Dakota and adjacent Morrison and Lower Mancos stratigraphy (Cretaceous and Jurassic) in the Holy Ghost Spring quadrangle, land of pinchouts, Jemez and Zia Indian reservations, New Mexico

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DAKOTA AND ADJACENT MORRISON AND LOWER MANCOS STRATIGRAPHY (CRETACEOUS AND JURASSIC) IN THE HOLY GHOST SPRING QUADRANGLE, LAND OF PINCHOUTS, JEMEZ AND ZIA INDIAN RESERVATIONS, NEW MEXICO

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Abstract—The Holy Ghost Spring Quadrangle (HGSQ) is the most important area on the east flank of the San Juan Basin for understanding the complex pinchouts in the intertongued Dakota Sandstone-lower Mancos Shale. All of the following stratigraphic units were mapped and correlated across the quadrangle: Encinal Canyon Member, Clay Mesa Shale, Paguate Sandstone, Whitewater Arroyo Shale, Twowells Sandstone, Greenhorn Limestone, and Semilla Sandstone, which all pinch out in the quadrangle, and the Jackpile Sandstone, Oak Canyon Member, Cubero Sandstone, and Juana Lopez Member, which all extend completely across the quadrangle, each providing a stratigraphic datum to constrain the pinchouts.

INTRODUCTION

All of the marine members of the intertongued Dakota Sandstone and lower Mancos Shale (Cretaceous) are present in the HGSQ (Figs. 1, 2) on the east flank of the San Juan Basin, but most of them pinch in and out in the quadrangle. The underlying Jackpile Sandstone Member of the Morrison Formation (Jurassic) is present across the whole quadrangle, but the overlying Greenhorn Limestone Member of the Mancos Shale has its last limestone bed pinch out southward in the quadrangle. Above the Greenhorn, the Semilla Sandstone Member of the Mancos Shale thins dramatically and pinches out in the southern part of the quadrangle. The Juana Lopez Member of the Mancos Shale is present across the whole quadrangle. Stratigraphic units present in the quadrangle are shown in Table 1.

Mapping the various members in the stratigraphic package between the continuous Jackpile at the base and the continuous Juana Lopez at the top in this quadrangle illustrates many key aspects of the complex Dakota/Mancos stratigraphy along the east flank of the San Juan Basin. Two geologic maps of this quadrangle have been published (Woodward and Martinez, 1974; Santos, 1975), but neither one shows the upper Morrison, Dakota, or lower Mancos stratigraphy very well. Therefore, we mapped this part of the stratigraphic section in detail during 1975 (Siemers and Owen) and 2005 (Owen and Owen). Our geologic map appears as Figures 1 and 2. Figure 3 is a stratigraphic cross-section across the HGSQ.

Owen and Siemers (1977) reported on Dakota stratigraphy along the east flank of the San Juan Basin in general. Lucas (2002) correlated Dakota members eastward across the Rio Grande rift. Owen et al. (2005) discussed the details of Dakota stratigraphy in the Chama Basin north of the HGSQ; Owen (1982) included description of the Dakota stratigraphy in the area south of the HGSQ. Landis et al. (1973) summarized Dakota stratigraphy in the Laguna area to the south and elsewhere. In this paper we provide details of Jackpile through Juana Lopez stratigraphy, including the many pinchouts, in the HGSQ and vicinity.

STRATIGRAPHY

Jackpile Sandstone Member of Morrison Formation

The Jackpile was formally named for the ore-bearing sandstone in the Jackpile Mine north of Laguna, NM by Owen et al. (1984), although it was in use informally for years earlier. It is a strikingly white, mostly cross-bedded, fine- to medium-grained sandstone of fluvial origin with an average thickness of 14 m. The sandstone is lightly cemented, but it does form a low upland above the soft Brushy Basin mudstones. It has a gradational contact through a few centimeters, but is locally scoured at the base of fluvial channel fills into the underlying Brushy Basin Member mudstone of the Morrison Formation. It extends without interruption across the HGSQ into adjacent quadrangles (Fig. 3). Some have suggested that this sandstone might be equivalent to the Burro Canyon Formation, but they have been separated, as the Burro Canyon seems to be present only north of Cuba, NM, on the outcrop. Because of their lithologic similarity, they might be considered homotaxial lithostratigraphic units, but they are apparently separated by the K1 unconformity, which separates Jurassic from Cretaceous strata (see Owen and Siemers, 1977, p. 179-180, for discussion). A few insect burrow casts are present in the Jackpile at the CV section (Fig. 3); no other fossils were observed. Cross-bedding measurements indicate a generally easterly flow of paleocurrents in the braided-stream system that deposited the Jackpile.

Encinal Canyon Member of Dakota Sandstone

The Encinal Canyon is a thin, discontinuous, gray, medium- to coarse-grained, cherty quartz sandstone with a few granules to small pebbles and abundant carbonaceous material, including carbonized wood fragments up to log-sized. Bedding is plane to cross-bedded. It rests on the K2 unconformity that separates the Upper Jurassic Morrison from the Upper Cretaceous Dakota. The Encinal Canyon Member fills shallow fluvial channels cut into

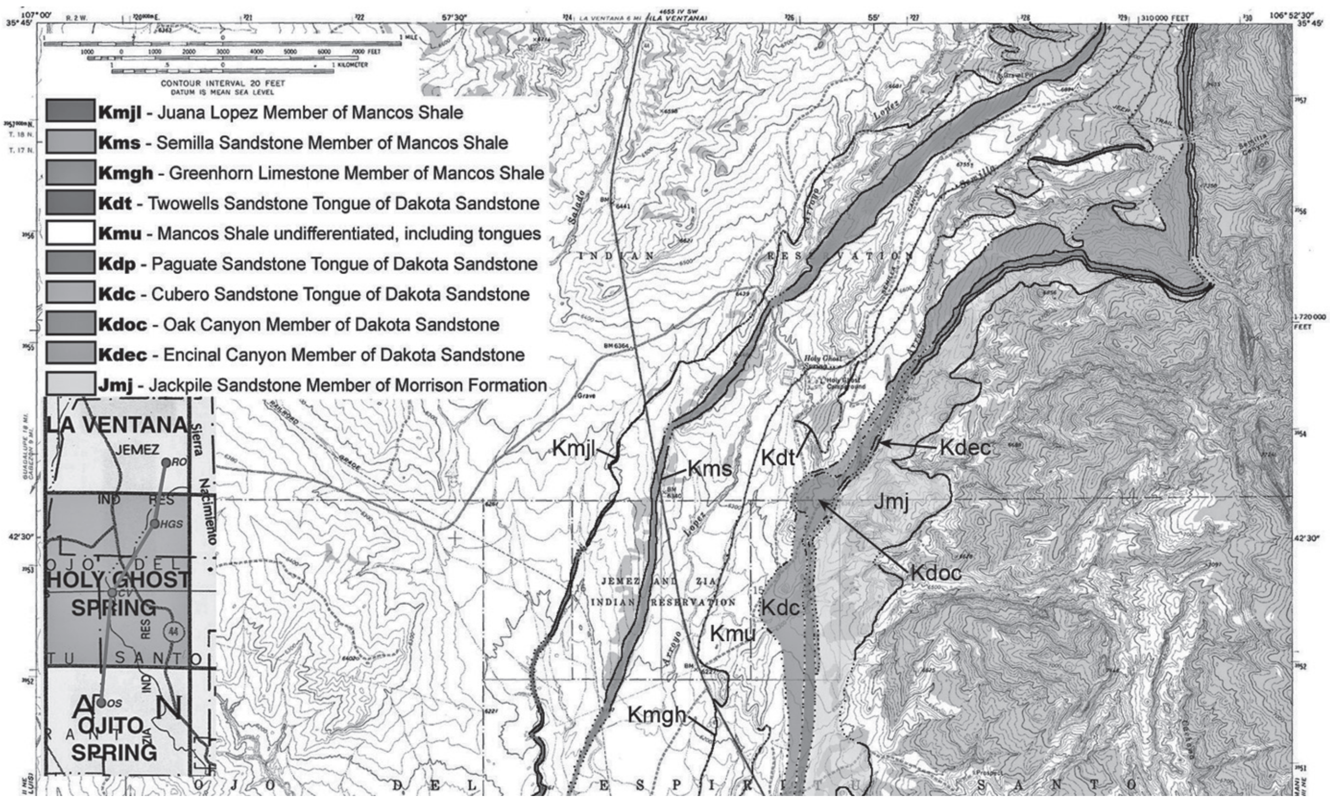

FIGURE 1. Geologic map of Jackpile, Dakota, and Mancos stratigraphic units of the north half of the Holy Ghost Spring Quadrangle, New Mexico. Jmj, Kdec, Kdoc, and Kdc are all present in the north-striking, steeply dipping, narrow outcrop belt along the Sierra Nacimiento front near the NE corner of the quadrangle. Note line of stratigraphic cross-section (Figure 3) in red on inset index map. RO = Rito Olguin measured section; HGS = Holy Ghost Spring measured section; CV = Chamisa Vega measured section; OS = Ojito Spring measured section. See Plate 9 on page 139 for a color version of this figure.

the underlying Jackpile, so it is quite discontinuous. Where present it caps the low upland of Jackpile sandstone. Maximum thickness observed in the study area is 6 m at the OS section (Fig. 3) on the south. It thins into the southernmost part of the HGSQ, pinching out 1 km north of its southern edge. It is absent through the middle part of the quadrangle where Oak Canyon Member shale is directly on the K2 unconformity, such as at the CV section (Fig. 3). It reappears as a thin unit, rarely more than 2 m thick, in the northern third of the quadrangle, and extends northward from the HGS section to the RO section (Fig. 3) and beyond. Farther north, near Elk Spring (La Ventana quadrangle), it thickens and contains boulders of Jackpile sandstone, indicating that the Jackpile was cemented when eroded during deposition of the Encinal Canyon. The Encinal Canyon may be older than the rest of the Dakota, which is Cenomanian; Lucas (2002, fig. 3) placed it in the upper Albian.

Oak Canyon Member of Dakota Sandstone

The Oak Canyon is a dark gray marine shale with a few thin, bioturbated very fine-grained sandstone beds with calcareous cement. Some of the sandstone beds contain a fauna of small gastropods, oysters, and clams. It has a fairly uniform thickness of approximately 17 m across the study area and forms a low area between the Jackpile-Encinal Canyon upland and Cubero cuesta. A regional San Juan Basin area marker bed, the A bentonite of Head and Owen (2005, p. 437, 441), is very thin (2-5 cm or less), but recognizable in all the sections in Figure 3. The A bentonite is 3-5 m above the base of the Oak Canyon, and has been Ar-Ar dated at 98.1 $\pm$2.4 Ma (Peters, 2004) at an outcrop near San Ysidro, 14 km southeast of the OS section. Where the underlying Encinal Canyon is absent, such as at the CV section (Fig. 3), the Oak Canyon shale rests directly on the K2 unconformity with striking color contrast on the white Jackpile (Fig. 4).

Cubero Sandstone Tongue of Dakota Sandstone

The Cubero is a prominent cuesta-forming sandstone that is a tan, very fine- to fine-grained, shoreface marine sandstone with a few silty zones. It is mostly bioturbated, but does show a little plane bedding. It varies between approximately 6-12 m thick in most of the area, averaging near 9 m, but it does thin to as little as 2 m for approximately 2 km west of the Rio Salado (near the CV section) to the area near Soda Spring on Cachulie Arroyo (Fig. 2). It is a continuous sandstone layer across the study area, the base of which is used as a datum for the sections in Figure 3. A few calcareous, concretionary concentrations of *Thalassinoides* and/or *Ophiomorpha* burrow casts occur locally at the top of the Cubero. A few fragments of oyster shells were found. A correlative conformity to the K3 unconformity developed farther west in the San Juan Basin (Owen and Owen, 2005, p. 228, 230) is placed near the base of the Cubero.

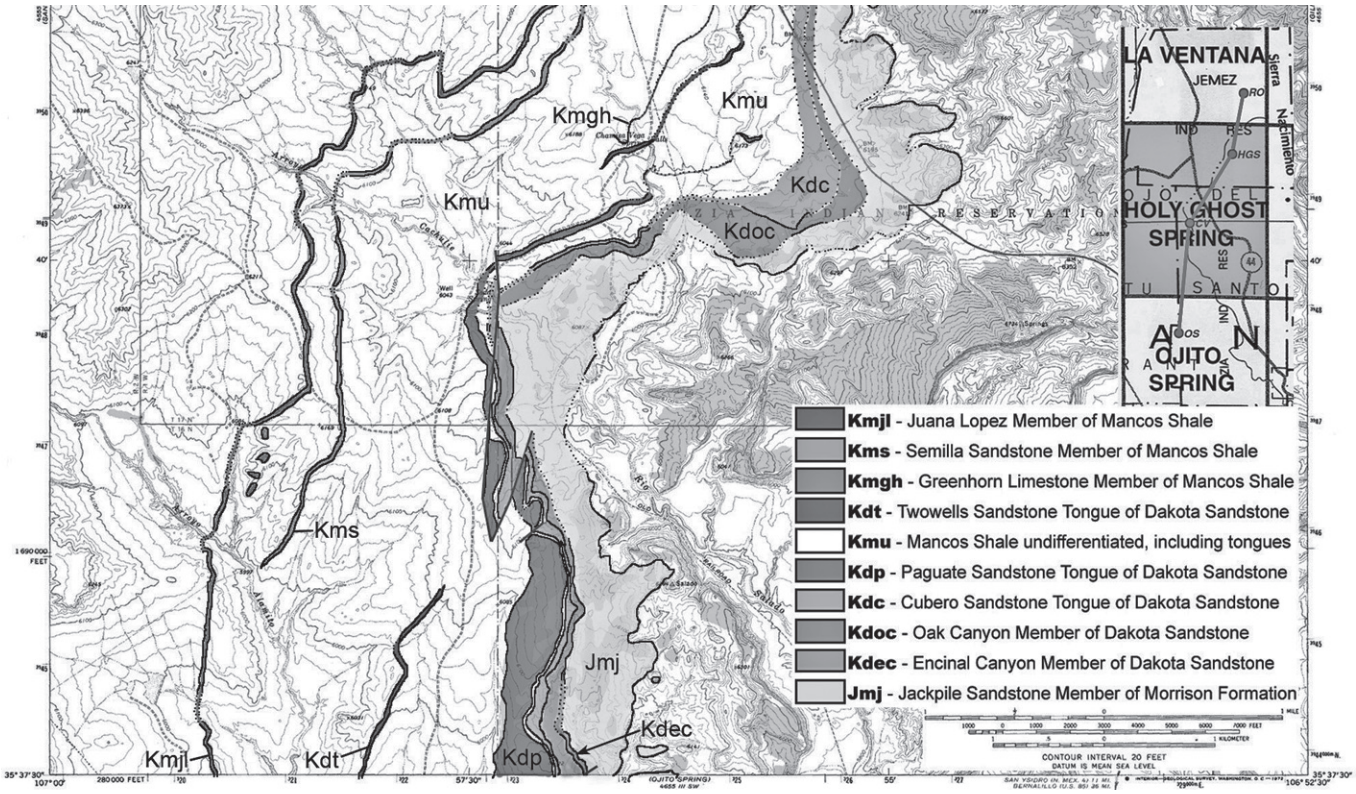

FIGURE 2. Geologic map of Jackpile, Dakota, and Mancos stratigraphic units of the south half of the Holy Ghost Spring Quadrangle, New Mexico. Note line of stratigraphic cross-section (Figure 3) in red on inset index map. RO = Rito Olguin measured section; HGS = Holy Ghost Spring measured section; CV = Chamisa Vega measured section; OS = Ojito Spring measured section. See Plate 9 on page 139 for a color version of this figure.

Clay Mesa Shale Tongue of Mancos Shale

The Clay Mesa is a tongue of typical gray, marine Mancos Shale in the southern part of the area. It cannot be differentiated from the rest of the Mancos shale northeast of highway NM-44 (now US-550) on the map (Figs. 1, 2) because of the pinch out of the overlying Paguate Sandstone just southwest of the highway. The Clay Mesa is generally 12-15 m thick where differentiated in the southern area, but is a poorly exposed, lowland-forming unit except where the overlying Paguate holds up a steep slope. It typically contains numerous calcareous concretions (Fig. 3).

Paguate Sandstone Tongue of Dakota Sandstone

The Paguate is a prominent, high-mesa capping sandstone up to 15 m thick in the southern part of the area (Fig. 4), but

TABLE 1. Idealized "layer cake" lithostratigraphy of the lower Mancos Shale, Dakota Sandstone, and upper Morrison Formation in the Holy Ghost Spring quadrangle, New Mexico. Many of these members intertongue and pinch out, so not all are present at a single locality.

Lithostratigraphic Name	Original Reference
Juana Lopez Member of Mancos Shale	Rankin, 1944; Dane et al., 1966
lower tongue of Mancos Shale (middle part)	(informal usage)
Semilla Sandstone Member of Mancos Shale	Dane et al., 1968
lower tongue of Mancos Shale (lower part)	(informal usage)
Greenhorn Limestone Member of Mancos Shale	Gilbert, 1896
Graneros Shale Member of Mancos Shale	Gilbert, 1896
Twowells Sandstone Tongue of Dakota Sandstone	Pike, 1947; Owen, 1966
Whitewater Arroyo Shale Tongue of Mancos Shale	Owen, 1966
Paguate Sandstone Tongue of Dakota Sandstone	Landis et al., 1973
Clay Mesa Shale Tongue of Mancos Shale	Landis et al., 1973
Cubero Sandstone Tongue of Dakota Sandstone	Landis et al., 1973
Oak Canyon Member of Dakota Sandstone	Landis et al., 1973
Encinal Canyon Member of Dakota Sandstone	Aubrey, 1988
Jackpile Sandstone Member of Morrison Formation	Owen et al., 1984
Brushy Basin Shale Member of Morrison Formation	Gregory, 1938

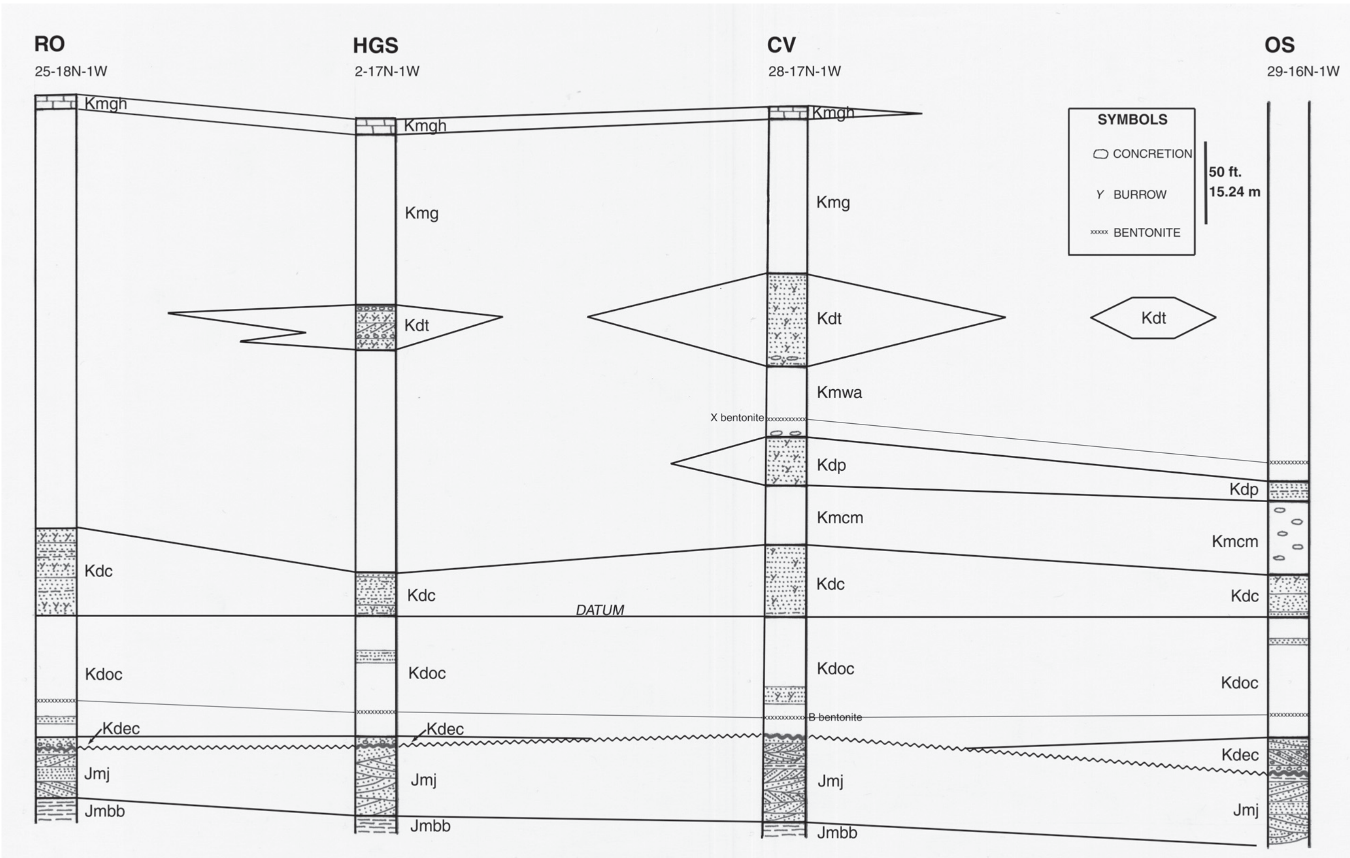

FIGURE 3. Stratigraphic cross-section from RO in La Ventana Quadrangle across Holy Ghost Spring Quadrangle, to OS in Ojito Spring Quadrangle. Abbreviations of measured sections and stratigraphic units same as on Figure 1 and 2 plus Kmg = Graneros Shale, Kmwa = Whitewater Arroyo Shale, Kmcm = Clay Mesa Shale, and Jmbb = Brushy Basin Member of Morrison Formation.

it becomes silty and thins sharply east of the Rio Salado (CV section) to its pinchout on a low, pediment gravel-capped mesa just west of the highway (Figs. 1, 2). It does not appear again to the north along the entire front of the Sierra Nacimiento, but is present again in the Chama Basin area (Owen et al., 2005). The Paguate in the study area is a very fine-grained, shoreface marine sandstone that becomes silty and clayey northward. It is generally completely bioturbated. Calcareous concretions are present in the Paguate and just above it in the overlying Whitewater Arroyo shale (Fig. 3).

Whitewater Arroyo Shale Tongue of Mancos Shale

The Whitewater Arroyo is a tongue of typical gray, marine Mancos Shale in the southern part of the area, much like the Clay Mesa. It cannot be differentiated from the other tongues of Mancos Shale except in some of the southern part of the area where both the underlying Paguate Sandstone Tongue and overlying Twowells Sandstone Tongue, the latter of which is a series of lenses across the HGSQ (Figs. 1-3), are present. The X bentonite, a regional San Juan Basin marker bed (Head and Owen, 2005, p. 435, 437) that extends into eastern New Mexico and Colorado, reaches its greatest observed thickness, 0.5 m (Fig. 5), in the southern half of the HGSQ (Fig. 3). It is well exposed in the channel wall of the Rio Salado approximately 0.6 km downstream of the road crossing at Chamisa Vega Spring (Fig. 2), between the waterfalls formed by the Twowells and Cubero sandstone ledges. It is also exposed along this road near the hilltop south of Soda Spring (Fig. 2). It was not observed in the HGS and RO sections (Fig. 3), but the shale interval where it should be is largely covered in its lowland outcrop belt.

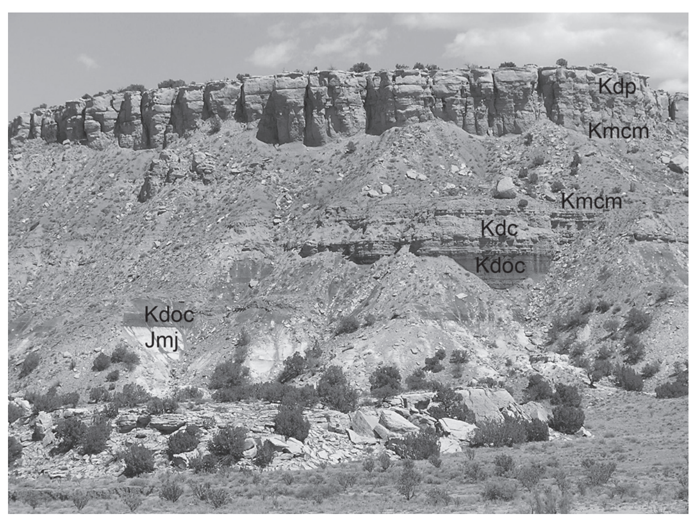

FIGURE 4. Photograph of stratigraphic section exposed on east-facing faceslope of escarpment in Sec. 4, T. 16 N, R. 1 W., approximately 3.8 km south of Chamisa Vega Spring. Abbreviations of stratigraphic units same as on Figures 1, 2, and 3.

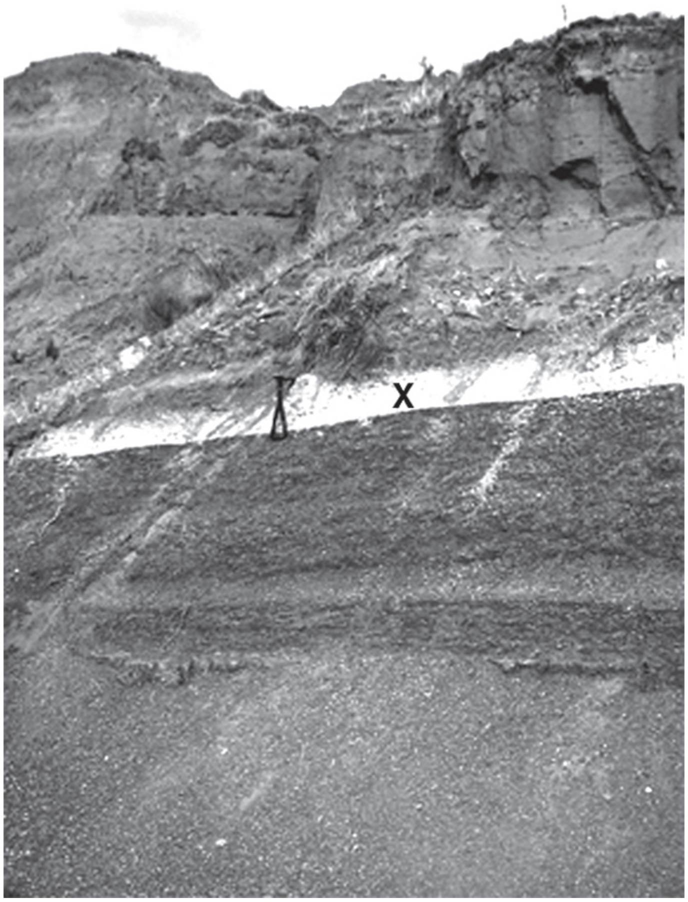

FIGURE 5. Photograph of X bentonite bed in lower part of Whitewater Arroyo Shale Tongue of Mancos Shale in east bank of Rio Salado at Chamisa Vega measured section. Note folding shovel, which is 0.5 m in length. X to right of folding shovel marks X bentonite bed.

Twowells Sandstone Tongue of Dakota Sandstone

In the HGSQ, the Twowells is a highly variable unit, both geographically and lithologically. It is present as three northwest-trending sandstone lenses, one in the north including the HGS section, a second in the middle including the CS section, and a third in the south between the HGS and OS sections (Fig. 3). The north lens is variable internally—it coarsens upward from a gradational very fine-grained to fine-grained shoreface sandstone with abundant *Ophiomorpha* and *Thalassinoides* burrow casts, with some beds having *Skolithos* burrow casts in a middle to upper series of cross-bedded pebbly sandstones. Some calcareous concretions and fossil bivalves are present as well. The middle lens gradually coarsens upward from a silty transition zone with calcareous concretions at the base to a very fine- to fine-grained, bioturbated shoreface sandstone with some *Ophiomorpha* and *Thalassinoides* burrow casts truncated by a marine-flooding surface. The south lens is a thin, fine-grained, bioturbated sandstone. The coarseness of the Twowells in many outcrops is unique among Dakota shoreface sandstones in the San Juan Basin—it probably reflects shallowing and wave erosion at a suspected sequence boundary in the Twowells (Owen et al., 2005, p. 225). The northwest-trending sandstone lenses may be the outcrop edges of sandstone lenses similar to the Twowells lenses in the subsurface described by Head and Owen (2005, figs. 12, 13) that are very productive of natural gas. The northern lens of Twowells Sandstone is the last sandstone in the Twowells interval on the east flank of the San Juan Basin except for the thin Las Jollas bed in a very small area of the southern Chama Basin (Owen et al., 2005, p. 225). Marine shale and siltstone was deposited offshore of the nearshore sandstones in this area to the north.

Graneros Shale Member of Mancos Shale

The Graneros is a tongue of typical gray, marine Mancos Shale in the northern part of the area, much like the Whitewater Arroyo. It cannot be differentiated from the other tongues of Mancos Shale except in the northern area near sections HGS and CV, where the underlying Twowells Sandstone Tongue and the overlying Greenhorn Limestone are present (Fig. 3). Some have used the term Graneros for all of the shale separating whatever is the uppermost Dakota Sandstone bed (Twowells, Paguate, or Cubero) from the Greenhorn, but that usage is not followed here. The Graneros is 27.5 m thick where it was carefully measured at the CV section. It contains at least one recognizable bentonite a few feet below the base of the overlying Greenhorn Limestone throughout most of the San Juan Basin.

Greenhorn Limestone Member of Mancos Shale

The Greenhorn is an excellent marine marker unit of alternating micritic limestone and calcareous shale that can be correlated from the HGSQ all the way to its stratotype near Pueblo, CO. It thins southward across the San Juan Basin toward the HGSQ. The southernmost limestone bed outcrop in the Greenhorn is 0.3 km south of the CV section (Figs. 2, 3). To trace the Greenhorn zone farther south, one must follow calcareous shales or index fossils. In the subsurface, the Greenhorn is a distinct resistive zone above the Graneros Shale, commonly used as a datum for structural contour maps. The calcareous shale can be correlated on logs almost as well as the limestones. Subsurface measurements of Greenhorn thickness always exceed outcrop measurements because the thickness of calcareous shale is included. For example, the Greenhorn is only up to 1.5 m thick on outcrops in the HGSQ, but it is 14.6 m thick in the log of the Candy Butte well, 13 km northwest of section CV (Fig. 6), thereby reducing the thickness of Graneros to only 11.3 m.

Thicknesses of other stratigraphic units marked on the Candy Butte log (Fig. 6) are comparable to outcrop measurements in the HGSQ. Note that the Twowells interval (includes the Whitewater Arroyo Shale) is siltstone and shale with no apparent development of sandstone. The Paguate interval (includes the Clay Mesa Shale) does contain sandstone in the Paguate Sandstone Tongue position (Fig. 6). Stratigraphically lower sandstones are well developed on the log. Note the two coarsening-upward silty parasequences in the Oak Canyon (Fig. 6). Such silty parasequences are typically seen more easily on gamma-ray logs than on outcrops.

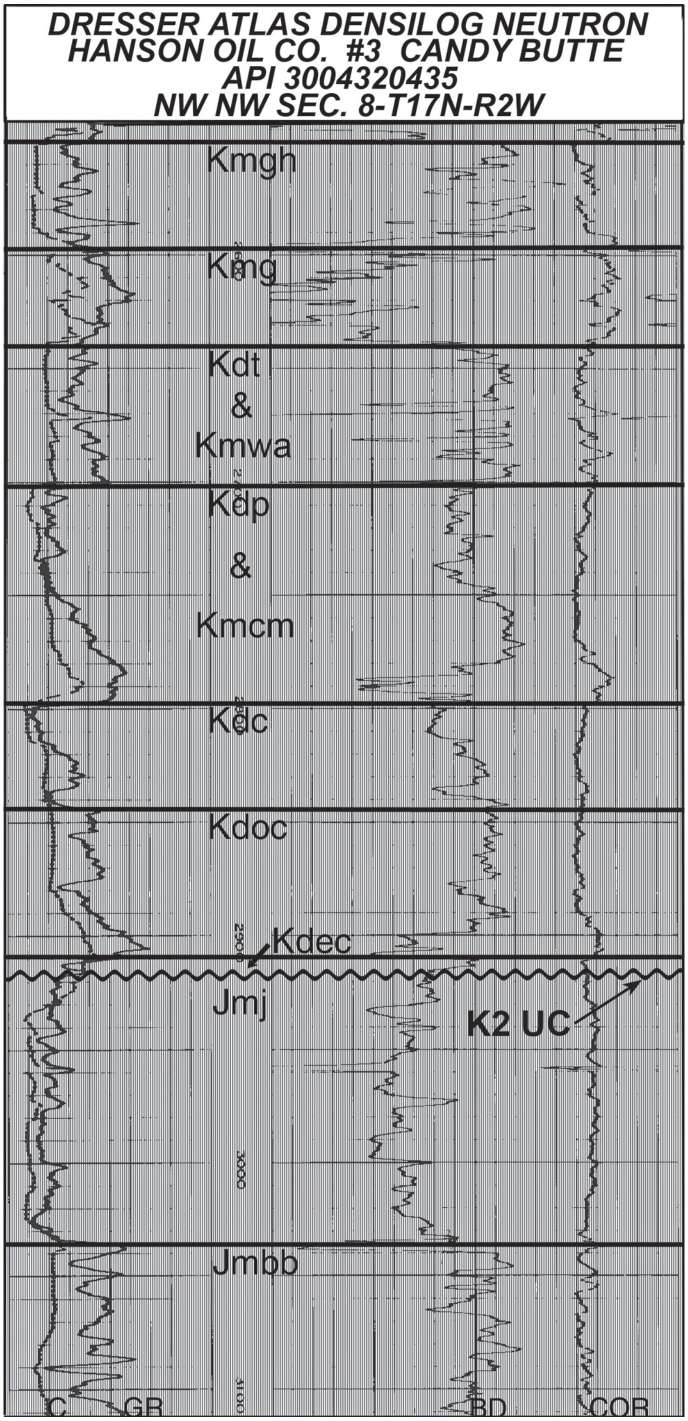

FIGURE 6. Portion of densilog neutron log of Hanson Oil Co. #3 Candy Butte well in NW, NW, Sec. 8, T. 17 N., R. 2 W., Sandoval County, NM. Abbreviations of stratigraphic units same as on Figures 1, 2, and 3. K2 UC = K2 unconformity. C = caliper trace; GR = gamma-ray trace; BD = bulk density trace; COR = correction trace. Depths on log are in feet.

Lower tongue of Mancos Shale (lower part)

The interval between the Greenhorn Limestone Member and the Semilla Sandstone Member of the Mancos Shale is not formally named; accordingly it is referred to informally as the lower tongue of Mancos Shale (lower part) here. The name Carlile Shale, from eastern Colorado, has been used for the interval between the Greenhorn and Juana Lopez by Molenaar et al., (2001), for example, but the original basis for correlation of this unit into the San Juan Basin was age, not lithology, a violation of Article 22e of the North American stratigraphic code (North American Commission on Stratigraphic Nomenclature, 2005), so use of Carlile in the HGSQ is not recognized in this paper. The Greenhorn Limestone is not called Bridge Creek Limestone in this paper for the same reason. This part of the Mancos is only quite locally exposed, mostly the uppermost part under thick parts of the overlying Semilla Sandstone, but consists of typical gray, marine Mancos Shale. It is approximately 67 m thick in the HGSQ.

Semilla Sandstone Member of Mancos Shale

The stratotype for the Semilla Sandstone is on the cliffs just northwest of Holy Ghost Spring (Fig. 1). A detailed study of the Semilla was published by La Fon (1981), who described it as a fossiliferous, marine, coarsening-upward sandstone that formed in an offshore bar environment. It has a lower part of silty, very fine-grained, calcareous concretion-bearing sandstone and an upper part of fine- to medium-grained, cross-bedded sandstone. He mapped what he called the Holy Ghost bar from just south of the highway north to near the OS section (Fig. 1). This is a northwest-trending lens up to 21 m thick, trending like the Twowells lenses, having a mapped length of at least 20 km and a width of 15 km (La Fon, 1981, p. 707). We were able to map this horizon from the Holy Ghost bar southward to Alamito Arroyo (Fig. 2), approximately 1.6 km from the south edge of the HGSQ, by following a thin sandy shale zone marked by concretions.

Lower tongue of Mancos Shale (middle part)

The unnamed interval between the Semilla Sandstone Member and the Juana Lopez Member of the Mancos Shale is referred to informally as the lower tongue of Mancos Shale (middle part) in this paper. This interval is only locally exposed, but consists of typical gray, marine Mancos Shale, approximately 145 m thick in the HGSQ.

Juana Lopez Member of Mancos Shale

The Juana Lopez is a widespread zone of fossiliferous calcareous sandstone marker beds in the Mancos Shale throughout northern New Mexico and the Four Corners area, where it holds up a relatively prominent cuesta. The stratotype is in Santa Fe County, NM, 68 km east of the HGSQ. Many marine fossils have been described from it (Sealey , 2006, and references therein). In the HGSQ, it contains much shale between the thin sandstones and has gradational boundaries and variable thickness, between approximately 3 and 10 m for the main sandy part. Where the thin sandstones are not present, it can be traced by a line of calcareous concretions. It was mapped completely across the area (Figs. 1, 2).

CONCLUSIONS

The Holy Ghost Spring quadrangle is the most important area on the east flank of the San Juan Basin for understanding the complex pinchouts in the intertongued Dakota Sandstone-lower Mancos Shale. The Encinal Canyon Member, Clay Mesa Shale, Paguate Sandstone, Whitewater Arroyo Shale, Twowells Sandstone, Greenhorn Limestone, and Semilla Sandstone all pinch out in the quadrangle. The continuous Jackpile Sandstone, Oak Canyon Member, Cubero Sandstone, and Juana Lopez Member each provide a stratigraphic datum to constrain the pinchouts.

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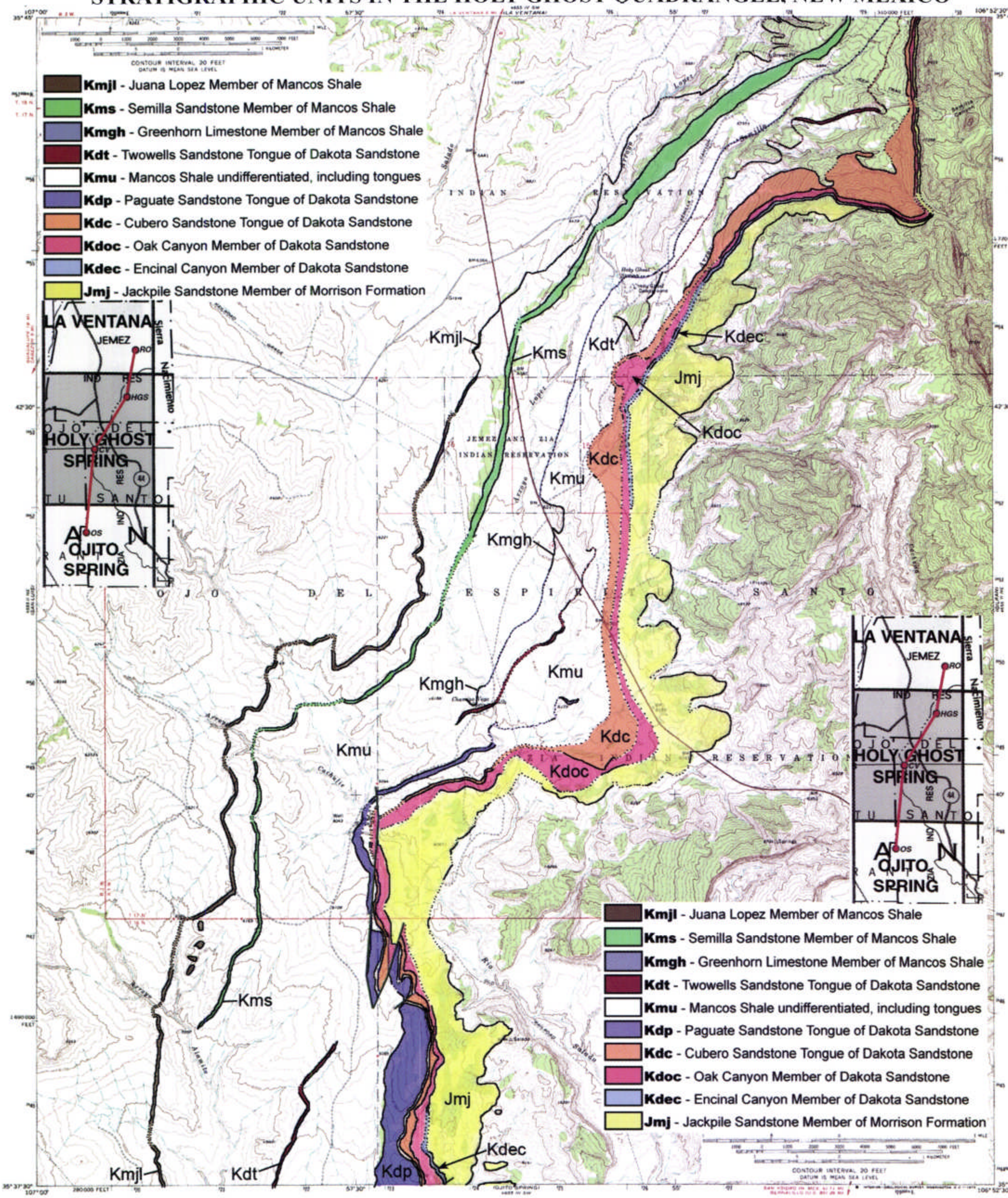
PLATE 9: GEOLOGIC MAP OF THE JACKPILE, DAKOTA, AND MANCOS STRATIGRAPHIC UNITS IN THE HOLY GHOST QUADRANGLE, NEW MEXICO



Geologic map of Jackpile, Dakota, and Mancos stratigraphic units of the Holy Ghost Spring Quadrangle, New Mexico. Jmj, Kdec, Kdoc, and Kdc are all present in the north-striking, steeply dipping, narrow outcrop belt along the Sierra Nacimiento front near the NE corner of the quadrangle. Note line of stratigraphic cross-section (Figure 3) in red on inset index map. RO = Rito Olguin measured section; HGS = Holy Ghost Spring measured section; CV = Chamisa Vega measured section; OS = Ojito Spring measured section. See article by Owen et al. on page 188.