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OIL AND GAS RESOURCES OF THE SAN JUAN BASIN, NEW MEXICO AND COLORADO*

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Abstract—The San Juan Basin of northwestern New Mexico and southwestern Colorado is the second-largest gas basin in the conterminous United States, second in total estimated gas reserves to the Hugoton field of Texas, Oklahoma, and Kansas. The basin is in the Four Corners area, near the common Corners of New Mexico, Arizona, Utah, and Colorado. The major tectonic element of the basin is the monocline bounding the central basin on the east, north, and west sides. The central basin has no southern structural boundary; its southern limit for purposes of this report is drawn roughly along the outcrop of the Pictured Cliffs Sandstone. Outside the monocline, rocks generally dip less steeply toward the basin's structural axis. The San Juan Basin comprises three elements: the central basin, Chaco slope, and Four Corners platform. All of the oil and gas fields discussed herein are within the San Juan Basin and the production statistics for the San Juan Basin are for fields within this area.

The structural axis, or deepest part of the central basin is arcuate and generally trends northwest in the northern part of the basin. Except along the monoclinal rim of the central basin, dips are gentle and range from less than one degree to commonly less than two degrees. Precambrian rocks crop out north of the San Juan Basin on the San Juan uplift, to the east on the Nacimiento uplift, to the south on the Zuni uplift, and to the southwest on the Defiance uplift.

Oil and gas production in the San Juan Basin through 2009 has been from more than 300 fields or reservoirs in New Mexico and Colorado. Most production has come from Upper Cretaceous rocks. Most of the basin's historical gas production has come from stratigraphic traps in Cretaceous fractured-sandstone reservoirs but starting in the late 1970s, Fruitland Formation coal-bed methane production has grown enormously. Cumulative gas production from all San Juan Basin fields (through late 2009) is 42.6 trillion cubic feet of gas (TCFG) with 26 TCFG coming from fractured sandstone reservoirs, 16 TCFG from Fruitland coal beds, and the remainder from smaller oil and gas fields. Cumulative oil production is 381 million barrels of oil (MBO) with 175 MBO coming from Tocito Sandstone fields. This "oil" production includes nearly 100 million barrels of condensate from the basin's three fractured-sandstone, gas-producing reservoirs. Nearly all the fields in the central basin area produce from stratigraphic traps whereas the relatively small oil and gas fields on the Four Corners Platform produce from structural traps. The Fruitland Formation's coal-bed methane is trapped by adsorption of the gas in the coal, and thus is in a category of trap all its own.

STRATIGRAPHY AND GEOLOGIC HISTORY

General discussion

The San Juan Basin of northwest New Mexico and southwest Colorado (Figs. 1, 2) is a Laramide asymmetric structural depression which contains Cambrian, Devonian, Mississippian, Pennsylvanian, Permian, Triassic, Jurassic, Cretaceous, Tertiary, and Quaternary rocks (Fig. 3). The maximum known thickness of sedimentary rocks in the basin was penetrated by the Amoco Production Company Hahn Jessie number 1 well in the SW1/4 sec. 15, T. 33 N., R. 8 W., La Plata County, Colorado. This well was drilled to a total depth of 14,503 ft and penetrated Precambrian rocks at 14,288 ft. This well was drilled to primarily test Pennsylvanian or other Paleozoic strata, but found no commercial hydrocarbons in those rocks. Paleozoic rocks have produced relatively small amounts of oil and gas from structural traps on the Four Corners Platform, but to date all tests of Paleozoic strata in the central basin area (with one exception) have proved to be barren of hydrocarbons, primarily because of the lack of porous or permeable reservoir rock.

Knowledge of the stratigraphy of San Juan Basin rocks is excellent for most of the Cretaceous, fair for the Mesozoic, and poor for the Paleozoic part of the section. This wide range of knowledge results from three factors:

1. Only about a dozen drill holes have penetrated the entire sequence of sedimentary rocks within the nearly 17,000 square-km central basin; the rest of the nearly 40,000 drill holes in the basin have stopped either in the Upper Cretaceous or have barely penetrated the top of the Jurassic.
2. Outcrops of Paleozoic rocks are limited to small areas on the perimeter of the basin. Middle Mesozoic rocks are fairly well exposed and more limited on the east and north sides.
3. All of the sedimentary rocks exhibit facies changes across the basin, and some of the pre-Cretaceous rocks of the same age have been assigned different stratigraphic names in various parts of the basin.

Tertiary rocks (except for the Ojo Alamo Sandstone), although well exposed and penetrated by a large number of wells, are still poorly understood basin wide. The primary reason for this lack of knowledge is that these rocks do not contain significant economic mineral deposits; thus, there has been little economic incentive

**This paper is an updated version of a paper by the same name published by Fassett (1991). The text is slightly modified, oil and gas production numbers have been updated through late 2009, and some new or modified illustrations have been added. New information regarding the enormous Fruitland Formation coal-bed methane play is included and the latest thinking regarding the nature of the fractured-sandstone- reservoir traps in the basin is discussed.*

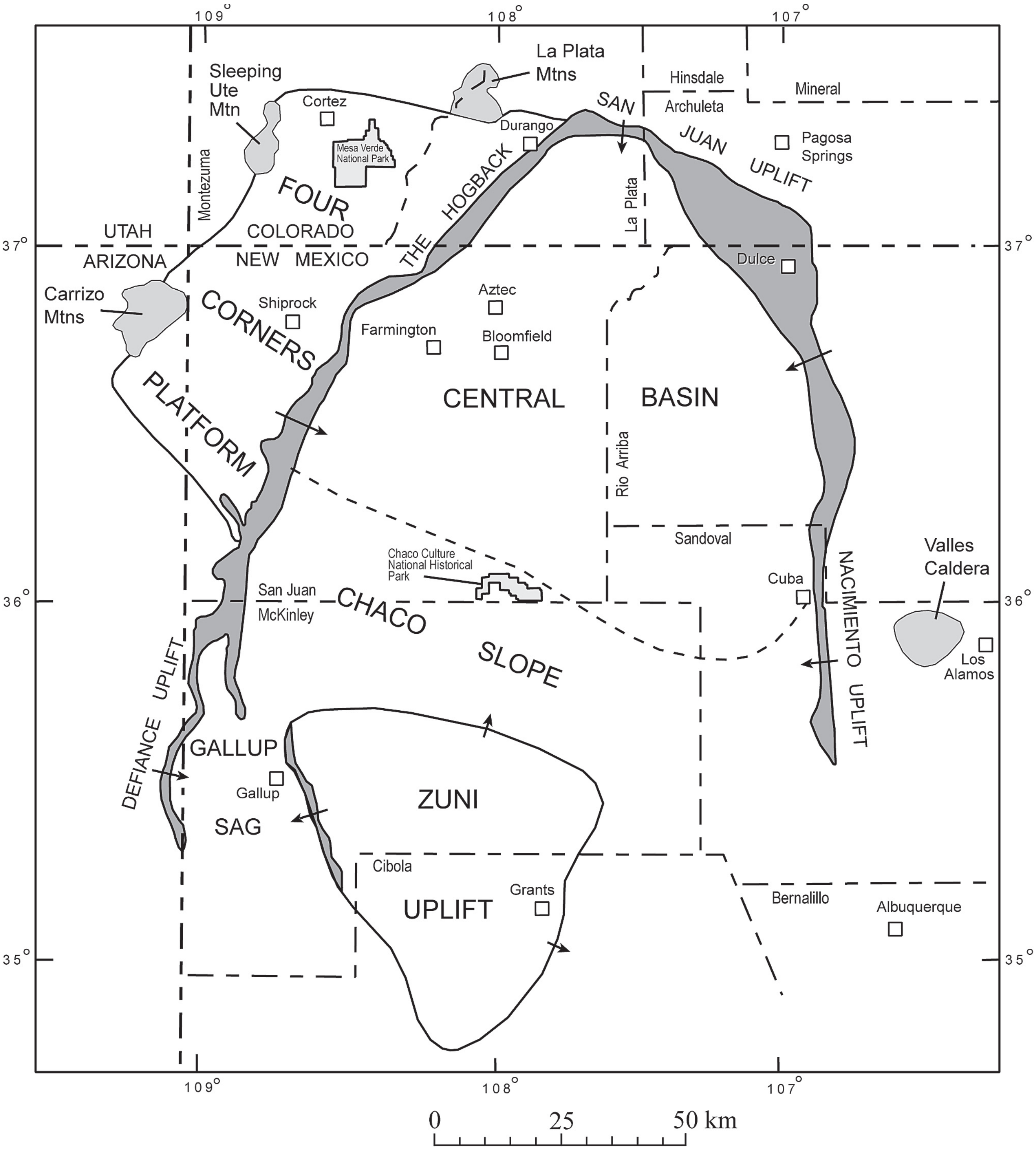

FIGURE 1. Index map showing the geographic and structural setting of the San Juan Basin. Structural elements were generalized from a structure map of the basin area by Thaden and Zech (1984). Areas of steeper dip (monoclines) are patterned; arrows indicate the direction of dip. The dashed line separating the central basin from the Chaco slope is drawn approximately along the outcrop of the Pictured Cliffs Sandstone.

to study them in detail. In addition, the rocks have not been consistently differentiated in the subsurface of the central basin area because their formation boundaries are difficult to locate on geophysical logs.

Paleozoic rocks (Fig. 3) in the San Juan Basin consist of Cambrian, quartzite; Devonian, limestone, dolomite, black shale, and glauconitic sandstone; Mississippian, principally limestone; Pennsylvanian, limestone, black shale, and sandstone; and Permian, mostly continental sandstone. These rocks are discussed by Armstrong and Mamet (1977), Baars and Stevenson (1977), Jentgen (1977), Stevenson and Baars (1977), Fassett (1983b), Stevenson (l983a, 1983b), and Huffman (1989).

Triassic rocks in the basin consist of continental sandstone, siltstone, and mudstone facies (O'Sullivan, 1977). Jurassic rocks

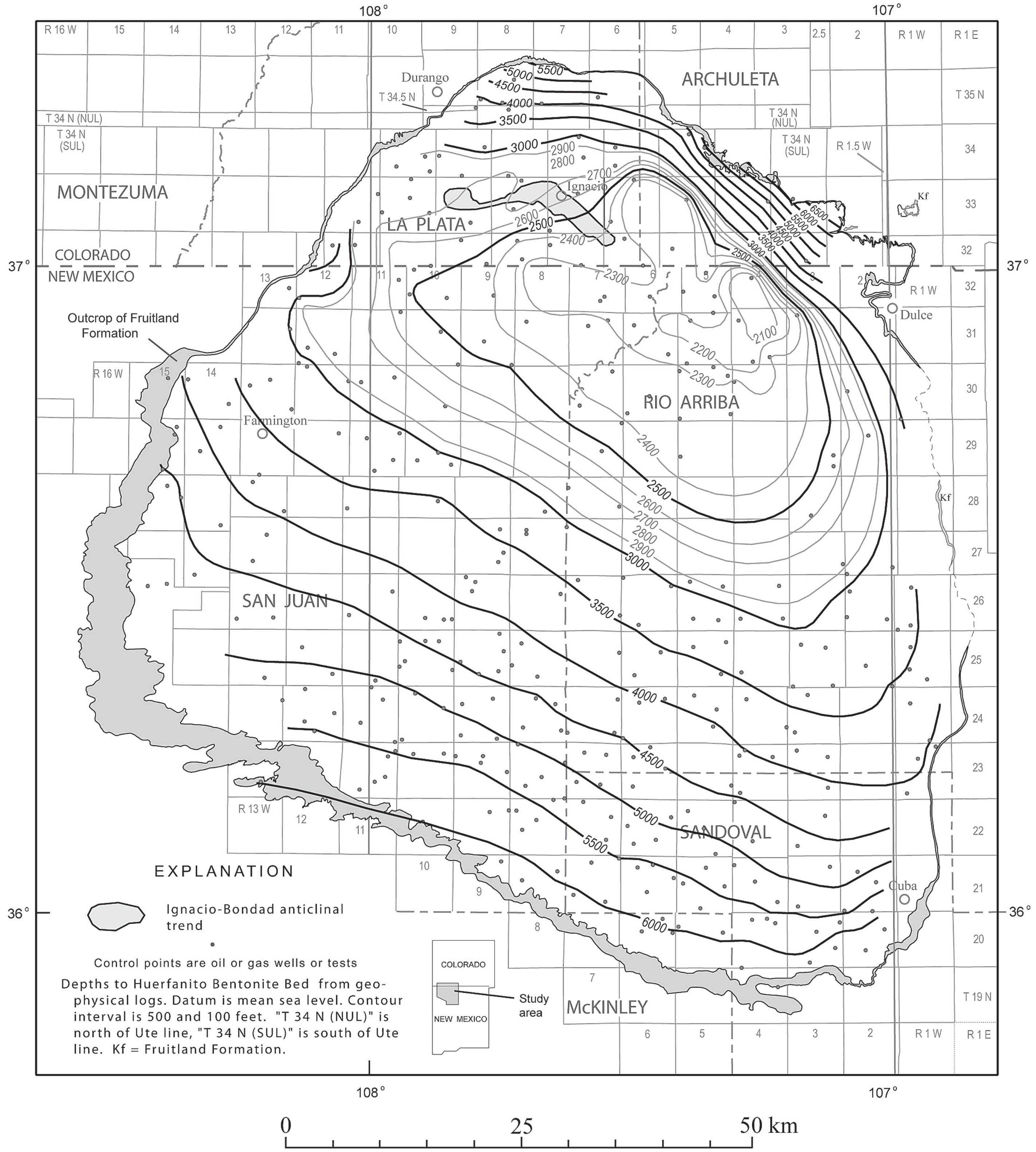

FIGURE 2. Structure contour map of the central San Juan Basin. Contours (in feet; 3.28 ft equal 1 m) are on the Huerfanito Bentonite Bed (Fig. 3) of the Lewis Shale, contour interval is 400 ft, datum is mean sea level. (Modified from Fassett and Hinds, 1971.)

consist of a variety of continental mudstone, siltstone, and sandstone beds, and marine limestone and anhydrite deposits. These rocks were discussed by Condon and Peterson (1986), Condon and Huffman (1988), and in other papers in Turner-Peterson and others (1986).

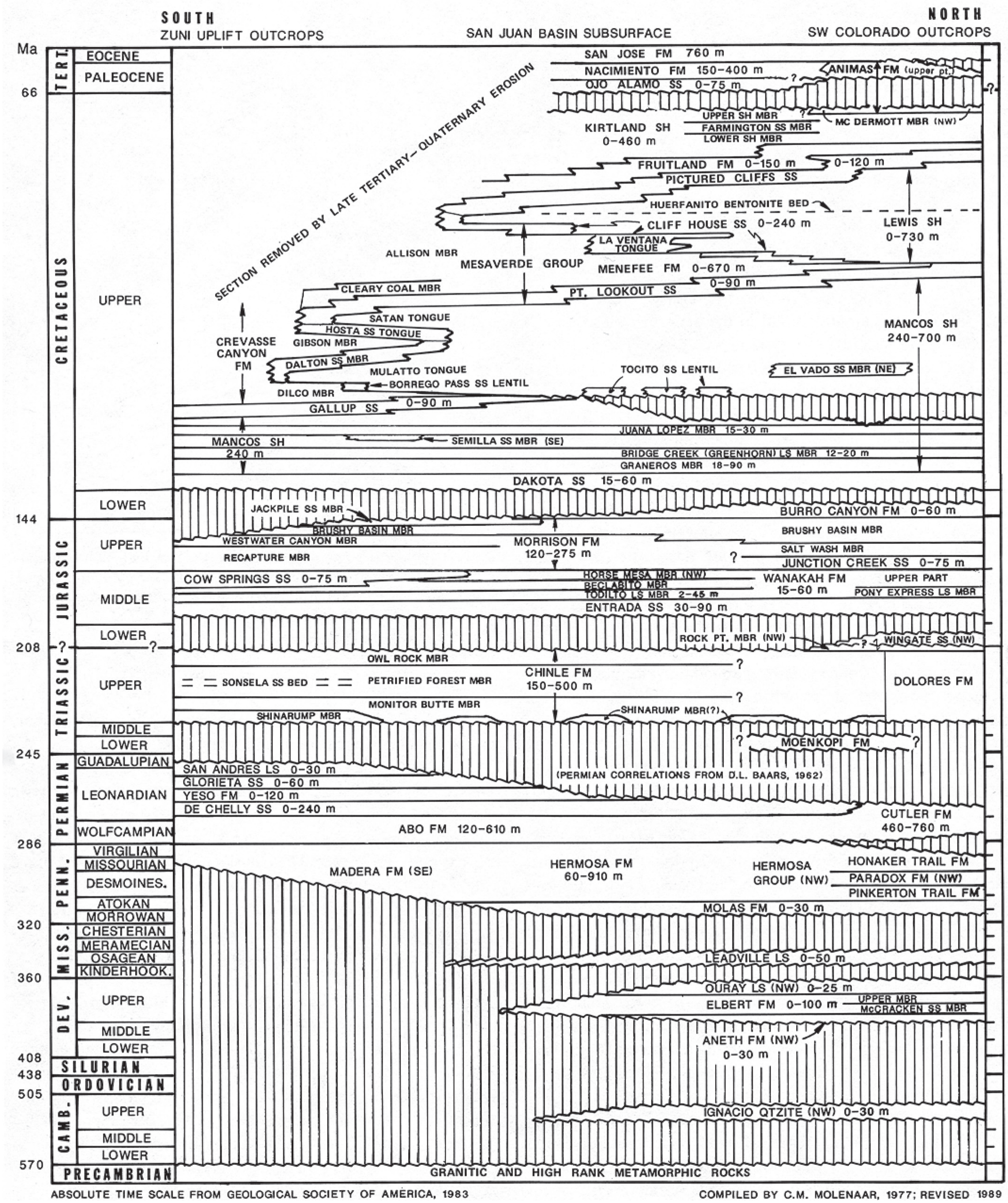

FIGURE 3. Correlation chart of sedimentary rocks in the San Juan Basin (modified from Molenaar, 1989).

Cretaceous rocks

The Lower Cretaceous Burro Canyon Formation overlies Jurassic rocks (Morrison Formation) in the northern San Juan Basin. Although the age of the lower part of the formation has not been determined, Craig (1981, p. 200) wrote that "it seems possible that [the Burro Canyon] represent[s] much of Early Cretaceous time." Craig further stated that deposition of the Burro Canyon appeared "to represent a continuation of Morrison deposition" although Burro Canyon deposition "may reflect a distinct period of uplift in the source areas and may have been accompanied by slight increase in gradients across the depositional plain." The Burro Canyon is conglomeratic sandstone, especially at its base, and was probably deposited by north flowing braided streams (Ridgley, 1977; Craig, 1981). Harr (1988, fig. 6) showed the expression of the Burro Canyon on a geophysical log in the northern (Colorado) part of the San Juan Basin and stated that the unit ranges from 0 to more than 30 m thick. The Burro Canyon thins southward across the basin and is not present in the southern part.

The Upper Cretaceous rocks of the San Juan Basin range from 0 to 1,800 m thick and consist of a series of alternating continental and marine rocks (Plate 3). These rocks represent a remarkably complete record of a series of transgressions and regressions of the western shoreline of the Western Interior seaway across the San Juan Basin area. Indeed, it was these rocks that provided the first model for transgressive and regressive shore-face deposits described in the now-classic paper by Sears and others (1941). That model, simply stated, supposed a continuously subsiding trough receiving clastic sediment at a varying rate from a southwestern source area. A high rate of sediment influx resulted in an outbuilding of the shoreline to the northeast (shoreline regression), and a low rate of sediment influx resulted in landward advance of the shoreline to the southwest (shoreline transgression). This engine operated for about 25 m.y. with streams bringing sediment into the basin area from the southwest and the northwest-trending shoreline rhythmically shifting back and forth across the basin area in response to the varying rates of sediment supply (Plate 3).

Many studies of the stratigraphy and depositional history of Upper Cretaceous rocks in the San Juan Basin have been published; therefore, a detailed exposition on those subjects is not included in this chapter. Some of the more relevant publications include: Fassett and Hinds (1971), Fassett (1976, 1977, 1978b, 1983b), Peterson and Kirk (1977), Molenaar (1977, 1983, 1988), Huffman (1989), Fassett (2000), and Fassett and Boyce (2005). Discussions of the geometry and lithology of Cretaceous and older, oil- and gas-bearing rocks are included in the "Oil and gas" section of this paper.

Tertiary rocks and structural evolution of the San Juan Basin

The following discussion is almost entirely from Fassett (1985, 2000). In latest Cretaceous time, and probably continuing into earliest Paleocene time, the San Juan Basin area was uplifted and tilted toward the northwest, resulting in widespread erosion and removal of as much as 650 m of Upper Cretaceous rock in the east-central part. Following this erosional episode, the basin area again began to subside and collect sediment. This time, however, the sediment source was from the north, a radical change from the southwest source during nearly all of Late Cretaceous time. The first unit deposited in Paleocene time was the Ojo Alamo Sandstone. The Ojo Alamo is a complex unit consisting of stacked multiple layers of sandstone, conglomeratic sandstone, and mudstone. The sandstone beds are poorly sorted, medium- to very coarse-grained quartzose sandstone. On the northwest side of the basin, conglomeratic sandstone is abundant; conglomerates are rare to nonexistent on the eastern side. The Ojo Alamo represents a braided fluvial-sandstone complex; the sandstone and conglomerate beds were deposited in river channels, and the mudstone interbeds represent overbank deposits. Streams in Ojo Alamo time flowed southeast (Powell, 1973) or south (Sikkink, 1986) in response to the first major pulse of Tertiary Laramide uplift in the San Juan and La Plata Mountain areas in southern Colorado.

The Ojo Alamo ranges from 0 to 150 m thick and covers all except the northern part of the central basin where it was eroded as the result of an early pulse of uplift there. The Ojo Alamo is early Paleocene in age and may be time-transgressive, becoming slightly younger eastward across the basin. The structural San Juan Basin had still not begun to form in Ojo Alamo time.

Conformably overlying the Ojo Alamo Sandstone in the southern part of the basin and unconformably overlying the Cretaceous Kirtland Shale in the northern part are the Animas and Nacimiento Formations of early Paleocene age. The Animas is present only in the northern part of the basin and grades southward into the laterally equivalent Nacimiento Formation. The Animas is a coarse-grained to conglomeratic sandstone containing abundant volcaniclastic rock fragments, especially in the north. The boundary between the Animas and Nacimiento Formations is drawn at the southern limit of conglomerates and macroscopic volcaniclastic rock fragments in the Animas. The Nacimiento Formation consists of interbedded mudstone, claystone, and sandstone beds, with sandstone generally becoming less abundant southward.

These rock units were deposited in early Paleocene time as a result of widespread volcanic eruptions in the San Juan volcanic center, northeast of the San Juan Basin. These eruptions produced a rapid influx of volcaniclastic material into the northern part of the basin, forming what is now the Animas Formation. Southward, the Nacimiento Formation was probably deposited by the same south-flowing streams that deposited the Animas to the north. Deposition of the 825-m-thick Animas Formation in the northern San Juan Basin area probably partly reflected subsidence on the south flank of the San Juan Mountains eruptive center and the beginning of the formation of the structural San Juan Basin.

Following deposition of the Paleocene Nacimiento and Animas Formations, subsidence of the basin ceased for as much as 7 m.y., as evidenced by extrapolation of a Nacimiento $^{40}Ar/^{39}Ar$ ash-bed age in the Nacimiento Formation in the southeast part of the basin (Fassett et al., 2010, this guidebook). The basin area again began to subside in early Eocene time, allowing deposition of the mostly fluvial San Jose Formation across the basin area. The San

Jose is more than 600 m thick in the northern part of the basin and consists of interbedded sandstone, siltstone, mudstone, and claystone beds. The San Jose was also deposited by mostly south-flowing streams, but some sediment influx may have come from the rising Nacimiento uplift to the east. The youngest San Jose in the basin is late early to early middle Eocene in age (Smith and others, 1985) based on mammal fossils.

The basin was continuing to subside into middle Eocene time, as evidenced by tilted San Jose rocks around the north and east sides of the basin. On the west side of the basin the Chuska Sandstone is preserved in a northwest-trending area straddling the New Mexico-Arizona border in the Chuska and Lukachukai Mountains (see fig. 1 of Fassett, et al., 2010, this guidebook). The Chuska outcrop is southwest of the Four Corners platform; its southeastern-most part barely extends into the western part of the Chaco slope. The Chuska is essentially flat-lying on an erosion surface that truncates rocks that dip eastward into the San Juan Basin. It reaches a thickness of more than 600 m and consists of a lower fluvial unit of conglomerate, sandstone, and mudstone and an upper massive unit of eolian sandstone containing layered volcanic ash beds. Thus, it seems clear that the San Juan Basin had ceased to subside, an episode of uplift and erosion followed, and finally the Chuska and equivalent rocks filled and overstepped the structural San Juan Basin.

The following is from Fassett, et al. (2010, p. 148, this guidebook):

> The ages for two altered volcanic ash beds from within the Chuska Sandstone were recently published by Cather, et al. (2003). An age of 34.75 ± 0.20 Ma was obtained from an ash bed in the lower Deza Member of the Chuska and an age of 33.31 ± 0.25 Ma was obtained for an ash bed in the upper Narbona Pass Member of the Chuska Sandstone. Of these two ages, Cather et al. suggested that the older age is the more precise of the two. These ages place the Chuska Sandstone in the uppermost Eocene-lowermost Oligocene according to Gradstein et al. (2004) who place this boundary at 33.9 Ma. Four samples of extrusive trachybasalts that overlie and post-date the Chuska in this area have yielded ages, according to these authors, ranging from 24.83 to 25.24 Ma with a weighted mean age of 25.05 ± 0.16 Ma.

Following deposition of the Chuska Sandstone and overlying volcanics, an extended period of erosion occurred leaving behind the Chuska Sandstone remnant that we see today. A period of aggradation occurred next, filling, or partially filling the San Juan Basin resulting in deposition of an unknown thickness of alluvial material over most of the present basin area. This alluvial material is now being eroded away revealing the buried paleo-topography that existed prior to deposition of this alluvial fill.

OIL AND GAS

Stratigraphic nomenclature

Any discussion of oil and gas production in the San Juan Basin must be prefaced with a few words about the nomenclature of the producing rocks. The nomenclature is confusing because rather arbitrary designations and definitions were given to many of the producing rock intervals in the basin by the New Mexico Energy and Minerals Division before most of the detailed stratigraphic work on these rock units had been completed. These definitions do not always coincide with formal stratigraphic nomenclature conventions as prescribed by the North American Commission on Stratigraphic Nomenclature. A detailed discussion of this subject is beyond the scope of this paper; however, it is comprehensively discussed in Fassett (l978b, 1983b). Here the rock units are discussed in terms of their formally accepted rock-stratigraphic names, unless otherwise noted.

History

The following history of oil and gas development in the basin is abstracted from Dugan (1977), Matheny and Ulrich (1983), Matheny and Talley (1983), and Dugan and Williams (1988). The first well-documented oil discovery in the San Juan Basin, and in New Mexico, was made in 1911 at the Seven Lakes field in the south-central part of the Chaco slope in a well drilled for water. The well produced about 12 barrels of oil (BO) per day from the Menefee Formation at a depth of about 100 m. The first discovery of gas in the basin was made in October 1921, in a well about 1.6 km south of Aztec, New Mexico. The well was completed in the Farmington Sandstone Member of the Kirtland Shale (Plate 3) at a depth of about 300 m, and a pipeline was built to Aztec, NM where the first natural gas in New Mexico was marketed. (It is ironic that oil and gas production from the rock units that produced these first discoveries today represents but a tiny fraction of a percent of the total oil and gas production from the San Juan Basin.)

In September 1922, oil was discovered in the Dakota Sandstone (Hogback field) at a depth of 245 m on the Four Corners platform, about 32 km west of Farmington (Fig. 4). This discovery triggered a flurry of exploration that continued throughout the 1920s. During this period, many of the surface structures on the Four Corners platform were drilled and found productive from Paleozoic and Cretaceous rocks. During this same era, gas was discovered in the central basin in the Pictured Cliffs Sandstone and the Mesaverde Group. In 1930, the first pipelines out of the basin were built to Albuquerque and Santa Fe, providing a greatly expanded market for San Juan Basin gas.

Over the next 20 years, modest development of oil and gas continued in the basin. The major discoveries during this period were two large Pennsylvanian gas fields on anticlinal structures on the Four Corners platform: the Barker dome and Ute dome fields (Fig. 4). These discoveries, plus the continuing gas discoveries in the Upper Cretaceous shore-face sandstone beds in the central basin, spurred interest in expanding the market for San Juan Basin gas even wider; in 1951, a 24-in pipeline to California was completed. With an outlet for large volumes of gas now available, the great drilling boom of the 1950s began, resulting in delineation of the three major gas-producing sandstone units in the central basin: the Dakota Sandstone, Mesaverde Group, and the Pictured Cliffs Sandstone. During this decade, the two larg-

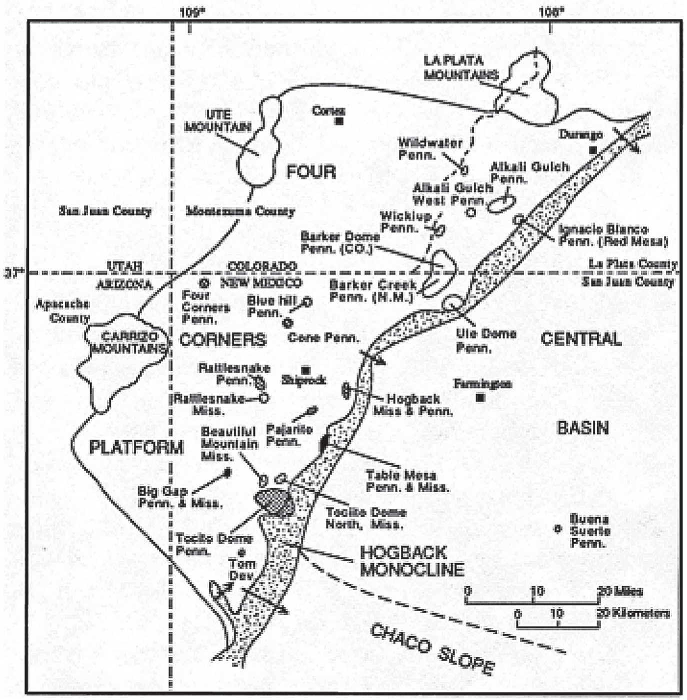

FIGURE 4. Map showing Paleozoic oil and gas fields on the Four Corners platform in the San Juan Basin. New Mexico and Colorado recognize 28 Paleozoic fields. Only 22 named fields are shown because some fields contain more than one named reservoir or pool within a named field. Oil fields are shown crosshatched, gas fields are white, and oil and gas fields are black. Producing systems are abbreviated: Dev. = Devonian, Miss. = Mississippian, and Penn. = Pennsylvanian.

est oil fields to produce from the Tocito Sandstone Lentil of the Mancos Shale were discovered: the Bisti and Horseshoe fields.

Since the 1960s, drilling in the basin has fluctuated, controlled by local events, such as changes in spacing orders, and global events, such as changes in prices for oil and gas, resulting from both political and supply-and-demand influences. No new large discoveries were made during this time until quite recently, when the large coal-bed methane resources in the Fruitland Formation were recognized. The rate of drilling for Fruitland gas accelerated rapidly in the 1980s and 1990s but is now leveling off with nearly 8000 Fruitland coal-bed methane wells now producing.

Oil and gas production

Detailed papers on each of the oil and gas fields in the basin known through 1978 are in Fassett (1978a, 1983a). Those volumes also contain papers on the geologic history and stratigraphy of the producing rocks, and the oil and gas production history of the Four Corners region. The paper by Fassett on the San Juan Basin (1983b) is especially relevant. The major significant discovery in the basin since the 1978 and 1983 papers has been the Fruitland Formation coal-bed methane play, mentioned above.

Oil and gas have been produced from more than 300 fields in the San Juan Basin. These fields produce (or have produced) from Devonian, Mississippian, Pennsylvanian, Jurassic, Cretaceous, and Tertiary rocks. New Mexico uses the term "pools" for producing reservoirs; Colorado uses the term "reservoirs." In this paper, I refer to producing reservoirs or pools as "fields." Cretaceous rocks have produced 93 percent of the oil and 99 percent of the gas in the San Juan Basin and most of the fields produce from Cretaceous rocks. (Production numbers included in this report are through late 2009.) Colorado has produced 7.7 trillion cubic feet of gas (TCFG) and 9.7 million barrels of oil (MBO) whereas New Mexico has produced 34.9 TCF of gas and 371 MBO. The total number of productive wells in the basin was 39,363; 3932 in Colorado and 35,431 in New Mexico. New Mexico has produced 78 percent of the gas and 99 percent of the oil from the San Juan Basin.

Oil-production totals for the basin include both oil from oil wells and condensate and oil from gas wells. It should be noted that New Mexico refers to all liquid hydrocarbon production from gas wells as "oil." Most of these liquids were gas-condensate; however, a small amount was oil.

Natural-gas production in the San Juan Basin comes mostly from four Cretaceous formations: the Dakota Sandstone, the Mesaverde Group, the Pictured Cliffs Sandstone, and the Fruitland Formation. Most of the gas produced from the Mesaverde Group has come from the Point Lookout Sandstone (Plate 3). The Dakota Sandstone has produced 7 trillion cubic feet of gas (TCFG), the Mesaverde Group has produced 12.9 TCFG, the Pictured Cliffs Sandstone has produced 4.5 TCFG, and the Fruitland Formation has produced 15.7 TCFG. A fifth producing interval, the Chacra Sandstone, has produced 0.3 TCFG.

Most gas-condensate production has come from the Dakota and the Point Lookout Sandstones. The Dakota has produced 49.6 million barrels of condensate (MBC), the Mesaverde Group has produced 47.3 MBC, and the Pictured Cliffs Sandstone has produced 1.2 MBC for a total of 98.1 MBC.

The highest percentage of true oil produced in the basin has come from the Tocito Sandstone Lentil and fractured-Mancos-Shale reservoirs (Plate 3). Together, these rocks have produced 204.3(MBO) of the 283 MBO recovered from oil fields in the basin. This production is from more than 70 fields. The two largest fields, the Bisti and the Horseshoe Gallup, have produced 74.7 MBO. The only statistically significant hydrocarbon production from non-Cretaceous rocks in the San Juan Basin is the 14-MBO production from the Pennsylvanian system; 13.5 MBO of this is from the Tocito Dome field (Fig. 4).

Non-Cretaceous fields

Oil and gas have been produced from Paleozoic rocks in ~30 fields in the San Juan Basin; more than half of these are gas fields (Fig. 4). With one exception, all of these fields are on the Four Corners platform. One field produced from the Devonian, 5 from the Mississippian, and the rest from the Pennsylvanian; 2 of the Pennsylvanian fields also produced minor amounts of oil or gas from Mississippian rocks. The Devonian field produced oil from a sandstone reservoir on an anticlinal structure; the Mississippian fields produced nonflammable, high-nitrogen, helium-bearing gas and a small amount of oil from porous limestone and dolomite beds on anticlines; and the Pennsylvanian rocks produced from carbonate beds containing zones of porosity developed within algal mounds (sometimes referred to as “carbonate build-ups”) mostly on structural features. A few Pennsylvanian fields produced from stratigraphic traps. Devonian and Mississippian production is confined to the southwestern part of the Paleozoic productive trend on the Four Corners platform.

Pennsylvanian rocks produce only gas in the northeastern part of the Four Corners platform where they increase in depth crossing from the oil into the gas window. These rocks produce both oil and gas in the southwestern part of the platform (Fig. 4). In the northeastern part of the platform, some zones in the Pennsylvanian produce sulfur-rich gas; H_2S from those zones ranges from 1 to more than 12 percent. Some of these Pennsylvanian wells also produce gas containing as much as 21 percent $C0_2$.

Most of the Paleozoic fields on the Four Corners platform are aligned in a northeast-trending band that parallels the Hogback monocline (Fig. 4). The structural features on the platform were probably created during the time the structural basin was forming, from middle to late Paleocene time and continuing into early Oligocene time (Fassett, 1985). The lone Paleozoic field (Buena Suerte, Fig. 4) within the central basin produced oil from Pennsylvanian rocks at a depth of 3,350 m. This one-well field is about 65 km east of the Four Corners platform and is reported to have produced over 5,000 BO. Oil production from this field is enigmatic because Pennsylvanian rocks are well below the oil window at this depth.

Paleozoic fields on the Four Corners platform generally become deeper from southwest to northeast; depths to producing zones range from 1,220 m to 3,050 m. All of the gas-producing fields in the northeastern part of the platform produce from depths in excess of 2,320 m; the oil fields to the southwest produce from depths less than 2,320 m.

Ten named and four undesignated oil fields produce from the Entrada Sandstone of Jurassic age. All but one of these fields are in the southeastern part of the basin in a 70-km-long, northwest-trending belt (Fig. 5). Production is from the eolian sandstone facies (upper part) of the Entrada. All of the Entrada fields produce from stratigraphic traps, with closure reported to be from relict sub aerial dune topography (Vincelette and Chittum, 1981); they suggested that the oil is trapped in the dune crests. The seal for the traps is the overlying Todilto Limestone Member of the Wanakah Formation. The thickness of the Todilto has an inverse relation to the Entrada paleo-topography; it thins over the Entrada highs and thickens over the Entrada lows. The Todilto, which is a fetid, organic-rich limestone and anhydrite deposit, is also thought to be the source rock for the Entrada oil. One of the fields (Media) is on a surface structural nose.

All of the Entrada fields are semicircular with a slightly longer north-to-northeast dimension. Vincelette and Chittum (1981, Fig. 16, p. 2558) presented a map of Entrada seismic anomalies in the southeastern San Juan Basin and stated that it showed a strong northeast trend to the “Entrada sand thicks or topographic highs.”

All of the fields have similar reservoir characteristics, with an average porosity of about 23 percent and permeability of about 300 millidarcies. The oil has a 29° to 36° API gravity and high pour point (50° to 90°F) that seasonally necessitates the use of insulated production equipment The amount of water produced with the oil has increased to 50 percent in a few months in all fields and to 95 percent or more after a year of production. Disposal of this water has been a problem. The total production from the Entrada in the basin is 6 MBO. Three Entrada fields-Eagle Mesa, Media, and Papers Wash-have produced three-fourths of the total Entrada production in the basin, from 1 to 1.5 MBO each. The number of productive wells in each field ranges from 1 to 6.

A few wells have produced natural gas from the Brushy Basin Member of the Morrison Formation in the Ignacio Blanco field in the northern part of the central basin in Colorado and in the Red Mesa field on the Four Corners platform in Colorado. According to Harr (1988), this production comes from fluvial channel sandstone beds. All of these wells are reported as Dakota-Morrison producers by the Colorado Oil and Gas Commission; thus, Morrison gas production cannot be quantified. A small amount of oil has been produced from the Morrison Formation in the Red Mesa field.

Cretaceous fields

Upper Cretaceous sandstone beds and silty to sandy mudstone beds are the primary producers of oil and gas in the San Juan Basin. Coal beds in the Fruitland Formation have produced large amounts of gas. Upper Cretaceous production has come from more than 250 fields. Historically, most of the natural gas was produced from the Dakota, Point Lookout, and Pictured Cliffs Sandstones. More than 80 percent of this gas comes from three New Mexico fields: Basin Dakota, Blanco Mesaverde, and Blanco Pictured Cliffs South. Fruitland Formation coal beds have become an increasingly large source of gas in the basin since the late 1970s. Most of the Cretaceous oil comes from the shelf-sandstone lenses of the Tocito Sandstone Lentil of the Mancos Shale (designated “Gallup” producing interval by New Mexico and Colorado) and from fractured shale reservoirs in the El Vado Sandstone Member of the Mancos. (New Mexico has classified some El Vado fields as “Mancos” fields and some as “Gallup” fields; Colorado calls them all “Gallup” fields). Most of this production has come from the central basin area; a few, relatively small fields produce Cretaceous oil from structural traps outside the central basin on the Chaco slope and on the Four Corners platform (Figs. 1 and 5).

Oil fields

The following oil-field names and the numbers of oil fields are from Fassett (1991). Many of these oil fields are now depleted or nearing depletion. Field production data are through late 2009. Most of the Upper Cretaceous oil (not including condensate) produced in the San Juan Basin has come from reservoirs within the lower part of the Upper Cretaceous section. Figure 5 shows the locations of these fields. Most oil production from this part of the section was from the Dakota Sandstone (39 fields), Gallup

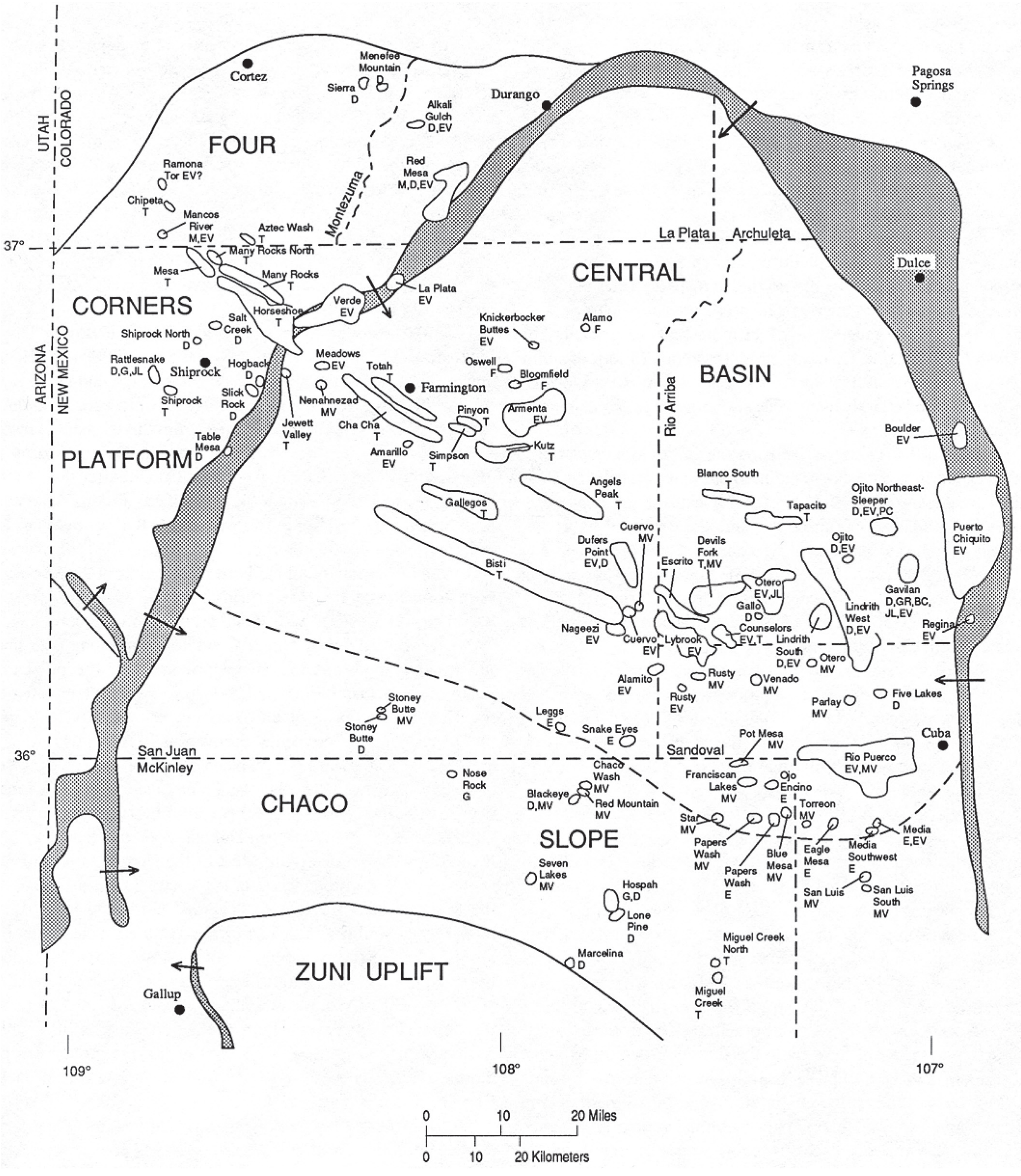

FIGURE 5. Map showing Jurassic and Cretaceous oil fields in the San Juan Basin. Undesignated New Mexico fields are not shown. Some fields produce from more than one formation and thus contain more than one designated pool or reservoir. Field names in New Mexico and Colorado always include the name of the producing interval, e.g., "Horseshoe Gallup" field. On this map, the names of the producing intervals are not included in the field names due to space limitations. Producing formations for each field are indicated by the following abbreviations: E, Entrada Sandstone; D, Dakota Sandstone; M, Mancos Shale; GR, Graneros Shale; BC, Bridge Creek Limestone Member of the Mancos Shale (formerly Greenhorn Limestone Member); JL, Juana Lopez Member of the Mancos Shale; G, Gallup Sandstone; T, Tocito Sandstone Lentil of the Mancos Shale; EV, El Vado Sandstone Member of the Mancos Shale; MV, Mesaverde Group; PC, Pictured Cliffs Sandstone; F, Farmington Sandstone Member of the Kirtland Shale.

Sandstone (6 fields), Tocito Sandstone Lentil (30 fields), and the El Vado Sandstone Member of the Mancos Shale (39 fields). About 10 percent of the oil has come from Dakota fields, 10 percent from Gallup fields, and 80 percent from Tocito and EI Vado fields. The source rock for this oil was most certainly the very black, organic-rich, lower Mancos marine shales. For a discussion of correlation of San Juan Basin oils to source rock, see Ross (1980).

The 39 Dakota Sandstone oil fields include structural and stratigraphic traps on the south flank of the basin, and structural traps on the Four Corners platform (Fig. 5). The Hogback, Rattlesnake, and Table Mesa fields are the largest Dakota fields on the Four Corners platform, having produced 5.8, 4.8, and 1.4 MBO, respectively. In the central basin, the largest Dakota producers are the Lindrith West (23.9 MBO) and Lindrith South (5.1 MBO) fields. Oil from these fields represents commingled production from the EI Vado Sandstone Member of the Mancos Shale (designated "Gallup" by the state of New Mexico) and the Dakota Sandstone; thus, Dakota production from this field cannot be precisely quantified. The Chacon field, which was merged with the Lindrith West field in 1984, had produced 3.2 MBO from the Dakota through 1983. At that time the Lindrith West field had produced 3.7 MBO from the Dakota and the EI Vado. On the Chaco slope, Dakota oil has been produced from the Lone Pine field (2.6 MBO) and the Hospah field (0.2 MBO). The largest Dakota oil field in the Colorado part of the basin is the Red Mesa field; it is on the Four Corners platform and has produced a little more than 1.4 MBO.

Four Gallup Sandstone fields produce oil on the Chaco slope (Fig. 5). On the Hospah structure (faulted anticline), the Hospah field has produced 8.6 MBO and the Hospah South field has produced 14.4 MBO. The Marcelina field on a faulted anticlinal nose has produced 61,000 BO and the Nose Rock field on the up-dip end of a paleo-stream-channel meander on a structural nose (Bruce Black, personal communication, 1989) has produced 66,000 BO. All of these fields apparently produce from the Torrivio Sandstone Member of the Gallup Sandstone. The Torrivio is a fine- to coarse-grained fluvial sandstone facies of the mostly marine to marginal marine Gallup sandstone and is the upper part of the Gallup. The Gallup Sandstone in the Chaco slope oil fields has porosities of 25 percent and greater, and permeabilities in the hundreds of millidarcies (Luce, 1978a, b; Bircher, 1978; Edmister, 1983). One Gallup field produces from the Rattlesnake anticline (Matheny, 1983) on the Four Corners platform.

Tocito Sandstone oil production has come from 30 fields in a northwest-trending, slightly arcuate band across the southern part of the central basin and onto the Four Corners platform (Fig. 5). The Tocito has produced more than 150 MBO. Tocito fields are stratigraphic traps consisting of shelf-sandstone lenses enclosed in marine shale. Most of these fields are within the central basin. Three New Mexico fields, the Many Rocks, Many Rocks North, and Mesa fields, are on the Four Corners platform. The Horseshoe field is mostly on the Four Corners platform, but its southeast end is draped over the northwestern monoclinal rim of the basin (Fig. 5). Trapping of the oil in these fields is both structural and stratigraphic (Matheny, 1978a). In Colorado, the Aztec Wash, Ramona, and Chipeta fields produce Tocito oil from sandstone lenses on the Four Corners platform.

Tocito sandstone beds are generally the best Cretaceous reservoir rocks in the central basin; they range from fine to coarse grained with porosities averaging around 15 percent and permeabilities ranging from 25 to well over 100 millidarcies. Many fields produce from two and sometimes three stacked sandstone beds, sometimes interconnected and sometimes not. A few Tocito fields contain fractured, low-permeability sandstone beds in which the fractures have created the reservoir. Generally, the Tocito reservoirs in the central basin are oil saturated and contain negligible water. The two largest Tocito fields are the Horseshoe, which has produced 40.2 MBO, and the Bisti, which has produced 41.8 MBO.

The EI Vado Sandstone Member of the Mancos Shale has produced more than 41 MBO from 39 fields (Fig. 5). Most of this production is from "fractured shale" reservoirs. Gorham et al. (1977) postulated that fractured shale reservoirs formed in the San Juan Basin in the carbonate-cemented, brittle, EI Vado sandstone and siltstone beds where they were tectonically stressed, both vertically and horizontally, especially in places where the monoclinal rim of the basin makes sharp bends. The EI Vado, where it is not fractured, generally has insufficient inherent porosity or permeability to make a reservoir. The EI Vado is present throughout much of the central basin and is as much as 180 m thick. The reference log for the EI Vado in the subsurface of the San Juan Basin is shown in Fassett and Jentgen (1978, p.238).

Fractured EI Vado reservoirs on the east edge of the basin are the Puerto Chiquito West, Puerto Chiquito East, and the Boulder field (Fig. 5); these fields have produced nearly 14.5, 4.8, and 1.9 MBO, respectively). These fields are classified by New Mexico as producing from the Mancos Shale. Fractured EI Vado reservoirs on the northwestern edge of the central basin in New Mexico are the Verde, La Plata, and Meadows fields (Fig. 5). These fields have produced 8.1, 0.7, and 0.2 MBO, respectively. New Mexico classifies these fields as "Gallup" producers. In Colorado, the Red Mesa field has produced more than 0.7 MBO from a fractured EI Vado reservoir located mostly on the Four Corners platform. The Red Mesa field is located on an anticlinal flexure (Lauth, 1983) and this structure may account for the fracturing of the EI Vado. Two other small fields have produced minor amounts of oil from the EI Vado on the Four Corners platform in Colorado. Colorado classifies this production as coming from the "Gallup."

Most of the rest of the EI Vado fields are clustered in the southeastern part of the central basin (Fig. 5). Many of these fields are associated with structural noses, which probably accounts for fracturing of the El Vado. A few fields, however, seem to have no apparent local structural control and appear to be fractured along narrow, northwest-trending lineaments.

Twenty-four small fields have produced nearly 1.5 MBO from the Mesaverde Group. Except for the Nenahnezad field in the west-central part of the central basin, all of the Mesaverde fields are in the southeastern part of the central basin and on the Chaco slope (Fig. 5). Most of these fields are stratigraphic traps consisting of channel sandstone beds enclosed by impermeable, finer-grained, overbank facies in the lowermost part of the Menefee

Formation. Many of these fields were discovered by mapping surface structures. A few of the fields produce from upper shoreface sandstone beds in the upper part of the Point Lookout Sandstone. Most of the fields are quite small; the largest, Franciscan Lake, has produced 0.6 MBO. The source of this oil is probably the organic-rich carbonaceous rocks of the lowermost Menefee Formation.

One Pictured Cliffs field and one undesignated Pictured Cliffs well have produced a little more than 100,000 BO. Four fields have produced slightly more than 100,000 BO from the Farmington Sandstone Member of the Kirtland Shale (Fig. 5). According to Matheny (l978b), the Pictured Cliffs oil is probably condensate that collected in the low part of a stratigraphic trap. The Farmington oil is high-gravity (56 to 59° API) and, according to D. D. Rice (personal communication, 1989), is probably condensate that has migrated into the Farmington from older rocks. The Farmington oil is trapped in channel-sandstone stratigraphic traps.

Gas fields

Natural gas in the three major gas-producing sandstone units, the Dakota Sandstone, Mesaverde Group, and Pictured Cliffs Sandstone, is concentrated largely in broad, overlapping, northwest-trending stratigraphic traps in the south-central part of the basin (Fig. 6, Plate 16). Each of these gas-bearing sandstone units is present throughout the basin, and each crops out around its periphery. The Pictured Cliffs Sandstone is missing in two narrow areas on the east side of the basin. A relatively small amount of gas is present in these three formations in smaller stratigraphic and structural traps in the northern and southeastern parts of the central basin. The trapping mechanism for these giant gas reservoirs has been controversial. With no apparent trap, why hasn't all of the gas migrated up-dip through the sandstone beds to the outcrop and escaped from this 45-m.y.-old structural basin?

Berry (1959) was the first worker to offer a solution to this conundrum; he suggested that the gas in these sandstone units had somehow been prevented from escaping by hydrodynamic forces.

The argument was that these gas-bearing rocks were under pressured, principally as the result of uplift of the Colorado Plateau in Miocene time resulting in the rapid erosion of a few thousand meters of overlying rock. The pressure release on the gas-bearing sandstone beds thus caused dilation of the pore space in these rocks and a decrease in temperature. With this pressure drop, meteoric water moved centripetally down the pressure gradient through the three gas-bearing sandstone units, sweeping the gas toward the deepest part of the basin. Berry's (1959) hydrodynamic-trap model was embraced by most subsequent workers. The hydrostatic-gas-trap hypothesis was subsequently evaluated by Cumella (1981, p. 168-175). Cumella discounted the hypothesis to some extent but did not completely dismiss it; further, he suggested that secondary kaolinite cement in the southwestern part of the basin, along with stratigraphic trapping of gas in the stair-steps of the Point Lookout and Pictured Cliffs Sandstones (Fig. 3 and Plate 3), were also factors contributing to the trapping of the gas in these rocks.

Later workers (Masters, 1979, Law, 2002), however, studying gas fields in other structural basins in the Western Interior, noticed that many large gas fields were concentrated in the deeper, central parts of these basins and a model emerged for gas trapping in these basins that came to be known as the basin-centered model. Fassett and Boyce (2005, p. 137) summarized the criteria for a basin-centered gas deposit as defined by these workers, as follows:

> The parameters listed by various workers that together define a basin-centered gas deposit are:
>
> 1. Gas trapped in the structural center of a basin in sandstone beds that outcrop around the periphery of the basin.
> 2. Low matrix porosity and permeability of reservoir rock.
> 3. Water in the pore space of the reservoir rock up dip from the gas reservoir.
> 4. No water in the gas reservoir or bottom water beneath the gas-charged rocks.
> 5. Physically continuous sandstone beds with interconnected permeability from the reservoir in the basin center to the outcrops around the basin's periphery.
> 6. An up dip water seal of some kind holding the gas in place in the basin center.

Both of the authors cited above who were directly involved in framing these parameters that defined a basin-centered gas deposit listed the San Juan Basin as a perfect example of such a deposit.

Fassett and Boyce (2005) conducted a detailed examination of the gas reservoirs located in the central part of the San Juan Basin (Fig. 6, Plate 16) in the Dakota Sandstone, Mesaverde Group, and the Pictured Cliffs Sandstone. On the basis of that examination, they concluded that the gas in each of the three giant gas reservoirs in the central San Juan Basin was trapped by stratigraphic pinch outs of the strata within these formations. They characterized these reservoirs as fractured-sandstone reservoirs and concluded that the "basin-centered" model did not apply to the San Juan Basin and further suggested that it probably did not apply in any of the other basin-centered gas deposits in the Western Interior.

The Dakota Sandstone consists of a complex of fluvial and offshore marine sandstone bodies (Deischl, 1973; Hoppe, 1978). In the New Mexico part of the basin, most of the Dakota gas is trapped within the upper, marine facies; the underlying fluvial facies is generally water saturated (Hoppe, 1978). Most Dakota gas, therefore, appears to be trapped in several offshore marine sandstone lenses surrounded by impervious marine shale. The Dakota is a tight (low-permeability) sandstone having an average porosity of 5 to 15 percent and permeabilities ranging from 0.1 to 0.25 millidarcy. "Fracturing, either natural or induced, is required to obtain commercial flow rates from the low-permeability [Dakota] reservoirs" (Rice, 1983, p. 1202). The principal areas of gas productive Dakota Sandstone are shown on Figure 6 and Plate 16.

The Point Lookout and Pictured Cliffs Sandstones are similar in their environments of deposition and geometry (Fassett, 1977, 1986; Fassett and Boyce, 2005), and thus are here discussed

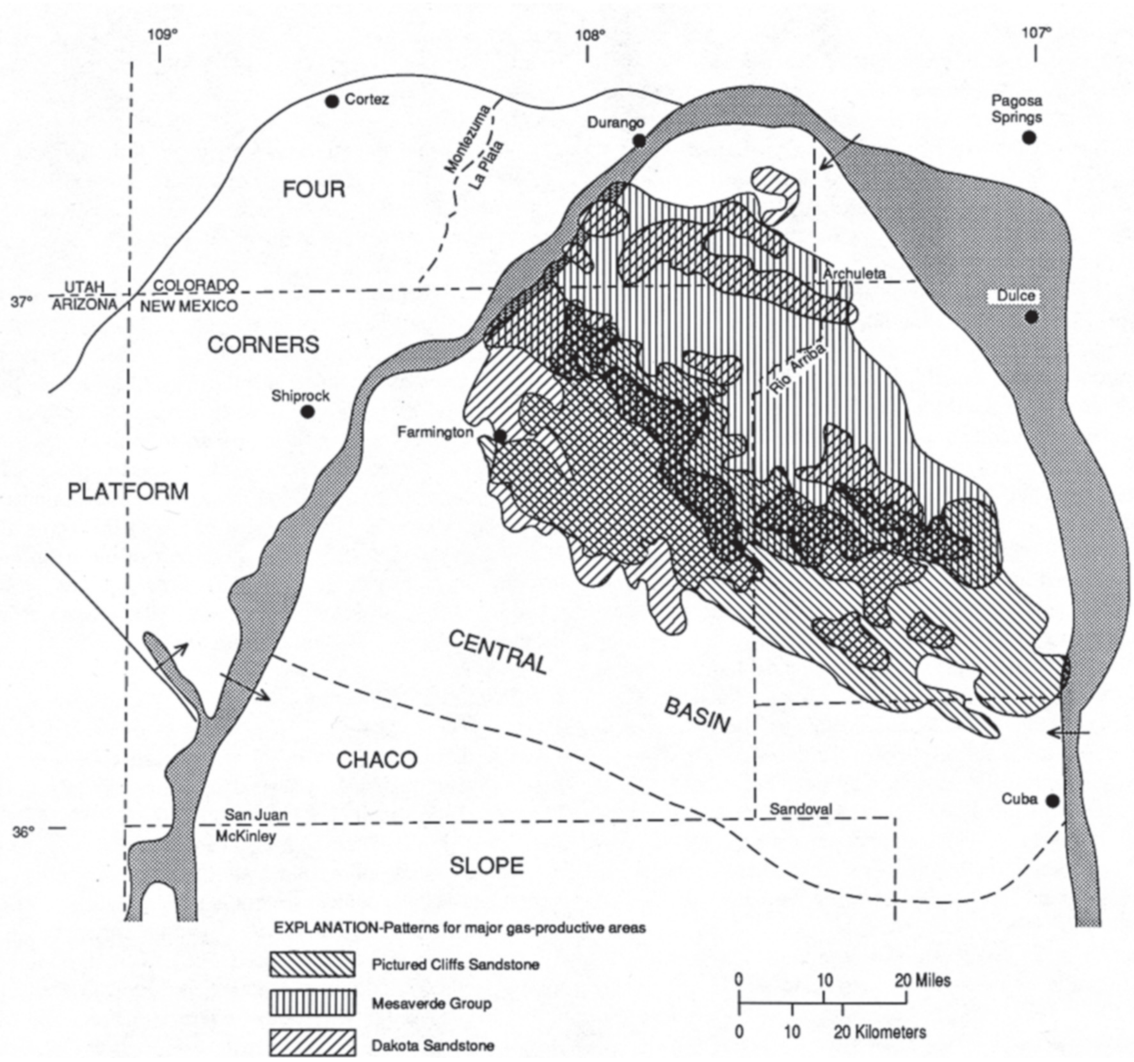

FIGURE 6. Map showing major gas-producing areas for the Upper Cretaceous Dakota Sandstone, Mesaverde Group, and Pictured Cliffs Sandstone in the San Juan Basin. Maps showing productive gas-wells for each of these formations are on Plate 16.

together. Both of these units represent regressive-marine shore face deposits laid down as the western shoreline of the Western Interior Seaway shifted across the basin from southwest to northeast. When viewed in northeast-oriented cross sections, these formations are seen to consist of a series of stair steps that rise stratigraphically northeastward across the basin (Fig. 3 and Plate 3). Detailed surface observations of these units at right angles to their paleoshoreline orientations show that they consist of a series of overlapping sandstone beds, commonly separated by impervious mudstone layers. Along the shoreline trend, the continuity of the shore face-sandstone beds is interrupted by distributary channel deposits and in places by complexes of storm-caused cut-and-fill features frequently containing mudstone drapes. Only relatively recently have detailed studies of these kinds of features been discussed in the literature (Flores and Erpenbeck, 1978; Wright, 1986).

Thus, rather than being homogeneous sheet sandstone beds with interconnected permeability throughout the basin, the Dakota, Point Lookout, and Pictured Cliffs Sandstones are complexes of individual sandstone bodies separated by impervious mudstone or claystone barriers. It is these permeability barriers that have trapped the natural gas in these sandstone beds. Where there is interconnected permeability in these rock units to the outcrop, the gas has, indeed, long ago escaped, thus explaining the gas-barren aureole around the shallower part of the central basin (Fig. 6, Plate 16). Water has subsequently moved down dip through these sandstones as far as their interconnected permeability existed, leaving them water-saturated around much of their peripheries.

The Point Lookout and Pictured Cliffs Sandstones both contain water in the southwestern part of the basin and are more tightly cemented in the northeastern part of the basin. Both formations are tight, with average porosities of 10 to 15 percent and permeabilities of from 0 to 5.5 millidarcies (Pritchard, 1978; C. F. Brown, 1978). Production of gas from these two formations is enhanced or may be controlled, to a large extent, by natural fractures. If this is true, the fractures are apparently confined to the more brittle sandstones and did not form or have not remained open in the intervening finer-grained mudstones and siltstones, thus maintaining the integrity of the impermeable seals trapping the gas. Cumella (1981, Fig. 28) presented a map showing the distribution of the initial potential for natural gas for wells completed in the Pictured Cliffs Sandstone, and suggested that the resulting pattern reflected shoreline trends for the Pictured Cliffs. An alternative interpretation of that map is that the pattern reflects not shoreline trends, but the distribution of natural fractures in the Pictured Cliffs.

In the northern (Colorado) part of the San Juan Basin, gas has been trapped in the Dakota and Point Lookout Sandstones on a broad, northwest-trending structural feature called the Ignacio Blanco anticline (Harr, 1988) (Plate 16). This structure is probably more complex than a simple structural anticlinal trap. Because of the inherently tight nature of the Dakota and Point Lookout, natural fractures in these rock units, created parallel to the axis of this anticline as it was formed in early Tertiary time, have probably greatly enhanced or, indeed, may have even created these reservoirs. The Pictured Cliffs Sandstone has produced minor amounts of gas from stratigraphic traps along a northwest trend in the Colorado part of the basin. (For a comprehensive discussion of the gas production in the northern San Juan Basin, see Harr, 1988 and Fassett and Boyce, 2005.)

Other, smaller Cretaceous fields produce gas from the El Vado Sandstone Member and Tocito Sandstone Lentil of the Mancos Shale (22 fields) and an interval in the Cliff House Sandstone (designated "Chacra" by New Mexico) (9 fields). El Vado production comes from areas where the commonly tight, fine-grained sandstone and siltstone beds of the El Vado are fractured or contain slightly more porous or permeable sandstone or siltstone. "Chacra" production comes from offshore marine sandstone beds of the La Ventana Tongue of the Cliff House Sandstone (Fassett, 1978b, Fig. 4; 1983b; and Fassett and Boyce, 2005).

Until the late 1970s, Fruitland Formation coal beds and channel-sandstone deposits had produced a modest amount of gas from 28 fields. Most of this gas was produced from coal beds. However, due to intermingled production in many of these fields, the amount of coal-bed methane produced cannot be determined exactly. Fassett (l989a) estimated that the coal-bed gas produced from these 28 fields totaled 85.1 billion cubic feet of gas (BCFG) through 1987. Most of the Fruitland coal-bed gas produced to that date has come from the Colorado part of the San Juan Basin, from within the Southern Ute Indian Reservation. The largest Fruitland coal-bed methane fields were the Ignacio Blanco Fruitland-Pictured Cliffs field (estimated coal-bed methane production, 40 BCF), the Cedar Hill Basal Coal (9.5 BCF of gas), and the Basin Fruitland (6.6 BCF of gas) (Fassett, 1989a).

Fruitland coal-bed methane (CBM) production sky-rocketed beginning in the 1980s and is discussed in detail in Fassett and Boyce (2005). Fruitland CBM production went from 85.1 BCFG in 1987 to a cumulative 15.7 TCFG through late 2009. The geometry, thickness, distribution, and physical characteristics of Fruitland coal beds are discussed in Fassett and Hinds (1971), Fassett 2000, and Fassett and Boyce (2005), and thus are not discussed in detail in this report. In summary, coal-bed methane is found in hundreds if not thousands of individual coal beds concentrated in the lower part of the Fruitland Formation. For the most part, each individual coal bed is a separate gas reservoir. Gas content increases down dip northeastward across the basin from less than 100 standard cubic feet per ton (scft) on the southwest flank of the basin to in excess of 800 scft in the deeper part of the basin north of the basin axis (Fig. 2). Gas content increases in tandem with an increase in thermal maturity of the coals down dip as measured by the vitrinite reflectance of the coal (Fassett, 2000; Fassett and Boyce, 2005). A high percentage of Fruitland CBM has come from a northwest-trending fairway in the north-central part of the basin containing wells that have produced more than 2 BCFG (Plate 16 and back cover of this guidebook). This fairway is so highly productive because in this part of the basin the net thickness of Fruitland coal is the greatest – up to 30 m – plus the coal beds in this area are highly naturally fractured. Some of the high-gas-content coal beds of the northeast part of the basin lie outside (northeast) of the Fruitland fairway and these coals produce low volumes of CBM because they are not fractured and thus have very low permeability. Some success has been obtained in increasing the CBM production rate many fold from tight coal beds in this area by horizontal drilling of individual coal beds. If some of the technical problems related to horizontal drilling of these coals can be overcome, the Fruitland's CBM reserves in the northeast part of the basin may be increased significantly. The Fruitland Formation coal-bed methane field in the San Juan Basin is currently, by far, the largest coal-bed methane field in the world.

The Farmington Sandstone Member of the Kirtland Shale has produced gas from four very small fields from channel sandstone deposits. All of these fields depleted rapidly, indicating limited reservoir size. The origin of this gas is unknown. Tertiary rocks have produced small amounts of gas from the Paleocene Ojo Alamo Sandstone and the Nacimiento Formation in some relatively small fields. Gas in these fields was trapped stratigraphically in channel sandstone deposits of limited lateral extent. Even though the potential for gas in Tertiary rocks appears to be minimal, these fields are of interest because the gas in them appears to have been generated from older, more mature, organic-rich continental rocks, and the gas has migrated upward (D. D. Rice, written communication, 1989).

THERMAL MATURITY

The thermal maturity of the sedimentary rocks in the San Juan Basin has been discussed in several papers (Rice, 1983; Meissner, 1984; Bond, 1984; Rice and others, 1988; Clarkson and Reiter, 1988). These early studies used essentially the same data base, which consists of two elements: the distribution of the fixed carbon and volatile content of Fruitland Formation coal beds as reported in Fassett and Hinds (1971), and the pattern of vitrinite reflectance values reported in Rice (1983). These data sets are in good agreement. Bond (1984) attempted to portray the thermal history of the basin on the basis of a reconstruction of the burial history of the geologic section penetrated in a well in the north central part of the basin. The general consensus of these writers is that thermal maturity increases toward the present structural axis of the basin, but that the area of maximum maturity may be slightly offset north of the basin axis. This offset has been attributed to a heat source to the north (the San Juan volcanic center), but this concept is controversial because of questions regarding the thermal conductivity of rock (Clarkson and Reiter, 1988). A simpler solution may be that the greatest depth of burial during the time between the Oligocene and the present was slightly north of the present axis of the basin. More recent work by Fassett (2000) has provided a very detailed isopach map of vitrinite-reflectance values. This map not only confirms the findings of earlier workers, but provides much more detail about the San Juan Basin's thermal maturity patterns.

On the southern limb of the San Juan Basin, where most of the oil fields are located, the greatest depths of oil production from the following rock units are (number in parentheses is elevation relative to mean sea level): Entrada Sandstone, 1,800 m (280 m); Dakota Sandstone, 2,290 m (-40 m); Tocito Sandstone Lentil 2,070 m (-90 m), and Mesaverde Group, 1,400 m (670 m). On the east rim of the basin, the deepest wells producing from fractured EI Vado Sandstone Member wells are 2,040 m (400 m). On the Four Corners platform, the deepest oil production from Pennsylvanian rocks is from around 2,130 m (-520 m); at depths greater than 2,500 m (-580 m); only gas is produced from Pennsylvanian rocks. An empirical conclusion based on these data is that oil is present in rocks in the south-central part of the basin down to at least 90 m below sea level – the bottom of the oil window; on the Four Corners platform, the maximum depth for Pennsylvanian oil production is between 520 and 580 m below sea level.

The difference of 460 m for maximum oil depth (-90 versus -550) between the central basin area and the Four Corners platform is probably the result of different burial histories for these two areas. Rice (1983) showed the down-dip limit of oil for the Pennsylvanian on the Four Corners platform and for the Dakota Sandstone and Mancos Shale (including the Tocito and EI Vado) in the central basin area. He also stated that the shallowest oil in the southern San Juan Basin is in rocks having vitrinite reflectance values less than 0.6 percent, and suggested that this oil migrated upward from where it was generated in more mature rocks in a deeper part of the basin.

An anomalous well has produced a little more than 5,000 BO from Pennsylvanian rocks at a depth of nearly 3,360 m in the south-central part of the basin. This depth equates to 1,400 m below sea level. This well, which constitutes the Buena Suerte oil field, is now abandoned. The vital statistics of the well were presented by H. H. Brown (1978). No oil should be present at this depth according to most theories of oil generation and thermal maturity. There is presently no explanation for the presence of oil at this depth in this well. The down-dip limit of wet gases (containing condensate) is discussed and depicted in detail in the Rice (1983) report.

POTENTIAL TARGETS

Conventional targets

Despite the more than 42,000 wells that have produced hydrocarbons in the San Juan Basin, the basin is still far from being completely explored. Most of the drilling has been concentrated in the gas-producing fairways (Fig. 6 and Plate 16) that trend northwest across the central part of the basin. Outside of those fairways, large areas of low drilling density still exist. Furthermore, only a few basement tests exist in the central basin area; most wells stop in Cretaceous rocks and, in a few places, in the Jurassic Entrada Sandstone.

The most promising plays in the future will be the virtually untested Paleozoic carbonate rocks in the central basin at depths where only gas can be expected. The tests drilled to date have not found reservoir rocks, and future plays will be based on an attempt to find algal mound porosity or possibly tectonic dolomite porosity over deep structures. Seismic-reflection analysis will be an important exploration tool for locating these features. There is still some potential for undiscovered Paleozoic oil or gas on the Four Corners platform, but all of the known surface structures there have been drilled and stratigraphic traps will be difficult to locate. Smaller plays will probably involve the search for additional oil-bearing Tocito Sandstone Lentil reservoirs along and south of the main productive trend. In addition, small Dakota oil fields may be found associated with subtle surface structures in the southern part of the basin. Very small Menefee Formation channel-sandstone oil accumulations are almost certainly present along the southwestern flank of the basin but these accumulations will be difficult to find because of their small size and absence of surface expression. Fractured reservoirs in the EI Vado Sandstone Member have potential for oil near the monoclinal rim of the basin wherever structural conditions may have stressed the EI Vado. El Vado oil and gas could also be present in the central basin area away from the basin's monoclinal rim where northwest-trending linear fracture zones may be present.

Harr (1988) discussed recent discoveries of limited gas resources in the Jurassic Morrison Formation and the Lower Cretaceous Burro Canyon Formation in the northern San Juan Basin in Colorado. He suggested that these rock units have further potential in that part of the basin.

Coal-bed methane

As Plate 16 and the back cover of this guidebook show, Fruitland Formation CBM wells are concentrated in about the northwest half of the basin. An isopach map of net-Fruitland-coal thicknesses in Fassett (2000, fig. 46) shows that these coals thin to less than 10-ft thick in a large part of the southern San Juan Basin and another area in the northeast part of the basin. These areas of thin Fruitland coal probably have limited potential for additional CBM production. However, there is a thick trend (> 40ft) shown on this isopach map extending southeastward across the east-central part of the basin that may have the potential for significant CBM reserves.

The Menefee and Crevasse Canyon Formations also contain significant coal deposits in the San Juan Basin, but their resources have not yet been assessed in detail throughout the basin area. Fassett (1989b) estimated the non-Fruitland coal resource in the basin to be about 15 billion tons. Non-Fruitland coal beds are relatively thin and discontinuous (Fassett, 1986) and, thus, will present a much more challenging exploration target, if they indeed are found to contain commercial quantities of coal-bed methane.

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