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Facies and Reservoir Characterization of the Morrow Sandstones, White City Penn Gas Pool, Eddy County, New Mexico

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Abstract

The White City Penn Gas Pool is a structural-stratigraphic gas field encompassing 29 sections or 18,560 acres in Eddy County, New Mexico. Hydrocarbon production in the field is from a thick section of Pennsylvanian and Permian age (Morrow, Atoka, Strawn, and Wolfcamp) clastics and carbonates that were deposited across the shallow, northwestern shelf of the Tobosa Basin in southeastern New Mexico. The majority of production in the field is from two sandstone sequences in the lower half of the Morrow Formation. The Morrow sandstones constitute a primary development and exploration play in the southeastern New Mexico region.

In 1980 a geological-engineering reservoir characterization of the Morrow sandstones in the White City Penn-Black River Gas Pool area was completed by the operator, Gulf Oil Exploration and Production Company. The study demonstrated that the erratic nature of these early Pennsylvanian sandstones could be deciphered and illustrated, and that a 640-acre well spacing was insufficient to effectively drain the reservoirs. Products of the study were used by operators to successfully convince the New Mexico Oil and Gas Conservation Division to change the rules to allow a second well on a 640 acre proration unit for the Morrow sandstones.

A slice mapping technique was used to characterize facies heterogeneity within reservoir intervals in the region. Facies types were determined from well cuttings and well-log curve pattern analyses. Time-slice reconstructions of variations in facies distribution, sandstone thicknesses and sand body geometries were completed for eight genetic sandstone intervals. The facies analysis was constrained by the well density and stratigraphic models of ancient and modern analogs. Combined with structural and engineering data, the study presented a three-dimensional assessment of porosity, permeability and reservoir performance throughout the field. Subsequent infill drilling and completion strategies utilized the detailed analysis.

Stratigraphic analyses revealed that the lower half of the Morrow Formation consisted of two distinct, coarsening-upward sandstone intervals, called the "Lower Morrow Clastics" and the "Middle Morrow Clastics". These intervals represented an overall southeastward progradation of fluvial-deltaic deposits during the early Pennsylvanian. Depositional facies types included distributary channel-fill sands and channel mouth bars, delta plain interdistributary siltstones and shales, coals, and delta front and prodelta shales. Sandstone deposition was interleaved with short aggradational and retrogradational cycles. Delta lobe abandonment and subsequent differential compaction of deltaic deposits and/or syndepositional faulting accounted for numerous cycles of marine incursion and shale deposition. The upper portions of many sandstone parasequences within these intervals contain units that represent reworked channel-mouth bars, beach and barrier-bar deposits. These in turn are capped by transgressive marine shales and thin units of carbonate rocks. Oolitic limestone is the dominate carbonate grainstone and represents shoaling across the tops and seaward flanks of isolated paleotopographic highs on a shallow marine shelf. Carbonate wackestones and mudstones more often occupy lower-energy interbar and shelfward flank settings.

The upper half of the Morrow Formation is dominated by the "Morrow Limestone" or "Upper Morrow" sequence. This interval is comprised of ramp carbonates and basinal shales that onlap the thick, clastic fluvial-deltaic sequence of reservoir sands. Detailed analysis of this unit was not included in the study.

All sandstone facies in the Morrow exhibit significant variations in thickness, distribution

and reservoir quality. Reservoir quality is most often a function of the type and quantity of clays and authigenic cements that are present in the sandstones. Both drilling and completion techniques have been customized to optimize gas production from the heterogeneous Morrow reservoirs.

Prior to 1981, the field was producing from 23 wells on a 640-acre well spacing. As of April 1, 1999, 44 wells have been drilled in the field, of which 38 are still actively producing. As of April 1, 1999, the field has produced approximately 166 billion cubic feet of gas, 51,000 barrels of condensate, and only 332,000 barrels of water from the Morrow sandstones, including minor contributions from Atoka sandstones and the Strawn limestone.

A combination of good structural and stratigraphic attributes makes the White City Penn an excellent Morrow case study. Additional field characterizations should be encouraged in the region for they serve as important guides in exploration and development in the Pennsylvanian reservoirs throughout the Permian Basin region and elsewhere.

Introduction

The White City Penn Gas Pool represents one of several stratigraphic-structural Pennsylvanian-age Morrow gas and oil fields. It is located near the late Permian margin of the Delaware Basin, in Eddy County, New Mexico (Fig. 1). The White City Penn Gas Pool, herein referred to as the WCP, is located 15 miles south of Carlsbad and 4 miles east of Whites City, New Mexico. It was discovered in April, 1960, by the Gulf Oil Exploration and Production Co. Federal Estill "AD" No. 1 well, later renamed as the White City Penn Com. Unit 1 No. 1 (NE/4 Sec. 29-T24S-R26E) (Fig. 2). Initial completion was in the Pennsylvanian Strawn carbonates for a calculated open-flow potential of 46.7 million cubic feet of gas per day. Later downhole completions tapped the gas-bearing sandstones of the lower Morrow Formation for a potential of 8.4 million cubic feet of gas per day.

Prior to the 1970s, primary targets in southeastern New Mexico were large oil deposits in the Silurian-Devonian carbonates. Pennsylvanian and Permian reservoirs served as the secondary targets in these deep oil plays. However, the gas-bearing sandstones of the lower Morrow Formation did not go unnoticed by drillers or geologists. Prior to the discovery of the WCP, Morrow sandstone gas production had been established in several fields in Eddy County, New Mexico. These fields included the Empire (1953), Duffield (1956), and Atoka (1958) (Fig. 3). A combination of poor economics and the challenges associated with exploring and developing these erratic sandstone reservoirs constrained the pace of Morrow development during the 1960s (Cairns, 1981; Mickey, 1983). Subsequent Morrow discoveries, like as the WCP, and a marked increase in interstate gas prices, led to the discovery of other economical Morrow fields such as the Indian Basin (1963), Dagger Draw (1965), Rock Tank (1968), South Carlsbad Morrow (1968), Washington Ranch (1971) and Burton Flats (1972) in Eddy County, New Mexico.

Prior to 1981, the WCP contained 23 Morrow gas wells. The field, operated by Gulf Oil Exploration and Production Company (now Chevron), was being developed on a 640 acres per well spacing in accordance with New Mexico Oil Conservation Division guidelines. Cumulative production as of 1-1-81 was in excess of 62 billion cubic feet of gas and 29,000 barrels of condensate. Cumulative production per well averaged approximately 2.7 billion cubic feet of gas and 1,300 barrels of condensate—all mostly from the Morrow sandstones. However, earlier preliminary estimates indicated that a tighter well spacing might allow infill wells to penetrate untapped gas reserves in the Morrow interval.

Therefore, in 1980, a detailed, geological-engineering reservoir characterization of the

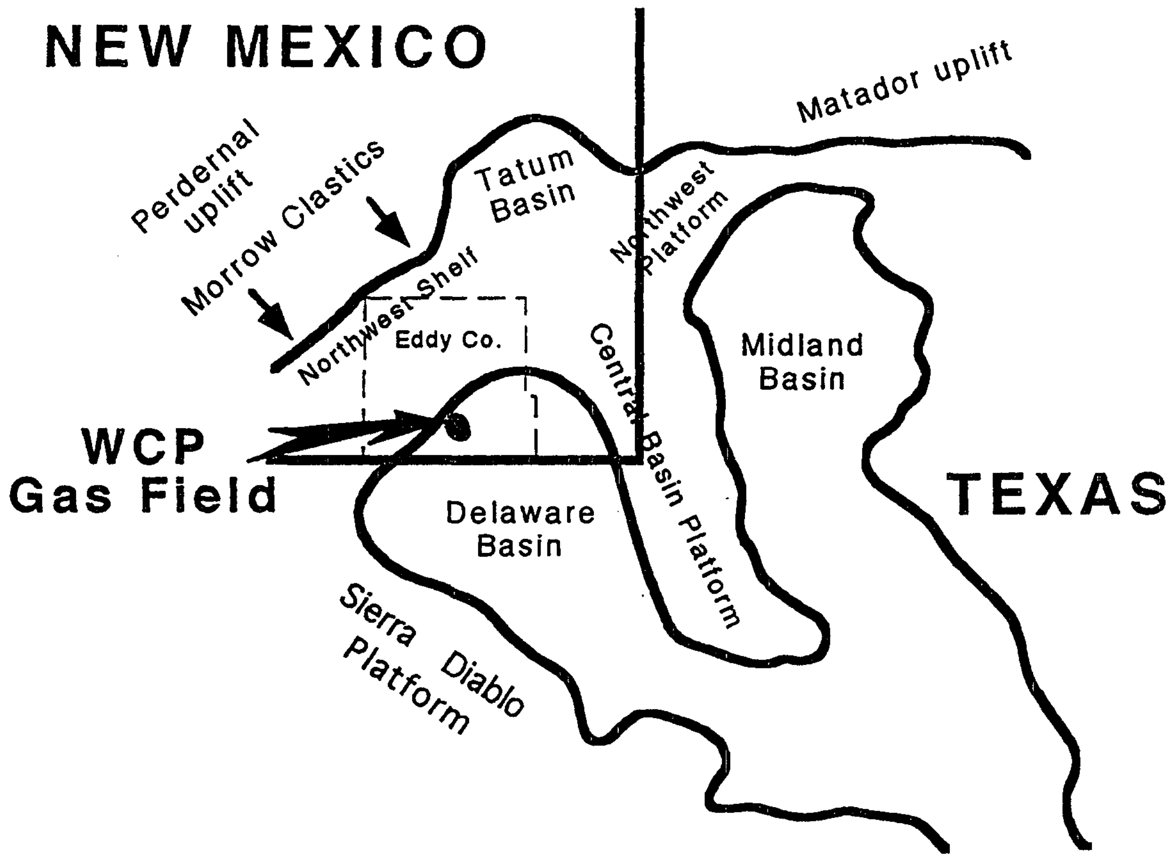


Fig. 1 Location of the White City Penn Gas Pool in relation to the Permian Basin region and Eddy County, New Mexico.

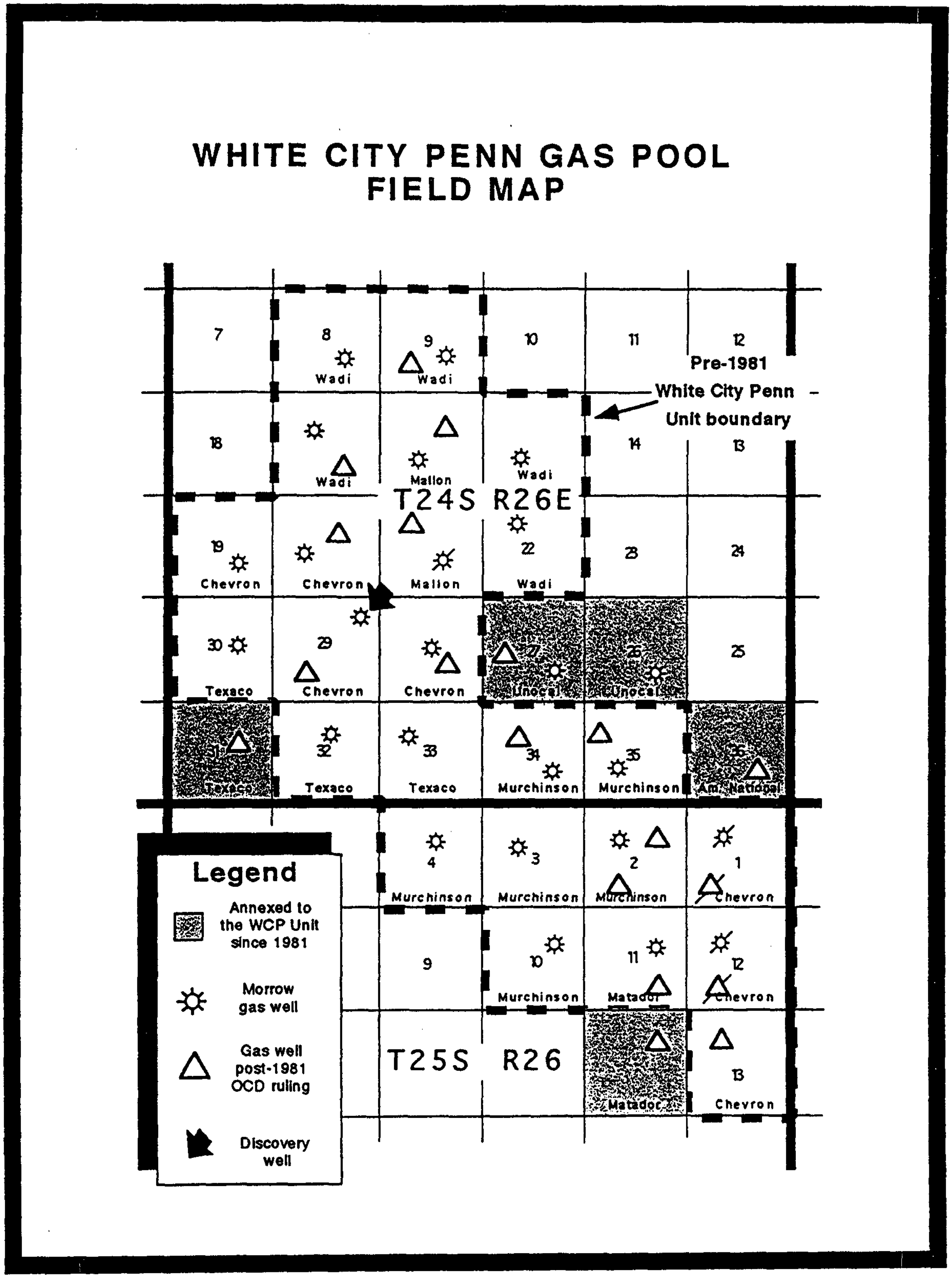


Fig. 2 Area map of the White City Penn Gas Unit showing all well locations including post-study field extension and infill wells drilled since 1981.

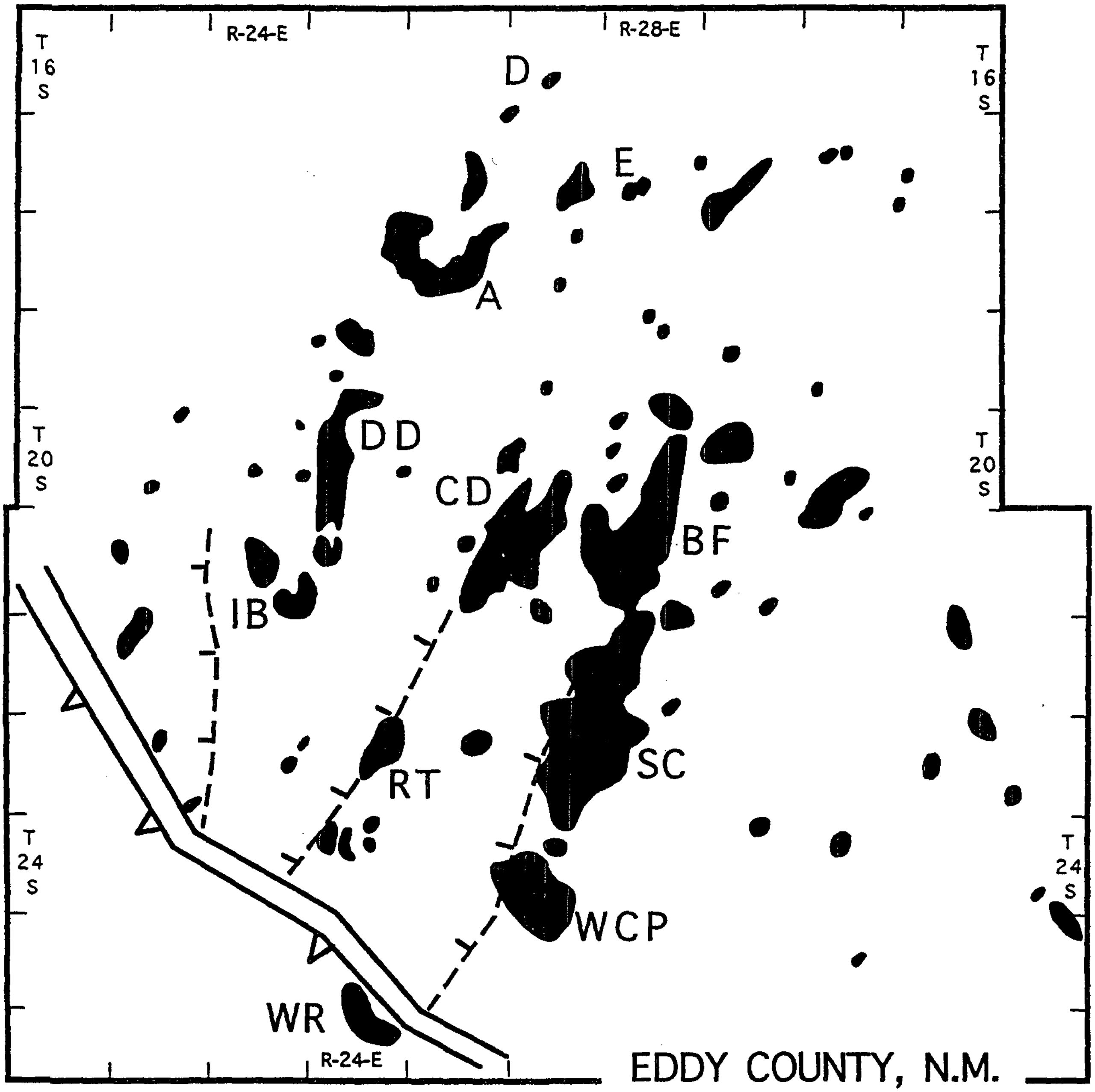


Fig. 3 Generalized map of Morrow gas fields in Eddy County, New Mexico (Modified from Jons and Stanley, 1976).
D = Duffield, E = Empire, A = Atoka, IB = Indian Basin, DD = Dagger Draw, RT = Rock Tank, CD = Catclaw Draw, SC = South Carlsbad, WCP = White City Penn

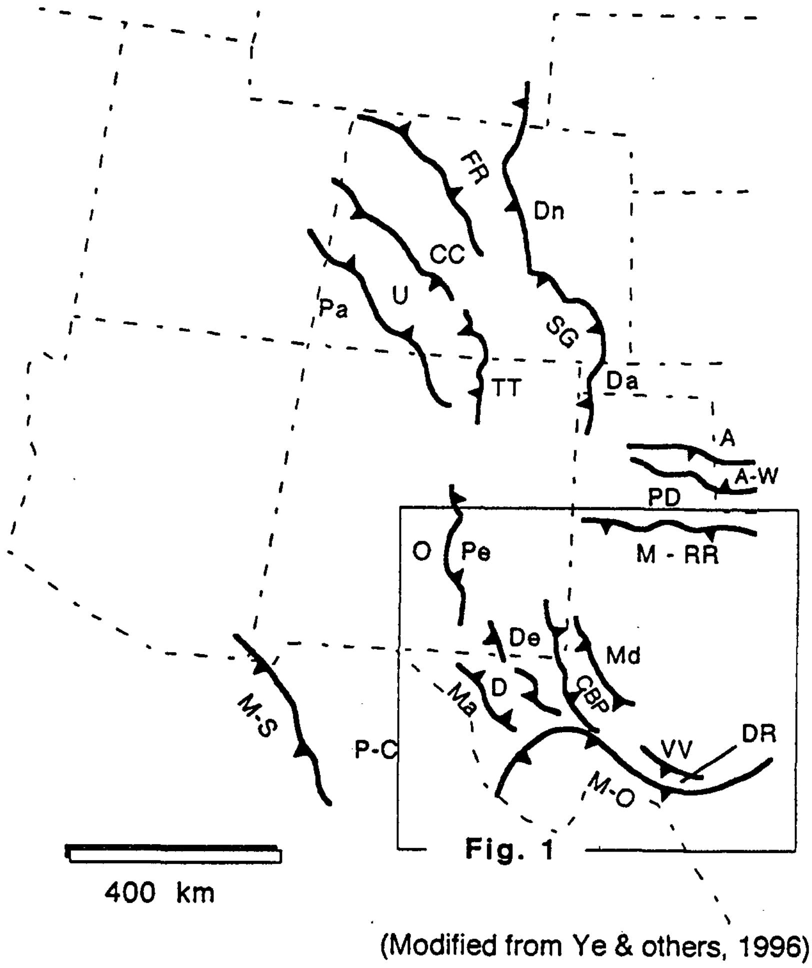


Fig. 4 Major Paleozoic thrust faults associated with the development of paired basins and uplifts during the Ancestral Rockies Orogeny. The Huapache Fault is the thrust fault complex, located on the northwest margin of the Delaware Basin. The box inset shows the area coverage in Figure 1.

Pa = Paradox Basin; U = Uncompahgre Uplift; CC - TT = Central Colorado - Taos Trough;
FR - SG = Front Range - Sierra Grande Uplift; Dn = Denver Basin; Da = Dalhart Basin;
A = Anadarko Basin; A-W = Amarillo - Wichita Uplift; PD = Palo Duro Basin;
M - RR = Matador - Red River Arch; O = Orogrande Basin; Pe - D = Pedernal - Diablo Uplift;
Ma = Marfa Basin; De = Delaware Basin; CBP = Central Basin Platform; Md = Midland Basin;
VV = Val Verde Basin; DR = Devils River Uplift; M-O = Marathon-Ouachita Fold-Thrust Belt;
P-C = Pedregosa - Chihuahua Basin; M-S = Magdelena - Sierra del Nido Uplift

Morrow sandstones, encompassing the White City Penn and Black River areas, was initiated by the company. The principle objective was to determine the optimal well spacing for recovery from these gas sands. As a result of the study and a subsequent New Mexico Oil and Gas Conservation Division hearing, the proration rules were changed to allow a second well to be drilled on each 640 acre proration unit (Fig. 2). The comprehensive study incorporated routine reservoir engineering analyses and geological analyses such as regional well log correlations, cross-sections, isopach and structural mapping, and cuttings and core analyses. However, it also employed a relatively underutilized technique at the time, known as "slice mapping", a method of detailed stratigraphic analysis that enabled geologists to characterize the erratic nature of the Morrow sandstones. The study coupled detailed facies and structural mapping to present a greatly improved two-dimensional and three-dimensional assessment of porosity and permeability distribution, and well performances throughout the field.

WCP working interest owners took full advantage of the study in designing their infill drilling and completion strategies. For example, results of the study convinced Gulf Oil to immediately drill four infill wells. Due of the favorable stratigraphic and structural positioning of the infill wells, more than 10 million cubic feet of gas per day was added to the company's portion of the unit production, which clearly made the small program an economical success (Cairns, 1981; Mickey, 1983).

This paper presents an overview of the regional geology and detailed geological and engineering characteristics of the Morrow sandstone reservoirs in the WCP. The slice mapping methodology and paleoenvironmental map interpretations are discussed. Some of the more important operational issues, tackled by operators developing the Morrow sandstones in Eddy County, New Mexico, are also presented.

Structure

Regional

Major tectonic features in the region include the adjacent Northwest Shelf of Delaware Basin (hereinafter referred to as Northwest Shelf), the Pedernal Uplift to the west and northwest, and the deep Delaware Basin and Central Basin Platform to the south and east, respectively (Fig. 1). The Pedernal Uplift is believed by many to have been the source area for the abundant terrigenous clastic input throughout Pennsylvanian and early Wolfcampian time in this region (e.g. Kottlowski and Bejnar, 1971; Kottlowski, 1968).

Prior to the formation of Delaware Basin in Late Mississippian, the WCP area occupied a small portion of a wide shallow shelf that rimmed the Tobosa Basin. The shelf was dominated by shallow-water limestone deposition (Galley, 1968; Hills and Galley, 1988). During Chesterian-Morrowan time, the greater Ancestral Rocky Mountains orogenic event differentiated the Tobosa Basin into several smaller northwest-trending basins in the southeast New Mexico and West Texas region. The Delaware Basin was one of these basins (Fig. 4). Paired regions of basement-cored uplift and rapid basin subsidence occurred nearly synchronously (Kluth and Coney, 1981; Ye et al., 1996). Regional compression and transpression continued through the end of the early Permian (late Wolfcampian) with only minor and local movements occurring since the Wolfcamp (Hills and Galley, 1988; Kottlowski and Bejnar, 1971; Kottlowski, 1968; Ye et al., 1996).

The Delaware Basin is a deep, north-northwest elongated marine basin. The structural architecture of its margin is characterized by basement-involved, high-angle reverse faults that have overthrusted basin strata (Broadhead, 1998; Galley, 1968; Hills, 1970; Ye et al., 1996). Many of these basin-bounding systems were previously characterized mostly in terms of dip-slip deformation (Galley, 1968; Ye et al., 1996). However, additional geological studies and improved seismic surveys now reveal that many of these basement fault complexes are wrench fault zones which have overprinted earlier episodes of normal and reverse faulting (Bauer et al., 1997; Clemons, 1998; Garmeezy et al., 1990; McDonald, 1997). The specific structural architecture of the Delaware Basin can be traced back to Proterozoic tectonics in which predominant regional compressional shearing was followed by crustal relaxation (i.e. transpressional and transtensional faulting). In many locations basement faulting took place predominantly along zones of pre-existing weakness associated with plate tectonic boundaries along the southern margin the northeast-trending Transcontinental Arch (e.g. Anderson, 1989; Burchfiel et al., 1992; Dickinson, 1989; Karlstrom and Bowring, 1988).

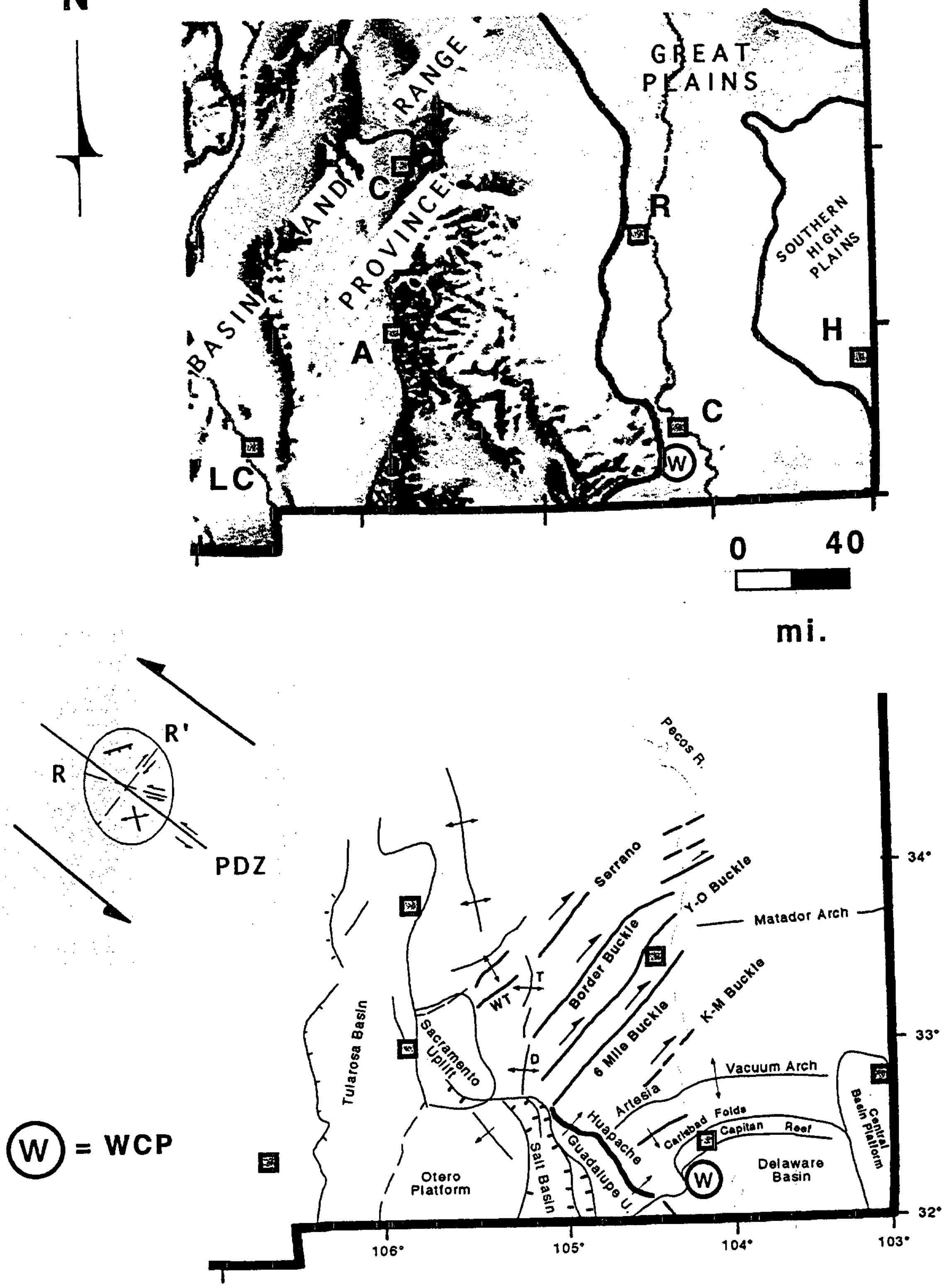
In New Mexico, numerous northeast, north and northwest-striking Proterozoic shear fabric and igneous emplacements reveal a history of fault rejuvenation and inversion which had a pronounced influence on Phanerozoic tectonics and deposition. Phanerozoic fault and dike orientations which compare well with attitudes of Proterozoic tectonic fabrics strongly suggest that reactivation of basement anisotropies is the rule, rather than the exception (e.g. Bowsher, 1991; Kelley, 1971; McDonald, 1997). In the vicinity of the WCP, prominent basement features include: the northwest-trending Huapache Fault Zone and its surface monoclinal expression (Hays, 1964; Meyer, 1966), located approximately 15 kilometers to the southwest; the Reef Anticline (Kelley, 1971), located just a few kilometers to the west and southwest of the field; and the northeast-trending buckle faults of the Pecos Valley region to the northwest (Kelley, 1971) (Fig. 5). Their kinematic relationship to the structure of the WCP is the subject of an on-going investigation by the authors.

White City Penn Field

Structure has played a key role in the productivity of the Morrow in southeast New Mexico (e.g. Carlile, 1997; Engwall, 1977; Jons and Stanley, 1976; Kornfeld, 1973; Miller and Butler, 1975b; Miller, 1975a; Stanley and Tipton, 1977). Detailed structural mapping shows that the long-lived Huapache Fault Zone and the northeast-trending faults directly influence a variety of fields in Eddy County (Fig. 3). These include White City Penn, Washington Ranch, Crooked Creek and Rock Tank fields. Production in less structurally-pronounced fields such as South Carlsbad, McKittrick Hills, Catclaw Draw, Dagger Draw, Indian Basin, and Burton Flat involve some degree of structural control, as evidenced by their positioning along similar fault trends and elongate geometries.

Structure maps on the Mississippian and Devonian formations indicate that the WCP occurs on an upthrown basement block which is tilted to the southeast, similar to the Pedernal uplift as described by Kelley (1971) and Kottlowski (1968). At the Morrow level, this structural deformation is expressed as an asymmetrical, north and northwest-trending doubly-plunging anticline (Fig. 6). Good closure exists on all flanks.

The western flank of the Rock Tank Field to the west, is interpreted to be bounded by a post-Morrow northeast-trending normal fault with vertical displacement of approximately 500 feet (Jons and Stanley, 1976). This fault apparently acted as barrier to the up-dip migration of gas in the Morrow sandstones. A



(Modified from Kelly, 1977;
Clemons et al., 1982)

Fig. 5 Shaded-relief and tectonic map of southeastern New Mexico showing detailed physiographic and tectonic features of the region.

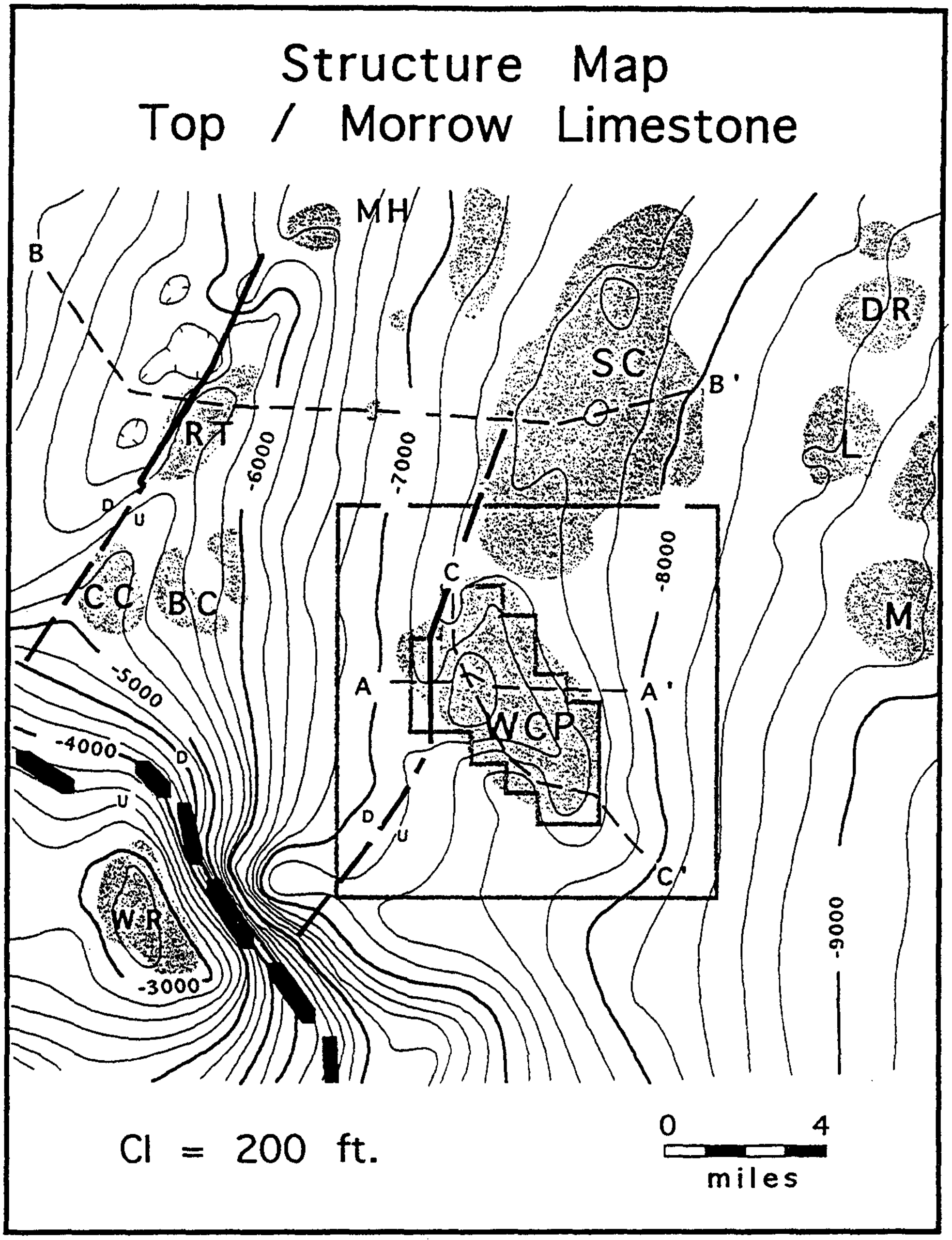


Fig. 6 Regional structure map. Shown are approximate Morrow field limits, the WCP boundary, major faults, and coverage of the facies study discussed in the text. Cross sections A-A", B-B' and C-C' refer to Figures 7, 17, and 8, respectively. The egnimatic NW-trending, asymmetrical anticlinal expression of the WCP is thought to be related to strike-slip displacement on NE-trending basement faults. WR = Washington Ranch, CC = Crooked Creek, BC = Baldridge Canyon, RT = Rock Tank, MH = McKittrick Hills, SC = South Carlsbad, WCP = White City Penn, M = Malaga, North, L = Loving, North, DR = Dublin Ranch.

parallel northeast-trending, down-to-the-west fault also bounds the west flank of the WCP field (Figs. 7). In places this fault exhibits greater than 300 feet of displacement. However, the nature of this fault has not been determined with any great certainty.

The general structural architecture of the WCP suggests that this bounding fault may be related to a transpressional wrench fault, similar to the basement-related linear buckles of Kelley (1997). Structural interpretation by the senior author indicates that the WCP has been structurally partitioned into discrete en echelon segments. This fault may have been reactivated as a Basin and Range normal fault in the mid-Tertiary. The sealing nature of the WCP fault at the Morrow level is even less certain. Unlike the Rock Tank Field, Morrow sandstone production in the WCP occurs on both sides of the fault. The linearity of many facies boundaries and the abrupt thinning and termination of Morrow sand bodies in separate intervals across the fault suggest the possibility of some syndepositional movement on the WCP fault (Fig. 8).

The pronounced structural closure which characterizes the WCP does not appear to be present in other fields that occur along the same northeast-trending fault (e.g. South Carlsbad Field). Morrow production on a per well basis in the northern fields (e.g. northern part of South Carlsbad, Burton Flat) might be more a function of their stratigraphic emplacement. Although it was long known that numerous hydrocarbon-bearing zones in the overlying Permian-Pennsylvanian formations exist behind pipe, the Morrow sandstones contribute the majority of production in the WCP. In some wells, shallow oil and gas production is obtained from youngest to oldest: the basinal sands of the Delaware Group, carbonate reservoirs of the Wolfcamp, Cisco, Canyon, and Strawn, and the Atokan sandstones. The multi-reservoir potential of the WCP is undoubtedly the result of its favorable structural as well as stratigraphic attributes.

Stratigraphy

Regional

During early Pennsylvanian, erosional processes were denuding the uplifting Pedernal massif in western and northwestern New Mexico. Large-scale fluvial systems transported medium to coarse grain clastics southeastward (basinward) across the northwest shelf of the Tobosa Basin (Kottlowski, 1968). Mapping and lithologic analyses of Morrow reservoirs throughout central and southeast New Mexico reveal that the southeastward progradation of a large clastic wedge during early Morrowan (Fig. 9) (Carlile, 1997; Casavant, 1986; Jons and Stanley, 1976; Mazzullo and Mazzullo, 1987). Large-scale fluvial deposition had taken place across the Northwest Shelf and the margins of other Pennsylvanian basins such as the Anadarko Basin and Eastern Shelf of the Midland Basin (e.g. Galloway and Brown, 1973; Krystinik et al., 1987; Webster, 1997). However, due to extensive erosion across the Northwest Shelf during the late Mississippian and early Pennsylvanian, proximal facies such as river channel and valley-fill deposits are generally absent or occur only as thin fillings of depressions throughout central New Mexico (Kottlowski, 1968). In contrast, Morrow clastics are abundant in southeastern New Mexico. Sediment types and distributions reflect siliciclastic and carbonate deposition at a marine-nonmarine interface in the form of estuarine, delta plain, delta front, fan-delta barrier-beach, and upper shoreface sands (e.g. Casavant, 1986; Jons and Stanley, 1976; Lambert and Berg, 1986).

As is common in most regressive sequences, the overall progradation of the deltaic sediments is interrupted by transgressive parasequences (transgressive systems tracts), containing interbedded marine shales and thin, reworked sand bodies. The most transgressive of these units are characterized by maximum-flooding surfaces, sometimes identified by the presence of a more radioactive gamma ray log signature relative to other marine shales and lag deposits. These shale units serve as excellent markers for subsurface correlation of genetic units across the region. Facies analyses reveal that the uppermost deltaic sand packages in the Morrow are characterized by barrier bar-beach sands and offshore bars which generally are capped by carbonate grainstones and wackestones. These deposits are the result of the reworking of distal deltaic channel mouth bar deposits by waves and longshore currents during transgressive and standstill episodes.

In most ancient and modern deltaic settings, sands are transported basinward, contributing to the formation of lower shoreface and outer shelf storm deposits and ultimately to the formation of submarine slope and fan deposits (e.g. Galloway and Brown, 1973; Shepard, 1981; Stricklin Jr., 1999; Williams et al., 1998). Early Pennsylvanian submarine fan or turbidite slope deposits have been interpreted in the deep Delaware Basin in Lea County, New Mexico (Martin et al., 1986).

White City Penn Field

A generalized stratigraphic section, constructed from several of the early wells in the White City Penn field, is shown in Figure 10. The section consists of approximately 9,300 feet of Permian strata, 2,185 feet of Pennsylvanian strata, 520 feet of Mississippian rock, 110 feet of Devonian shales, and more than 75 feet of the upper Silurian dolomite. The early Pennsylvanian Morrow Formation in the WCP field occurs at depths of approximately -6850 feet to -7625 feet. Average thickness of the Morrow Formation is approximately 1375 feet. It equates to more than 60 percent of the total thickness of the Pennsylvanian rocks in the area.

The Morrow Formation rests unconformably on Mississippian-age rocks. In the WCP-South Carlsbad area Morrow rocks are in contact with the underlying Mississippian Chester Limestone. Farther to east and southeast of the WCP, the Morrow is deposited on the younger and radioactive Mississippian-age Barnett Shale, depending on the degree of local erosion on the unconformity surface and/or structural deformation (Kauffman, 1968; Kottlowski, 1968). The basal unit of the Morrow Formation is represented by a dark, transgressive marine shale, locally known as the "Lower Morrow Shale". This is illustrated in the log profile of the discovery well, White City Penn Com. Unit 1 No. 1 (NE/4 Sec. 29-T24S-R26E) in Figure 11. Because of subtle facies changes within this shale unit, its proximity to a major unconformity at the top of the Mississippian and the similarity of its log character to the Mississippian Barnett Shale, the use of the "Lower Morrow Shale" as a regional datum is not recommended.

Overlying the "Lower Morrow Shale" is the fluvial-deltaic and nearshore sandstone interval which is called the "Lower Morrow Clastics" (Fig. 11). It is a parasequence set (Van Wagoner et al., 1990) that contains a succession of three genetically related deltaic sandstone units or parasequences. In the WCP the gross thickness of the "Lower Morrow Clastics" averages approximately 162 feet. The distribution of the "Lower Morrow Clastics" is more localized, considerably thinner and petrographically less mature than the overlying sandstones of the "Middle Morrow Clastics". This observation has been supported by trend analyses and types of major clay species within the Lower Morrow (Mazzullo and Mazzullo, 1987).

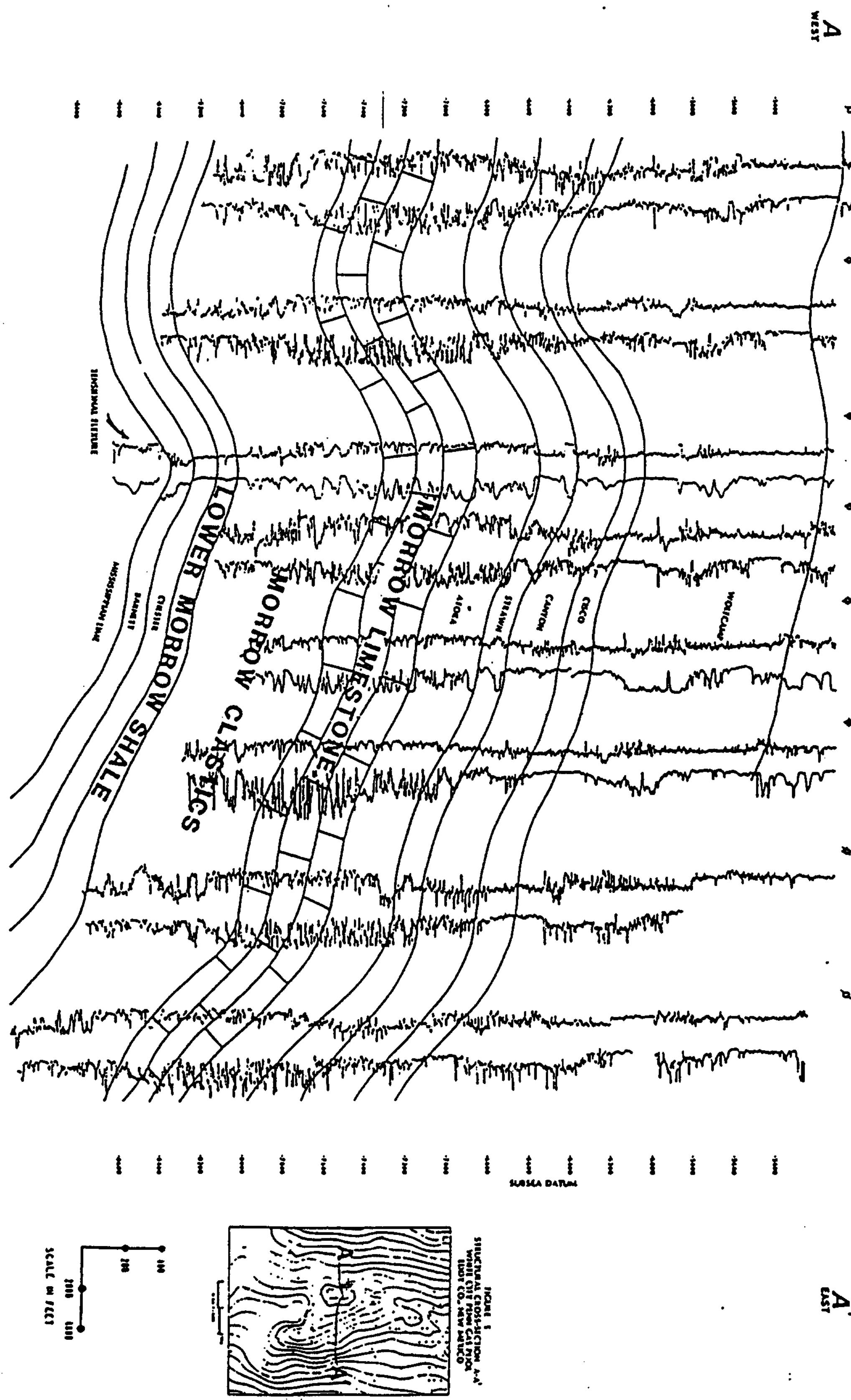


Fig. 7 West-east structural cross section A-A' across the WCP. The pronounced west-bounding fault or flexure and the tilted down-to-the-east basement block are associated with a NE-trending fault zone which intersects the Huapache Fault to the south.

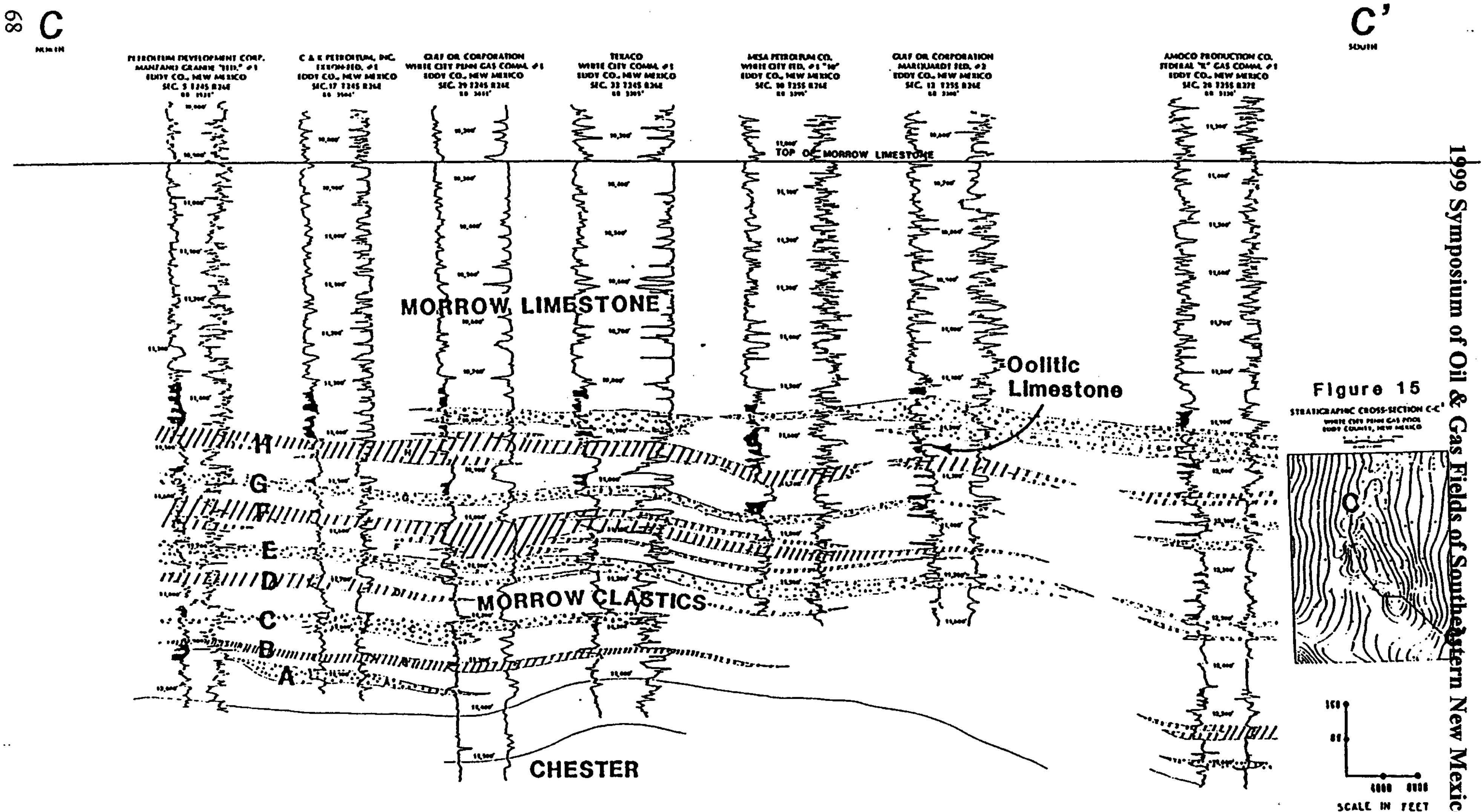


Fig. 8 North to south-southwest stratigraphic dip section C-C' along the structural axis in the WCP. Datum is the top of the Upper Morrow. The Morrow Clastics interval has been differentiated into 7-8 distinct parasequences. Note the changes in sand distribution and the abrupt thinning and termination of sands along the flanks of the Mississippian high—suggesting paleotopographic relief and structural control on sand deposition.

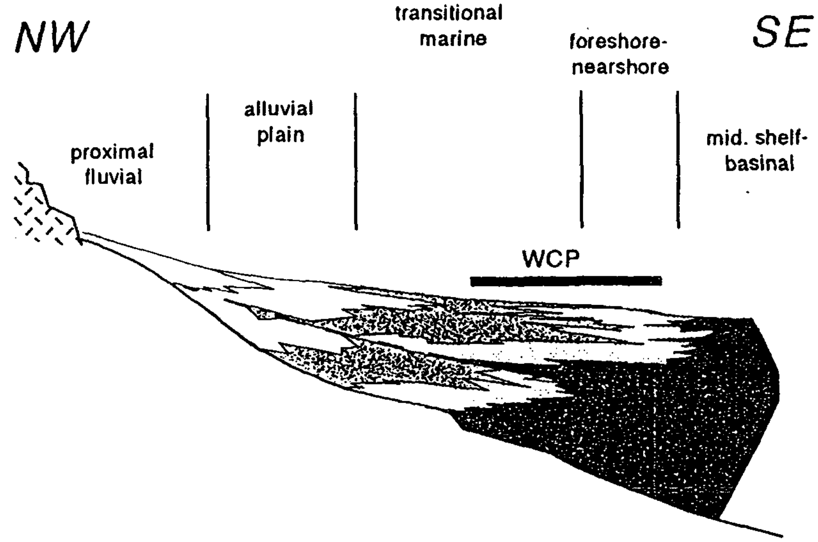


Fig. 9 Schematic regional cross section of the Morrow reservoir section in southeastern New Mexico illustrating the lateral transition of major facies belts. (Taken from Fig. 2 of Mazzullo and Mazzullo, 1987)

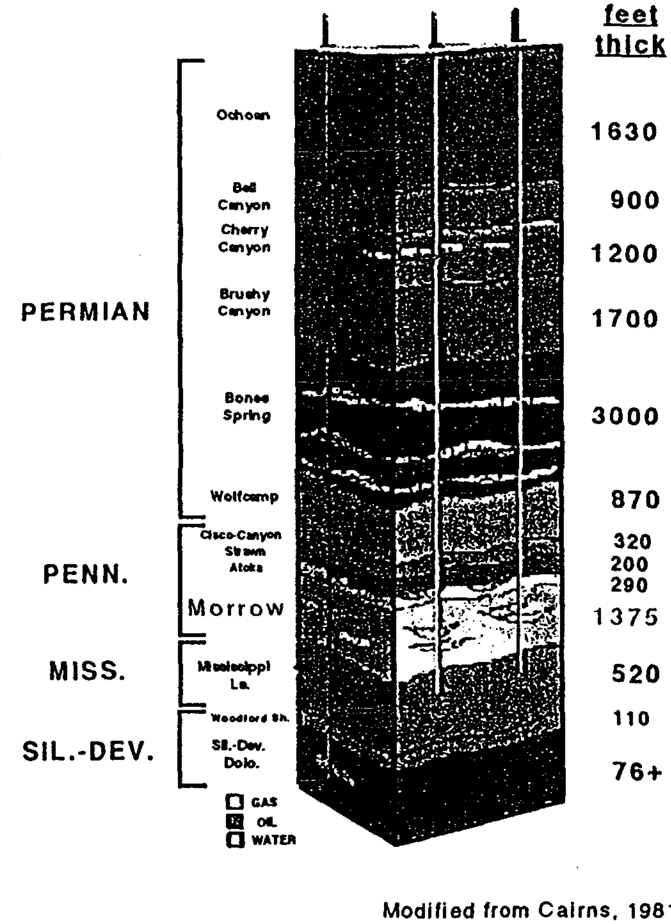


Fig. 10 Generalized stratigraphic column White City Penn Gas Pool, Eddy Co., N.M.

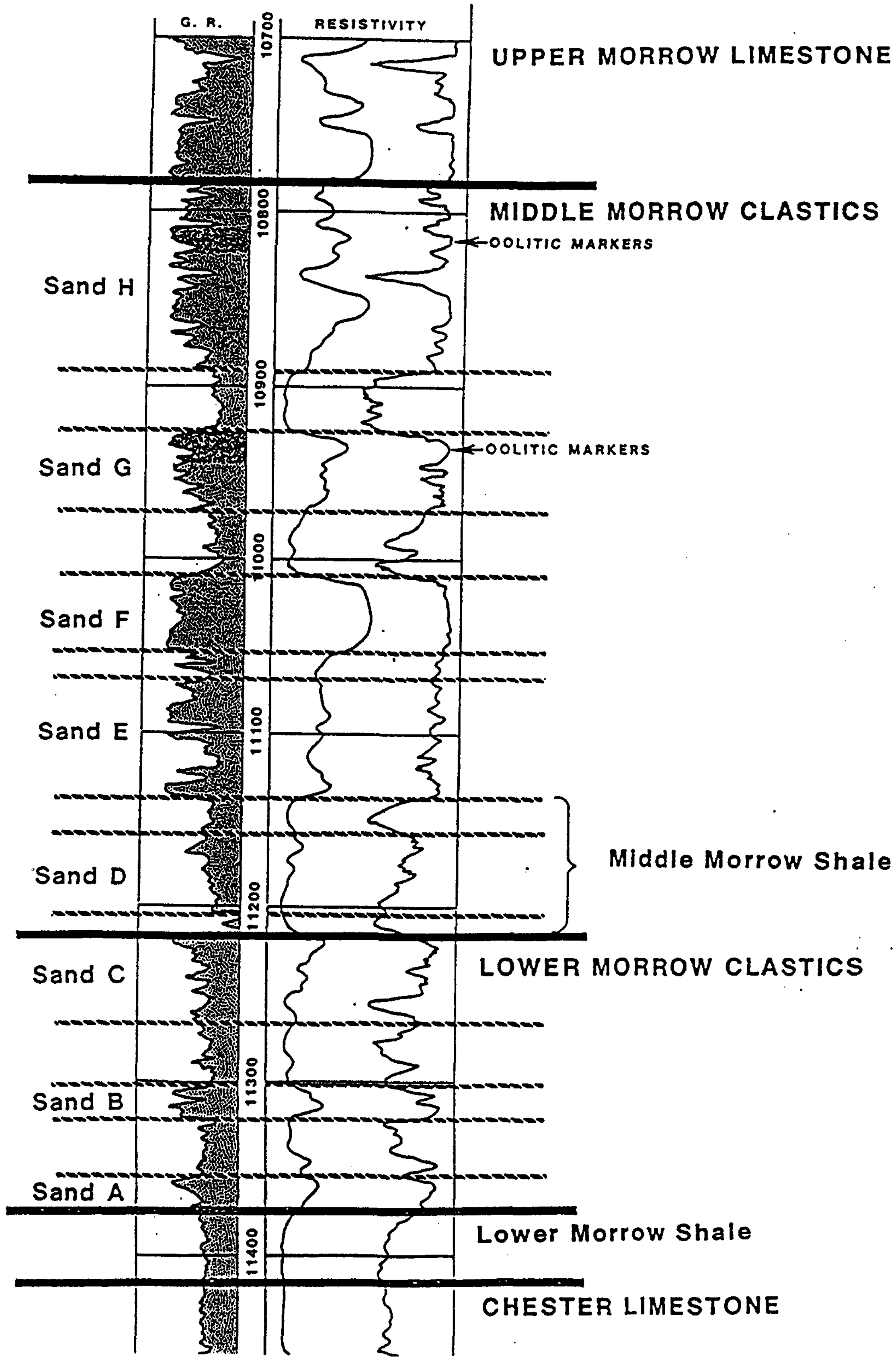


Fig. 11 Type log of the Morrow Clastics in the White City Penn Gas Pool. The well log is the discovery well, the White City Penn Com. 1 No. 1, located in NW/4 of Sec. 29-T24S-R26E. Differentiated are the major Morrow intervals and various sand-rich parasequences. Oolitic marker beds are indicated by a darker stipple pattern.

The sandstones of the "Lower Morrow Clastics" interval contain a higher density of interbedded marine shale and generally exhibit the lowest porosities and permeabilities of all the Morrow sandstones, due to poorer sorting and a larger percentage of subangular grains shapes. Intervals of sand deposition are interrupted by intermittent, short-period transgressive cycle associated with delta lobe switching, abandonment and subsidence. The tops of parasequences are bounded by a 20 to 40 foot-thick transgressive marine shale interval. Wave-dominated processes have remobilized and reworked much of the upper sandstones in the more distal positions.

Overlying the "Lower Morrow Clastics" is an interval that is called the "Middle Morrow Shale". This unit is the basal parasequence of the sand-rich "Middle Morrow Clastics". The lowermost 10-15 feet of the "Middle Morrow Shale" is defined by a regional and pronounced radioactive shale bed that serves as an excellent marker bed for well log correlation throughout the area. The "Middle Morrow Shale" is composed of mostly marine shales, but does contain a variable number of thin fine-grained sandstones beds. A abruptly thickened sandstone unit exists in the northwesternmost part of the field.

Previously, geologists and drillers called the "Middle Morrow Clastics", the "Upper Morrow Sands" (e.g. Casavant, 1989; Jons and Stanley, 1976). The gross thickness of "Middle Morrow Clastics" interval ranges from approximately 340 to 500 feet. The interval contains from five to six vertically-stacked sand packages or parasequences that exhibit higher sand-shale ratios and are considerably thicker than any of the sands in the lower interval. Each contains massive sandstone units that are interbedded with thin siltstones and shales beds.

The overall wireline log signature of the entire "Middle Morrow Clastics" parasequence set can be highly variable. Both fining-upward and coarsening-upward log signatures characterize sandstone units within the interval. Despite the variability, isopach mapping and correlation of log signatures easily establishes these parasequences as deltaic and nearshore deposits (Ali, 1977; Coleman and Wright, 1975; Saxena, 1979; Serra, 1985). A common log pattern in the lowermost parasequences of the "Middle Morrow Clastics" is a smooth bell or serrated funnel shape that often coarsens and thickens-upward pattern. The pattern is typical of prograding mouth bar deposition over delta-marine fringe sands. The other common log pattern is the smooth or slightly serrated bell-shaped, fining-upward signatures of alluvial-deltaic point bar and distributary channel fill deposits.

The log signatures of uppermost parasequences in the "Middle Morrow Clastics" are less gradational. They are often characterized by abrupt changes in log character, signifying rapid termination or commencement of sand deposition. Most are generally massive sands that exhibit the typical coarsening-upward signature and a sharp fining-upward section. These are interpreted as beach-barrier bar deposits which resulted from rapid marine incursion and the reworking and winnowing of delta front and lower delta plain sand by wave-dominated processes. Some of the uppermost sandstone units in the "Middle Morrow Clastics" are not massive. These sand bodies often have sharp and scoured bases and their tops exhibit a thin, fining-upward log pattern. We interpret this signature as representing transgressive sands. Isopach mapping confirms this interpretation. Relatively thin carbonate units locally cap these sands. All sandstone units transition into interbedded marine fringe sands and shales in a southeasterly or basinward direction (Figs. 8 and 9).

Overlying the Morrow clastics is a 380 to 550 foot-thick sequence that was informally called the "Morrow Lime" or "Limestone" in earlier days (e.g. Casavant, 1986; Jons and Stanley, 1976). Later studies have assigned the name "Upper Morrow" to this carbonate-rich sequence (e.g. Carlile, 1997; Mazzullo and Mazzullo, 1987). The top of the Morrow Limestone is used as a structural datum throughout southeastern New Mexico. The unit represents an overall, transgressive event or highstand systems tract, and consists primarily of organic-rich, ramp carbonates and basinal shales. The lowermost portion of this thick transgressive unit contains several intervals of shallow-water oolitic facies that grade upward into the more massive and muddier, deep-water facies. The "Upper Morrow" represents a marked increase in the subsidence of the Delaware Basin. No facies analysis was completed on this non-reservoir interval.

Interpretation Techniques

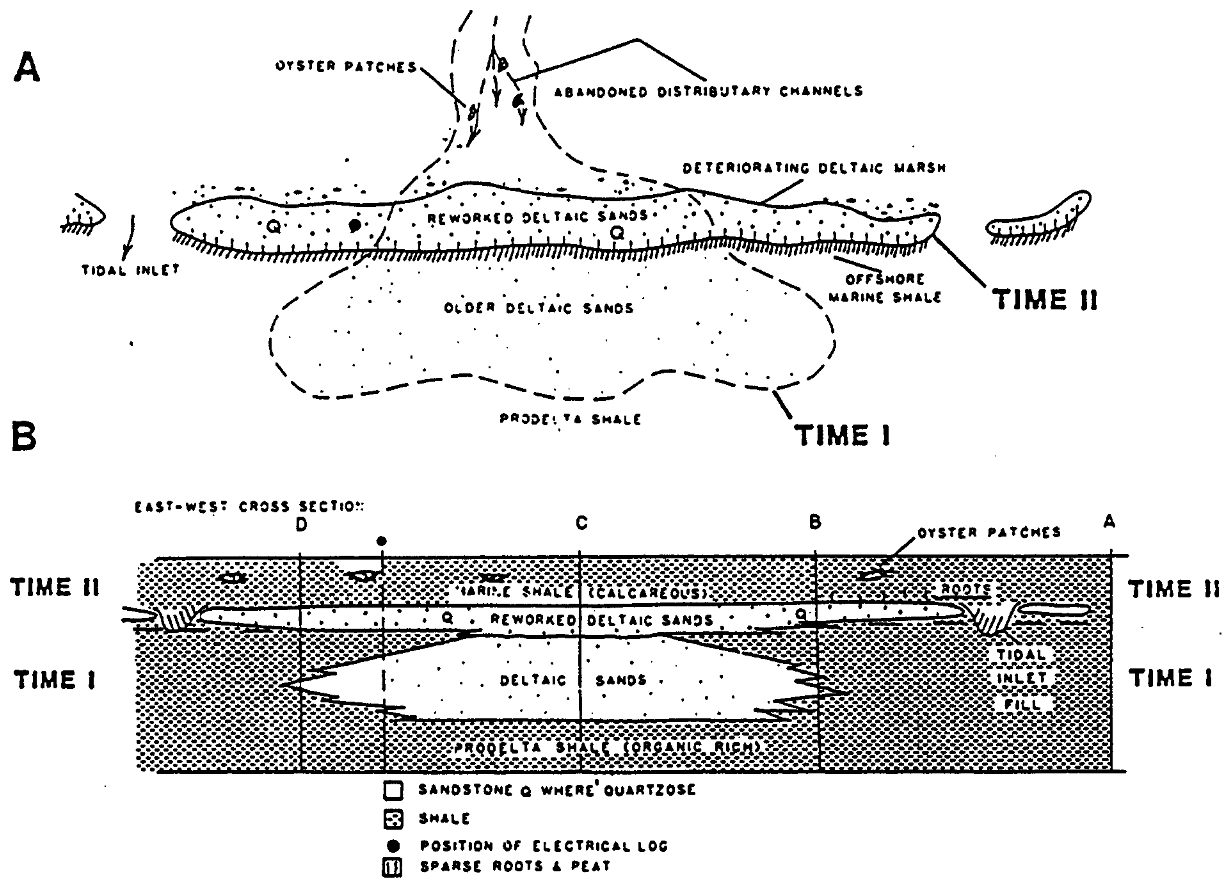
Slice mapping

Because of its pronounced structural closure, early development strategies in the WCP mostly involved targeting structurally up-dip positions in the area. However, a structural interpretation of the WCP confirmed earlier observations that moving up-structure did not always guarantee better Morrow production. This point is confirmed by the presence of some Morrow sandstones and production on the downdropped fault block. Good production in the WCP requires that wells also penetrate the greatest thickness of quality sandstone units (e.g. coarser channel and mouth bar sands). Any successful infill drilling program in the WCP had to increase reserves by tapping new, smaller sand lenses, and draining the more continuous sands that were behind pipe.

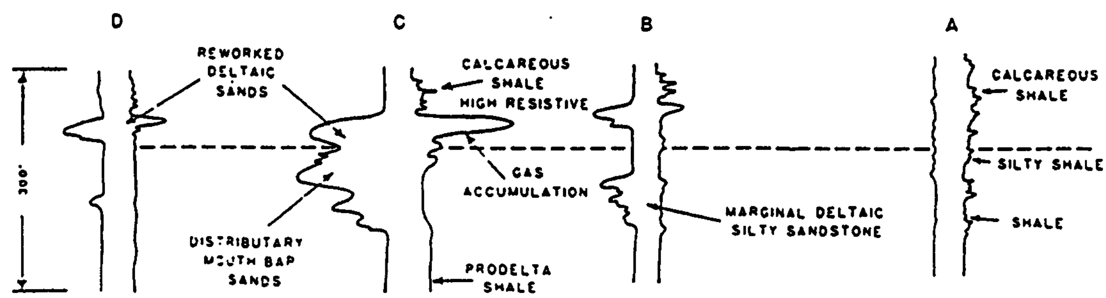
However, deposition of fluvio-deltaic and nearshore deposits is almost always characterized by frequent, and often abrupt, facies changes (e.g. Elliott, 1978; Morgan, 1970; Reading, 1978). Sediments accumulate, erode, and shift both spatially and temporally in response to relative changes in sea level and tectonic forces. Besides rapid lateral changes, the geologist and engineer must also deal with similar heterogeneity in the vertical plane. This three-dimensional exercise creates a challenge to interpreters when attempting to reconstruct the architecture of any deltaic sequence (Coleman and Wright, 1975; Elliott, 1978).

The WCP infill program depended largely on Gulf's ability to predict and illustrate the facies variations which translated into changes in reservoir quality and performance. To accomplish this task stratigraphic and structural analyses which included cross sections, net and gross sand isochore maps, structure maps, and a variety of engineering analyses were undertaken. In addition, a modified and underutilized "slice mapping" technique, developed in the late 1970s (Silver, 1980), was employed to capture the erratic distributions, geometries and orientations that typify the Morrow reservoir sandstones.

What is slice-mapping? Slice-mapping is a simple method of breaking down a complex three-dimensional data set into interpretable two-dimensional map products. The methodology is roughly the forerunner of the stratigraphic analysis technique known today as sequence stratigraphy (e.g. Sarg, 1988; Vail, 1987; 1991; Van Wagoner et al., 1990). Using well logs, cores, or outcrops, the goal of slice mapping is to map lateral facies changes within conformable, genetic stratigraphic intervals that are correlative — in other words, lithostratigraphic units that have a high probability of being lateral facies equivalents in space and time (i.e.



Depositional model for reworked deltaic sands. (A) Plan view setting, (B) Cross section geometry. Note the thickness variations and the differences of areal extent between the lower deltaic sands and the upper reworked sands.



An electric log cross section showing the lateral variation of sandstones in the reworked deltaic setting. This cross section is keyed to the lithologies in above. (After Saxena, 1979)

Fig. 12 Schematic example of the stratigraphic slice mapping concept. Note the interactive processing between cross-section and plan-view perspectives. (Modified from Saxena, 1979).

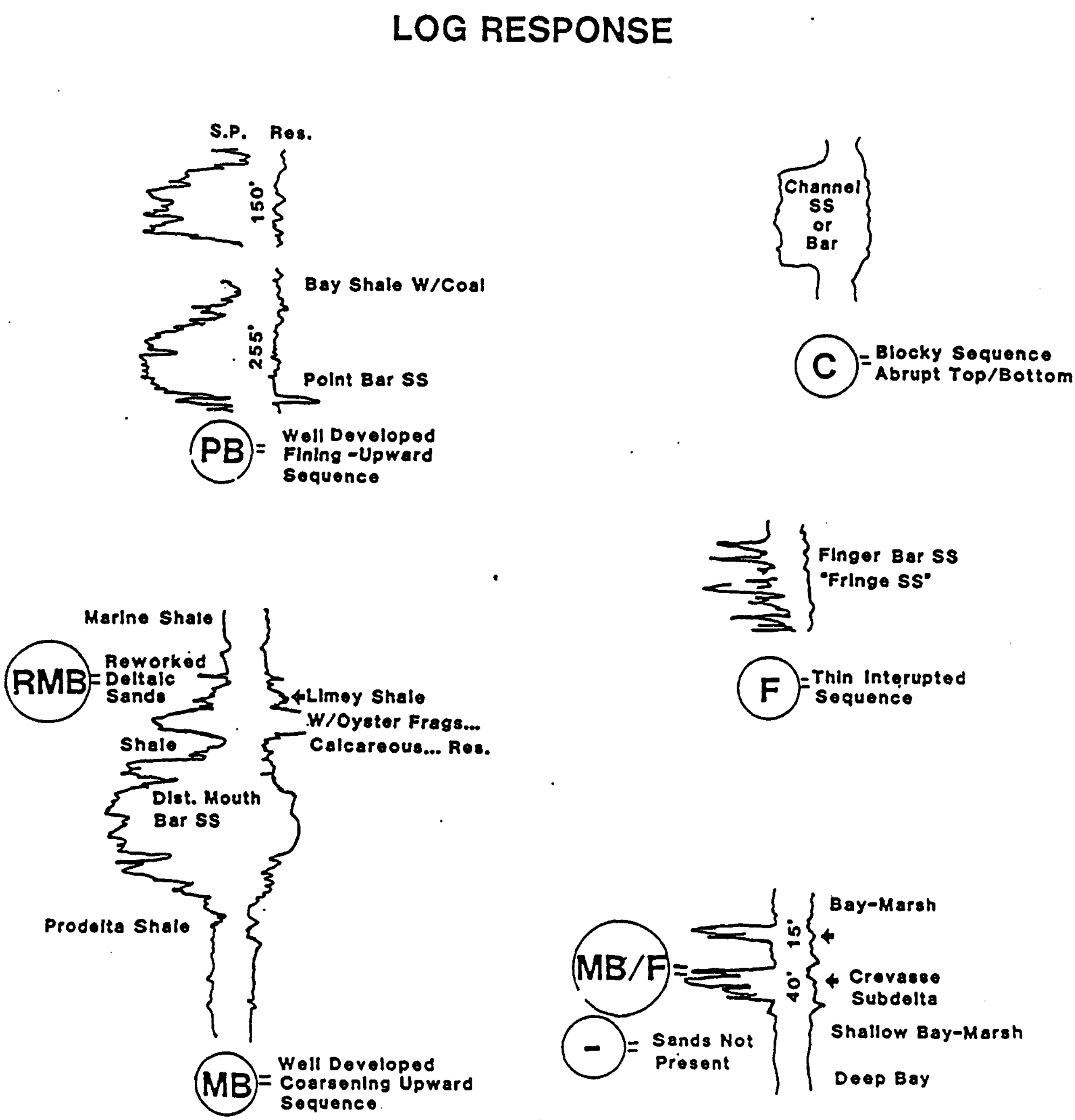


Fig. 13 In each well, gamma ray and resistivity well log responses for sandstone units were interpreted for each separate sandstone interval. Different log patterns are related to different depositional settings. This data was simplified, then plotted and used to construct a series of paleoenvironmental (facies) maps. PB = point bar, C = channel-like, MB = channel mouth bar and beach-barrier bar, RMB = reworked mouth bar, stacked thin barrier bar, MB/F = crevasse splay, mouth bar fringe, F = finger bar, delta fringe sands

chronostratigraphy) (e.g. Saxena, 1979; Silver, 1980) Fig. 12).

Map units are often defined by bounding surfaces such as unconformities, shared or related fossil marker bed assemblages, or well-defined rock units such as a transgressive marine shale, basal lag deposits or a terrestrial volcanic ash unit which exist across the area of study (Campbell, 1967; Galloway, 1989; Krumbein and Sloss, 1963; Loutit et al., 1988; Wilson, 1975). In the WCP, laterally persistent transgressive marine shales serve as the bounding units for each of the sand packages and aid in the determination of genetic units. Correlations that were not constrained by well logs and cuttings were guided by accepted models of ancient and modern analogs (Coleman and Prior, 1982; Curtis, 1970; Elliott, 1978; Ferm, 1970; Galloway, 1989).

Prior to 1980, industry and academic researchers had already developed detailed facies models of deltaic and nearshore clastic depositional environments and related these models to diagnostic well log patterns (e.g. Ali, 1977; Coleman and Wright, 1975; Saxena, 1979; Selley, 1974). Log patterns and cuttings and core can provide important information about a variety of paleoenvironmental factors that directly and indirectly controlled the distribution, orientation and internal geometry of deltaic deposits in an area. Such paleoenvironmental factors include climate, morphology, vegetation, water discharge, sediment load, river-mouth processes, waves, tides, winds, currents, shelf slope and the tectonics and geometry of the receiving basin (Coleman and Wright, 1975; Elliott, 1978; Morgan, 1970).

In the WCP the total Morrow clastics interval was subdivided or sliced into eight correlative sandstone intervals—labeled "A" through "H" (Fig. 11). For each well a facies interpretation was assigned to each of the sand intervals, depending on the predominant type of well log signature. Map symbols were assigned, denoting stacked or single coarsening-upward and fining-upward signatures, abrupt top and bottom sand contacts, thinly interbedded sequences referred to as fringe sands, and combinations of the above (Fig. 13). The detailed facies data was simplified and plotted across the study area for each slice map interval (Fig. 14). Paleoenvironmental maps were then constructed (Figs. 15a, 15b). Predictions or estimations of lateral facies changes were guided by well density, net sand isopach mapping (e.g. Fig. 16), and accepted depositional models.

What was powerful about the slice map approach was its simplicity of use. A three-dimensional "feel" for the distribution of lithologies and reservoir properties was almost always realized. The paleodeposition of the reservoir rock units could be viewed a layer at a time with movements or changes in their distribution and development noted for each slice. When the two-dimensional slice maps were stacked in vertical space, the orientations and geometry of the porosity and permeability distribution were easily understood in a three-dimensional sense. With today's sophisticated and commonplace three-dimensional interactive computer graphics and GIS programs, geoscientists and engineers can easily combine other data sets (e.g. structure, engineering data) with the facies maps, to gain an immediate visualization of reservoir connectivity and performance (e.g. Caldwell et al., 1984; Griesbach et al., 1986).

Morrow Facies Analysis and Paleoenvironmental Reconstruction

The primary objective of the slice mapping analysis was to illustrate the variability in distribution and geometry of the Morrow sandstones in the WCP. The following discussion presents interpretations derived from a sequence of paleoenvironmental maps that were constructed from facies analysis in each slice map interval (Figs. 15a, 15b). The WCP field outline has been illustrated in each figure for spatial reference.

Slice maps "A" through "D"

Based on the geometry, limited distribution and the progradational nature of the "Lower Morrow Clastics", we interpret the "A" and "B" sands in the WCP to represent distal deposits of a river-dominated delta. Isopach maps and cross-sections reveal that the these sandstone units trend mostly south-southeastward. A regional, west-east dip cross-section B-B' (Figs. 6 and 17) illustrates that the Lower Morrow "A" sand in the WCP-South Carlsbad area was deposited during a younger prograding cycle than the Lower Rock Tank Sand (Jons and Stanley, 1976). "A" sand deposition is generally characterized by narrow lobes or finger-like channel and mouth bar sands that trend slightly oblique and normal to the interpreted east-northeast-trending paleoshoreline for the region (Fig. 15a). The lobes pinch out to the west, south, and east further supporting the delta interpretation. Two delta lobes have prograded into the northwestern part of the WCP area. The "A" sand complex appears to be a distal extension of a larger deltaic system, located to the north outside the study area. Note that some distal areas of the "A" sand accumulation have been influenced by wave processes.

Transition to the slice map interval "B" appears to be include progradational, aggradational, and retrogradational movements of the sands depending on one's location within the field. In general, deposition in interval "B" reflects a similar orientation and style to that of "A", except that there appears to be less strandline deposition and the size of isolated and distal sand deposits are smaller. The positions of most of the sand fingers have changed. In particular, the 6-7 mile long, south-trending lobe along the western edge of the field boundary in interval "A" is absent during "B" time. Note also that the axis of the major prograding finger of sand in "B" is situated precisely between the position of the major sand lobes in the "A" interval. The delta supplied "B" sands to a topographic low that had formed between two previous "A" mouth bars—the result of the differential compaction of the interdistributary shales relative to the sands. This change in sand distribution reflects the processes of channel avulsion and delta lobe abandonment.

In the "B" interval, we also observed that sediment input into the WCP area had started to diminish. As a result, nearshore currents and waves reworked and transported sand out of the area during the final stages of "B" sand deposition. As the next two slice map intervals demonstrate, this starved shelf setting and backstepping of clastic units in the upper part of the "Lower Morrow Clastics" interval represents a retrogradational (transgressive) succession within the overall progradational sequence.

Geometries, orientation and composition of the Lower Morrow "A" and "B" sands infer a paleoenvironmental setting that was probably characterized by low-intermediate wave energy, low tidal range, low-moderate longshore drift, a low shelf slope, and a moderate, mostly fine-grained sediment yield. The distribution of sands in each of the "A" and "B" intervals approximates a pattern of sand bodies that resembles a hybrid delta classification somewhere between a Type 1 (fingered delta lobe) and a Type 4 (coalesced channel and mouth bar sands fronted by offshore barrier islands), as defined by Coleman and Wright (1970).

The slice map interval "C" (Fig. 15a) illustrates the final, but thickest interval of

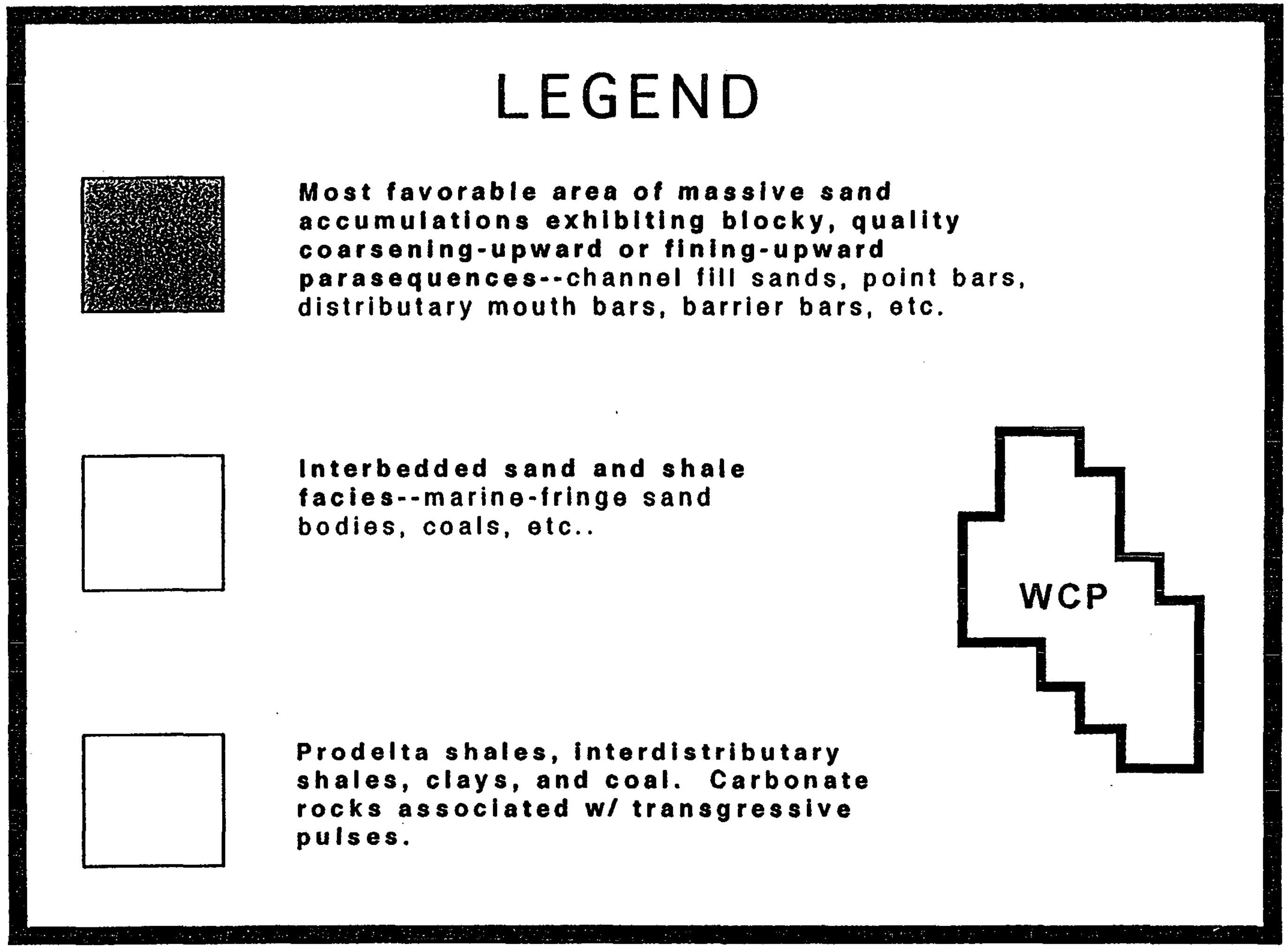


Fig. 14 Legend for the WCP paleoenviromental slice maps (Figs. 15a, 15b). Well locations and the field boundary provide a spatial reference for comparison between slice maps.

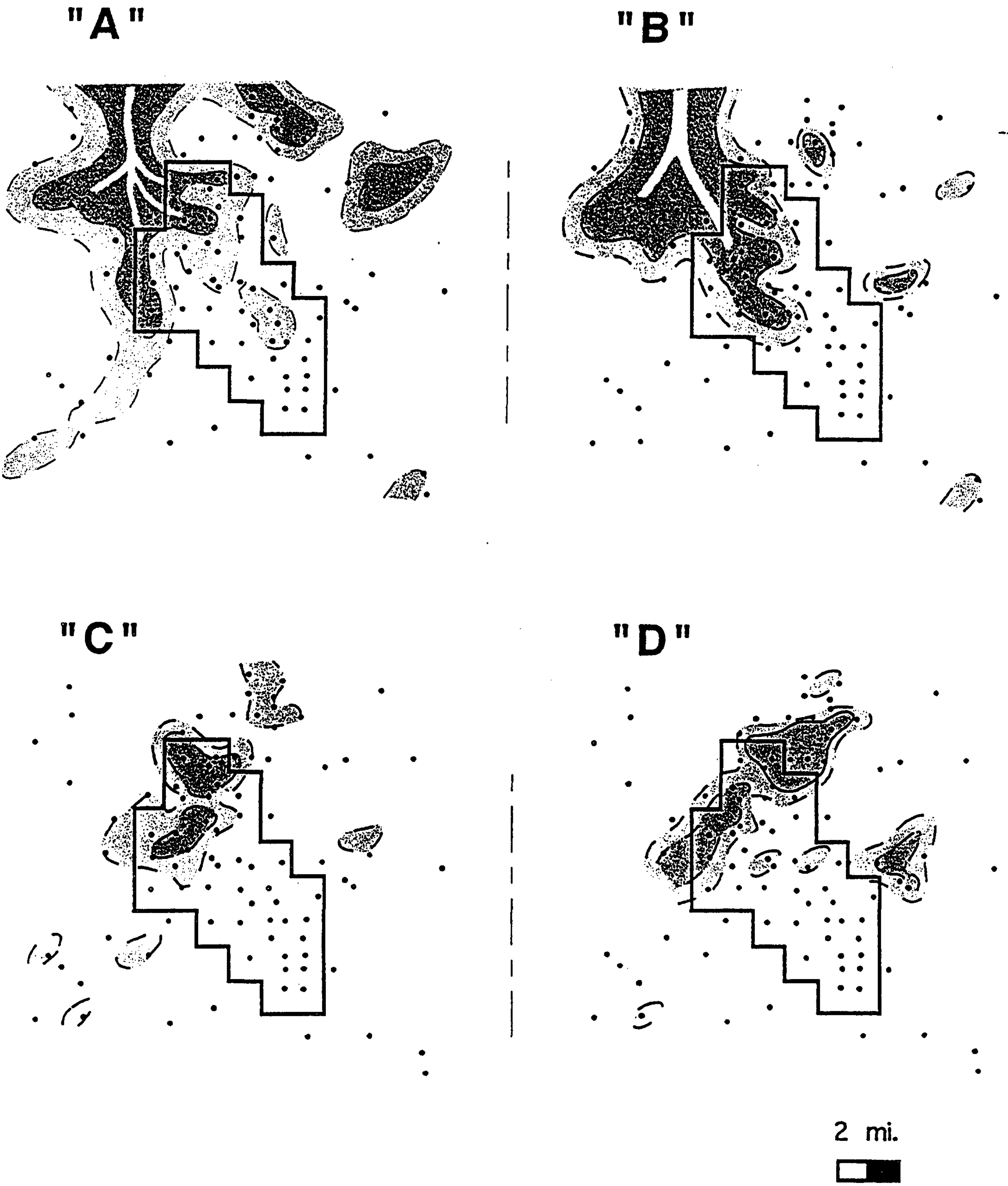


Fig. 15a Slice intervals map "A" through "C" represent deltaic parasequences in the Lower Morrow Clastics interval. Slice map interval "D" is synonymous with the Middle Morrow Shale parasequence. See text for detailed interpretations of map intervals.

sand deposition in the "Lower Morrow Clastics" parasequence set. This parasequence reflects the early stages of a regional transgressive event that was due either to a rise in eustatic sea level, or to local subsidence of the shelf as a result of distributary channel migration, lobe abandonment and compaction. Characterized mostly by low-resistivity marine shales and isolated linear sand masses which are oriented sub-parallel to the basin margin, the "C" sand interval reflects a transgressive systems tract that involved the deposition of wave-dominated sandstone bodies and culminated in the deposition of a condensed shale section in the base of the overlying Middle Morrow Shale or slice map interval "D".

The Middle Morrow Shale (slice map interval "D") separates the "Lower Morrow Clastics" from the overlying "Middle Morrow Clastics". This interval ranges in gross thickness from 60 to 90 feet and is almost entirely comprised of dark marine shales except in the most northwestern region of the field area, where an otherwise thin and poorly developed fringe marine sand abruptly thickens to 14 feet of pay sand (e.g. Wadi Petroleum Pennzoil Federal "9" Com. #2 well, in section 9-T24S-R26E). Note that the "D" sand accumulations appear even more strandline in appearance than those in the underlying "C" interval. Note too that the axis of the maximum sand development is located slightly shelfward, relative to the "C" sands. During the "D" interval the WCP occupied a position on a low gradient shelf that experienced little or no sediment input. The area experienced a maximum transgression as is characterized by a shale-rich parasequence that is bounded at its base by a highly radioactive shale bed that we interpret as a marine-condensed section that is floored by a maximum flooding surface. Towards the end of the transgression, the area experienced a short period of marine standstill as represented by the input of thin, erratic deposits of reworked fringe and outer shelf sands. Shoaling of deltaic sands was established during upper "D" time in the northwest part of the field. This transition from a deltaic setting into a shallow, wave-dominated shelf setting appears to be common cycle in the Morrow sandstones.

The consistency in trend and position of the "C" and "D" sand deposits suggests that a particular topographic feature localized sand deposition during both periods. It is also noteworthy that the axis of the reworked sand bodies in the "C" and "D" intervals to lies along a northeast-trending lineament. We note that this NE-orientation is also common to the sandstone of the overlying "Middle Morrow Clastics" interval. Although the northeast orientation of the delta front and barrier bars is considered by many geologists to simply represent the depositional strike of the basin margin in this area, the role of the basement architecture in defining the Morrowan shoreline and localizing delta and nearshore sands is suspected. This issue is currently under investigation.

Slice maps "E" through "H"

The thick "Middle Morrow Clastics" is an overall coarsening-upward parasequence set which contains at least four well-developed sand-rich parasequences. These parasequences form the basis of the slice map intervals "E" through "H" (Fig. 15b). These sandstones differ considerably from the lower sands in that they are thicker, exhibit better reservoir quality and are more widely distributed. Their distribution and facies relationships are remarkably similar to rock units that comprise highstand systems tracts which have been described on the Eastern Shelf of the Midland Basin in the upper Pennsylvanian and lower Permian (Galloway and Brown, 1972).

Cross sections and isopach maps illustrate that intervals "E" and "F" contain the thickest and best-developed sandstone bodies within the entire Morrow formation in the WCP area. These sandstones are also the best producers in the WCP. Sandstone bodies of "E" and "F" consist mostly of medium to coarse-grained, fairly sorted and subangular to subrounded sand grains that constitute distributary channel and distributary mouth bar deposits. The presence of thick and coarsening-upward sand bodies that are separated by thinner packages of alternating sands, silts, shales and coals is indicative of delta plain deposition. Stacked intervals of "smooth bell", "slightly serrate bell" and "smooth cylinder" shaped gamma ray-resistivity log patterns (Ali, 1977) are characteristic of point bars and distributary channel fill sands. Log patterns and sand body distributions also confirm the presence of distributary channel sands that trend normal to the shoreline, and by the presence of lower delta plain deposits that include interdistributary bay and coalesced mouth bar deposits. The presence of coals fragments (more common in the "E" sand) is indicative of rapid burial and little reworking of the sediments (Selley, 1976).

The first significant progradation of high-quality and coarse-grained reservoir sands is observed within the "E" sand interval (Fig. 15b). Sandstone units of the delta plain grade laterally into siltstones and mudstones and pinch out distally into marine shales of delta front and prodelta settings. It is noted that abundant and abrupt facies changes within the thick "E" sandstone units often correlate with significant variations in well performance within the WCP field. By the time the upper "F" sands are deposited, a marked reduction of clastic input has occurred. Consequently, in the eastern part of the field, many of the uppermost "F" sands exhibit diagnostic "multiple serrated funnel" shaped and "multiple smooth funnel" shaped log responses that are diagnostic of a delta-marine fringe setting (Ali, 1977). Environmental conditions during "E" and "F" time most likely included low to intermediate wave energy, low tidal ranges, moderate longshore drift, and moderate to high sediment yield across a shallow stable shelf.

Two relatively thick, transgressive marine shale packages occur at the top of the "E" and "F" sand intervals. Each averages approximately 25 feet in thickness. Interestingly, their log signatures appear remarkably similar tin character to that of the Middle Morrow Shale or slice map interval "D", however, they are not as radioactive. The lowermost portion of each of these shale units contains a 6 to 10 foot-thick shale unit that exhibits a very abrupt base (scoured surface?). A condensed marine shale section, containing a maximum flooding surface at its base is also interpreted for these two shale intervals. More often than not, they exhibit a coarsening-upward signature that is gradational with the lower fringe sands of the "F" and "G" intervals.

Well-developed "G" and "H" sands are present throughout all of the WCP unit area. The majority of the sandstones in the "G" and "H" slice map intervals are composed of fine- to medium-grained, well-sorted and subrounded quartz sands. Intervals "G" and "H" appear to be mostly aggradational in nature. Interval "H" actually represents a parasequence set, or compilation of several stacked sand bodies, that vary in character and thickness from marine fringe sands that are 6 feet thick to moderately well-developed barrier bar sand bodies that thicken up to 35 feet. The stacked subunits of the "H" interval were treated as one unit in the study for simplicity sake, since there was little difference in the distributions and orientations of the individual sands throughout the gross interval.

The difference in sandstone distribution between the "G" and "H" intervals and the

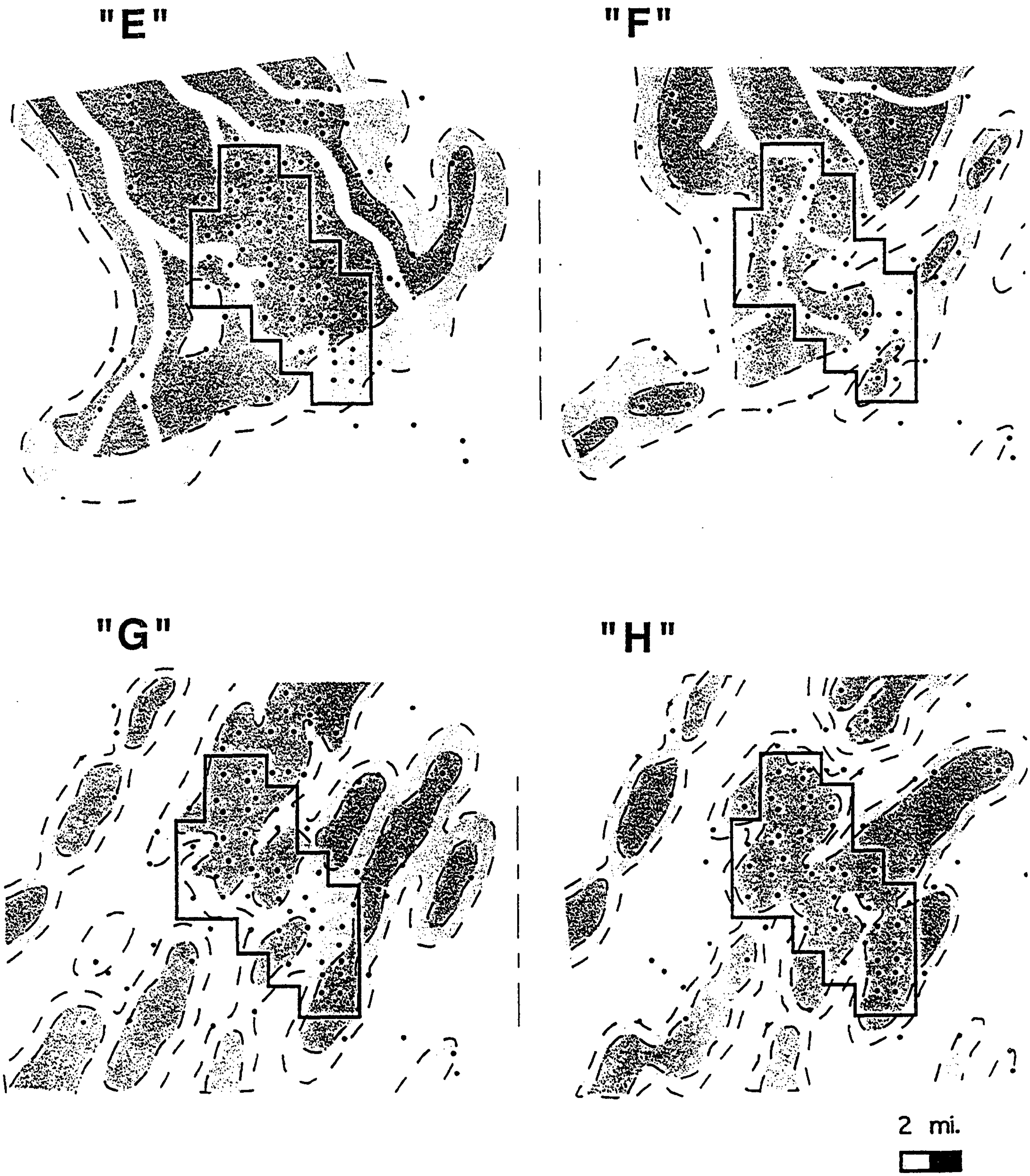


Fig. 15b Slice intervals map "E" through "H" represent the thick and well defined sandstones of the Middle Morrow Clastics interval. See text for detailed interpretations of map intervals.

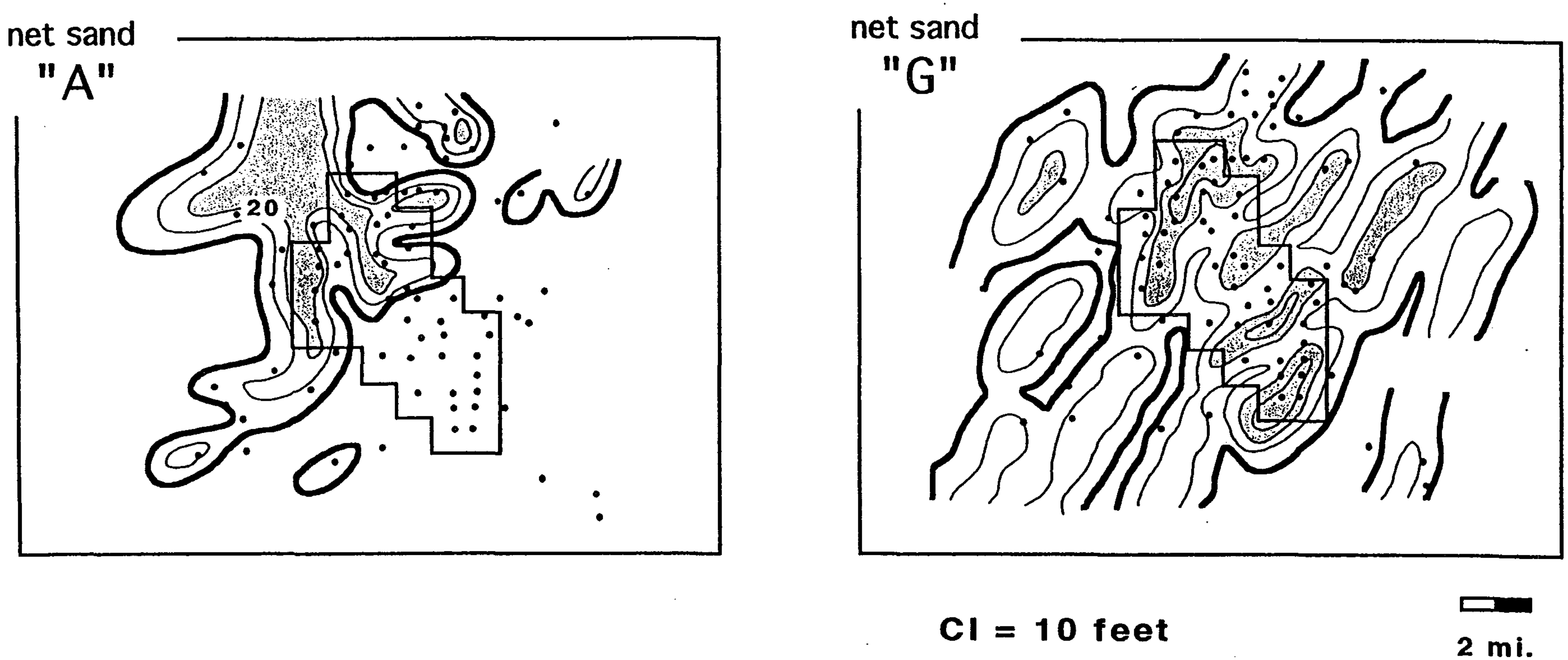


FIG. 16 NET ISOPACH MAPS VERIFY THE GEOMETRY AND QUALITY OF SANDSTONES AS DETERMINED BY THE PALEOENVIRONMENTAL SLICE MAPS. THESE MAPS WERE USED IN COMBINATION TO ENHANCE THE SELECTION OF INFILL WELL LOCATIONS AND TO BETTER CHARACTERIZE WELL PERFORMANCES.

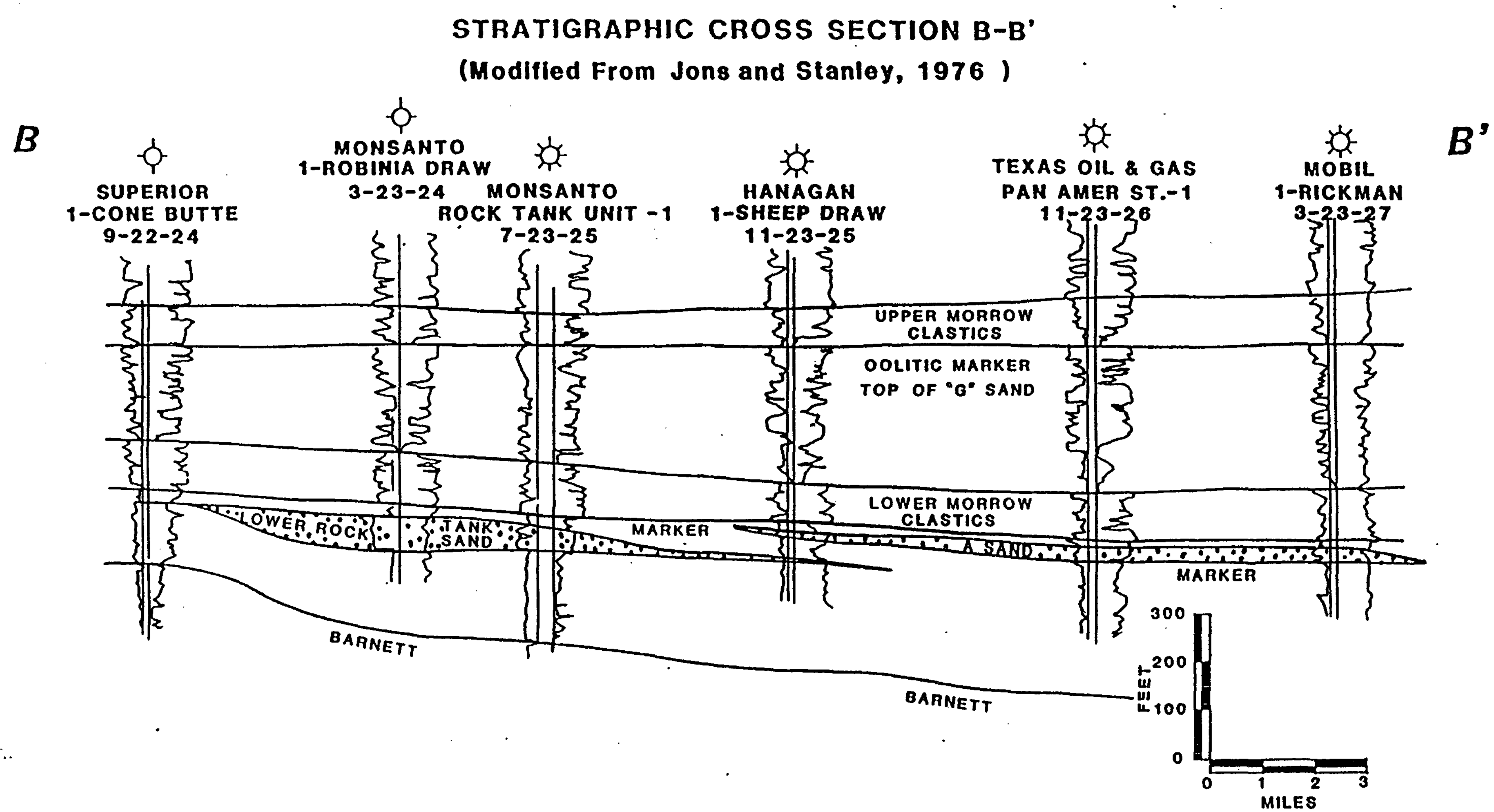


Fig. 17 West-east stratigraphic cross section B-B' in Figure 6. Profiles of the "Lower Rock Tank Sand" and the "A" sand in South Carlsbad Field appear to be deltaic, based on log profiles, sediment type and sand body geometry. The South Carlsbad Field (a northern extension of the WCP) appears to be a younger prograding cycle.

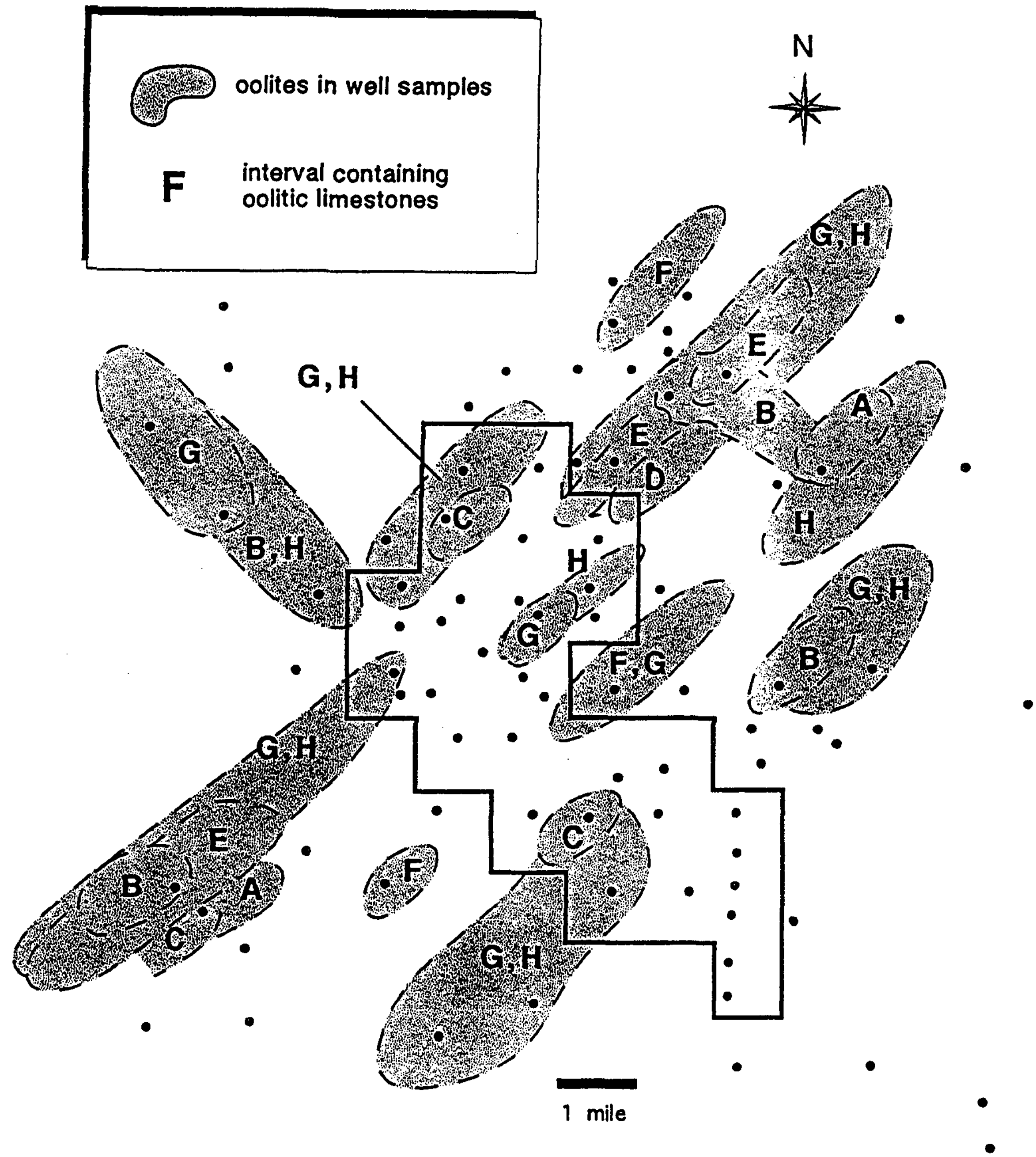


Fig. 18 This figure shows an approximate distribution of shallow-water carbonate grainstones (dominated by oolitic limestone) in the study area. They occur as thin units within the upper portions of every sand-rich interval or parasequence within the Morrow Clastics. Note that the greatest frequency and distribution occur in the uppermost "G" and "H" sands of the Middle Morrow Clastics. A strong orthogonal, linear organization to their distribution matches that of known fault trends, suggesting that like the sands, their deposition is related to a structurally-controlled shelf topography.

underlying "E" and "F" intervals is significant. The distribution pattern of "G" and "H" sandstone bodies reflect laterally persistent barrier-bar sands that are the product of reworking and redistribution of distal deltaic sediments during the early phases of a major transgressive episode. The change in distribution mimics the evolution from Type 3 to Type 5 sand patterns that occur in typical modern-day wave-dominated deltas as categorized by Coleman (1975). During "G" and "H" times, environmental conditions included moderate to high persistent wave energy, moderate longshore drift, low-moderate sediment yields and a slightly steeper shelf gradient.

In total, the highly variable composition and distributions of Morrow sandstones are the products of cyclic progradational, aggradational, and backstepping or retrogradational modes of deposition which took place within the WCP region. Progradation and retrogradation of Morrow sandstones have been recognized in other gas fields in southeastern new Mexico .(e.g. Carlile, 1997; Jons and Stanley, 1976).

Carbonate facies within the Morrow Clastics interval

A variety of shallow-marine carbonate rocks, ranging from mudstones to grainstones, have be found in the upper portions of every Morrow sandstone parasequences in the WCP (e.g. Fig. 8). However, the thickest and most abundant carbonate deposits are concentrated in the upper sections of the "G" and "H" intervals. This carbonate deposition coincides generally with the brief transgressive cycles or periods of standstill that characterized by shallowing conditions, increased wave action and subsequent winnowing of fine-grained materials at the closing stages of each sand deposition.

Carbonate mudstones and wackestones facies are usually encountered on the landward and lateral flanks of sand bars and range in total thickness from less than 3 feet to more than 38 feet in the "C" interval and 60 feet in the "H" interval. They range in color from tan and brown to dark gray and contain fusilinids, crinoids, and chert.

In contrast, grainstone deposits of mostly oolitic limestones, appear to be spatially associated with the topographic highs and seaward flanks of beach-barrier-bar sands where wave activity and shoaling processes would have dominated. Well cutting descriptions of the sands immediately beneath the oolitic members indicate that the sands are well sorted, coarser-grained and contain more rounded grains relative to adjacent facies—suggesting an association between beach-barrier bar formation and oolite deposition (Fig. 18). Crinoid-rich units are often noted to be intermixed with the oolitic facies on the seaward flanks of some paleotopographic highs. The distribution of a few oolitic limestone deposits that trend normal to the paleoshoreline in slice map intervals "B", "G" and "H", could reflect shoaling on top of tidal ridges or former channel levee deposits (Fig. 18). They could be oolite sediments that were deposited landward in tidal channels.

The spatial coincidence and predominance of northeast-trending oolite deposition throughout the entire Morrow Clastics interval and orthogonal linear organization to their distribution could be structurally-controlled. Their distribution does match known and inferred fault trends. This relationship is currently being investigated.

Engineering Analysis

An engineering study of all the wells in the WCP was made to determine the areal extent that hydrocarbons were being drained in the Pennsylvanian formations. Reservoir parameters used in the analysis were compiled from log data, completion data, drill stem test information, well performance curves, and P/Z (bottom hole pressure vs. time) curves. The data covered the period of time from the completion of the discovery well in April, 1960, up to approximately January, 1981.

The analysis demonstrated that the average drainage per well in this gas field was 257 acres. An original gas in place (OGIP) per acre was computed and then compared with the OGIP obtained from actual well performance as seen on P/Z curves. From this comparison, the calculated drainage per well was obtained. Pressure versus time plots were prepared for each well in the field. Well plots were then partitioned into three geographical sections and displayed.

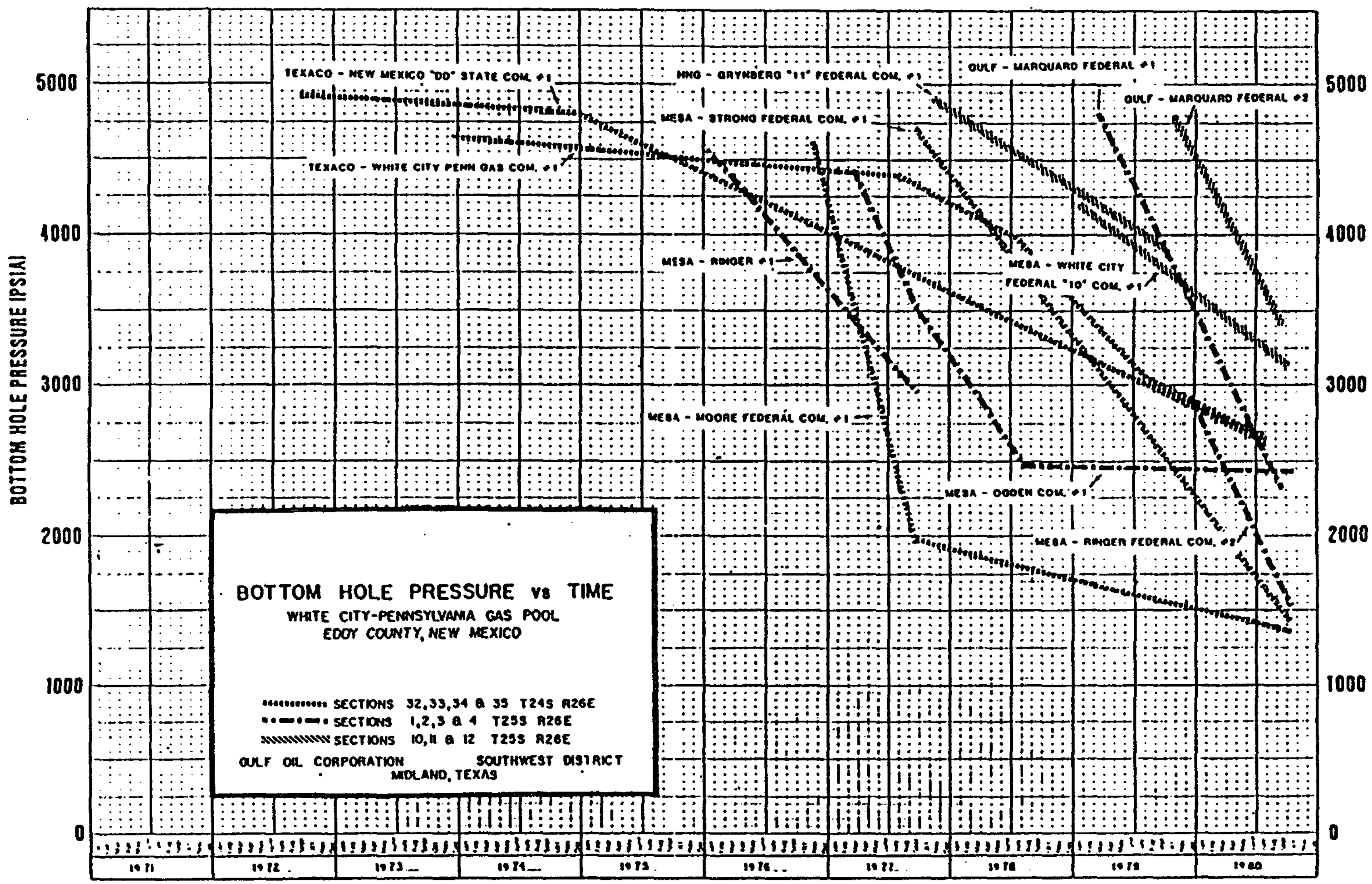
Figure 19 illustrates some of well plots in the southern part of the field. Observed is a lack of interference between offset wellbores. As new wells were drilled, almost all initially were at or near virgin reservoir pressure. This was the case for most throughout the field. Note also the considerable variation in the bottom hole pressure of offset wellbores. Such plots verified that the connectivity of reservoir units was lower than previously thought, and that the Morrow sandstones reservoirs were not being effectively drained. An expected average ultimate gas recovery per well of 4.01 billion cubic feet was obtained from extrapolation of P/Z plots. It was estimated from this analysis that the drilling of WCP infill wells would recover at least an additional 1.48 billion cubic feet of gas per well.

Morrow Sandstone Reservoir Properties

Based on well logs, the thickness of the individual productive sandstone bodies ranges from 5 to 55 feet. The average thickness is 8 feet. Reservoir porosity varies from 5 to 20 percent with the average being 9 percent. Permeability varies from less than 1.0 millidarcy to 50 millidarcies, the former being the most prevalent. Water saturation averages 30 percent, but ranges from less than 10 percent to 47 percent.

Detailed petrographic analyses of well cuttings and cores from Morrow sandstones in southeastern New Mexico (e.g. Kauffman, 1974a) reveal that the sands are composed of 50-95 percent white monocrystalline quartz. They are poorly to well sorted, subangular to subrounded, and fine to coarse grained. The sandstones contain minor amounts of glauconite, calcite, feldspars, micas, pyrite, biotite, horneblende, zircon, and various clays, predominantly kaolinite and montmorillonite with traces of illite and chlorite (Kauffman, 1974a; Kauffman, 1974b; Mazzullo and Mazzullo, 1987). Some portions of the grains are strained, while others are minutely fractured, crushed or sheared. Occasional pressure solution and sutured contacts are observed (Kauffman, 1974a). Feldspars are present and include microcline, albite-oligoclase, and rare orthoclase, but constitute less than 3 percent of the total rock composition (Kauffman, 1974a). These petrographic analyses reveal that the parent rocks were granites and granite gneisses.

Pieces of coal and very carbonaceous materials are occasionally observed in well cuttings. Carbonates are present in most of the intervals and are second only to the quartz component in their abundance and distribution. Of the carbonate types observed, calcite dominates over dolomite and is both interstitial and matrix (Kauffman, 1974a). Lithologic units are moderately-consolidated to well-consolidated with calcite and quartz as the most prevalent cements. Shales are present as very thin laminae. Cements and clays reduce porosity and permeability by filling intergranular pores and increasing the specific surface area and tortuosity of the sands (Fig. 20) (Neasham, 1977; Wilson and Pittman, 1977). However, a certain amount of



SOUTHERN PART - WCP GAS POOL

Fig. 19 Pressure versus time plots of wells in the southern portion of the WCP. The plot illustrates the lack of interference between offset wellbores. Considerable variation in the bottom hole pressure of offset wellbores can also be seen. New wells drilled in the field exhibited near-virgin reservoir pressures.

Fig. 20 Scanning electron microscope image (magnification 2500x) of a Morrow reservoir sandstone. Gas flows through a tortuous and fragile network of authigenic carbonate and silica cements and detrital and authigenic clay particles. Clay platelets (kaolinite) and mixed-layered clay-coated sand grains are shown. Porosity and permeability are greatly reduced if proper drilling and completion practices are not employed when developing the Morrow sandstones.

secondary porosity in the Morrow sands is also derived from the leaching of cements, particularly the carbonate cements.

The considerable variation in physical properties and composition of the Morrow reservoir sandstones translates into a wide range in reservoir performance. Table 1 summarizes the reservoir properties in the WCP.

Drilling & Completion Issues

The Morrow sandstones are extremely sensitive to many typical drilling and completion practices. They contain a variety of authigenic and detrital clays, mobile particles or "fines", carbonate material, and other matter including iron-bearing minerals. Since cements and clays in the Morrow can reduce porosity and permeability, by filling intergranular pores and increasing the specific surface area and tortuosity of the sands (Fig. 19). Significant filtrate damage can occur if drilling fluids are not weighted properly or treated with low water loss additives (e.g. a brine polymer fluid containing a 2-5% potassium chloride mixture or an oil-based mud). Furthermore, intergranular clays such as montmorillonite can swell up and greatly reduce permeability within the sandstones. Some operators add a water-wetting surfactant for additional water-blocking prevention (Kornfeld, 1973). For the Morrow sandstones, many operators strive to maintain a water loss of less than 7.5 % of total fluid volume to the formation.

The wrong type of drilling fluid can also mobilize clay "fines" such as kaolinite platelets and particles of illite crystals which are broken off or dislodged and travel through the reservoir, clogging pore throats and reducing reservoir permeability. Deposition of these detrital clays in a permeable medium also reduces the macroscopic porosity (Neasham, 1977; Panda and Lake, 1995). If acid systems or oxygen scavengers are not used, iron hydroxides can also precipitate. These components also block pore throats and severely damage the productivity of the near borehole environment.

When a Morrow well is completed, determination of the correct production rate is also critical. If the fines are pulled too hard, flow channels such as pore throats and minute fractures can become clogged too quickly and permeability is reduced. Similar damage has sometimes resulted when drill stem test tools were released and extracted from the potential intervals.

In drilling to the Morrow, the Wolfcamp, and Pennsylvanian Strawn and Atoka formations are penetrated. In some locales these formations are overpressured. This is especially common for the Atoka Formation which has been the cause of many well kicks, and in some instances, deadly well fires. Therefore, drilling fluids are carefully monitored for quality and are gradually weighted-up and other safeguards prepared (e.g. loss circulation materials on hand) when drilling through these intervals. Casing is set in the Morrow limestone and drilling proceeds into the Morrow sandstone intervals with treated, light-weight fluids.

Most Morrow sandstones are either completed natural, or are given small acid or acid/fracture treatments to enhance near-well permeabilities. The reservoir sands are perforated overbalanced. During the 1980s some operators set a "burst disc" above the perforated interval. The overlying fluid was then swabbed out. An iron "bar" was dropped and the disc broken, causing the well to surge on.

Another method of completion which was commonly employed during the early- to mid-1980s, involved what was called the "Van Assembly". Its configuration allowed for the potential reservoir interval to be isolated and perforated underbalanced and produced through the same downhole assembly—minimizing both borehole damage and costs. A common method of completion was (and is) simply to swab the well in with any one of a variety of treated completion fluids after perforating with a casing gun. If low permeabilities were encountered as a result of the presence of finer-grained sandstones, then small interval-specific acid/fracture treatments were often applied. The economics and/or the predicted formation damage were the major factors that determined the completion method that was used.

It is probable that completion practices have evolved since our study as a result of improved technologies and knowledge. Table 2 is a summary list of the major drilling and completions issues that were associated with Morrow development during the previous three decades.

Conclusions

In 1980 the major WCP unit operator, Gulf Oil Exploration and Production Company, undertook a detailed geological-engineering reservoir characterization of the erratic Morrow sandstones in the WCP-Black River-South Carlsbad area. The study utilized a "slice mapping" technique to characterize the reservoir sands.

Significant results of the study were as follows:

1) The company gained an enhanced understanding of facies, depositional environments, reservoir heterogeneity and production characteristics of the complex Morrow reservoir sands.
2) The previously suspected insufficient drainage of Morrow reservoirs with one well per 640 acres was demonstrated conclusively.
3) The planning and design of reservoir management strategies was aided and became more efficient and successful than in the past.
4) The study was instrumental in obtaining approval from the New Mexico Oil Conservation Division to change the pool rules to allow a second well to be drilled on a 640-acre proration unit.
5) Subsequent infill drilling verified the study's conclusions.

Since 1981 the total number of wells in the WCP increased from twenty-four to forty-four. Fifteen infill wells have been drilled within the former unit boundary, and five adjacent sections, containing six wells, have been annexed to the WCP Pool. The total production added to the WCP since 1981 from annexation and infill drilling is approximately 47.5 billion cubic feet of gas, 20,000 barrels of condensate, and 118,308 barrels of water; thus the average per well cumulative for these additional wells is approximately 2.3 billion cubic feet of gas, 949 barrels of condensate and 5,634 barrels of water. In other words, the infill/expansion program added approximately 30% more gas, 40% more condensate and 38% more water to the total field production.

As of April 1, 1999, eight operating companies produce gas and condensate from 38 active wells. Six wells are currently shut-in. Total field cumulative production is approximately 166 billion cubic feet of gas, 51,000 barrels of condensate and only 332,000 barrels of water from the Morrow and a few Atoka sandstones. The current average cumulative production per WCP gas well is approximately 3.8 billion cubic feet of gas, 1,160 barrels of condensate and 7,545 barrels of water. The current average daily production per well is approximately 200,000 cubic feet of gas (it appears that some operators are in the "caretaker mode"). Of the forty-four WCP wells, thirty have cumulative