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Correlation of Late Permian (Ochoan) Rustler, Alibates, Day Creek, and lower Cloud Chief Formations from West Texas and New Mexico to Oklahoma and Kansas

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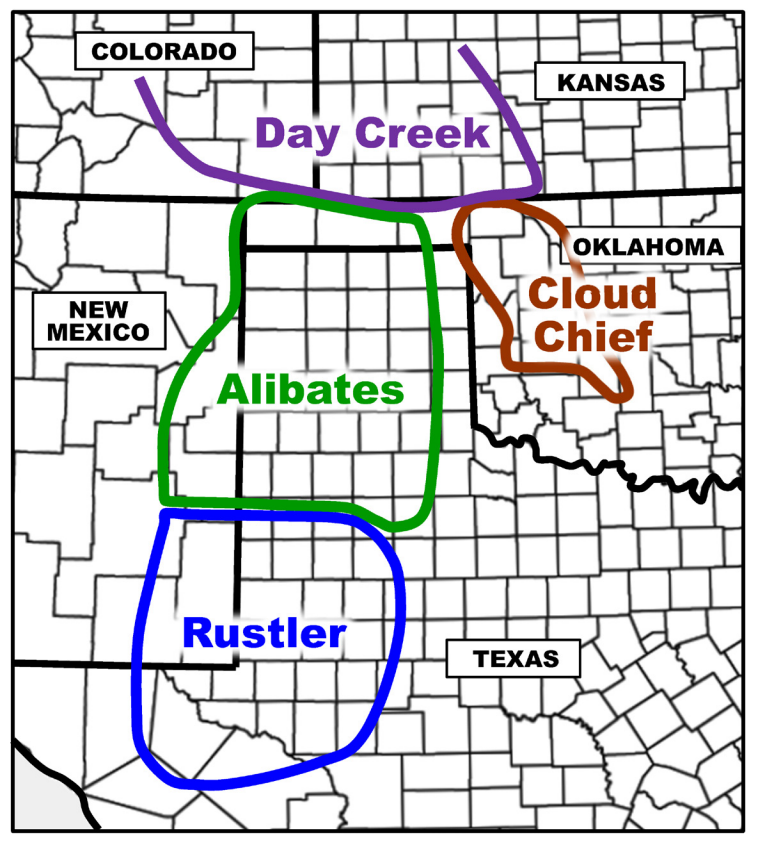

The University of Oklahoma
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OKLAHOMA GEOLOGICAL SURVEY

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Map showing approximate areas where the Rustler, Alibates, Day Creek, and Cloud Chief Formations are mainly recognized and described.

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Correlation of Late Permian (Ochoan) Rustler, Alibates, Day Creek, and lower Cloud Chief Formations from West Texas and New Mexico to Oklahoma and Kansas

Kenneth S. Johnson
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ABSTRACT.—The Late Permian (Ochoan) Rustler, Alibates, Day Creek, and Cloud Chief Formations are recognized in different parts of the Greater Permian Evaporite Basin (GPEB) of Texas, New Mexico, Kansas, and Oklahoma. Local correlation of these formations in parts of the region has been shown or suggested at times in the past, but proof of their equivalence throughout the entire region has not been presented. The current study shows six cores that characterize each of the formations in different parts of the region, along with six cross sections that show the bed-by-bed physical correlation of the Rustler, Alibates, Day Creek, and lower Cloud Chief Formations throughout the region—from West Texas to western Kansas and Oklahoma. A Late Permian (Ochoan) age for these strata is affirmed by the following: 1) Ochoan marine invertebrate and conodont fossils in the Rustler and Alibates at sites in West Texas and the Texas Panhandle; 2) radiometric dates (U–Pb) of volcanic ash show that the Permian–Triassic boundary is present in the Dewey Lake Formation that overlies the Alibates Formation in the Texas Panhandle; and 3) paleomagnetic data indicate that at least the lower part of the overlying Dewey Lake in Texas and New Mexico is Late Permian in age. Although independent verification of age is not available in the unfossiliferous Day Creek or lower Cloud Chief in Kansas or Oklahoma, bed-by-bed physical correlation of these strata shows their equivalence to the Ochoan Rustler and Alibates Formations in Texas and New Mexico.

INTRODUCTION

Correlation of the Late Permian (Ochoan) Rustler Formation of West Texas and southeast New Mexico with equivalent strata to the northeast in the study region of Texas Panhandle, western Kansas, and western Oklahoma (Fig. 1) has been the subject of debate and uncertainty for more than 100 years. The Rustler has been reliably correlated with the Alibates Formation in the Texas Panhandle, but the uncertainty arose in extending correlation of the Alibates with the Day Creek Dolomite in western Kansas, and then correlating the Alibates or the Day Creek with the lower Cloud Chief Formation in western Oklahoma. The current study region includes a number of major basins and uplifts (Fig. 2A), and the area where each of these four formations is generally recognized is shown in Figure 2B. Based on cores of each of these formations, and a series of cross sections across the region, correlation and equivalence of the Rustler, Alibates, Day Creek, and lower Cloud Chief Formations is herein established.

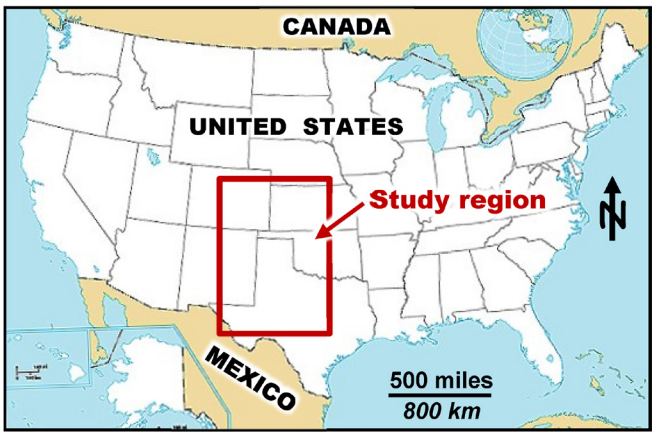


Figure 1. Map showing location of study region within the United States.

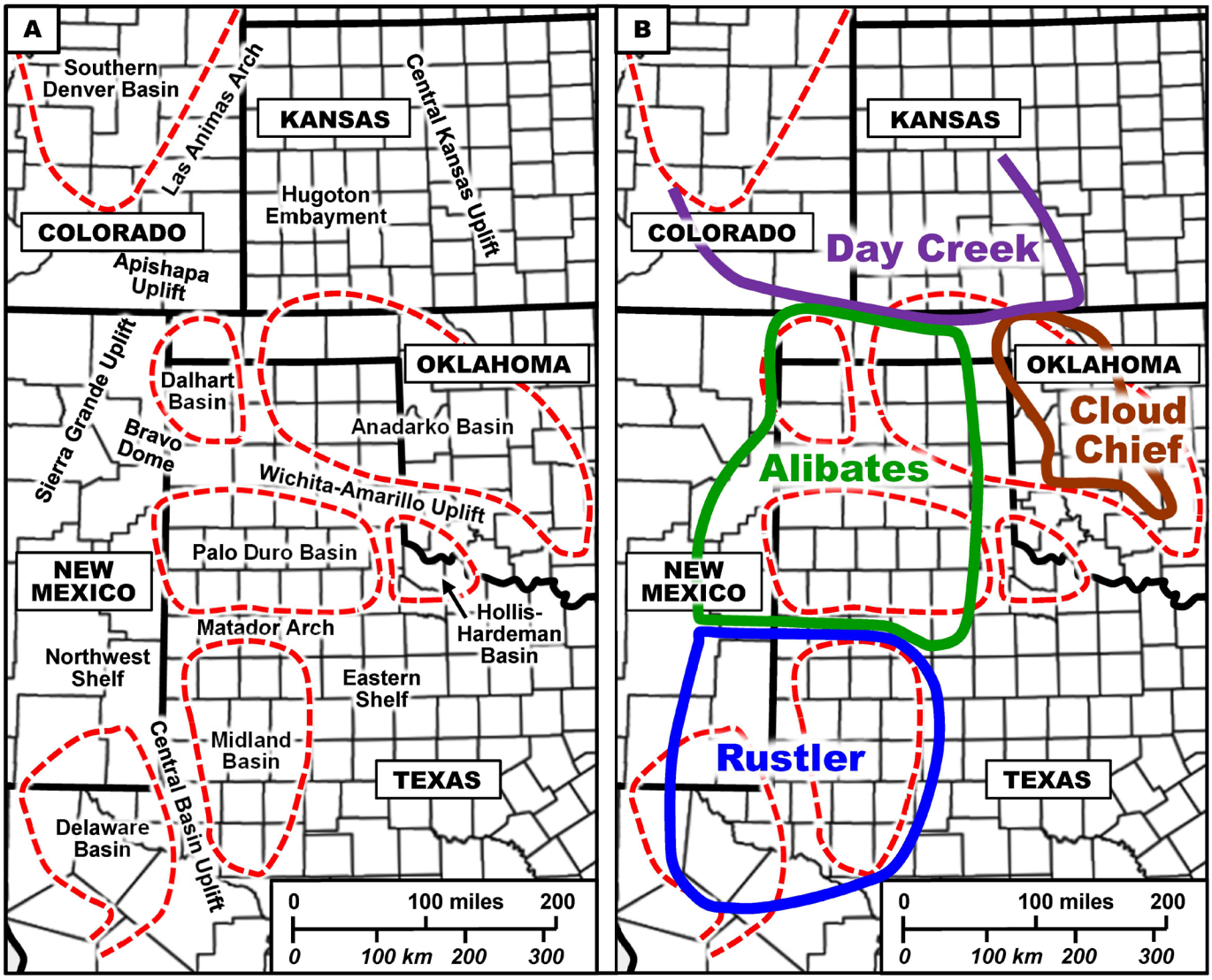


Figure 2. A) Map showing principal basins and uplifts in region of Rustler, Alibates, Day Creek, and Cloud Chief Formations. B) Same map as in "A," also showing approximate area where each of the four formations is mainly recognized and described.

STRATIGRAPHY

The Rustler, Alibates, Day Creek, and Cloud Chief Formations were deposited near the end of the Permian Period (Fig. 3) and comprise the final sequence of Permian evaporites and/or carbonates deposited in the Greater Permian Evaporite Basin (GPEB), a region of about 250,000 mi^2 (650,000 km^2) where Permian-age rocks are largely characterized by the presence of evaporites—mainly salt (halite) and gypsum or anhydrite (Johnson, 2021a). The GPEB contains eight major evaporite sequences that collectively are about 1,640–4,920 ft (500–1,500 m) thick in parts of Texas, New Mexico, Oklahoma, Kansas, and Colorado. Equivalence of the Rustler, Alibates, Day Creek, and lower Cloud Chief throughout the study region was indicated earlier by Dunbar and others (1960) (Fig. 4), and the cores and cross sections in the current study show that these formations are correlative and are Ochoan in age.

The age assignment of the Day Creek and other Late Permian units in this paper (Fig. 3) does not agree with their age assignment in Kansas. The Kansas Geological Survey has considered the Whitehorse, Day Creek, and Big Basin to be Guadalupian, and the Nippewalla Group to be Leonardian (Zeller, 1968; Sawin and others, 2008; West and others, 2010; Foster and others, 2014). However, the current report shows that the Day Creek (and probably the lower part of the Big Basin) is Ochoan, and other studies show that the Nippewalla Group is Guadalupian (Dunbar and others, 1960 [Fig. 4 in this report];

Hills and Kottlowski, 1983; Johnson, 2021a; Johnson and Timson, 2023).

Underlying the Rustler, Alibates, Day Creek, and Cloud Chief Formations are: 1) the Salado Formation in West Texas and southeast New Mexico; 2) the Salado–Tansil Formations (in subsurface) or the Whitehorse Group (in outcrops) in the Texas Panhandle; 3) the Whitehorse Formation in Kansas; and 4) the Rush Springs Sandstone of the Whitehorse Group in Oklahoma (Fig. 3). Overlying the Rustler, Alibates, Day Creek, and Cloud Chief Formations are: 1) the Dewey Lake Formation in West Texas and southeast New Mexico; 2) the Dewey Lake Formation (in subsurface) or Quartermaster Formation (in outcrops) in the Texas Panhandle; 3) the Big Basin Formation in Kansas; and 4) the Doxey Formation of the Quartermaster Group in Oklahoma (Fig. 3).

Marine invertebrates and conodonts in the Rustler and lower Dewey Lake Formations at several sites in Texas show that those formations are Late Permian in age: fossils are lacking, however, in Day Creek or Cloud Chief strata. The Permian–Triassic boundary has been established above the Alibates Formation in the Texas Panhandle, where volcanic-ash samples from the lower part of the overlying Dewey Lake (Quartermaster) Formation have been dated radiometrically by uranium/lead (U–Pb) analyses (described below). The Dewey Lake is stratigraphically equivalent to the Big Basin Formation in Kansas and the Doxey Formation in Oklahoma, so it is most likely (but not yet proven) that the Permian–Triassic boundary is in the lower part of those equivalent strata in Kansas and Oklahoma (Fig. 3).

CORES AND LOGS OF RUSTLER, ALIBATES, DAY CREEK, AND CLOUD CHIEF FORMATIONS

Six cores show the character of the Rustler, Alibates, Day Creek, and Cloud Chief Formations in the study region, and six cross sections show correlation of the four formations throughout the region (Fig. 5). Two cores of the Rustler Formation are from West Texas and southeast New Mexico, two cores of the Alibates Formation are from the Texas Panhandle, one core of the Day Creek Dolomite is from western Kansas, and one core of the Cloud Chief Formation is from western Oklahoma. A good suite of geophysical logs is available for most of the cored wells, and interpretation of geophysical logs in

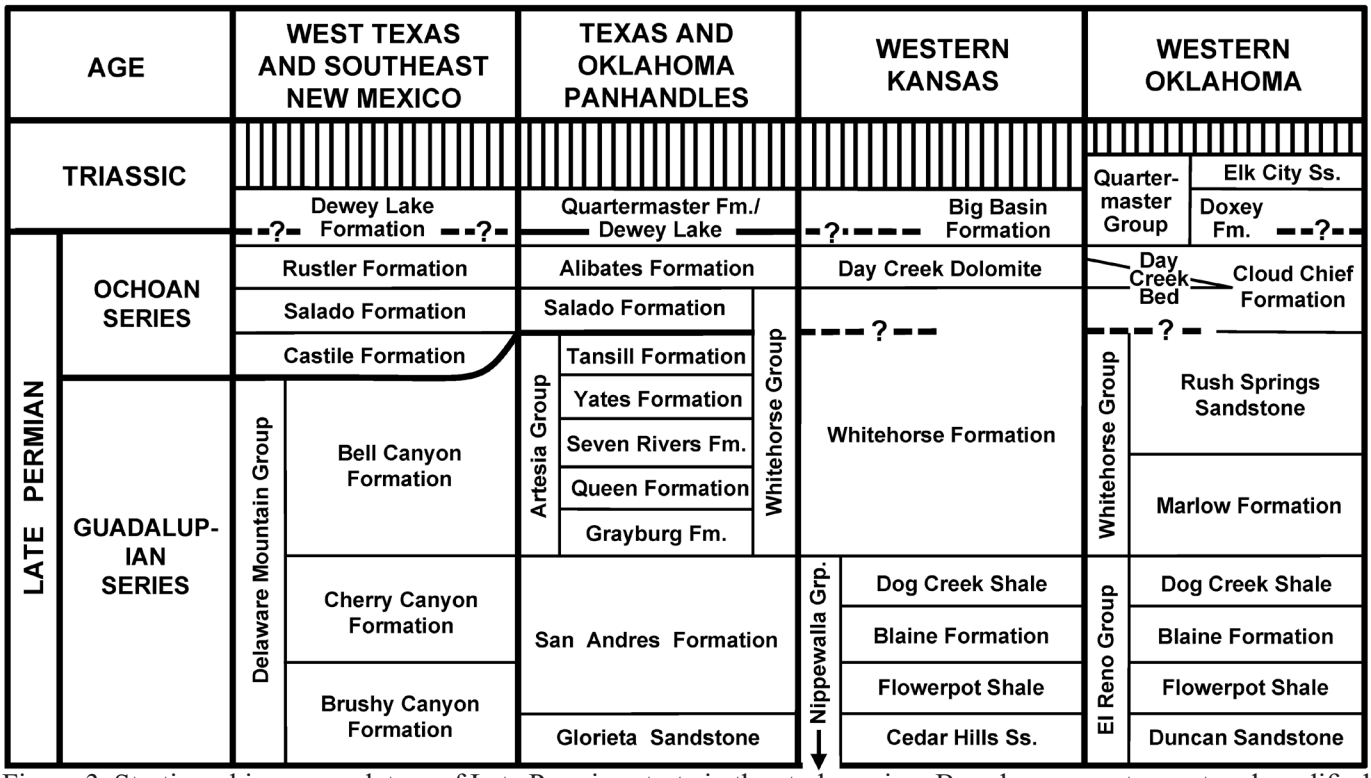


Figure 3. Stratigraphic nomenclature of Late Permian strata in the study region. Based on current report and modified from Dunbar and others (1960), Johnson (1978, 2021a), McGillis and Presley (1981), and Hills and Kottlowski (1983).

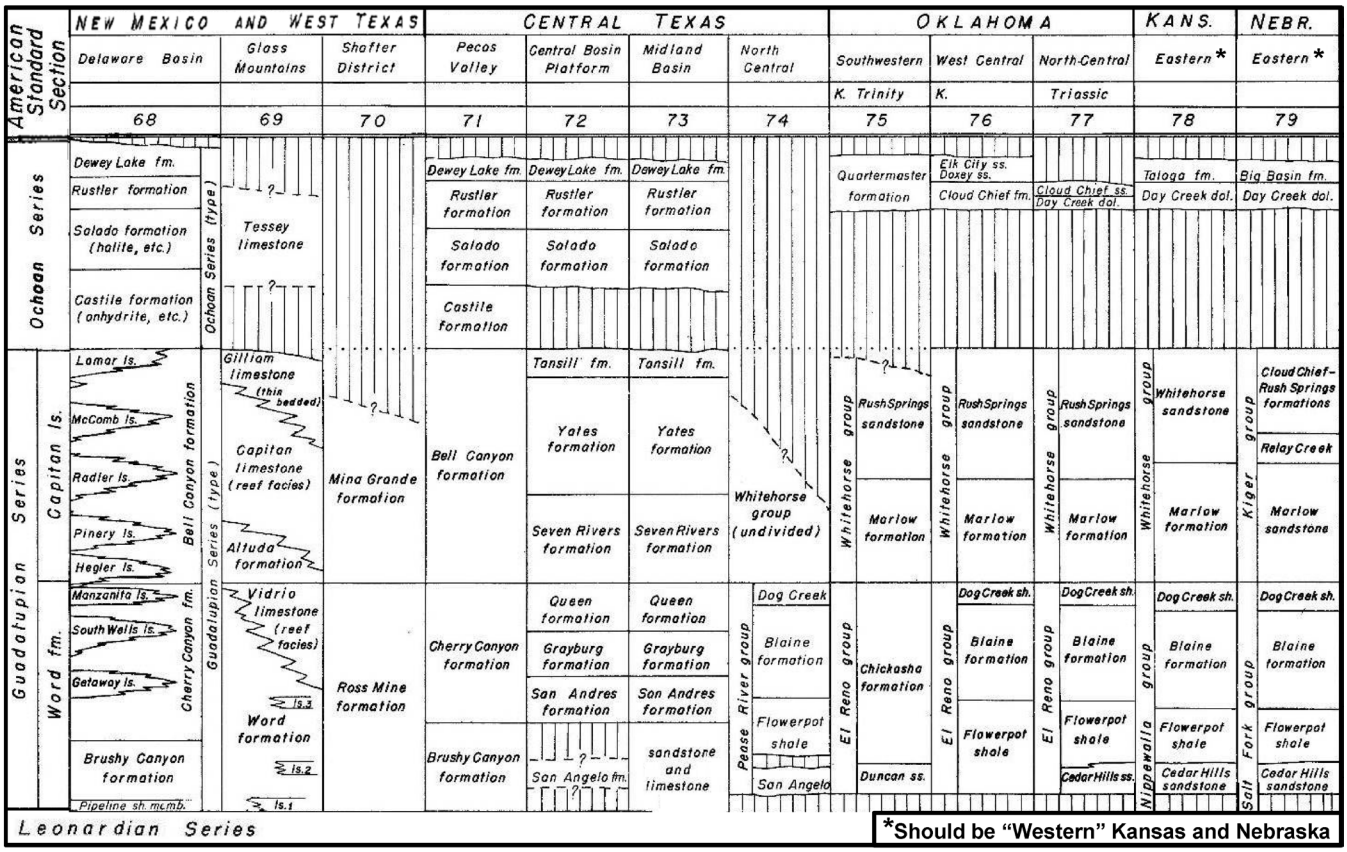


Figure 4. Chart showing correlation of Permian formations in the southern Midcontinent as established by the Permian Subcommittee of the National Research Council's Committee on Stratigraphy (Dunbar and others, 1960).

evaporite sequences in the GPEB has been discussed by Johnson (2021b).

Rustler Formation in West Texas and Southeast New Mexico

The Rustler Formation was named by Richardson (1904) for 150–200 ft (46–61 m) of magnesium limestones and sandstones with poorly preserved fossils that crops out near Rustler Springs in the Rustler Hills of Culberson County, Texas. Subsurface work to the east in the Delaware Basin (Lang, 1935; Adams, 1935) further refined definition of the Rustler to embrace 370 ft (113 m) of anhydrite, magnesian limestone, sandstone, and red beds above the Salado Formation and below the Pierce Canyon red beds (now the Dewey Lake Formation). Adams (1944) introduced the terms Magenta and Culebra for the two dolomite units, noting that they were originally proposed by his co-worker Walter B. Lang. The current five-member status of the Rustler was established by Vine (1963), and formal naming of the Los Medaños Member at the base was by Powers and Holt (1999).

Two cores were drilled through the Rustler Formation in the Delaware Basin of West Texas and southeast New Mexico (Fig. 6): the two wells are about 45 mi (72 km) apart. In 1981, Texasgulf, Inc., cored the Rustler Formation and associated strata in the northeast part of Culberson County, Texas, as part of a sulfur-exploration program (Eager, 1983). The Texasgulf well was drilled about 12 mi (19 km) southwest of the town of Orla, and about 6 mi (10 km) east of the Rustler Hills, the type area for the Rustler Formation. The second Rustler core, designated as C-3977, was drilled in 2016–2017 to obtain representative core for the proposed site of a new exhaust shaft at the Waste Isolation Pilot Plant (WIPP): it is located about 25 mi (40 km) east of Carlsbad, New Mexico, in Eddy County (Powers and others, 2018).

The Rustler is divided into five members in the Delaware Basin, ranging from the Los Medaños at the bottom to the Forty Niner at the top (Fig. 6). Gypsum and/or anhydrite are the major rock types in the Rustler in both cores, along with two dolomites, the Culebra and Magenta Members. Calcium-sulfate rock in the deeper C-3977 core occurs as anhydrite, whereas in the shallower Texasgulf core the pre-existing anhydrite is largely hydrated to gypsum. Salt is present in the upper part

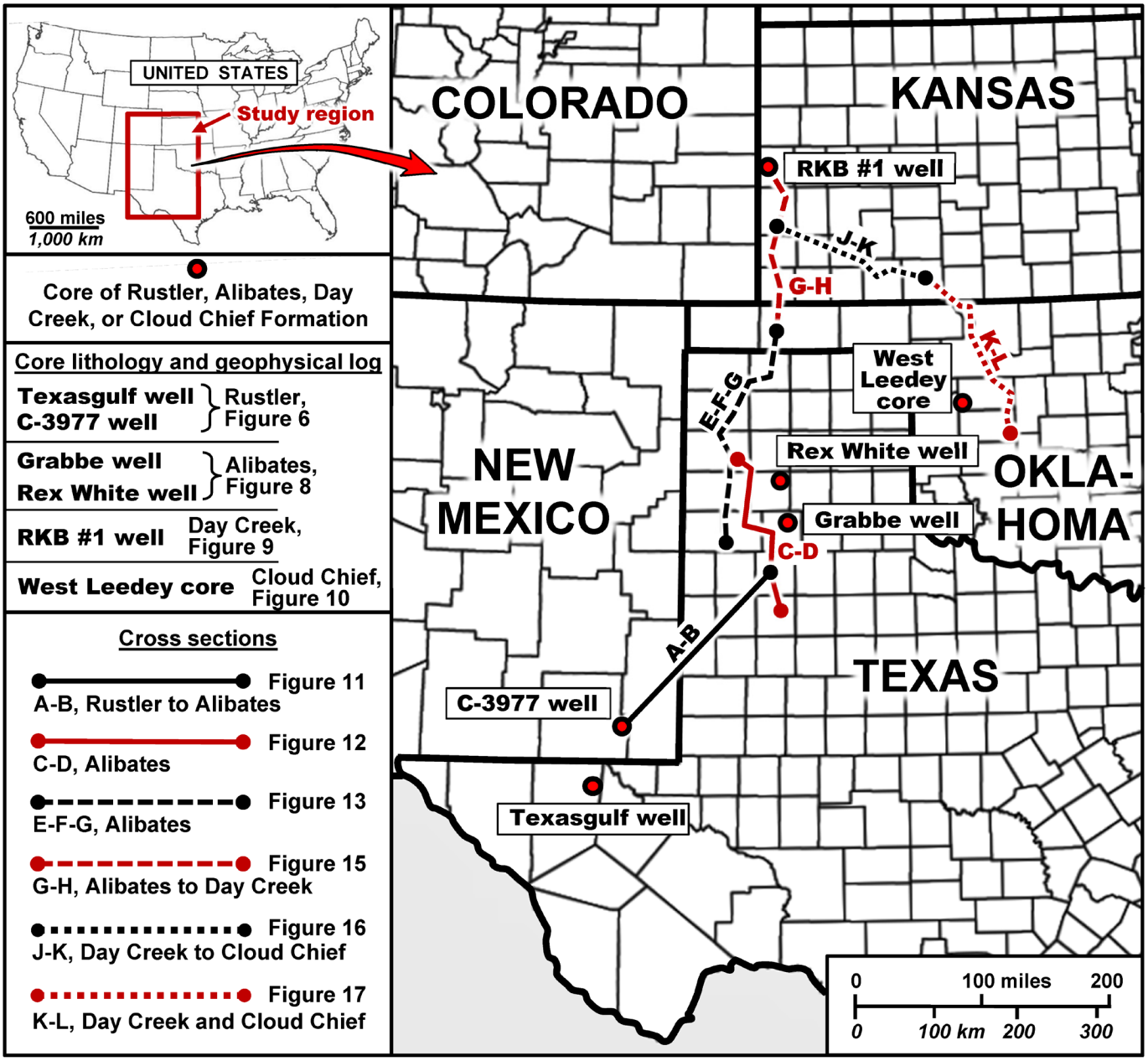


Figure 5. Map of study region and location of six cores and six cross sections showing correlation of Rustler, Alibates, Day Creek, and Cloud Chief Formations.

of the Los Medaños Member in C-3977, where the rock is quite deep, but is absent in the Texasgulf well where equivalent strata are much shallower, and any salt that may have been present is dissolved.

The thickness of the Rustler Formation is about 415 ft (126 m) in the Texasgulf well, and about 318 ft (97 m) in the C-3977 well (Fig. 6). Most of the individual members of the Rustler are also thinner to the north in the C-3977 well: only the Magenta Dolomite Member is thicker in the C-3977 well.

Alibates Formation in Texas Panhandle

The type locality for the Alibates is in northeast Potter County, Texas (Gould, 1907), where the formation consists of lower and upper dolomite beds separated by a bed of mudstone. Throughout the Texas Panhandle and western Kansas, two beds of dolomite/anhydrite/gypsum are characteristic of the Alibates Formation and are a "dyad" that is readily recognized on geophysical logs in those areas ("dyad" comes from the Greek word "dyas," meaning "the number two," or "a group of two;" also, "two

things of the same or similar kind"). Within the Texas Panhandle and western Kansas, the dyad of dolomite/anhydrite/gypsum is separated by a medial bed of shale/siltstone/mudstone.

In a measured section at the type locality the Alibates dyad is 18 ft (5.5 m) thick (Fig. 7C): the lower and upper

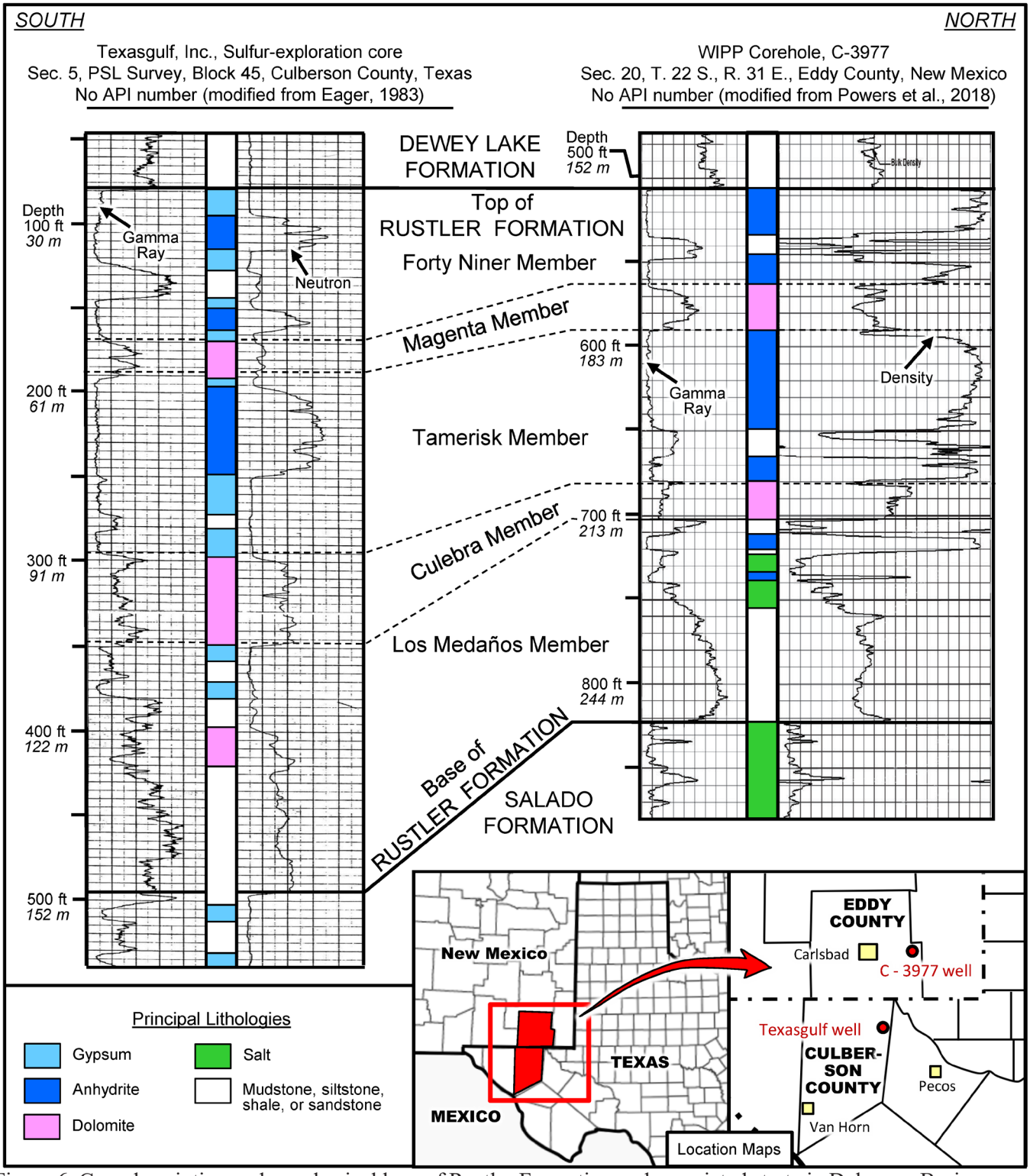


Figure 6. Core description and geophysical logs of Rustler Formation and associated strata in Delaware Basin area of West Texas and southeast New Mexico. Wells are about 45 mi (72 km) apart.

dolomite members are, respectively, about 10 ft (3.0 m) and 3 ft (0.9 m) thick, and they are separated by about 5 ft (1.5 m) of mostly red-bed mudstone (Bowers, 1975). The dolomite beds are medium to finely crystalline, pinkish gray, laminated, and they contain brown chert nodules. The Pioneer Natural Resources, Bivins 142R well (Fig. 7A,B), drilled about 1 mi (1.6 km) north of the Alibates type locality, penetrated the Alibates Formation at a depth of 48–68 ft (15–21 m): this thickness of 20 ft (6.1 m) is almost identical to the thickness at the nearby type locality. In the Bivins well, the San Andres/Blaine Formation is 236 ft (72 m) thick, and its top is 346 ft (105 m) below the Alibates (Fig. 7A).

From 1977 through 1987, the Bureau of Economic Geology at The University of Texas conducted studies of the Permian salts and associated strata in the Texas Panhandle to identify a potential site for the safe, long-term disposal and containment of high-level radioactive wastes. As part of these studies, a series of cores were drilled by the U.S. Department of Energy (D.O.E.) through the salt units, and two of those cores, about 30 mi (48 km) apart, recovered complete sections of the Alibates Formation (Fig. 8). The Alibates and associated strata in those two wells, the D.O.E.–Gruy Federal, Grabbe No. 1, and the D.O.E.–Gruy Federal, Rex White No. 1, drilled in Swisher and Randall Counties, Texas, respectively, were described and illustrated by McGillis and Presley (1981).

The Alibates dyad is 43 ft (13.1 m) thick in the Grabbe well and 47 ft (14.3 m) thick in the Rex White well. In the two wells, the lower gypsum/anhydrite/dolomite unit is 21–26 ft (6.4–7.9 m) thick, and the upper unit is 13–14 ft (4.0–4.3 m) thick; the intervening mudstone is 7–9 ft (2.1–2.7 m) thick. The Alibates cores, as described by McGillis and Presley (1981), consist of dolomite, gypsum, anhydrite, and mudstone (Fig. 8). Dolomite in the cores is laminated, buff to light brown, fine grained, and thinly interlaminated with dark-gray, wispy laminae of organic muds. Gypsum and anhydrite beds in both cores are laminated and range from tan to bluish gray and dark gray. The laminae typically are 0.1–0.4 in. (2.5–10.2 mm) thick and are separated by thin carbonate films up to 0.1 in. (2.5 mm) thick. The laminated gypsum and anhydrite, and the interlaminated dolomite and anhydrite, are regarded as evidence of relict algal mats by McGillis and Presley (1981). At greater depths, as in the Grabbe well, the calcium-sulfate layers commonly occur as anhydrite; but at shallower depths, as in the Rex White well, most of the anhydrite is hydrated to gypsum. The middle unit of the Alibates is a red-bed mix of mudstone and siltstone.

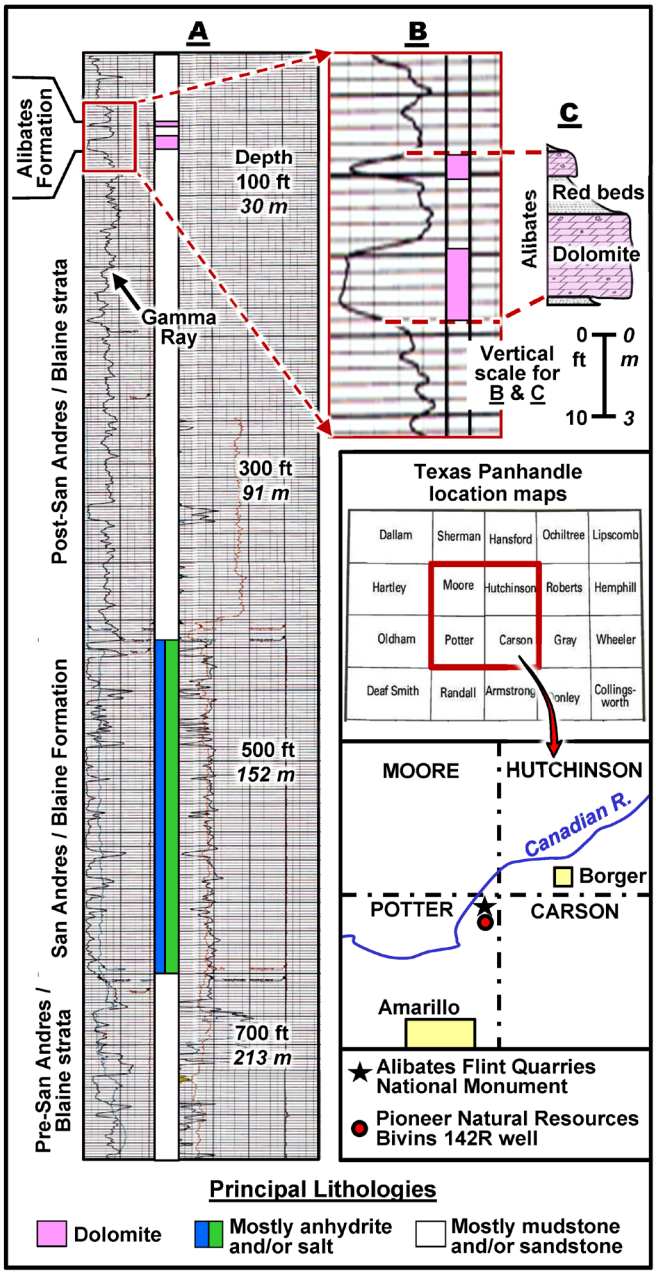


Figure 7. Alibates Formation at Alibates Flint Quarries National Monument in Potter County, Texas. A) Neutron-Density microlog for Pioneer Natural Resources, Bivins 142R well, sec. 31, BLK M20, G&M Survey, Potter County, API# 42-375-31763. B) Enlarged segment of Bivins log showing Alibates Formation. C) Outcrop measured section at type locality of Alibates Formation (Bowers, 1975), 1 mi. (1.6 km) south of Bivins well.

In the Texas Panhandle the Alibates Formation is overlain by the Dewey Lake Formation (in subsurface) or the Quartermaster Formation (in outcrops), and is underlain by Salado–Tansill strata (in subsurface) or the Whitehorse Group (in outcrops). Red-bed clastics beneath the

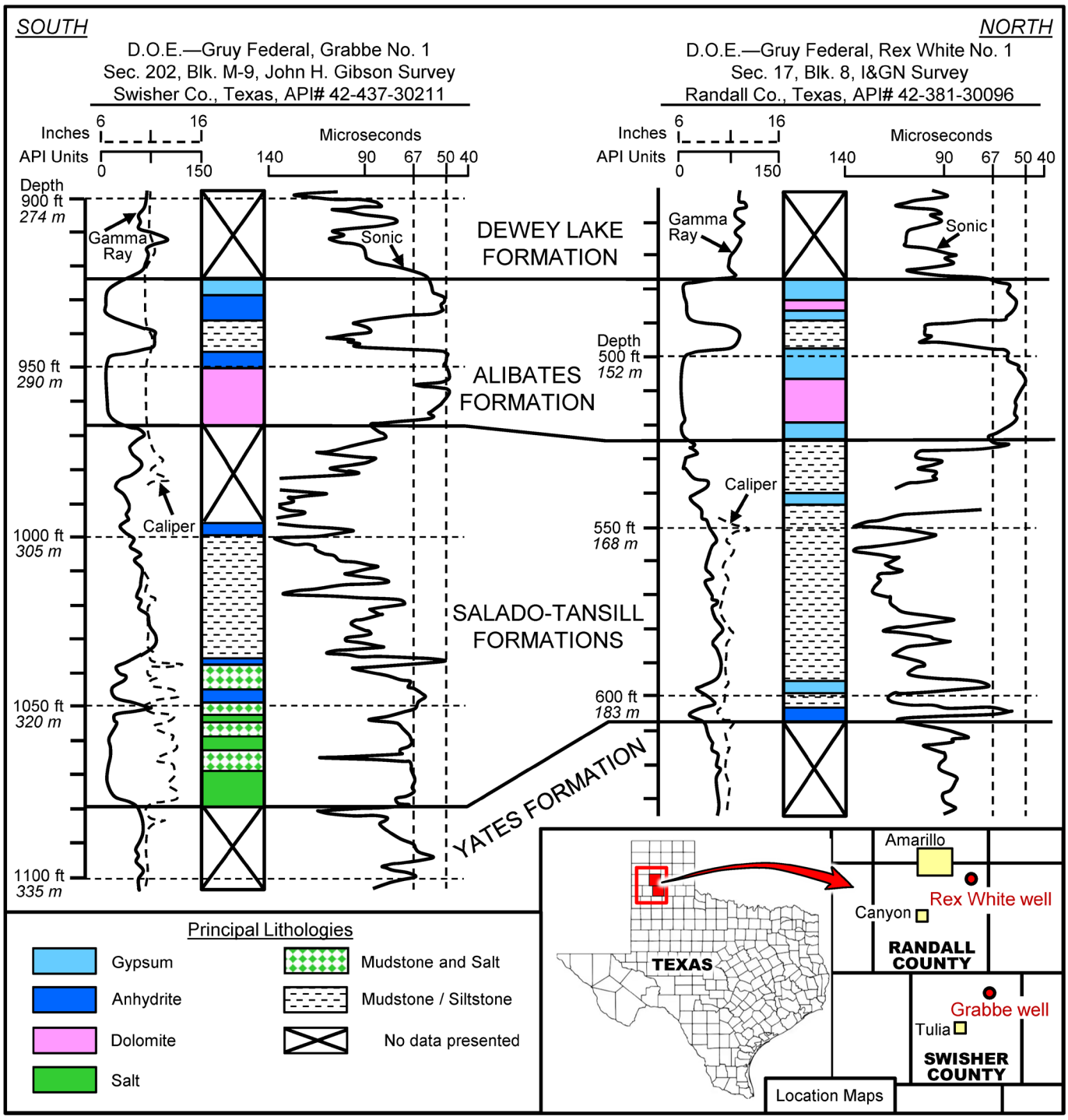


Figure 8. Core description and geophysical logs of Alibates Formation and associated strata in Palo Duro Basin area of Texas Panhandle. Wells are about 30 mi (48 km) apart. Modified from McGillis and Presley (1981).

Alibates in the Rex White well and in much of the Texas Panhandle are referred to as the Whitehorse Group (Roth and others, 1941). The Alibates is considered to be in the upper part of the Whitehorse Group in outcrops by Barnes (1968, 1969) and Tabor and others (2022).

Day Creek Dolomite in Western Kansas

The Day Creek Dolomite was originally named for exposures of a single 1–5 ft (0.3–1.5 m) thick bed of white dolomite exposed at the head of Day Creek in Clark County, Kansas (Cragin, 1896). Swineford (1955) reports

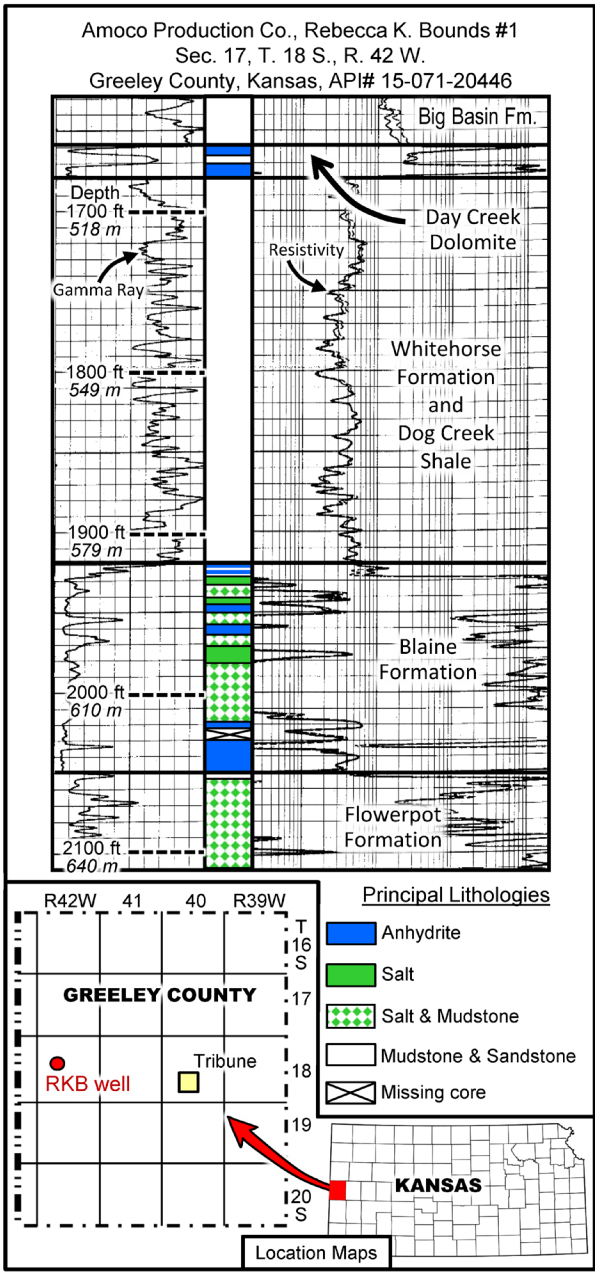


Figure 9. Core description and geophysical log of Day Creek Dolomite, Blaine Formation, and associated strata in western Kansas. Description of Rebecca K. Bounds #1 core from Zambito and others (2012) and Benison and others (2013). Note that here the Day Creek Dolomite Formation is anhydrite that contains dolomite.

that in Kansas outcrops it typically is 2–3 ft (0.6–0.9 m) of dolomite, and at some localities it contains chert nodules and disseminated chert. The type section for both the Day Creek Dolomite and the older Moccasin Creek Bed (at the base of the Cloud Chief Formation) is an exposure in sec. 8, T. 28 N., R. 18 W., at the headwaters of West Moccasin Creek in Woods County, Oklahoma (Fay, 1965). At this latter site, the Day Creek is a single bed of white to light-gray dolomite 2 ft (0.6 m) thick and about 31 ft (9 m) above the Moccasin Creek Bed.

In 1988, Amoco Production Company drilled the Rebecca K. Bounds #1 (RKB) core in Greeley County, Kansas, near the Colorado border (Fig. 9). The core penetrated the full thickness of Permian strata, and the core is now located in the core repository of the Kansas Geological Survey in Lawrence, Kansas: photos of the core can be viewed at https://chasm.kgs.ku.edu/ords/qualified.cimg2.CoreImages?f_well=1006067111 The Permian portion of the RKB core was examined and described by Zambito and others (2012), Benison and others (2013), and Pritt (2016). The portion of the core and geophysical logs from the Day Creek and Big Basin Formations down to the Blaine and Flowerpot Formations are shown in Figure 9.

The Day Creek Dolomite core in the RKB well is a dyad of anhydrite and gypsum with an intervening siltstone/mudstone: the dyad is 17 ft (5.2 m) thick at a depth of 1,659–1,676 ft (505.7–510.8 m) (Pritt, 2016). The upper anhydrite/gypsum is about 4 ft (1.2 m) thick, and the lower anhydrite/gypsum is about 7 ft (2.1 m) thick: they are separated by about 6 ft (1.8 m) of orange siltstone/mudstone. In a petrographic study of the Day Creek core, Pritt (2016) describes the two evaporite beds as a whitish-pink to blue mixture of gypsum and/or anhydrite that also contains dolomite, quartz grains, and some halite as crystals or possible pseudomorphs.

Cloud Chief Formation in Western Oklahoma

The Cloud Chief was originally named by Gould (1924) for thick gypsums and red shales that: 1) overlie what he presumed to be the Day Creek Dolomite or, where it is missing, the Whitehorse Sandstone (now Whitehorse Group); and 2) that underlie the Quartermaster Formation (now Doxey Formation in Oklahoma). The basal gypsum (previously called the Cloud Chief Gypsum) was re-named the Moccasin Creek Bed by Fay (1965), and that name now applies to the gypsum, dolomite, multiple gypsums or dolomites, or greenish-gray zones that locally are at the base of the Cloud Chief Formation. The type area for the Cloud Chief Formation is the region around the town of Cloud Chief in Washita County, Oklahoma, but inasmuch as only the lower part of the Cloud Chief is present in that area, Fay (1965, 1978) proposed a provisional type section in secs. 6 and 7, T. 16 N., R. 20 W., in Dewey County, Oklahoma, where the West Leedey core and nearby outcrops embrace the entire Cloud Chief

Formation (Fig. 10). The West Leedey core, drilled in sec. 7, penetrated the lower 78% of the Cloud Chief, and outcrops in sec. 6 contain the upper 22% of the formation.

At its provisional type section (Fig. 10) the Cloud Chief Formation is 171 ft (52 m) thick: the lower 134 ft (41 m) is present in the West Leedey core, and the remaining 37 ft (11 m) is exposed nearby (Fay, 1978). The formation here consists mainly of interbedded sandstone, siltstone, and shale. Most of these rocks are orange brown in color (in contrast to the red-brown color of the overlying Doxey Formation) and are weakly indurated. The Moccasin Creek Bed, at the base, is 13.5 ft (4.1 m) thick and consists of three white to light-orange gypsum beds 0.7–3.0 ft (0.2–0.9 m) thick, interbedded with red-brown to orange-brown siltstone and shale; the lowest gypsum is dolomitic at its base. The Day Creek Bed is 3 ft (0.9 m) of white to light-orange, fine-grained gypsum located 28 ft (8.5 m) above the Moccasin Creek Bed. So, the Day Creek Bed here is clearly equivalent to, and is part of, the lower part of the Cloud Chief Formation: it is 28 ft (8.5 m) above the top of the Moccasin Creek Bed, and 41.5 ft (12.6 m) above the base of the Cloud Chief Formation. This is similar to the position of the Day Creek Bed at its type section in Woods County, Oklahoma, where the Day Creek is about 31 ft (9 m) above the Moccasin Creek Bed (see "Day Creek Dolomite in western Kansas," above).

CORRELATION OF RUSTLER FORMATION WITH ALIBATES FORMATION

The Rustler Formation is extensive throughout the Delaware Basin and surrounding areas. Although in Culberson-County outcrops the Rustler is 150–200 ft (46–61 m) of dolomitic limestones and sandstones, to the east in subsurface within the Delaware Basin the formation also contains gypsum/anhydrite, red-bed mudstones, and salt (Figs. 6, 11). The Rustler is generally thickest in the eastern part of the Delaware Basin, where it is commonly 300–500 ft (91–152 m) thick, and locally almost 1,000 ft (305 m) thick (Ewing and others, 2012). The Rustler dips to the east in the Delaware Basin, and the greater thickness of the formation to the east results, in part, from the presence of salt that is protected from dissolution because of the greater depth of the Rustler to the east (Holt and Powers, 1988; Powers and Holt, 2000, 2021; Powers and others, 2006).

It has been suggested or stated in the past that the Rustler is correlative with the Alibates Formation in the Texas Panhandle (Gould, 1927; Roth 1941; Dunbar and others, 1960; Dixon, 1967; Johnson, 1978, 2021a; McGillis and Presley, 1981; Hills and Kottlowski, 1983; John-

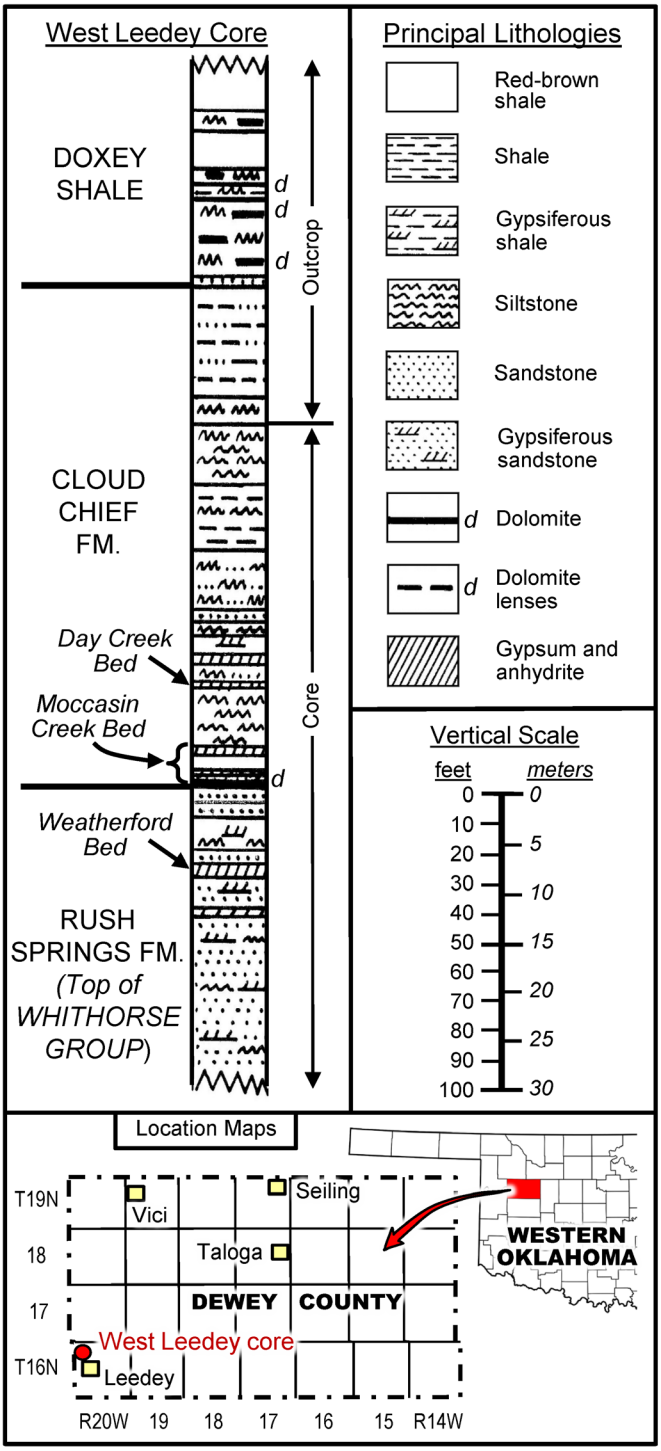
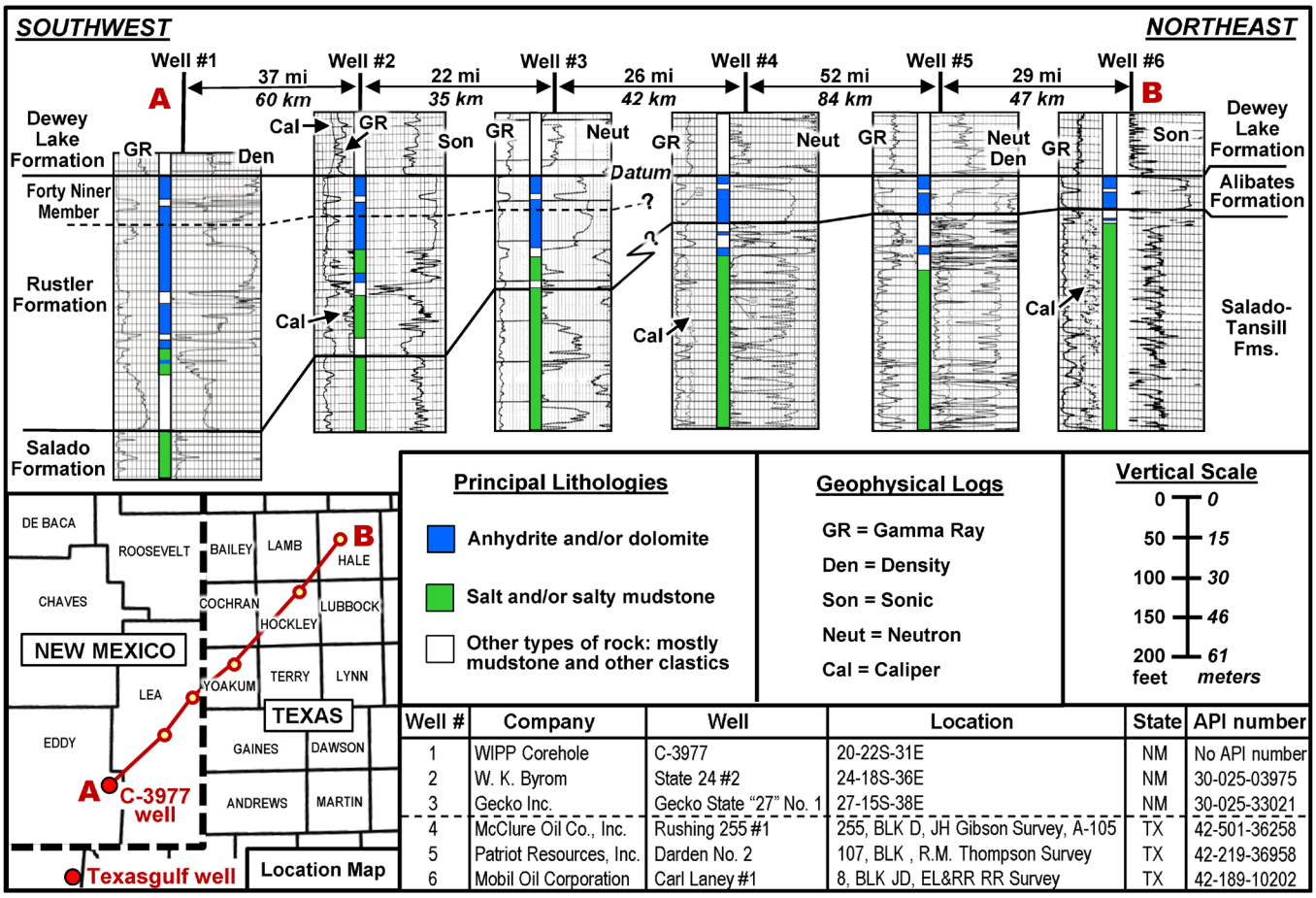


Figure 10. Core and outcrop description of provisional type section for Cloud Chief Formation proposed by Fay (1978). Location is Fay's measured section #17 in secs. 6 and 7, T. 16 N., R. 20 W., Dewey County, Oklahoma (Fay, 1978).



Well #	Company	Well	Location	State	API number
1	WIPP Corehole	C-3977	20-22S-31E	NM	No API number
2	W. K. Byrom	State 24 #2	24-18S-36E	NM	30-025-03975
3	Gecko Inc.	Gecko State "27" No. 1	27-15S-38E	NM	30-025-33021
4	McClure Oil Co., Inc.	Rushing 255 #1	255, BLK D, JH Gibson Survey, A-105	TX	42-501-36258
5	Patriot Resources, Inc.	Darden No. 2	107, BLK , R.M. Thompson Survey	TX	42-219-36958
6	Mobil Oil Corporation	Carl Laney #1	8, BLK JD, EL&RR RR Survey	TX	42-189-10202

Figure 11. Stratigraphic cross section A–B showing correlation of Rustler Formation in Eddy County, New Mexico, with the Alibates Formation in Hale County, Texas. Note that well #6 here is the same as well #6 in cross section C–D (Fig. 12).

son and others, 1989; Powers and Holt, 1999; Hovorka and Nava, 2000; Steiner, 2001, 2006; Tabor and others, 2022), and the current report shows that they are correlative. As shown in Figure 11, the upper anhydrite of the Forty Niner Member is regionally correlative with the upper anhydrite/dolomite of the Alibates to the north, and the mudstone in the middle of the Forty Niner Member is correlative with the mudstone that separates the upper and lower anhydrite/dolomite of the Alibates dyad farther north. What happens to the lower anhydrite of the Forty Niner and underlying Rustler strata to the north is unclear. Presumably the lower anhydrite of the Forty Niner persists to the north, but the underlying Rustler strata either are thinner due to northward onlap and become part of the lower anhydrite/dolomite unit of the Alibates, or some (or all) of these underlying strata pinch out to the north. As shown in Figure 11 (wells #4–6), in the Texas Panhandle and farther to the north the Alibates is a dyad, consisting of a lower and upper anhydrite/dolomite separated by a middle mudstone. This dyad is well represented by the two cores of the Alibates in the Palo Duro Basin (Fig. 8).

Above the Rustler/Alibates is the Dewey Lake Formation, which contains the Permian–Triassic boundary in the Texas Panhandle—based on radiometric dating (U–Pb), described below. The Dewey Lake is largely a red-brown or orange-brown siltstone with interbeds of sandstone and shale in the Delaware Basin: it is generally 200–500 ft (61–152 m) thick and locally up to 600 ft (183 m) thick (Schiel, 1988). This unit is also referred to as the Quartermaster Formation in outcrops farther north in the Texas Panhandle, as the Doxey Formation in western Oklahoma, and it appears to be equivalent, in part, to the Big Basin Formation in western Kansas (Fig. 3).

Beneath the Rustler/Alibates are the Salado and Tansill Formations (the Whitehorse Group in Texas-Panhandle outcrops). The Salado and Tansill are predominantly salt (halite) with lesser amounts of anhydrite and mudstone that are indistinguishable in the Palo Duro Basin area, where they are regarded as a single unit (Fig. 8). In the Rex White well, the salt interval is shallower and

is dissolved (McGillis and Presley, 1981)—leaving the Salado–Tansill as a unit consisting mainly of mudstone/siltstone with minor gypsum and anhydrite.

CORRELATION OF ALIBATES FORMATION WITH DAY CREEK DOLOMITE

The Alibates Formation is recognized and correlated throughout the Texas and Oklahoma Panhandles, and the term Alibates has also been used for Rustler strata farther south in the Midland Basin (Hovorka and Nava, 2000). Two cross sections (Figs, 12, 13), prepared by the Texas Bureau of Economic Geology, clearly show correlation of the Alibates dyad across the Texas Panhandle and north into the Oklahoma Panhandle. Both cross sections are fairly close to the Grabbe and Rex White cores (Fig. 8) that establish the general character of the Alibates in the Palo Duro Basin. The dyad throughout this area consists of lower and upper gypsum/anhydrite/dolomite beds, separated by a mudstone unit. Whereas the lower and upper members are dolomite (and flint) in the type-area outcrops (Fig. 7), it is difficult to distinguish the varying amounts of gypsum/anhydrite and/or dolomite present in the dyad (on geophysical logs) elsewhere in the Panhandle without seeing the rock in a core or outcrop. The top two beds of the Alibates are correlative with the upper anhydrite and the middle mudstone of the

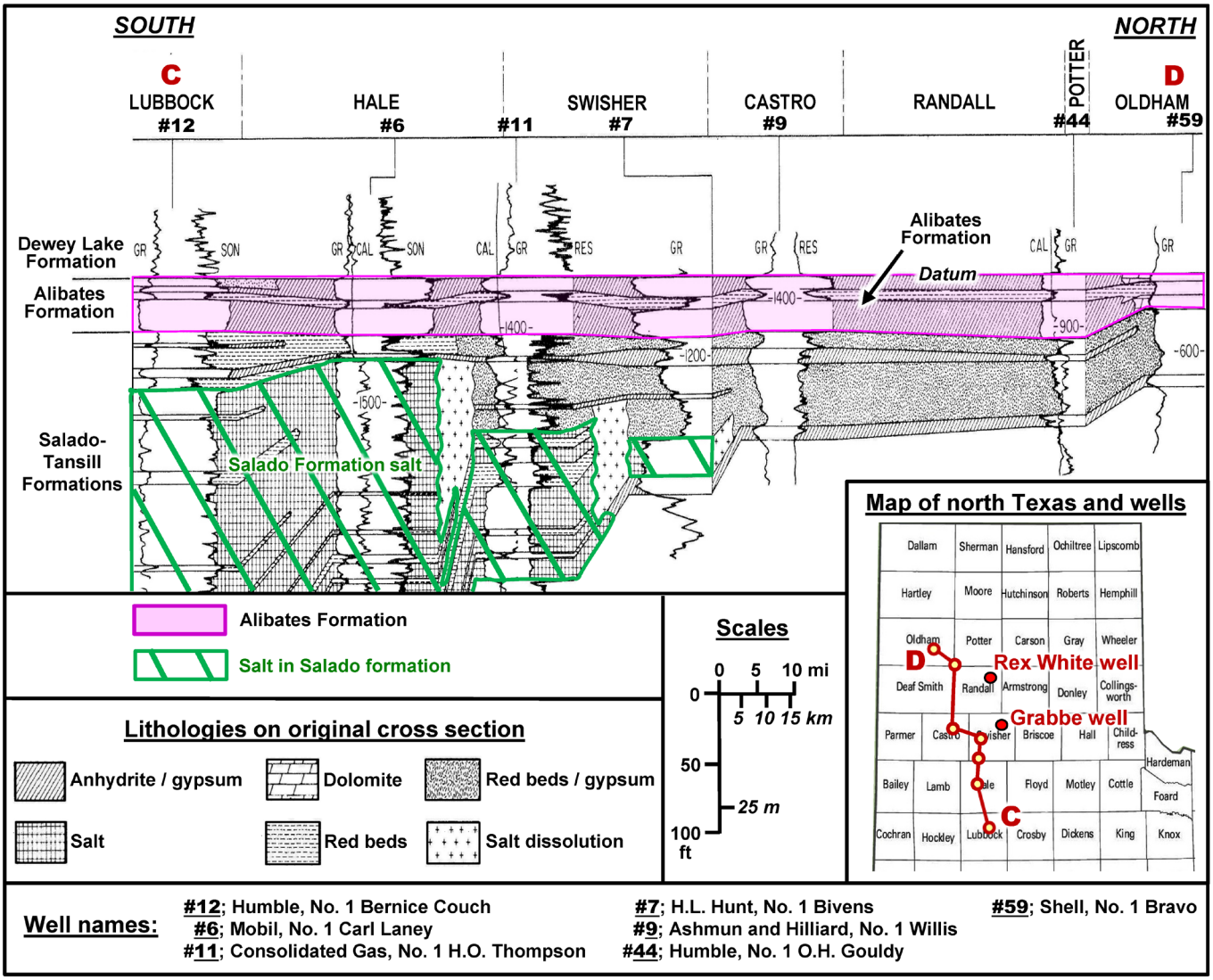


Figure 12. Stratigraphic cross section C–D showing correlation of Alibates and Salado-Tansill Formations in Texas, from Lubbock County (south) to Oldham County (north). Modified from McGillis and Presley (1981): well locations and API numbers not given in original. Note that well #6 here is the same as well #6 in cross section A–B (Fig. 11).

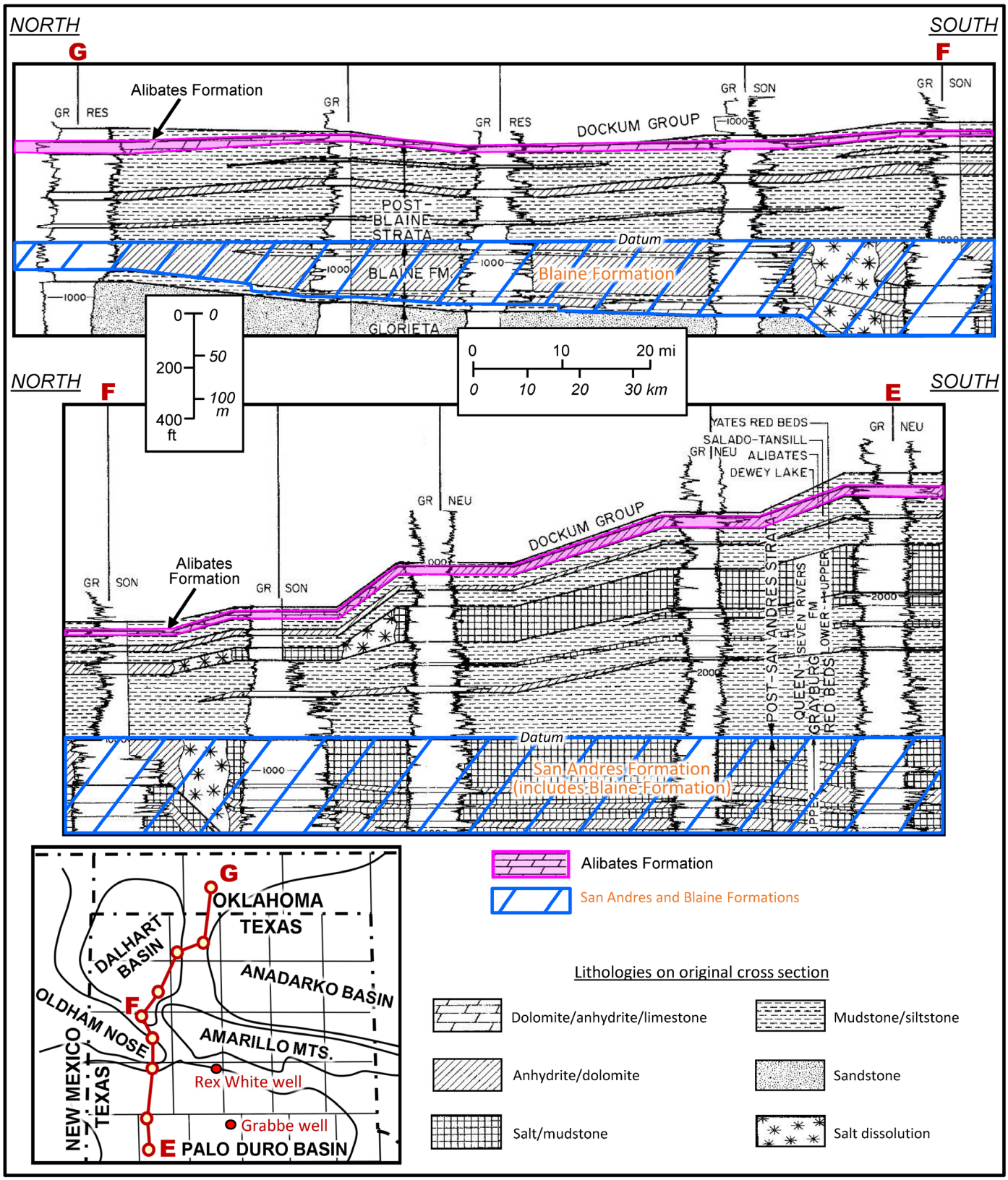


Figure 13. Stratigraphic cross section E–F–G showing correlation of Alibates and San Andres/Blaine Formations from Lamb County, Texas (Palo Duro Basin in south), to Texas County, Oklahoma (Anadarko Basin in north). Modified from Presley (1981): well names, locations, and API numbers not given in original. Note that the well at north end of this cross section ("G") is the same as well #1 in cross section G–H (Fig. 15).

Forty Niner Member in southeast New Mexico (Fig. 11), and the bottom bed is correlative with the lower anhydrite of the Forty Niner and probably some of the underlying Rustler strata.

The lower and upper units of the Alibates Formation are mainly anhydrite and/or gypsum in the south half of the Texas Panhandle, and they are mainly dolomite farther north (McGillis and Presley, 1981; Fig. 14). The Alibates Formation is 20–40 ft (6–12 m) thick in most parts of the Panhandle, and locally reaches 60–80 ft (18–24 m) thick to the southwest in Cochran County, Texas, and nearby parts of New Mexico (Fig. 14). To the east and the west, the Alibates thins to less than 10 ft (3 m) and cannot be readily recognized on geophysical logs, or it is eroded. Perhaps, in the future, a direct correlation will be made of the Alibates in the Anadarko Basin of Texas with Cloud Chief strata farther east in Oklahoma: at present there are insufficient data to show that correlation, and so it is necessary to show correlation of the Alibates with the Day Creek in Kansas, and then show correlation of the Day Creek with the lower Cloud Chief in Oklahoma.

Correlation of the Alibates with the Day Creek has been suggested or stated in the past (Gould, 1907, 1927; Gould and Lewis, 1926; Adams, 1935; Dunbar and others, 1960; Rascoe, 1968; Rascoe and Baars, 1972; Bowers, 1975; Maughan, 1980), and the current report shows that to be the case in cross section G–H (Fig. 15). Well #1, at the south end of cross section G–H, is the same well that is at the north end of cross section E–F–G (Fig. 13). Therefore, the Alibates dyad, present in the Texas–Oklahoma Panhandles, grades laterally into the Day Creek Dolomite dyad of western Kansas. The lower and upper members of the Alibates in the northern part of the Texas Panhandle are mostly dolomite (Fig. 14), but in western Kansas they are anhydrite in the RKB core at the north end of cross section G–H (Figs. 9, 15). There are no data on the lithology of the lower and upper members of the Alibates in the other wells in western Kansas, so they are shown here as consisting of "dolomite and/or anhydrite." It is reasonable to assume that the middle member of the Alibates is mudstone or siltstone, as in the RKB, Rex White, and Grabbe cores.

Overlying the Alibates in most of the Texas–Oklahoma Panhandles is the Dewey Lake Formation (Figs. 3, 4, 8, 11–13), also referred to as the Quartermaster Formation (or Quartermaster Group) in outcrops. The term "Quartermaster" has been used in Texas-Panhandle outcrops to include all strata above the Whitehorse Group (with the Alibates in the upper part) and below the Triassic Dockum Group (Barnes, 1968, 1969; Tabor and others, 2022). "Quartermaster" has been used in various ways in Oklahoma to include, at times, the Cloud Chief, Day Creek, Doxey, and Elk City Formations (Fay, 1978). The Dewey Lake in the Texas Panhandle is the same formation that overlies the Rustler in the Delaware Basin to the south. Unconformably above the Dewey Lake Formation in most of the region is the Triassic Dockum Group, which consists of fluvial, deltaic, and lacustrine systems deposited in a large continental basin (McGowan and others, 1979). At a few places the Dockum has eroded through the Dewey Lake and rests directly on the Alibates (middle of cross section F–G, Fig. 13).

Underlying the Alibates in the Texas–Oklahoma Panhandles are strata equivalent to the Salado–Tansill or the Whitehorse Group (Figs. 3, 4, 8, 11–13). Salt at the top of the Salado is a good marker in parts of the Palo Duro Basin, but farther north the most reliable pre-Alibates marker beds are gypsum/anhydrite in the San Andres/Blaine Formation. In the Bivins well (Fig. 7) the top of the San Andres/Blaine Formation is 346 ft (105 m) below the Alibates, and the top of the Blaine Formation is 350–400 ft (107–122 m) below the Alibates in the Dalhart Basin and Oklahoma Panhandle (Fig. 13).

Flint is abundant in the Alibates Formation in northeast Potter County (Bowers, 1975). Much of the dolomite has been agatized locally to a beautiful combination of colors—mainly red, blue, and white. Native Americans have quarried the Alibates Flint for thousands of years from this area to make arrow points and other implements, and these were used and traded widely in southwest United States (Wycoff, 2005). The flint occurs mainly in a 10-mi^2 (26-km^2) area near Lake Meredith, and 1,000 acres (405 ha) containing about 700 Native American quarries have been set aside as the Alibates Flint Quarries National Monument (AFQNM) to preserve this historic place. The border of the AFQNM is about 400 ft (122m) north of the Bivins 142R well (Fig. 7). The website for the AFQNM is: https://www.nps.gov/alfl/index.htm

CORRELATION OF DAY CREEK DOLOMITE WITH LOWER CLOUD CHIEF FORMATION

The Day Creek Dolomite dyad is 19–45 ft (6–14 m) thick in the western part of Kansas (Fig. 15), but it thins to 15–20 ft (5–6 m) to the east and becomes a single bed at and near its outcrop in Clark County (Fig. 16, Well #6 and MS #13). A maximum thickness of 120 ft (37 m)

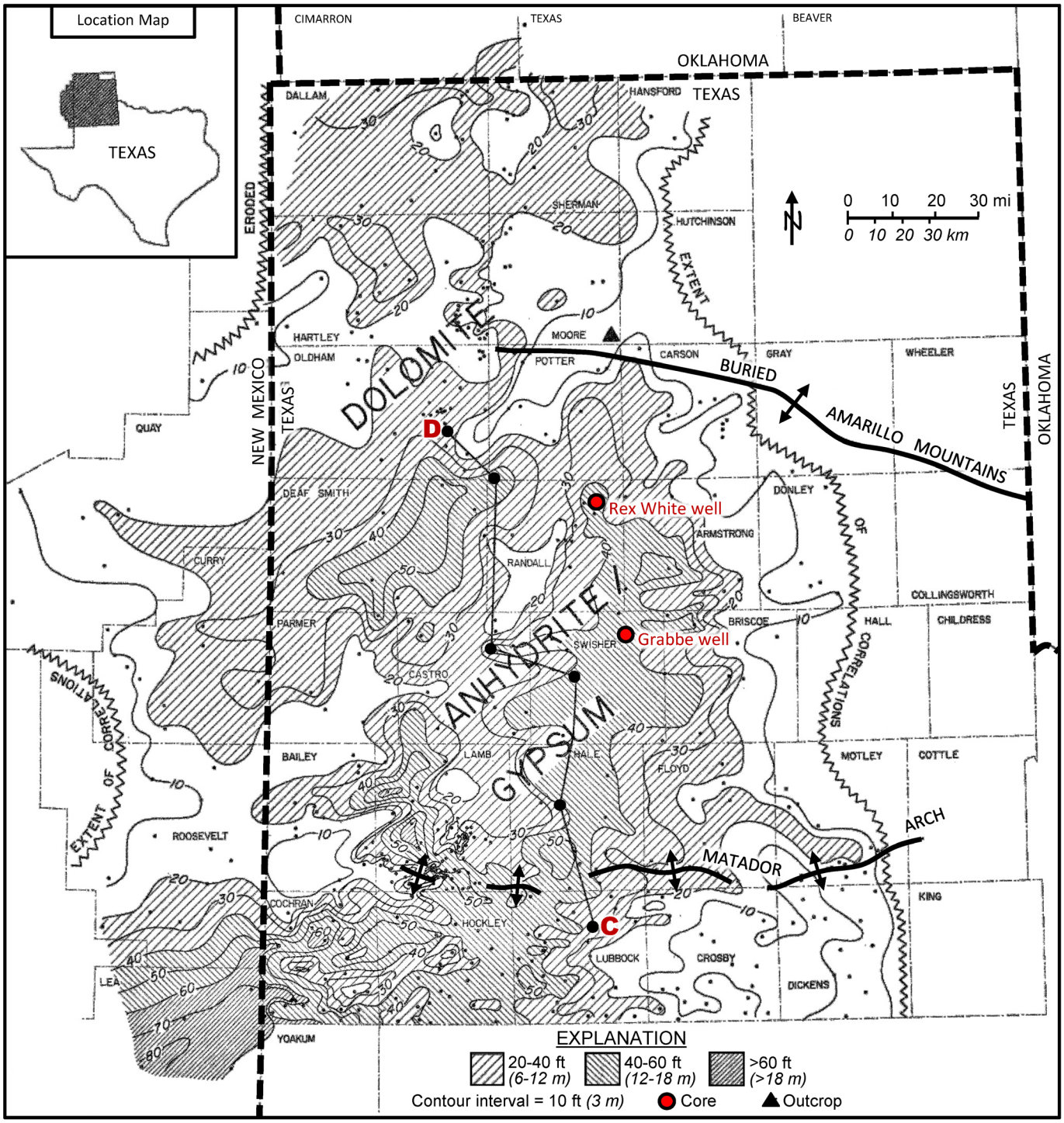


Figure 14. Map showing thickness and principal lithology of Alibates Formation in Texas Panhandle (modified from McGillis and Presley, 1981). Serrate lines in east and west mark limits of correlation or erosional boundary. Also shown are location of Grabbe and Rex White wells (Fig. 8), and cross section C–D (Fig. 12).

for the formation in Morton County, Kansas, was erroneously reported by Maher and Collins (on Sheet 3, 1952), based on the sample log of a well in sec. 17, T. 32 S., R. 40 W.: a current review of the radioactivity log for that same well, the Stanolind Oil & Gas Co., Alice Bear no. 1 (API# 15-129-00126), shows that the Day Creek here is only 45 ft (14 m) thick. In addition to being recognized in Kansas and Oklahoma, the Day Creek has also been identified farther west in the Denver Basin of Colorado (Table 1 and Plate 16 in McKee, Oriel, and others, 1967)

and to the north in Nebraska (Fig. 4).

Correlation of the Day Creek with part of the Cloud Chief Formation has been suggested or stated by a number of workers in the past (Gould and Lewis, 1926; Evans, 1931; Adams, 1935; Roth and others, 1941; Miser, 1954; Myers, 1959; Dunbar and others, 1960; Rascoe, 1968; Morton, 1980; Hills and Kottlowski, 1983), and correlation of the Day Creek with the lower part of the Cloud Chief was finally confirmed and demonstrated by Fay (1965, 1978): that correlation is supported here (Figs. 3, 10, 16, 17).

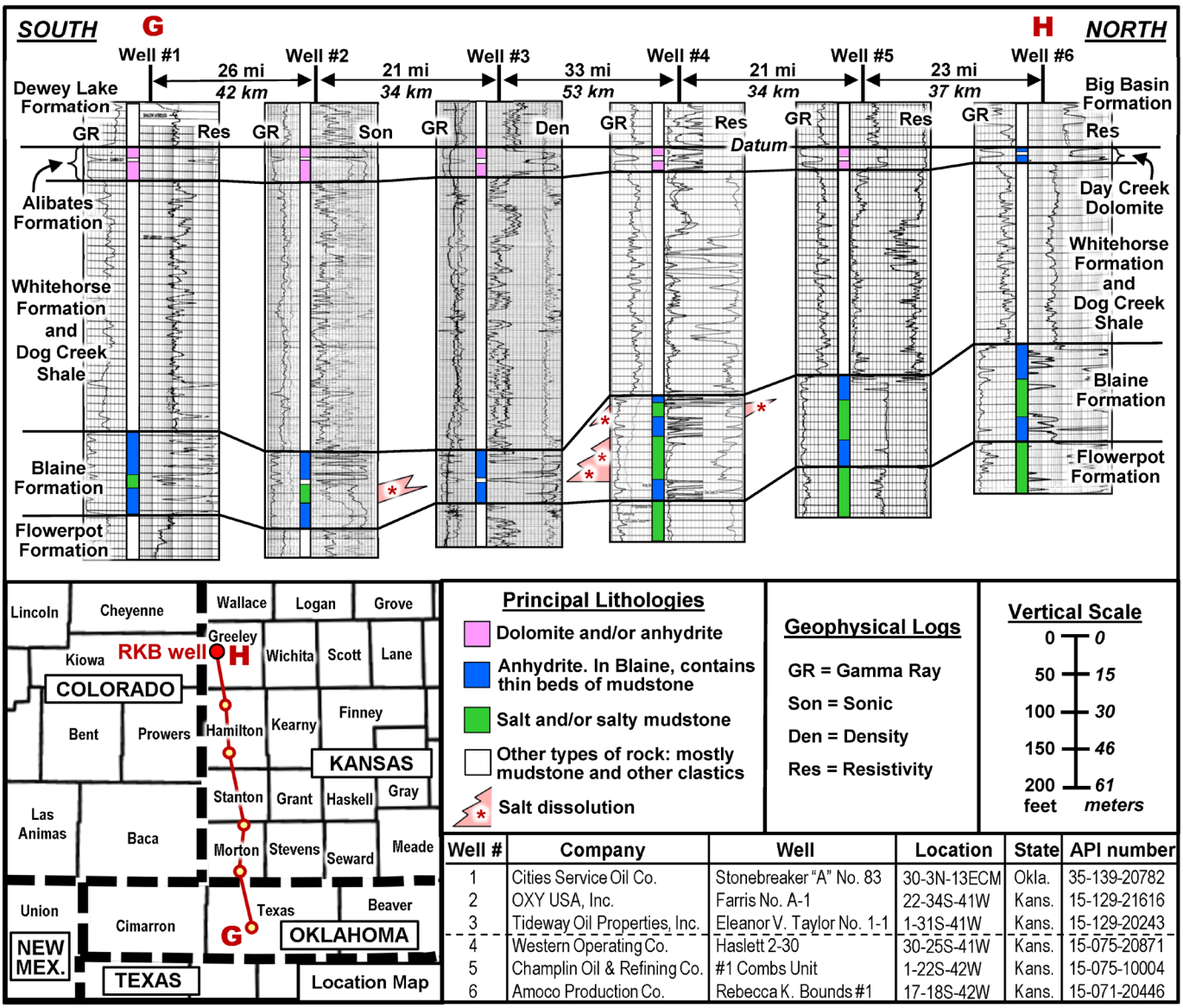
Measured section 13 (MS #13) on Figures 16 and 17 represents outcrops in the vicinity of Day Creek in Clark County, and it shows the correct position of the Day Creek Dolomite relative to the Moccasin Creek Bed, which is at the base of the Cloud Chief Formation. In subsurface, to the north and west of MS #13, a second dolomite and/or gypsum/anhydrite bed is present (Fig. 16) to form the dyad that is characteristic of the Day Creek and Alibates in most of western Kansas and the Texas–Oklahoma Panhandles. The relation of this second bed to the originally named single bed of Day Creek Dolomite is unknown: the original Day Creek may split into two beds to the north and west, or the second bed could occur either above or below the single bed seen in Clark County outcrops—based on information in Oklahoma (below), it appears that the original Day Creek Dolomite is the lower of the two beds.

Above the Day Creek Dolomite in Kansas is the Big Basin Formation (previously the Taloga Formation), which consists of red mudstones and fine-grained sandstones with some layers of anhydrite and dolomite: the formation reaches about 45 ft (14 m) thick in outcrops, but it is reported to be as much as 300 ft (91 m) thick in subsurface (West and others, 2010). Beneath the Day Creek in Kansas, the Whitehorse Formation is very fine-grained red sandstone with some mudstone and thin dolomites (West and others, 2010): in subsurface it is difficult to identify the contact between the Whitehorse and the underlying Dog Creek Shale on geophysical logs, so they are not differentiated here. Anhydrite or gypsum beds in the Blaine Formation are excellent marker beds beneath the Whitehorse and Dog Creek Formations (Figs. 15, 16).

Based on extensive field work on the Permian in southwest Kansas and northwest Oklahoma, Fay (1965) established the type section for both the Day Creek and the Moccasin Creek Beds in SE¼ SE¼ sec. 8, T. 28 N., R. 18 W., Woods County, Oklahoma. At its type section the Moccasin Creek Bed consists of three units (Fay, 1978, p. 21): 1) an upper greenish-gray, quartzose limestone or dolomite 4 in. (10.2 cm) thick; 2) a middle red-brown shale and siltstone 1 ft (0.3 m) thick; and 3) a lower greenish-gray calcitic sandstone 1.5 ft (0.46 m) thick. At this same site the Day Creek Bed is 2 ft (0.61 m) of white to light-gray, compact, thin-bedded, well-indurated dolomite that is about 31 ft (9.4 m) above the Moccasin Creek Bed and 34 ft (10.4 m) above the base of the Cloud Chief Formation (Fay, 1978, p. 25). Clearly at its type section, the Day Creek Dolomite Bed is equivalent to the lower part of the Cloud Chief Formation, and the same is also shown in the provisional type section of the Cloud Chief Formation in the West Leedey core (Fig. 10).

In northwestern Oklahoma, Evans (1931) describes the Day Creek as consisting of two beds of dolomite in much of the area. He notes that the lower bed corresponds to the type Day Creek Dolomite in Clark County, Kansas, whereas the upper bed is "a thinner pinkish or purplish calcitic or dolomitic bed, about 3 inches [7.6 cm] in thickness, 3 feet [0.9 m] above the Lower Day Creek dolomite" (Evans, 1931, p. 426). Separating the two dolomites is a brown shale that weathers maroon. Evans (1931) points out that in some places the lower Day Creek is very sandy, and even grades into sandstone with no indication of calcium carbonate. Fay (1965, 1978) also describes the Day Creek as a double dolomite in parts of Oklahoma, and this is similar to the dyad nature of the Day Creek in the subsurface of western Kansas. Fay (1978) recognized a triple-dolomite sequence at a site in central southern Custer County, Oklahoma: the Day Creek here is about 10 ft (3 m) thick and consists of, in ascending order, 0.3 ft (0.1 m) of white dolomite, 2.4 ft (0.7 m) of sandstone, 0.9 ft (0.3 m) of dolomite, 2.8 ft (0.9 m) of sandstone, and 3.7 ft (1.1 m) of dolomite.

The Day Creek Bed is correlative with the lower part of the Cloud Chief Formation in northwest Oklahoma and in Clark County, Kansas (Figs. 3, 10, 16, 17; Myers, 1959; Fay, 1965, 1978). Suffel (1930) provides detailed descriptions of the Day Creek Dolomite in several counties of northwest Oklahoma. Fay (1965) examined outcrops of the Day Creek Bed and associated strata throughout northwest Oklahoma and Clark County, Kansas, and provides descriptions of these strata in most parts of this area. He notes that the Day Creek Bed is typically a dolomite 1–3 ft (0.3–1 m) thick, and locally it is a double dolomite, as also described by Evans (1931). It is commonly 25–40 ft (8–12 m) above the Moccasin Creek Bed, but in the Weatherford area it appears to be equivalent to the middle or upper part of the massive gypsum in



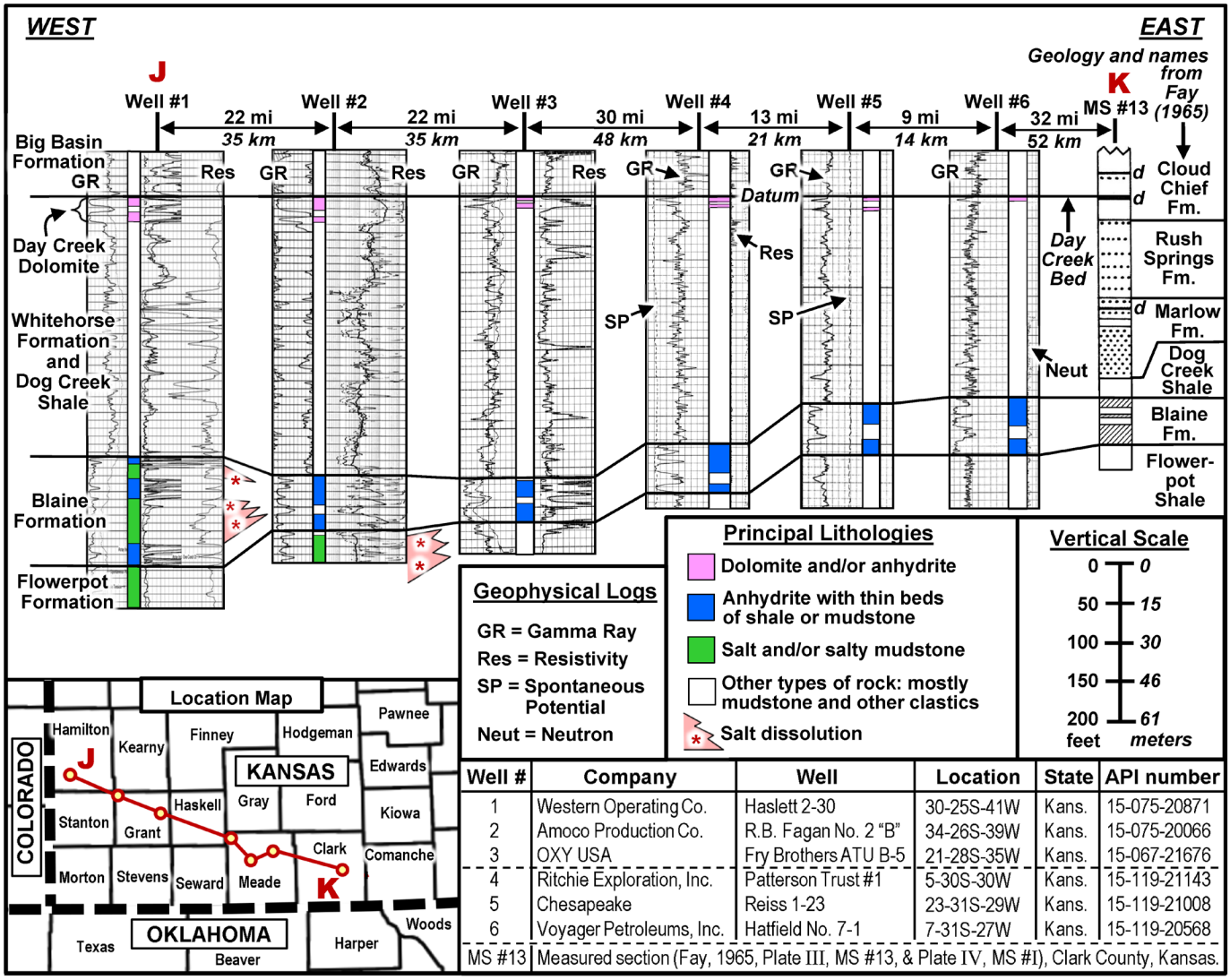
Well #	Company	Well	Location	State	API number
1	Cities Service Oil Co.	Stonebreaker "A" No. 83	30-3N-13ECM	Okla.	35-139-20782
2	OXY USA, Inc.	Farris No. A-1	22-34S-41W	Kans.	15-129-21616
3	Tideway Oil Properties, Inc.	Eleanor V. Taylor No. 1-1	1-31S-41W	Kans.	15-129-20243
4	Western Operating Co.	Haslett 2-30	30-25S-41W	Kans.	15-075-20871
5	Champlin Oil & Refining Co.	#1 Combs Unit	1-22S-42W	Kans.	15-075-10004
6	Amoco Production Co.	Rebecca K. Bounds #1	17-18S-42W	Kans.	15-071-20446

Figure 15. Stratigraphic cross section G–H showing correlation of Alibates Formation in Texas County, Oklahoma, with the Day Creek Dolomite in Greeley County, Kansas. Note that well #1 here is the same as the well at north end of cross section E–F–G (Fig. 13), and that well #4 here is the same as well #1 in cross section J–K (Fig. 16).

the Moccasin Creek Bed (previously called the "Cloud Chief Gypsum") that here is locally more than 100 ft (30 m) thick (Fig. 17).

AGE OF RUSTLER, ALIBATES, DAY CREEK, AND LOWER CLOUD CHIEF FORMATIONS

The Ochoan Series, established by Adams and others (1939) in the Delaware Basin in Lea County, New Mexico, includes Late Permian strata between the Permian Guadalupian Series and Triassic strata in West Texas and southeast New Mexico. This includes the Castile, Salado, Rustler, and Dewey Lake Formations in the type area (Figs. 3, 4), and would also include strata equivalent to these formations elsewhere in the region. Regional correlations by Dunbar and others (1960) (Fig. 4) showed the Rustler, Day Creek, and Cloud Chief to all be equivalent and Ochoan in age (no mention of the Alibates). Later regional correlations by Hills and Kottlowski (1983) showed: 1) the Rustler and Alibates are equivalent and Ochoan in age; 2) the Cloud Chief is Guadalupian and Ochoan in age; and 3) that the Day Creek is below the Alibates, is Guadalupian in age, and correlates with the lower or middle Cloud Chief. The current study agrees with the earlier work by Dunbar and others (1960) and shows



Well #	Company	Well	Location	State	API number
1	Western Operating Co.	Haslett 2-30	30-25S-41W	Kans.	15-075-20871
2	Amoco Production Co.	R.B. Fagan No. 2 "B"	34-26S-39W	Kans.	15-075-20066
3	OXY USA	Fry Brothers ATU B-5	21-28S-35W	Kans.	15-067-21676
4	Ritchie Exploration, Inc.	Patterson Trust #1	5-30S-30W	Kans.	15-119-21143
5	Chesapeake	Reiss 1-23	23-31S-29W	Kans.	15-119-21008
6	Voyager Petroleums, Inc.	Hatfield No. 7-1	7-31S-27W	Kans.	15-119-20568
MS #13	Measured section (Fay, 1965, Plate III, MS #13, & Plate IV, MS #I), Clark County, Kansas.				

Figure 16. Stratigraphic cross section J–K showing correlation of the Day Creek Dolomite in Hamilton County, Kansas, with the lower part of the Cloud Chief Formation in Clark County, Kansas. Note that well #1 here is the same as well #4 in cross section G–H (Fig. 15), and that the upper part of MS #13 here is also shown in cross section K–L (Fig. 17) along with symbols for MS #13.

bed-by-bed that the Rustler, Alibates, and Day Creek are correlative, and they are also correlative with the lower part of the Cloud Chief Formation; therefore, the first three formations, and at least the lower part of the Cloud Chief Formation, are Late Permian (Ochoan) in age.

A Late Permian (Ochoan) age for the Rustler and Alibates in Texas and southeast New Mexico is based on the following data: 1) fossils show that the Rustler and at least the lowest part of the Dewey Lake (Quartermaster) in West Texas and the Texas Panhandle are Late Permian; and 2) both radiometric and paleomagnetic dating in the Texas Panhandle show that the Permian–Triassic boundary is in the lower part of the Dewey Lake (Quartermaster), which is above the Alibates. In southeast New Mexico and West Texas, Schiel (1988) provides a comprehensive review of studies that suggest that the Permian–Triassic boundary is somewhere within the lower part of the Dewey Lake, although Lucas and Anderson (1993, 1994) point out that much of that work shows that all of the Dewey Lake is Late Permian in age.

As shown in this study, physical tracing of stratigraphically equivalent gypsum/anhydrite/dolomite strata in the Rustler and Alibates Formations from Texas and New Mexico, where the age is established, shows that the Day Creek and lower Cloud Chief in Kansas and Oklahoma are also Ochoan. Unfortunately, there are no data in Kansas or Oklahoma that independently establish the age of the Day Creek or Cloud Chief Formations. Smith and oth-

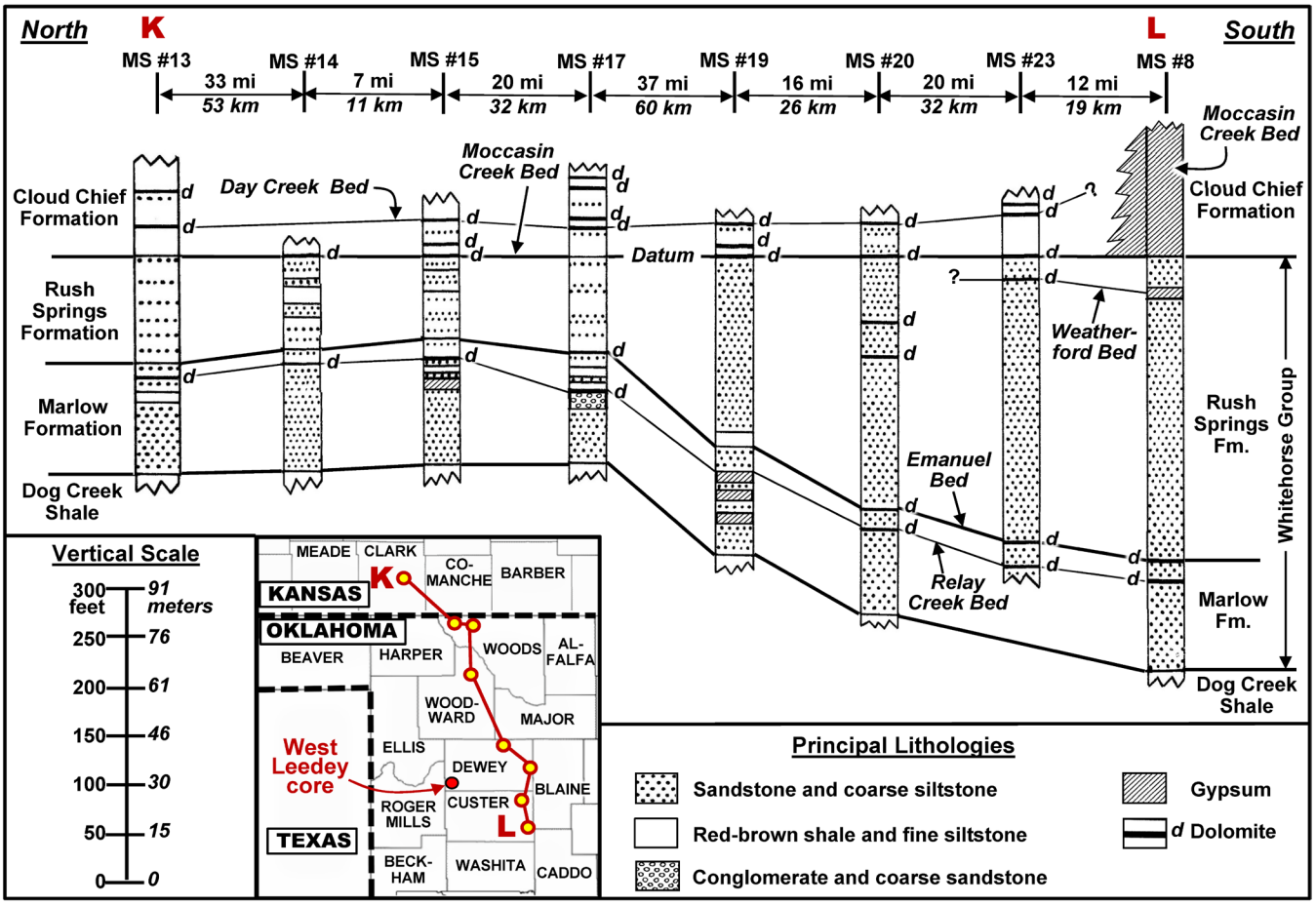


Figure 17. Stratigraphic cross section K–L showing correlation of the Day Creek Bed in Clark County, Kansas, with the lower part of the Cloud Chief Formation in Custer County, Oklahoma. All measured sections (MS) are from Fay (1965, Plate III) and are numbered the same as in that report. Note that MS #13 here is also shown as the upper part of MS #13 in cross section J–K (Fig. 16).

ers (2015) showed that the Big Basin Formation, which overlies the Day Creek at Point of Rocks (an important landmark in the southwest corner of Kansas), contained a single detrital zircon grain dated to 263.8±12.1 Ma. This indicates that the maximum (oldest) depositional age of the Big Basin Formation could be late Guadalupian (Capitanian Stage [Menning and others, 2006]). However, that date shows the age of zircon formation in an igneous or metamorphic rock in a perhaps-distant source area, but does not indicate the age of its deposition in the Big Basin Formation. Thus, the zircon shows that the Big Basin and underlying Day Creek are at least Guadalupian in age, but physical correlation with the Rustler and Alibates shows that the Day Creek is Ochoan.

Fossil Evidence

Late Permian strata throughout the region are characterized by red beds and evaporites and they are generally lacking in fossils. However, diagnostic fossils have been found in the Rustler Formation in West Texas and in the lower Dewey Lake Formation in the Texas Panhandle.

The Rustler Formation has yielded marine invertebrate and conodont fossils that are of Permian age. Donegan and DeFord (1950) and Walter (1953) describe a fauna of brachiopods and gastropods in the Virginia Draw Member (now the Los Medaños Member) in the Rustler Hills of Culberson County, Texas, and nearby areas that they regard as Late Permian. Also, conodonts in the Rustler Formation in the same area are assigned a Changhsingian age (Croft, 1978; Wardlaw and Grant, 1992), which is the last stage of the Permian Period (Ochoan Age).

Three pelecypod species recovered from the lower Dewey Lake in Briscoe County, Texas Panhandle, suggest a Permian age (Roth and others, 1941). They were collected from a 2-ft (0.6-m) thick dolomite located 10 ft (3 m) above the base of the Dewey Lake Formation at a site about 10 mi (16 km) slightly east of due north

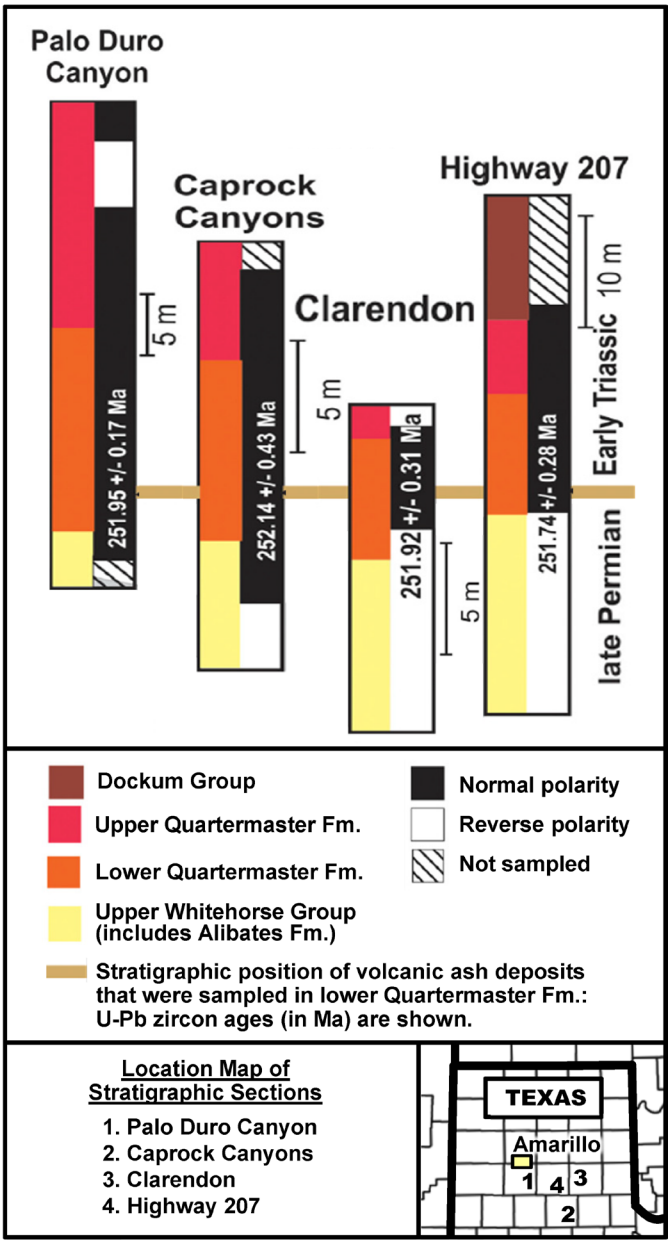


Figure 18. Four stratigraphic sections in Texas Panhandle where volcanic-ash beds in the lower Dewey Lake (Quartermaster) Formation have yielded U–Pb radiometric ages in zircons showing that the Permian-Triassic boundary is above the upper Whitehorse Group, which here includes the Alibates Formation (modified from Tabor and others, 2022). This affirms a Late Permian age for the Alibates. Also shown are the zones of normal and reverse polarities in each stratigraphic section.

from the town of Quitaque. Therefore, the underlying Alibates Formation would also be Permian. Roth and others (1941) noted that these pelecypods resemble a fauna also present in the Guadalupian Whitehorse strata of western Oklahoma, as described by Newell (1940), and concluded that both collections are of Late Permian age. Newell (1940) believed that the Whitehorse Group fauna in Oklahoma may be contemporaneous with the Capitan fauna of West Texas (Late Guadalupian) or may even be younger than the Capitan—yet still be pre-Triassic in age (Late Guadalupian or Ochoan).

Radiometric Dating

The internationally accepted reference point for the Permian–Triassic boundary is the end of the Changhsingian Stage in the Meishan section in Zhejiang Province, China (Menning and others, 2006; Burgess and others, 2014; Tabor and others, 2022). U–Pb dating of zircon in volcanic ash from the boundary at this site shows that the Permian–Triassic extinction occurred approximately 251.9 Mya, and this age (251.9 Ma) is now regarded as marking the Permian–Triassic boundary.

Radiometric dating of volcanic ash beds in the lower part of the Dewey Lake (Quartermaster) Formation began when Fracasso and Kolker (1985) discovered two ash beds at several sites in the Texas Panhandle. They collected Dewey Lake material from ash beds located 13–66 ft (4–20 m) above the top of the Alibates gypsum/dolomite in three areas: 1) outcrops in Palo Duro Canyon, 2) outcrops in Caprock Canyons State Park, and 3) from core in the D.O.E.–Gruy Federal, Grabbe No. 1 well (Fig. 8). They analyzed one sample collected 18 ft (5.5 m) above the Alibates in the Grabbe well, and two splits of a sample from Caprock Canyons State Park: the three analyses showed potassium–argon (K–Ar) isotopic dates of 251±4 Ma, 257±9 Ma, and 261±9 Ma, and the authors concluded that all ages were well within the Late Permian.

Chang (2008) and Mitchell (2014) collected volcanic-ash samples from the Dewey Lake Formation for geochronology studies at a number of sites in the Texas Panhandle. Chang (2008) collected ten samples at Caprock Canyons, Dickens, and Palo Duro Canyon for Ar^{40}/Ar^{39} and U–Pb analyses. Her data suggested that five distinct tuffs are present in the Dewey Lake Formation, and that all these tuffs were erupted within several hundred thousand years of each other. Mitchell (2014) collected samples from five areas, including sites in Caprock Canyons, Clarendon, Dickens, Highway 207, and Palo Duro Canyon. His results showed U–Pb ages between 251.5 and 252.0 Ma. Both Chang (2008) and Mitchell (2014) concluded that the Permian–Triassic boundary should be placed in the lower Dewey Lake (Quartermaster) Formation, above the Alibates.

Tabor and others (2022) collected seven volcanic-ash samples from the lower part of the Dewey Lake (Quartermaster) Formation at five outcrops in the Texas Panhandle, and they show data for four of those sites (Fig. 18). The seven samples from these sites yielded U–Pb ages ranging from 252.19±0.30 to 251.74±0.28 Ma. These dates, so close to the Permian–Triassic extinction at 251.9 Mya, indicate that the Permian–Triassic boundary is present in the lower part of the Dewey Lake (Quartermaster) Formation. A detrital zircon in sandstone a few meters below the top of the Dewey Lake in Caprock Canyons yielded a U–Pb age of 244.5 Ma (Tabor and others, 2022), thus further indicating that the Permian–Triassic boundary is somewhere within the lower part of the Dewey Lake Formation. Therefore, the underlying Alibates Formation would be Late Permian (Ochoan) in age.

Although volcanic ash beds have only been identified and analyzed so far in Dewey Lake strata in the Texas Panhandle, it is likely that these ash beds, or perhaps others, are also present in the Dewey Lake, Big Basin, middle/upper Cloud Chief, or Doxey Formations in other parts of the region. If such ash beds can be found and analyzed, it would greatly aid in firmly establishing the age of those formations and the age of the underlying Alibates-equivalent formation in those areas.

As mentioned above, a detrital zircon grain with a radiometric age of 263.8±12.1 Ma was found in the Big Basin Formation (above the Day Creek Dolomite) in Point of Rocks in southwest Kansas. This date shows the age of the zircon crystal when it formed in an igneous or metamorphic rock, but does not indicate the age of its deposition, much later, in the Big Basin Formation.

Paleomagnetic Dating

Earth's magnetic poles can change locations and can also shift orientations (reversal of north and south magnetic poles) through time, so magnetic minerals in a rock line up with, and show the orientation of, the Earth's magnetic field at the time that rock is formed: this can help determine the age of the rock. Red beds, such as most of the Permian rocks in the southern Midcontinent, are especially useful in containing paleomagnetic data.

Molina-Garza and others (2000) collected paleomagnetic samples of the Dewey Lake Formation from 24 sites at the Maroon Cliffs, near Carlsbad, New Mexico, and determined that the magnetostratigraphy of the Dewey Lake is consistent with latest Changhsingian (end of Permian) stage; thus indicating that the underlying Rustler must also be Late Permian. Steiner (2001) came to the same conclusion by studying the magnetostratigraphy of the Dewey Lake in southeast New Mexico (Nash Draw) and in the Texas Panhandle (Caprock Canyons and Dickens sites). In addition, Steiner (2001) regards the entire Dewey Lake to be Late Permian based on its magnetostratigraphy at Caprock Canyons State Park near Quitaque in Briscoe County, Texas, further affirming a Late Permian age for the underlying Alibates Formation. Soreghan and others (2015), however, propose that magnetostratigraphy suggests that in western Kansas the Day Creek and Big Basin are Guadalupian in age. Hounslow and Balabanov (2016) showed that the Rustler/Alibates and at least the lower part of the Quartermaster/Dewey Lake are Late Permian in the West Texas–New Mexico area.

Tabor and others (2022) established that all the ash beds radiometrically dated from 252.19±0.30 to 251.74±0.28 Ma in Dewey Lake strata at four sites in the Texas Panhandle (see "Radiometric Dating" above) are in a normal-polarity magnetozone (Fig. 18). The Permian–Triassic boundary at the Meishan section in Zhejiang Province, China, also occurs within a normal-polarity chron, thought to be of about 700 ka duration. Inasmuch as they identified reverse-polarity magnetozones above the ash beds at two of the sites, and below the ash beds at the other three sites (Fig. 18), they propose that this further substantiates that the lower Dewey Lake sites in the Texas Panhandle contain the Permian–Triassic boundary. Therefore, the Alibates Formation, which underlies the Dewey Lake Formation, would be Late Permian.

SUMMARY AND CONCLUSIONS

The purpose of this study was to determine whether the Rustler, Alibates, Day Creek, and lower Cloud Chief Formations can be correlated from West Texas and southeast New Mexico northward into the Texas Panhandle, and then into western Kansas and western Oklahoma. Such correlations have been suggested or stated before, but proof of the equivalence of these strata has not been presented. In the current study, a series of six cores show the character of each of the four formations in different parts of the study region, and a series of six cross sections show their bed-by-bed correlation and equivalence throughout the region.

The age of these four correlative formations is shown to be Late Permian (Ochoan). Permian strata in the region

are predominantly red beds and evaporites, and they generally lack fossils that can be used for accurately dating their age. However, marine invertebrates and conodonts occurring in the Rustler and lower Dewey Lake Formations at several sites in Texas indicate a Late Permian age. Seven samples of volcanic ash collected in the Texas Panhandle from the lower part of the Dewey Lake (Quartermaster) Formation, just above the Alibates, have been dated at 252.19±0.30 to 251.74±0.28 Ma: these dates are close to the Permian–Triassic boundary (251.9 Ma) and indicate that the boundary is present in the lower part of the Dewey Lake (Quartermaster) Formation. Also, paleomagnetic dating in southeast New Mexico and the Texas Panhandle indicates that at least the lower part of the Dewey Lake Formation is Late Permian, and thus the underlying Rustler and Alibates must also be Permian. Inasmuch as a Late Permian (Ochoan) age has been shown for the Rustler and Alibates Formations in West Texas, southeast New Mexico, and the Texas Panhandle, it follows that, based on bed-by-bed correlations, the stratigraphically equivalent Day Creek and lower Cloud Chief Formations in western Kansas and western Oklahoma are also Late Permian (Ochoan) in age.

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