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

VOLUME II

DISSERTATION

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David W. Oldham
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CHAPTER 6
INFLUENCE OF SALT DISSOLUTION ON SHALLOW NIOBRARA GAS PRODUCTION, EASTERN COLORADO

INTRODUCTION

This chapter discusses the distribution of Permian salt and its relationship to the location of shallow Niobrara gas fields in eastern Colorado. The study area (Figure 6-1) covers a 2900 sq mi (7400 sq km) area of Yuma and eastern Washington Counties, Colorado.

Figure 6-1 shows the distribution of oil and gas fields which are productive from the Niobrara Formation on the eastern flank of the northern Denver basin. Oil and thermally-derived gas are produced from the Niobrara in the deeper part of the basin (stippled area) where the Niobrara and adjacent rocks are thermally mature (>0.5% R_o, calculated on the basis of log resistivities; Smagala et al., 1984). Gas and condensate are produced from the Niobrara in Wattenberg field, a basin-centered gas accumulation, whereas oil and associated gas are produced in the Silo field area of southeastern Wyoming.

The shallow gas producing area of eastern Colorado and adjacent parts of northwestern Kansas and southwestern Nebraska is situated east of the area where the self-sourcing Niobrara is thermally mature. In these areas, biogenic gas has accumulated on highly faulted anticlines within in a porous chalk zone at the top of the Niobrara

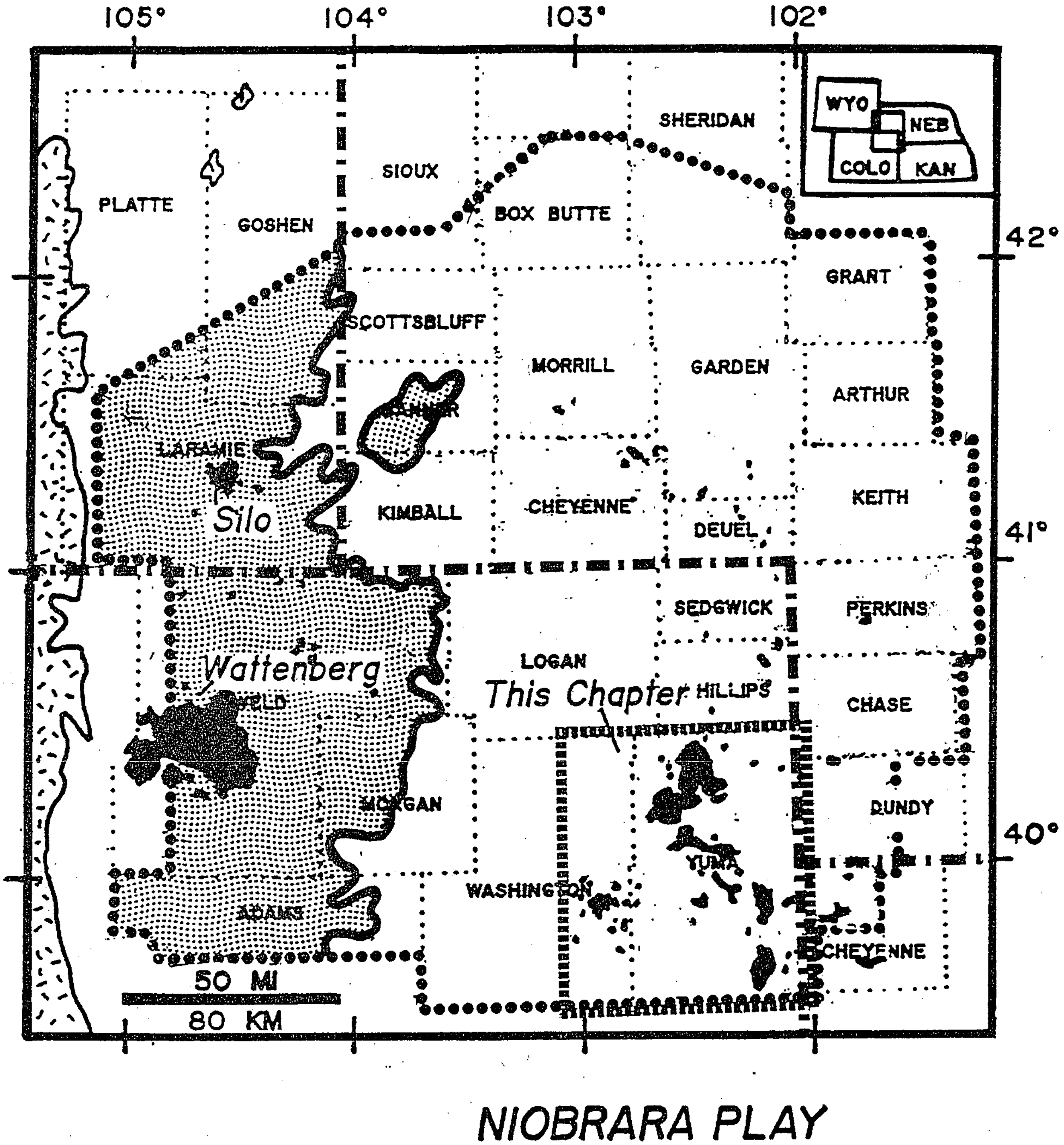


Figure 6-1. Location of oil and gas fields in the northern Denver basin which are productive from the Niobrara Formation.

Formation (Upper Cretaceous). This chapter focuses on a salt dissolution origin for shallow, gas-productive anticlines in eastern Colorado. Chapter 7 focuses on Eckley field, which has the highest cumulative production of all shallow Niobrara fields.

SHALLOW NIOBRARA GAS PLAY

Development of Play

Shallow gas in the Niobrara was first produced in the area which would eventually become the Beecher Island field in southeastern Yuma County, Colorado (Figure 6-2). In 1919, Midfields Gas Company, formed by local rancher H.F. Strangways, drilled a cable-tool well in Sec.14, T2S, R43W, which was completed for a reported 2000 MCFGPD flow (Barb, 1946; Lockridge and Pollastro, 1988). Gas from this and subsequent wells was used on the Strangeways ranch.

In 1936, a 5592-ft (1704-m) dry hole was drilled to the Precambrian in Sec. 21, T2S, R43W. This well was drilled on an anticline which was identified from reflection-seismic data (Lockridge, 1977). Another deep test of the structure, drilled to the Precambrian during 1952 in Sec. 8, T2S, R43W, was unsuccessful.

In 1972, Mountain Petroleum completed five gas wells from the Niobrara at Beecher Island field to establish the

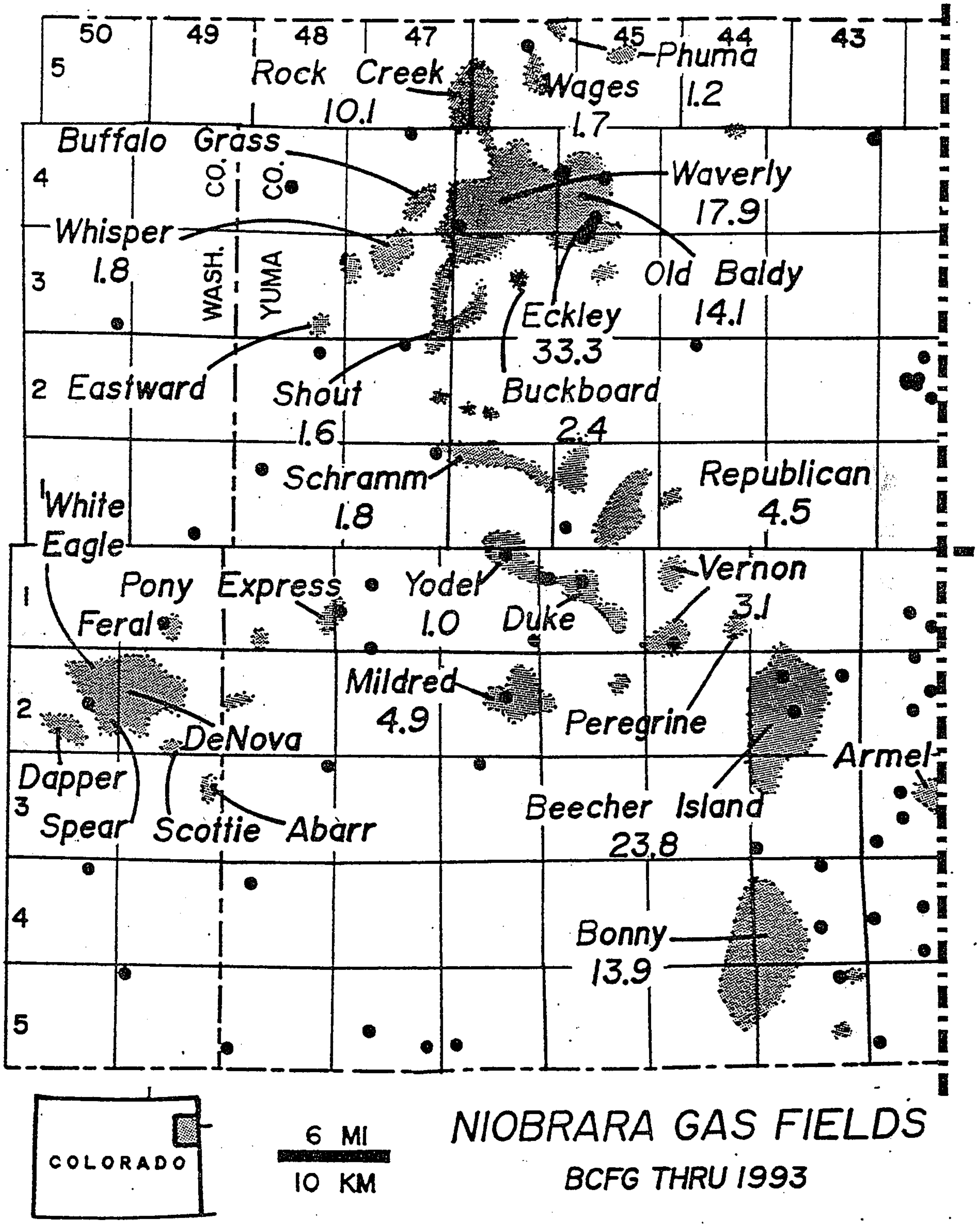


Figure 6-2. Location of shallow Niobrara gas fields in Yuma and eastern Washington counties. Solid circles on this and subsequent maps denote Paleozoic penetrations.

first commercial production in this area. Favorable gas prices and improved stimulation and completion techniques sparked a flurry of drilling activity in the area during the late 1970s and early 1980s (Lockridge and Pollastro, 1988), resulting in the development of numerous gas fields in eastern Colorado whose distribution is shown on Figure 6-2.

Seismic-based exploratory drilling during the 1950s and 1960s in Yuma County and adjacent areas concentrated on deeper objectives. Deep targets included the Cretaceous D and J Sandstones (in response to the discovery of several oil and gas fields in the D-J fairway to the west and northwest) and subsalt Paleozoic reservoirs (following the discovery of oil at Sleepy Hollow field to the east).

The shallow Niobrara was overlooked as a commercial pay during the wave of drilling in the 1950 and 1960s. This was due to a number of factors, including a weak or nonexistent gas market, lack of gas pipelines, low reservoir pressures, and low in-situ permeability. Moreover, low resistivity readings on electrical logs recorded across the Niobrara pay zone, due to the high porosity of the chalk along with high water saturations, contributed to the failure of operators to recognize the gas zone. Lockridge and Pollastro (1988) noted that resistivities as low as 3-5 ohm-m can result in gas production. In fact, Niobrara production was not established in the DeNova field area of Washington County until 1977, 21 years after the discovery of oil from the deeper J Sandstone had prompted the drilling of numerous Lower Cretaceous tests on seismic highs in the immediate area (Davis, 1982).

Through 1993, the Niobrara has produced over 139 BCFG in Yuma County (Figure 6-2). Cumulative production, in BCFG, is shown for each field in Yuma County which has produced over 1 BCFG. Beecher Island field has produced nearly 24 BCFG from 1972 through 1993. In northern Yuma County, Eckley field, with a cumulative production of over 33 BCFG, is the largest field in terms of cumulative production and per-well yield. Eckley field is part of the Waverly complex which includes Old Baldy, Waverly, Wages, and Rock Creek fields (Jeffrey, 1982). Cumulative production (through 1993) at the Waverly complex is in excess of 77 BCFG.

Niobrara Stratigraphy

The Upper Cretaceous Niobrara Formation (Coniacian, Santonian, and Campanian; Kauffman, 1977) is situated between the overlying Sharon Springs Member of the Pierre Shale and the underlying Carlile Shale (Figure 6-3), and is about 500 to 600 ft (150 to 180 m) thick in Yuma County. The Niobrara is divided into two members, the lower Fort Hays Member and the upper Smoky Hill Member.

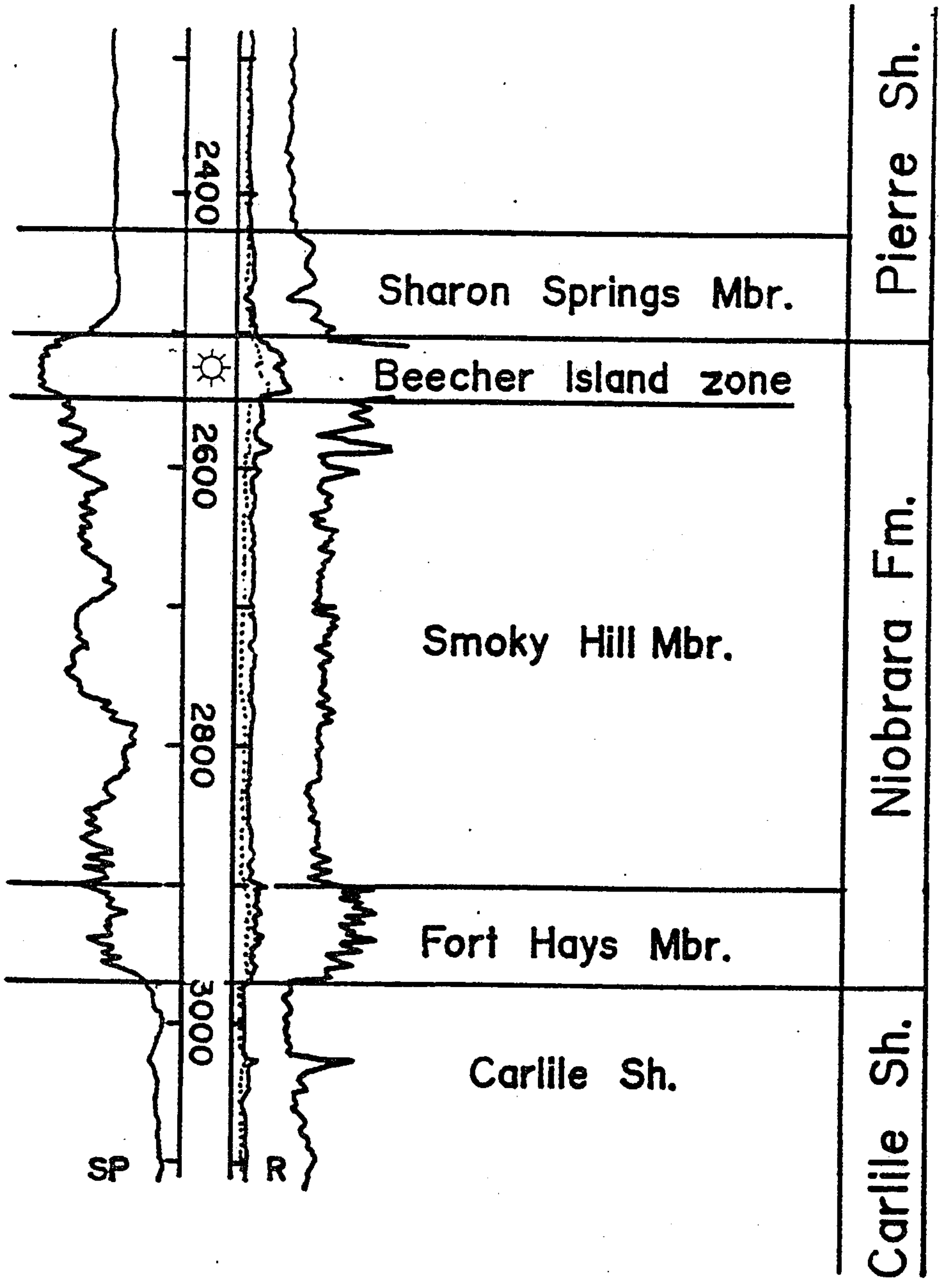


Figure 6-3. Representative well log across Upper Cretaceous Niobrara Formation showing gas-productive "Beecher Island zone" (Lockridge, 1977) at top of Smoky Hill Member. Well log is from J-W Operating Kitzmiller 2, NWNW Sec.4, T3N, R45W, Eckley field.

In eastern Colorado and adjacent areas the Fort Hays Member is comprised of about 60 ft (20 m) of chalk and shaly chalk with interbedded chalky shale. The Smoky Hill Member, about 400 to 500 ft (120 to 150 m) thick, consists of gray to white chalky shale with locally massive chalk beds (Lockridge and Scholle, 1978). Gas is produced from a porous chalk interval at the top of the Smoky Hill Member, informally named the "Beecher Island zone" (Lockridge, 1977).

Niobrara Reservoir

The Beecher Island zone averages 30 ft (10 m) in thickness across eastern Colorado. In Yuma County and adjoining areas, the reservoir is a porous chalk. Porosity ranges from 45 percent at a depth of 900 ft (275 m) at Goodland field in northwestern Kansas to 30 to 35 percent at a depth of about 2800 ft (850 m) at several fields in western Yuma County.

Lockridge and Scholle (1978) demonstrated that the porosity of the Niobrara reservoir is dependent on burial depth. Gas production in the eastern Denver basin is from a reservoir characterized by high microporosity and low permeability that requires stimulation, usually by a foam-fracture treatment (Lockridge and Scholle, 1978; Brown et al., 1982; Lockridge and Pollastro, 1988). In contrast, oil and thermally-generated gas production from the Niobrara in the deeper part of the basin is dependent on fracture porosity, due to the extreme reduction of matrix porosity by chemical compaction (Lockridge and Scholle, 1978; Pollastro and Martinez, 1985; Pollastro and Scholle, 1986; Sonnenberg and Weimer, 1993; Svoboda, 1995). Unless the Niobrara is overpressured or fractured, a burial depth of 3000 to 4000 ft (1000 to 1200 m) represents a lower economic depth limit on shallow gas production (Lockridge and Scholle, 1978).

The chalk reservoir is comprised of coccospheres, coccolith plates, and rabdolith plates (Scholle, 1977). Primary pore space, which occurs within and between the planktonic skeletal plates, has been only slightly reduced by cementation and compaction at the shallow depths of the eastern Denver basin (Lockridge and Scholle, 1978).

Due to the extremely small grain size (2 to 10 microns), permeability of the Beecher Island zone is low (less than 1 md), requiring fracture stimulation to achieve commercial production (Lockridge and Pollastro, 1988). Brown et al. (1982) cited a well in Beecher Island field which had a pre-stimulation drill stem test rate of 5.6 MCFGPD which, following foam-fracture treatment, tested at an initial potential of 721 MCFGPD.

Because of the low permeability, complete segregation of gas and connate water has not occurred. Rather than a well-defined gas-water contact, commercial production is from a gas-water transition zone whose gas saturation increases with structural position (Jeffrey, 1982). This transition zone can be as much as several hundred feet thick (Brown et al., 1982).

Source of Gas

Dry gas produced from the Niobrara at shallow depths is composed almost entirely of methane with minor amounts of nitrogen and carbon dioxide and has a heating value of 965 to 1035 BTU/SCF (Lockridge and Pollastro, 1988). Isotopic analyses indicate that the gas is isotopically light, with $\delta^{13}C$ values ranging from -65 ppt at a depth of about 1100 ft (330 m) to -55 ppt at 2700 ft (840 m)(Rice, 1984).

Rice (1984) concluded that the chemically dry and isotopically light gases are of biogenic origin. Gas was generated at shallow depths by microorganisms in a low-temperature, anaerobic environment (Rice and Claypool, 1981) and organic-rich laminae within the chalk served as an indigenous immature source rock for gas. Rice (1984,1986) discounted a deeper, thermally mature source for the gas, due to the low permeability of the chalk which would have inhibited long-range migration from the west.

Niobrara Structure

Structure on top of the Niobrara (Figure 6-4) reveals that the Yuma County area lies along the southeastern flank of the Denver basin. Structure contours are derived primarily from Lockridge and Pollastro (1988) and Lockridge and Scholle (1978). Contours have been modified from Cockerham (1982) in the Vernon field area and from mapping by the author in the Eckley field area.

Regional dip is to the northwest at less than one degree. Because of the northwesterly dip, depth to the top of the gas-productive Niobrara chalk ranges from about 1800 ft (550 m) at Bonny field in southeastern Yuma County to about 2800 ft (850 m) in the northwest part of the Waverly complex in northern Yuma County.

Niobrara gas fields produce from faulted anticlines, whose locations are indicated by broadening of contours or closure at this regional scale and whose relief locally exceeds 200 feet (60 m). Gas-productive structures have no apparent regional lineation (Lockridge and Pollastro, 1988). More detailed structural interpretations across shallow Niobrara fields include those by Lockridge (1977), Lockridge and Scholle (1978), Tremain (1980, cited in Brown et al., 1982), and Lockridge and Pollastro (1988) for Beecher Island field; Cockerham (1982) across Vernon field; Jeffrey (1982)

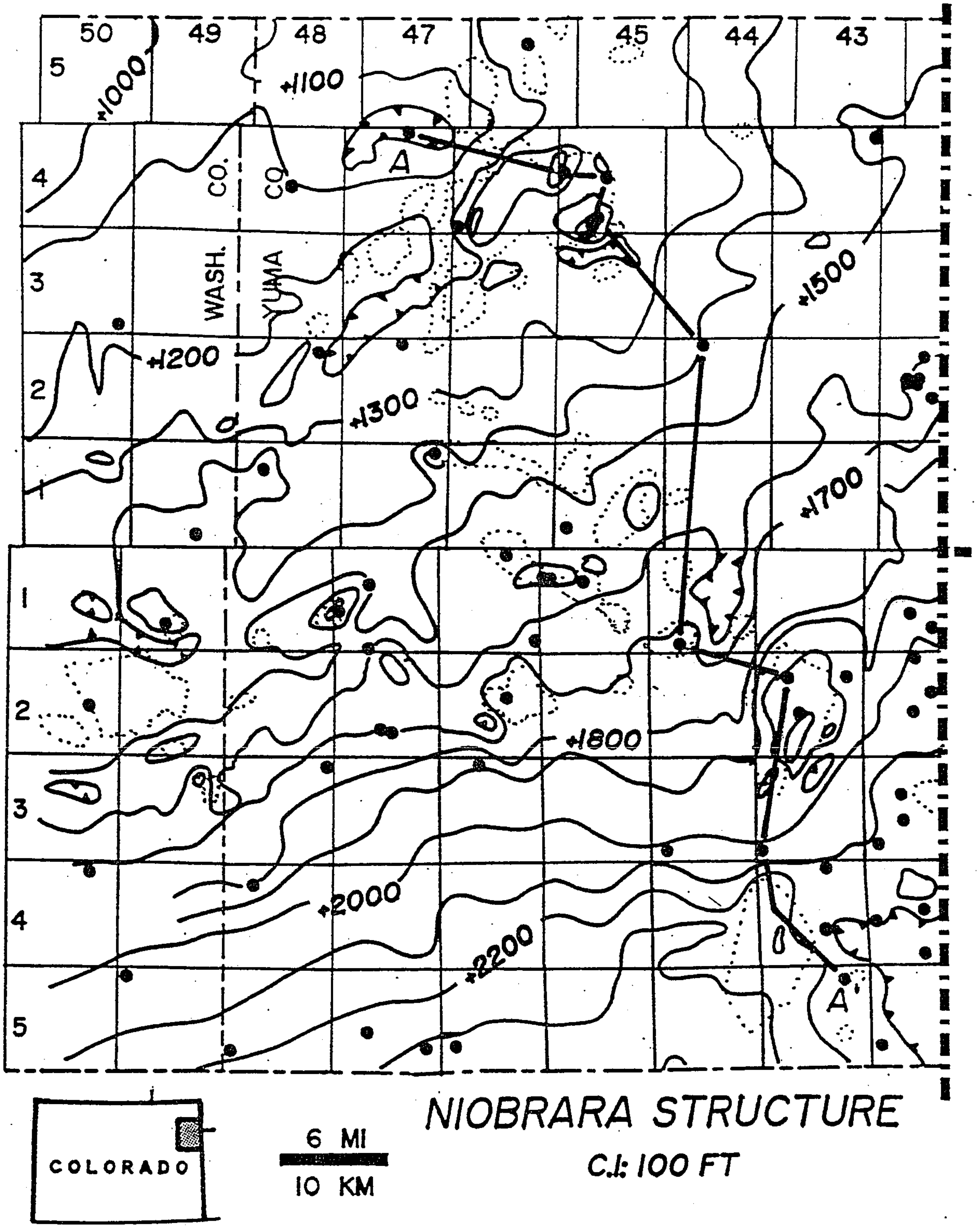


Figure 6-4. Regional structure on top of Niobrara Formation. Contour interval 100 ft (30 m). Structure contours are from Lockridge and Pollastro (1988), Lockridge and Scholle (1978), Cockerham (1972), and from mapping by the author. Cross section A-A' is shown on Figure 6-20.

across the Waverly complex, which includes Waverly, Rock Creek, Wages, Old Baldy, and Eckley fields; Smagala (1981), Davis (1982), and Lockridge and Pollastro (1988) for DeNova and surrounding fields; and Jamison (1982) for Goodland field in northwestern Kansas.

Producing structures are cut by numerous listric faults which Lockridge and Pollastro (1988) interpreted to be early compactional features. Smagala (1981) showed that structure at the level of the Niobrara is more complex than that at the level of the underlying D Sandstone and attributed this to an increase in faulting due to the brittle nature of the Niobrara reservoir. Tremain (1980) interpreted faulting to be related to deep basement structures.

DEEP STRUCTURE

Structure at the subsalt level (Figure 6-5), drawn on the top of the Wolfcampian Chase Group, which occurs about 1800 to 2000 ft (550 to 600 m) below the Niobrara, also reveals a northwesterly dip of less than one degree across the shallow Niobrara producing area. Deep-well control is shown as solid circles. Although this interpretation is based on far less subsurface control than the shallow Niobrara structure (Figure 6-4), no deep structural closures are apparent in areas where the Niobrara is productive. In fact, a subsalt structural high occurs outside of the

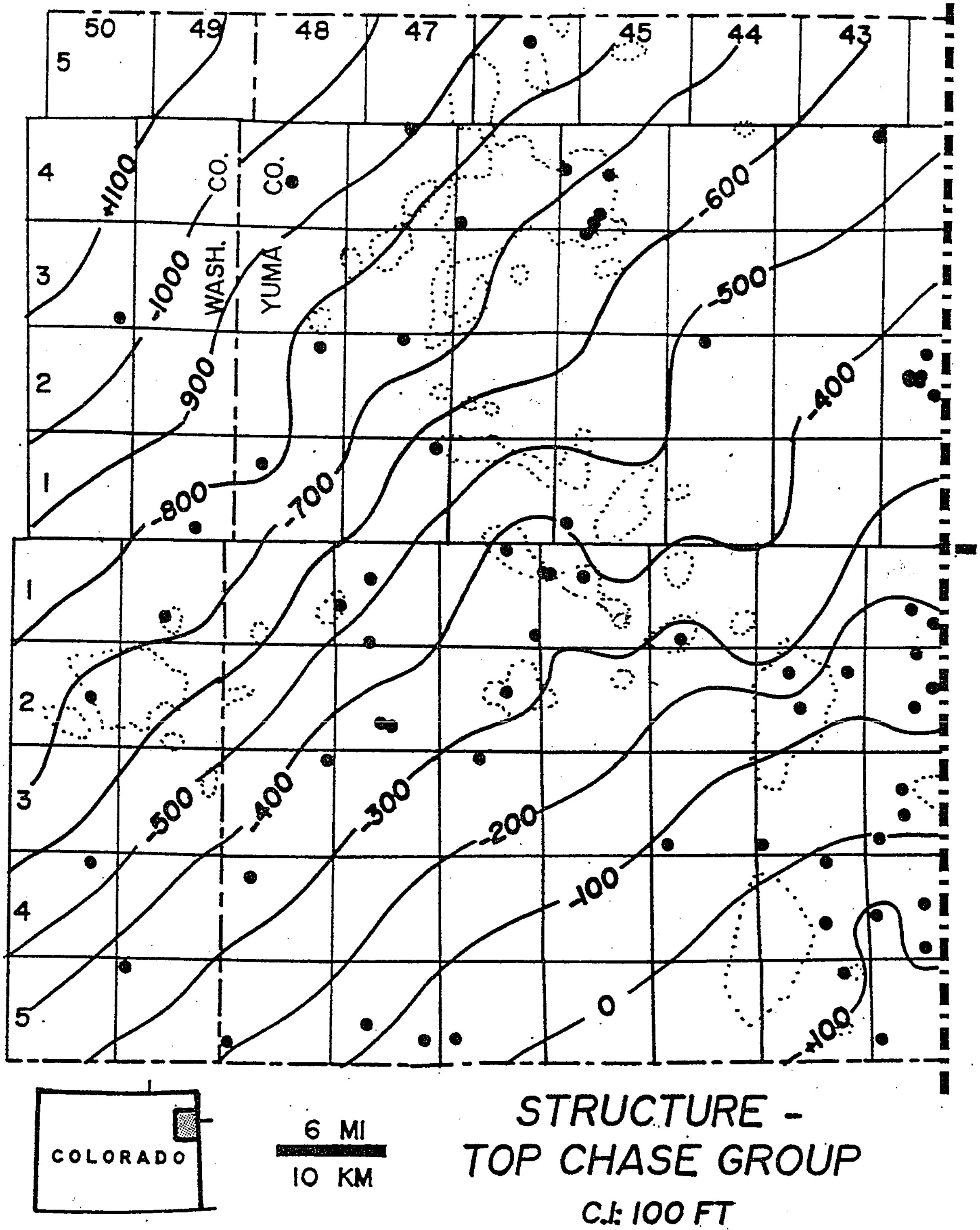


Figure 6-5. Regional subsalt structure on top of Wolfcampian Chase Group. Contour interval 100 ft (30 m).

producing area, just to the east of Bonny field, in T4S, R42W, and a subsalt structural low is present below Beecher Island field in T2S, R43W. The only subsalt structural high in an area of Niobrara production which can be drawn based on existing deep control occurs to the northeast of Beecher Island field, centered in T1S, R45-46W and T1N, R45-46W, below Yodel and Duke fields. No subsalt closure is evident in the Eckley field area, T3-4N, R45W, where over 200 ft (60 m) of closure exists at the Niobrara level.

Structural discordance between the Niobrara and the subsalt Wolfcampian suggests significant variability in stratigraphic thickness between the two horizons. The discussion that follows demonstrates that the extreme variability in thickness and occurrence of Permian salts, caused by post-Niobrara dissolution and resultant collapse, is responsible for much of the structural discordance and the formation of gas-productive faulted anticlines at the Niobrara level.

PERMIAN SALT INTERVAL

Of the 13 Permian salt zones identified in the northern Denver basin subsurface (Chapter 3), seven have been identified in Yuma and eastern Washington Counties. These include salt 4 (Guadalupian) and salts 5, 6, 7, 8, 9. and 10 (all within the upper Leonardian Nippewalla Group). With the exception of salt 4 (which occurs in a limited area of eastern Washington County), Guadalupian salts, if originally present in this area, have been removed by near-surface dissolution during the Jurassic. Lower Leonardian and upper Wolfcampian salt (salts 11, 12, and 13) apparently did not accumulate in this part of the basin.

Figure 6-6 shows a representative well log recorded across the salt-bearing interval in the shallow Niobrara gas-producing area of Yuma County. Salt 5, which occurs between the upper and lower Blaine Anhydrite beds, salt 7, which occurs between a shale marker below the lower Blaine Anhydrite and the top of the Flower-pot Shale, and salt 10, which occurs below the Stone Corral Anhydrite, were encountered in this well.

Stratigraphic positions of salts which have been identified elsewhere in the Denver basin but are absent in this well, including salts 4, 6, 8, 9, 11, 12, and 13, are shown. Triassic rocks as well as most of the Guadalupian Series, including the interval which includes salts 1, 2, and 3, have been removed by pre-Late Jurassic erosion this far east in the basin. In addition to salts 5, 7, and 10, other salts which have been identified on well logs drilled in Yuma County include salt 6, which occurs between the base of the lower Blaine Anhydrite and a thin shale marker, salt 8, which occurs at the base of the Flower-pot Shale, immediately above the Flower-pot Anhydrite, and salt 9,

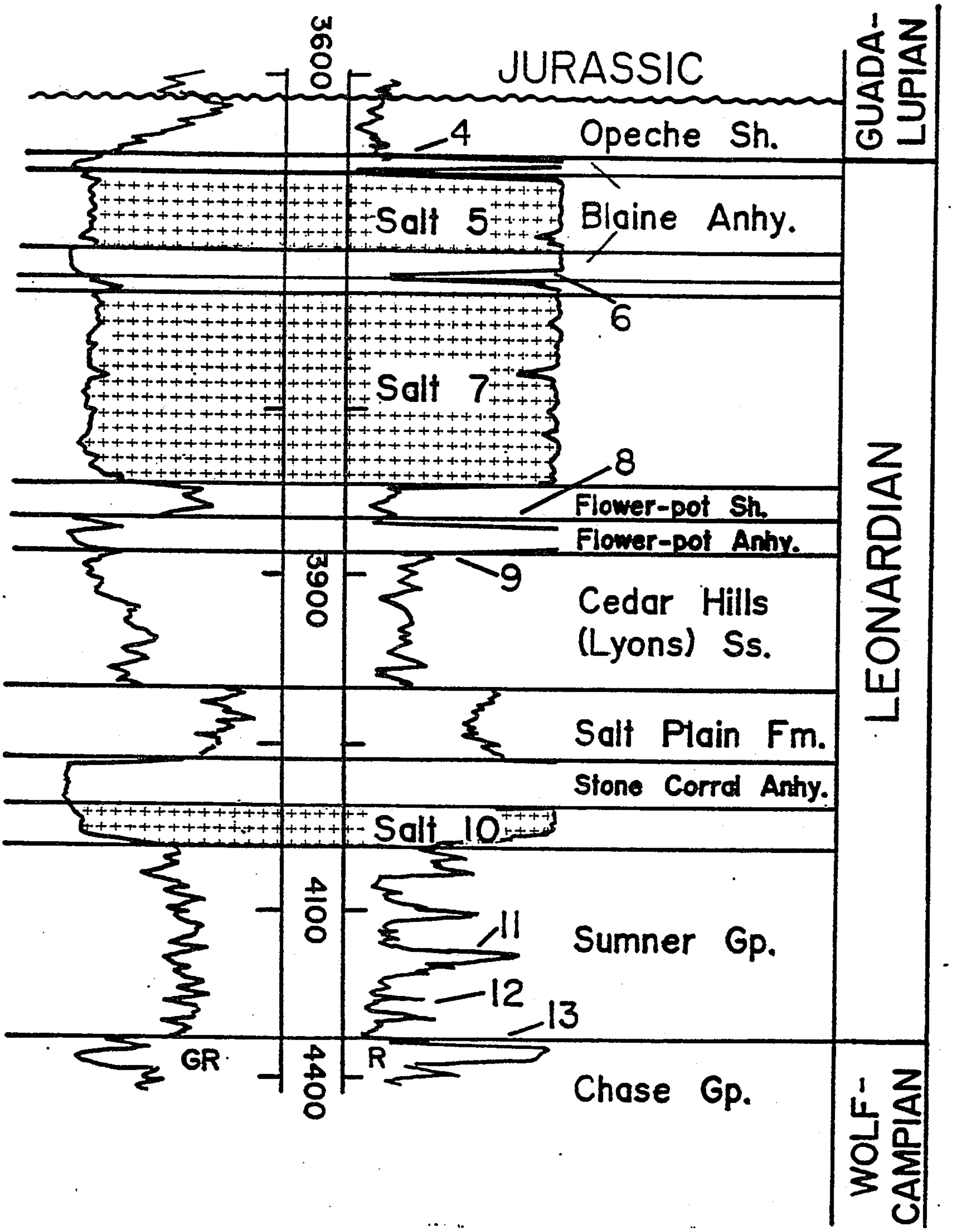


Figure 6-6. Representative well log across Permian salt-bearing interval. Numerals indicate stratigraphic position of salt intervals. Well log is from Marathon Oil Allison 1, NESW Sec. 14, T2S, R46W, Yuma County, Mildred field.

which occurs immediately below the Flower-pot Anhydrite. Except for salt 4, all salts identified in this area are of Leonardian age, which includes strata from the top of the upper Blaine Anhydrite to the the base of the Sumner Group.

SALT IN THE BEECHER ISLAND FIELD AREA

Structure on top of the Beecher Island zone across the Vernon, Beecher Island, and Bonny fields in southeastern Yuma County (Figure 6-7) reveals significant departure from regional northwesterly dip. Contours are from Lockridge and Pollastro (1988) for Beecher Island and Bonny fields and are modified from Cockerham (1982) for Vernon field. Gas production at all three fields is from faulted anticlines with over 200 ft (60 m) of relief. Locations of Permian or deeper tests are shown by circled wells.

An isopach of the Leonardian Series (Figure 6-8), which includes all of the salts which have been identified in this area, reflects the discontinuous nature of salts. Salts are present in the area of isopach maxima below Beecher Island and Vernon fields and just off the west margin of the map, in the Mildred field area of T2S, R46W. In the Bonny field area, a speculated isopach maximum of about the same scale as the Beecher Island-Vernon anomaly is based on an increase in interval thickness toward the field in surrounding wells and on structural relief of the gas-productive anticline at

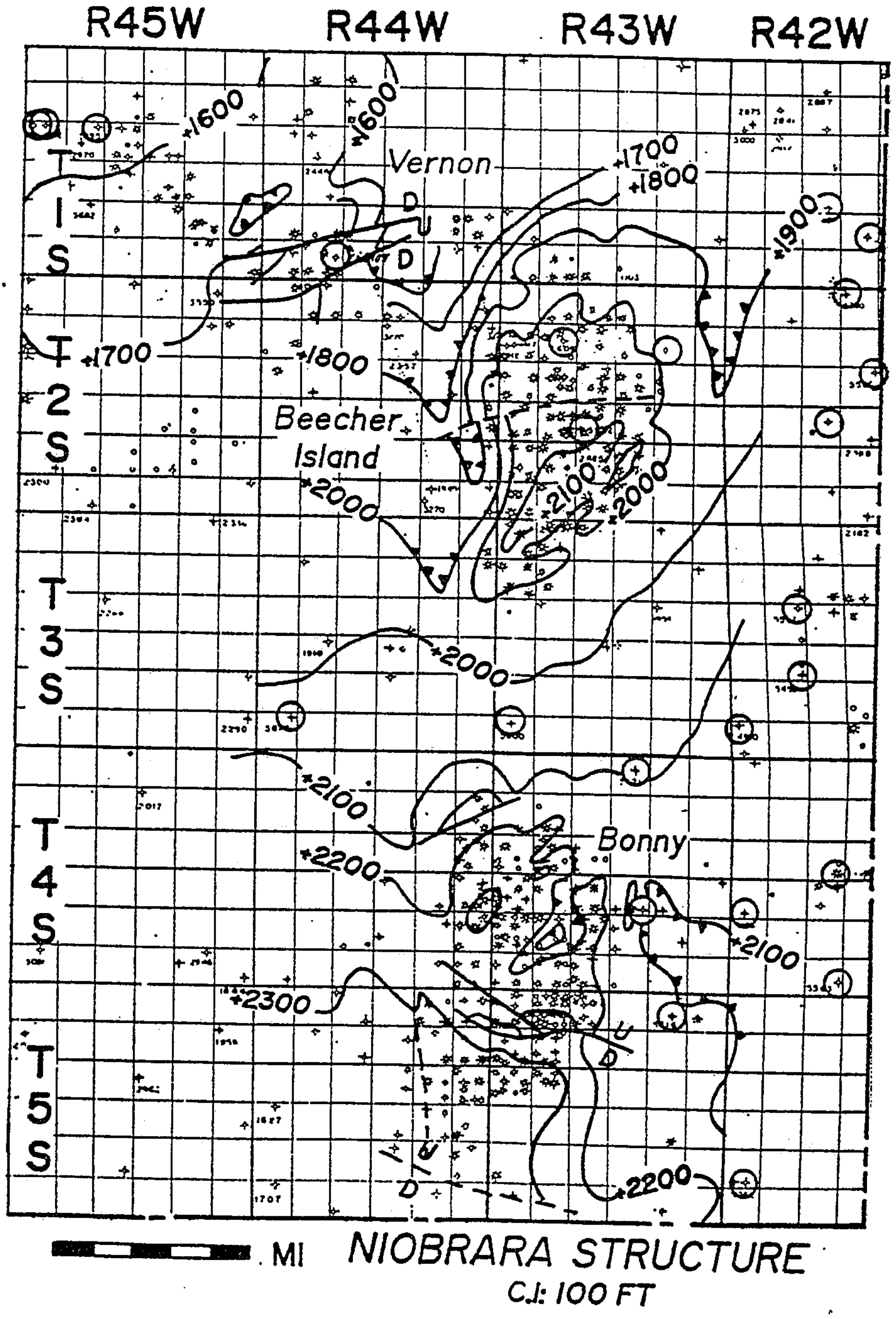


Figure 6-7. Structure on top of Beecher Island zone across Vernon, Beecher Island, and Bonny fields. Contour interval 100 ft (60 m). Contours are from Lockridge and Pollastro (1988) for Beecher Island and Bonny fields and modified from Cockerham (1982) for Vernon field. Base map from Mapco Diversified, Inc., reproduced with permission.

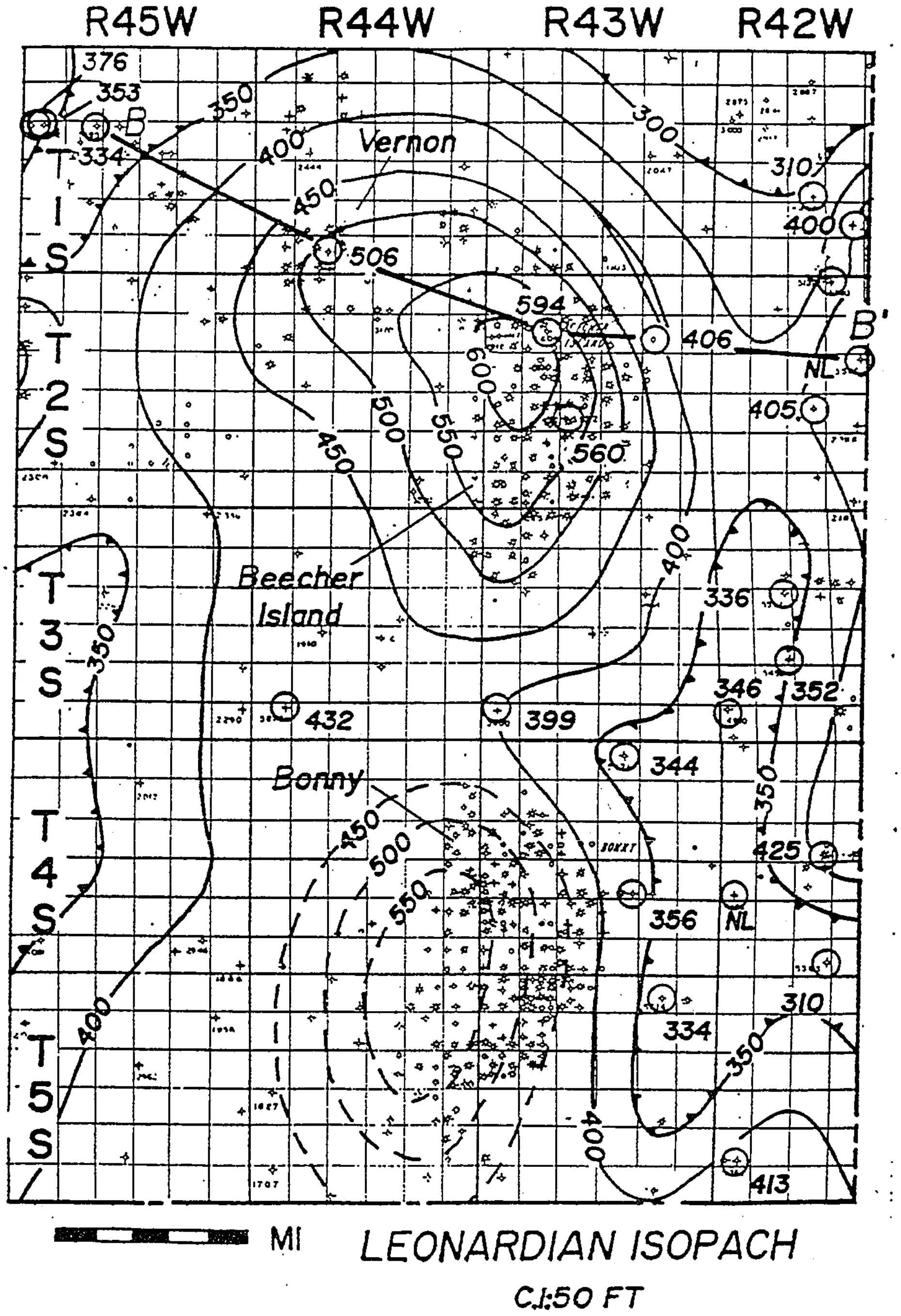


Figure 6-8. Isopach of the Leonardian Series below Vernon, Beecher Island, and Bonny fields. Base map from Mapco Diversified, Inc., reproduced with permission.

Bonny field. Isopach minima to the northwest of Vernon field , to the northeast and southeast of Beecher Island field, and to the east of Bonny field reflect the absence of Permian salts in these areas.

Figure 6-9 is a stratigraphic cross section showing the salt zones which are present below Niobrara production at Vernon and Beecher Island fields. Available deep control indicates that salt 7 is present below both fields and that salt 9 is present only in the Beecher Island field area. Thickness of the Leonardian interval encountered in wells on this cross section ranges from 334 ft (102 m) in well 2078 northwest of Vernon field, where salt is absent, to 594 ft (181 m) in well 2089 under Beecher Island field, where about 125 ft (40 m) of salt 7 and and about 50 ft (15 m) of salt 9 are present. Although the Sumner Group, Stone Corral Anhydrite, and Salt Plain Formation are slightly thicker in well 2089 at Beecher Island field, most of the 260-ft (79-m) difference in Leonardian interval thickness can be explained by the combined salt thickness of 175 ft (53 m) under Beecher Island field. This is slightly less than the structural relief across the field at the Niobrara level. The lack of positive structure below the fields at the subsalt level (Figure 6-5) supports the argument that most of the structural relief responsible for entrapment of gas at these fields is rootless, not basement-involved as interpreted by Tremain (1980).

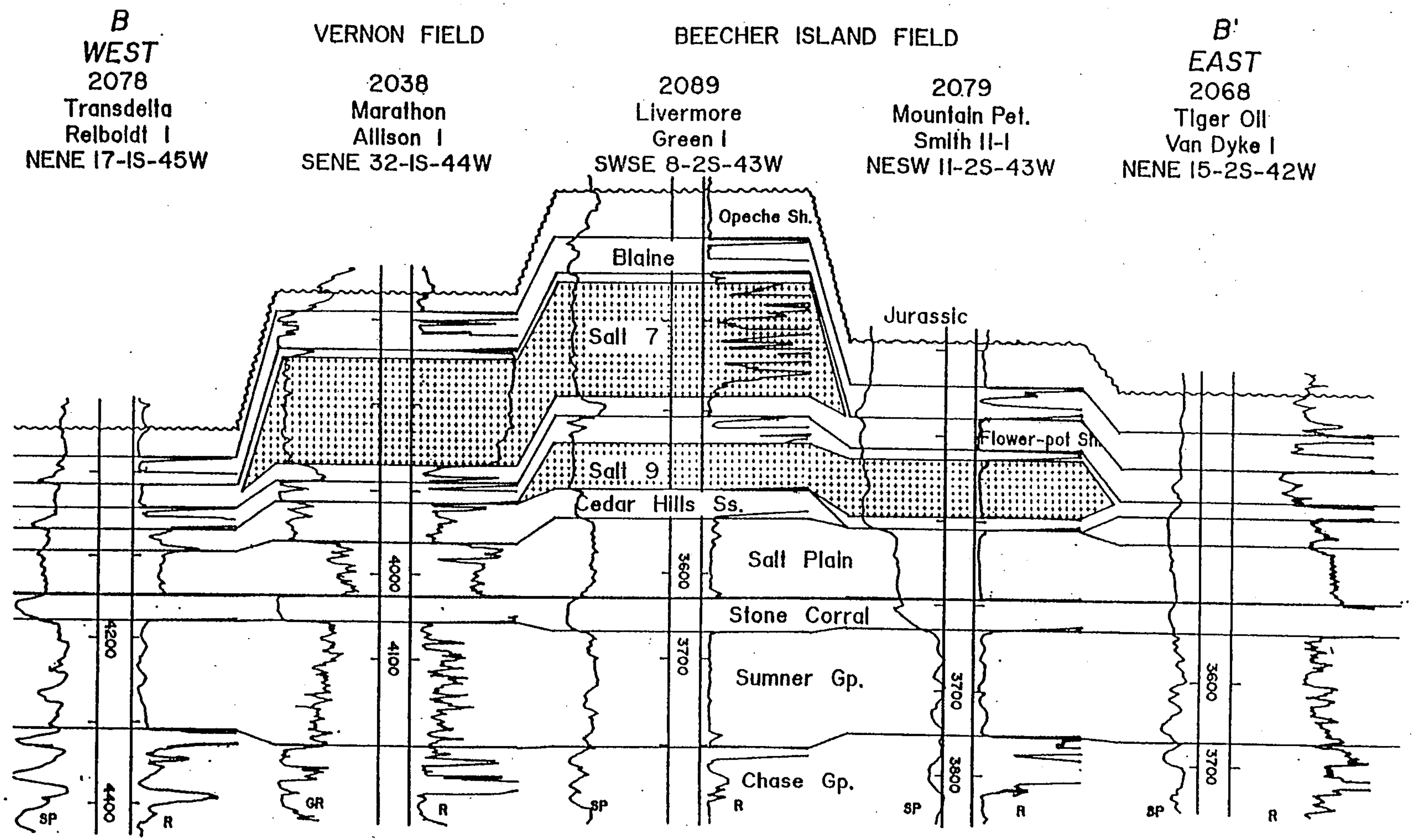


Figure 6-9. Stratigraphic cross section through Permian salt interval below Vernon and Beecher Island fields. Datum is top of Stone Corral Anhydrite. Well depths are in feet.

THICKNESS VARIATION IN LEONARDIAN STRATA

An isopach of the Leonardian Series across the Niobrara gas producing area of eastern Colorado (Figure 6-10) reveals that extreme variability in Leonardian thickness is not restricted to the area of Vernon, Beecher Island, and Bonny fields in southeastern Yuma County. Isopach maxima are present at Mildred field in T2S, R46W, at Pony Express field in T1S, R47-48W, at Yodel field in T1S, R46W, in the Denova field and surrounding areas of T2S, R49-50W, and in the Waverly complex area in the northcentral part of Yuma County. Thickness of Leonardian strata exceeds 500 ft (150 m) at each of these gas fields.

At Mildred field (Figure 6-11), T2S, R46W, the Leonardian encountered in well 2035 is 527 ft (161 m) thick, due to the presence of 40 ft (12 m) of salt 5, 120 ft (37 m) of salt 7, and 15 ft (5 m) of salt 10. The Leonardian thins to 370 ft (113 m) to the west in well 2032, and to 331 ft (101 m) to the north in well 2088, where salt is absent in both wells. Rapid lateral thickness change in the Leonardian interval, interpreted as evidence of salt dissolution, is demonstrated on the western side of the cross section, where salt 7, which is 45 ft (14 m) thick in well 2033, is absent in well 2032, less than one mile to the east.

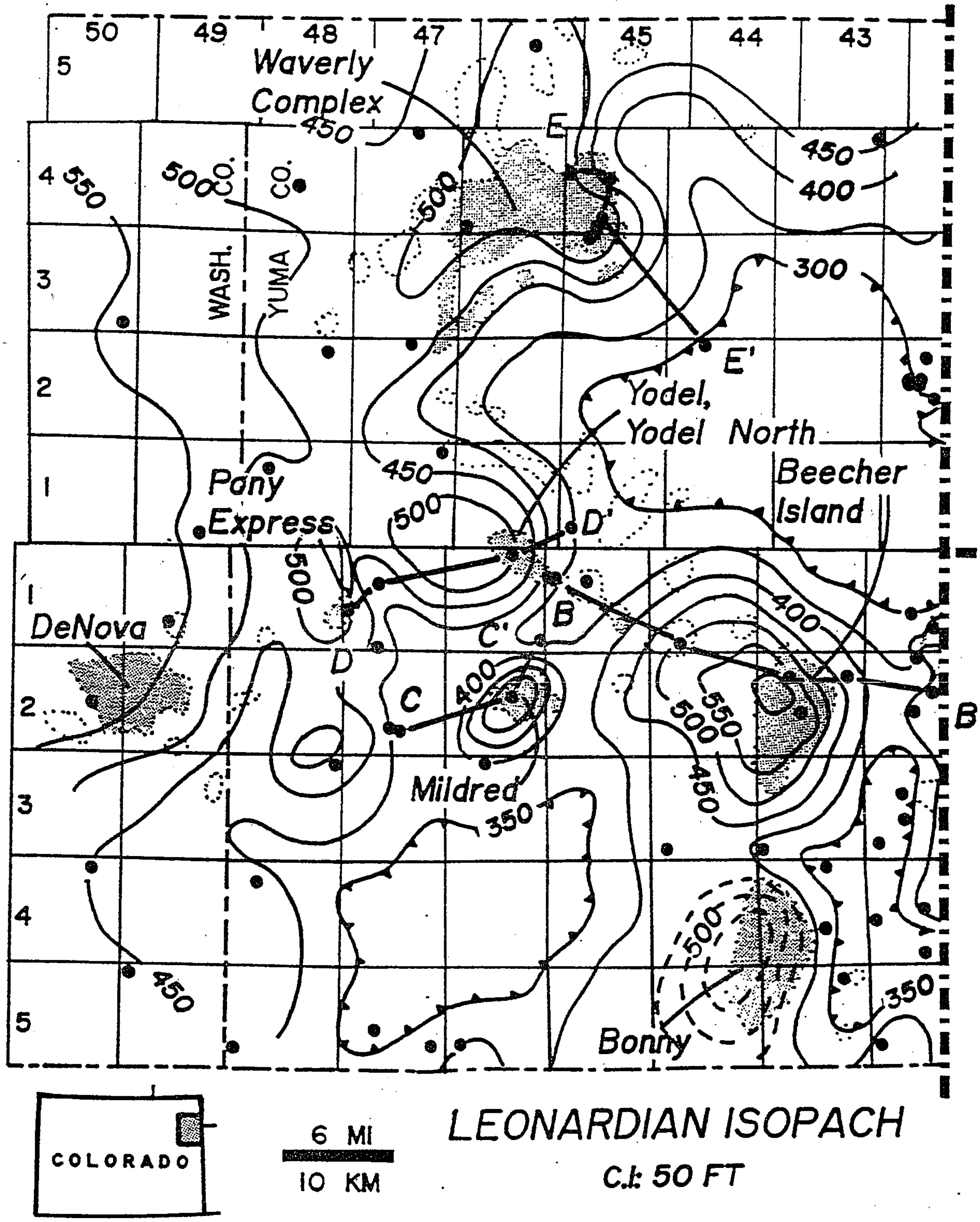


Figure 6-10. Isopach of the Leonardian Series in the shallow Niobrara gas producing area of eastern Colorado. Contour interval 50 ft (15 m).

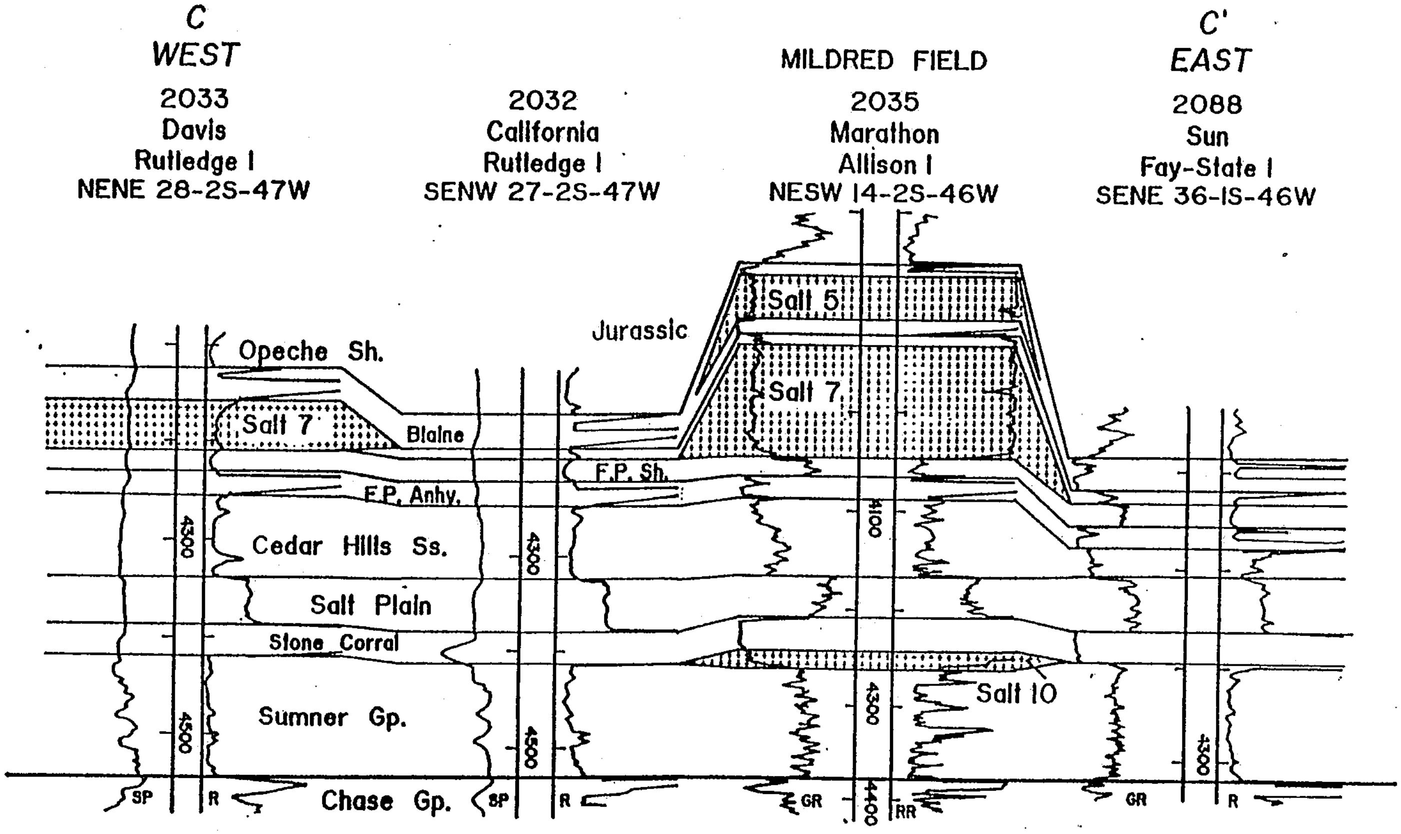


Figure 6-11. Stratigraphic cross section through Permian salt interval in Mildred field area. Datum is top of Wolfcampian Chase Group. Well depths are in feet.

Leonardian thickness variability at Pony Express and Yodel North fields is shown on Figure 6-12. Salts 6 and 7 (25 and 80 ft or 8 and 24 m thick respectively), are present at Pony Express field, where the Leonardian is 501 ft (153 m) thick in well 2040. Just to the northeast, in well 2043, both salts are absent and the Leonardian thins to 426 ft (130 m). Salt 7 is again present at Yodel North field, T1S, R46W, where 130 ft (40 m) of salt results in a Leonardian thickness of 504 ft (154 m) in well 2045. The Leonardian thins to less than 400 ft (122 m) to the east of Yodel North field, including the area of well 2046, where it is only 349 ft (106 m) thick and salt is absent.

Variability in the thickness of the Leonardian Series in the northern part of Yuma County is shown on Figure 6-13, a cross section of the Old Baldy and Eckley fields along the eastern margin of the Waverly complex. The Leonardian thins from 519 ft (158 m) in well 2058, where 110 ft (34 m) of salt 7 and 40 ft (12 m) of salt 10 were encountered below Old Baldy field, to 420 ft (128 m) in well 2057, a dry hole just east of the field in which salt 7 is absent. At Eckley field, in well 2075, the Leonardian is 516 ft (157 m) thick where 110 ft (34 m) of salt 7 and 45 ft (16 m) of salt 10 are present. About 10 ft (3 m) of salt 8, situated at the base of the Flower-pot Shale, were encountered in well 2075 and adjacent deep tests at Eckley field. To the southeast of Eckley field and the Waverly complex, both salts are

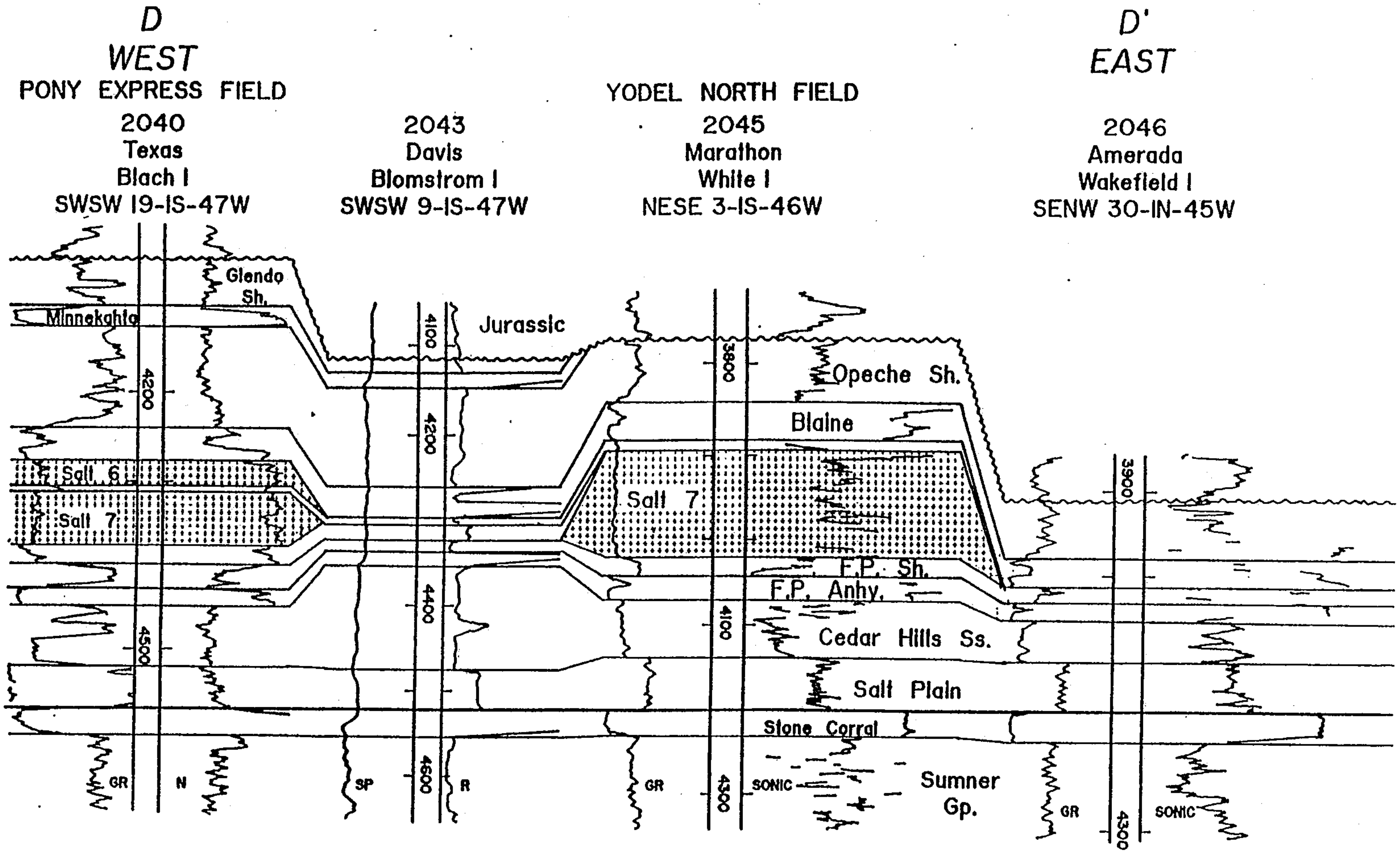


Figure 6-12. Stratigraphic cross section through Permian salt interval below Pony Express and Yodel North fields. Datum is top of Stone Corral Anhydrite. Well depths are in feet.

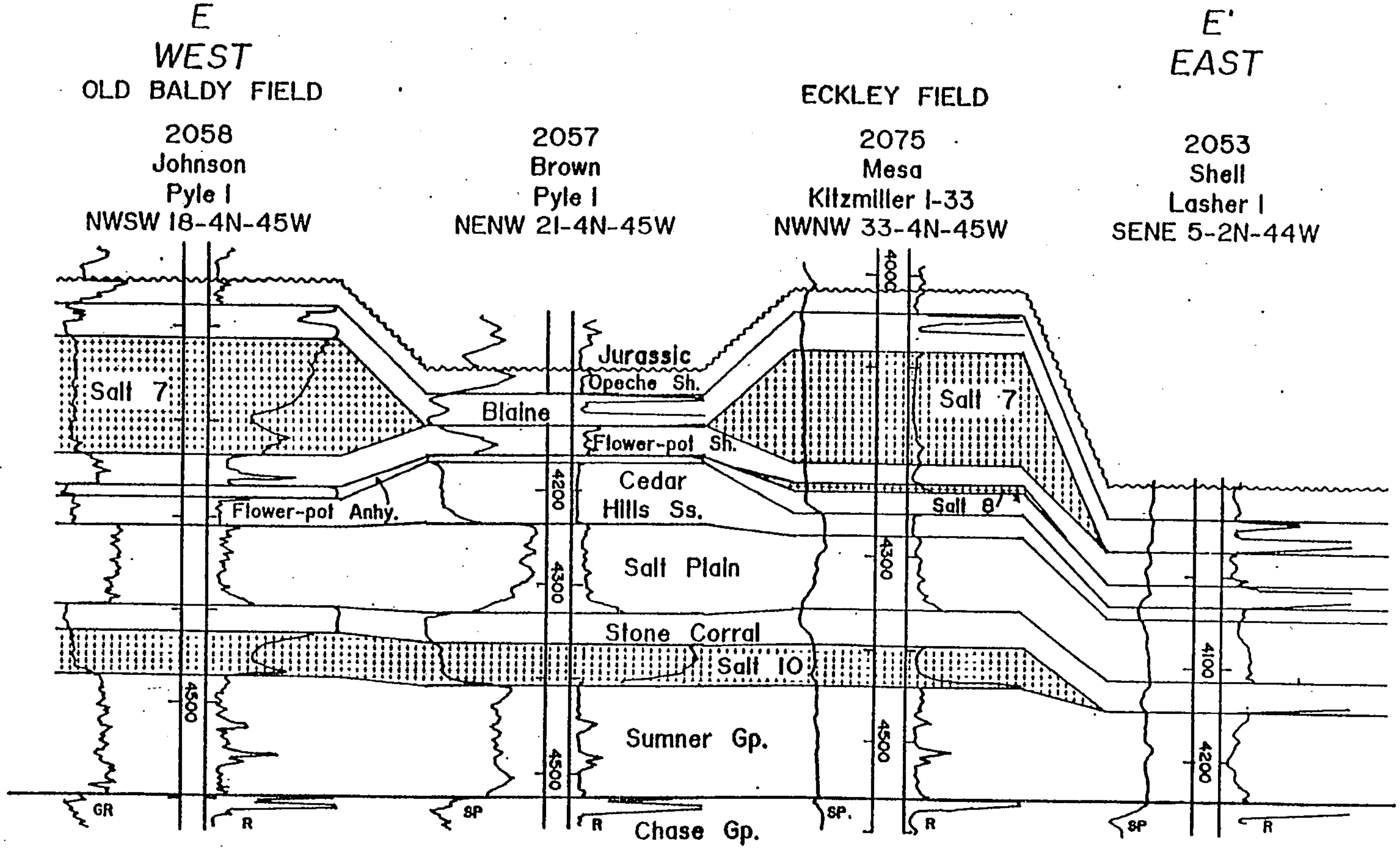


Figure 6-13. Stratigraphic cross section through Permian salt interval below Old Baldy and Eckley fields. Datum is top of Wolfcampian Chase Group. Well depths are in feet.

absent in well 2053, where the Leonardian Series is only 297 ft (91 m) thick. Thinning of Leonardian strata by about 200 ft (60 m) to the southeast of Eckley field (well 2053), interpreted to be caused by dissolution of salt, is about the same as the Niobrara-level structural relief along the southeast margin of Eckley field.

DISTRIBUTION OF SALTS

Salts 4, 5, 6, 7, 8, 9, and 10 have been identified on well logs of deep tests drilled in the shallow Niobrara gas producing area of Yuma County and adjacent areas. Isopach maps of individual salts reveal the relationship between salt occurrence and the location of Niobrara gas fields.

Salt 10 (Figure 6-14), which occurs below the Stone Corral Anhydrite, is over 50 ft (15 m) thick, but is present only in the northern and western parts of the area. Rapid thinning of the salt to the southeast suggests that the present salt margin may represent a northwesterly-retreating dissolution edge and that salt 10 may have originally been present to the southeast. A 15 ft- (5 m-) thick outlier of salt 10 at Mildred field may represent a remnant of salt which has been removed in surrounding wells. Abrupt thinning of salt 10 to the east and southeast of the Waverly Complex, the western part of Schramm field, and the DeNova field may contribute to counterregional dip which is

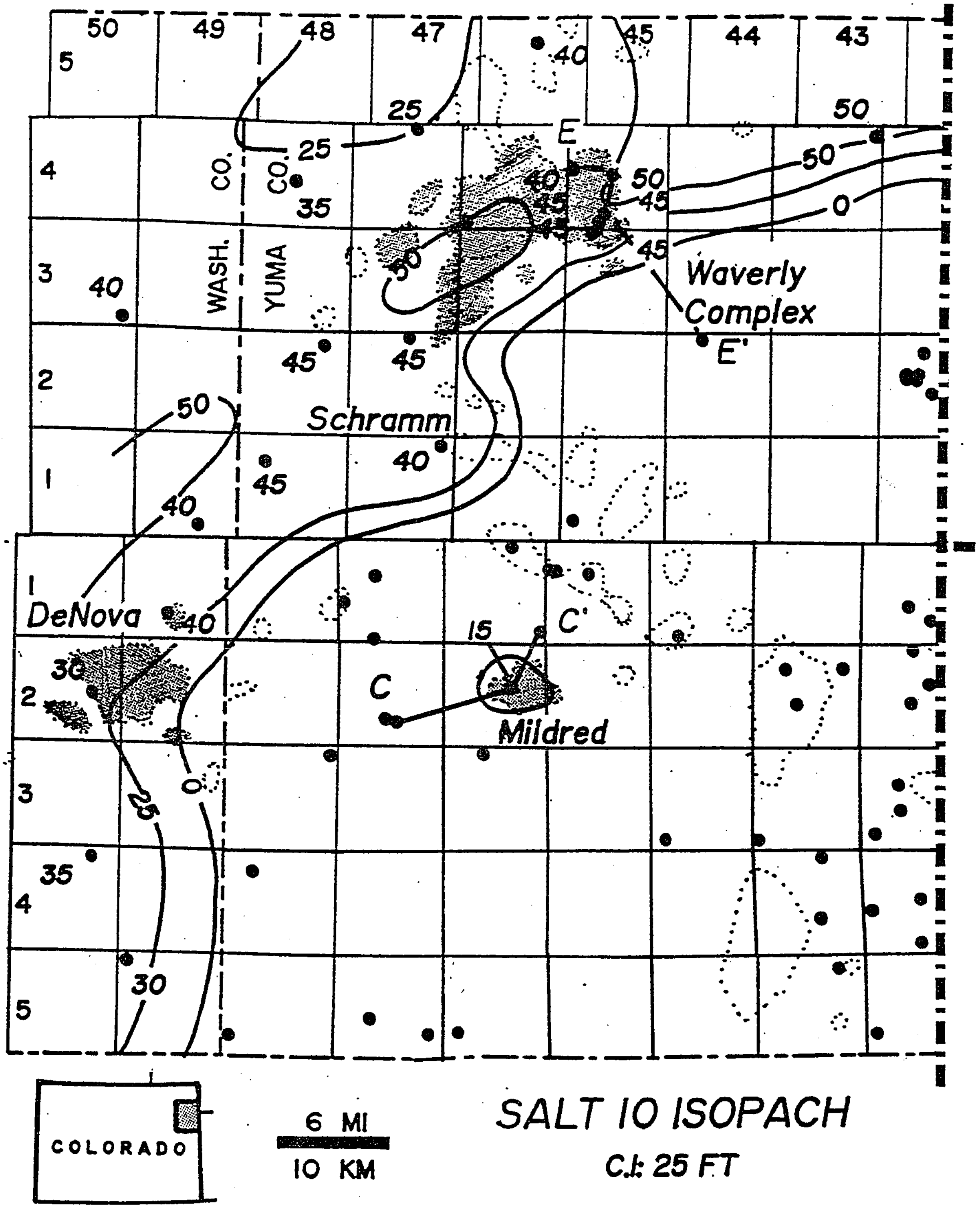


Figure 6-14. Salt 10 isopach. Contour interval 25 ft (8 m).

responsible for commercial gas accumulation in these areas (Figure 6-4).

Salt 9 (Figure 6-15), which occurs below the Flower-pot Anhydrite, has been identified in this area only in an outlier below Beecher Island field, where it exceeds 50 ft (15 m) in thickness, and in eastern Washington County. An outlier of salt 9 is inferred in the Bonny field area on the basis of structural relief across the gas-productive anticline.

Salt 8 (Figure 6-16), which does not exceed 15 ft (5 m) in thickness, is situated at the base of the Flower-pot Shale, and has been identified only in 4 closely spaced wells in the Eckley field area. This salt has not been recognized on well logs elsewhere in the Denver basin beyond this isolated occurrence.

Salt 7 (Figure 6-17), which is situated between a thin shale bed at the base of the lower Blaine Anhydrite and the top of the Flower-pot Shale, is the thickest salt zone identified in the shallow Niobrara producing area and the Denver basin. The salt is over 100 ft (30 m) thick in the Waverly complex area, and at Yodel, Pony Express, and Mildred fields. At Vernon and Beecher Island fields, 125 ft (38 m) of salt 7 was identified on well logs. An outlier of salt 7 is inferred at Bonny field, where the structural relief at the level of the Niobrara (over 200 ft or 60 m) is approximately equivalent to that at Beecher Island field.

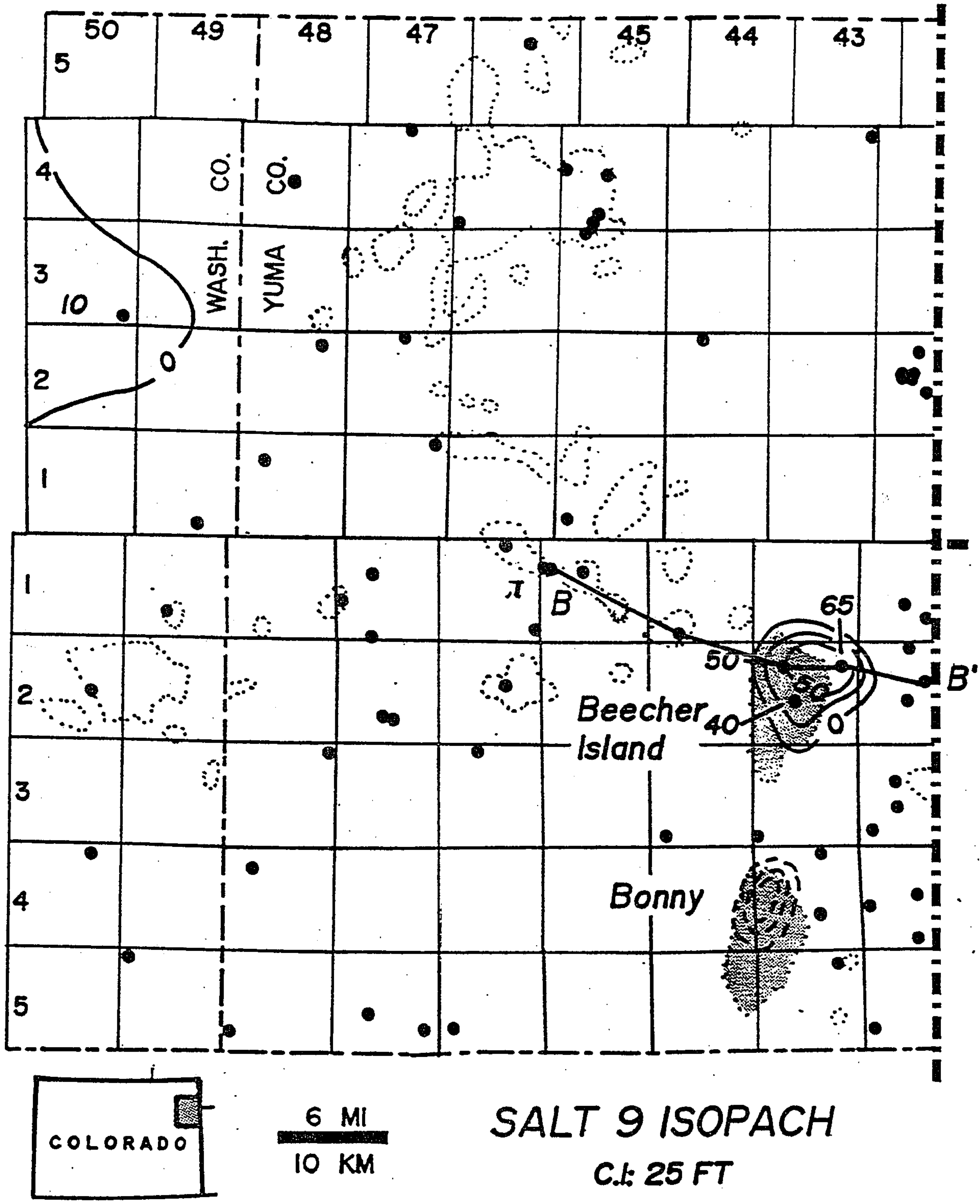


Figure 6-15. Salt 9 isopach. Contour interval 25 ft (8 m).

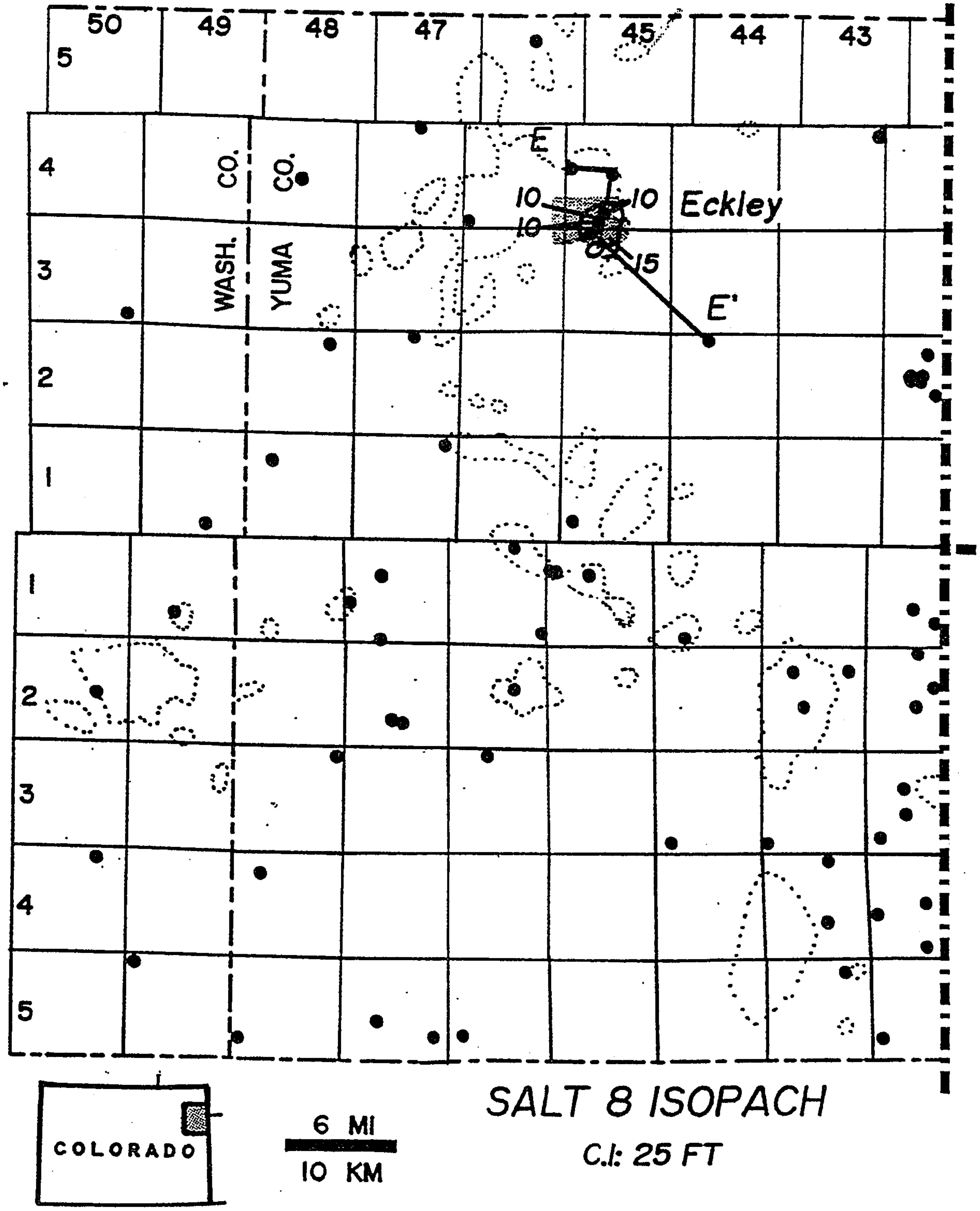


Figure 6-16. Salt 8 isopach. Contour interval 25 ft (8 m).

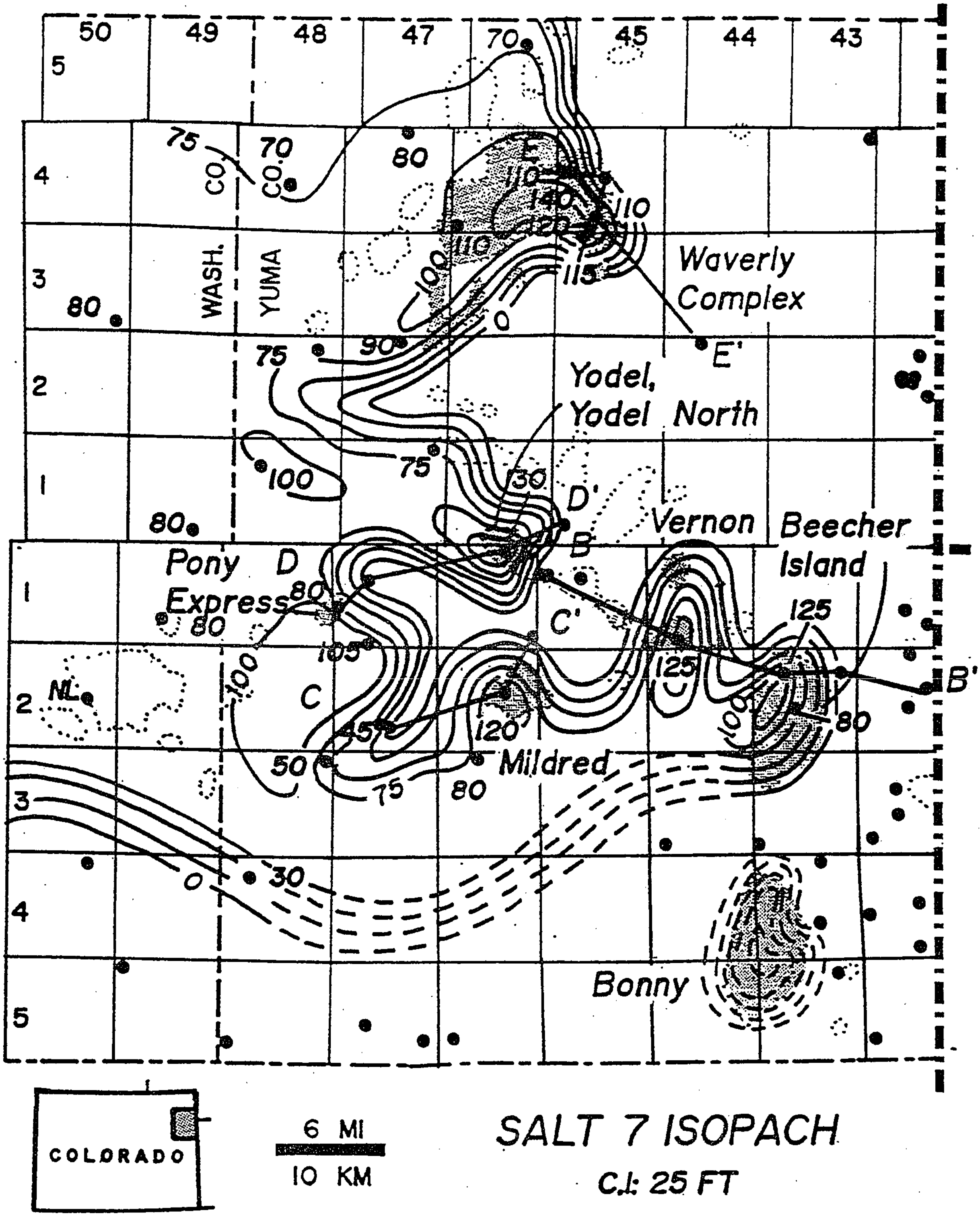


Figure 6-17. Salt 7 isopach. Contour interval 25 ft (8 m).

Abrupt thinning of the salt to the east at the Waverly complex, at Yodel and Pony Express fields, and at Beecher Island field, interpreted to be caused by salt dissolution, results in counterregional dip which forms gas-productive structural traps in these areas (Figures 6-4 and 6-7). It is likely that a similar situation exists to the southeast of Mildred, Vernon, and Bonny fields, where existing deep subsurface control is too sparse to confirm the presence of salt.

Because of its thickness, its complex eastern margin, and abrupt thinning along its margin, salt 7 appears to exert the most influence on Niobrara structure, enhancing closure across gas-productive anticlines which results in increased gas saturation at the top of the gas-water transition zone.

Salt 6 (Figure 6-18), which is found below the lower Blaine Anhydrite, is generally about 10 ft (3 m) thick to the northwest, except at Pony Express field, where 25 ft (8 m) were encountered, and in an area of southcentral Yuma County.

Salt 5 (Figure 6-19), situated between the upper and lower Blaine Anhydrite beds, is present in eastern Washington County, and in what is interpreted as a dissolution remnant at Mildred field, where it is 40 ft (12 m) thick. The eastern limit of salts of Guadalupian and late Leonardian age, including that of salt 5, is regionally

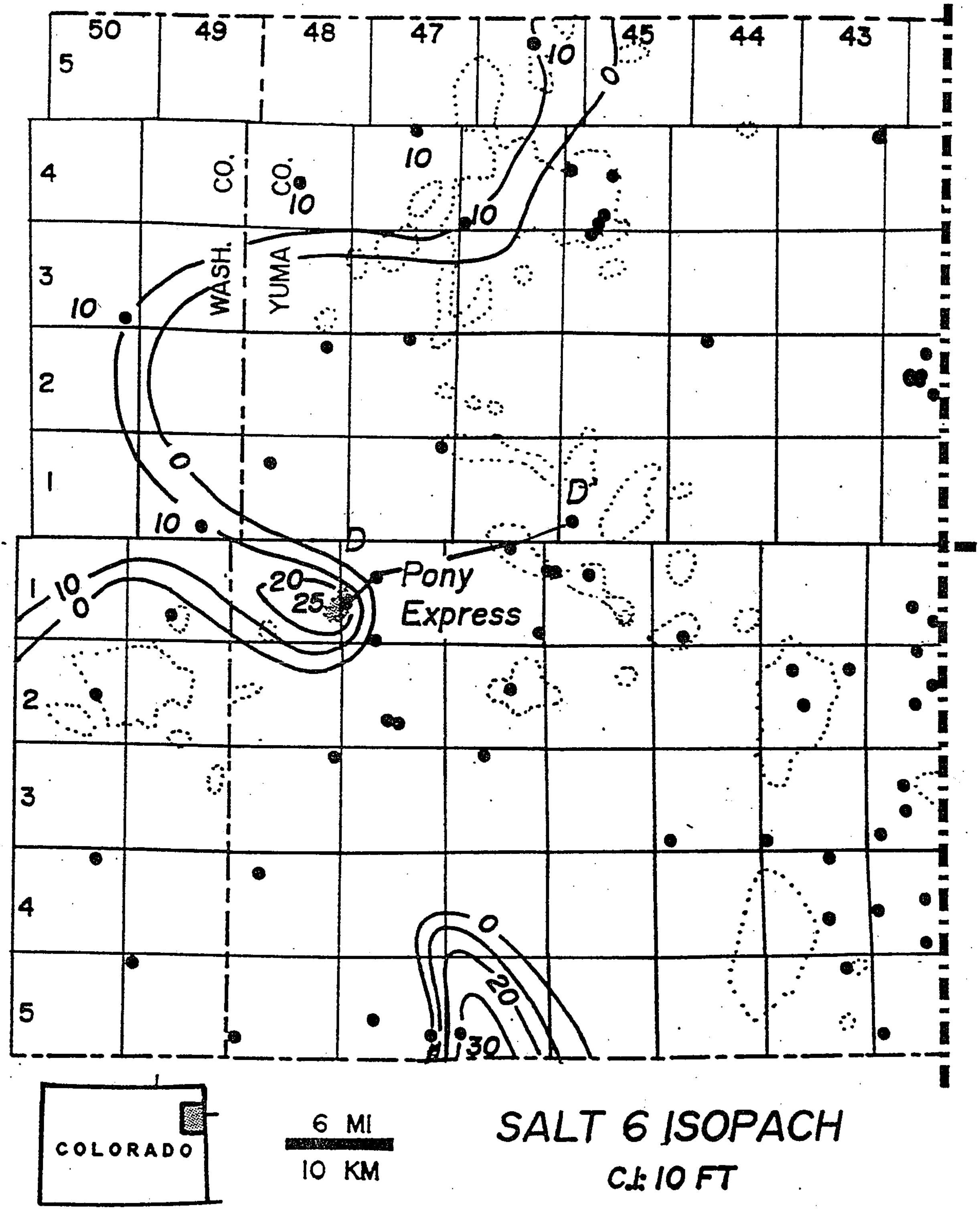


Figure 6-18. Salt 6 isopach. Contour interval 10 ft (3 m).

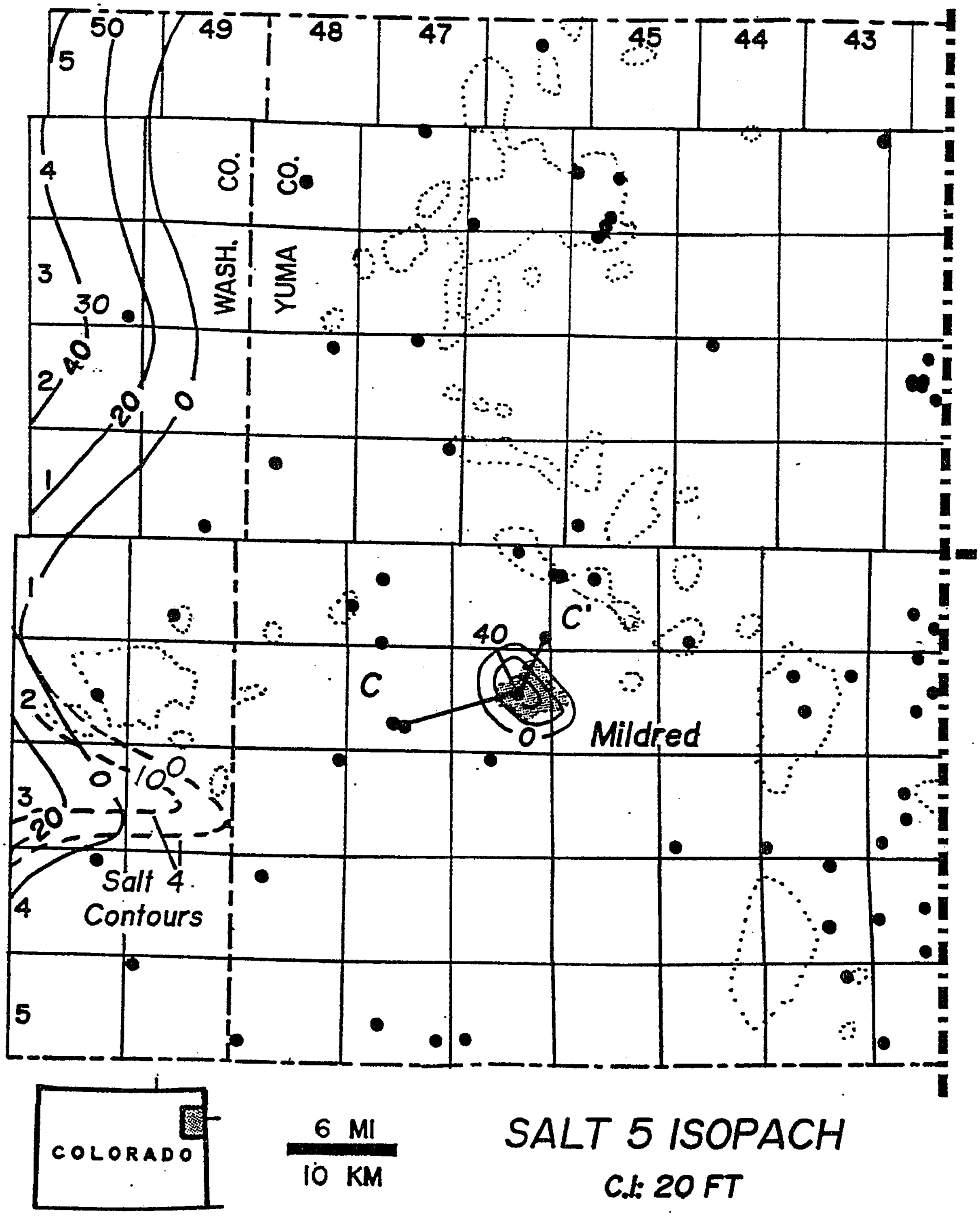


Figure 6-19. Salt 5 isopach. Contour interval 20 ft (6 m). Salt 4 contours are shown in western part of mapped area.

controlled by erosion or near-surface dissolution below a pre-Late Jurassic unconformity (Chapters 3 and 8). This isolated occurrence of salt 5 at Mildred field is in an area where the overlying Opeche shale has been partially truncated below the unconformity. Apparently, near-surface removal of salt was incomplete in this isolated area. Salt 5 contributes 40 ft (12 m) of structural relief to the gas-productive Mildred anticline, which is also influenced by salts 10 and 7 (Figures 6-11, 6-14 and 6-17).

Salt 4, situated above the upper Blaine Anhydrite, is limited in this area to one well in the DeNova field area (Figure 6-19).

Figure 6-20, a north-south structural cross section through Yuma County from Waverly field to Bonny field, a distance of about 70 mi (110 km), demonstrates the regional relationship between Permian salts and gas-productive anticlines at the level of the Niobrara Formation. Salts 7 and 10 are present below Niobrara production at Waverly and Old Baldy fields (wells 2087 and 2058). The syncline which separates Old Baldy and Eckley fields, in which well 2057 was drilled, is caused by dissolution of salt 7 and resultant collapse of overlying strata. Both salts 7 and 10 are present below Eckley field (well 2075), along with a thin salt 8. Counterregional (southeast) dip at the south limit of Eckley field is caused by the abrupt thinning of salts 7, 8, and 10 due to dissolution.

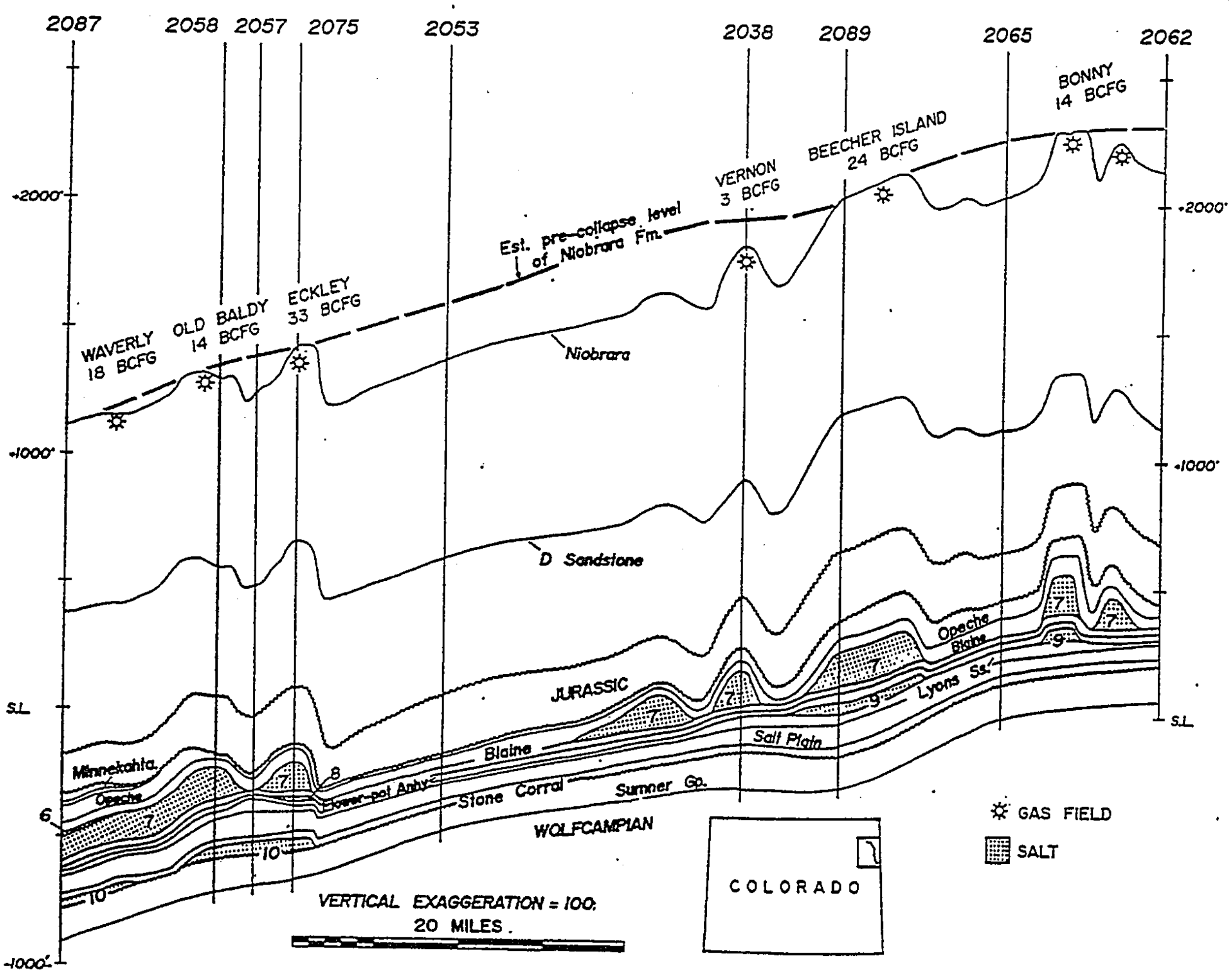


Figure 6-20. Regional structural cross section from Waverly complex southeast to Bonny field, showing relationship of Niobrara structure to Permian salt dissolution remnants. Line of cross section shown on Figure 6-4.

Eckley field has the highest cumulative production of all shallow Niobrara gas fields in eastern Colorado (33 BCFG) as well as the highest per-well production in the Waverly complex (over 358,000 MCFG/well compared with an average of 215,000 MCFG/well for all wells in 9 fields in the Waverly Complex and adjacent areas). Its high structural position along the southeastern (regionally updip) limit of production in this area places it at an elevation in the upper part of the gas-water transition zone, which enhances gas saturation and results in higher-yield wells.

South of Eckley field, no salt is present in well 2053, and only regional northwest dip is present at the level of the Niobrara north and south of well 2053, suggesting that this is an area which may be entirely devoid of salt due to removal by dissolution.

Salt 7 is present below Vernon field in well 2038 (Figure 6-20). Synclines which flank Vernon field are interpreted to be formed by dissolution of salt 7 and collapse of overlying strata (including the Niobrara). Salts are present at Beecher Island field (well 2089), but are absent in a syncline (well 2065) which separates the field from Bonny Field to the south. Although no deep tests have been drilled in Bonny field, the presence of salts 7 and 9 at depth is inferred on the basis of Niobrara structural relief (about 200 ft or 60 m), which is equivalent to the relief at Beecher Island field and approximates the combined thickness of salts 7 and 9 (175 ft or 53 m). No salt was encountered in well 2062, drilled in a syncline to the south of the Bonny structure.

Coincidence of high-relief gas-productive anticlines with the occurrence of thick salt at depth indicates that much of the removal of salt post-dated the deposition of Niobrara Chalk. Estimated pre-collapse position of the Niobrara is shown on Figure 6-20 as a dashed line. Collapse synclines, interpreted to be caused by post-Niobrara salt removal, are present between Niobrara gas fields.

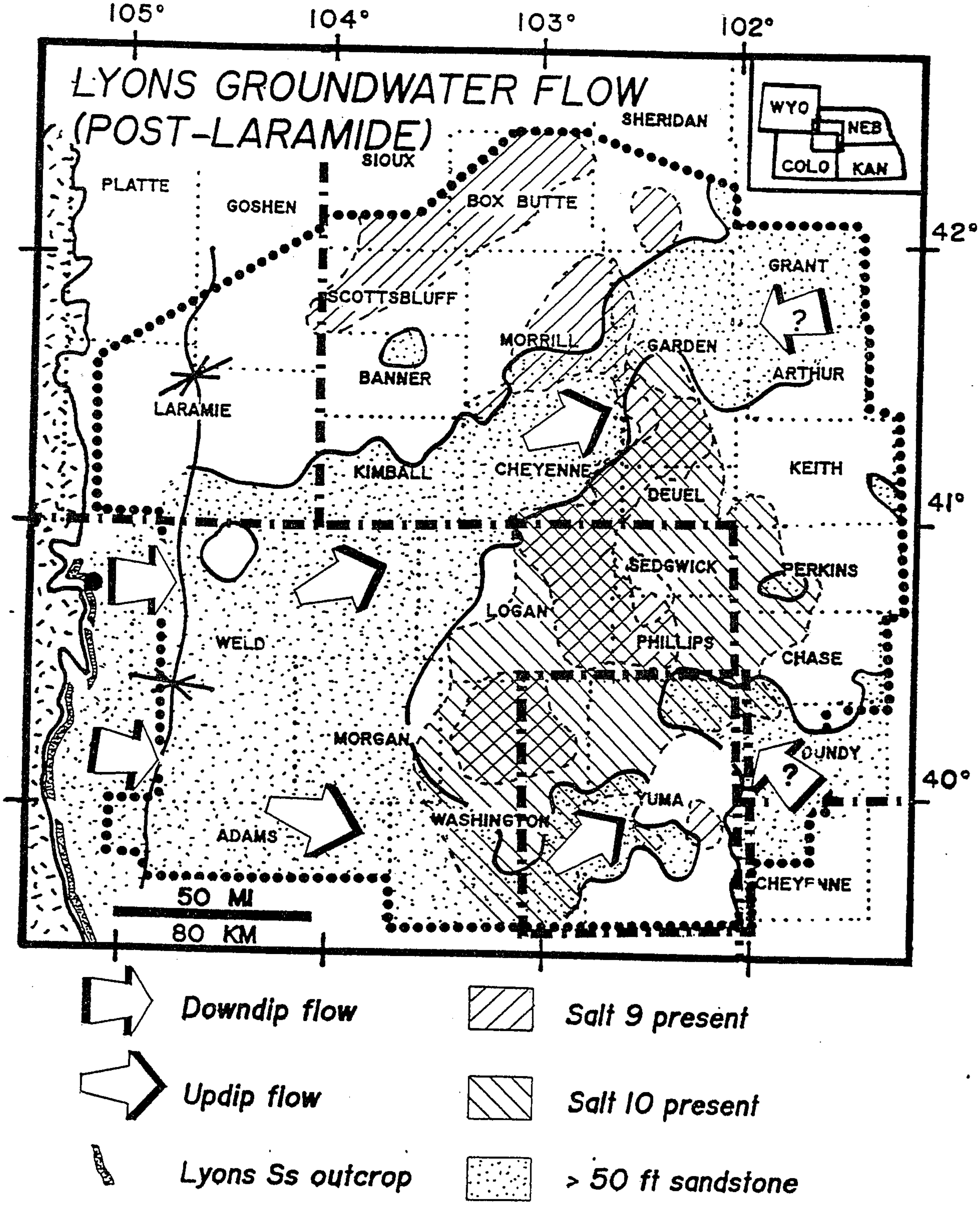
SALT DISSOLUTION MODEL

Eastward-directed groundwater flow within the Lyons Sandstone regional aquifer, in response to Laramide (Late Cretaceous - Eocene) uplift along the Front Range, is discussed in Chapter 4 as a probable mechanism for removal of salt in the Sidney trough area of western Nebraska. 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 supplied relatively fresh water to the Leonardian salt interval at its abrupt facies change to sandstone (Figures 4-23, 4-28, and 4-29). 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 Cretaceous-level structural relief across the regional depression. Incomplete removal of salt in areas marginal to the Sidney trough created salt-cored anticlines which produce oil and gas from the D and J Sandstones.

Post-Laramide removal of salt in the western Nebraska part of the D-J fairway was concentrated in areas where thick Lyons Sandstone abruptly pinches out to the east (updip) into thick Leonardian salt. A similar situation exists in the Yuma County, Colorado, area (Figure 6-21) and may explain the removal of salt below shallow Niobrara gas fields.

The Lyons (Cedar Hills) Sandstone is stratigraphically equivalent to salt 9 in Yuma County. Salt 10 (associated with the Stone Corral Formation) occurs at a stratigraphic position which is lower than the Lyons - Cedar Hills in Yuma County and adjacent areas.

Evidence as to the source of fluids responsible for salt dissolution includes recognition of incomplete dissolution of multiple salt beds. Two simplified situations may exist. In the first case, localized removal of an upper salt without disturbance of deeper salt(s) may indicate a shallow source of water or a source of water which is situated between the overlying (dissolved) salt and



(Levandowski et al. 1973)

Figure 6-21. Interpreted regional groundwater flow within Lyons aquifer. Eastern Colorado Niobrara gas area is highlighted.

the underlying (preserved) salt. A second possibility exists, wherein localized removal of a lower salt without disturbance of upper salt may indicate a deep source of water, or, as above, a source of water between the upper and lower salts. In western Nebraska, presence of deeper salt below the Sidney trough collapse area (Figures 4-18 and 4-19) is taken as evidence that fluids were not introduced from a deep (subsalt) source, and that the likely source was the Lyons, situated within the salt interval.

Examination of the Old Baldy - Eckley field cross section (Figure 6-13) reveals that salts 7 and salt 10 are present below both fields. However, in the syncline which separates the two fields, drilled by well 2057, salt 10 is present, but salt 7 is absent. This suggests a source of water responsible for the localized removal of salt from either above salt 7 or between salt 7 and salt 10. A likely formation to introduce fluids into this area is the Lyons-Cedar Hills Sandstone.

Salt 5, 7, and 10 remain as outliers below Mildred field (Figure 6-11). Removal of all three salts in marginal areas is complete. As a result, inferences as to the source of dissolving fluids are not possible. A similar situation exists at Pony Express and Yodel fields (Figure 6-12).

Although removal of salts 7 and 9 at Vernon and Beecher Island fields (Figure 6-9) is incomplete, there is no consistent pattern. At the center of Beecher Island field (well 2089), both salts are present. Just to the east of the Beecher Island structure (well 2079), salt 9 is present, but salt 7 has been removed. At Vernon field, salt 7 is present, but salt 9 is absent. This complex salt pattern suggests that several factors may have contributed to localized removal of salts, including multiple stages of dissolution, localization of vertical fractures, and heterogeneity of regional aquifer(s) which introduced the dissolving fluids.

Additional evidence as to the flow of water from salts involves formation water salinity anomalies. Several factors can influence formation water salinity, including chemistry of connate water and concentration and dilution effects due to compaction of fine-grained sediments. 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.

Formation water salinity in the D and J Sandstones of western Nebraska is higher in areas where salt removal post-dated deposition of the reservoirs (Chapter 4). High-salinity formation water within Cretaceous reservoirs may be due to upward migration of salt solution-derived brines. Because there have been very few wells drilled deeper than the Niobrara in Yuma County, and because no D or J Sandstone production exists in this area, no formation water salinity data are available.

Thickness of the Lyons-Cedar Hills Sandstone (Figure 6-22) ranges from less than 10 ft (3 m) to about 130 ft (40 m) in Yuma County. Sandstone is thinnest in a north-south-trending area just east of Beecher Island and Bonny fields. Sandstone is also thin in the Waverly complex area.

Salt 9 and the top of the Lyons-Cedar Hills Sandstone occupy the same stratigraphic position (between the Flowerpot Anhydrite and the Salt Plain Formation). Regional isopach patterns (Chapter 8) reveal that there is a general inverse relationship between sandstone thickness and thickness of salt 9 across the basin.

The Lyons-Cedar Hills, which accumulated in eolian and shallow water environments (Sonnenberg and Weimer, 1981), is thicker in areas along and immediately adjacent to paleohighs associated with the Transcontinental arch to the northwest of Yuma County, and on the Yuma high of Sonnenberg and Weimer (1981). The Yuma high may be related to Maughan and Perry's (1986) northeast-trending Cañon City lineament (Figure 2-3). Finer-grained sediments, including those of the Salt Plain Formation, along with salts accumulated in adjacent evaporite basins.

In Yuma County, a likely area in which thick salt 9 may have originally precipitated is a north-south-trending area in the southeastern part of the county, just east of Beecher

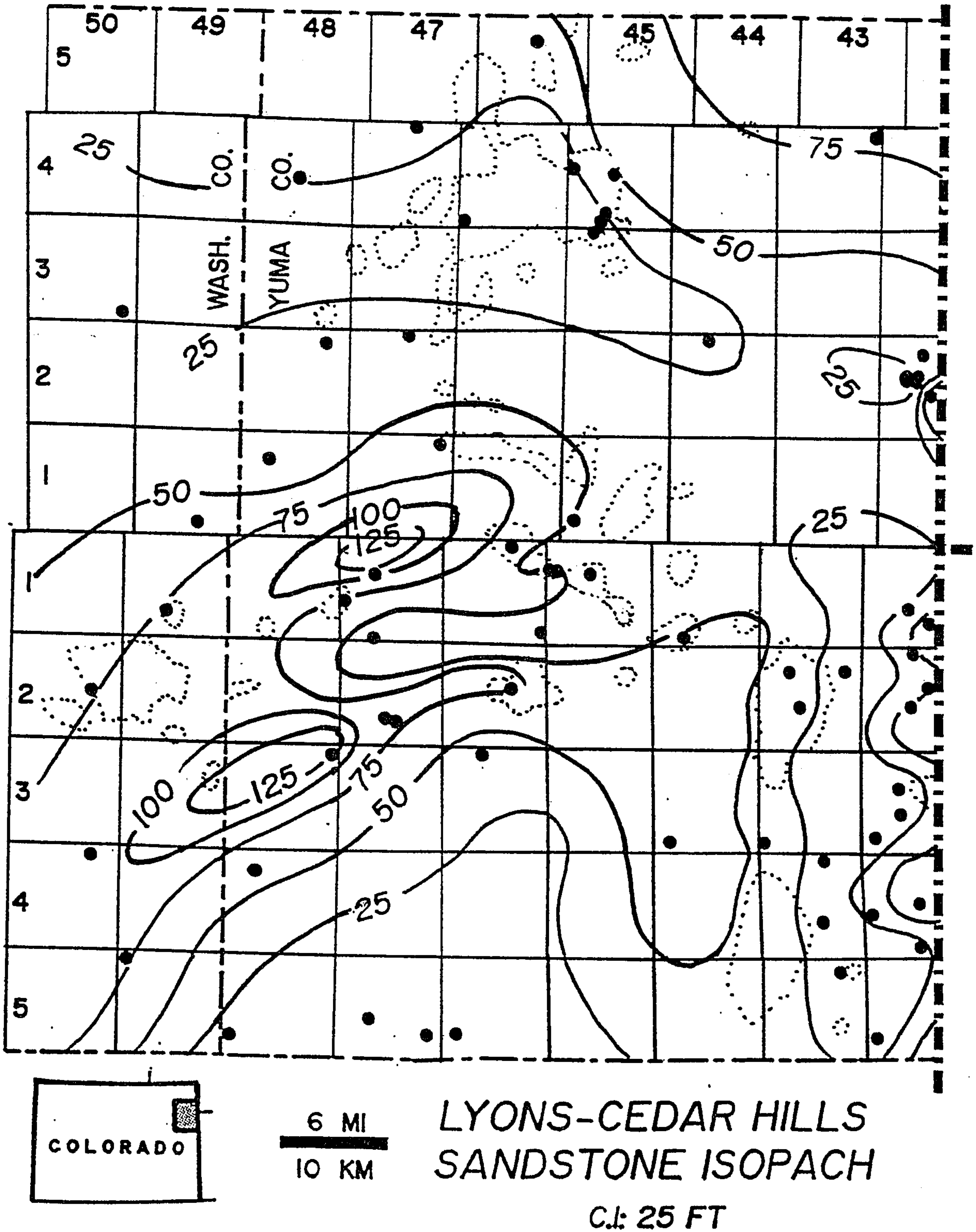


Figure 6-22. Isopach of Lyons-Cedar Hills Sandstone. Contour interval 25 ft (8 m).

Island and Bonny fields, where the Lyons-Cedar Hills is less than 25 ft (8 m) thick. However, salt 9 is present on well logs of only 3 deep tests in in the Beecher Island field area (Figure 6-9), suggesting that substantial removal of salt 9 may have occurred in this area.

Another possible area in which Lyons-Cedar Hills deposition may have influenced salt accumulation is in the area of the Waverly complex extending to the southeast in the northern part of the county, where sandstone is less than 25 ft (8 m) thick. Although salt 9 has not been identified in this area, salt 8 was encountered in deep tests drilled in the Eckley field at the southeastern limit of the Waverly complex (Figures 6-13 and 6-16). This is the only place within the Denver basin study area where salt 8 has been identified. It is possible that salt 8 (and perhaps salt 9) originally extended over a larger part of this paleolow.

Assuming that the Lyons-Cedar Hills Sandstone was a major source of salt-dissolving groundwater, the following discussion offers an explanation for dissolution-induced collapse responsible for the general distribution of Niobrara gas fields in Yuma County, particularly those whose structural closure appears to be related to the presence of salts 9 and 7, the two thickest salts encountered in this area.

With the onset of Laramide 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. 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 6500 ft (2000 m) higher than its elevation of about 1000 ft (300 m) below sea level in northwestern Yuma County and about 5200 ft (1600 m) higher than its elevation of about 300 ft (100 m) above sea level in southeastern Yuma 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). Flow would have been directed within thick, permeable Lyons conduits in two areas on the basin's eastern flank (Figure 6-21): the D-J fairway of western Nebraska, and 2) the Yuma County area.

Laramide-induced eastward flow within the Lyons-Cedar Hills aquifer is shown on Figure 6-23. In Yuma County, regional eastward flow would have been restricted by thickness and permeability variations related to facies change from porous sandstone to salt 9. As a result of

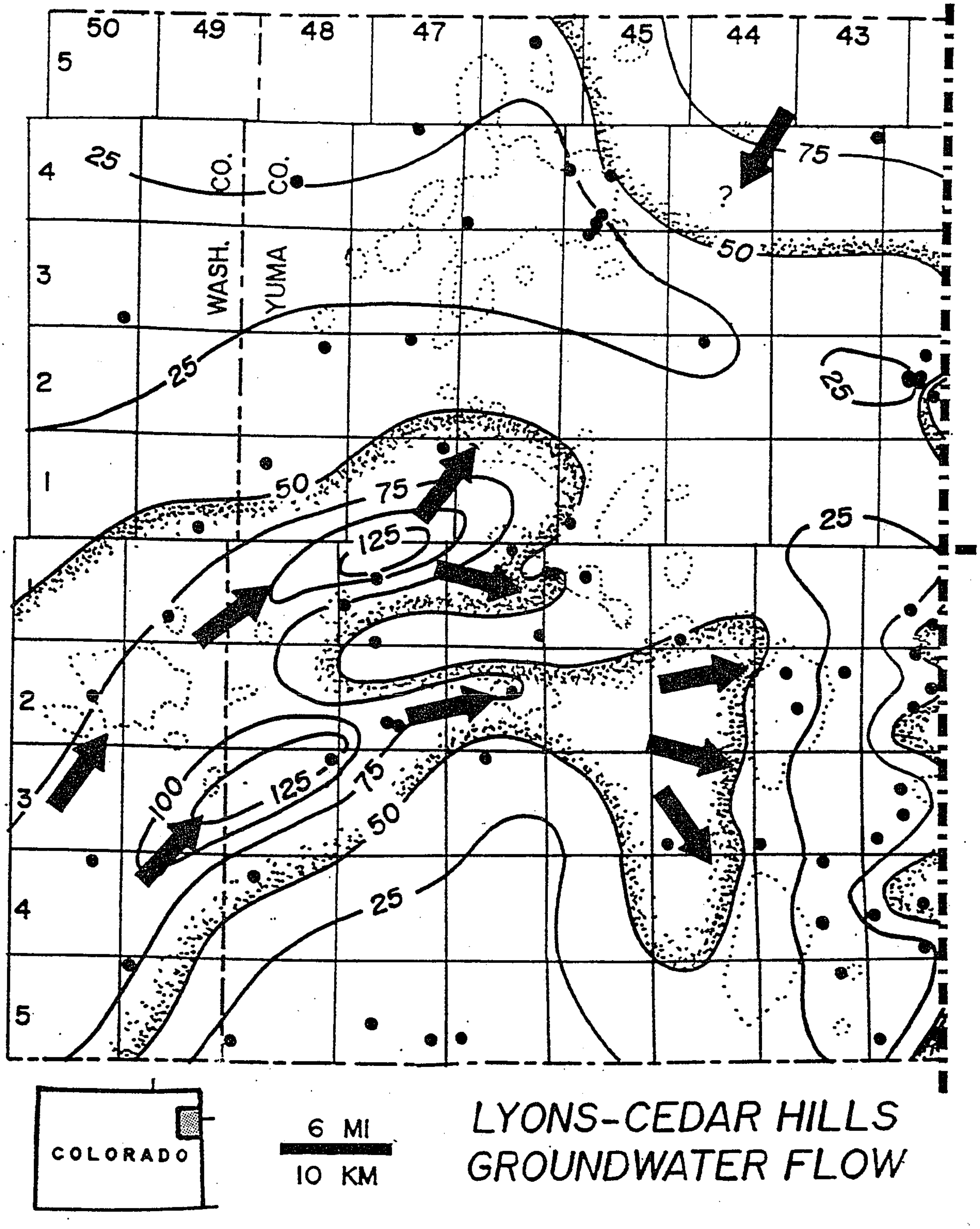


Figure 6-23. Interpreted Laramide-induced groundwater flow within Lyons-Cedar Hills regional aquifer in Yuma County.

reduced thickness and permeability of the aquifer, gravity-driven groundwater would flow vertically from the Lyons-Cedar Hills through fractures into adjacent strata.

Areas in which sandstone thickness and permeability are reduced (Figure 6-23) are spatially related the location of many of the larger Niobrara gas fields. These include the Waverly complex and Beecher Island and Bonny fields, where dissolution of thick salt 7 has affected the relief of gas-productive anticlines. Upward-directed flow of groundwater from the Lyons-Cedar Hills presumably caused incomplete dissolution of salt 7 (and possibly other salts) initially along a trend of reduced Lyons thickness and permeability (estimated on Figure 6-23 as areas of less than 50 ft (15 m) of sandstone). Continued incomplete removal of salt occurred away from sites of initial dissolution, resulting in solution collapse and a distribution of Niobrara gas fields that generally follows the 50-ft (15-m) Lyons-Cedar Hills isopach.

Depositional and post-depositional controls on the occurrence of Permian salts and their influence on the distribution of Niobrara gas fields are depicted on Figure 6-24, a simplified model across Yuma County. Salts 10 and 9 accumulated in evaporite basins whose configurations were influenced by subtle basement movement (Figure 6-24a). Eolian and shallow-water sands (Lyons-Cedar Hills Sandstone) accumulated on and adjacent to subtle paleohighs. Original

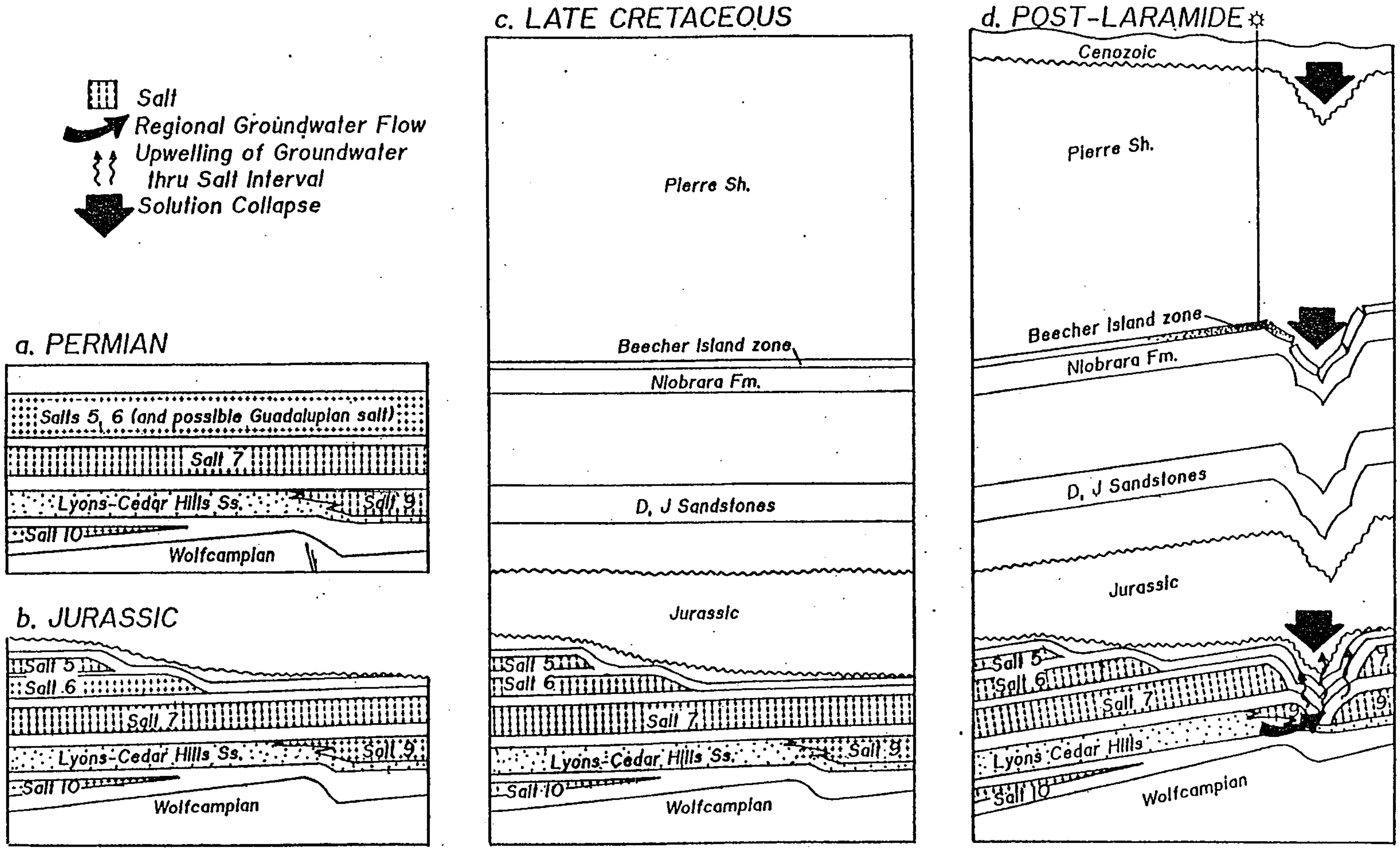


Figure 6-24. Simplified model for depositional and post-depositional controls on salt distribution and its influence on distribution of Niobrara gas fields. No scale.

distribution of late Leonardian salts, including salt 7 and possibly salts 6 and 5, was influenced less by subtle tectonics. Precipitation of Guadalupian salts, including salts 4, 3, 2, and 1, this far southeast is speculative.

Pre-Late Jurassic erosion and near-surface dissolution removed salts 6 and 5 (and, possibly, younger salts) to the east (Figure 6-24b). Permian salts and related strata were buried by at least 4000 ft (1200 m) of sediment (Figure 6-24c), represented by shales and sandstones of the Upper Jurassic Morrison Formation, Lower Cretaceous marine shales and nonmarine sandstones (including the D and J Sandstones), and thick sequences of Upper Cretaceous marine limestones and shales (including the Niobrara Formation and Pierre Shale).

Laramide (Late Cretaceous - Eocene) uplift along the Front Range caused eastward-directed gravity-driven groundwater flow through the Lyons-Cedar Hills regional aquifer (Figure 6-24d). Salt 9, where present, was dissolved along the regional facies change. Reduction in sandstone permeability due to thinning and facies change, coupled with salt 9 dissolution-induced fracturing of overlying strata, allowed for upwelling of groundwater and dissolution of overlying salt(s), including thick salt 7. Fractures, formed by continued collapse, acted as conduits for further introduction of water and continued salt removal. Collapse of overlying strata, including the

Niobrara Formation, resulted in the formation of salt-cored faulted anticlines on which biogenic gas accumulated.

EXPLORATION IMPLICATIONS

The above discussion supports the hypotheses that post-Niobrara dissolution of Permian salts caused collapse of overlying strata and that Cretaceous-level structure in Yuma County and adjacent areas is rootless. Because dissolution was incomplete, isolated salt-cored structural highs exist on which Niobrara gas production occurs.

On a regional scale, one of the more significant relationships between Niobrara production and Permian salt-bearing strata is the occurrence of Leonardian isopach maxima (Figure 6-10) in areas of Niobrara gas production. Where salt has been locally preserved, Leonardian strata are over 500 ft (150 m) thick. These include the Waverly, Yodel, Pony Express, Mildred, Vernon, and Beecher Island field areas. Combined cumulative production from these fields exceeds 110 BCFG, nearly 80 percent of the Niobrara production total for Yuma County.

Until the early 1970s, the Niobrara was overlooked as a commercial source of gas, due to its low permeability and low resistivity on well logs. Prior to the first commercial discovery and development of Niobrara gas at Beecher Island field in 1972, 50 Paleozoic tests had been drilled in Yuma

County and six deep tests had been drilled in townships 49W and 50W in Washington County. Since 1972, only 14 additional Paleozoic tests were drilled in Yuma County.

Figure 6-25 is an isopach of the Leonardian Series which was contoured using only pre-1972 deep well control. This map was prepared to determine if sufficient data were available prior to commerical development at Beecher Island field to identify prospective Niobrara trends based on the location of Leonardian isopach maxima.

Only minor changes from the interpretation shown on Figure 6-10 (which is based on all currently available deep control) result from excluding post-1972 control. Isopach maxima are still present in areas which would later prove to be gas-productive, including the Waverly complex and adjoining areas, Yodel field, Pony Express field, Mildred field, Vernon field, and Beecher Island field.

This relationship between thickness of salt-bearing Permian strata and Niobrara gas production should exist in other areas of the Denver basin, including areas of established production from the D and J Sandstones as well as relatively underexplored parts of the basin. Chapter 9 discusses additional areas of the Denver basin which have been structurally influenced by dissolution of Permian salt and are potentially favorable for exploration for salt dissolution-influenced Niobrara gas accumulations.

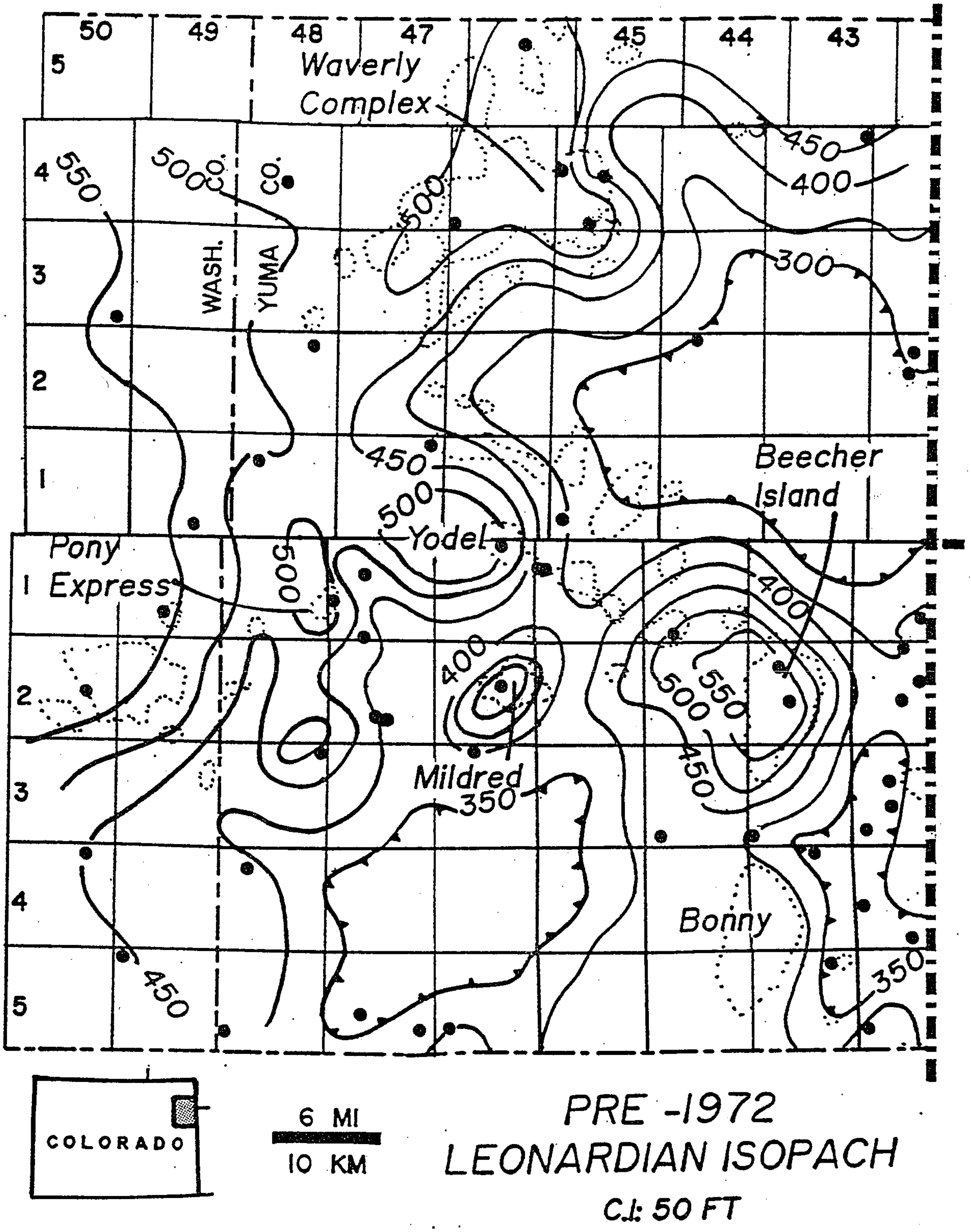


Figure 6-25. Pre-1972 Leonardian isopach. Contour interval 50 ft (15 m).

SUMMARY AND CONCLUSIONS

This chapter focused on the influence of Permian salt dissolution on the distribution of shallow Niobrara gas fields in Yuma County and eastern Washington County, Colorado. Subsurface analysis of the distribution and thickness of Permian salts and the Lyons-Cedar Hills Sandstone relative to the occurrence of Niobrara gas accumulations leads to the following conclusions:

1. Of 13 salt zones of Guadalupian, Leonardian, and late Wolfcampian age identified in a Denver basin subsurface study, 7 zones have been identified in the shallow Niobrara gas area of eastern Colorado. With the exception of one Guadalupian salt (salt 4), salts are within the Nippewalla Group (Leonardian) and include salts 5, 6, 7, 8, 9, and 10.

2. Younger, Guadalupian-age salts (salts 1,2, and 3) are absent in this part of the Denver basin. If originally present, these younger salts (as well as Triassic rocks) have been removed by erosion or near-surface dissolution below a pre-Late Jurassic unconformity. Distribution of salts 5 and 6, which occur only in the western part of the Yuma County study area, was likely affected by pre-Late Jurassic truncation.

3. Thick salts occur below Niobrara production. No significant Niobrara production exists in areas where salt

is absent. Structural relief on faulted, gas-productive anticlines is related to thickness changes in the Leonardian Series, which are caused by incomplete post-Niobrara dissolution of salt.

4. Significant dissolution took place in response to Laramide (Late Cretaceous-Eocene) orogeny. Although fluids may have been introduced through fractures associated with Laramide faulting, a more likely source of water is the Lyons-Cedar Hills Sandstone. Eastward gravity-driven flow of water within the Lyons-Cedar Hills, a regional aquifer, occurred in response to hydraulic gradient and recharge along the Front Range uplift.

5. Due to regional permeability reduction, groundwater may have been forced out of the Lyons-Cedar Hills Sandstone, migrating to the salt interval. Introduction of water caused incomplete salt dissolution and collapse of overlying strata, enhancing fracturing which exposed younger salts, including thick salt 7, to Lyons-Cedar Hills groundwater. This resulted in further collapse of overlying strata.

6. Thickness of salts which have been subjected to dissolution may be important in controlling the amount of gas trapped within the Niobrara. Where thick salts are preserved, structural relief is greater, the gas-water transition zone is thicker, and gas saturation is higher at the crests of the faulted anticlines.

7. Sufficient deep well control existed prior to commerical development of the Niobrara play in the early 1970s to identify general potentially favorable areas for Niobrara exploration. Subsurface mapping of salt-related Permian thickness trends, including a Leonardian isopach and isopachs of individual salts, reveals that isopach maxima are associated with gas accumulations in the overlying Niobrara Formation. A similar relationship may exist in other parts of the Denver basin where salts have been subjected to dissolution and where Niobrara chalk is of sufficient thickness, porosity, and gas saturation to have commercial potential. Potentially favorable trends outside of the main Niobrara shallow gas area are discussed in Chapter 9.

CHAPTER 7
ECKLEY NIOBRARA GAS FIELD, YUMA COUNTY, COLORADO

INTRODUCTION

Eckley field, located in north-central Yuma County (Figure 7-1), has produced more gas than any other shallow Niobrara gas field in eastern Colorado. Discovered in 1978, the field has produced over 33 BCFG through 1993. Gas production is from porous chalk in the "Beecher Island zone" (Lockridge, 1977) at the top of the Smoky Hill Member of the Upper Cretacous Niobrara Formation.

Regional relationships between dissolution of Permian salt and the distribution of shallow Niobrara gas fields in eastern Colorado are discussed in Chapter 6 of this report. Collapse of overlying strata, including the Niobrara, in response to salt dissolution is considered to be the primary factor contributing to structural relief across faulted anticlines in which gas has accumulated. This chapter deals specifically with the influence of Permian salts on trap formation and Niobrara gas production at Eckley field. Reflection seismic data are used to support a salt dissolution origin for the gas-productive structure at Eckley field.

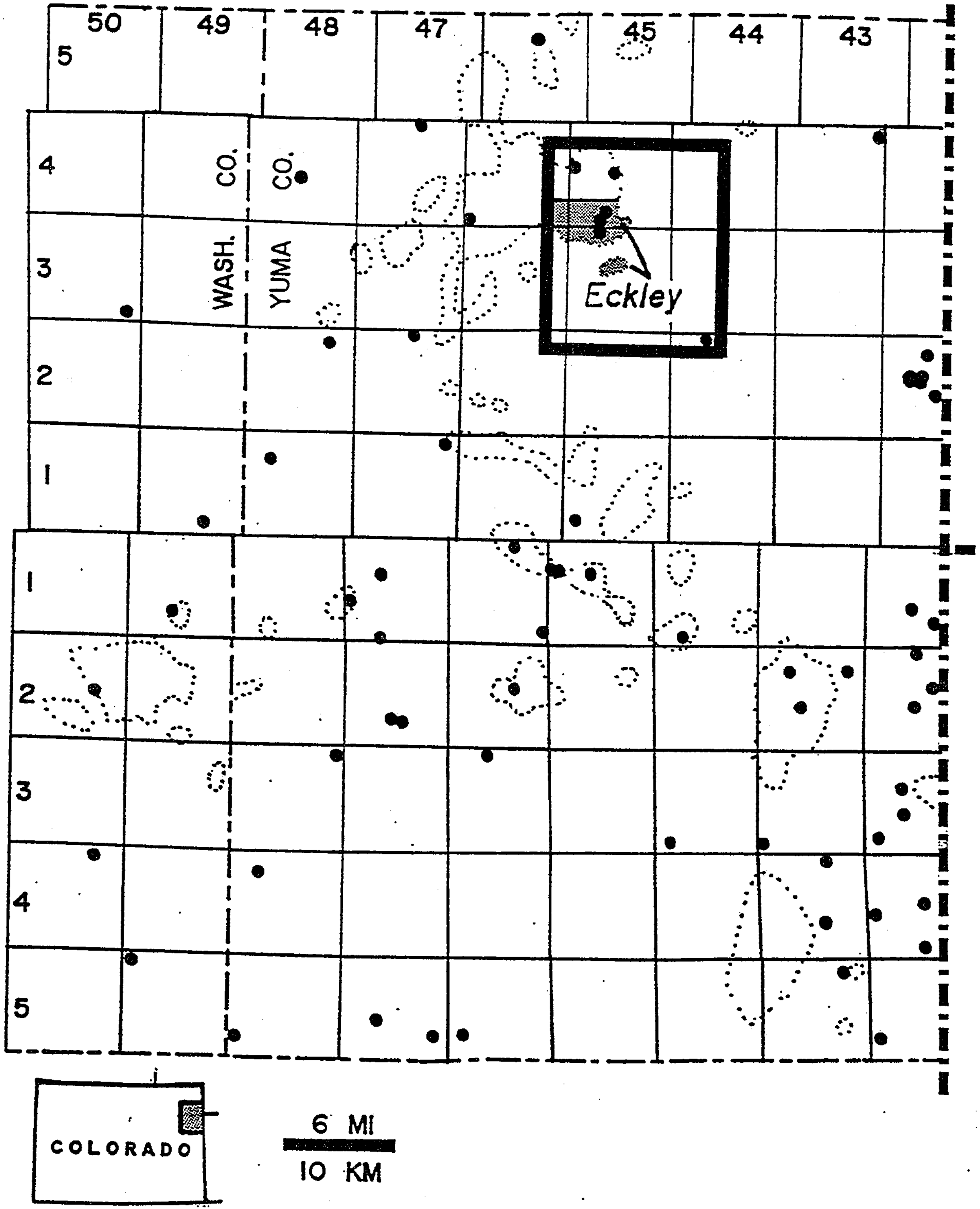


Figure 7-1. Location of Eckley field, in northern part of shallow Niobrara gas producing area, Yuma County, Colorado. Outlines of Niobrara gas fields are shown, along with locations of Paleozoic tests (solid circles).

DEVELOPMENT OF ECKLEY FIELD

Eckley field is one of five gas fields which comprise the Waverly complex (Figure 7-2). Eckley field, along with Old Baldy, Waverly, Wages, and Rock Creek fields, was designated as part of the complex by the Colorado Oil and Gas Conservation Commission for well-spacing purposes (Jeffrey, 1982). The five fields which comprise the Waverly complex have produced in excess of 77 BCFG through 1993. Other Niobrara fields in the immediate area of the Waverly complex include Phuma, Buffalo Grass, Whisper, Shout, and Buckboard fields (Figure 7-2), whose combined cumulative production through 1993 totals nearly 8 BCFG. Thus, ten fields in the immediate area of the Waverly complex account for over 85 BCFG of the 133 BCFG produced in Yuma County.

The Paleozoic potential of the area which would become the Waverly complex was originally evaluated by a number of seismic-based deep tests drilled in the 1950s and early 1970s. Following commercial development of the Niobrara Formation at Beecher Island field in the early 1970s, log analysis in the Waverly area indicated potential for Niobrara production (Lockridge and Pollastro, 1988).

The discovery well for the Waverly Complex was drilled in 1977 in SWSE Sec. 31, T4N, R46W, to a total depth of 3040 ft (927 m). Following foam-fracture treatment, the well was completed for an initial potential of 744 MCFGPD from

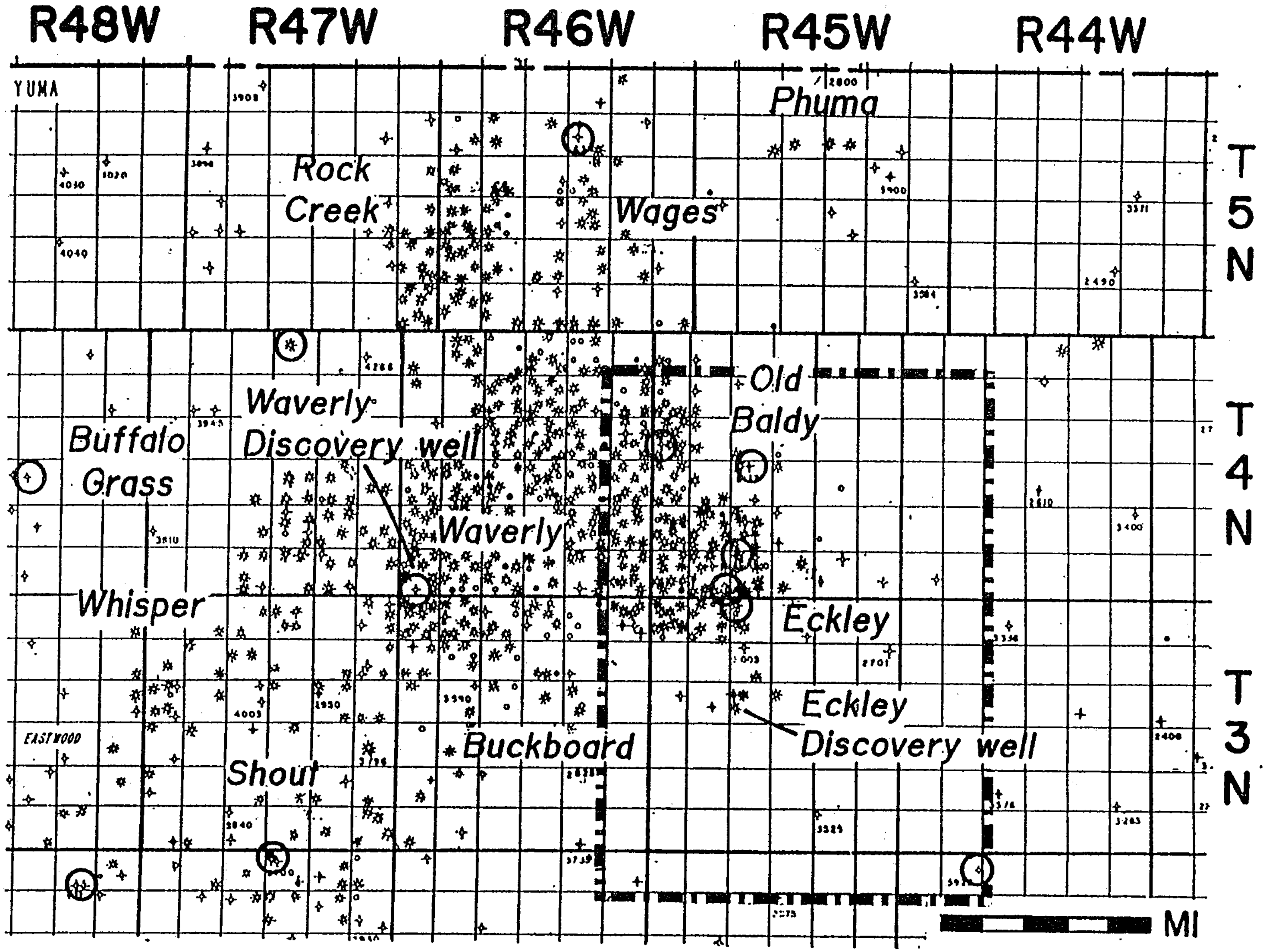


Figure 7-2. Location of Eckley field along southeastern part of Waverly complex. Waverly complex includes Waverly, Rock Creek, Wages, Old Baldy, and Eckley fields. Circled wells denote Paleozoic tests. Base map from Mapco Diversified, Inc., used with permission.

perforations between 2688 and 2698 ft (819 and 822 m) (Jeffrey, 1982). In 1993, over 330 wells produced gas in the Waverly complex. Additional wells are presently being completed as a result of downspacing and offset drilling.

Eckley field comprises the southeast portion of the Waverly complex (Figure 7-2), and covers parts of T3N, R45-46W and T4N, R45-46W. Although the discovery well for Eckley field was drilled in NWSW Sec. 16, T3N, R45W (Figure 7-3), development in the immediate area is limited. Most gas production occurs a few miles to the north in the part of the field which adjoins Waverly field to the west and Old Baldy field to the north. In 1993, 93 wells produced 1,714,557 MCFG, for a cumulative production since 1978 of 33,295,522 MCFG (33 BCFG). Of all eastern Colorado shallow Niobrara gas fields, Eckley ranks highest not only in cumulative production, but also in average cumulative production per well (358,016 MCFG/well).

NIOBRARA STRATIGRAPHY

The Upper Cretaceous Niobrara Formation is situated between the overlying Sharon Springs Member of the Pierre Shale and the underlying Carlile Shale (Figure 6-3), and is 500 to 600 ft (150 to 200 m) thick in northern Yuma County. The Niobrara is divided into two members, the lower Fort Hays Member and the upper Smoky Hill Member.

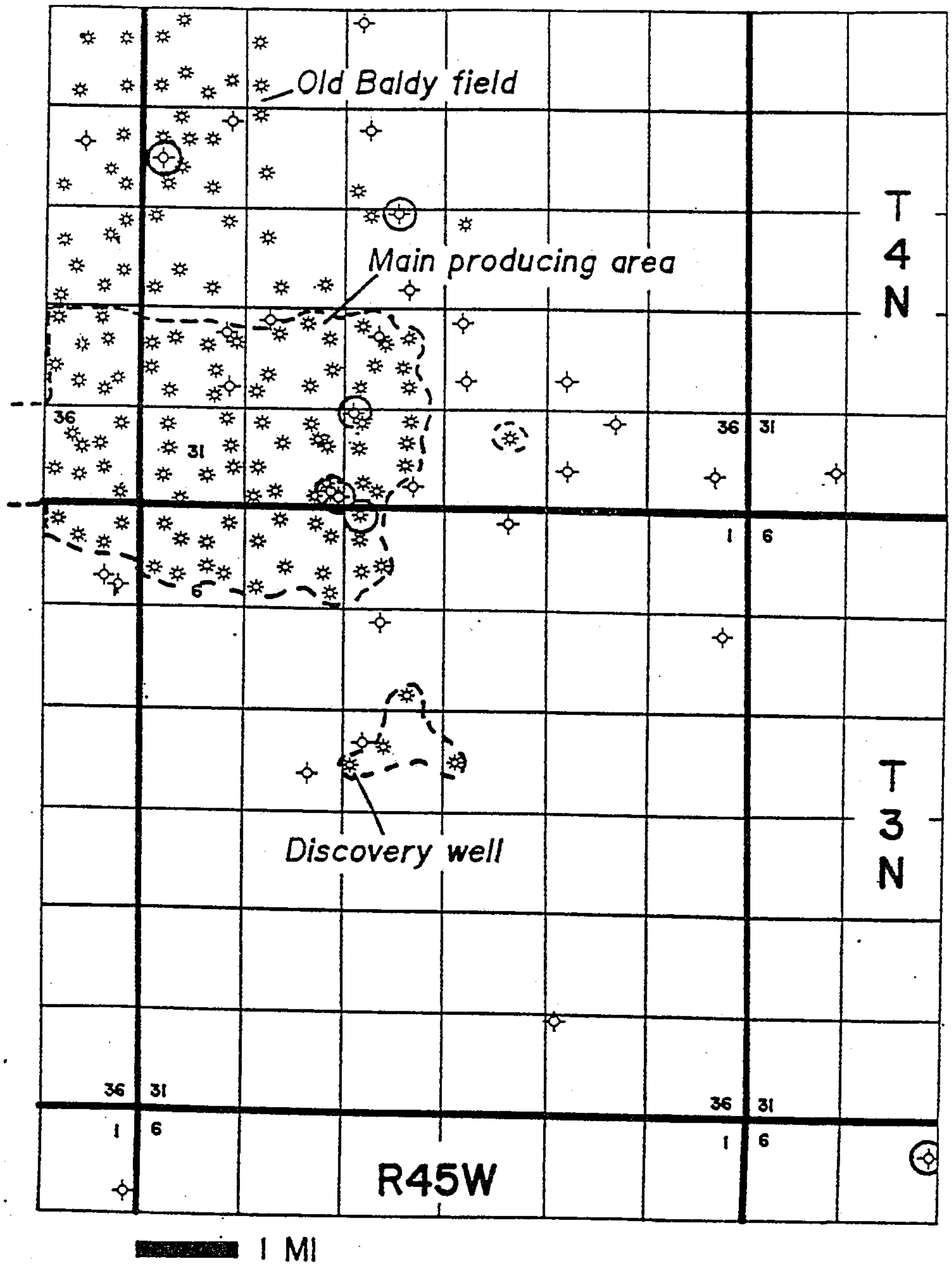


Figure 7-3. Eckley field base map, showing outline of area included in field production totals. Circled wells denote Paleozoic tests.

The Fort Hays Member is comprised of about 60 ft (20 m) of chalk and shaly chalk with interbedded chalky shale. The Smoky Hill Member, about 420 to 520 ft (130 to 160 m) thick, consists of gray to white chalky shale with locally massive chalk beds (Lockridge and Scholle, 1978). As with all shallow Niobrara fields in eastern Colorado, the pay zone at Eckley field is a porous chalk at the top of the Smoky Hill Member, informally named the Beecher Island zone (Lockridge, 1977).

BEECHER ISLAND ZONE RESERVOIR

The Beecher Island zone at Eckley field averages over 30 ft (10 m) in thickness. Porosity of the chalk, which is dependent on burial depth (Lockridge and Scholle, 1978), ranges from 45 percent at a depth of 900 ft (275 m) at Goodland field in northwestern Kansas to 30 to 35 percent at a depth of about 2800 ft (850 m) in the area of the Waverly complex. Although the Beecher Island zone is a high-porosity reservoir, permeability is extremely low (less than 1 md; Lockridge and Scholle, 1978). Due to the low permeability, a gas-water transition zone exists, wherein water saturations approaching 100 percent occur at low structural positions, and gas saturation increases with structural elevation within localized traps.

Because there is little variation in reservoir porosity and thickness across a given area, volume of gas-in-place is primarily a function of gas saturation, which is dependent on the position of the well on the structure. (Several other factors, including size and success of foam-fracture treatment, density and orientation of natural fractures, and well spacing, also contribute to per-well yield.)

NIOBRARA STRUCTURE

Structure on top of the Beecher Island zone (Figure 7-4) shows that an anticline with four-way closure is present at Eckley field. The crest of the producing structure, where the top of the pay zone exceeds an elevation of 1400 ft (425 m) above sea level, is centered around Sec. 5, T3N, R45W and Sec. 32, T4N, R45W. This places the field at a structural position which is about 100 ft (30 m) higher than the highest parts of Old Baldy and Waverly fields, located to the north and west, or regionally downdip of Eckley field.

Structural lows which have no apparent lineation (Figure 7-4) separate the main producing area of Eckley field from the structural crest at Old Baldy field to the north. Structural depressions are also present to the east, southeast, and south of the Eckley field high, or regionally updip to the field. Structural relief between the crest of

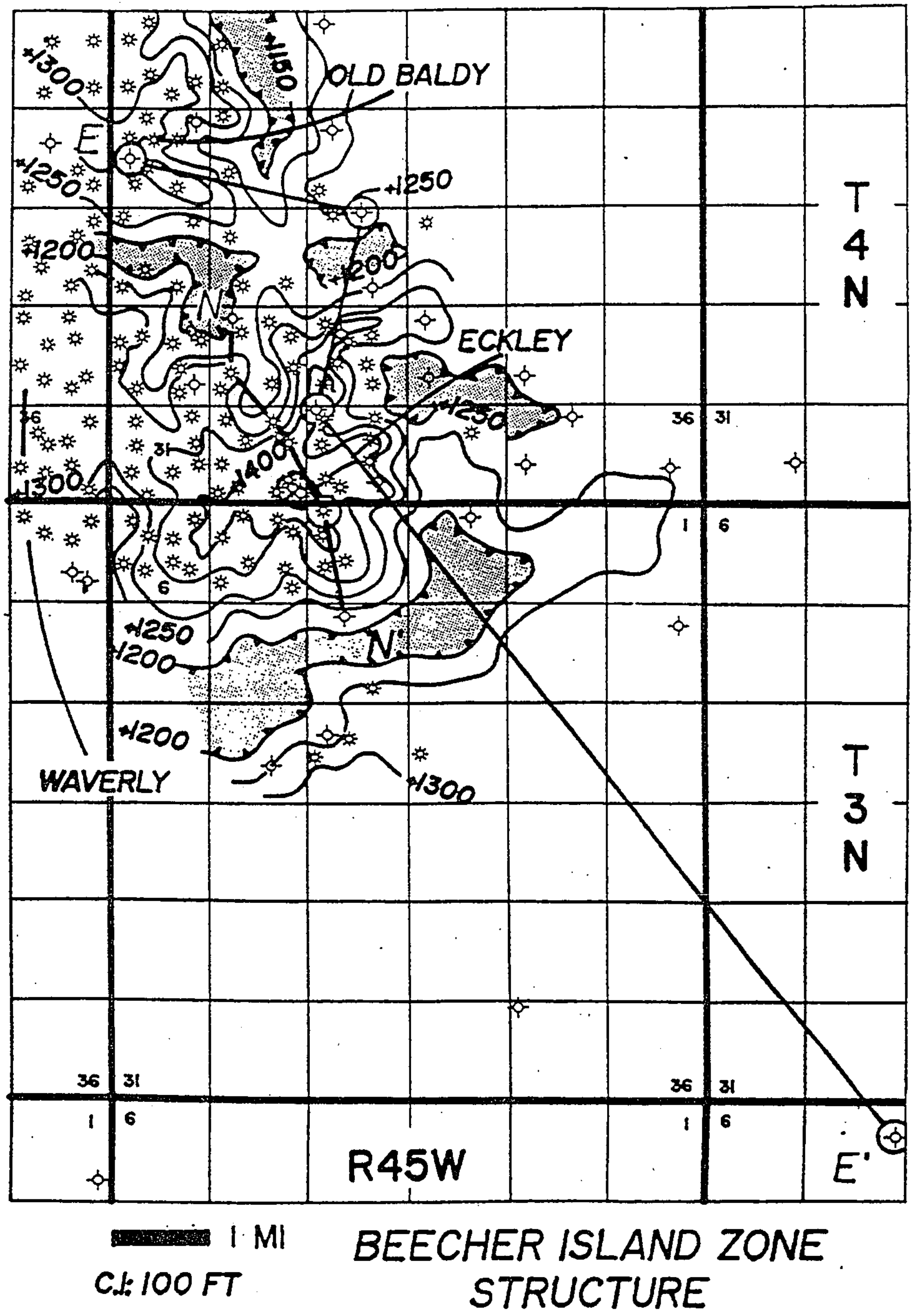


Figure 7-4. Eckley field structure, drawn on top of Beecher Island zone. Contour interval 50 ft (16 m).

the Eckley structure and the structural lows marginal to the field is about 200 ft (60 m).

The Eckley structure is highly faulted and the pay zone is thin or absent in some wells due to faulting. Inasmuch as detailed mapping of faults is beyond the scope of this study, faults are not shown on Figure 7-4. However, Jeffrey's (1982) structural interpretation across the Waverly complex included several northeast-trending faults at Eckley field. Although his map was based on far less control than is presently available, Jeffrey noted that faulting in the Niobrara occurred in about 10 percent of the wells, with displacements of 40 to 150 ft (10 to 45 m), and suggested that faulting is probably much more prevalent than well control identifies.

Jeffrey (1982) did not recognize faulting below the base of the Smoky Hill Member and interpreted the faulting to be listric, having occurred shortly after deposition of the Niobrara. He noted, however, that some of the faults can be recognized at the top of the the Pierre Shale (Cretaceous-Tertiary boundary in this area), and that although not infallible, Pierre Shale structure can be used as an exploration tool.

Lockridge and Pollastro (1988) attributed modification of producing structures in the Niobrara play to listric faulting, with listric-normal faults flattening into bedding plane faults within the Niobrara or underlying shales. The authors considered the faults to be early compactional features. Listric faulting in the Niobrara has also been discussed in Lockridge and Scholle, 1978); Brown et al (1982), Cockerham (1982); and Davis (1982).

Figure 7-5 depicts how listric faulting may modify structure at the level of the Niobrara. Vertical movement, due to basement faulting or, in the case of the diagram (Figure 7-5), salt dissolution collapse has a greater effect on the brittle Niobrara chalk than on the underlying D and J sandstones. Listric-faulted blocks of Niobrara slump toward the collapse area. Well A would encounter a faulted Niobrara section, with no evidence of faulting at the level of deeper strata, even though the offset which prompted the listric faulting affects strata at depth.

Figure 7-6, a north-south structural cross section through Eckley field, shows the relationship between structural position in the field and gas in the Beecher Island zone. The Beecher Island zone is 34 to 38 ft (11 to 12 m) thick at the field. Gas effect, indicated by neutron-density cross-over, is present on logs from four wells on the cross section. Values in parentheses within the gas zone represent the maximum deep resistivity recorded through the chalk. Readings as low as 3 to 5 ohm-m indicate the likelihood of gas production; resistivities over 5 ohm-m result in water-free gas production (Lockridge and Pollastro, 1988). The dry hole at the north end of the

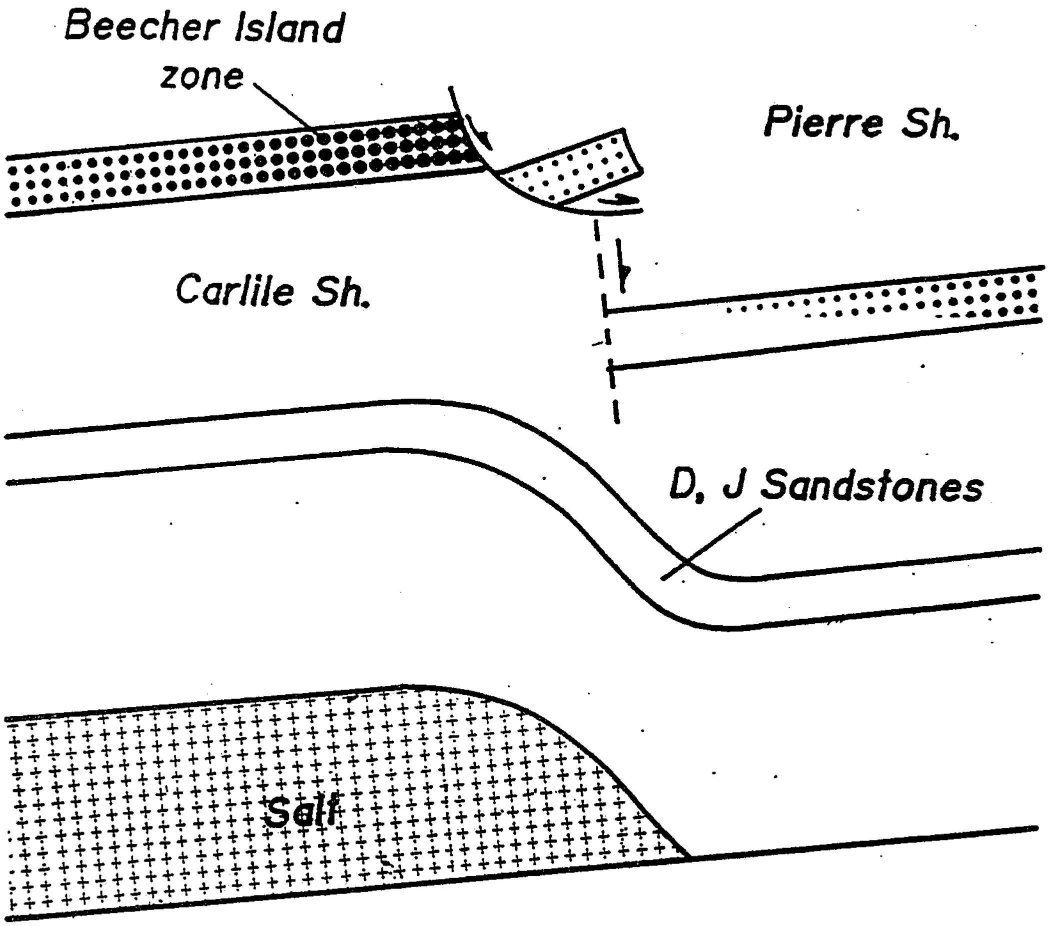


Figure 7-5. Diagram showing listric faulting within Niobrara.

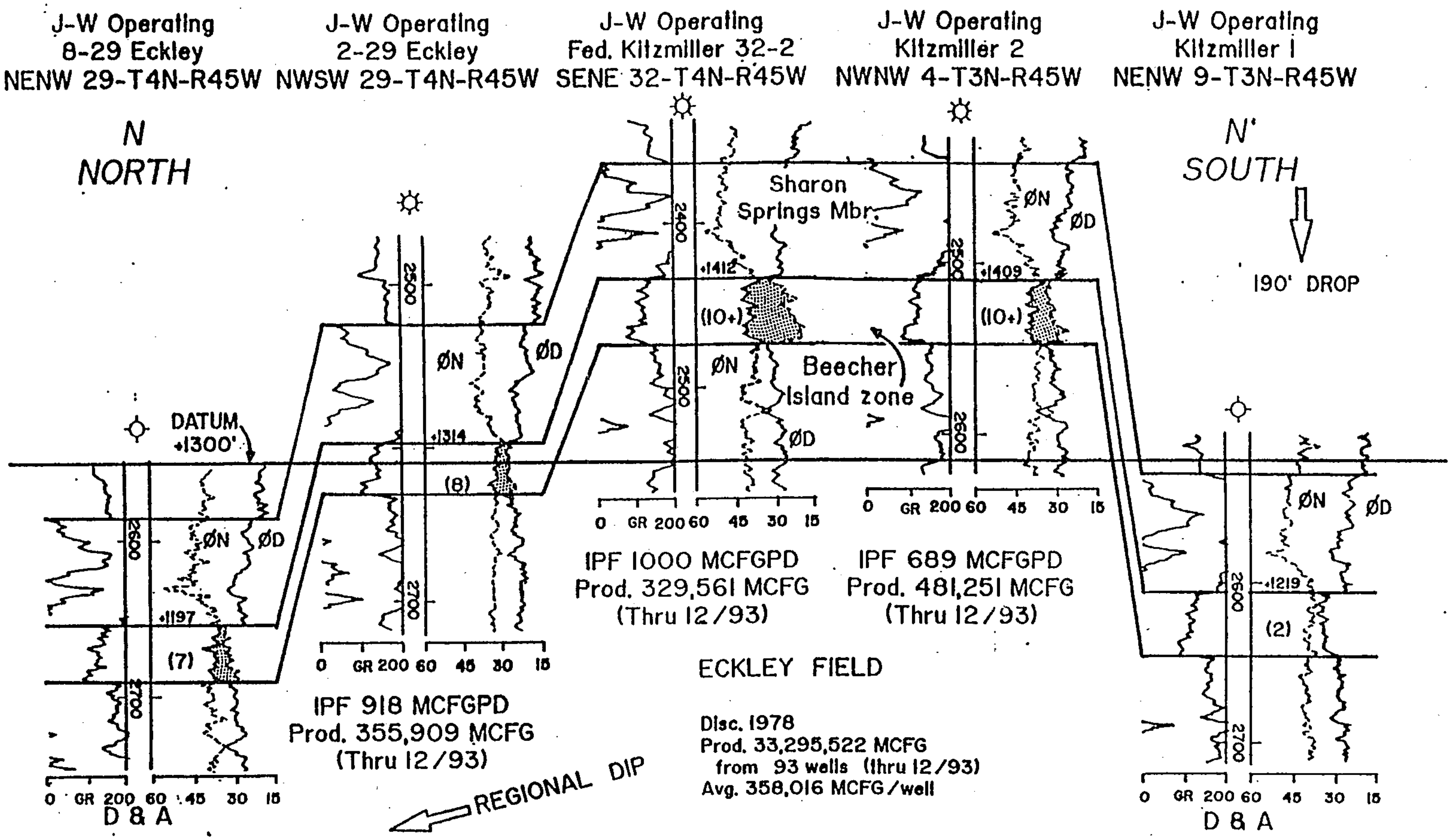


Figure 7-6. Structural cross section through Niobrara interval at Eckley field. Well depths are in feet. No horizontal scale.

cross section, which exhibited neutron-density cross-over and 7 ohm-m resistivity across the Beecher Island zone, could likely have been completed as a gas well.

Resistivity values in excess of 10 ohm-m were recorded across the Beecher Island zone on the crest of the Eckley structure, where the reservoir lies at an elevation of over 1400 ft (425 m) above sea level (Figure 7-6). To the north, resistivity decreases to 8 ohm-m in a well which encountered the chalk at +1314 ft (+401 m) and to 7 ohm-m at +1197 ft (+365 m) in a well which indicated gas effect on the neutron-density log, but was completed as a dry hole. Immediately south of the main producing area of the field, the elevation of the Beecher Island zone drops about 190 ft (58 m) in a dry hole located in Sec. 9, T3N, R45W. Although the chalk was encountered at an elevation which is over 20 ft (6 m) higher to the well on the north end of the cross section, no gas effect is observed and a maximum resistivity of only 2 ohm-m occurs across the chalk.

RELATIONSHIP OF RESISTIVITY TO STRUCTURE

Figure 7-7 shows the relationship of structure to formation resistivity indicated on the Eckley field structural cross section (Figure 7-6). The Niobrara reservoir at Eckley field is highly faulted, due to the brittle nature of the chalk. The Pierre shale serves as top

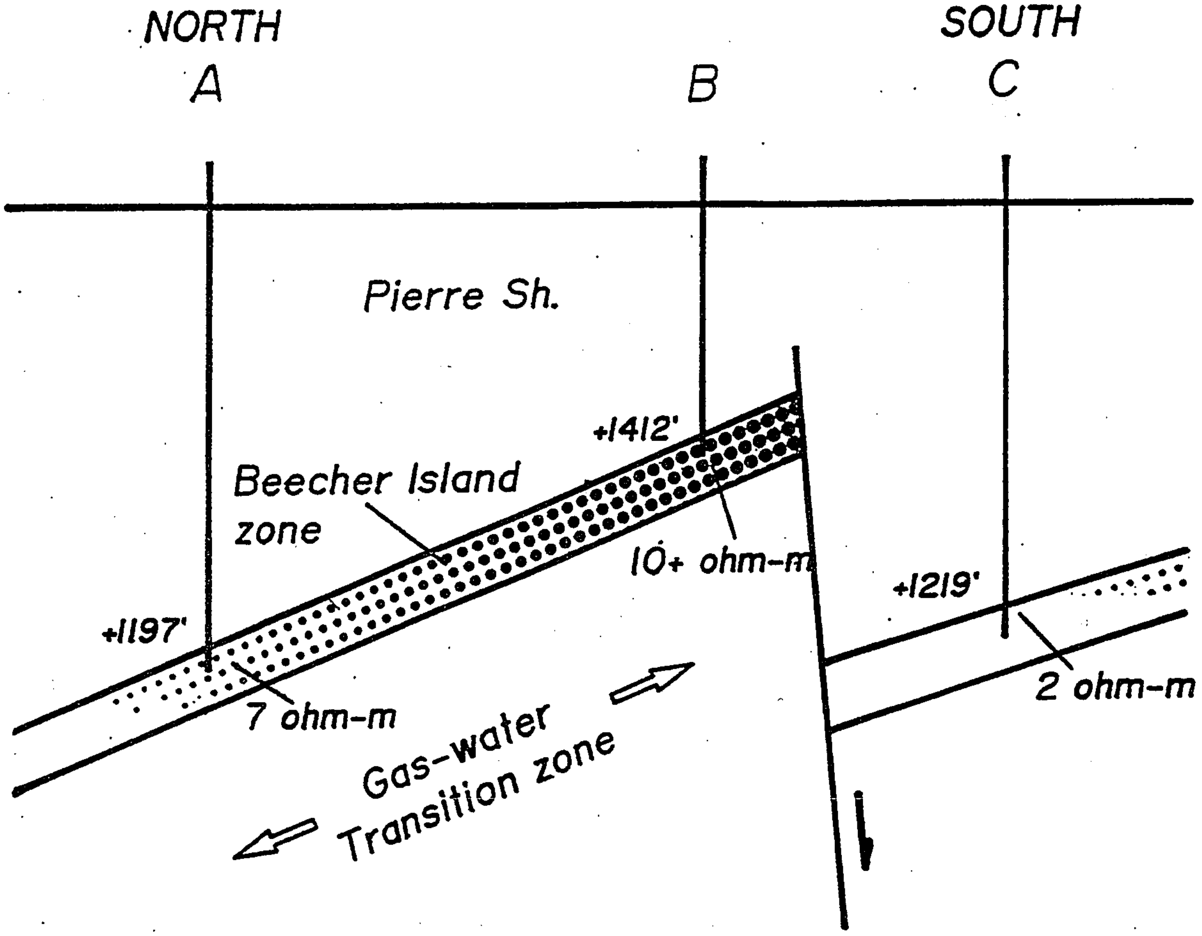


Figure 7-7. Diagram used to explain relationship between gas saturation (as indicated by formation resistivity) and structural position along southern margin of main Eckley producing area.

seal and fault seal. Gas saturation, which is indicated by high resistivity and neutron-density crossover, increases with structural position within each fault trap. Gas saturation, indicated by size of stippling, is highest near the structural crest or highest part of the fault block (well B). Although the northernmost well (well A) was completed as a dry hole, a resistivity reading of 7 ohm-m indicates that it encountered the gas-water transition zone. The southernmost well (well C), with a resistivity of 2 ohm-m, is low to the gas-water transition zone in the next trap to the south, despite being structurally high to well A.

The relationship between structure and gas saturation is evident on Figure 7-8, an isoresistivity map across Eckley field. Data used in the interpretation are maximum deep resistivity values recorded across the Beecher Island zone. Because resistivity logs are influenced less by mud-filtrate invasion than neutron-density logs (Lockridge and Pollastro, 1978), they provide a more accurate estimate of gas saturation. Hann (1981) conducted a detailed analysis of the interrelationships between Niobrara gas reservoirs and well-log properties.

Maximum deep-resistivity of the Beecher Island zone (Figure 7-8) generally increases with structural position at Eckley field. Highest resistivity readings, in excess of 10 ohm-m, were recorded in the area of Secs. 4 and 5, T3N, R45W and Secs. 32 and 33, T4N, R4W, where the Beecher Island zone

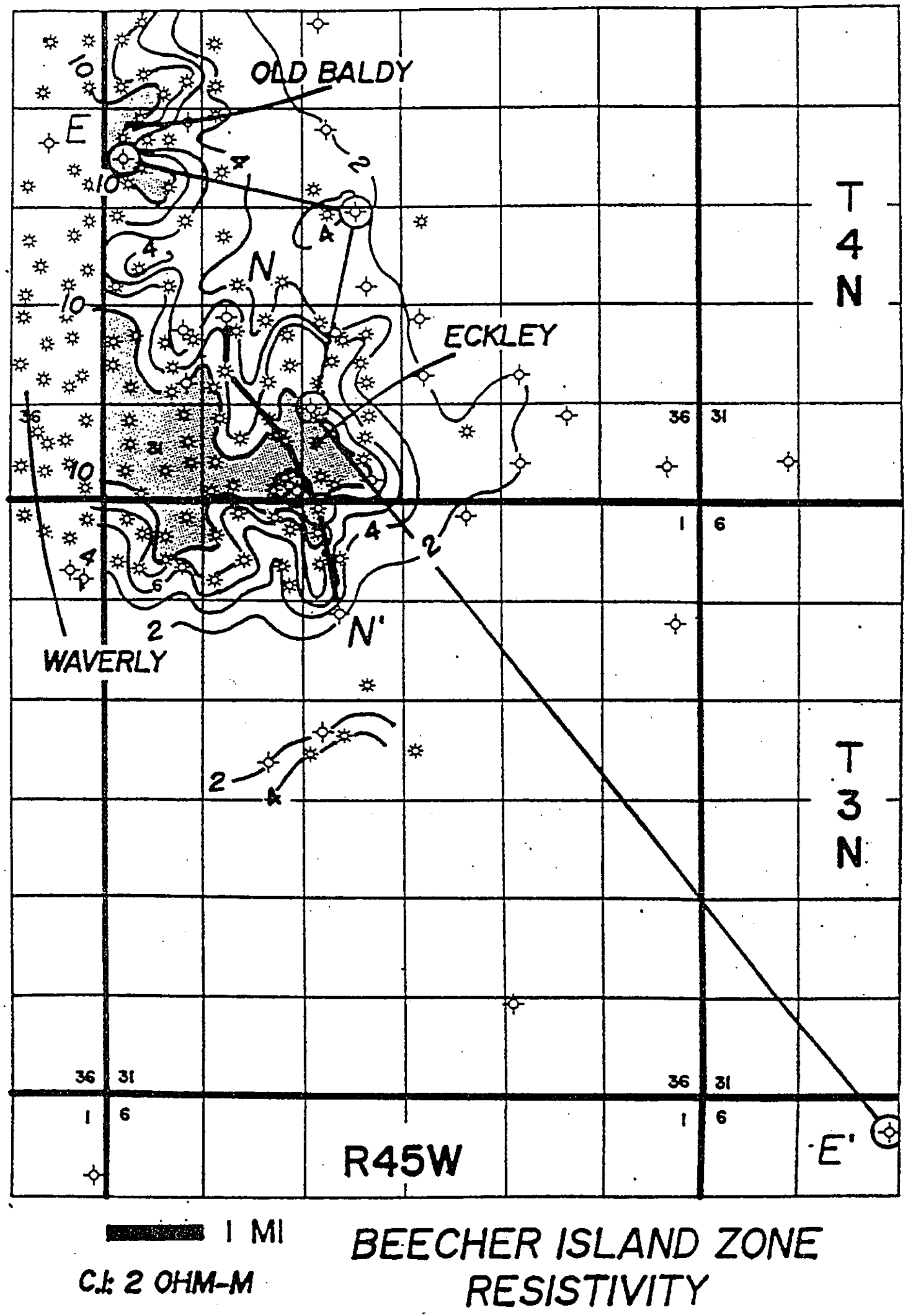


Figure 7-8 . Isoresistivity map of Beecher Island zone at Eckley field. Data are maximum deep resistivity values recorded across gas-productive chalk reservoir. Contour interval 2 ohm-m. Values greater than 10 ohm-m are shown in shaded area.

is present at an elevation greater than 1400 ft (425 m) above sea level (Figure 7-4) and in the part of Old Baldy field, centered around Sec. 18, T4N, R45W, where the reservoir occurs higher than 1300 ft (400 m) above sea level. A large area of high resistivity situated in the general area of Sec. 31, T4N, R45W is associated with a northwest-trending anticline which joins the Eckley field structural high with the Waverly field to the west.

DEEP STRUCTURE

Reflection seismic surveys were recorded across the general area of the Eckley field in the 1950s, as part of a flurry of exploratory activity following the dicovery of oil in the Nebraska panhandle at Gurley field in 1949. Drilling of seismically-defined structures in Yuma County during the 1950s and 1960s, which focused on the D and J sandstones as well as deeper Paleozoic objectives, overlooked the Niobrara as a potentially commercial objective. The Niobrara was not developed as an economic gas resource in this area until the 1970s, with the development of Beecher Island field to the south. Lockridge and Pollastro (1988) noted that most Niobrara fields in this area coincide with seismically-defined structural highs identified by surveys conducted in the 1950s. Although deep exploratory activity in the

Waverly area was unsuccessful, numerous deep tests allow for study of the salt interval and deep (subsalt) structure.

Figure 7-9, a structural interpretation drawn on top of the subsalt Chase Group (Permian, Wolfcampian) reveals regional dip of less than one degree to the northwest. Deep well control in the Waverly complex area averages about one well per township. Despite a concentration of deep control points in the Eckley field area, there is no deviation from the homoclinal structural pattern which exists elsewhere in the general area of the Waverly complex.

Seven deep wells have been drilled in the area shown on detailed Eckley field maps (outlined area on Figure 7-9). Structural elevation on top of the Chase Group within this detailed area ranges from about 460 ft (140 m) below sea level in Sec. 5, T2N, R44W, to about 750 ft (230 m) below sea level at Old Baldy field in Sec. 11, T4N, R46W. Along the southeastern edge of the main Eckley producing area, the Chase Group is at an elevation of about 650 ft (200 m) below sea level. Thus, there is about 100 ft (30 m) of regional structural relief between Eckley field and Old Baldy field at the subsalt level.

PERMIAN SALTS

Stratigraphic position of Permian salts which occur about 1500 to 2000 ft (500 to 600 m) below the Niobrara in

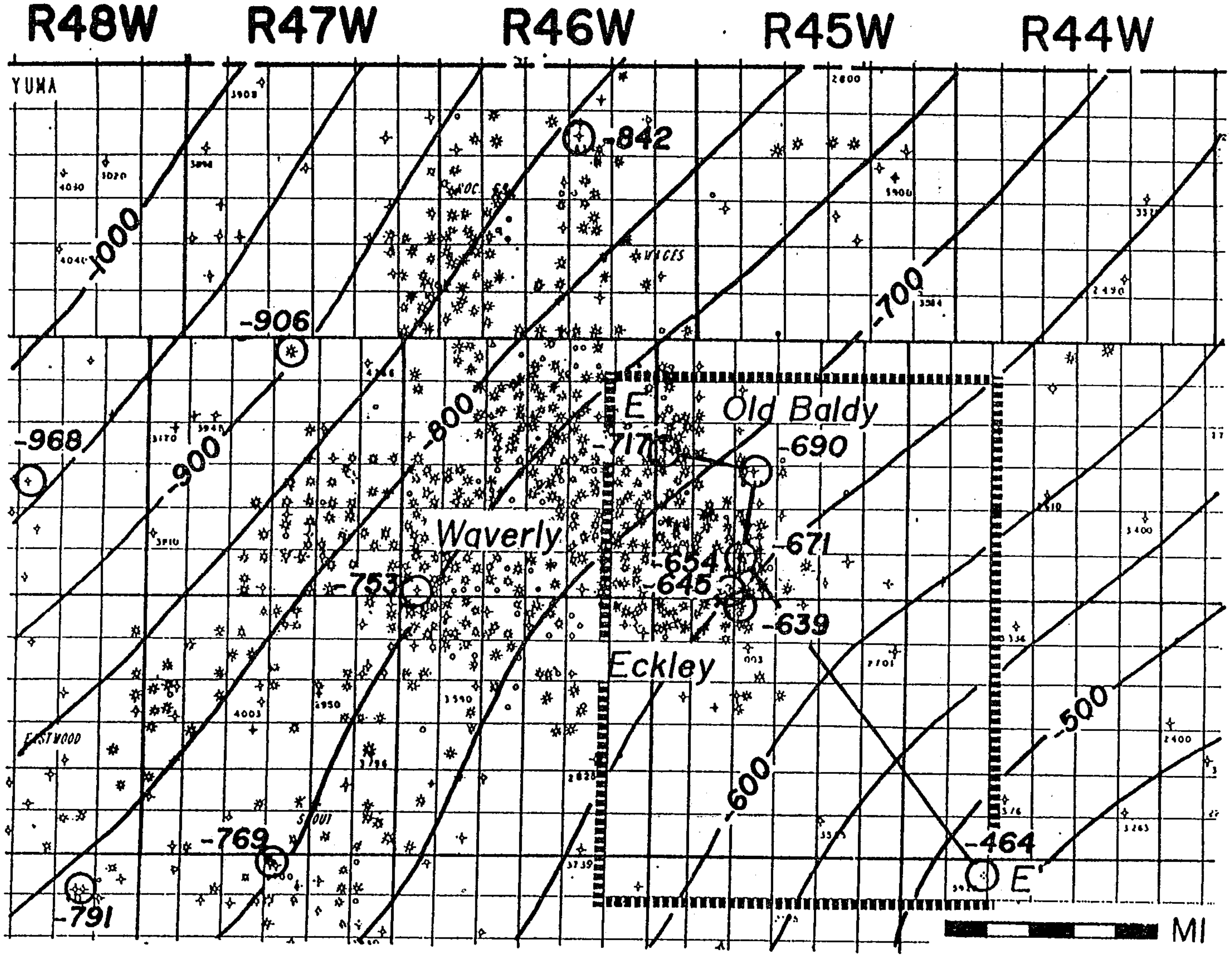


Figure 7-9. Subsalt structure, drawn on top of Wolfcampian Chase Group. Contour interval 50 ft (15 m). Circled wells denote Paleozoic tests. Base map from Mapco Diversified, Inc., used with permission.

the Eckley field area is shown on Figure 6-13. Three salt zones have been identified on well logs. Salt 7, which ranges from 0 to 140 ft (40 m) in thickness, occurs between the lower Blaine Anhydrite and the Flower-pot Shale. Salt 8, ranging from 0 to 15 ft (5 m) in thickness, is situated at the base of the Flower-pot Shale, just above the Flower-pot Anhydrite. Salt 10, which ranges in thickness from 0 to 50 ft (15 m), occurs just below the Stone Corral Anhydrite. All salts which have been identified in the Eckley field area are within the Nippewalla Group (Leonardian).

Thickness of the Leonardian Series is directly related to the presence of salt (Figure 6-13). The Leonardian is 519 ft (158 m) thick in a well 2058, drilled in 1959 in the area which would later be developed as Old Baldy field. Salts 7 and 10 are present in this well. At Eckley field, salts 7, 8, and 10 were encountered in well 2075, drilled in 1972, in which Leonardian strata total 516 ft (157 m). Between Eckley and Old Baldy fields, the Leonardian is 420 ft (128 m) thick in well 2057, drilled in 1951, which encountered salt 10, but no salt 7 or 8. To the southeast of Eckley field, in well 2053, drilled in 1956, no salt was encountered, and the Leonardian is only 297 ft (90 m) thick.

Deep-well control indicates a Leonardian isopach maximum in the general area of the Waverly complex (Figure 7-10). The line of cross section shown is for Figure 6-13. The Leonardian exceeds 450 ft (140 m) in thickness where

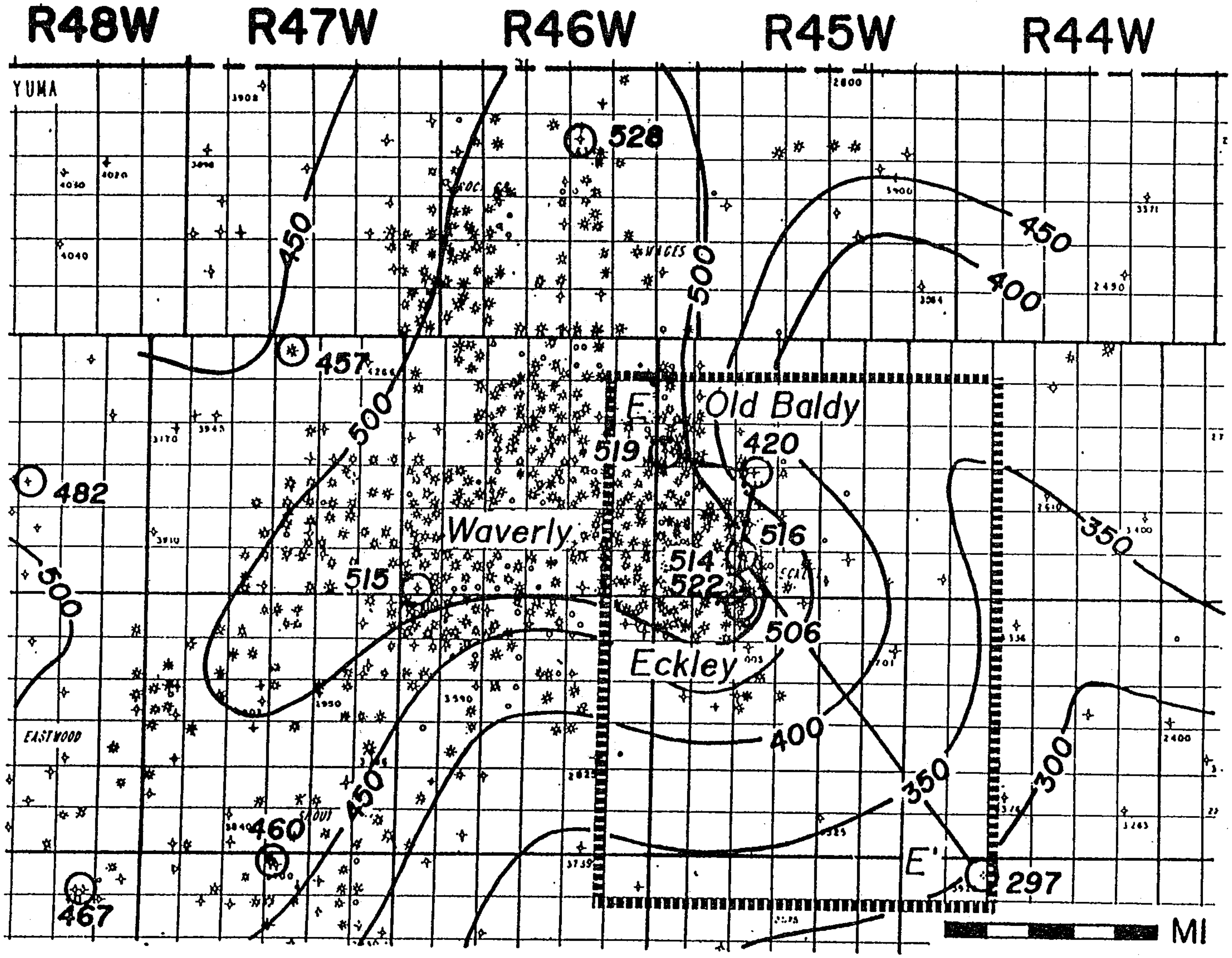


Figure 7-10. Isopach of the Leonardian series. Contour interval 50 ft (15 m). Circled wells denote Paleozoic tests. Base map from Mapco Diversified, Inc., used with permission.

salts 7 and 10 are present. To the east and northeast, where salt 10 only is present, the Leonardian is less than 450 ft (140 m) thick. To the southeast, where no salt is present, Leonardian strata are less than 300 ft (90 m) thick.

Salt-influenced Leonardian isopach maxima and their relationship to Niobrara gas accumulations are discussed on a subregional scale in Chapter 6 of this report. The discussion which follows includes an analysis of seismic data and focuses on the influence of Permian salt dissolution on the formation of the gas-productive structure at Eckley field.

ECKLEY FIELD SEISMIC STUDY

Eckley Seismic Line

A reflection seismic line (Figure 7-11), which was shot across the area which would later be developed as Eckley field, was provided by KN Production Company, Lakewood, Colorado. Permission to use and publish the seismic section was obtained from KN Production Company and from Mesa Petroleum Company, Dallas, Texas, which holds the license for the seismic data. The line is a north-south profile across the Eckley field area; however the specific location of traverse is kept confidential in this report. The

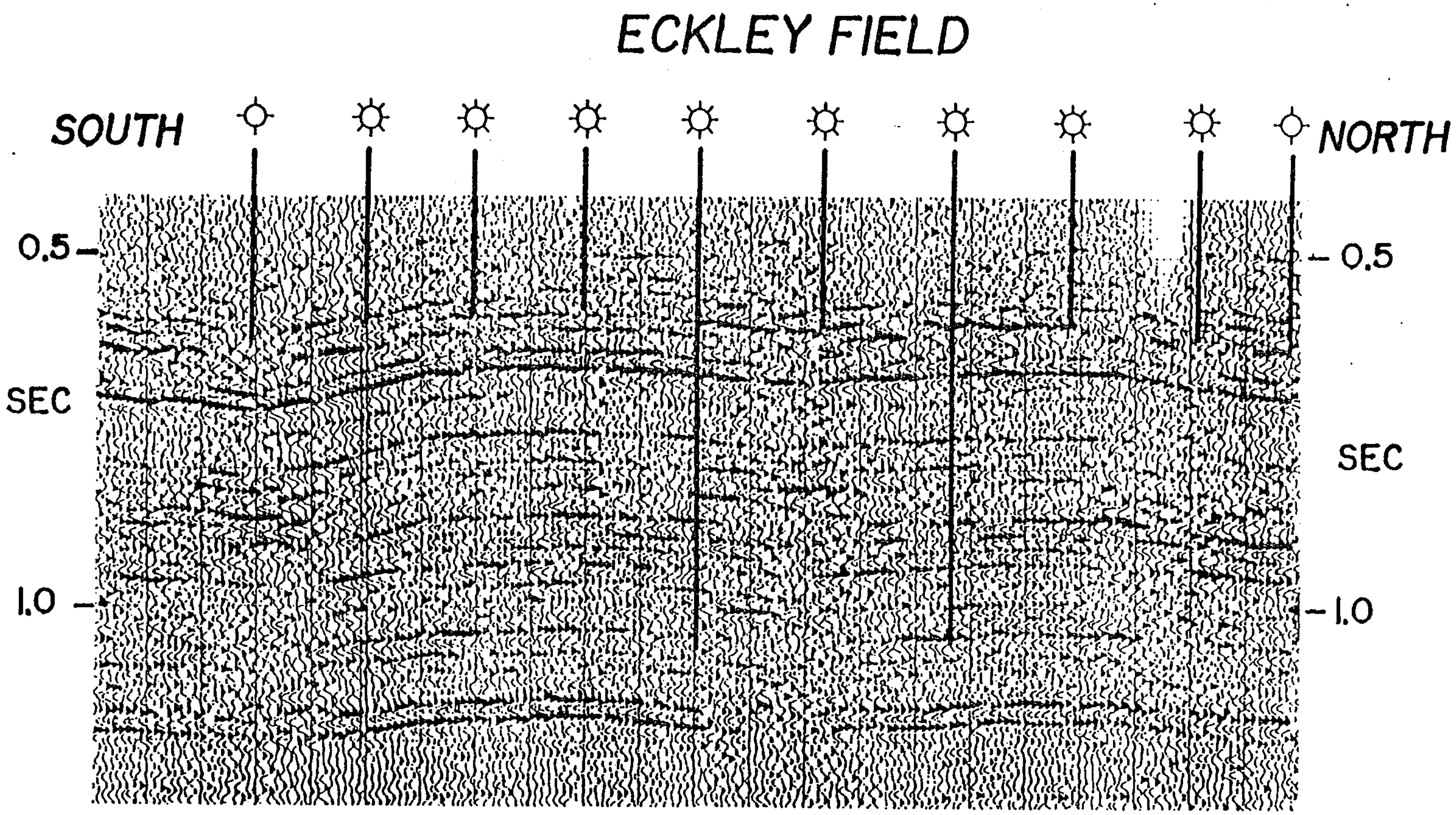


Figure 7-11. Uninterpreted north-south seismic profile across Eckley field. Length of profile shown is 3.7 mi (5.9 km). Seismic line courtesy of Mesa Petroleum Corporation and K-N Production Company, used with permission.

seismic data, acquired in 1972, were shot using dynamite as an energy source. The seismic profile is a 6-fold common depth point (CDP) display.

A 5-mi- (8-km-) long section of the seismic line was analyzed in the present study. A 3.7-mi (5.9-km) part of the line is shown on Figure 7-11. For this study, shot points along the line were renumbered from 1 at the south end of the line to 31 at the north end. Several strong reflectors are apparent, including one at 0.7 sec. two-way time. Another strong reflector at about 1.2 sec. is believed to be related to the basement.

Synthetic Seismogram

In order to relate seismic reflection events to subsurface stratigraphy in the Eckley area, a synthetic seismogram was generated. Acoustic data used as input for the synthetic seismogram were derived from the closest available sonic log. The sonic log was recorded in well 2058, the S.D. Johnson Pyle 1, NWSW Sec. 18, T4N, R45W, drilled in 1959 in the area which would later be developed as Old Baldy field. Well 2058 is located about 2 mi (3 km) from the northern end of the seismic line. A section of the sonic log through the Permian salt interval (Figure 7-12) shows that 110 ft (34 m) of salt 7 and 45 ft (14 m) of salt 10 were encountered in well 2058. A strong velocity

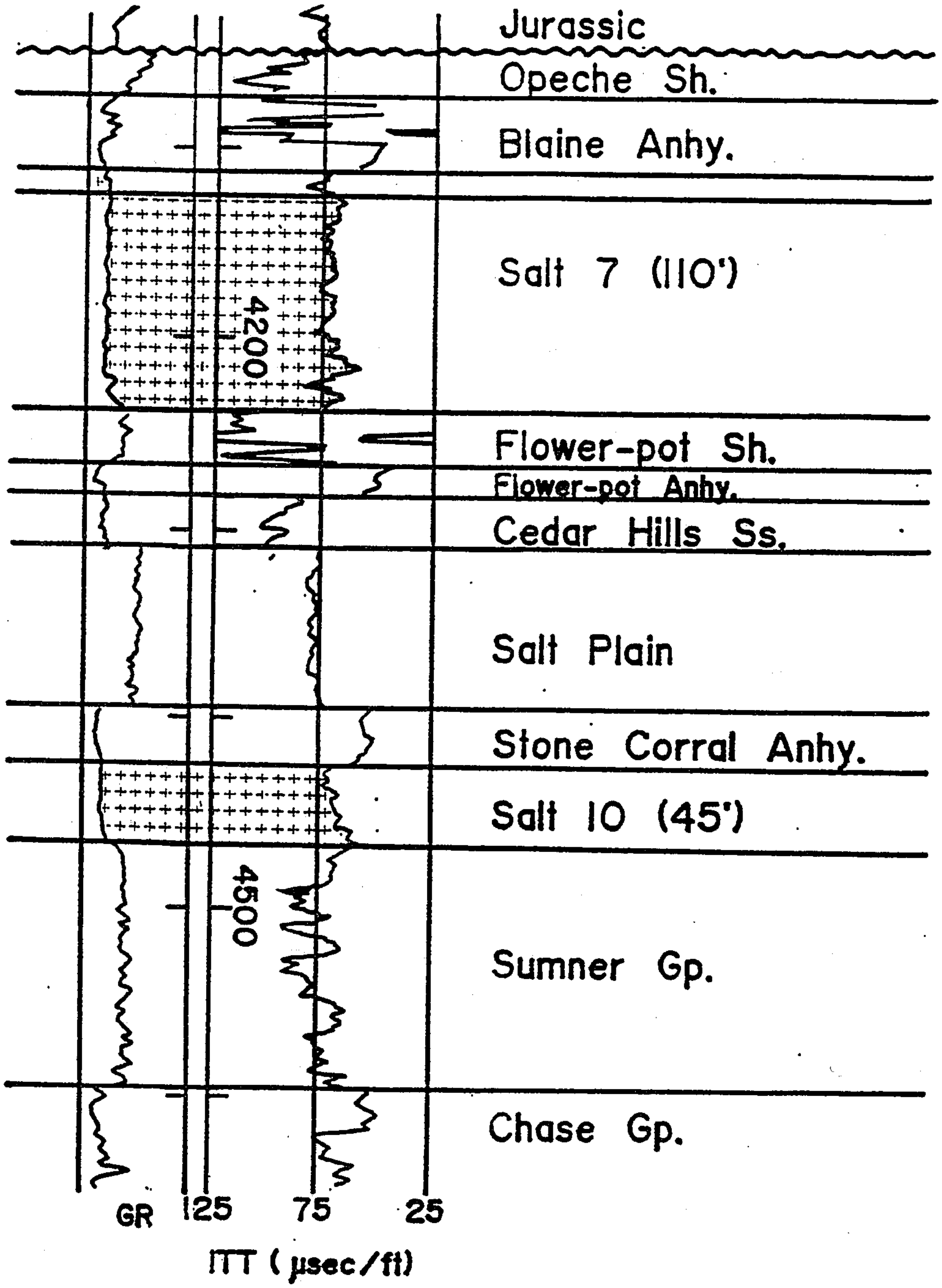


Figure 7-12. Sonic log across Permian salt interval in Eckley field area. Log is from well 2058, S.D. Johnson Pyle 1, NWSW Sec. 18, T4N, R45W, Old Baldy field.

contrast occurs between the Opeche Shale and the underlying high-velocity Blaine Anhydrite. A similar strong velocity contrast occurs between shales and siltstones of the Sumner Group and the anhydrite which is present at the top of the Chase Group. Inasmuch as the Leonardian Series comprises the interval between the top of the Blaine and the base of the Sumner, it is anticipated that these velocity contrasts might relate to persistent reflectors on the seismic line.

A section of the sonic log from well 2058 across the Niobrara (Figure 7-13) shows an increase in interval transit time (or a decrease in interval velocity) across the Sharon Springs Member of the Pierre Shale and at the top of the Niobrara, across the Beecher Island zone. Interval velocity across the Beecher Island zone is affected by gas saturation (Claussen, 1981; Lockridge and Pollastro, 1988), which can also affect seismic amplitude at the Niobrara level. Rather than using the top of the Niobrara as a seismic correlation point, interpreters of Denver basin seismic data commonly use a strong reflection related to the Fort Hays Member as a more reliable seismic pick. High-velocity limestone of the Fort Hays occurs between low-velocity calcareous shales of the Smoky Hill Member and the low-velocity Carlile Shale (Figure 7-13).

A synthetic seismogram from well 2058 (Figure 7-14) shows strong reflection events associated with the Fort Hays as well as the Blaine Anhydrite and Chase Anhydrite. As no

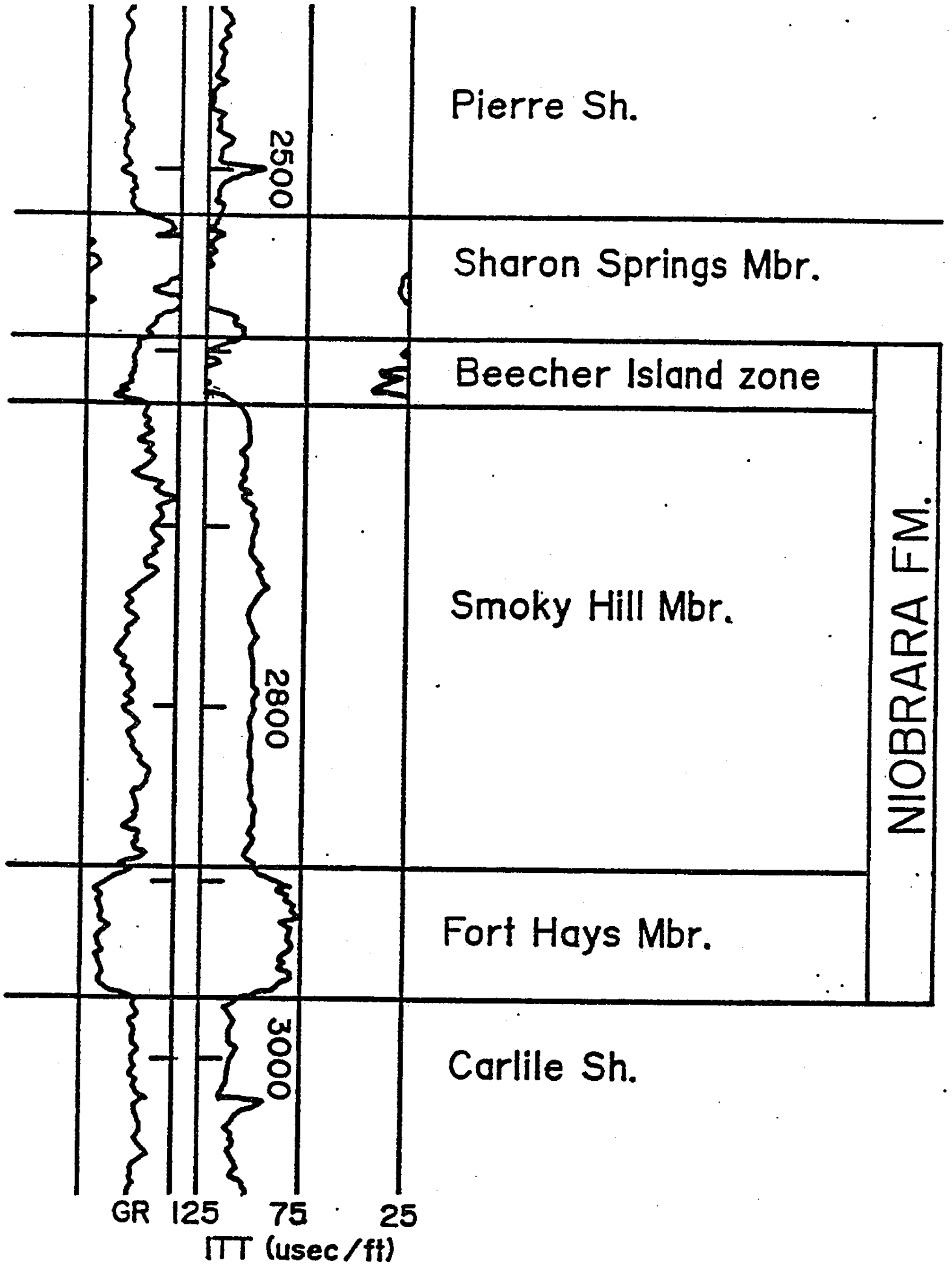


Figure 7-13. Sonic log across Upper Cretaceous Niobrara Formation. Log is from well 2058, S.D. Johnson Pyle 1, NWSW Sec. 18, T4N, R45W, Old Baldy field.

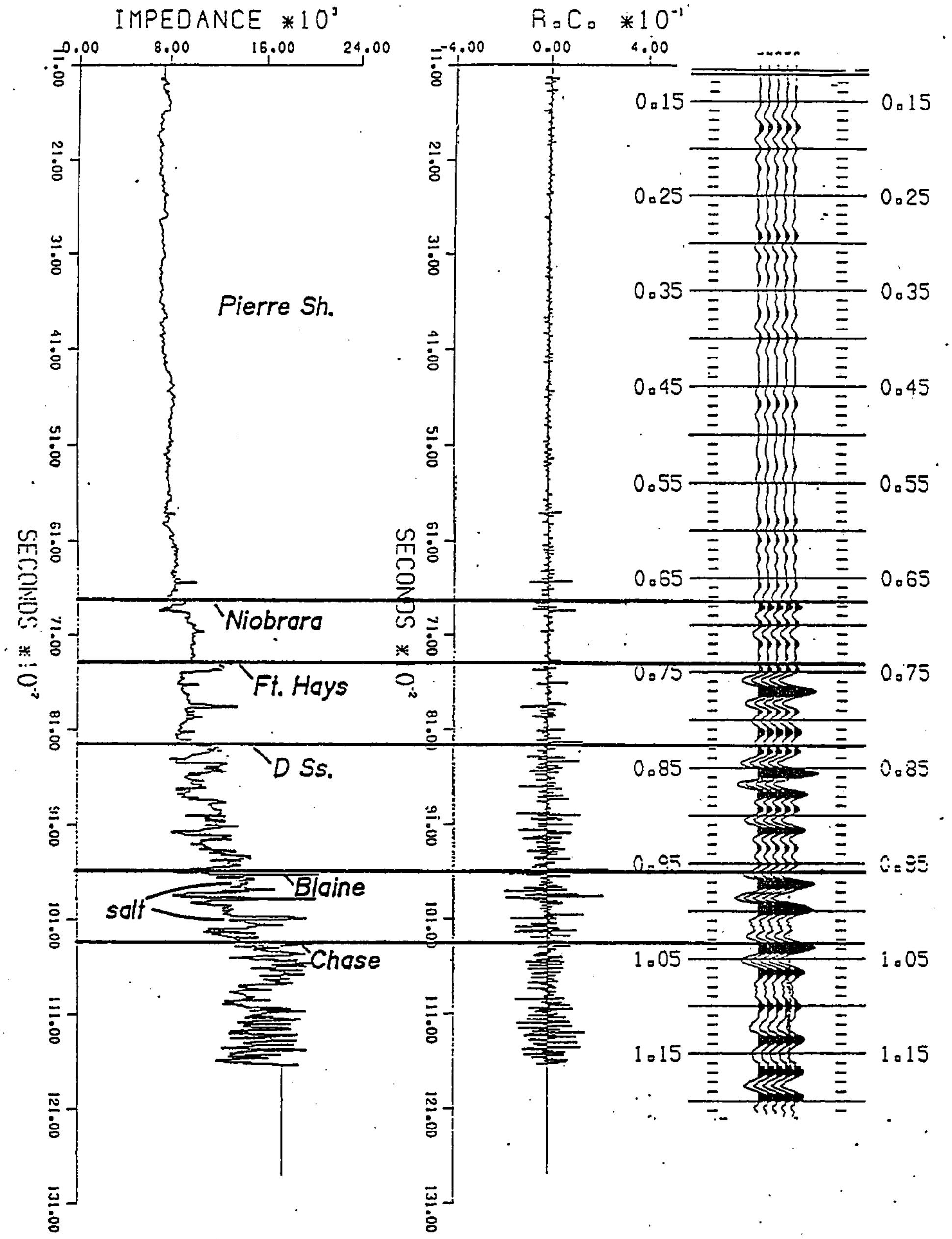


Figure 7-14. Synthetic seismogram generated from sonic log from well 2058, NWSW Sec. 18, T4N, R45W, Old Baldy field.

density log was recorded in this well, the impedance plot is based on sonic log data only. Interval transit times used as input for the synthetic seismogram are from the depth interval from 440 ft (134 m) at the base of surface casing to 5612 ft (1710 m), the total depth of the well.

Figure 7-15 compares synthetic seismogram traces from well 2058 to a portion of the seismic line in the area of shotpoints which were assigned numbers 18 and 19 in this study. A strong trough at about 0.76 sec. on the synthetic seismogram, which is related to velocity contrasts at the level of the Fort Hays Member, correlates with a trough at about 0.65 sec. on the seismic line. A strong peak at about 0.97 sec. on the synthetic seismogram, which is associated with the Blaine Anhydrite, correlates with a reflector at about 0.87 sec. on the seismic line. The reflector associated with the Chase Anhydrite, at about 1.04 sec. on the synthetic seismogram, correlates with a strong peak at about 0.93 sec. on the seismic line segment. A strong reflector at about 1.15 sec. on the seismic line, believed to be related to the basement, is not represented on the synthetic seismogram, because well 2058 was drilled and logged only to the Pennsylvanian.

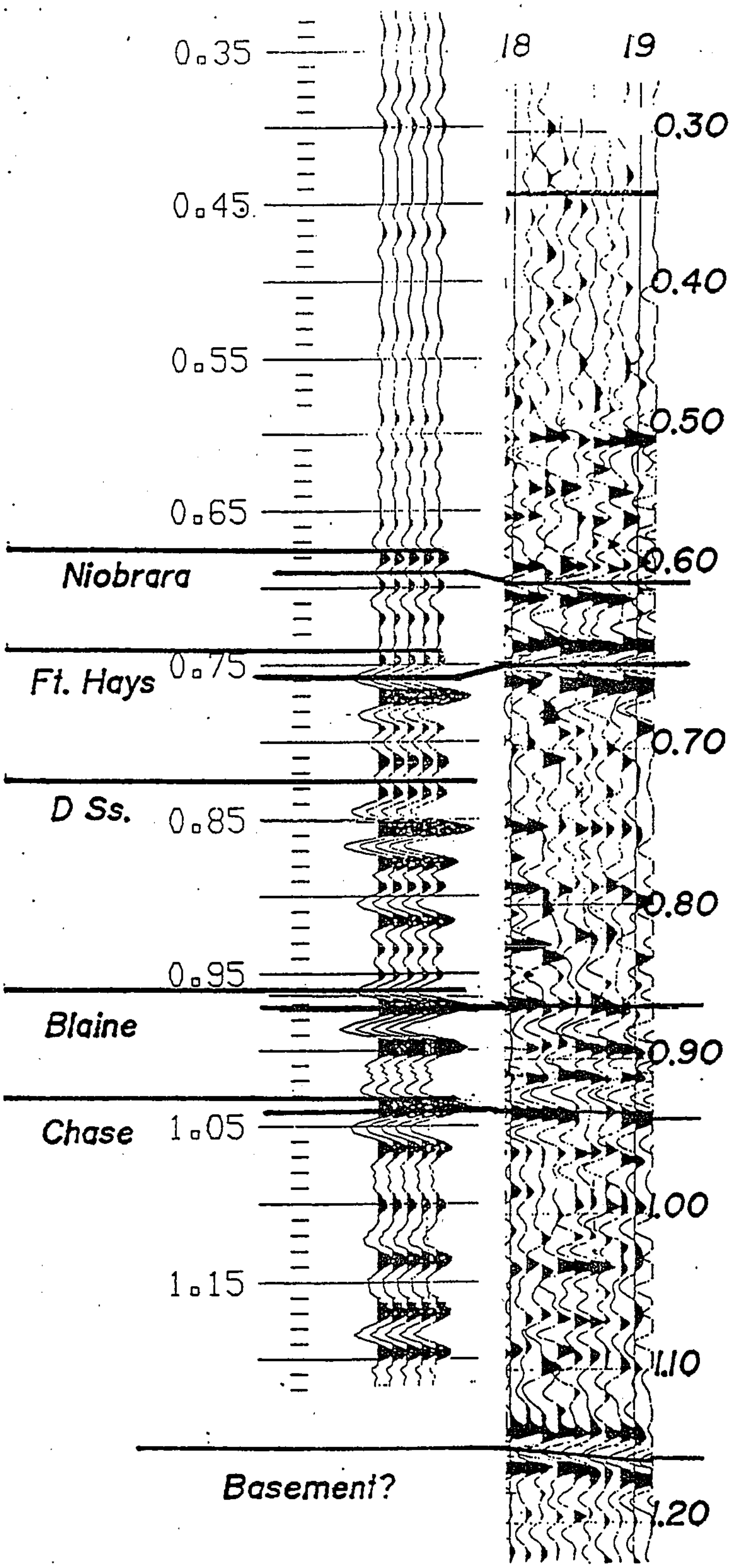


Figure 7-15. Comparison of synthetic seismogram and portion of Eckley field seismic profile at shot points 18 and 19, showing reflectors identified in seismic interpretation.

Interpreted Seismic Line

A part of the seismic line, interpreted on the basis of correlations with the synthetic seismogram, is shown on Figure 7-16. Locations of nearby shallow Niobrara wells and deep tests are shown. A positive structural feature is apparent across Eckley field at the level of all reflectors, including those related to the Niobrara, Fort Hays, Blaine, Chase, and basement. A decrease in travel time between the Blaine and Chase reflectors can be observed away from the crest of the structure at the ends of the seismic profile.

Isochron "thinning" of the Blaine-to-Chase interval and its relationship to structure is shown on a detailed part of the seismic profile at the south end of Eckley field (Figure 7-17). In the Eckley field area, where Blaine-Chase travel time is greater, two peaks are present between the Blaine and Chase reflectors. A single peak is present between the two reflectors in areas marginal to the Eckley structure. Two-way travel time across the Blaine - Chase interval varies by 28 msec, ranging from a maximum of 73 msec at shot point 18 (under Eckley field) to a minimum of 45 msec at shot points 10, 11, and 12 (in the structural low marginal to the field).

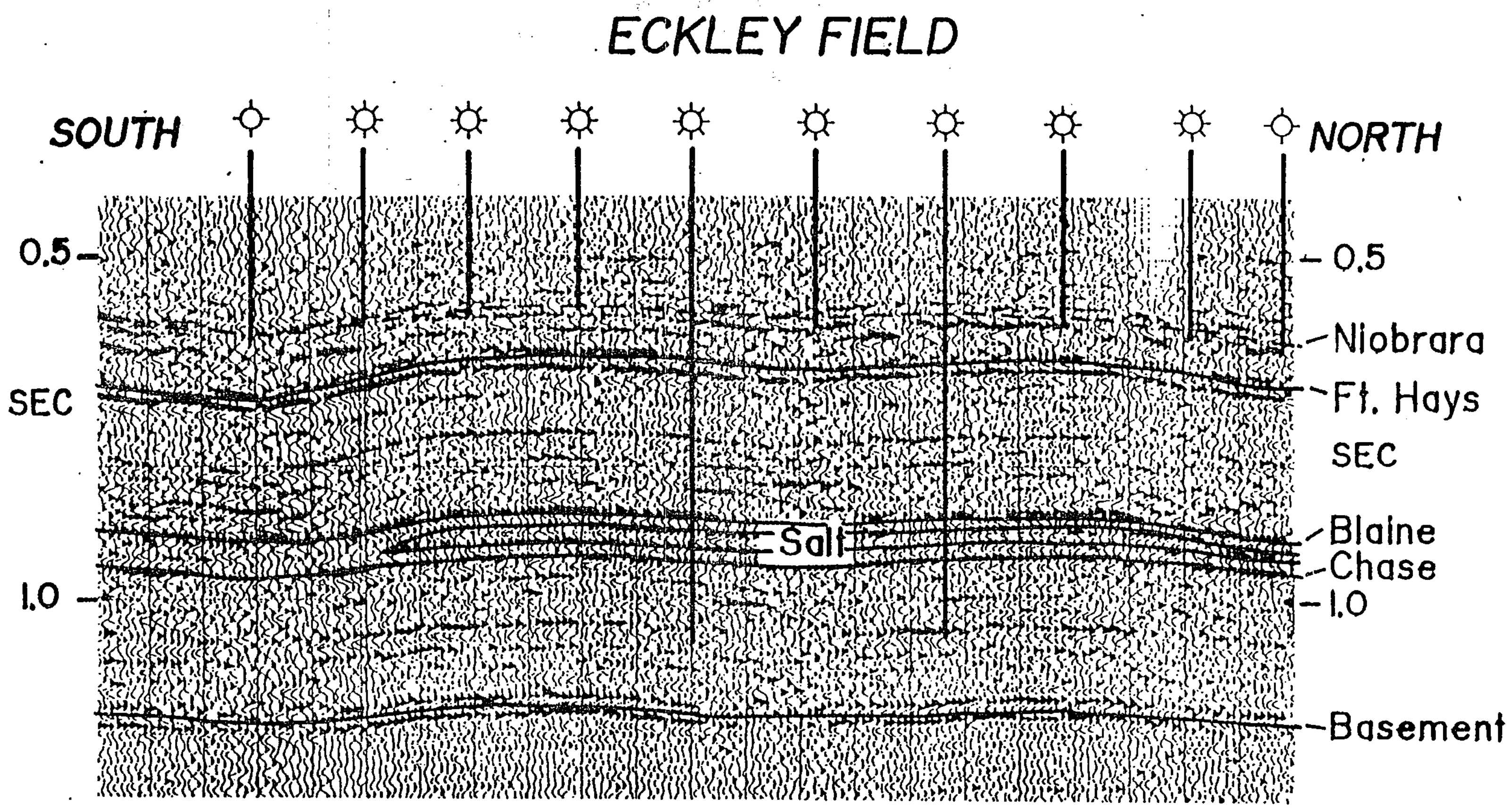


Figure 7-16. Interpreted north-south seismic profile across Eckley field. Length of profile is 3.7 mi (5.9 km). Seismic line courtesy of Mesa Petroleum Corporation and K-N Production Company, used with permission.

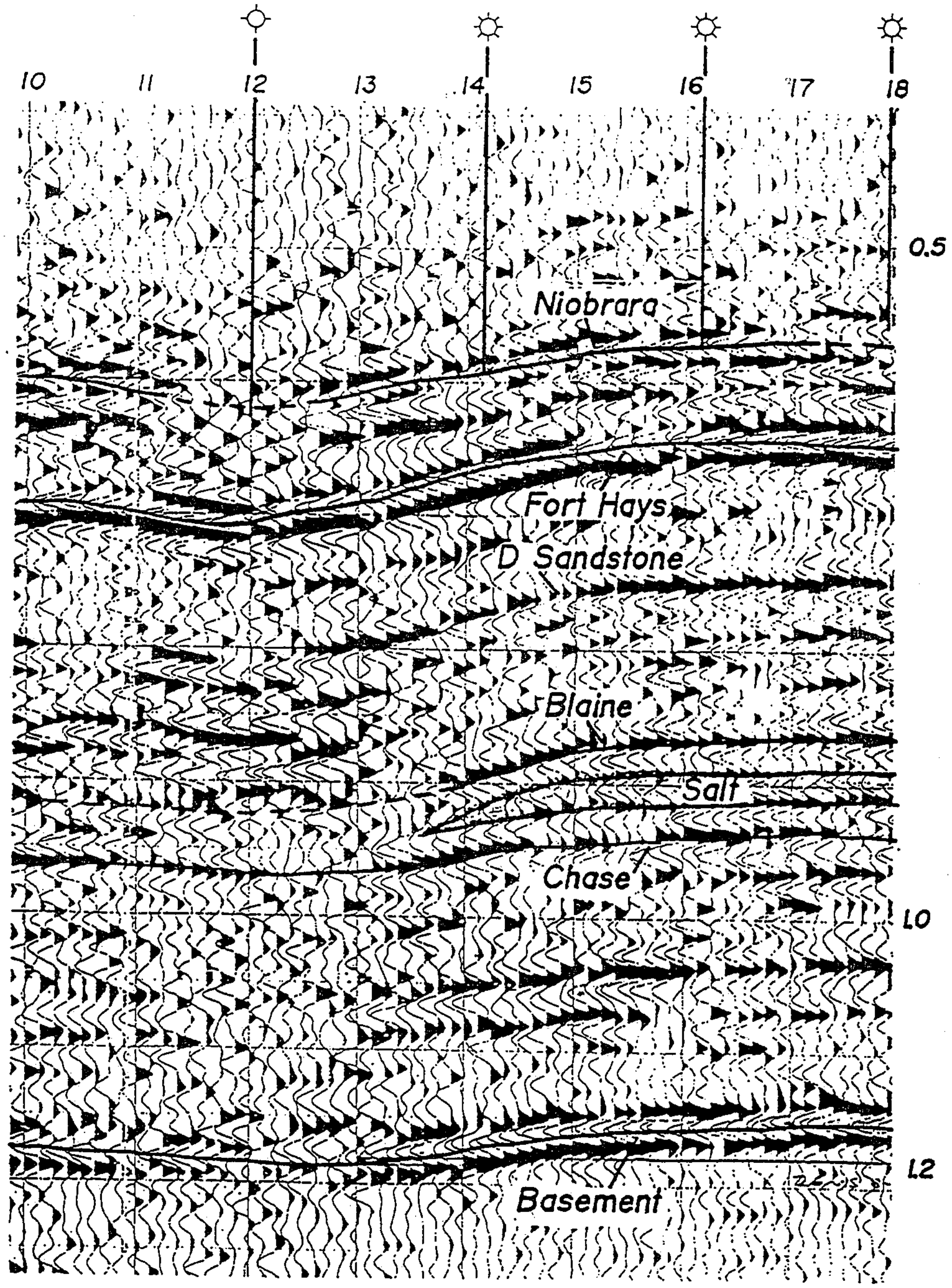


Figure 7-17. Portion of seismic line at southern end of main Eckley producing area. Length of profile is 1.3 mi (2.1 km).

Salt Dissolution Model

Figure 7-18a shows a simple 4-layer salt dissolution depth model. Removal of salt by dissolution marginal to the outlier (layer 3) took place during deposition of layer 1. The model uses the following assumptions:

1. Additional thickness of layer 1 (collapse fill) in areas marginal to the salt outlier = thickness of salt = d_3.
2. Thickness and velocity of layer 2 (d_2, v_2) are constant across the model.
3. Velocity of layer 1 (v_1) is constant across the model, and is lower than the velocity of salt (v_3).

The presence of the salt outlier (layer 3) causes an increase in travel time between layers 2 and 4 in the center of the model. Two-way travel time across the salt outlier can be expressed as

$$t_3 = \frac{2d_3}{v_3}$$

This time interval will be represented on seismic data as an isochron thick between two reflectors which are related to strata immediately above and below the salt.

The presence of salt will also cause a velocity anomaly at the level of subsalt reflectors, due to lateral variations in thickness of collapse fill and salt and the contrast in their velocities (v_1 and v_3). Two-way travel time to layer 4 (subsalt reflector) varies, depending on

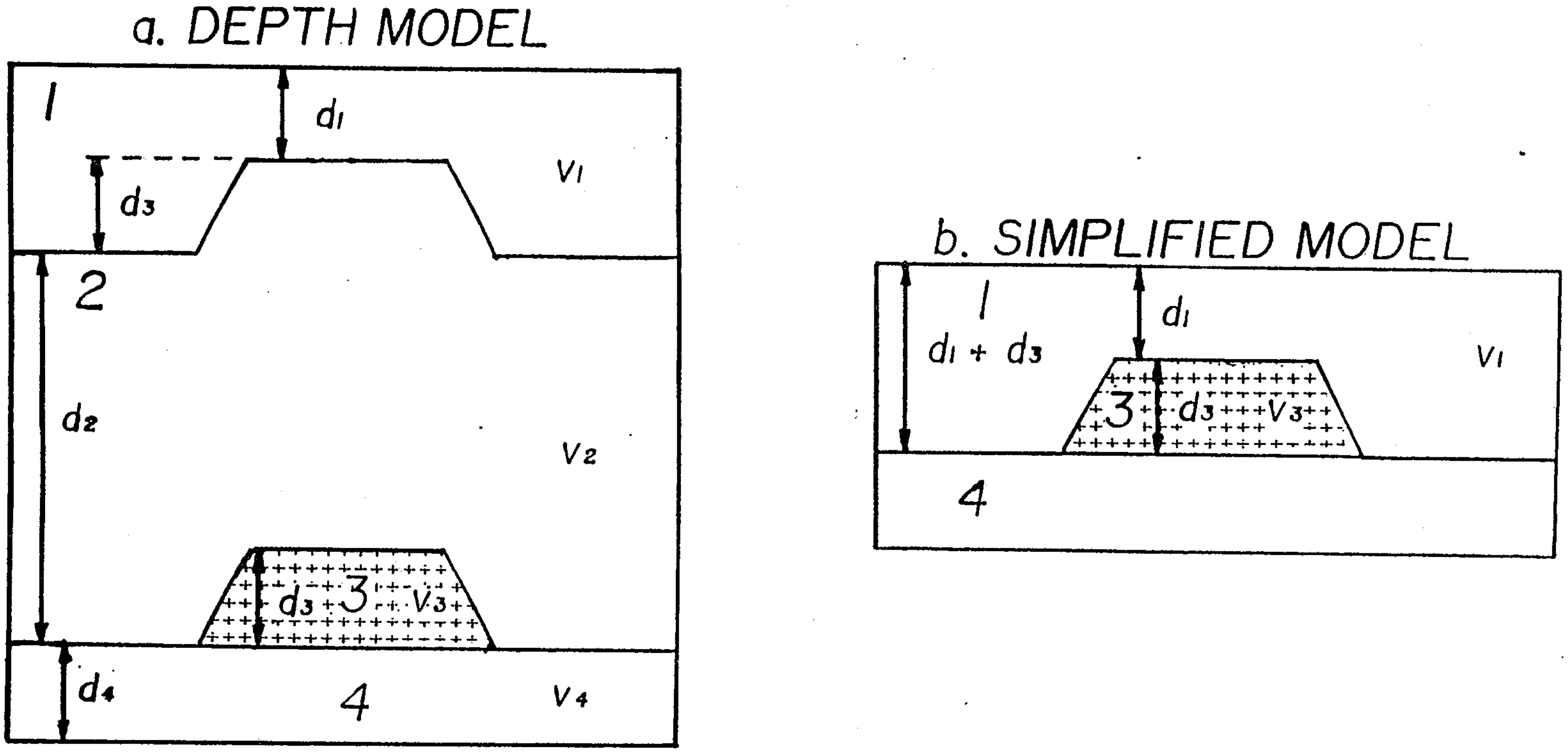


Figure 7-18. Salt dissolution depth model.

whether salt is encountered. If salt is present, two-way travel time to the subsalt reflector (boundary between layers 3 and 4) can be expressed as

$$t_{salt} = \frac{2d_1}{v_1} + \frac{2d_2}{v_2} + \frac{2d_3}{v_3}$$

If salt is absent, two-way travel time to the subsalt reflector (boundary between layers 2 and 4) can be expressed as

$$t_{nosalt} = \frac{2(d_1+d_3)}{v_1} + \frac{2d_2}{v_2}$$

Difference in two-way travel time to the subsalt reflector,

$$\Delta t_{subsalt} = t_{salt} - t_{nosalt}$$

or,

$$\begin{aligned}\Delta t_{subsalt} &= \frac{2d_1}{v_1} + \frac{2d_2}{v_2} + \frac{2d_3}{v_3} - \frac{2(d_1+d_3)}{v_1} + \frac{2d_2}{v_2} \\ &= \frac{2d_1}{v_1} + \frac{2d_2}{v_2} + \frac{2d_3}{v_3} - \frac{2d_1}{v_1} - \frac{2d_3}{v_1} - \frac{2d_2}{v_2} \\ &= \frac{2d_3}{v_3} - \frac{2d_3}{v_1}\end{aligned}$$

Because the thickness and velocity of layer 2 (d_2, v_2) are assumed to be constant across the model, layer 2 does not contribute to the subsalt velocity anomaly. As a result, the model can be simplified (Figure 7-18b).

If the velocity of the salt is higher than that of the collapse fill ($v_3 > V_1$), then $\Delta t_{subsalt}$ is a negative value, reflecting a velocity pullup below the salt outlier. The amount of pullup is a function of salt (and collapse fill) thickness (d_3) and the contrast between salt velocity (v_3) and collapse fill velocity (v_1).

Eckley Field Model

A simple depth model which depicts a salt dissolution origin for the Eckley field structure is shown on Figure 7-19a. The model includes a residual salt outlier situated between the Blaine Anhydrite and the Chase Group. Thickness of salt is 195 ft (59 m), and is based on the maximum aggregate thickness of salts 7, 8, and 10 encountered in wells at Eckley field. Average velocity across the salt interval, estimated from the sonic log from well 2058, is 14,300 ft/sec.

Structural relief of about 190-200 ft (60 m) along the southern margin of the field (where salt is presumed to be absent) occurs at the Niobrara level (Figures 7-4 and 7-6) as well as at the level of strata which lie just below the base of surface casing on well logs, near the boundary between Cretaceous and Tertiary strata. Thus, salt solution-collapse (and infilling of the collapse area) presumably occurred during the Tertiary, and possibly as late as the Quaternary. Velocity of the shallow Cenozoic collapse fill (which cannot be determined because it lies behind surface casing) would be low relative to that of the salt. Velocity of the Upper Cretaceous Pierre Shale

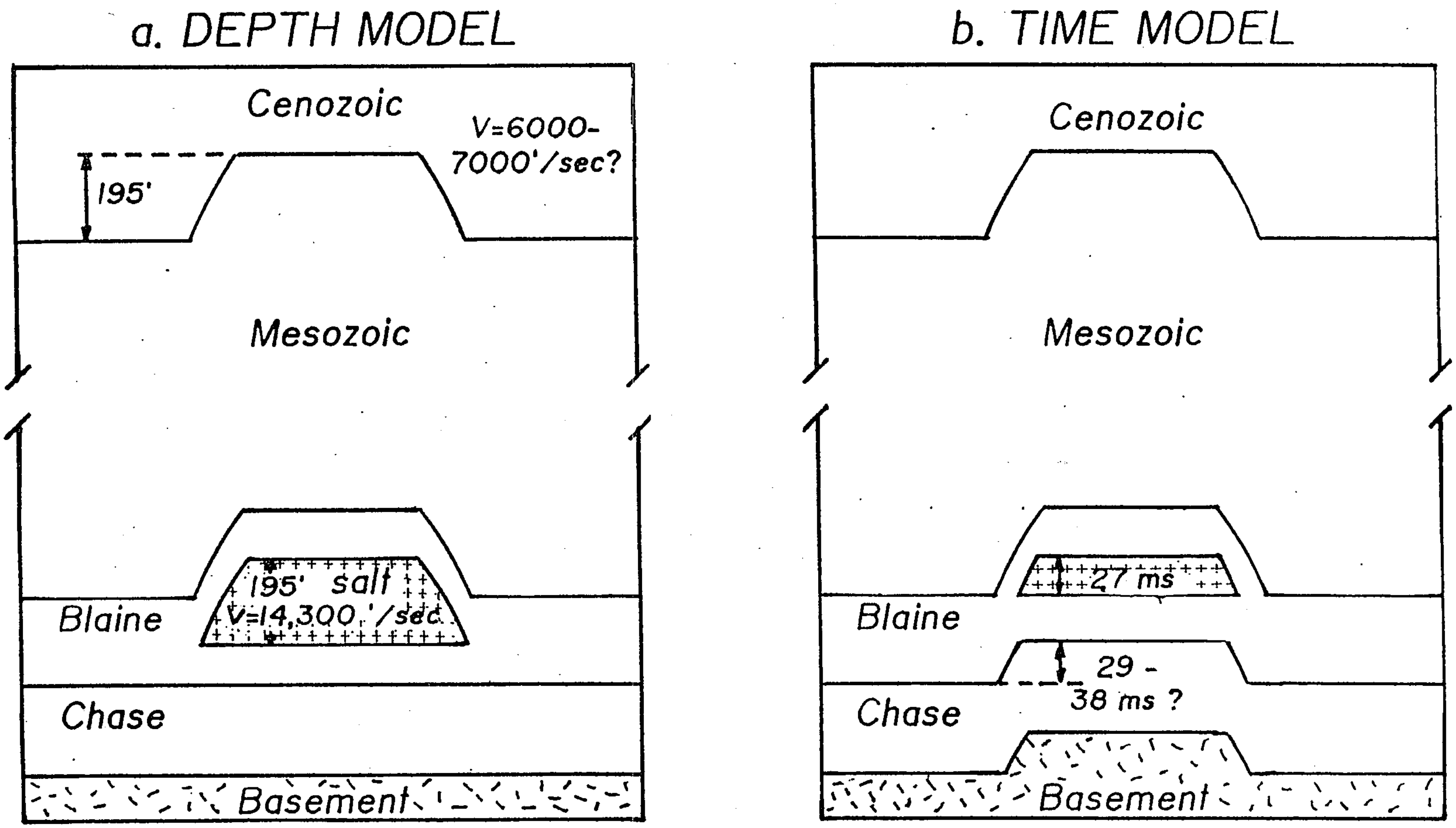


Figure 7-19. Simple depth and time models for a salt outlier at Eckley field.

averages about 7000 ft/sec immediately below the base of surface casing in well 2058. Shallow, low-velocity strata include Tertiary sandstones and gravels, with velocities lower than 7000 ft/sec. In addition, Pleistocene dune sands blanket the surface in the Eckley area. Velocity of dune sands in this area may be as low as 3500 ft/sec (Richard Lockhart, Lockhart Geophysical, personal communication). Effects of these uppermost layers, however, have likely been removed by static corrections, during processing of seismic data. Although the velocity of the presumed collapse fill (v_1) cannot be determined, it is likely to be 7000 ft/sec or less. Thickness of the collapse fill is assumed to be equal to the thickness of the salt (d_3 = 195 ft). Because salt dissolution is presumed to have taken place during deposition of shallow (Cenozoic) strata (layer 1), thickness and velocity of layer 2 (Mesozoic strata) (d_2, v_2) are constant across the model.

Simplified seismic response to the depth model (Figure is shown on Figure 7-19b. A 195-ft (59-m) thick salt outlier (with an average velocity of 14,300 ft/sec) results in a predicted increase in Blaine - Chase travel time of 27 msec. This agrees favorably with the 28-msec increase in Blaine - Chase travel time observed between shot points 12 and 17 on Figure 7-17.

The contrast between high-velocity salt and low-velocity near-surface sediments causes a velocity pullup in the area of the salt outlier. If near-surface low-velocity sediments compensate for the salt in collapse areas, a false structure occurs at the level of reflectors below the salt outlier, because travel time through the high-velocity salt is shorter than travel time through younger, low-velocity sediments.

The amount of subsalt velocity pullup cannot be predicted, because the near-surface (Cenozoic) collapse-fill interval velocity (v_1) is unknown. If $v_1 = 7000$ ft/sec, a subsalt velocity pullup of 29 msec is expected; if $v_1 = 6000$ ft/sec, a subsalt velocity of 38 msec is expected.

Analysis of Seismic Data

Two-way travel times to reflectors associated with the Fort Hays, Blaine, and Chase along the Eckley seismic profile are plotted on Figure 7-20. Plots include data from shot points along a 5-mi (8-km) portion of the seismic line. A positive feature at Eckley field is apparent at the level of all three reflectors. A seismic low occurs at shot point 12, just south of the field. Seismic highs are present at shot points 17 and 26.

Travel time to the reflector associated with the Fort Hays varies by 63 msec, and ranges from 643 msec at shot point 17, at the crest of the Eckley field structure, to 706 msec at shot point 12, one mile south in a structural

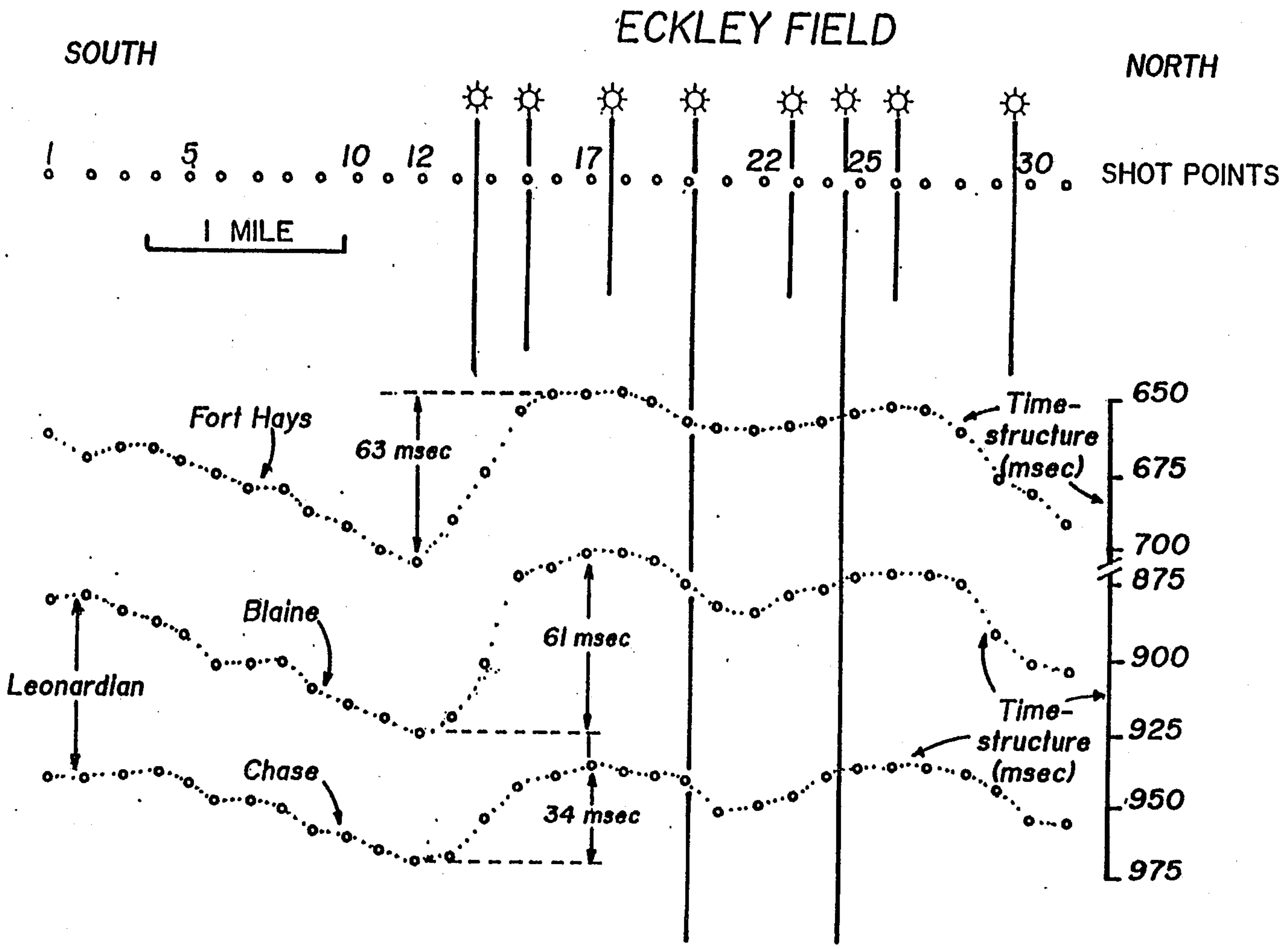


Figure 7-20. North-south time structure profiles showing relationship of Fort Hays, Blaine, and Chase reflectors to Eckley field.

depression which separates the main producing area of the field from the area of discovery and initial development. Variation in travel time to the reflector associated with the Blaine Anhydrite is 61 msec, ranging from 863 msec at shot point 17 to 924 msec at shot point 12. Travel time to the reflector associated with the Chase Anhydrite varies by 34 msec, and ranges from 1150 msec at shot point 17 to 1184 msec at shot point 12.

Well control-based structural profiles at the Niobrara (Beecher Island zone) and Chase levels are compared to seismic travel time profiles on Figure 7-21. The Beecher Island zone structural profile is plotted in feet above sea level and is derived from the Beecher Island zone structural interpretation (Figure 7-4), which is based on well control. The Chase structural profile is derived from the the subsalt structural interpretation (Figure 7-9), which is based on deep well control only.

The Beecher Island zone elevation profile parallels the Fort Hays time profile, except at the north end of Eckley field, where a listric fault is interpreted to explain the discordance between the upper and lower members of the Niobrara. Comparison of the Beecher Island zone and Chase elevation profiles reveals significant structural discordance between suprasalt and subsalt strata.

Two-way travel time difference between the Blaine and Chase reflectors (Figure 7-22), which is interpreted to

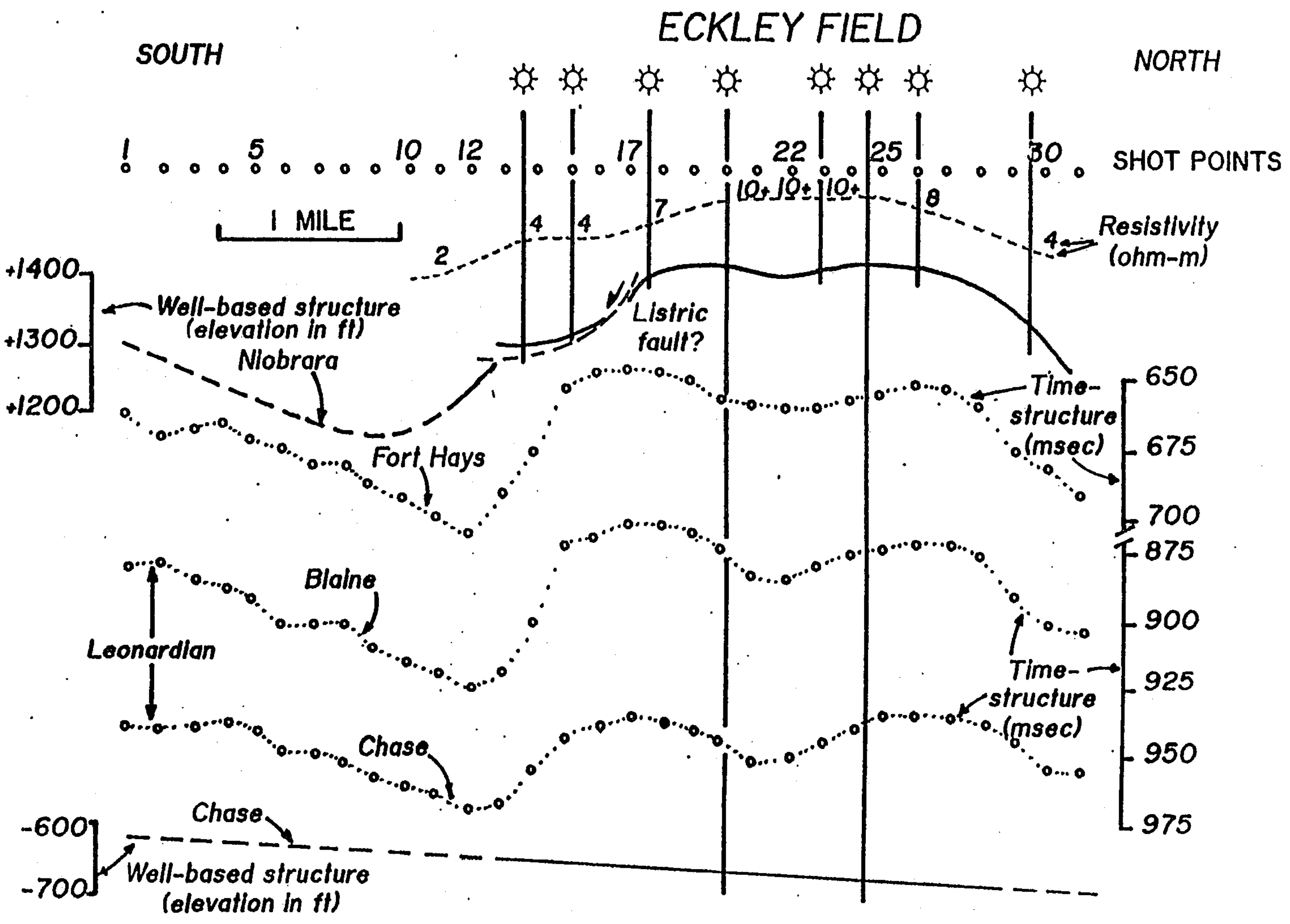


Figure 7-21. North-south time structure profiles showing relationship of Fort Hays, Blaine, and Chase reflectors to well-based Niobrara and Chase structure.

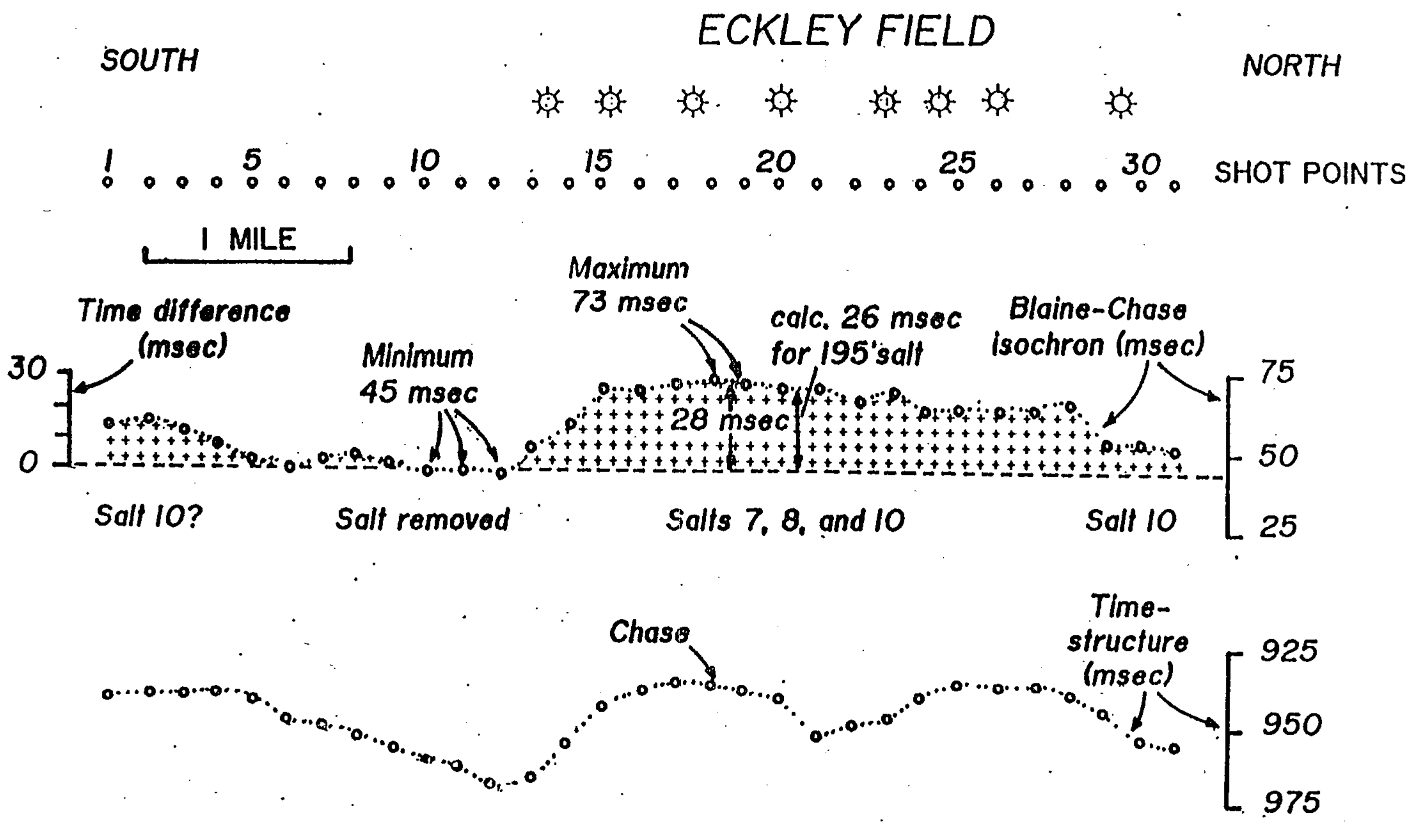


Figure 7-22. North-south profile showing Blaine-Chase isochron thinning at Eckley field margins and Chase time structure.

represent the approximate interval travel time through the Leonardian salt interval, ranges from a maximum of 73 msec at shot points 18 and 19 to a minimum of 45 msec at shot points 10, 11, and 12. Assuming that all variation in Leonardian interval travel time is due to variation in salt thickness, the minimum of 45 msec is interpreted to reflect the complete absence of salt. Leonardian isochron values which plot above the 45-msec. line are interpreted to indicate presence of salt.

Values of as high as 73 msec (28 msec greater than the 45 msec no-salt "baseline") occur at shot points 18 and 19, on the crest of the Eckley field, where salts 7, 8, and 10 were encountered in deep tests. Salt is interpreted to be thin or absent just to the south at shot points 10, 11, and 12. Salt may be present farther to the south, near the area of the Eckley field discovery well. At the north end of the plot, values of 53 to 55 msec (8 to 10 msec greater than the 45 msec "baseline") are interpreted to be due to the presence of about 50 ft (15 m) of salt 10 only, which was encountered nearby in well 2057, located between Eckley and Old Baldy fields.

Thinning of the Leonardian isochron by 28 msec south of Eckley field compares favorably with a 27-msec value predicted by the simple salt outlier model (Figure 7-19). This supports the hypothesis that salt dissolution is responsible for Niobrara-level structural relief, which controls the accumulation of gas at Eckley field.

The model (Figure 7-19) also indicated that a 195-ft (59-m) thick salt outlier would cause a subsalt velocity pullup ranging from 29 msec (using a Cenozoic collapse fill velocity (v_1) of 7000 ft/sec) to 38 msec (using a v_1 of 6000 ft/sec). A 34-msec pullup occurs at the level of the Chase reflector (Figures 7-20 and 7-22) between shot point 12 (where salt is interpreted to be absent) and shot point 17 (where well control indicates that thick salt is present). This 34-msec pullup is within the 29 to 38 msec range predicted above. Assuming that the subsalt (Chase-level) pullup is due entirely to the contrast in velocity of salt (v_3) and collapse fill (v_1), and is not due in part to subsalt fault offset, the 34-msec pullup indicates an average collapse fill velocity (v_1) of 6400 ft/sec. This appears to be a reasonable value for Tertiary strata which lie behind surface casing.

A key assumption in the above discussion is that the subsalt velocity anomaly is due only to the thickness of the salt outlier (d_3) and the velocity contrast between shallow collapse fill (v_1) and salt (v_3), and that no lateral variation in thickness or velocity occurs in the interval between collapse fill and salt. This assumption likely represents an oversimplification of the subsurface geology in the Eckley field area. Some lateral variation in travel time can be observed between the Fort Hays and Blaine reflectors. Variation may be due to subtle syndepositional basement fault movement, or listric faulting of Upper Cretaceous strata. Nevertheless, it appears that much of the deep velocity pullup which occurs below Eckley field can be attributed to the presence of a relatively high-velocity salt outlier.

Deep Exploration Implications

Salt-related velocity pullups at the level of deep reflectors can result in false Paleozoic-level structures in the Denver basin. Most of the nearly 70 Paleozoic tests drilled in Yuma County are in areas which would later be developed as shallow Niobrara gas fields. Although 6000 BO were produced from the Pennsylvanian at Laird field in T2N, R42W, no commercial Paleozoic production exists in the area. Subsalt velocity pullups on seismic data likely encouraged the drilling of numerous deep exploratory failures in Yuma County and adjacent areas of the Denver basin. Identification of Permian-level seismic isochron variations (caused by localized variations in salt thickness and distribution) is critical to accurate interpretation of deeper Paleozoic structure.

DISTRIBUTION OF LEONARDIAN SALT

Thickness and occurrence of Leonardian salts at Eckley field (Figure 7-23) are interpreted on the basis of deep well data, seismic data, and Niobrara structure (Figure 7-4). Salts 7, 8, and 10 are present in an area centered around Secs. 32 and 33, T4N, R45W. This area coincides with the crest of the Eckley structure and with Leonardian (Blaine-Chase) seismic isochron maxima. Salts 7 and 10 are interpreted to be present in an area centered around Sec. 18, T4N, R45W, coincident with a structural high at Old Baldy field. Only salt 10 is present to the northeast of Eckley field. Salt is interpreted to be completely absent in the area immediately to the east and south of the main Eckley producing area, between Eckley and Old Baldy fields, and to the east of Old Baldy field. Presence of salt in the area of the Eckley field discovery is inferred on the basis of an increase in travel time between reflectors associated with the Blaine and Chase anhydrites at the south end of the seismic line.

A Leonardian isopach (Figure 7-24), based on seismic data and Niobrara structure as well as deep well control, likely represents a more accurate interpretation than the Leonardian isopach which is based on well control alone (Figure 7-10). The Leonardian is less than 400 ft (122 m) thick where salt is presumed to be absent. Where salt 10

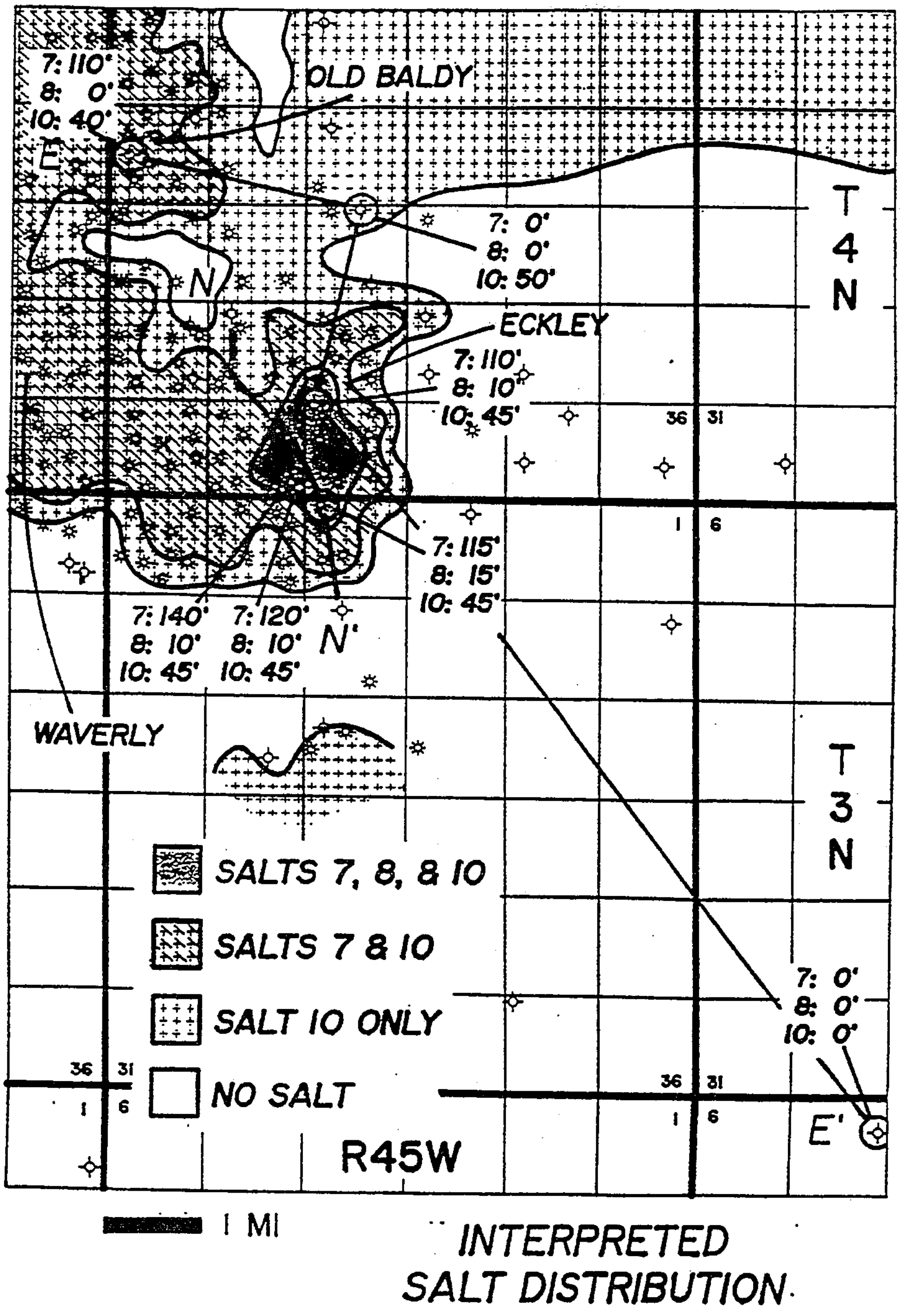


Figure 7-23. Thickness of salts present in Eckley field and interpreted distribution of salt zones. Salt distribution is based on Niobrara structure and seismic data.

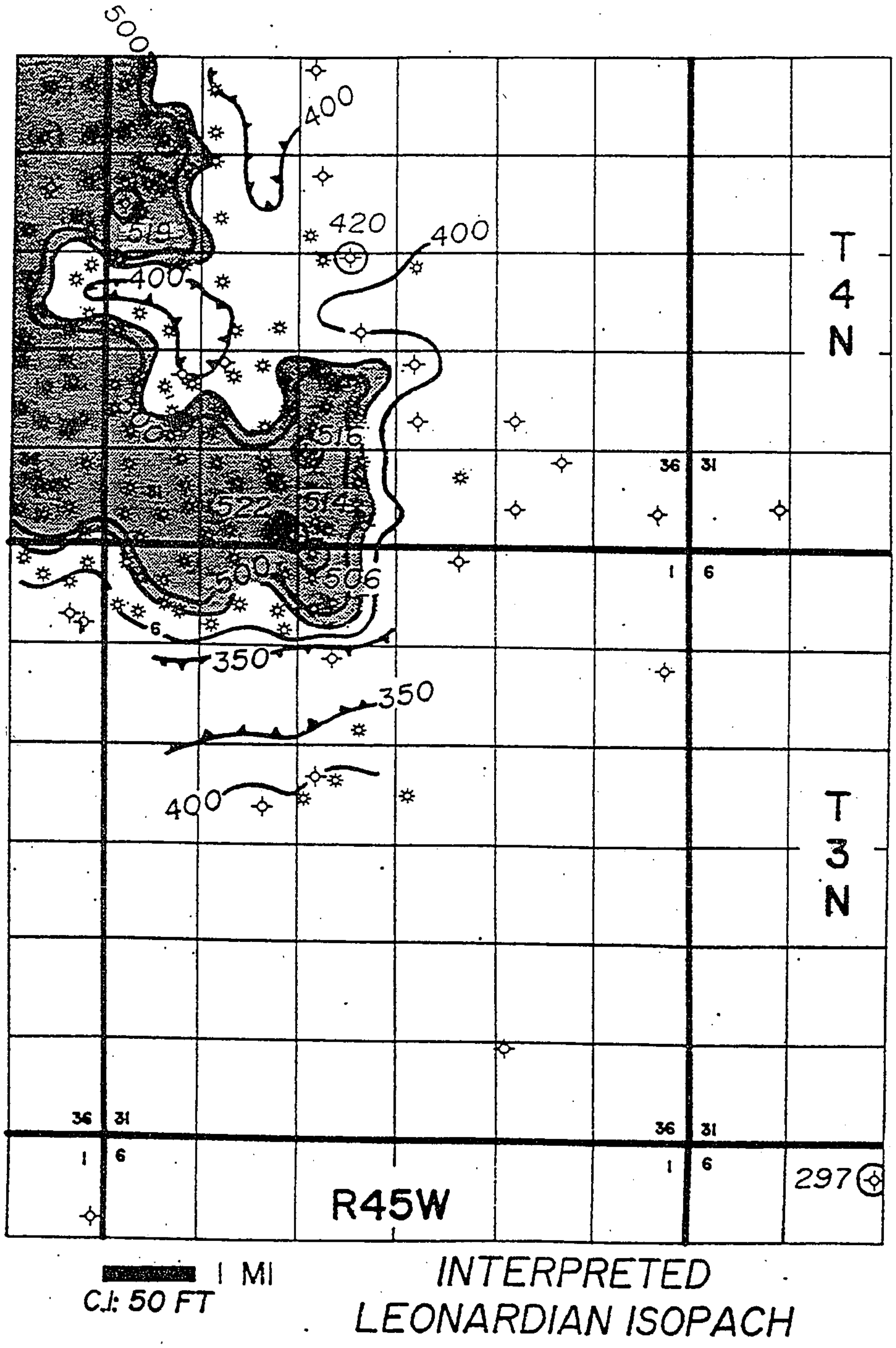


Figure 7-24. Interpreted Leonardian isopach in Eckley field area. Interpretation is based on deep well control, Niobrara structure, and seismic data.

only is present, the Leonardian is between 400 and 450 ft (122 and 137 m) thick and is over 450 ft (137 m) thick where salts 7 and 10 are both present.

CUMULATIVE GAS PRODUCTION

Cumulative gas production through 1993 is plotted on Figure 7-25. Values are shown as cumulative production per 80 acres, the approved well spacing in the field. Cumulative production is divided into 4 categories: (1) less than 200,000 MCFG per 80 acres, (2) 200,000 to 400,000 MCFG per 80 acres; (3) 400,000 to 600,000 MCFG per 80 acres; and (4) greater than 600,000 MCFG per 80 acres. In some areas, such as SE Sec. 6, T3N, R45W and Sec. 36, T4N, R46W, production cannot be shown on an 80-acre basis, because production is reported on a lease basis rather than a per-well basis. Orientation of 80-acre areas (north-south vs. east-west) does not necessarily correspond to actual spacing units ("standup vs. laydown 80s"). Production was not plotted to the north at Old Baldy field because many of these wells do not have a sufficiently long production history to make meaningful comparisons with Eckley field.

A comparison of the distribution of high-yield wells (Figure 7-25) to Beecher Island zone structure (Figure 7-4) reveals that gas production is not related entirely to structural position. Many of the highest-yield wells,

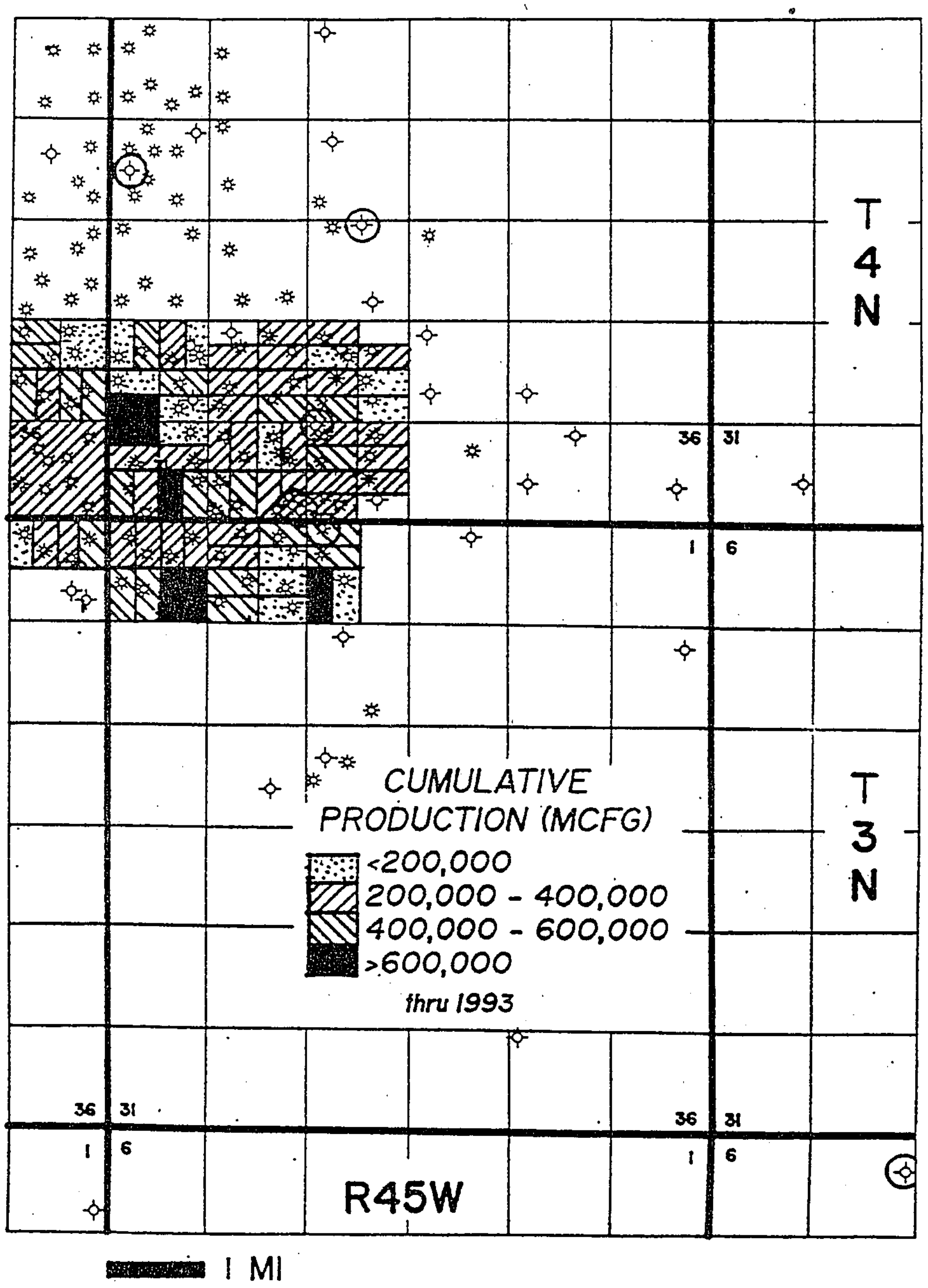


Figure 7-25. Cumulative production per 80-acres in Eckley field.

including those located in NWSW Sec. 3, T3N, R45W; NWSE and NESE Sec. 6, T3N, R45W; SW Sec. 30, T4N, R45W; and NW Sec. 31, T4N, R45W, are not situated on the highest part of the Eckley structure. These wells are located in areas above interpreted salt edges (Figure 7-23), particularly that of thick salt 7.

Although gas saturation (as inferred by isoresistivity contours on Figure 7-8) can be related to structure, actual gas production is presumably a function of additional factors. Because foam-fracture treatment is necessary for economic production, geologic factors which contribute to the success of fracture treatment, such as localized natural fractures, should affect total gas production. Presumably, enhanced fracturing due to normal and listric faulting along collapse areas exerts a stronger control on well yield than structural position and gas saturation. If this is true, then salt-solution edges exert a significant influence on economics at Eckley field and elsewhere in the shallow Niobrara play.

SUMMARY AND CONCLUSIONS

This chapter focused on Eckley field, the largest field in the shallow Niobrara gas play of eastern Colorado. Subsurface analysis of well data from Niobrara wells, along with deep well data and seismic data across the field, result in a number of interpretations which relate the occurrence of Permian salt to the formation of a faulted, gas-productive anticline. The following conclusions result from a subsurface study of Eckley field:

1. The main producing area of Eckley field is situated at the southeastern end of the Waverly complex. Eckley field, which has produced more gas than any other shallow Niobrara field, also has the highest per-well yield. High per-well production is believed to be due the regionally updip position of the field relative to other fields in the Waverly complex.

2. The main producing structure is a highly-faulted anticline with about 200 (60 m) of relief. Structural depressions separate the main producing area at Eckley field from the area of field discovery and initial development to the south, and from Old Baldy field to the north.

3. Resistivity of the Beecher Island zone reservoir, which is a function of gas saturation within a gas-water transition zone of over 200 ft (60 m), increases with structural position.

4. Structural discordance between a faulted anticline at the level of the Upper Cretaceous gas reservoir and homoclinal structure at the level of the subsalt Chase Group (Permian, Wolfcampian) is directly related to the presence

of Leonardian salts, whose distribution is influenced by dissolution.

5. As with many other shallow Niobrara gas fields in eastern Colorado, a Leonardian isopach maximum (due to the presence of thick, residual salt) is present in the Eckley field and Waverly complex areas.

6. Seismic data and modelling support a salt dissolution origin for the Eckley field structure. Abrupt thinning of the Leonardian interval, interpreted to be due to salt dissolution, occurs at the updip limit of the main Eckley producing area.

7. Velocity pullup at the level of subsalt reflectors may be observed on a seismic profile across Eckley field. Pullup is probably due primarily to the lateral velocity contrast between residual Permian salt (below the field) and shallow, low-velocity Cenozoic collapse-fill (marginal to the field). False structures at the Paleozoic level have likely contributed to a number of early seismic-based deep exploratory failures in this area prior to the development of the shallow Niobrara gas resource.

8. Although gas saturation (indicated by deep resistivity) within the Beecher Island zone is generally related to structural position, cumulative production appears to be controlled by a number of additional factors. Several of the highest-yield wells are located where natural

fracturing may be enhanced, presumably induced in part by faulting in response to salt dissolution.

CHAPTER 8
REGIONAL DISTRIBUTION AND CONTROLS ON SALT OCCURRENCE

The objectives of this chapter are to present a series of regional-scale isopach maps of salts and related strata and to discuss syn- and post-depositional controls on salt distribution. Subregional structural-stratigraphic studies of Permian evaporite-bearing rocks and overlying strata in western Nebraska and eastern Colorado (Chapters 4 and 6 of this report) show that the distribution and thickness of individual salt beds are controlled by: 1) the configuration of the evaporite basins during precipitation; 2) truncation or near-surface dissolution below a pre-Late Jurassic unconformity; and 3) subsurface dissolution which occurred at various times since the Jurassic. This chapter expands on those studies to discuss the distribution of salt and controls on its occurrence across the regional study area.

WOLFCAMPIAN SALT AND RELATED STRATA

Salt 13

Salt 13 (Figure 8-1), situated at the top of the Chase Group (upper Wolfcampian), is present in the Nebraska panhandle and northeastern Colorado. The salt is up to 30 ft (9 m) thick in parts of Banner, Morrill, and Cheyenne

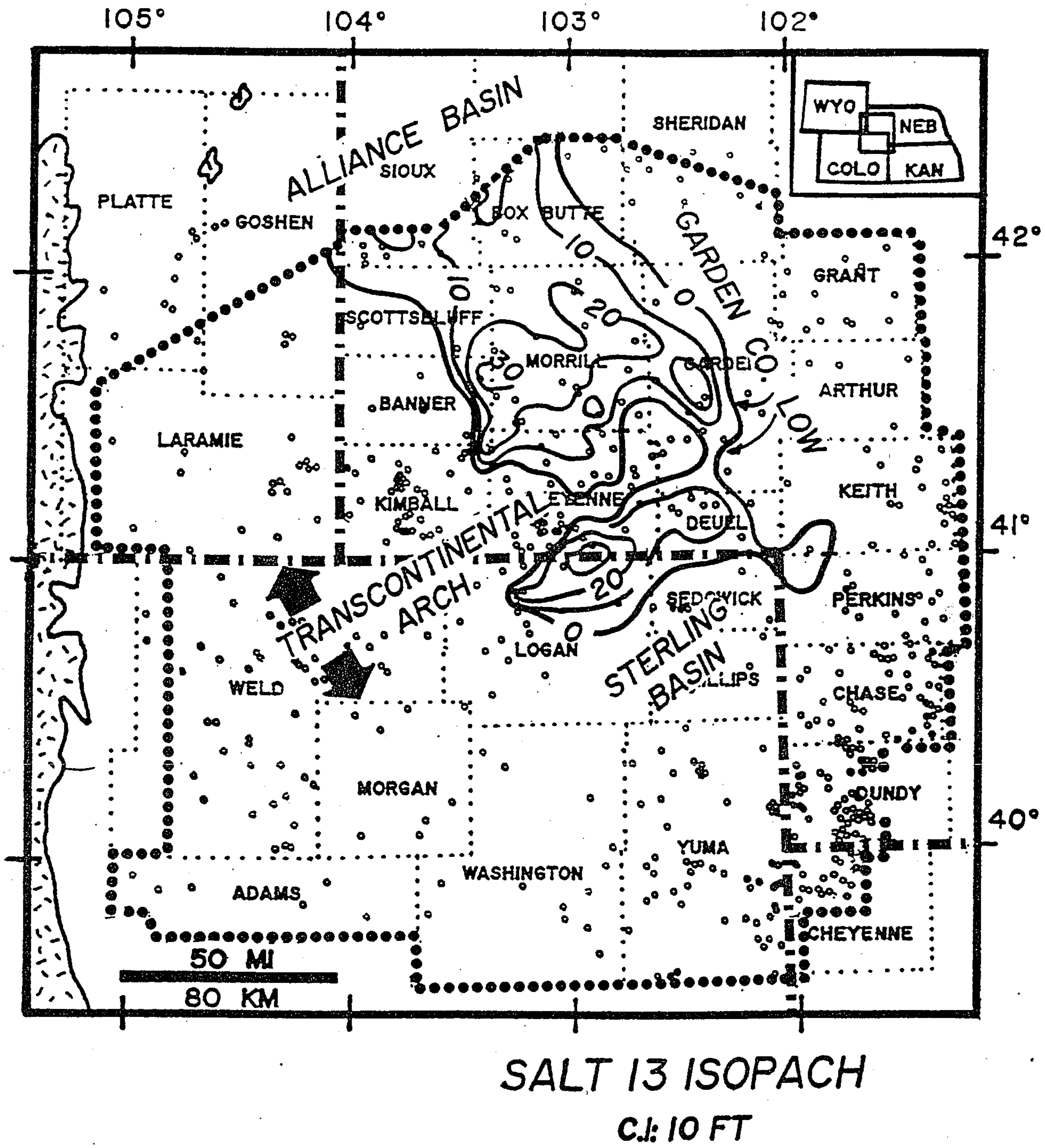


Figure 8-1. Isopach map of salt 13, situated at top of Wolfcampian Chase Group. Contour interval 10 ft (3 m).

Counties, Nebraska, and Logan County, Colorado. Salt is absent in a narrow northeast-trending area of Cheyenne and Garden Counties, Nebraska.

To the north of the study area, in the Alliance basin area, salt is present at the level of salt 13 as well as lower in the Wolfcampian (Maughan, 1966; Rascoe and Baars, 1972). This is an area which was interpreted by Garfield et al. (1988) as a restricted backramp, in which halite accumulated. The backramp was separated from a more open-marine setting to the southeast by a northeast-trending paleopositive feature related to basement faulting along the Transcontinental arch. This linear paleohigh area was termed the "Morrill County high" (MacLachlan and Bieber, 1963). Based on isopach studies of Wolfcampian and "upper Permian" rocks (which roughly equate to the combined Leonardian/Guadalupian of this study), Sonnenberg and Weimer (1981) interpreted two parallel, northeast-trending positive areas, the Morrill County high and the "Wattenberg high" to the southeast (Figure 2-4). The two paleohighs were separated by their "Cheyenne County low." Sonnenberg and Weimer attributed areas of thinning to convergence over uplifted basement blocks. The relative abundance of deep subsurface control available now allows for the recognition that, rather than convergence, thinning of Permian strata, particularly those of Leonardian and Guadalupian age, is largely due to pre-Late Jurassic truncation and subsequent salt dissolution.

Although salt 13 is absent in the area of the paleohigh, it occurs in a narrow northwest-trending area in Garden County, Nebraska, which appears to have linked the Sterling basin (extreme northeastern limit of Rall and Loeffler's (1994) "Denver embayment") to the Alliance evaporite basin. This apparent transverse sag across the Transcontinental arch is termed the "Garden County low" (Oldham, 1996).

Isopach maps of stratigraphic units associated with salt 13 were prepared, in an effort to provide support for non-deposition (associated with the paleohigh) rather than subsequent dissolution as an explanation for the no-salt area centered around Cheyenne County. An isopach map of the uppermost evaporite bed in the Wolfcampian Chase Group (Figure 8-2), termed the "W-1" evaporite in this study (Figure 3-2), reveals thickness variation of the uppermost Chase anhydrite (or salt 13 where halite is present). A northeast-trending isopach minimum in the southern Nebraska panhandle corresponds to the area where salt 13 is absent on Figure 8-1. As with salt 13, the "W-1" evaporite is thick to the north, toward the Alliance basin area, and in Deuel County, Nebraska, and Logan County, Colorado, just southeast of the apparent paleohigh. The "W-1" evaporite pinches out in Kansas and adjacent areas along the southeastern margin

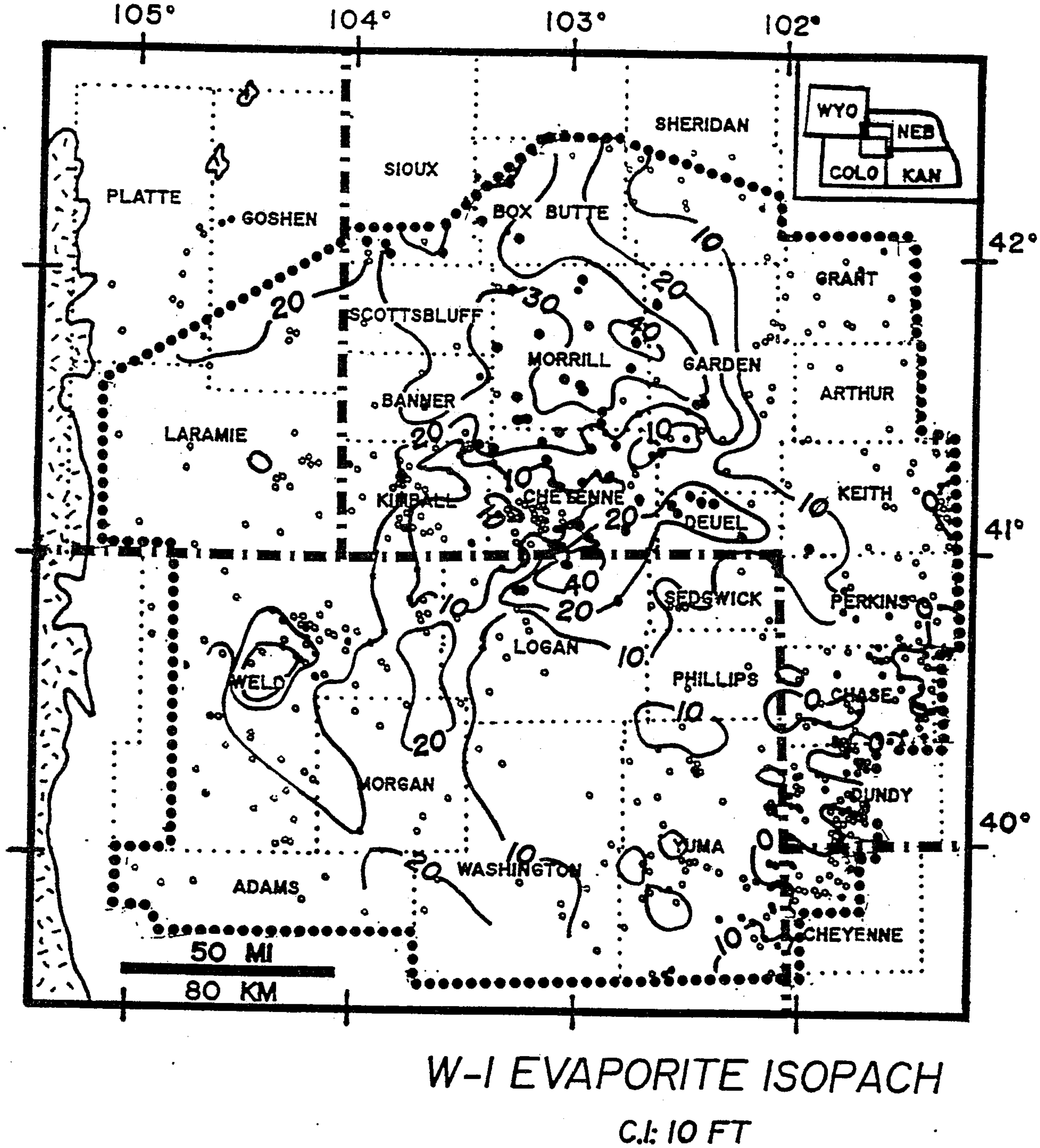


Figure 8-2. Isopach map of "W-1" evaporite, situated at top of Wolfcampian Chase Group. Contour interval 10 ft (3 m). Solid circles denote wells in which halite (salt 13) was encountered.

of the study area, reflecting an intertonguing with upper Wolfcampian clastics.

This southeastward facies change from evaporites to clastics is also reflected on an isopach map of the "W-2" evaporite (Figure 8-3), an anhydrite which is more than 20 ft (6 m) thick over most of the study area (Figure 3-2). This anhydrite is less than 10 ft (3 m) thick in the southeastern corner of the study area, where it intertongues with clastic rocks (Rascoe and Baars, 1972). Upper Wolfcampian clastic sediments accumulated in this area as part of the "Apishipa delta" (Rall and Loeffler, 1994). Rascoe's (1978) regional isopach maps, centered around an area to the southeast of the present study area, reflect the influence of the ancestral Las Animas arch on sedimentation during the Pennsylvanian and Permian, and its role in the southeastward facies change within upper Wolfcampian strata.

The "W-2" evaporite (Figure 8-3) is thickest (more than 60 ft or 18 m) in the Alliance basin area along the northern edge of the study area, and is over 50 ft (16 m) thick in parts of Weld and Morgan Counties, Colorado, at the northwestern margin of Rall and Loeffler's (1994) "Denver embayment". Slight thinning of the "W-2" evaporite occurs along the same northeasterly trend in the Nebraska panhandle in which isopach minima for the "W-1" evaporite (Figure 8-2) and salt 13 (Figure 8-1) were observed. Anhydrite in the "W-2" interval should be less sensitive to dissolution at

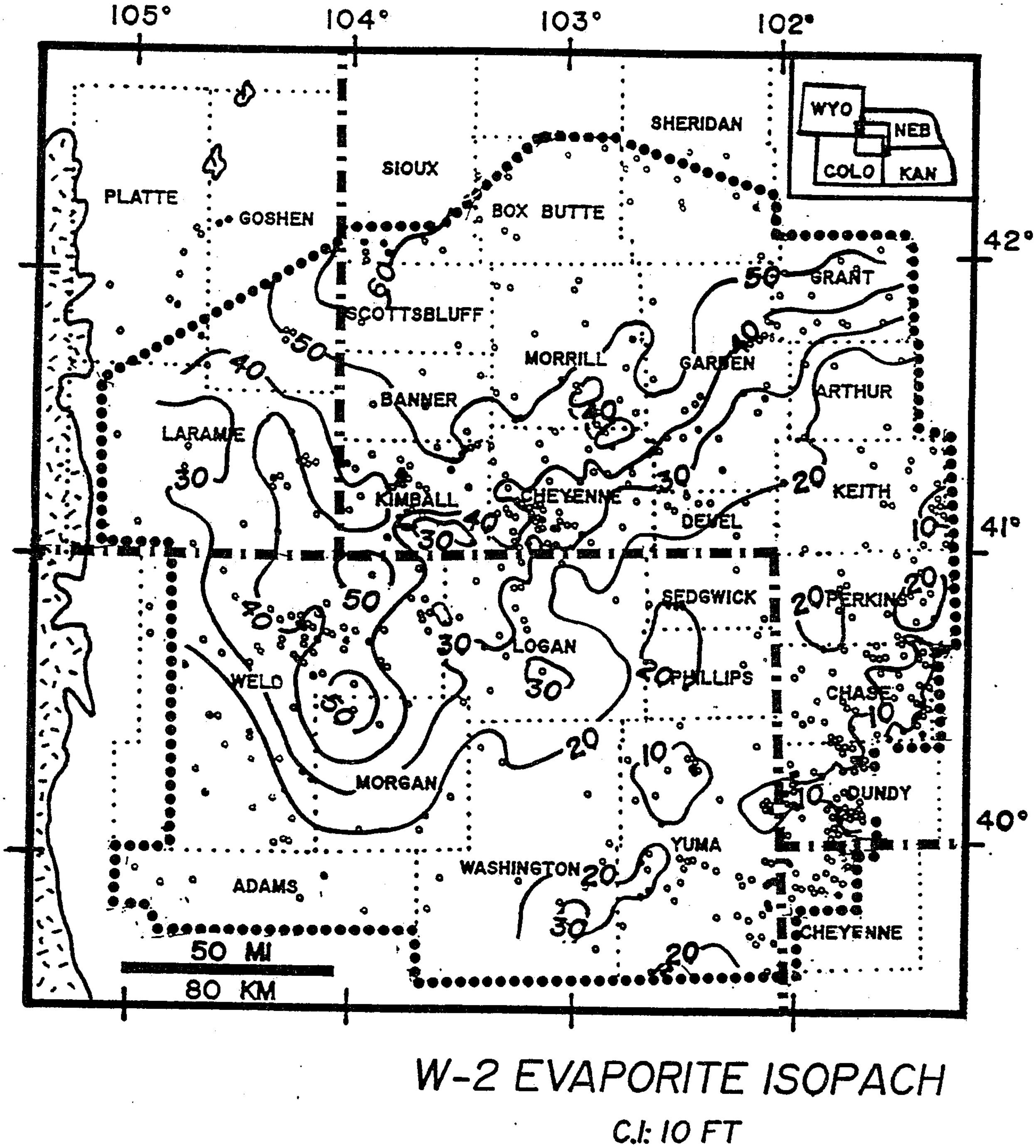


Figure 8-3. Isopach map of "W-2" evaporite (anhydrite), situated near top of Wolfcampian Chase Group. Contour interval 10 ft (3 m).

depth than halite within the "W-1" evaporite interval (salt 13). Thus, areas of "W-2" evaporite thinning should more accurately reflect syndepositional evaporite basin geometry rather than post-depositional controls (dissolution), which may influence distribution of the more soluble halite. This is supported by more detailed study of salt distribution in the Nebraska panhandle (Chapter 4), including Figures 4-16 and 4-17. These cross sections in the Sidney trough area reveal that salt 13 is present in several places where overlying salts have been removed by dissolution. If salt dissolution, rather than non-deposition, were responsible for the absence of salt 13 across the paleohigh, one would also expect it to be absent in areas where nearly complete removal of overlying salts has occurred.

Present-day distribution of salt 13 (Figure 8-1) suggests that subtle basement-involved uplift along a local paleohigh associated with the Transcontinental arch in the Nebraska panhandle and adjacent areas may have locally partitioned salt accumulation in latest Wolfcampian time. Precipitation of salt occurred to the north into the Alliance basin area and immediately to the south of the local paleohigh in the newly-formed Sterling basin area of Deuel County and southeastern Cheyenne County, Nebraska, and Logan County, Colorado. The two evaporite basins were joined across the "Garden County low."

Localized thinning of the pre-Leonardian Paleozoic interval, reflected by an isopach of the interval from the top of the Wolfcampian to the top of Precambrian basement (Figure 8-4), occurs in an area centered around Cheyenne County, Nebraska. Pre-Leonardian thickness patterns have been influenced by the Transcontinental arch in this area at times throughout the Paleozoic as well as during Permian salt accumulation. Thinning of the pre-Leonardian interval also occurs at the northeastern margin of the study area in the "Chadron proto-arch" area of Momper, 1963). Pre-Leonardian isopach maxima are present along the northwestern margin of the study area in the Alliance basin area and to the south in the Colorado portion of the study area (northern limit of the "Denver embayment" of Rall and Loeffler, 1994).

Further discussion of the influence of the Transcontinental arch on thickness of Wolfcampian and older Paleozoic rocks, which is beyond the scope of this study, can be found in MacLachlan and Bieber (1963), Rascoe (1978), Wilson (1978), Sonnenberg and Weimer (1981), Billo (1985), Garfield et al (1988) and Rogers and Longman (1988).

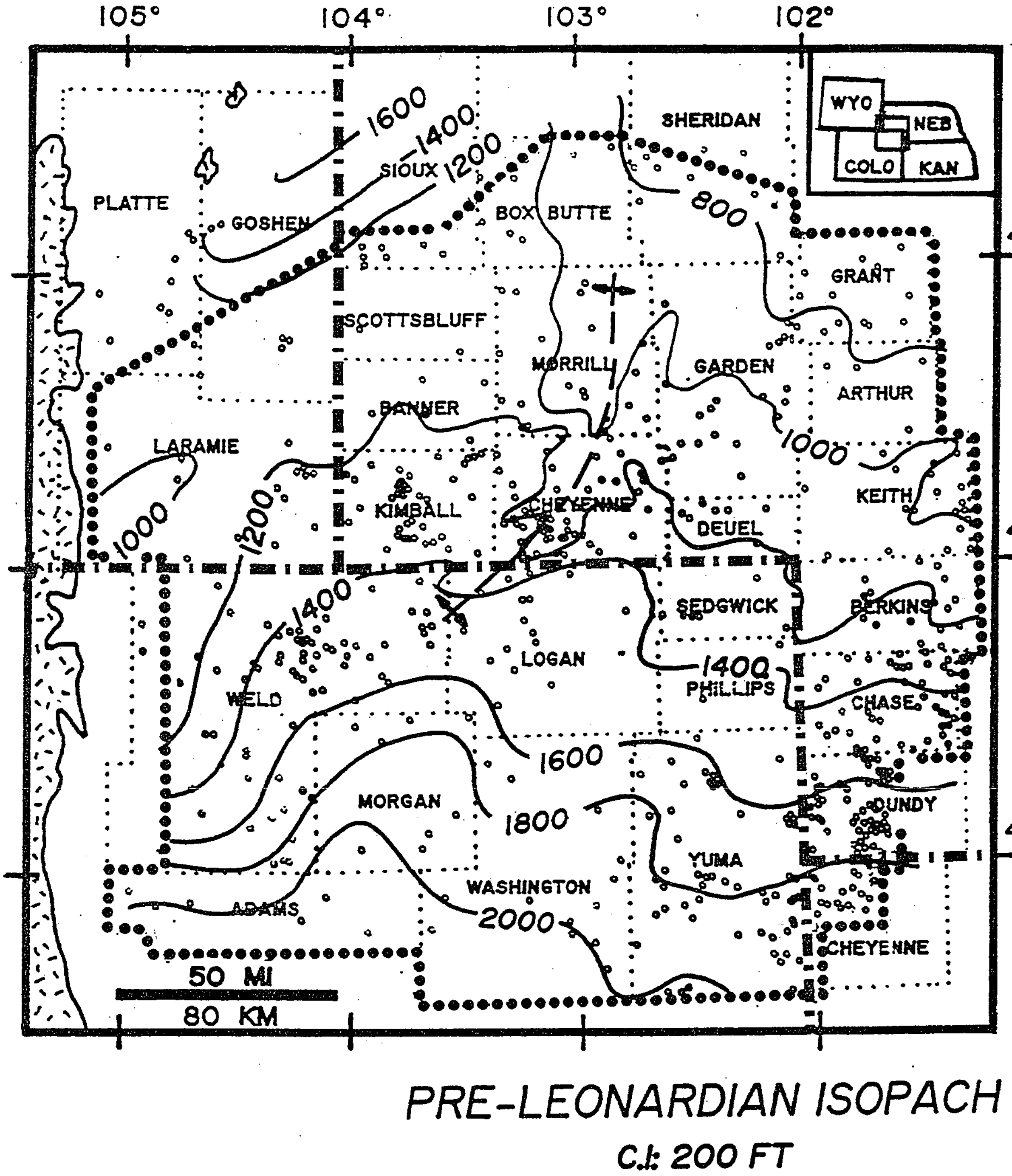


Figure 8-4. Isopach map of the pre-Leonardian Paleozoic interval (top of Wolfcampian to top of Precambrian). Contour interval 200 ft (60 m).

LOWER LEONARDIAN (SUMNER GROUP) SALTS

Salts 11 and 12

Combined thickness of Sumner Group salts (salts 11 and 12, Figure 8-5) exceeds 20 ft (6 m) in parts of Deuel, Morrill, and Garden Counties, Nebraska, and in Logan and Sedgwick Counties, Colorado, where 40 ft (12 m) of salt was encountered. Shading on Figure 8-5 in western Sedgwick County marks an area where Sumner salts are interpreted to have originally existed prior to post-Cretaceous subsurface dissolution. This area corresponds to a no-salt area and related Cretaceous-level structural depression (Red Lion anomaly) discussed in Chapter 2 (Figures 2-14 and 2-15). As with salt 13, salts 11 and 12 accumulated in the "Garden County low" between the Sterling and Alliance evaporite basins.

UPPER LEONARDIAN (NIPPEWALLA GROUP) SALTS AND RELATED STRATA

Six salt zones within the upper Leonardian Nippewalla Group were identified in the northern Denver basin subsurface (Figure 3-2). Distribution of Nippewalla salts and the Lyons (Cedar Hills) Sandstone is discussed below.

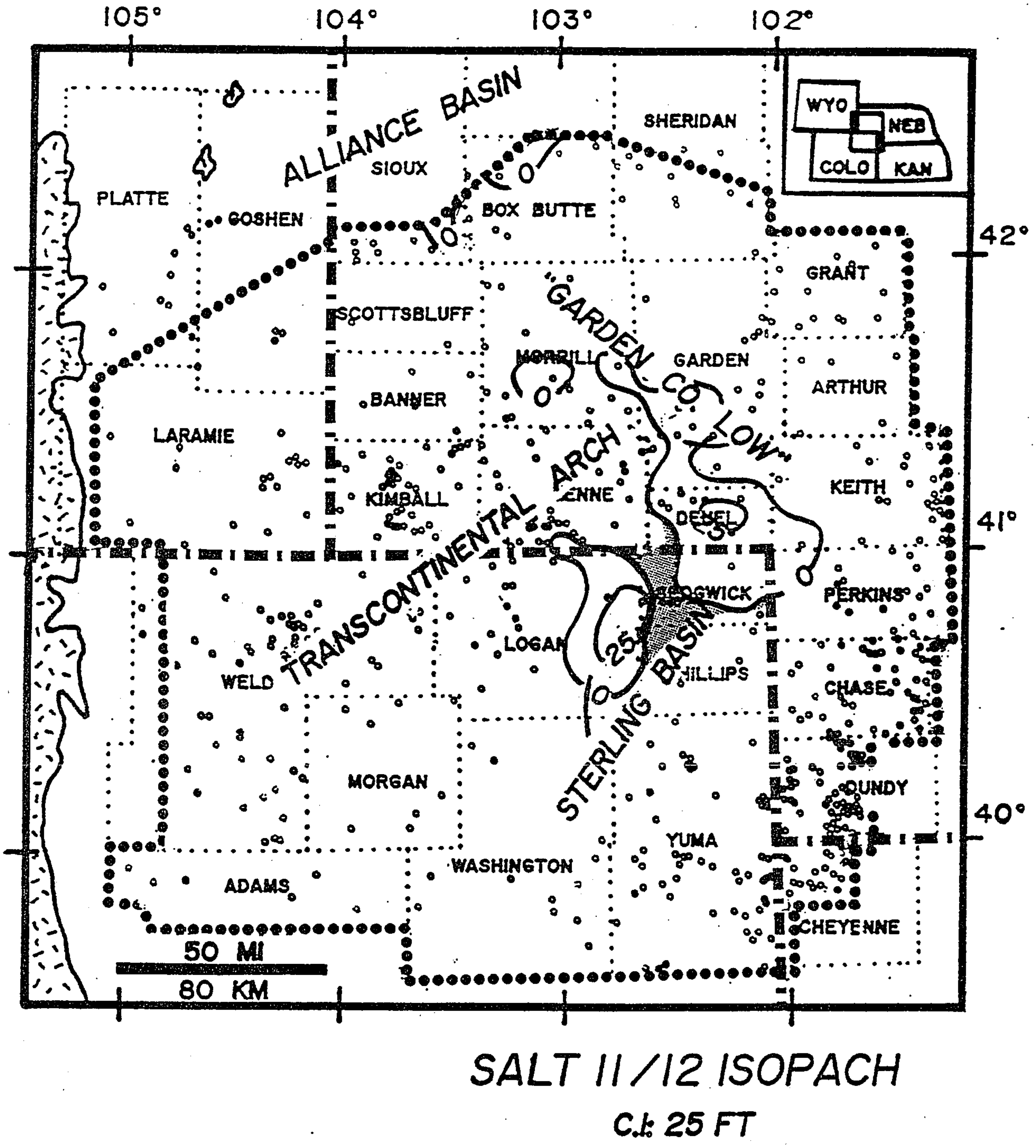
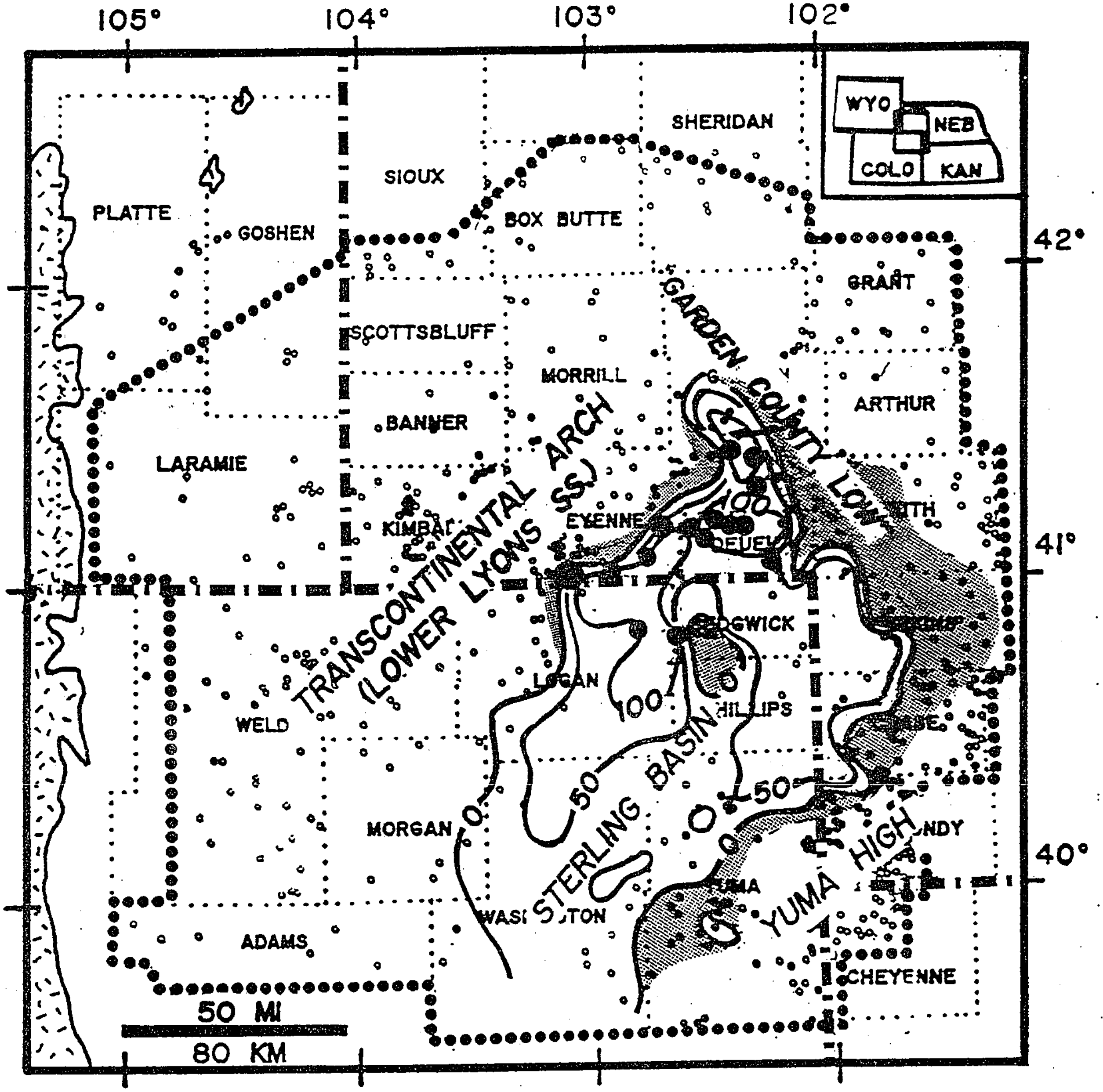


Figure 8-5. Isopach map of combined thickness of salts 11 and 12, situated within the Lower Leonardian Sumner Group. Contour interval 25 ft (8 m). Shading on this and subsequent regional salt isopachs indicate areas where salt is interpreted to have existed prior to removal by dissolution.

Salt 10

Salt 10, which occurs at the Stone Corral level, is thickest in Garden, Deuel, and southeastern Cheyenne Counties, Nebraska, and in parts of Sedgwick and Logan Counties, Colorado (Figure 8-6). Salt exceeds 100 ft (30 m) in thickness in these areas, which are directly southeast of an abrupt linear facies change from salt to lower Lyons sandstone. Distribution of thick salt at the Stone Corral level appears to have been strongly influenced by the configuration of the Sterling basin, whose northwestern margin was defined by a northeast-trending paleohigh associated with the Transcontinental arch, on which eolian Lyons sand accumulated (Chapter 4 of this report).

Generally, where salt 10 exceeds 100 ft (30 m) in thickness (in the "Garden County low" and northwestern Sterling basin areas) gamma-ray logs reveal the presence of two highly radioactive zones within the salt. Log analysis indicates that the source of natural radioactivity recorded across the two zones is predominantly from potassium, and that the potassium is likely contained within sylvite. As discussed in Chapter 4 of this report, the presence of sylvite in this area reflects highly evaporative conditions during salt accumulation as well as post-depositional conditions which allowed for the preservation of the highly soluble salt.



SALT 10 ISOPACH

C.I: 50 FT

Figure 8-6. Isopach map of salt 10, associated with the Stone Corral Formation (Upper Leonardian Nippewalla Group). Contour interval 50 ft (15 m). Solid circles denote wells in which sylvite? was encountered within the halite zone. Shading indicates areas where salt is interpreted to have existed prior to removal by dissolution.

Areal distribution of highly radioactive salt zones (sylvite?) within salt 10 (denoted by solid circles on Figure 8-6), generally coincides with that of salts 11/12 and 13 in the "Garden County low" and northwest Sterling basin areas. This distribution suggests that highly restricted conditions existed during precipitation of these lowermost salts in the area immediately to the east and southeast of the northeast-trending paleohigh.

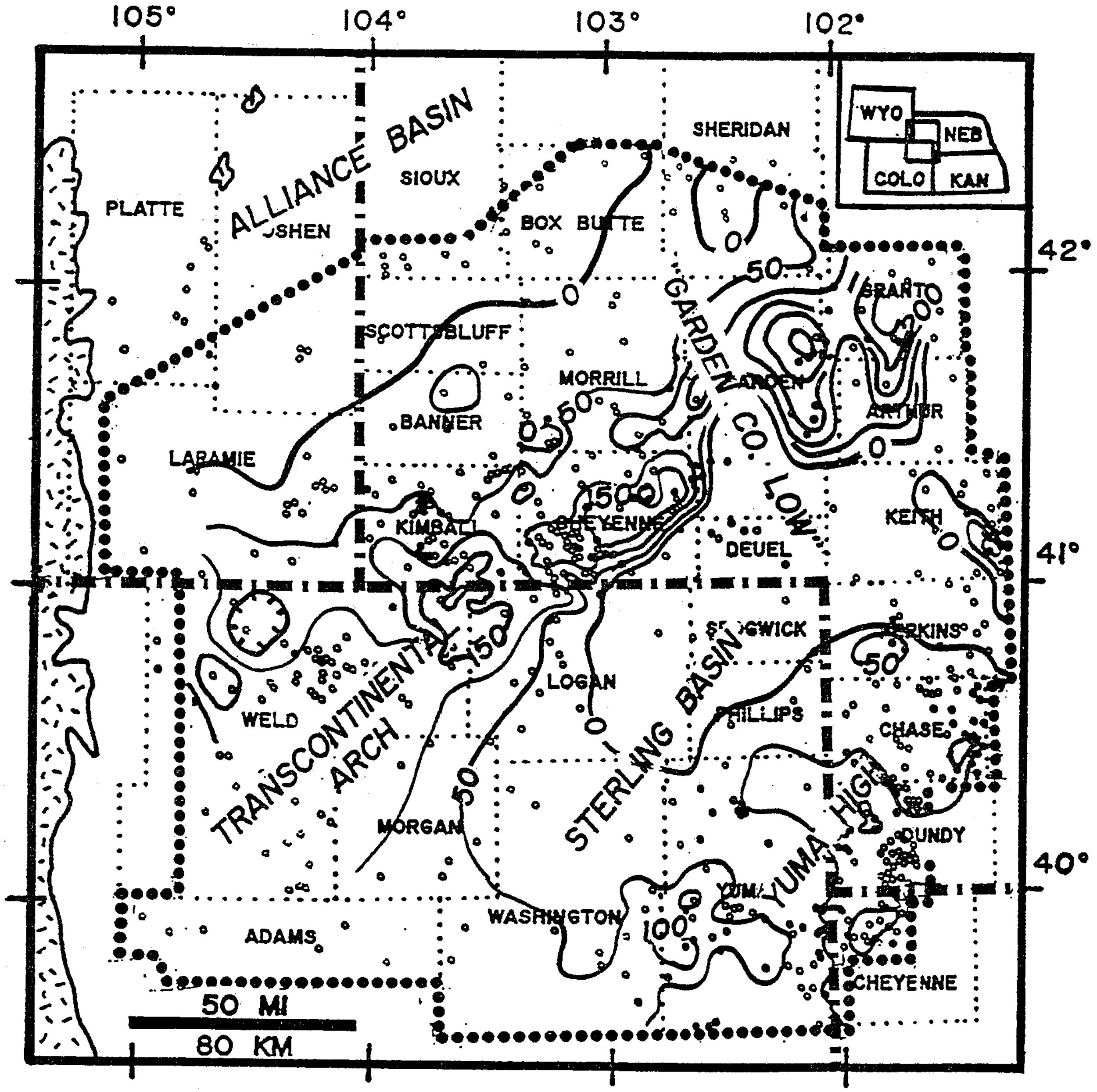
Salt 10 is also present to the south, in parts of Phillips, Washington, and Yuma Counties, Colorado, and in western Perkins and Chase Counties, Nebraska. Distribution of salt 10 near its southeastern limit in Colorado is discussed in more detail in Chapter 6. Distribution of salt 10 along its eastern limit in Nebraska is discussed further in Chapter 9.

Study of the spatial relationship between Cretaceous-level structural anomalies and the eastern limit of salt 10, including seismic interpretation at Big Springs and Eckley fields (Chapters 5 and 7), indicates that post-Cretaceous dissolution is responsible for the abrupt eastern margin of the salt. Dissolution has removed salt 10 along its eastern margin in Garden, Deuel, Keith, Perkins, Chase, and Dundy Counties, Nebraska, and Yuma County, Colorado, and in a local area in Sedgwick County, Colorado.

Lyons - Cedar Hills Sandstone

Inferences as to the original easternmost extent of salt 10 in the Sterling basin (shaded areas on Figure 8-6) cannot be made with certainty due to post-depositional removal by dissolution. However, Lyons - Cedar Hills Sandstone thickness patterns may be used to suggest a configuration of the Sterling Basin during precipitation of salt 10. Thickness of the Lyons-Cedar Hills Sandstone across the study area (Figure 8-7) varies from 0 to over 200 ft (60 m). Eolian sand accumulated along a northeast-trending paleohigh related to the Transcontinental arch. Localized thinning of sand occurred in the Garden County low area, where the Sterling and Alliance evaporite basins appear to have been joined. Thick sand also accumulated in the "Yuma high" (Sonnenberg and Weimer, 1981) area, near the southeastern corner of the study area. The Yuma high may have been a paleopositive feature associated with the ancestral Las Animas arch, which influenced sedimentation and deposition throughout the Late Paleozoic (Rascoe,1978).

Regional correlations indicate that the lower Lyons is stratigraphically equivalent to salt 10 along the northwestern margin of the Sterling basin. Generally, thick Lyons Sandstone is present where salt 10 (and salt 9) is absent. Conversely, sandstone is generally absent where salts occur (Chapter 4). Sand accumulated along the



LYONS (CEDAR HILLS) SANDSTONE ISOPACH

C.I: 50 FT

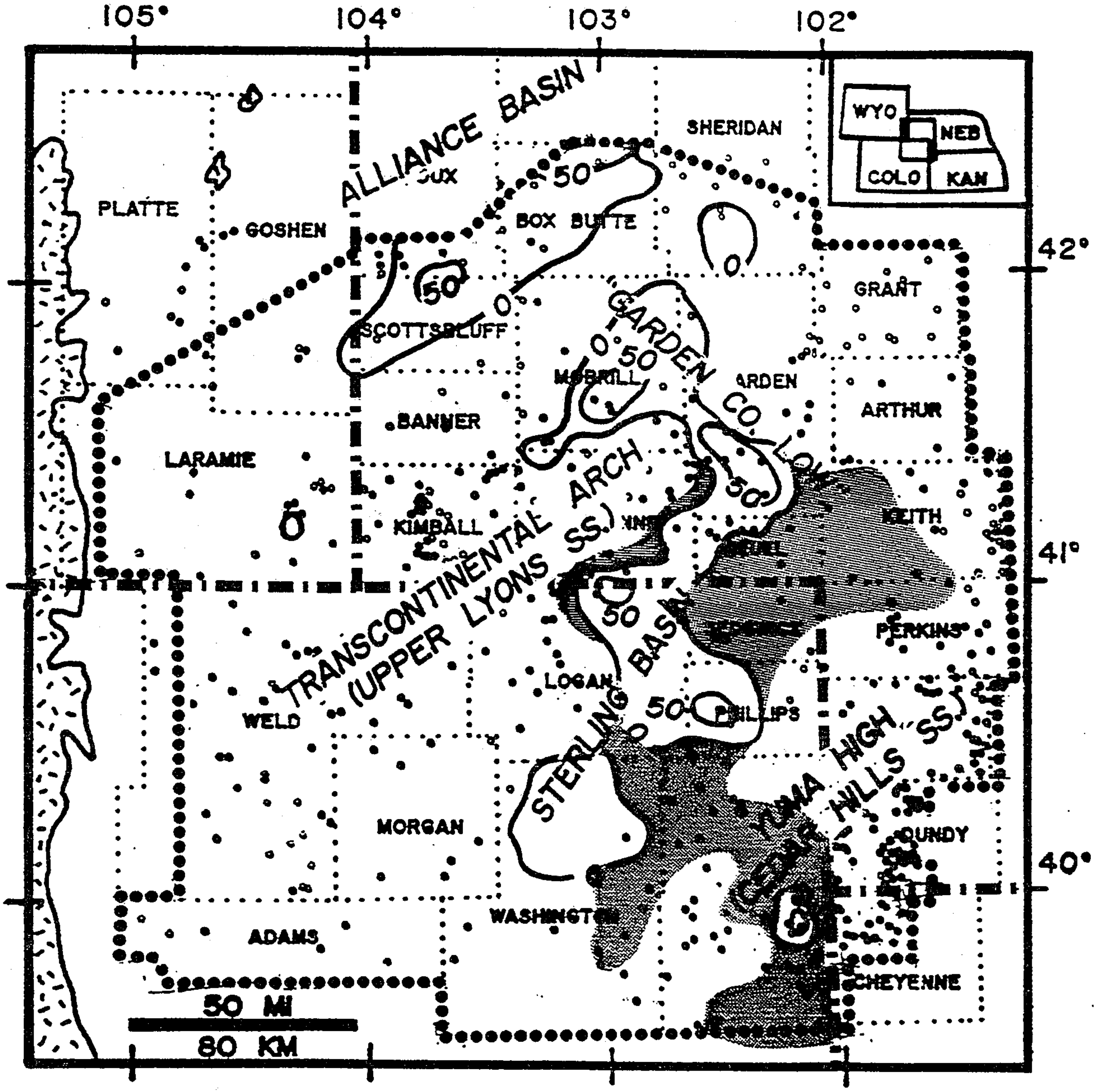
Figure 8-7. Isopach map of the Lyons (Cedar Hills) Sandstone (upper Leonardian Nippewalla Group). Contour interval 50 ft (15 m).

Transcontinental arch while red mud and silt of the Salt Plain Formation and the halite of salts 10 and 9 accumulated in the evaporite basin to the southeast.

Little or no sand accumulated in parts of Keith and Perkins Counties, near the eastern margin of the study area (Figure 8-7). This area may have marked the eastern limit of the Sterling basin. Although the present eastern limit of salt 10 occurs at an abrupt dissolution edge, the pre-dissolution limit of salt probably extended farther to the east, including the area shaded on Figure 8-6, which generally corresponds with where sandstone is less than 50 ft (15 m) thick. The Garden County low area, in which salts 13, 12, 11, 10, and 9 occur, is marked by thinning of the Lyons Sandstone. Thin Lyons Sandstone suggests that salts were present in the Garden County low during Leonardian time.

Salt 9

Salt 9, which occurs at the top of the Salt Plain Formation, just below the "Flower-pot Anhydrite", is greater than 70 feet (20 m) thick in parts of Morrill and Garden Counties, Nebraska, and Yuma County, Colorado (Figure 8-8). Salt appears to have accumulated in the Alliance and Sterling evaporite basins and Garden County low, and in a local area in Yuma County, corresponding to a Lyons- Cedar Hills Sandstone isopach minimum (Chapter 6). Post-



SALT 9 ISOPACH

C.I: 50 FT

Figure 8-8. Isopach map of salt 9, situated at the base of the Flower-pot Anhydrite (stratigraphic equivalent of upper Lyons Sandstone, Upper Leonardian Nippewalla Group). Contour interval 50 ft (15 m). Shading indicates areas where salt is interpreted to have existed prior to removal by dissolution.

Cretaceous dissolution has removed salt in places along its eastern margin, as evidenced by solution collapse structures, as well as along its western margin in the Sidney trough area of Cheyenne and Garden Counties, Nebraska (Chapter 4).

Sandstone thickness (Figure 8-7) is used to suggest the original (pre-dissolution) distribution of salt 9 in the eastern and southeastern parts of the study area. An outlier of thick salt, present in east-central Yuma County, Colorado below the Beecher Island gas field (Figure 6-15) occurs in an area of thin sandstone. Niobrara structure indicates that salt in this outlier represents a dissolution remnant.

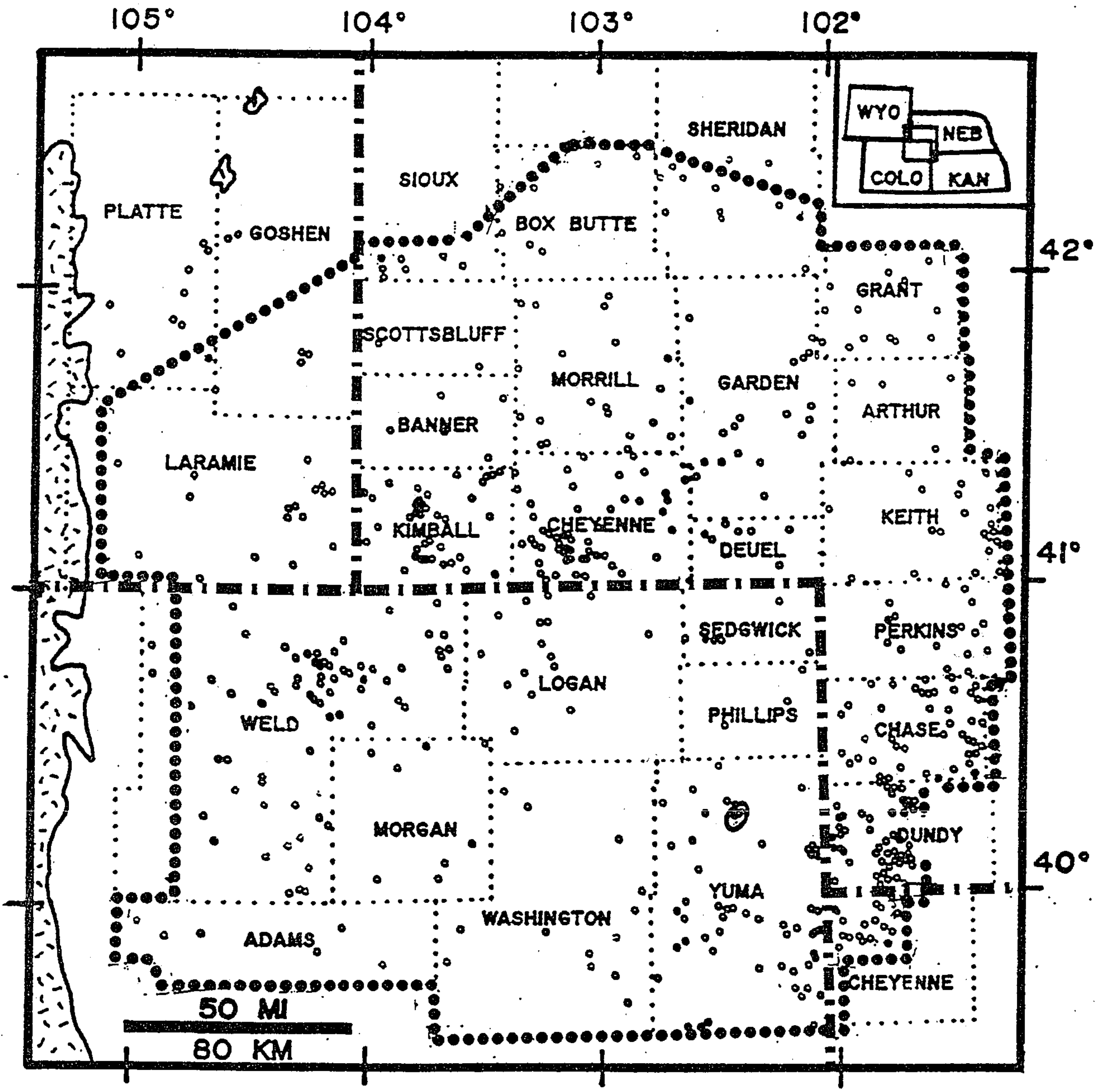
As with salt 10, salt 9 may have originally extended to the east into Sedgwick County, Colorado, and eastern Deuel, and Keith and Perkins Counties, Nebraska (shaded on Figure 8-8). This is an area where sandstone thickness is generally less than 50 ft (15 m). Likewise, salt 9 may have originally occurred across a larger area of Yuma and Washington Counties, Colorado, prior to removal by eastward-directed groundwater flow within the Lyons-Cedar Hills Sandstone regional aquifer (Chapters 4 and 6).

Salt 8

Salt 8 has been identified only in an isolated area of Yuma County, Colorado (Figure 8-9) where it is 10 to 15 ft (3 to 4 m) thick. Salt 8 occurs immediately above the "Flower-pot Anhydrite", at the base of the Flower-pot Shale. The isolated occurrence of salt 8 along the dissolution edges of salts 7 and 10 at Eckley field (Chapters 6 and 7) indicates that it may be a dissolution remnant. However, no effort is made to determine if this salt was originally present elsewhere within the study area.

Salt 7

Salt 7 (Figure 8-10), which occurs below the lower Blaine Anhydrite and just above the Flower-pot Shale, is the most widespread salt zone identified in the study area. Generally 50 to 100 ft (15 to 30 m) thick, the salt extends from the Alliance basin area south to the southern margin of the study area, where it is over 125 ft (35 m) thick. Farther to the southeast, into western Kansas, over 200 ft (60 m) of salt is present at this stratigraphic position on cross sections by Rascoe and Baars (1972) and Holdoway (1978).



SALT 8 DISTRIBUTION

Figure 8-9. Distribution of salt 8, situated near the base of the Flower-pot shale, just above the Flower-pot Anhydrite (upper Leonardian Nippewalla Group).

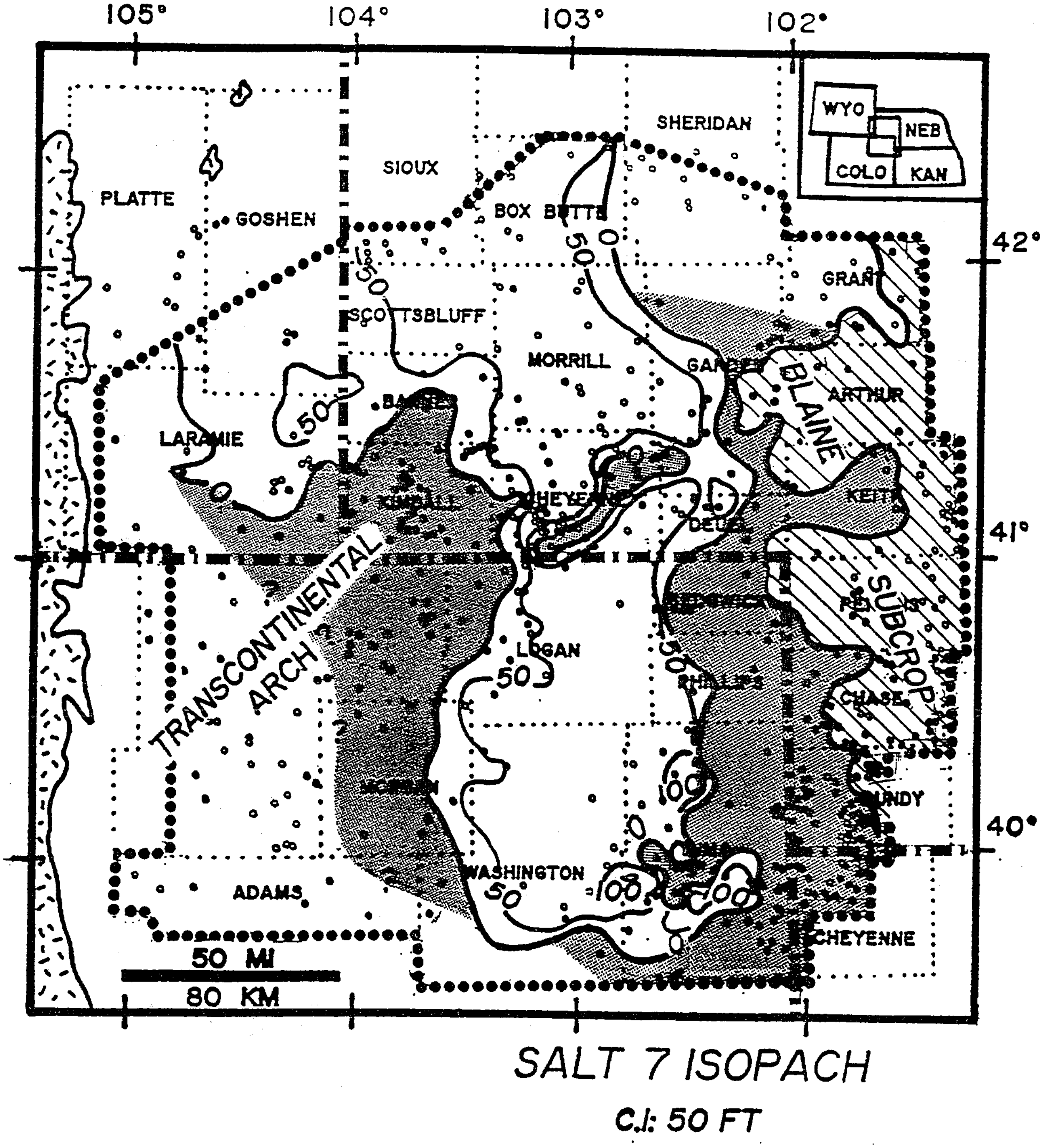


Figure 8-10. Isopach map of salt 7, situated between the lower Blaine anhydrite bed and the Flower-pot Shale (Upper Leonardian Nippewalla Group). Contour interval 50 ft (15 m). Shading indicates areas where salt is interpreted to have existed prior to removal by dissolution.

Post-Cretaceous dissolution occurred along the eastern margin of salt 7 in Garden and Deuel Counties, Nebraska, and Sedgwick County, Colorado (Chapters 2 and 4) and in Yuma County, Colorado (Chapters 6 and 7). Post-Cretaceous salt removal also occurred in the northeast-trending Sidney trough area of Cheyenne and Garden Counties, Nebraska (Chapter 4).

Although the present limits of salt 7 are controlled by subsurface dissolution in response to the Laramide orogeny (Chapters 4, and 6), its limit may have been modified earlier by near-surface dissolution below the pre-Late Jurassic unconformity. The Blaine Anhydrite, which directly overlies salt 7, was partially truncated prior to deposition of the Late Jurassic strata (Morrison and Sundance Formations) along the eastern margin of the study area. The western margin of the Blaine subcrop generally parallels the eastern limit of salt 7 (Figure 8-10). This suggests that pre-Late Jurassic removal of salt occurred downdip (to the west) of the Blaine subcrop, perhaps due to introduction of meteoric water during lowstands associated with the formation of the unconformity. Further westward retreat, in response to the Laramide orogeny, was responsible for the present eastern salt edge.

Inasmuch as salt 7 is thickest along its present southeastern margin, the original depositional axis may have been much farther to the east. The estimated extent of the evaporite basin in which salt 7 was precipitated is shaded on Figure 8-10 but that extent may have been farther to the east of the Blaine subcrop.

Chapter 4 includes a discussion of Jurassic and Early Cretaceous removal of salt 7 and younger salts in the western part of the southern Nebraska panhandle. Localized thickening of the Morrison Formation (Upper Jurassic) and Cheyenne Formation (Lower Cretaceous) occurs where Upper Leonardian and Guadalupian salts are absent, in an area centered around southern Kimball County. Removal of salt may have been in response to compaction-induced flow of water from the Lyons Sandstone.

Regional isopachs of Jurassic and Lower Cretaceous (top of D Sandstone to base of Cretaceous) strata (Figures 8-11 and 8-12) are based on well-log data which are more limited in number than Paleozoic data. Nevertheless, the two interpretations reveal possible areas beyond Kimball County where salt dissolution and resultant collapse provided additional accommodation space for Jurassic and Lower Cretaceous sediments. A north-south-trending Jurassic isopach maximum (Figure 8-11), extends from Kimball County southward into northeastern Weld, western Logan, and western Washington Counties, Colorado. A Lower Cretaceous isopach maximum (Figure 8-12) extends southward from Kimball County into western Logan, eastern Morgan, and southern Washington Counties, Colorado. Locations of these isopach maxima

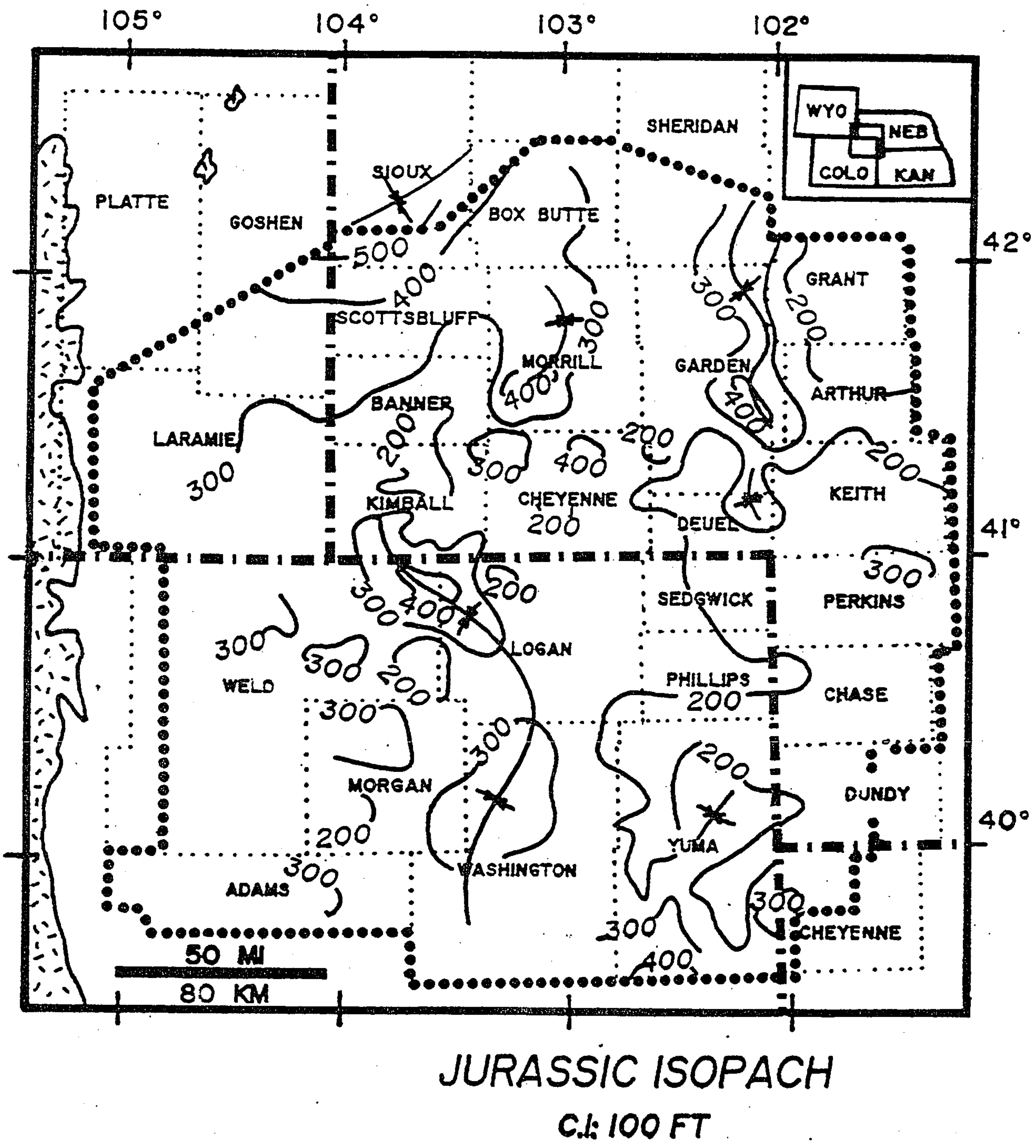
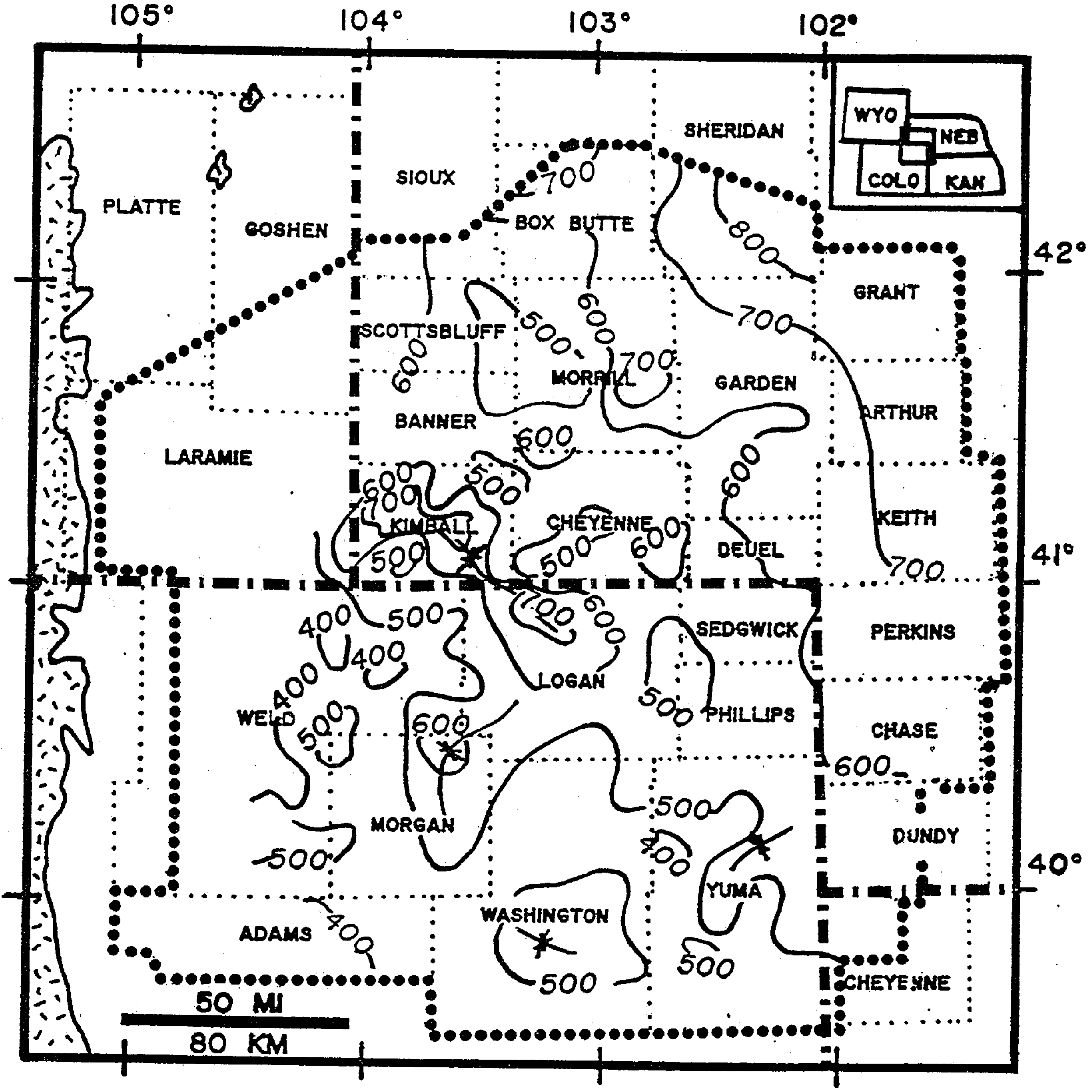


Figure 8-11. Isopach map of the Jurassic System. Contour interval 50 ft (15 m).



LOWER CRETACEOUS ISOPACH

C.I: 100 FT

Figure 8-12. Isopach map of the "Lower Cretaceous" (top D Sandstone to base Cretaceous). Contour interval 50 ft (15 m).

generally coincide with the western margin of salt 7 in Colorado and southwestern Nebraska.

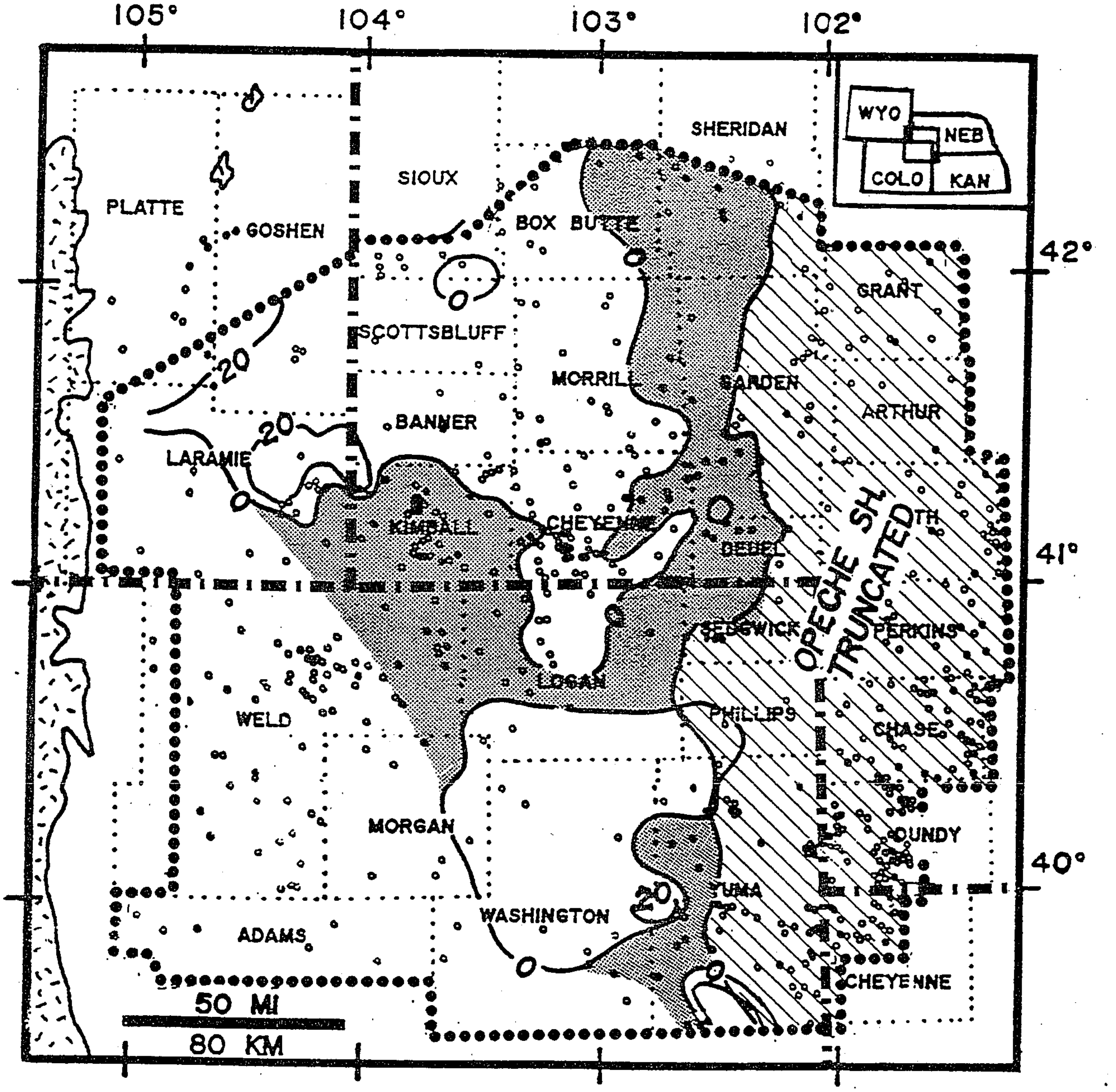
The abrupt thinning of the present western limit of salt 7 in Colorado (Figure 8-10) suggests that dissolution took place along that margin. Coincidence of Jurassic and Lower Cretaceous isopach maxima with the absence of salt 7 (as well as younger salts) in Kimball County, and the extension of this spatial relationship to the south into Colorado, suggests that the western and southwestern margins of salt 7 are controlled by dissolution. Salt removal may have occurred mainly during Jurassic and Early Cretaceous time. If so, salt 7 originally extended west of its present limit.

Localized Jurassic isopach maxima (Figure 8-11) also occur in eastern Garden and western Arthur Counties, in northern Perkins County, Nebraska, and in Yuma County, Colorado, east and south of the present limit of salt 7. This suggests that pre-Late Jurassic removal of salt (including salt 7) may have created topographic lows on the Jurassic truncation surface, which were later filled with Jurassic sediments. However, inasmuch as the Jurassic System in the study area is bounded by unconformities, more detailed study is needed to separate solution collapse-influenced Jurassic thickness anomalies from those caused by pre-Jurassic and pre-Cretaceous erosion.

Perhaps the most significant observation that can be made regarding the distribution of salt 7 is that, in contrast to lower salts, it extends across the Nebraska panhandle. The paleopositive area associated with the Transcontinental arch, which separated the Sterling and Alliance basins during accumulation of salts 9, 10, 11, 12, and 13, appears to have had little or no influence during precipitation of salt 7. (A narrow northeast-trending no-salt area in Cheyenne and Garden Counties is due to post-Laramide dissolution in the Sidney trough area, rather than non-deposition, and is discussed in Chapter 4.)

Salt 6

Salt 6, which occurs immediately below the lower Blaine Anhydrite, is less than 20 ft (6 m) thick, except in southeastern Wyoming and in Yuma County, Colorado, where it is slightly thicker (Figure 8-13). Although not as thick, its distribution is similar to that of salt 7, except that it does not extend as far east as salt 7. As with salt 7, the present eastern limit may be controlled by near-surface removal associated with a pre-Late Jurassic lowstand. Except for an area to the south, the eastern limit of salt 6 parallels the western margin of the pre-Late Jurassic subcrop of the overlying Opeche Shale.



SALT 6 ISOPACH

C.I: 20 FT

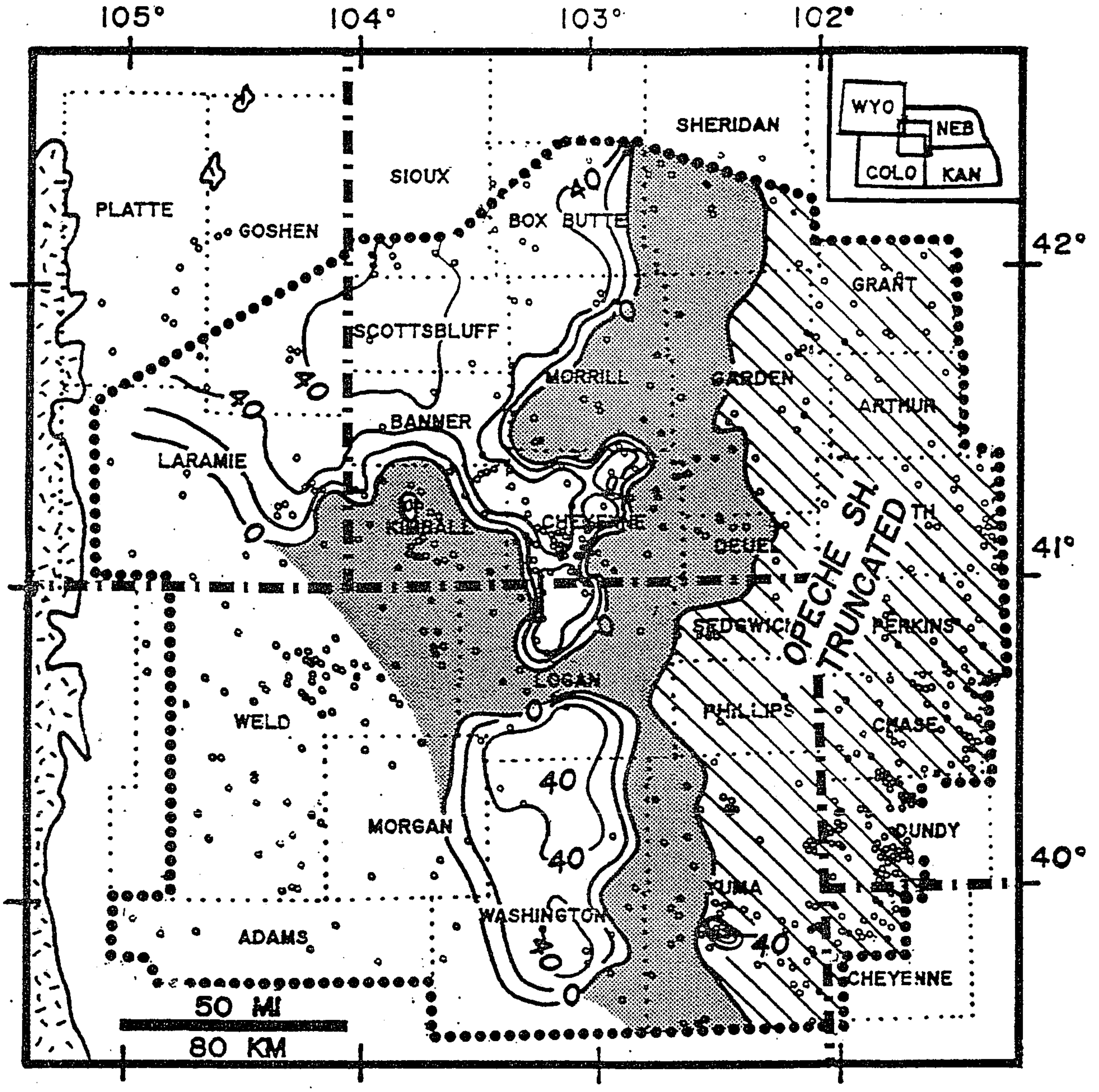
Figure 8-13. Isopach map of salt 6, situated below the lower Blaine anhydrite bed (Upper Leonardian Nippewalla Group). Contour interval 20 ft (6 m). Shading indicates areas where salt is interpreted to have existed prior to removal by dissolution.

Post-Laramide dissolution further removed salt along the eastern margin of salt 6, and in the Sidney trough area of Nebraska. Removal of salt during the Jurassic and Early Cretaceous, which took place in Kimball County, Nebraska, and adjacent areas (Chapter 4), may have also occurred along the western margin of the salt in Colorado.

Salt 5

Salt 5, which occurs between the upper and lower Blaine anhydrites, is the uppermost Leonardian salt zone identified in the study area. Where present, it is generally about 40 ft (12 m) thick (Figure 8-14). As with salt 6, the eastern limit of salt 5 parallels the western margin of the pre-Jurassic Opeche subcrop, reflecting the influence of the pre-Late Jurassic unconformity on salt distribution. An outlier of salt 5 in the Mildred field area of Yuma County, Colorado (Chapter 6, Figures 6-11 and 6-19) occurs below the partially truncated Opeche Shale. This suggests that salt 5 may have originally extended well east of the shaded area on Figure 8-14.

The abrupt eastern limits of salt 5 in the Sidney trough area of Cheyenne County, Nebraska, and south into Logan County, Colorado, are due to post-Laramide dissolution (Chapter 4). Incomplete dissolution of salt 5 during the Jurassic and Early Cretaceous occurred in Kimball County,



SALT 5 ISOPACH

C.I: 20 FT

Figure 8-14. Isopach map of salt 5, situated between the upper and lower Blaine anhydrite beds (Upper Leonardian Nippewalla Group). Contour interval 20 ft (6 m). Shading indicates areas where salt is interpreted to have existed prior to removal by dissolution.

Nebraska, as evidenced by salt outliers (Figure 4-8). As with salts 7 and 6, the western limit of salt 5 in Colorado may have been influenced by Jurassic and Early Cretaceous dissolution.

GUADALUPIAN SALTS

Salt 4

Distribution of salt 4 (Figure 8-15), which is situated at the base of the Opeche Shale, just above the upper Blaine Anhydrite, is more limited than that of salt 5. Where present, salt 4 is generally about 10 ft (3 m) thick in northwestern Cheyenne, eastern Banner, and eastern Scotts Bluff Counties, and appears to become more widespread in the Alliance basin area at the northwestern margin of the study area. In Colorado, salt 4 is present in parts of Logan, Morgan, and Washington Counties, where it is generally 20 to 30 ft (6 to 9 m) thick.

The eastern limit of salt 4 generally parallels but is far removed (50 mi or 80 km) from the western margin of the pre-Late Jurassic subcrop of the overlying Opeche Shale (Figure 8-15). With the exception of an area in southeastern Washington County, Colorado, the eastern limit of salt 4 is west of the eastern limit of salt 5 (Figure 8-

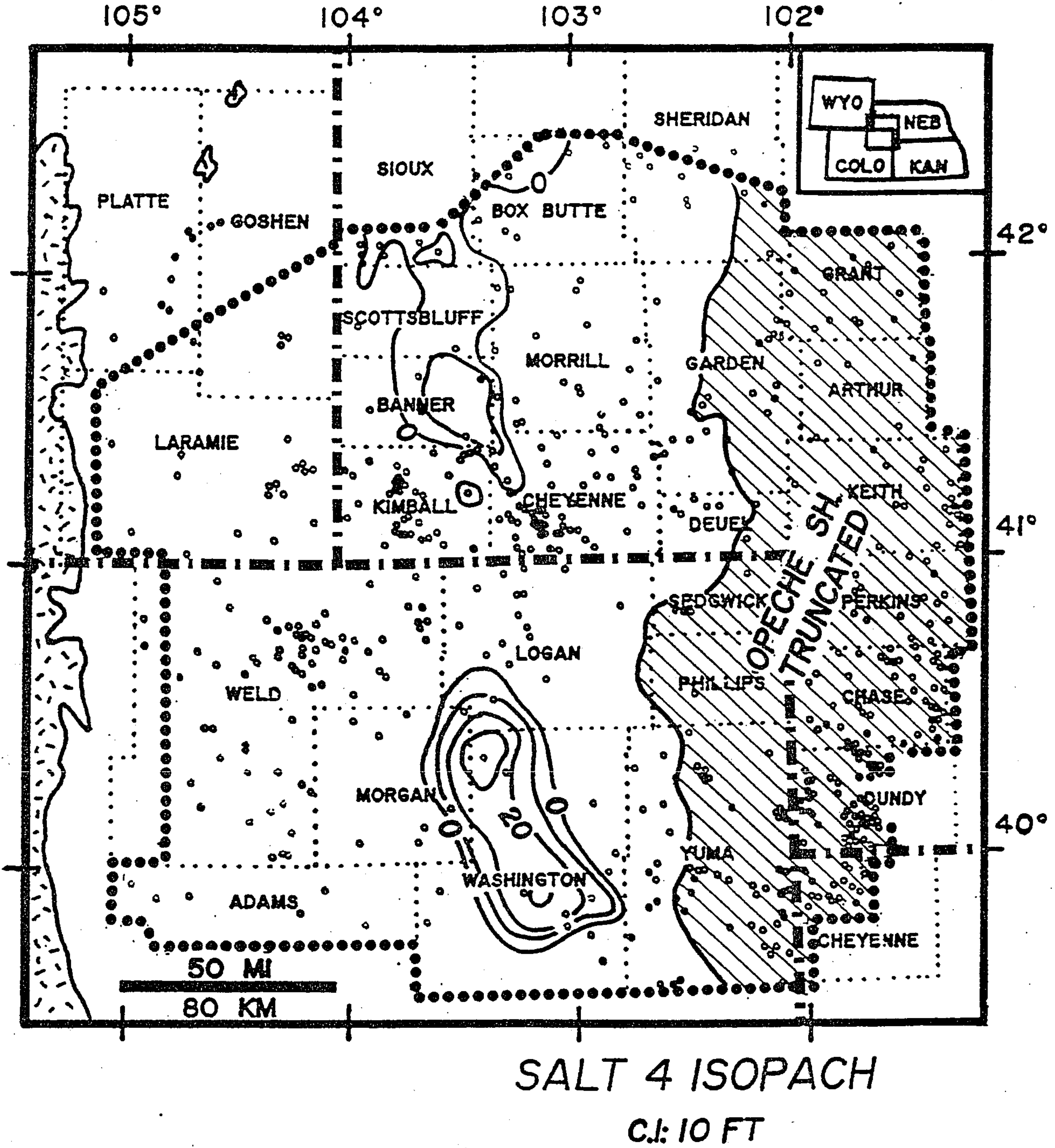


Figure 8-15. Isopach map of salt 4, situated at base of Opeche Shale (Guadalupian Goose Egg Formation). Contour interval 10 ft (3 m).

14), reflecting the stepwise removal to the west of younger salts below the pre-Late Jurassic unconformity.

Salt 3

Salt 3, which is situated at the top of the Opeche Shale, just below the Minnekahta Limestone, is over 75 ft (18 m) thick in the northwestern part of the study area and is over 50 ft (15 m) thick in a narrow area which includes eastern Banner, northern Kimball, and western Cheyenne Counties, Nebraska (Figure 8-16). In Colorado, thinner salt occurs at the salt 3 level in southwestern Logan, northwestern Washington, and eastern Morgan Counties. A thin outlier of salt 3 is present in the Silo field area of Laramie County, Wyoming.

Although the present eastern limit of salt 3 is partially controlled by post-Laramide removal (Chapter 4), pre-Late Jurassic removal appears to have played a more important role. As with salts 7, 6, and 5 (and perhaps to a more limited degree salt 4), the eastern limit of salt 3 parallels the western margin of the pre-Jurassic subcrop of an overlying stratigraphic unit. In the case of salt 3, this is the Minnekahta Limestone.

Removal of salt 3 along its southwestern margin in Nebraska occurred predominantly during the Jurassic and Early Cretaceous. This is inferred on the basis of an

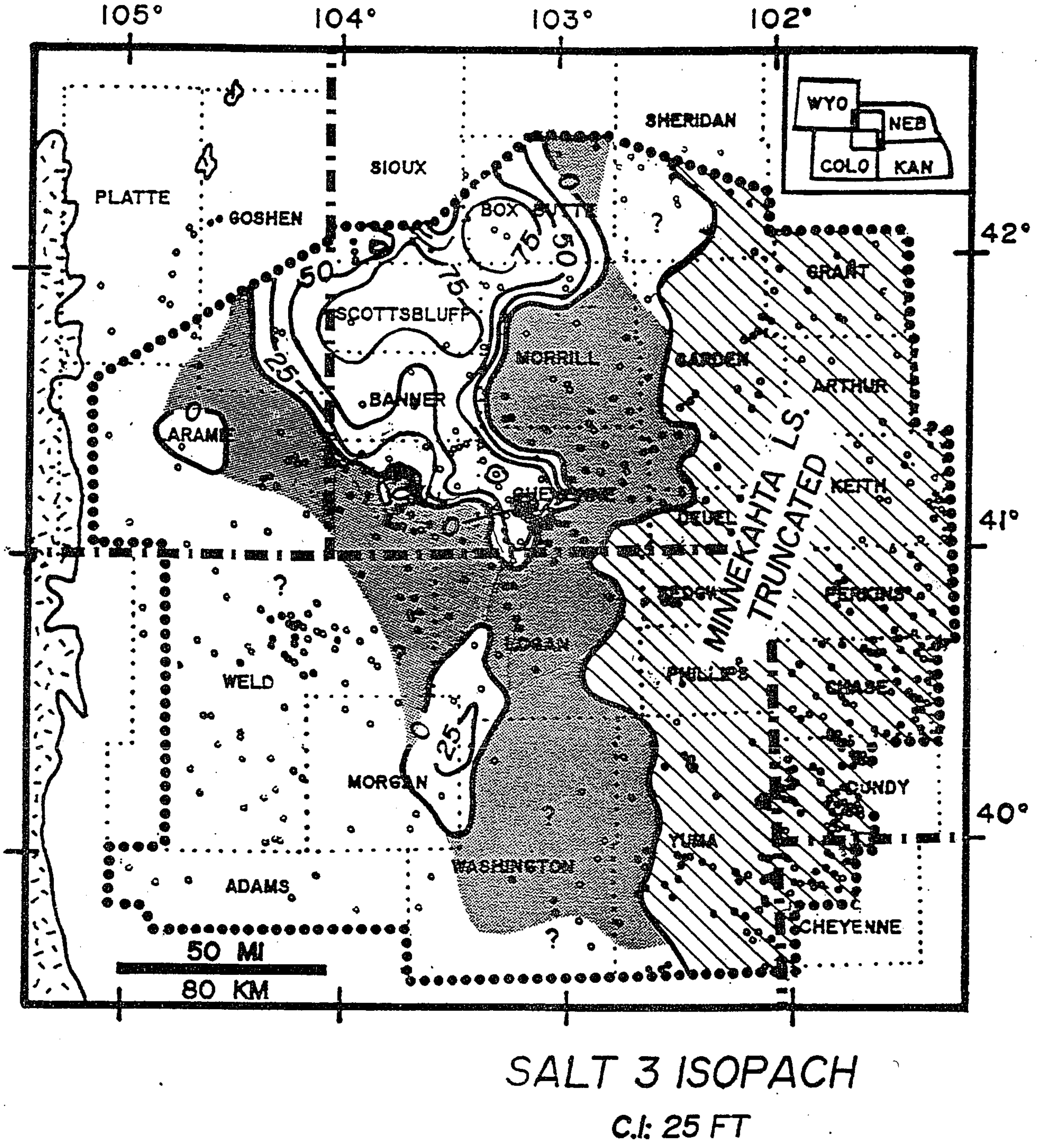


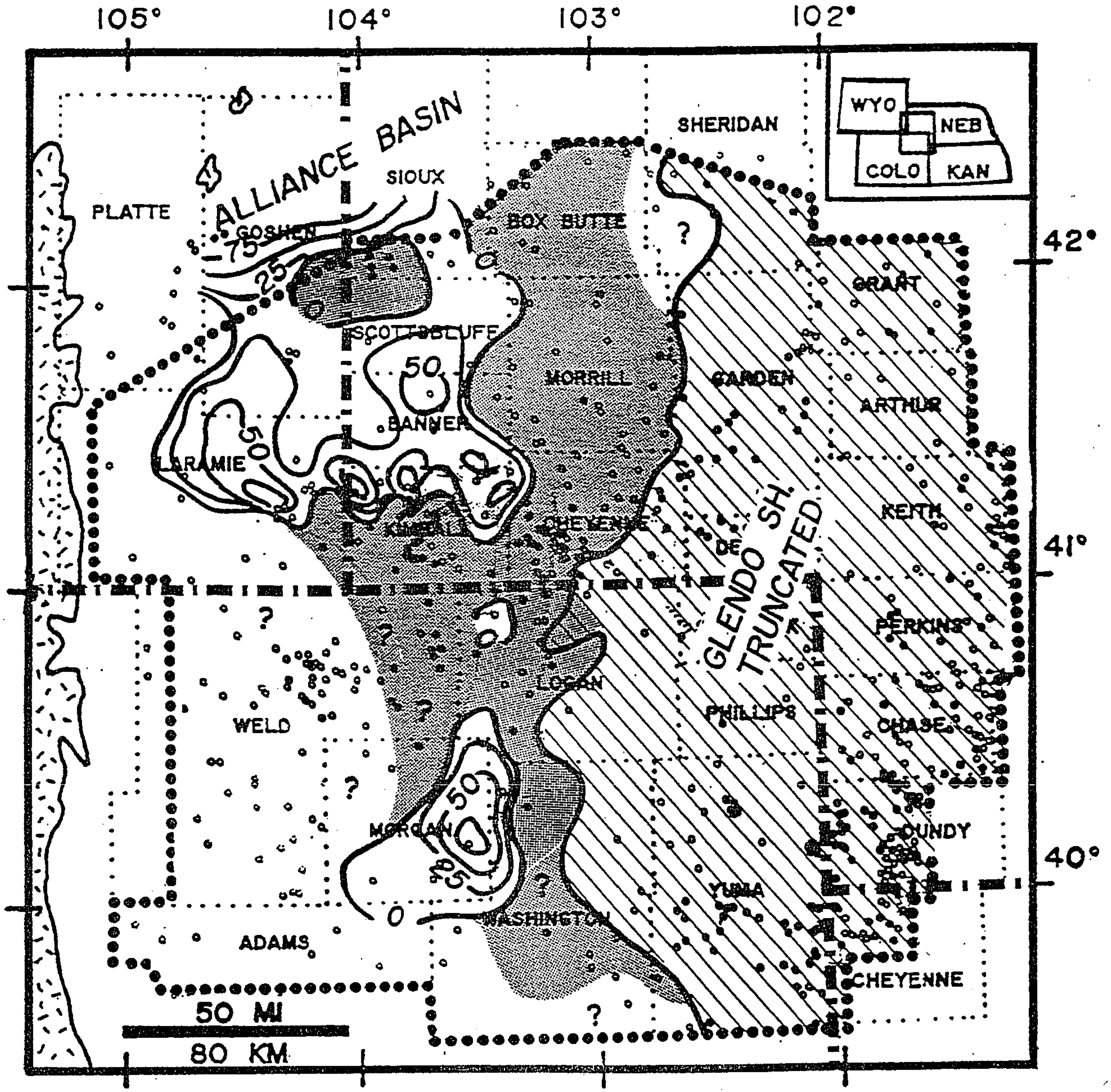
Figure 8-16. Isopach map of salt 3, situated between Minnekahta Limestone and Opeche Shale (Guadalupian Goose Egg Formation). Contour interval 25 ft (8 m). Shading indicates areas where salt is interpreted to have existed prior to removal by dissolution.

abrupt salt edge and outlier in Kimball County, whose locations coincide with localized thickening of the Jurassic Morrison and Lower Cretaceous Cheyenne Formations (Chapter 4). As may have taken place with salts 7, 6, and 5, Jurassic and Early Cretaceous removal of salt may have also occurred to the south along the western margin of salt 3 in Colorado.

Where it is more widespread to the northwest, salt 3 is thicker than salt 7 (75 ft or 23 m in contrast to 50 ft or 15 m). This may suggest that salt 3 may have originally accumulated over an area at least as widespread as salt 7, and that its more limited present extent is due to subsequent removal. The estimated minimum original distribution of salt 3 beyond its present limits is shaded on Figure 4-16, and is based on the present limit of salt 7. Although speculative, it seems reasonable to assume (based on the distribution of salt 7) that salt 3 originally was present even farther east of the pre-Jurassic Minnekahta subcrop, inasmuch as salt 7 is thickest in this area (Figure 8-10).

Salt 2

Salt 2, situated above the Minnekahta Limestone, at the base of the Glendo Shale, is over 50 ft (15 m) thick in parts of Scotts Bluff, Banner, northern Kimball, and northwestern Cheyenne Counties, Nebraska (Figure 8-17).



SALT 2 ISOPACH

C.I.: 25 FT

Figure 8-17. Isopach map of salt 2, situated between Glendo Shale and Minnekahta Limestone (Guadalupian Goose Egg Formation). Contour interval 25 ft (8 m). Shading indicates areas where salt is interpreted to have existed prior to removal by dissolution.

Salt thickness exceeds 75 ft (23 m) in Laramie County, Wyoming, and in the Alliance basin area of Goshen County, Wyoming, and Sioux County, Nebraska. Salt 2 is also thick in eastern Morgan and western Washington Counties, Colorado.

As with underlying salts, the eastern margin of salt 2 generally parallels the western margin of the pre-Late Jurassic subcrop of an overlying stratigraphic unit. In the case of salt 2 this is the Glendo Shale. The eastern salt 2 limit is to the west of that of salt 3, further evidence that stepwise removal of younger salts took place below the pre-Late Jurassic unconformity.

Abrupt thinning of salt 2 occurs in Kimball County, Nebraska, and Laramie County, Wyoming. As with salts 3, 5, 6, and possibly 7, this is due to removal of salt during the Jurassic and Early Cretaceous. Jurassic and Lower Cretaceous isopach maxima (Figures 8-11 and 8-12) indicate that syndepositional removal of salt also took place in eastern Weld and eastern Morgan Counties, Colorado.

As with salt 3, the inferred original extent of salt 2 covers the area in which salt 7 presently occurs. However, salt 2 may have extended east of the the western margin of the Glendo Shale subcrop.

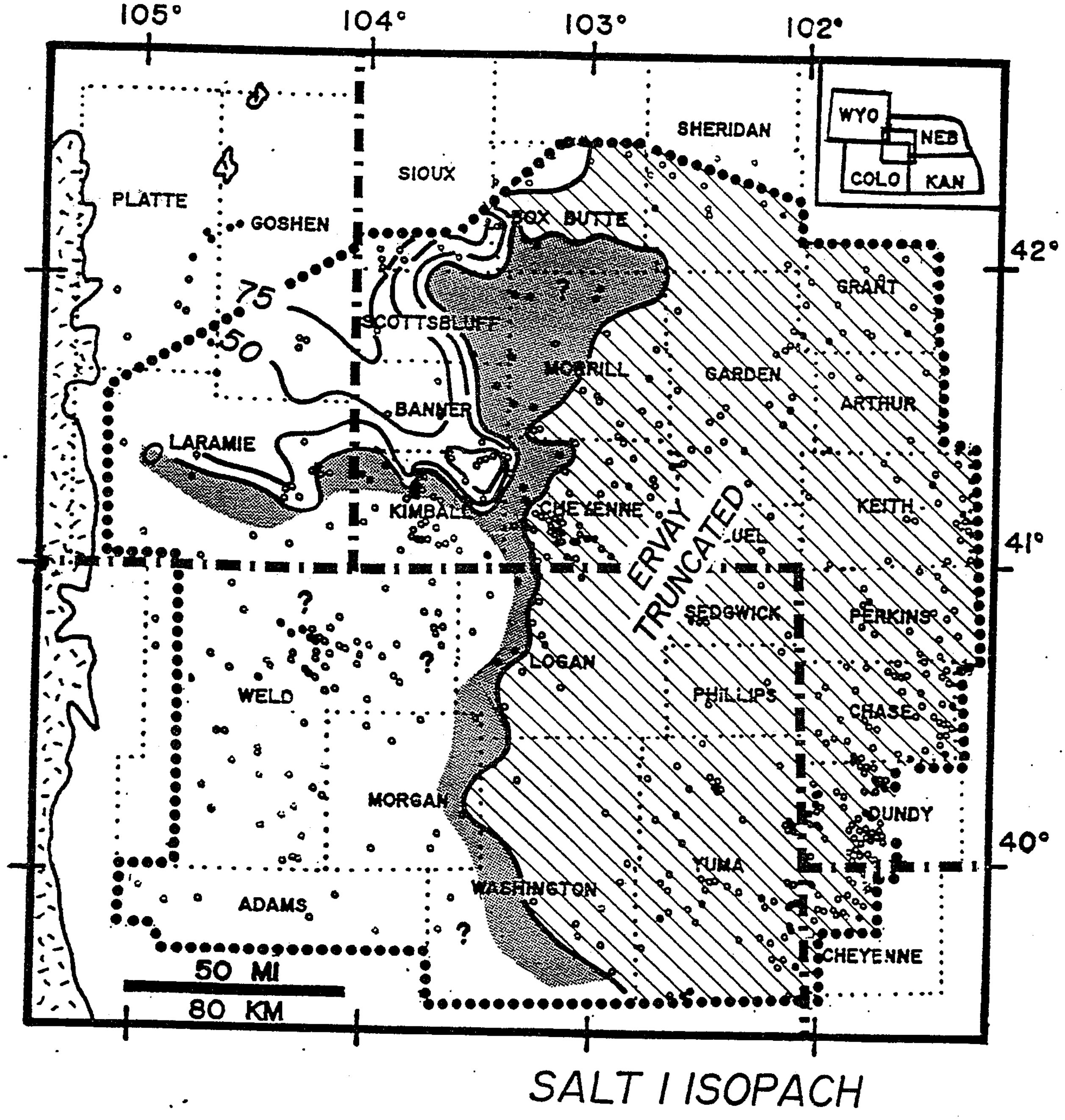
Salt 1

Salt 1, which is situated between the Forelle Limestone and the Glendo Shale, is over 50 ft (15 m) thick in parts of Banner and northern Kimball Counties, Nebraska, and Laramie County, Wyoming (Figure 8-18). The salt thickens to over 75 ft (23 m) toward the Alliance basin area of Scotts Bluff and Sioux Counties, Nebraska, and Goshen County, Wyoming.

The eastern margin of salt 1 in Nebraska is west of the western margin of the pre-Late Jurassic subcrop of the overlying Ervay Member. Abrupt thinning of salt 1 occurs in western Cheyenne County, where the salt margin parallels the Ervay subcrop, indicating that salt was removed in response to pre-Late Jurassic truncation. The eastern salt 1 limit is west of the salt 2 limit, reflecting stepwise removal of younger salts below the unconformity.

Abrupt thinning of salt 1 occurs in an area of Kimball County, Nebraska, and Laramie County, Wyoming, which coincides with removal of salts 2, 3, 5, 6, and possibly 7. As with underlying salts, this is likely due to removal of salt during the Jurassic and Early Cretaceous.

Although salt 1 is present only in Nebraska and Wyoming, it may have originally extended into Colorado. Jurassic and Lower Cretaceous isopach maxima (Figures 8-11 and 8-12) indicate that syndepositional removal of salt which occurred in southern Kimball County may have also



SALT I ISOPACH

C.I: 25 FT

Figure 8-18. Isopach map of salt 1, situated between Forelle Limestone and Glendo Shale (Guadalupian Goose Egg Formation). Contour interval 25 ft (8 m). Shading indicates areas where salt is interpreted to have existed prior to removal by dissolution.

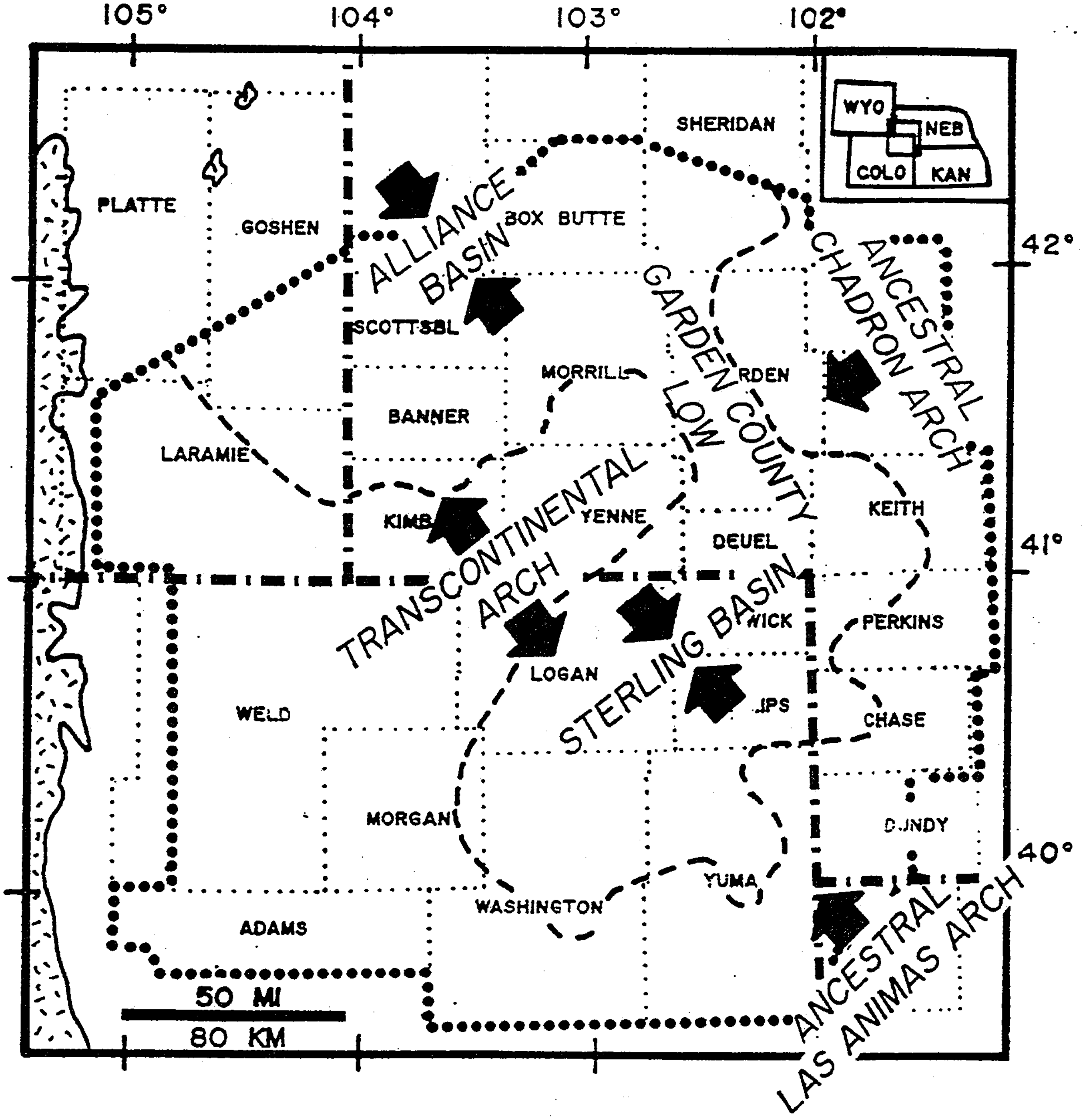
taken place in eastern Weld, western Logan, and eastern Morgan Counties, Colorado. Moreover, pre-Late Jurassic truncation of the Ervay Member in Colorado may have allowed for introduction of meteoric water during Jurassic lowstands which dissolved salt 1 downdip (to the west) of its subcrop.

SUMMARY OF CONTROLS ON REGIONAL SALT DISTRIBUTION

Subsurface analyses at the local scale (Chapters 5 and 7), at the subregional scale (Chapters 4 and 6), and at the regional scale (this chapter) reveal that the present distribution of salt in the Denver basin is influenced by a number of post-depositional controls. In addition to the configuration of the evaporite basins during precipitation, salt distribution is controlled by near-surface removal related to pre-Late Jurassic truncation, by subsurface dissolution during the Jurassic and Early Cretaceous, and by post-Laramide (Late Cretaceous - Early Tertiary or later) subsurface dissolution.

Basin Configuration

Paleotectonic elements which influenced salt accumulation are shown on Figure 8-19. Paleotectonic influence appears to have been greatest during precipitation of upper Wolfcampian, lower Leonardian, and lowermost upper



LATE WOLFCAMPIAN - EARLY LEONARDIAN PALEOTECTONIC ELEMENTS

Figure 8-19. Paleotectonic elements which influenced accumulation of late Wolfcampian and early Leonardian salts. Arrows indicate dip direction.

Leonardian salts (salts 13, 11/12, 10, and 9). The Alliance and Sterling evaporite basins were separated by a positive element related to the Transcontinental arch. The two evaporite basins were joined by a transverse sag in the Garden County area (Garden County low). The southeastern margin of the Sterling basin was controlled by a positive element associated with the ancestral Las Animas arch (Yuma high). The northeast limit of evaporite deposition may have been controlled by positive features associated with the ancestral Chadron arch.

Pre-Late Jurassic Salt Removal

Near-surface salt removal associated with pre-Late Jurassic truncation generally occurred along and downdip (west) of north-south-trending outcrops of Permian salt and related strata which were exposed during Early Jurassic lowstands. Outcrop patterns are reflected by a pre-Late Jurassic subcrop map (Figure 3-3). Successively older units within the Permian salt-bearing interval are truncated to the east. Leonardian strata are partially truncated along the eastern margin of the study area. Guadalupian strata, which have been removed entirely along the eastern margin, are partially truncated along a north-south belt within the study area. Triassic strata, absent to the east, have been partially removed along a north-south belt farther to the west.

The influence of the pre-Late Jurassic unconformity on Triassic thickness patterns is shown on Figure 8-20. Triassic strata, which are over 500 ft (150 m) thick at the western margin of the study area, systematically thin to the east due to pre-Late Jurassic truncation. Triassic rocks are not present in the eastern half of the study area.

Influence of the pre-Late Jurassic unconformity on salt distribution is evident on Figure 8-21. Eastern limits of thicker Guadalupian and Upper Leonardian salts (salts 1, 2, 3, 5, and 7) show a pattern of stepwise removal below the unconformity. Younger salts (salts 1, 2, and 3), which may have originally extended much farther east, have been more strongly affected by truncation or near-surface dissolution.

Jurassic isopach maxima in Garden and Deuel Counties, Nebraska and in Yuma County, Colorado (Figure 8-11) may reflect infill of lows on the unconformity surface created by removal of thick salt 7. Likewise, a Jurassic isopach maximum in Morrill County, Nebraska, may be related to removal of thick salts 3 and 5 in this area. An increase in Jurassic thickness to the northwest does not coincide with removal of salt and probably reflects renewed subsidence in the Alliance basin during the Jurassic.

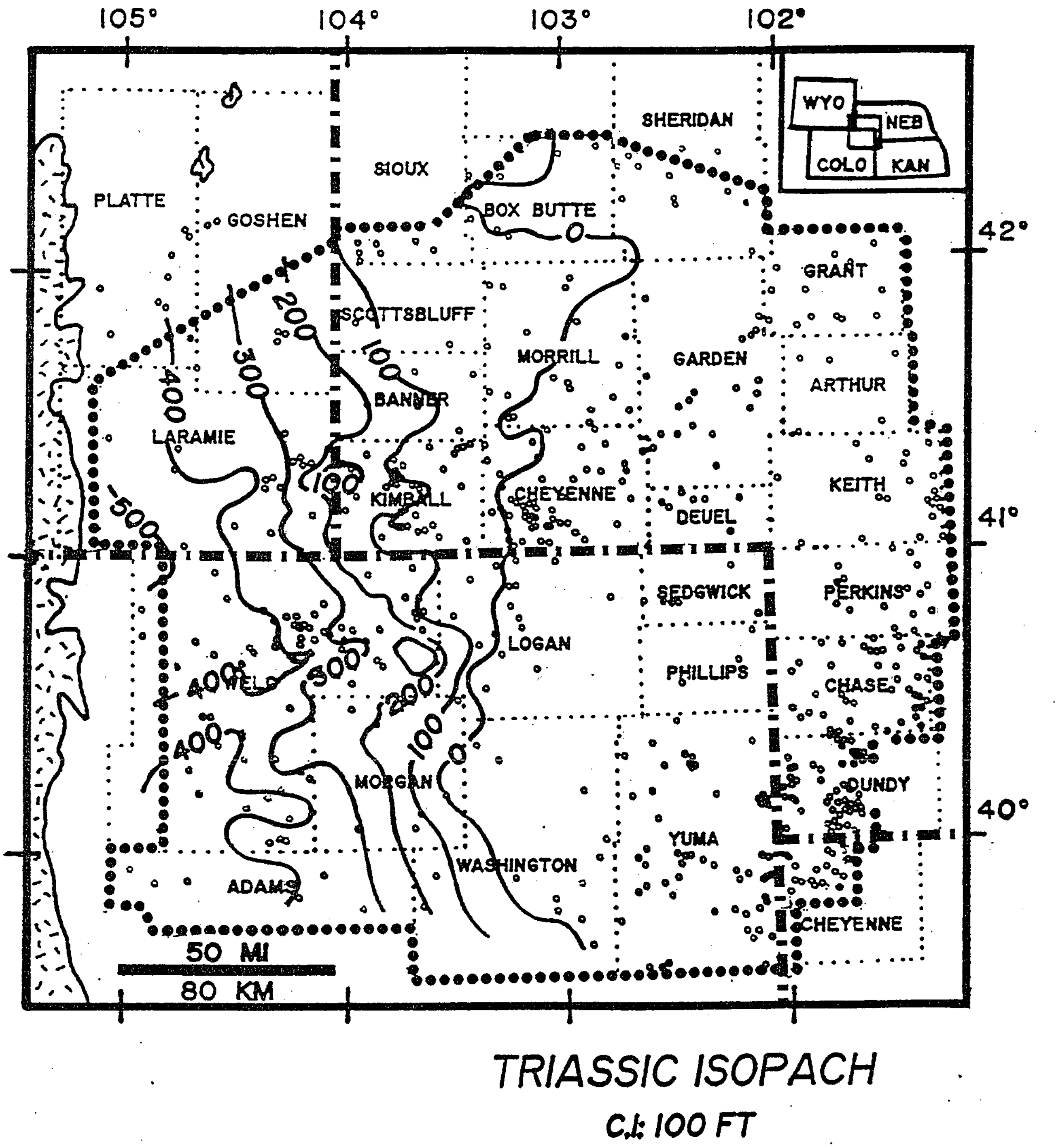


Figure 8-20. Isopach map of the Triassic. Contour interval 100 ft (30 m).

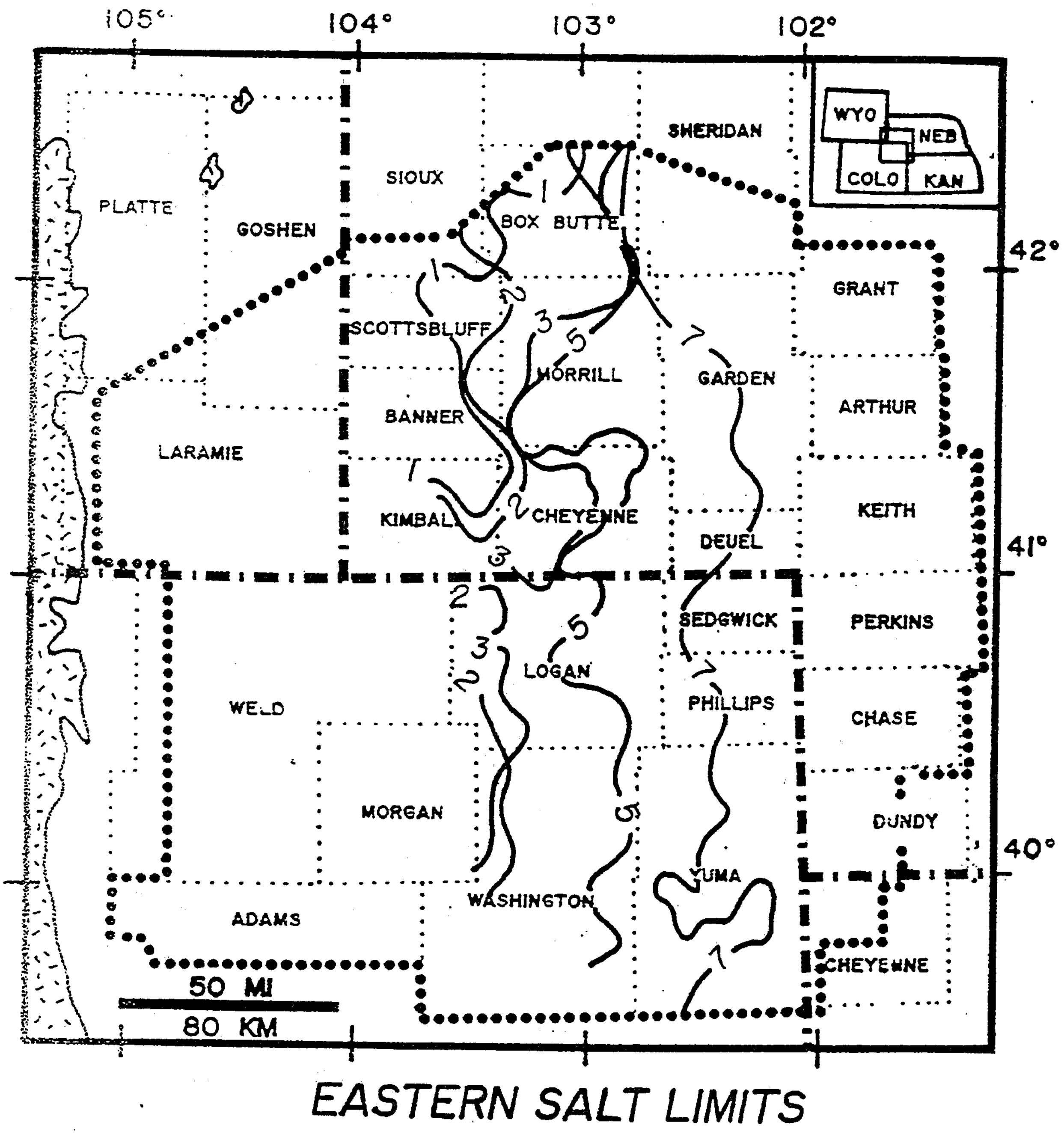


Figure 8-21. Present eastern limits of thick salts 1, 2, 3, 5, and 7.

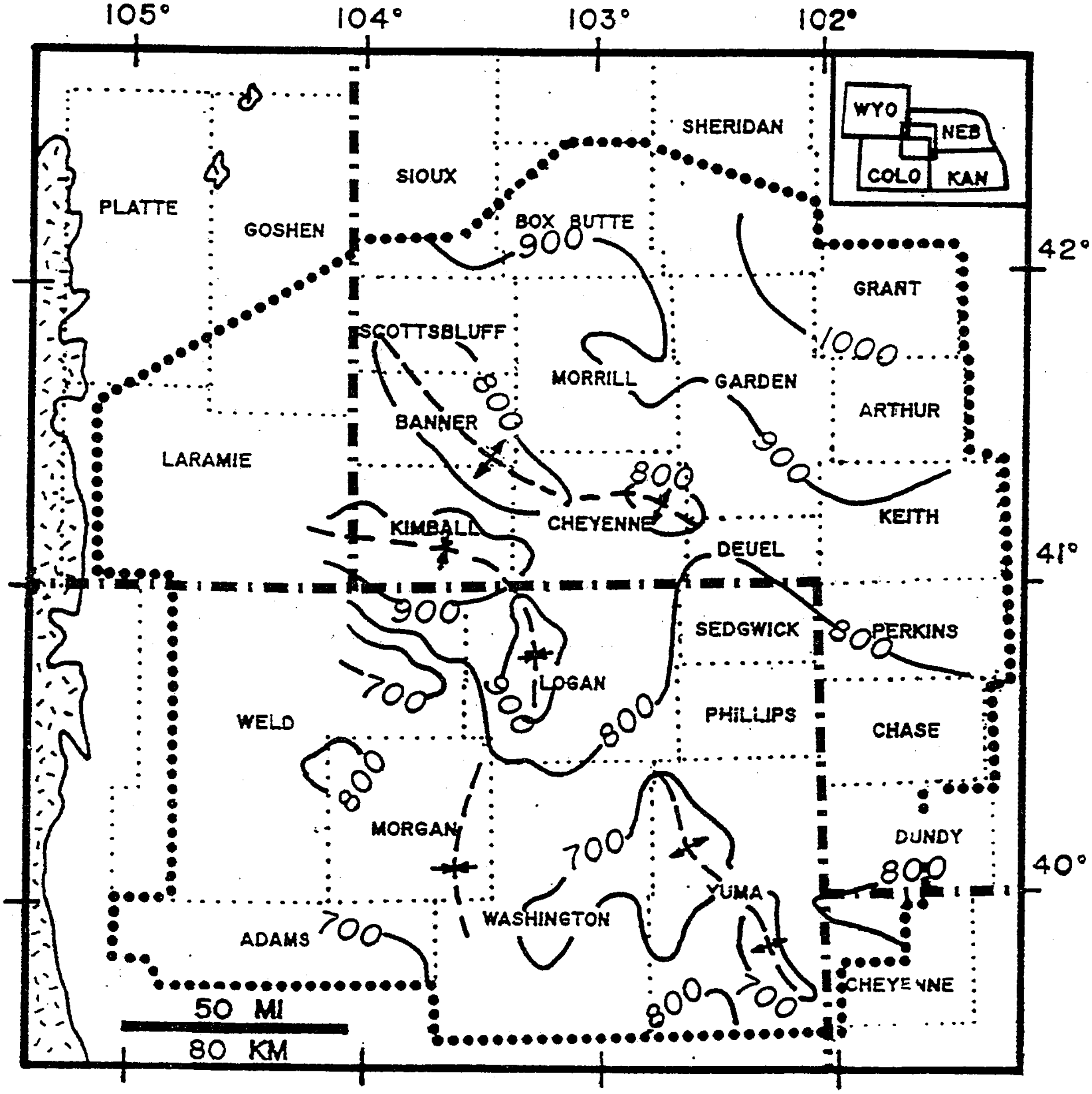
Jurassic and Early Cretaceous Salt Removal

Removal of salts 1 through 7 took place in Kimball County, Nebraska, and adjacent areas, as discussed earlier in this chapter and in Chapter 4. Jurassic and Lower Cretaceous isopach maxima (Figures 8-11 and 8-12), which extend southward from Kimball County into Weld, Logan and Morgan Counties, Colorado, coincide with the western limits of salts 2 through 7. This distribution suggests that the western margins of these salts are controlled largely by dissolution during the Jurassic and Early Cretaceous. Compaction-driven westward flow of water within the Lyons Sandstone may have acted as a source of water to dissolve the salts.

A combined Jurassic-Early Cretaceous isopach maximum (Figure 8-22), which extends southward from Kimball County into Colorado, shows the area of most complete dissolution. Isopach minima in Scotts Bluff, Banner, and Cheyenne Counties, Nebraska, and in Yuma and Washington Counties, Colorado, correspond to areas where thick salts are preserved.

Post-Laramide Salt Removal

In the course of the present study, structure was mapped at the level of Cretaceous oil and gas reservoirs.



LOWER CRETACEOUS - JURASSIC ISOPACH

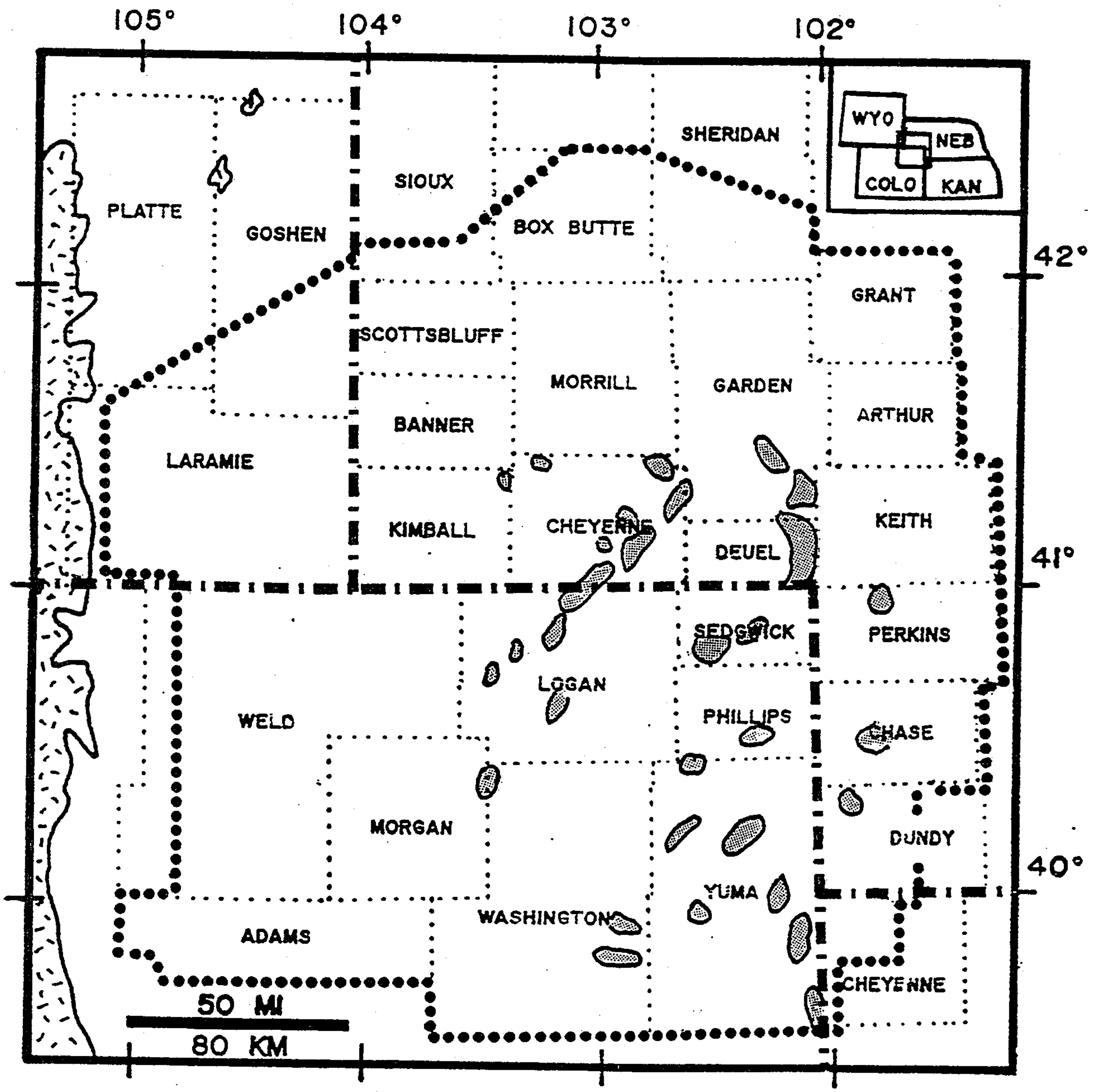
C.I: 100 FT

Figure 8-22. Isopach map of combined thicknesses of Lower Cretaceous and Jurassic rocks (interval from top of D Sandstone to base of Jurassic). Contour interval 100 ft (30 m).

This includes mapping at the level of the D Sandstone in the southern Nebraska panhandle (Chapter 4), and in the shallow D Sandstone gas area of Garden and Deuel Counties, Nebraska, and Sedgwick and Phillips Counties, Colorado (Chapter 2). Structure at the Niobrara level in Yuma and eastern Washington Counties, Colorado, was the focus of Chapters 6 and 7. Niobrara structure along the eastern margin of the study area, in Perkins, Chase, and Dundy Counties, Nebraska, is discussed in Chapter 9.

Structural mapping at the level of Cretaceous reservoirs reveals a number of deep structural depressions in the eastern part of the Denver basin, with structural relief of over 100 ft (30 m). Major depressions are shown on Figure 8-23. Structural anomalies in Logan and Morgan Counties, Colorado, are taken from published regional maps (Rocky Mountain Association of Geologists, 1961; Pruit, 1978; Geomap, 1985).

Structure at the level of the Wolfcampian Chase Group (Figures 1-8, 4-3, 6-5 and 7-10) reveals that Cretaceous-level structural depressions do not extend to the subsalt Paleozoic level. Relief across the rootless depressions is related to post-Cretaceous removal of salts. Removal of salt occurred in response to introduction of relatively fresh groundwater within the Lyons-Cedar Hills aquifer following Laramide orogeny, and, possibly, along Laramide-activated fault zones.



CRETACEOUS-LEVEL STRUCTURAL DEPRESSIONS

Figure 8-23. Significant Cretaceous-level structural lows.

Structural depressions on Figure 8-23 are believed to represent areas of relatively recent (Tertiary or later) salt-solution collapse. These areas generally coincide with the present limits of one or more salt zones. Chapter 9 relates the spatial relationship of these structural anomalies to oil and gas production.

Salts 9, 10, 11/12, and 13

Present distribution of salts 9, 10, 11/12, and 13 is shown on Figure 8-24, along with the 50-ft (15-m) limit of the Lyons-Cedar Hills Sandstone. Distribution of these lowermost salts is concentrated in areas adjacent to thick Lyons Sandstone (northern Sterling basin, Garden County low, and southern Alliance basin).

Maximum extent of salts 9, 10, 11/12, and 13 (Figure 8-25) is controlled by the northeast-trending Transcontinental arch, which separated the Alliance and Sterling evaporite basins. Thick salts accumulated in the Garden County low. Northeastern and southeastern limits of the evaporite basins were probably controlled by positive features related to the ancestral Chadron and Las Animas arches. Salt 10 may have extended farther east of its present limit, but was removed by pre-Late Jurassic dissolution. Post-Cretaceous removal took place just east of the present salt limit, perhaps due to renewed introduction of water.

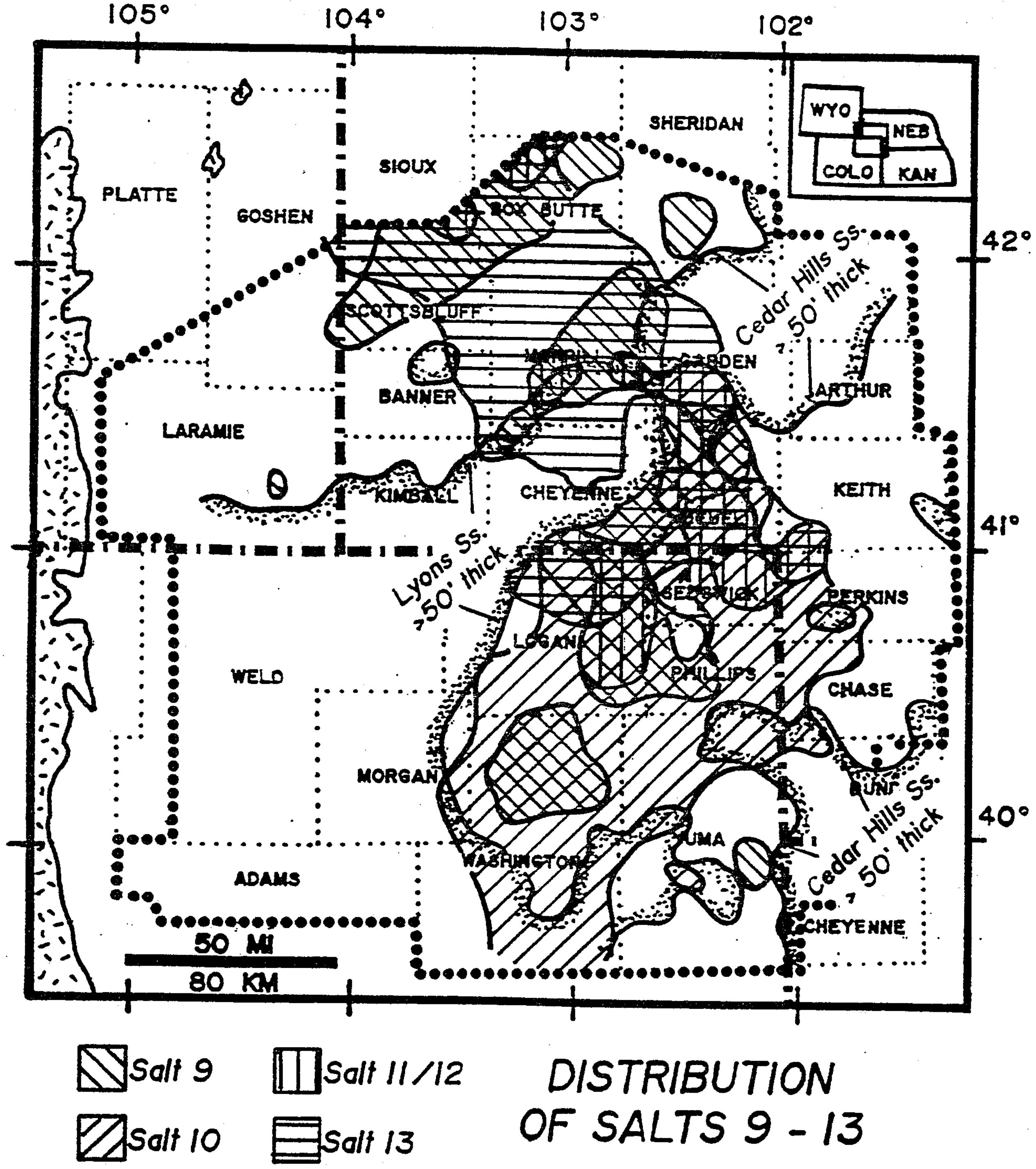


Figure 8-24. Regional distribution of salts 9, 10, 11/12, and 13.

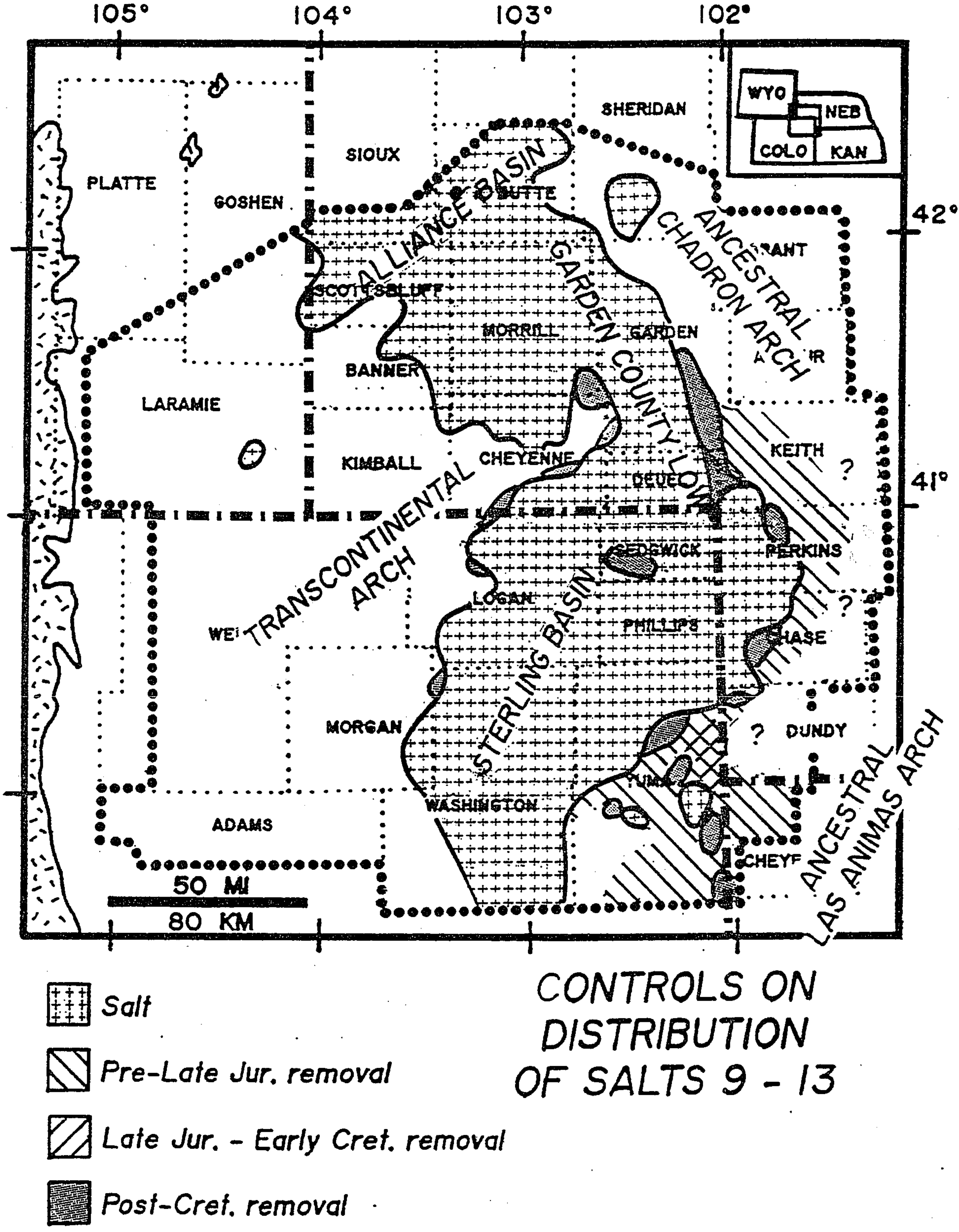


Figure 8-25. Inferred controls on regional distribution of salts 9, 10, 11/12, and 13.

Post-Cretaceous removal of salt also took place at the facies change between the Lyons Sandstone and salts 9 and 10 in the Sidney trough area of Cheyenne County, Nebraska, and to the south into Logan and Washington Counties, Colorado. Salts were also dissolved in the Yuma County area, where thick Cedar Hills Sandstone pinches out to the east into salt. An area of no salt in Sedgwick County (Red Lion anomaly), which is not related to a pinchout of the Lyons Sandstone, may be related to a major shear zone which was mapped by Squires (1986).

Regional Cretaceous-level structural flexure in Deuel and Garden Counties (associated with Big Springs, McCord-Richards and related shallow gas fields, chapter 2) is associated with the northeast limits of salts 9, 10, 11/12, 13 (and possibly 7). Possible mechanisms for salt removal along this trend (including basement faulting and regional groundwater flow within the Cedar Hills Sandstone and Jurassic strata) are briefly discussed in Chapter 5.

Cretaceous-level structural lows in the Sidney trough area of western Nebraska are 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 in Chapter 5 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. Regional groundwater flow within Jurassic strata (3) as a possible mechanism for salt removal is the subject of the following discussion.

Jurassic strata (Morrison and possibly Sundance Formations) presently lie directly below Oligocene strata along the crest of the Chadron arch (DeGraw, 1969, 1971; Swinehart et al., 1985). Pre-Oligocene subcrop limits of Jurassic rocks (from DeGraw, 1971) are shown on Figure 8-26. 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 (H.M. DeGraw, personal communication).

Downdip groundwater flow to the southwest from recharge areas on the pre-Oligocene truncation surface along the

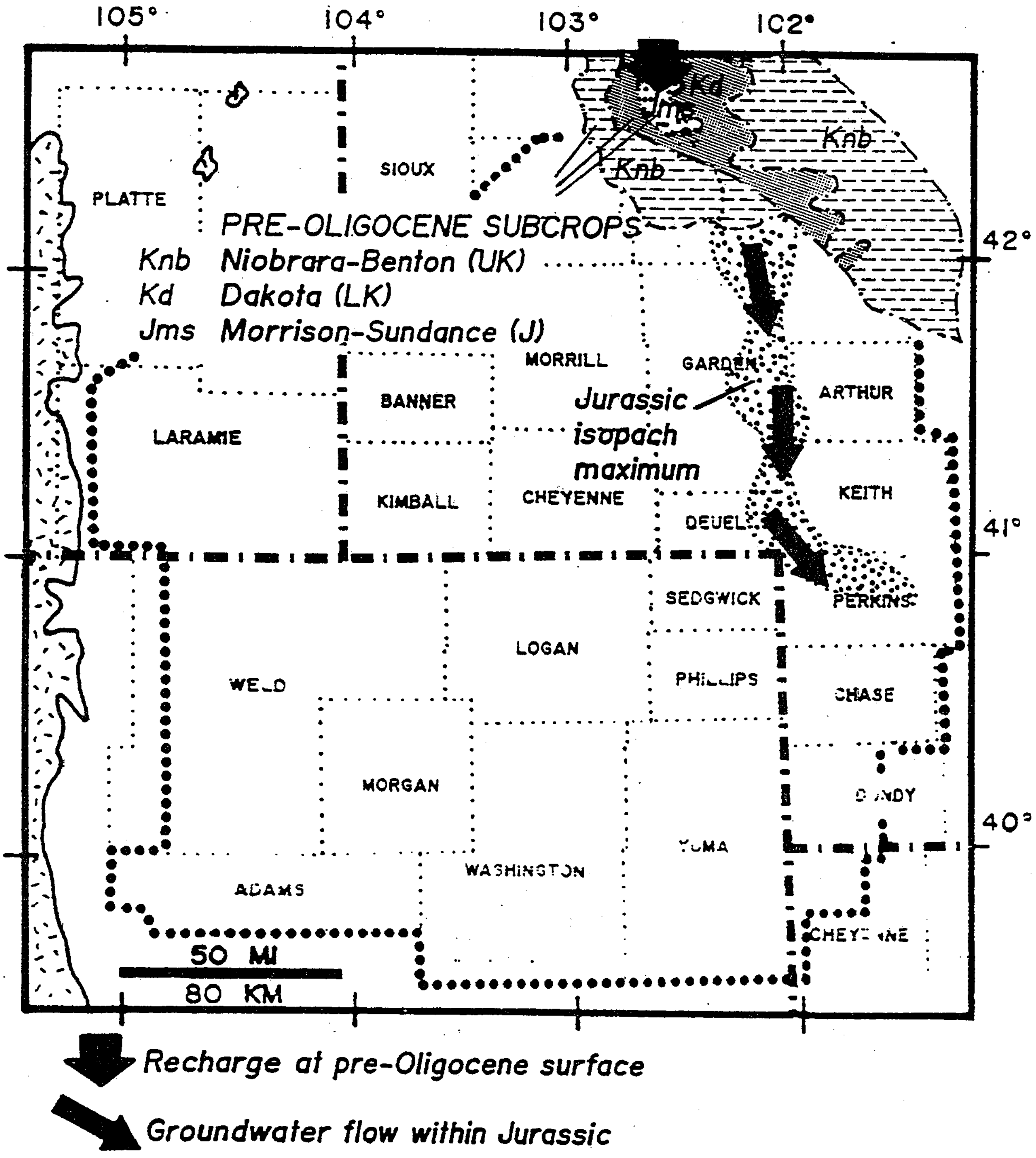


Figure 8-26. Possible southward regional groundwater flow within Jurassic strata from Jurassic outcrops at pre-Oligocene surface along Chadron arch. Subrops from DeGraw (1971).

Chadron arch may have been redirected to the south (Figure 8-26) within thick Jurassic sandstone units (reflected by a north-south-trending Jurassic isopach maximum, Figure 8-11). Groundwater may have been introduced to the Leonardian salt interval (Figure 8-27b), which lies directly below the pre-Late Jurassic unconformity in this part of the basin (Figures 3-3 and 4-11) due to partial truncation of overlying Leonardian strata this far east (Figure 8-27a).

Cross-formational groundwater flow may have taken place from Jurassic strata to the Cedar Hills Sandstone, where the Cedar Hills lies directly below the pre-Late Jurassic unconformity. Gravity-driven flow within the Cedar Hills may have introduced water which dissolved deeper salts Figure 8-27b). This may have created fractures, which allowed groundwater to flow from the Jurassic to the level of deeper salts. Removal of Leonardian salts caused regional collapse of overlying strata, including Cretaceous reservoir rocks downdip (west) of the Jurassic isopach maximum. This north-south regional flexure contributed to entrapment of gas within the D Sandstone and Niobrara Formation at Big Springs and nearby fields. Recharge may have been restricted with the deposition of relatively impermeable sediments of the White River and Arikaree Groups on the pre-Oligocene surface.

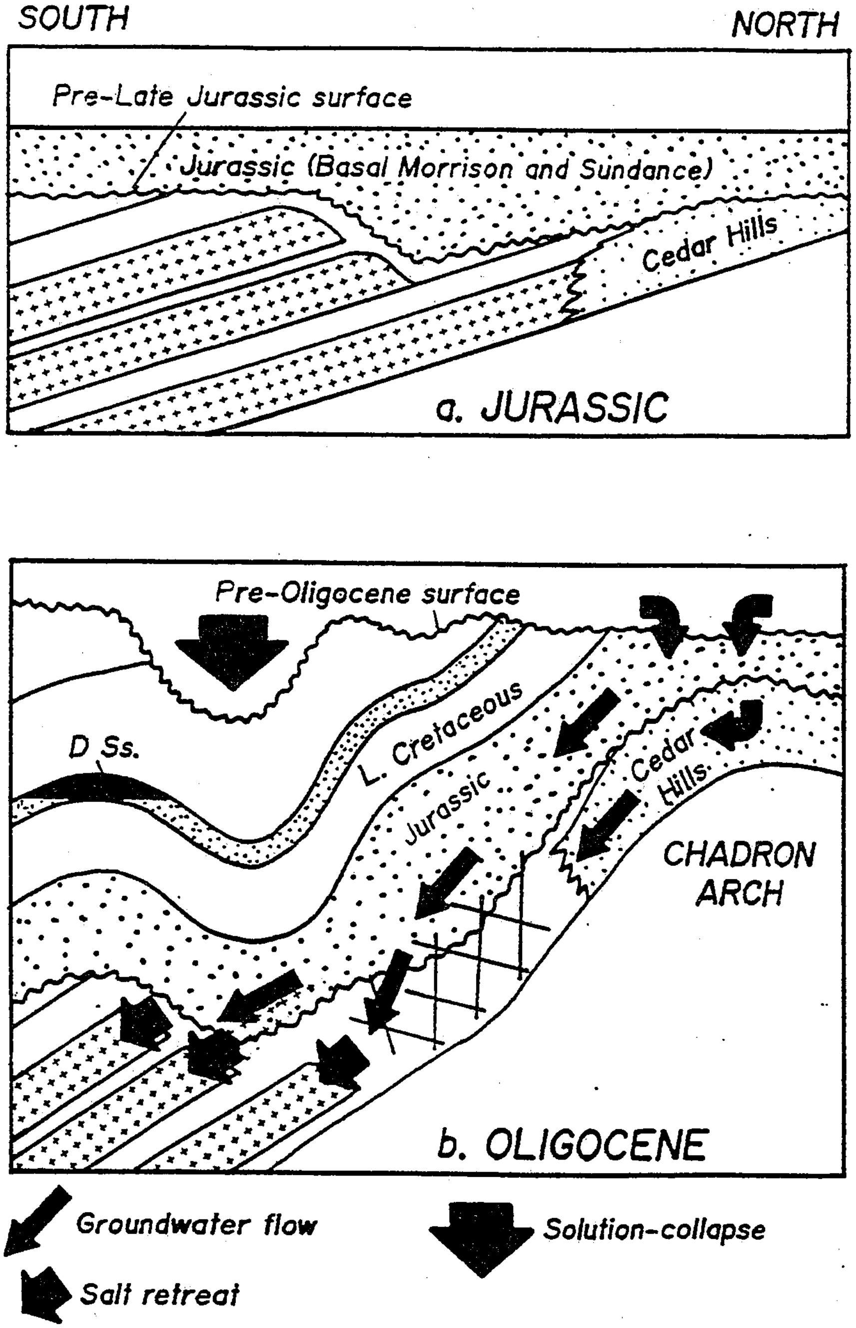


Figure 8-27. Diagrammatic cross sections depicting possible southward regional groundwater flow within Jurassic strata related to northeast limits of Leonardian salts. Pre-Late Jurassic removal of salt (a) created a collapse area and accommodation space for Jurassic sediments. Groundwater recharge (b) at the pre-Oligocene surface along the Chadron arch (Laramide) re-introduced water to the salt interval.

Salts 5, 6, 7, and 8

Salts 5 through 8 (Figure 8-28) extend across the Alliance basin area, across the Transcontinental arch area of the southern Nebraska panhandle, and into eastern Colorado. The eastern limit of salt 6 occurs west of the salt 7 limit. Likewise, the eastern limit of salt 5 is west of the salt 6 limit. By contrast, the western limits of salts 5, 6, and 7 generally coincide.

Unlike lower salts, precipitation of salts 5 through 7 was not influenced by the Transcontinental arch (Figure 8-25). With the exception of the Sidney trough area, salt extends continuously across the southern Nebraska panhandle. Salt was removed to the east of the present salt 7 limit in response to pre-Late Jurassic truncation (Figure 8-29). Partial pre-Late Jurassic removal of salt occurred between the eastern margin of salt 7 and the eastern margin of salt 5.

Jurassic and Early Cretaceous removal of salts 5, 6, and 7 took place along their western margins in Kimball County, Nebraska, and areas to the south in Colorado and to the west in Wyoming. Post-Cretaceous dissolution further removed salts near their present limits. Removal was particularly intense in the Sidney trough area and in Yuma County, Colorado.

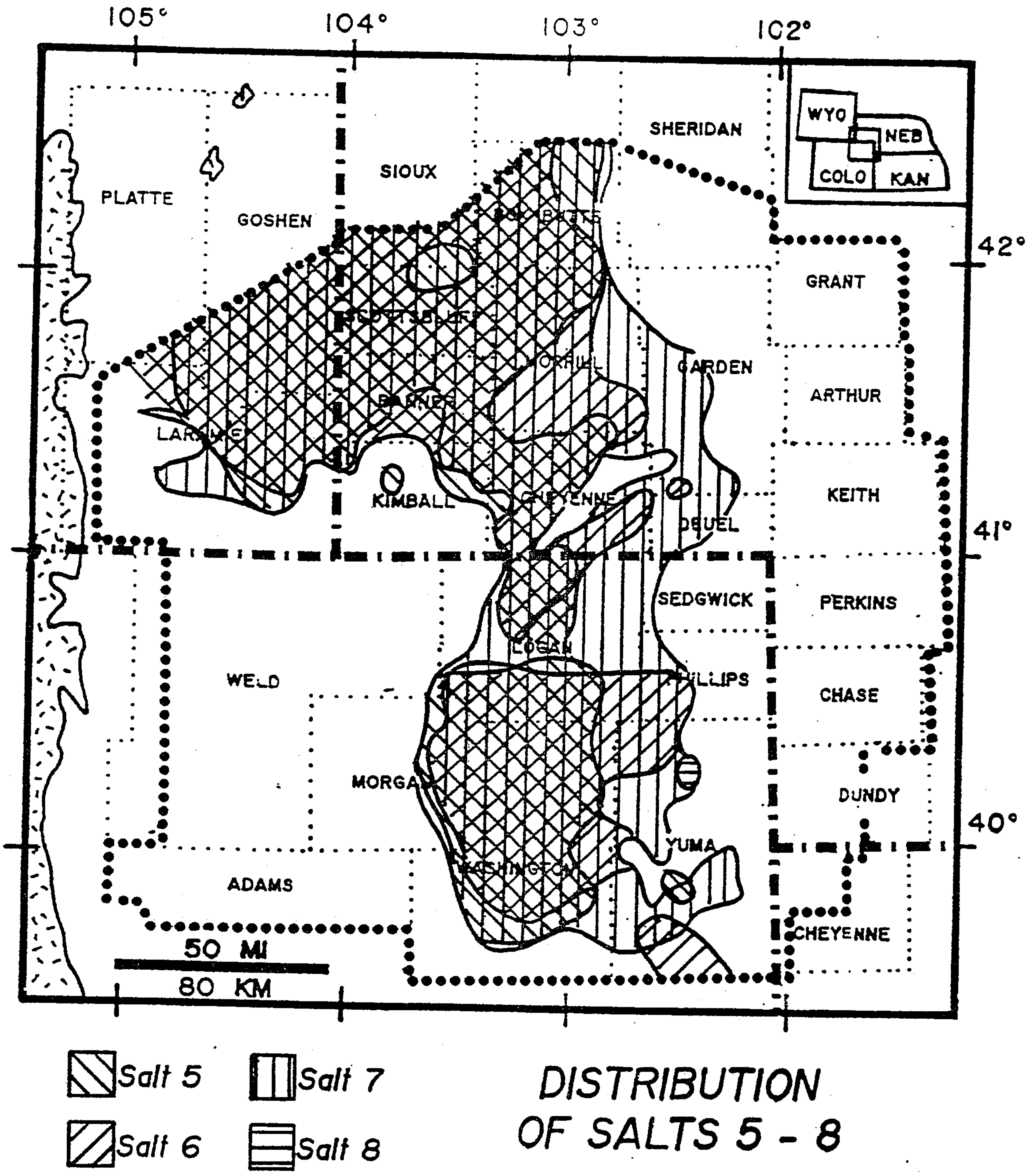


Figure 8-28. Regional distribution of salts 5, 6, 7, and 8.

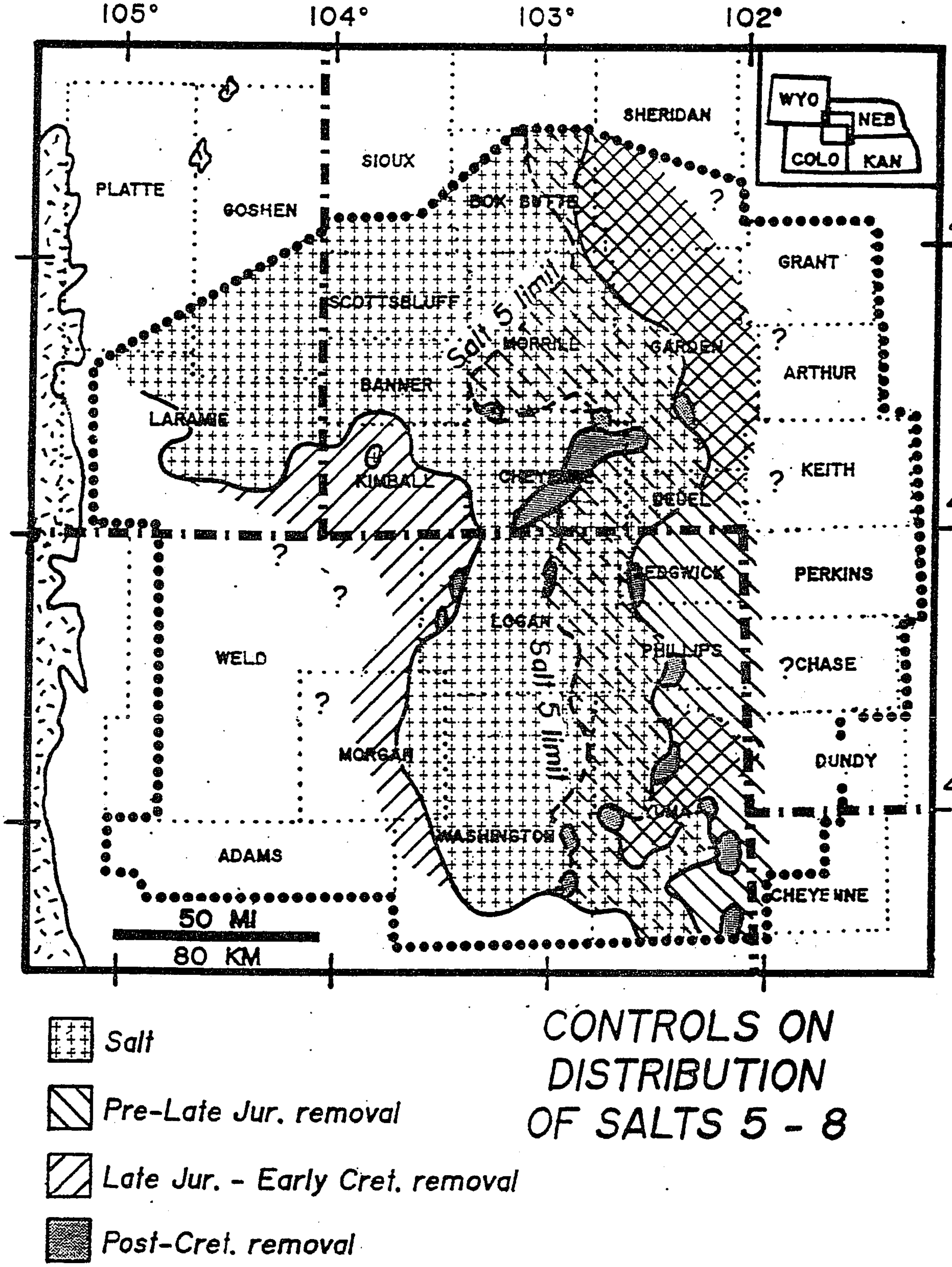


Figure 8-29. Inferred controls on regional distribution of salts 5, 6, 7, and 8.

Salts 1, 2, 3, and 4

Guadalupian salts (salts 1 through 4, Figure 8-30) are present in the Alliance basin area of western Nebraska and southeastern Wyoming, and, except for salt 1, in parts of Logan, Morgan, and Washington Counties, Colorado. In Nebraska, salt 2 generally extends to the east of the eastern limit of salt 1. Likewise, salt 3 extends to the east of salt 2. The western limits of salts 1, 2, and 3 in Wyoming and Nebraska and salts 2, 3, and 4 in Colorado generally coincide.

Inferred controls on present distribution of Guadalupian salts are shown on Figure 8-31. As with salts 5, 6, and 7, the Transcontinental arch does not appear to have been active during precipitation of salts 1 through 4. The eastern limit of salt is related to complete removal due to pre-Late Jurassic truncation. Partial pre-Late Jurassic removal of salts 1, 2, and possibly 4 occurred between the eastern margin of salt 3 and the eastern margin of salt 1. Salt 1 may have originally extended into Colorado.

Jurassic and Early Cretaceous removal of salts 1, 2, and 3 took place along their southwestern margins in Kimball County, Nebraska, and Laramie County, Wyoming, whereas salts 2, 3, and 4 were removed to the south in Colorado. Post-Cretaceous dissolution removed salt 3 in the Sidney trough area of Nebraska and Colorado, and in Morrill County,

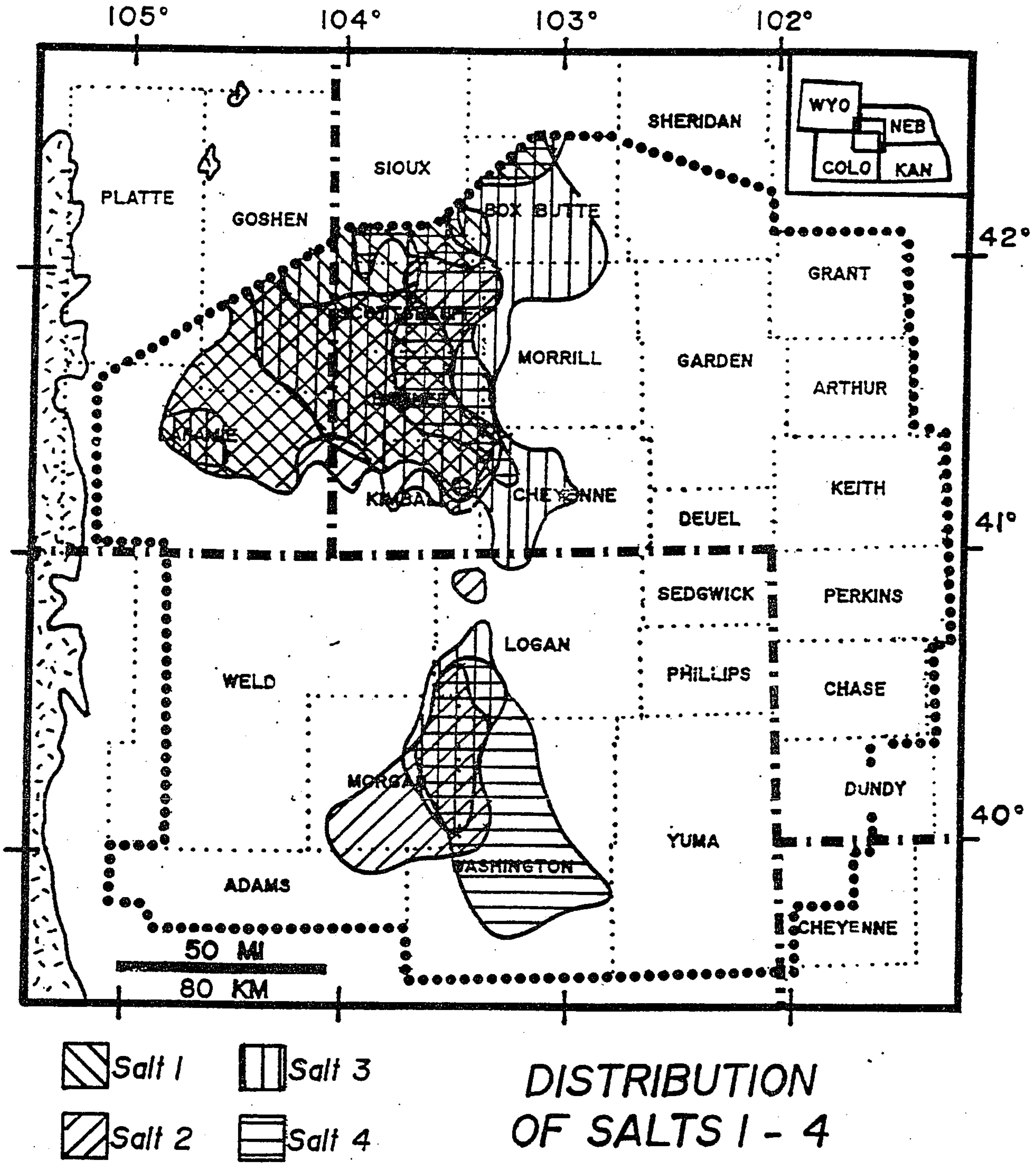


Figure 8-30. Regional distribution of salts 1, 2, 3, and 4.

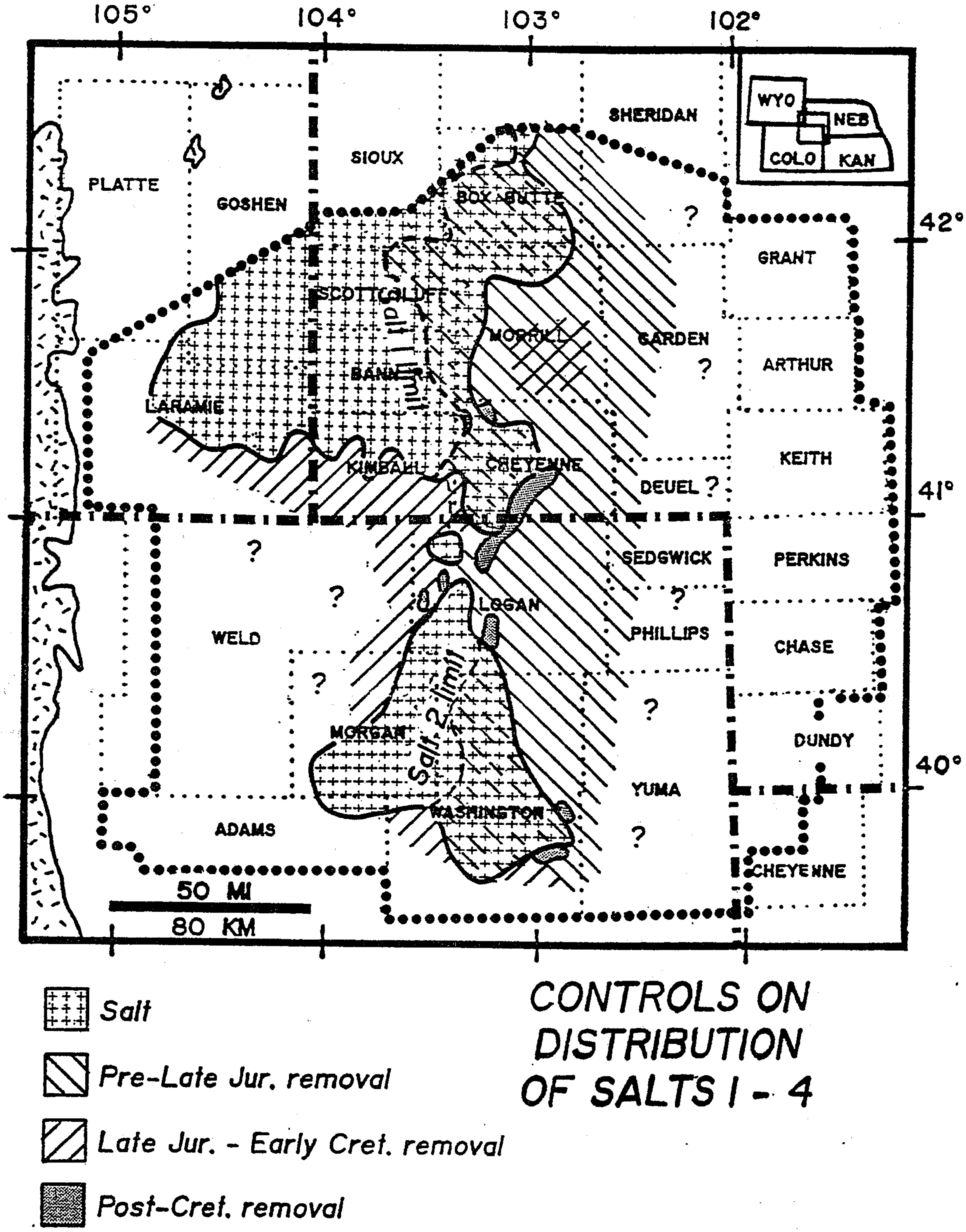


Figure 8-31. Inferred controls on regional distribution of salts 1, 2, 3, and 4.

Nebraska. Salt 4 was removed along its margin in eastern Washington County, Colorado.

Leonardian Thickness

Thickness of the Permian System and its series, including the Leonardian, has been used by previous workers (Momper, 1963; MacLachlan and Beiber, 1963; Rascoe and Baars, 1972; Rascoe, 1978; and Sonnenberg and Weimer, 1981) to infer the configuration of evaporite basins. The discussion above, along with discussions in Chapters 4 and 6, however, demonstrates that post-depositional processes have significantly influenced the thickness of Leonardian salts and related strata. Moreover, substantially more subsurface data are presently available in the Denver basin to construct a more accurate Leonardian isopach (Figure 8-32) and to refine the interpretation for thickness variations.

Leonardian thickness patterns reflect the distribution and thickness of salts 5 through 12. In contrast to interpretations of previous workers, however, thickness of Leonardian strata is strongly controlled by salt removal. Isopach mimima in the southern Nebraska panhandle area, previously attributed to convergence on the Morrill County and Wattenberg highs, can now be related to removal of salt. Leonardian strata are less than 300 ft (90 m) thick in

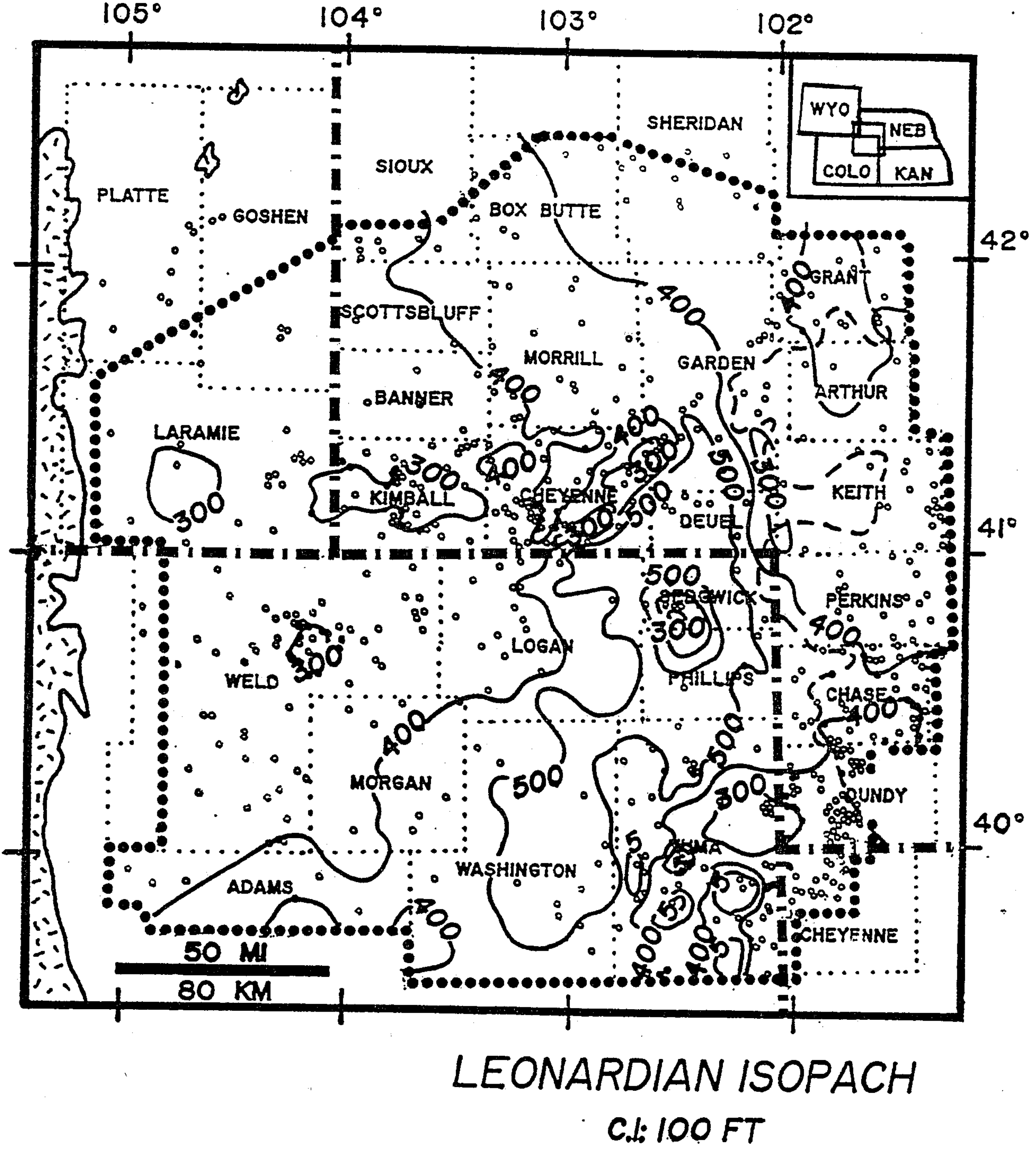


Figure 8-32. Isopach map of the Leonardian (interval which includes salts 5 through 12). Contour interval 100 ft (30 m). Leonardian rocks are partially truncated below pre-Late Jurassic unconformity to the east of dashed line.

Kimball County and adjacent areas of Wyoming and Colorado, where salts 5, 6, and 7 were removed during the Jurassic and Early Cretaceous. Leonardian strata are less than 300 ft (90 m) thick in the Sidney trough area of Cheyenne County, Nebraska, in eastern Deuel and Garden Counties, and in Sedgwick and Yuma Counties, Colorado, where dissolution primarily occurred after the Laramide orogeny. Leonardian strata are thickest (greater than 500 ft or 150 m) in the Sterling basin area of Colorado and Nebraska where thick salts are preserved.

Guadalupian Thickness

As with the Leonardian, regional variation in thickness of Guadalupian strata (Figure 8-33) is related to post-depositional controls on salt distribution. Guadalupian rocks are over 300 ft (90 m) thick along the northwestern margin of the study area, where salts 1 through 4 are preserved, and in Morgan and Washington Counties, Colorado, where salts 2, 3, and 4 are present.

Guadalupian strata are generally less than 100 ft (30 m) thick to the east of a north-south dashed line which marks the western limit of partial truncation of the Guadalupian below the pre-Late Jurassic unconformity. Guadalupian rocks are absent along the eastern margin of the study area, where complete pre-Late Jurassic truncation

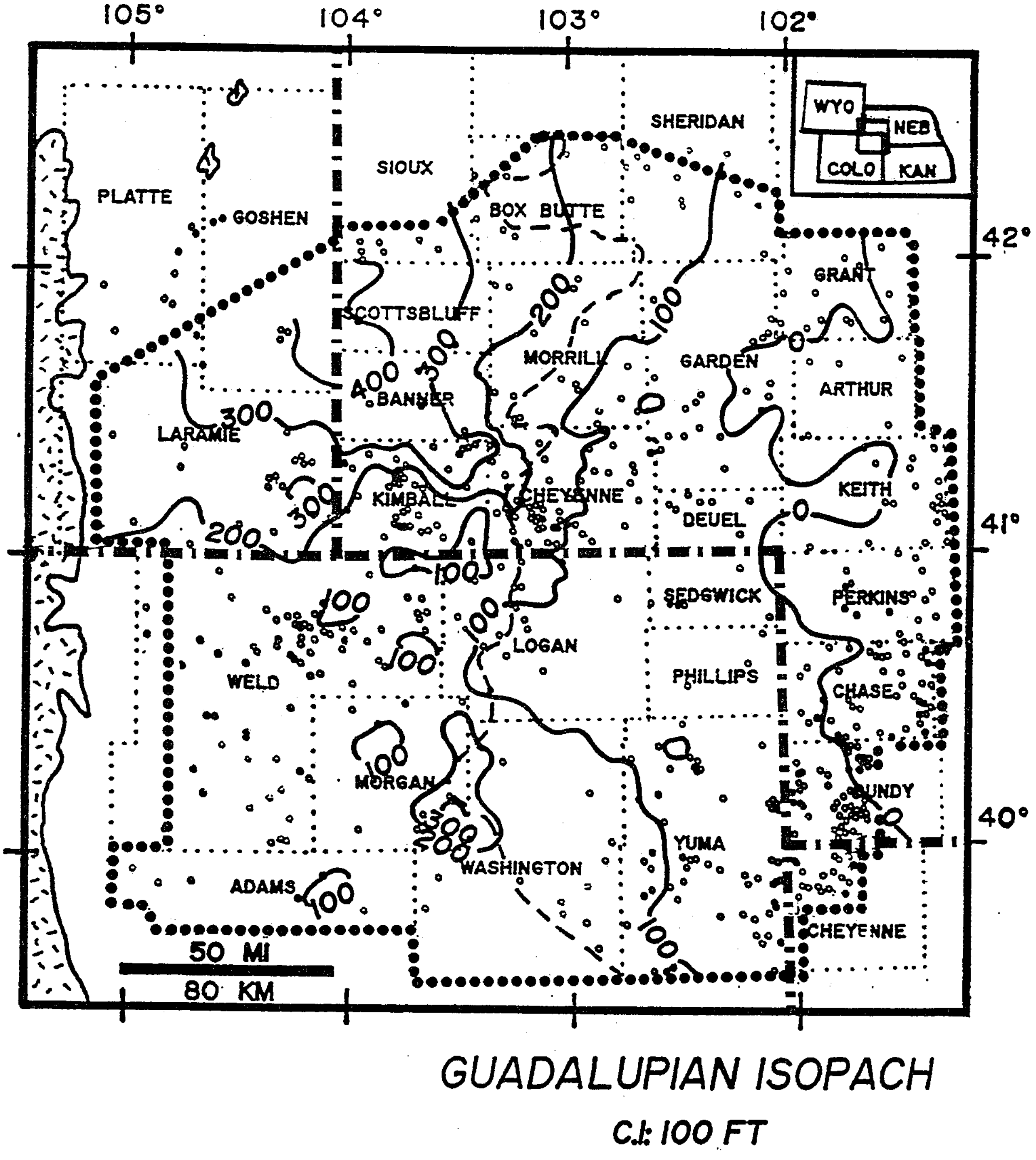


Figure 8-33. Isopach map of the Guadalupian (interval which includes salts 1 through 4). Contour interval 100 ft (30 m). Guadalupian rocks are partially truncated below pre-Late Jurassic unconformity to the east of dashed line.

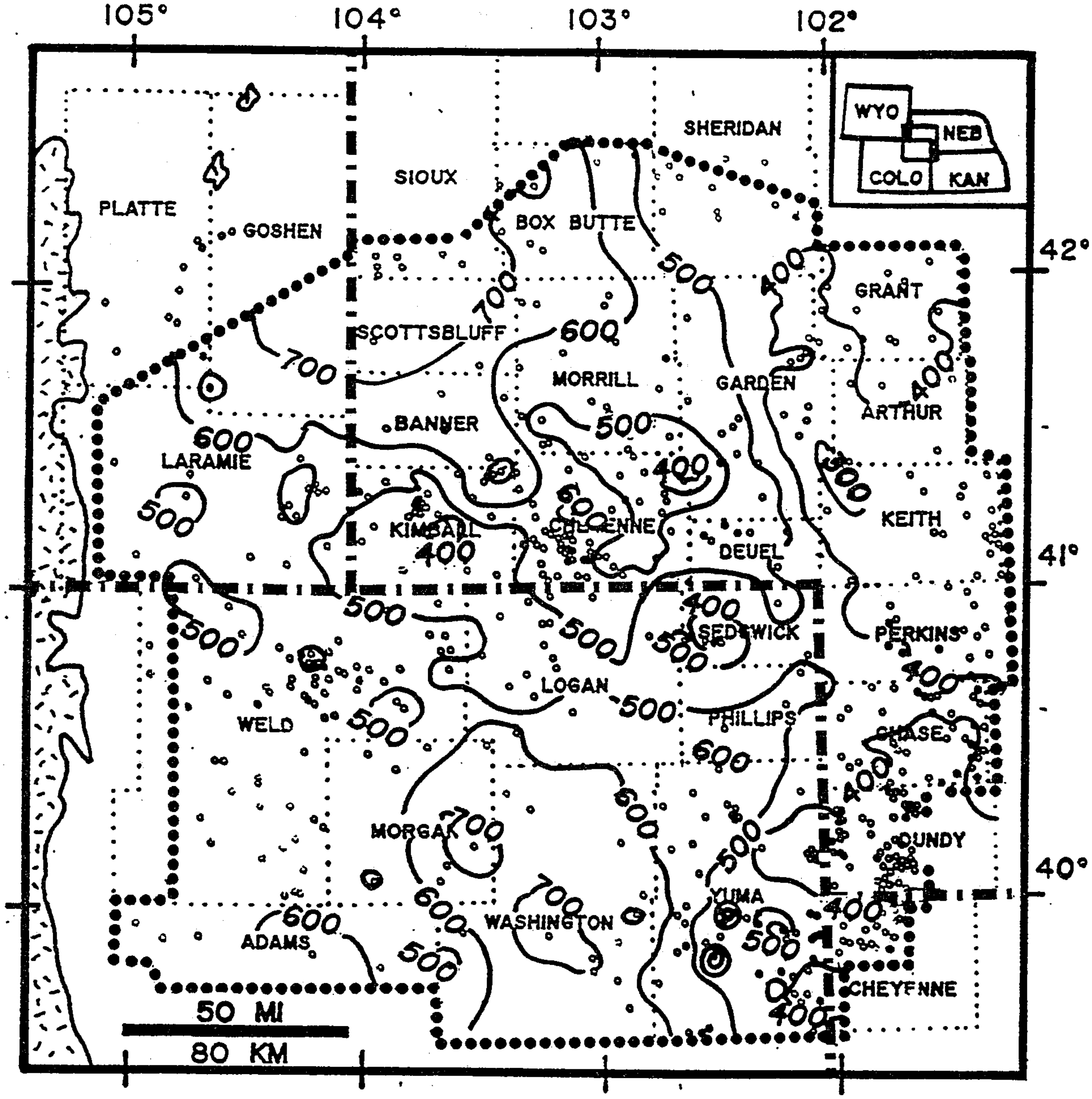
occurred. In southern Kimball County, Nebraska, and areas to the south, Guadalupian strata are about 100 ft (30 m) thick, where complete removal of salts took place during the Jurassic and Early Cretaceous.

Although thick Guadalupian salts accumulated in the Alliance basin area, Guadalupian isopach maxima to the northwest more likely reflect the preservation of salts 1 through 4 from pre-Late Jurassic and Jurassic and Early Cretaceous dissolution rather than evaporite basin subsidence.

Combined Guadalupian and Leonardian Thickness

Combined thickness of Guadalupian and Leonardian strata (Figure 8-34) also reflects the preservation of thick salts, rather than patterns of deposition. Guadalupian and Leonardian strata combine for a total thickness of more than 700 ft (210 m) along the northwestern margin of the study area, where salts 1, 2, 3, 4, 5, 6, 7, 9, 11, and 12 have been preserved, and in the south-central part of the study area, where salts 2, 3, 4, 5, 6, 7, 9, and 10 are present.

Total thickness of Leonardian and Guadalupian strata is less than 400 ft (120 m) along the eastern margin of the study area, where pre-Late Jurassic truncation removed Guadalupian strata and partially removed Leonardian strata, including salt 7. The interval is also less than 400 ft



GUADALUPIAN + LEONARDIAN
ISOPACH

C.I: 100 FT

Figure 8-34. Isopach map of the combined thicknesses of Guadalupian and Leonardian rocks. Contour interval 100 ft (30 m).

(120 m) thick where Jurassic and Early Cretaceous removal of Leonardian and Guadalupian salts took place in Kimball County and adjacent areas, and where post-Cretaceous salt dissolution occurred in parts of Cheyenne County, Nebraska, and Sedgwick and Yuma Counties, Colorado.

Isopach minima centered around Kimball County (caused by Jurassic and Early Cretaceous removal of salt) and Cheyenne County (caused by post-Cretaceous removal of salt) may correspond to Sonnenberg and Wiemer's (1981) Morrill County and Wattenberg highs. Sonnenberg and Weimer attributed thinning of the Guadalupian/Leonardian interval in these areas to syndepositional convergence over basement-related paleohighs. Detailed study of individual salt zones and related stratigraphic units, using substantially more subsurface data than were available at the time of Sonnenberg and Weimer's (1981) study, reveals that Guadalupian and Leonardian thickness patterns are more strongly affected by post-depositional salt removal than by syndepositional basin configuration.

SUMMARY AND CONCLUSIONS

Subsurface stratigraphic and structural study of Permian salt-bearing rocks was expanded in this chapter to include the entire Denver basin study area. Regional mapping of 13 Permian salt zones and associated related clastic and evaporite strata along with mapping of Mesozoic stratigraphic intervals leads to the following conclusions:

1. A northeast-trending positive feature associated with the Transcontinental arch influenced evaporite deposition during late Wolfcampian and early Leonardian time, by partitioning the Alliance and Sterling evaporite basins. A transverse sag across the arch (Garden County low) locally connected the Alliance and Sterling basins.

2. Eolian sand (Lyons Sandstone) accumulated on the arch while red silts and clays and salt (salts 9 and 10) accumulated in evaporite basins marginal to the positive feature. Areal limits of salt were controlled by the configuration of the evaporite basins.

3. By contrast, evaporite deposition during late Leonardian and Guadalupian time was more widespread. Salt accumulation occurred across the area formerly occupied by the Transcontinental arch. At least five periods of significant salt accumulation took place , resulting in thick salts 1, 2, 3, 5, and 7.

4. Present eastern limits of upper Leonardian and Guadalupian salts do not reflect the original eastern extent of salt accumulation. Erosion and near surface dissolution

below the pre-Late Jurassic unconformity (due perhaps to introduction of meteoric water during late Jurassic lowstands) removed salts to the east. Successively younger salts were affected more by pre-Late Jurassic removal.

5. Western limits of upper Leonardian and Guadalupian salts were modified by dissolution during the Jurassic and Early Cretaceous. Removal of salt may have been caused by introduction of water to the salt interval through the Lyons Sandstone by compaction-induced (centrifugal) flow.

6. Limits of all salts were further modified by post-Laramide subsurface dissolution. Removal of salt was likely caused by introduction of water to the salt interval by regional gravity-driven (centripetal) flow within the Lyons Sandstone, and possibly within Laramide-induced fracture zones. Northeastern limits of Leonardian salts may be due to introduction of groundwater to the salt interval within Jurassic strata (and possibly the Cedar Hills Sandstone) by southwest- and south-directed gravity-driven flow. Recharge may have taken place at pre-Oligocene outcrops of Jurassic strata along the crest of the Chadron arch.

7. Post-Laramide salt dissolution is marked by deep structural anomalies at the levels of Cretaceous reservoirs.

Regional influence of salt dissolution on oil and gas entrapment is discussed in Chapter 9.

8. Because of the possibility of truncation and subsurface removal of salt, stratigraphic interpretations which are based on intervals which include salts must be made with caution. Interpretations of salt-bearing strata which attribute isopach minima to paleohighs and isopach maxima to subsidence, without consideration to post-depositional (dissolution) influence on interval thickness, may be erroneous.

CHAPTER 9

REGIONAL RELATIONSHIPS OF SALT DISTRIBUTION TO OIL AND GAS PRODUCTION AND POTENTIAL AND DRILLING PROBLEMS

Regional analysis of the relationships between salt distribution and Cretaceous-level structural and stratigraphic anomalies (Chapter 8) reveals that subsurface removal of Permian salt occurred at various times since the Jurassic. This chapter discusses the relationship of salt distribution to (1) regional oil and gas production and potential on the eastern flank of the basin and (2) drilling and completion problems related to the presence of thick salts and associated hydrated shales.

RELATIONSHIP TO HYDROCARBON ENTRAPMENT

Background work in the northeastern part of the Denver basin (Chapter 2) reveals a relationship between eastern (regionally updip) limits of Permian salts and the location of shallow gas production from the D Sandstone at Big Springs and nearby fields (Figure 9-1). Seismic data are used to support a salt-dissolution origin for the gas-productive anticline at Big Springs field (Chapter 5).

Subregional-scale study of the southern Nebraska panhandle area (Chapter 4) reveals a relationship between an eastern limit of salt and the eastern limit of oil and gas

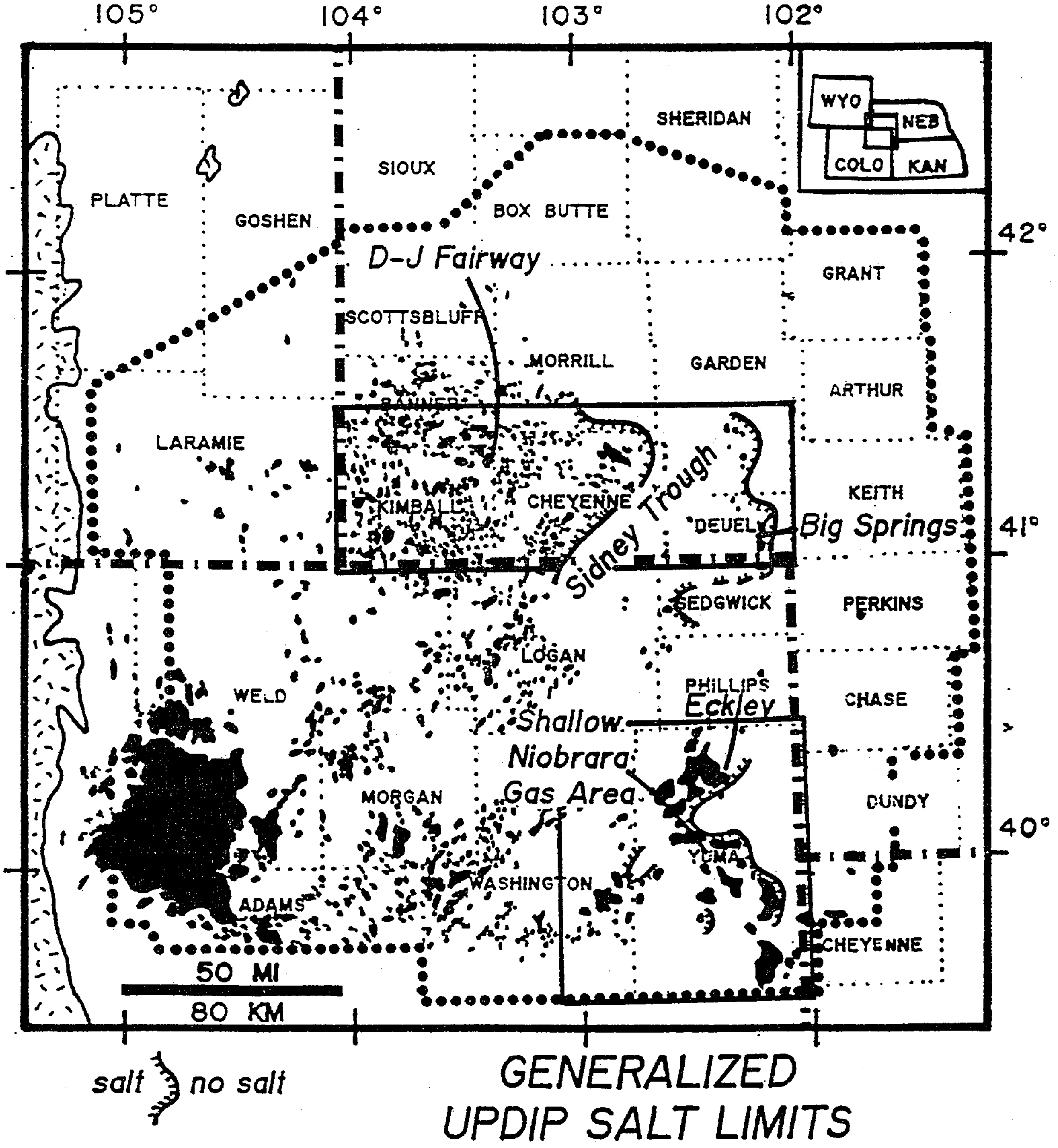


Figure 9-1. Location of generalized regional salt limits associated with Nebraska portion of D-J fairway, Big Springs and nearby shallow D Sandstone gas fields, and eastern Colorado shallow Niobrara gas area.

production within the D-J fairway. Structural entrapment of hydrocarbons in the eastern part of the fairway, just west of the Sidney trough, is attributed to incomplete post-reservoir removal of salt. Oil and gas were localized where D and J Sandstone reservoirs draped over salt-cored anticlines. Location of the Sidney trough is attributed to salt removal along an abrupt facies change from Lyons Sandstone to Leonardian salt.

Subregional-scale study of the eastern Colorado Niobrara play (Chapter 6) reveals a relationship between eastern limits of salts and the distribution of shallow Niobrara gas fields (Figure 9-1). Accumulation of gas in the Niobrara is attributed to entrapment on structural highs situated above salt edges or outliers. Seismic data are used to support a salt-dissolution origin for the faulted anticline at Eckley field (Chapter 7).

The purpose of the first part of this chapter is to provide an overview of the influence of Permian salt dissolution on hydrocarbon production and potential on the eastern flank of the basin. Regional distribution of salt is analyzed in relation to the location of significant structural features and to distribution of oil and gas plays in the following sections.

Structural Depressions

Structural mapping at the level of Cretaceous reservoirs on the eastern flank of the basin reveals a number of significant structural depressions, many with over 100 ft (30 m) of relief. Locations of major depressions relative to mapped salt edges are discussed in Chapter 8 (Figure 8-23). Where available, deep control indicates that structural relief does not extend to the subsalt level. Relief across the rootless depressions is attributed to post-Cretaceous removal of salts. Salt removal was likely caused by introduction of fluids by the Lyons-Cedar Hills regional aquifer following Laramide orogeny or along Laramide-activated fault zones.

Locations of significant structural depressions are compared to oil and gas field distribution on Figure 9-2. Structural lows exist immediately to the east of: (1) the D-J fairway in Nebraska and Colorado; (2) Big Springs and nearby fields in the shallow D gas area in the northeastern part of the basin; and (3) Niobrara gas production in Yuma County, Colorado.

D-J Fairway

The eastern (regionally updip) limit of the D-J fairway (Figure 9-3) extends southward from Morrill and Cheyenne Counties, Nebraska, through Logan and Washington Counties,

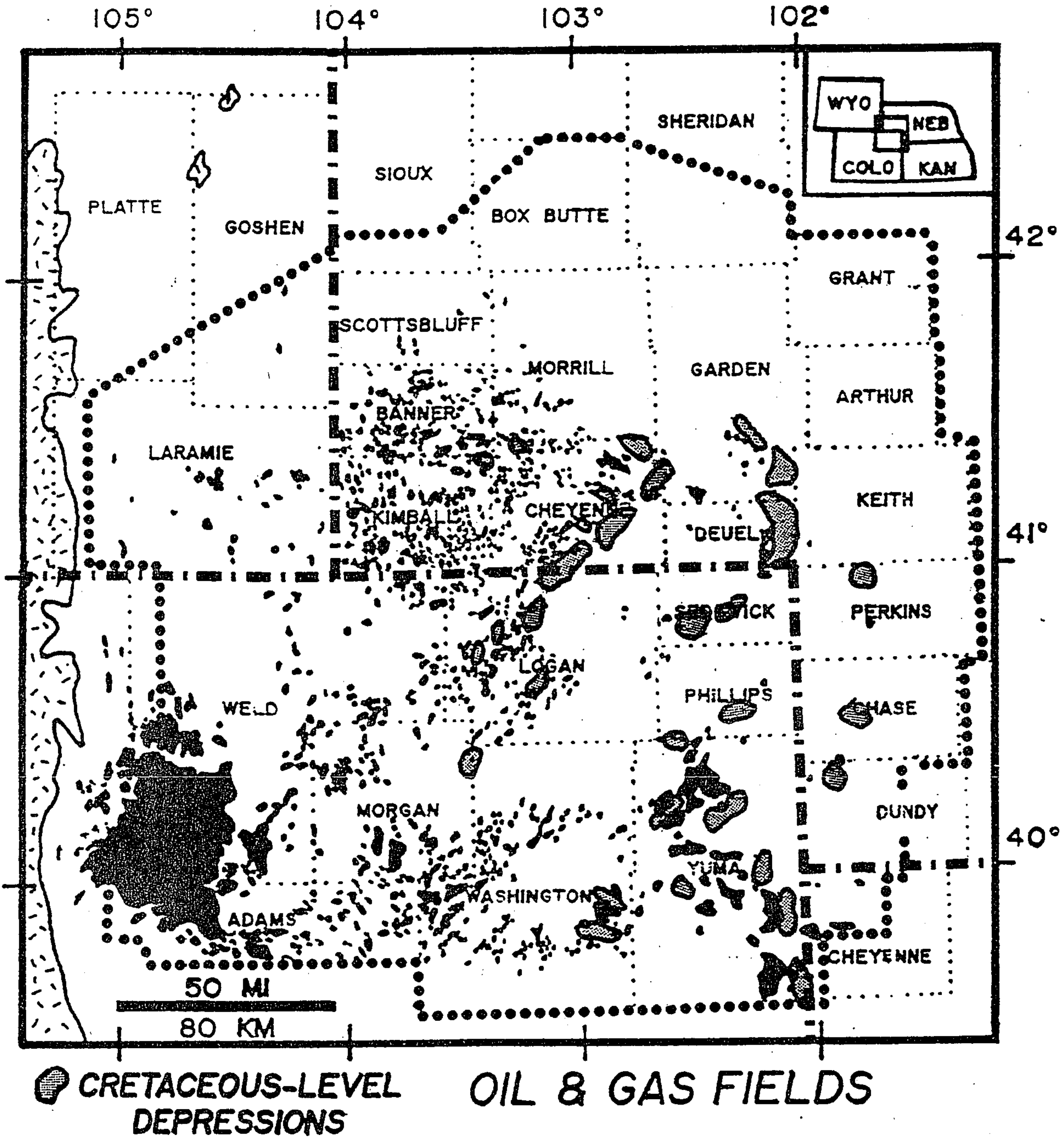


Figure 9-2. Location of significant Cretaceous-level structural depressions (shaded) associated with eastern limits of D-J fairway, shallow D gas area, and shallow Niobrara gas area.

Colorado. As was demonstrated in the southern Nebraska panhandle (Chapter 4), Cretaceous-level structure becomes increasingly complex along the eastern margin of the fairway (shaded area).

Clayton and Swetland (1980) geochemically correlated oil produced from the D and J Sandstones with a Cretaceous source-rock interval that includes the Carlile Shale, Greenhorn Limestone, Graneros Shale (including the Huntsman Shale), and Mowry Shale. Tainter (1984) concluded that gas which is produced in the fairway did not result from thermal cracking of oil, but was likely derived from gas-prone organic material in the J Sandstone - Skull Creek Shale interval. Thermally mature source rocks (Figure 9-3) are confined to the axial portion of the basin (Clayton and Swetland, 1980; Tainter, 1984).

Tainter (1984) related the distribution of production within the fairway to source rock interval, maturation history, stratigraphy of carrier and reservoir rocks and paleostructural evolution of the basin to determine patterns of hydrocarbon migration. Tainter interpreted regional migration patterns, using sandstone isolith maps for the D and J (both of which act as regional carrier beds and reservoirs) in conjunction with basin subsidence profiles. Tainter concluded that the J Sandstone was in contact with mature source rocks by Middle Eocene time. By the end of the Tertiary, the D Sandstone was in contact with mature

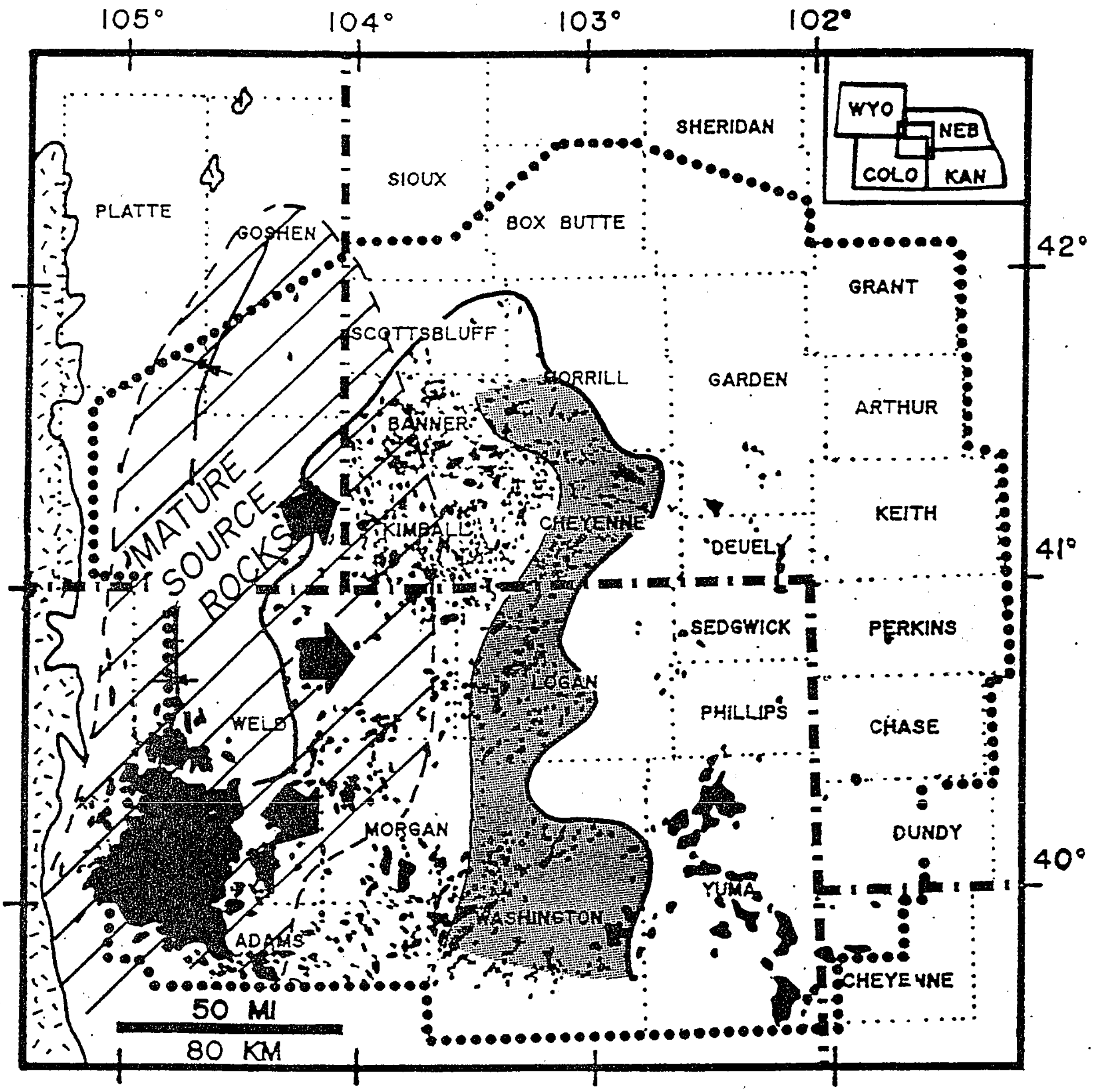


Figure 9-3. Location of D-J fairway in Colorado and Nebraska. Area of mature source rocks in axial part of basin from Tainter (1984). General direction of hydrocarbon migration shown by arrows. Eastern part of fairway which is more structurally complex is shaded.

source rocks. Eastward-directed migration of hydrocarbons was concentrated in areas of thicker, more permeable sandstone.

Except for more recent regional uplift, the present-day structural configuration of the basin is essentially the same as that which existed at the end of the Tertiary. Tainter (1984) found no regional mechanism (such as regional facies changes or structural reversal) to prevent eastward migration of hydrocarbons past the fairway limit and out of the basin. He called upon broad paleostructural highs, which were present by Campanian time and which coincide with production in the fairway, to act as broad regional trapping areas, preventing further eastward migration.

Subregional study (Chapter 4) reveals that entrapment in the D and J Sandstones becomes more structurally controlled in the eastern side of the fairway (Figure 9-3) and that the eastern limit of production in Nebraska coincides with the Sidney trough. Structural complexity in Cheyenne County was attributed to incomplete removal of salt. Location of the Sidney trough was related to essentially complete removal of salt along the Lyons Sandstone - salt facies change.

Deep subsurface data are relatively sparse along the eastern side of the fairway in Colorado, but are sufficient to observe stratigraphic relationships which are similar to those in Nebraska. A regional west-to-east facies change from Lyons Sandstone to salt (salts 9 and 10) extends from the Sidney trough area of Nebraska southwestward into Logan County, Colorado (Figure 9-4). Salts 9 and 10 accumulated in the Sterling basin east of this facies change.

Regional eastward-directed groundwater flow in the Lyons aquifer to its updip pinchout into salt was discussed as a mechanism for removal of salt in the Sidney trough area (Chapter 4) and in Yuma County (Chapter 6). Removal of salt may have also been localized where the Lyons pinches out to the east between these two areas, in Logan and Washington Counties. Deep data are limited in these counties, and the eastern Lyons pinchout may be more abrupt than shown on Figure 9-4. Removal of salt in this area may account for the more complex structure along the eastern part of the fairway, as is the case in Nebraska.

Eastern (regionally updip) limits of selected thick salt zones (salts 1, 2, 3, 4, 5, 7, and 9) in the general area of the D-J fairway are plotted on Figure 9-5. Eastern limits of thick salts 3, 5, and 7 coincide with the eastern limit of production in Nebraska. Limits of salt in Colorado are based on sparse data. However, there appears to be a general relationship between the eastern limit of salts and the eastern limit of production in the fairway. Eastern limits of salts, 2, 3, 4, and 5 are situated within the more structurally complex part of the fairway. This may indicate that the eastern margins of the salt beds in Colorado have

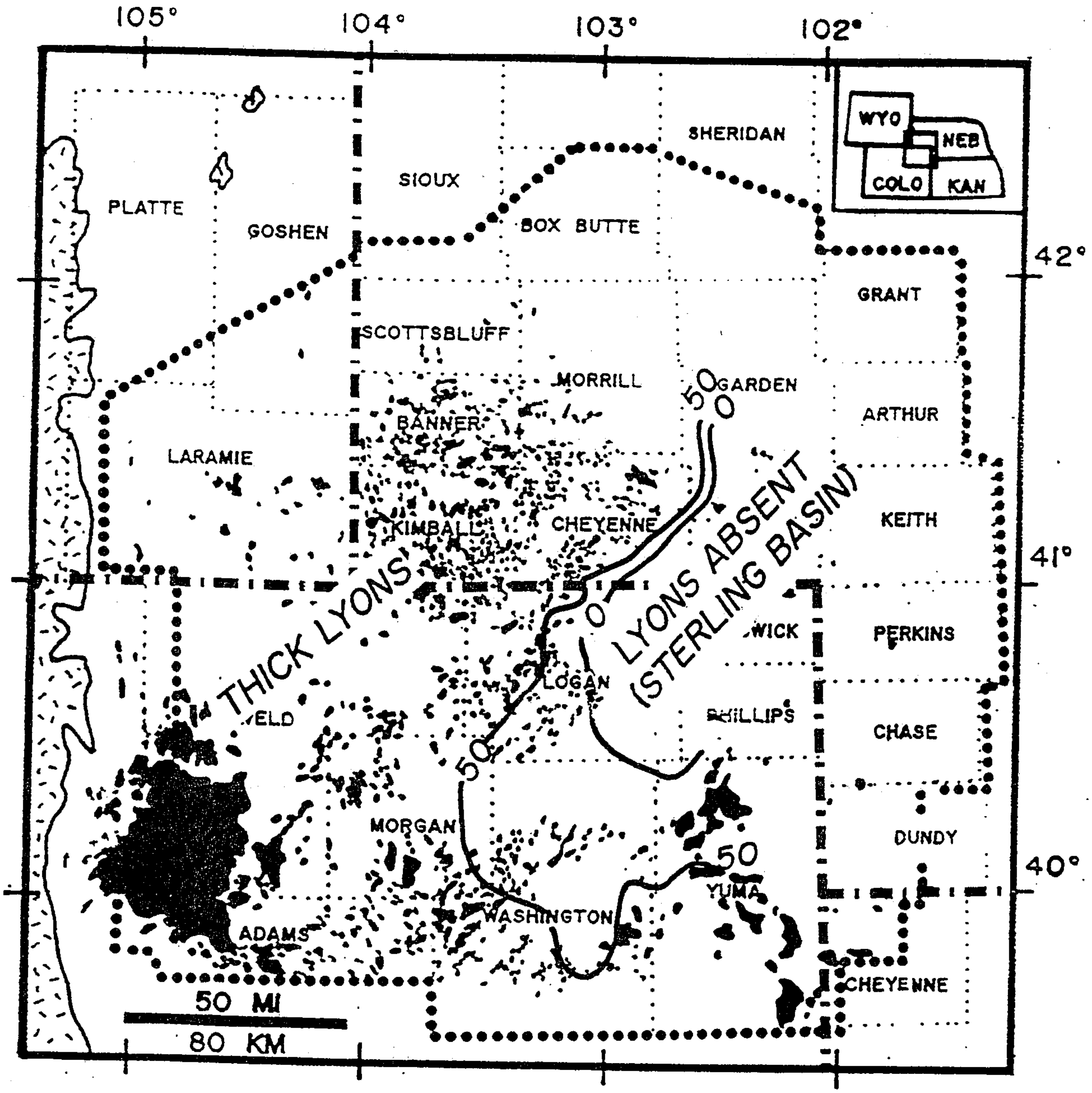


Figure 9-4. Regional relationship of eastern margin of D-J fairway to eastern limit of Lyons Sandstone. Lyons pinches out into salts in Sterling basin area.

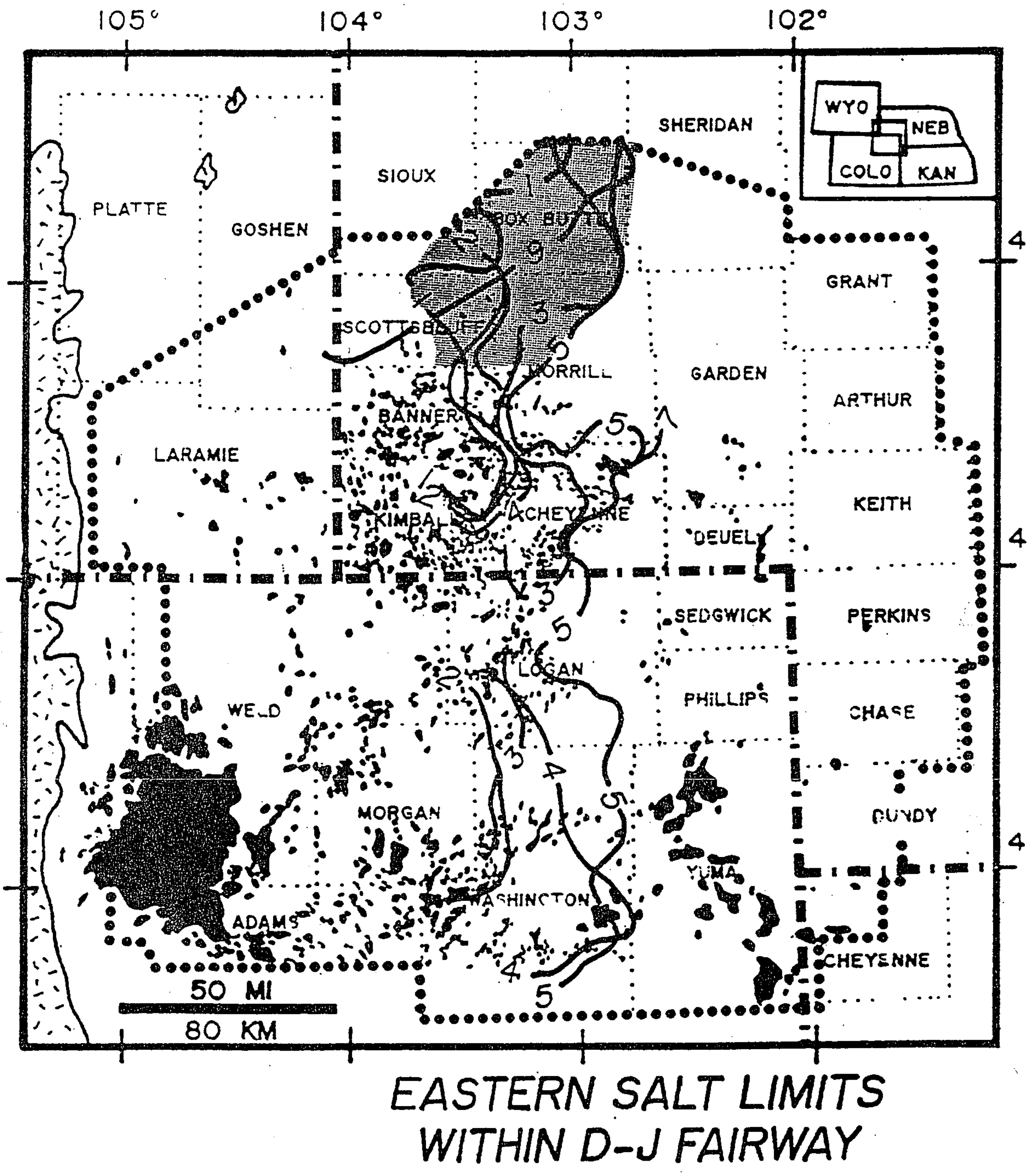


Figure 9-5. Regional relationship of eastern margin of D-J fairway to eastern limits of thick salts (salts 1, 2, 3, 4, 5, 7, and 9). Potential northern salt-related extension of fairway is shaded.

been affected by post-reservoir dissolution, as is the case in Nebraska.

Potential for additional salt-dissolution traps exists north of the present fairway limit (shaded area on Figure 9-5), in parts of Scotts Bluff, Morrill, Sioux, and Box Butte Counties. This is an underexplored part of the basin; much of this area has a well density of less than three Cretaceous tests per township. This area is near the "Scotts Bluff trend" (Silverman, 1988), a group of ten J Sandstone oil fields. Tainter's (1984) interpretations indicate the potential for migration of oil from mature source rocks into this area along D and J Sandstone conduits.

A relationship exists between the southeastern edge of salt 9 across Scotts Bluff County, Nebraska, and the northeasterly "Scotts Bluff trend". This may be due to recurrent movement along basement faults which not only influenced the configuration of the Alliance Basin during salt precipitation, but may also have localized fluids responsible for salt dissolution.

Western limits of selected thick salt zones (salts 1, 2, 3, 5, and 7) generally coincide with areas of the fairway where stratigraphic traps predominate at the D and J level (Figure 9-6). The area with no salt (shaded), surrounding the juncture of Wyoming, Nebraska, and Colorado, coincides with Jurassic (Figure 8-11) and Lower Cretaceous (Figure 8-

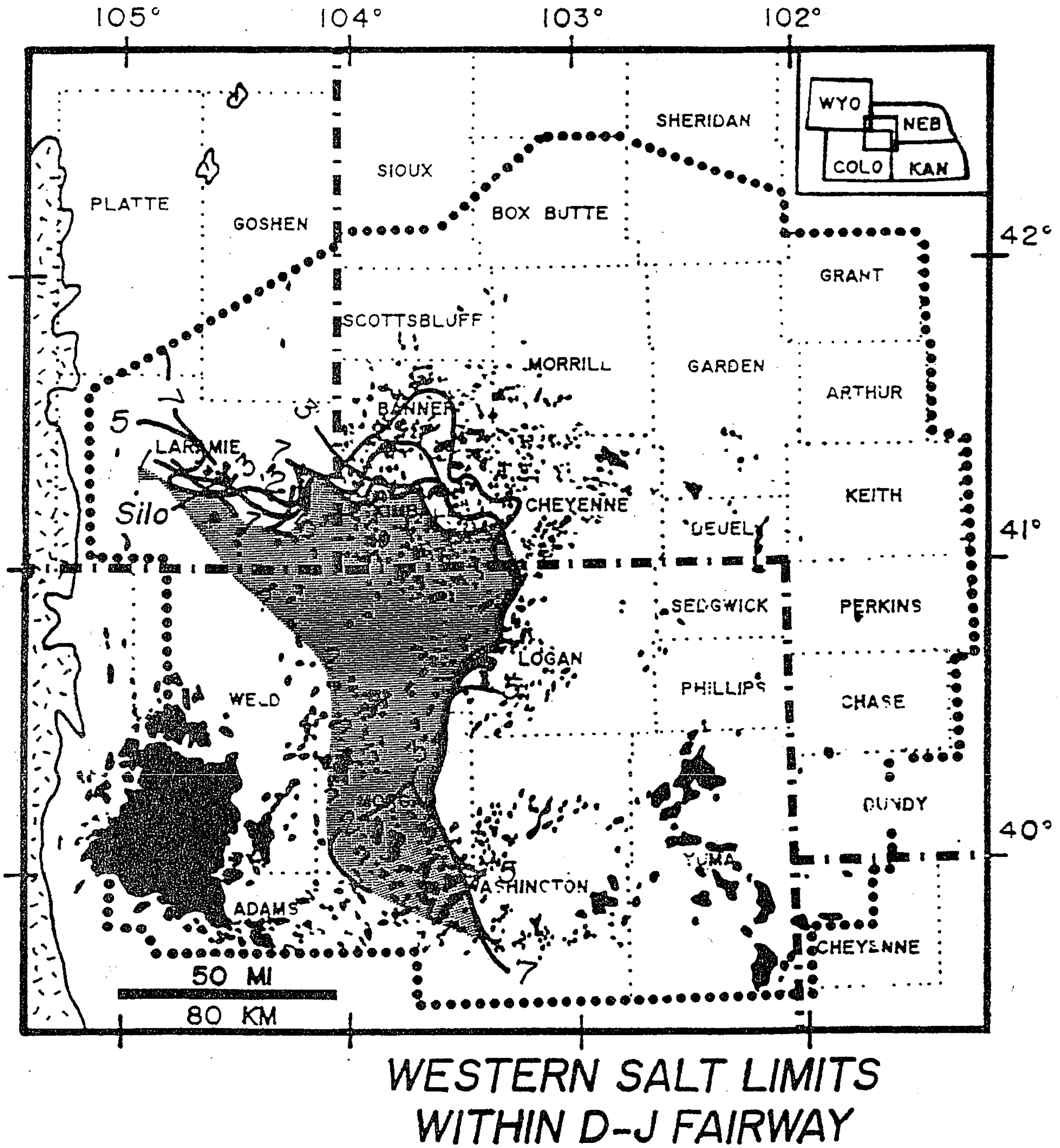


Figure 9-6. Regional relationship of western part of D-J fairway to western limits of thick salts (salts 1, 2, 3, 5, and 7). Salt was removed in shaded area prior to deposition of D and J Sandstones.

12) isopach maxima. Removal of salt in this area appears to have been nearly complete prior to deposition of D and J Sandstones. As a result, salt dissolution has had no influence on entrapment in this part of the fairway.

Western limits of thick salts (salts 1, 2, 3, 5, and 7) are also shown in the Silo field area of southwestern Wyoming (Figure 9-6). Seismic studies in this area (Lewis, 1989; Davis and Lewis, 1990; Coates and Torn, 1993; Svoboda, 1995) identified a southeast-trending salt edge at the southern limit of Silo field. Most recently, Svoboda (1995) concluded that salt dissolution is not the primary cause of fracturing in the Niobrara oil reservoir at Silo field. Svoboda used isochron evidence to demonstrate that salt removal took place during Jurassic and Early Cretaceous time, prior to Niobrara deposition. This is consistent with the results of the present study which indicate that the broad area of no salt centered around the juncture of the three states resulted from pre-reservoir dissolution.

O Sand Potential in the Fairway

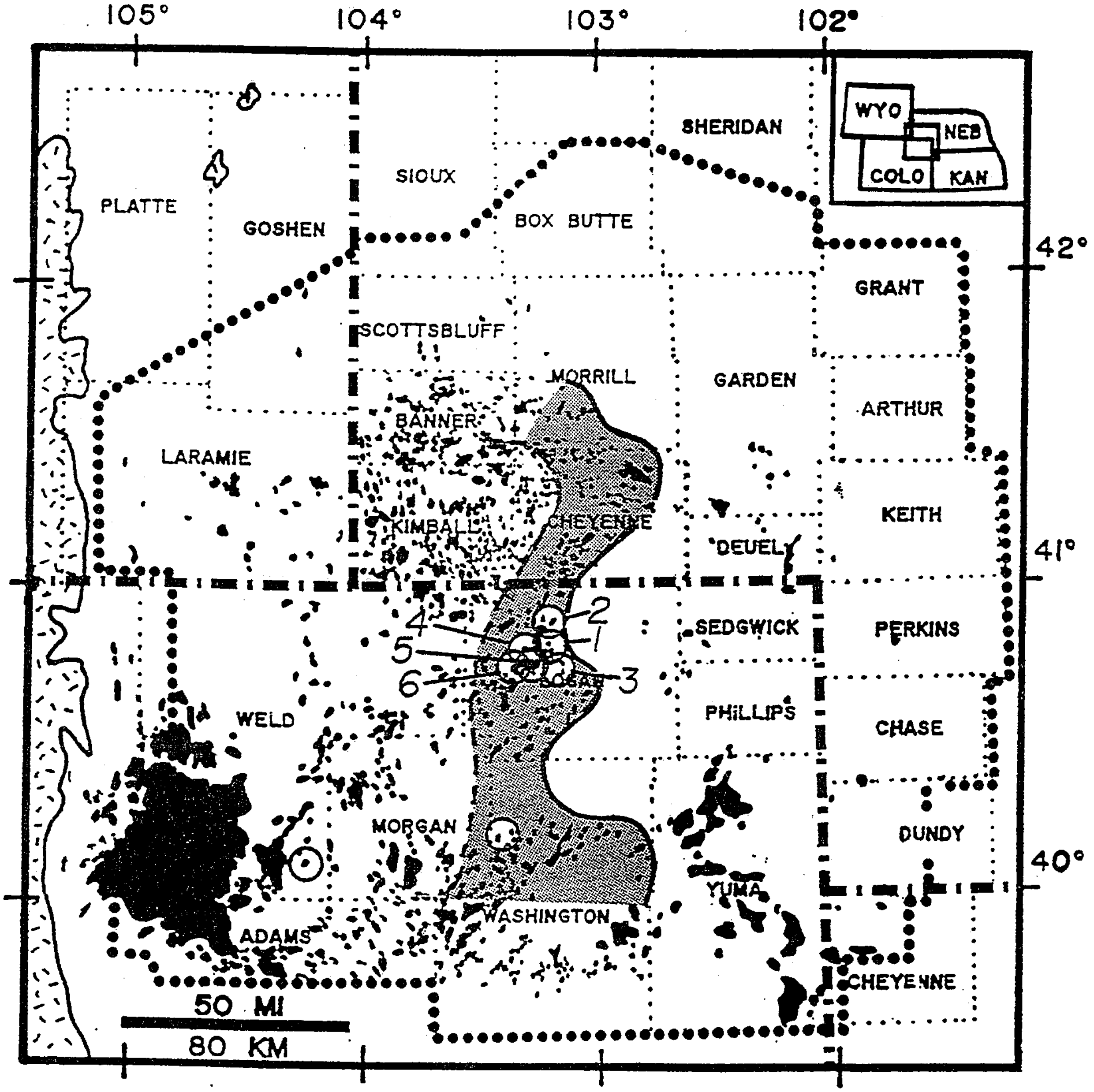
The O Sand represents an underexplored Cretaceous target in the Denver basin, with potential for production that may be related to the occurrence of Permian salt. "O Sand" is a driller's term for the second well-defined sandstone encountered in the "M" - "O" - "R" - "T" series of

Lower Cretaceous sandstone units which lie within the Dakota Group below the J Sandstone. Subsurface terminology for this interval also includes the names Cheyenne Sandstone, Fall River Formation, Lakota Formation, Plainview-Lytle Formations, and Cloverly Formation.

Relative to the D and J Sandstones, which are more prone to stratigraphic entrapment due to their variable reservoir quality, the O Sand is a more continuous blanket deposit. In Logan County, Colorado, the O is a very fine-grained sandstone that is well sorted, highly porous (18 percent), and permeable (150 md) (Goodier, 1963). Because of its blanket nature, the concensus among workers in the basin is that structural closure is required for hydrocarbons to be trapped in the O Sand.

To date, the O Sand has produced oil at only a few scattered fields in Weld, Logan, and Washington Counties, Colorado, with marginally economic results in most cases. One exception is West Padroni field, located in central Logan County, where the O Sand has yielded in excess of 3 MMBO. The O Sand has produced minor amounts of oil from several nearby fields, including Armstrong, Hamil Ranch, Shoreline, Walker, and Mount Hope East (Figure 9-7). No O Sand production has been established in Nebraska.

Part of the the reason for the lack of O Sand production can be attributed to the lack of O Sand penetrations in the basin. Most D and J Sandstone tests are



O SAND FIELDS

Figure 9-7. Location of fields which have produced oil from Lower Cretaceous O Sand. Numbered fields in Logan County include West Padroni (1), Armstrong (2), Hamil Ranch (3), Shoreline (4), Walker (5), and Mount Hope East (6). Structurally complex eastern part of D-J fairway is shaded.

drilled only to the Skull Creek Shale, which is situated above the O Sand. Subsurface information for the O Sand is generally limited to well logs of Paleozoic tests, which represent less than two percent of the wells drilled in the basin.

In contrast to the D and J Sandstones, the O Sand is not situated stratigraphically within a source rock interval. Oil produced from the O at West Padroni field is very low gravity (16° API)(Goodier, 1963). Source rock analysis (Clayton, 1989) indicates a Paleozoic source (Pennsylvanian black shales and marls) for the oil produced from the O Sand. Clayton noted that accumulation of Paleozoic oil in the O Sand is probably more limited by migration contraints than by the volume of hydrocarbons available for primary migration from the source rock.

The presence of thick, laterally continuous Permian salts (situated between Pennsylvanian source rocks and the Lower Cretacoues O Sand) would act to retard vertical migration of Paleozoic oil. Thus, for Paleozoic oil to accumulate in the O Sand where it lies above thick, continuous salts, oil would need to migrate vertically elsewhere, then migrate laterally to traps at the O Sand level.

The structurally complex eastern part of the D-J fairway (Figure 9-7) represents a potentially favorable trend for entrapment of Paleozoic oil in the O Sand. Two important elements which occur in this area, and which relate to Permian salt occurrence, include (1) partial dissolution of salt, which could have removed a major barrier to vertical migration through Leonardian and Guadalupian strata and would have created collapse-induced fractures, and (2) development of salt-cored closures at the O Sand level into which oil would accumulate.

With the exception of one field in Weld County which primarily produced gas, all other O Sand "fields" are situated within the more structurally complex eastern margin of the fairway (Figure 9-7) Although deep-well data in Logan and Washington Counties are sparse relative to the Nebraska panhandle, a few deep wells are available in areas of O Sand production to determine if salt is present below the productive structures.

Thick salt (salts 5, 6, and 7) is present in well 1608 at West Padroni field. Likewise, salts 5, 6, and 7 were encountered in wells 1599 and 1606 at Armstrong field to the north. To the west, salts 5, 6, and 7 were drilled in well 1590 at Mount Hope East field. No deep control exists at Hamil Ranch, Walker, or Shoreline fields to confirm the existence of salt. The presence of salt below West Padroni, Armstrong, and Mount Hope East fields, coupled with the existence of Cretaceous-level closures, is analogous to the structurally complex area of Cheyenne County, Nebraska, discussed in Chapter 4. Although deep data are sparse in this part of Colorado, it appears that the salt-cored anticlinal trend of Cheyenne County extends southward into Logan County and perhaps farther south in Colorado.

Thus, the eastern part of the fairway (shaded on Figure 9-7), which produces D and J oil from traps and which are more structurally influenced, may represent the most favorable area for additional traps at the O Sand level. This area extends southward from Cheyenne and Morrill Counties, Nebraska, through Logan County, to Washington County. The O Sand should be included as a secondary objective of Paleozoic tests in this area, particularly if they are located on D- and J-level closures.

Shallow D Gas Area

Eastern limits of thick salts (salts 7, 9, and 10) are plotted in the northeastern part of the basin (Figure 9-8). Salts 7, 9, and 10 mark the easternmost occurrence of salt in this part of the basin. Younger salts did not accumulate or were removed in this area by erosion and near-surface dissolution prior to Late Jurassic time.

The D Sandstone is gas-productive in this area at McCord-Richards (M-R), Oshkosh (O), Big Springs (B), Chappell (C), and Red Lion (R) fields. Structural flexure associated with the eastern limit of thick salt can be

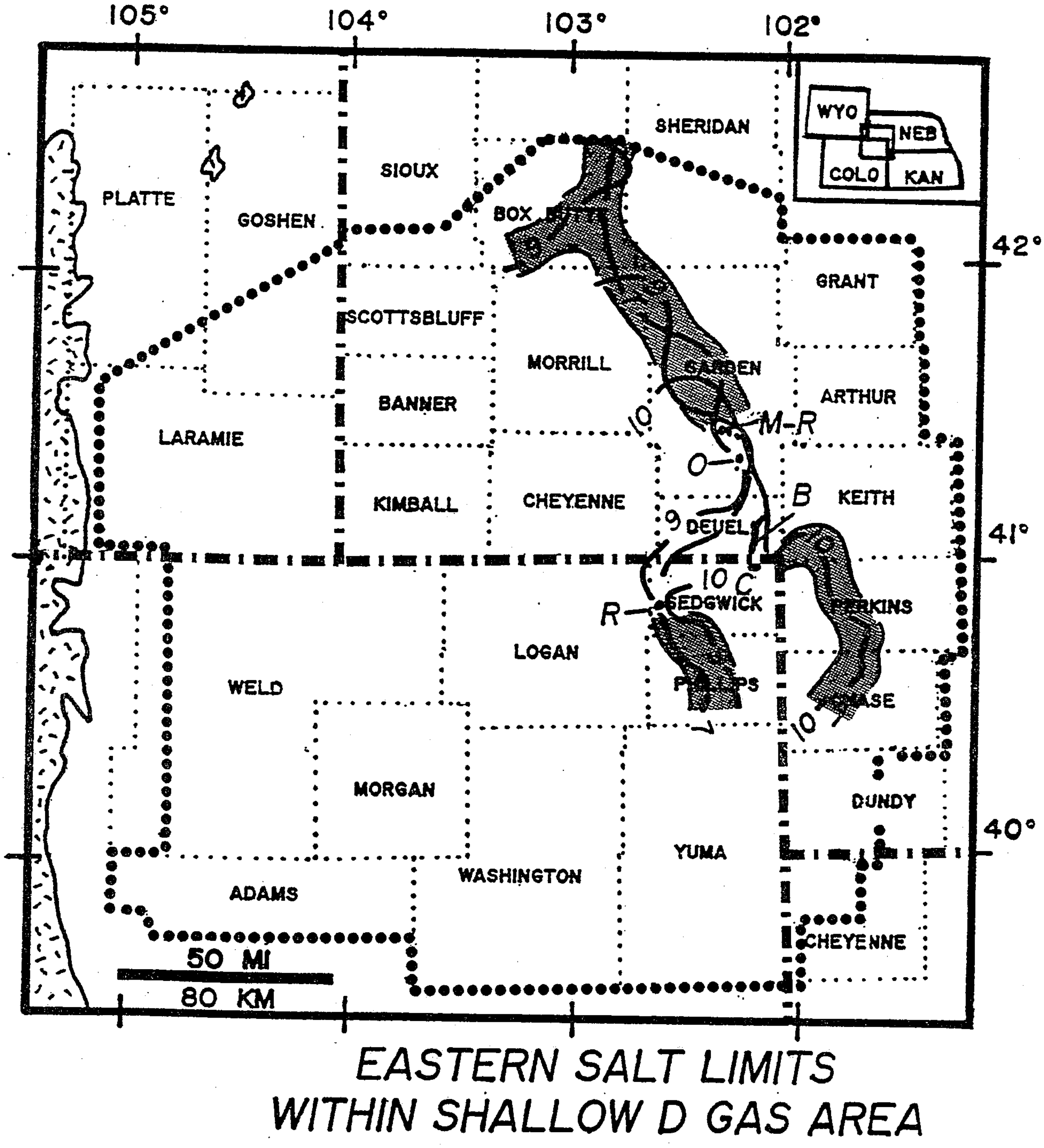


Figure 9-8. Regional relationship of D Sandstone shallow gas area to eastern limits of thick salts (salts 7, 9, and 10). Potential salt-related extensions of this trend are shaded.

mapped in the area extending from McCord-Richards to Red Lion fields (Chapter 2).

Mapped eastern limits of thick salts extend northward through Garden County into parts of Morrill and Box Butte Counties, Nebraska. Eastern limits of thick salts 7 and 9 appear to extend southward from the Red Lion field area of western Sedgwick County, through Phillips County, into Yuma County. Salt 10 is also locally absent east of Red Lion Field. The easternmost limit of salt 10 extends southeastward from Big Springs field into Keith, Perkins, and Chase Counties, Nebraska.

Assuming that post-reservoir removal of salt occurred along the eastern margins of these salts in these areas, a number of areas (shaded on Figure 9-8) may be favorable for gas entrapment in the D Sandstone. These areas include parts of Phillips County, Colorado, and parts of Keith, Perkins, and Chase Counties, Nebraska, southeast of Big Springs field. Another area of possible salt-influenced structure at the D level extends northwestward from McCord and Richards fields, through Garden County, into parts of Morrill and Box Butte Counties. Because this is one of the most underexplored parts of the basin (some townships have never been drilled), the potential exists for additional accumulations which are analogous in size and origin to Big Springs.

Shallow Niobrara Gas Area

To date, most shallow Niobrara gas production occurs in the Niobrara "fairway" of eastern Colorado in Yuma and eastern Washington Counties and in adjoining parts of Kansas (Figure 9-9). However, development of shallow Niobrara gas reserves is also beginning to focus on other areas of the basin. Intense drilling has taken place in the past few years to exploit Niobrara gas at McCourt and nearby fields in northeastern Cheyenne County, Nebraska. Recently, drilling at Big Springs field has targeted the Niobrara. Seven wells were drilled at Big Springs in 1994 and 1995. Four of these (Figure 9-10) were completed as gas wells.

Because the Niobrara is its own source rock for biogenic gas (Rice, 1984) and because the chalk reservoir of the "Beecher Island zone" is homogeneous over wide areas, the search for commercial Niobrara gas accumulations focuses on structure. The most favorable area lies roughly between the 1000-ft (300 m) and 3500-ft (1000 m) present-depth contours (Figure 9-9). Lower reservoir pressures east of the 1000-ft (300-m) depth contour result in reduced reserve potential. West of the 3500-ft (1000-m) depth contour, reserves are reduced due to loss of porosity and permeability by compaction.

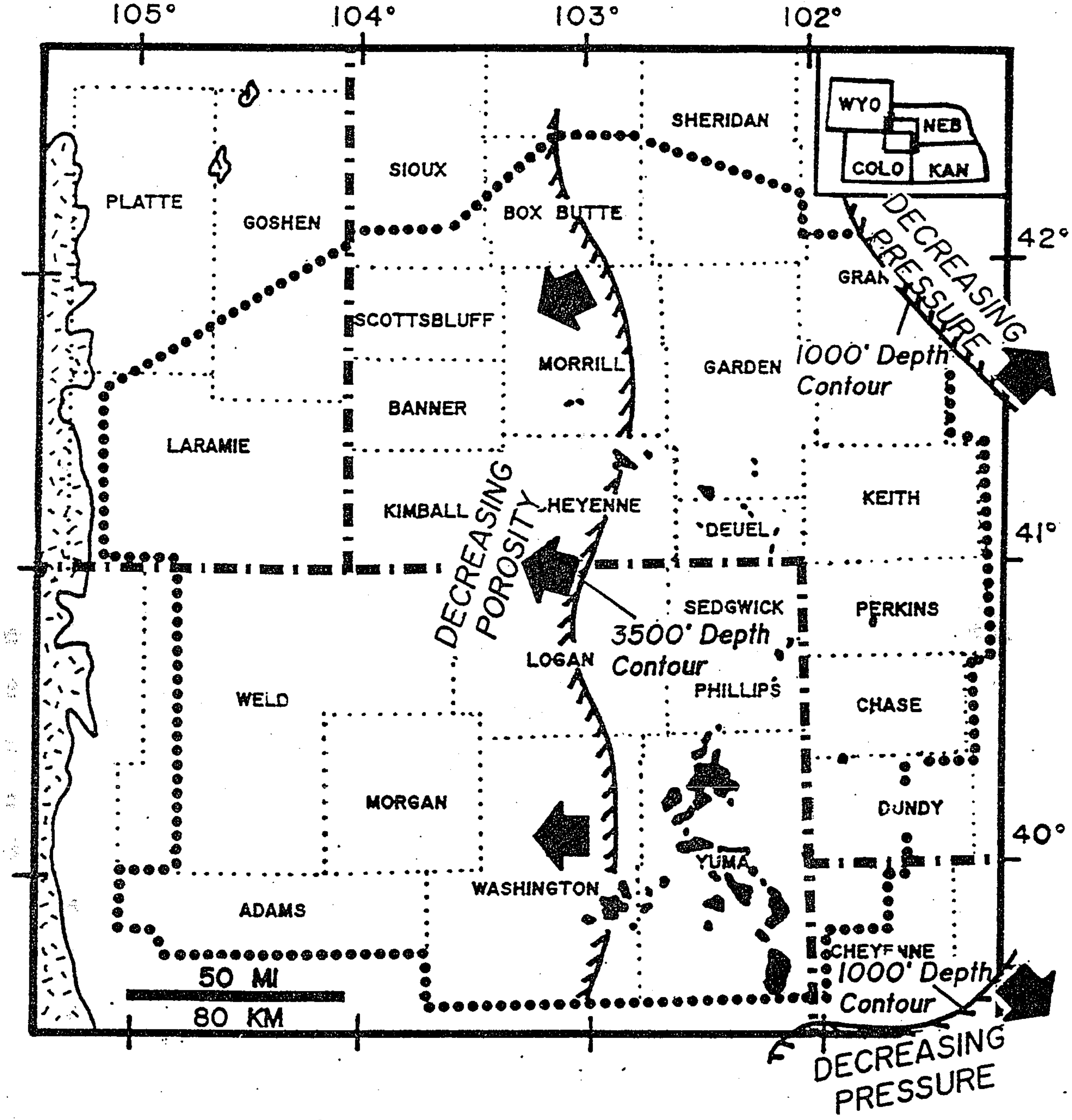


Figure 9-9. Areas of shallow Niobrara gas production in Nebraska and eastern Colorado. Depth contours are from Hann (1981).

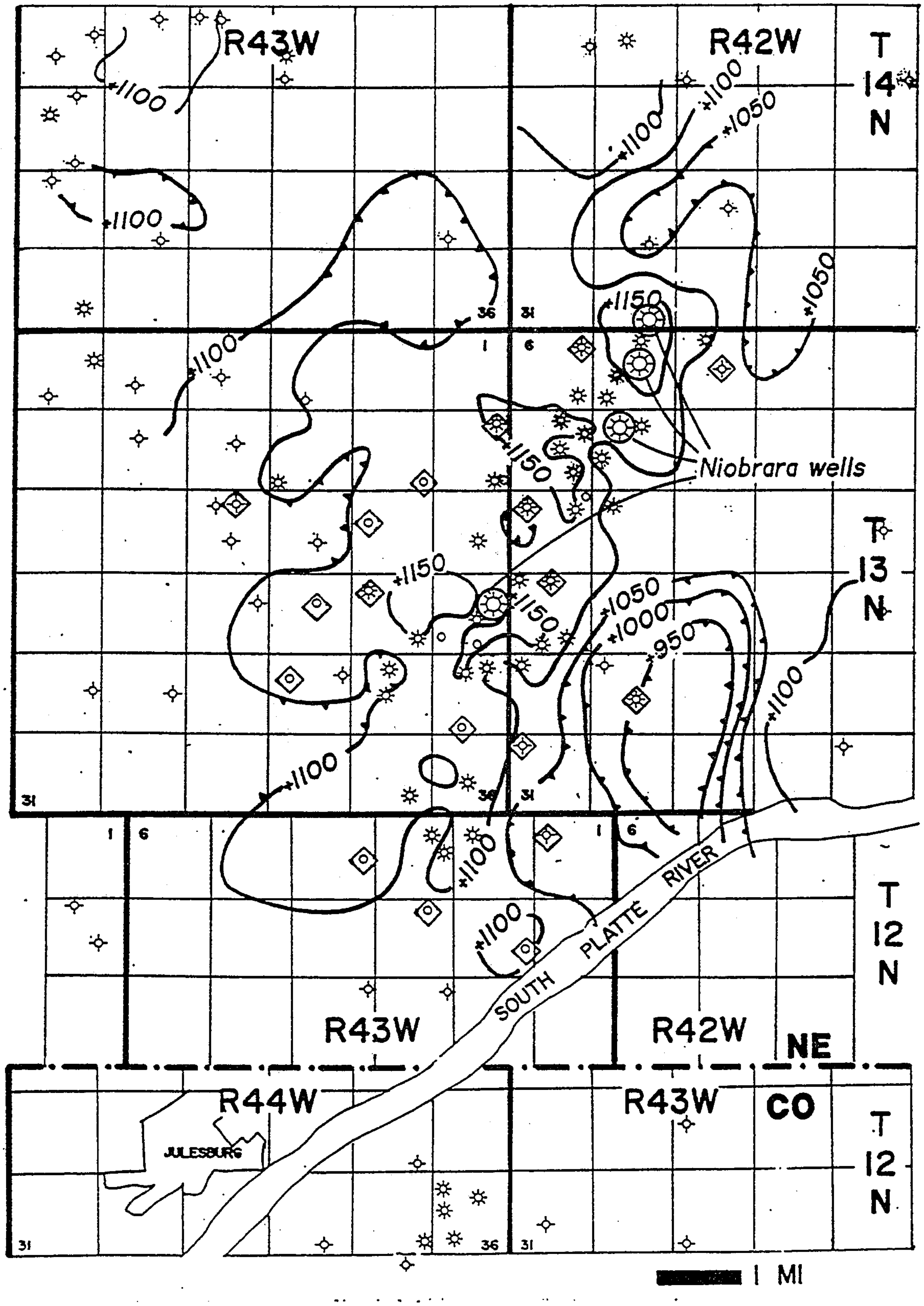


Figure 9-10. Structure drawn on top of Niobrara Formation at Big Springs field, showing recently-drilled Niobrara wells (circled). Contour interval 50 ft (15 m).

Eastern limits of thick salts (salts 1, 2, 3, 4, 5, 7, 9, and 10) are plotted on Figure 9-11, along with the location of shallow Niobrara gas fields. Production in the Yuma County area coincides with the eastern limits of salts 5, 7, 9, and 10. Minor shut-in fields are associated with the eastern limit of salt 10 to the northeast in Nebraska. (This area is discussed in the following section.) Gas entrapment at Big Springs field (B) is associated with the eastern limit of salt 10.

The producing structure at McCourt field (M) is situated within the more structurally complex eastern part of the D-J fairway (shown by diagonal lines in Figure 9-11). McCourt field lies along the eastern margins of thick salts 5 and 7. Denova field (D), at the southern limit of the D-J fairway in Colorado, lies along the eastern limits of salts 4, 5, and 10.

Potential exists for additional shallow salt-related Niobrara gas accumulations (shaded on Figure 9-11) northeast of Yuma County, in Chase and Perkins Counties, Nebraska. Potential also exists northwest of Big Springs fields along the eastern limits of salts 7, 9, and 10. Niobrara gas may also be localized on closures in the eastern part of the D-J fairway, between McCourt and DeNova fields.

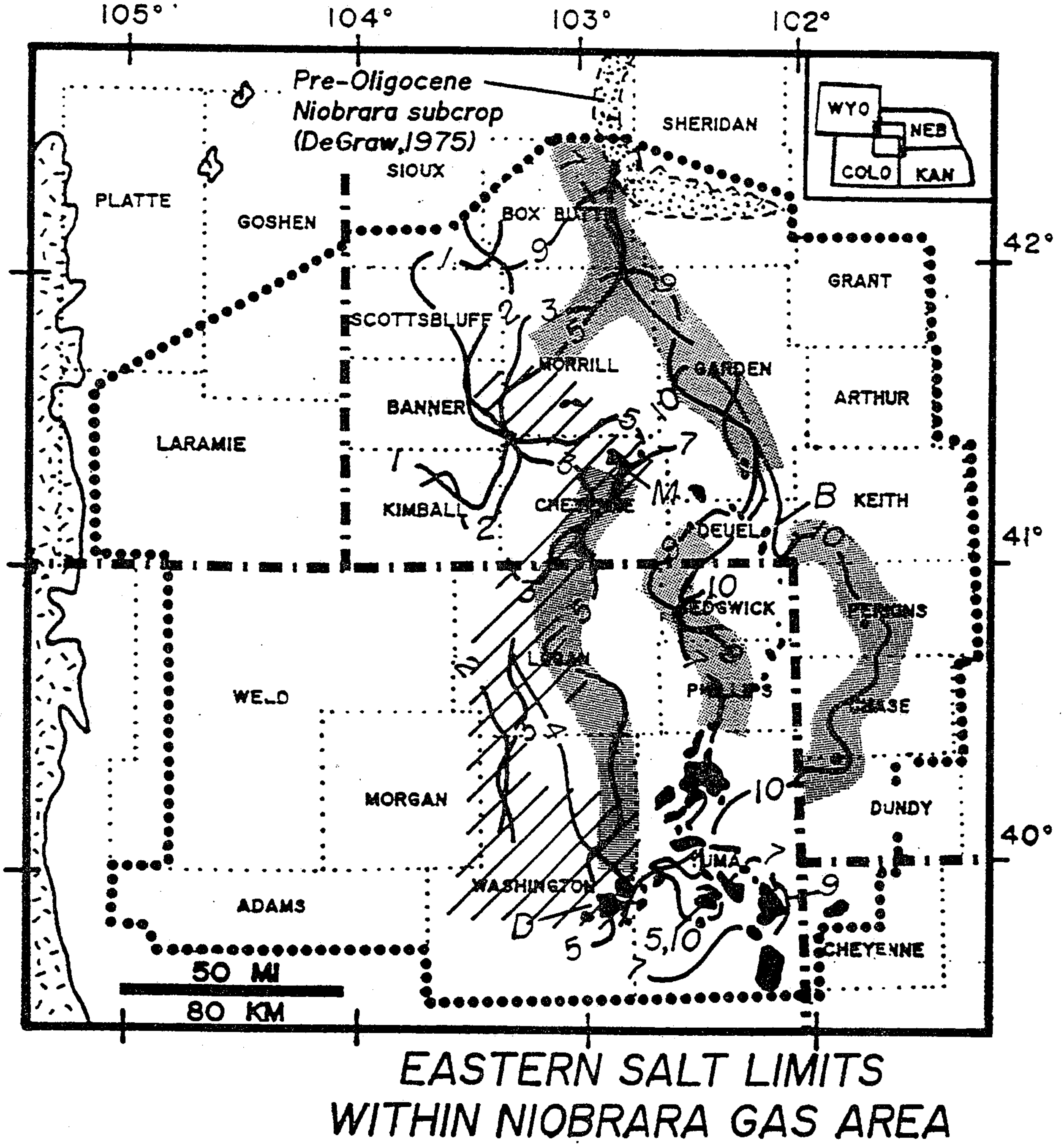


Figure 9-11. Regional relationship of shallow Niobrara gas area and D-J fairway to eastern limits of thick salts (salts 1, 2, 3, 4, 5, 7, 9, and 10). Potential salt-related extensions of Niobrara gas trends are shaded.

Application of Salt Dissolution Studies to Shallow Exploration

Sub-regional and field-scale studies in this report demonstrate that significant oil and gas production in the Denver basin is associated with regionally updip salt edges. The eastern limit of the D-J fairway in Nebraska coincides with an eastern limit of thick Guadalupian and Leonardian salt. Although deep subsurface data are relatively sparse, this relationship appears to extend southward along the eastern margin of the fairway in Colorado. D Sandstone gas production (along with recent development of Niobrara gas) at Big Springs field and adjacent areas is related to removal of Leonardian salt. The eastern Colorado shallow Niobrara gas area represents a regional salt-edge play, associated with removal of Leonardian salt.

One goal of the research presented in this report was to determine if salt dissolution trends could be predicted using shallow-subsurface control. Study in the structurally complex eastern half of the Nebraska panhandle and in the shallow Niobrara gas area in eastern Colorado confirms that complex shallow (Cretaceous reservoir-level) structure reflects the distribution and thickness of underlying salt. Another goal of this research, however, has been to determine if a dissolution model for salt occurrence can be used to predict favorable areas for *shallow* exploration.

Figure 9-12 illustrates how regional interpretations of salt distribution can be used as a predictive tool to more effectively explore for hydrocarbons at shallow depth in a hypothetical subsurface setting. In the model, deep drilling encountered thick salt in wells A and B. Salt is absent in wells C and D. If this is an area (like the Denver basin) which is prone to salt dissolution, then a salt dissolution edge or zone should exist between wells B and C. Assuming that removal of salt took place after formation of the prospective reservoir (R), a regional flexure zone should exist at the reservoir level which may localize hydrocarbon accumulation. Thus, a higher exploration priority is assigned to area B - C, relative to areas A - B and C - D.

Southwestern Nebraska Shallow Gas Play

A portion of southwestern Nebraska just east of the Colorado line (Figure 9-13) can be used as an example of how salt mapping can be used to effectively prioritize areas for land acquisition and exploration. The area, situated east and northeast of the eastern Colorado Niobrara gas play, includes parts of Keith, Perkins, Chase, and Dundy Counties.

Figure 9-14 shows deep-well control which existed in this area prior to the development of the shallow Niobrara gas play in eastern Colorado during the early 1970s. Most

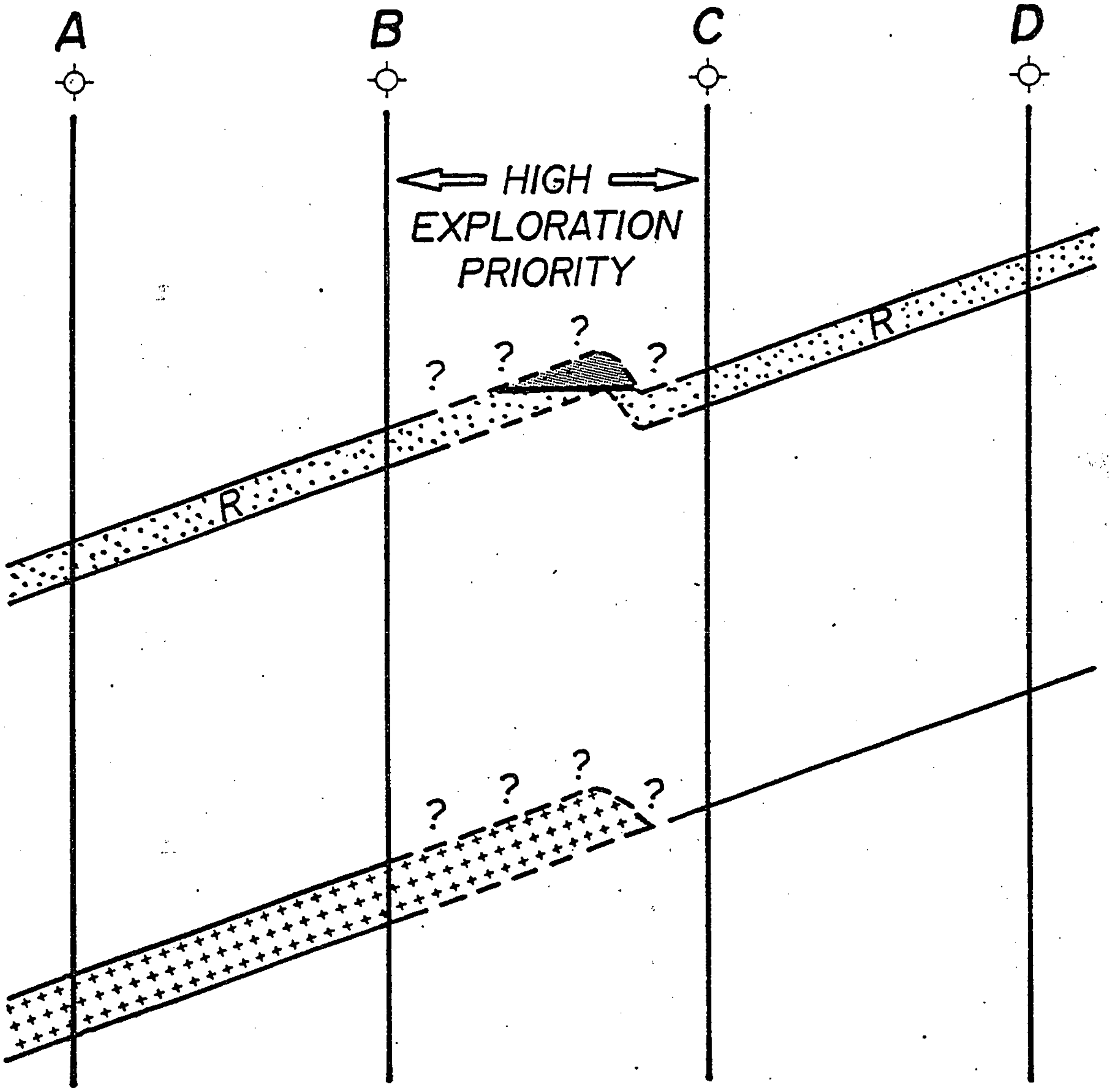


Figure 9-12. Cross section diagram illustrating how a salt dissolution model can be used to assign exploration priorities for shallow plays in a hypothetical basin.

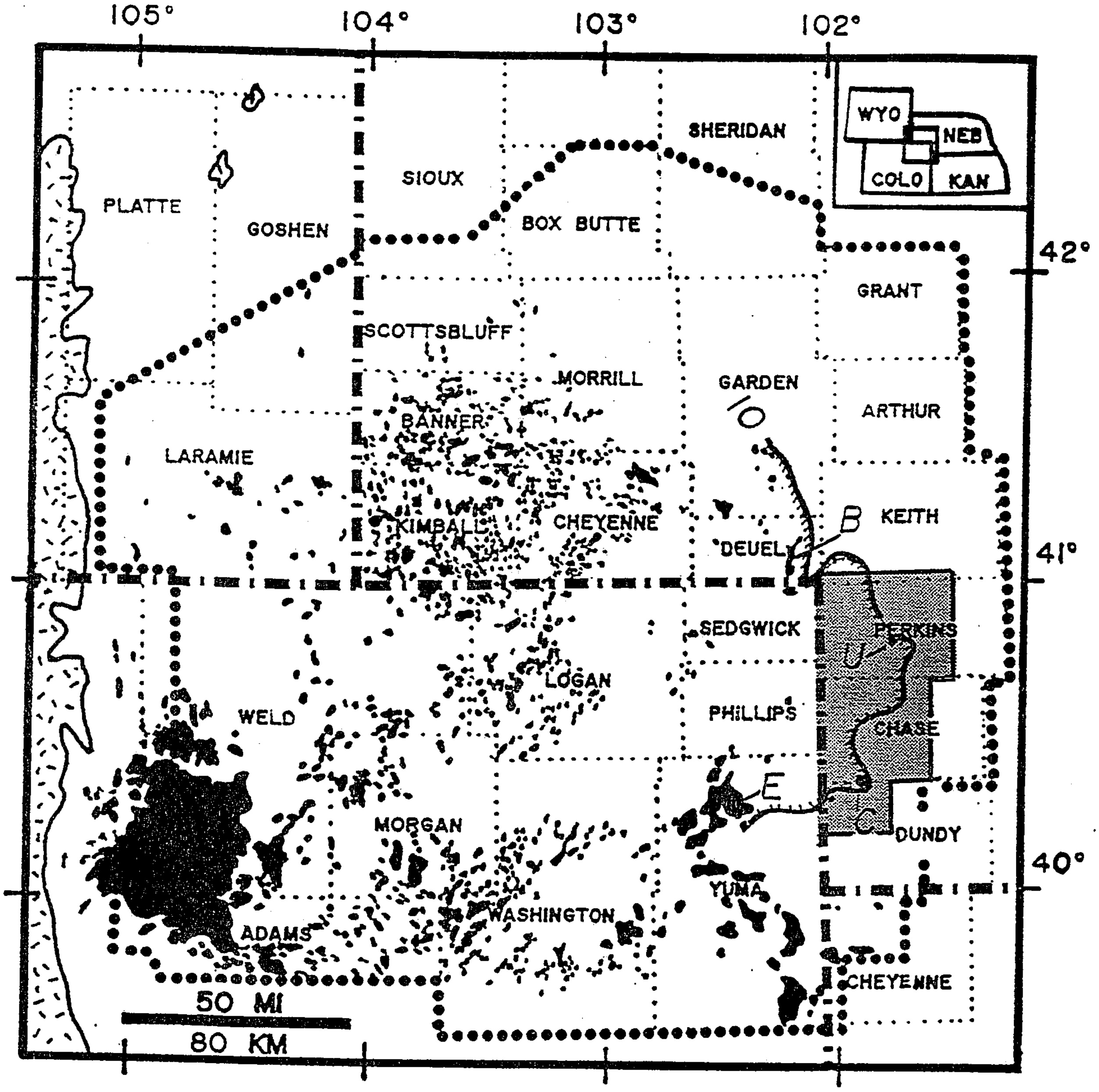


Figure 9-13. Index map of southwestern Nebraska portion of study area. Eastern (regionally updip) limit of salt 10 (10) extends northward from Eckley field (E) in eastern Colorado Niobrara play through Chundy field (C) and an unnamed field (U) in southwestern Nebraska and Big Springs field (B) in the Nebraska panhandle.

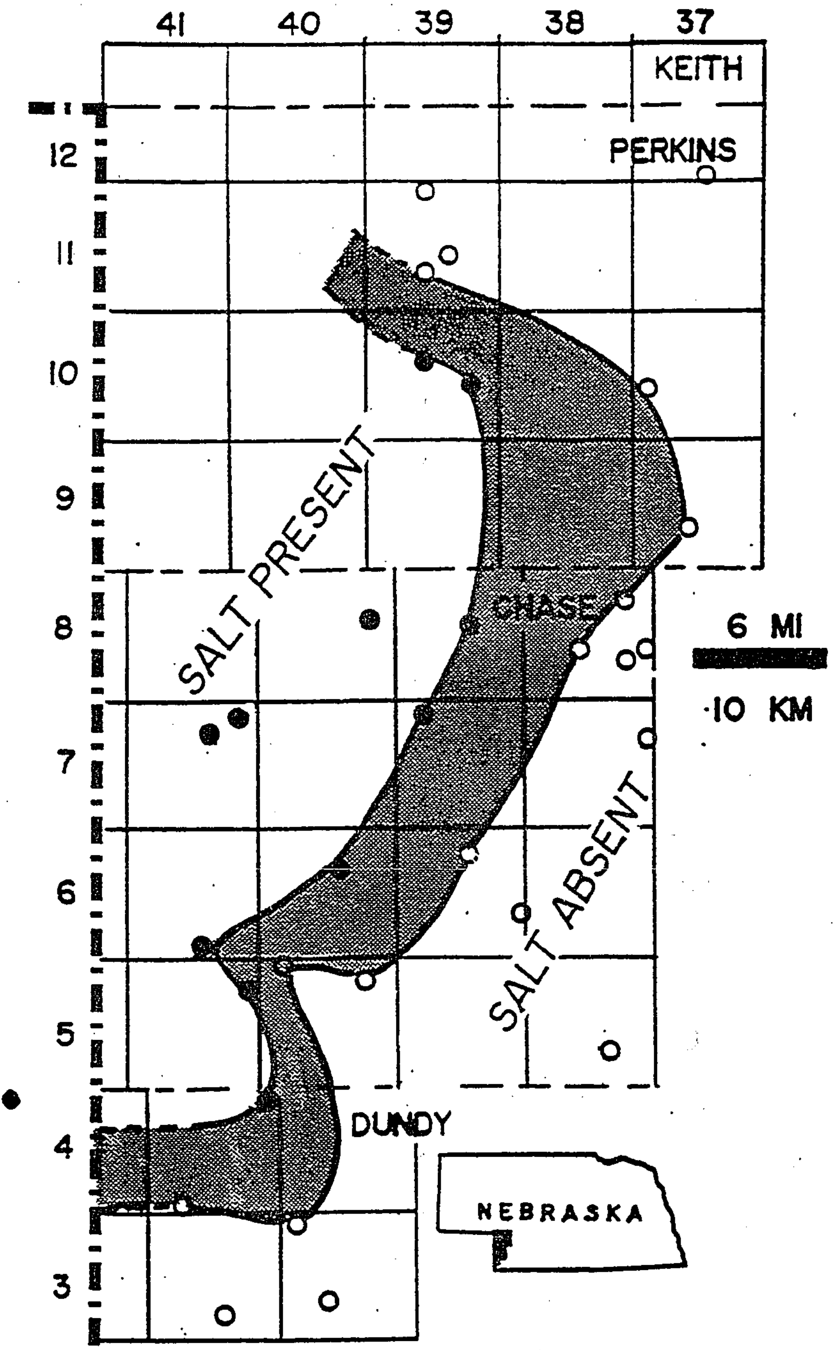


Figure 9-14. High-priority shallow exploration area (shaded) based on distribution of salt as interpreted from deep control which existed prior to 1970s (prior to development of Niobrara play in eastern Colorado).

of these wells were drilled during 1961 and 1962, in response to Paleozoic oil discoveries further east along the Cambridge arch. Wells which encountered thick salt 10 are shown as solid circles. Wells which did not encounter salt are shown as open circles.

Applying the strategy for assigning exploration priority described above, a north-south-trending area of predicted salt dissolution (equivalent to hypothetical area B - C on Figure 9-12) can be drawn (Figure 9-14). This represents a zone where the regional Cretaceous-level flexure associated with the salt 10 edge is likely to occur, and where hydrocarbons may be localized on structural highs above salt outliers or salients. West of this area, salt 10 is more likely to be laterally continuous; east of this area, salt 10 is more likely to be absent.

Mapping of salt 10 using all presently available deep control reveals that the salt 10 solution edge which is present at Eckley field in Colorado extends to the northeast into Nebraska (Figure 9-15). The salt 10 margin continues northward and northwestward toward the southeast corner of the Nebraska panhandle near Big Springs field, where Niobrara gas production has been recently established.

Four stratigraphic cross sections through the salt interval illustrate the abrupt limit of salt 10. Cross section A-A' (Figure 9-16) includes well 1654 in Keith County which encountered 70 ft (20 m) of salt 10 below the

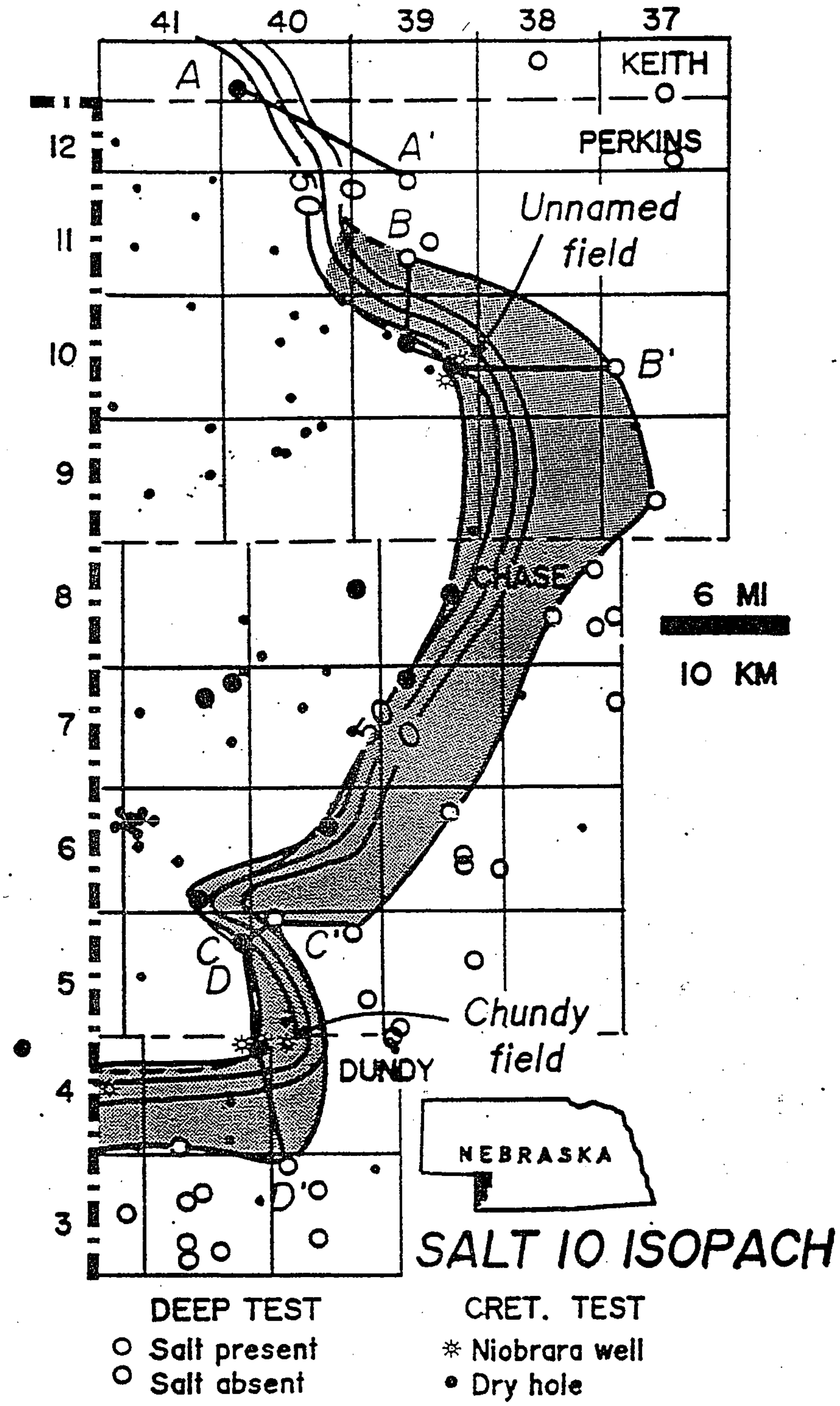


Figure 9-15. Salt 10 isopach, based on presently available deep control. Contour interval 50 ft (15 m).

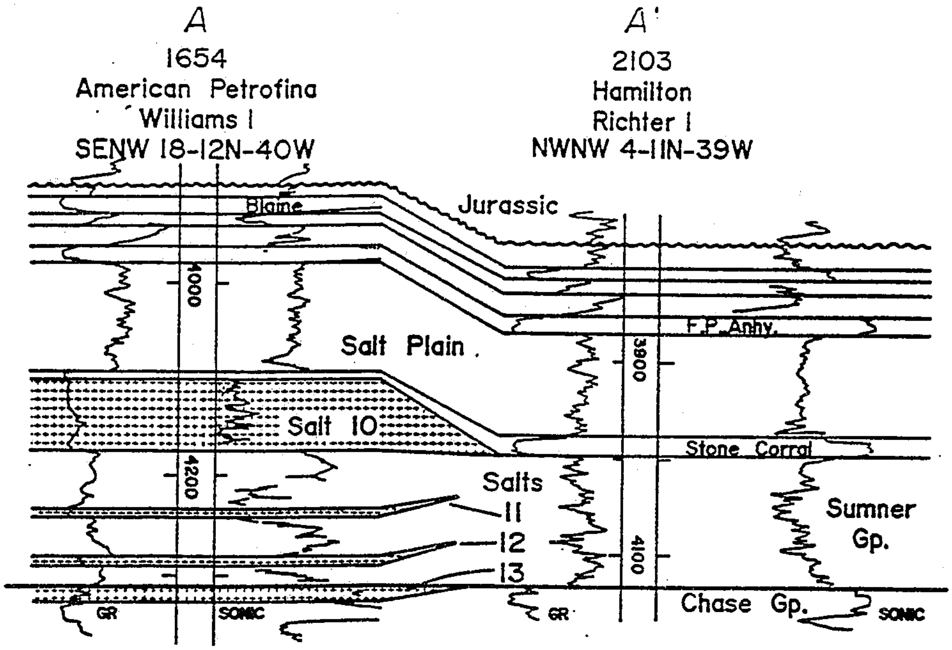


Figure 9-16. Stratigraphic cross section A-A′ across salt 10 edge in Keith and Perkins Counties, Nebraska. Well depths are in feet. Datum is top of Wolfcampian Chase Group.

Stone Corral Anhydrite, as well as thin salts 11, 12, and 13. Combined salt thickness in well 1654 is comparable to that present at Big Springs field. No salt is present in well 2103, the nearest deep test to the east.

Cross section B-B' (Figure 9-17), located in Perkins County, includes wells 2096 and 2094, drilled in 1950 and 1951, which encountered 60 ft (18 m) of salt 10. Well 2094 is situated between two shallow Niobrara gas wells drilled in 1978 and 1982. One well flowed 346 MCFGPD after fracture stimulation and was shut-in waiting on gas pipeline connection. Neither well in this unnamed field was connected and both were plugged and abandoned in the 1990s.

Cross section C-C' (Figure 9-18), located in Chase County, includes wells 775 and 779, drilled in the 1960s. Well 775 drilled 60 ft (18 m) of salt 10. Salt is absent in well 777, located less than 2 mi (3 km) to the northeast.

Cross section D-D' (Figure 9-19) includes well 775 in Chase County and wells 1279 and 1275 in Dundy County. Well 775 encountered 60 ft (18 m) of salt. No well log is available for well 1279, however sample tops reveal that the Stone Corral - Chase interval in this well is slightly thicker than the same interval in well 775. This would suggest that salt 10 is at least as thick in well 1279 as it is in well 775 (60 ft or 18 m). Well 1279, drilled in 1957, is located next to the Chundy field, a shut-in Niobrara gas

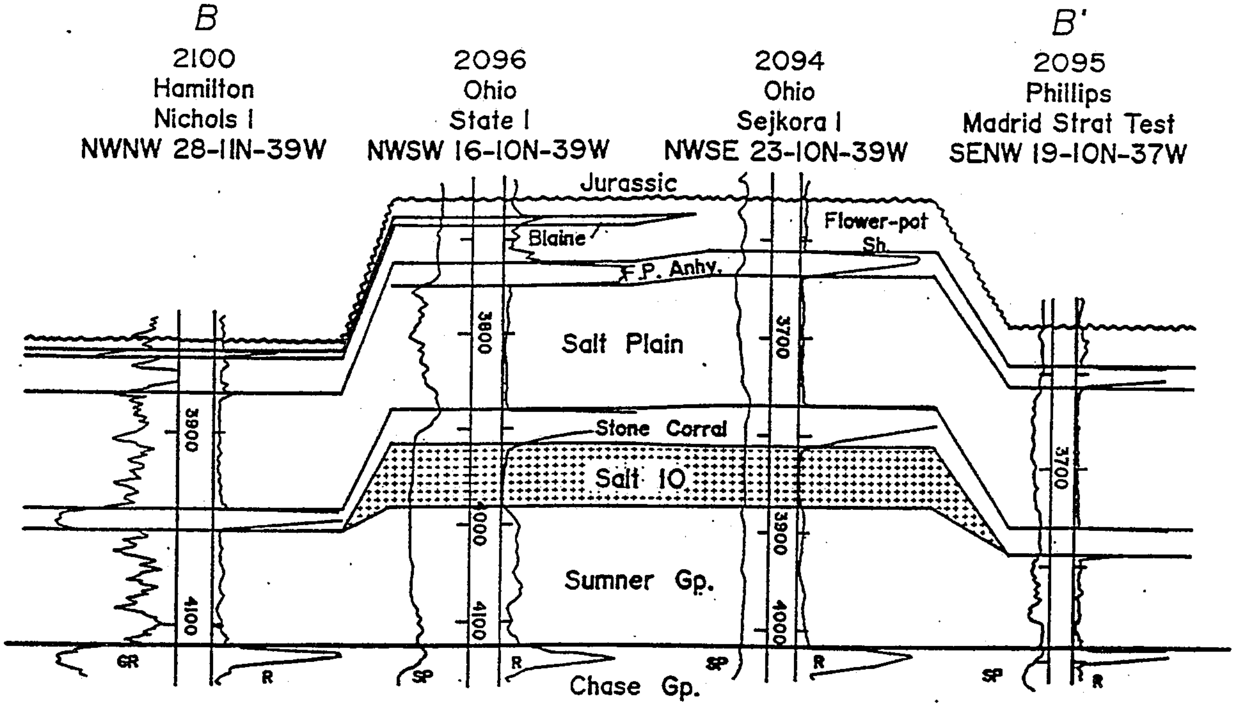


Figure 9-17. Stratigraphic cross section B-B′ through Permian salt interval below unnamed Niobrara gas field in Perkins County, Nebraska. Well depths are in feet. Datum is top of Wolfcampian Chase Group.

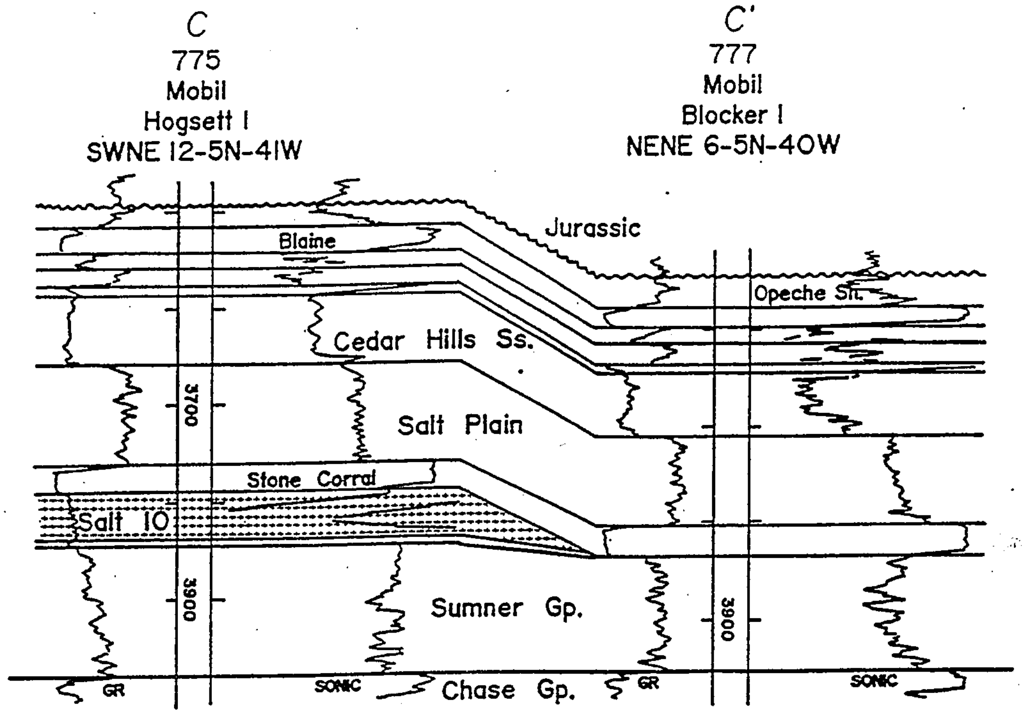


Figure 9-18. Stratigraphic cross section C-C′ through Permian salt interval in Chase County, Nebraska. Well depths are in feet. Datum is top of Wolfcampian Chase Group.

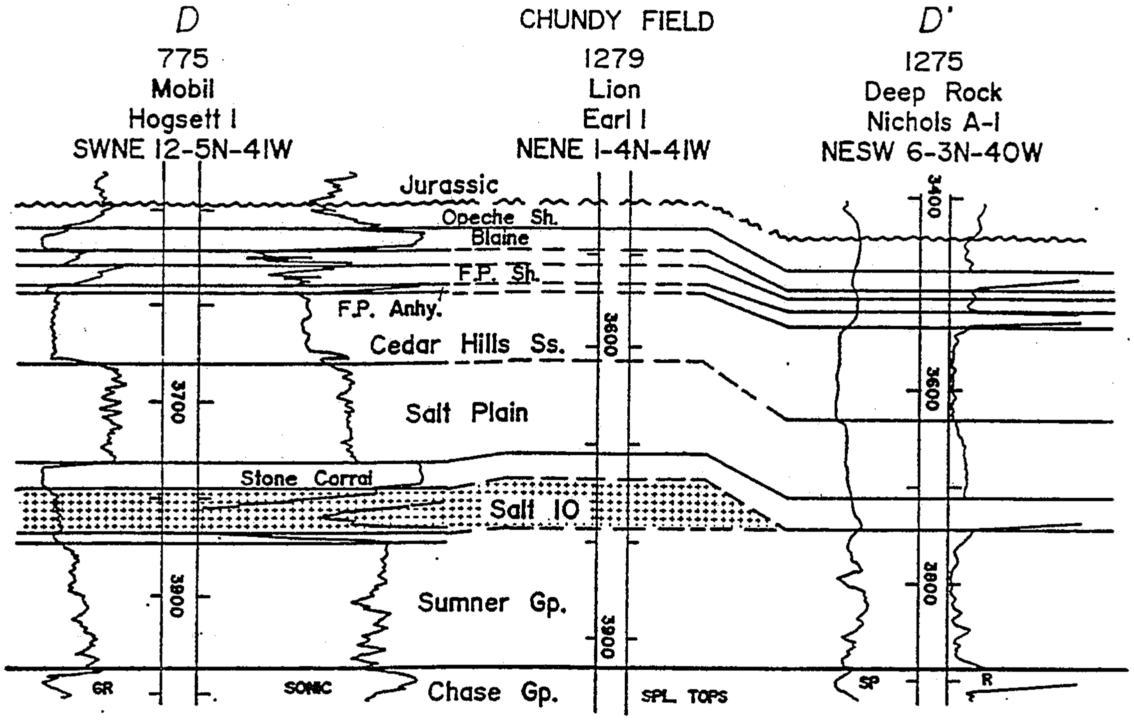


Figure 9-19. Stratigraphic cross section D-D' through Permian salt interval below Chundy Niobrara gas field, Chase and Dundy Counties, Nebraska. Well depths are in feet. Datum is top of Wolfcampian Chase Group.

field drilled in 1978 and 1979. Flow rates of as high as 840 MCFGPD were reported at Chundy field.

Figure 9-15 shows that the unnamed field in Perkins County and Chundy field both lie immediately west of the mapped salt edge. Production is associated with structural noses at the Niobrara level (Figure 9-20), which may be related to salt salients. Both fields lie within the pre-1970s exploration priority area, based on the presence or absence of salt 10, which was used to "predict" the possibility of hydrocarbon accumulation in this part of the Denver basin.

This part of the Denver basin is currently in a "chicken and egg" situation that typically exists during the early stages of development of a gas play: an adequate gas gathering infrastructure is not yet in place to encourage significant exploration in the area, yet sufficient gas reserves have not been established to warrant development of gas gathering systems. Nonetheless, this area does serve as an example of how a salt dissolution model can be effectively used to prioritize areas for leasing or seismic acquisition in underexplored parts of this or other geologically comparable basins.

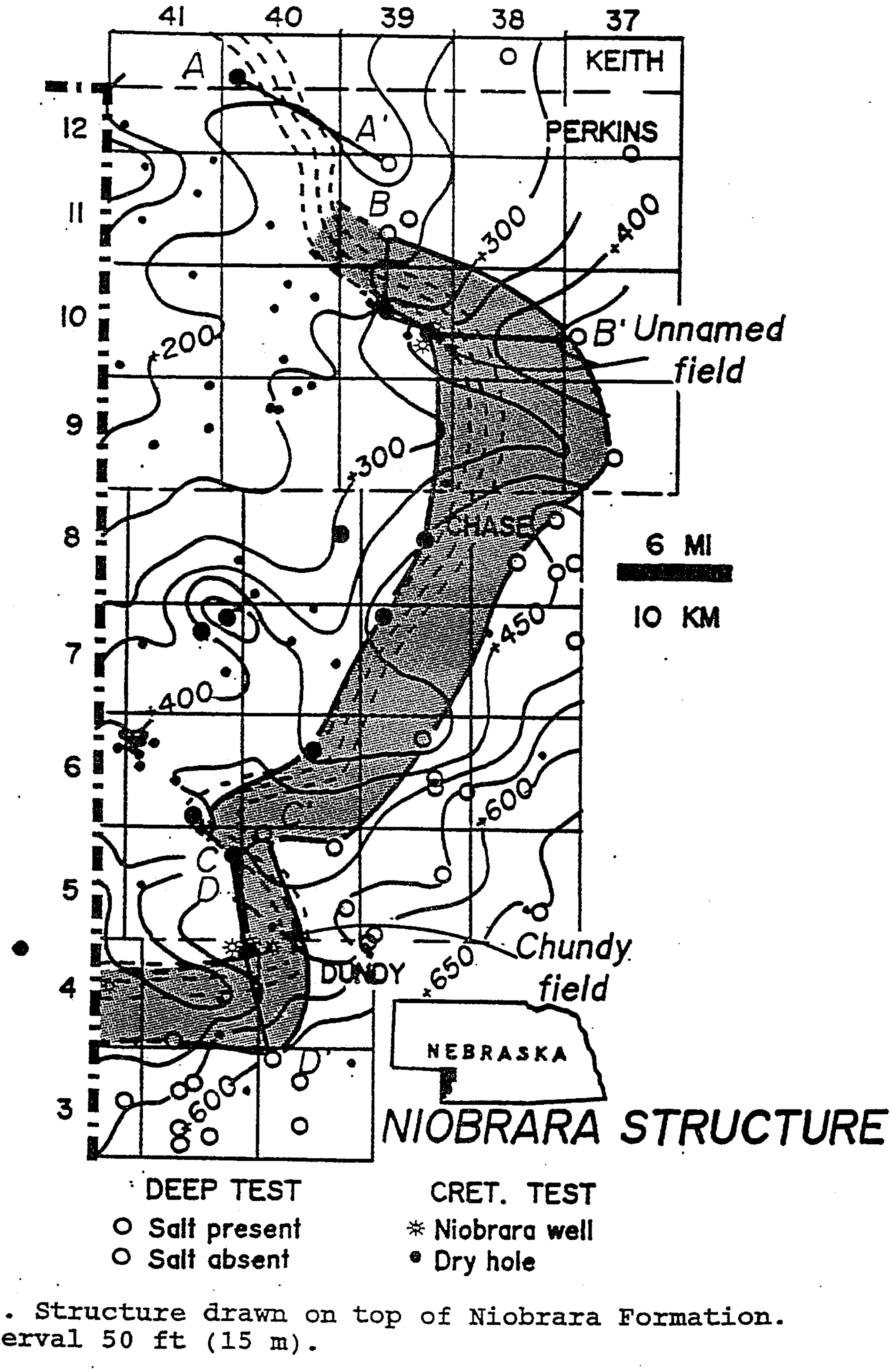


Figure 9-20. Structure drawn on top of Niobrara Formation. Contour interval 50 ft (15 m).

SALT-RELATED DRILLING PROBLEMS

Operators drilling to Paleozoic targets in certain parts of the Denver basin have encountered serious drilling and completion problems caused by the presence of Permian salt. These problems increase drilling and completion costs, can force the abandonment of wells during drilling, and can adversely affect formation evaluation.

Thick Salt

Drilling through thick salt sections requires the use of a more costly salt-based mud system to minimize washouts due to dissolution of salt by undersaturated drilling fluids. Washouts can cause bridging of the hole by collapse of undercut strata which can result in stuck drill pipe, logging tools, or casing. Hole washout also results in higher borehole volumes, raising the cost of casing cement jobs. Moreover, salt-based muds cause corrosion of drilling equipment and pose more of a problem for site cleanup.

The presence of salt can also force operators to run an intermediate string of casing to prevent caving or to protect uphole pay zones from formation damage from salt-based muds. In addition to the cost of the casing, this procedure adds to the completion cost of the well, because it requires a larger diameter hole as well as an additional open-hole logging job.

Bubble-Gum Shale

A more serious salt-related problem involves the so-called "bubble-gum shale" (Montgomery, 1987; Sahl et al., 1993). The bubble-gum is an operator's term for reddish-orange or pink hydrated shale that is encountered between salt beds in places in the Denver basin. The enclosing salts act as effective seals, which prevent fine-grained sediments from dewatering during compaction. The undercompacted, relatively overpressured shale "gums up" the drill bit, causing a dramatic decrease in drill rate. The shale also exhibits plastic flow into the wellbore, causing seizing and "twisting off" of the drill string or casing collapse if sufficiently high mud weights are not maintained. "Mudding up", however, can lead to invasion of relatively underpressured subsalt targets, causing lost circulation (Sahl et al., 1993), formation damage (Montgomery, 1987), and log evaluation problems (F. Pritchett, personal communication).

The potential for encountering the "dreaded" (Sahl et al., 1993) bubble-gum has changed the manner in which drilling companies contract their services. Some contractors bid wells on a daywork basis (rather than a turnkey or fixed-price contract basis) in bubble-gum-prone areas. In some cases a clause in the contract allows the contractor to switch from turnkey to daywork if bubble-gum is encountered (R. Gilmore, personal communication). The presence of shale can result in drill rates as low as 10 to 15 ft (3 to 4 m) in a 24-hour period.

Problem Areas

Bubble-gum shale has received the most attention in the Nebraska panhandle, due to a flurry of drilling activity to subsalt targets in this area during the 1980s and 1990s. (In Kimball County, Nebraska, alone, 90 of 97 Paleozoic tests were drilled in the past 10 years.) Bubble-gum shale is a significant drilling problem in southern Sioux County, Nebraska (Montgomery, 1987), the site of intense deep exploratory activity over the past ten years. Sioux County is located at the northern limit of the study area (S, Figure 9-21). Another problem area in the southern Nebraska panhandle is centered around the juncture of Banner, Morrill, Kimball, and Cheyenne Counties (J, Figure 9-21). Several wells in this area have met with disaster, including a number which were junked and abandoned.

In contrast, salt is largely absent in southern Kimball County, in the densely drilled Kleinholz - Terrestrial field area (K), which produces oil from Wolfcampian reservoirs.

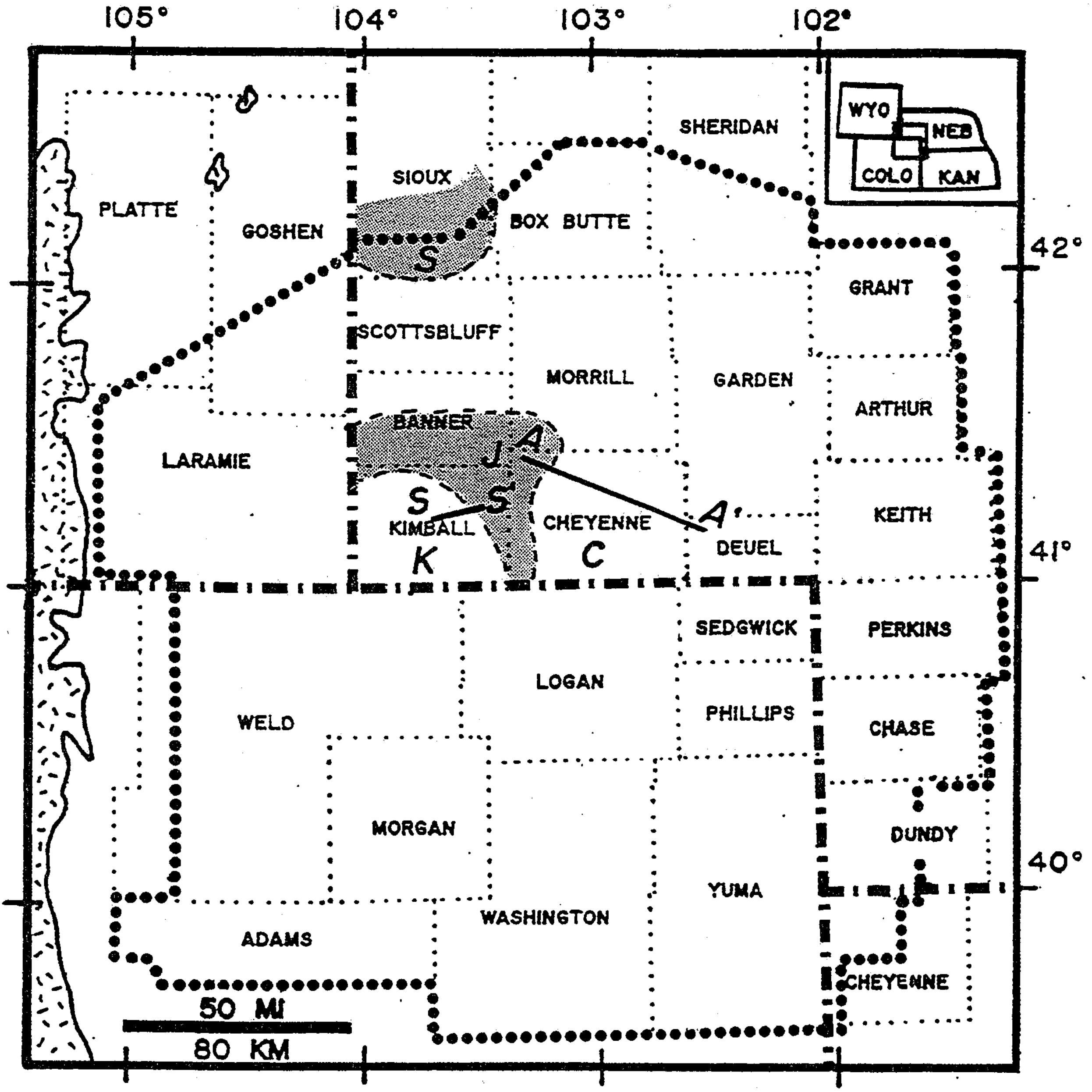


Figure 9-21. Primary areas of reported drilling problems related to bubble-gum shale in the Nebraska panhandle: S - southern Sioux County; J - juncture of Banner, Morrill, Kimball, and Cheyenne Counties. The area of Scotts Bluff and northern Banner Counties is sparsely drilled.

Here, the shale is dewatered and indurated (Sahl et al., 1993). Shale-related drilling problems are also less prevalent under much of central Cheyenne County (C), despite the presence of thick salts (R. Gilmore, personal communication).

Potential Problem Zones

Although one particular shale bed has not been identified as *the* bubble-gum, problems appear to be primarily related to shale units associated with Guadalupian salts. Stratigraphic positions of shale intervals which are encased by salt in places within the study area are shown on Figure 9-22. Two Goose Egg Formation (Guadalupian) shale intervals likely pose the greatest potential for problems:

1. the Glendo Shale, where it lies between salts 1 and 2; and
2. the Opeche Shale, where it lies between salts 3 and 4. The potential for problems also exists where the Opeche lies between salt 3 and salt 5, situated below the upper Blaine Anhydrite.

Two Nippewalla Group (Leonardian) shale intervals which lie between thick salt beds, and may present problems locally include:

3. the Flower-pot Shale, where it lies between salts 7 and 9; and
4. the Salt Plain Formation, where it lies between salts 9 and 10.

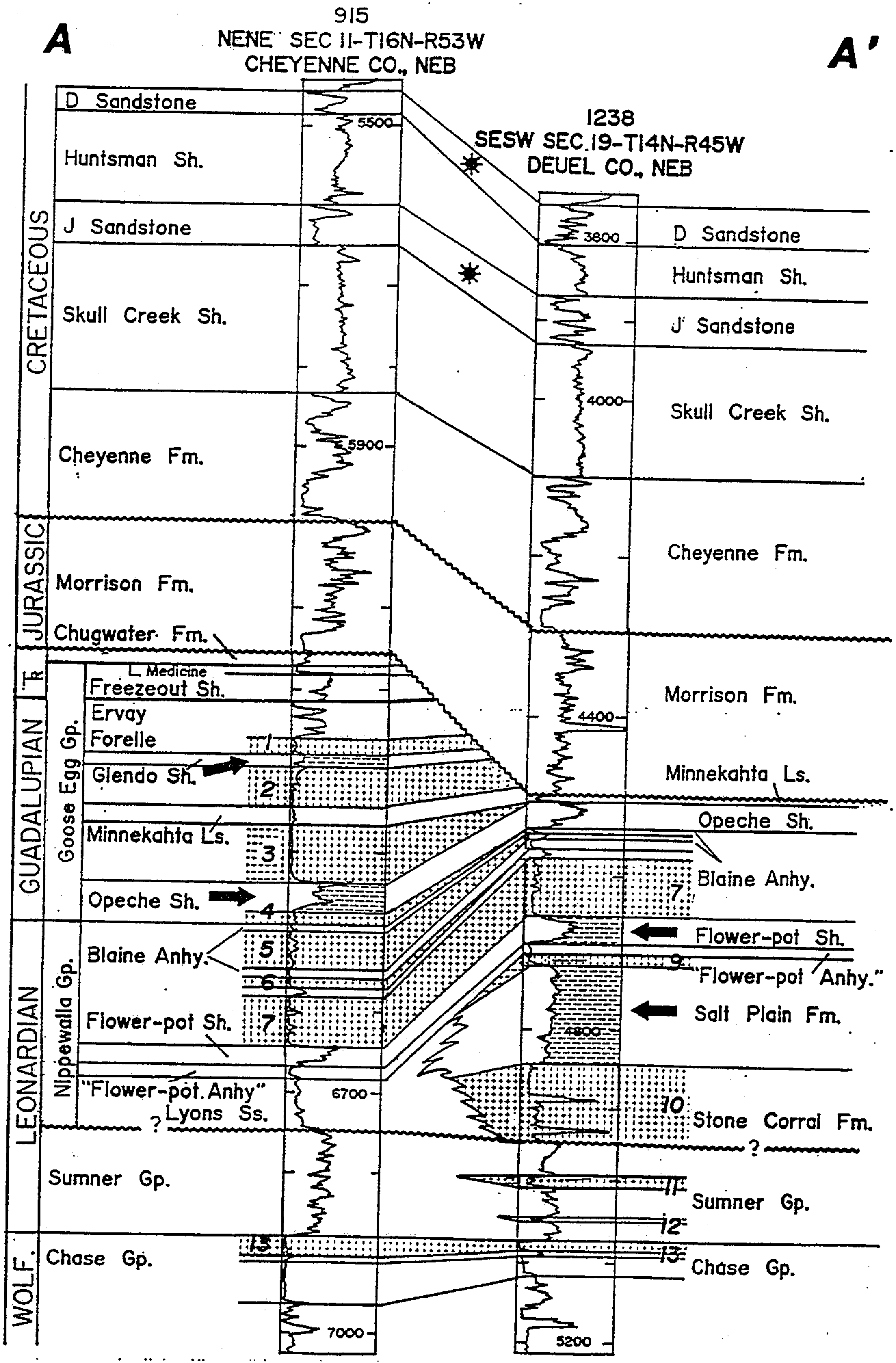


Figure 9-22. Stratigraphic positions of shale intervals which are locally encased by salt. Well depths are in feet.

Figure 9-23, a two-well stratigraphic cross section through part of Kimball County, includes well 1679, drilled in the Kleinholz field area, and well 1675, drilled in an area which is more prone to bubble-gum shale problems. Well 1679 encountered no salt. Thickness of the interval from the top of the Little Medicine Tongue to the top of the Flower-pot Anhydrite in well 1279 is 230 ft (70 m). (Some operators use the names "Day Creek" and "Stone Corral", respectively, for these markers in this area.) The Little Medicine - Flower-pot Anhydrite interval is 410 ft (125 m) thick in well 1675, which encountered salts 1, 2, 3, 4, and 5. Problems with bubble-gum shale in the vicinity of well 1675 appear to primarily involve the Glendo Shale (between salts 1 and 2) and the Opeche Shale (between salt 3 and salt 4 and/or salt 5).

Potential Problem Areas Across the Basin

Figure 9-24 shows areas within the basin in which salt 1 overlies salt 2. These represent areas where the potential is more likely to exist for encountering drilling problems at the level of the Glendo Shale. Based on available subsurface control, salts 1 and 2 are both present in southwestern Nebraska, including southern Sioux County, southern Scott Bluff County, most of Banner County, northern Kimball County, and northeastern Cheyenne County, and in

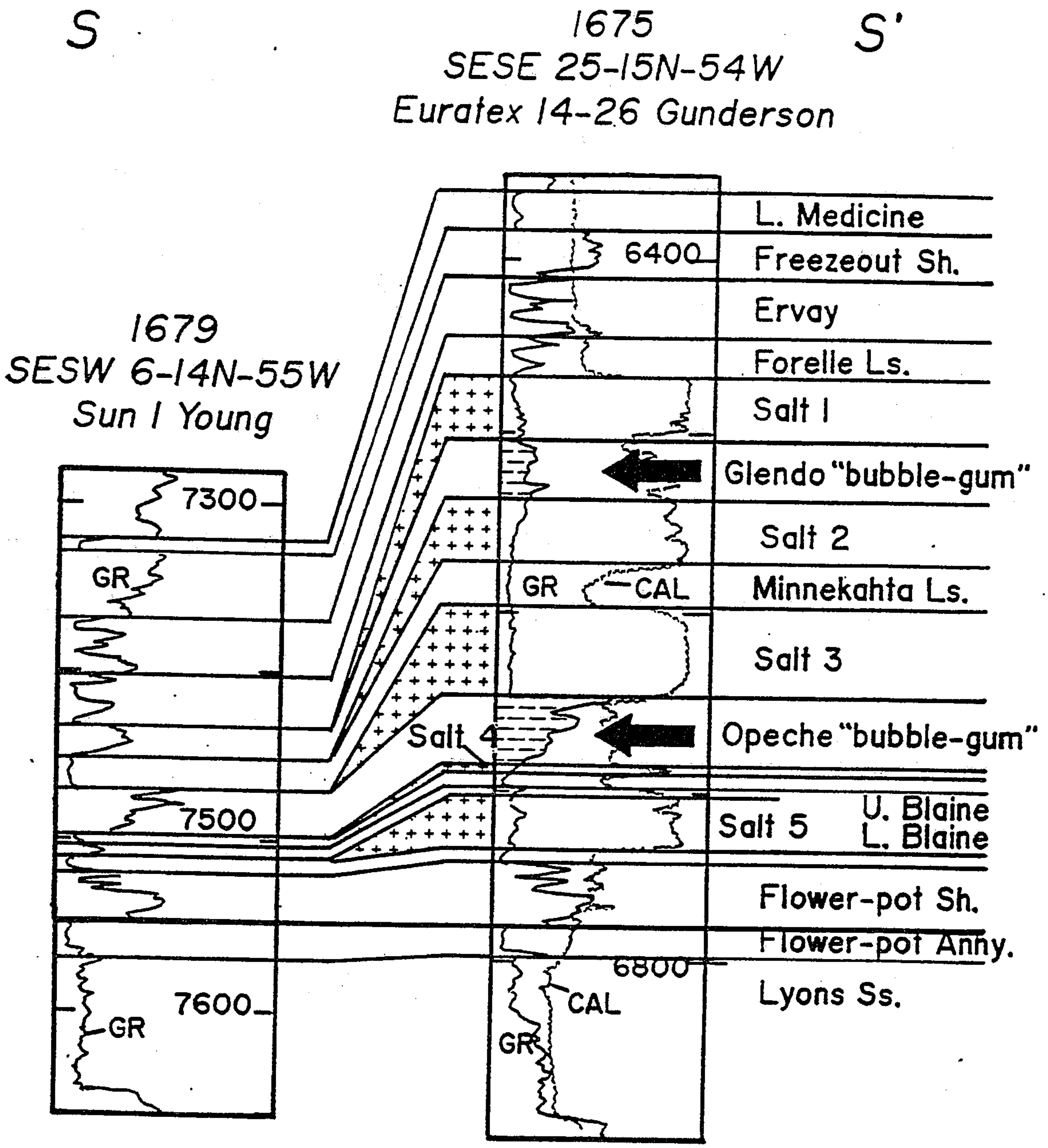


Figure 9-23. Stratigraphic cross section in Kimball County, Nebraska. Salt, which prevents dewatering of Glendo and Opeche Shales in bubble-gum shale-prone areas (well 1675), is largely absent in the Kleinholz field area (well 1679). Well depths are in feet.

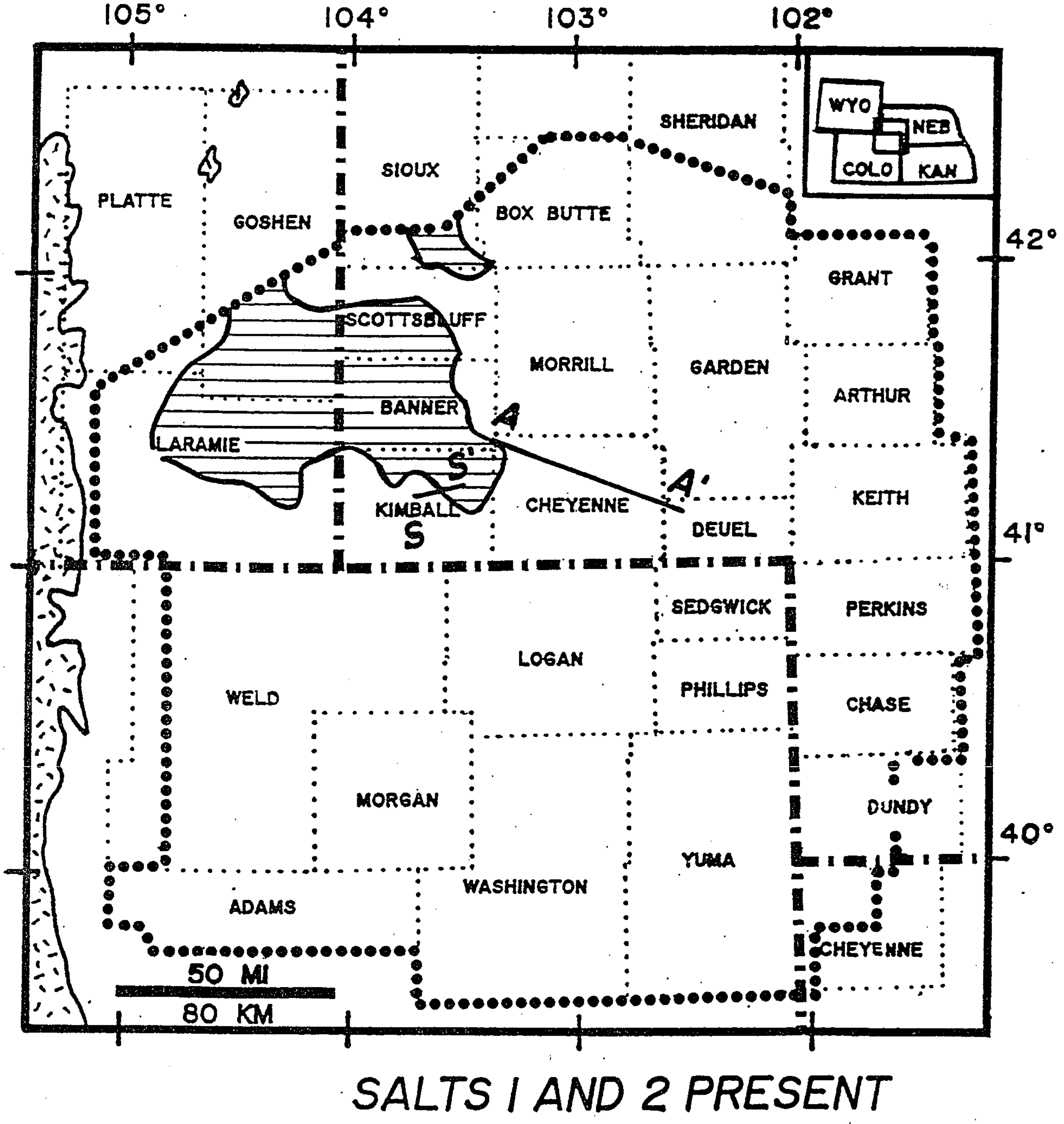


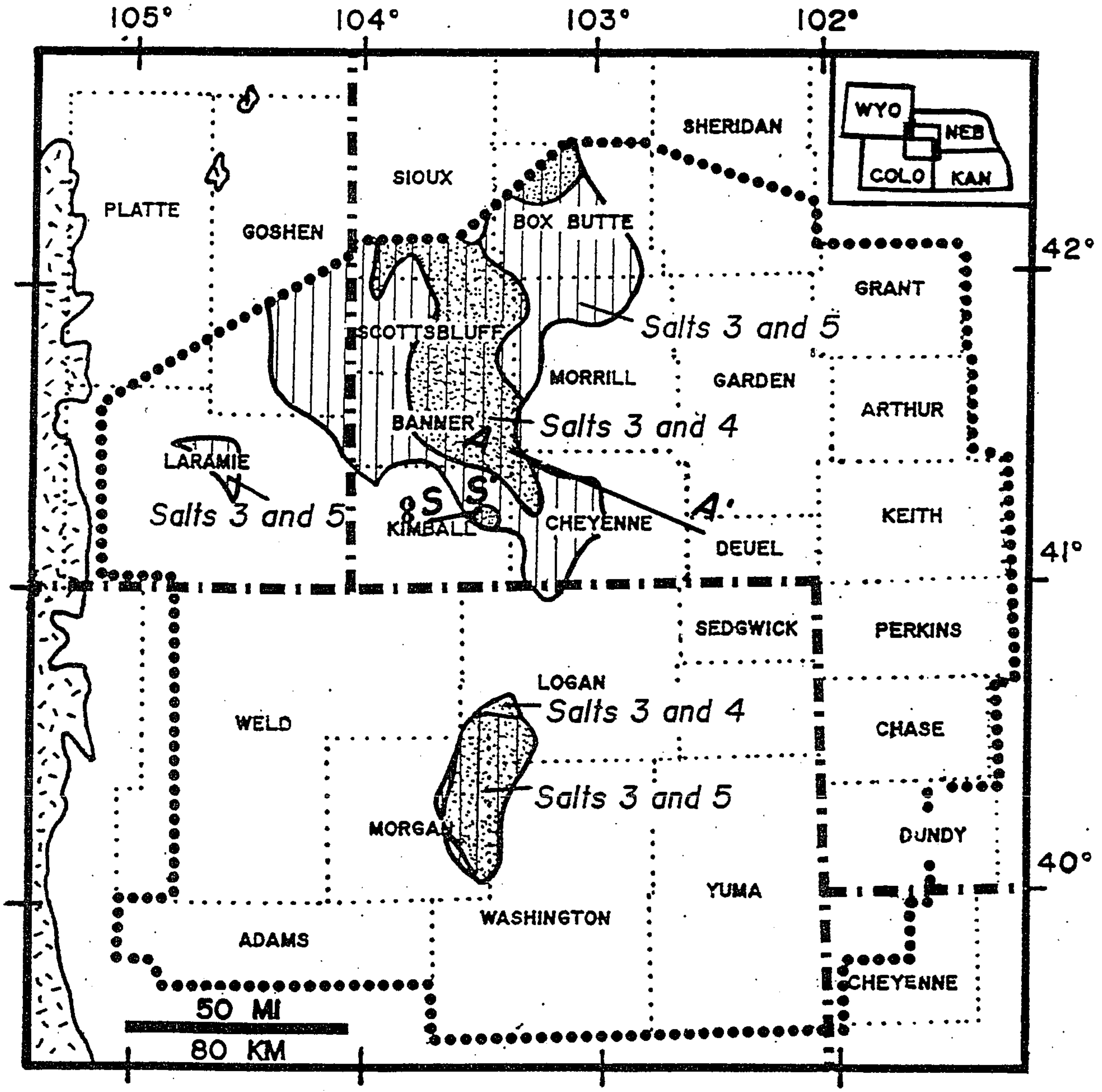
Figure 9-24. Areas in which Glendo Shale is situated between salts 1 and 2, and is potentially undercompacted. (Based on subsurface control that is limited in places.)

southeastern Wyoming, in northeastern Laramie County and southern Goshen County.

Figure 9-25 shows areas in which salt 3 overlies salt 4 and/or salt 5. These are potential areas of drilling problems associated with the Opeche Shale. Available subsurface control indicates that the Opeche may pose a risk over a wider area than the Glendo. In addition to parts of Sioux, Scotts Bluff, Banner, and northern Kimball Counties, the Opeche may present drilling problems in parts of Box Butte, Morrill, and Cheyenne Counties, Nebraska, as well as parts of Laramie and Goshen Counties, Wyoming, and Logan, Morgan, and Washington Counties, Colorado.

Potential problems may also exist where the Flower-pot Shale is sandwiched between salts 7 and 9 (Figure 9-26). The potential for undercompaction of the Flower-pot Shale exists primarily in parts of Sioux, Box Butte, Scotts Bluff, Morrill, Garden, Deuel, and Cheyenne Counties, Nebraska, as well as parts of Logan, Phillips, and Washington Counties, Colorado. The Salt Plain Formation may present problems where it lies between both salts 9 and 10 (Figure 9-27), in essentially the same parts of Garden, Deuel, and Cheyenne Counties, Nebraska, and Logan, Phillips, and Washington Counties, Colorado.

The combined potential for encountering undercompacted shale at the Glendo, Opeche, Flower-pot, and Salt Plain levels is summarized on Figure 9-28. Areas which appear to



SALTS 3 AND 4/5 PRESENT

Figure 9-25. Areas in which Opeche Shale is situated between salts 3 and 4 and/or 5, and is potentially undercompacted. (Based on subsurface control that is limited in places.)

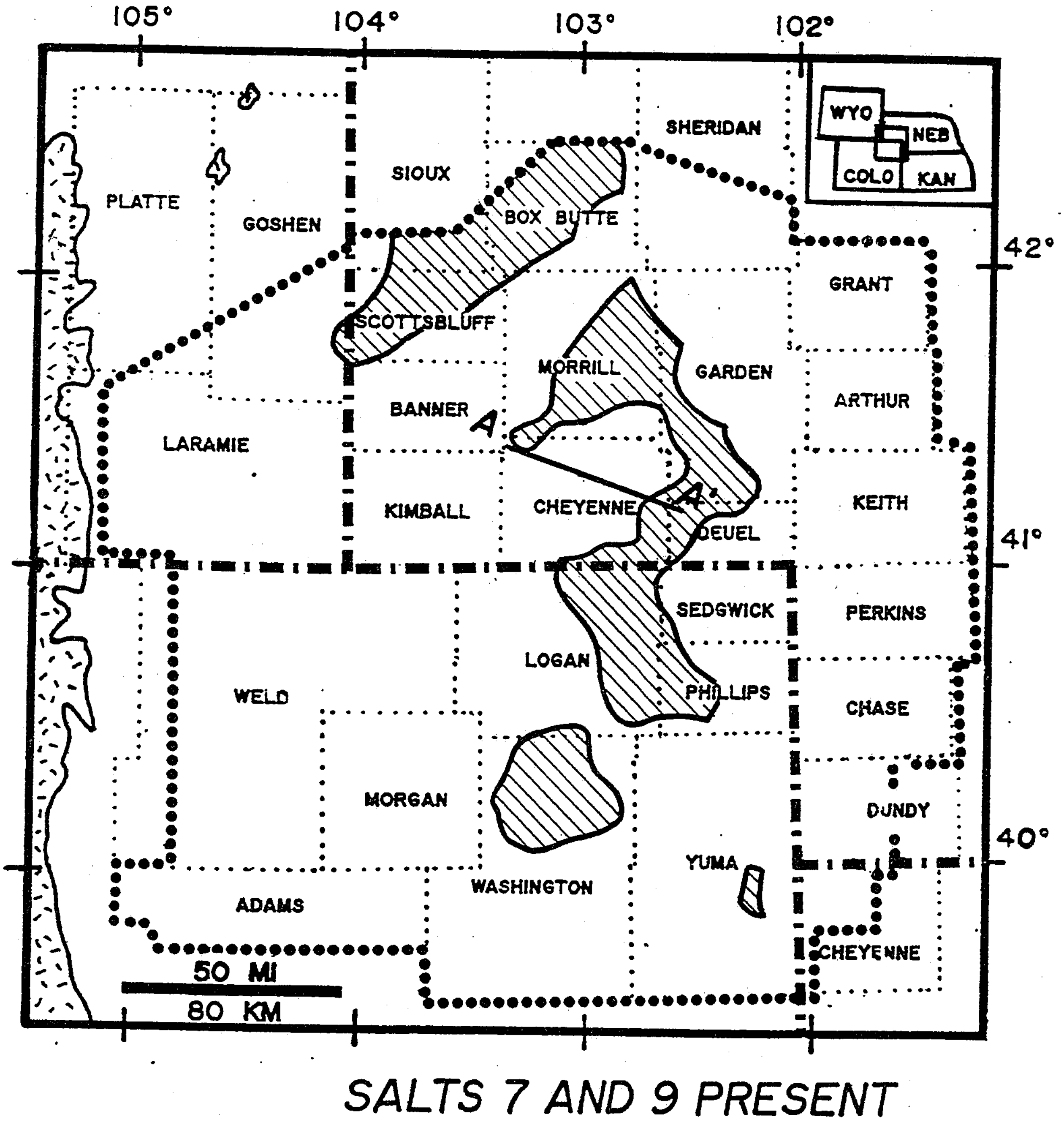


Figure 9-26. Areas in which Flower-pot Shale is situated between salts 7 and 9, and is potentially undercompacted. (Based on subsurface control that is limited in places.)

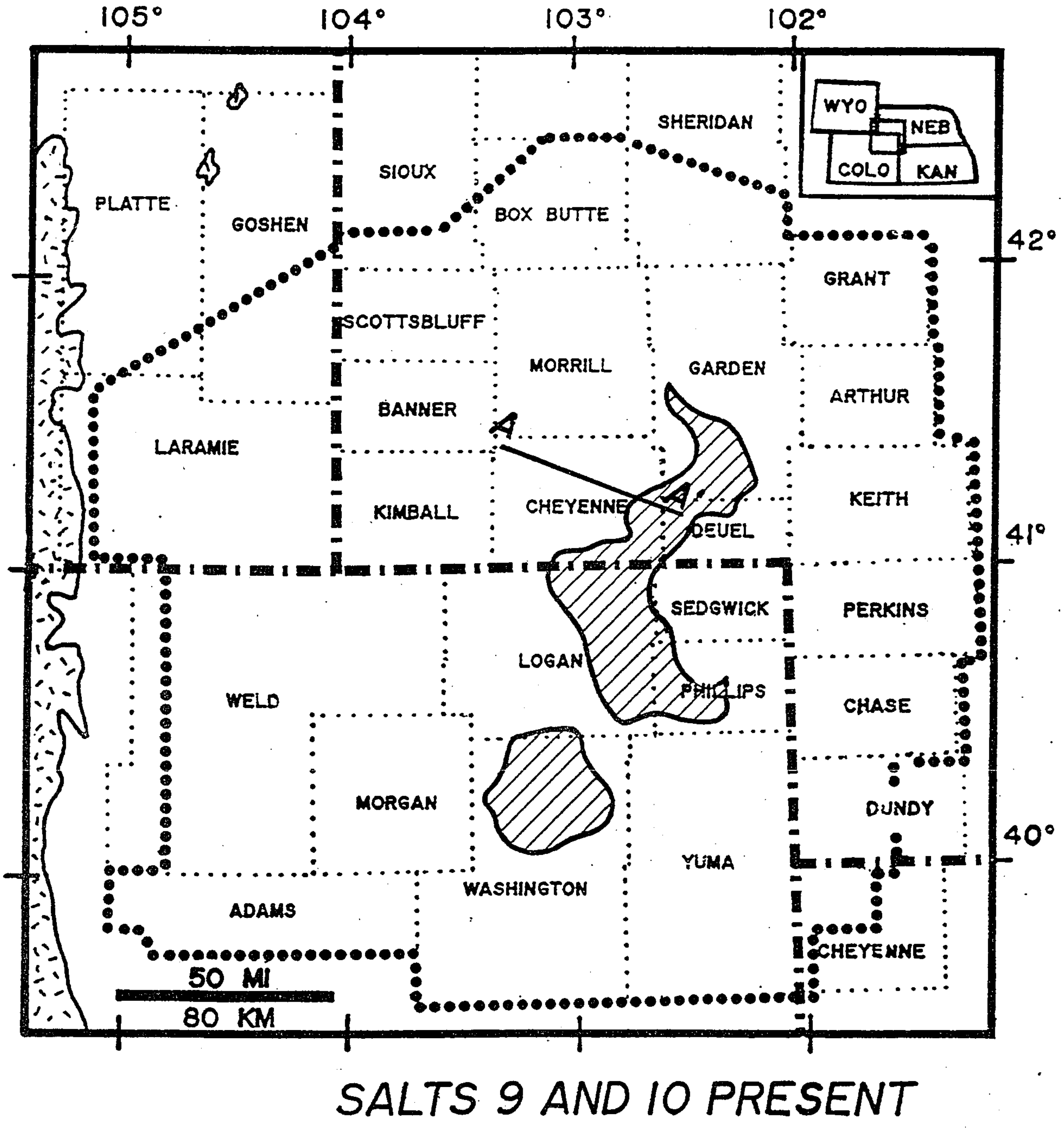


Figure 9-27. Areas in which shale in the Salt Plain Formation is situated between salts 9 and 10, and is potentially undercompacted. (Based on subsurface control that is limited in places.)

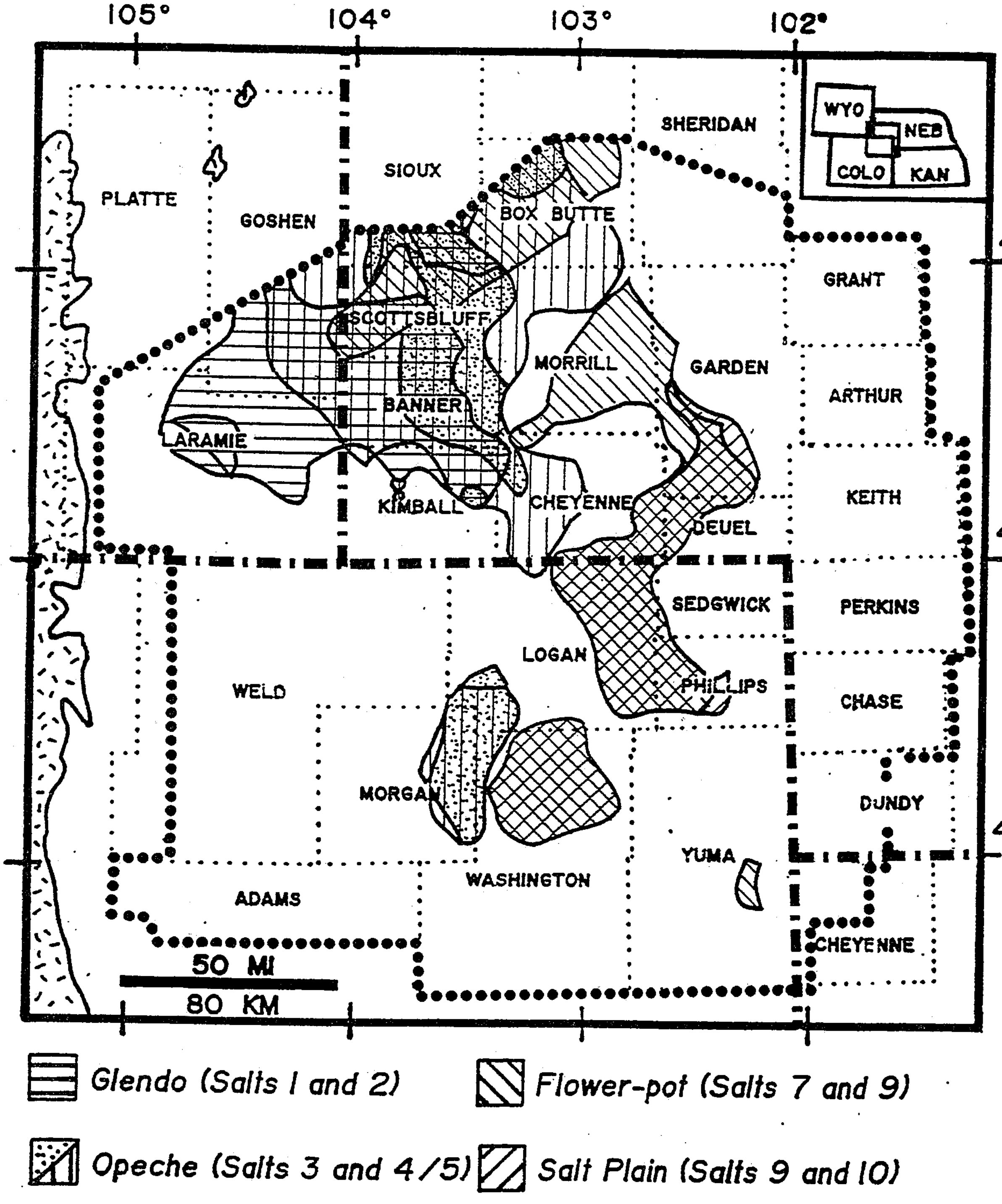


Figure 9-28. Combined distribution of potentially undercompacted shale zones, including Glendo Shale, Opeche Shale, Flower-pot Shale and /or Salt Plain Formation. (Based on subsurface control that is limited in places.)

pose the greatest risk include parts of Box Butte, Sioux, Scotts Bluff, Banner, Kimball, and Cheyenne Counties, Nebraska, central Laramie County, Wyoming, and an area centered around the juncture of Logan, Morgan, and Washington Counties, Colorado.

In the southern Nebraska panhandle (where most recent deep drilling activity has taken place), available subsurface control indicates a relatively low risk of encountering bubble-gum shale in two areas: (1) southern Kimball County (where salt was removed predominantly during Jurassic and Early Cretaceous time); and (2) central Cheyenne County (where post-Cretaceous salt removal took place in the Sidney trough area).

It should be noted that, as with most subsurface interpretations, maps become more complex with the addition of more data. An example of this is seen in the Kleinholz - Terrestrial field area of central Kimball County. The Kleinholz - Terrestrial area is the most densely drilled part of the study area. The higher density of deep data allows for more detailed mapping of salts. This results in more complex interpretations of salt distribution in this area (Figures 4-8, 4-9, 9-24, and 9-25). As a result, Figures 9-24 through 9-28 generally indicate where potential drilling problems associated with "bubble-gum shale" zones may (or may not) be encountered, but should not be used to negotiate drilling contracts or to design drilling and completion procedures for specific deep wells in the basin.

SUMMARY

Permian salts have influenced the regional distribution of oil and gas plays across much of the northern Denver basin. The eastern limit of oil and gas production within the D-J fairway in Nebraska and Colorado appears to be related to regional removal of salt along a facies change from Lyons Sandstone to salt. Structure at the D and J level is more complex along the eastern part of the fairway, where partial post-reservoir removal of salt has created salt-cored anticlines and closures. Here, D- and J-level traps are strongly influenced by structure. In contrast, stratigraphic traps predominate in the western part of the fairway, where pre-reservoir removal of salt took place.

Eastern limits of thick salts are associated with shallow D Sandstone gas production in the northeastern part of the basin. Shallow Niobrara gas production is also associated with the eastern limits of thick salts in eastern Colorado and adjoining areas.

Potential exists for additional salt-related productive trends in relatively unexplored parts of the Denver basin. Potential for salt-related oil and gas entrapment at the D and J Sandstone levels exists north of the present D-J fairway limit in Nebraska. Shallow D gas potential exists northwest, southeast, and south of the Big Springs area.

Potential salt-related shallow Niobrara gas trends exist in the northern part of the basin in Nebraska, north of the D-J fairway and in the shallow D gas area. Niobrara gas potential also exists along a regional salt edge in southwestern Nebraska. This area is used an example of how a dissolution model for salt occurrence can be applied to the prediction of favorable areas for shallow exploration.

The potential exists also for salt-related plays along the densely drilled eastern margin of the D-J fairway of Nebraska and Colorado. Salt-cored anticlines may provide traps for gas in the Niobrara as well as for oil in the O Sand.

The presence of salt in the Guadalupian and Leonardian interval can present drilling and completion problems in deep wells. Additional drilling and completion costs can result from salt washouts and flowage related to thick salts. However, a more serious salt-related problem is the presence of hydrated shale (bubble-gum shale). Bubble-gum shale is undercompacted and overpressured because it is sandwiched between impermeable salt beds.

Most problems related to bubble-gum shale have occurred in the Nebraska panhandle, due, perhaps, in part to the amount of deep drilling that has taken place in this area.

However, most reported problems have involved shale intervals (Glendo and Opeche Shales) which are enclosed by Guadalupian salts. Maps which show the extent of the combined occurrence of selected salts can be used to predict where the risk of encountering bubble-gum shale is high. Although potentially hydrated shale intervals exist in Guadalupian and Leonardian strata, the highest risk appears to be in areas where Guadalupian salts have been preserved. Regionally, these include the "Alliance basin" area of Nebraska and Wyoming and a less extensive area in the Colorado portion of the D-J fairway.

CHAPTER 10
SUMMARY AND RECOMMENDATIONS FOR FUTURE STUDIES

SUMMARY

Subsurface stratigraphic analysis of upper Wolfcampian, Leonardian and Guadalupian strata reveals a complex pattern of salt thickness and occurrence across the Denver basin. Subsurface correlations of persistent carbonate, anhydrite, and red-shale markers across the basin provide a stratigraphic framework with which to identify 13 intervals which locally include salt. Guadalupian-age salt occurs at four stratigraphic levels (salts 1-4), Leonardian salt is present at eight levels (salts 5-12), and one salt (salt 13) is identified at the top of the Wolfcampian.

A consistent stratigraphic nomenclature for Permian salt-bearing strata in the Denver basin subsurface has been lacking in the past because: 1) the basin is situated along an indefinite boundary between the Rocky Mountain and Mid-Continent regions, contributing to complex and overlapping stratigraphic terminology; and (2) until recently, sparse deep subsurface control had precluded accurate correlations of individual discontinuous salt zones. Subsalt Paleozoic discoveries during the past ten years or so prompted a flurry of drilling activity. This produced denser, higher-quality well-log control, with which to more accurately study salts and related strata. In order to reduce confusion regarding formation names for salt-bearing rocks in the Denver basin subsurface, a nomenclature is recommended that uses Mid-Continent terminology (Nippewalla and Sumner Groups and associated lower-rank units) for Leonardian strata and Rocky Mountain terminology (Goose Egg Formation and associated lower-rank units) for the Guadalupian.

Controls on Salt Distribution

Present-day regional distribution of individual salts is due to a number of depositional and post-depositional influences:

1. *Configuration of evaporite basins*. Precipitation of upper Wolfcampian (salt 13) and lower Leonardian salts (salts 9-12) was influenced by low-relief paleohighs which bounded the evaporite basins. The Yuma high (ancestral Las Animas arch) and the ancestral Chadron arch limited the accumulation of salts 9-13 along the southeastern and northeastern margins, respectively, of the study area. A northeast-trending paleohigh associated with the Transcontinental arch (Morrill County high) partitioned the Alliance basin in southeastern Wyoming and western Nebraska from the Sterling basin to the southeast in the eastern Nebraska panhandle and northeastern Colorado. A transverse sag across the paleohigh in the eastern part of the Nebraska

panhandle ("Garden County low") locally connected the two evaporite basins. Sand (Lyons and Cedar Hills Sandstones) accumulated in eolian and shallow-water environments associated with the paleohighs coeval with accumulation of red silt and mud (Salt Plain Formation) and halite (Salts 9 and 10) within the evaporite basins.

By contrast, upper Leonardian and Guadalupian evaporite distribution was more widespread. Syndepositional thinning of these salts does not occur across the Transcontinental arch paleohigh.

2. *Pre-Late Jurassic salt removal.* Present-day eastern limits of upper Leonardian and Guadalupian salts are strongly influenced by erosion or near-surface dissolution below a pre-Late Jurassic truncation surface. Eastern limits of thick salts parallel pre-Jurassic subcrops of associated carbonate, anhydrite and red-shale units. Leonardian strata are partially removed, and Guadalupian and Triassic strata are absent along the eastern margin of the study area. Jurassic isopach maxima in these areas may be due to the creation of additional accommodation space by pre-Late Jurassic salt solution collapse.

3. *Jurassic and Early Cretaceous Salt Removal.* Jurassic and Lower Cretaceous isopach maxima associated with present limits of upper Leonardian and Guadalupian salts (particularly their western limits), indicate Jurassic and Early Cretaceous removal of salt. Removal of salt may have

been in response to introduction of water from the Lyons Sandstone due to compaction-induced (centrifugal) flow. An extensive area of Jurassic-Early Cretaceous salt removal is centered around the juncture of Colorado, Nebraska, and Wyoming.

4. Post-Cretaceous (Laramide-induced) salt removal. Distribution of all salts was further modified by post-Cretaceous dissolution, believed to be in response to Laramide orogeny. Removal of salt was likely caused primarily by introduction of water by regional gravity-driven (centripetal) flow within the Lyons Sandstone, and possibly within Laramide-induced fracture zones. Post-Cretaceous salt removal (indicated by Cretaceous-level collapse structures) is concentrated in areas where thick Lyons Sandstone pinches out updip (to the east) into salt (salts 9 and 10). Removal of salt along the northeastern part of the study area may be related to Laramide-induced southward groundwater flow within Jurassic strata from pre-Oligocene outcrops on the Chadron arch to the salt interval directly below the sub-Jurassic unconformity.

Because truncation, near-surface dissolution, and dissolution at depth have modified the original distribution of salt, stratigraphic interpretations of the Permian which are based on present-day thickness of salt-bearing intervals may not accurately reflect the paleotectonic framework during evaporite accumulation.

Relationship of Salt Distribution to Hydrocarbon Entrapment

Dissolution of Permian salt has influenced the regional distribution of oil and gas plays across much of the eastern flank of the Denver basin:

1. *D-J Fairway.* The eastern limit of oil and gas production within the D-J fairway in Nebraska and Colorado appears to be related to regional post-Cretaceous (post-reservoir) removal of salt. The eastern margin of the fairway is spatially related to a regional Lyons Sandstone - salt facies change. Here, D- and J- level traps are strongly influenced by structure. Incomplete post-reservoir salt removal has created salt-cored anticlines and closures. In this more structurally complex part of the fairway, per-well reserves are higher due to localization of oil on salt-cored anticlines, stacking of pays, and perhaps fracturing. High-salinity formation waters in the D and J may reflect post-reservoir movement of dissolution brines in this area.

The eastern limit of the D-J fairway in Nebraska (and northernmost Colorado) is marked by the Sidney trough, a regional northeast-trending depression. Location of the Sidney trough is spatially related to an abrupt eastward facies change from thick Lyons Sandstone to thick salt (salts 9 and 10). Complete dissolution of salts 9 and 10 caused collapse of overlying strata, prompting the dissolution of younger salts, which further enhanced the structural relief along the linear depression. The Sidney trough likely acted as a regional, salt-related barrier to oil migrating from mature source rocks in the axial portion of the basin to the west.

In contrast, stratigraphic traps predominate in the western part of the fairway, where salts have not been removed or where salt dissolution pre-dated deposition of D and J reservoirs.

Potential exists for a northward extension of the D-J fairway in Nebraska, along the eastern margins of thick salts. Potential also exists within the existing developed eastern part of the fairway for salt-related structural traps at the level of the Upper Cretaceous Niobrara Chalk (shallow biogenic gas) and the Lower Cretaceous O Sand (Paleozoic-sourced oil).

2. *Shallow D Sandstone gas area.* Production of shallow gas from the D Sandstone in the northeastern part of the basin is spatially related to the eastern limits of thick Leonardian salts. Post-reservoir removal of salt created a north-south regional flexure through Big Springs and nearby D gas fields. Single-point seismic data across Big Springs field support a salt-dissolution origin for the gas-productive structure.

Potential exists for northward and southward extensions of the shallow D gas area, along eastern margins of thick Leonardian salts. Potential also exists along this trend at the level of the Niobrara Chalk, as indicated by recent shallow development of the Niobrara gas reservoir at Big Springs.

3. Shallow Niobrara gas area. Distribution of shallow Niobrara gas fields in eastern Colorado and adjacent areas is spatially related to the occurrence of thick Leonardian salts. Structural relief across faulted, gas-productive anticlines is related to variations in thickness of Leonardian strata, which are caused by incomplete dissolution of salt. Post-Niobrara salt dissolution likely was caused by introduction of water from the Lyons (Cedar Hills) Sandstone at its updip pinchout into salt, which occurs below the shallow Niobrara gas area. Seismic data support the presence of a salt-cored anticline at Eckley field, the highest-yield shallow Niobrara gas field.

Potential exists for extension of the shallow Niobrara gas trend into adjacent parts of northeastern Colorado, the eastern part of the Nebraska panhandle, and southwestern Nebraska. The southwestern Nebraska area was used to demonstrate the use of a salt dissolution model in predicting favorable areas for shallow exploration.

Relationship of Salt Distribution to Drilling Problems

Thick Guadalupian and Leonardian salts can present drilling and completion problems in deep wells. The most serious problem involves hydrated shale ("bubble-gum" shale) which is sandwiched between thick salt beds. Impermeable salts prevent compaction and dewatering of shales. Although Leonardian salts locally encase shales of the Salt Plain Formation and Sumner Groups, most bubble-gum shale problems are related to the occurrence of Guadalupian salts. The Glendo Shale (where it occurs between thick salts 1 and 2) and the Opeche Shale (where it occurs between thick salts 3 and 4 and/or 5) appear to present the most problems. Regionally, these areas include the Alliance basin area of Nebraska and Wyoming and a less extensive area in the Colorado portion of the D-J fairway.

RECOMMENDATIONS FOR FUTURE STUDIES

Study of the Permian salts and related strata should by no means end here. In fact, as with most research, as many questions are prompted by this study as are answered. Some of these questions and suggestions for additional salt-related research (beyond the scope of this study) which may provide answers are:

1. *Can present-day eastward-directed groundwater flow within the Lyons Sandstone be confirmed?* A cursory look at Lyons drill-stem test data reveals fluid recoveries that place the Lyons potentiometric surface at a level well above

the stratigraphic position of the D and J Sandstones. A comparison of the J Sandstone potentiometric surface mapped by Pruit (1978) and a calculated Lyons potentiometric surface of Belitz and Bredehoeft (1983) (Figure 4-28) reveals that the Lyons potentiometric surface lies above that of the J across the eastern flank of the basin. This indicates that cross-formational flow of water from the Lyons to the level of Cretaceous reservoirs is possible and may explain high-salinity D and J formation waters in areas of post-reservoir salt removal along the eastern margin of the D-J fairway.

Pruit's work is based on data available through the early 1970s. Since then a tremendous amount of D and J Sandstone drill-stem test data have been acquired and the Lyons has been tested a number of times. A study which uses Lyons and D and J drill-stem test data to prepare updated potentiometric interpretations may provide insight into subsurface fluid flow patterns and their possible relationships to post-Laramide salt removal and hydrocarbon migration and entrapment.

2. Can high-salinity formation water in the D and J Sandstones be chemically "fingerprinted" to a Permian salt source, thereby confirming a salt-solution origin for the brines? Can study of formation water chemistry and its *possible relationship to salt removal be used to predict areas of by-passed low-resistivity pays?* Further study of existing formation-water analyses from producing wells and from drill-stem tests may be useful in confirming a deep, salt solution-related source for salinity anomalies. Existing data can be supplemented by sampling of produced water in active fields. Should a more detailed relationship between water salinity and post-reservoir salt removal be determined, interpreted or predicted areas of salt removal may represent areas where potential pays have been overlooked, due to anomalously low formation resistivities.

3. Has syndepositional salt removal influenced the distribution of the D and J Sandstone intervals, and thus migration patterns and reservoir distribution? Regional-scale stratigraphic analysis reveals that salt has been removed at various times, including pre-Late Jurassic, Jurassic-Early Cretaceous, and post-Cretaceous. Detailed structural mapping (involving nearly 9000 wells) at the J Sandstone level in the southern Nebraska panhandle (Chapter 4) revealed that post-reservoir salt removal took place in the more structurally complex eastern part of the D-J fairway.

In contrast, structure is relatively simple at the J Sandstone level in the western part of the fairway, where salt removal predated reservoir deposition. Here, areas of salt coincide with thick sandstones of the Cheyenne Formation, which lies below the D and J Sandstones. It is reasonable to assume that, because both pre-reservoir and post-reservoir salt removal has been interpreted in the Nebraska panhandle, the possibility exists for syn-reservoir salt removal to have occurred.

A logical area in which to initiate a study of the possible syndepositional influence of salt removal on the distribution of the D and J Sandstone intervals is the southern Nebraska panhandle. This is an area which includes nearly 9000 Cretaceous tests and nearly 200 Paleozoic penetrations and includes over 400 D and J oil and gas fields. Thus, it represents an ideal area in which to investigate the possible relationship of salt removal to oil and gas migration patterns and entrapment within the D and J in the Denver basin.

4. Has the presence of thick salts affected the regional maturation patterns of Cretaceous source rocks? Salt has a much higher thermal conductivity than sandstone. Thus, at a constant depth, heat flow to Cretaceous source rocks which overlie thick salts should be higher than heat flow to source rocks which occur in areas of pre-source rock salt removal (where solution-collapse has resulted in thick Cheyenne Sandstone). A possible example may be a mature source rock (Niobrara) outlier in Banner County, Nebraska (Figure 6-1). Here, the thermally mature Niobrara (as mapped by Smagala et al., 1984) overlies thick Guadalupian and upper Leonardian salts. At an equivalent depth immediately to the south in Kimball County, the Niobrara is immature, where Jurassic and Early Cretaceous salt removal allowed for deposition of thick Cheyenne Formation Sandstones in the collapse low.

Detailed geothermal modelling could be used to predict critical thickness and thermal conductivity contrasts required for measurable differences in maturation levels. If stratigraphic variations associated with salt in the Denver basin satisfy these requirements, then a study which compares thermal maturity data to salt occurrence may provide insight into regional maturation patterns in the basin.

5. Can surface structural mapping be related to Cretaceous-level structure (and interpreted salt distribution) in areas of post-Cretaceous salt removal? How recently has salt removal occurred? The Nebraska panhandle represents an ideal area to study the relationship of surface structure to Cretaceous-level salt collapse-induced structure. Diffendal (1980) concluded that his Cenozoic "Rush Creek-Lisco structural basin" ("R", Figure 4-13) in

Garden and Morrill Counties is a northern extension of the Sidney trough, but offerred no cause for the deformation. Salt is absent in this area, suggesting salt removal as a mechanism for the folding. Coarse sand and gravel of the Quaternary Broadwater Formation descends from a position 160 ft (48 m) above the North Platte River to a position 80 ft (24 m) above the river in the basin, suggesting that deformation occurred at least in part within the past few million years. Moreover, Pliocene drainage diversion was interpreted in the Rush Creek area by Swinehart et al. (1985).

Detailed studies of surface formations across salt-related flexures in the Sidney trough and Big Springs areas may confirm a relationship to salt removal and may help to establish timing of salt-related deformation.

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GSA	Geological Society of America
RMAG	Rocky Mountain Association of Geologists
WGA	Wyoming Geological Association
USGS	United States Geological Survey

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APPENDIX

LIST OF DEEP WELLS

This Appendix includes a listing of deep wells within and adjoining the study area that were used in a subsurface analysis of the Permian salt interval. Well numbering system is unique to this study, and is derived from listings provided by Petroleum Information Corporation and the Nebraska Oil and Gas Conservation Commission.

All township (TWP) designations are north of the baseline, except as noted in listings for Adams, Washington and Yuma Counties, Colorado, and Cheyenne County, Kansas. All range (RGE) designations are west.

Well listings are sorted as follows:

1. State, according to amount of deep well control (Nebraska, Colorado, Wyoming, then Kansas);
2. County, alphabetically within each state;
3. Township;
4. Range; then
5. Section.

NEBRASKA

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
19	HAMILTON	PACKARD 1	ARTHUR	17	37	13	SWSW
20	US SMELTING	WILSON 1-35	ARTHUR	17	40	35	NWSW
17	VOLENTINE SHARP	MILDALE 1	ARTHUR	20	36	33	SENE
21	HAMILTON	STATE 1	ARTHUR	20	39	36	NWNW
18	DAVIDOR	MEYERS LAND 1	ARTHUR	20	40	35	NENE
22	SINCLAIR	SINGLETON 17	BANNER	17	53	19	NWNE
25	SINCLAIR	SINGLETON 1-A	BANNER	17	53	19	NWNE
23	STANOLIND	LOVERCHECK 3	BANNER	18	55	21	NWNE
29	COORS ENERGY	ANSLEY 3-22	BANNER	18	57	22	SENW
24	SHELL	BROWN 1-B	BANNER	19	53	15	NWNW
28	EXXON	OLSEN 1	BANNER	19	55	8	SENW
30	SHELL	STURGEON 1	BOX BUTTE	24	47	1	SWSW
4042	WHITTAKER	COOK 2	BOX BUTTE	25	51	20	NENW
40	SOHIO	CRAWFORD 21-7	BOX BUTTE	25	51	21	SWNE
38	BIRD	BIRD-HAIN 31-15	BOX BUTTE	26	52	31	SWSE
32	HELMS	SULZBACH 1	BOX BUTTE	27	47	1	SWNE
31	LITTLE	HUCKE 1	BOX BUTTE	27	49	19	NENE
37	CONOCO	TUREK 8-1	BOX BUTTE	27	51	8	NWSW
41	SOHIO	MANNING 34-12	BOX BUTTE	27	52	34	NESW
36	TEXACO	HUGHES-NCT 1	BOX BUTTE	28	47	2	SENE
34	SHELL	WILDY 1	BOX BUTTE	28	48	1	SESE
33	SHELL	PITTS 1	BOX BUTTE	28	49	10	SESW
778	JACKSON	RESLER 1	CHASE	5	36	1	NWNE
774	NEBRASKA DRLRS	DUDEK 1	CHASE	5	36	17	NENE
801	DAVIS	NORSHAUSEN 1	CHASE	5	36	28	NENE
808	MURFIN	BRESSIE 1-23	CHASE	5	37	23	SWSE
773	NEWTON	PRIBBENO 1	CHASE	5	37	29	SWSW

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
5827	STANOLIND	BAILEY 1	CHASE	5	38	27	NW
807	MURFIN	MEESKE 1-14	CHASE	5	39	14	SENW
813	BEARD	MONTEITH 1-13-32	CHASE	5	39	32	SWSW
776	GENL RESOURCES	BROWNING 1	CHASE	5	40	2	SESW
777	MOBIL	BLOCKER 1	CHASE	5	40	6	NENE
806	STOEPPLEWORTH	CIRCLE SPEAR 1	CHASE	5	40	26	NENE
775	MOBIL	HOGSETT 1	CHASE	5	41	12	SWNE
818	KALER	WHEELER 1	CHASE	6	36	23	SESE
817	KALER	MOODY	CHASE	6	36	13	SENW
816	KALER	KANOST 1	CHASE	6	36	21	NESE
781	JONES SHELBURNE	KANOST 1	CHASE	6	36	21	NWSE
819	KALER	WHEELER 2	CHASE	6	36	23	SESW
5822	KALER	WHEELER 2-23	CHASE	6	36	23	NENW
820	KALER	WELLS 1	CHASE	6	36	24	SESW
814	GOLDEN EAGLE	KRAUSNICK 2	CHASE	6	36	33	SESE
815	KALER	KRAUSNICK 2	CHASE	6	36	33	SWSE
802	CARTER	SMITH 1	CHASE	6	37	9	NWSW
783	BRINKERHOFF	FANNING 1	CHASE	6	37	12	SESE
784	NEWTON	MATTHEWS 1	CHASE	6	39	10	NWNW
809	HUGHES	TEPLEY 1	CHASE	6	39	22	SENE
810	HUGHES	TEPLEY 2	CHASE	6	39	22	SENE
780	NEWTON	TEPLY 1	CHASE	6	39	24	SESE
782	STOPPLEWORTH	MAYNARD 1	CHASE	6	40	10	SWSE
779	WESTLUND	SCHULTZ 1	CHASE	6	41	34	NWNW
785	PRIZE-KEE	FANNING 1	CHASE	7	36	26	NENE
812	SOHIO	MADDUX 28-16	CHASE	7	36	28	SESE
786	GAGE	MADDUX 1	CHASE	7	37	15	NWSE
805	ADOBE	MADDUX LAND 1	CHASE	7	37	34	NENE
787	NEWTON	RAKER 1	CHASE	7	38	12	SESE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
789	OHIO	BREMER 1	CHASE	7	39	5	SWSW
804	TAYLOR	ADAMS 1	CHASE	7	41	1	SWNW
788	HUBER	COLSON 1	CHASE	7	41	10	NWSE
794	ALLADIN	ONIEL 1	CHASE	8	36	15	SWSW
798	MILES DRLG	BRADLEY 1	CHASE	8	36	28	SWNE
790	DONNELL DRLG	ONIEL 1	CHASE	8	36	35	SWSW
811	SOHIO	LEE 2-8	CHASE	8	37	2	SENE
797	SMITH	LEE 1	CHASE	8	37	10	NWNE
793	JONES SHELBURNE	ROBERTSON 1	CHASE	8	37	24	NWNW
800	MILES DRLG	PETERSON 1	CHASE	8	37	30	NESE
796	SMITH	COOPER 1	CHASE	8	38	11	SENW
791	NEWTON	EBERHARDT 1	CHASE	8	38	21	SESW
799	MILES DRLG	NORDHAUSEN 1	CHASE	8	38	23	SWSE
792	NORTHERN NAT	BALDWIN 1	CHASE	8	38	24	NWNE
795	SKELLY	KILPATRICK 1	CHASE	8	39	15	NWSW
803	MILES DRLG	SVOBODA-HANNAH	CHASE	8	40	14	NENE
905	MARATHON	BALL 7-1	CHEYENNE	12	50	7	SWNE
860	AM PETROFINA	MAHR 1	CHEYENNE	12	50	10	NWNW
859	AM PETROFINA	ACKERMAN 1	CHEYENNE	12	50	18	NWSE
861	AM PETROFINA	MILLER 1	CHEYENNE	12	51	1	NWSW
928	BASS ENTERPRISES	BRAURER 6-13	CHEYENNE	12	51	6	SENW
880	SUN	MICHAELS 1	CHEYENNE	12	52	15	NENW
856	SOUTHLAND RLTY	ZALESKY 1	CHEYENNE	13	47	18	NWNW
903	EXXON	RAPP-WOOD 1	CHEYENNE	13	49	7	NWSE
922	UNION OF CALIF	REZANINA 1-M21	CHEYENNE	13	49	21	SWSW
862	AM PETROFINA	FRIEDA NARJES 1	CHEYENNE	13	49	35	NWSW
909	MARATHON	SCHAF 10-2	CHEYENNE	13	50	10	NWSW
899	MARATHON	BRAUER 14-1	CHEYENNE	13	50	14	NWNE
849	MARATHON	STATE 1	CHEYENNE	13	50	16	NWSW

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
889	MARATHON	KURZ 2	CHEYENNE	13	50	17	SWNE
917	WMX	MCMILLAN 2-1	CHEYENNE	13	51	2	NENE
925	ANTELOPE PROD	CHURCH 1	CHEYENNE	13	51	2	NWNW
881	CELSIUS	MCMILLAN 3-1	CHEYENNE	13	51	3	NWNW
879	COLTON	DRENGUIS 2-4	CHEYENNE	13	51	4	NWSE
875	CELSIUS	BIRD 4-1	CHEYENNE	13	51	4	NWNE
886	CELSIUS	BIRD 4-2	CHEYENNE	13	51	4	SENE
876	SUN	ANDERSON 1	CHEYENNE	13	51	10	NWNW
904	ORBIT DRLG (WMX)	MOLLY 2	CHEYENNE	13	51	11	NESW
890	ORBIT DRLG	MOLLY 1	CHEYENNE	13	51	11	SESE
930	Z & S CONST	BAIRD 93-1	CHEYENNE	13	51	11	SWSW
929	OHIO	CHAMBERS 3	CHEYENNE	13	51	14	SWSW
877	MILLER	WALKER 2	CHEYENNE	13	52	23	NESW
920	BASS ENTERPRISES	WALTERS 35-13	CHEYENNE	13	52	35	SENW
857	WEBB	LEHMKUHL 1	CHEYENNE	14	47	15	NENE
851	OHIO	FENDER 1	CHEYENNE	14	48	2	NWSW
850	OHIO	PAHL 3	CHEYENNE	14	49	7	SWNW
872	MARATHON	HAUPT 3-27	CHEYENNE	14	50	27	SWSW
921	MILLER	GEORGE 1	CHEYENNE	14	51	8	NENE
865	DIA SHAM (EVANS)	MATHEWSON 13-35	CHEYENNE	14	51	15	NWSW
923	MILLER	CLIFF FARMS 1-X	CHEYENNE	14	51	18	NWSW
878	CELSIUS	MATHEWSON 20-1	CHEYENNE	14	51	20	NWNE
867	WEXPRO	LYNGHOLM 1-23	CHEYENNE	14	51	23	SESE
871	CELSIUS	OLSEN 1-25	CHEYENNE	14	51	25	SWSW
908	BORCHERT	OLSEN 1	CHEYENNE	14	51	25	NWNW
924	WESTERN OPER	MCMILLAN 1	CHEYENNE	14	51	28	NWSW
873	CELSIUS	LIVINGSTON 1-33	CHEYENNE	14	51	33	SESE
932	CELSIUS	LIVINGSTON 33-2	CHEYENNE	14	51	33	SESW
910	BORCHERT	BORCHERT 1	CHEYENNE	14	51	34	SESW

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
893	CELSIUS	MCMILLAN 34-2	CHEYENNE	14	51	34	SENW
916	MILLER	MCMILLAN 1	CHEYENNE	14	51	34	SWNW
918	BORCHERT	BORCHERT 2	CHEYENNE	14	51	34	SWSW
902	CELSIUS	MCMILLEN 35-1	CHEYENNE	14	51	35	SESW
912	EURATEX	CLIFF FARMS 41-13	CHEYENNE	14	52	13	NWNW
884	SLAWSON	CLIFF FARMS 1-13A	CHEYENNE	14	52	13	NESE
863	DIA SHAMROCK	CHRISTENSON 34-21	CHEYENNE	14	52	21	SWSE
885	MILLER	RGM CORP 44-27	CHEYENNE	14	52	27	SWSW
864	DIA SHAMROCK	DEAVER 12-27	CHEYENNE	14	52	27	SWNW
919	MILLER	RGM 3	CHEYENNE	14	52	27	SWSW
858	DIA SHAMROCK	MCMILLAN 1	CHEYENNE	14	52	28	NENE
906	EURATEX	RGM 13-28	CHEYENNE	14	52	28	NESE
866	VAUGHAN BROS	LARSON 1	CHEYENNE	14	52	30	NWSE
913	EURATEX	TERMAN 11-34	CHEYENNE	14	52	34	NENE
887	MILLER	TERMAN 14-34	CHEYENNE	14	52	34	NWNW
927	MAGNOLIA	HERBOLDSHEIMER	CHEYENNE	14	53	35	SWSW
900	DOHENY	GUINOUARD 1	CHEYENNE	15	48	8	NENE
852	OHIO	EGGING 1	CHEYENNE	15	49	11	NENE
891	DAVIS	FJF 1	CHEYENNE	16	49	20	NESW
907	MARATHON	PREBLE 25-1	CHEYENNE	15	49	25	NWSE
888	DAVIS	BEYER 1	CHEYENNE	15	50	19	NWSW
898	BORCHERT	STATE 10	CHEYENNE	15	52	16	SWNE
892	BEARD	CLIFF FARMS 1	CHEYENNE	15	52	33	SENE
914	TRUE	RUSH CREEK 31-17	CHEYENNE	16	46	17	NWNE
870	AM PETROFINA	SCHOU 1-A	CHEYENNE	16	47	16	NESW
868	AM PETROFINA	SCHOU 1	CHEYENNE	16	47	33	SESW
869	K-N (APCOT)	TOOF 1	CHEYENNE	16	48	3	NWSW
901	BASS ENTERPRISES	ERNEST 10-33	CHEYENNE	16	49	10	SESE
926	SUN	HOLT 1	CHEYENNE	16	51	2	SWNE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
897	SUN	CLARA STATE 1	CHEYENNE	16	51	36	NWNE
915	EURATEX	CIZEK 1	CHEYENNE	16	53	11	NENE
853	SUPERIOR	TRAVIS-STATE	CHEYENNE	16	53	36	NENW
9232	COPE AND ASSOC.	SAISER 1	DEUEL	12	45	2	NESE
1235	STODDARD	ZIMMERMAN 1	DEUEL	13	43	25	NWNE
1232	COPE DRLG	SCHWARTZ 1	DEUEL	13	44	32	NENW
1236	MAGNOLIA	ROBB 1	DEUEL	14	42	18	SENE
1237	HALBOUTY	TRI-K FARMS 1	DEUEL	14	44	7	SESE
1239	TEXACO	WRIGHT 14-1	DEUEL	14	44	14	SWNE
1234	WARD	CERNY 1	DEUEL	14	45	2	NWSW
1238	TEXACO	PETERSON 19-1	DEUEL	14	45	19	SESW
1233	WARD	LINDSEY 1-24	DEUEL	14	46	24	NENE
1250	DOW-MCHUGH	HANSEN 1	DUNDY	1	39	1	NWNW
1455	DEVON	HANSEN 3-2	DUNDY	1	39	2	SENW
1392	DEVON	HANSEN 1	DUNDY	1	39	2	NENE
1291	ANTELOPE GAS	HANSEN 1	DUNDY	1	39	3	SWSW
1290	ANTELOPE GAS	HANSEN A-1	DUNDY	1	39	12	NENE
1243	STANOLIND	ANDERSON 1	DUNDY	1	39	28	NWNW
1242	SUNRAY DX	ANDERSON 1	DUNDY	1	39	28	SWNE
1454	DEVON	WILLIAMS 1-30	DUNDY	1	39	30	NESE
1292	ANTELOPE GAS	HINES B-1	DUNDY	1	40	11	NESW
1456	DEVON	BUSH 1-22	DUNDY	1	40	22	SESE
1305	HARRISON	ROYAL WOODS III - 1	DUNDY	1	41	10	NWSE
1570	HEWIT	WALL 11-30	DUNDY	1	41	30	NWNW
1326	MURFIN DRLG	MCGLASHAW 1-15	DUNDY	2	39	15	SWSW
1286	HARRISON	STAMM 1	DUNDY	2	39	24	SWSW
1476	MURFIN DRLG	HARDWICK 1-26	DUNDY	2	39	26	SESE
1323	MURFIN DRLG	BROSIUS 5	DUNDY	2	39	30	SWNW
1304	MURFIN DRLG	BROSIUS 2	DUNDY	2	39	30	NESE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1366	DILLIE	BROSIUS 3-31	DUNDY	2	39	31	SWSE
1343	DILLIE	BROSIUS 2-31	DUNDY	2	39	31	NESE
1287	MURFIN DRLG	BROSIUS 1-31	DUNDY	2	39	31	SENE
1316	MURFIN DRLG	BROSIUS 4	DUNDY	2	39	31	NE
1285	HARRISON	STAR-BROSIUS 1	DUNDY	2	39	31	NENE
1323	MURFIN	BROSIUS 5	DUNDY	2	39	32	NW
1303	MURFIN DRLG	BROSIUS 3	DUNDY	2	39	32	SW
1389	DEVON	HANSEN 2	DUNDY	2	39	34	NESW
1262	TENNESSEE	NICHOLS 1-A	DUNDY	2	40	11	SWSW
1282	WADLEY	PECK 1	DUNDY	2	40	11	SENE
1284	STOEPPLEWORTH	STARR 1	DUNDY	2	40	14	SWNE
1352	MURFIN DRLG	HUNTER 1-14	DUNDY	2	40	14	SWSW
1466	OXFORD	BRUNSWICK 35-1	DUNDY	2	40	35	NENE
1254	WOODY-KIEL-BURNS	HUEY 1	DUNDY	2	41	17	SESW
1425	DEPCO	SEWARD 44-20	DUNDY	2	41	20	SESE
1432	DEPCO	CREWS ESTATE 43-12	DUNDY	2	42	12	NESE
1499	LUFF	ADKIN H-1	DUNDY	3	39	1	SENE
1540	LUFF	ADKINSON C-1	DUNDY	3	39	1	NENW
1507	LUFF	STANM J-1	DUNDY	3	39	1	NWSE
1521	BEARD	FRASIER 2-308	DUNDY	3	39	8	NENW
1339	SANCHEZ-OBRIEN	LUTZ 1-A	DUNDY	3	39	11	NESW
1337	SANCHEZ-OBRIEN	LUTZ 1	DUNDY	3	39	11	NESW
1517	BEARD	HANSEN 1-1626	DUNDY	3	39	26	SESE
1329	MURFIN DRLG	LUTZ 1	DUNDY	3	39	27	SENE
1361	MURFIN DRLG	HANSEN 1	DUNDY	3	39	27	SESE
1275	DEEP ROCK	NICHOLS A-1	DUNDY	3	40	6	NESW
1433	DEPCO	SEWARD 44-8	DUNDY	3	40	8	SESE
1273	WADLEY	CLEGG 1	DUNDY	3	40	29	NENE
1274	WADLEY	CLEGG 1	DUNDY	3	40	29	NENE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1437	DEPCO	KNIGHT-NEB 14-9	DUNDY	3	41	9	SWSW
1426	DEPCO	KNIGHT-NEB 41-17	DUNDY	3	41	17	NENE
1268	DONNELL DRLG	DANIELS 1	DUNDY	3	41	27	SWSW
1330	STOEPPLEWORTH	HARFORD 1	DUNDY	3	41	29	SENE
1394	DEPCO	HARFORD RCH 41-32	DUNDY	3	41	32	NENE
1428	DEPCO	BAMFORD LAND 14-13	DUNDY	3	42	13	SWSW
1548	BEARD	MARTIN 2-1606	DUNDY	4	39	6	SESE
1490	DEPCO	FRASIER 12-8	DUNDY	4	39	8	SWNW
9492	BEARD	FRASIER 2-308	DUNDY	4	39	8	NENW
1539	BEARD	NELSON 1-1410	DUNDY	4	39	10	SESW
1524	BEARD	FRASIER 1-415	DUNDY	4	39	15	NWNW
1533	HEWIT	STATE 41-16	DUNDY	4	39	16	NENE
1491	DEPCO	SHRUM11-17	DUNDY	4	39	17	NWNW
1373	MURFIN DRLG	ALSBURY 1-32	DUNDY	4	39	23	SWSW
1459	MURFIN DRLG	ALSBURY 2-23	DUNDY	4	39	23	SESW
1562	HEWIT	COX 2-25	DUNDY	4	39	24	SESW
1508	HEWIT	COX 1-25	DUNDY	4	39	25	SWSW
1567	HEWIT	KITT-LINGO 3-26	DUNDY	4	39	26	SWSE
1528	HEWIT	KITT LINGO 2-26	DUNDY	4	39	26	NESE
9529	HEWIT	ALSBURY 32-26	DUNDY	4	39	26	SWNE
1503	HEWIT	STATE 4-36	DUNDY	4	39	26	SENW
1504	HEWIT	KITT-LINGO 1-26	DUNDY	4	39	26	SESE
1506	CANNON	GRAMS 2-35	DUNDY	4	39	35	NENE
1487	SNOW	GRAMS 35-16	DUNDY	4	39	35	SESE
1488	CANNON	GRAMS 1-35	DUNDY	4	39	35	NE
9489	HEWIT	STATE 9-36	DUNDY	4	39	36	SWSW
9490	HEWIT	STATE 1	DUNDY	4	39	36	NWSE
9491	HEWIT	STATE 4-36	DUNDY	4	39	36	SWNW
1561	HEWIT	STATE 8-36	DUNDY	4	39	36	SESW

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1529	HEWIT	STATE 7-36	DUNDY	4	39	36	SWSW
1463	HEWIT	STATE 1-36	DUNDY	4	39	36	NENE
1498	HEWIT	STATE 3-36	DUNDY	4	39	36	SWSE
1485	HEWIT	STATE 2-36	DUNDY	4	39	36	NESW
1510	HEWIT	STATE 6-36	DUNDY	4	39	36	NESE
1509	HEWIT	STATE 5-36	DUNDY	4	39	36	NWSW
1484	DEPCO	MARTIN 41-1	DUNDY	4	40	1	NENE
1489	DEPCO	MARTIN 31-1	DUNDY	4	40	1	NWNE
1280	NEWTON	WATT 1	DUNDY	4	40	1	NENE
1279	LION	EARL 1	DUNDY	4	41	1	NENE
1283	TENNESSEE	NICHOLS 1-A	DUNDY	4	41	32	SWSW
1572	PURE	BLANCHARD 1	GARDEN	16	43	32	SWSW
1590	TRUE	RUSH CREEK 24-10	GARDEN	16	46	10	SESW
1573	BRINKERHOFF	PAULSEN 1	GARDEN	17	43	29	NENW
1587	LEXICON	12-14 STATE	GARDEN	17	44	16	SWNW
1589	SOUTHLAND RLTY	WITHERS 1	GARDEN	17	45	26	NWNW
1588	SOUTHLAND RLTY	RUSH CREEK 1	GARDEN	17	45	30	SESW
1577	TUCKER & BEER	ORR 1	GARDEN	18	41	8	SWSW
1574	TUCKER & BEER	STATE 1	GARDEN	18	42	36	NWNW
1586	CLAYTON	MARRITT LAKE 1	GARDEN	18	44	10	SWNW
1576	SMITH	HUWALDT 1	GARDEN	18	44	17	NWNE
1591	TREND	SUGARLOAF HILL 1	GARDEN	18	44	17	NWNE
1575	OHIO	FARRELL 1	GARDEN	18	45	25	NWNE
1580	BRITISH AMERICAN	RUSH CREEK 1	GARDEN	19	41	28	NENW
1578	SINCLAIR	DELATOUR 1	GARDEN	19	42	33	SWSW
1585	PHILLIPS	SWAN LAKE STRAT	GARDEN	19	46	10	SENE
1581	TEXACO	GILBAUGH 1	GARDEN	20	42	10	NENE
1582	JONES SHELBURNE	CURRY 1	GARDEN	21	41	28	NENE
1584	LUCERNE	PETERSON 1	GARDEN	22	46	12	NWSE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1610	THOMAS	VINTON 1	GRANT	21	37	12	SWSE
1612	BLAIR-MURFIN	FARRAR 1-B	GRANT	21	38	9	NENW
1613	OIL HUNTERS	FARRAR 1	GRANT	21	38	9	NENW
1611	CLARK	FARRAR 1	GRANT	21	38	9	SENE
1609	PLACID	LOWE 1	GRANT	21	39	9	SWSW
1622	PHILLIPS	LOWE A-1	GRANT	21	40	24	NWNE
5623	LUBAR	SUTTON 1	GRANT	21	41	3	SWSE
1614	THOMAS	EGAN 1	GRANT	22	36	8	SWSW
1615	THOMAS	MINOR 1	GRANT	22	39	5	SWSW
1616	OIL EXPLORATION	ABBOTT 1	GRANT	22	41	2	NWSW
1618	TEXACO	LOWE 1	GRANT	23	38	1	SWSW
1617	JOHNSON	ABBOTT 1	GRANT	23	41	12	NENE
1621	MCHALE	MONAHAN 2	GRANT	24	37	12	NWNW
1620	MCHALE	MONAHAN RANCH 1	GRANT	24	37	12	NWNW
1619	BYRD	ABBOTT 1	GRANT	24	38	28	NENW
1637	MAN	SOUTHWELL 1	KEITH	12	35	11	NWNE
1636	PAN AMERICAN	HEINRICH 1	KEITH	12	36	12	NWSW
1655	AMOCO	HOLSHER 1	KEITH	12	38	9	NENE
1654	AM PETROFINA	WILLIAMS 1	KEITH	12	40	18	SENW
1639	PLACID	HARMS 1	KEITH	13	35	1	NWNW
1638	PLACID	ANDERSON 1	KEITH	13	35	15	SESE
1648	WEBB	CHANDLER 13-3	KEITH	14	35	13	NENW
1647	PLACID	SUDMAN 1	KEITH	14	35	25	SWNW
1652	SCHULEIN	NORDSTROM 1	KEITH	14	35	25	NENE
1640	PAN AMERICAN	HUMPHREY 1	KEITH	14	35	26	NWNE
1646	ROCKHILL	ABLES 1	KEITH	14	37	21	SWNE
4657	CALIF-NEB	STURM 1	KEITH	14	37	21	NWNW
1651	DUNCAN	ROBINSON 1	KEITH	15	35	24	NESW
1643	OSBORN	MCGINLEY 1	KEITH	15	36	9	NENE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1641	PLACID	SILLASEN 1	KEITH	15	36	35	SWSE
1642	TUCKER DRLG	MCCONAHEY 1	KEITH	15	41	22	SWSW
1653	BEARD	KEYSTONE RANCH 1	KEITH	15	41	22	SWNW
1650	NCRA	KRAMER 1	KEITH	16	35	21	NENE
1649	NATIONAL	SILLASEN 1	KEITH	16	36	34	NWNE
1645	OSBORN	WHITETAIL CK 1	KEITH	16	37	31	NESW
1644	HAMILTON	MCGINLEY 1	KEITH	16	38	15	NWNE
1676	SUN	MATHEWSON 1	KIMBALL	12	54	2	NENW
2730	ADVANTAGE	LONG 11-10	KIMBALL	12	55	10	NESW
1657	ROCKHILL	WREDE 1	KIMBALL	13	55	15	SENE
2752	ADVANTAGE	CULEK 15-19	KIMBALL	13	55	19	SWSE
2731	ADVANTAGE	SWEINER 16-20	KIMBALL	13	55	20	SESE
1677	SUN	PALMER STATE 1	KIMBALL	13	55	36	NESW
2743	BOSWELL	SCHRACK 1-6	KIMBALL	13	56	6	SWSE
2753	HEADINGTON	STATE 44X-16	KIMBALL	13	56	16	SESE
1673	MILLER	PRAIRIE STATE A-2	KIMBALL	13	56	16	NWSW
1667	SUN	PRAIRIE STATE 1	KIMBALL	13	56	16	SESW
2742	BOSWELL	TREVETHAN 1-17	KIMBALL	13	56	17	SESE
1656	DAVIS	PHILLIPS 1	KIMBALL	13	56	19	SENW
1727	HEADINGTON	SWANSON 11X-21	KIMBALL	13	56	21	NWNW
1674	MILLER	HEIDEMAN 41-23	KIMBALL	13	56	23	NWNW
1668	PETERS	HAUG 3	KIMBALL	13	57	35	NW
1683	TEXACO	GEISEKING 1	KIMBALL	14	55	3	SWSW
1679	SUN	YOUNG 1	KIMBALL	14	55	6	SESW
2754	HEADINGTON	GEISEKING 41X-9	KIMBALL	14	55	9	NENE
1678	MILLER	GIBBS 24-1	KIMBALL	14	56	1	SWSE
2755	EVERTSON	FLYING EAGLE 3	KIMBALL	14	56	2	NWSE
1725	EVERTSON	FLYING EAGLE 1	KIMBALL	14	56	2	SWSW
1726	EVERTSON	FLYING EAGLE 2	KIMBALL	14	56	2	SWNW

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1700	EVERTSON	STAHLA 1	KIMBALL	14	56	3	SWNW
1702	ADVANTAGE	STAHLA 1	KIMBALL	14	56	3	NWSW
1710	ADVANTAGE	GROSS BROS C-1	KIMBALL	14	56	3	SWSE
1711	ADVANTAGE	GROSS BROS C-2	KIMBALL	14	56	3	SWNE
1693	EXXON	QUINN 1	KIMBALL	14	56	4	SWSE
1705	EXXON	QUINN 2	KIMBALL	14	56	4	SENE
1688	EXXON	VOLKMER 1	KIMBALL	14	56	8	SENE
1689	EXXON	MILLER 1	KIMBALL	14	56	8	NWSE
1704	ADVANTAGE	GROSS BROS B-1	KIMBALL	14	56	10	NWNW
1703	EVERTSON	READ-VOLKMER 1	KIMBALL	14	56	8	SENE
1690	EXXON	TERRESTRIAL 1	KIMBALL	14	56	9	SENW
1684	EXXON	HAGSTROM 1	KIMBALL	14	56	9	NENE
1681	EXXON	WYKERT 1	KIMBALL	14	56	9	NWSW
1692	EXXON	HAGSTROM B-1	KIMBALL	14	56	9	NWSE
1698	ADVANTAGE	GROSS BROS 1	KIMBALL	14	56	10	NWSW
1709	ADVANTAGE	GROSS BROS 2	KIMBALL	14	56	10	SWNE
1716	EXXON	FREDRICK 1	KIMBALL	14	56	10	SWSE
2758	EXXON	FREDRICK	KIMBALL	14	56	11	NWNW
1672	SUN	EVERTSON 1	KIMBALL	14	56	12	NENE
2744	EXXON	FARMER 1	KIMBALL	14	56	15	SENW
1687	EXXON	NEB STATE B-1	KIMBALL	14	56	16	NENW
1717	EXXON	NEB STATE B-3	KIMBALL	14	56	16	NENE
2746	EVERTSON	KOENIG 4	KIMBALL	14	56	17	NWSE
1665	EXXON	KOENIG 1	KIMBALL	14	56	17	NENW
1706	EVERTSON	KOENIG 2X	KIMBALL	14	56	17	NE
1669	EXXON	KOENIG 2	KIMBALL	14	56	17	NENE
1712	EVERTSON	KOENIG 3	KIMBALL	14	56	17	SESE
2741	MILLER	MOCKET 1	KIMBALL	14	56	18	NE
1729	STANCO	TORGESON 1	KIMBALL	14	56	23	NWNE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1723	COORS	HAGSTROM 8-27	KIMBALL	14	56	27	NENE
1713	COORS	ND CEDARBURG 8-28	KIMBALL	14	56	28	SESE
2740	ADVANTAGE	NEB STATE 7-36	KIMBALL	14	56	36	SWNE
1685	EXXON	FORSLING-VAVRA 1	KIMBALL	14	57	12	SESE
1701	COORS	HOTTELL 1-14HW	KIMBALL	14	58	14	NENW
2745	BOSWELL	BERRY 1-32	KIMBALL	14	58	32	NENE
2747	TORCH OPER	PETERSON 7-2	KIMBALL	15	54	7	NWNE
1675	MILLER	GUNDERSON 14-26	KIMBALL	15	54	26	SESE
2748	ADVANTAGE	KIMBALL UNIT DP 1	KIMBALL	15	55	31	NWNW
1699	NEW LONDON	SCHADEGG 1-R	KIMBALL	15	56	4	SENE
2734	WESTERN INT	LUKASSEN 1-7	KIMBALL	15	56	7	SESE
1691	NEW LONDON	LUKASSEN 1	KIMBALL	15	56	8	SWNW
1719	MILLER	LUKASSEN 1	KIMBALL	15	56	17	NESE
2738	WESTERN INT	LUKASSEN 3-17	KIMBALL	15	56	17	SWSE
2739	WESTERN INT	LUKASSEN 2-17	KIMBALL	15	56	17	SESW
2749	CHI OPER	PLATTE 1	KIMBALL	15	56	18	SESE
1707	ADVANTAGE	GROSS-STOHL D-1	KIMBALL	15	56	34	SWSW
1708	NEW LONDON	CAMPBELL 2	KIMBALL	15	56	20	SESE
2750	NEW LONDON	CAMPBELL 3-20	KIMBALL	15	56	20	NWNE
2733	WESTERN INT	CAMPBELL 4-20	KIMBALL	15	56	20	SENW
2735	WESTERN INT	CAMPBELL 5-20	KIMBALL	15	56	20	NESW
1724	NEW LONDON	TRAVELERS 2-21	KIMBALL	15	56	21	NWNE
2732	WESTERN INT	TRAVELERS 3-21	KIMBALL	15	56	21	NWSW
1715	NEW LONDON	TRAVELERS 1	KIMBALL	15	56	21	NWNW
1659	SHELL	SCHNIEDER 2	KIMBALL	15	56	26	SENE
1697	NEW LONDON	SCHWINDT 1	KIMBALL	15	56	28	NWSW
1694	EXXON	LINN-TERRESTRIAL 1	KIMBALL	15	56	29	SWNE
1695	EXXON	LINN-TERRESTRIAL 2	KIMBALL	15	56	29	SWSW
1696	EXXON	MAST-SAUNDERS 1	KIMBALL	15	56	30	NENE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1718	EXXON	CAMIN 1	KIMBALL	15	56	33	NESE
1721	NEW LONDON	FERGUSON 2-34	KIMBALL	15	56	34	SWNW
1720	NEW LONDON	FERGUSON 1	KIMBALL	15	56	34	SWNE
2737	ADVANTAGE	GROSS BROS C-3	KIMBALL	15	56	34	SWSE
1722	MONAHAN	FERGUSON 1-G-82	KIMBALL	15	56	35	SWNW
1714	CHI OPER	LODGEPOLE STATE 1	KIMBALL	15	57	36	NW
1682	DENVER LAND EXPL	UPRR DJP 1	KIMBALL	15	58	15	NWNW
1663	SUNDANCE	SCHNEIDER-SCOTT 1	KIMBALL	16	53	5	NWSE
2751	JORDAN	GUNDERSON 1-11	KIMBALL	16	54	11	SWSW
1671	JORDAN	GUNDERSON 2-11	KIMBALL	16	54	11	SWSW
1661	SHELL	SCHMID 1	KIMBALL	16	54	12	NENW
1660	SHELL	TRAVIS 18	KIMBALL	16	54	15	NESW
2757	CONSOLIDATED	STANDER 1	KIMBALL	16	55	10	NESW
2736	WESTERN INT	JANICEK 1-31	KIMBALL	16	55	31	SENW
1666	DAVIS	EVERTSON 1	KIMBALL	16	56	30	SWNE
2756	PARKER & PARSLEY	CROMIE 1-19	KIMBALL	16	57	19	SWNE
1664	CHEVRON	CHEVRON-DUNCAN 1	KIMBALL	16	58	31	SESE
2023	MILLER	AURICH 1	MORRILL	17	48	7	NESW
2018	EXXON	NEBRASKA 1	MORRILL	17	48	16	NESW
2019	CELSIUS	GREENWOOD 15-1	MORRILL	17	50	15	SENW
3028	HEADINGTON	LINDBERG 42X-6	MORRILL	17	51	6	SENE
2020	HUNT	COOPS-LINDBERG 1	MORRILL	17	52	1	SESE
3027	HEADINGTON	LINDBERG 43X-1	MORRILL	17	52	1	NESE
2004	DANIELS	BUCHANAN 1X	MORRILL	18	47	7	SENW
2014	SOUTHLAND RLTY	JESSEN 1	MORRILL	18	47	26	NENE
2013	SOUTHLAND RLTY	CRANMORE 1	MORRILL	18	48	29	SWSW
2006	CARTER	BLOOME 1	MORRILL	19	49	20	NESE
2022	SWIFT	HART 1	MORRILL	19	49	32	NESE
2011	DEVON	LAPASOETES 1	MORRILL	19	50	14	SESE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
2005	SHELL	RICE 1	MORRILL	19	52	27	SESE
3024	FUNDLINGLAND	BROWN 1	MORRILL	19	52	31	NENW
3025	PAULEY	STEVENS 1	MORRILL	20	47	33	SENW
2010	DEVON	KOESTER 1	MORRILL	20	49	5	NWNE
2012	DEVON	HOUSTON 1	MORRILL	20	49	28	NWSW
2021	YOUNG	DURNAL 1	MORRILL	20	52	7	NENW
3026	PHILLIPS	SWAN LAKE 2	MORRILL	21	47	25	NWNE
2007	SOHIO	DOVE 1	MORRILL	21	49	1	SWSE
2015	SUNDANCE	PETERSON 2-24	MORRILL	21	51	24	NENE
2009	PRICE	HALL 1	MORRILL	23	49	10	SESE
2008	RYAN CONSOL	HALL RANCH 1	MORRILL	23	49	27	NWSW
2017	MALLON	JUERGENS RCH 21-15	MORRILL	23	52	21	SWSE
2016	SOHIO	CAREY 25-2	MORRILL	23	52	25	NWNE
2092	PHILLIPS	MADRID STRAT TEST 3	PERKINS	9	35	5	NESW
2093	PHILLIPS	MADRID STRAT TEST 4	PERKINS	9	36	6	SENE
2091	PHILLIPS	MADRID STRAT TEST 1	PERKINS	9	37	28	NWSE
2098	PHILLIPS	MADRID STRAT TEST 5	PERKINS	10	35	7	NWNE
2106	PAN AMERICAN	SELLERS 1	PERKINS	10	35	23	NESE
2107	STOEPPLEWORTH	CUMMINGS 25-15	PERKINS	10	35	25	SESW
2099	PHILLIPS	MADRID STRAT TEST 6	PERKINS	10	36	6	SWSE
2097	CARTER	STRAT 8	PERKINS	10	36	9	SESE
2095	PHILLIPS	MADRID STRAT TEST 2	PERKINS	10	37	19	SENW
2096	OHIO	STATE 1	PERKINS	10	39	16	NWSW
2094	OHIO	SEJKORA 1	PERKINS	10	39	23	NWSE
2102	HAMILTON	LAW 1	PERKINS	11	35	12	SENW
3107	CORAL PROD	THEILER 4-9	PERKINS	11	36	4	NESE
2103	HAMILTON	RICHTER 1	PERKINS	11	39	4	NWNW
2101	PAN AMERICAN	NICHOLS CO 1	PERKINS	11	39	22	NWNE
2100	HAMILTON	NICHOLS CO 1	PERKINS	11	39	28	NWNW

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
2105	PAN AMERICAN	PERLINGER 1	PERKINS	12	36	19	NWSE
2104	JONES SHELBURNE	BREDER 1	PERKINS	12	37	33	SESE
2110	YOUNG	JOHNS 3-12	SCOTTSBLUFF	20	54	3	NWSW
2109	HOPE	GOODELL 1	SCOTTSBLUFF	21	57	7	SESW
2111	TUCKER & BEER	FINEGAN 1	SHERIDAN	24	41	20	SWSE
2138	HASENAUR	BRENNAN 1	SHERIDAN	26	41	20	NWSE
2115	TEXACO	MUSSER-MOSLER 1	SHERIDAN	26	42	10	NWSE
2113	SHELL	MEYERS LAND 1	SHERIDAN	26	44	17	SESE
2112	TEXACO	CALDWELL 1	SHERIDAN	26	44	20	SENW
2114	LUCERNE	KRAUSE 1	SHERIDAN	26	46	17	NENE
2116	TUCKER & BEER	HERMAN 1	SHERIDAN	27	44	19	SENE
2117	SHELL	JAGGERS 1	SHERIDAN	27	46	1	SESW
5139	SUPERIOR	SANDOZ 47-18	SHERIDAN	28	42	18	SESW
2118	TUCKER & BEER	ECKERLE 1	SHERIDAN	28	43	33	SWSE
2137	EQUITX	ORR 1	SHERIDAN	28	44	27	NENE
2131	TEXACO	SMITH 1	SHERIDAN	28	44	28	NENE
2130	TEXACO	NICKELS 1	SHERIDAN	28	46	3	SWSW
2120	TUCKER & BEER	NICKELS 1	SHERIDAN	28	46	14	SENE
2119	SHELL	JAGGERS 2	SHERIDAN	28	46	22	SENE
2128	BANNER	RAY 2	SHERIDAN	29	46	18	NWNW
2132	HARRISON	STATE 16-1	SHERIDAN	31	45	16	SWSW
2210	TRUE	MORRISON 11-17	SIOUX	24	54	17	NWNW
2165	BROOKS	BIRDSALL 1-6	SIOUX	24	56	6	NWNW
2177	BIRD	DOWNER 18-8	SIOUX	24	56	18	SENE
2207	COORS	VALLEY VIEW 1-16	SIOUX	24	57	16	NWSW
2139	MCELROY	NICKOLS 1	SIOUX	24	57	20	SESE
2198	BIRD	SPEAR DIA RCH 32-9	SIOUX	25	54	9	SWNE
2196	TRUE	ELLIOT 11-13	SIOUX	25	54	13	NWNW
2208	TRUE	ELLIOT 42-14	SIOUX	25	54	14	SENE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
2195	TRUE	FEIDLER 23-18	SIOUX	25	54	18	NESW
2204	TRUE	LEBAR 14-28	SIOUX	25	54	28	SWSW
2178	BIRD	BIRD-LAUCOMER 2-3	SIOUX	25	55	2	NENW
2199	BIRD	BIRD-DEITRICH 7-16	SIOUX	25	55	7	SESE
2193	TRUE	LAUCOMER 13-28	SIOUX	25	55	8	NWSW
2202	BIRD	BIRD-MURPHY 8-6	SIOUX	25	55	8	SENW
2200	SMOKEY	LAUCOMER 33-22	SIOUX	25	55	22	NWSE
2211	TRUE	WEILLS 33-25	SIOUX	25	55	25	NWSE
2189	BIRD	BIRD-CORMAN 11-16 2X	SIOUX	25	56	11	SESE
2187	BIRD	BIRD-CORMAN 11-16X	SIOUX	25	56	11	SESE
2182	BIRD	BIRD-CORMAN 11-16	SIOUX	25	56	11	SESE
2184	BIRD	BIRD-DEITRICH 13-3	SIOUX	25	56	11	NENW
2185	BIRD	BIRD-HUGHSON 12-7	SIOUX	25	56	12	SWNE
2194	TRUE	HUYGHSON 22-14	SIOUX	25	56	14	SENW
2201	BIRD	BIRD-HUGHSON 14-8	SIOUX	25	56	14	SENE
2192	TRUE	DUNCAN 32-28	SIOUX	25	56	28	SWNE
2163	CONTINENTAL	CONOCO-PERKINS 1	SIOUX	25	57	23	NESE
2164	CONTINENTAL	CONOCO-DUNCAN 35-1	SIOUX	25	57	35	NWSW
	COLORADO						
1	GINTHER	NOONEN RANCH 1	ADAMS	3S	59	24	SENW
15	RKY MTN PROD	UPRR JEK 34-9	ADAMS	3S	61	9	SWSE
5	LADMER	UPRR & GAIR 1	ADAMS	2S	60	9	SWNW
3	LION OIL	ROLOC 1	ADAMS	2S	62	14	NESE
6	JOHNSON	UPRR-AUSTIN	ADAMS	2S	65	17	SESE
2	USA CORPS ENG	RKY MTN ARSENAL 1	ADAMS	2S	67	26	NWNE
7	HUNT	KOCH 1	ADAMS	1S	68	34	SWNE
1592	SHAWNEE	RODMAN-STATE 1	LOGAN	7	52	1	NWSW

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1602	TENNECO	POMEROY 4-26	LOGAN	7	54	26	SWNE
1594	SHELL	STATE 2-B	LOGAN	8	53	16	NWSE
1595	BRITISH-AMERICAN	YENTER 18-B	LOGAN	8	54	3	NENW
1593	UTAH SOUTHERN	STATE 1-B	LOGAN	8	54	34	SWSE
1608	LEWIS AND CLARK	ARCO-SINDT 6-15	LOGAN	9	52	6	SWSE
1601	ROMAC	HOUSTON 20-1	LOGAN	9	52	20	SWSW
1596	SHELL	GREEN A-16	LOGAN	9	53	30	NWNW
2604	COUGAR	ROBERTS 1	LOGAN	10	49	2	NWSW
1598	DOHENY	MIDDELSTADT 1	LOGAN	10	53	23	SESE
1597	WESTERN CENTRAL	KESTER 1-28	LOGAN	10	55	28	SESW
1599	BRITISH-AMERICAN	SEGELKE 4	LOGAN	11	53	26	SENW
1606	PERLMAN	SEGELKE 1	LOGAN	11	53	26	NENE
1603	ENSERCH	CASEMENT TRUST 1-7	LOGAN	11	54	7	SENE
1600	AM PETROFINA	MCNISH 1	LOGAN	12	51	22	SESW
1607	SUN	ROELLE 1	LOGAN	12	53	24	SWNW
1605	TRANSIERRA	ROBERTS 1-32X	LOGAN	12	53	32	SENW
1623	LION	KAUFFMAN 1	MORGAN	1	56	18	SWSW
1624	HERNDON DRLG	HEGARTY 1	MORGAN	1	59	14	NWNW
1625	HUNT	HUEY 4	MORGAN	2	56	32	NWNE
1626	SUPERIOR	WEISS 45-32	MORGAN	3	55	32	NESW
1627	REASOR	PATTERSON 1	MORGAN	5	58	4	SENE
1632	TIDEWATER	WILLIAMS 7-30	MORGAN	5	60	30	SWSW
1630	ANDERSON-PRICH	BLANCHARD 1	MORGAN	6	55	11	SENE
1629	CARTER	BLANCHARD 1	MORGAN	6	55	11	SENE
1631	TWIN T DRLG	NICKLAS 1-10	MORGAN	6	57	10	SWNW
1628	LANDAUER	NEWROCK 1	MORGAN	6	59	21	NWNE
1633	OHIO	GALL 1	PHILLIPS	7	46	23	NESW
1635	TEXOTA	HANSEN 1	PHILLIPS	8	43	30	SWSW
1634	SUNRAY	HOTALING 1-A	PHILLIPS	9	43	27	NWSW

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1743	BEARD	HYATT FARMS 1	SEDGWICK	10	43	35	SWSE
1741	MORGAN	STATE 1	SEDGWICK	10	46	6	NWSW
1734	WESTERN OPER	GERK & BLOCKOWITZ	SEDGWICK	10	46	9	SWSW
1735	STUARCO	SPRAGUE 1	SEDGWICK	10	47	18	SESE
1740	INTERCONTINENTAL	STATE 3	SEDGWICK	10	47	12	NWSE
1739	INTERCONTINENTAL	N MARKS BUTTE S-2	SEDGWICK	10	47	12	NWSW
1742	GERBER	STATE 4	SEDGWICK	10	47	12	S2SW
1737	INTERCONTINENTAL	STATE 1	SEDGWICK	10	47	12	NESW
1736	VIERSON COCHRAN	DIECH 1	SEDGWICK	11	44	2	NWNE
1738	SOUTHLAND RYLTY	STATE 1-36	SEDGWICK	11	46	36	NWSW
1744	DEEP ROCK	ERNST 1	WASHINGTON	5S	49	6	NWSE
1745	DAVIS	GALBREATH 1	WASHINGTON	4S	50	3	NENE
1748	CHICAGO CORP	SCHEETZ 1	WASHINGTON	3S	51	11	SESW
1747	UNION TEXAS	JONES-DUPREE 4	WASHINGTON	3S	51	26	SENE
1761	CONOCO	STATE 16-1	WASHINGTON	3S	56	16	NWNW
1750	LION	THIM 1	WASHINGTON	2S	50	23	SWNE
1751	AMERADA HESS	HEYEN 1	WASHINGTON	2S	52	7	NWSE
1752	SOHIO	KEJR 5-C	WASHINGTON	2S	56	11	NENE
1753	CARTER & FOSTER	VORCE 1	WASHINGTON	1S	49	28	NENE
1757	SKILES	BROWER 1	WASHINGTON	1	49	34	SENE
1758	CARTER	GLADE-STANSFIELD 1	WASHINGTON	3	50	35	NESE
1760	HUNT	SCHMIDT 1-28	WASHINGTON	4	53	28	NWNW
1759	HUNT	BRUNKHARDT 1-33	WASHINGTON	5	54	33	SWSE
1969	H & M OIL PROD	STANGER 1	WELD	1	62	27	SESE
1765	WHITTAKER	UPRR 1	WELD	1	62	33	NWSE
1764	WHITTAKER	KLAUSNER 1	WELD	1	62	34	NESE
1915	ENERGY MINERALS	JAMES 1	WELD	2	61	31	SWNE
1772	SHELL	PROSPECT ROYALTY 1	WELD	2	62	5	NESW
1768	BAIRD AND PREIFER	MADDUX 1	WELD	2	63	28	NENE

WELL OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1940 CHICAGO	KATCHEN 1	WELD	2	65	3	SWNE
1774 CONTINENTAL	PROSPECT ROYALTY 1	WELD	3	61	3	SW
1909 PLANET	PAINTER 1	WELD	3	61	11	NENE
1941 MURPHY	STATE 1	WELD	3	62	26	SWSW
1987 AMOCO	UPRR 39 PAN AM F	WELD	3	65	5	NESW
1775 KING	ORR 1-A	WELD	4	62	27	NENW
1776 BRITISH AMERICAN	UPRR 1-C	WELD	4	63	21	SWSE
1777 SHARPLES	EHRLICH 1	WELD	4	64	4	SENW
1975 NORDIC	KAMMERZELL 1-5	WELD	4	66	5	SWSE
1780 OHIO	NORDLOH 1	WELD	5	63	20	SESE
1781 CALIFORNIA	HAYES 1	WELD	5	66	20	SENE
1785 EISENHOWER DRLG	NILES 1	WELD	6	61	13	SWSE
1787 TENNESSEE GAS	BOLIN 1	WELD	6	61	18	NWNW
1784 JOHNSON	SANDER 1	WELD	6	64	30	SWSW
1986 COORS	LYSTER 8-26	WELD	6	65	26	SWSE
1800 SHELL	WILSON 1	WELD	7	59	20	SESW
1966 DOME	DOME-HILL 1-6	WELD	7	60	6	SESE
1901 DUNWICK	WEITZEL 1	WELD	7	61	12	NESE
1802 BRITISH AMERICAN	HENRICH 1	WELD	7	61	14	SESE
1889 TEXACO	BENDER 1	WELD	7	63	11	NWNE
1957 ENSERCH	DIXON 1-28	WELD	8	58	28	SESE
1819 HELMERICH PAYNE	SNYDER 1	WELD	8	58	34	NWSE
1862 SHELL	COLO NATL BANK 1	WELD	8	60	12	NENE
1861 FALCON SEABOARD	DUELL 1	WELD	8	61	11	NWSE
1934 ST MICHAEL	GRACE-WISE 19-1	WELD	8	61	19	NW
1849 BRITISH AMERICAN	WISE 1	WELD	8	61	19	SWNW
1972 ST MICHAEL	CENSOR 13-28	WELD	8	61	28	NWSW
1832 WEAVER	HEINZE 1	WELD	8	61	29	NESE
1935 ST MICHAEL	GRACE-MARATHON 3-1	WELD	8	62	3	NENW

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
1982	SUN	SHARK FED 1	WELD	8	63	3	SESE
1858	SUPERIOR	BALL 16-14	WELD	8	63	14	NWSW
1996	UPRR	COAL CK FED 6-1	WELD	8	63	32	NE
1886	CHEVRON	UPRR-JONES-USA 1	WELD	8	64	18	NENE
1864	ROGERS	LOVE-MCFARLIN 1	WELD	8	65	4	NENW
1837	CALIFORNIA	UPRR PERCH 1	WELD	8	66	27	SENE
1871	SHELL	NICKLAS 1	WELD	9	56	17	SENW
1872	GLASSCOCK	BRADBURY 1	WELD	9	58	15	NENW
1902	MCCULLOCH	STATE 1-16A	WELD	9	59	16	SESE
1899	MCCULLOCH	GOVT 1-18	WELD	9	59	18	NWNW
1911	BENNETT	RAINBOW-SCHULL 1	WELD	9	59	31	SWNW
1900	MCCULLOCH	STATE 1-36	WELD	9	59	36	NENW
1896	MCCULLOCH	STATE 1-16	WELD	9	60	16	SWSW
1897	MCCULLOCH	STRASSER 1-27	WELD	9	60	27	NENE
1990	AZTEC RESOURCES	BACHOR 1-A	WELD	9	61	5	SESE
1877	SHERROD	STEINKE-GILLETTE 2	WELD	9	61	8	NWNE
1875	OKLAHOMA	GILLETTE 14	WELD	9	61	9	NWNW
1876	SHERROD	MILES & GILLETTE 8	WELD	9	61	9	NWNW
1878	CONTINENTAL	SCHEETZ 1	WELD	9	61	9	NWNE
1874	SHERROD	WILLIAMSON 2	WELD	9	61	9	NWSW
1873	SHERROD	MILES & GILLETTE 9	WELD	9	61	9	NWSE
1870	CONTINENTAL	PERRY 1	WELD	9	61	13	SWNW
1866	CHRISTMANN	GIBBS 1	WELD	9	61	28	SWSW
1932	GEMINI	FRANKS 2	WELD	9	61	33	SWSE
1894	DUNWICK	SOHIO-STATE 2	WELD	9	61	36	SWNE
1997	FELMONT	CLARK 1-3	WELD	9	62	3	SWNW
1867	SHERROD	RENSICK 1	WELD	9	62	27	SWNE
1880	SHELL	FEDERAL 1-4728	WELD	10	56	18	NWSE
1967	MARATHON	MARATHON-AVALO 1-32	WELD	10	56	32	SENE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
2003	NERDLIHC	TOEDTLI 1-10	WELD	10	57	10	NESW
2001	NERDLIHC	SHAPLEY 1-25	WELD	10	57	25	SESW
1924	MARATHON	HORSETAIL CK 1-36	WELD	10	57	36	NWNW
2000	EDDY	LUCKY LADY 16-4	WELD	10	60	16	NWNW
1942	LA GLORIA	MINERAL FEE 1	WELD	10	61	25	SENE
1879	OHIO	MCVICAR-GOVT 1	WELD	10	62	30	SWNE
1925	BLACK DAHLIA	STATE 1	WELD	10	62	36	SWSW
1978	ANADARKO	COLO-STATE A-1	WELD	10	64	10	SENE
1995	UPRR	WECO STATE 2B-28 1	WELD	10	67	28	NE
1884	SHELL	BIGGS 1	WELD	11	57	2	SESW
1883	SHELL	KLINGINGSMITH 1	WELD	11	59	1	SESE
1882	TEXAS CRUDE	COX 1-A	WELD	11	64	5	NWSW
2025	FARMER	VAN METER 1	YUMA	5S	42	30	SWSE
2062	TAYLOR	GOVT 1	YUMA	5S	43	2	NWSE
2063	PLAINS	LIPPLEMAN 1	YUMA	5S	46	30	NENE
2066	MCDANNALD	YOUNG 1	YUMA	5S	47	21	NWSW
2064	PLAINS	GULLEY 1	YUMA	5S	47	25	SWSW
2024	LEBSACK	WATMORE 1	YUMA	5S	48	30	NWSW
2083	CABOT	STATE 16-16	YUMA	4S	42	16	SESE
2071	INTL NUCLEAR	TERRY 1	YUMA	4S	42	19	SESW
2072	INTL NUCLEAR	WILEY 1	YUMA	4S	42	33	NESE
2027	STERLING	WALZ 1	YUMA	4S	43	3	SWNE
2084	AMOCO	DICKSON B-1	YUMA	4S	43	22	SESE
2026	DAVIS	SMITH 1	YUMA	4S	48	8	NWNE
2030	GADDIS	KAMLA 1-A	YUMA	3S	42	17	NENE
2029	FARMER	RODGERS 1	YUMA	3S	42	20	SESE
2028	GRYNBERG	WARNER 1	YUMA	3S	42	31	NWNW
2065	TAYLOR	WINGFIELD 1	YUMA	3S	43	31	NENW
2067	KATZ	DEIKMAN	YUMA	3S	44	31	NENE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
2031	PLAINS	HIMES 1	YUMA	3S	46	4	NWSW
2061	CALIFORNIA	MUMM 1	YUMA	3S	48	1	NENE
2036	PHILLIPS	ANDREWS 1	YUMA	3S	42	14	NWNW
2068	TIGER	VAN DYKE 1	YUMA	2S	42	15	NENE
2069	TIGER	VAN DYKE 1-21	YUMA	2S	42	21	SWNE
2089	LIVERMORE	GREEN 1	YUMA	2S	43	8	SWNE
2079	MOUNTAIN PET	SMITH 1-11	YUMA	2S	43	11	NESW
2034	ITIO	STRANGWAYS 1	YUMA	2S	43	21	NWSW
2035	MARATHON	ALLISON 1	YUMA	2S	46	14	NESW
2032	CALIFORNIA	RUTLEDGE 1	YUMA	2S	47	27	SENW
2033	DAVIS	RUTLEDGE 1	YUMA	2S	47	28	NENE
2076	MCARTHUR	WILLOW CK RANCH 1	YUMA	1S	42	21	SWSE
2070	CLEARY	CLEARY-BRETHAUER 1	YUMA	1S	42	27	NWSE
2038	MARATHON	ALLISON 1	YUMA	1S	44	32	SENE
2078	TRANS DELTA	REIBOLDT 1	YUMA	1S	45	17	NENE
2042	JOHNSON	ROCKWELL 1	YUMA	1S	45	18	NWNW
2041	KINNEY	ROCKWELL 1	YUMA	1S	45	18	NENW
2039	WARD	DICKSON 1	YUMA	1S	45	26	NESW
2045	MARATHON	WHITE 1	YUMA	1S	46	3	NESE
2088	SUN	FAY STATE 1	YUMA	1S	46	36	SENE
2043	DAVIS	BLOMSTROM 1	YUMA	1S	47	9	SWSW
2040	TEXAS COMPANY	BLACH 1	YUMA	1S	47	19	SWSW
2037	CONTINENTAL	STULP 1	YUMA	1S	47	33	NWSW
2046	AMERADA	WAKEFIELD 1	YUMA	1	45	30	SENW
2048	US SMELTING	STULP 1-1	YUMA	1	47	1	SW
2047	MANNING	HENIK 1	YUMA	1	48	8	NWSE
2077	TRANS DELTA	CERES LAND 1	YUMA	2	42	9	NWNW
2082	GIBSON WELL SVC	LAIRD-STATE 1	YUMA	2	42	16	NWSW
2050	JOHNSON	STATE 1	YUMA	2	42	16	SWSW

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
2086	HIGH SUMMIT	MENTER 1	YUMA	2	42	17	NESE
2049	PANHANDLE PROD	NICKLAS 1	YUMA	2	42	17	SESE
2051	TENNESSEE	NICKLAS 1-A	YUMA	2	42	17	NESE
2085	DEPCO	SEWARD 41-21	YUMA	2	42	21	NENE
2053	SHELL	LASHER 1	YUMA	2	44	5	SENE
2081	KANSAS-NEBRASKA	BRAND 11-3	YUMA	2	47	3	NWNW
2052	LION	CHRISHER 1	YUMA	2	48	2	SWSE
2080	J-W OPERATING	KITZMILLER 2	YUMA	3	45	4	NWNW
2059	SHELL	KENNIE 1	YUMA	4	43	1	SWNE
2058	JOHNSON	PYLE 1	YUMA	4	45	18	NWSW
2057	BROWN	PYLE 1	YUMA	4	45	21	NENW
2074	MESA	KITZMILLER 1-32	YUMA	4	45	32	SESE
2054	OHIO	KITZMILLER 1	YUMA	4	45	32	SESE
2075	MESA	KITZMILLER 1-33	YUMA	4	45	33	NWNW
2055	OHIO	BROPHY 1	YUMA	4	46	31	SESW
2087	STELBAR	FRANSON 1	YUMA	4	47	3	SENW
2056	SHELL	OLSEN 1	YUMA	4	48	21	SENE
2060	CANADA SOUTHERN	NIEMAN 1	YUMA	5	46	10	NWSW
	WYOMING						
68	CONOCO	ELLIS 3	GOSHEN	19	65	3	SESW
64	GENL AMERICAN	HAWK-FEE 1-2	GOSHEN	20	62	2	NWNW
65	PHILLIPS	HAWK-FEE 1-35	GOSHEN	21	62	25	SESW
67	TRUE	LANE 13-25	GOSHEN	22	62	25	NWSW
59	SHELL	STATE 42X-9	GOSHEN	25	64	9	SENE
58	SHELL	GOVT 12-13	GOSHEN	25	65	13	SWNW
91	WOLVERINE	CHILDERS 13-7	LARAMIE	12	65	7	NWSW
84	TRANS-TEXAS	UPRR-PALM 1-21	LARAMIE	13	62	21	SESW

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
83	TRANS-TEXAS	MILLER 1-18	LARAMIE	13	63	18	SESW
69	CALIFORNIA	KING 1	LARAMIE	13	68	13	NWSW
70	GINTHER	FRITZ 1	LARAMIE	14	61	36	SENE
89	WOLVERINE	HUTCH 44-20	LARAMIE	15	62	20	SESE
88	AMOCO	BASTIAN 1-21	LARAMIE	15	62	21	NESE
85	AMOCO	LOUTH 1	LARAMIE	15	62	26	NENE
81	AMOCO	CHAMPLIN 318-1	LARAMIE	15	62	29	NENW
71	GLOBE	WARREN LIVESTOCK	LARAMIE	15	66	11	SWSW
86	TEXACO	LORENZ 1	LARAMIE	15	70	25	SENE
80	AMOCO	CHAMPLIN 564-1	LARAMIE	16	60	31	SWNW
72	PURE	RINEHART 1	LARAMIE	16	61	22	SESW
78	GROSS	SCHEEL 1	LARAMIE	16	61	26	SWSW
82	UNION TEXAS	HANSON 28-2	LARAMIE	16	61	28	NWNW
79	DAVIS	BERRY 1	LARAMIE	16	66	13	NWSW
77	SOUTHERN MINS	ROMSA 1-26	LARAMIE	17	62	26	NENE
87	MOBIL	T84X-31G	LARAMIE	17	68	31	SENE
73	GENERAL	GOVT 78-31G	LARAMIE	17	68	31	SESE
76	OCCIDENTAL	MATHIEU 1	LARAMIE	19	67	3	SENW
75	GULF	JORDAN-FED 1	LARAMIE	19	69	29	NESW
845	EXXON	JACKSON 1	PLATTE	21	65	33	NWNW
837	OBERMAN	HOME RANCH 1	PLATTE	21	68	30	NWSE
843	BASS	GOERTZ 20-13	PLATTE	22	66	20	SENW
848	AMOCO	LEUVEN 1	PLATTE	22	66	28	SWNE
844	BASS	BASS 16-31	PLATTE	23	66	16	NWSE
838	WITTENBERGER	MCLEOD 1	PLATTE	23	69	26	SESW
821	GENERAL	GOVT 34-15G	PLATTE	24	66	15	SENW
822	SEABOARD	WILSON 1	PLATTE	25	65	29	SWSW
823	JACOBS	GRAYROCK 1	PLATTE	25	66	13	NENW

KANSAS

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
3036	BEARD	MILLS RANCH 1	CHEYENNE	1S	40W	8	SENE
3037	FARMER	CRABTREE 1	CHEYENNE	1S	40	14	SESE
3038	SHAKESPEARE	WHITE 1	CHEYENNE	1S	40	20	NENE
3039	OHIO	ROSE 1	CHEYENNE	1S	40	35	NENE
3040	SOWLE	FIEBLER 1	CHEYENNE	1S	40	35	NWNW
3041	JENKINS	OCHSNER 1	CHEYENNE	1S	41	30	NWSE
3042	CABOT	PALMER 1	CHEYENNE	1S	41	30	NESW
3043	MURFIN	PALMER 1-30	CHEYENNE	1S	41	30	SWNW
3045	DEEP ROCK	CLARK 1	CHEYENNE	1S	42	23	SWSW
3047	TIGER	HILT 1	CHEYENNE	1S	42	36	NESE
3049	MURFIN	HILT 1-36	CHEYENNE	1S	42	36	SWSE
3065	FARMER	WAGNER 1	CHEYENNE	2S	40	15	SWSW
3066	HAWTHORNE	TOPPING 11-7	CHEYENNE	2S	40	7	NWNW
3067	MACK	COOK 1	CHEYENNE	2S	40	9	SESE
3068	PAN AMERICAN	CARMICHAEL 1	CHEYENNE	2S	40	14	SESE
3069	SMITH	SWEYGARDT 1	CHEYENNE	2S	40	34	SWSW
3070	ATHENS	RATH 1	CHEYENNE	2S	41	11	NWNW
3071	F & M	NORTHRUP A 1	CHEYENNE	2S	41	19	NWSE
3072	HAWTHORNE	OLEARY 13-21	CHEYENNE	2S	41	21	NWSW
3073	MACK	RAILE 1	CHEYENNE	2S	41	25	SESE
3074	ATHENS	ZIMBLEMAN 1	CHEYENNE	2S	41	28	SW
3076	CITIES SERVICE	RAILE 1	CHEYENNE	2S	42	24	NWSW
3077	CITIES SERVICE	NORTHRUP C 1	CHEYENNE	2S	42	25	SWNW
3079	CITIES SERVICE	NORTHRUP A 2	CHEYENNE	2S	42	26	NESE
3081	CITIES SERVICE	NORTHRUP A 1	CHEYENNE	2S	42	26	NWSE
3082	CITIES SERVICE	NORTHRUP B 1	CHEYENNE	2S	42	26	SENW
3083	CITIES SERVICE	NORTHRUP A 3	CHEYENNE	2S	42	26	SESE

WELL	OPERATOR	WELL NAME	COUNTY	TWP	RGE	SEC	SPOT
3084	CITIES SERVICE	NORTHRUP A 4	CHEYENNE	2S	42	26	SWSE
3086	ATHENS	SWEYGARDT 1	CHEYENNE	2S	42	34	SESE
3087	HILLEN-SIMON	OCHSNER 31616121	CHEYENNE	2S	41	16	NWSW

APPROVAL OF EXAMINING COMMITTEE

Alan C. Donaldson

Alan C. Donaldson, Ph.D.

Robert C. Shumaker, Ph.D.

Thomas W Kammer

Thomas W. Kammer, Ph.D.

Thomas H. Wilson

Thomas H. Wilson, Ph.D.

Royal J. Watts

Royal J. Watts, M.S.

Richard A. Smosna, Ph.D., Chair

1/18/97

Date