SHALLOW MARINE DEPOSITS IN THE UPPER CRETACEOUS PIERRE SHALE OF THE NORTHERN DENVER BASIN AND THEIR RELATION TO HYDROCARBON ACCUMULATION

by

Louise W. Kiteley[1]

ABSTRACT

Recent surface and subsurface study of the Upper Cretaceous Pierre Shale in the northern Denver basin has established a regional lithologic and time-stratigraphic framework for sandstone units within the Pierre Shale. Paleontologic information indicates that the "Shannon" and "Sussex" sandstones of informal subsurface usage of drillers in the Denver basin are entirely different in age and depositionally unrelated from the type Shannon and Sussex Sandstone Members of the Upper Cretaceous Steele Shale in Wyoming. Instead, stratigraphic correlations indicate that the so-called "Shannon" and "Sussex" sandstones are approximately equivalent to the Parkman Sandstone Member and younger beds of the Upper Cretaceous Mesaverde Formation in the Powder River basin. For these reasons, the outcrop names — Hygiene and Terry Sandstone Members of the Pierre Shale — should be used in the place of "Shannon" and "Sussex" in the Denver basin.

In the northern Denver basin the upward increase in a northwestward direction from Boulder, Colorado, of sandstone interbeds within the Pierre Shale indicates a major eastward regression of the strandline. Analyses of outcrop data suggest that the lower third of the Pierre was deposited in open-marine environments, the middle third in shallow marine environments, and the upper third in open-marine to very near shore environments. Computed rates of deposition for the Hygiene and Terry Sandstone Members indicate that the source of sand for these members probably was a delta, which lay to the north and northwest in north-central Colorado and south-central Wyoming. Stratigraphic relations and computed rates of deposition of the Hygiene Sandstone near Boulder, Colorado, where it is thickest, indicate rapid accumulation in a locally subsiding basin. The rapid accumulation in this area, where both the Hygiene and Terry produce oil and gas, is believed to have favored preservation of potential source rocks. Hydrocarbon accumulation in producing sands is in an area of facies change from sand to lower energy siltstones and shales.

The criteria for production at Spindle-Surrey and Singletree oil fields are (1) a local subsiding basin, in which rapid accumulation of fine-grained sediments produced a favorable regime for preservation of potential source rocks; and (2) potential reservoir sandstones lying above and updip from these source rocks. At present it appears that these criteria are unique to these fields. However, elsewhere in the northern Denver basin similar but smaller petroleum pools may be found either where the above-mentioned criteria are met, or where favorable reservoir rocks are found updip from potential source rocks and marginal to areas shown by isopach maps of the Hygiene and Terry. In the Pierre Shale, the Rocky Ridge, Larimer, and Richard Sandstone Members, and member A (unit A of Kiteley, 1976) offer favorable reservoir conditions for future exploration in many parts of the northern Denver basin. Members B and C (units B and C of Kiteley, 1976) are less favorable than the more deeply buried member A, because of lowered porosity and permeability in member B, and probable communication with surface waters in member C.

[1] U.S. Geological Survey, Box 25046, Denver Federal Center, Denver, Colorado 80225.

AREA AND PURPOSE OF REPORT

This study establishes a regional lithologic and time-stratigraphic framework for Upper Cretaceous strata in the northern Denver basin (Ts. 1-24 N., Rs. 54-70 W.), Colorado and Wyoming, and delineates depositional patterns of sandstone units within the Pierre Shale. The Upper Cretaceous Pierre Shale, consisting of sandstone, siltstone, and noncalcareous shale, lies above the chalky Niobrara Formation and below the Fox Hills Sandstone, both of Late Cretaceous age. Members of the Pierre Shale discussed in this paper are those of the so-called middle third and part of the upper third (Porter, 1976, p. 253) of the Pierre Shale; from base to top, these are the Hygiene, Terry, Rocky Ridge, Larimer, and Richard Sandstone Members, and member A of Kiteley (1976). All sandstone members are separated from one another by intervals of shale or sandy shale and hence are easily distinguishable in the field. This study was initiated for two reasons:

(1) Available paleontologic information indicated that the subsurface sandstone units of the Pierre in the northern Denver basin were not age equivalents of the Shannon and Sussex Sandstone Members of the Steele Shale, and Parkman Sandstone Member of the Mesaverde Formation of the Powder River basin, and (2) previously undescribed and untested sandstone units that may have potential for future petroleum exploration exist within the upper part of the Pierre Shale in the northern Denver basin.

SOURCES OF DATA AND ACKNOWLEDGMENTS

Data on environments of deposition, regional shoreline trends, and reservoir quality of sandstones within the Pierre Shale have been gathered from outcrops along the east flanks of the Front and Laramie Ranges. Well log data used in subsurface correlation of outcropping units are from the Rocky Mountain Well Log Service and American Stratigraphic Co.

The author would like to express her gratitude to several U.S. Geological Survey colleagues who provided helpful suggestions and support during the course of this study. All megafaunal collections were identified by W. A. Cobban, who, in the company of E. Allen Merewether and G. R. Scott, provided invaluable aid in field collections of megafossils. J. D. Powell, identified foraminiferal collections and offered suggestions on environments of deposition of the Pierre Shale. E. D. McKee aided in identification of sedimentary structures of sandstone members in the Pierre and provided helpful suggestions regarding hydrodynamic interpretation.

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REGIONAL STRATIGRAPHY

The Pierre Shale was deposited in the western interior Upper Cretaceous seaway that extended southeastward from the Arctic Ocean to the Gulf of Mexico (Fig. 1). The eastern shore of the seaway was a low stable cratonic platform in the central part of the United States and Canada. This area appar-

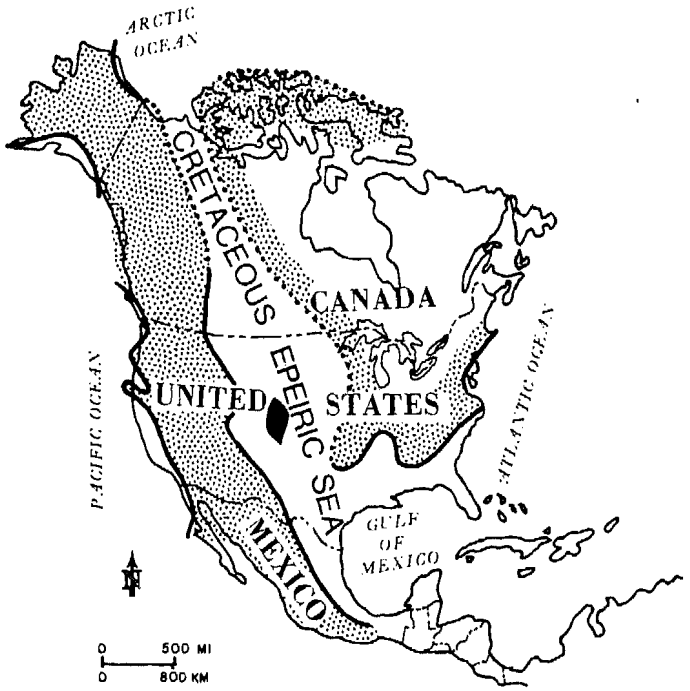

Fig. 1 — Probable distribution of land and sea in North America during late Campanian time showing the geographic position of the Cretaceous seaway that divided the continent into eastern and western parts. Area of Denver basin shown in west-central part of the seaway. (Modified from Gill and Cobban, 1973.)

ently supplied clay-sized sediment, which forms the bulk of the formation in many areas. The source of course terrigenous sediment for sandstone members, which wedge out eastward in the Pierre Shale, was an area of highlands to the west of the northern Denver basin in Nevada and Utah. The sandstones were deposited in shallow water environments along the western shore of the seaway. The approximate position of strandlines during deposition of sandstones in the middle part of the Pierre, as proposed earlier by Gill and Cobban (in McGookey et al, 1972), is shown in Figure 2. These sandstones include, from base to top, the Hygiene, Terry, and Rocky Ridge Sandstone Members. Both the Hygiene and Terry produce oil and gas from stratigraphic traps (Moredock and Williams, 1976) in a large

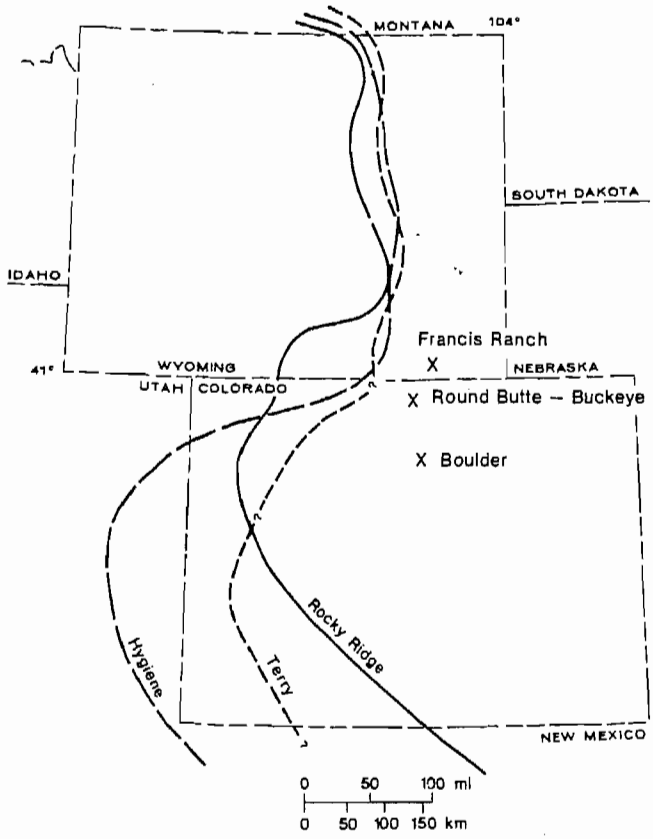

Fig. 2 — Approximate positions of strandlines in Late Cretaceous time during deposition of the Hygiene, Terry, and Rocky Ridge Sandstone Members of the Pierre Shale, as proposed by Gill and Cobban (in McGookey et al, 1972). X, location of key measured section of the Pierre Shale.

area east of Boulder. Sandstone sequences in the Hygiene Sandstone Member of the Pierre Shale are upward coarsening, fine to medium grained, burrowed, glauconitic, thick bedded, and highly crossbedded, especially at the tops of beds. The Terry Sandstone Member of the Pierre, mostly poorly exposed along the mountain front, differs from the Hygiene in that beds are planar to ripple laminated with numerous concretion horizons indicating that deposition took place more slowly. Using the average time span for ammonite zones as determined by Gill and Cobban (1973), I have determined that average rates of deposition were 934 ft per million years (285 m/my) for the Hygiene, as compared to 142 ft per million years (43 m/my) for the Terry. Stratigraphically younger sandstones in the Pierre, including the Rocky Ridge, Larimer, and Richard Members, and members A, B, and C are generally fine to medium grained, crossbedded at low to high angles, and burrowed. Environments of deposition of these sandstones, were probably very near shore, as opposed to shallow marine for the glauconitic Hygiene and Terry.

At the Round Butte-Buckeye and Boulder localities (Fig. 2), the Pierre Shale contains abundant marine fossils, including ammonites and inoceramids. The Pierre on the west side of the Denver basin has been zoned by W. A. Cobban of the U.S. Geological Survey. At the Francis Ranch locality (Fig. 2), the Pierre contains less abundant marine fossils than at Round Butte-Buckeye or Boulder. Correlation of these three dated, measured surface sections with well logs provides a time-stratigraphic framework for subsurface lithologic units.

Members of the Upper Cretaceous Pierre Shale measured at Round Butte-Buckeye, Boulder, and Francis Ranch are shown in Figure 3. Western Interior Cretaceous fossil zones found in these members are indicated on the left side of Figure 3, but some zones were omitted for simplicity. Each ammonite zone represents, on the average, a time span of about 0.5 million years (Gill and Cobban, 1973). The section measured at Francis Ranch includes all the members of the Pierre shown in Figure 3. Interstratified between the sandstone members — the Hygiene, Terry, Rocky Ridge, Larimer, Richard, and informal members A and C — are locally thick unnamed units of shale, sandy shale, and siltstone which commonly contain one or two ammonite zones.

SERIES	STAGE	WESTERN INTERIOR Zone Fossils	FORMATIONS IN THE NORTHERN DENVER BASIN	
Upper Cretaceous	Campanian	*Scaphites (Coahuilites)*	FOX HILLS SANDSTONE *	
		Baculites clinolobatus	MEMBER C	PIERRE SHALE
		Baculites baculus	MEMBER B	
			MEMBER A *	
		Baculites jenseni- *Baculites reesidei*	RICHARD, LARIMER, AND ROCKY RIDGE SANDSTONE MEMBERS *	
		Exiteloceras jenneyi	TERRY SANDSTONE MEMBER *	
		Baculites scotti- *Baculites gregoryensis*	HYGIENE SANDSTONE MEMBER	
		Baculites perplexus- *Baculites asperiformis*	MITTEN BLACK SHALE MEMBER	
		Baculites obtusus	SHARON SPRINGS MEMBER	
		Baculites sp. (smooth)	GAMMON FERRUGINOUS MEMBER	
		Scaphites hippocrepis III	NIOBRARA FORMATION	

Fig. 3 — Generalized sequence and selected Western Interior Upper Cretaceous zone fossils of the Pierre Shale and Fox Hills Sandstone in the northern Denver basin. *, interbeds of shale.

STRATIGRAPHY

Members of the lower and middle third of the Pierre Shale in the Denver basin, as first used by Griffitts (1949) and

modified by Kiteley (1976), and correlative units in the Powder River basin are shown in Figure 4. The so-called "Shannon" of informal subsurface usage of the Denver basin is equivalent to the Parkman Sandstone Member of the Mesaverde Formation of the Powder River basin on the basis of fossil evidence (Kiteley, 1976) and thus is much younger than the type Shannon Sandstone Member of the Steele Shale of the Powder River basin. Therefore, I propose that the following changes be made in the subsurface nomenclature of the Denver basin: the use of informal subsurface drillers' names "Shannon" and "Sussex" should be abandoned, the Hygiene Sandstone Member should be used in place of "Shannon," and the Terry Sandstone Member should be used in place of "Sussex."

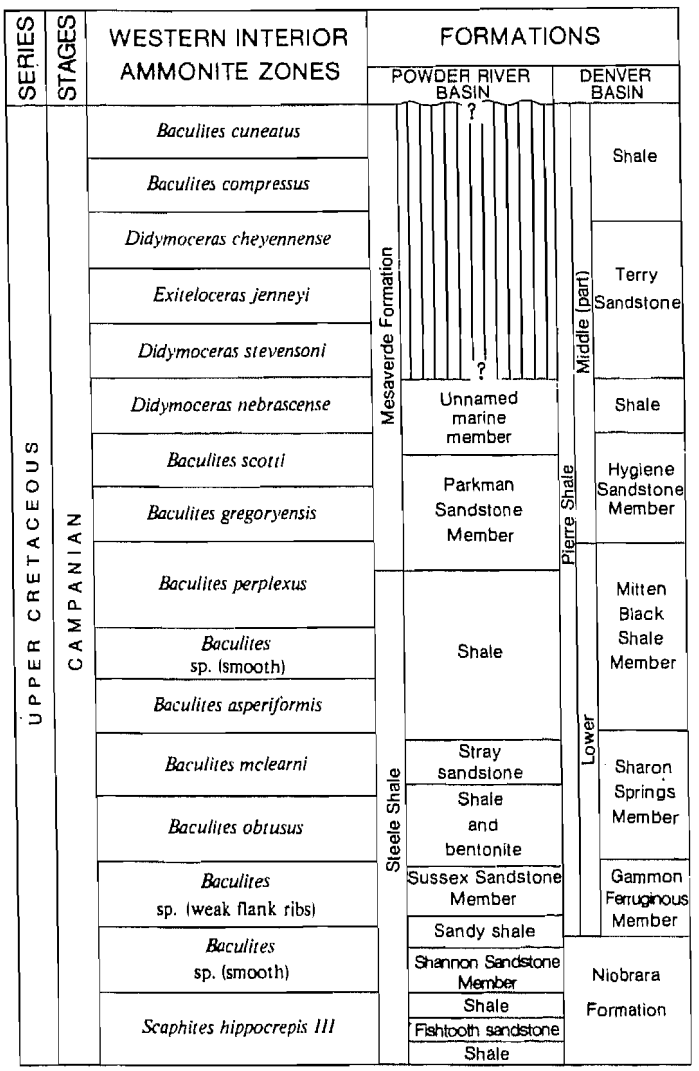

Fig. 4 — Chart showing members of part of the Pierre Shale in the Denver basin and correlative units in the Powder River basin, Wyoming (modified from Gill et al, 1970).

Cross sections utilizing outcrops and well logs have been prepared for the Denver basin along the three lines of section shown on Figure 5. Oil fields that produce from sandstones within the Pierre Shale are located only in northeastern Colorado. These are the Loveland, Boulder, Singletree, Spindle-Surrey, New Windsor, Antelope, and Hambert fields. All oil fields shown in Wyoming produce from Lower Cretaceous rocks. In general, sandstones in the Pierre form thick wedges along the east flanks of the Front Range and Laramie Mountains. These wedges show a gradual thinning eastward into the basin, where a lateral facies change from sandstone to siltstone and shale occurs. An upward increase in the number and thickness of these sandstone tongues (members A, B, and C) occurs from about Fort Collins northward.

Cross section A-A' (Fig. 6) shows diagrammatically the eastward thinning of the Hygiene, Terry, and combined Rocky Ridge, Larimer, and Richard Sandstone Members in the middle part of the Pierre Shale in southeastern Wyoming. Time lines within the Pierre generally follow formational boundaries in this cross section.

Cross section B-B' (Fig. 7) (see Kiteley, in press) shows the stratigraphic relations of sandstone members in the middle third of the Pierre Shale from north to south in the Denver basin. The Hygiene Sandstone Member in the vicinity of Round Butte-Buckeye consists of two thin lenticular sandstones that intertongue with a wedge of southward thickening sandy shale. The overlying Terry Sandstone Member consists of two or three lenticular sandstones ranging in age from *Didymoceras stevensoni* to D. *cheyennense* zone. *Exiteloceras jenneyi*, normally associated with the Terry Sandstone Member in Colorado, has not been found at localities to the north of Round Butte-Buckeye. The time line marking the zone of *Baculites scotti* occurs at about the middle of the Hygiene Sandstone Member. This time line, as well as the base of the Hygiene Member, which is approximately in the position of *B. perplexus*, drops stratigraphically from north to south in relation to the *D. nebrascense* datum above. According to these time relationships, the thick wedge of dominantly fine clastic sediments in the Hygiene east of Boulder (Figs. 7 and 8) appears to have accumulated in a locally subsiding basin.

Rates of sedimentation strongly suggest that the Hygiene was deposited near a local source area that was probably the delta first postulated by Weimer (1961) on the basis of stratigraphic studies and later delineated by Gill and Cobban (1973) on the basis of ammonite distribution located in north-central Colorado and south-central Wyoming. A coaly sequence, as much as 75 ft (25 m) thick, has been reported by Hail (1965) in the Hygiene equivalent in northwestern North Park, Colorado. This delta, which may have originated in northwestern Colorado

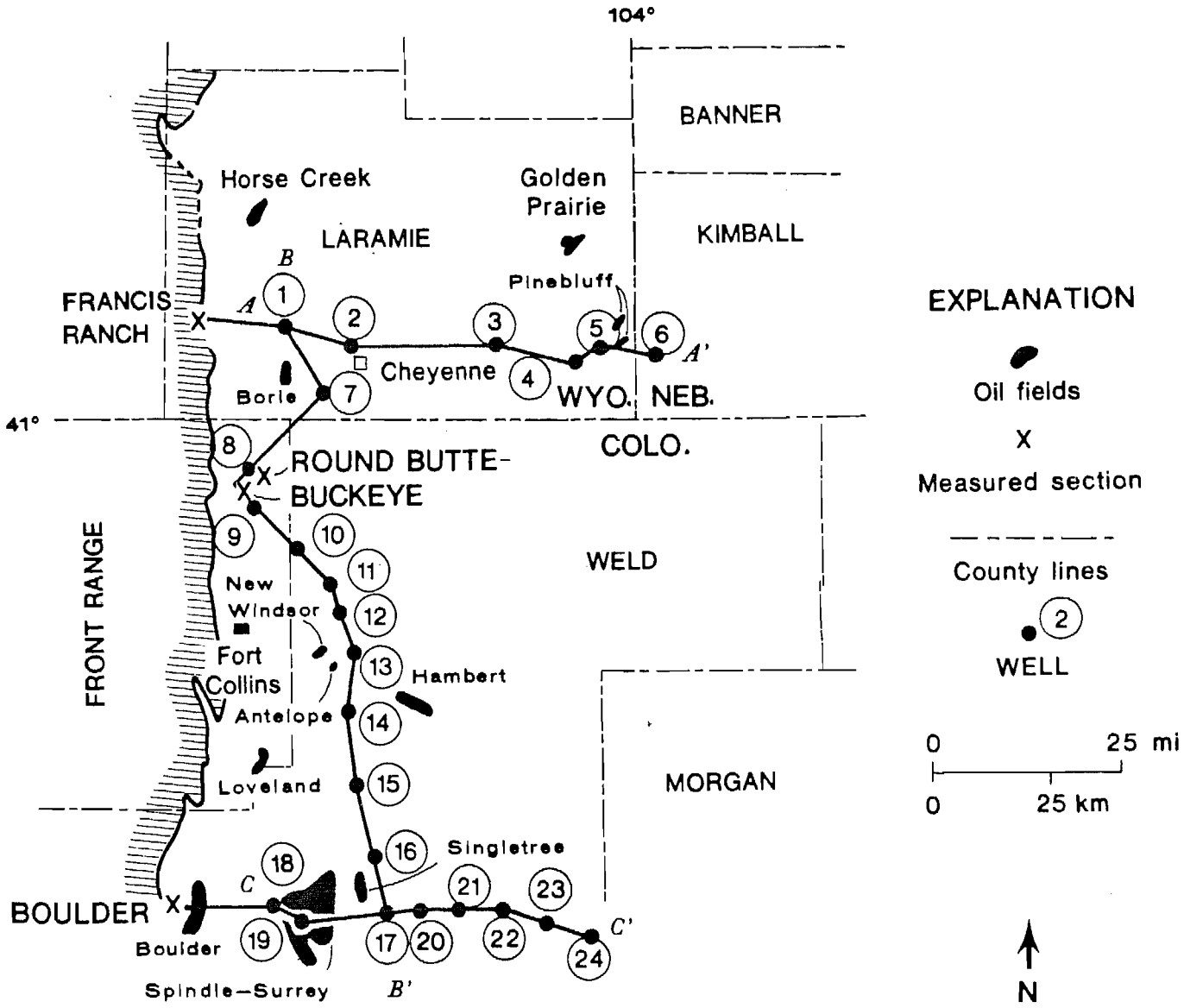

Fig. 5 — Map showing lines of cross sections (shown in Figures 6, 7, and 8) and selected oil fields in the Denver basin.

(Weimer, 1970), brought sediment eroded from the highland area into the Late Cretaceous seaway. This sediment was then carried southward by longshore currents to the area of high sedimentation rates in the Hygiene and Terry near Boulder.

Cross section C-C' (Fig. 8) (Kiteley, in press) shows stratigraphic relations of the Hygiene and Terry Sandstone Members from west to east through the Spindle-Singletree fields east of Boulder. In outcrop near Boulder, the Hygiene Member is sandstone, but it changes facies to sandy shale just to the east in the subsurface and then wedges out into shale. The Terry Sanstone, above the Hygiene, is extremely thin to absent in outcrop at Boulder but is represented in the subsurface to the east by lenticular sandstones encased in marine shales. The oldest of these sandstones prograded eastward toward the basin. Stratigraphically younger sandstones were deposited transgressively in a westward or landward direction (Moredock and Williams, 1976). This reversal in direction of sand transport probably occurred because of deepening of the water and shifting of longshore currents landward, perhaps in response to subsidence in the Boulder area that began during deposition of the Hygiene and continued during deposition of the Terry.

RATES OF SEDIMENTATION

Rates of sedimentation have been computed for the Hygiene and Terry Sandstone Members on the basis of their restored

thicknesses and of the number and average duration (0.5 million years) of faunal zones included in each member. The average rate of sedimentation of the Hygiene was quite high (934 ft or 285 m per million years) as compared to that of the Terry (142 ft or 43 m per million years). In the Boulder area, the Hygiene was deposited at a rate of about 1,700 ft (518 m) per million years, a very high rate of sedimentation, equivalent to those computed by Gill and Cobban (1973, p. 35) for areas slightly offshore from the strandline of the Cretaceous seaway in eastern Utah. Rates for the Terry in the Boulder area are also higher than rates computed at Round Butte-Buckeye and Francis Ranch: 185 ft (56 m) per million years at Boulder as compared to 121 ft (37 m) per million years at Round Butte-Buckeye and Francis Ranch. These lower rates for the Terry are equivalent to rates computed by Gill and Cobban (1973, p. 35) for areas in southeastern Montana and North and South Dakota far from the strandline in eastern Utah. Depositional rates in the Hygiene decrease to about 817 ft (249 m) per million years at Round Butte-Buckeye to the north, and they are even lower in southeastern Wyoming at Francis Ranch — 400 ft (122 m) per million years.

INTERPRETATION OF ISOPACHED INTERVALS

Isopach maps of dominantly sandstone intervals in the Pierre Shale in the northern Denver basin of southeastern Wyoming and northeastern Colorado are shown in Figures 9-12. These maps were compiled on the basis of 90 control points — 87 wells and 3 outcrop sections.

Figure 9 is an isopach map of the Hygiene Sandstone Member. Oil fields that have produced from the Hygiene are Spindle, Boulder, and Johnstown (Moredock and Williams, 1976). Maximum thickness of the Hygiene is east of Boulder, where the member is composed dominantly of fine-grained clastics. Other areas of thickening are to the north in Wyoming, where sandstone dominates. An area of thinning lies along the Colorado-Wyoming State line.

The isopach map of the Terry Sandstone (Fig. 10) shows the

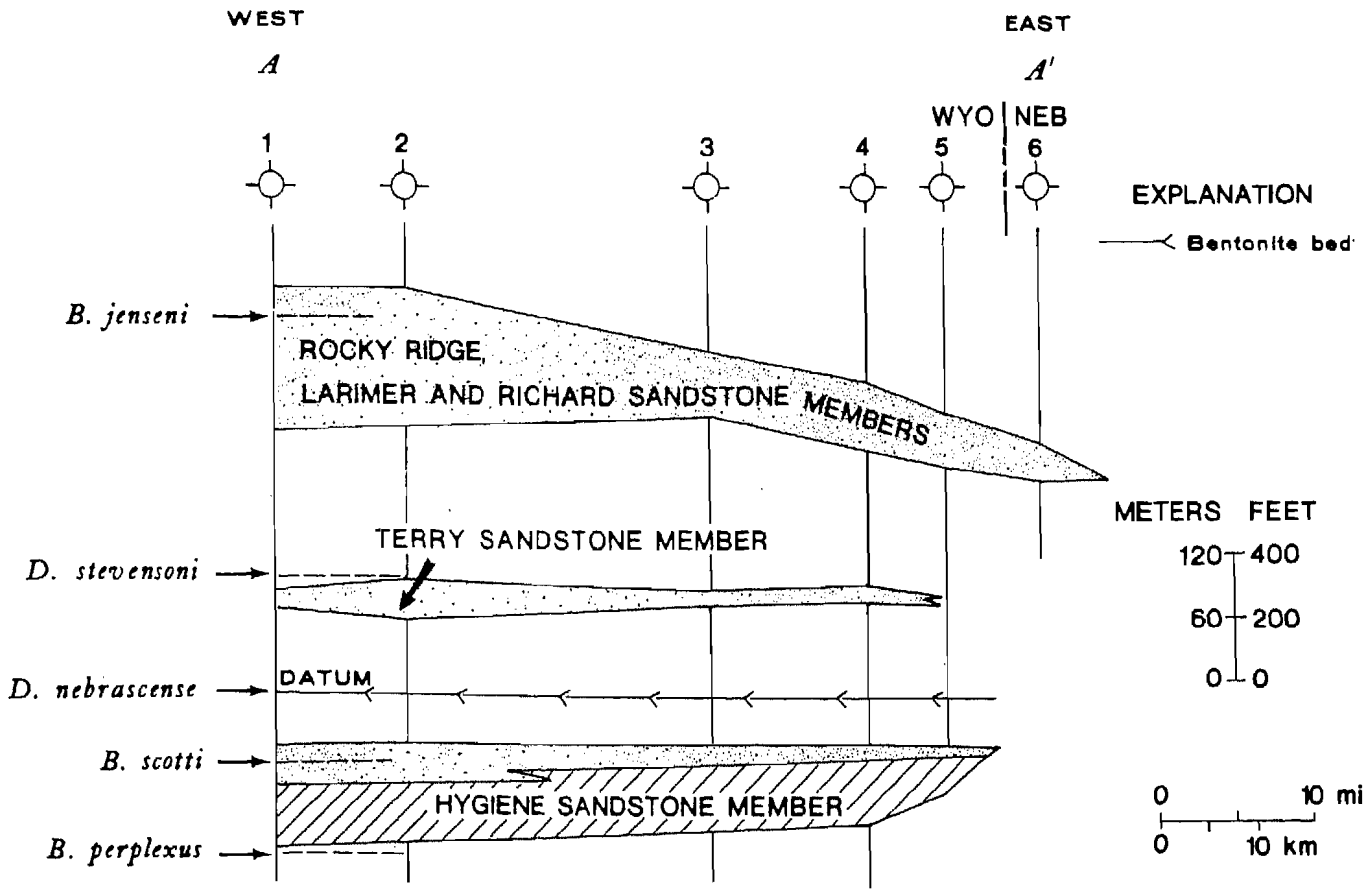

Fig. 6 — Diagrammatic cross section A-A' from southeastern Wyoming eastward to southwestern Nebraska showing eastward thinning of sandstone members and position of Upper Cretaceous zone fossils in the Pierre Shale. Datum is a bentonite bed that coincides with the position of the ammonite zone *Didymoceras nebrascense* in a large portion of the northern Denver basin.

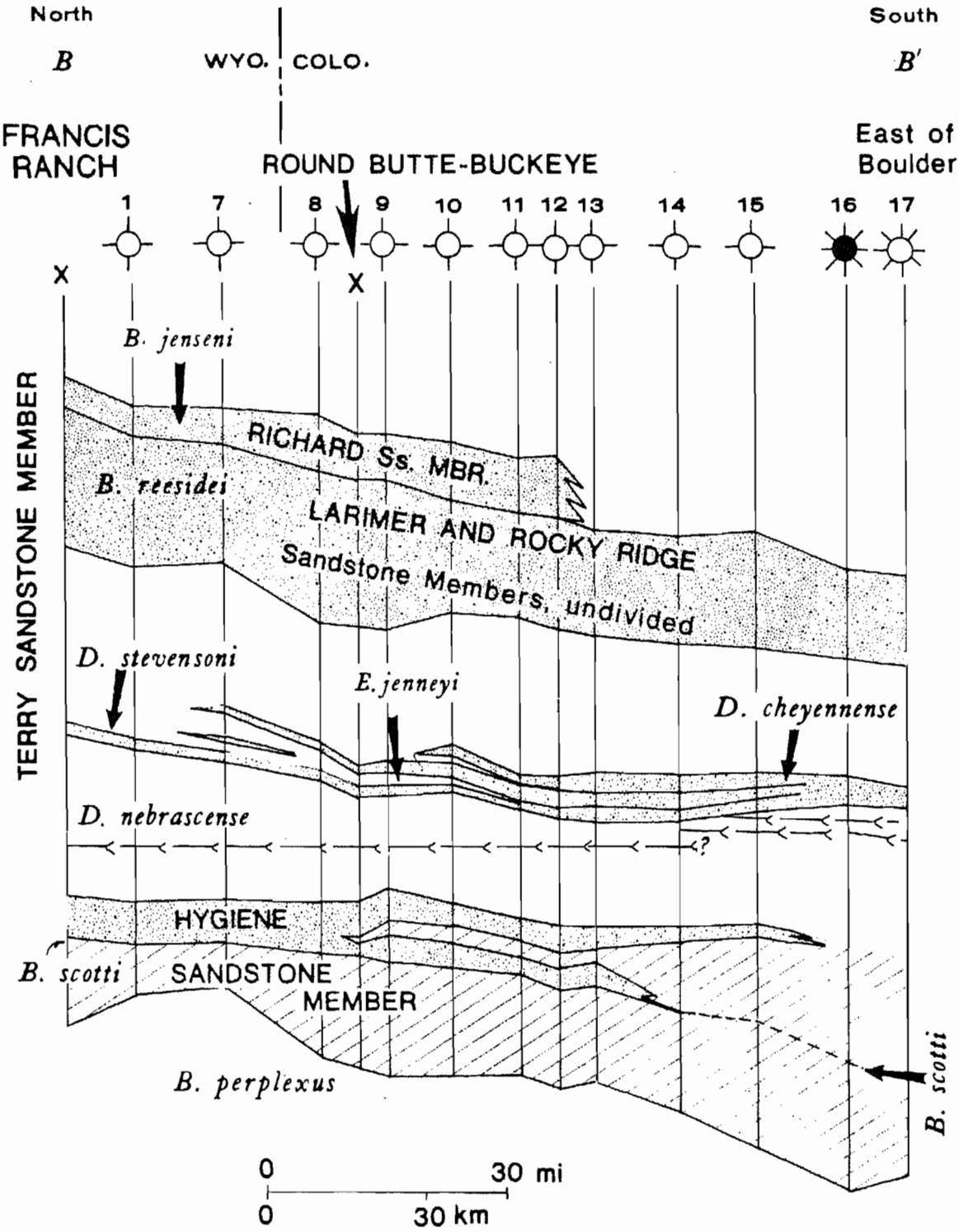

Fig. 7 — Cross section B-B′ from north to south in the Denver basin in northern Colorado, showing the Hygiene, Terry, Rocky Ridge, Larimer, and Richard Sandstone Members of the Upper Cretaceous Pierre Shale and position of zone fossils. Datum is a bentonite marker which coincides with the position of the ammonite zone *Didymoceras nebrascense* in a large portion of the northern Denver basin. Stippled areas represent sandstone; diagonal pattern represents sandy shale.

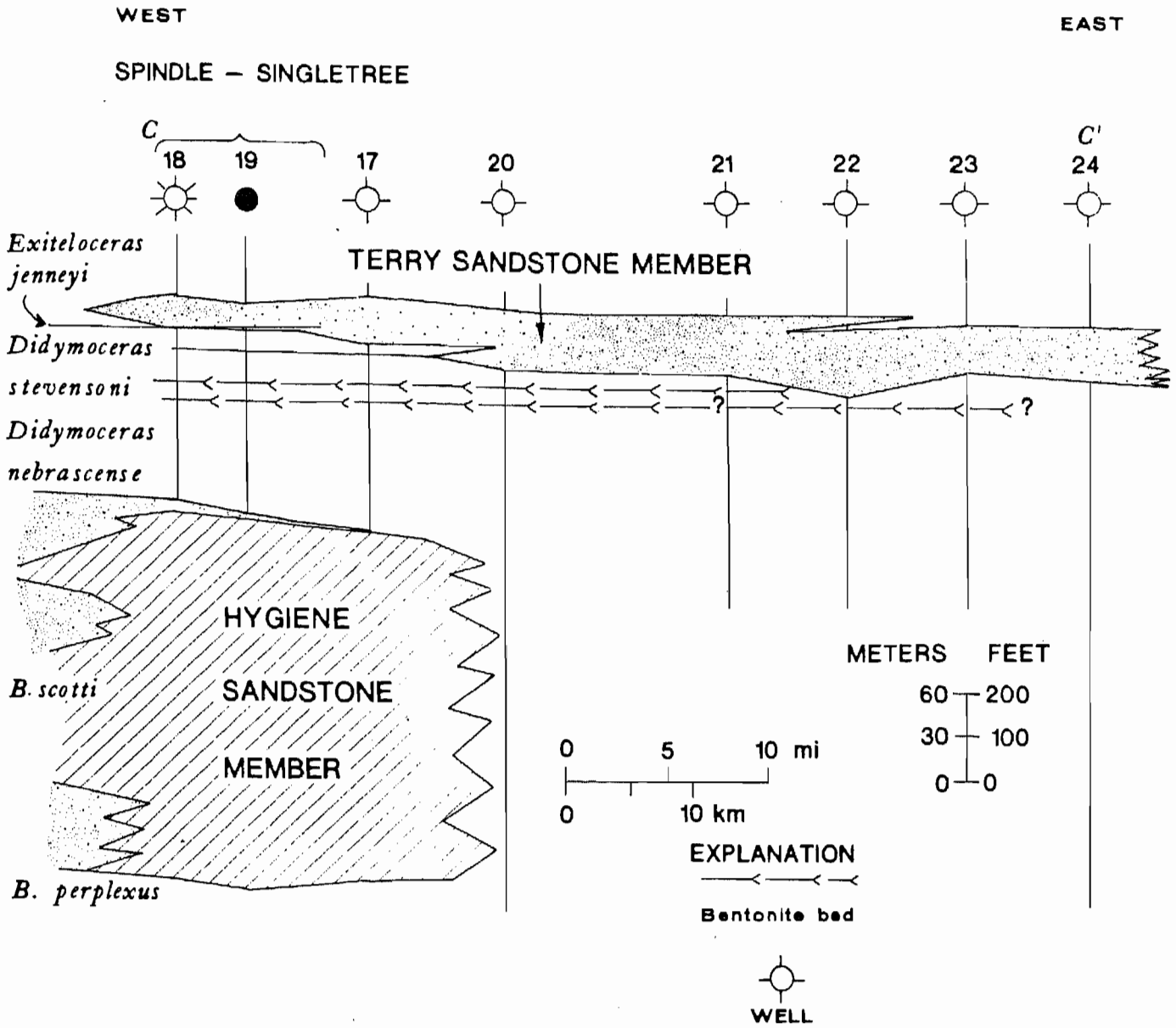

Fig. 8 — Cross section C-C′ from Spindle and Singletree oil fields eastward, in northern Colorado, showing Hygiene and Terry Sandstone Members of the Upper Cretaceous Pierre Shale and position of zone fossils. Datum is a bentonite marker which coincides with the ammonite zone *Didymoceras nebrascense* in a large portion of the northern Denver basin. Stippled areas represent sandstone; diagonal pattern represents sandy shale.

aggregate thickness of all lenticular sandstones within the member. The oil fields that produce from the Terry are the Singletree, Spindle-Surrey, New Windsor-Antelope, and Hambert fields. A comparison of this isopach map with that of the Hygiene (Fig. 9) shows that in some places where the Hygiene is thin or absent, the Terry thickens or progrades beyond the limits of the Hygiene, reflecting infilling into lowland areas during eastward regression of the shoreline. The eastward thinning of the Terry is related to tonguing out of lenticular sandstones into adjacent marine shale. The depositional axes of these sandstones trend approximately parallel to the strandlines proposed by Gill and Cobban (1973; Fig. 2). The source of sediment in the Terry was to the northwest (Moredock and Williams, 1976), but the fact that sedimentation rates were lower in the Terry than in the Hygiene suggests that deltaic centers may have shifted between Hygiene to Terry deposition.

The combined thickness of the Rocky Ridge, Larimer, and Richard Sandstone Members is shown in Figure 11. These members prograde beyond the limits of the Terry and eventually

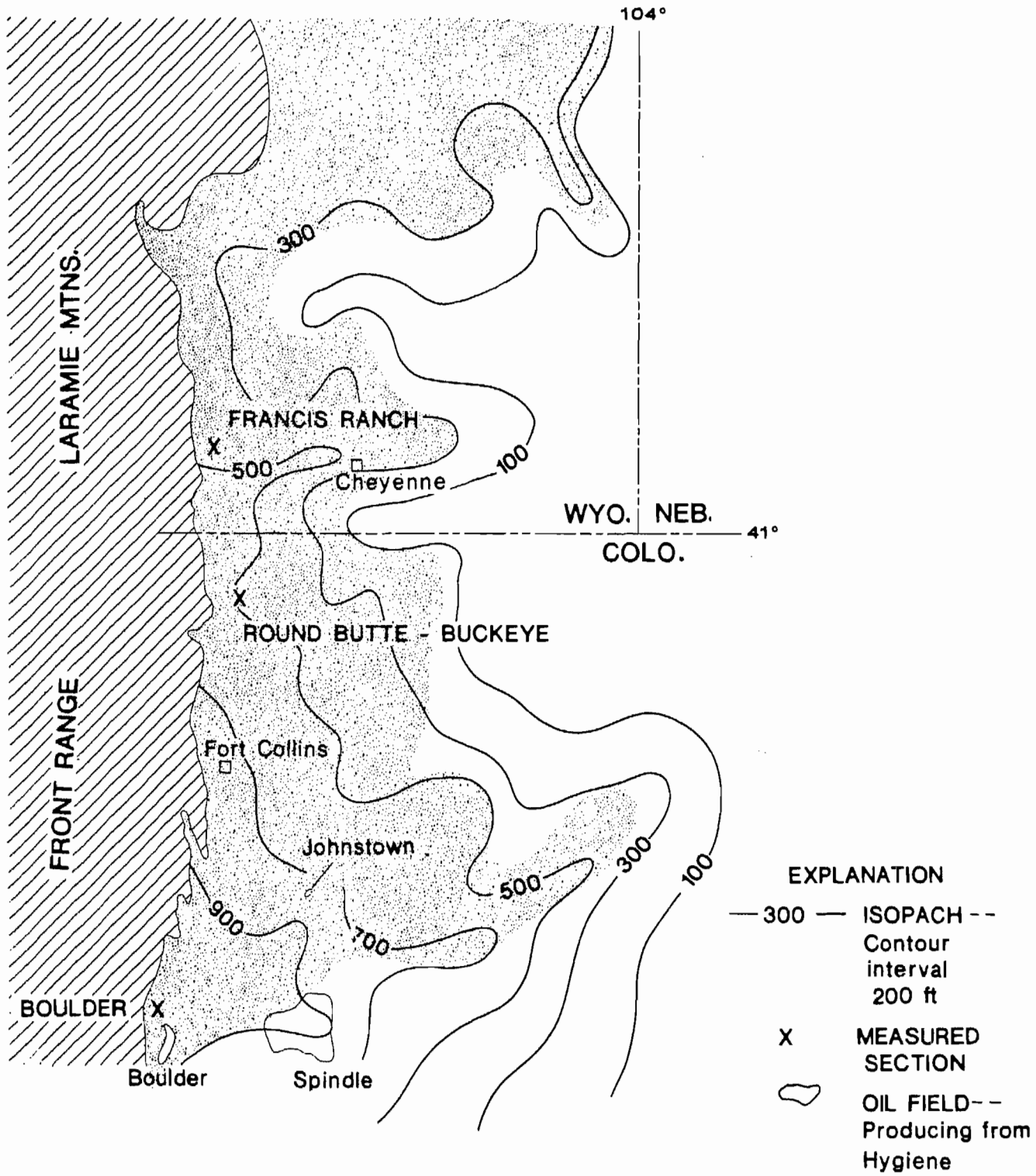

Fig. 9 — Isopach map of Hygiene Sandstone Member of the Upper Cretaceous Pierre Shale in the northern Denver basin, showing distribution of sandstone by stippled pattern; the unpatterned area to the east is dominantly sandy shale and shale.

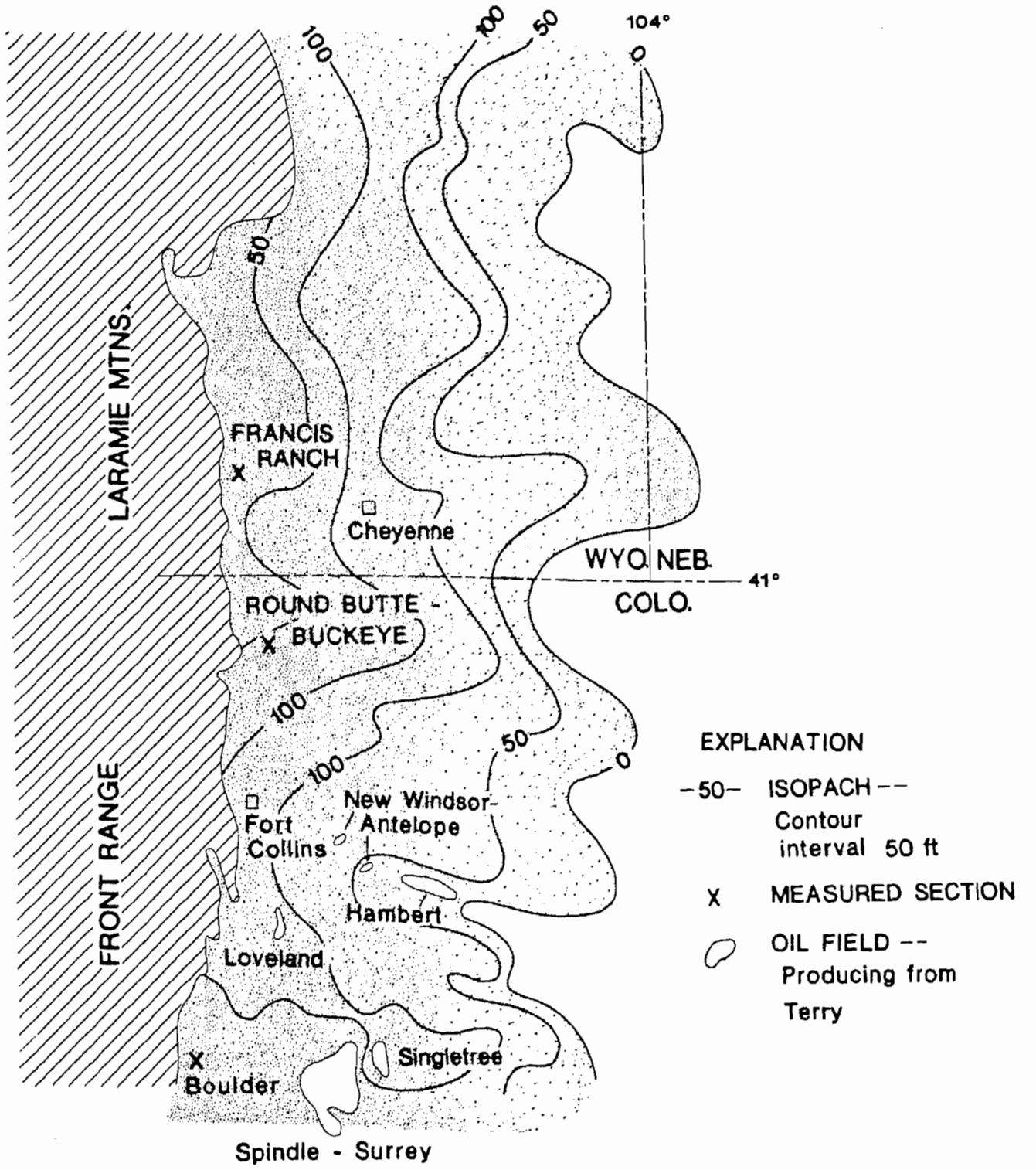

Fig. 10 — Isopach map showing aggregate thickness of lenticular sandstones in Terry Sandstone Member of the Upper Cretaceous Pierre Shale in the northern Denver basin; distribution of sandstone shown by stippled pattern.

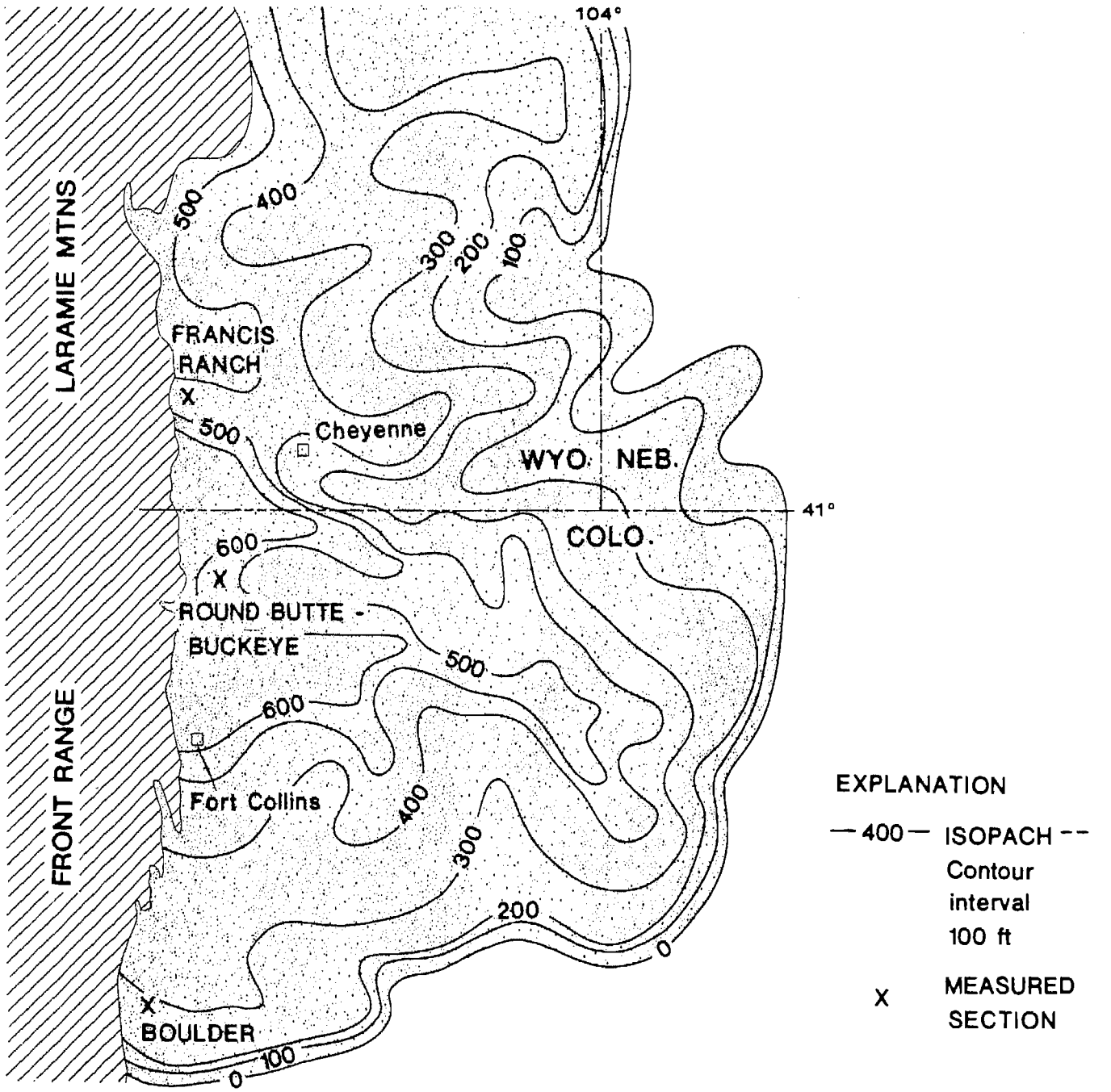

Fig. 11 — Isopach map showing combined Rocky Ridge, Larimer, and Richard Sandstone Members of the Pierre Shale in the northern Denver basin; distribution of sandstone shown by stippled pattern.

wedge out towards the south and east by facies change to shale. Production has not been established to date from these sands; however, production might be expected in areas of sand pinchout beyond the margins of the Terry isopach map (Fig. 10).

Figure 12 is an isopach map of the first unnamed sandstone (member A) above the Richard Sandstone Member. This sandstone progrades eastward beyond the Richard and thickens over areas of thinner combined Rocky Ridge and Larimer. These areas of thickening suggest infilling of the sandstone, probably in response to loading and compaction of shales below member A and above the combined Rocky Ridge and Larimer Members. The thickened areas may offer objectives for future exploration as they are in an updip position from potential source beds below.

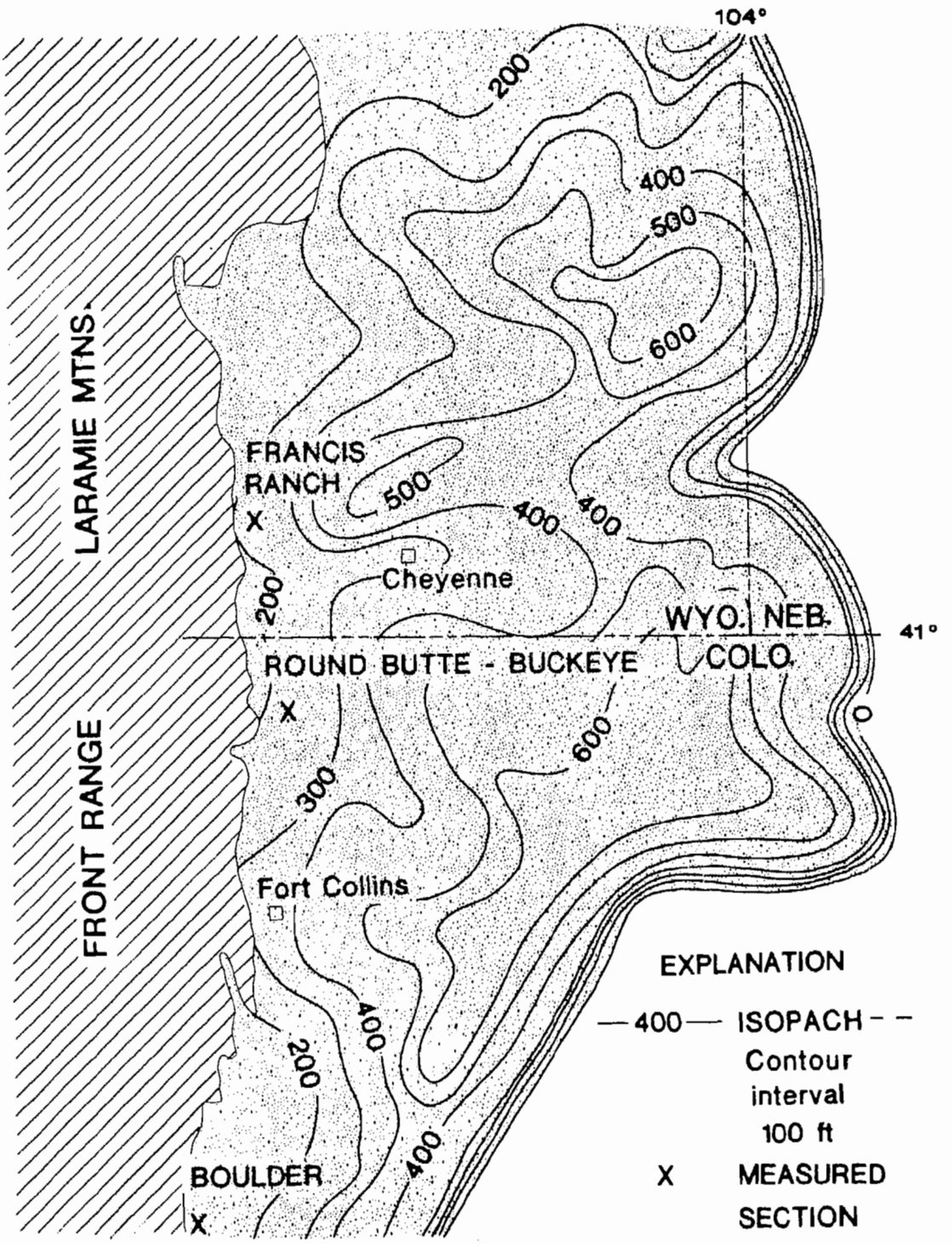

Fig. 12 — Isopach map of first unnamed sandstone (member A) above the Richard Sandstone Member of Pierre Shale; distribution of sandstone shown by stippled pattern.

ENVIRONMENTS OF DEPOSITION

The lower part of the Hygiene Sandstone Member consists dominantly of a phosphatic, glauconitic, mostly thoroughly bioturbated sandy shale facies grading up into a thick-bedded, highly crossbedded, burrowed, glauconitic, fine- to medium-grained sandstone facies with thinly interbedded shales. The lower, sandy shale facies of the Hygiene ranges in thickness from about 250 to 800 ft (76 to 244 m), and the upper sandstone facies ranges in thickness from about 10 to 100 ft (3 to 30.5 m) along the outcrop belt. Bedding in the lower sandy

shale facies of the Hygiene is flat to ripple stratified indicating very quiet, probably relatively deep-water deposition. The base of this facies appears conformable and gradational from shales and sandy shales of the underlying Mitten Black Shale Member (Fig. 3) to coarser detrital sequences of the Hygiene. The Mitten Black Shale Member has been interpreted on the basis of foraminifera (Powell, written commun., 1975) as an offshore shale sequence.

The upper, generally thinner sandstone facies of the Hygiene consists of coarsening-upward, predominantly thick-bedded sandstone sequences that at many localities exhibit high-angle tabular planar crossbedding (Fig. 13). Tops of these beds are generally bioturbated and commonly separated from overlying beds by thin layers of shale. In outcrop, the upper surfaces of the tabular, planar crossbeds appear as long, straight-crested megaripples that are generally covered by smaller cuspate ripples. The cuspate ripples indicate that the strength of currents decreased occasionally, because megaripples are formed in the upper part of the lower flow regime and cuspate ripples in the lower part of the lower flow regime (E. D. McKee, oral commun., 1976). Crossbed directions measured perpendicular to the long, straight-crested megaripples indicate that currents flowed almost unidirectionally southward, with slight variations to the southwest or southeast. The upper sandstone facies of the Hygiene is interpreted as having been deposited as sublittoral sand sheets and bars at or above wave base. Clay clasts, common at the tops of these sandstones, indicate reworking of consolidated material by strong storm systems offshore. Currents responsible for deposition of these sandstones probably resulted from a combination of oceanic or tidal currents (Ryer, 1976) and storm waves. Rip-up clay clasts in the Hygiene indicate that episodic storms, such as those postulated by Spearing (1976) for the Shannon of the Powder River basin, overprinted circulation patterns of the oceanic currents. Effects of the two processes are almost indistinguishable from each other.

The Terry Sandstone Member, poorly exposed along the mountain front, is similar in lithology to the Hygiene Member. However, the Terry contains sedimentary structures indicative of much slower deposition, such as predominantly planar- to ripple-laminated beds and horizons of concretions.

Diverse foraminifera faunas, identified and interpreted by J. D. Powell (written comm., 1975), generally indicate shallow marine depositional environments for both the Hygiene and Terry Members. In terms of depth of water, I interpret shallow marine as meaning from about 3 m (10 ft) to a maximum of about 30 m (99 ft) based on comparisons with modern shelf environments (Reineck and Singh, 1973).

Shoreline trends, proposed by Gill and Cobban (1973) for the Hygiene and Terry Members and generalized in Figure 14, strongly suggest the existence of a local source, probably a

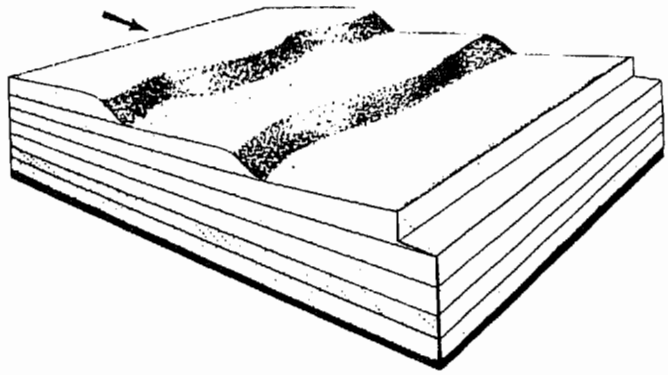

Fig. 13 — Megaripple bedforms typical of those found in the upper part of the Hygiene Sandstone Member of the Upper Cretaceous Pierre Shale of the northern Denver basin. Arrow shows direction of current flow. (Modified from Reineck and Singh, 1973, p. 30.)

delta in north-central Colorado and south-central Wyoming. Computed rates of sedimentation for the Hygiene and Terry add additional support for the existence of this deltaic area. Facies changes and southward sediment transport in the Hygiene indicate that coarse clastics were brought into the Late Cretaceous seaway from the shoreline area to the west and were redistributed seaward by strong southward-moving longshore currents (Fig. 14) that were reinforced at times by storm-generated waves. Deposits of sand in the Hygiene and Terry accumulated on a gently sloping muddy bottom as both thin sheets and bars, depending upon sediment supply and the variability of oceanic depositional processes.

In the outcropping Pierre Shale, the Rocky Ridge, Larimer, and Richard Sandstone Members, and the stratigraphically higher sandstone members (members A, B, and C) are generally fine to medium grained, clayey, and fossiliferous; locally they contain large calcite-cemented concretions. Crossbedding is low to high angle. The dominant burrows are of suspension feeding organisms; these are particularly abundant at places in the Rocky Ridge and in member C. Environments of deposition were probably very nearshore, or in terms of energy levels, shoreface to foreshore. Except where porosity and permeability have been lessened by diagenetic clays and local calcite cement, the sandstones in the Rocky Ridge, Larimer, and Richard should have fairly good porosity and permeability because of deposition in higher energy environments.

PETROLEUM POTENTIAL

Sandstones in the Pierre Shale that produce oil and gas are located mainly just east of Boulder, Colorado, in the Spindle-

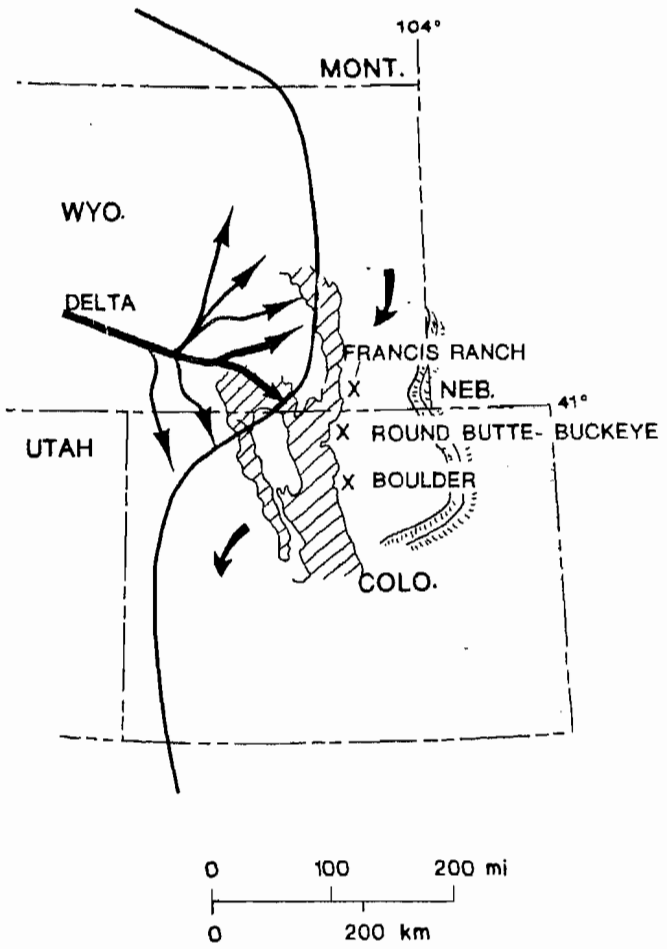

Fig. 14 — Generalized shoreline trend in Late Cretaceous time of Hygiene and Terry Sandstone Members of Pierre Shale, showing approximate location of hypothesized delta in northwestern Colorado and southwestern Wyoming. Dominant southward direction of longshore oceanic current is shown by arrows during the time of deposition of shallow marine deposits in the Hygiene Sandstone Member. Stippled areas show distribution of sandstone; dashes show distribution of shale. Areas in which Cretaceous rocks are absent due to erosion shown by cross-hatching. X, measured section.

Surrey and Singletree oil fields, an area of approximately 100 mi² (160 km²). In these fields, the reservoir sands in the Hygiene and Terry Sandstone Members form stratigraphic traps. Typical electric log characteristics, producing intervals, and fossil zones of these members are shown by Figure 15 which was adapted from an electric log of the Amoco Production Co. 43-1 UPRR well in the Spindle Field. Combined daily production from the Hygiene and Terry in Spindle-Surrey and Singletree fields was 8,555 barrels as of January 1, 1976. These fields were discovered late in 1971 and had a cumulative production through January 1, 1976 of 7.6 million barrels of oil and 20.5 billion cubic feet of gas from 325 wells. No estimates of ultimate reserves are available. Sedimentation rates computed for the

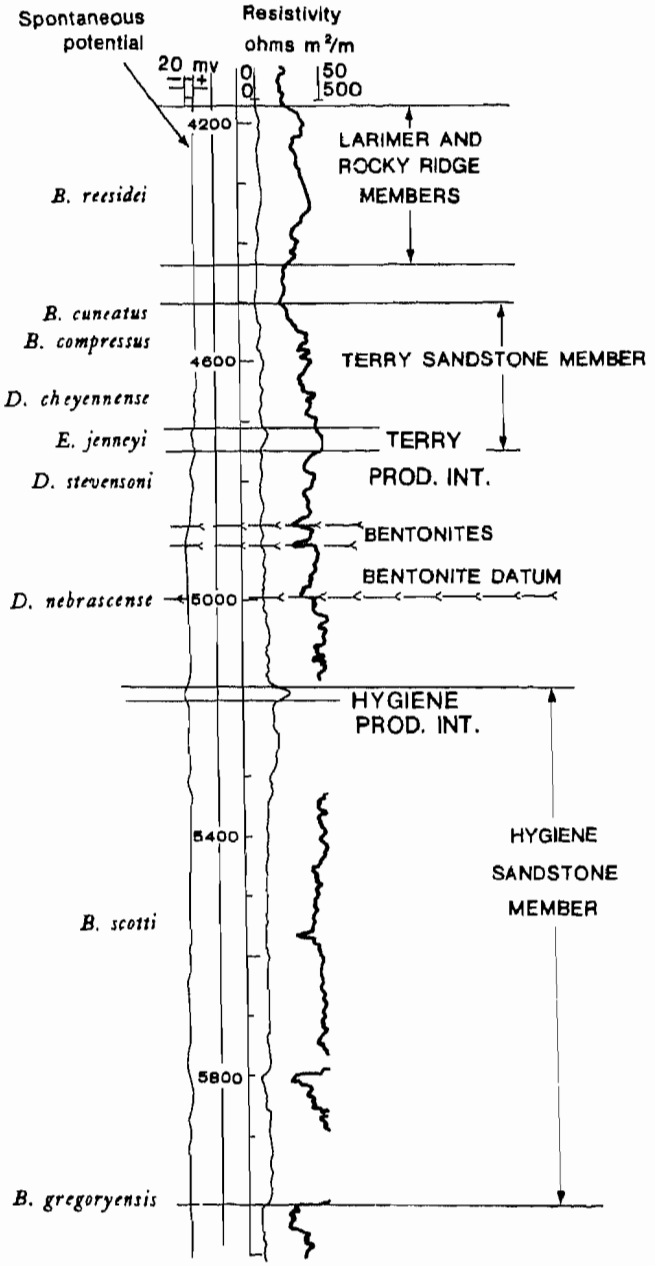

Fig. 15 — Electric log of Hygiene, Terry, Rocky Ridge, and Larimer Sandstone Members of the Upper Cretaceous Pierre Shale in Amoco 43-1 UPRR, SW ¼ SW ¼ sec. 3, T. 1 N., R 68 W., Spindle field, showing producing interval and positions of Western Interior zone fossils. Depths shown are in feet.

Hygiene indicate that this area was the site of a rapidly accumulating, thick sediment wedge consisting mostly of fine-grained clastics. The more rapidly deposited shales in this area probably favored preservation of potential source beds. Hydrocarbons generated from shales below and downdip from the Hygiene migrated into reservoir sands in the Hygiene and Terry where they were stratigraphically trapped by facies changes to overlying and updip lower energy, less permeable and less porous siltstones and shales.

From the standpoint of reservoir quality, the Hygiene and Terry Sandstone Members of the Pierre Shale are dominantly tight shaly sands, but local improvements in porosity and permeability may result from variations in the depositional energy regime. Better reservoir conditions can be expected in higher energy sandstones where porosity is improved by increased winnowing of fine sediment leaving more abundant coarse sediment. The presence of authigenic clays (Porter, 1976, p. 253-254) and calcite cement locally reduces reservoir quality.

In summary, the criteria for petroleum accumulation at Spindle-Surrey and Singletree fields near Boulder are (1) a local subsiding basin in which rapid accumulation of fine-grained sediment produced a favorable regime for preservation of potential source rocks; and (2) potential reservoir rocks lying above and updip from these source rocks. These criteria at present may only be defined at the Spindle-Surrey and Singletree fields. However, I believe that other areas in the northern Denver basin may contain similar but smaller accumulations of petroleum either where the above-mentioned conditions are met or where favorable reservoir rocks are found updip from potential source rocks and marginal to the areas shown by the isopach maps of the Hygiene and Terry Sandstone Members (Figs. 9 and 10). Reservoir conditions in these areas are in general favorable in the Rocky Ridge, Larimer, and Richard Sandstone Members and member A, which consist of fine- to medium-grained sandstones deposited in shoreface to foreshore environments. Sandstones deposited in these high energy environments are in general efficiently winnowed of fine-grained sediment. The reservoir quality of these sands is locally complicated by the presence of clays and calcite cement, but if favorable source rocks are present downdip or adjacent to these sands, petroleum accumulation could occur. Members B and C are considered to be less favorable because of probable communication with fresh surface water in member C and lack of porosity and permeability in member B. Member C crops out near Sterling in northeastern Colorado and member B nearly everywhere contains dominantly shaly sandstone.

REFERENCES CITED

Gill, J. R., and W. A. Cobban, 1973, Stratigraphy and geologic history of the Montana Group and equivalent rocks, Montana, Wyoming, and North and South Dakota: U.S. Geological Survey Prof. Paper 776, 37 p.

Gill, J. R., E. A. Merewether, and W. A. Cobban, 1970, Stratigraphy and nomenclature of some Upper Cretaceous and Lower Tertiary rocks in south-central Wyoming: U.S. Geological Survey Prof. Paper 667, 53 p.

Griffitts, M. O., 1949, Zones of the Pierre formation of Colorado: Am. Assoc. Petroleum Geologists Bull., v. 33, no. 12, p. 2011-2028.

Hail, W. J., Jr., 1965, Geology of northwestern North Park, Colorado: U.S. Geological Survey Bull. 1188, 133 p.

Kiteley, L. W., 1976, Marine shales and sandstones in the Upper Cretaceous Pierre Shale at the Francis Ranch, Larimer Co., Wyoming: The Mountain Geologist, v. 13, no. 1, p. 1-19.

_____, in press, Stratigraphic sections of Cretaceous rocks of the northern Denver basin, northeastern Colorado and southeastern Wyoming: U.S. Geol. Survey Oil and Gas Charts.

McGookey, D.P., et al, 1972, Cretaceous System, *in* Mallory, W. W., ed., Geologic Atlas of the Rocky Mountain Region: Rocky Mtn. Assoc. Geologists, p. 190-228.

Moredock, D. E., and S. J. Williams, 1976, Upper Cretaceous Terry and Hygiene Sandstones, Singletree, Spindle, and Surrey fields, Weld Co., Colorado, *in* Epis, R. C., and R. J. Weimer, eds., Studies in Colorado Field Geology: Colorado School of Mines, Prof. Contrib., no. 8, p. 264-274.

Porter, K. W., 1976, Marine shelf model, Hygiene Member of Pierre Shale, Upper Cretaceous, Denver basin, Colorado, *in* Epis, R. C., and R. J. Weimer, eds., Studies in Colorado Field Geology: Colorado School of Mines, Prof. Contrib., no. 8, p. 251-263.

Reineck, H. E., and I. B. Singh, 1973, Depositional sedimentary environments: Berlin, Heidelberg, New York, Springer-Verlag, 439 p.

Ryer, T. A., 1976, Tides in the interior Cretaceous seaway of western North America: Geol. Soc. America Abs. with Programs, v. 8, no. 6, p. 1082.

Sliter, W. V., and R. A. Baker, 1972, Cretaceous bathymetric distribution of benthic foraminifers: Jour. of Foram. Res., v. 2, no. 4, p. 167-183.

Spearing, D. R., 1976, Upper Cretaceous Shannon Sandstone: an offshore, shallow-marine sand body, *in* Geology and energy resources of the Powder River: Wyoming Geol. Assoc., 28th Ann. Field Conf. Guidebook, Casper, Wyoming, Sept. 1976, p. 65-72.

Weimer, R. J., 1961, Upper Cretaceous delta on tectonic foreland, northern Colorado and southern Wyoming (Abs.): Am. Assoc. Petroleum Geologists Bull., v. 45, no. 3, p. 417.

_____1970, Rate of deltaic sedimentation and intrabasin deformation, Upper Cretaceous of Rocky Mountain region, *in* Morgan, J. P., and R. H. Shavar, eds., Deltaic sedimentation, modern and ancient: Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. 15, p. 270-292.