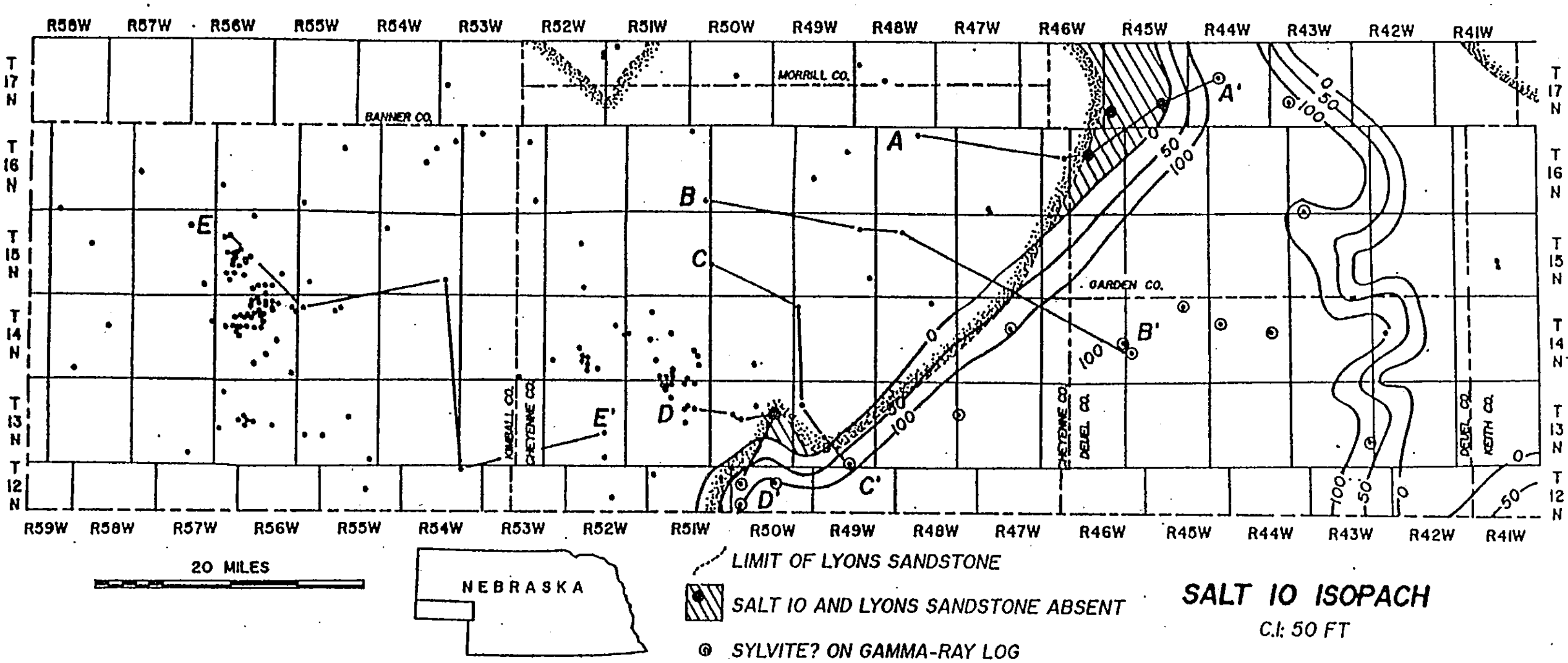


Figure 4-6. Salt 10 isopach, southern Nebraska panhandle study area. Contour interval 50 ft (15 m).

The abrupt western margin of salt 10 (Figure 4-6) coincides with the southeastern limit of the Lyons Sandstone (Figure 4-5) and the location of the Sidney trough (Figure 4-2). Although deep drilling in the trough area is limited, a few wells (black dots, Figure 4-6) drilled through the Leonardian interval without encountering either thick Lyons Sandstone or salt 10. In these wells, the Lyons/salt 10 interval is represented by a thin anhydritic zone. This zone likely represents insoluble residue where salt has been dissolved along its northwestern margin, at its abrupt facies change to the lower part of the Lyons Sandstone.

Salt 9 (Figure 4-7) is 90 ft (27 m) thick along the southern limit of the Alliance basin in southern Morrill County and in the Garden County low area. As with salt 10, the northwestern limit of salt 9 in the Sterling basin area coincides with the southeastern limit of the Lyons Sandstone. The Lyons Sandstone and salt 9 are both absent in wells drilled along this trend. This suggests that salt was once present, but was subsequently removed by dissolution along its northwestern margin where it is stratigraphically equivalent to the upper part of the Lyons Sandstone. This trend also coincides with the location of the Sidney trough, suggesting that this regional Cretaceous structural low, which defines the eastern limit of oil production with the D-J fairway, is a salt dissolution feature.

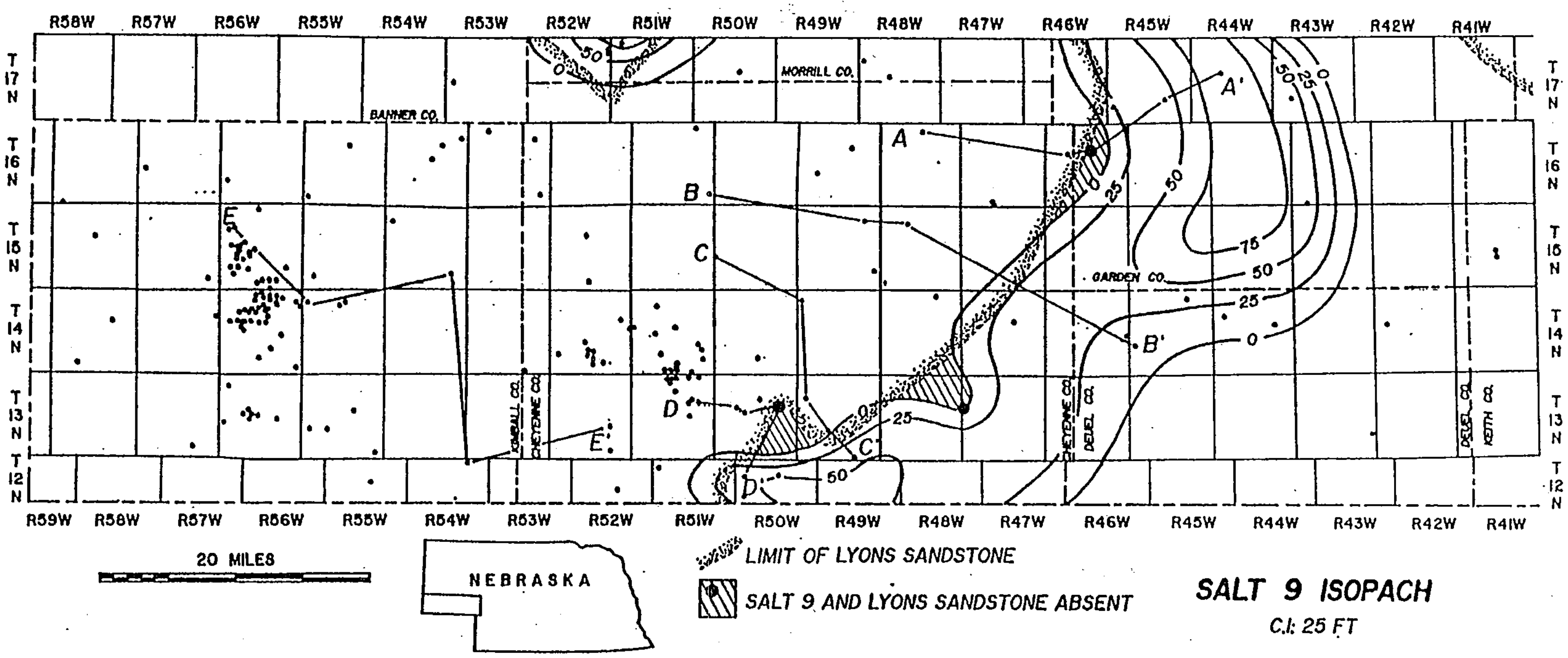


Figure 4-7. Salt 9 isopach, southern Nebraska panhandle study area. Contour interval 25 ft (8 m).

Upper Leonardian Salts

In contrast to lower Leonardian and upper Wolfcampian salts, distribution of upper Leonardian salts 5, 6, and 7 (Figure 4-8) is not restricted to the Alliance and Sterling basin areas. Salt 8 is absent in the Nebraska panhandle and has been identified only in an isolated area of Yuma County, Colorado.

Salt 7, which is up to 85 ft (25 m) thick in Deuel County, is present across the area of Cheyenne County in which salts 9, 10, 11, 12, and 13 were absent. This suggests that the subtle paleohigh associated with the Transcontinental arch, which partitioned the Alliance and Sterling evaporite basins and allowed for accumulation of eolian sand (Lyons Sandstone), was not present during precipitation of salt 7. Regional influence of the Transcontinental arch on evaporite basin configuration is discussed in Chapter 8).

Salt 6, where present, averages about 10 ft (3 m) in thickness, and generally occurs in the same areas as salt 7, except to the east in Deuel and Garden Counties. In this area, salt 6 has likely been removed by dissolution beneath a pre-Late Jurassic unconformity.

Salt 5, which is generally 45 to 50 ft (15 m) thick in this area, occurs in the same general areas as salts 6 and

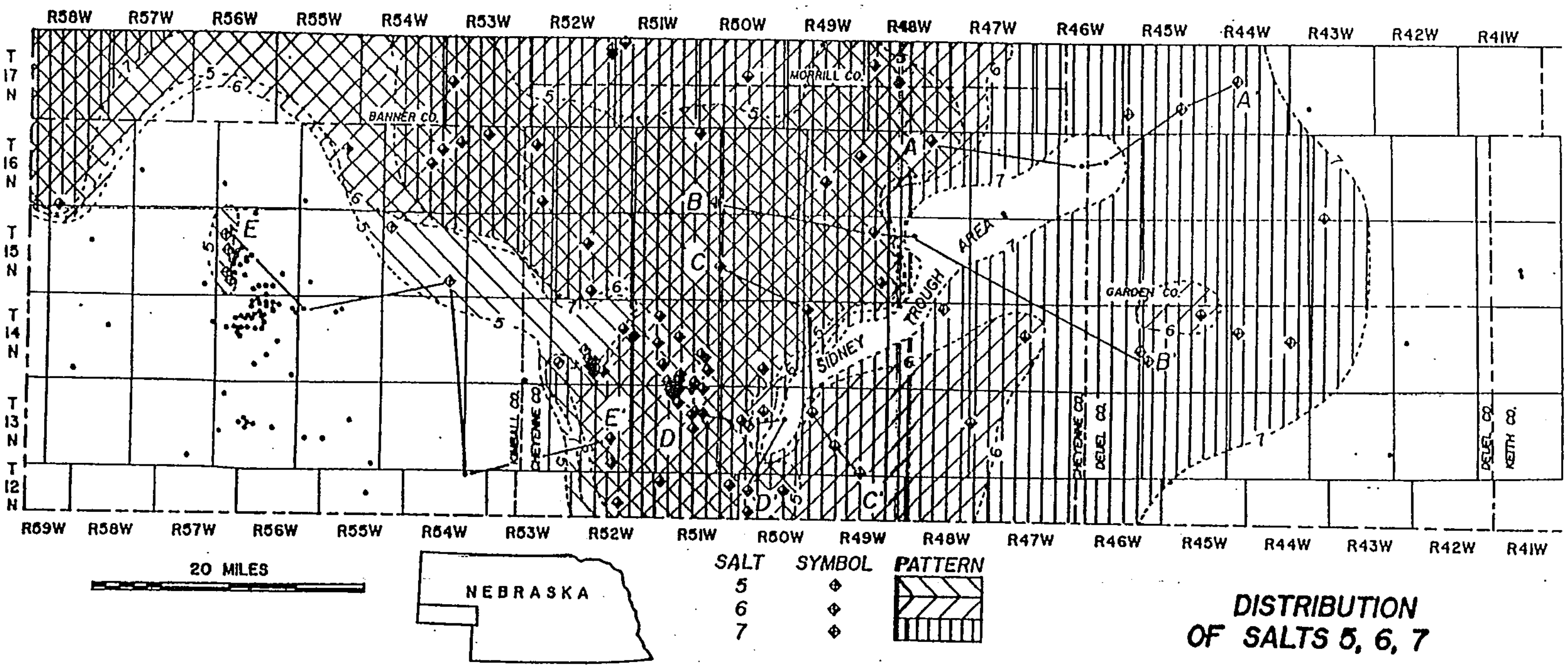


Figure 4-8. Distribution of salts 5, 6, and 7 in southern Nebraska panhandle study area.

7. This salt, however, does not extend as far to the east as salts 6 and 7, due to pre-Late Jurassic removal. An outlier of salt 5 occurs in T15N, R56W, suggesting that salt 5 (and perhaps salts 6 and 7) may have originally been present in other parts of Kimball County, but was removed by dissolution.

Salts 5, 6, and 7 are absent in a narrow northeast-trending area of eastern Cheyenne County and southwestern Garden County. This area generally coincides with that area where salts 9 and 10 are absent along the Lyons Sandstone/salt facies change. This trend also coincides with the axis of the Sidney trough, suggesting that partial dissolution of salts 5, 6, and 7, as well as salts 9 and 10, contributed to collapse of overlying strata and structural relief of the regional syncline.

Guadalupian Salts

Distribution of Guadalupian salts (salts 1, 2, 3, and 4) is shown on Figure 4-9. Salt 4 is thin (up to 20 ft or 6 m thick, but generally 10 ft or 3 m thick), and has a limited areal extent.

Salt 3, which is up to 80 ft (25 m) thick, averages about 50 to 55 ft (15 m) in thickness in Cheyenne County. This salt extends northwestward into the Alliance basin area of Nebraska and Wyoming. In the Nebraska panhandle, the

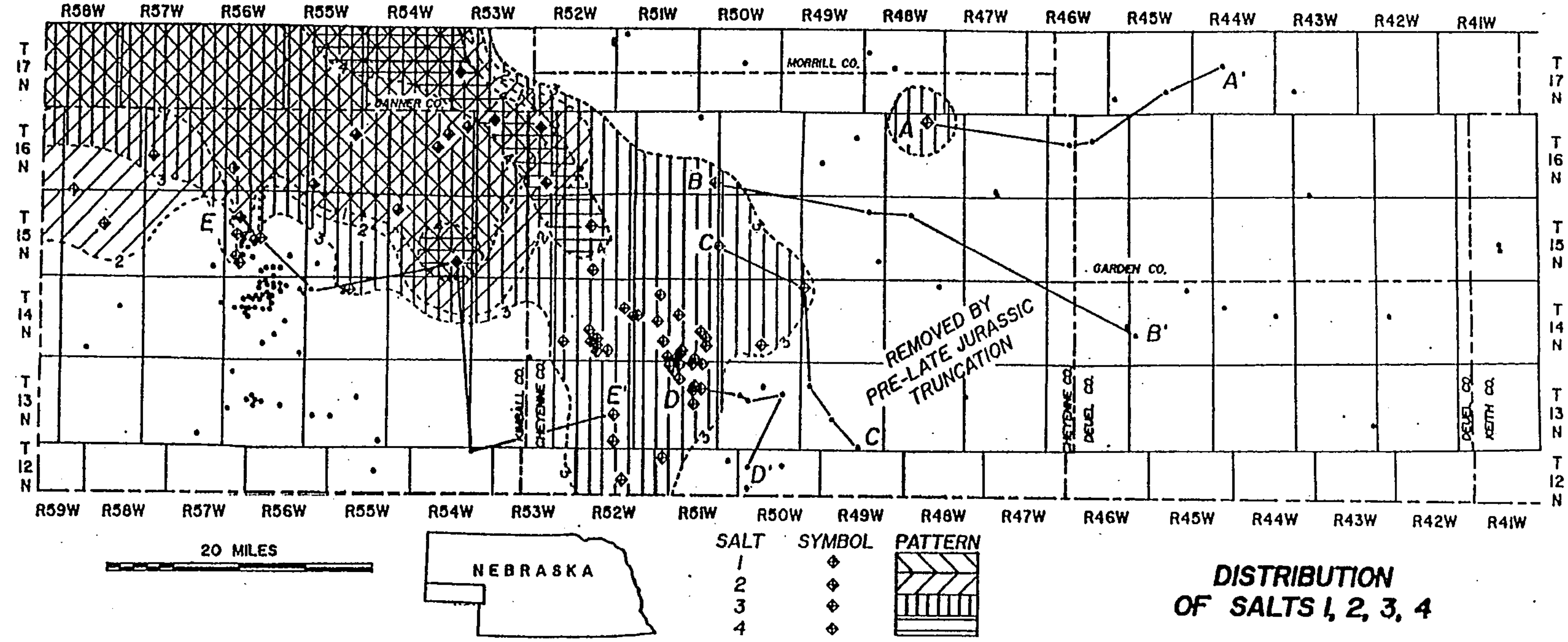


Figure 4-9. Distribution of salts 1, 2, 3, and 4 in southern Nebraska panhandle study area.

eastern limit of salt 3 is just west of the eastern limit of salt 5, reflecting the influence of the pre-Late Jurassic unconformity on the distribution of these younger salts. Outliers or salients of salt 3 occur in central Kimball County. These coincide with the location of a salt 5 outlier (Figure 4-8), suggesting that incomplete salt dissolution took place in this area.

Salt 2 is up to 90 ft (27 m) thick in northern Kimball County. Its eastern limit does not extend as far east as that of salt 3. Likewise, the eastern limit of salt 1 does not extend as far east as that of salt 2. As with salts 3, 5, and 6, this reflects the stepwise removal of salt due to pre-Late Jurassic erosion or near-surface dissolution. This suggests that these younger salts may have originally extended farther east of their present limits. As with salts 3 and 5, salts 1 and 2 occur as outliers in parts of Kimball County, suggesting that incomplete dissolution of these salts occurred in this area.

PERMO-TRIASSIC THICKNESS TRENDS

Leonardian Series

An isopach of the Leonardian Series (Figure 4-10) reflects the distribution of salts 5 through 13. The Leonardian is thickest (over 550 ft or 170 m) in the

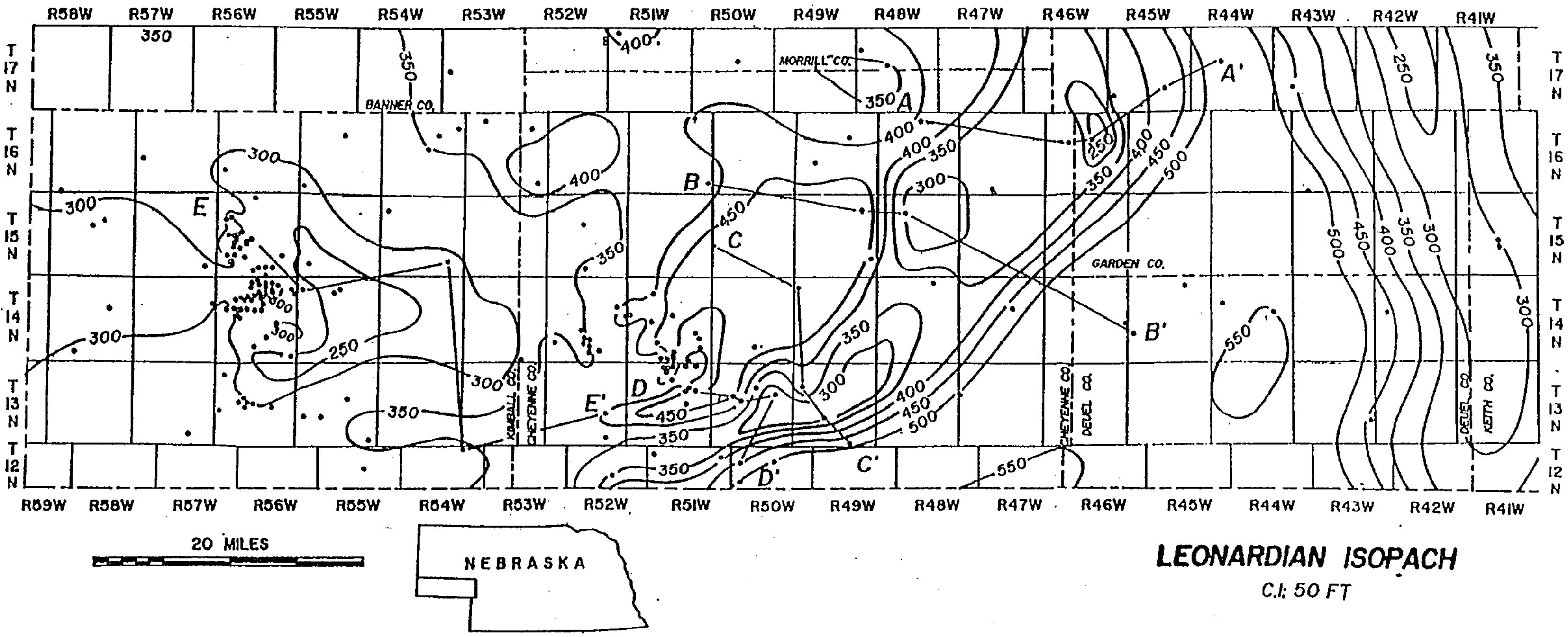


Figure 4-10. Leonardian isopach, southern Nebraska panhandle study area. Contour interval 50 ft (15 m).

Sterling basin area of Deuel, southeastern Cheyenne, and southern Garden Counties and in the Garden County low area, where salts 6, 7, 9, 10, 11, 12, and 13 are present. East of this area, along the Deuel - Keith County line, the Leonardian thins to less than 300 ft (90 m) where salt is absent. This area also coincides with a regional Cretaceous-level flexure (Figure 4-2) just east of the Oshkosh-Lewellen and Big Springs anticlines, indicating that this structural low was caused by salt solution collapse.

Abrupt thinning of the Leonardian from more than 500 ft (150 m) to less than 300 ft (90 m) occurs in a northeast-trending area of south-central and northeastern Cheyenne County and southwestern Garden County. This isopach minumum reflects the absence of salt, particularly salts 5, 6, 7, 9, and 10, at the Lyons Sandstone/salt facies change, and coincides with the location of the Sidney trough.

To the northwest, in central and northern Cheyenne County, the Leonardian is over 450 ft (140 m) thick, reflecting the occurrence of salts 5, 6, and 7, as well as thick Lyons Sandstone. Farther west, the Leonardian is less than 250 ft (75 m) thick in central Kimball County, where the Lyons Sandstone is thin, salts 6 through 13 are absent, and salt 5 is present only in a small outlier in the western part of T15N R56W.

Guadalupian Series

An isopach of the Guadalupian Series (Figure 4-11) reflects the distribution of salts 1 through 4 as well as progressive truncation of Guadalupian strata to the east at the pre-Late Jurassic unconformity. The Guadalupian is over 350 ft (105 m) thick in northern Kimball and southern Banner Counties, where salts 1, 2, 3, and 4 are preserved. An area in western Cheyenne County, where the Guadalupian is over 150 ft (45 m) thick, coincides with the occurrence of salt 3 (Figure 4-9).

Gradual eastward thinning of the Guadalupian, which generally corresponds with pre-Late Jurassic subcrop trends, is due to truncation of successively older Guadalupian strata to the east. The zero-isopach of the Guadalupian in Keith County coincides with the Opeche Shale - Blaine subcrop contact.

By contrast, thinning of the Guadalupian in southern Kimball County from over 300 ft (90 m) to less than 100 ft (30 m) is not related to truncation at the pre-Late Jurassic unconformity. In this area, the Chugwater Formation and Little Medicine Member of the Goose Egg Group, both Triassic in age, are preserved beneath the unconformity. As the Guadalupian has not been partially truncated in this area, thinning is likely due to removal of salts 1, 2, and 3 by dissolution. Outliers of these three salts in central

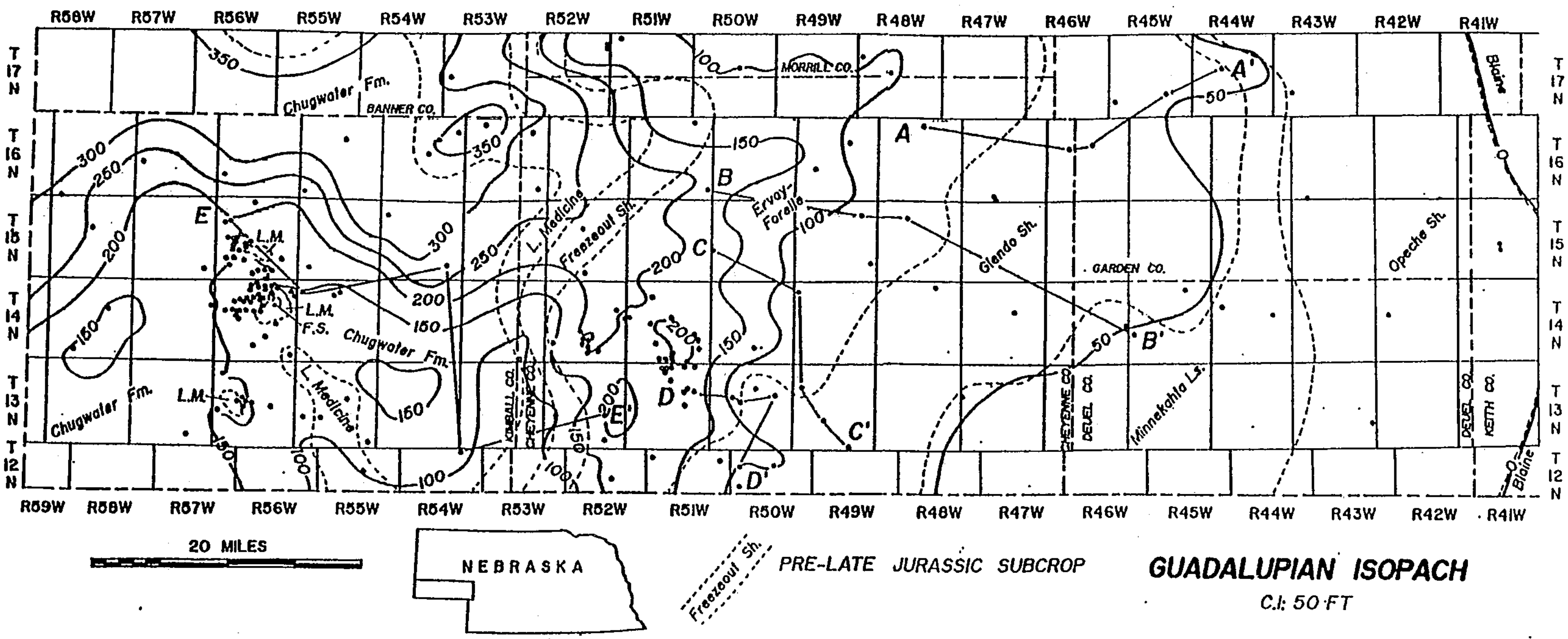


Figure 4-11. Guadalupian isopach and pre-Late Jurassic subcrop map, southern Nebraska panhandle study area. Contour interval 50 ft (15 m).

Kimball County support a salt dissolution origin for thinning of the Guadalupian in this southwestern part of the Nebraska panhandle.

Triassic System

An isopach of Triassic-age rocks, represented by the Chugwater Formation and Little Medicine and Freezeout Shale Members of the Goose Egg Group, is shown on Figure 4-12, along with pre-Late Jurassic subcrops of Triassic strata. Triassic thickness patterns are related to pre-Late Jurassic truncation. In western Kimball and southwestern Banner Counties, where the Chugwater Formation is thickest, the Triassic is over 150 ft (45 m) thick. To the east, Triassic strata are less than 50 ft (15 m) thick where the Chugwater Formation is absent and the Little Medicine and Freezeout Shale lie below the pre-Late Jurassic unconformity. The zero-isopach of the Triassic in western Cheyenne County coincides with the sub-unconformity pinchout of the Freezeout Shale.

Thinning of the Triassic in southern Kimball County, which is due to localized removal of the Chugwater, coincides with thinning of the Guadalupian Series. This suggests that suspected dissolution of Guadalupian (and possibly Leonardian) salts in this area may be related to

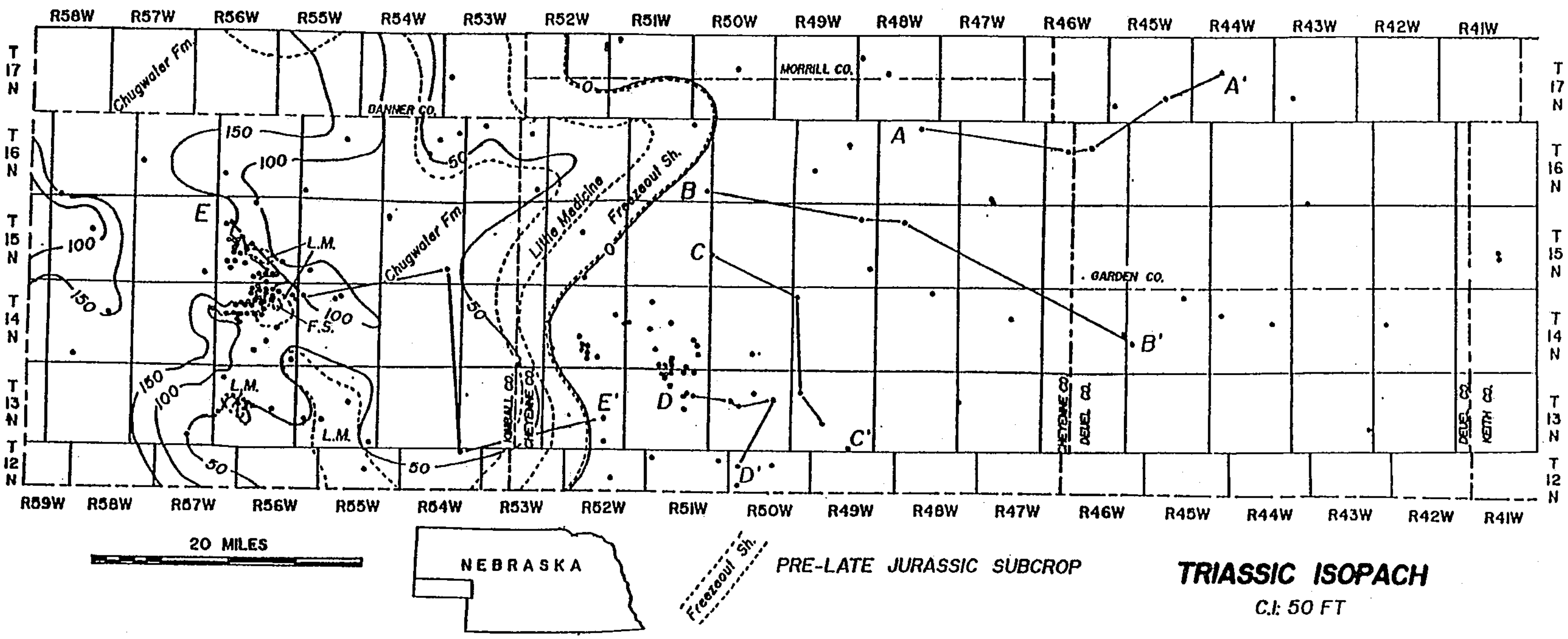


Figure 4-12. Triassic isopach and pre-Late Jurassic subcrop map of Triassic strata, southern Nebraska panhandle study area. Contour interval 50 ft (15 m).

enhanced pre-Late Jurassic erosion of the Triassic in this area.

INFLUENCE OF SALT DISSOLUTION ON HYDROCARBON ENTRAPMENT

Most oil and gas production in the Nebraska panhandle (Figure 4-2) is from the Cretaceous Niobrara Chalk and D and J Sandstones). Although much of the oil and gas is produced from stratigraphic traps, structural mapping across the basin at the level of Cretaceous reservoirs reveals a number of anomalous structural depressions which result in more than 100 ft (30 m) of localized structural reversal. Many of the lows are situated immediately east (regionally updip) of oil and gas fields. Studies of gas fields which include seismic data (Chapters 5 and 7) demonstrate that Permian salts are absent below field-bounding structural lows and gas-productive anticlines lie above salt dissolution edges or outliers.

Major structural features present in the southern Nebraska panhandle which occur at the level of the D and J Sandstone reservoirs are shown on Figure 4-2. The Sidney trough, which marks the eastern limit of oil and gas production within the D-J fairway, trends northeast across the area. Also, a north-south-trending syncline (discussed in Chapter 2) is present just east of shallow D Sandstone and Niobrara gas production at the eastern margin of the study area.

No significant regional-scale structural anomalies are present in the western half of the southern Nebraska panhandle, even though numerous oil and gas fields produce from the D and J Sandstones and despite the erratic distribution of salt at depth in this area (Figures 4-4, 4-8, and 4-9). A more detailed look at the relationship of D Sandstone structure to salt distribution reveals that timing of salt dissolution is critical to the development of structural traps.

D Sandstone Structure

The D Sandstone structure map across the southern Nebraska panhandle is shown on Figure 4-13. Nearly 9000 D Sandstone formation tops, compiled by the author and provided by Petroleum Information Corporation, were used to construct the map. Circled wells are Permian or deeper penetrations. Double-circled wells penetrated thick Permian salt(s).

The D Sandstone ranges in elevation from over 500 ft (150 m) above sea level along the eastern margin of the mapped area to more than 2000 ft (610 m) below sea level at the Wyoming line, along the western margin of the map. Regional dip is less than one degree to the west. In the

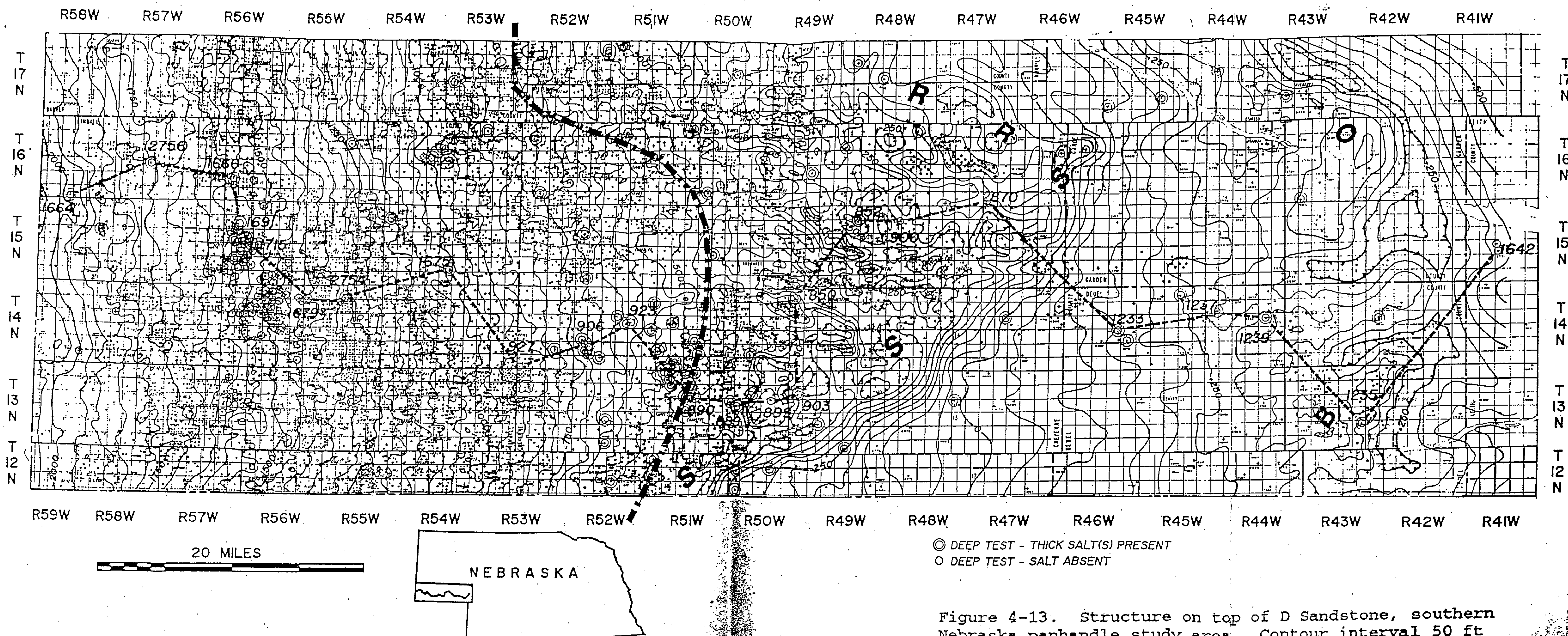


Figure 4-13. Structure on top of D Sandstone, southern Nebraska panhandle study area. Contour interval 50 ft (15 m). Circled wells denote Paleozoic tests. Double-circled wells encountered thick Permian salt. Structural features in more complex eastern half include Sidney trough (S), Rush Creek - Lisco structural basin (R), Oshkosh - Lewellen anticline (O), and Big Springs anticline. Cross section shown on Figure 4-14. Base map from Mapco Diversified, Inc., used with permission.

western half of the area, homoclinal dip is locally modified by minor structural nosing caused by differential compaction across thick D or J Sandstone lenses.

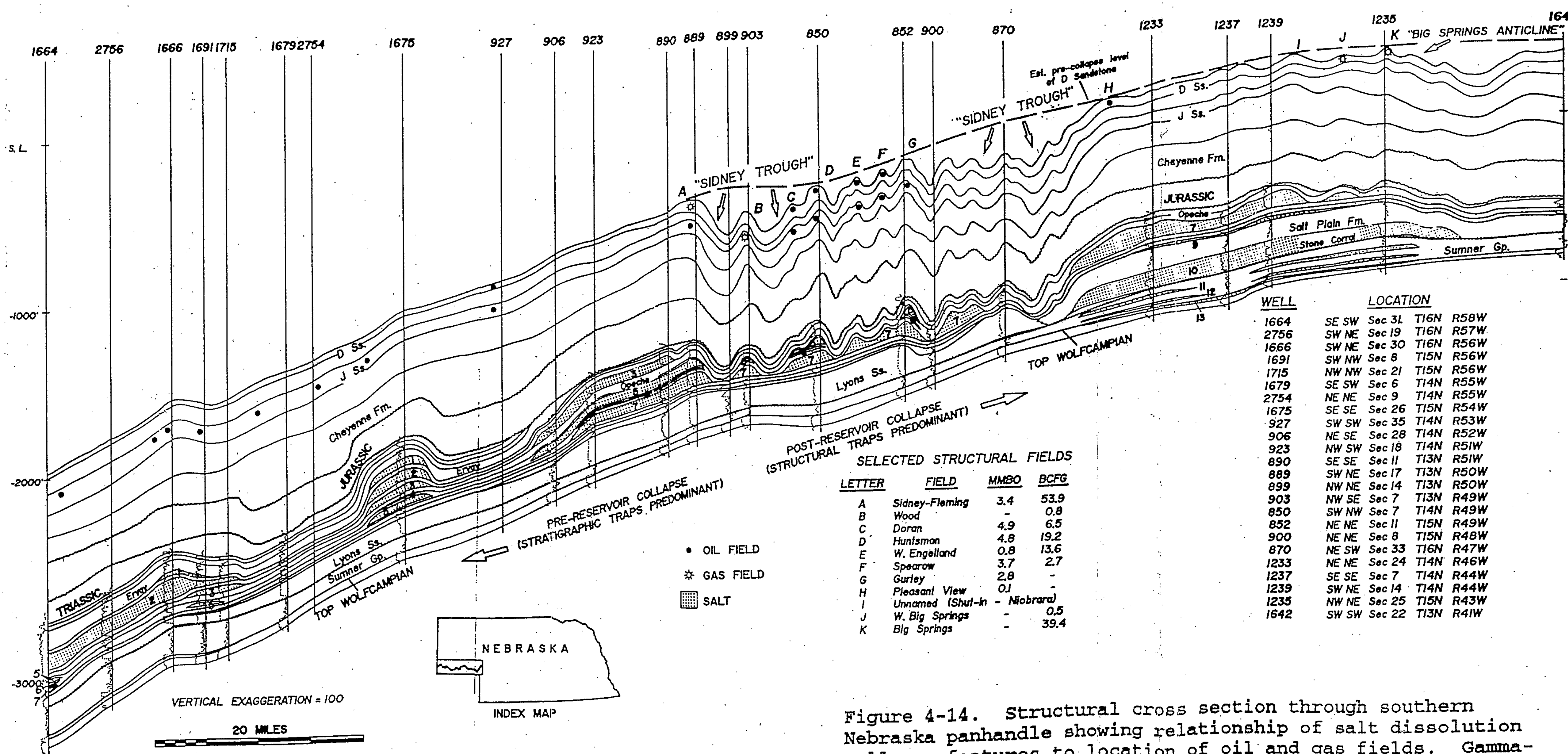
By contrast, the eastern half of the map is more structurally complex. Prominent structural features include the northeast-trending Sidney trough (S), with over 250 ft (75 m) of relief, and a northwest-trending low, (R), which may be related to the Cenozoic "Rush Creek - Lisco structural basin" of Diffendal (1980). These two synclines define the eastern (regionally updip) limit of the D-J fairway in Nebraska. Subsidiary synclines, which branch off from the main trough, add to the structural complexity of the area, particularly just west of the Sidney trough.

Near the eastern margin of the map, a north-south-trending flexure with over 150 ft (30 m) of relief includes a regional syncline situated immediately to the east of DeGraw's (1969, 1971) "Big Springs" (B) and "Oshkosh - Lewellen" (O) anticlines, which coincide with the eastern limit of shallow biogenic gas production.

Two different trap types result from the difference in structural complexity between the western and eastern parts of the area. A north-south dashed line on Figure 4-13 marks the approximate boundary between the two areas. In the *structurally complex area* (eastern half), including eastern Cheyenne County, Deuel County, and part of Garden County, production is from reservoir-quality sandstones which are draped across small, high-relief anticlines situated just west of the regional synclines. In the *structurally simple area* (western half), including Kimball County and western Cheyenne County, structure is relatively simple at the level of the D and J Sandstones. Stratigraphic traps predominate in this western area.

A structural cross section (Figure 4-14) illustrates the relationship of timing of salt dissolution to trap development. In the western half of the fairway, dissolution occurred during Jurassic and Early Cretaceous time, providing additional accommodation space for the Jurassic Morrison Formation and Lower Cretaceous Cheyenne Formation. Dissolution is incomplete, as evidenced by salt outliers below thin Cheyenne Formation. Removal of salt largely took place prior to deposition of D and J sandstones, resulting in relatively simple stucture at the level of these reservoirs, and stratigraphic traps are predominant in this area. In the eastern half of the fairway, however, where significant dissolution post-dated deposition of Cretaceous reservoirs, structure is complex at the level of the reservoirs, and structural or structural-stratigraphic traps predominate.

Regional subsalt structure, at the level of the Wolfcampian (Figures 4-3 and 4-14), lacks the complexity of Cretaceous structure that is present in the eastern part of the area. (Apparent monoclinal folding at the subsalt level



SELECTED STRUCTURAL FIELDS

LETTER	FIELD	MMBO	BCFG
A	Sidney-Fleming	3.4	53.9
B	Wood	-	0.8
C	Doran	4.9	6.5
D	Huntsman	4.8	19.2
E	W. Engelland	0.8	13.6
F	Spearow	3.7	2.7
G	Gurley	2.8	-
H	Pleasant View	0.1	-
I	Unnamed (Shut-in - Niobrara)		
J	W. Big Springs	-	0.5
K	Big Springs	-	39.4

WELL	LOCATION			
1664	SE SW	Sec 31	T16N	R58W
2756	SW NE	Sec 19	T16N	R57W
1666	SW NE	Sec 30	T16N	R56W
1691	SW NW	Sec 8	T15N	R56W
1715	NW NW	Sec 21	T15N	R56W
1679	SE SW	Sec 6	T14N	R55W
2754	NE NE	Sec 9	T14N	R55W
1675	SE SE	Sec 26	T15N	R54W
927	SW SW	Sec 35	T14N	R53W
906	NE SE	Sec 28	T14N	R52W
923	NW SW	Sec 18	T14N	R51W
890	SE SE	Sec 11	T13N	R51W
889	SW NE	Sec 17	T13N	R50W
899	NW NE	Sec 14	T13N	R50W
903	NW SE	Sec 7	T13N	R49W
850	SW NW	Sec 7	T14N	R49W
852	NE NE	Sec 11	T15N	R49W
900	NE NE	Sec 8	T15N	R48W
870	NE SW	Sec 33	T16N	R47W
1233	NE NE	Sec 24	T14N	R46W
1237	SE SE	Sec 7	T14N	R44W
1239	SW NE	Sec 14	T14N	R44W
1235	NW NE	Sec 25	T15N	R43W
1642	SW SW	Sec 22	T13N	R41W

Figure 4-14. Structural cross section through southern Nebraska panhandle showing relationship of salt dissolution collapse features to location of oil and gas fields. Gamma-ray log traces are shown through salt interval except well 927. Map view of cross section traverse shown on Figure 4-13.

on Figure 4-14 between wells 1666 and 1691 and between wells 903 and 850, is due to changes in the direction of cross section traverse from dip-parallel to strike-parallel in these areas.) Structural discordance between the D Sandstone and the Wolfcampian in the eastern half of the area is due to incomplete dissolution of Permian salt. To the west, where salt dissolution pre-dated deposition of the D and J Sandstones, Cretaceous and subsalt Permian structure are concordant.

Figures 4-15 and 4-16 show the structural configuration at the D Sandstone-level in the more structurally complex eastern half of the area. Figure 4-15, a northeast view, shows the northeast trend of the Sidney trough and complex structure just west of the trough. Locations of selected fields are shown. Shallow gas production at Big Springs, Oshkosh and McCord fields is associated with a north-south regional flexure at the D level. Figure 4-16, a southwest view, shows the abrupt drop in structural elevation in the Sidney trough area. A widespread structurally high area, situated between the trough and flexure at Big Springs and McCord-Richards field coincides with the occurrence of thick Leonardian salts.

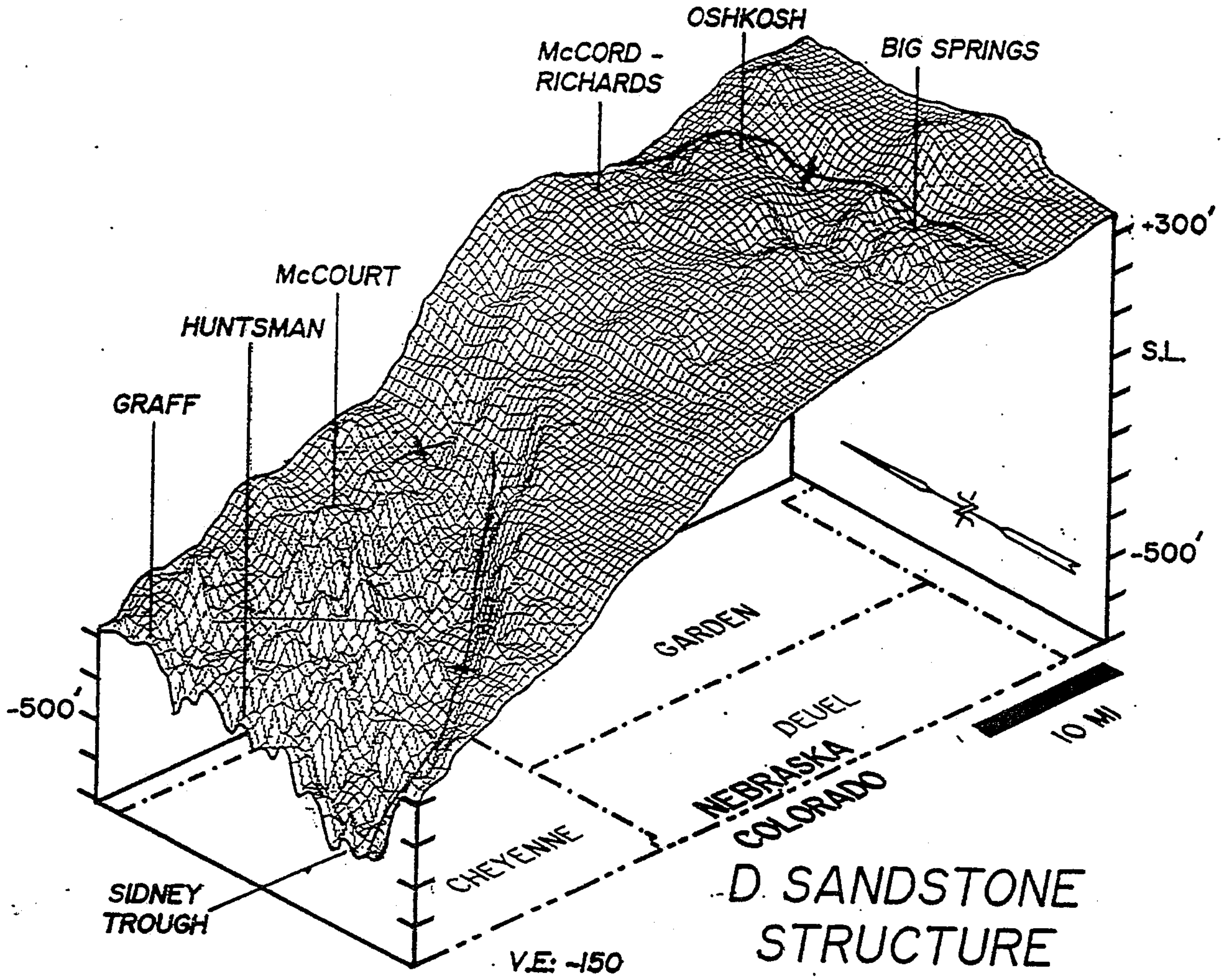


Figure 4-15. Surface plot showing structural configuration of D Sandstone in structurally complex eastern half of southern Nebraska panhandle. View is to the northeast.

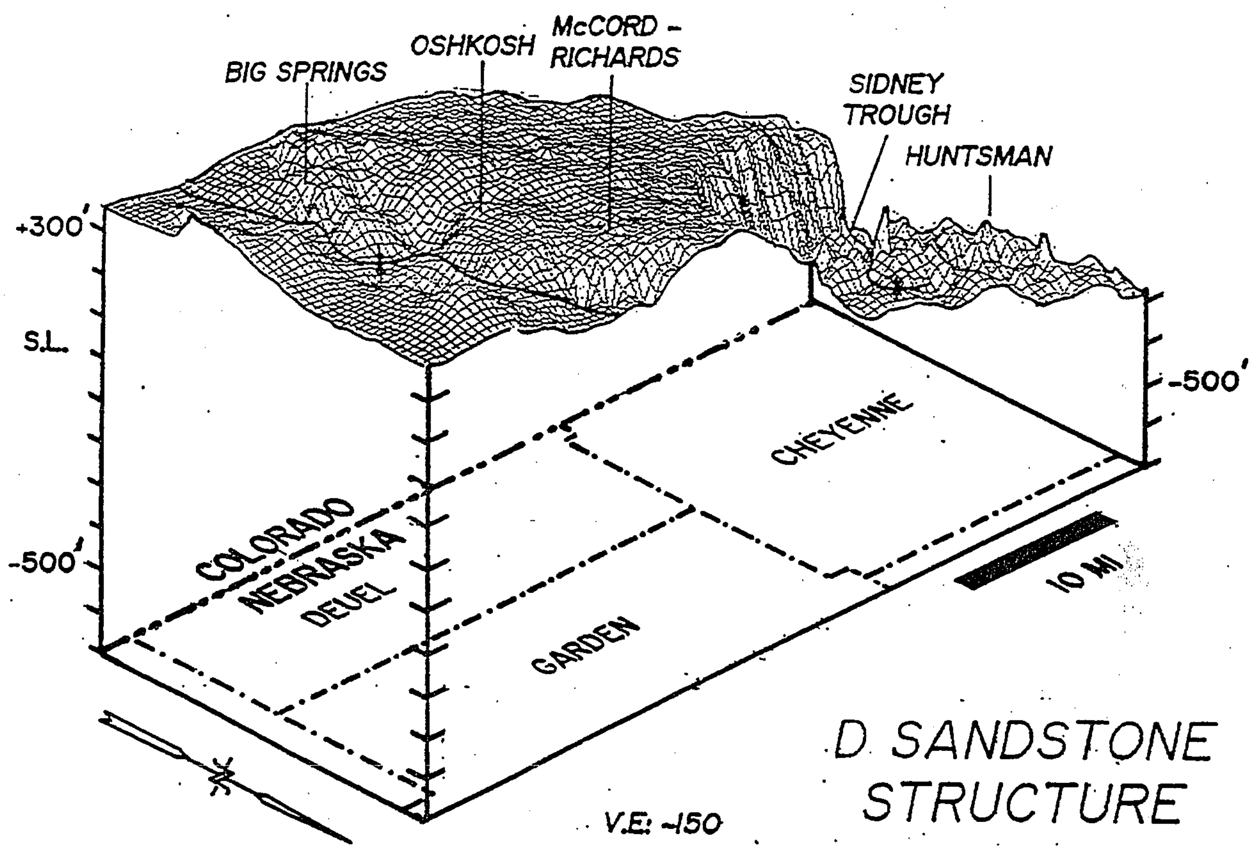


Figure 4-16. Surface plot showing structural configuration of D Sandstone in structurally complex eastern half of southern Nebraska panhandle. View is to the southwest.

Sidney Trough Area

Salt distribution maps (Figures 4-4, 4-8, and 4-9) reveal that salt is absent in the immediate area of the Sidney trough. The Sidney trough is also an area marked by an abrupt facies change from thick Lyons Sandstone to salts 9 and 10 (Figures 5, 6, and 7). Four Permian-level stratigraphic cross sections across the Sidney trough (Figures 4-17 through 4-20) illustrate how removal of salt along the Lyons/salt facies change has influenced Permian salt-bearing interval thickness and its effect on structure at the Cretaceous level. Cross section traverses are shown on Figures 4-4 through 4-9.

Cross section A-A' (Figure 4-17) traverses the Sidney trough in townships 16N and 17N, from McCourt gas field, a recently-developed Niobrara producer, to the Oshkosh - Lewellen anticline, near D Sandstone production at McCord, Richards, and Jackson fields. Salts 3, 5, 6, and 7 are present in well 869. All three salts are absent in well 914 in the Sidney trough area. The Lyons Sandstone, which is 76 ft (23 m) thick in well 914, thins abruptly at well 1590, in which no salts were encountered. Below the Oshkosh-Lewellen Anticline, salts 7, 9, and 10 (which accumulated in the Garden County low) are present in well 1587. In well 1589, however, salt 10 is replaced by an anhydritic zone which is believed to represent post-dissolution residue of salt 10.

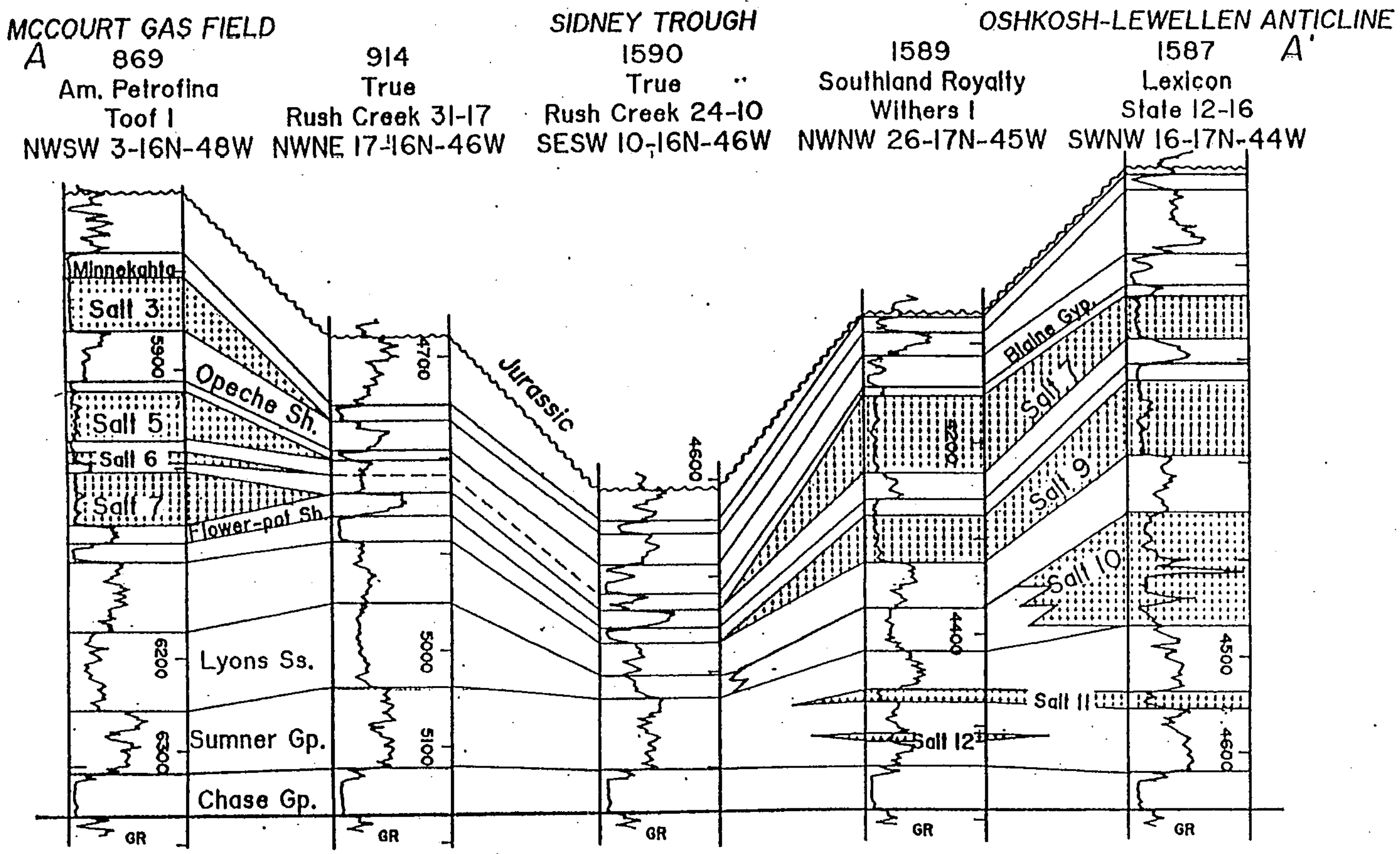


Figure 4-17. Stratigraphic cross section A-A' of Permian salt-bearing interval across McCourt Gas field, Sidney trough, and Oshkosh-Lewellen anticline. Datum is base upper Chase Group anhydrite.

Although salt 10 is absent in well 1589, salts 7 and 9 as well as salts 11 and 12 are present. Leonardian strata (interval from the top of the Blaine Gypsum to the base of the Sumner Group) range in thickness from 530 ft (162 m) in well 1587 to 210 ft (64 m) in well 1590. The Leonardian is 408 ft (124 m) thick in well 869, where salts 3, 5, 6, and 7 are preserved. Much of the Leonardian thickness range can be attributed to dissolution of salt in the Sidney Trough area. Pre-Late Jurassic erosion has resulted in eastward truncation of post-Minnekahta strata (Ervay and Glendo Members of the Guadalupian Gosse Egg Group).

Cross section B-B' (Figure 4-18) traverses the Sidney trough area in townships 14N to 16N, including the Gurley field, a J Sandstone producer and the first commercial oil discovery on the eastern flank of the basin. The Leonardian is 480 ft (146 m) thick in well 852, where salts 5, 6, and 7 and thick Lyons Sandstone are present, and is 528 ft (161 m) thick in well 1238 where salts 7, 9, 10, 11, and 13 are present. Well 900, drilled in the Sidney Trough, encountered only 278 ft (85 m) of Leonardian strata, including thin Lyons Sandstone. Although no salt is present above the Lyons Sandstone in this well, thin salt 13 is preserved below.

Cross section C-C' (Figure 4-19) traverses the Sidney trough in townships 13N to 15N, including the Huntsman field, a D and J Sandstone producer. The Leonardian is 470

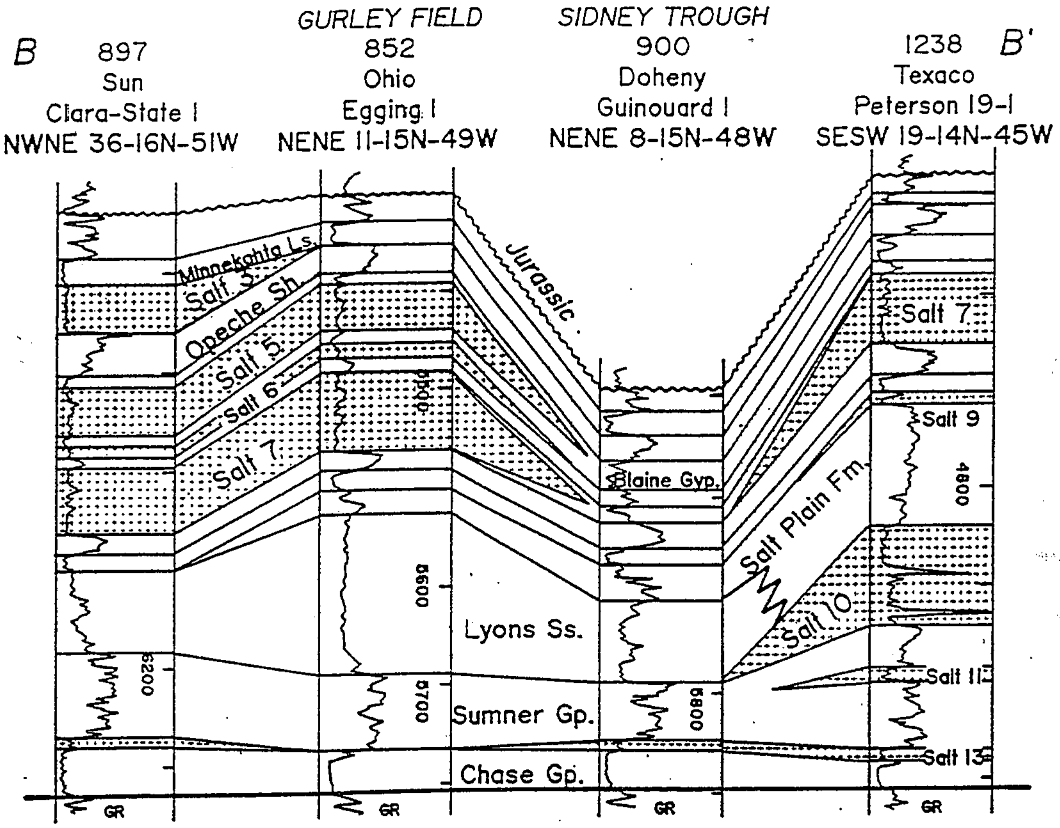


Figure 4-18. Stratigraphic cross section B-B' of Permian salt-bearing interval across Gurley field and Sidney trough. Datum is base upper Chase Group anhydrite.

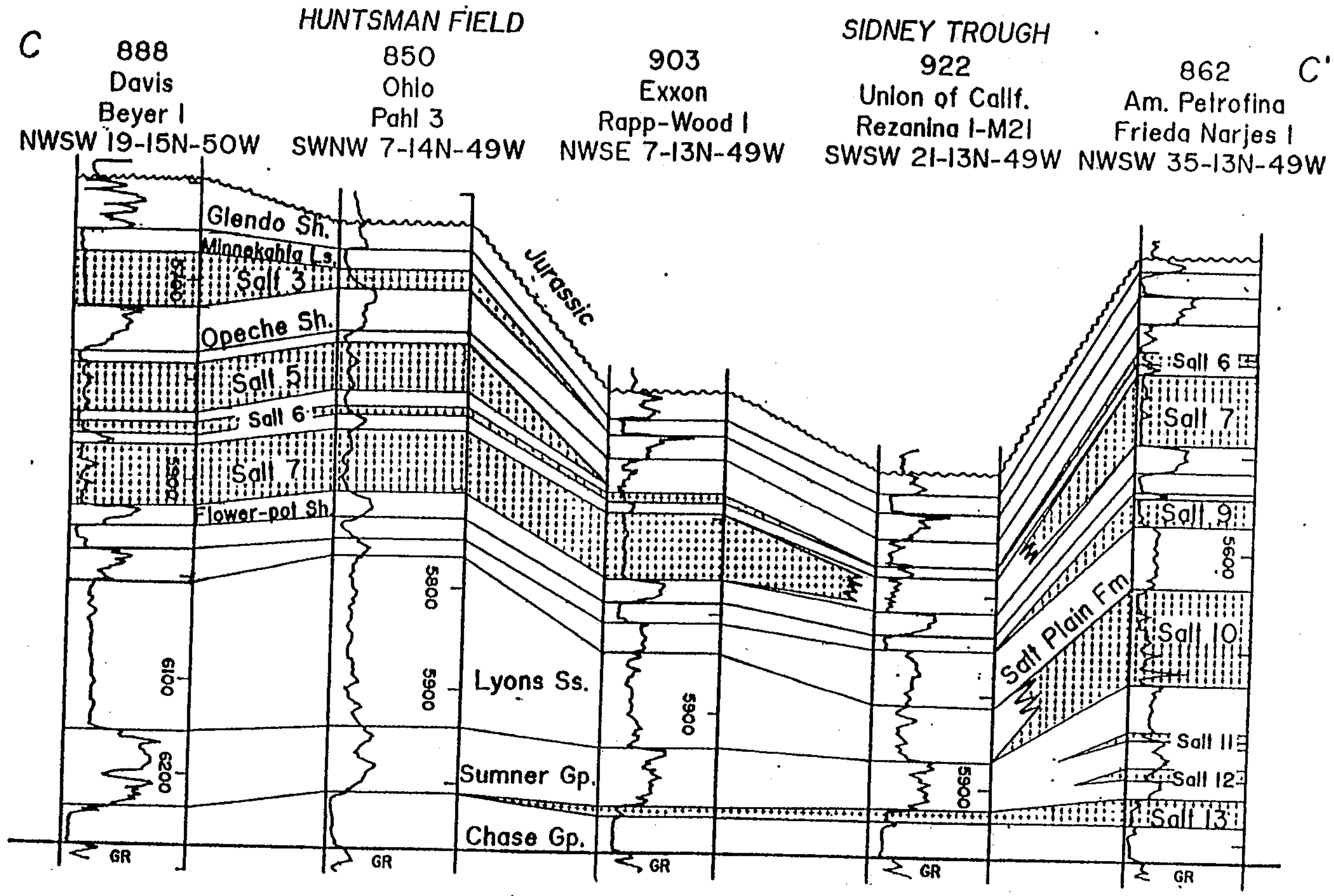


Figure 4-19. Stratigraphic cross section C-C' of Permian salt-bearing interval across Huntsman field and Sidney trough. Datum is base upper Chase Group anhydrite.

ft (143 m) thick in well 850, where salts 3, 5, 6, and 7 and thick Lyons Sandstone are present. Well 922, drilled in the Sidney trough, encountered no salt at or above the level of a thin Lyons Sandstone, but drilled through a thin salt 13. The Leonardian is 274 ft (84 m) thick in this well. Two mi (3 km) southeast, salts 6, 7, 9, 10, 11, 12, and 13 were drilled in well 862, in which the Leonardian is 484 ft (147 m) thick.

Cross section D-D' (Figure 4-20) traverses the Sidney trough in townships 12N and 13N, including the area of Sidney, Dimick, and Fleming fields. The Leonardian is 439 ft (134 m) thick in well 890, in which salts 3, 5, 6, and 7 were encountered. Salts 5, 6, 7, and thick Lyons Sandstone are present in wells 889 and 849, which encountered 458 and 402 ft (140 and 123 m) of Leonardian strata, respectively. In the Sidney trough area (well 899), the Lyons Sandstone is thin, no salt is present, and the Leonardian is only 270 ft (82 m) thick. Well 905, located to the south of the Sidney trough, encountered 504 ft (154 m) of Leonardian strata, including salts 5, 6, 7, 8, 9, 10, and 13.

Cross sections shown on Figures 4-17 through 4-20 illustrate that the Sidney trough area is marked by an abrupt facies change from thick Lyons Sandstone to salt (salts 9 and 10). Where the Lyons is present, even if it is thin, salts 9 and 10 are absent. Conversely, where salts 9 and 10 are present, the Lyons is absent. Wells which were

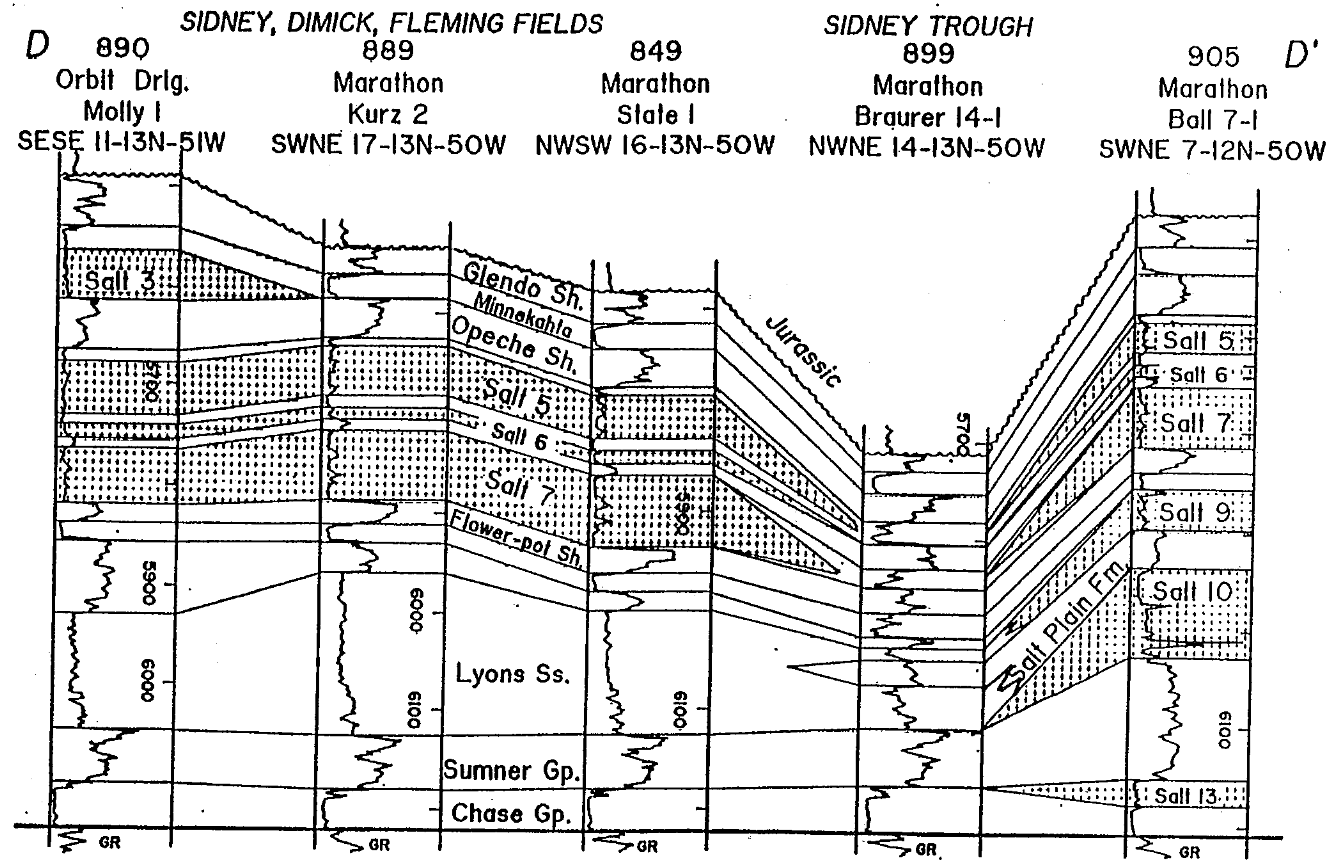


Figure 4-20. Stratigraphic cross section D-D' of Permian salt-bearing interval across Sidney, Dimick and Fleming field area and Sidney trough. Datum is base upper Chase Group anhydrite.

drilled in the axis of the Sidney trough encountered no salt and thin or no sandstone, suggesting that salt was originally present, but was subsequently removed by dissolution. Overlying salt zones (salts 5, 6, and 7) are also absent in the structural low, resulting in substantial thinning of the Leonardian due to dissolution. Thick salts are present southeast of the trough.

By contrast, cross section E-E' (Figure 4-21) in the western part of the Nebraska panhandle (where D Sandstone structure is relatively simple) reveals that salt dissolution occurred primarily during Late Jurassic to Early Cretaceous time. This allowed for additional space for the accumulation of sand (Cheyenne Formation) in solution-collapse lows. The Cheyenne Formation is over 350 ft (105 m) thick in wells 1679 and 1676, in which no salt is present, whereas it is only about 200 ft (60 m) thick where it is underlain by salts. Because salt removal pre-dated deposition of Cretaceous reservoirs (D and J Sandstones, situated above Skull Creek Shale), reservoir-level structure is concordant with subsalt structure. By contrast, structure at the Jurassic and Triassic levels (Morrison - Freezeout interval) is discordant with subsalt structure.

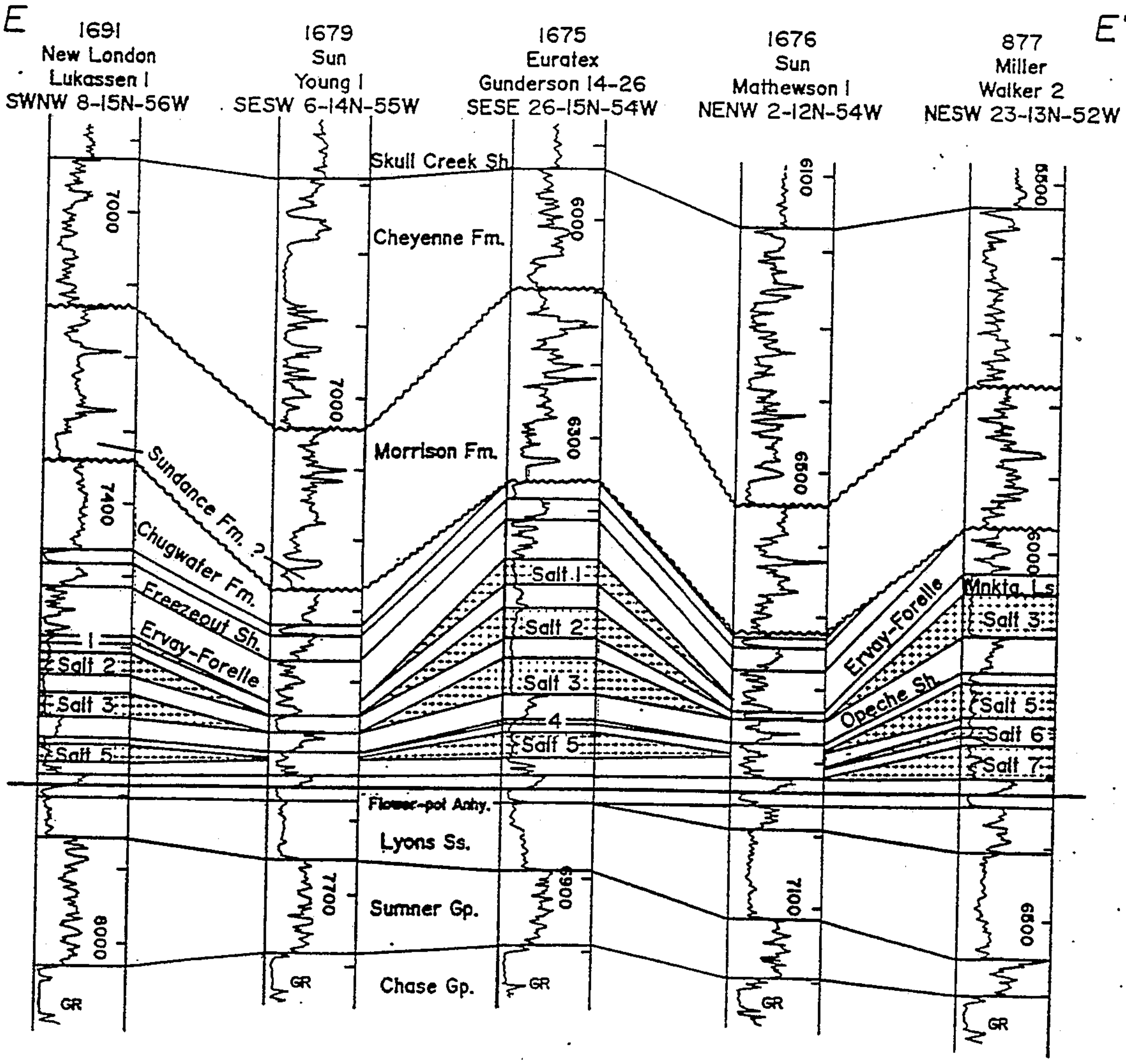


Figure 4-21. Stratigraphic cross section E-E' of Permian salt-bearing interval, Jurassic Morrison Formation, and Lower Cretaceous Cheyenne Formation in western part of southern Nebraska panhandle study area. Datum is top Flower-pot Anhydrite.

Mechanism for Post-Reservoir Salt Dissolution

Distribution of Permian salts in the Denver basin is primarily controlled by three factors: (1) original distribution of salts, which is dependent on evaporite basin configuration; (2) removal by erosion or near-surface dissolution below a pre-Late Jurassic unconformity; and (3) removal by dissolution at depth at various times since the Jurassic.

In order for salt dissolution to occur at depth, unsaturated groundwater must come into contact with the salt. Possible mechanisms for introduction of water at depth, discussed in Chapter 2, include centrifugal (compaction-induced) or centripetal (basinward gravity-driven) fluid flow. Possible conduits for water can be fracture-controlled or facies-controlled. Coincidence of the northeast-trending Lyons/salt 9 and 10 facies change with the location of the Sidney trough (interpreted to be a salt dissolution feature) strongly suggests that the Lyons served as the main source and conduit of water for the dissolution process. The Lyons is the thickest, most widespread coarse clastic unit within the Permian evaporite section and represents the only regional aquifer associated with salts. In the Nebraska panhandle, the upper part of the Lyons is equivalent to the top of the Salt Plain Formation, which contains salt 9. The lower part of the Lyons is equivalent to salt 10.

During post-salt basin subsidence and burial (through Late Cretaceous time), compaction would have caused centripetal flow of water from the Lyons aquifer toward the basin margins. With the onset of Laramide (Late Cretaceous-Early Tertiary) orogeny, uplift along the Front Range to the west raised the Lyons to a structural position well above that of the sandstone on the eastern flank of the basin. Trimble (1980) estimated the elevation of the Front Range at between 8200 and 20,000 ft (about 2500 to 6000 m). In calculated flow models for the Lyons Sandstone, Lee and Bethke (1994) used a elevation difference of about 6500 ft (2000 m) between the Front Range and the eastern margin of the basin. With erosion, the present elevation of the Lyons outcrop along the Front Range is about 5500 ft (1700 m) above sea level, about 7000 ft (2100 m) higher than its average elevation of about 1500 ft (500 m) below sea level in the Sidney trough area of Cheyenne County.

Laramide uplift and tilting of the western flank of the basin initiated eastward-directed topographically-driven flow within the Lyons aquifer due to hydraulic gradient and to recharge at high-elevation outcrops (Lee and Bethke, 1994). This eastward groundwater flow regime continues today (Belitz and Bredehoeft, 1988). Although it is likely that present flow rates are lower due to erosion of the

Front Range, calculations of eastward groundwater migration indicate that post-Laramide gravity-driven flow was much more rapid than pre-Laramide compaction-driven flow (Lee and Bethke, 1994). In models used to explain the relationship of Lyons Sandstone diagenesis and oil accumulations in the western part of the basin, Lee and Bethke concluded that additional groundwater migrated upward from the Fountain Formation, where the Fountain grades laterally from sandstone to less permeable shale and dolomite to the east, into the Lyons aquifer, where it continued its eastward flow.

The Lyons crops out along the steeply-dipping western flank of the Denver basin in northern Colorado (Figure 4-22). The photograph, a south view, was taken at Horsetooth Reservoir, just west of Fort Collins. The Lyons, which forms a hogback ridge, crops out between red shales and siltstones of the underlying Sumner Group (Lower Satanka of the Front Range) and red shales and thin carbonates of the overlying Goose Egg Group (Lower Lykins of the Front Range) which is situated below the reservoir. A series of hogback ridges to the east (left of photograph) is formed by the Dakota Group (including the J Sandstone and Cheyenne Formation). To the west (right of photograph), the Ingleside Formation, a clastic equivalent to the Wolfcampian Chase Group, forms a scarp. Conglomeratic arkose of the Pennsylvanian Fountain Formation crops out between the

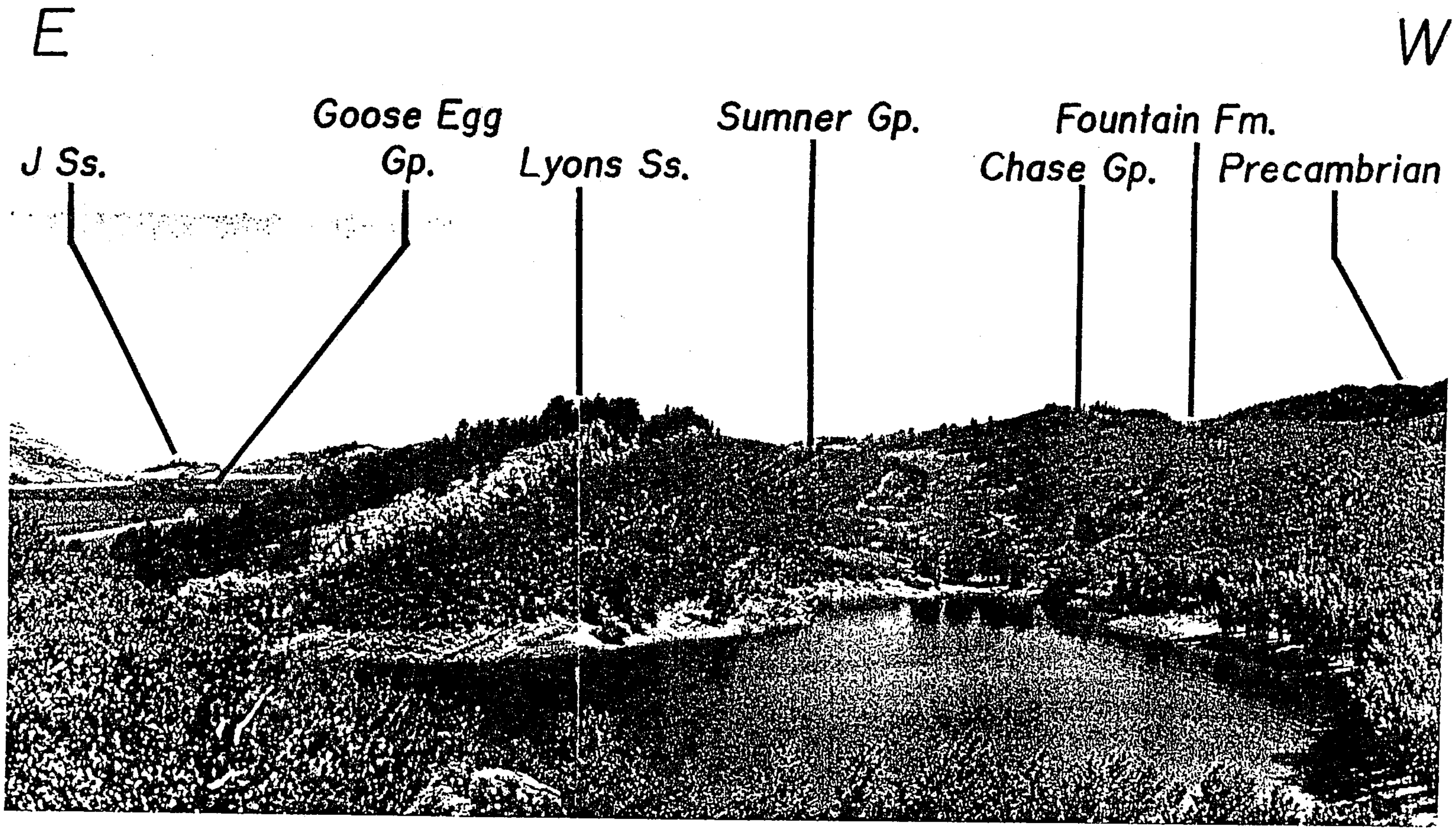
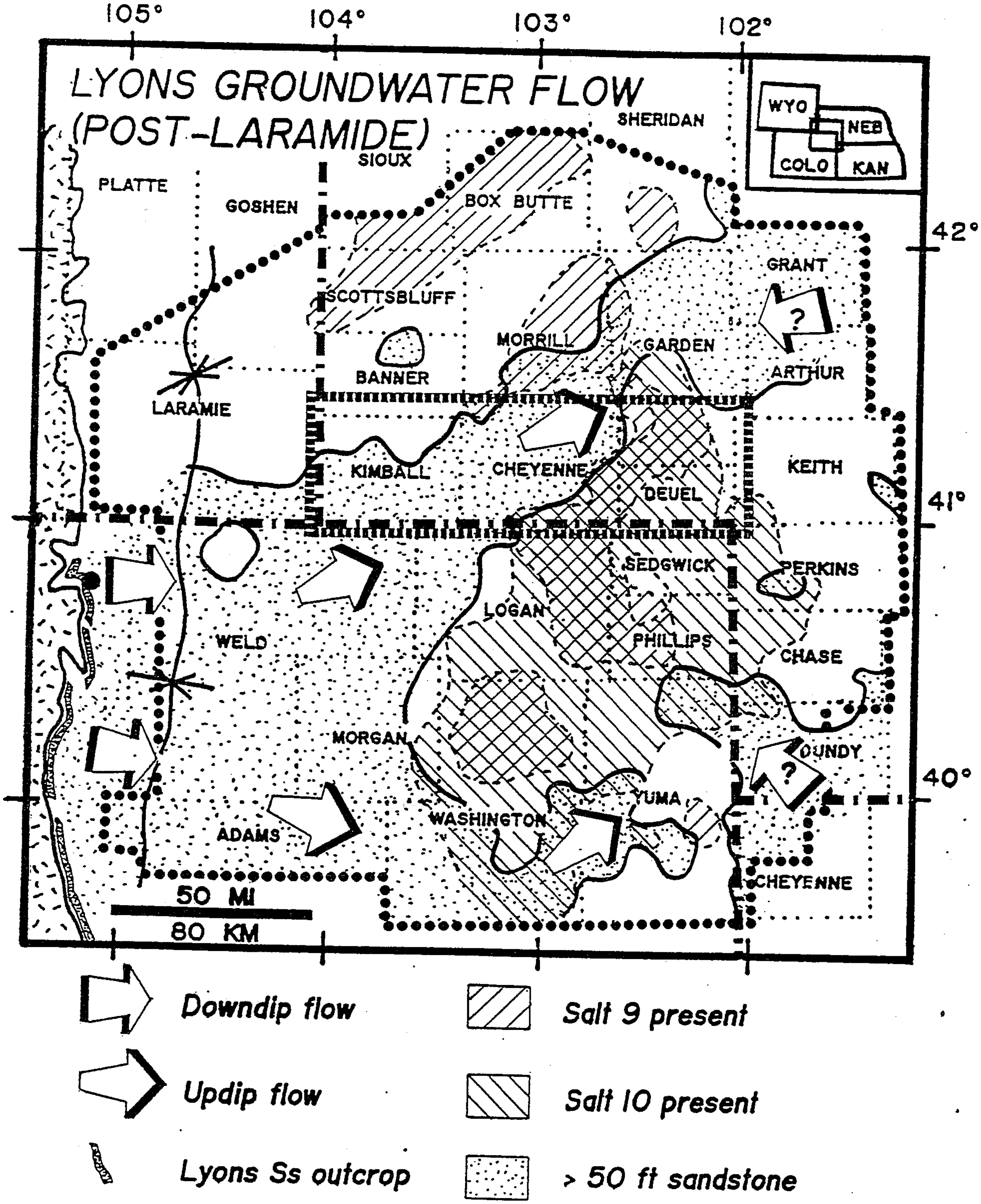


Figure 4-22. Photograph of Lyons Sandstone outcrop along Front Range uplift immediately west of Fort Collins, Colorado. View is to the south.

Ingleside and Precambrian rocks of the Front Range foothills.

Lyons Sandstone outcrops and interpreted regional groundwater flow are shown on Figure 4-23. Eastward flow resulted from hydraulic gradient and recharge at the outcrop in response to Laramide uplift. Near the basin axis, additional water migrated to the Lyons from the deeper Fountain Formation along a clastic - carbonate/anhydrite facies change within the Fountain (Lee and Bethke, 1994). Flow proceeded to the east within the Lyons to the abrupt facies change from sandstone to salt, which occurs in Cheyenne and Garden Counties, Nebraska, as well as in Logan and Yuma Counties, Colorado.

Groundwater flow to the east was impeded in the Garden County low area, where the Lyons is thin or absent. Dissolution of salts 9 and 10 initially occurred at the updip sandstone/salt interface in Logan, Cheyenne, and Garden counties. Dissolution-induced collapse is believed to have created fractures and opened existing fractures in overlying strata, allowing for cross-formational flow of water to the level of salts 7, 6, and 5. This resulted in removal of these younger salts and further collapse of overlying strata.



(Levandowski et al. 1973)

Figure 4-23. Interpreted regional groundwater flow within Lyons Sandstone in response to Laramide orogeny. Solid circle at outcrop marks location of photograph shown on Figure 4-22.

Origin of Sidney Trough

Figures 4-24 through 4-29 summarize the interpreted origin of the Sidney trough in western Nebraska and northern Colorado, which acts as a regional barrier to eastward migration of oil in the Nebraska portion of the Denver basin.

In Leonardian time (Figure 4-24), a subtle high associated with the Transcontinental arch separated the area now occupied by the northern Denver basin into the Sterling and Alliance evaporite basins. A northwest-trending transverse sag, termed the "Garden County low" in this study, served to connect the two basins. Sand (Lyons Sandstone), derived from the west and northeast, was redirected to the south by northerly winds, and accumulated as dune and shallow water deposits in eolian and basin-margin environments (Sonnenberg and Weimer, 1981). Salts 9 and 10 and red mud and silt (Salt Plain Formation) accumulated in restricted, hypersaline waters of the evaporite basins.

The linear and abrupt sand/evaporite facies change suggests basement fault control on sedimentation along the basin margin. Northeast-trending basement fault control of the northwest margin of the Sterling basin may be indicated by its alignment with (1) the northeast-trending Idaho Springs - Ralston Creek shear zone (1, Figure 2-1), (2) the

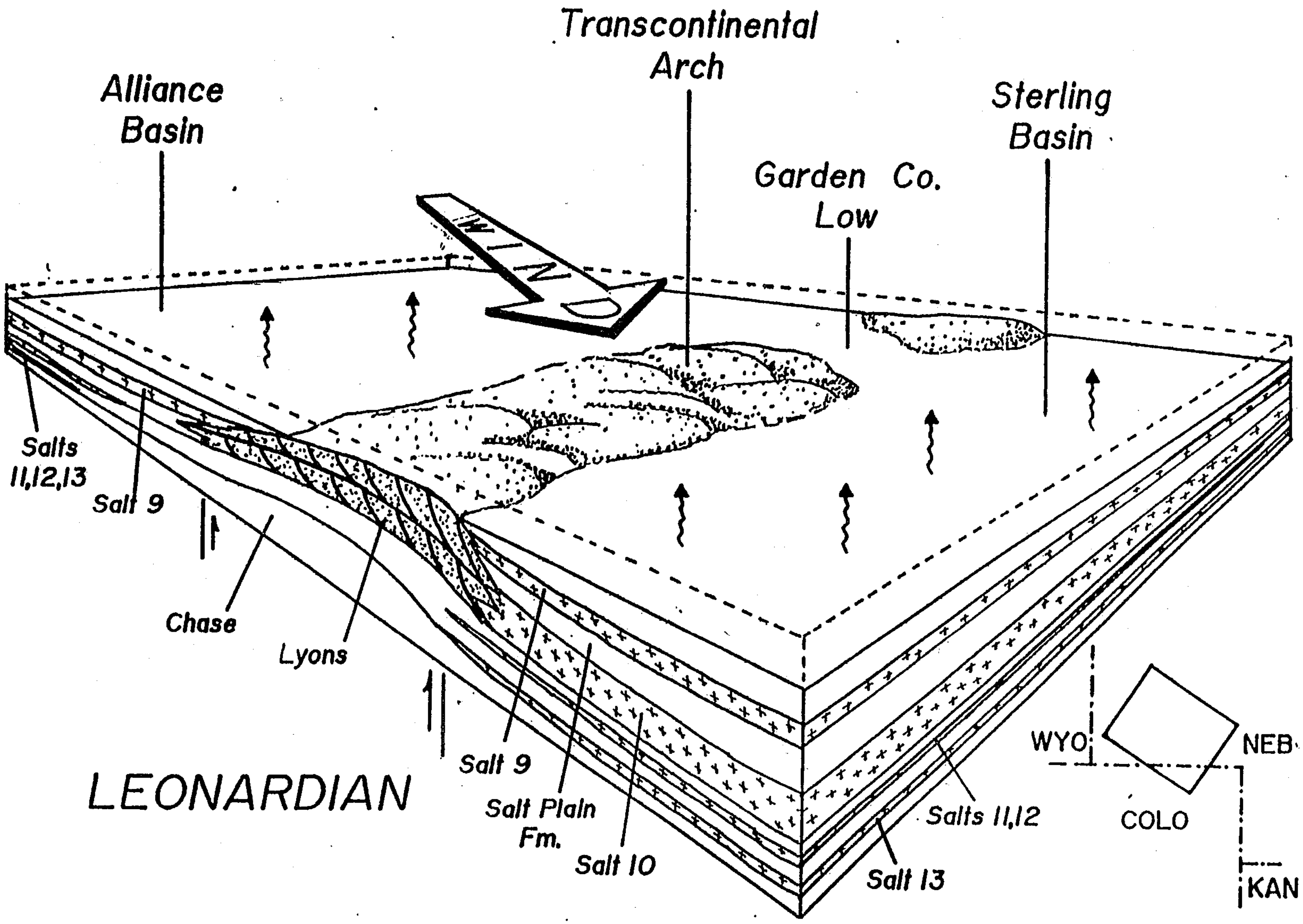


Figure 4-24. Block diagram model during deposition of Lyons Sandstone and precipitation of salt 9 (Leonardian).

generalized boundary between granitic and metamorphic basement terranes (5, Figure 2-1), (3) the Front Range Mineral Belt lineament and subparallel lineaments (Figure 2-3), and (4) the Wattenberg high (Figure 2-4) of Sonnenberg and Weimer (1981).

Basement faulting along the Transcontinental arch apparently had little influence during accumulation of younger salts and related sediments (Figure 4-25). Salts 7, 6, 5, (and probably salts 3, 2, and 1) appear to have accumulated in a single broad evaporite basin which covered both the Sterling and Alliance basin areas and possibly areas to the east.

Removal of salt by erosion or near-surface dissolution occurred in response to pre-Late Jurassic exposure and truncation (Figure 4-26). Eastern limits of Guadalupian salts (salts 1, 2, and 3) were influenced more than those of deeper salts. Although the distribution of salt 7 may have been influenced by the unconformity farther east, it was not removed during the Jurassic in the Nebraska panhandle.

During the Early Cretaceous (Figure 4-27), dissolution of salt occurred in the southwestern part of the panhandle. Evidence for this is an inverse relationship between the occurrence of salts and thick Cheyenne Formation (Figure 4-21). In a compaction-driven centrifugal flow model (in response to Paleozoic and Mesozoic basin infilling), Lee and Bethke (1994) invoked westward flow during the Cretaceous

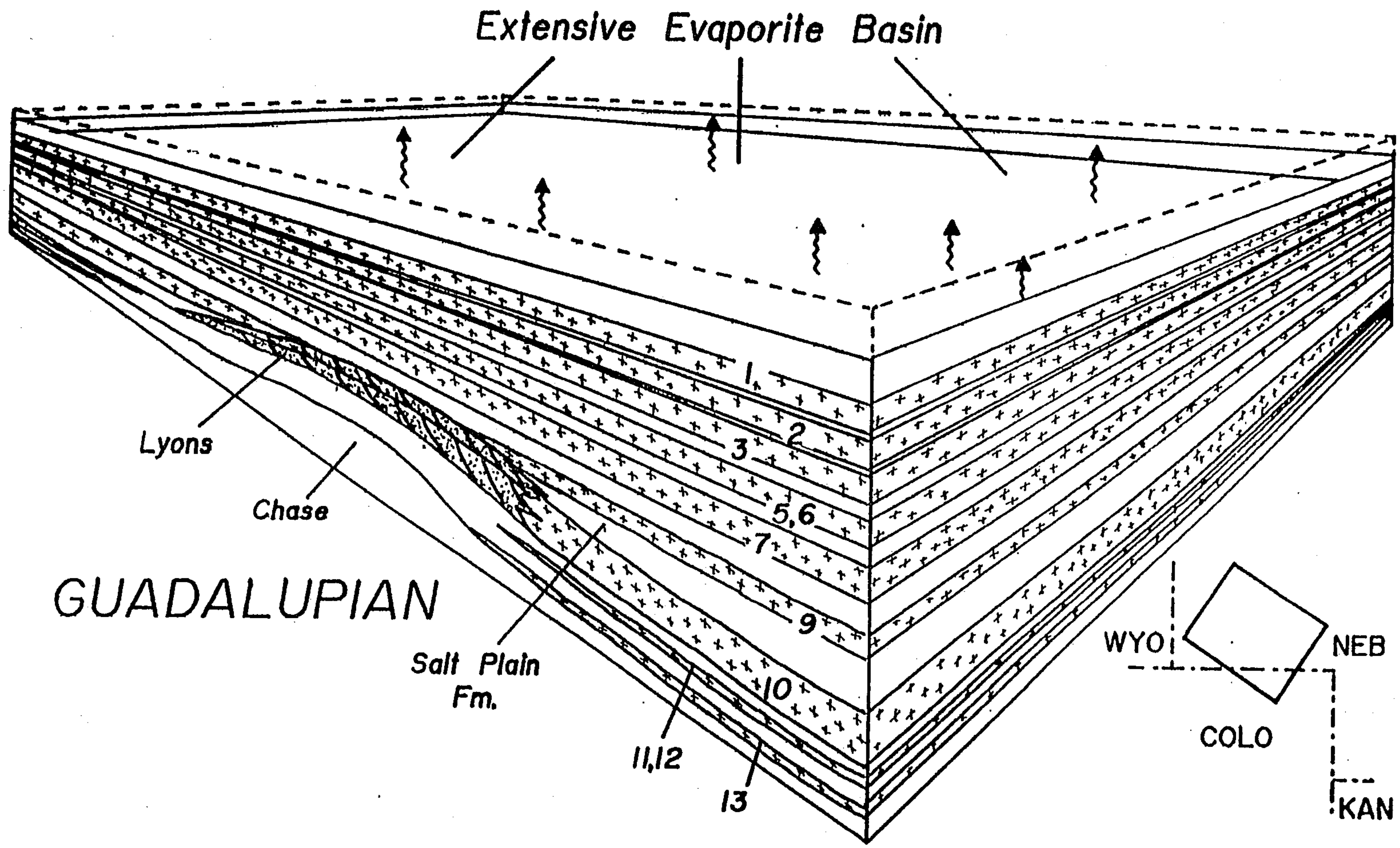


Figure 4-25. Block diagram model during precipitation of Guadalupian salts.

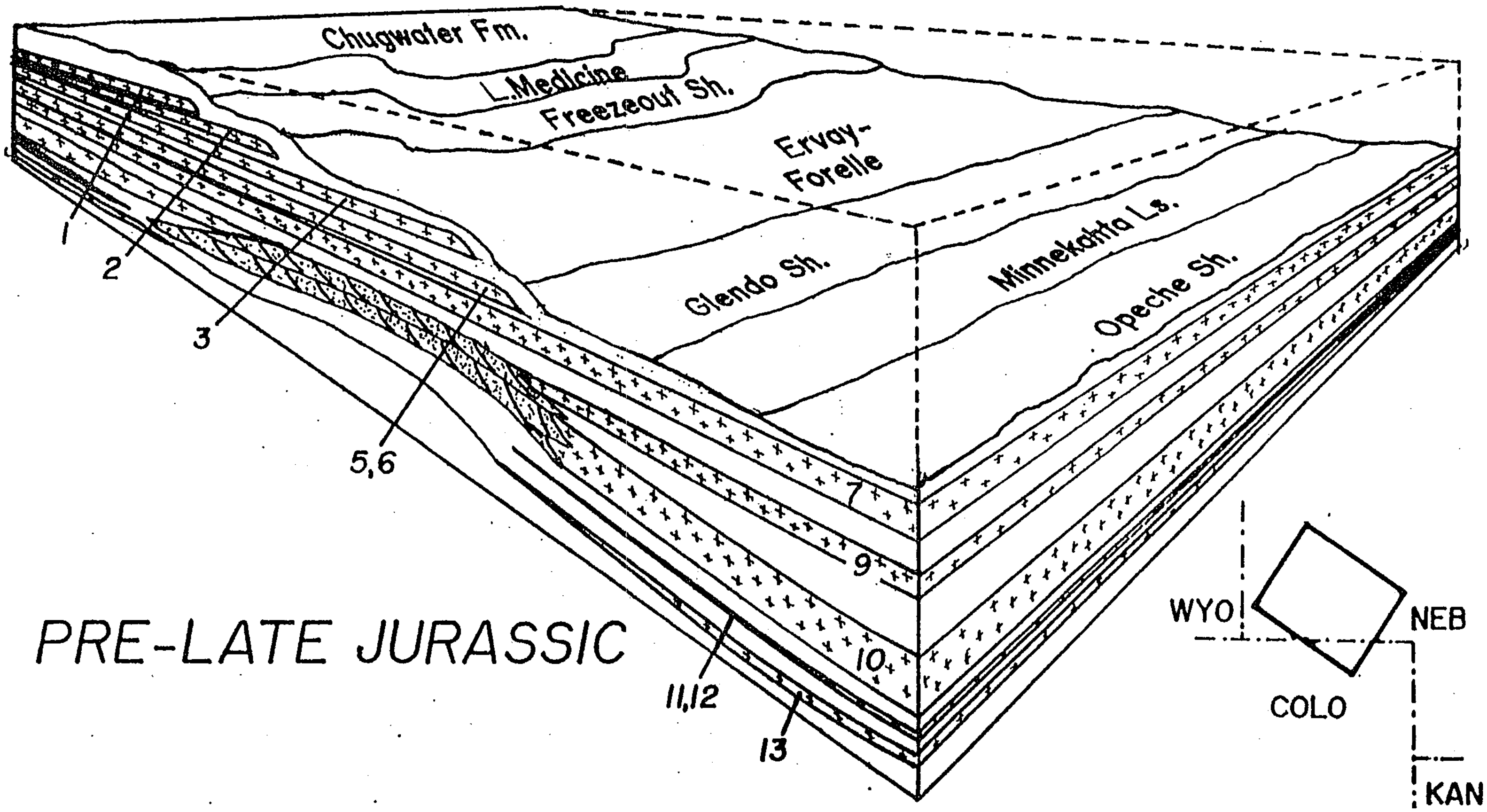


Figure 4-26. Block diagram model following pre-Late Jurassic truncation of Permo-Triassic strata and related salts.

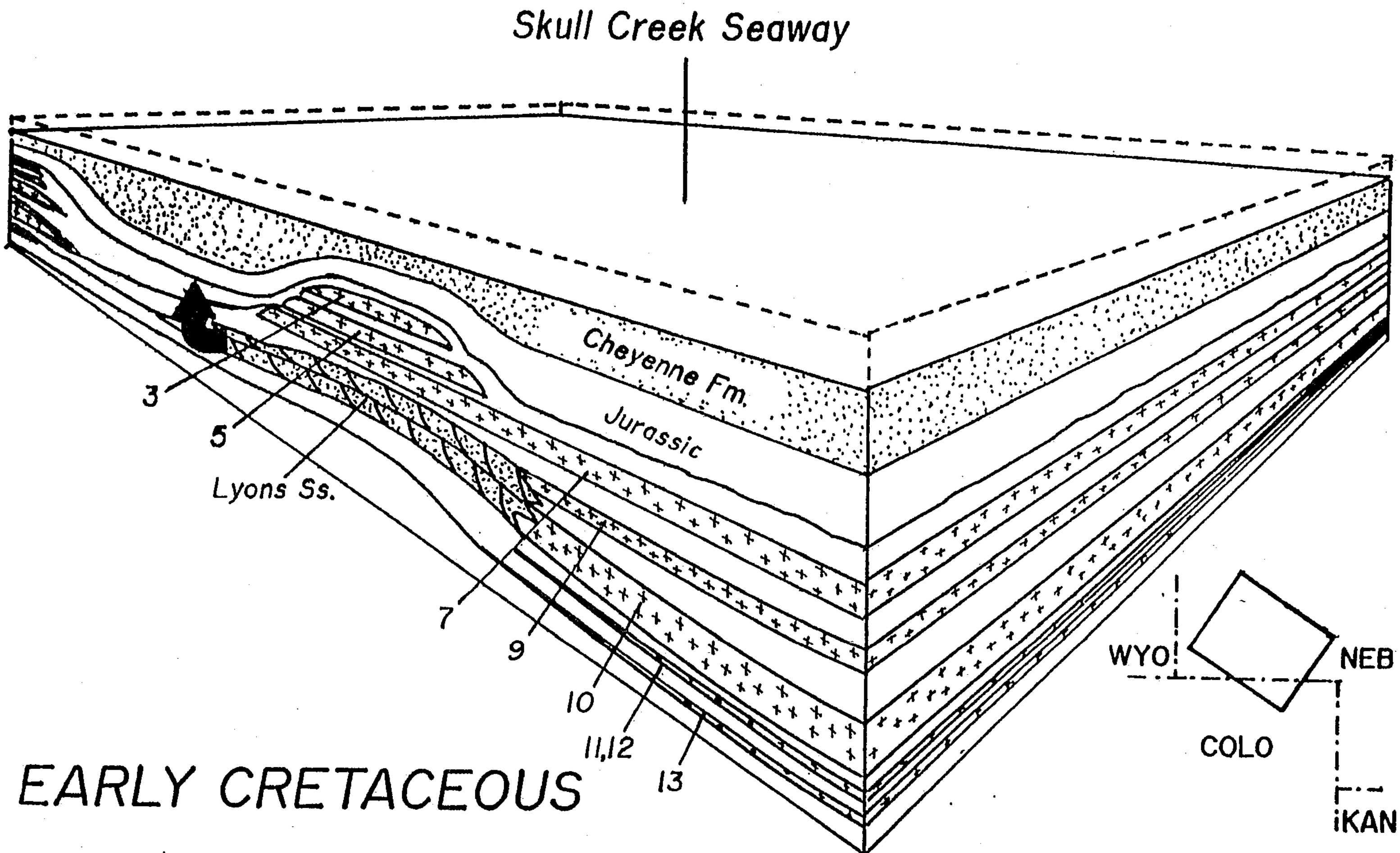


Figure 4-27. Block diagram model during early Cretaceous showing compensatory thickening of Cheyenne Formation in response to salt dissolution. Possible compaction-induced groundwater flow from Lyons shown by arrow.

flow within the Lyons away from its eastern pinchout into salt. Westward-directed flow may have been impeded in Kimball County, where the Lyons becomes thinner. Migration of water upward out of the Lyons (shown by an arrow) may have caused dissolution of overlying salts in this area during the Early Cretaceous.

Laramide orogeny caused the formation of the Denver basin, with a gently-dipping eastern flank (Figure 4-28). Uplift to the west, along the steeply-dipping western flank of the basin, resulted in eastward gravity-driven groundwater flow within the Lyons Sandstone (supplemented by water from the Fountain Formation near the basin axis) to the eastern pinchout of sandstone into salt. Higher elevations during the Eocene would have resulted in a hydraulic gradient which was greater than that of present-day. The Lyons potentiometric surface is approximate and is from Belitz and Bredehoeft (1988). The J Sandstone potentiometric surface, from Pruit (1978), lies below that of the Lyons.

Dissolution of salt 9 and 10 took place at the Lyons/salt facies change (Figure 4-29). In places, salts 11, 12, and 13 remain where overlying salts have been removed (Figures 4-17, 4-18, and 4-19). This suggests that water migrated from the Lyons upward (narrow arrows) through the collapse area, rather than from deeper zones. Fractures, induced by dissolution of salts 9 and 10 and

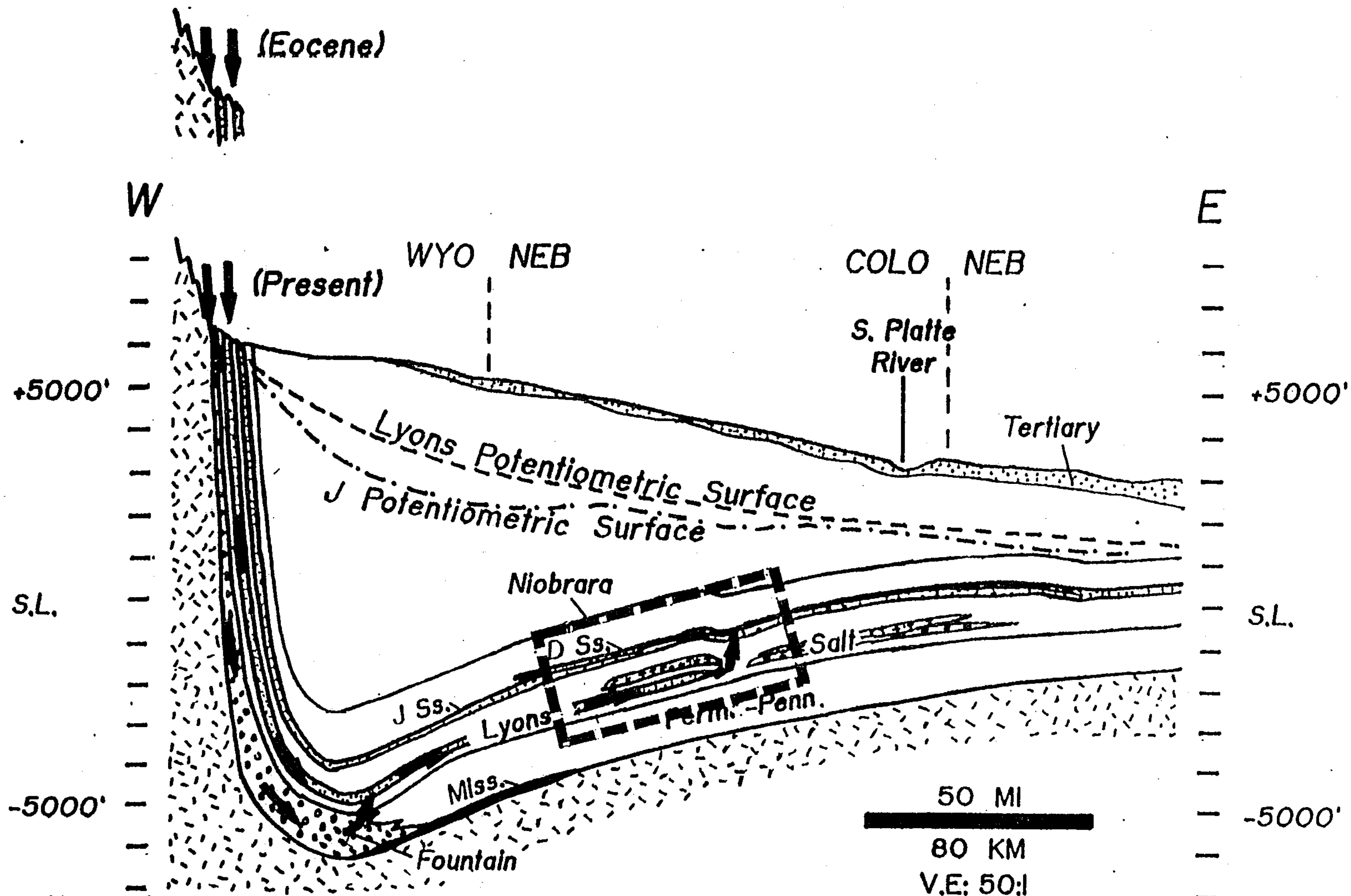


Figure 4-28. Structural cross section along 41st Parallel (northern border of Colorado) showing interpreted regional groundwater flow within Lyons regional aquifer in response to Laramide uplift. Lyons potentiometric surface from Belitz and Bredehoeft (1983). J Sandstone potentiometric surface from Pruit (1978). Outlined area shown in detail on Figure 4-29.

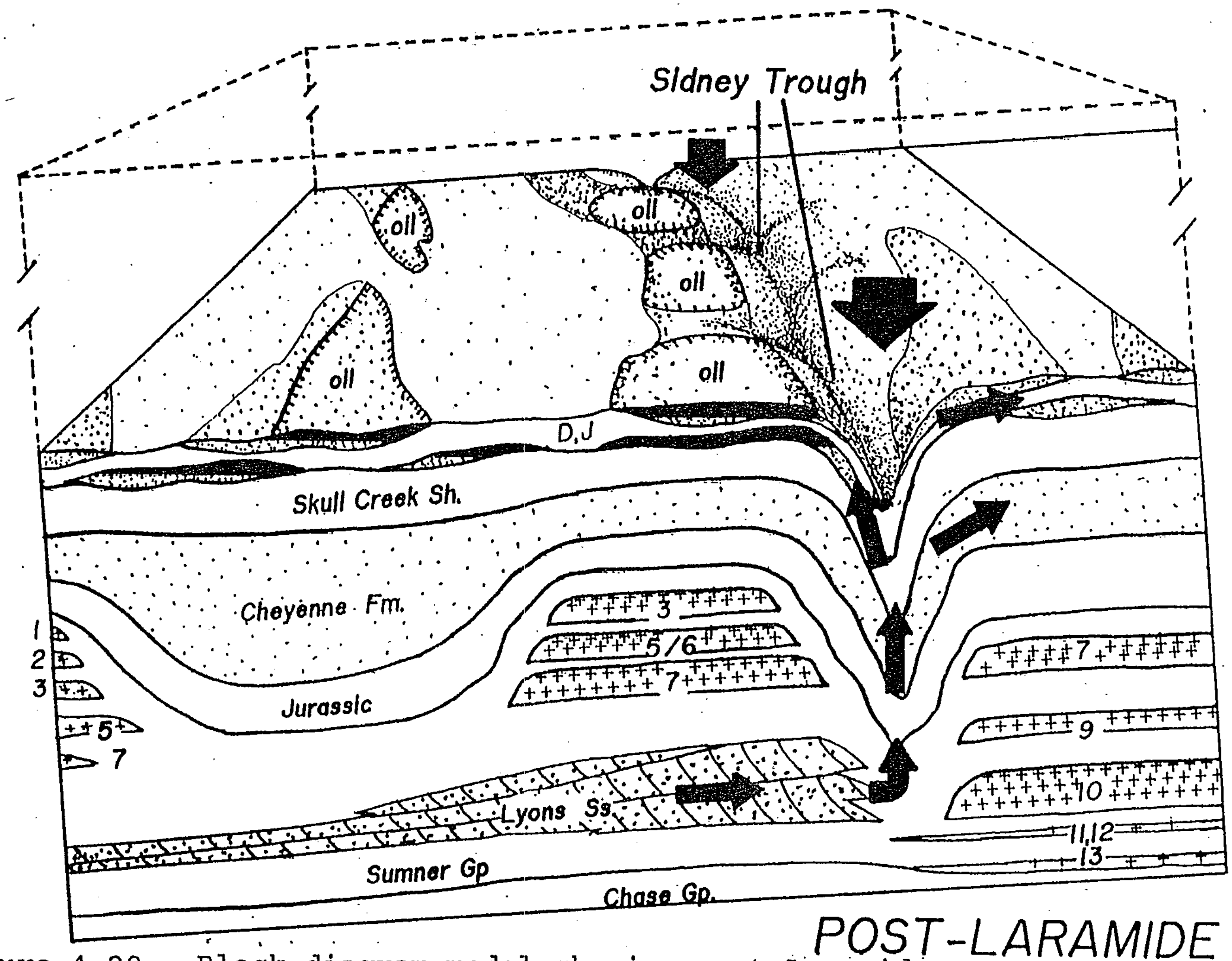


Figure 4-29. Block diagram model showing post-Laramide formation of Sidney trough at Lyons Sandstone - evaporite facies change. View is to the northeast. Narrow arrow denote groundwater flow from Lyons regional aquifer at sandstone/salt facies change. Broad arrow denote collapse in Sidney trough area resulting from salt removal. View is to the northeast. Cross section length is approximately 75 mi (120 km).

resultant collapse, allowed for upward migration of groundwater. This resulted in removal of overlying salts, including salts 7, 6, 5, and 3.

Upper Cretaceous and Tertiary strata have been removed in Figure 26 to illustrate in three dimensions the effect of salt dissolution on oil entrapment in the D and J Sandstones. Oil and thermally-generated gas migrating from mature source rocks in deeper parts of the basin to the west accumulated in D and J Sandstone stratigraphic traps. Complete removal of salt along the linear Lyons/salt contact caused collapse of overlying strata (broad arrows), forming the Sidney trough. Dissolution of salts away from the trough, perhaps along Laramide-induced fracture zones, resulted in the formation of a number of small anticlines at the D and J levels, in which oil and gas accumulated where reservoir-quality sandstone was present. By contrast, oil and gas accumulated in stratigraphic traps to the west. Structure at the level of the D and J Sandstones is not as complex in this western area, because salt dissolution and collapse pre-dated deposition of the reservoirs.

Timing of salt removal relative to formation of the D and J Sandstone reservoirs (Figure 4-30) is interpreted from salt distribution interpretations (Figures 4-4, 4-8, and 4-9) and the D Sandstone structure map (Figure 4-13). (This map does not reflect pre-Late Jurassic removal of younger salts to the east.) Complete removal of salt took place

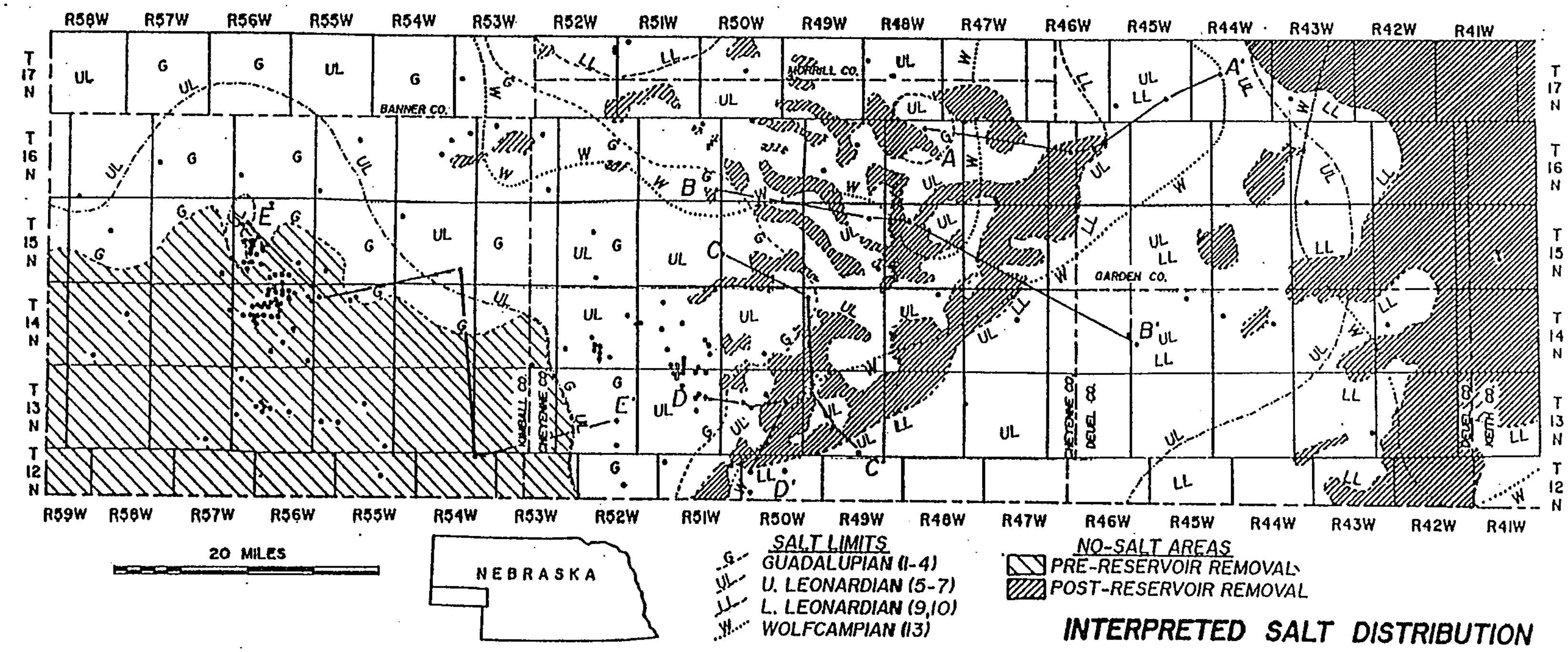


Figure 4-30. Interpreted salt distribution in southern Nebraska panhandle area.

prior to deposition the D and J in the southwest corner of the Nebraska panhandle. Removal of salt in the Sidney trough area post-dated reservoir deposition. Incomplete post-reservoir removal of salt below subsidiary synclines west of the Sidney trough responsible for complex reservoir-level structure in this area. Post-reservoir salt removal also occurred along the eastern margin of the Nebraska panhandle study area, associated with the north-south Cretaceous-level flexure.

Because it forms a regional flexure, and because of its structural relief, the Sidney trough acts as a regional barrier to eastward migration of oil and thermally-generated gas. With minor exceptions, the few fields east of the trough produce gas of biogenic origin.

Influence of Salt Dissolution on Formation Water Salinity

Dissolution of salt would have raised the salinity of Lyons-sourced groundwater migrating upward through the salt collapse area (narrow arrows on Figure 4-29). Brines, which reached the D and J Sandstones by cross-formational flow through fractures, would have raised the formation water salinities of these units. By contrast, D and J formation water salinities would be unaffected to the west, where salt dissolution pre-dated deposition of reservoir sand.

The largest source of data with which to estimate formation water salinities are water resistivity (R_w) values, reported in ohm-meters. Water produced with hydrocarbons and water recovered in drill-stem tests are the most common sources of samples for R_w measurements.

Formation R_w data were compiled, in order to test if D and J formation waters were affected by salt dissolution in the Denver basin. Data for the Denver basin are available from a number of sources (Crawford, 1964; Denver Well Logging Society, 1964; Slizeski, 1981; and Denver Well Logging Society, 1986). Formation R_w values are reported at some standard temperature (generally 68°F, but also at 75°F and 150°F). Resistivity values were converted to salinity ranges using a conversion chart (Schlumberger, 1972, p. Gen-9). Five salinity ranges and their corresponding resistivity values at the three most commonly reported temperatures are listed in Table 4-1.

Over 650 R_w values of produced water or water recovered from drill-stem tests in the southern Nebraska panhandle were converted and grouped by salinity range. In places, particularly in producing areas, more than one value per section (1 sq mi) is available. Where this occurs, the analysis with the highest salinity in each section is plotted on Figure 4-31 (335 total). This was done in an effort to reduce the potential of sample dilution due to contamination by drilling fluid filtrate.

TABLE 4-1. SALINITY RANGES USED IN FORMATION WATER PLOT AND CORRESPONDING RESISTIVITY VALUES.

Salinity (ppm NaCl)	Rw @ 68°F (ohm-m)	Rw @ 75°F (ohm-m)	Rw @ 150°F (ohm-m)
<5,000	>1.2	>1.1	>0.56
5,000 - 20,000	1.2 - 0.33	1.1 - 0.30	0.56 - 0.15
20,000 - 50,000	0.33 - 0.15	0.30 - 0.13	0.15 - 0.07
50,000 - 100,000	0.15 - 0.08	0.13 - 0.075	0.07 - 0.04
>100,000	<0.08	<0.075	<0.04

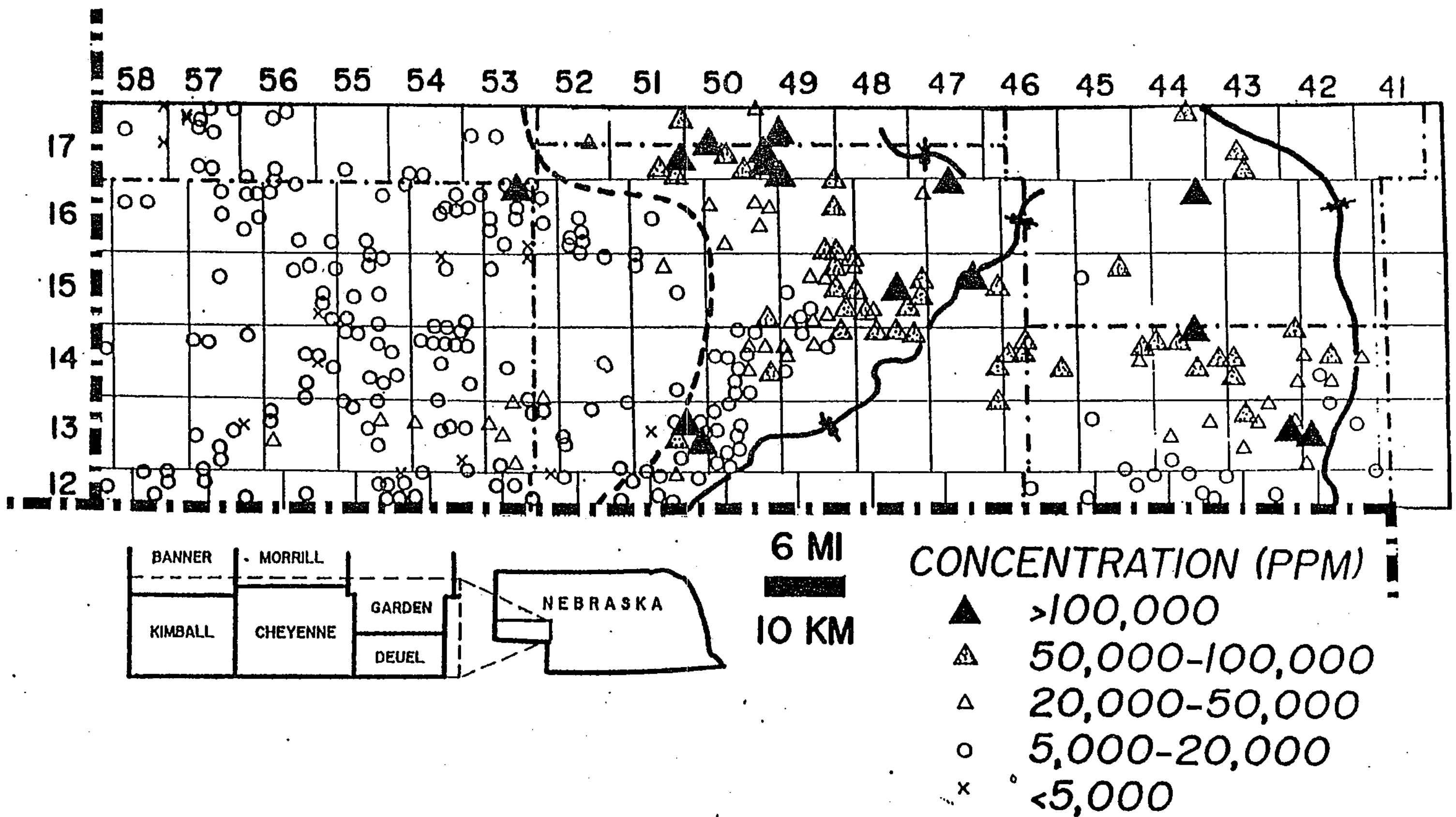


Figure 4-31. Plot of D and J Sandstone formation-water salinities in southern Nebraska panhandle.

A north-south dashed line, derived from Figure 4-13, marks the approximate boundary between the structurally simple area to the west (where salt dissolution did not occur or where removal pre-dated the reservoirs) and the structurally complex area (where salt removal post-dated the reservoirs). Major synclinal axes are shown, including the Sidney trough and a north-south syncline just east of Big Springs field. With one exception (which occurs just west of the the boundary in northeastern Kimball County), all D and J formation water salinities fall below 50,000 ppm NaCl equivalent in the structurally simple area. Of these, all but one in the 20,000 to 50,000 ppm range plot in the T13N area of Kimball County, where salt is absent, and where dissolution is interpreted to have occurred concurrent with deposition of the Cheyenne Formation. The remainder of values in the western part of the southern Nebraska panhandle fall within the 5,000 to 20,000 and <5,000 ppm ranges.

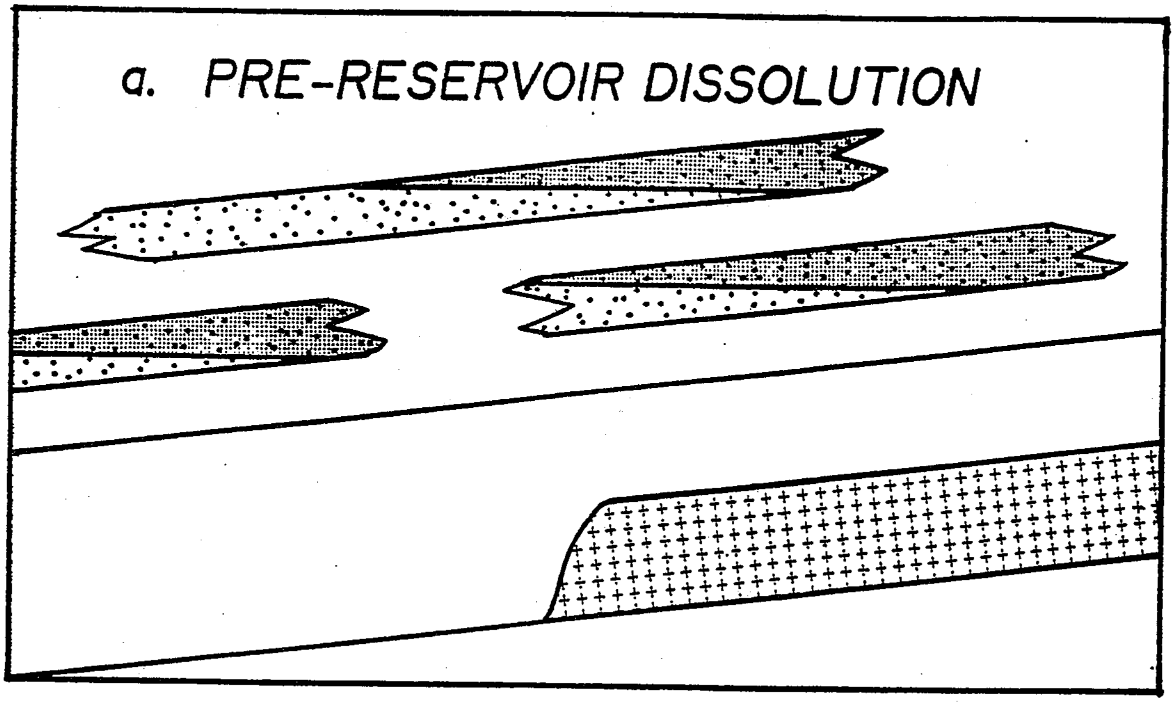
Higher-salinity values plot east of the dashed line, in the structurally complex area. All values in the 50,000 to 100,000 ppm range and all but one of the values in excess of 100,000 ppm plot within this area. Many of the high-salinity values are associated with oil fields which produce from anticlines just west of the Sidney trough. High-salinity water was reported at Big Springs field in T13N, R42 - 43W. D Sandstone water, with a salinity of over

110,000 ppm, was recovered on a drill-stem test in T16N, R44W, Garden County. Crawford (1964) reported that this water was essentially a solution of sodium chloride.

Spatial distribution of salinity data indicates that D and J Sandstones produce highly saline formation water only in the eastern, more structurally complex post-reservoir collapse area. A number of additional factors can influence formation water salinity, including chemistry of connate water and effects of fine-grained sediments (which act as semi-permeable osmotic membranes during compaction). Nonetheless, salinity anomalies observed in formations above the salt interval in areas of salt dissolution may reflect upward movement of salt solution-derived brines, and may help to explain basin hydrodynamics responsible for dissolution.

Influence of Salt Dissolution on Reserve Potential

Figure 4-32 depicts how timing of salt dissolution has influenced the entrapment of oil in Nebraska portion of the D-J fairway. To the west (Figure 4-32a), where salt either has not been removed or was removed prior to deposition of D and J Sandstone reservoirs, oil has accumulated in structurally simple stratigraphic traps, at the updip pinchouts of fluvio-deltaic and marginal marine sands.



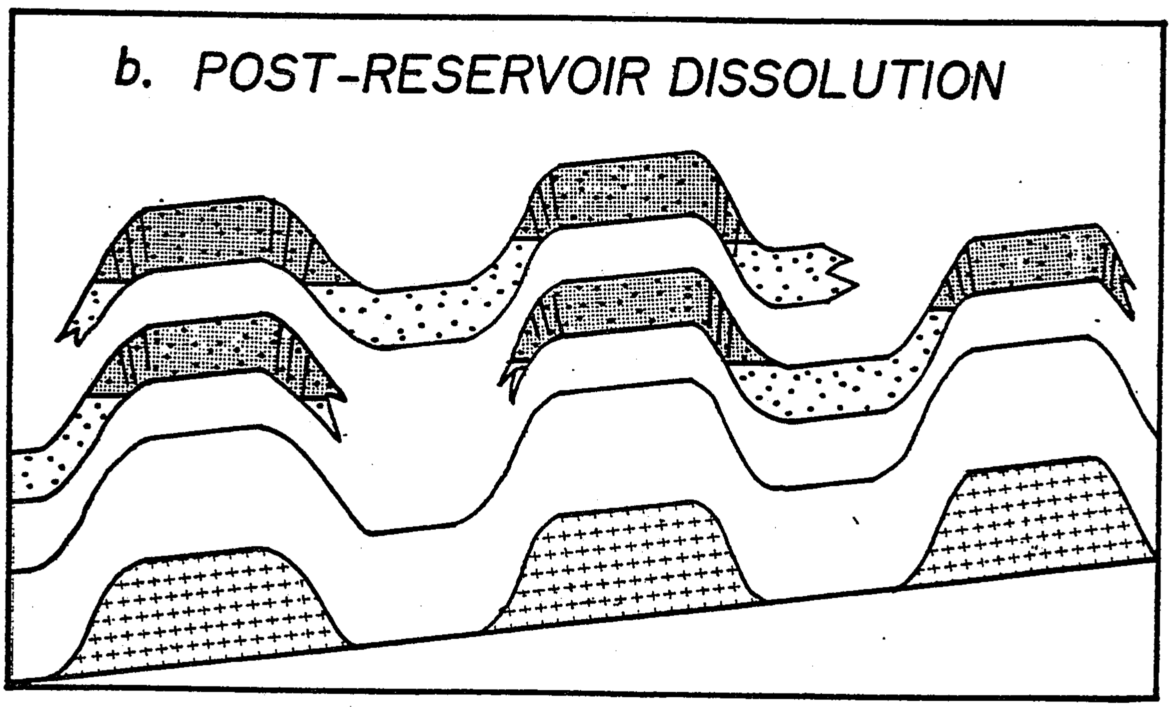


Figure 4-32. Comparison of field size and and reserve potential related to timing of salt dissolution.

Because oil is not localized on structural highs, fields cover a broad area.

To the east (Figure 4-32b), where incomplete dissolution of salt post-dated reservoir deposition, oil within each reservoir has been localized on salt-cored anticlines. Structural relief enhances segregation of oil and water, resulting in expanded oil columns and reduced water saturation on the anticlines. Collapse-induced fracturing may enhance permeability. In places, stacking of oil-saturated reservoirs occurs above salt remnants.

Enchanced oil columns, reduced water saturation, fracturing, and stacking of pays may act to enhance the per-well reserve potential of fields in the structurally complex eastern part of the fairway. Although oil fields in the western part of the fairway may be more areally extensive and have higher cumulative production, per-well yield should be lower than that of the more structurally complex eastern area, because the oil has not been localized on structures. (This assumes that all other factors, including the following, are comparable between the two areas: thickness and number of sandstone pays; reservoir porosity and permeability; reservoir pressure; gas-oil ratio; oil viscosity; and oil shrinkage factor. Other development-related factors include success of completion; pressure maintenance; flaring or venting of gas; well spacing; and water flooding.)

Production data in the southern Nebraska panhandle area were analyzed to determine if a significant difference exists between reserves produced from anticlinal fields in the eastern part of the fairway and reserves from stratigraphic fields to the west. Data for 420 fields, including discovery date, field size (in acres), cumulative oil production, cumulative gas production, cumulative barrels oil equivalent (BOE), oil production per 40 acres (BO/40 ac) were compiled from oil and gas township plats from the Nebraska Oil and Gas Conservation Commission and from published production records (Petroleum Information Corporation, 1994). Gas production from the Niobrara Formation and Paleozoic oil production were not included in the totals.

Discovery Date

A frequency plot of oil and gas field discovery dates for 420 fields in the southern Nebraska panhandle (Figure 4-33) reveals a peak in new field discoveries during 1956 and 1957. Drilling in the Denver basin reached its peak during this boom in 1955, with the drilling of 1097 exploratory wells and 1189 development wells (Volk, 1972).

The first six fields discovered (during 1949 and 1950) and 19 of 26 fields discovered through 1952 produce from anticlines. This is not uncommon in the early stages of a

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1949      A
1950      AAAAA
1951      AAAAAA  SSSS
1952      AAAAAAA  SSS
1953      AAAAAA  SSSSSSSS
1954      AAAAAAAA  SSSSSSSSSSSSSSSS
1955      AAAAAA  SSSSSSSSSSSSSSSSSSSSSSSSS
1956      AAAAA  SSSSSSSSSSSSSSSSSSSSSSSSSS
1957      AA  SSSSSSSSSSSSSSSSSSSSSSSSSSS
1958      AAA  SSSSSSSSSSSSSSSSSSSSSSSSSS
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1970      AA  SS
1971      AAA  SS
1972      AA  SS
1973      AA  SS
1974      A  SSS
1975      AAA  SSSSS
1976      AA  SSSSSS
1977      AAAAA  SSSSS
1978      AAA  SSSSS
1979      AAAA  SSSSSSSS
1980      SSSS
1981      SSSSSSSSS
1982      A  SSSS
1983      AA  SSSSSSS
1984      A  SSSS
1985      SSSSS
1986      A  S      A = Anticlinal field(east)
1987      A         S = Stratigraphic field(west)
1988      S
1989
1990
1991
1992      S
1993      A  S
```

Figure 4-33. Frequency distribution of field discoveries in southern Nebraska panhandle by discovery date and trap type.

basin's exploration and development. Structural traps, which are more apparent at the surface or on seismic data, are generally identified earlier than more subtle stratigraphic traps.

Fields discovered during 1949 and 1950 are shown on Figure 4-34. With the exception of Big Springs field, early discoveries are located just west of the Sidney trough in the highly-folded area formed by post-reservoir salt dissolution.

Field Size

Productive area, in acres, was derived from Nebraska Oil and Gas Conservation Commission township plats. Oil fields which cover at least 640 acres (1 sq mi) are listed in Table 4-2. Of the 33 largest fields, all of the top nine and 17 of the 20 largest fields are stratigraphic traps. Sloss field is the largest, with 4520 acres. The largest field in the structurally complex area is Juelfs-Gaylord, with 1320 acres.

The nine most areally extensive oil fields are shown on Figure 4-35. All of these fields are located in the western, structurally simple area, where folding has not localized oil accumulations into smaller pools.

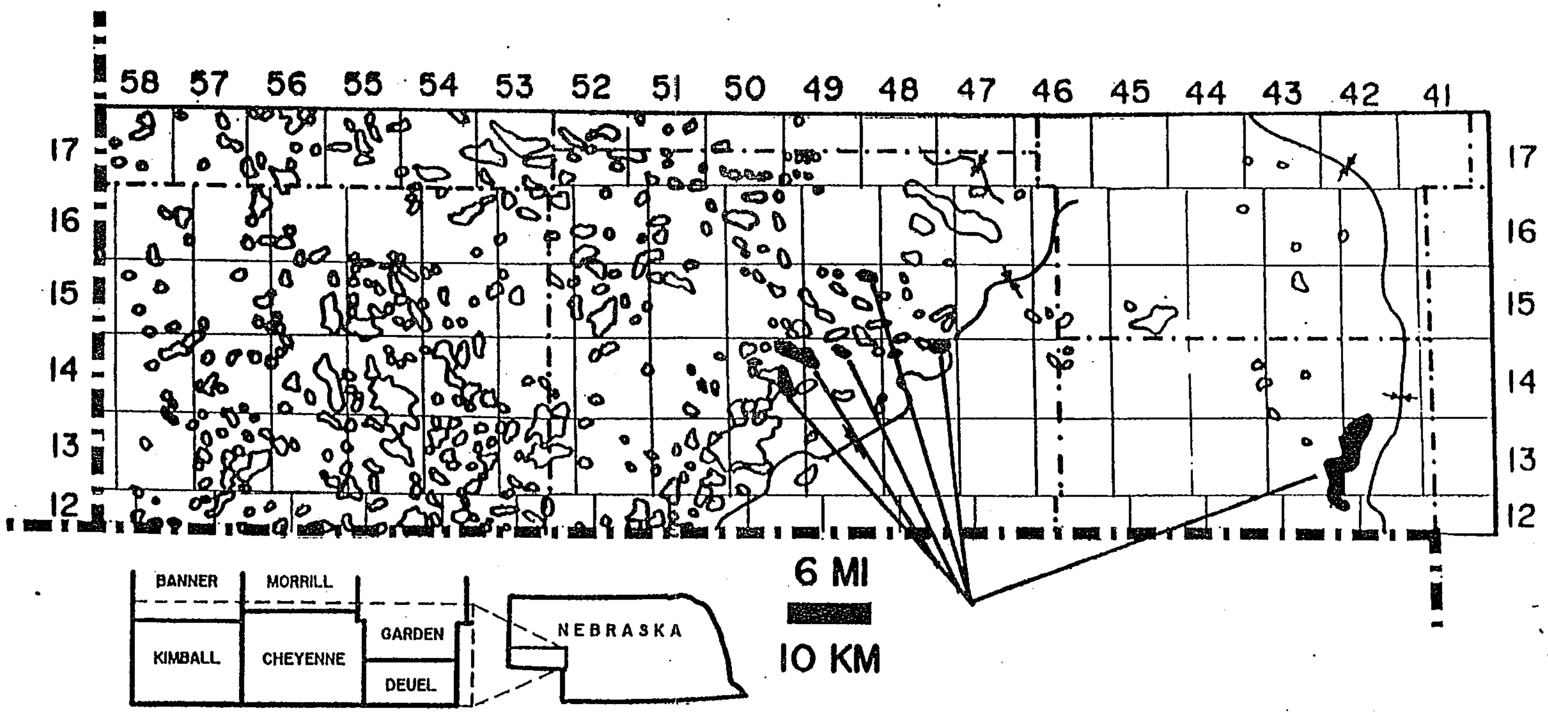


Figure 4-34. Location of fields discovered during 1949 and 1950.

TABLE 4-2. OIL FIELDS IN SOUTHERN NEBRASKA PANHANDLE COVERING 640 OR MORE ACRES.

FIELD	TRAP	CTY	TWP	RGE	ACRES
SLOSS	STRAT	K	14	55	4520
TORGESON	STRAT	K	14	56	2520
POTTER SOUTHWEST	STRAT	CK	14	53	2400
KIMBALL	STRAT	K	15	55	2120
LONG	STRAT	K	12	55	1960
ENDERS	STRAT	K	13	55	1920
SINGLETON	STRAT	B	17	53	1880
WILLSON RANCH	STRAT	B	17	53	1680
SIMPSON	STRAT	K	15	54	1360
JUELFS-GAYLORD	ANT	CM	17	51	1320
BALTENSPERGER	STRAT	K	13	57	1320
AUE-GRIFFITH	STRAT	K	13	55	1240
SLAMA	STRAT	C	15	52	1240
HUNTSMAN	ANT	C	14	49	1200
VEDENE	STRAT	B	17	56	1200
BARRETT	STRAT	BK	16	56	1200
VOWERS	STRAT	B	17	54	1120
HEIDEMANN	STRAT	K	15	56	1080
DORAN	ANT	C	14	50	1040
HOUTBY	STRAT	K	14	54	1040
JACINTO	STRAT	K	16	54	1040
DORMAN	ANT	C	14	50	960
PEBBLE	ANT	C	12	51	960
SWEARINGEN	STRAT	K	14	55	840
SUSAN	STRAT	K	14	54	800
IBEX	STRAT	K	12	54	800
SPEAROW	ANT	C	15	49	720
CIZEK	STRAT	BK	17	53	720
MINTKEN	STRAT	K	12	56	720
MALEY	ANT	C	13	49	680
GURLEY	ANT	C	15	49	640
ENGELLAND WEST	ANT	C	15	49	640
ROHLFING NORTH	ANT	C	12	51	640

STRAT-Stratigraphic; ANT-Anticlinal;
K-Kimball; C-Cheyenne; B-Banner; M-Morrill

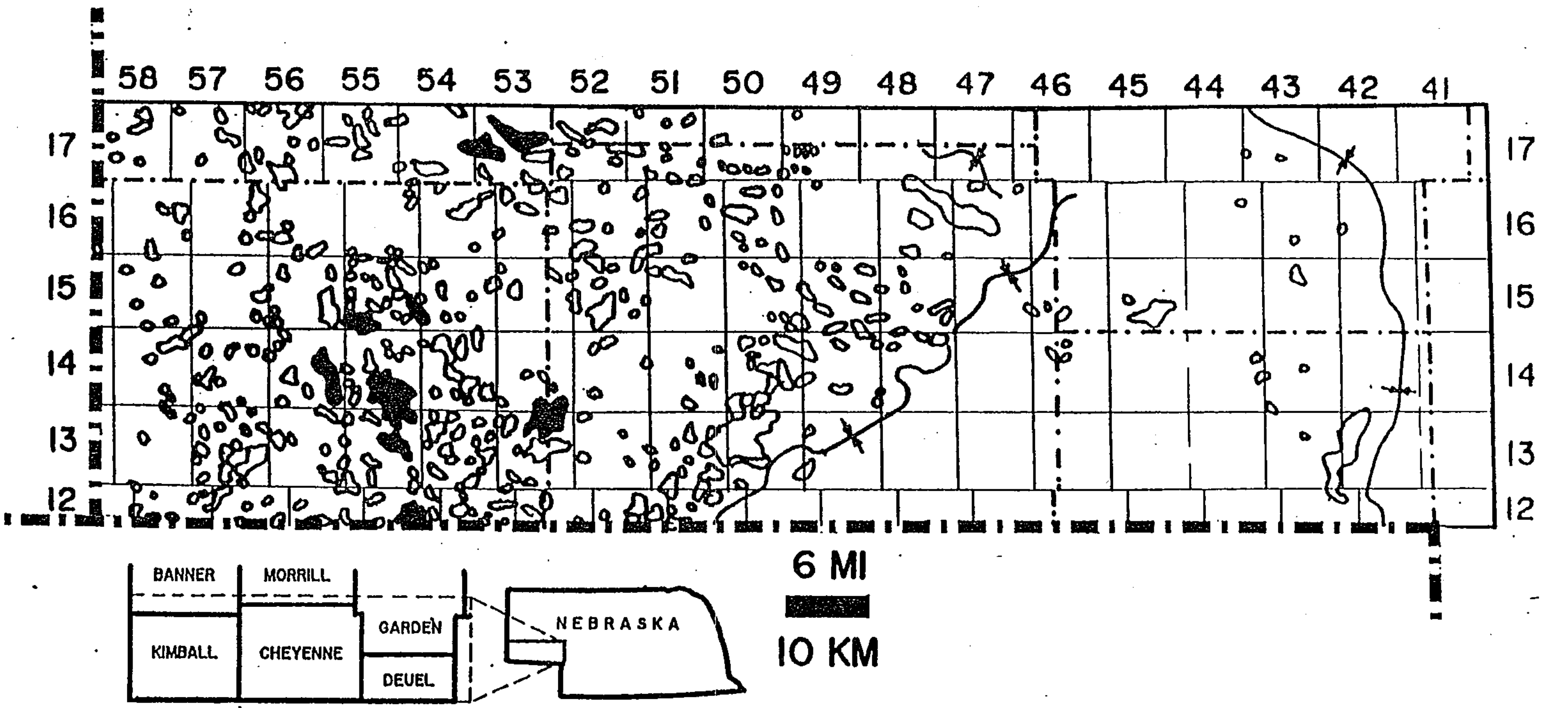


Figure 4-35. Location of fields with large areal extent.

Cumulative Oil Production

Cumulative oil production through 1993 is listed by field in Table 4-3 for 33 fields which produced in excess of 2,000,000 BO (2MMBO). All of the top eight and 13 of the top 20 oil producers produce from stratigraphic traps.

Fields which have produced in excess of 5,000,000 BO (5 MMBO) are shown on Figure 4-36. All but two of these fields are located in the western, structurally simple area. Most of the top oil producers are also at the top of the listing by size (Figure 4-34), indicating that high-per field yields in this area are related to size of field (number of wells).

Cumulative Gas Production

Cumulative gas production through 1993 is listed by field in Table 4-4 for fields which produced in excess of 1,000,000 MCFG (1 BCFG). It is uncertain if gas production figures are as reliable as those of oil production, due to the possibility of flaring or venting of gas, use on site, or reinjection for pressure maintenance, which may go unreported. Nonetheless, of the 37 fields, 21 produce from anticlines in the eastern half of the panhandle, including all of the top seven, and ten of the top 12.

Ten fields which have produced over 4,000,000 MCFG (4 BCFG) are shown on Figure 4-37. With the exception of two

TABLE 4-3. OIL FIELDS IN SOUTHERN NEBRASKA PANHANDLE WHICH HAVE PRODUCED OVER 2,000,000 BO (2000 MBO).

FIELD	TRAP	CTY	TWP	RGE	OIL(MBO)
SLOSS	STRAT	K	14	55	17021
SINGLETON	STRAT	B	17	53	10825
ENDERS	STRAT	K	13	55	9202
WILLSON RANCH	STRAT	B	17	53	8266
POTTER SOUTHWEST	STRAT	CK	14	53	7330
JACINTO	STRAT	K	16	54	6972
KIMBALL	STRAT	K	15	55	6755
LONG	STRAT	K	12	55	5804
DORMAN	ANT	C	14	50	5186
COOK	ANT	C	15	48	5055
DORAN	ANT	C	14	50	4985
HUNTSMAN	ANT	C	14	49	4786
JUELFS-GAYLORD	ANT	CM	17	51	4667
TORGESON	STRAT	K	14	56	4662
AUE-GRIFFITH	STRAT	K	13	55	4384
JOHNSON	ANT	C	15	49	4247
VEDENE	STRAT	B	17	56	3814
SPEAROW	ANT	C	15	49	3752
HOUTBY	STRAT	K	14	54	3563
BARRETT	STRAT	BK	16	56	3529
VOWERS	STRAT	B	17	54	3374
HEIDEMANN	STRAT	K	15	56	3303
REIMERS	ANT	C	16	50	3273
PREBLE	ANT	C	15	48	3106
GURLEY	ANT	C	15	49	2816
FERNQUIST	STRAT	K	16	53	2637
ALLCHIN	STRAT	K	12	56	2327
JORMAR	ANT	C	15	50	2257
MALEY	ANT	C	13	49	2135
RIGGS	STRAT	K	13	57	2099
BROOK	STRAT	K	16	56	2075
SIMPSON	STRAT	K	15	54	2045
RUSSELL	STRAT	K	16	58	2013

STRAT-Stratigraphic; ANT-Anticlinal;
K-Kimball; C-Cheyenne; B-Banner; M-Morrill

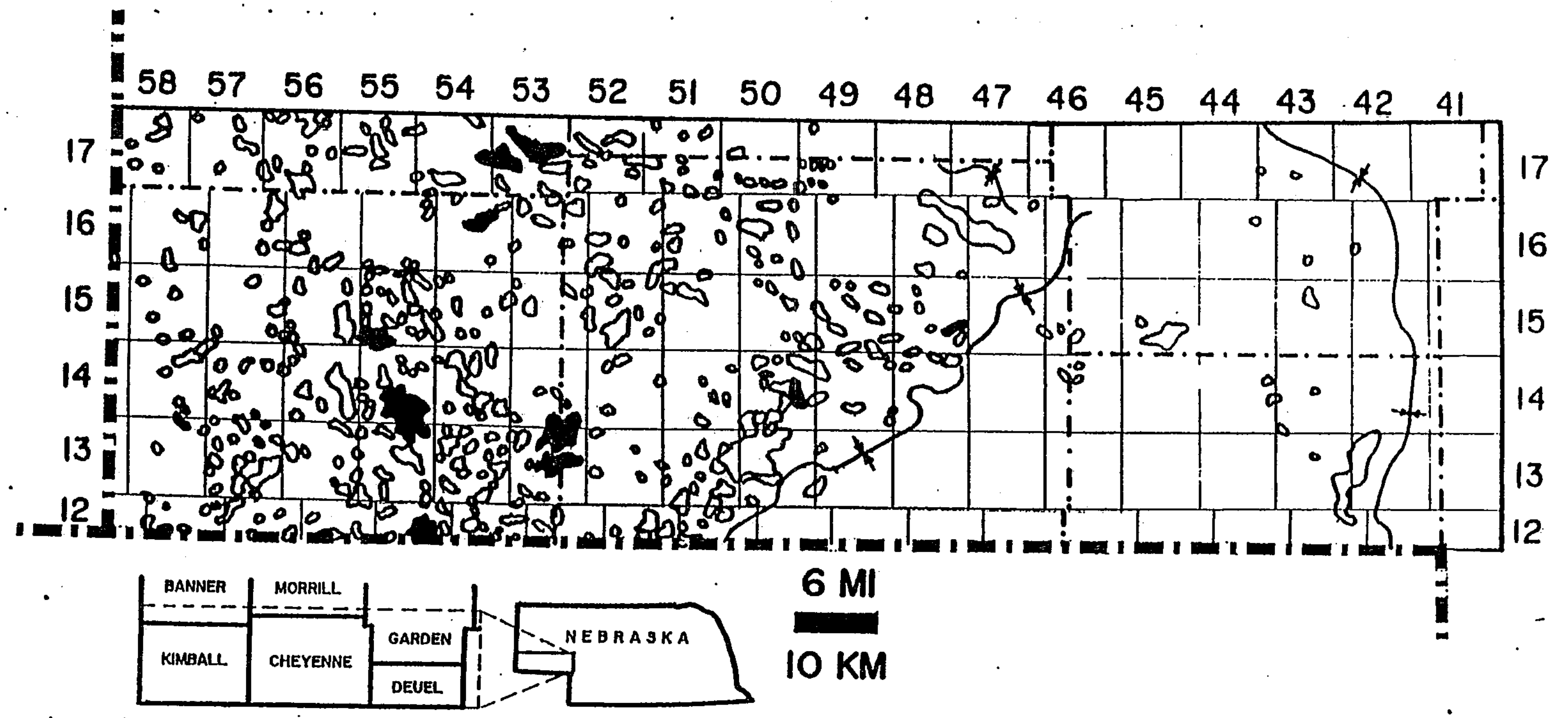


Figure 4-36. Location of fields which have produced over 5 MMBO through 1993.

TABLE 4-4. FIELDS IN SOUTHERN NEBRASKA PANHANDLE WHICH HAVE PRODUCED OVER 1 BCFG THROUGH 1993.

FIELD	TRAP	CTY	TWP	RGE	GAS(BCF)
SIDNEY SOUTHWEST	ANT	C	13	50	53.941
BIG SPRINGS	ANT	D	13	42	39.390
HUNTSMAN	ANT	C	14	49	19.225
DORAN	ANT	C	14	50	15.193
ENGELLAND WEST	ANT	C	15	49	13.571
MARLOWE	ANT	C	15	49	6.795
DORMAN	ANT	C	14	50	6.587
IBEX	STRAT	K	12	54	5.006
SLOSS	STRAT	K	14	55	4.948
REIMERS	ANT	C	16	50	4.375
JOHNSON	ANT	C	15	49	3.395
FLEMING	ANT	C	13	50	3.067
WILLSON RANCH	STRAT	B	17	53	2.720
SPEAROW	ANT	C	15	49	2.703
ALLCHIN	STRAT	K	12	56	2.661
LONG	STRAT	K	12	55	2.636
PEBBLE	ANT	C	12	51	2.292
SIDNEY NORTH	ANT	C	14	49	2.266
SINGLETON	STRAT	B	17	53	2.013
SIOUX	ANT	C	15	49	1.969
ROHLFING/BENTLEY	STRAT	C	12	52	1.772
KIMBALL	STRAT	K	15	55	1.707
POTTER SOUTHWEST	STRAT	CK	14	53	1.705
SUNOL	ANT	C	14	48	1.699
JUELFS-GAYLORD	ANT	CM	17	51	1.515
KUGLER	ANT	C	14	48	1.467
JACINTO	STRAT	K	16	54	1.410
ENDERS	STRAT	K	13	55	1.406
VEDENE	STRAT	B	17	56	1.396
DIMICK WEST	ANT	C	13	50	1.228
EGGLESTON	ANT	C	13	51	1.203
BARRETT	STRAT	BK	16	56	1.103
DRAW	STRAT	CK	13	53	1.098
ROHLFING NORTH	ANT	C	12	51	1.094
PHILLIPS	STRAT	K	12	54	1.091
AUE-GRIFFITH	STRAT	K	13	55	1.055
MOHATT	ANT	C	13	50	1.028

STRAT- Stratigraphic; ANT-Anticlinal;
K-Kimball; C-Cheyenne; B-Banner; M-Morrill

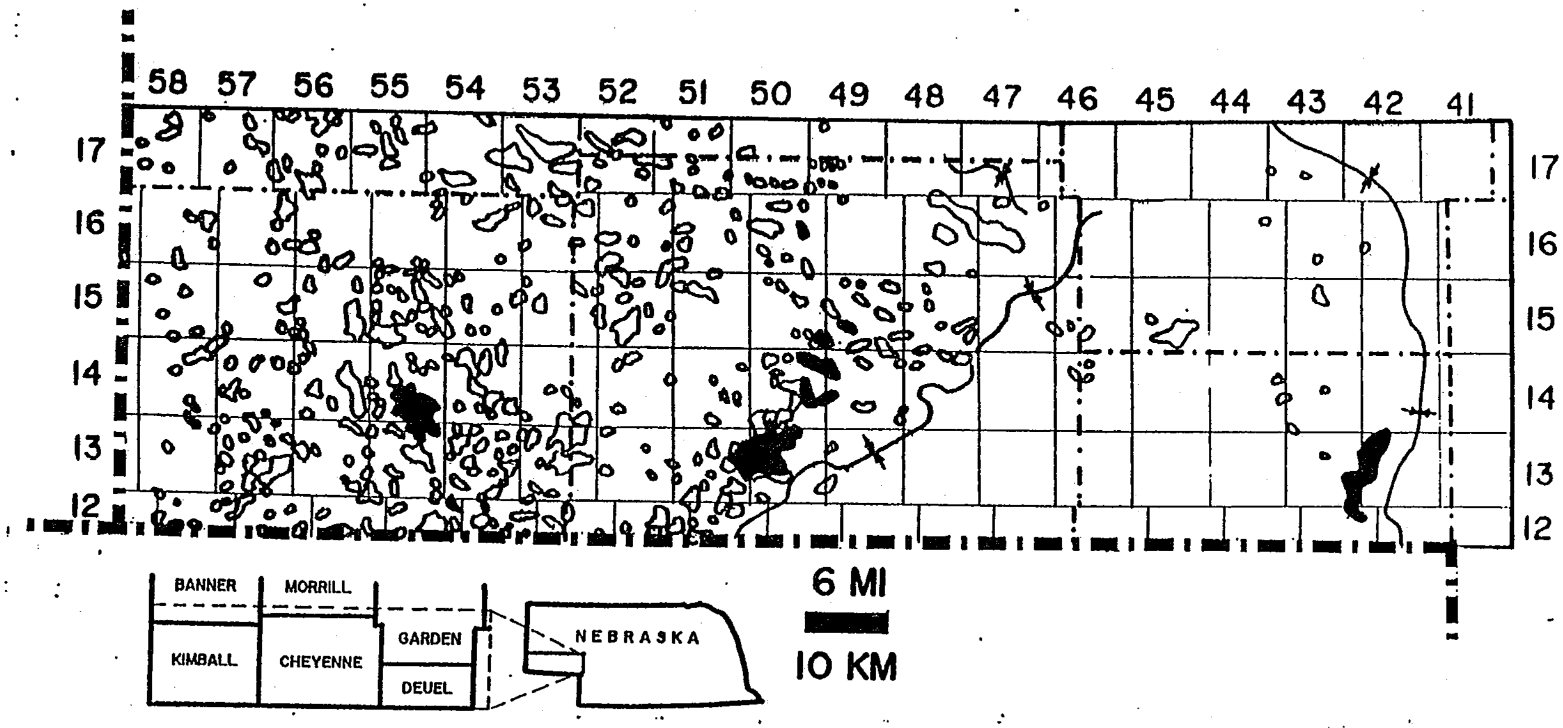


Figure 4-37. Location of fields which have produced over 4 BCFG through 1993.

fields to the west and Big Springs field to the east (which produces biogenic gas and is not in the D-J fairway, fields with the highest gas yield are located on anticlines just west of the Sidney trough. This suggests that the proportion of gas produced (relative to oil) increases to the east toward the updip limit of the D-J fairway, where partial regional-scale segregation of oil and gas has occurred.

Combined Cumulative Oil and Gas Production

Oil and gas production figures were combined as barrels oil equivalent (BOE), at a factor of 7 MCFG/BO. Twenty fields which produced over 4,000,000 BOE (4MMBOE) are listed in Table 4-5. No trend by trap type is apparent when fields are ranked by BOE. Anticlinal and stratigraphic traps are equally represented, with nine and 11, respectively, in the top 20.

Fields which have produced over 5 MMBOE (14 total) are shown on Figure 4-38). Rather than clustering toward the west (as with cumulative oil production on Figure 4-36) or to the east (as with cumulative gas production on Figure 4-37) fields are more or less distributed evenly across the southern panhandle.

TABLE 4-5. FIELDS IN SOUTHERN NEBRASKA PANHANDLE WHICH HAVE PRODUCED OVER 4 MMBOE THROUGH 1993.

FIELD	TRAP	CTY	TWP	RGE	MBOE
SLOSS	STRAT	K	14	55	17728
SINGLETON	STRAT	B	17	53	11113
SIDNEY SOUTHWEST	ANT	C	13	50	9661
ENDERS	STRAT	K	13	55	9402
WILLSON RANCH	STRAT	B	17	53	8654
POTTER SOUTHWEST	STRAT	CK	14	53	7574
HUNTSMAN	ANT	C	14	49	7533
DORAN	ANT	C	14	50	7258
JACINTO	STRAT	K	16	54	7173
KIMBALL	STRAT	K	15	55	6999
LONG	STRAT	K	12	55	6181
DORMAN	ANT	C	14	50	6127
BIG SPRINGS	ANT	D	13	42	5627
COOK	ANT	C	15	48	5187
JUELFS-GAYLORD	ANT	CM	17	51	4884
TORGESON	STRAT	K	14	56	4789
JOHNSON	ANT	C	15	49	4732
AUE-GRIFFITH	STRAT	K	13	55	4535
SPEAROW	ANT	C	15	49	4138
VEDENE	STRAT	B	17	56	4014

STRAT-Stratigraphic; ANT-Anticlinal;
K-Kimball; C-Cheyenne; B-Banner; M-Morrill

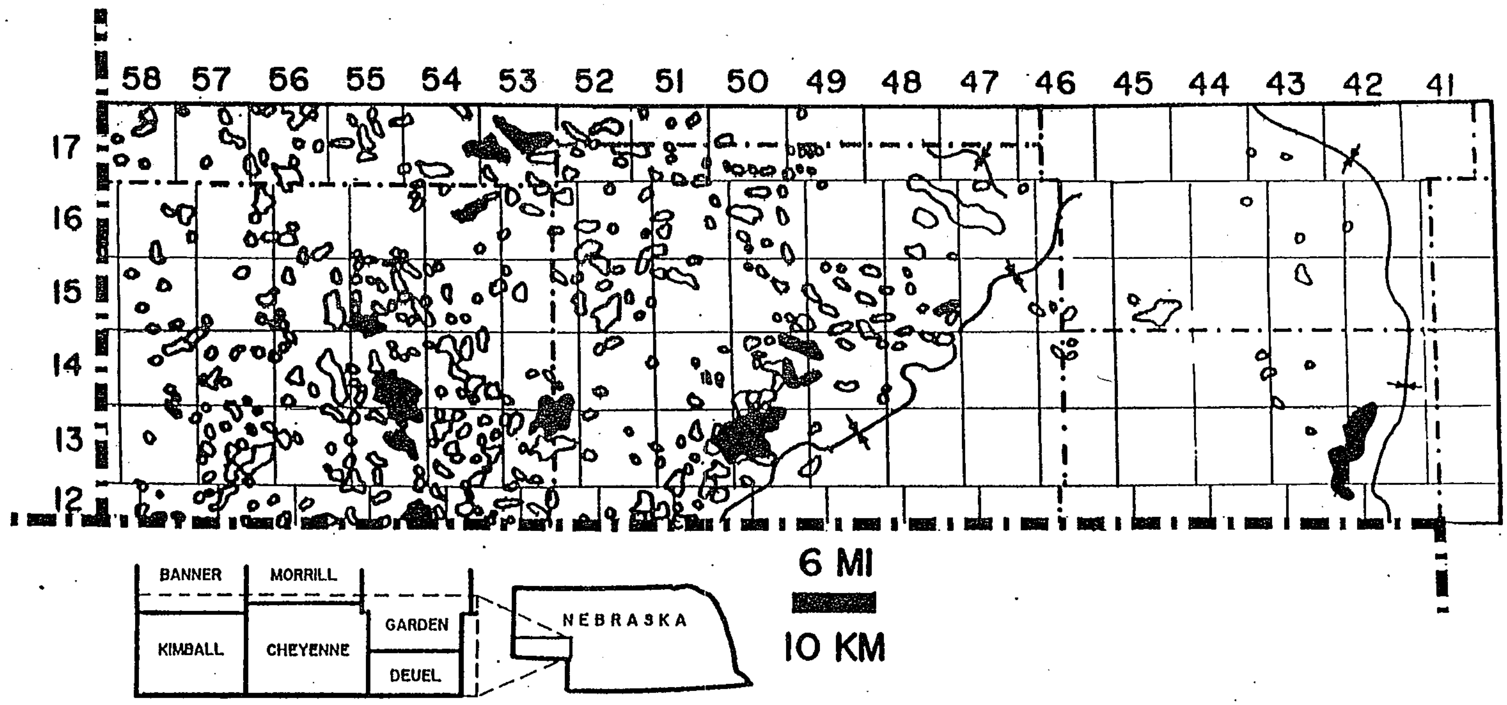


Figure 4-38. Location of fields which have produced over 5 MMBOE through 1993.

Oil Production per 40 Acres

At the beginning of the discussion on the influence of salt dissolution on reserve potential, Figure 4-32 was used to depict how post-reservoir salt dissolution could cause localization of oil accumulations on anticlines formed by drape across salt outliers. Although field size and total production per field may be reduced, enchanced oil columns, increased oil saturation, possible fractures, and stacking of pays would result in higher per-well reserves.

Cumulative oil production in each field was divided by the number of 40-acre tracts contained within the field limits (BO/40 ac). This approach is similar to that used by Pruit (1978), who used 80-acre areas to discuss "quality of reserves" in the Denver basin. Although standard statewide spacing for oil wells is 40 acres, in places fields are more densely drilled. For this reason, production per unit area (40 acres) rather than per well was calculated.

Fields which have produced over 200,000 BO/40 ac (23 total) are listed in Table 4-6. Of these, 15 fields produce from anticlinal traps, including all of the top seven and nine of the top 10. Only one of the fields included in the top 10 cumulative oil producers (Table 4-4), Jacinto field, is in the top 10 fields ranked by BO/40 ac. Although Jacinto field, located in T16N, R54W, is west of the line separating the structurally simple and structurally complex

TABLE 4-6. OIL FIELDS IN SOUTHERN NEBRASKA PANHANDLE WHICH HAVE PRODUCED OVER 200,000 BO/40 ACRES.

FIELD	TRAP	CTY	TWP	RGE	BO/40ac
FARO	ANT	C	16	50	550678
REIMERS	ANT	C	16	50	467548
COOK	ANT	C	15	48	459567
GRAFF	ANT	C	17	49	349389
PREBLE	ANT	C	15	48	310630
JOHNSON	ANT	C	15	49	303368
SIDNEY NORTH	ANT	C	14	49	285580
JACINTO	STRAT	K	16	54	268151
JORMAR	ANT	C	15	50	250681
SELL	ANT	C	15	48	241359
ALLCHIN	STRAT	K	12	56	232741
RAYMOND	STRAT	B	17	54	231208
SINGLETON	STRAT	B	17	53	230324
GOODWIN	STRAT	K	13	54	228943
LUKASSEN	STRAT	K	15	55	225672
COVE	ANT	C	14	48	224644
DORMAN	ANT	C	14	50	216070
MIDDLE CREEK	ANT	CM	17	50	210329
SPEAROW	ANT	C	15	49	208454
PERSON	STRAT	L	12	58	207249
FARO NORTH	ANT	C	17	49	206163
WORDEN	ANT	C	17	49	203381
FERNQUIST	STRAT	K	16	53	202841

STRAT-Stratigraphic; ANT-Anticlinal;
K-Kimball; C-Cheyenne; B-Banner; M-Morrill

areas, it is associated with a strong southwest-plunging nose (Figure 4-13) and overlies thick upper Leonardian and Guadalupian salts (Figures 4-8 and 4-9). Miller (1963) used Jacinto field as an example of a trap formed by an "updip facies change on a nose." Although no closure is present at the field, trapping may have been influenced by post-reservoir salt dissolution. Additional evidence of late dissolution may be represented by the only highly-saline water analysis in the western half of the area, just northeast of Jacinto field in T16N, R53W (Figure 4-31).

Oil fields which have produced over 150,000 BO/40 ac (54 total) are highlighted on Figure 4-39. Major synclinal axes, derived from Figure 4-13, are also shown. A north-south line separates fields which are associated with closures from predominantly stratigraphic traps to the west. All six fields with over 300,000 BO/40 ac, nine of 17 fields in the 200,000 to 300,000 BO/40 ac range, and 10 of 31 fields in the 150,000 to 200,000 BO/40 ac range produce from anticlines. Although anticlinal fields represent only 26 percent of all fields in the study area, they account for 46 percent of the fields which average over 150,000 BO/40 ac.

A "t" test was used to determine if average per-acre oil yield of fields in areas of post-reservoir salt dissolution (structurally complex area) is significantly different from the per-acre yield of all fields in southern Nebraska panhandle part of the D-J fairway. Although per-

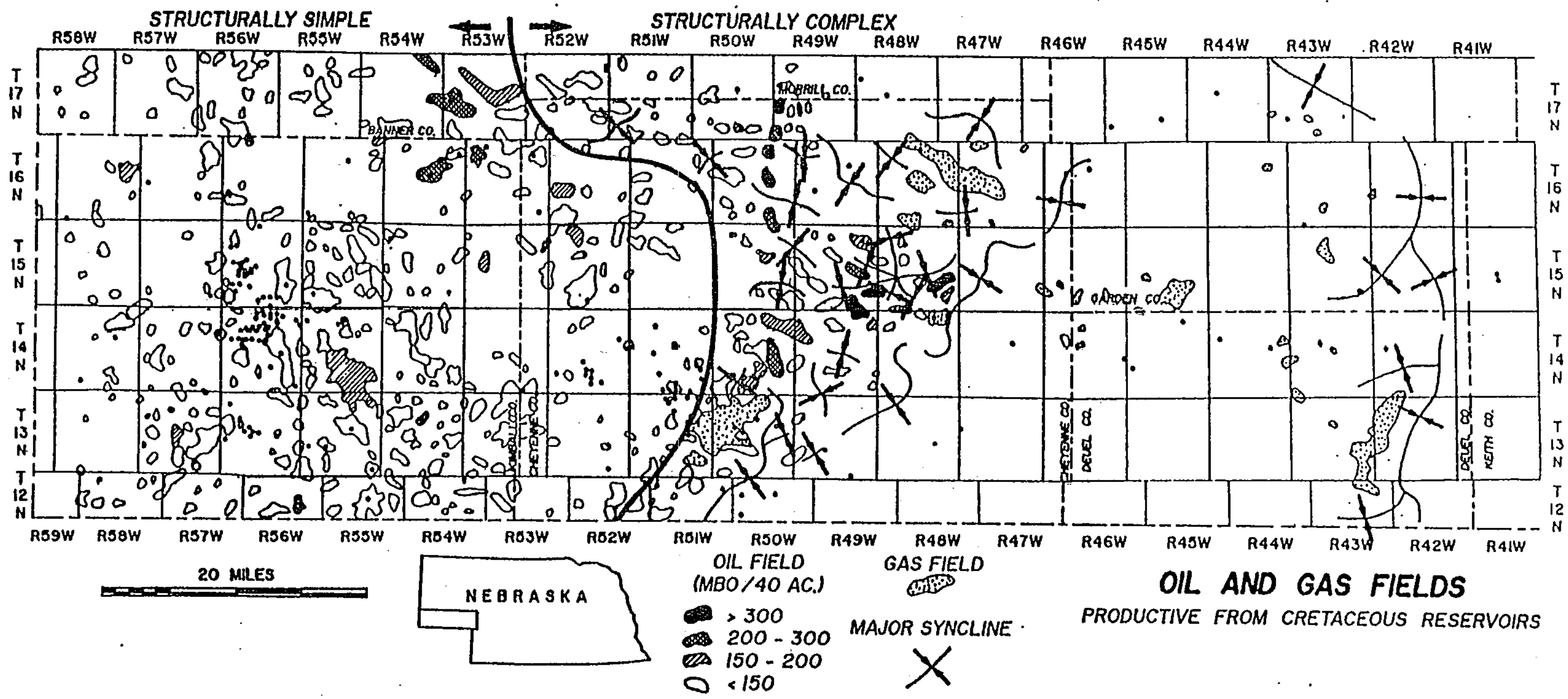


Figure 4-39. Oil and gas fields in southern Nebraska panhandle, oil production per 40 acres, and significant structural depressions.

acre oil production, rather than per-acre BOE production was used as the dependent variable to reduce error caused by incomplete gas production reporting, or gas flaring and venting, the two sets of data are similar. The analysis, limited to 410 oil fields in the D-J fairway, excluded three gas fields within the fairway and seven fields east of the Sidney trough.

In the "t" test, the average BOE/40 ac for 410 fields (74,095 BO/40 ac) was used to represent μ, the population average. Sample average, X, for 102 anticlinal fields, is 99,379 BO/40 ac. With 101 degrees of freedom, a "t" value of 2.41 is significant at the .02 level. Thus, the discrepancy between X and μ cannot be explained by sampling error. Thus, a statistically significant difference exists between average cumulative oil production per 40 acres (BO/40 ac) between salt-cored anticlinal fields and average BO/40 ac for all 410 oil fields within the D- J fairway.

SUMMARY AND CONCLUSIONS

This chapter examined the influence of Permian salt dissolution on oil and gas entrapment in the southern Nebraska panhandle area of the Denver basin. Subsurface analysis of the distribution and thickness of salts and the Lyons Sandstone, along with analysis of formation water salinity data and oil and gas production figures, leads to the following conclusions.

1. Of 13 salt zones of Guadalupian, Leonardian, and late Wolfcampian age identified in the Denver basin subsurface, 12 zones have been identified in the Nebraska panhandle. Salt 8 was not identified on well logs in this area.

2. Distribution of individual salt zones is controlled by : a) configuration of evaporite basins and facies changes (both of which were influenced by positive elements associated with the Transcontinental arch); b) truncation and near-surface dissolution below a pre-Late Jurassic unconformity; and c) subsequent subsurface dissolution at various times since the Jurassic. The Transcontinental arch exerted more influence on the shape of the evaporite basins during precipitation of upper Wolfcampian, lower Leonardian, and lowermost upper Leonardian salts. The original eastern limits of salts, particularly those of late Leonardian and Guadalupian age, was likely well beyond their present sub-Jurassic limits, and the present distribution of these salts does not reflect the original geometry of the evaporite basins.

3. Eolian and shallow water sand (Lyons sandstone) accumulated along a northeast-trending paleohigh which separated the Sterling and Alliance evaporite basins during the Leonardian. Basement fault influence on sedimentation

is reflected in an abrupt linear facies change from sandstone to evaporites (salts 9 and 10) along the northwestern margin of the Sterling basin, and in the Garden County low, which connected the Sterling and Alliance basins during late Wolfcampian and Leonardian time.

4. Timing of salt dissolution has significantly influenced the distribution and trapping mechanism of oil and gas fields which are productive from Cretaceous-age D and J Sandstone reservoirs in the Nebraska panhandle. To the west, in Kimball and western Cheyenne counties where salt dissolution pre-dated deposition of reservoirs, stratigraphic traps are predominant. To the east, in areas where salt dissolution post-dated the reservoirs, in Deuel, southern Garden, and eastern Cheyenne Counties, solution collapse has contributed to the formation of numerous hydrocarbon-productive structural traps.

5. In the eastern part of the area, Cretaceous reservoir-level structure is rootless and is discordant with subsalt homoclinal structure. To the west, where salts have not been dissolved or were removed prior to deposition of Cretaceous reservoirs, reservoir-level and subsalt structure are relatively concordant, and Cretaceous structure may be more reliable as an estimate of subsalt Paleozoic structure.

6. Location of a linear, northeast-trending salt dissolution depression, which coincides with a regional Cretaceous-level syncline (Sidney trough), is controlled by

the Lyons Sandstone/evaporite facies change. Eastward gravity-driven groundwater flow within the Lyons occurred in response to hydraulic gradient and recharge along the Front Range uplift following Laramide orogeny. Salts 9 and 10 were dissolved at the facies change. Collapse of overlying strata produced fractures through which cross-formational flow occurred. Younger salts were dissolved, enhancing relief across the regional depression. Subsidiary synclines which branch off from the main trough, formed by retreat of salt edges possibly along Laramide-induced fractures. Oil- and gas-productive anticlines occur in this area.

7. High-salinity formation water in the D and J Sandstones is restricted to the eastern area, where salt dissolution post-dated reservoir deposition. Cross-formational flow from the Lyons Sandstone through the salt interval into the Cretaceous reservoirs is believed to be the source of brines. Salinity anomalies are absent to the west, where salt was removed prior to D and J deposition.

8. Timing of salt dissolution is believed to have influenced the size, cumulative production, and per-acre reserves of oil fields in the southern Nebraska panhandle. The largest fields, both in terms of areal extent and cumulative oil production, are in the the area of stratigraphic traps to the west. However, oil is localized on salt dissolution anticlines to the east, resulting in significantly higher reserves per well. Structural

complexity of this area allowed for identification of potential traps and drilling of prospects earlier than those to the west where traps are more subtle.

CHAPTER 5
BIG SPRINGS D SANDSTONE GAS FIELD, DEUEL COUNTY, NEBRASKA

INTRODUCTION

Big Springs gas field is located in southeastern Deuel County, Nebraska, near the eastern edge of the Nebraska panhandle subregional study area (Figure 5-1). With cumulative gas production of over 41 BCFG, Big Springs field ranks second in the state, behind Sidney Southwest field, and accounts for more than 15 percent of Nebraska's total cumulative gas production. Prior to conversion to a gas-storage field, gas was produced from the Lower Cretaceous D Sandstone.

Big Springs field is one of three fields discussed in Chapter 2 which are situated along a possible north-south Permian salt dissolution edge in the northeastern part of the Denver basin. Study of salt distribution within the Nebraska panhandle subregional study area (Chapter 4) confirms that Leonardian and Upper Wolfcampian salts are absent to the east of a north-south line which extends across the Big Springs area. This chapter focuses on a possible salt-solution origin for the gas-productive anticline at Big Springs. Seismic data are used to support a salt solution-collapse origin for the Big Springs structure.

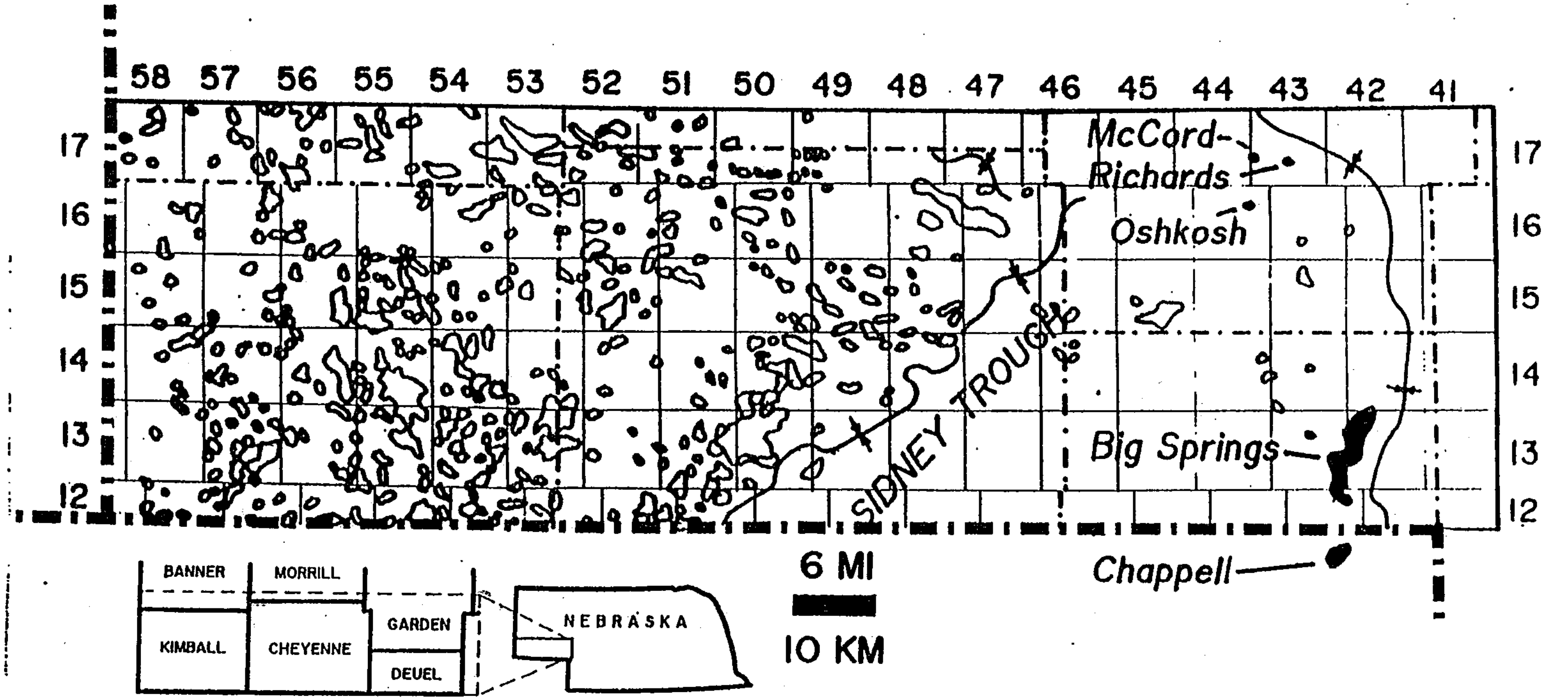


Figure 5-1. Location of Big Springs gas field in southern Nebraska panhandle area. Other fields situated to the west of the regional syncline are shown, along with Sidney trough.

DEVELOPMENT OF BIG SPRINGS FIELD

Because of its size and significant gas production, Big Springs field represents an important area to study the relationship of salt removal to Cretaceous hydrocarbon entrapment in the Denver basin. The gas field, discovered in 1950, produced over 41 BCFG from 24 wells until 1975, when it was converted to a gas-storage field. The productive reservoir (and the present-day storage reservoir) is the Cretaceous D Sandstone, at a depth of about 3200 ft (1000 m).

Discovery of gas at Big Springs resulted from a flurry of exploratory drilling activity in western Nebraska following the Gurley field discovery in 1949. In the early 1950s the Denver basin led the Rockies in drilling activity, resulting in the discovery and development of hundreds of D and J Sandstone structural and stratigraphic fields.

Although a well had been drilled to the D Sandstone and abandoned in October 1949 in NENW Sec.19, T13N, R42W, the discovery well was not completed until September 1950. This well, the Ideal Drilling Bosley 2, located in SESW Sec. 19, T13N, R42W (Figure 5-2), produced 1.9 BCFG, was shut-in in 1964, and was plugged and abandoned in 1973.

Development drilling of the D Sandstone gas pool continued in the early 1950s. By the end of 1951 eight wells were producing and two were shut-in, and by 1954 the

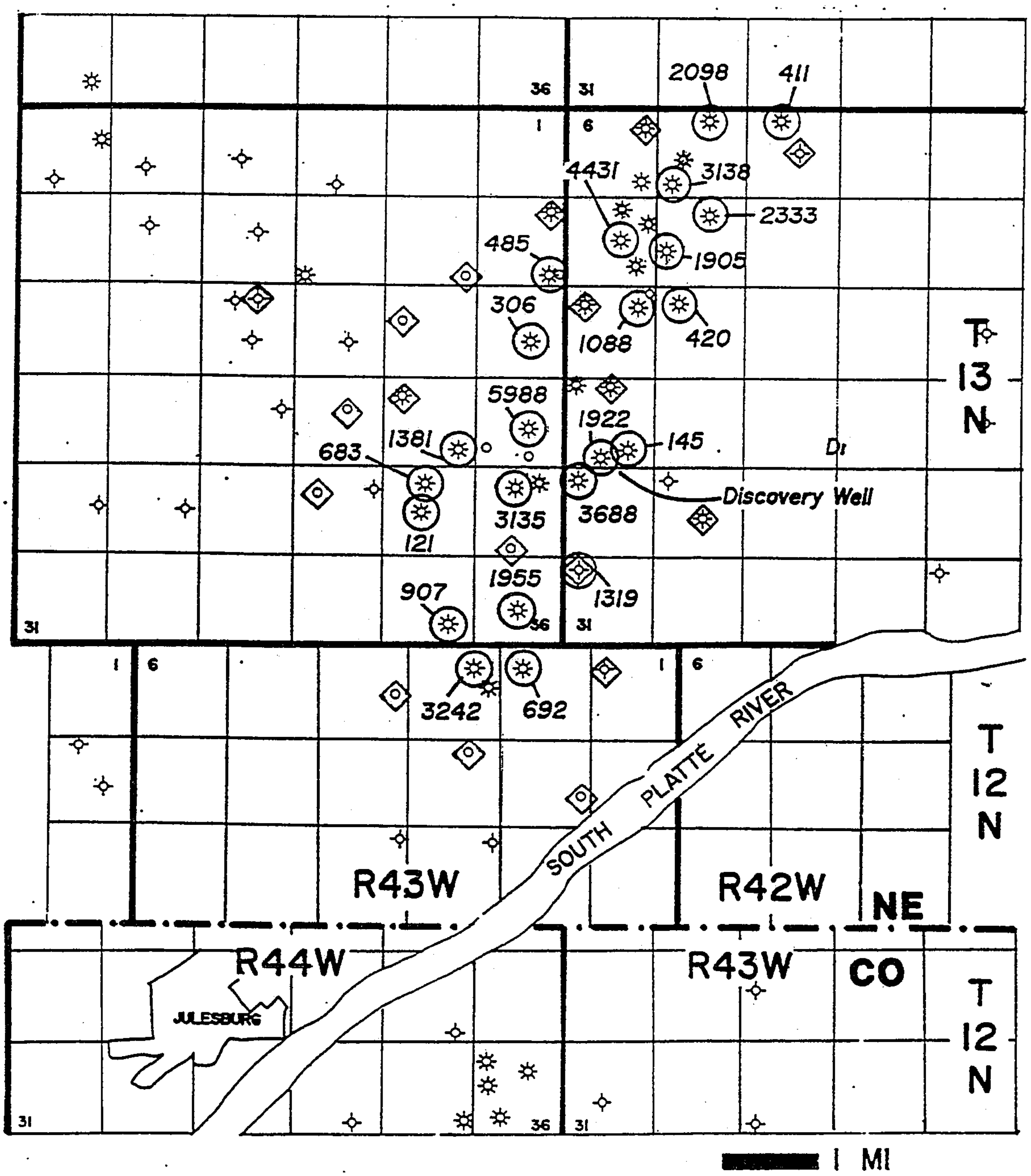


Figure 5-2. Cumulative production from gas wells at Big Springs field prior to conversion to gas storage in 1975 (circled wells). Gas volumes are in MMCFG. Wells with diamond symbol on this and subsequent maps denote gas-storage field observation wells.

field was nearly fully developed by 21 wells (King, 1956). Concurrent with drilling was the acquisition of a seismic reflection survey across the new field and adjacent areas. The seismic survey was shot in 1952 and 1953 to define the producing structure at Big Springs, thereby minimizing risk in drilling offset wells. This seismic survey and its application to the study of underlying salts is discussed later in this chapter.

Original D Sandstone gas wells and dry holes, along with subsequent gas injection/withdrawal and observation wells within the gas storage field are shown on Figure 5-2. Twenty-four gas wells which existed prior to conversion to gas storage are highlighted. Per-well cumulative production figures are shown for these wells. Several wells produced over 3 BCFG. The best well, located in Sec. 24, T13N, R43W, produced over 5 BCFG.

STRUCTURE

Structural mapping on top of the D Sandstone gas reservoir (Figure 5-3) reveals a north-south-trending anticline. This feature coincides with DeGraw's (1969, 1971) "Big Springs anticline." Elevation at the top of the productive sandstone ranges from about 330 ft (100 m) above sea level at the gas-water contact to slightly over 400 ft (120 m) at the crest of the structure.

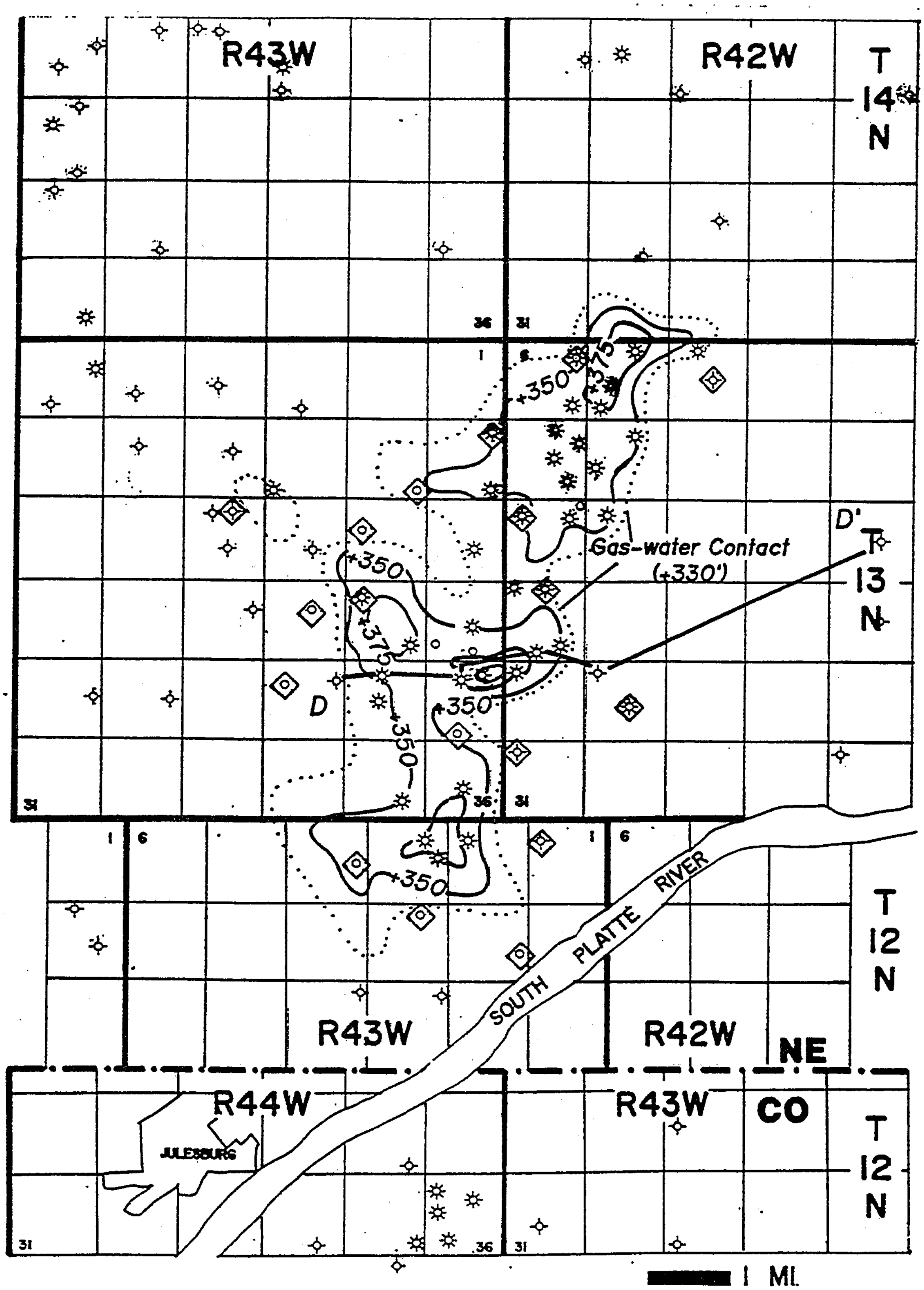


Figure 5-3. Structure drawn on top of D Sandstone gas reservoir at Big Springs field. Field limit is defined by gas-water contact. Contour interval 25 ft (8 m). Wells with diamond symbols denote gas storage injection wells.

Structure on top of the D Sandstone in an expanded area surrounding the field (Figure 5-4) reveals a signficant structural anomaly just east of production. A north-south-trending syncline parallels the eastern margin of the field. Well control indicates that the D Sandstone in the synclinal axis lies at least 150 ft (45 m) low to the crest of the producing structure. Comparable structural relief exists at the northern and southern limits of the field, along the axes of two east-west-trending subsidiary synclines. The southernmost syncline separates Big Springs field from D Sandstone gas production at Chappel field, located across the state line in Colorado.

An east-west structural cross section through the field (Figure 5-5) shows the relationship of structure to gas production. Downdip wells at the field margins encountered a thick upper D Sandstone bench which was water-bearing. Structurally high wells, which encountered the reservoir at an elevation higher than the gas-water contact (330 ft or 100 m above sea level), are gas-productive.

STRATIGRAPHY

The D Sandstone or "D Sand" (Cenomanian) is a driller's term for the first "Dakota sand" encountered in the Denver basin subsurface. Many geologists who "work" the basin lump the D into the Dakota Group, because it is closely

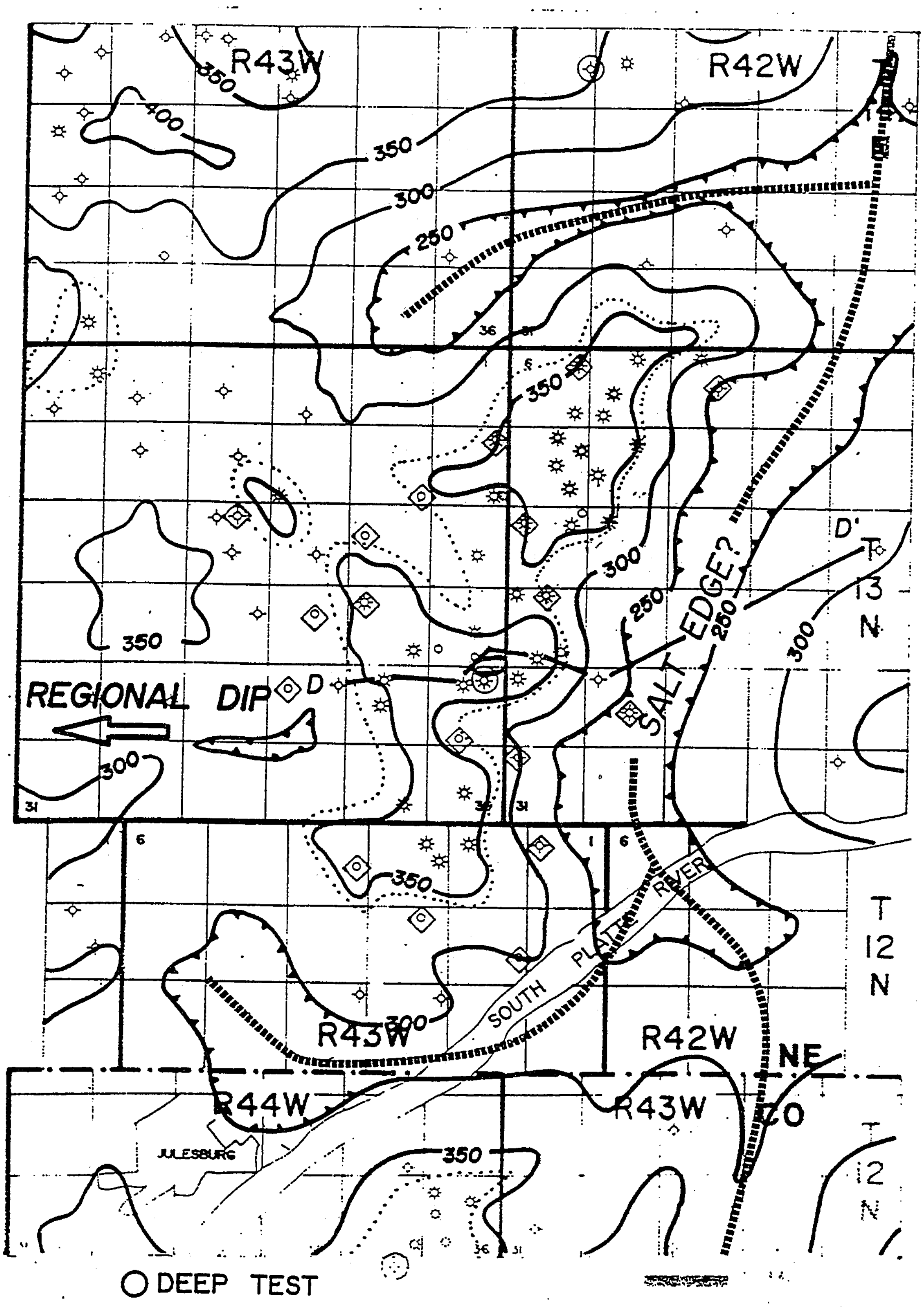


Figure 5-4. D Sandstone structure at Big Springs field and surrounding areas. Contour interval 50 ft (15 m).

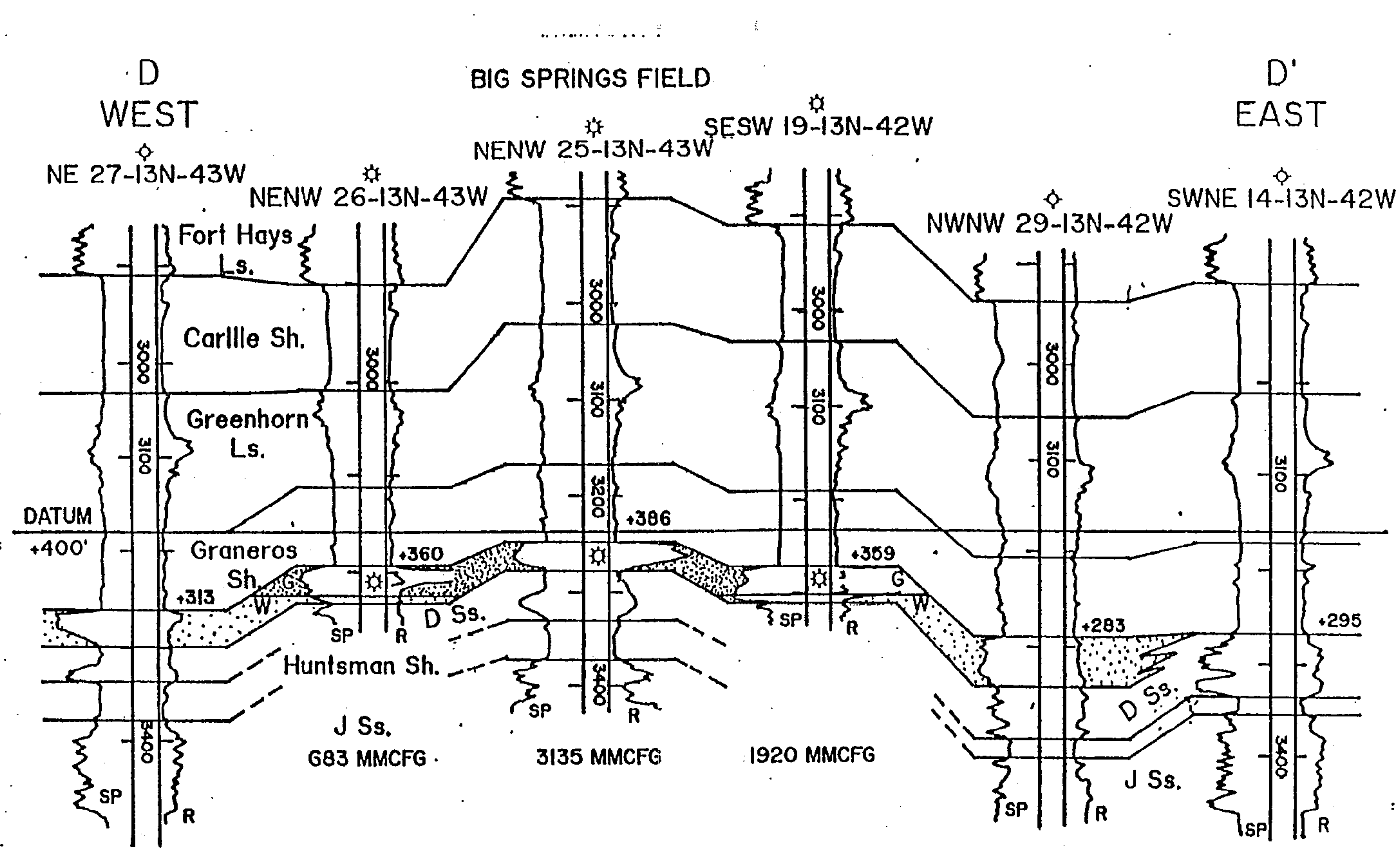


Figure 5-5. East-west structural cross section through Big Springs field. Well depths are in feet. No horizontal scale.

associated with the J Sandstone and deeper sandstones of the Dakota. Where present in the basin, the D Sandstone is situated within the Graneros Shale (Benton Group). The lower Graneros tongue (below the D Sandstone) is commonly referred to as the Huntsman Shale (Figure 5-5). Because of its intertonguing relationship with the Graneros and Huntsman, it is more appropriate to include the D in the Benton Group rather than the Dakota Group.

Deposition of the D Sandstone was in response to a regression of the Western Interior Cretaceous seaway. The D interval is over 100 ft (30 m) thick along the eastern margin of the basin where it merges with the J Sandstone, at the zero isopach of the Huntsman Shale (Figure 5-6). Regionally, the unit forms a wedge which thins westward to zero just east of the basin axis (Figures 5-6 and 1-2). By contrast, the underlying J Sandstone extends to the west in the subsurface to its outcrop along the Front Range.

The relative drop in sea level created a lowstand surface of erosion which was then onlapped and infilled with sand. Fluctuations in relative sea level resulted in a facies mosaic of nearshore marine, valley fill, and fluvio-deltaic sands, along with lagoonal and floodplain/interdistributary muds within the D interval. The sediment source was to the east. Although exceptions are common, the sand units within the lower part of the D interval are either valley-fill deposits (formed on top of the lowstand

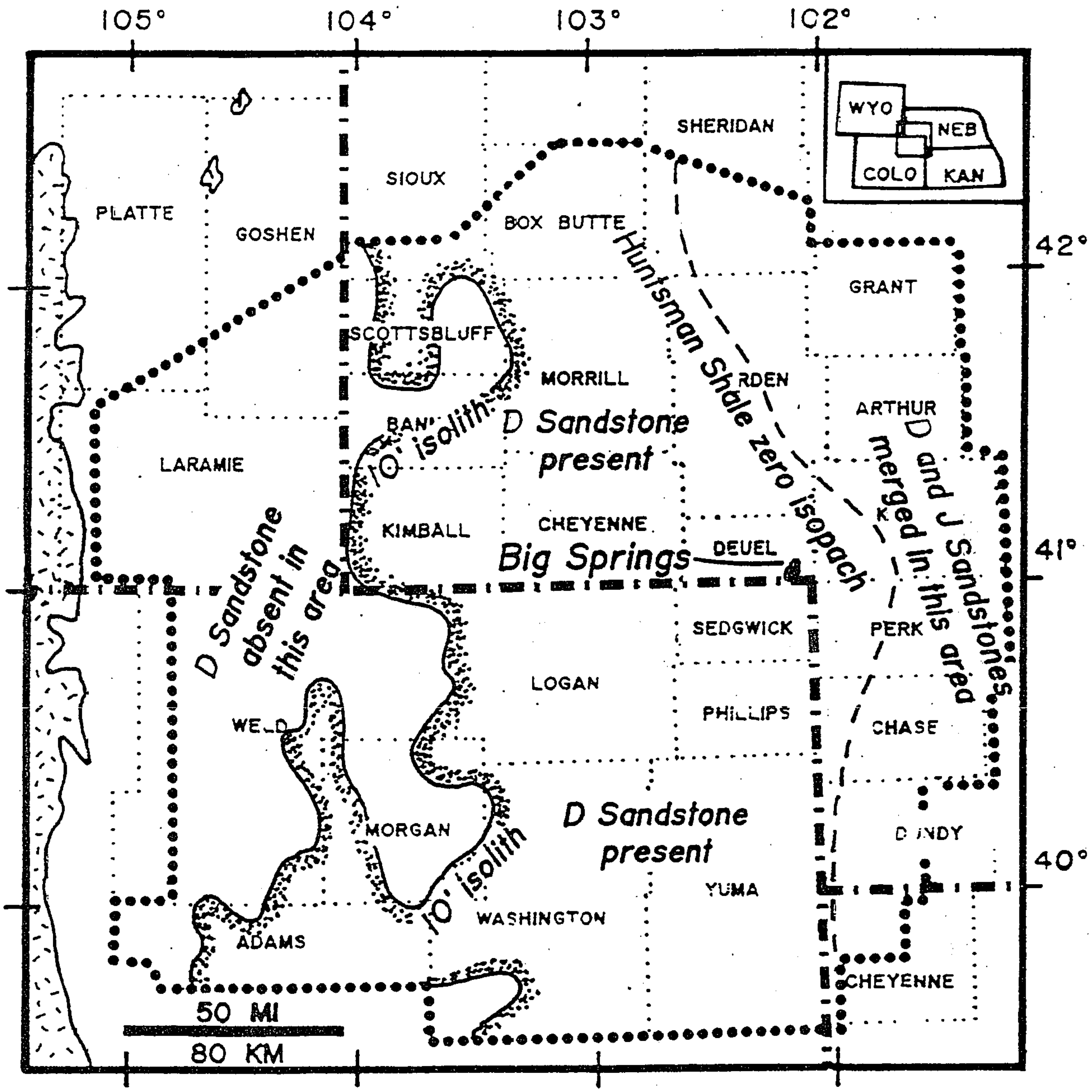


Figure 5-6. Regional distribution of D Sandstone in the Denver basin study area. Adapted primarily from Haun (1963), Tainter (1982), and Geological Mapping Services (1985).

surface of erosion) or prograding coastal plain/deltaic deposits. By contrast, more marine-influenced sand units, deposited within a transgressive systems tract, are generally confined to the upper part of the D interval.

BIG SPRINGS GAS RESERVOIR

In the Big Springs area the D Sandstone lies about 100 to 150 ft (30 to 45 m) above the J Sandstone (Figure 5-5). Here the D is actually a group of sandstone units separated by thin shales. The Big Springs gas reservoir lies at the top of the interval. The reservoir averages 35 ft (11 m) in thickness. Thick (greater than 50 ft or 15 m) sand is present within a northwest-southeast-trending area which cuts across the central part of the gas field, and in localized areas at the northeast and south margins of the field (Figure 5-7). Although thick sand is present in places within the field limits, there is no apparent spatial relationship between sand thickness and production. Rather, the overriding influence of structure controls the gas accumulation.

Two D Sandstone cores from Big Springs were examined at the USGS Core Research Center in the Denver Federal Center. The cores are from BSU 26 and BSU 25 wells, drilled in 1976 by Kansas-Nebraska Natural Gas Corporation (now K-N Energy), at the onset of gas storage operations. Two samples of the

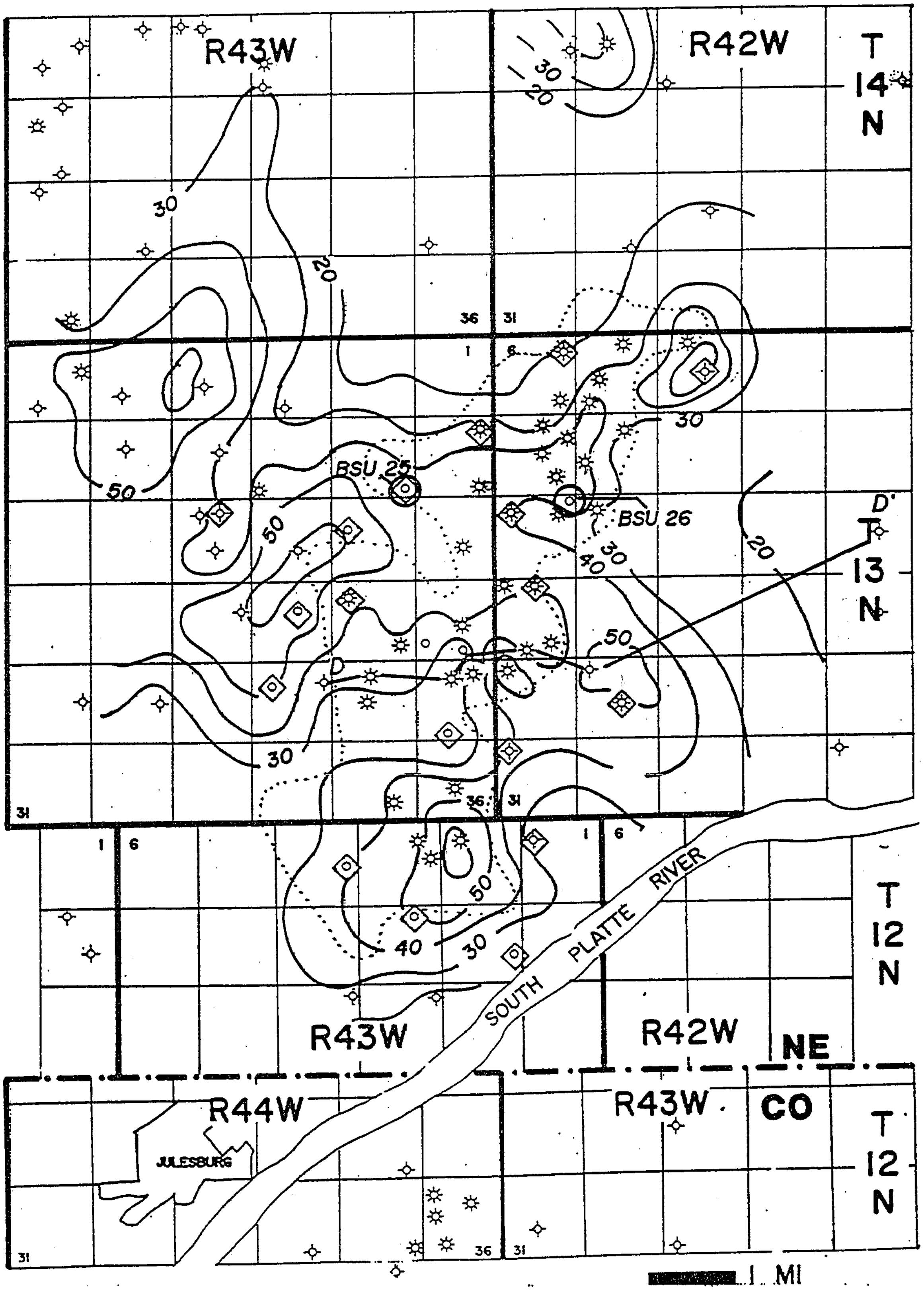


Figure 5-7. Isopach of upper D Sandstone gas reservoir in Big Springs field area. Contour interval 10 ft (3 m).

BSU 26 core and three samples of the BSU 25 core were furnished by the USGS for thin section study. Following thin section preparation and petrographic analysis, the five thin sections were donated to the USGS Core Research Center.

BSU 26 Core

BSU 26, located in Sec. 18, T13N, R42W, encountered about 45 ft (14 m) of upper D Sandstone, and about 28 ft (9 m) of net pay (gas-saturated) sand. All but the bottom 10 ft (3 m) of sand was cored. Porosity of the cored sand ranges from 21 to 26 percent and averages 23 percent (Figure 5-8). Permeability ranges from about 20 md to over 200 md. Permeability is highest near the top of the reservoir, corresponding to the "cleanest" gamma-ray response on the wireline log and core gamma-ray curves. Core analyses from other wells in the field have reported permeabilities in excess of 750 md.

The D gas reservoir in BSU 26 is predominantly a fine grained sandstone containing abundant shale laminae and carbonaceous fragments (Table 5-1). The sandstone is highly bioturbated (Figure 5-9), with numerous shale laminae distorted by abundant burrows which are predominantly small and horizontal. A thin reddish-brown shale zone (Figure 5-10) is interbedded with very fine-grained sand near the base of the cored interval.

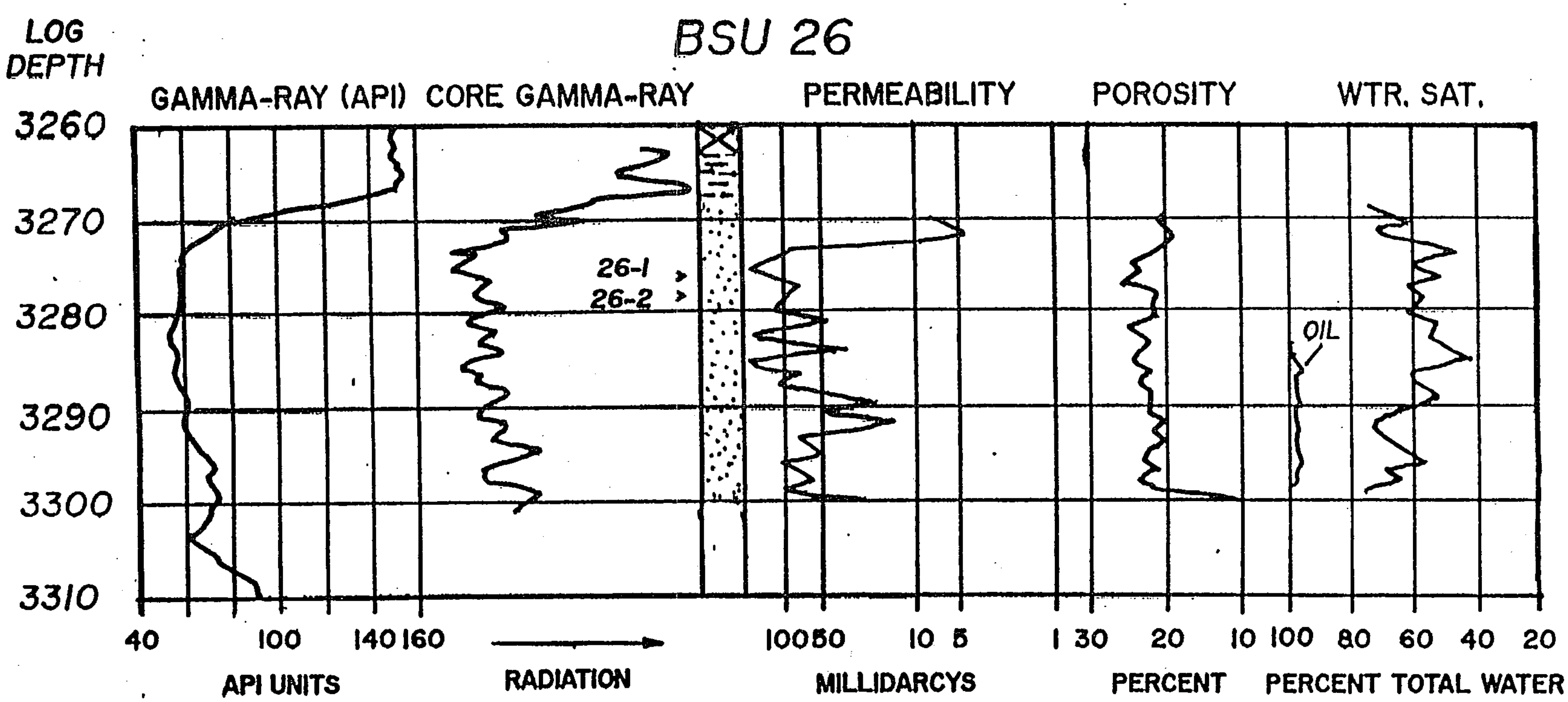


Figure 5-8. Depth plot of log and core gamma-ray response, permeability, porosity, and water saturation of D Sandstone interval cored in BSU 26 well. Locations of samples taken for thin sections (26-1, 26-2) are shown. Core depths have been adjusted upward 22 ft to log depth.

TABLE 5-1

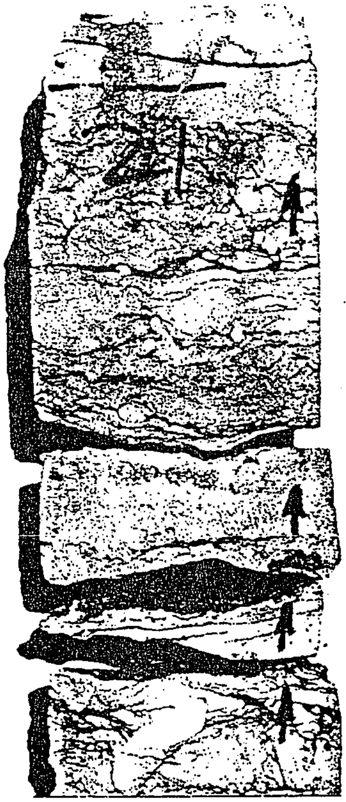
D SANDSTONE CORE DESCRIPTION*, BSU 26 WELL
NENE SEC 18, T13N, R42W, DEUEL COUNTY, NEBRASKA

Core depths adjusted 22′ to log depths - core depth interval of 3290-3322 adjusted to 3268-3300′ log depth.

<u>3268-3273′:</u>
Ss, vf-fgr, num Sh Lam distorted by abun Bur (pred sml and hor) and by compaction; abun carb Frag, rk Frag, cl Mtrx, Fspr

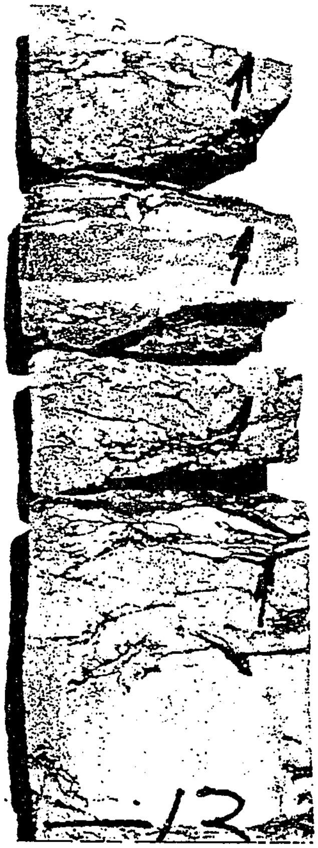
<u>3273-3300′:</u>
Ss, fgr, a/a, but w/o carb Frag, num sh Lam, distorted by abun Bur and compaction; Bd 1-2″ thk, cln fgr Ss, also bioturb but w/o sh scat randomly thru section; slt Mtrx (compared to cl Mtrx of shly ss) or no mtrx. Zone of fgr Ss, bioturb at <u>3286′,</u> w/ Calc Nod (Calc cmt Ss), Nod are 1/2″ or less in Dia; Calc also at <u>3271, 3273, 3268, and 3298′</u>. Sh?, rdsh-brn at <u>3290′</u> 1/2″ Bd intbd w/ 1/2″ Zn of vfgr calc Ss; Sh zone is 2″ thk; Btm 4″ (at 3300′) Sh w/ abun Calc Nod, nod Lyrs.

*Description by R.A. Smosna and K.R. Bruner at USGS Core Center, Denver Federal Center, Lakewood, CO, June 1994



BSU 26 NENE Sec. 18, T13N, R42 W
3299' log depth (3321' core depth)

Figure 5-9. Photograph of D Sandstone core from 3299 ft log depth in BSU 26 well, showing abundant shale laminae distorted by burrows.



BSU 26 NENE Sec. 18, T13N, R42W
3291' log depth (3313' core depth)

Figure 5-10. Photograph of D Sandstone core from 3290 ft log depth in BSU 26 well, showing shale zone (reddish-brown) interbedded with sandstone.

BSU 25 Core

BSU 25, located in Sec. 11, T13N, R43W, encountered about 45 ft (14 m) of upper D Sandstone, and about 20 ft (6 m) of gas-saturated sand. The entire upper sand was cored. Porosity of the sandstone ranges from 20 to 29 percent and averages 25 percent (Figure 5-11). Permeability ranges from about 50 md to over 1350 md. Permeability is highest in the uppermost and lowermost parts of the cored interval.

Part of the D interval cored in BSU 25 is similar to the interval cored in BSU 26, in that it is comprised of fine- to very fine-grained sandstone, with numerous shale laminae. As in BSU 26, the shale laminae are distorted by abundant burrows (Table 5-2 and Figure 5-12). In contrast to BSU 26, however, much of the interval cored in BSU 25 is clean, fine grained, bedded sandstone (Figure 5-13) with relatively few shale laminae ("BEDDED" intervals of Table 5-2). Depths of the bedded intervals, shown on Figure 5-11, generally correspond with "cleaner" gamma-ray readings, higher permeability and higher porosity.

Much of the bedded interval cored in BSU 25 corresponds with a lower, oil-stained interval (Figure 5-14), situated below the gas-water contact. Oil saturation within this interval approaches 20 percent of total pore volume; however oil has not been produced at Big Springs. In this part of

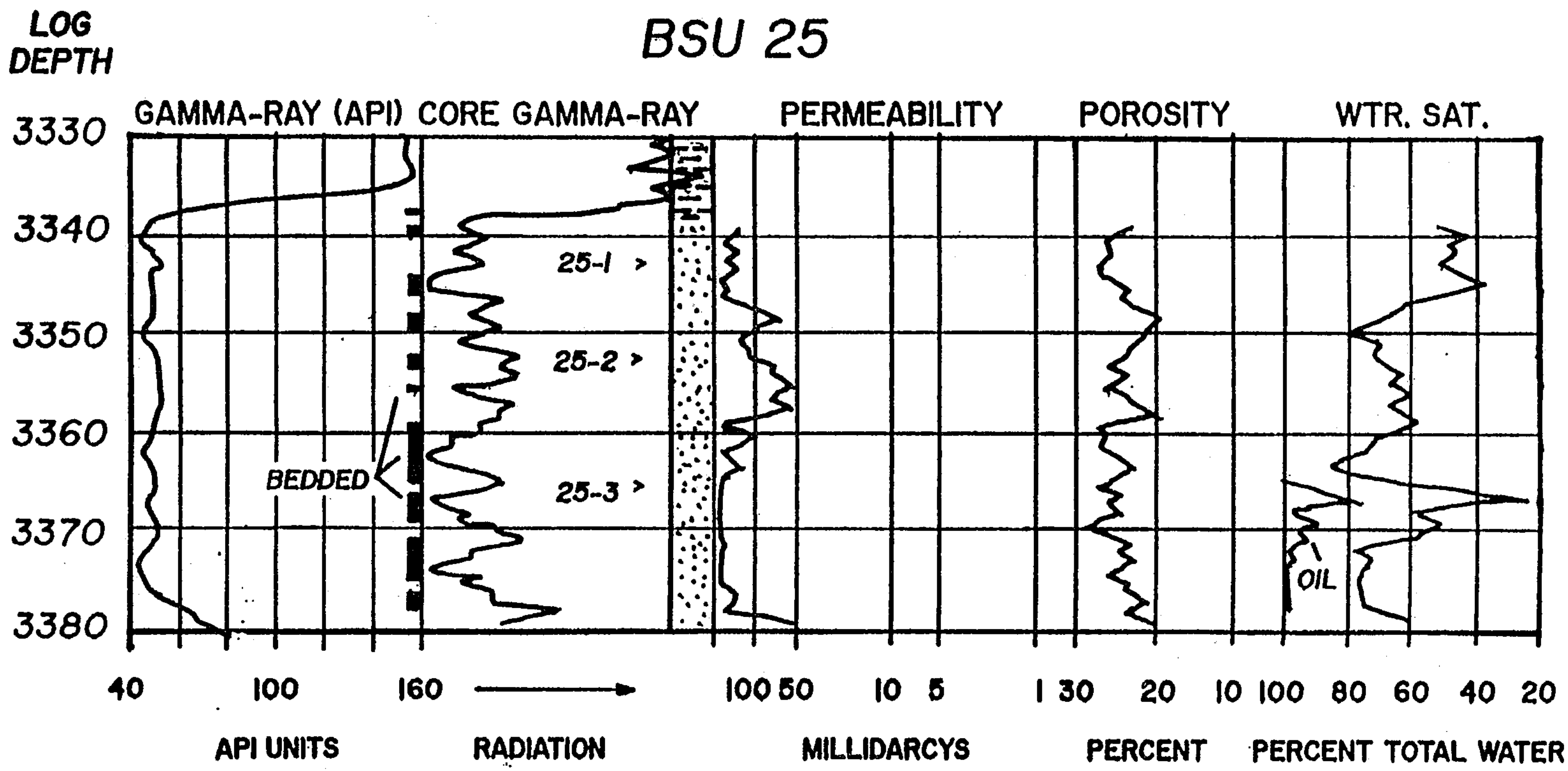


Figure 5-11. Depth plot of log and core gamma-ray response, permeability, porosity, and water saturation of D Sandstone interval cored in BSU 25 well. Locations of samples taken for thin sections (25-1, 25-2, 25-3) and bedded zones are shown. Core depths have been adjusted upward 14 ft to log depth.

TABLE 5-2

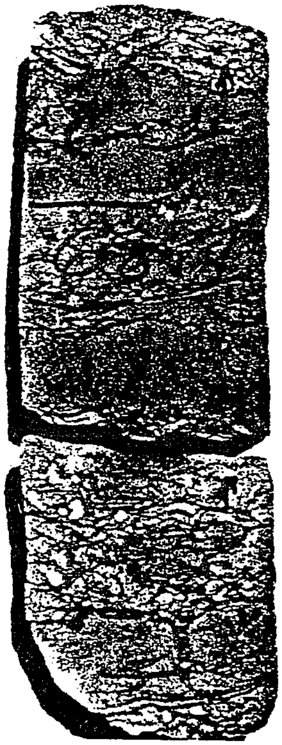
D SANDSTONE CORE DESCRIPTION*, BSU 25 WELL
SESE SEC. 11, T13N, R43W, DEUEL COUNTY, NEBRASKA

Core depths adjusted 14′ to log depths - core depth interval of 3351-3392′ adjusted to 3337-3378′ log depth.

<u>3337-3359′:</u>
(a) BEDDED: Ss, fgr, cln, horiz to hi-ang incl Lam, org Mat along bdg planes, abnd org Frags, sml Calc Nod and loc Calc Cmt, Sh Clasts; Cl resemble cl mtrx in Ss, Clast of brn Sh sim to brn Sh at 3290′ in BSU 26 well; loc f mtrx, incl trough Bdg, 1-4″ thk; v few Bur in bd Ss. Bdd Zones shown on BSU 25 coregraph.
(b) BIOTURBATED: Ss, shly, as in BSU 26 well, Sh Lam disturbed by bioturb and compaction, w/ 1-2″ cln Ss (though still burrowed); Bur mostly horiz, some vertical.

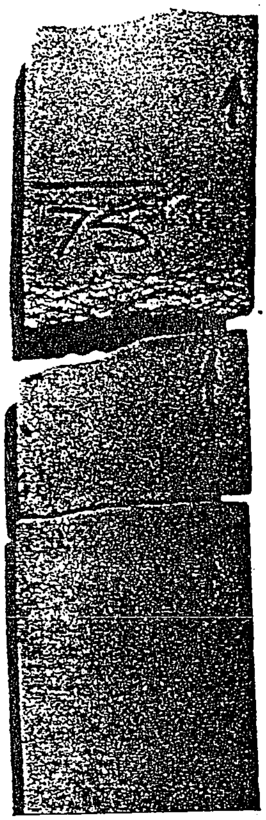
<u>3359-3378′:</u>
(a) BEDDED: Ss, fgr, cln, sli calc, horiz to include trough bdd; Bdg highlighted by org Mtr on partings and Sh Clasts; Bed sets up to 12′ thk; Ss, fgr mostly, medgr in troughs of incl Bdg; No mtrx in bdd Ss, little mtrx around Bur. Fining upward seq (m - fgr) 7″ thk at 3375′; f-mgr at 3375-3378′; Ripples at 3378′; brn Sh Clast at 3378 (sim to BSU well at 3290′. Bdd Zones shown on BSU 25 coregraph.
(b) BIOTURBATED: Ss, vf-fgr, shly, sh Lam disturbed by abun Bur and compaction; Beds 1′ thk.

*Description by R.A. Smosna and K.R. Bruner at USGS Core Center, Denver Federal Center, Lakewood, CO, June 1994



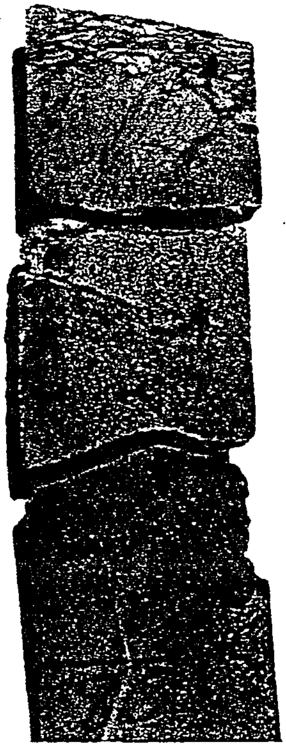
BSU 25 SESE Sec. 11, T13N, R43W
3354' log depth (3368' core depth)

Figure 5-12. Photograph of D Sandstone core from 3354 ft log depth in BSU 25 well, showing abundant shale laminae distorted by burrows.



BSU 25 SESE Sec. 11, T13N, R43W
3361' log depth (3375' core depth)

Figure 5-13. Photograph of D Sandstone core from 3361 ft log depth in BSU 25 well, showing zone of clean, bedded sandstone separated by thin burrowed zone.



BSU 25 SESE Sec. 11, T13N, R43W
3366' log depth (3380' core depth)

Figure 5-14. **Photograph** of D Sandstone **core from** 3366 **ft log depth in** BSU 25 **well,** showing oil **staining.**

the Denver basin, the D Sandstone has yielded oil only in the McCord - Richards field area, located about 20 miles (32 km) to the north.

Petrographic Analysis

Petrographic analysis reveals that the D Sandstone in both cores is comprised predominantly of fine- to very fine-grained sand (Figure 5-15A), with the majority of grains ranging from 0.07 to 0.2 mm in diameter. Sand grains exhibit good to very good sorting. Most grains are subangular; however in most cases the original shape of the grains has been altered by quartz-cement overgrowths.

The predominant mineral present is quartz, followed by dispersed or laminated shale fragments and clay. An estimate of the percent abundance of mineral grains is as follows:

Mineral	Abundance (%)
Quartz	85
Clay and shale	8
Polycrystalline quartz (including chert)	2
Pyrite	2
Feldspar	2
Other (mica, collophane rock fragments)	1

Based on the above mineral percentages, the D Sandstone at Big Springs can be classified as a sublitharenite, using McBride's (1963) classification.

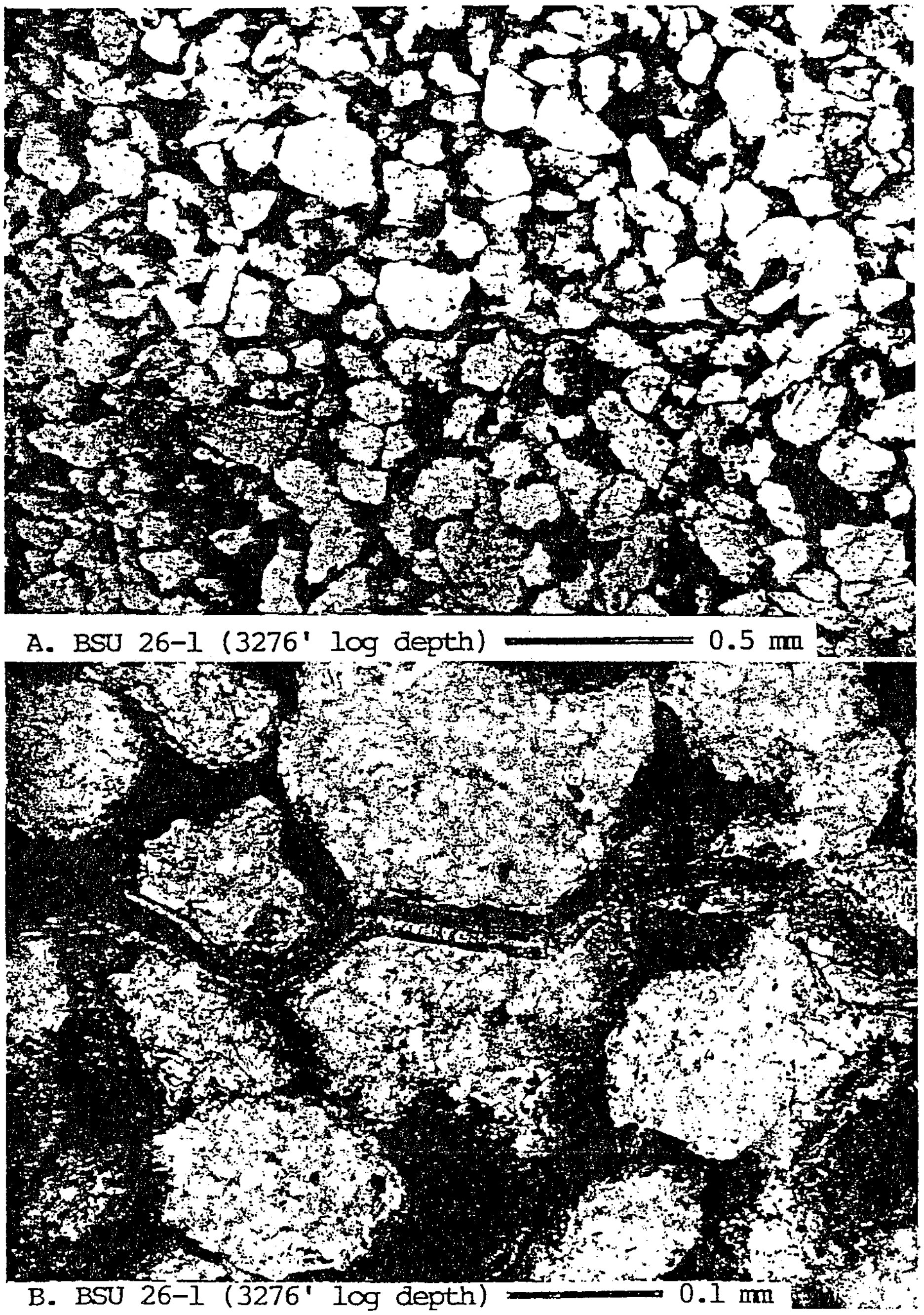


Figure 5-15. (A): Thin section 26-1 photomicrograph of D Sandstone core from 3276 ft log depth in BSU 26 well. (B): higher magnification view of (A) showing collophane (fish bone?) fragment deformed by surrounding grains due to compaction.

Abundant quartz cement overgrowths indicate that primary porosity was substantially reduced during lithification. However, the presence of oversized pores (Figure 5-16), "floating" grains, and partial dissolution of grains (Figure 5-17) indicates that substantial leaching has occurred, resulting in the enhancement of secondary porosity. Pore diameters range from less than 0.05 mm to as large as 0.2 mm where a grain has been completely removed by leaching (Figure 5-16). Permeability is reduced by the presence of shale and pyrite laminae (Figure 5-18).

Depositional Environment

Reservoir geometry and orientation of the upper D Sandstone (Figure 5-7) suggest marine influence during the deposition of sand. Thick sand covers a broad area at Big Springs, in contrast to most D channel sandstones in the basin which are commonly less than 1 mi (2 km) wide. Moreover, the stratigraphic position of the Big Springs reservoir at the top of the D interval suggests reworking of sand during the Graneros transgression. Wave, current, and tidal energy likely redistributed sand in this area.

Buildup of thick upper D sand in the Big Springs area is reflected in an isopach of the overlying Graneros Shale (Figure 5-19). The Graneros, which is more than 90 ft (27 m) thick to the east and west of the field, thins to about

Figure 5-16. Thin section 25-1 photomicrograph of D sandstone core from 3343 ft log depth in BSU 25 well, showing cemented grain contacts and oversized pore, formed by leaching of chemically unstable grain. Pore is rimmed by clay and possibly siderite.

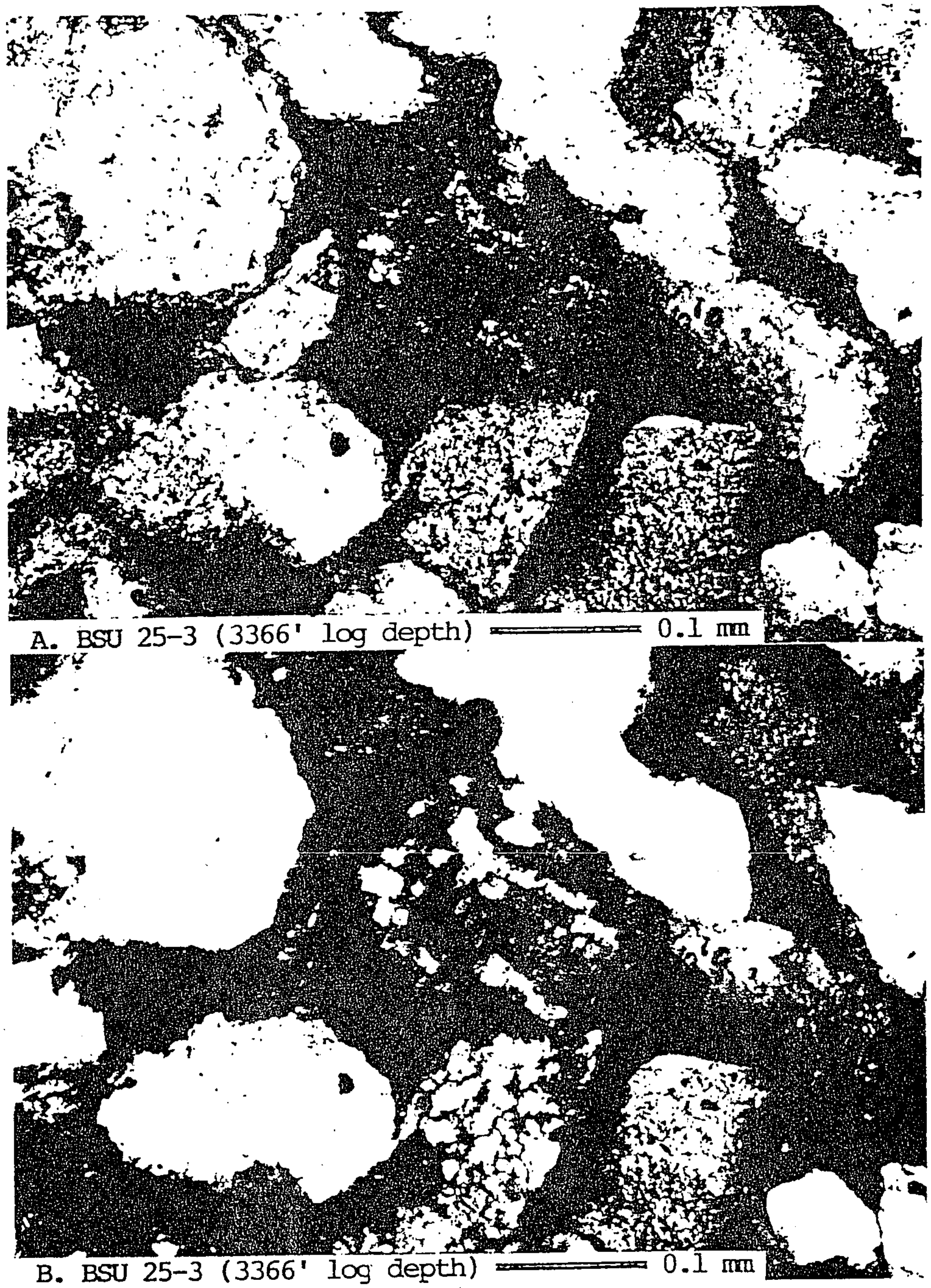


Figure 5-17. (A): Thin section 25-3 photomicrograph of D Sandstone core from 3366 ft log depth in BSU 25 well, showing partially leached grain, resulting in both intergranular and intragranular porosity. Oil staining is evident on grain surfaces. (B): Same as (A), but with crossed polarizers, showing polycrystalline quartz grain below leached grain.

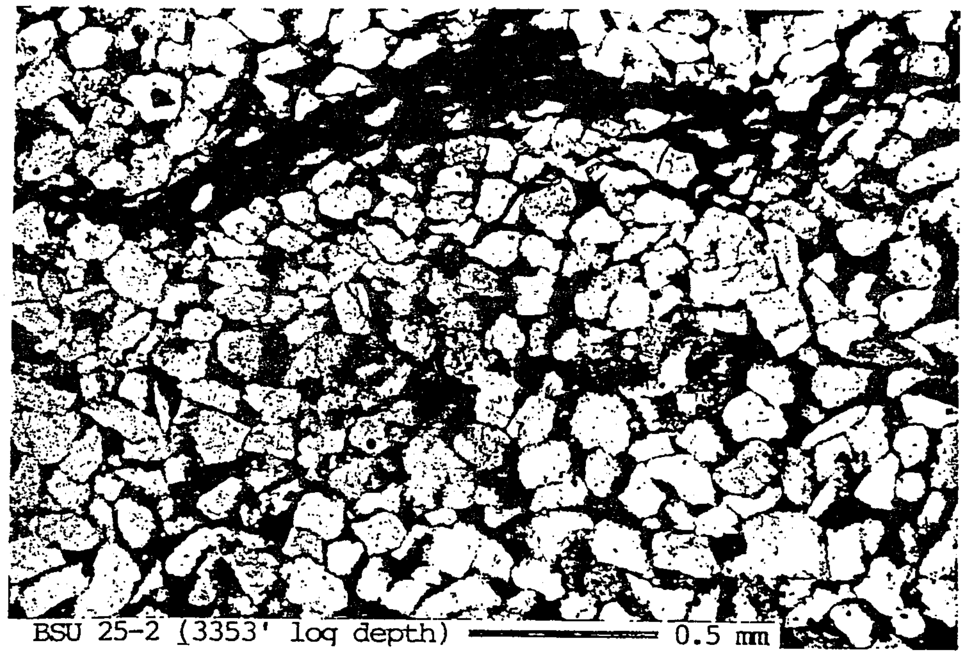


Figure 5-18. Thin section 25-2 photomicrograph of D Sandstone core from 3353 ft log depth in BSU 25 well, showing interstitial shale and pyrite laminae, which act to reduce permeability.

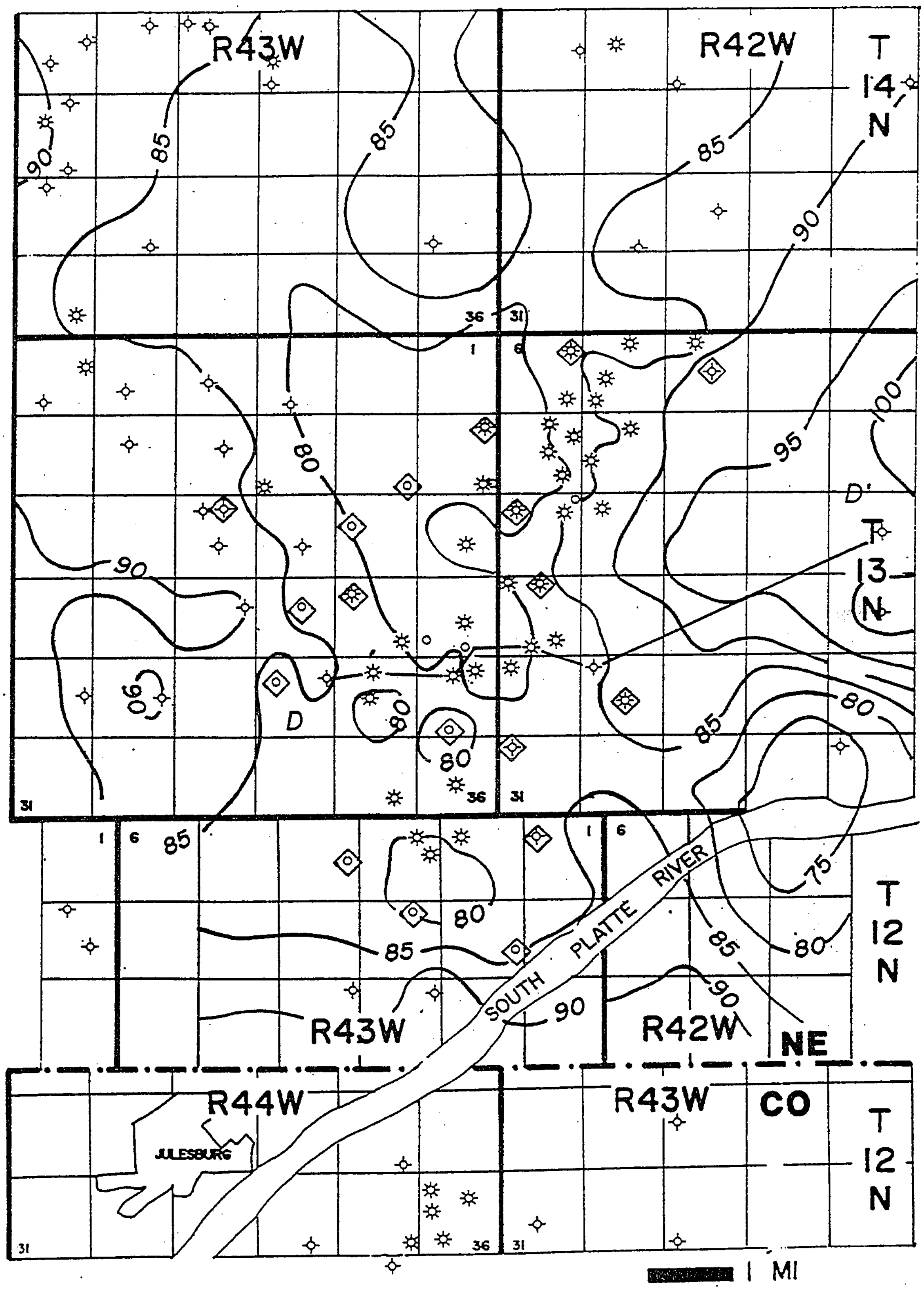


Figure 5-19. Graneros shale isopach. Contour interval 5 ft (1.5 m).

75 ft (23 m) along a northwest trend which generally coincides with areas of thick upper D sand (Figure 5-7). Thinning of Graneros above thick upper D sand is likely related to the compaction contrast between D sand and laterally equivalent fine-grained sediments of the Graneros.

Sandstone cored in BSU 25 is cleaner than that cored in BSU 26, which overall has more shale laminations and is more highly bioturbated. The BSU 25 sandstone is also more permeable than the BSU 26 sandstone. This suggests that sand deposited in the vicinity of BSU 25 was subjected to higher-energy conditions which removed more mud and were less favorable to burrowing organisms, perhaps associated with a marine-bar or tidal-channel environment. In contrast, the sand in BSU 26, located slightly to the east (paleo-landward) of BSU 25, likely accumulated in a lower-energy setting, protected from wave, current, or tidal energy by the buildup of sand along a northwest-trending bar.

ORIGIN OF BIG SPRINGS STRUCTURE

Shallow Structure

Preliminary work (Chapter 2), followed by subsurface study of the distribution of Permian salts on subregional (Chapter 4) and regional scales (Chapter 8) reveals that salt is present under Big Springs field, but is absent in deep wells to the east. A similar relationship occurs to the north at the McCord-Richards field area of Garden County, and to the southwest at the Red Lion field area in Sedgwick County, Colorado. Each of these fields is associated with a structural flexure which is present at the level of the D Sandstone. Production at each field is associated with an anticline which is situated to the west (regionally downdip) of a regional syncline. Structural mapping based on Cretaceous well control indicates that this syncline extends more or less continuously from an area north of McCord-Richards field to south of Red Lion field.

Relative to the Big Springs and surrounding areas, the the western two-thirds of the Nebraska panhandle subregional study area (Chapter 4) has been more densely drilled, to both the Cretaceous and Paleozoic levels. Paleozoic well control in Cheyenne County, including several deep tests drilled within the Sidney trough, is sufficiently dense to indicate that Permian salt is absent below the trough.

In contrast, subsurface study of the eastern third of the area, which includes Big Springs, suffers from a lack of deep well control. No deep tests have been drilled within the regional syncline in this part of Nebraska. As a result, a salt-solution origin for the north-south-trending syncline at Big Springs and adjoining areas cannot be confirmed on the basis of well control alone.

In the Big Springs area, the Upper Cretaceous Niobrara Formation lies about 800 ft (240 m) above the D Sandstone (Figure 5-20). Structure at the Niobrara level (Figure 5-21) is generally concordant with structure at the level of the D Sandstone (Figure 5-4). A northeast-trending Niobrara structural high extends across Big Springs field. Structural depressions occur to the north and east of the field at the Niobrara level. (Recently, several gas wells have been completed in the Niobrara at Big Springs. This new play is discussed in Chapter 9.)

The Niobrara is overlain by nearly 2000 ft (600 m) of Upper Cretaceous Pierre Shale (Figure 5-20). The top of the Pierre in this area is truncated and capped by Oligocene and younger strata of alluvial and pyroclastic origin. Generally, the Cenozoic interval at Big Springs is not logged, because it lies behind surface casing. As a result, a correlation point (P-1 marker of this study) near the top of the Pierre is the uppermost subsurface datum available for structural mapping that can be derived from oil and gas well logs.

As with the Niobrara, structure at the P-1 level (Figure 5-22) reveals a north-south-trending depression just east of the gas field. Structural relief is as much as 200 ft (60 m) in places. Structural flexure at the Cenozoic level in this area was also observed by DeGraw (1969, 1971) and by Swinehart et al.(1985).

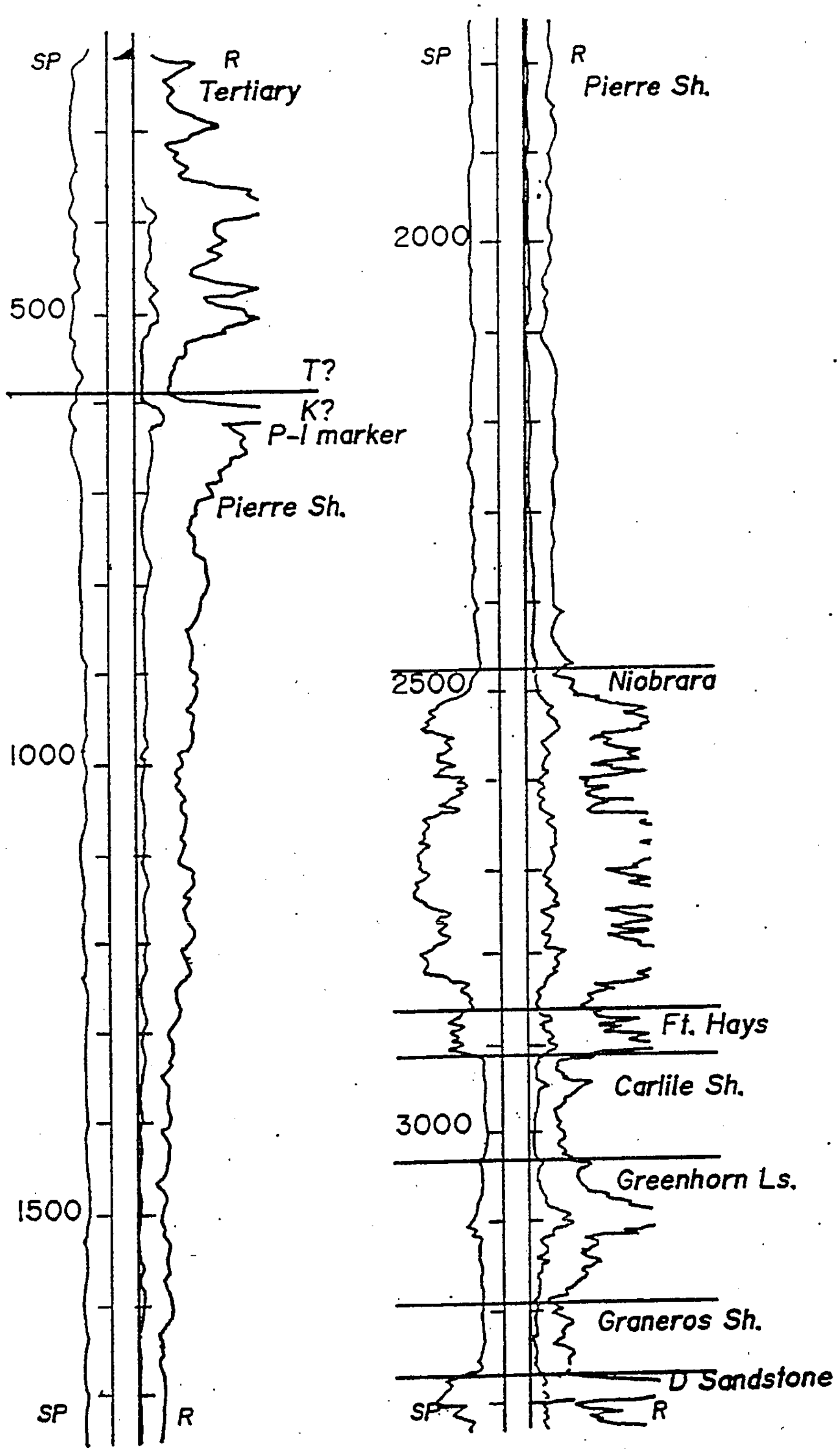


Figure 5-20. Type log at Big Springs field. Well depths are in feet. Well log is from discovery well, Ideal Drilling 2 Bosley, SESW Sec. 19, T13N, R42W.

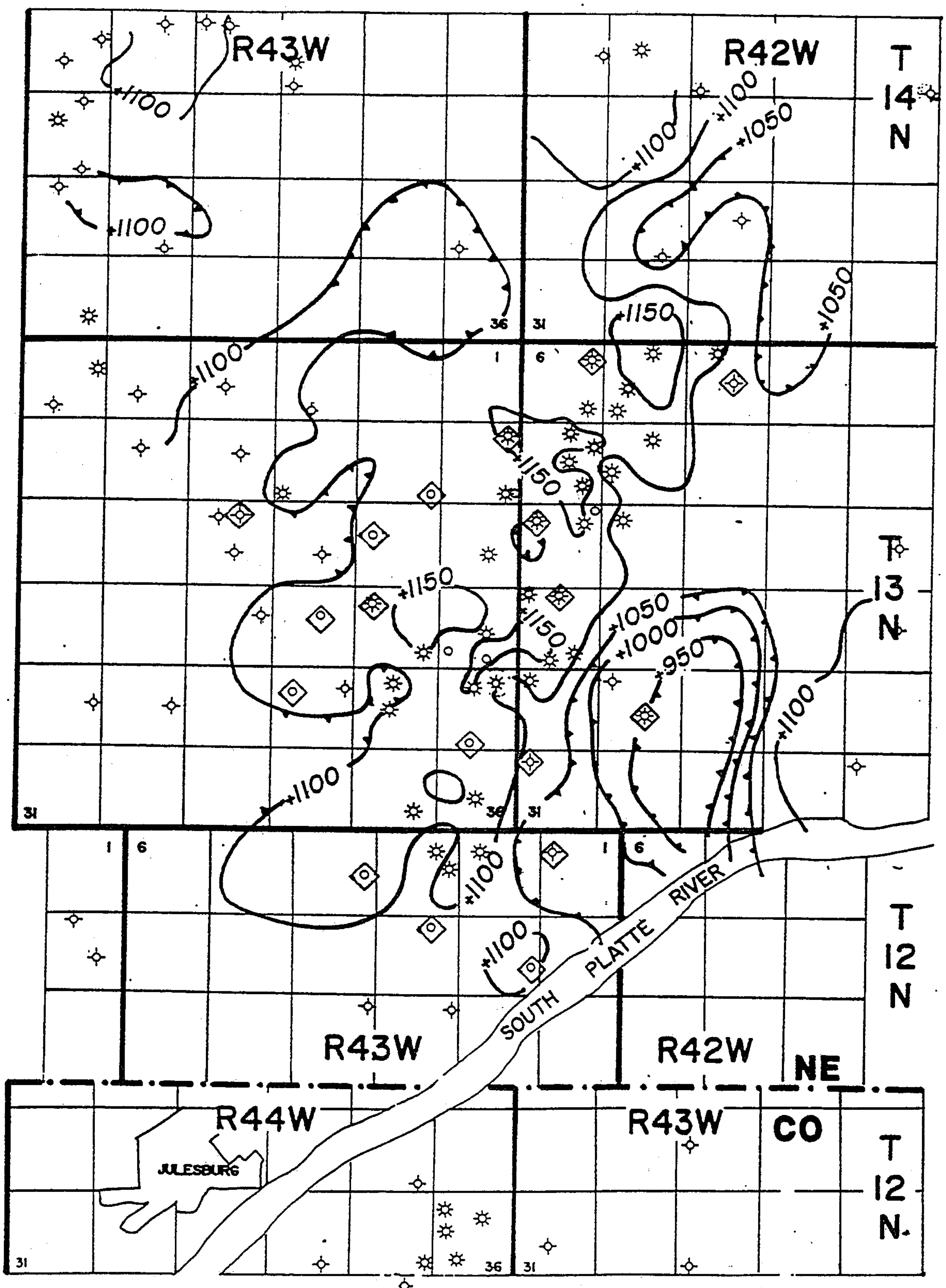


Figure 5-21. Structure drawn on top of Niobrara Formation. Contour interval 50 ft (15 m).

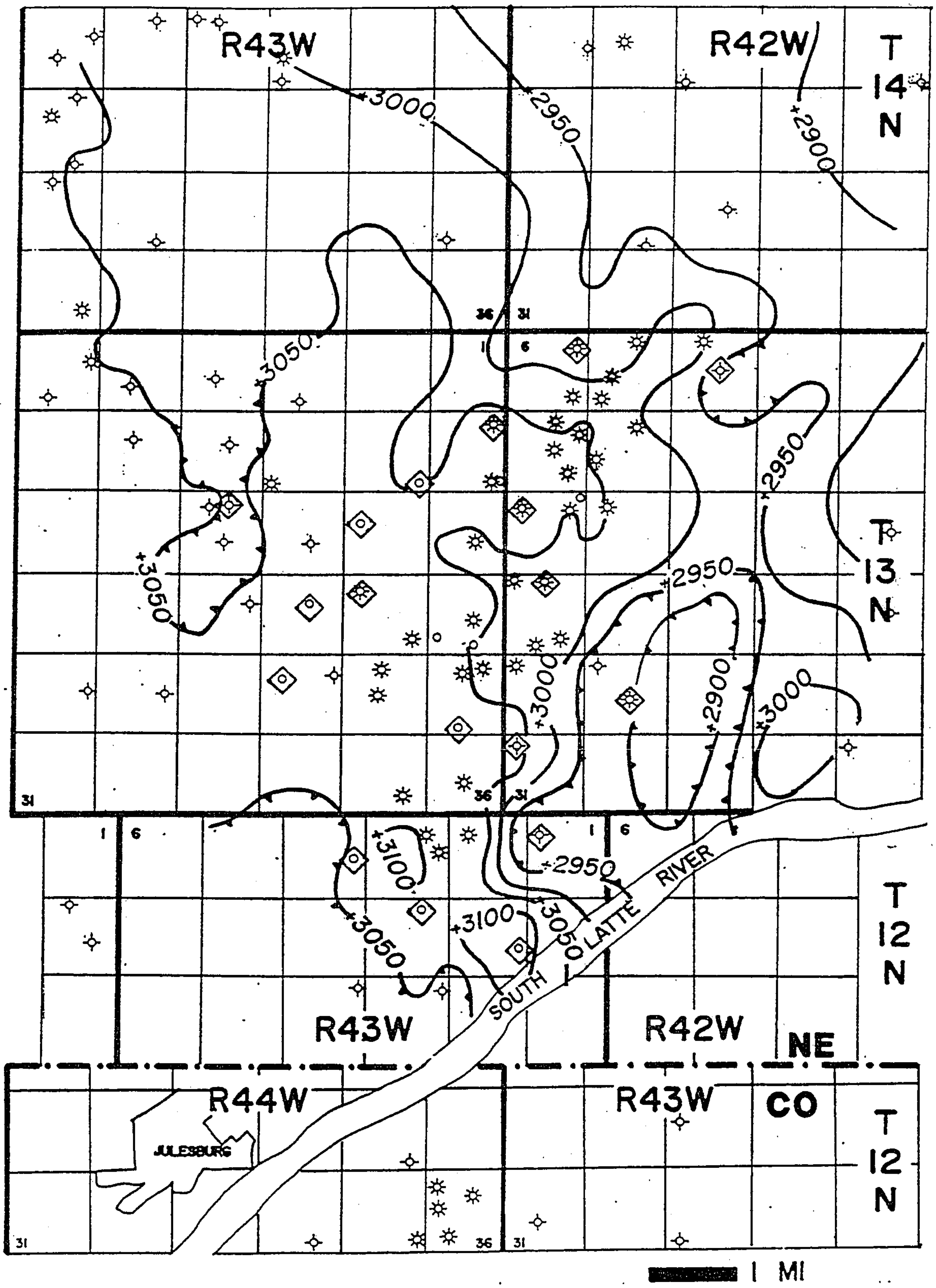


Figure 5-22. Structure drawn on top of P-1 marker in Pierre Shale (approximate top of Cretaceous). Contour interval 50 ft (15 m).

Structural concordance between the D Sandstone and shallower units indicates that deformation at Big Springs was post-Cretaceous. Detailed surface mapping of Cenozoic units in the Big Springs area, which is beyond the scope of this study, may be useful in more accurately determining the timing of deformation.

Permian Salts

Deep well control is insufficient for a detailed study of Permian salts below Big Springs gas field. Only one deep test, located in NWNE Sec. 25, T13N, R43W, lies within the field. The Stoddard 1 Zimmerman (well 1235 on Figure 4-14) was drilled to Precambrian basement in 1965 following development of the field. The well encountered 445 ft (135 m) of Leonardian strata and over 100 ft (30 m) of salt, including about 72 ft (22 m) of Salt 10, 24 ft (7 m) of Salts 11/12, and 6 ft (2 m) of Salt 13.

Well logs from deep tests drilled north and south of Big Springs also reveal the presence of salt. Well 1235, located in NESE Sec. 18, T14N, R42W, encountered about 465 ft (140 m) of Leonardian strata, including 110 ft (34 m) of salt. At Chappel field in Colorado, well 1736 (Sec. 2, T11N, R44W) drilled 540 ft (165 m) of Leonardian section, including 90 ft (27 m) of salt.

Further to the west in Deuel County, five deep wells (1233, 1234, 1237, 1238, and 1239) encountered over 500 ft (150 m) of Leonardian strata (Figures 4-13 and 4-14). In addition to salts 10, 11/12, and 13, salts 7 and 9 are present in these wells. The Leonardian is thickest (552 ft or 170 m) in well 1239, located in Sec. 14, T14N, R44W (Figure 4-14). Well control is insufficient to determine the eastern limits of salts 7 and 9, situated somewhere between well 1239 and well 1235 at Big Springs.

To the northeast of Big Springs, the Leonardian is less than 300 ft (140 m) thick. Well 1642 (Figure 4-14) located in Sec. 22, T15N, R41W, drilled 293 ft (130 m) of Leonardian and encountered no salt. A cross section (Figure 5-23) which includes well 1642 and well 1235 (Big Springs deep test) reveals thinning in the Leonardian to the east associated with the absence of salt. Although deep well control is inadequate to determine the limit of salt east of Big Springs, it is reasonable to speculate that the Big Springs anticline represents a flexure associated with a thick salt edge.

Seismic Survey

A reflection seismic survey report (National Geophysical Company (NGC), 1953) was acquired and reviewed, to seek support for the hypothesis that salt dissolution and resultant collapse of overlying rock units played a role in

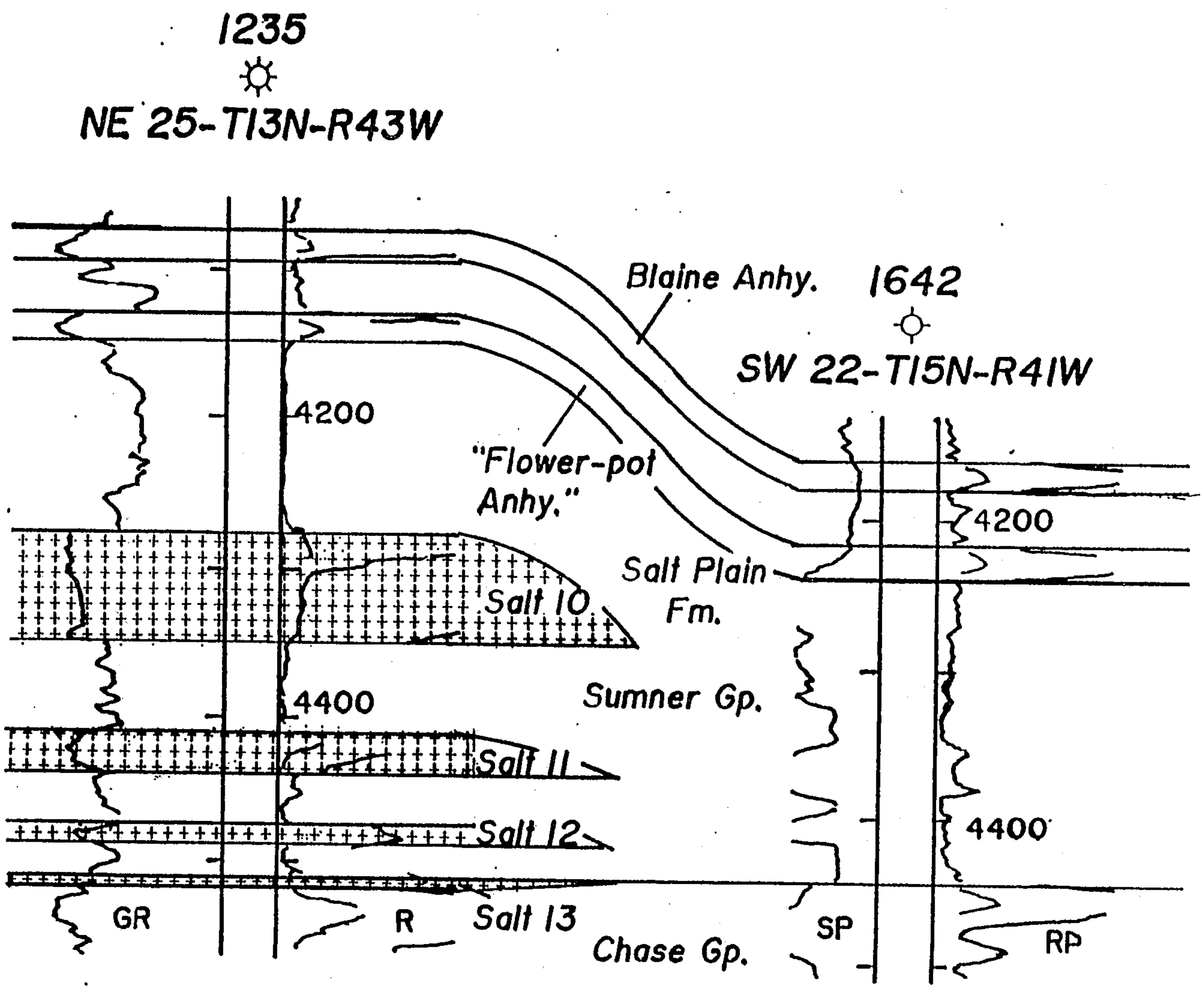


Figure 5-23. Stratigraphic cross section through Permian salt interval at Big Springs field. Datum is top of Wolfcampian Chase Group. No horizontal scale.

forming the Big Springs structure. The report was furnished by KN Energy, Lakewood, Colorado, operator of the gas-storage field.

Reflection seismic data were recorded from isolated correlation spreads, wherein a shot hole was drilled, a recording spread was laid out, and seismic data were recorded with 24-channel instruments. This recording technique is also referred to as single-point or jump correlation (McGuire and Miller, 1989), as opposed to continous profiling. Seismic records were obtained from over 240 shot points during the survey (Figure 5-24).

The seismic survey was shot in 1952 and 1953 during the development of the field in order to more accurately define the producing structure at Big Springs, thereby minimizing risk in drilling offset wells. Locations of wells which had been drilled prior to the seismic survey are shown on Figure 5-24. A likely secondary objective of the survey was to evaluate the Paleozoic potential associated with deep structure in the area.

The final NGC report presents only a summary of the survey results. With the exception of two seismic records (shot points 51 and 78), which were included to show typical records, the original records are not included in the NGC report. The report as-received includs seismic-based subsurface interpretations for Lakota (Lower Cretaceous) structure and "Basal Permian" structure. A Greenhorn (Upper

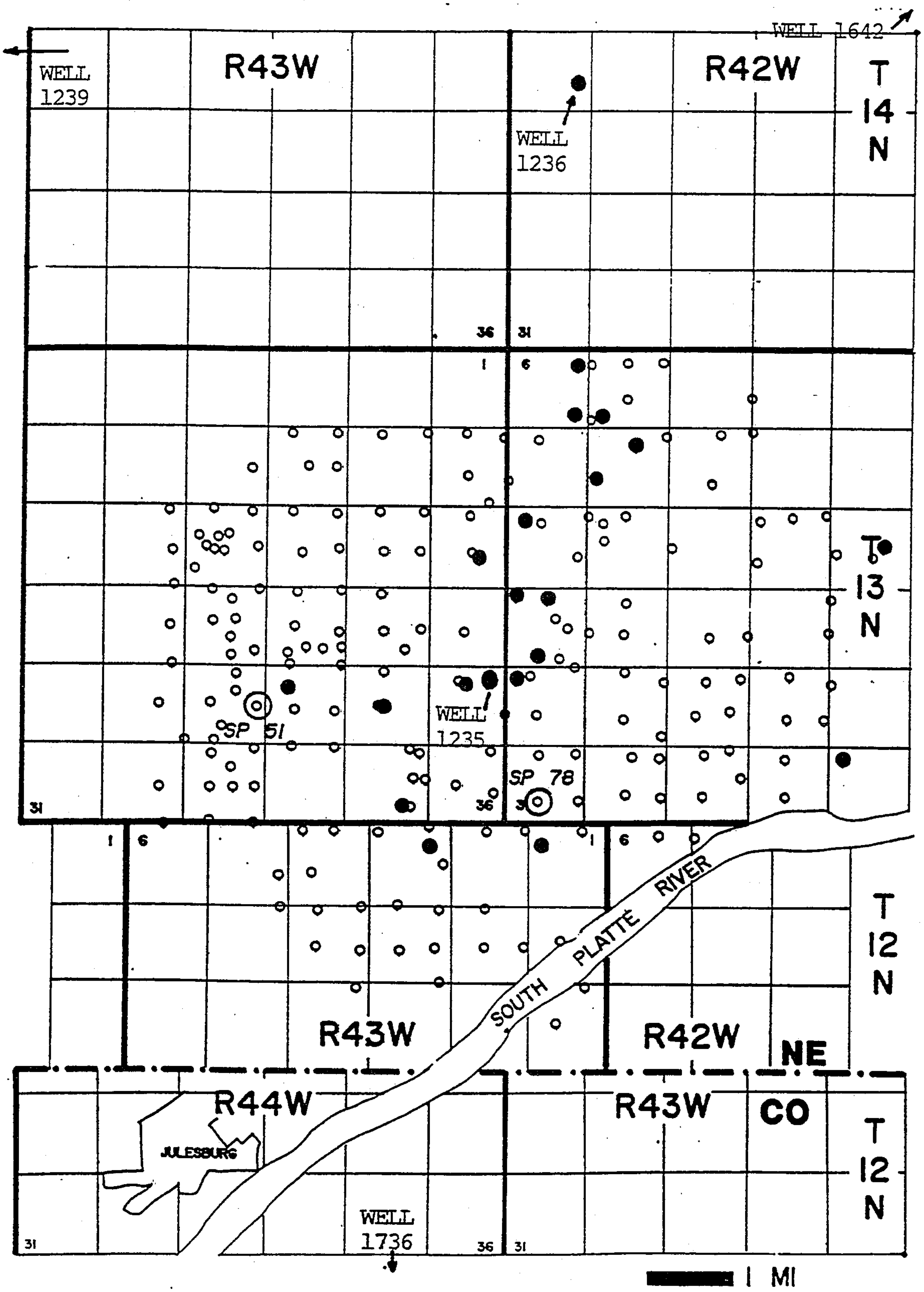


Figure 5-24. Shot point map for NGC Big Springs seismic survey. Wells drilled prior to seismic survey shown as solid circles. Deep wells (drilled later) are numbered.

Cretaceous) structural map and a Greenhorn - Basal Permian isochron, originally included in the report, were missing from the copy in KN Energy's files.

Structural elevations for the Lakota and Basal Permian are depth values which were derived from correlation picks by NGC interpreters from the original seismic records, and were converted from two-way time to depth using a linear velocity function. These structural data at each shot point were used in the present study to generate independent interpretations of Lakota structure, Basal Permian structure, and a Lakota - Basal Permian isopach.

A part of a sonic log from well 1235 (Figure 5-25) shows formation tops for the interval between the D Sandstone and the Wolfcampian Chase Group. A synthetic seismogram (Figure 5-26) generated from sonic-log data is compared to the seismic record at shot point 51, located about 2.5 mi (4 km) east of well 1235. Original (NGC) picks for reflectors believed to be associated with the Niobrara, Greenhorn, Dakota (D Sandstone), Lakota, and "Basal Permian" are shown on the shot point 51 seismic record. The shot point record and the reverse polarity synthetic seismogram correlate at the Niobrara, D Sandstone, and Lakota levels. The Basal Permian reflector on the seismic record appears to be associated with an acoustic contrast deeper than the Wolfcampian pick from the synthetic seismogram.

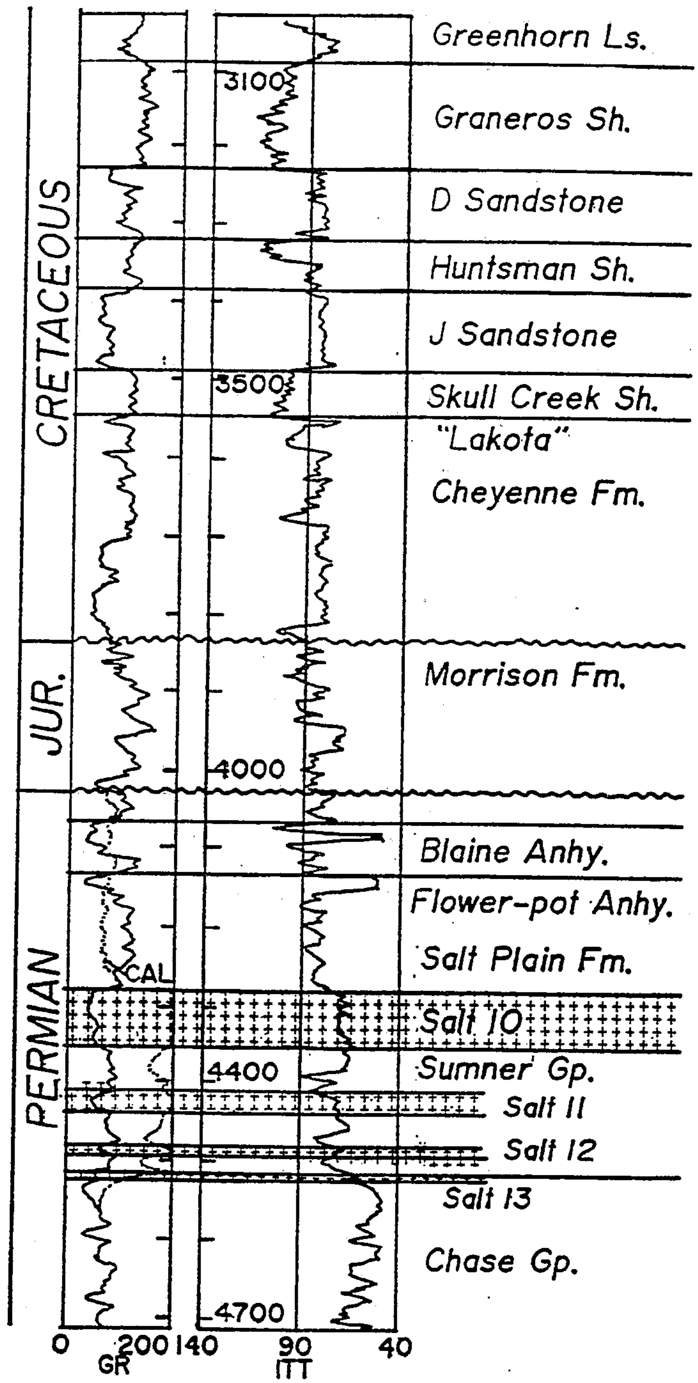


Figure 5-25. Sonic log across interval from D Sandstone to Wolfcampian Chase Group. Log is from well 1235, NWNE Sec. 25, T13N, R43W. Well depths are in feet.

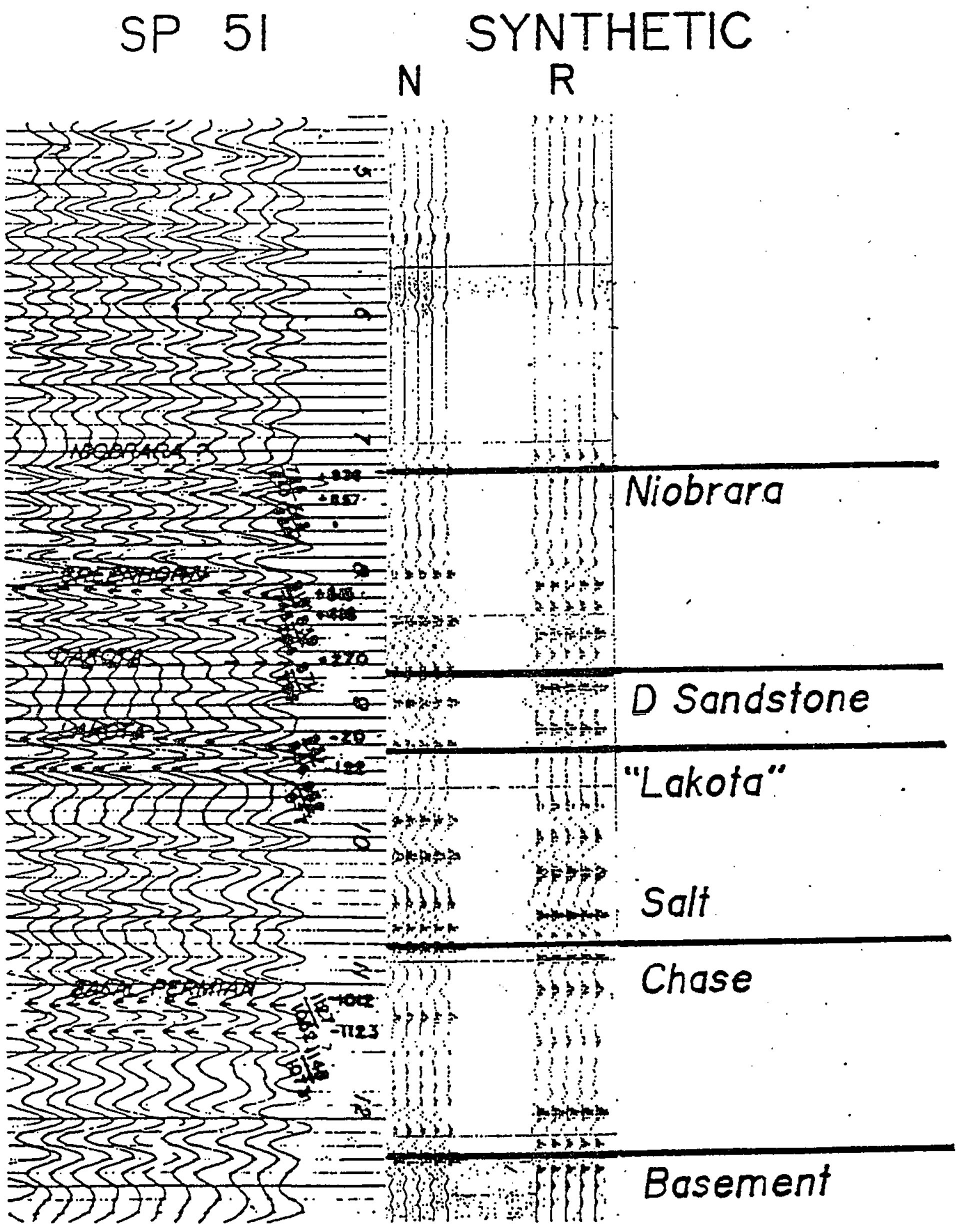


Figure 5-26. Comparison of well 1235 synthetic seismogram to seismic record at shot point 51.

Seismic structure at the level of the Lakota reflector (Figure 5-27), generated by the author using original NGC seismic record picks, reveals the Big Springs anticline and the pronounced structural depression immediately to the east. Based on this interpretation, over 200 ft (60 m) of structural relief exists at the Lakota level.

Assuming the Big Springs structure is related to flexure over a Permian salt edge, the amount of salt-related seismic isochron thinning within the Permian can be predicted. Figure 5-28 shows the calculated amount of thinning within the Leonardian, based on three assumptions: (1) that a total of 100 ft (30 m) of lower Leonardian and Wolfcampian salt (salts 10, 11/12 and 13 encountered in well 1235) is present along the eastern margin of the field; (2) that salt is absent immediately east of the field; and, possibly, (3) that the eastern limit of salts 7 and 9 (present in well 1239) may extend as far east as the western part of the seismic survey area.

Calculated two-way travel time through 100 ft (30 m) of salt, with an average velocity (for pure halite) of 14,925 ft/sec, is 13 msec. Calculated two-way travel time through 220 ft (67 m) of salt (the combined thickness of salt drilled in well 1239, which encountered salts 7, 9, and a thicker salt 10) is 29 msec. Thus, assuming that salt thickness is the primary control on the thickness of the interval between the Lakota and subsalt Permian strata (as

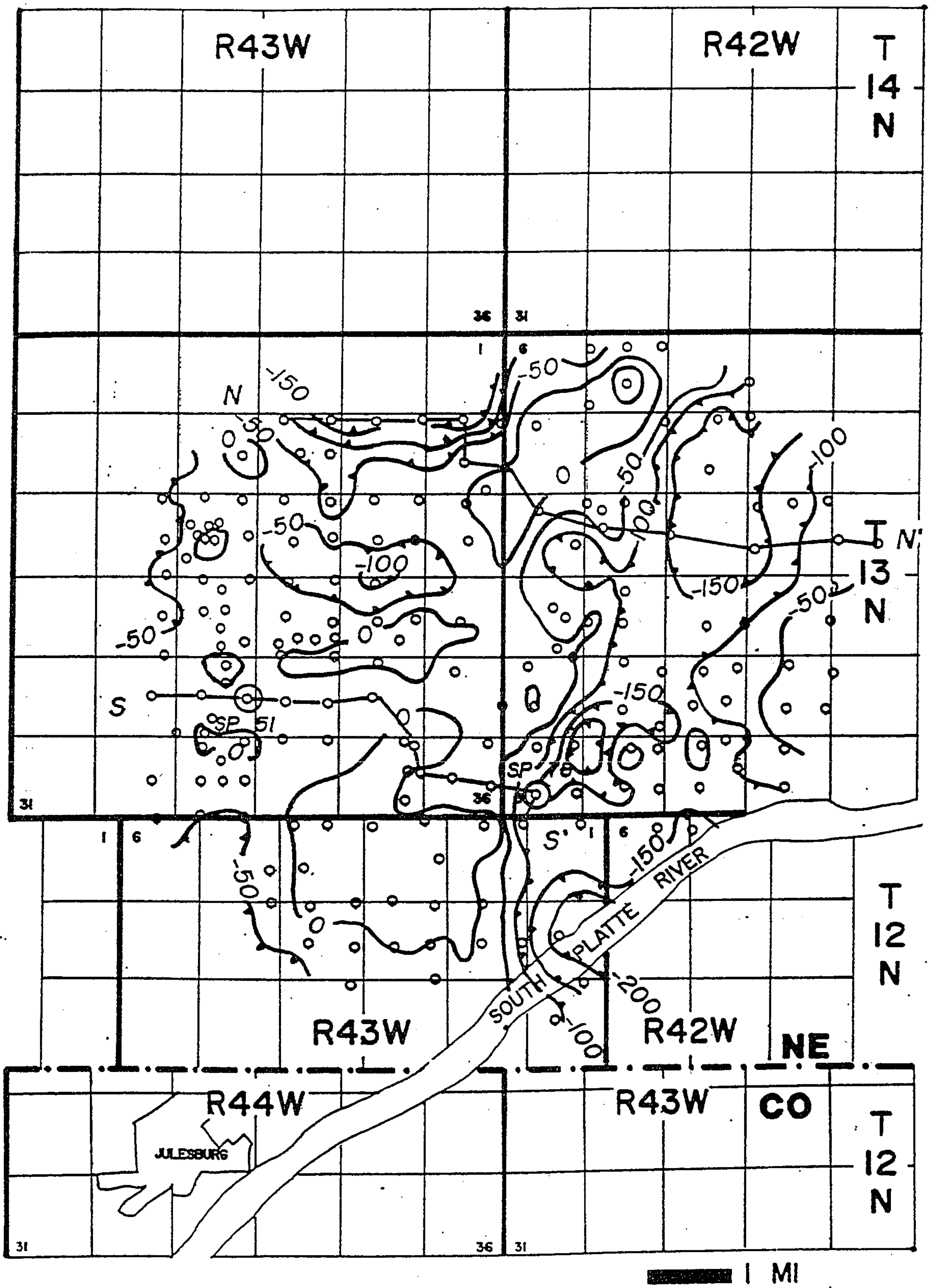


Figure 5-27. Seismic structure drawn on Lakota reflector, using NGC correlation picks. Contour interval 50 ft (15 m).

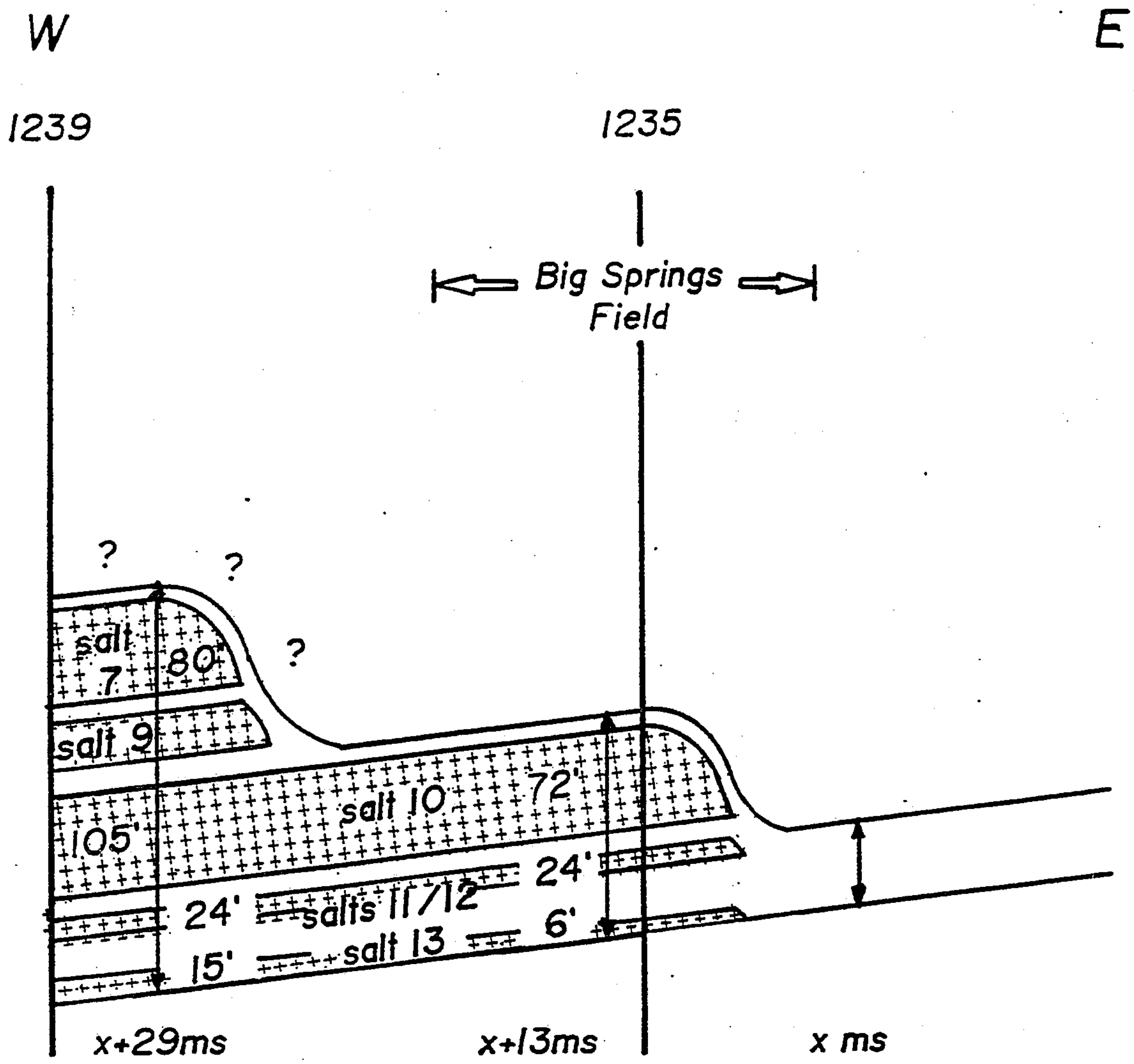


Figure 5-28. Diagrammatic cross section showing calculated relative two-way travel times through Permian salt interval at Big Springs field.

well as the D Sandstone - subsalt interval), removal of all of the salt could result in as much as 29 msec of isochron thinning from the western part of the seismic survey area to the synclinal area east of the field.

One problem which may introduce error using the above assumptions is that the salt intervals on the well 1235 sonic log do not appear to be pure halite. Average velocity through the salt zones appears to be closer to 14,300 ft/sec (due to the presence of impurities, shale breaks, and thin anhydrite zones), rather than 14,925 ft/sec for pure salt. However, dissolution would remove only the soluble halite, leaving insoluble residue in the collapse areas. Although the net halite thickness cannot be determined from the sonic log, it is apparent that the amount of interval thinning due to salt removal would be somewhat less than the gross salt thickness.

Another possible source of error involves the original correlation picks on the seismic records by NGC interpreters and the conversion of these time values to depth values, using a linear velocity function. Because original seismic records are not available (with the exception of two), the author must rely on the original NCG picks and depth conversion for data which are used in structural and isopach interpretations.

Fortunately, the two seismic records (SP 51 and SP 78), which are included in the NGC report as typical records

(Figure 5-29) were acquired in areas which allow for study of a salt dissolution origin for the Big Springs structure. The interval between a reflector believed to be associated with the Lakota and a Basal Permian reflector thins from 196 msec at shot point 51 (located in an area of presumed thick salt) to 174 msec at shot point 78 (located in a presumed no-salt area). Assuming that thinning is due to complete removal of salt at shot point 78, 22 msec of thinning corresponds to an calculated salt thickness of 164 ft (50 m) at shot point 51. This estimate appears to be reasonable, since it is intermediate between the 102 ft (32 m) of salt in well 1235 and over 200 ft (60 m) of salt in wells to the west.

Thickness values for the Lakota - Basal Permian interval at each shot point were calculated by the author from seismic-based structural data (depth values) in the NGC report for the Lakota and Basal Permian reflectors. A Lakota-Basal Permian isopach (Figure 5-30) reveals an area of significant thinning just east of the field, which is coincident with the suspected no-salt area on the D Sandstone and Lakota structure maps (Figures 5-4 and 5-27). Interval isopach values, which range from over 1000 ft (300 m) along the western edge of the seismic survey area to less than 850 ft (250 m) just east of the field.

An area in the central part of the survey coincides with the area of field discovery and initial development.

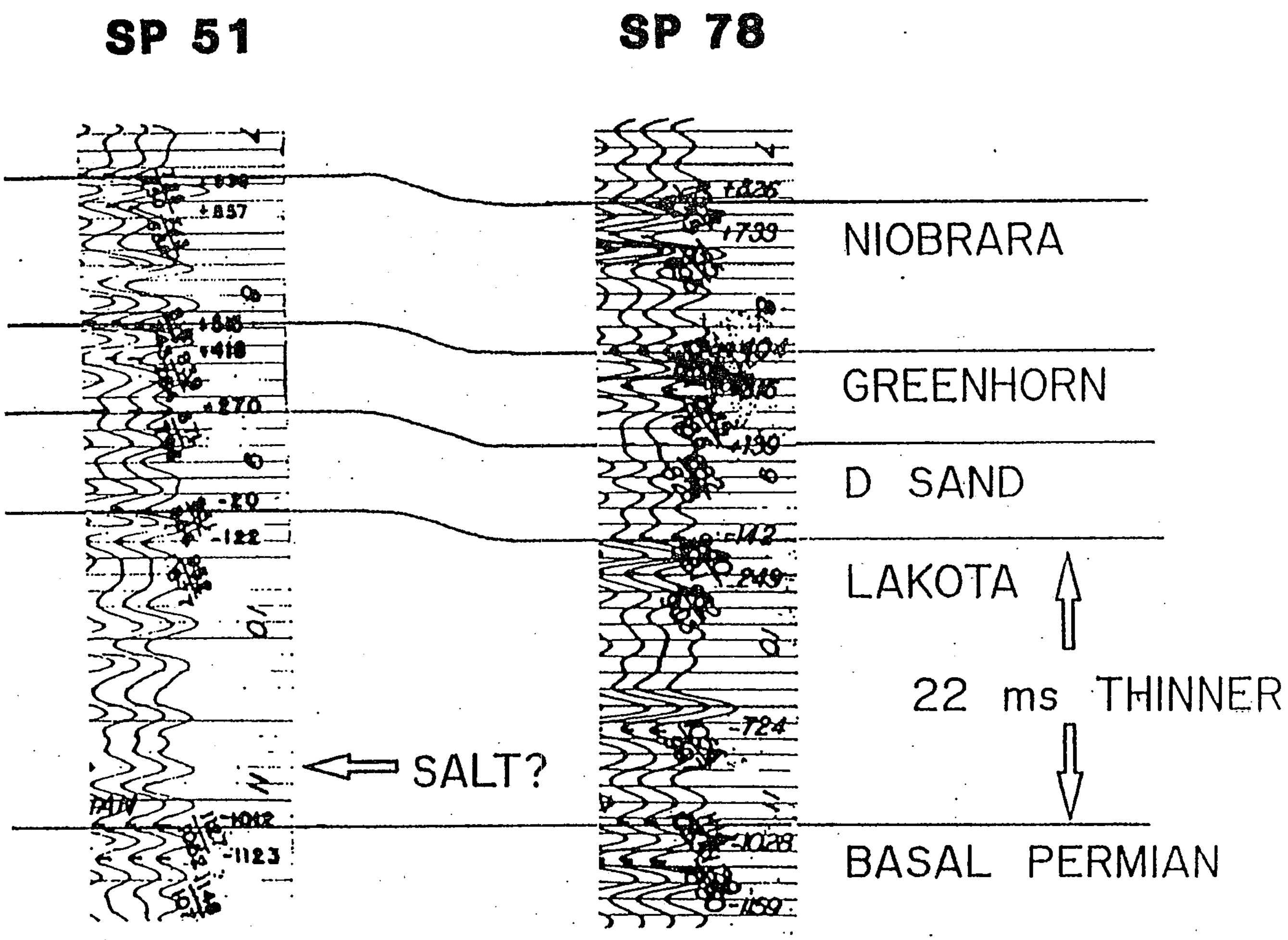


Figure 5-29. Comparison of two seismic records across Big Springs field, showing NGC correlation picks.

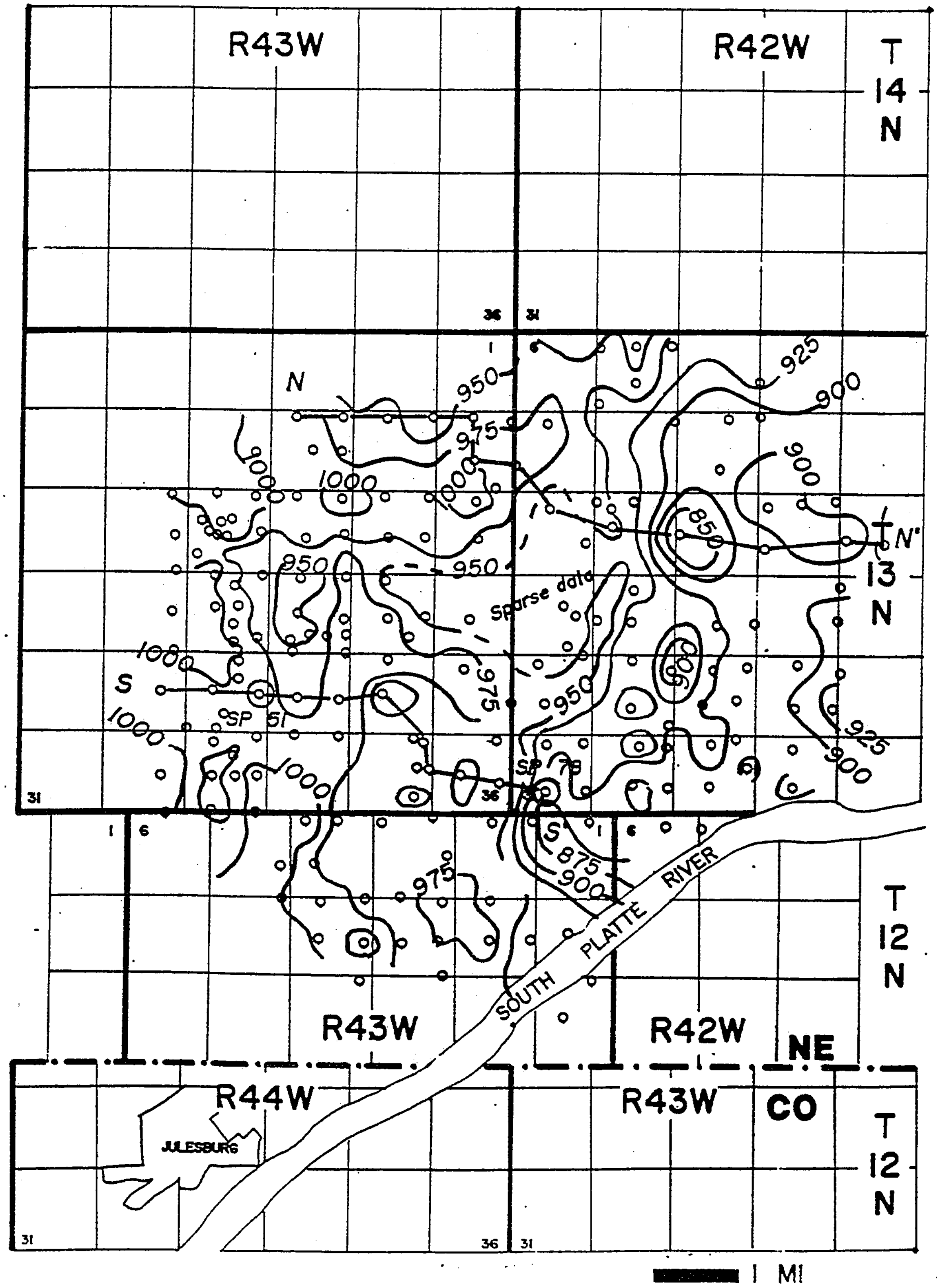


Figure 5-30. Seismic-based Lakota - Basal Permian isopach, using NGC correlation picks. Contour interval 25 ft (8 m).

This is an area of sparse seismic control, probably due to concerns dealing with the distance between shot points and producing wells which existed at the time of the seismic survey.

Lakota - Basal Permian interval thinning at the eastern margin of the field is apparent in cross-section view (Figures 5-31 and 5-32). On each of these cross sections, D Sandstone structure, derived by the author from wells located near the shot point traverses, is compared to seismic-based Lakota structure and seismic-based Lakota-Basal Permian interval thickness, using data from the NGC report. Structural discordance between the D and the Lakota can be attributed to (1) higher density of seismic data along each line of cross section relative to a limited number of wells and (2) position of wells off the seismic traverse lines.

Lakota - Basal Permian thickness maxima of about 1000 ft (300 m) below the field along the southern traverse (Figure 5-31) contrast with a minimum of 870 ft (265 m) at the eastern end of the line. The interval thins from 992 ft (300 m) below the field to 840 ft (255 m) in the synclinal area along a traverse to the north (Figure 5-32). An increase in interval thickness to over 900 ft (275 m), coupled with a seismic-based Lakota-level anticline at the eastern end of this cross section may be due to incomplete removal of salt and may indicate a salt outlier to the east.

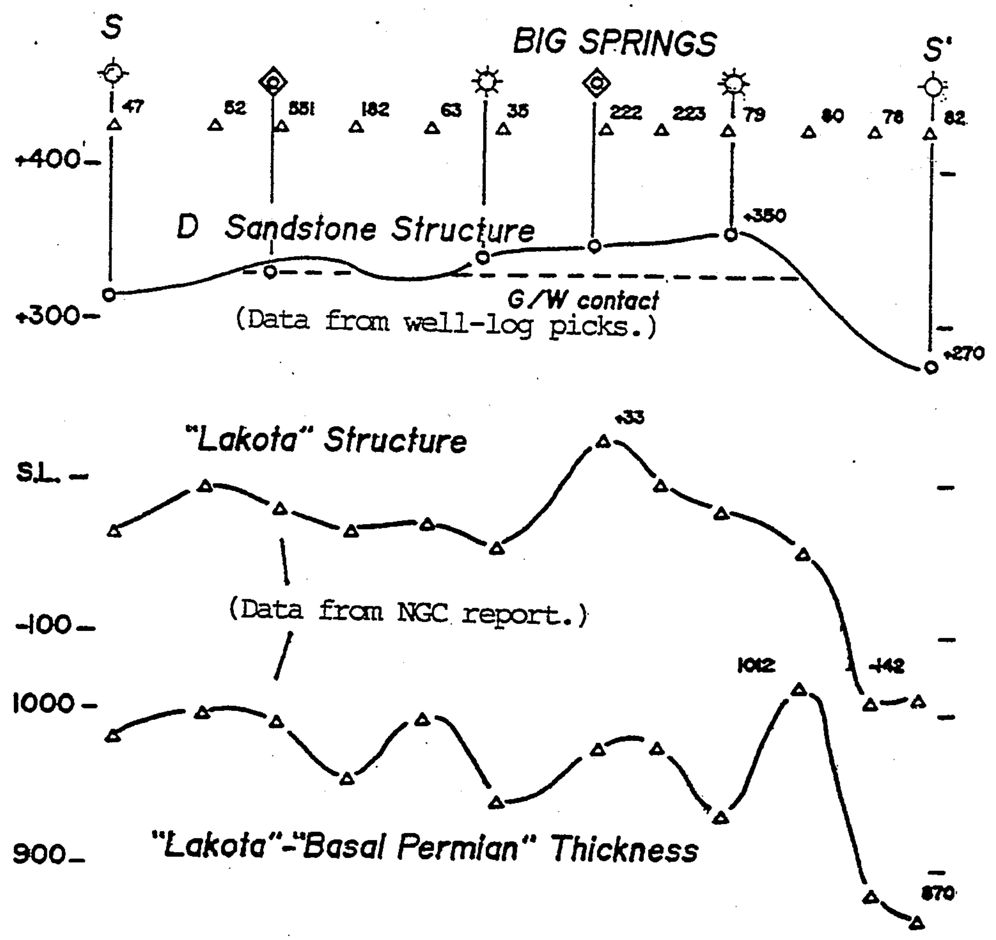


Figure 5-31. East-west seismic and well log cross section across southern portion of Big Springs field.

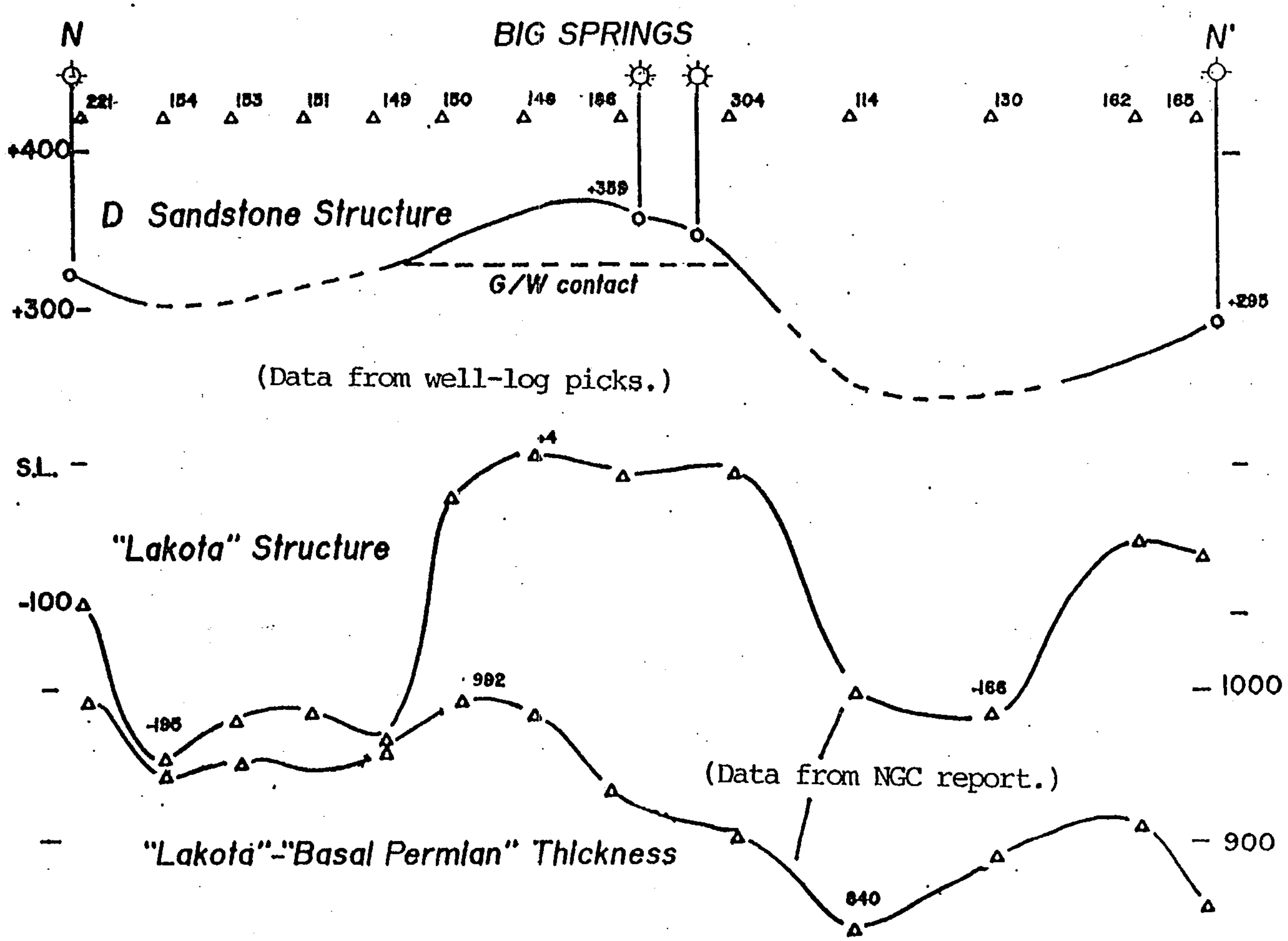


Figure 5-32. East-west seismic and well log cross section across northern portion of Big Springs field.

Seismic-based thickness trends across the Lakota - Basal Permian interval (Figure 5-30) appear to support a salt dissolution hypothesis for the Big Springs structure. Northeast-trending isopach minima to the east of the field are believed to be due to thinning or absence of salt, whereas isopach maxima to the west are likely due to an increase in salt 10 thickness or the presence of salts 7 and/or 9.

An additional line of support for salt dissolution at Big Springs is water-salinity data. A plot of D and J sandstone formation-water salinity (Figure 4-27) reveals several high-salinity values at Big Springs. This may be an indication of upward movement of salt solution-derived brines into Cretaceous reservoirs.

Possible Mechanisms for Salt Removal

Removal of salt in the Sidney trough area (Chapter 4) was ascribed to regional groundwater flow from the Lyons Sandstone along a linear facies change to salt. In contrast, existing deep-well data do not indicate the presence of an updip facies change from sandstone at the Lyons (Cedar Hills) level to salt in the area of Deuel and Garden Counties, Nebraska, surrounding Big Springs field (Figures 4-5 and 4-21). Thus, eastward-directed groundwater flow in the Lyons is not a likely cause for removal of salt at Big Springs.

Three alternate explanations are offerred as possible mechanisms for the abrupt disappearance of salt to the east of Big Springs: (1) introduction of water through basement-related faults; (2) southwestward-directed regional groundwater flow within the Cedar Hills Sandstone from the Chadron arch; and (3) south-directed regional groundwater flow within Jurassic strata from outcrops along the Chadron arch during the Early Tertiary. These mechanisms, which are discussed briefly below, are discussed on a more regional scale in Chapter 8.

Using seismic data, Squires (1986) interpreted a major basement-related shear complex in Sedgwick County, Colorado. This shear zone extends northeastward through the Red Lion salt dissolution feature (Figure 2-14) toward the northeast corner of Colorado (southern limit of Big Springs field). Basement faults were also shown in this area (Figure 2-1) by Tweto (1980), although the basis for the locations of his faults is unknown. Basement faulting along the eastern edge of Big Springs field may be reflected on a basal Permian (subsalt) structural interpretation (Figure 5-33). Although some of the structural relief at the subsalt level can be attributed to false velocity pullup below salt, the Permian-level depression may also be partly due to vertical basement-involved movement. This may indicate the presence

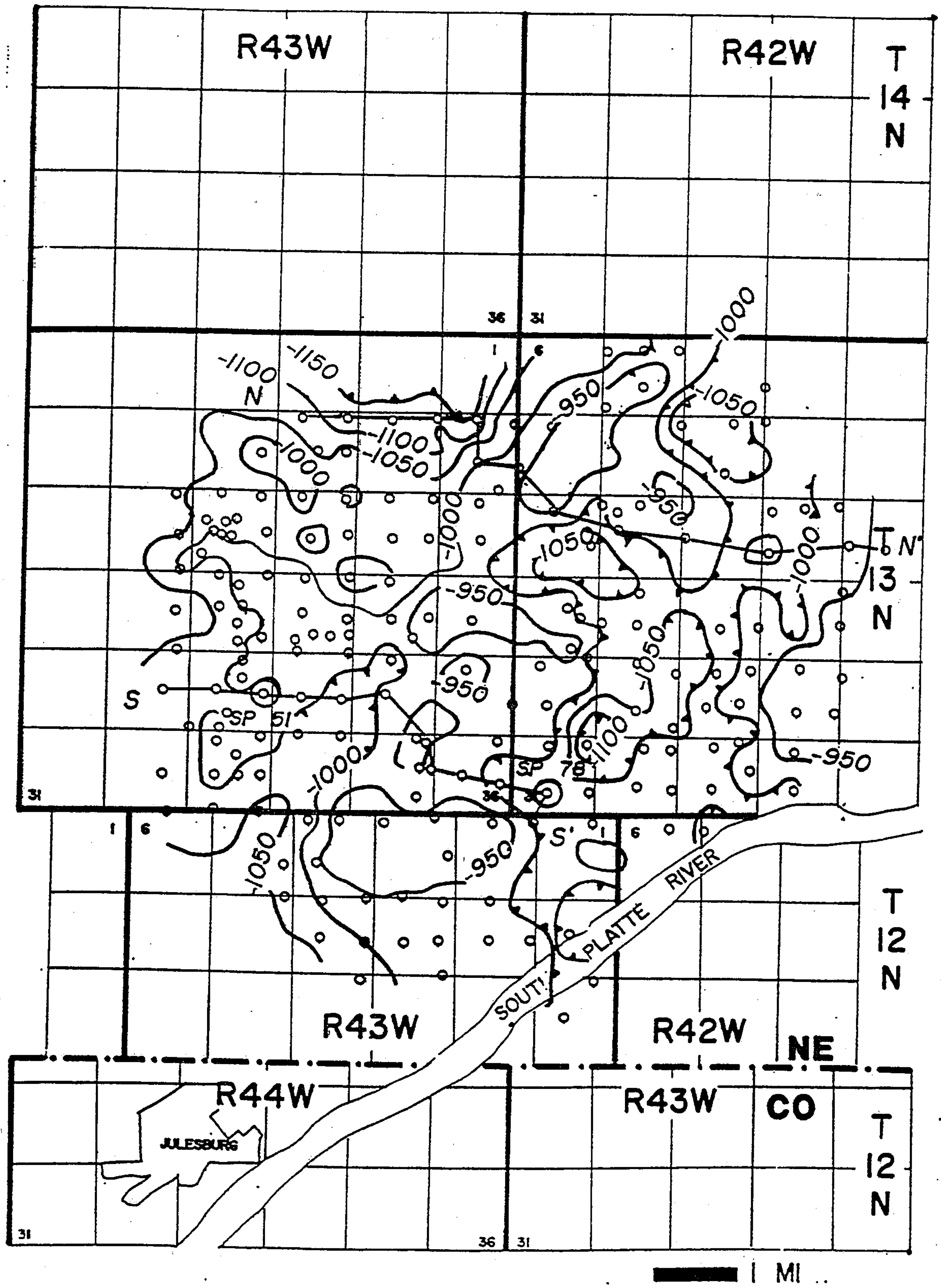


Figure 5-33. Seismic-based basal Permian Structure, using NGC correlation picks. Contour interval 50 ft (15 m).

of fractures which may have allowed for introduction of fluids to the salt interval along fractures, initiating salt dissolution and resultant collapse of overlying strata.

A second possible explanation for salt removal at Big Springs invokes regional, southwestward-directed groundwater movement from the Cedar Hills Sandstone (Lyons equivalent to the east, Figure 4-21). Thick Cedar Hills sandstone is present on the Chadron arch, in the northeastern corner of the regional study area. Laramide uplift along the arch may have initiated downdip (southwesterly) groundwater flow within the regional aquifer. Hydraulic gradient may have forced the migration of water from the Cedar Hills along a regional facies change from sand to salts (whose original extent was east and northeast of Big Springs field. Continued introduction of water and resultant collapse-induced fracturing may have allowed for a southwestward "frontal attack" of salt, resulting in removal salt to its present limit east of Big Springs, Chappell, and McCord-Richards fields.

A third possible explanation for salt removal at Big Springs invokes regional south-directed groundwater flow within Jurassic sandstone units (Morrison Formation and possibly Sundance Formation) during Early Tertiary to Oligocene time. Jurassic rocks presently lie directly below Oligocene strata along the crest of the Chadron arch (DeGraw, 1969, 1971; Swinehart et al., 1985). Thus, the basal sandstone member of the Morrison (and perhaps sandstone units of the Sundance) were exposed along the arch in response to Laramide (Late Cretaceous - Eocene) uplift and erosion. Subaerial exposure (and possible groundwater recharge) lasted into the Oligocene.

Downdip groundwater flow to the southwest from recharge areas on the arch may have been redirected to the south, within thick Jurassic sandstone units (within a north-south-trending Jurassic isopach maximum, Chapter 8). Groundwater may have been introduced to the Leonardian salt interval, which lies below the pre-Late Jurassic unconformity in this part of the basin (Figures 3-3 and 4-11). Recharge may have been restricted with the deposition of relatively impermeable sediments of the White River and Arikaree Groups on the pre-Oligocene surface.

SUMMARY AND CONCLUSIONS

This chapter focuses on the Big Springs field, the second largest gas field in Nebraska. Subsurface analysis, which incorporated well data from D Sandstone wells, seismic data across the field, deep well data in the vicinity, and D Sandstone core and petrographic analysis, results in a number of interpretations which relate the occurrence of Permian salt at depth to the gas-productive anticline at Big

Springs. The following conclusions result from a subsurface study of Big Springs field:

1. Gas at Big Springs is structurally trapped along the axis of a north-south-trending anticline. Production is from a thick sand unit at the top of the D Sandstone interval.

2. The D Sandstone reservoir is a fine- to very fine-grained, well sorted sublitharenite. Sandstone cores contain both clean, bedded zones and highly bioturbated zones with abundant shale laminae, which act to reduce permeability. Reservoir porosity and permeability are enhanced by leaching of chemically unstable grains.

3. Reservoir geometry and orientation and the stratigraphic position of the reservoir at the top of the D Sandstone interval suggest that the upper D gas reservoir formed in a marine environment. Sand was likely reworked during transgression which resulted in deposition of the overlying Graneros Shale.

4. The gas-productive anticline is located along a north-south-trending regional flexure. A deep Cretaceous-level syncline is present just east of the field. Structural relief is over 200 ft (60 m) in places. Structural concordance at the D Sandstone level with shallow structure suggests post-Cretaceous deformation.

5. Single-point reflection seismic data reveal Lakota-level (Lower Cretaceous) structural concordance with D

Sandstone structure based on well data. However, seismic data indicate that structural discordance is present between the Lakota and subsalt basal Permian reflectors.

6. Thinning of the Lakota - basal Permian interval on seismic data coincides with Cretaceous-level structural lows just east of the field. Interval thinning is attributed to removal of Permian salt.

7. In contrast to the Sidney trough (where salt appears to have been removed along its facies change into sandstone), explanation of a cause for salt removal at Big Springs is more problematic. Several alternate mechanisms for introduction of water to the salt interval at Big Springs can be offerred. These include fracturing associated with basement movement, southwestward regional groundwater flow from the Chadron arch within the Cedar Hills Sandstone, and Early Tertiary groundwater flow from the Chadron arch within thick Jurassic sandstone units.