Lithostratigraphy of Permian Red Beds and Evaporites in the Rebecca K. Bounds Core, Greeley County, Kansas

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Introduction

This report focuses on the lithostratigraphy of the Rebecca K. Bounds (RKB) core, Greeley County, Kansas, between core depths of ~1600 ft to ~3400 ft. Figure 1 shows the location of the RKB core and the counties of Kansas. This interval of the core was examined in November and December of 2011 at the Kansas Geological Survey (KGS) in Lawrence, Kansas. Description of the RKB core provided here focuses on macroscopic lithology and lithologic transitions, i.e., the relative stacking order of lithologic units, changes in the proportions of different lithologic units through the study interval, and the nature of contacts and possible unconformities observed.

The goal of this report is to assign stratigraphic units from the standard KGS stratigraphic column (fig. 2) to the RKB core in order to develop a working framework for subsequent research. Subsequent publications by the authors will provide more detailed information on sediment provenance, fluid inclusion chemistry, sedimentary petrology, grain-size analysis, paleoenvironmental and paleoclimate reconstructions, detrital



Adapted from: http://www.kshs.org/tourists/graphics/county_map2.jpg

Figure 1: Location of RKB core



Figure 2: Surface (mostly) standard stratigraphic column (adapted from Zeller, 1968).

zircon geochronology, etc. Following these additional investigations, integration of all data will be used to refine the stratigraphic framework presented herein. We recognize that SI units are preferable, but because the majority of background literature was undertaken using feet and the core was marked in feet, the majority of measurements presented here use English units; however, metric units are given in the stratigraphic column for the interval described herein.

Numerous workers have discussed the problems of subsurface correlation of the Permian red bed and evaporite succession of western Kansas, from the pioneering work of Norton (1939, and references therein), to more recent efforts (Holdoway, 1978; Benison, 1997; Benison and Goldstein, 2001; Benison and Zambito, in review). This correlation is complicated because the outcrops used to describe these units are located ~300 km (~186 mi) from the RKB drill site in south-central Kansas and north-central Oklahoma, and, furthermore, have undergone near-surface late diagenesis and evaporite dissolution (reviewed in Benison and Zambito, in review). As stated by Holdoway (1978, p. 3), "Correlation and nomenclature are made difficult by the fact that evaporites, including thick salt beds, generally occur in the subsurface, where they are protected from solution, and the formations with which they are associated are described and classified in outcrop. In the subsurface of western Kansas, unnamed salt and anhydrite beds occur in most of the formations of the Nippewalla Group." That said, a survey of the literature reveals a number of studies on the stratigraphic relationships of the Permian red bed and evaporite succession in the subsurface of western Kansas that identified marker beds of potential use for formation-level correlations. Relatively few of these studies present detailed lithologic observations of the subsurface (e.g., Norton, 1939; Holdoway, 1978; Benison, 1997; Benison and Goldstein, 2001); the others focused primarily on well log data. Shumaker (1966) and Holdoway (1978) are notable exceptions that incorporate both data types. In this report, we use a combination of lithologic description from the type sections and other outcrops in conjunction with lithologic descriptions and stratigraphic patterns reported in previous subsurface studies to provisionally identify the stratigraphic units present in the RKB core.

Materials

The Rebecca K. Bounds Core No. 1 (API 15-071-20446) was drilled by Amoco Production Company in March and April of 1988 in Greeley County, Kansas (T. 18 S., R. 42 W., sec. 17, NE SE NE 3526 North, 30 West, from SE corner; Long. -101.97456, Lat. 38.48963). In the interval studied, recovered core diameter is ~3.25 inches from ~1600 ft to 2648 ft, and ~2.5 inches from 2648 ft to ~3400 ft. Core recovery rate for the interval studied exceeds 98%. Excellent recovery of halite suggests that salt-saturated drilling fluids were used. The core, including the interval studied herein, was housed at an Amoco facility in Tulsa, Oklahoma, where Amoco undertook biostratigraphic analysis and collected drill plugs from the core during this time (G. Wahlman, personal communication, 2012). In 1992, the Cretaceous interval of the core was transferred to the U.S. Geological Survey in Denver, where it was slabbed and archived (Arthur, 1993; Dean et al., 1995). The entirety of the core was transferred to the Kansas Geological Survey (KGS) (http://cjonline.com/stories/081601/ swn geosurvey.shtml) around 2001.

Background

A variety of studies have been undertaken on the Permian in the subsurface of western Kansas, based on the stratigraphic framework developed at outcrops of central Kansas. In Appendix 1, we review the standard stratigraphic succession and descriptions of units for the Permian of Kansas. In Appendix 2, we review relevant subsurface stratigraphic work done previously in western Kansas. Figures from past studies are presented in roughly chronologic order of publication and referenced in Appendix 2 with the details of the previous studies. Figures adapted from previous studies as well as those showing details of the RBK core include:

Figure 1: Map of Kansas counties showing the location of the RKB core.

Figure 2: Standard stratigraphic column of Kansas from the KGS.

- Figure 3: Subsurface correlation of Permian strata in south-central and northwestern Kansas (Norton, 1939).
- Figure 4: Subsurface correlation of Permian and post-Permian strata in central and western Kansas (Norton, 1939).
- Figure 5: Subsurface correlation of Permian and post-Permian strata and wireline logs in westernmost Kansas (Merriam, 1963).
- Figure 6: Subsurface correlation of wireline logs through Permian and post-Permian strata in north-central and northwestern Kansas (Merriam, 1963).
- Figure 7: Subsurface correlation of Permian and post-Permian strata in central and northwestern Kansas (Merriam, 1963).
- Figure 8: Subsurface correlation of Whitehorse Formation, Day Creek Dolomite, "Taloga Formation" (Big Basin Formation), and post-Permian strata from Kansas Sample Log Service data (based on drill cuttings?) in westernmost Kansas (Merriam, 1963).
- Figure 9: Subsurface correlation of Nippewalla Group and later Permian strata from Kansas Sample Log Service data (based on drill cuttings?) in westernmost Kansas (Merriam, 1963).
- Figure 10: Surface and subsurface distribution of different lithologies of the Stone Corral Formation in central and western Kansas (Merriam, 1963).
- Figure 11: Subsurface correlation of wireline logs through the Stone Corral Formation in southwestern Kansas (Merriam, 1963).
- Figure 12: Subsurface correlation of Stone Corral Formation, Nippewalla Group, post-Nippewalla, and post-Permian strata in and around Greeley County, Kansas, after drill cutting and wireline log data presented in Schumaker (1963), and, also including the Rebecca K. Bounds core after the section measured in this study.
- Figure 13: Subsurface correlation of wireline logs through the Nippewalla Group in western Kansas (Rascoe, 1968).
- Figure 14: Subsurface correlation of wireline logs through the Nippewalla Group strata in western Kansas (Holdoway, 1978).
- Figure 15: Thickness of Cedar Hills Sandstone in the subsurface of western Kansas based on data from geophysical and sample logs (Holdoway, 1978).
- Figure 16: Thickness of Flower-pot Shale in the subsurface of western Kansas based on data from geophysical and sample logs (Holdoway, 1978).
- Figure 17: Thickness of Blaine Formation in the subsurface of western Kansas based on data from geophysical and sample logs (Holdoway, 1978).
- Figure 18: Thickness of the Cedar Hills Sandstone in the subsurface of southwestern Kansas based on geophysical logs and supplementary subsurface information (Macfarlane, 1993).
- Figure 19: Thickness of the Salt Plain Formation and the Harper Sandstone in the subsurface of southwestern Kansas based on geophysical logs and supplementary subsurface information (Macfarlane, 1993).

Observations and Placement of Stratigraphic Units

Figure 20 shows the lithostratigraphic succession of the RKB core.

Chase and Council Grove Groups

Cyclothems are not easily recognized in the Chase and Council Grove Groups in the RKB core because the facies present do not match those present in outcrops in eastern and central Kansas. This was previously noted for Greeley County, where most of the cyclothems of the Chase and Council Grove Groups transition to continental deposits and record deposition upslope of the axis of the Hugoton embayment (Dubois et al., 2005, 2012; Olson et al., 1997). The only marine unit that persists from the basin to the updip portions of the Hugoton field appears to be the Neva limestone (Dubois et al., 2005, 2012). G. Wahlman, who worked at Amoco on the RKB core, noted (personal communication, 2012) that the top of the Neva Limestone (Council Grove) was logged at 3256 ft. We tentatively assign the depth of 3264 ft 11 inches to the top of the Neva, in order to include the highest marine fossil-bearing strata that we observed in the RKB core. Furthermore, G. Wahlman (personal communication, 2012) noted that the fusulinids *Tricites* cf. *cellamagnus* and *T*. cf. *meeki* comprise a fauna identified in a sample from 3425 ft to 3430 ft in the RKB core that is most similar to the Foraker Limestone of Kansas outcrops; these fossils suggest an age of latest Virgilian (Pennsylvanian) for this interval. Furthermore, the top of the Foraker, marked as an unconformity, is placed at 3413 ft (G. Wahlman, personal communication, 2012).

The contact of the Chase and Council Grove Groups in the RKB core is not apparent because biostratigraphic data are lacking, and typical cyclothem patterns are absent. According to the well completion form filed with the Kansas Corporation Commission, the top of the Council Grove Group was placed at 2976 ft. We tentatively place it at 2984 ft 6 inches, at the top of a thick, distinctly peach-colored siltstone; this color, while relatively rare, is more commonly found in strata below 2984 ft 6 inches than above. Similarly, the contact between the Sumner and Chase Groups is also not apparent in the RKB core. According to the well completion form filed with the Kansas Corporation Commission, the top of the Chase Group is placed at 2730 ft. In examining the lithologic succession of the RKB core (fig. 20), it is unclear why the top of the Chase Groups lower (2754 ft 7 inches) at the base of a succession of thinner units relative to the majority of units found below this depth. These boundary placements result in a thickness of ~230 ft for the Chase Group in the RKB core. Hemsell (1939) reports a similar thickness of ~230 ft for the Chase Group in nearby southern Grant County; no other previous studies give a thickness for this unit.

Sumner Group

Ninnescah Shale and Wellington Formation (2588 ft 7 inches to 2754 ft 7 inches)

The Ninnescah Shale and Wellington Formation are not easily differentiated in the RKB core, and ~170 ft in the RKB core (2588 ft 7 inches to 2754 ft 7 inches) is assigned to the Ninnescah and Wellington. As described above, in general, relatively thinner units are observed than in the underlying strata; the overlying strata are similarly composed of relatively thicker units compared to the interval identified as the Ninnescah

and Wellington. Siltstone and sandstone with laminated crystalline, nodular, and disseminated anhydrite forms the predominant lithology from ~2754 ft 7 inches to ~2695 ft. Siltstone and interbedded sandstone with disseminated anhydrite occur from 2619 ft to ~2695 ft. The interval from 2588 ft 7 inches to 2619 ft (total 30 ft 5 inches) is predominantly sandstone, and overlain by crystalline anhydrite of the Stone Corral Formation (see below).

In outcrop, the Ninnescah is a predominantly silty shale, mostly red, but containing some gray shale, argillaceous limestone and dolomite, and calcareous siltstone (Zeller, 1968). Conchostrocans are typical of the Ninnescah (Zeller, 1968; West et al., 2010). In the subsurface of south-central and western Kansas, the Ninnescah is described as locally containing salt-bearing units interbedded with anhydrite and mudstone in the upper part of the formation (Mudge, 1967). Both Shumaker (1966) and Sorenson (1996) described the Wellington of southwestern Kansas as laminated anhydrite and shale, with the anhydrite component thinning westward to near zero along the Kansas–Colorado border. Norton (1939), Merriam (1963), and Watney et al. (1988) all identified the western margin of the Hutchinson Salt Member at Seward, Haskell, Finney, and Graham counties, all east of the RKB core (figs. 1, 3, 4, 6, and 7).

Table 1 lists thicknesses of the Ninnescah and Wellington in the RKB core and nearby subsurface studies. The ~170-ft interval assigned to the Ninnescah and Wellington in the RKB core is much thinner than the correlative interval suggested by Norton (1939), Hemsell (1939), Schumaker (1966), or Mudge (1967). However, with the exception of the Stone Corral Formation, the Sumner Group, and in particular the Wellington and Ninnescah, apparently thins to a feather's edge from the Hugoton field in southwestern Kansas to the northwest of the state (figs. 6 and 7). The large variation in thicknesses (table 1), as well as facies changes and the inferred thinning of this interval, complicate recognition of these units in the RKB core.

Source	Thickness (ft)	Location
This Study	~170	Greeley County, KS
Hemsell (1939)	250	Hamilton County, KS
Norton (1939); see fig. 4	440 (220 ft Ninnescah and 220 ft Wellington)	Hamilton County, KS
Mudge (1967)	270	south-central and western KS
Schumaker (1966)	200-340	Greeley and Wallace counties, KS

Table 1: Thickness of Ninnescah/Wellington formations in this and previous studies.

Although speculative, the sandstone interval at the top of the strata assigned to the undifferentiated Ninnescah/Wellington interval in the RKB core may be the Runnymede Sandstone Member. In outcrop the Runnymede Sandstone Member is a 7–8-ft-thick, gray to grayish-green siltstone to very fine sandstone that marks the top of the Ninnescah Shale (fig. 2; Zeller, 1968; West et al., 2010). Only Rascoe (1968; fig. 13) differentiated this unit in the subsurface. In the RKB core, the Runnymede is tentatively identified as the 30 ft 5 inches interval of orange, peach, and pink sandstone and minor siltstone below the Stone Corral, and transitional from the underlying Ninnescah. While this is certainly much thicker than the Runnymede Sandstone Member

as described from outcrop, those outcrops occur ~300 km (180 mi) away in south-central Kansas. Differences in color between subsurface and outcrop may be facies or exhumation related. Identification of the Runnymede Sandstone Member at this level is consistent with the predominance of sandstone directly underlying the Stone Corral, and the near lack of sandstone below ~2695 ft, as would be predicted by comparison with the current stratigraphic framework (fig. 2; Zeller, 1968; West et al., 2010).

Stone Corral Formation (2564 ft to 2588 ft 7 inches)

In the RKB core, the strata found from 2564 ft to 2588 ft 7 inches, a thickness of 24 ft 7 inches, is assigned to the Stone Corral Formation. The Stone Corral lies conformably on the Ninnescah (Runnymede Sandstone Member), as noted by previous workers (i.e., Norton, 1939). In the RKB core, the lowermost Stone Corral is a transitional, sandy anhydrite bed from 2587 ft 3 inches to 2588 ft 7 inches. With the exception of the sandy anhydrite, the majority of the Stone Corral is pale-blue anhydrite with purple-maroon mottling and streaking, halite pseudomorphs of bottom-growth gypsum, and uncommon, medium (~1-ft) mudstone beds. Possible microbialite features, such as wavy/crinkly thick lamina and centimeter-scale mound-like features, are common in the anhydrite interval, as well as in the dolomitic (?) interval near the top of this unit. The Stone Corral is gradationally overlain by the bedded halite of the lowermost Harper Sandstone and Salt Plain Formation; we place a unit of coarsely crystalline halitic anhydrite from 2564 ft to 2564 ft 10 inches within the uppermost Stone Corral.

The Stone Corral Formation is often termed the most persistent and easily identified key marker bed in the Permian of Kansas (Norton, 1939; Zeller, 1968). However, its lithology is highly variable. It consists of dolomite, anhydrite, gypsum, and halite, ranging from 6 ft at the outcrop to up to 100 ft locally in the subsurface, where anhydrite predominates (Zeller, 1968; West et al., 2010). The color is typically gray, but red and pink streaks and mottles occur locally (Merriam, 1963; Zeller, 1968). The succession identified as the Stone Corral in the RKB core is thinner than previously published thicknesses for this unit in western Kansas, in Greeley and nearby counties, where it is described as ~30 to 50 ft thick (figs. 4, 13, and 14C; Norton, 1939; Hemsell, 1939), although these authors may be including within the Stone Corral any overlying halite that is present (fig. 12; see discussion below). In southwestern and south-central Kansas, the Stone Corral consists of two anhydrite units separated by a shale or salt unit of variable thickness (figs. 10 and 11; Norton, 1939; Merriam, 1963; Sorenson, 1996); however, this succession is not expected in the Stone Corral of the RKB core given the location of the RKB core relative to the occurrence of this facies (fig. 10 and 11).

Nippewalla Group

Undifferentiated Harper Sandstone and Salt Plain Formation (2423 ft 10 inches to 2564 ft)

In the RKB core, the undifferentiated Harper Sandstone and Salt Plain Formation are found at depths from 2423 ft 10 inches to 2564 ft. The lowest 1 ft 6 inches, from 2562 ft 6 inches to 2564 ft, consists of bedded halite with disseminated anhydrite, transitional from the underlying Stone Corral (see discussion above). This 140 ft 2 inches interval assigned to the undifferentiated Harper-Salt Plain interval consists of orange-hued bedded halite in the lower ~68 ft and predominantly reddish-orange and reddish-brown siltstone and displacive halite in the upper ~70 ft, with a 1 ft 6 inches transitional halite unit in between.



Figure 3: Surface to subsurface correlation across Kansas (adapted from Norton, 1939).

In outcrop, the Harper Sandstone and Salt Plain Formation are primarily differentiated by grain size, and each are subdivided into multiple units. Zeller (1968) described the Harper as chiefly red argillaceous siltstone and very fine silty sandstone, and the Salt Plain as red, flaky, silty shale with siltstone. However, in the subsurface the Harper and Salt Plain are not easily differentiated (Malone, 1966; Schumaker, 1966; Holdoway, 1978; Macfarlane et al., 1993; although see Norton, 1939). Campbell (1963) placed the beginning of salt deposition in the Nippewalla at the base of the Harper–Salt Plain interval. Rascoe (1968), Norton (1939, see fig. 3 herein), and Hemsell (1939) also noted the presence of halite above the Stone Corral. Holdoway (1978) reported a thickness for this interval of ~85 ft in eastern Greeley County (fig. 14). Macfarlane et al. (1993) reported thicknesses of ~100 ft to 150 ft in Greeley County (fig. 19). As illustrated in fig. 12, the thickness of the Harper/Salt Plain formations in the RKB core agrees well with that identified by Schumaker (1966) in nearby wells.



Figure 4: Subsurface correlation of Permian and post-Permian strata in central and western Kansas (Norton, 1939).

Cedar Hills Sandstone (2322 ft 6 inches to 2423 ft 10 inches)

In the RKB core, the Cedar Hills Sandstone occurs from ~2322 ft 6 inches to 2423 ft 10 inches. The lower part of this interval is "typical" Cedar Hills Sandstone, i.e., reddish-orange sandstone. The presence of a ~10-foot interval of sandy, bedded halite within this sandstone from 2342 ft to 2352 ft 3 inches, as well as the presence of a 14 ft 11 inches interval of crystalline anhydrite from 2322 ft 6 inches to 2337 ft 5 inches in the upper portion of the interval assigned to the Cedar Hills, is consistent with previous subsurface studies (Campbell, 1963; Shumaker, 1966; Rascoe, 1968; Holdoway, 1978, and references therein). In the RKB core, we place the upper boundary of the Cedar Hills Sandstone at 2322 ft 6 inches, at the top of the anhydrite bed, which is easily recognizable in wireline logs (fig. 12; Schumaker, 1966; Holdoway, 1978). Assigning the interval of 2322 ft 6 inches to 2423 ft 10 inches in the RKB core to the Cedar Hills Sandstone results in a total thickness of 101 ft 4 inches for this formation. This is nearly identical to the ~100-ft thicknesses reported for throughout Greeley County by Schumaker (1966) as seen in fig. 12, by Holdoway (1978) as shown in figs. 14 and 15, and by MacFarlane et al. (2003) as shown in fig. 18.

The Cedar Hills Sandstone is described in outcrop by Zeller (1968), as comprising "feldspathic sandstone, siltstone, and silty shale, chiefly red, and beds of white sandstone in the upper and lower parts. The upper sandstone bed contains 'snowballs of white gypsum'." However, Swineford (1955) did not describe feldspathic



Figure 5: Cross section from Cheyenne County to Morton County showing correlation and stratigraphic relation of Mesozoic rocks (from Merriam, 1963).

grains in the Cedar Hills Sandstone. In the subsurface, Rascoe (1968) described a lens of salt, locally up to 100 ft thick, that occupies the stratigraphic position of the Cedar Hills to the north and east of Greeley County (fig. 13). We observed that this interval consists of sandstone that is poorly cemented with halite, and in some cases (2342 ft to 2352 ft 3 inches) consists of "dirty halite" in which sand-sized grains are floating in a matrix of bedded halite. Rascoe (1968) also identified a thin anhydrite marker bed (10 to 15 ft thick) overlying the Cedar Hills Sandstone in western Kansas (fig. 13). Schumaker (1966) recognized this same marker bed throughout western Kansas (fig. 12). Holdoway (1978) also mentioned the presence of salt within the subsurface Cedar Hills as well as the anhydrite marker bed, particularly in northwest Kansas; she placed the anhydrite within the uppermost Cedar Hills (fig. 14). Shumaker (1966) and Rascoe (1968) placed this anhydrite in the basal Flowerpot Shale, whereas Campbell (1963) placed it in the Cedar Hills Sandstone because he observed interfingering of the anhydrite and sandstone; he termed this anhydrite the "Y-anhydrite marker bed." Herein, we follow Campbell (1963), which takes precedence, and place this anhydrite bed as part of the uppermost Cedar Hills Sandstone unit.



Figure 6: Subsurface correlation of wireline logs through Permian and post-Permian strata in north-central and northwestern Kansas (Merriam, 1963).

Alternatively, the top could be placed at ~2300 ft based on the presence of large anhydrite "snowballs" from ~2300 ft to ~2310 ft that fit the description of those found in the uppermost bed of the Cedar Hills Sandstone in outcrop (Zeller, 1968). However, the depth of 2322 ft 6 inches is preferred because it is more practical for comparison in future subsurface studies, especially those using wireline logs, and follows on the precedent set by Campbell (1963) for the subsurface stratigraphy of western Kansas. Furthermore, these "snowballs" occur in a siltstone, not in sandstone as described from outcrop.

Flower-pot Shale (2053 ft to 2322 ft 6 inches)

In the RKB core, the interval identified as the Flower-pot Shale contains all strata below the Cedar Springs Dolomite Bed (see below) and above 2322 ft 6 inches, a thickness of 269 ft 6 inches. The basal contact of the Flower-pot is the top of the Y-anhydrite marker bed discussed in detail above. With the exception of anhydrite, mudstone, and sandstone in the upper 3 ft of this interval and the ~10 ft of siltstone near the base of this interval, the Flower-pot in the RKB core consists almost exclusively of displacive halite within a reddish-orange mudstone matrix with varying ratio of halite to siliciclastics.



Figure 7: Northwest-southeast electric-log cross section in northwestern Kansas showing relation of Permian units to each other and to adjacent beds (from Merriam, 1963).

In outcrop, the Flower-pot Shale consists of reddish-brown gypsiferous mudstone to silty mudstone with a few thin beds of sandstone and siltstone and conspicuous beds of gypsum; in the subsurface, it consists mostly of displacive halite within a siltstone matrix, and bedded halite (Zeller, 1968; Holdoway, 1978; Benison and Goldstein, 2001; West et al., 2010). Rascoe (1968) described a thickness of up to 400 ft for the "salt body" that occupies the Flower-pot interval to the north and east of the study area (fig. 13). Holdoway (1978) described a thickness of ~250 ft for the Flower-pot in Greeley County (figs. 14 and 16). The thickness of the Flower-pot Shale as identified in the RKB core agrees well with that reported by Schumaker (1966) for western Kansas, as seen in fig. 12.



Figure 8: Southwest-northeast cross section showing stratigrpahic relations of beds in upper Permian in southwestern Kansas. Note uniform thickness of Whitehorse Formation, lateral persistence of Day Creek Dolomite, which is mostly anhydrite, and northward thinning of Big Basin Formation ("Taloga") by post-Permian erosiun (from Merriam, 1963).

Blaine Formation (1928 ft to 2053 ft)

In the RKB core, a 6-inch pale-gray pseudo-oolitic (*Microcodium sensu* Benison, 1997; Benison and Goldstein, 2001) dolostone at depths of 2052 ft 6 inches to 2053 ft, and underlying a > 20-ft succession of anhydrite, is identified as the Cedar Springs dolomite. This is the most unique marker bed in the core. No attempt was made to differentiate the four members of the Blaine Formation identified in Kansas (from oldest to youngest: Medicine Lodge Gypsum, Nescatunga Gypsum, Shimer Gypsum, and Haskew Gypsum Members) because this interval of the core is missing some section and contains, in addition to crystalline anhydrite, both abundant bedded and displacive halite as well as halite pseudomorphs after bottom-growth gypsum; these are lithologic types and diagenetic features not seen in outcrop (Benison and Zambito, in review). For this same reason, Campbell (1963) and Holdoway (1978) both stated that the members of the Blaine Formation can not be easily differentiated in the subsurface. For the reasons discussed below, we provisionally place the contact between Blaine and Dog Creek Formations in the RKB core at 1928 ft.

In outcrop, the Blaine Formation consists of interbedded anhydrite/gypsum, dolomite, and red siliciclastic units named for exposures in Blaine County, Oklahoma. Fay (1964) documented the stratigraphy of the Blaine along the main exposure belt of the Blaine Escarpment in Oklahoma and Kansas. A number of distinct beds have been mapped in outcrop, notably the Cedar Springs Dolomite at the base of the Blaine Formation, described as a light-gray fine-grained oolitic massive dolomite of up to 12 inches thick along the outcrop belt, and in Kansas reported as 6 inches to 1 ft thick (Fay, 1964; Zeller, 1968). Holdoway (1978) described the Cedar Springs Dolomite as 6 inches thick in the subsurface of Wichita County, just east of Greeley County. Malone (1962), Schumaker (1966), Holdoway (1978), and Benison and Goldstein (2001) all reported halite in the Blaine interval in the subsurface of western Kansas.



Figure 9: Cross section in southwestern Kansas showing stratigraphic position of salt in Nippewalla Group in Permian red-bed sequence. Where not possible in subsurface to differentiate Dog Creek, which is stratigraphic top of Nippewalla, top of Blaine is shown. Note lateral equivalent of "solid" salt (from Merriam, 1963).

Source	Thickness (ft)	Location
This Study	125	Greeley County, KS
Malone (1962)	100–125	Wichita, Hamilton, Kearney, and Finney counties, KS
Merriam (1963; see fig. 9 herein)	~50 to 100	Hamilton, Kearney, and Finney counties, KS
Schumaker (1966; see fig. 12 herein)	137	Harris No. 1 well, Greeley County, KS
Holdoway (1978; see figs. 14 and 16 herein)	50-75	Greeley and Wichita counties, KS

Table 2: Thickness of the Blaine Formation in this and previous studies.

As identified in the RKB core, the Blaine Formation exhibits a total thickness of 125 ft, which is in agreement with previous studies in western Kansas (table 2; fig. 12). The variation in thicknesses reported probably results from the difficulties in differentiating the Blaine and Dog Creek contact, and, furthermore, members within the Blaine Formation, as described above, have yet to be determined to be laterally continuous in the subsurface of western Kansas as has been suggested for more eastern sections (Fay, 1964).



Figure 10: Generalized surface and subsurface distribution of lithologic types in the Stone Corral Formation. North of Rice County, eastern limit of formation is covered by later deposits, whereas formation crops out discontinuously south of east-central Rice County (from Merriam, 1963).

Dog Creek Formation (1928 ft to 1839 ft 8 inches)

In the RKB core, the provisional Dog Creek–Blaine contact is placed at 1928 ft. Below this depth the thickest anhydrite beds and uppermost bedded and displacive halites of the Blaine Formation occur. Above 1928 ft pedogenic features are common, whereas they are rare below this level. The top of the Dog Creek Formation is tentatively placed at 1839 ft 8 inches, at the disconformity discussed in detail below. This yields a total thickness of 88 ft 4 inches for the Dog Creek in the RKB core, of predominantly reddish-brown mudstone, and orangish-red siltstone and fine sandstone with bounding contacts ranging from sharp to gradational over a few centimeters. Many of the shale beds assigned to the Dog Creek in past outcrop studies are believed to be mostly unlaminated mudstones. The mudstones are commonly pedogenically altered with slickensides and reduction spots. The reduction spots range from 1mm to 3cm in diameter and commonly contain black nuclei. Many of the siltstone and fine sandstone units in the Dog Creek contain peculiar discontinuous thick lamina of convolute bedding. This disrupted bedding is common from 1899 ft to 1739 ft and records soft-sediment deformation. Cements in the Dog Creek are mostly red iron oxide clays, with minor anhydrite and halite. A very thin bed of bottom-growth gypsum appears at 1854 ft. The lowermost Dog Creek contains two anhydrite beds at 1927 ft and 1923 ft 9 inches containing alternating laminae of reddish-brown mudstone and pale-blue-gray anhydrite.

Zeller (1968) described the Dog Creek in Kansas as maroon silty shale, siltstone, very fine grained feldspathic sandstone, thin layers of dolomite, dolomitic sandstone, and gypsum, ranging from 14 ft to 53 ft in total thickness. The top is marked by about 3 ft of maroon shale underlain by a persistent 6-ft bed of white



Figure 11: West-east electric-log cross section of area in southwestern Kansas where Stone Corral ("Cimarron anhydrite" of subsurface terminology) consists of two anhydrite beds separated by red silty shale. Datum is top of uppermost anhydrite bed. To west and east the formation has characteristic "kick" on logs and consists of one bed of anhydrite (from Merriam, 1963).

and red fine-grained sandstone. In the subsurface, it is difficult to differentiate the Blaine Formation from the overlying Dog Creek Formation, as exemplified in a statement by Norton (1939, p. 1801), "In the subsurface, if the gypsum content is 50 per cent or more it can be considered to be Blaine; if the upper part of the Blaine is red shale exceeding this percentage, it may possibly be regarded as Dog Creek." In fact, Norton (1939) considered the Blaine and Dog Creek a single gypsum-rich formation. Subsequent workers reached similar conclusions on the difficulties of identifying the Blaine–Dog Creek contact in the subsurface (Malone, 1962; Mudge, 1967; Holdoway, 1978; West et al., 2010).

Malone (1962) described the Dog Creek in Hamilton County as a sandstone, similar in appearance to the overlying Whitehorse Formation, but retaining a thickness comparable to outcrop in Kansas. Our assignment of the sandstone in the upper part of the interval to the Dog Creek agrees with Malone's (1962) description of the Dog Creek. This may account for our thinner Whitehorse Formation relative to the descriptions provided by Merriam (1963) and Shumaker (1966), if they included these sandstone units in the Whitehorse Formation. Merriam (1963; figs. 8 and 9 herein) noted difficulty in recognizing the Dog Creek in the subsurface of western Kansas. Finally, note that the only maroon shale between the Stone Corral and the Morrison Formation occurs in the upper part of this (Dog Creek) unit, at about 1860 ft; this might be expected given the description of a maroon shale in the uppermost Dog Creek in the field (see Zeller 1968).

Post-Nippewalla Strata

Whitehorse Formation (1676 ft to 1839 ft 8 inches)

Subsurface study of post-Blaine strata is limited, and no detailed lithologic descriptions are available from the subsurface. In the RKB, the strata from 1676 ft to 1839 ft 8 inches, for a total thickness of 163 ft 8 inches, are assigned to the Whitehorse Formation. We do not differentiate the Marlow Sandstone, Relay Creek Dolomite, unnamed member, or the Kiger Shale Member that (Zeller, 1968) identified in outcrop. Strata in this interval are dominated by reddish-orange and reddish-brown sandstone, siltstone, and mudstone, commonly





containing large sandy and muddy "blobs" suggestive of soft-sediment deformation; due to different (gypsum/ anhydrite?) mineralogy, these "blobs" are not the calcitic "sand balls" that Norton (1939) suggests are diagnostic of the Whitehorse Formation. The sandy blobs are observed at depths of ~1866 ft, ~1850 ft, ~1820 ft, ~1805 ft, ~1789 ft, ~1730 ft, ~1680 ft, and according to our measured section these features do not occur above 1676 ft. The disconformity at the base of the Whitehorse Formation (1839 ft 8 inches) is a mudclast conglomerate of tan, lightorange, and blue subangular clasts within an orange silty matrix. The disconformity also represents a change to thinner and less common zones of pedogenic alteration and a general decrease in mud-dominated strata. Norton (1939) discussed in detail the lack of a major erosional surface at the base of the Whitehorse Formation. Note also that similar disconformities occur at 1687 ft and 1717 ft.

In outcrop, the Whitehorse Formation is described as red beds of feldspathic sandstone, siltstone, and shale with minor dolomite, characterized by small calcite-cemented "sand balls," and common crossbedding (Zeller, 1968). In the RKB core, the 163 ft 8 inches assigned to the Whitehorse, plus the 88 ft 4 inches assigned to the Dog Creek, yields a total thickness of 252 ft of strata between the Blaine Formation and Day Creek Dolomite (see below). This is consistent with the ~250-ft thickness reported by Norton (1939; see figs. 3 and 4 herein) and ~300-ft thickness reported by Merriam (1963; see figs. 8 and 9 herein) for nearby subsurface measurements. Furthermore, this thickness is consistent with data from numerous subsurface sections provided by Schumaker (1966) from nearby wells as seen in fig. 12.

Day Creek Dolomite (1659 ft to 1676 ft)

The Day Creek Dolomite is recognized in the RKB core from depths of 1659 ft to 1676 ft, for a total of 17 ft. Within this interval are two packages of anhydrite, ~7 ft and ~4 ft thick, separated by ~6 ft of orange mudstone.

Zeller (1968) described the Day Creek Dolomite in outcrop as light-gray to pink, dense, fine-grained dolomite



combination of displacive and bedded halite, and not the evaporite sulfate mineral.









Figure 14: Subsurface correlation of wireline logs through the Nippewalla Group strata in western Kansas (Holdoway, 1978).



Figure 15: Thickness of Cedar Hills Sandstone in the subsurface of western Kansas based on data from geophysical and sample logs (Holdoway, 1978).

locally containing chert nodules and disseminated chert. In the subsurface, Norton (1939) described the Day Creek Dolomite as predominantly chert-free, and in western Kansas consisting of anhydrite and gypsum. Sorenson (1996) noted that the Day Creek in western Kansas was gypsum and anhydrite similar to the Blaine. The thickness assigned to the Day Creek in the RKB core is consistent with Norton (1939; figs. 3 and 4 herein), Merriam (1963; figs. 8 and 9 herein), and Schumaker (1966; fig. 12 herein).

Big Basin ("Taloga" of older literature) Formation (1627 ft 4 inches to 1659 ft)

The strata from depths of 1627 ft 4 inches to 1659 ft in the RKB core consist of reddish-orange and reddishbrown siltstone, sandy siltstone, and fine sandstone with distinct sub-horizontal thin and thick gypsum veins. This is unconformably overlain by a distinct bluish-white sandstone (described below). This results in a total thickness of 31 ft 8 inches for the Big Basin Formation in the RKB core.

In outcrop, the Big Basin consists of red silty shale, siltstone, dolomitic siltstone, and very fine-grained feldspathic sandstone (Zeller, 1968). In the subsurface of western Kansas, the Big Basin has been recognized in several cores by Merriam (1963), although it is extremely thin and/or absent in Greeley County (figs. 8 and 9). Both Merriam (1963) and Schumaker (1966) report that the Big Basin thins into Greeley County from the south, as it is progressively truncated northward by superjacent Jurassic units (fig. 8). Taking into account this thinning, the thickness of the Big Basin in the RKB core is consistent with that recognized in nearby wells by Norton (1939; figs. 3 and 4 herein), Merriam (1963; figs. 8 and 9 herein), and by Schumaker (1966; fig. 12 herein).

? Dockum Group and/or Entrada Sandstone ? (1601 ft 9 inches to 1627 ft 4 inches)

A succession of sandstone-dominated strata from 1601 ft 9 inches to 1627 ft 4 inches is tentatively assigned to the Triassic Dockum Group and/or the Jurassic Entrada Sandstone. Neither the Dockum Group nor the Entrada Sandstone are officially recognized stratigraphic units in Kansas, but may be present (Macfarlane, 1993; note also unnamed Jurassic unit in fig. 2). From 1627 ft 4 inches to 1617 ft 1 inch is a bluish-white sandstone with a slight orange tinting and rare orange cements possessing high-angle, tangential crossbedding and lustrous, blocky patches of cement. A 1-ft bed of tan, black, and blue anhydrite and mudstone with a clotted and microbialitic appearance is found at depths from 1616 ft 1 inch to 1617 ft 1 inch. The interval in the RKB core from 1616 ft 1 inch to the unconformity observed at 1605 ft 6 inches, consists of peach-colored fine-grained sandstone and siltstone with minor anhydrite nodules. A unit of tan sandstone with bladed and lustrous overgrowth cements, rounded white cement-patches resulting in a clotted appearance, and very faint bedding is found from 1601 ft 9 inches to 1605 ft 6 inches.

Zeller (1968) reported the Entrada Sandstone from southwest Kansas (Morton County) underlying the Morrison Formation and overlying the Big Basin Formation. Norton (1939) noted the presence of Triassic strata in the Oklahoma panhandle (fig. 4). Merriam (1963) detailed prior studies into the possibility of Dockum strata in western Kansas. However, Zeller (1968, and references therein) suggested that previous reports of sandstone of the Triassic Dockum Group in Kansas, are actually strata of Jurassic age (see also figs. 5–8). As seen in fig, 12, these sandstones are not found in nearby sections. It is worth noting that predominant bluish-white sandstone is a lithology that is not recognized in the uppermost Permian succession elsewhere in Kansas, central and western Oklahoma, or the Texas Panhandle (J. Zambito, unpublished field notes).



Figure 16: Thickness of Flower-pot Shale in the subsurface of western Kansas based on data from geophysical and sample logs (Holdoway, 1978).



Figure 17: Thickness of Blaine Formation in the subsurface of western Kansas based on data from geophysical and sample logs (Holdoway, 1978).



Thickness of the Cedar Hills Sandstone Aquifer

Figure 18: Thickness of the Cedar Hills Sandstone in the subsurface of southwestern Kansas based on geophysical logs and supplementary subsurface information (Macfarlane, 1993).

Morrison Formation (base at 1601 ft 9 inches)

At 1601 ft 9 inches in the RKB core is the base of a brownish-maroon and tan siltstone with ripple crossbedding and large anhydrite nodules that are distinctly different than any anhydrite nodules observed lower in the core. Further up core, at 1545 ft (not shown in fig. 20), we observed a buff-green fine sandstone with pink and gray chert. Based on our observations, we assign the strata above 1601 ft 9 inches to the Morrison Formation. Determining the thickness of the Morrison Formation in the RKB core is beyond the scope of this study.

In the subsurface of western Kansas, the Morrison Formation ranges in thickness from 100 ft to 350 ft, the lower beds containing pink chert, anhydrite, and gypsum (Mudge, 1967). As seen in fig. 12, the identification of the Morrison in the RKB core is consistent with Schumaker (1966). The reader is also referred to the detailed discussion in Merriam (1963; see also figs. 5–7 herein) and Macfarlane (1993).



Figure 19: Thickness of the Salt Plain Formation and the Harper Sandstone in the subsurface of southwestern Kansas based on geophysical logs and supplementary subsurface information (Macfarlane, 1993).

Conclusions

The RKB core, with its exceptional recovery, provides a unique window into the Permian succession in the subsurface of western Kansas. Based on comparison with previous studies, a number of traceable marker beds and distinct units/lithofacies in the Permian succession can be identified in the RKB core with relative certainty, including the Stone Corral Formation, Cedar Hills Sandstone, Y-anhydrite bed, Flower -pot Shale, Cedar Springs dolomite bed, Blaine Formation, Day Creek Dolomite, and the Big Basin Formation. However, the identification of some units and contacts can only be identified provisionally or not at all (i.e., Council Grove and Chase Groups, Wellington Formation and Ninnescah Shale (including their contact), the contact between the Harper Sandstone and Salt Plain Formation, the Dog Creek Formation and its contact with the overlying Whitehorse Formation, and the (possibly post-Permian?) sandstone units between the Big Basin and Morrison Formations).





Figure 20: Stratigraphic column for the Rebecca K. Bounds core (sec. 17, T. 42 W., R. 18 S.).

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APPENDIX 1: The Permian System in Kansas

A review of the Permian (in part) stratigraphic succession in Kansas is given below (from youngest to oldest) and divided into post-Permian (in part), Guadalupian, Leonardian, and Wolfcampian (in part). The descriptions of the stratigraphic units are from outcrop exposures and the subsurface of Kansas. Unless otherwise noted, descriptions of stratigraphic units are for Kansas. The Ochoan Series is probably not present in Kansas (Sawin et al., 2008). Many researchers have contributed to the understanding of Kansas Permian stratigraphy (summarized in West et al., 2010). The following summary and stratigraphic framework is based on the most recent literature review and revision of the Kansas Permian System by the Kansas Geological Survey (KGS) in West et al. (2010, see references therein for further details) and the detailed lithological descriptions of Zeller (1968, chart revised by KGS in March 1, 2010, http://www.kgs.ku.edu/General/Strat/Chart/index.html, included as fig. 2). Note that the lithostratigraphic descriptions of West et al. (2010), Zeller (1968), and previous general Permian "red bed" lithostratigraphic succession reports are, for the most part, based on the work originally done by Norton (1939).

a) Post-Permian (in part) strata

Strata overlying the Permian succession in Kansas are difficult to identify due to isolated exposures and lack of fossils (Zeller, 1968; West et al., 2010)

- (1) Neogene—Along the border with Oklahoma in the southwestern part of the state, Neogene strata overlie the Permian (Mudge, 1967).
- (2) Cretaceous—Most of the post-Permian strata in Kansas are of Cretaceous age (Zeller, 1968). In Clark County, an erosional unconformity occurs between Permian red beds and the overlying lighter-colored sandstone, siltstone, and mudrock of Cretaceous age (West et al., 2010).
- (3) Jurassic—From Zeller (1968), "In Morton County undifferentiated beds of red siltstone and buff, green, and white sandstone that are believed to be equivalent in part to the Entrada Sandstone of

Colorado underlie the Morrison Formation and overlie the Permian Big Basin Formation. The maximum exposed thickness is about 40 feet, but in the subsurface of Stanton and Hamilton counties, the thickness is about 250 feet...", and "The upper Morrison beds are chiefly green sandy shale containing limestone lenses. The lower shale beds contain pink chert, anhydrite, and gypsum. Where noted in wells, the Morrison Formation ranges in thickness from 100 to 350 feet (Merriam, 1963)."

(4) Triassic—In southwestern Kansas, Upper Triassic sandstone of the Dockum Group were recognized in some areas (MacLachlan, 1972), although subsequently these were reclassified as Jurassic in age (Zeller, 1968, and references therein).

b) Guadalupian Series

i) No group-level name in Kansas

(1) Big Basin Formation

From West et al. (2010), "The uppermost Permian unit in Kansas is the Big Basin Formation, named for Big Basin, a depression in Clark County. Lithologically, it is similar to the other Permian red-bed units of Kansas—red silty mudrocks and fine-grained red silty sandstones with some anhydrite and dolomite ... According to Zeller (1968, p. 53), the maximum thickness is 13.7 m (45 ft) at the outcrop, but Merriam (1963, p. 81) reported a thickness of 91.4 m (300 ft) in the subsurface."

From Zeller (1968), "Beds of red silty shale, siltstone, dolomitic siltstone, and very finegrained feldspathic sandstone, the 'Taloga' of earlier reports, belong to the Big Basin Formation (O'Connor, 1963). It crops out in western Clark and eastern Meade counties. These strata are seemingly equivalent, all or in part, to the Quartermaster Formation in Oklahoma. The maximum exposed thickness is about 45 feet."

(2) Day Creek Dolomite

From West et al. (2010), "Although the Day Creek Dolomite is thin, 0.6–0.9 m (2–3 ft) at the outcrop (Zeller, 1968, p. 53), Swineford (1955, p. 92) reported a thickness of 36.6 m (120 ft) in the subsurface. At the surface this formation is a fine-grained, dense dolomite with some chert nodules associated with red silty mudrocks. In the subsurface, anhydrite and red mudrocks are conspicuous, and where the Day Creek is thickest, it is mostly anhydrite (Mudge, 1967, p. 115; fig. 66)."

From Zeller (1968), "This formation is a light-gray to pink, dense, fine-grained dolomite cropping out in Clark County and locally in southern Comanche County. At some localities the formation contains chert nodules and disseminated chert. The thickness is about 2 to 3 feet."

(1) Whitehorse Formation

From West et al. (2010), "At the outcrop, the Whitehorse is a very fine grained red sandstone and siltstone with some mudrock and dolomite (Swineford, 1955, p. 92; fig. 65). The two intervals of this formation that contain beds of dolomite are the thin Relay Creek (?) dolomite and Kiger shale members. Maher (1946, p. 2; 1947, p. 3) indicated that the White Horse is mostly red mudrock to sandy red mudrock with some red sandstone and thin beds of dolomite in the subsurface."

From Zeller (1968), "Red beds of feldspathic sandstone, siltstone, and shale with a minor amount of dolomite comprise the Whitehorse Formation. Crossbedding is common and the formation is characterized by small calcite-cemented 'sand balls.' It crops out in Clark, Comanche, Barber, and southeastern Kiowa counties. The thickness is about 270 feet."

(a) Kiger Shale Member

From Zeller (1968), "The Kiger Shale Member (O'Connor, 1963) comprises beds of silty shale, siltstone, and a minor amount of very fine-grained sandstone, mostly brick-red or maroon. Locally it contains a bed of dolomite in the basal part and a bed of gray-green sandy shale or argillaceous sandstone in the upper part. The thickness is about 38 feet."

(b) unnamed member

From Zeller (1968), "Overlying the Relay Creek(?) Member is a very fine-grained sandstone and shaly siltstone 'member' that is mostly even-bedded but locally is crossbedded in the upper part. It contains 'sand balls' and 'sand crystals.' The color is brick-red and maroon, and the thickness is about 100 feet."

(c) Relay Creek (?) dolomite

From Zeller (1968), "This member consists of two beds of dolomite separated by about 21 feet of red and white fine-grained sandstone. The dolomite beds are found only in southern Comanche County. They range in thickness from 0.3 to about 1 foot, and in places one or both may be absent. Locally anhydrite or gypsum occupies this interval. The sandstone is crossbedded at some localities. The member is about 22 feet thick."

(d) Marlow Sandstone Member

From Zeller (1968), "The Marlow Sandstone Member consists of about 100 feet of massive, fine-grained, locally argillaceous or silty, crossbedded red sandstone. 'Sand balls' are locally prominent."





c) Leonardian Series

iii) Nippewalla Group

From Zeller (1968), "This group includes the generally unfossiliferous strata below the Whitehorse Formation and above the Stone Corral Formation and is widely exposed in south-central Kansas south of the Arkansas River. The rocks are mostly red beds that form a nearly featureless plain. In Barber County and adjacent areas, where gypsum beds make prominent escarpments, the Nippewalla forms highly dissected badland topography. It contains thick salt beds in the subsurface. The total thickness on the surface is about 930 feet."

(1) Dog Creek Formation

From West et al. (2010), "... the base of the Blaine, and the top of the Dog Creek, are easily recognized in the subsurface, but it is hard to differentiate between the two; therefore, they are commonly lumped together in subsurface studies."

From Zeller (1968), "Maroon silty shale, siltstone, very fine-grained feldspathic sandstone, thin layers of dolomite, dolomitic sandstone, and gypsum comprise the Dog Creek Formation (formerly Dog Creek shale). The top generally is marked by about 3 feet of maroon shale, but locally a gypsum bed about 1 foot thick and having red and white laminae occurs at the top. The most persistent part is a 6-foot bed of white and red very fine-grained sandstone that locally is capped by dolomitic sandstone, which occurs next below the upper maroon shale. The outcrops are in southeastern Kiowa, eastern Comanche, and western Barber counties. The thickness ranges from 14 to 53 feet. Where the upper three gypsum members of the Blaine Formation are missing, the Dog Creek includes the shales overlying the Medicine Lodge Member."

(1) Blaine Formation

From Zeller (1968), "This formation consists mainly of gypsum beds separated by dolomite and red shale. It is divided into four members. In many places the upper three members are absent (Swineford, 1955). Outcrops are found in Clark, Comanche, Kiowa, and Barber counties. The thickness is about 50 feet."

(a) Haskew Gypsum Member

From Zeller (1968), "This member consists of 1 foot or less of gypsum underlain by about 5 feet of red shale. The gypsum in most places has been removed by solution."

(b) Shimer Gypsum Member

From Zeller (1968), "The Shimer Gypsum Member consists of 13 to 23 feet of gypsum overlying 0.5 foot to 1.5 feet of oolitic dolomite."

(c) Nescatunga Gypsum Member

From Zeller (1968), "This member includes 8 feet or less of red shale underlying 2 to 8 feet of gypsum, which is overlain by 8 feet or less of red shale. The gypsum bed pinches out in Comanche County and is absent in Barber County."

(d) Medicine Lodge Member

From Zeller (1968), "This is the thickest bed of gypsum in Kansas, and it forms a conspicuous rim rock at the top of steep slopes of the Flower-pot Shale. Ordinarily there is a bed of oolitic dolomite and anhydrite at the base, which ranges from 0.5 to 1 foot in thickness. The maximum thickness of the member is 30 feet or more; the average is 20 feet."

Cedar Springs dolomite

Originally described by Fay (1964, p.32) as, "the dolomite at the base of the Blaine, conformably [?] overlying the Flowerpot Shale and grading upward into the Medicine Lodge Gypsum", and at its type area Major County, OK, "a light-gray fine-grained oölitic massive dolomite about 9 inches thick with locally occurring argillaceous compact nonoölitic portions", and in Blaine County, OK as, "the same as in the type area except that it is 1 or 2 inches thick, or missing in places, and at several localities it contains stains of a green copper mineral, probably malachite."

(2) Flower-pot Shale Formation

From West et al. (2010), "Beds of gypsum are particularly conspicuous in the Flower-pot, as are thin beds of coarse siltstone and coarse to fine sandstone ... The Flower-pot Shale contains up to 76.2 m (250 ft) of halite in northwestern Kansas in a localized basin called the Syracuse basin (Holdaway, 1978). The halite is distinctive, coarsely crystalline and clear, and has apparently displaced a red siltstone matrix, referred to as a chaotic red bed salt. The halite in the Flower-

pot Shale is in marked contrast to the Hutchinson Salt Member that is typically a distinctively bedded, cloudy halite with thin continuous layers of gray mudrock." From Zeller (1968), "The Flower-pot Shale (formerly Flowerpot) consists of about 180 feet of reddish-brown gypsiferous shale and silty shale with a few thin beds of sandstone and siltstone. A thin lenticular bed of dolomitic sandstone has been observed in the middle part, and the formation is cut by intersecting veins of satin spar (gypsum). Thin fine-grained sandstones occur near the top. The formation is exposed in Barber, southeastern Kiowa, southeastern Clark, and Comanche counties. Outcrops are strewn with white, pink, and red satin spar and clear crystals of selenite."

(3) Cedar Hills Sandstone Formation

From Zeller (1968), "The Cedar Hills Sandstone comprises feldspathic sandstone, siltstone, and silty shale, chiefly red, and beds of white sandstone in the upper and lower parts. The upper sandstone bed contains 'snowballs' of white gypsum. Shaly siltstones are interbedded with the more resistant and more massive coarse siltstones and very fine sandstones. The Cedar Hills crops out in Barber County. The thickness is about 180 feet."

(4) Salt Plain Formation

From West et al. (2010), "is composed of silty mudrocks with beds of coarse silty sandstone ... Salt is associated with some of the mudrocks below the Crisfield sandstone bed in the lower part of the formation (Zeller, 1968)."

From Zeller (1968), "This formation is composed chiefly of red, flaky, silty shale and some siltstone. There are two prominent coarse silty sandstone beds, the lower one, the Crisfield sandstone bed, about 29 feet thick, occurring about 115 feet below the top of the formation, and the upper, about 25 feet thick, occurring about 42 feet below the top of the formation. The coarse silty sandstones are in part crossbedded. Outcrops in eastern Barber, Harper, and southern Kingman counties form a surface of low relief. The thickness is about 265 feet."

(5) Harper Sandstone Formation

From West et al. (2010), "a formation 67.1 m (220 ft) thick of mostly red argillaceous siltstone and very fine silty sandstone (fig. 58). The two members, Chikaskia sandstone below and the Kingman sandstone above, are lithologically very similar. They are separated by a prominent 0.9-m (3-ft) bed of white, sandy siltstone.

From Zeller (1968), "This formation is chiefly red argillaceous siltstone and very fine silty sandstone divided into two members. It crops out in Harper, Kingman, Reno, and Rice counties. The thickness is about 220 feet."

(a) Kingman Sandstone Member

From Zeller (1968), "The Kingman Sandstone Member is a red argillaceous siltstone and silty sandstone with a few beds of red shale and white sandstone. A prominent bed of white sandy siltstone, 3 feet thick, occurs at the base. The thickness is about 80 feet."

(b) Chikaskia Sandstone Member

From Zeller (1968), "The Chikaskia is composed of siltstone, silty sandstone, and shale, which are predominantely red but may be gray or other colors. It contains fine-grained, ripple-marked, and locally crossbedded sandstone in the lower part. Some white sandy siltstone and dolomite lenses and concretions occur in the upper part. This member thins northward along the outcrop. The thickness ranges from about 100 to 160 feet."

i) Sumner Group

(1) Stone Corral Formation

From West et al. (2010), "The Stone Corral Formation, at the top of the Sumner Group, is in surface exposures basically a dolomite to dolomitic mudrock with evaporites—anhydrite and gypsum ... In the subsurface of south-central and west-central Kansas, near the depositional axis, the Stone Corral Formation includes thin halite beds that occur both above and below dolomite-anhydrite layers (Merriam, 1963). Because of the solubility of these evaporates, this unit is often vuggy in surface exposures. In the subsurface it may be mostly anhydrite (Mudge, 1967, p. 109). This 2–30.5-m (6–100-ft)-thick formation is an easily recognized "marker bed" in the red-bed sequence of Kansas."

From Zeller (1968), "The Stone Corral Formation is composed of dolomite, anhydrite, gypsum, and salt. The anhydrite, gypsum, and salt portions are lost through solution in exposed sections and the remaining dolomite ledge is cellular or contains numerous calcite-filled or gypsum-filled vugs. The dolomite ledge is not well developed south of Rice County. Parts of the formation are oolitic in Rice County. The color is chiefly gray but locally there are red and pink streaks. Ripple marks are common. At some exposures the formation is chiefly red shale, bounded above and below by thin dolomite beds. The outcrop belt is interrupted in eastern Rice, western McPherson, and other counties to the south by eastward overlap of Cenozoic deposits. The Stone Corral is one of the most readily recognized "key beds" in the Kansas subsurface red-beds section, as it produces well-marked reflections in seismograph surveys. Maximum measured thickness at the outcrop is about 6 feet."

(2) Ninnescah Shale Formation

From West et al. (2010), "The Ninnescah Shale is 91.4 to 137.2 m (300–450 ft) of essentially red anhydritic, dolomitic, calcareous mudrock that thins to about 15.2 m (50 ft) in the subsurface near the Nebraska line (Zeller, 1968, p. 50–51; fig. 56). In northwestern Kansas, sandstones and sandy mudrocks are present, but interbedded salt, anhydrite, and mudrock occur in south-central and western Kansas where it is thickest (Martinez et al., 1996). Mudge (1967, p.110, fig. 38) shows the distribution of salt in the Ninnescah Shale. Conchostracans ("clam shrimp") have been found in the non-red beds ... At the base of the Ninnescah Shale (Zeller, 1968) is an unnamed member that is overlain by the Runnymede Sandstone Member."

From Zeller (1968), "The Ninnescah is a predominantly silty shale, mostly red, but containing some gray shale, argillaceous limestone and dolomite, and calcareous siltstone. Some weathered surfaces show bright-green copper carbonate. Several distinctive beds of calcareous or dolomitic siltstone and calcareous shale have been traced for long distances. Clam shrimp—*Cyzicus* (*Lioestheria*)—are common, particularly in nonred layers. Some of the beds show ripple marks. Rosette-shaped calcareous concretions occur in the middle part. Weathering and erosion of these beds have produced the "Red Jaw" country in Reno County. This unit contains much salt in the subsurface in southwestern Kansas. The formation thins northward and is only about 50 feet thick in the subsurface near the Nebraska state line. The maximum outcrop thickness, however, is about 450 feet; the average thickness is about 300 feet."

(a) Runnymede Sandstone Member

From West et al. (2010), "The Runnymede sandstone is a 2–2.4-m (7–8-ft)-thick, gray to grayish-green siltstone to very fine sandstone (Zeller, 1968, p. 51). A disconformity separates this formation from the underlying Sumner Group and although the Runnymede is absent because of erosion in some areas, the Stone Corral Formation, which overlies the Runnymede, is commonly present (Rascoe, 1988)."

From Zeller (1968), "This member, which marks the top of the Ninnescah Shale, is a very fine grained, gray to grayish-green siltstone and sandstone. The thickness is about 7 to 8 feet."

(3) Wellington Formation

From West et al. (2010), "...nearly 700-ft (214-m)-thick Wellington Formation with the marine deposits in the lower part (Zeller, 1968, p. 50). Three of the six members in the Wellington Formation are thin, argillaceous, dolomitic limestones: the Hollenberg and Carlton in the lower part and the Milan at the top of the formation. As reported by Zeller (1968, p. 50), the Hollenberg is 0.3–1.5 m (1–5 ft) thick, the Milan is up to 2.4 m (8 ft) thick, and the Carlton is lenticular (fig. 53). Fossil insects have been reported from the Carlton at some localities (Zeller, 1968, p. 50). The Milan Limestone Member is typically a succession of discontinuous, thin carbonate beds (Berendsen and Lambert, 1981; Watney et al., 2003). The two unnamed shale members of the Wellington separate the Hollenberg from the underlying Herington Limestone Member of the Nolans Limestone (Chase Group) and the Carlton from the Hollenberg. Overlying the Carlton and underlying the Milan is the thickest and economically most important member of the Wellington Formation, the Hutchinson Salt Member. The solubility of the salt precludes its exposure at the surface but it has been reported as 213 m (700 ft) thick in the subsurface of Clark County (Kulstad, 1959). The distribution of the Hutchinson Salt Member in Kansas is shown in fig. 54 (see also Watney et al., 1988). As noted by Mudge (1967, p. 109), the salt originally extended farther east but has been removed by erosion. In general the lower part of the Wellington is gray anhydritic mudrock interbedded with anhydrite; the middle part, the thickest, is mostly red mudrock, anhydrite, and salt; and the upper part is interbedded gray anhydritic mudrock and red mudrock."

From Zeller (1968), "In its outcrop area the Wellington is predominantly shale with minor amounts of limestone and dolomite, siltstone, and gypsum and anhydrite (Swineford, 1955). The shales are chiefly gray and greenish-gray, with some red, maroon, and purple shale. The limestones and dolomites are generally light colored and argillaceous. Thick beds of salt are present in the subsurface. The Wellington includes marine and brackish- and fresh-water deposits. *Lingula, Derbyia*, mollusks, ostracodes, and cup corals are found in the lower part. Conchostracans (clam shrimp) and carbonized plant remains are found in much of the Wellington with the exception of the uppermost part (Tasch, 1964 [1966]). Well-preserved fossil insects occur at several horizons. The thickness of the formation is about 700 feet."

(a) Milan Limestone Member

From Zeller (1968), "The Milan Limestone Member consists of one to three thin beds of greenish-gray shaly limestone or fine-grained dolomitic limestone containing barite, which on the outcrop are characterized by bright-green copper carbonate. A thin bed of maroon and gray shale commonly underlies the topmost limestone bed. Where the member is absent the change in color from gray to purplish-red shale or reddish-brown shale may be regarded as the upper boundary. The member may be as much as 8 feet in thickness."

(b) Hutchinson Salt Member

From Zeller (1968), "The Hutchinson Salt Member occurs in the subsurface in central Kansas. Because it is highly soluble, it is not found in outcrops of the Wellington. The thickness of the member in the subsurface exceeds 700 feet in Clark County (Kulstad, 1959)."

(c) Carlton Limestone Member

From Zeller (1968), "The lenticular Carlton Limestone Member (in some places dolomitic) occurs below the Hutchinson Salt Member. Freshwater deposits in this member contain fossil insects."

(d) Hollenberg Limestone Member

From Zeller (1968), "A bed of argillaceous, dolomitic limestone, not definitely known to be of widespread occurrence, has been named the "Hollenberg Limestone Member" in Washington County and tentatively identified in Cowley and Clay counties. The thickness is 1 to 5 feet."

c) **Wolfcampian Series**

iii) Chase Group

(3) Nolan Limestone Formation

From West et al. (2010), "The uppermost formation of the Chase Group in Kansas, the Nolans Limestone, is 7 to 11 m (23–36 ft) thick, and consists of, from bottom to top, the Krider limestone, Paddock shale, and Herington limestone..."

From Zeller (1968), "This formation consists of an upper and a lower limestone member separated by a shale member in northern and central Kansas outcrops. In southern Kansas outcrops, the member boundaries are not clearly defined. Thickness ranges from about 22 to 40 feet."

(a) Herington Limestone Member

From West et al. (2010), "The upper surface of the Herington, the uppermost carbonate of the Wolfcampian, marks the top of the Chase Group. It is a 2 to 4.9-m (6.5–16-ft)-thick interval of calcitic dolomites and laminated dolomites (fig. 47). Calcite and silica-replaced evaporite nodules (geodes) are typically abundant. At the base, where it is fossiliferous, it contains an assemblage of pectinids, myalinids, and gastropods."

From Zeller (1968), "The Herington is composed of yellowish-tan, dolomitic limestone and dolomite. It is more dolomitic in southern and central Kansas outcrops than in the northern outcrops. The Herington is characterized by siliceous and calcareous geodes and concretions, and cauliflower-like masses of chert and quartz. Fossil mollusks are locally abundant. The thickness ranges from 6 to 10 feet in the northern part of the outcrop area and is about 30 feet in the southern part of Kansas."

(b) Paddock Shale Member

From West et al. (2010), "An olive to yellowish-gray poorly fossiliferous mudrock, 3 to 4.9 m (10–16 ft) thick, is defined as the Paddock. In the south it is composed of yellowish-gray calcareous mudrocks with bivalves and brachiopods. Within the mudrock are cryptalgal laminations, calcite-replaced evaporite nodules, and laminae of "palisade calcite crystals" (Mazzullo et al., 1995, 1997)."

From Zeller (1968), "The Paddock is a gray shale, which in northern Kansas outcrops contains stringers and vein fillings of calcite. In southern Kansas outcrops it is buff colored and contains dolomite in the lower part. Pelecypods are locally abundant in northern and central Kansas outcrops. The thickness ranges from about 7 to 13 feet."

(c) Krider Limestone Member

From West et al. (2010), "The Krider is 0.7 to 2.8 m (2.4–9.3 ft) of porous dolomites and mudrocks to the north and relatively fossiliferous limestones and mudrocks to the south (Mazzullo et al., 1995, 1997) with the maximum thickness in southernmost Cowley County (Mazzullo et al., 1997, p. 104). It contains bivalves, pyramidellid gastropods, brachiopods, bryozoans,

and crinoids."

From Zeller (1968), "This member commonly comprises two beds of limestone separated by a bed of shale, each generally slightly more than 1 foot thick. In southern Kansas outcrops

the separating shale is somewhat thicker. The color is yellowish-brown. The characteristic thickness is about 4 feet."

(1) Odell Shale Formation

From West et al. (2010), "Overlying the Winfield is the Odell Shale, another variegated mudrock unit that ranges from 6.1 to 12.2 m (20–40 ft) thick. Calcareous shales at the top and bottom are transitional with the over- and underlying carbonates..."

From Zeller (1968), "The Odell Shale is chiefly red and green shale with some gray and yellow shale. The thickness ranges from 20 to 40 feet."

(2) Winfield Limestone Formation

From West et al. (2010), "The 7–13.7-m (23–45-ft)-thick Winfield Limestone is divided into three members, in ascending order, the Stovall limestone, Grant shale, and Cresswell limestone..."

From Zeller (1968), "This formation consists of a thin limestone member that is locally cherty overlain by a member that comprises about 10 feet of fossiliferous gray shale, and a thick upper limestone member that is locally cherty. The two lower members are not definitely identified in southeastern Kansas. The combined thickness is about 25 feet."

(a) Creswell Limestone Member

From West et al. (2010), "The Cresswell is a massive limestone with abundant large concretions and scattered chert nodules (fig. 42). Thin-bedded and shaly limestone beds, previously referred to as the "Luta limestone" (Zeller, 1968, p. 49), occur above this massive limestone. The combined interval ranges in thickness from 3 to 11 m (10–36 ft), with a dramatic thickening in Marion County (Mazzullo, 1998). The lower Cresswell is quite fossiliferous with echinoid spines, bryozoans, and brachiopods being common. To the south, this interval becomes an oncolite grainstone with infaunal bivalves. The upper Cresswell consists of carbonate mudrock with cryptalgal laminations, silicified evaporite nodules, evaporite molds, and desiccation polygons (Mazzullo, 1998)."

From Zeller (1968), "This member consists of a massive fossiliferous limestone in the lower part and locally shale in the middle and upper parts. Echinoid spines and other fossils are plentiful in the lower massive limestone. The shaly middle part commonly contains calcareous concretions, geodes, and some chert. Cavernous weathering is characteristic. Throughout a considerable distance the lower massive ledge is about 3 feet thick. South of Butler County the lower part of the Cresswell consists of two massive beds of hard gray limestone separated by a thin limy shale; these have an aggregate thickness of 8 to 10 feet. Near the State line this part of the Cresswell is a single massive bed about 12 feet thick. Above the massive part of the Cresswell, rocks consisting of a thin-bedded limy shale and shaly limestone have been called the "Luta limestone," but these are now considered to be a part of the Cresswell. The boundary between the Cresswell and the Odell Shale is not distinct. The maximum thickness of the member is 25 feet."

(b) Grant Shale Member

From West et al. (2010), "Brachiopods, bivalves, bryozoans, and crinoids characterize the 2 to 4-m (6.5–13-ft)-thick gray to yellowish-gray Grant shale. In southern Kansas the Grant is a shaly wackestone to packstone with abundant oncolites (Mazzullo et al., 1995, 1997)." From Zeller (1968), "This member is a gray, calcareous and fossiliferous shale. It is a distinct unit except in southern Kansas. The Grant is abundantly fossiliferous at some exposures. Thickness in northern outcrops is about 10 to 12 feet; in central outcrops it is about 6 feet."

(a) Stovall Limestone Member

From West et al. (2010), "The Stovall is a very thin limestone nearly everywhere less than 0.9 m (3 ft) thick, typically 0.3–0.5 m (1–1.5) ft thick. Over much of the outcrop belt, it contains abundant chert and a fossil assemblage of brachiopods, bryozoans, and crinoid ossicles. In southern Kansas it becomes a thin shaly calcareous mudrock with bivalves and occasionally oncolites (Mazzullo et al., 1995, 1997; Mazzullo, 1998)."

From Zeller (1968), "The Stovall Member is a dense, gray limestone with an abundance of gray chert in northeastern Kansas. It becomes thicker and less cherty in Chase County, but it thins southward and is absent in Cowley County. Fossils are rare. The thickness is commonly about 1 foot."

APPENDIX 2: Subsurface stratigraphic work from previous studies in western Kansas

This appendix contains a detailed review of relevant subsurface stratigraphic work done previously in western Kansas.

Hemsell (1939)

Described the strata of the Hugoton gas field, primarily the Council Grove and Chase.

In south Grant County, the center of the Hugoton field, he described a salt bed a short distance above the Stone Corral. The Stone Corral is described as about two-thirds anhydrite and one-third dolomite. Gives a thickness of \sim 750 feet for the strata between the Blaine and Stone Corral, and a thickness of 225 to 370 feet of gray shale and anhydrite for the Wellington. Thickness of \sim 20–30 ft for Day Creek.

Stone Corral is 30–50 ft in Hamilton, Kearney, and Finney counties.

In Hamilton County, west of the main Hugoton area, the Chase Group and Wellington have transitioned to "red clastic sediments." The Wellington has thinned considerably, to a featheredge, and there is ~ 400 feet of Sumner equivalents below the Stone Corral.

In Finney and Kearney County, he described ~ 250 feet of strata between the top of the Chase and the base of the Stone Corral.

Norton (1939)

See Figures 3 and 4.

Norton's work is the primary source for many subsequent lithological descriptions. Norton also summarizes all previous literature that defined the Permian in Kansas, including Cragin's work.

Day Creek

(p. 1,812–1,813), regarding the Day Creek dolomite, "In the subsurface it is predominantly chert-free ... In at least one western Kansas well [fig. 4, Hamilton County] anhydrite and gypsum are associated with this bed, as is expected of all Permian dolomites when traced basinward in the subsurface."

Whitehorse

(p. 1,810), regarding the Whitehorse Fm. in the subsurface, "In the subsurface of western Kansas, the Whitehorse sandstone is commonly indistinguishable from the other redbeds, as shown in the cross sections [figs. 3 and 4], save for the juxtaposition with the overlying Day Creek dolomite or with the underlying Dog Creek–Blaine formation ... in Kansas ... west of the outcrops of the formation, the Big Basin and other sink-hole areas of southwestern Kansas being developed by the caving-in of the surface beds to the caverns developed in the Whitehorse beds from which the included salt has been removed."

Dog Creek-Blaine

(p. 1,801), "In few places in the subsurface, can the Dog Creek shale be distinguished from the beds of the underlying Blaine because of the increase in gypsum content of the Dog Creek. Actually the Blaine–Dog Creek is a single gypsiferous formation both at the surface and underground ... In the subsurface, if the gypsum content is 50 per cent or more it can be considered to be Blaine; if the upper part of the Blaine is red shale exceeding this percentage, it may possibly be regarded as Dog Creek."

Flower-pot Formation

(p. 1,792), "Where traced underground, this formation [Flower-pot] is recognized in many places, at least in part, although its thickness is variable according to the amount of sandy beds increasing at its expense in the lower part of these strata. The amount of selenite veining commonly varies, and some sections show rock salt at this horizon..."

Cedar Hills sandstone

(p. 1,791), "In the subsurface, any sand near this approximate horizon is often, and somewhat loosely, labelled Cedar Hills, the more especially if the grains are the rounded, frosted, orange-colored and polished sandstones of erratic distribution, both vertically and horizontally..."

Salt Plain

subsurface not discussed in detail.

Harper Sandstone

(p. 1,782), regarding the basal Harper Sandstone in outcrop, "At the base, is a highly variable sand and shale section, the soft red sandstones containing grotesque concretions and salt casts, the more resistant red sandstones, several feet thick, weathering at the ordinary exposure to an exfoliated, bulgy or pot-bellied appearance," and p. 1,784, "Removal by solution of pre-existing anhydrite or gypsum beds, and possibly some salt, in the underlying Stone Corral member, has necessarily confused the stratigraphy along the exposed contact so that there is no uniformity of intervals between individual beds and every section exhibits differences..."

Stone Corral Dolomite–Anhydrite

(p. 1,774–1,775), "... one of the most persistent and easily identified key markers in the redbeds of the Kansas Permian, and is consequently of greatest value in making subsurface correlations..."

(p. 1,777–1,779), "The Stone Corral dolomite has lost its anhydrite and gypsum portions at the outcrop through hydration and solution of percolating ground waters. The remaining cellular dolomite ledge has its maximum development near its north-most exposed limits ... the color is normally gray, but locally red and pink streaks appear ..."

(p. 1,781), "In the subsurface ... Normal thicknesses ranging from 30 to 50 feet ... has a normal thickness in the Hugoton gas area, and reaches its maximum development in Kansas in a well in Scott County where it is 100 feet thick. It extends still farther westward into eastern Colorado as shown in the cross section [fig. X]... Normally there are two main gypsum anhydrite beds separated by a few feet of gypsiferous red shale, although locally one or more other beds occur higher above these."

(p.1,782), "Subsurface studies in Kansas ... the several hundred feet of redbed strata between the Stone Corral and Blaine formations are so closely related, except at the surface, that their dividing boundaries are in many places obscure or unrecognizable, thus making a group designation desirable."

Malone (1962)

Subsurface study in westermost KS focusing on the Blaine Formation using wirelogs and cuttings.

In Hamilton County, Malone described the Dog Creek as sandy, resembling the overlying Whitehorse Formation.

Within the Blaine in Kearney, Finney, and Grant counties, salt is present.

The Blaine can be up to 185 ft thick in Finney County, but is observed to be 100–125 in Wichita, Kearney, and Hamilton counties.

Top of Blaine to top of Stone Corral in Hamilton, Wichita, Kearney, and Finney counties is 600 to less than 800 ft.

Campbell (1963)

Cedar Hills

(p. 13) Describes anhydrite and anhydritic shale in the Cedar Hills, that locally interfingers with the sandstones. According to his Plate 1, the anhydrite is located near the top of the Cedar Hills.

Harper-Salt Plain

(p. 33) Places the beginning of salt deposition within the Harper–Salt Plain.

Merriam (1963)

See Figures 5–11.

Upper Permian Units

"The three formations not assigned to a group are (in descending order): "Taloga Formation," Day Creek Dolomite, and Whitehorse Formation—in other words, all Permian rocks in Kansas above the Dog Creek Formation."

"In Kansas the thickness of these upper Permian units ranges from a featheredge to a maximum of slightly more than 700 feet in the southwestern corner. The "Taloga" ranges in thickness to about 300 feet, the Day Creek to 65 feet, and the Whitehorse to 400 feet. Inasmuch as the upper boundary of the Permian is defined by an erosion surface, thickness of the strata varies with configuration of the surface, but in general it decreases to the north and east. On the outcrop, thicknesses of the "Taloga," Day Creek, and Whitehorse are about 45, 2, and 270 feet, respectively."

Nippewalla Group

"Two of the formations are sufficiently distinct to be recognized with certainty in the subsurface, the Blaine Formation and Cedar Hills Sandstone. With sufficient study it might be possible to differentiate the other formations according to their lithologic characteristics."

"Generally speaking, the units are thinnest along the outcrop and thickest near the deeper part of the Hugoton embayment."

Stone Corral Formation

"In the Permian redbed section, which is about 1,900 feet thick, few beds can be traced very far laterally; the Stone Corral is one formation that is persistent over a large area."

"Because of the diverse lithologies found within the formation, Lee (1953, p. 6) proposed that the descriptive term "dolomite" be dropped and "formation" substituted. This suggestion was followed by Lee and Merriam (1954a) when they referred to the Stone Corral Formation."

"A short distance downdip from the outcrop of the Stone Corral, the formation consists almost entirely of anhydrite. To the south, in an area comprising parts of Reno, Kingman, Harper, Barber, and Comanche counties, the Stone Corral is represented by anhydritic or dolomitic shale (fig. 40). Farther west and throughout a considerable part of western Kansas, the unit consists of pure to dolomitic anhydrite, or it includes a dolomite bed in the lower part or at the base of the formation. In southwestern Kansas in an area covering parts or all of 21 counties, the formation is split into two anhydrite beds separated by red shale The lower anhydrite is dolomitic in most places and is less extensive than the upper bed. The shale in parts of Meade, Seward, Stevens, Haskell, Finney, Lane, Scott, and Logan counties is saliferous. In Logan and Thomas counties the anhydrite is locally saliferous. In the subsurface the formation is underlain and overlain by beds of red silty shale and shaly sandstone. A gypsiferous red shale is present above the Stone Corral in some areas, whereas in others a saltbearing shale is present below the formation."

"Because the Stone Corral is composed mostly of anhydrite in the subsurface, and also was named Cimarron, it is commonly called the "Cimarron anhydrite." Most of this anhydrite is pinkish white or white mottled gray, massive, and crystalline. It may be finely crystalline and have a sugary texture. Rarely present is a thin limestone. Most of the shale is silty and red, although gray shale is not uncommon."

"The thickness of the Stone Corral in the subsurface is generally between 25 and 45 feet. In southwestern Kansas, however, in Gray, Finney, Kearny, and Grant counties, the maximum thickness of the formation, 90 to 100 feet, was deposited near the center of the area in which the formation consists of two anhydrite beds separated by shale. It seems that this area was near the center of the depositional basin."

"By means of samples and electric and radioactivity logs, it is possible to trace the Stone Corral into the adjacent states of Nebraska, Colorado, New Mexico, and possibly Oklahoma. Maher (1948) remarked that because of its irregularity and because of the presence of other unnamed anhydrite beds, the Stone Corral is not so easily identified in eastern Colorado as in western Kansas. He was able, however, to trace the unit to the Front Range in Colorado, where he correlated it with the "contact limestone" at the top of the Fountain Formation (Maher, 1953a, p. 921)."

Schumaker (1966)

See Figure 12.

The appendix of this study provides a wealth of data for the surface and subsurface Permian and post-Permian of Kansas. Some of these data have been used to make fig. 12.

Wellington-Ninnescah

(p.22) In the subsurface of central and southern Kansas, the Milan limestone cannot be distinguished. The Wellington–Ninnescah Shale contact usually cannot be determined from electric logs. In well cuttings, however, the dominantly gray and maroon Wellington shales and the reddish brown shales of the overlying Ninnescah can usually be distinguished in central and southern Kansas. The Wellington in the subsurface of most areas is usually more anhydritic than the overlying Ninnescah Shales. Anhydrite is abundant at the contact between the Wellington and Ninnescah in southern and central Kansas.

(p. 23) In the subsurface of western Kansas, the Wellington changes from anhydrites and shales to siltstones, fine-grained sandstones and shales. The Wellington–Chase contact becomes almost indeterminable because the underlying carbonates also grade westward into dolomitic siltstones and sandstones. The Ninnescah shales undergo a similar facies change, such that they are undifferentiated from the Wellington.

Nippewalla

(p. 36) cannot differentiate the Harper and Salt Plain in the subsurface.

(p.37) In western Oklahoma, the Texas Panhandle, and western Kansas, there are halitic shales [displacive halite] and pure salt beds that overlie the Stone Corral. These are included in the Salt Plain. (p. 45) thin anhydrite is present at the base of the Flower-pot in northwest Kansas, 10 to 25 feet.

(p.60) in southern Greeley County, the Blaine consists of shaly, halitic, gypsum and anhydrite, and is 137 ft thick.

post-Nippewalla

(p. 65) Whitehorse is 250–350 ft thick in western Kansas and the members are undifferentiated; 330 ft thick in central Greeley County.

(p.69) in Greeley County, the northwest limit of the Day Creek dolomite, the unit is observed to be 16 ft thick. (p.71) in Greeley County, the Big Basin is only 70 ft thick, this is near its northwest erosional limit.

Mudge (1967)

Blaine–Dog Creek

(p. 110), "The Blaine Formation is easily recognized throughout the subsurface of Kansas, easternmost Colorado ... The overlying Dog Creek is combined here with the Blaine Formation, as the two units are not easily distinguished in subsurface sections ... In Kansas the Blaine Formation is composed mostly of gypsum and anhydrite ... The outcropping Blaine also contains beds of dolomite and red mudstone, and it is overlain by maroon silty mudstone, dolomite, and dolomitic siltstone of the Dog Creek Shale ... In subsurface the Blaine is dominantly evaporite rock with some thin interbedded red mudstone..."

Flowerpot, Cedar Hills, Salt Plain, Harper

(p. 109–110), "In subsurface, rocks between the Stone Corral and Blaine differ lithologically. The lower strata (possibly the Harper Siltstone and Salt Plain Formation) consist mainly of red mudstone, in part sandy. The upper strata (possibly Cedar Hills Sandstone and Flowerpot Shale) generally consist of red mudstone and many beds of sandstone and sandy mudstone ... Locally in western and southwestern Kansas as much as 300 feet of strata beneath the Blaine Formation [and above the Cedar Hills ?] ... consists of salt interbedded with anhydrite and mudstone."

Stone Corral

(p. 109), "The Stone Corral is the most conspicuous layer in the subsurface Permian of Kansas. Along the outcrop it is dolomite with dolomitic mudstone ... but a short distance downdip in the subsurface it is almost entirely anhydrite. In southern Kansas it is largely anhydritic or dolomitic mudstone; farther west it is dolomitic mudstone to pure anhydrite but locally includes a dolomite bed; in the southwest it consists of two beds of anhydrite separated by red mudstone ..."

Ninnescah

(p. 109), "The Ninnescah Shale ... in south-central and western Kansas, salt-bearing units are interbedded with anhydrite and mudstone in the upper part of the formation ... The Ninnescah is as much as 270 feet thick."

Rascoe (1968)

See fig. 13.

(p. 135), "There are four members of the Nippewalla Group that apparently are not present on the outcrop and have not been formally designated ... 1) A section of anhydrite, gypsum, and possibly salt that

ranges in thickness from 0 to75 feet overlies the Stone Corral Anhydrite ... in western Kansas ... 2) A lens of salt 0 to 100 thick occupies the stratigraphic position of the Cedar Hills ... in an evaporite basin located in western Kansas ... 3) A thin anhydrite marker, which is normally 10 to 15 feet in thickness, overlies the Cedar Hills ... and its equivalent salt lens over most of Kansas ... This marker is indispensible to the establishment of stratigraphic relationships across the evaporite basin in western Kansas ... 4) Salt with some interbedded gypsum and anhydrite occupies the Flowerpot Shale interval between the Blaine Gypsum and the thin anhydrite marker discussed above ... The maximum thickness of the salt body that occupies the Flowerpot interval is approximately 400 feet ... It is not always possible to distinguish between this salt body and the one that occupies the Cedar Hills ... unless the thin anhydrite marker discussed ... above, is present."

Holdoway (1978)

See figs. 14–17

(p. 3), "Correlation and nomenclature are made difficult by the fact that evaporites, including thick salt beds, generally occur in the subsurface, where they are protected from solution, and the formations with which they are associated are described and classified in outcrop. In the subsurface of western Kansas, unnamed salt and anhydrite beds occur in most of the formations of the Nippewalla Group."

Blaine Formation

(p. 20–23), "A thin dolomite bed which is usually present at the base of the formation was named the Cedar Springs dolomite by Fay (1964) The remainder of the Blaine Formation in outcrop is divided into four members on the basis of the most prominent gypsum beds. In ascending order these are the Medicine Lodge Gypsum Member, Nescatunga Gypsum Member, Shiner Gypsum Member, and Haskew Gypsum Member ... The Blaine can be traced in the subsurface to the north and west of the outcrop area. ... The Dog Creek Shale (fig. 3) is also anhydritic in the subsurface and, in some cases, particularly in southwestern Kansas, the upper part of the section mapped as Blaine may be equivalent to Dog Creek (Malone, 1962).

The Cedar Springs dolomite is light gray, fine grained and often oolitic (Fay, 1964). In Kansas, it ranges from 0.5 to 1 ft. (0.15–0.3 m) in thickness, and is ripple marked in places (Norton, 1939). In the core from A.E.C. Test Hole 5, the Cedar Springs is about 0.5 ft. (0.15 m) thick (1701.5–1701 ft.; 519–518.6 m). It overlies several feet of red, rubbly mudstone probably a solution breccia) of the uppermost Flower-pot ..., and grades upward into the herring-bone anhydrite of the Blaine The Cedar Springs is a fine-grained, non-fossiliferous, dolomitized mudstone often with faint outlines of pelletoid grains grading upward into coarse-grained dolomite rhombs. The dolomite becomes progressively more anhydritic towards the top of the bed; and dolomite grains in the overlying anhydrite are pellet-shaped, often containing inclusions in the centers of the grains ... "

Flower-pot Shale

(p. 11–12), "The Flower-pot Shale occurs in the subsurface west and northwest of the area where it crops out in south-central Kansas... Overall, the Flower-pot thins to the west and north, except in the two areas where evaporites were deposited, one in extreme western Kansas and contiguous Colorado... "

Cedar Hills Sandstone

(p.8–9), "From where it crops out in south-central Kansas, the Cedar Hills Sandstone can be traced in the subsurface throughout western Kansas ... The interval generally considered to be the Cedar Hills in the subsurface is distinctive on geophysical logs [fig. 14]. The upper boundary is marked by a thin shale horizon throughout much of the basin [fig. 14], but in the northern part of the basin a thin anhydrite bed occurs at the top of the Cedar Hills section. The lower boundary of the Cedar Hills is picked where there is a slight increase and change in response on the resistivity log [fig. 14]. The boundaries of the Cedar Hills in the subsurface may not coincide exactly with those of the unit in outcrop. The occurrence of salt and anhydrite in the Cedar Hills and Flower-pot in the Syracuse Basin leads to some difficulties in correlating sediments of Cedar Hills age. A thin anhydrite bed (Y on [Fig. 14], A–A', B–B') occurs at the top of the Cedar Hills north of T. 19 S., in the area mapped. This anhydrite was mapped by Campbell (1963), and Schumaker (1966), and was noted by Rascoe (1968) to be a valuable marker bed in northwestern Kansas. The anhydrite is generally between 10 and 15 ft (3–4.6 m) thick, but in a few areas it is more than 30 ft (9 m) thick. In sample logs, the anhydrite is described as a white or gray, massive or shaly anhydrite."

Harper Sandstone and Salt Plain Formation

(p. 7–8), "The similarity in lithology and response on geophysical logs makes it very difficult to distinguish between the Harper Sandstone and Salt Plain Formation in the subsurface (Schumaker, 1966) [fig. 14], and for subsurface correlation purposes, these formations are undifferentiated."

Macfarlane et al. (1993)

See figs. 18 and 19.

Undifferentiated Jurassic and Triassic deposits

The undifferentiated Jurassic and Triassic deposits mapping units consist of strata between the base of the Cretaceous System and the top of the Permian System. Strata within this mapping unit may belong to either the Dockum Group, the Entrada Sandstone, or the Morrison Formation. Neither the Dockum Group nor the Entrada Sandstone are officially recognized stratigraphic units in Kansas. Maclachlan (1972) describes the Dockum as consisting of distinct upper and lower portions. The lower portion of the Dockum Group consists of orange-red, fine- to medium-grained sandstone. Thin beds of coarse-grained sandstone, conglomeratic mudstone, limestone, and dolomite are common in this interval. The upper part of the Dockum consists of variegated mudstone interbedded with sandy mudstone, marlstone, limestone, dolomite, and sandstone. Limestone and dolomite pebbles are reported to be abundant at some localities. The Entrada Sandstone in Baca County, Colorado, consists of massive beds of white, friable, very fine to medium extensively crossbedded quartzose sandstone and a few thin discontinuous layers of shale and siltstone (McLaughlin, (1954). The Morrison Formation consists of shale, sandstone, and limestone with minor amounts of chert and anhydrite (Merriam, 1955; Doveton and Chang, 1991). Two lithologic units are persistent: an upper unit that consists of sandy shale with limestone stringers and a lower unit that consists of shale with chert and anhydrite.

Undifferentiated strata above the Cedar Hills Sandstone

"Undifferentiated Permian strata above the Cedar Hills Sandstone include the Flower-pot Shale, the Blaine Formation, the Dog Creek Formation, the Whitehorse Formation, the Day Creek Dolomite, and the Big Basin Formation. This unit consists entirely of interbedded siltstone, shale, sandstone, and evaporites. The proportion of sandstone relative to the other clastic components increases near the Kansas–Colorado ... Thick bedded evaporites occur in the Flower-pot Shale and Blaine Formations in the Syracuse basin of west-central Kansas (Holdoway, 1978). The total thickness of Permian strata in this unit ranges up to more than 1,000 ft in central Hamilton County near the Syracuse basin axis."

Cedar Hills Sandstone

"The Cedar Hills Sandstone consists of medium- to fine-grained sandstone and feldspathic sandstone with interbeds of sandy mudstone. Zones of sandstone are massive bedded for the most part, but may exhibit horizontal stratification and even high-angle cross stratification (Holdoway, 1978). In the subsurface, the gamma-ray logs indicate that locally up to more than 90% of the Cedar Hills consists of loosely cemented sandstone ... In the Syracuse basin of west-central Kansas the Cedar Hills is salt-cemented beneath thick bedded evaporites in the overlying Flower-pot Shale (Holdoway, 1978) and in parts of Meade, Clark, and Ford counties (Macfarlane, 1993). The total thickness of the aquifer ranges from more 350 ft in parts of Rush and Ness counties to less than 50 ft in northern Hamilton, northern Wichita, and southern Logan counties in the Syracuse basin."

Undifferentiated Salt Plain Formation and Harper Sandstone

"In the subsurface of southwestern Kansas the Harper Sandstone can not be distinguished from the overlying Salt Plain Formation on a gamma-ray log and thus they are considered undifferentiated. This undifferentiated unit is described as a sequence of brownish-red to reddish-brown interbedded siltstone, shale, and sandstone (Fader and Stullken, 1978). Schumaker (1966) reports finding zones of shaly, broken, halitic, anhydrite above the Stone Corral Formation in the Finney County area. Holdoway (1978) reported nodules of anhydrite in core samples from the upper part of the Salt Plain Formation in the Syracuse basin. The total thickness of this unit ranges from more than 400 ft in Clark, southern Barton, portions of Rush, and northeastern Pawnee counties to less than 100 ft in western Hamilton, Greeley, and southwestern Wallace counties. Elsewhere, in central Kansas this unit is typically 300–350 ft in thickness."

Sorenson (1996)

Studied the Hugoton embayment area (specifically Morton, Stevens, Stanton counties) using wireline log data.

Day Creek

Approximately 400 ft above the Blaine and ranging from anhydrite to gypsum in a manner similar to that observed in the Blaine. No associated salt beds have been preserved. This evaporite section is sometimes absent due to either dissolution or erosional truncation near the unconformity at the top of the Permian. Where present, the Day Creek is the shallowest Permian correlation marker in this part of the Hugoton embayment.

Blaine

Located 300–600 ft above the Stone Corral, with a composition ranging from anhydrite to gypsum, with dramatic changes between wells, between beds, or even abrupt mineralogical changes within discrete beds.

Stone Corral Formation

The Stone Coral Formation is composed of three parts: 1) the upper unit contains one or two thin (<5 ft) anhydrite beds interbedded and resting on shale, 2) a middle unit of salt, 35–70 ft thick at the top of which is a thin interval of dense, complex mineralogy likely representing a dissolution surface, and 3) the lower unit a 10–20-ft-thick anhydrite bed, which is the primary Permian correlation point west of the Hugoton field.

Wellington

The Wellington Formation is composed of laminated anhydrite and shale in this area, with the anhydrite component thinning westward to near zero along the Kansas–Colorado border. To the east in Seward County, is the western margin of the Hutchinson Salt Member (Watney et al., 1988). Its absence in the mapped area appears to result from nondeposition rather than dissolution.

Olson et al. (1997)

Most of Chase Group is progradational.

On the western margin of the Hugoton field, marine limestone of the Chase and Council Grove are seen to thin and turn red.

Dubois et al. (2005)

Most of the Chase and the Council Grove above the Neva is nonmarine in Hamilton County. Insect burrows, root traces, pedogenic features are all present.

G. Wahlman (personal communication, 2012)

KB = 3836 DF = 3833 GL = 3824

From a fusulinid chart compiled by George Verville and George Sanderson at Amoco Production Company. Sample 3425–3430 ft assigned to "Bursumian" (latest Virgilian), uppermost Pennsylvanian based on the presence of *Triticites* cf. *cellamagnus* and *T*. cf. *meeki* and a fusulinid fauna most similar to the Foraker Limestone of Kansas outcrops.

Tops marked on logs include the top of the Neva Limestone at 3256 ft and top of the Foraker (marked as an unconformity) at 3413 ft.