FOSSIL ENERGY

DOE/BC/15026-4
(OSTI ID: 784573)

SEQUENCE STRATIGRAPHIC ANALYSIS AND FACIES ARCHITECTURE OF THE CRETACEOUS MANCOS SHALE ON AND NEAR THE JICARILLA APACHE INDIAN RESERVATION, NEW MEXICO—THEIR RELATION TO SITES OF OIL ACCUMULATION

Final Report
January 22, 1998-March 31, 2000

By:
Jennie Ridgley

Date Published: August 2001

Work Performed Under Contract No. DE-FG26-98BC15026

U.S. Geological Survey
Denver, Colorado

National Energy Technology Laboratory
National Petroleum Technology Office
U.S. DEPARTMENT OF ENERGY
Tulsa, Oklahoma

DOE/BC/15026-4
Distribution Category UC-122

Sequence Stratigraphic Analysis and Facies Architecture of the Cretaceous Mancos Shale on and Near the Jicarilla Apache Indian Reservation, New Mexico—Their Relation To Sites of Oil Accumulation

By
Jennie Ridgley

August 2001

Work Performed Under DE-FG26-98BC15026

Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

Virginia Weyland, Project Manager
National Petroleum Technology Office
P.O. Box 3628
Tulsa, OK 74101

Prepared by
U.S. Geological Survey
MS 939 Box 25046DFC
Denver, CO 80225

TABLE OF CONTENTS

List of Figures

List of Tables

List of Plates

ABSTRACT

Oil distribution in the lower part of the Mancos Shale seems to be mainly controlled by fractures and by sandier facies that are dolomite-cemented. Structure in the area of the Jicarilla Apache Indian Reservation consists of the broad northwest- to southeast-trending Chaco slope, the deep central basin, and the monocline that forms the eastern boundary of the San Juan Basin. Superimposed on the regional structure are broad low-amplitude folds. Fractures seem best developed in the areas of these folds. Using sequence stratigraphic principals, the lower part of the Mancos Shale has been subdivided into four main regressive and transgressive components. These include facies that are the basinal time equivalents to the Gallup Sandstone, an overlying interbedded sandstone and shale sequence time equivalent to the transgressive Mulatto Tongue of the Mancos Shale, the El Vado Sandstone Member which is time equivalent to part of the Dalton Sandstone, and an unnamed interbedded sandstone and shale succession time equivalent to the regressive Dalton Sandstone and transgressive Hosta Tongue of the Mesaverde Group.

Facies time equivalent to the Gallup Sandstone underlie an unconformity of regional extent. These facies are gradually truncated from south to north across the Reservation. The best potential for additional oil resources in these facies is in the southern part of the Reservation where the top sandier part of these facies is preserved. The overlying unnamed wedge of transgressive rocks produces some oil but is underexplored, except for sandstones equivalent to the Tocito Sandstone. This wedge of rocks is divided into from two to five units. The highest sand content in this wedge occurs where each of the four subdivisions above the Tocito terminates to the south and is overstepped by the next youngest unit. These terminal areas should offer the best targets for future oil exploration. The El Vado Sandstone Member overlies the transgressive wedge. It produces most of the oil (except for the Tocito Sandstone) from the lower Mancos. In the central and southern part of the Reservation, large areas, currently not productive or not tested, have the potential to contain oil in the El Vado simply based on the trend of the facies and structure. There has been little oil or gas production from the overlying regressive-transgressive wedge of rock and much of this interval is untested. Thus, large areas of the Reservation could contain hydrocarbon resources in these strata.

Most of the Reservation lies within the oil generation window based on new Rock-Eval data from the Mancos Shale just south of the southern part of the Reservation. If these observations are valid then oil could have been generated locally and would only have needed to migrate short distances in to sandy reservoirs and fractures. This does not rule out long distance migration of oil from the deeper, more thermally mature part of the basin to the north. However, low porosity and permeability characterize sandier rocks in the Mancos, with the exception of Tocito-like sandstones. These factors could retard long distance oil migration through the sediment package, except through fracture or fault conduits. Thus, it is suggested that future oil and gas explorations in the Mancos treat the accumulations and reservoirs as unconventional and consider whether the source and reservoir are in closer proximity than has previously been assumed.

INTRODUCTION

The purpose of phase 1 and phase 2 of the Department of Energy funded project Analysis of oil- bearing Cretaceous Sandstone Hydrocarbon Reservoirs, exclusive of the Dakota Sandstone, on the Jicarilla Apache Indian Reservation, New Mexico was to define the facies of the oil-producing units within the Mancos Shale and interpret the depositional environments of these facies within a sequence stratigraphic context. As currently defined, there are two principal intervals of oil production within the Mancos Shale. The bulk of the oil production comes from sandy facies in the lower part of the Mancos in what is termed by drillers as the "Gallup sandstone" or El Vado Sandstone; lesser production is from fractured shale. The focus of this report will center on 1) redefinition of the areal and vertical extent of the "Gallup sandstone" or El Vado Sandstone Member of the Mancos Shale (Fassett and Jentgen, 1978), 2) determination of the facies distribution within the "Gallup sandstone" and other oil-producing sandstones within the lower Mancos, placing these facies within the overall depositional history of the San Juan Basin, 3) application of the principals of sequence stratigraphy to the depositional units that comprise the Mancos Shale, and 4) evaluation of the structural features on the Reservation as they may control sites of oil accumulation. Discussion of the above is found in the text below and in a series of five cross sections (plates 1-5), one structure map (plate 6), and one appendix. The appendix includes a set of logged cores through various intervals in the Mancos and photographs of the core.

REGIONAL GEOLOGY

The Jicarilla Apache Indian Reservation is located on the northeast side of the San Juan Basin in northwestern New Mexico (fig. 1). The Reservation boundary is irregular and because of this both geologic formations and structural elements cross the Reservation at odd angles. As a result of the orientation of both the geology and structural features with respect to the Reservation boundary, certain facies are not always present within the Reservation confines, although they may be present in areas adjacent to the Reservation. Similarly, structural features may lie wholly or partially within the Reservation or be totally absent, although they occur in adjacent areas. Outcrops of Cretaceous rocks that are the focus of this investigation are confined to the northeast side of the Reservation.

STRATIGRAPHY

Upper Cretaceous rocks that crop out on and near the Reservation in ascending order include: Dakota Sandstone, Mancos Shale, Dalton Sandstone Member of the Crevasse Canyon Formation, Mesaverde Group, Lewis Shale, Pictured Cliffs Sandstone, Fruitland Formation, and Kirtland Shale. The stratal relationships of those formations addressed in this report are summarized in figure 2. Some of these formations are present only south of the Reservation. Summaries of the Cretaceous formations can be found in (Fassett, 1974; Landis and Dane, 1967; Landis and others; 1974; Molenaar, 1974; 1977). Only rock units in the interval from the base of the Bridge Creek Limestone Member of the Mancos Shale through the top of the Mancos Shale will be treated more fully below. This interval is marked by intertonguing relations between the Mancos Shale and several clastic formations. Their relationships to the overall San Juan Basin stratigraphy are shown in figure 3.

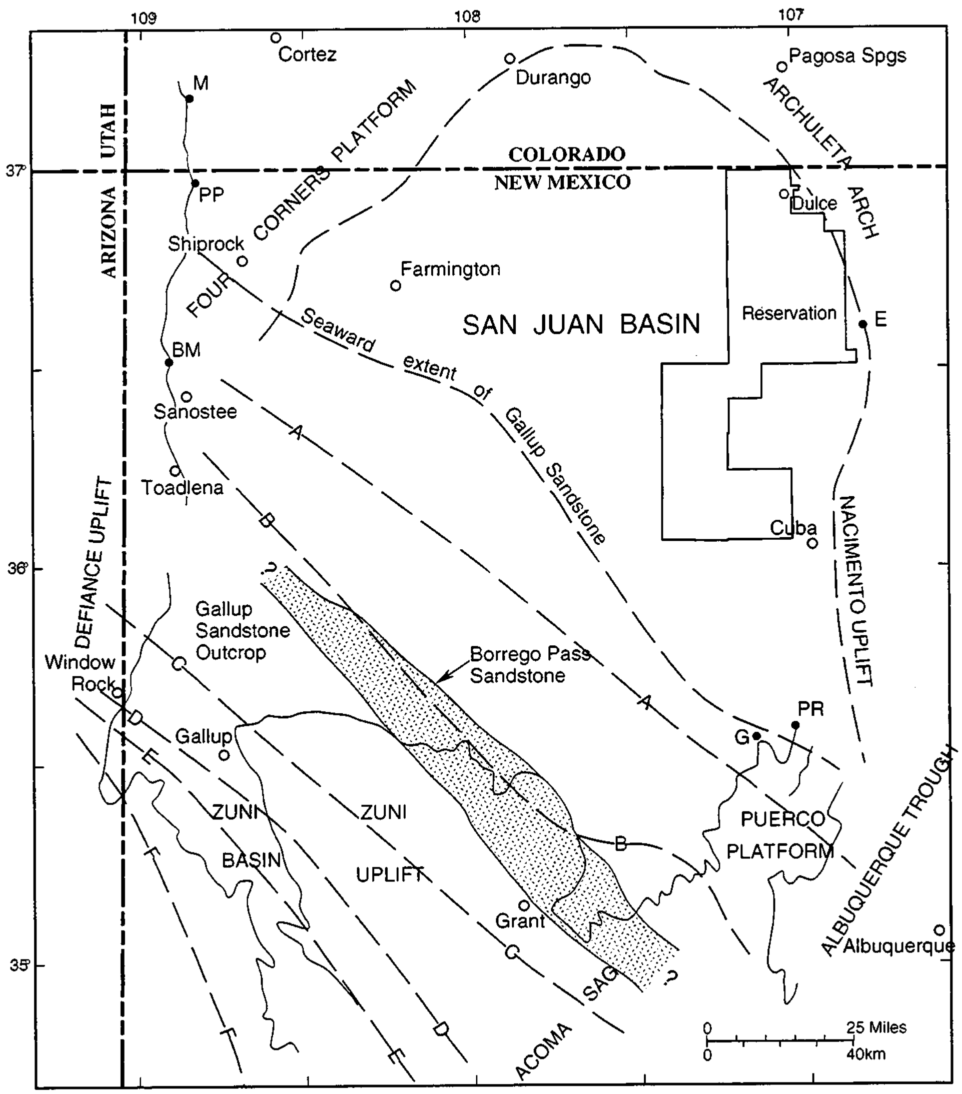


Figure 1. Map of the San Juan basin showing position of the Gallup A - F shorelines, Jicarilla Apache Indian Reservation and location of outcrops discussed in the report. M, Mounds outcrop; p, Plunge pool outcrop; BM, Beautiful Mountain outcrop; G, Guadalupe outcrop; outcrop; PR, pipeline road outcrop; and E, El Vado Reservoir outcrop. Modified from Molenaar (1973, 1983).

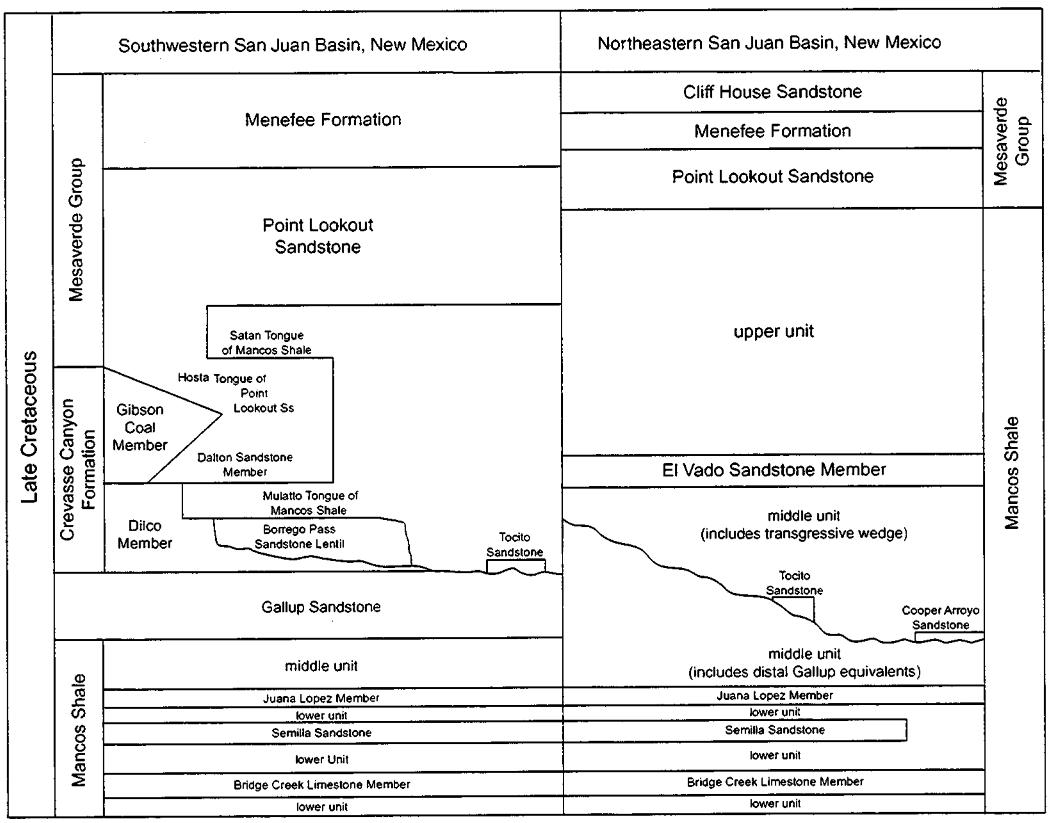


Figure 2. Chart showing correlation of selected Cretaceous formations in the southwestern and northeastern part of the San Juan Basin.

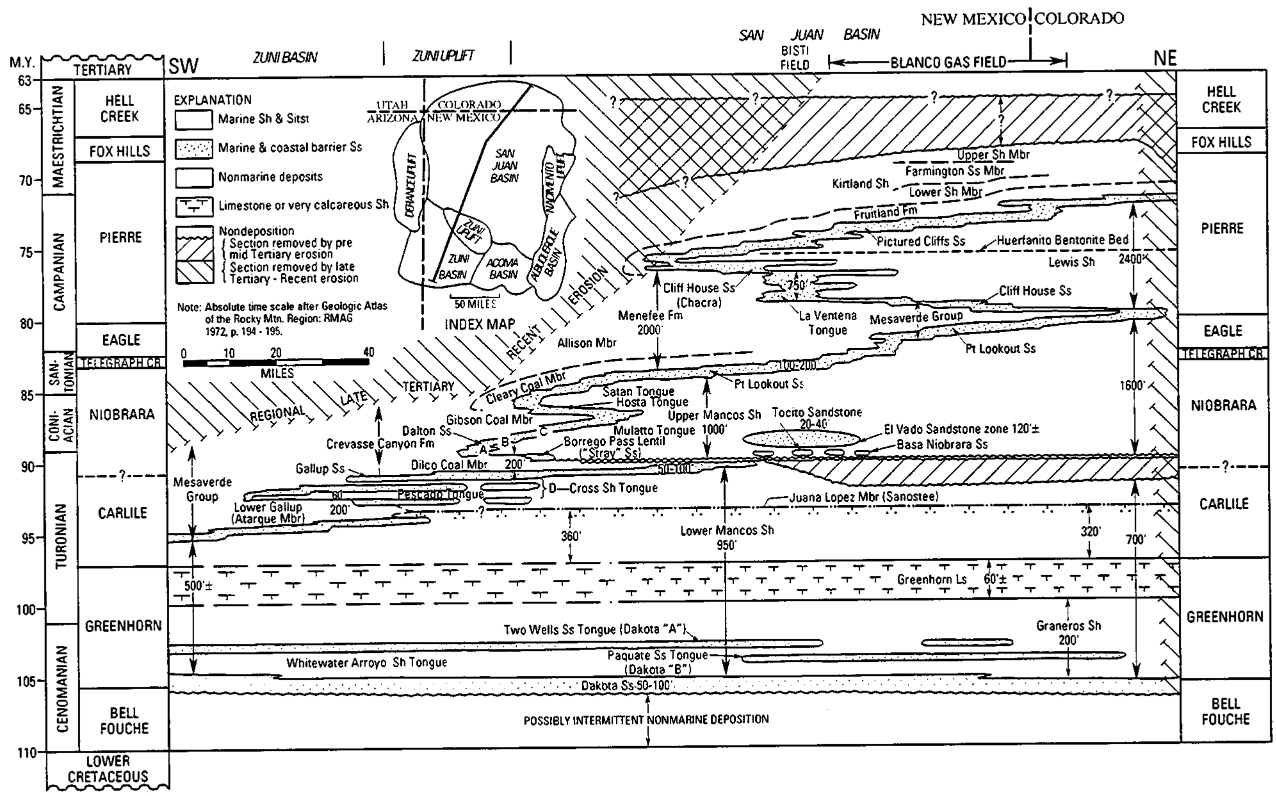


Figure 3. Time - stratigraphic cross section of Upper Cretaceous and Tertiary rocks in the San Juan Basin. Modified from Pantilla (1964) and Molenaar, 1974). Position of the A, B, and C intervals of the Dalton Sandstone discussed in the report are shown.

Mancos Shale

As shown in figure 3, the Mancos Shale covers a significant portion of the San Juan Basin. The Mancos Shale consists of as much as 1600 ft (487.8 m) of dark gray to black calcareous and noncalcareous shale and sandstone of marine origin. In the Mancos, there are isolated limestone or sandstone units, such as the Bridge Creek Limestone, Semilla Sandstone, and Juana Lopez and a thicker sequence of interbedded thin shale, sandstone, and siltstone, referred to by drillers as the "Gallup sandstone", basal Niobrara sandstones, or El Vado Sandstone (Fassett and Jentgen, 1978; Fassett, 1991) that are confined to the lower two-thirds of the formation. This interbedded sequence referred to as the "Gallup sandstone" or El Vado Sandstone is the principal focus of this report. To the south, southwest, and northwest, the Mancos Shale intertongues with various clastic-rich formations, such as the Dakota Sandstone, Gallup Sandstone, Dalton Sandstone Member of the Crevasse Canyon Formation, and Hosta Tongue of the Point Lookout Sandstone of the Mesaverde Group. These clastic-rich formations represent the continental and shoreward facies that are laterally time-equivalent to the marine shale facies that define the Mancos Shale. An unconformity of regional extent occurs within the Mancos and separates shale that intertongues with the Dakota Sandstone and the Gallup sandstone below the unconformity from shale that intertongues with the Dalton Sandstone immediately above the unconformity. Where thick tongues of Mancos Shale separate clastic depositional systems, individual names have be applied to these marine shale wedges (fig. 3). The Mulatto Tongue and Satan Tongue are of main interest to this report as they form the lower and upper boundary of the regressive-transgressive wedge that defines the Dalton Sandstone and Hosta Tongue. The Mancos is presumed to be the source of both the oil and the gas in the Cretaceous Mancos reservoirs.

Bridge Creek Limestone Member

The Bridge Creek Limestone Member of the Mancos Shale crops out on the east side of the Reservation near El Vado Reservoir in the Tierra Amarilla Quadrangle (Landis and Dane, 1967; fig. 1). In this vicinity, the Bridge Creek consists of 45 to 60 ft (13.7 to 18.3 m) of limestone, silty limestone, and calcareous shale. The Bridge Creek makes an excellent marker unit in the subsurface where it ranges in thickness from 30 to 70 ft (9.1 to 21.3 m). The base of the unit, most likely a persistent bentonite or a low resistivity shale of undetermined composition, was used as the datum for the structure map on the Reservation.

Semilla Sandstone Member

The Semilla Sandstone Member of the Mancos Shale crops out south of the study area near La Ventana. At the type section, the Semilla consists of 70 ft (21.3 m) of sandstone deposited as an offshore marine bar (Dane and others, 1968). It has been described as very fine to fine grained, becoming locally medium grained and crossbedded in the upper part. In the subsurface in the study area, the Semilla averages 10 ft in thickness, but may be as much as 20 ft (6 m) thick in the southernmost sections (plates 1 and 2). The Semilla pinches out to the north, somewhere between township 25 and 26 (plates 1 and 2). In the subsurface of the study area, the Semilla forms a persistent marker bed located 10 to 20 ft (3 to 6 m) below the base of the Juana Lopez Member of the Mancos Shale (plates 1-3).

Juana Lopez Member

The Juana Lopez Member (often called Sanastee, especially in drilling completion reports) crops out in the study area near El Vado Reservoir (fig. 1). In this area, it consists of 90 to 125 ft (27.4 to 38.1 m) of dark gray to very dark gray shale. The base and top of the member is delineated by beds of hard, very fine grained, orange- to yellow-brown weathering, fossiliferous calcarenite (Landis and Dane, 1967). Elsewhere, thin sandstone may also be present (Molenaar, 1977). The Juana Lopez was deposited in marine environments in a shallow sea of low clastic input (Molenaar, 1973). Throughout the subsurface in the study area, the Juan Lopez forms a prominent marker interval characterized by more resistant beds at the base and top (calcarenites). Because of its persistent character, it likely represents a time line over much of the study area and for this reason, the top of the Juana Lopez was chosen as the datum in the regional cross sections (plates 1-5). However, there is some indication (Molenaar, 1977) that the top of the member (at least the prominent top calcarenite) may be diachronous on a basinwide scale.

Mulatto Tongue

The Mulatto Tongue of the Mancos Shale is a wedge of marine shale that separates the Dalton Sandstone Member of the Crevasse Canyon Formation from the Gallup Sandstone in the southwest part of the Basin. At its maximum transgressive extent, the Mulatto rests with apparent disconformity on top of the Dilco Coal Member of the Crevasse Canyon Formation (fig. 3). Seaward, marine shale that is time equivalent to the transgressive Mulatto tongue unconformably overlies marine shale that was deposited during the Gallup regression. Where the Mulatto separates the Dalton from the Gallup, it is about 500 ft (152.4 m) in thickness (Molenaar, 1977) and locally is sandy.

Basal Niobrara Sandstones and Siltstones

Locally at the outcrop and in the subsurface of the Reservation, the Mancos Shale above the unconformity (above the Juana Lopez) and below the Point Lookout Sandstone of the Mesaverde Group consists of, in ascending order: 1) shale with discrete sandstone lenses, 2) interbedded thin sandstone, siltstone, and shale, and 3) shale with scattered thin sandstone and siltstone laminae. In the area of the Reservation, the basal lenticular sandstone has been named the Cooper Arroyo Sandstone (Landis and Dane, 1967). The Cooper Arroyo is similar to Tocito-like sandstone lenses found in a similar stratigraphic position in the northwest part of the basin (see discussions of the Tocito in Tillman, 1985; Jennette and others, 1991; Jennette and Jones, 1995; Nummedal and Riley, 1999. Where it crops out near El Vado Reservoir (fig. 1), the Cooper Arroyo Sandstone, consists of approximately three feet (0.9 m) of coarse-grained, glauconitic, and locally, pebbly sandstone (Landis and Dane, 1967). The sandstone consists of wavy beds that are locally burrowed and bioturbated.

At El Vado Reservoir (fig. 1), the Mancos Shale immediately above the Cooper Arroyo Sandstone, consists of 150 to 180 ft (45.7 to 54.9 m) of gray, silty, calcareous shale, local thin siltstone laminae, and a few thin bentonites. This predominantly shale facies passes laterally, in the subsurface, into interbedded sandstone, siltstone, and shale that have been assigned to the lower part of the El Vado Sandstone Member (Fassett and Jentgen, 1978; Fassett, 1991). At the outcrop approximately 90 to 100 ft (27.4 to 30.5 m) of interbedded sandstone, siltstone, and shale (sandstone is the dominant lithology) overlie the shale sequence above the Cooper Arroyo. This interbedded sandstone, siltstone, and shale facies was defined as the El Vado Sandstone Member of the Mancos Shale by Landis and Dane (1967). The El Vado as described originally by Landis and Dane is a more restricted unit than that defined in the subsurface (Fassett and Jentgen , 1978; Fassett, 1991). The type El Vado Sandstone, as originally defined, is discussed below. Overlying the El Vado Sandstone, at the outcrop and in the subsurface, is a shale interval as much as 1200 ft (365.9 m) thick. This shale interval is assigned to the upper unit of the Mancos Shale. It consists mainly of silty shale with thin sandstone beds near the base where it is transitional with the underlying El Vado Sandstone and near the top where it is transitional into the overlying Point Lookout Sandstone of the Mesaverde Group.

El Vado Sandstone Member

The El Vado Sandstone Member of the Mancos Shale crops out in the vicinity of El Vado Reservoir in the Tierra Amarilla quadrangle. At the type section, the El Vado consists of 90 to

100 ft (27.4 to 30.5 m) of interbedded sandstone, shale and siltstone (Landis and Dane, 1967). The sandstone is described as fine-grained, calcareous, locally rippled or crossbedded; sandstone is most prominent in the upper one-half of the formation. Siltstone is more abundant in the lower half where it is interbedded with shale. Fauna consists of plates of *Inoceramus platinus*, *Ostrea congesta*, fish remains, and a variety of trace fossils (Landis and Dane, 1967) and inoceramids *Volviceramus involutus* and a radially ribbed Inoceramus species (King, 1974). South of the study area near Cabezon Peak, poorly preserved inoceramids which resemble *I. stantoni* have been reported from the lower part of the El Vado (King, 1974) as have selachian teeth which are also common (Williamson and Lucas, 1992). *I. stantoni* has been reported from the lowermost part of the Dalton Sandstone (see discussion in King, 1974).

Satan Tongue of the Mancos Shale

The Satan Tongue of the Mancos Shale is a wedge of transgressive marine shale, as much as 300 ft (91.5 m) thick (Molenaar, 1977), that separates the underlying Hosta Tongue of the Point Lookout Sandstone from the main regressive sandstones of the Point Lookout Sandstone. Seaward of the Hosta-Dalton pinchout, the Satan Tongue merges into the main body (upper unit) of the Mancos Shale. Landward to the southwest it becomes sandier and eventually merges with sandstone of the combined Hosta and Point Lookout. Where it crops out near Crownpoint, New Mexico, it consists of about 100 ft (30. 5 m) of thinly interbedded very fine-grained sandstone, and fissle, gray shale (Molenaar, 1977).

Gallup Sandstone

In the San Juan Basin, the Gallup Sandstone was deposited as a northeast-prograding wedge of sediments (see more complete discussion in Molenaar, 1973; 1974; Nummedal and Molenaar, 1995). At the outcrop and in the subsurface where sandstone is the dominant lithology, the Gallup has been subdivided into 6 principal sandstone units labelled A-F, with F being the oldest (Molenaar, 1973; 1983). Each of the sandstone units progrades slightly more to the northeast than the preceding unit. The northeast pinchout of the A-sandstone unit marks the maximum northeast progradation of the Gallup. The northeast limit of each of the sandstone units has been used to define the approximate orientation and position of the various shorelines throughout Gallup deposition (fig. 1). Basinward (to the northeast) each of the Gallup sandstone units changes facies laterally into a vertically stacked, interbedded sequence of thin sandstone and shale. This thin sandstone and shale sequence changes facies basinward into predominantly shale. In this report, the interbedded sandstone and shale and shale facies in the lower Mancos that directly overlies the Juana Lopez and below the regional unconformity are referred to as distal Gallup equivalents (fig. 2).

Distal equivalents of the Gallup Sandstone are present only in the subsurface in the study area. In the southern part of the study area, distal Gallup equivalents are as much as 450 ft (137.2 m) thick (plates 1 and 2). This succession of distal Gallup equivalents is gradually truncated to the north beneath an unconformity of regional extent (Molenaar, 1974; King, 1974; Molenaar and others, 1996. In township 32 north, only 20 ft (6 m) of Mancos Shale (distal Gallup equivalents) remains between the unconformity and the top of the underlying Juana Lopez (plates 1 and 2). Interpretation of facies that are assigned to distal Gallup Sandstone equivalents in the subsurface is based on evaluation of wireline logs, reports of cored intervals by drillers (very few of these) on completion forms, and description of productive facies in producing oil fields (Fassett, 1978; 1983).

Crevasse Canyon Formation

The Crevasse Canyon Formation does not crop out in the study area and members that define the Crevasse Canyon at the outcrop cannot be mapped in the subsurface in the study area. The

Crevasse Canyon includes the rock interval between the top of the Gallup Sandstone and the base of the Mesaverde Group (Point Lookout Sandstone). In ascending order, members of the Crevasse Canyon include the Dilco Coal Member, Dalton Sandstone Member, Bartlett Barren Member, and Gibson Coal Member (fig. 2). The Dilco, Barlett Barren, and Gibson Coal Members consist of continental deposits landward of coastal barrier and shoreface sandstone of the Dalton Sandstone (fig. 3). The Dilco Coal Member rests with conformable relation to the underlying Gallup Sandstone. South of the study area, south of Guadalupe (fig. 1), the Dilco is truncated below the transgressive Mulatto tongue of the Mancos shale and thus, it is not present in the study area.

The Dalton Sandstone consists of a series of stacked, northward to northeast stepping regressive coastal barrier and shoreface sandstone (fig. 3). At least three stepped sequences comprise the overall 500 ft (152.4 m) of stratigraphic rise observed in the Dalton. These are shown as A-C, with A the oldest, on figure 3. The Dalton Sandstone is not present in the subsurface of the Reservation, however, lateral equivalents of the Dalton within the Mancos Shale are, in part, assigned to the El Vado Sandstone Member of the Mancos Shale.

Hosta Tongue of the Point Lookout Sandstone (Mesaverde Group)

The Hosta Tongue of the Point Lookout Sandstone is a transgressive marine sandstone that at its most seaward extent rests with apparent little disconformity on the underlying Dalton Sandstone, where the Dalton reaches its maximum regression seaward. From the Dalton turn around point (fig. 3), the Hosta stratigraphically rises about 100 to 150 ft (30.5 to 45.7 m) to the southwest. It consists of approximately 130 ft (39.6 m) of sandstone deposited as an upward fining succession during the water deepening event associated with the transgression (Sabins, 1964). The Hosta Tongue is not present in the subsurface of the study area. Time equivalents are represented by shale and sandy shale lithofacies in the Mancos.

AGE RELATIONSHIPS

An understanding of the age relationships of the units comprising the Gallup Sandstone-Mancos Shale interval is an important component of the sequence stratigraphic modeling. New biostratigraphic data from this interval (Jennette and Jones, 1995; Nummedal and Riley, 1999; W.A. Cobban, oral commun.) help to constrain the timing of the regional unconformity between the Gallup Sandstone and its distal equivalents and overlying units of the Mancos Shale. Most of the new biostratigraphic data is from the west side of the San Juan Basin in the vicinity of the Four Corners Platform. Some new biostratigraphic data is also reported from the southeast side of the basin near Guadalupe, New Mexico and the pipeline road near San Luis, New Mexico (fig. 1; Molenaar and others, 1996, and W.A. Cobban, written commun.). Biostratigraphic data from the lower Mancos Shale section, including the El Vado Sandstone Member, immediately above the Juana Lopez have been reported from the type El Vado section near El Vado Reservoir, New Mexico (King, 1974; fig. 1). The relationship of the inoceramid and ammonite sequences that form the basis for the biostratigraphic analysis shown in figure 4.

The Tocito Sandstone, on the west side of the San Juan Basin, is the basal unit in the Mancos Shale which immediately overlies the regional unconformity. The Tocito Sandstone has been subdivided into four sandstone-shale genetic units, each underlain by a sequence boundary (Jennette and Jones, 1995). The sequence boundaries were shown to overstep each other in a paleolandward direction (to the south), and thus, were deposited within an overall transgression. The oldest sequence boundary at the base of the Tocito, observed basinward from the Gallup outcrop belt, incised deeply into older distal Gallup equivalents, thus, removing all intermediate strata. The youngest sequence boundary incised into the Torrivio Sandstone in the southwest part of the basin and into the upper part of an older Tocito Sandstone to the north. The other two sequence boundaries occur between the oldest and youngest in the northwest part of the basin. On the west side of the basin where the Tocito has been mapped at the outcrop, the Tocito has been shown to rest on rocks of different ages (from the Juana Lopez to the type Gallup). This relationship suggests the presence of a regional unconformity at the base of the Tocito (see discussion in Jennette and Jones, 1995). The erosional surface that defines the unconformity was considered to be cut by submarine processes rather than by fluvial incision. However, some have argued against the unconformity being regional in scale (Campbell, 1979; Nummedal and others, 1989) and instead suggest that the erosional surfaces below the various Tocito sandstones local in extent.

The origin of the Tocito on the west side of the basin is not specifically covered in this report, and the reader is referred to the summaries of its origin in Jennette and Jones (1995) and Nummedal and Riley (1999). The new biostratigraphic data that was presented in these reports however, does shed light on whether the surface between the Tocito and Gallup or Torrivio is regional or local in extent. This has important implications for understanding the subsurface geology of the lower Mancos Shale in the northeast part of the San Juan Basin and on the Jicarilla Reservation. As shown in the two south-north cross sections A-A' and B-B' (plates 1 and 2), there is significant loss (as much as 425 ft or 129.5 m) of distal Gallup equivalents from south to north below the regional unconformity and juxtaposition of younger and older fine-grained, genetically unrelated facies across the unconformity. On the west side of the basin, new palynomorph data from outcrop and core indicate a Coniacian age for the Tocito and from outcrop a late Turonian age for the Gallup (Jennette and Jones, 1995). Although the palynomorph data indicated only a Turonian for the Gallup, elsewhere, inoceramids indicate an early Coniacian age for the Gallup A sandstone at its pinchout (Molenaar, 1973; Nummedal and Riley, 1999; W.A. Cobban oral commun.).

The oldest Tocito Sandstone on the west side of the basin is within the range of *Inoceramus (Cremnoceramus) deformis* (fig. 4) of late early Coniacian age. This age was determined from specimens of this species collected from the Tocito at the Mound outcrop in northwest Colorado (fig 1; Dane, 1960). The Tocito at this outcrop was projected to align with the Tocito in the subsurface at the Horseshoe oil field in northwest New Mexcio. The Tocito at the Horseshoe field rests on the oldest sequence boundary of Jennette and Jones (1995). At the Hogback oil field, which is south of the Horseshoe oil field, a specimen of the ammonite *Peroniceras westphalicum* was recovered from the lower Tocito as was a specimen of *Cremnoceramus deformis* (Nummedal and Riley, 1999). [Note: Per W.A. Cobban *P. westphalicum* was actually found as float at the outcrop and a robust inoceramid bivalve observed high in the cliff, but not collected, might be *C. deformis*.] Because neither inoceramid bivalve was actually identified in place, the precise age of this Tocito is not known and it could be early (if *C. deformis* is present)or middle Coniacian (if *P. Westphalicum* is present) in age. (fig. 4). The Tocito at the Hogback oil field rests on the second oldest sequence boundary of Jennette and Jones (1995). No megafossils have been collected from the Tocito Sandstone that rests on the third oldest sequence boundary of Jennette and Jones (1995). *Magadiceramus stantoni* was reported from the Tocito Sandstone that rests on the youngest sequence boundary of Jennette and Jones (1995) in the Beautiful Mountain area (Nummedal and Riley, 1999; fig. 1). This index inoceramid indicates a late Coniacian age for the Tocito (fig. 4) above the youngest sequence boundary. At the Beautiful Mountain locality, the Tocito rests unconformably on the Gallup Sandstone (Nummedal and Riley, 1999). *Magadiceramus stantoni* has also been recovered from the Tocito at the Plunge Pool outcrop (fig. 1) north of Beautiful Mountain. The ammonites *Gauthiericeras roquei* and *Peroniceras tridorsatum* were also recovered from the Tocito at this locality. This fossil assemblage is middle Coniacian in age. The presence of M. stantoni suggests that at least part of the Tocito the Plunge Pool locality is time equivalent to the Tocito at Beautiful Mountain.

STAGES		AMMONITE SEQUENCE	INOCERAMID SEQUENCE
Santonian	Upper	*Desmoscaphites bassleri*	*Sphenoceramus lundbreckensis*
		Desmoscaphites erdmanni	
		Clioscaphites choteauensis	*Cordiceramus muelleri*
	Middle	*Clioscaphites vermiformis*	*Platyceramus cycloides*
	Lower	*Clioscaphites saxitonianus*	*Magadiceramus subquadratus crenelatus*
Coniacian	Upper	*Scaphites depressus*	*Magadiceramus stantoni* *Volviceramus involutus*
	Middle	*Scaphites ventricosus*	*Volviceramus koeneni* *Cremnoceramus deformis*
	Lower	*Forresteria alluaudi*	*Cremnoceramus erectus* *Cremnoceramus waltersdorfensis*
Turonian	Upper	*Forresteria peruana*	*Mytiloides scupini*
		Prionocyclus germari	
		Prionocyclus quadratus	*Mytiloides incertus*
		Scaphites nigricollensis	
		Scaphites whitfieldi	*Inoceramus dakotensis* *Inoceramus perplexus*
	Middle	*Scaphites ferronensis*	
		Scaphites warreni	*Inoceramus dimidius*
		Prionocyclus macombi	
		Prionocyclus hyatti	*Inoceramus howelli*
		Collignoniceras praecox	
		Collignoniceras woollgari	*Mytiloides hercynicus* *Mytiloides subhercynicus*

Figure 4. Ammonite and inoceramid zone chart for part of the Turonian and Coniacian (provided by W.A. Cobban).

On the east side of the San Juan Basin, outcrops of Tocito-like sandstone rests on a thin black shale assigned to the Mulatto Tongue of the Mancos Shale (Molenaar and others, 1996). The basal part of the Mulatto Tongue separates the Tocito sandstones from the underlying Gallup Sandstone near Guadalupe (fig. 1; also see fig. 6 of Nummedal and Molenaar, 1995). *Cremnoceramus erectus* was reported from the basal Tocito-like sandstone (Nummedal and Riley, 1999). *C. erectus* was also recovered from the Gallup Sandstone, indicating an early Coniacian age for the Gallup. *Cremnoceramus crassus* and *C. browni* were recovered from concretions in the Mulatto Shale overlying the Tocito (W.A Cobban, oral commun.). The inoceramids *C. crassus* and *C. browni* are both in the *C. deformis* biozone and indicate a late early Coniacian age for this stratigraphic interval. To the north at the pipeline road locality (fig. 1), the ammonite *Forresteria peruana* was reported from a Tocito-like sandstone (Molenaar and others, 1996; Nummedal and Riley, 1999). [Note: Per W.A. Cobban only fragments of *F.* sp were collected at the pipeline road locality; the bivalves were collected from the Gallup Sandstone which, at the Guadalupe locality to the southwest (fig. 1), is in the zone of *C. erectus* and from the underlying shale and not the Tocito.] The Tocito at the pipeline road locality has been considered to be late early Coniacian age (Nummedal and Riley, 1999). At the Guadalupe locality, approximately 100 ft (30.5 m) above the Tocito, *Volviceramus involutus* has been recovered from the Mulatto Tongue (W.A Cobban, oral commun.). This index inoceramid indicates a middle or a late Coniacian age for these strata (fig. 4). Slightly higher in the section, above *V. involutus*, *Magadiceramus stantoni* were recovered from a sandy shale sequence assigned to the El Vado Sandstone (W.A. Cobban, oral commun.). *M. stantoni* indicates a late Coniacian age for these strata (fig. 4).

To the north along the east side of the basin near El Vado Reservoir (fig. 1) at the type El Vado Sandstone section, the coarse-grained, crossbedded, pebbly, glauconitic Cooper Arroyo Sandstone (Landis and Dane, 1967) rests unconformably(?) on underlying shale in the lower Mancos. The Cooper Arroyo contains a *Cremnoceramus deformis* fauna (W.A. Cobban oral commun). This Tocito-like sandstone is within the *C. deformis* inoceramid zone which is the same zone as that of the lowermost Tocito sandstones at the Guadalupe and Mounds outcrops (fig. 1). Approximately 203 ft (61.9 m) of silty shale occurs between the Cooper Arroyo Sandstone and the type El Vado Sandstone at the El Vado Reservoir outcrop (fig.1; Landis and Dane, 1967; King, 1974). The first specimens of *Volviceramus involutus* were reported from this shale about 73.8 ft (22.5 m) from the top of the Cooper Arroyo Sandstone (King, 1974). *V. involutus* was found throughout the remainder of the shale section and in the El Vado Sandstone. *V. involutus* is a long-ranging species extending from middle through upper Coniacian, and it first occurs in the ammonite *Scaphites ventricosus* zone (fig. 4). The position of *V. involutus* relative to the Cooper Arroyo Sandstone is similar to that found at Guadalaupe. At El Vado Reservoir, approximately 45 ft (13.7 m) above the first appearance of *Volviceramus involutus*, I. sp. (radial ribs) were recovered and these inoceramids were originally thought to be a variant of *Magadiceramus stantoni,* although now are thought to represent *Magadiceramus subquadratus crenelatus* (fig. 4). *V. involutus* in conjunction with the I. sp. (radial ribs)(*M. subquadratus crenelatus*) were found in the remainder of the shale section below the El Vado Sandstone. In the type El Vado Sandstone, specimens of I. sp. (radial ribs) as float are similar to *M. subquadratus crenelatus* (W.A. Cobban, oral commun.) which is found in the first major regressive sandstone of the Dalton Sandstone and the shale immediately below it (B and C interval on fig. 3). *M. subquadratus crenelatus* is late Conacian in age. Thus, the El Vado Sandstone at El Vado Reservoir and Guadalupe and the Tocito Sandstone (above the youngest sequence boundary) at Beautiful Mountain and Plunge pool are all late Coniacian in age (fig. 4).

The inoceramid succession at the type El Vado Sandstone section between the Cooper Arroyo and the El Vado is similar to that found at the Guadalupe section to the south between the

Tocito-like sandstone and the El Vado Sandstone. At the type Cooper Arroyo section about 60 ft (18.3 m) of shale occurs between the Cooper Arroyo and the underlying middle Turonian Juana Lopez [based on projection from the subsurface section nearest this outcrop (plate 2, well 17)]. Juxtaposition of the Cooper Arroyo (*C. deformis* zone) on a much thinner Mancos Shale shale above the Juana Lopez suggests that biozones between the middle Turonian and early Coniacian are absent at this locality. On the west side of the San Juan Basin at Plunge Pool (fig. 1) where the unconformity has deeply incised into the Mancos Shale, *Inocermus dimidius* and *Lopha lugubris* recovered from the Mancos Shale directly below the Tocito Sandstone are middle Turonian in age (Nummedal and Riley, 1999). Thus, the similarity in juxtaposition of lower Coniacian rocks on a surface deeply incised in the lower Mancos above the Juana Lopez in both the northwest and northeast parts of the San Juan Basin indicates that the unconformity below the Tocito Sandstone is regional in scale.

The biozones within the Gallup Sandstone and overlying Mancos Shale succession, including Tocito-like sandstones and the El Vado Sandstone (as defined at the type locality) along the east side of the San Juan Basin from Guadalupe to El Vado Reservoir, indicate that the regional unconformity is within the *C. erectus* or *C. deformis* biozone. The presence of *C. erectus* in the lowermost Tocito-like sandstone near Guadalupe (Molenaar and others, 1996) is hard to reconcile with its absence in other Tocito-like sandstones that appear to rest unconformably on the Mancos Shale. Two explanations are possible: 1) the *C. erectus* is reworked and not indigeneous to the sandstone, and 2) this is not a Tocito sandstone but possibly a remnant sandstone time-equivalent to the Torrivio or the Gallup. The Torrivio is a coarse-grained sandstone that at places overlies the Gallup and at Beautiful Mountain (fig. 1) underlies the Tocito (Nummedal and Riley, 1999). The Torrivio and Tocito are petrographically similar (Riley, 1993). No fauna have been recovered from the shale section between this sandstone and the underlying Gallup Sandstone at Guadalupe to resolve the age issue.

The Tocito-type sandstones are generally accepted to represent either transgressive or lowstand deposits (see discussions in Jennette and Jones, 1995; Nummedal and Riley, 1999) deposited on an unconformity of local or regional extent. Subsurface correlations (plates 1 and 2) which show progressive loss of the lower Mancos (distal Gallup equivalents) and the relationships between biozones as discussed above clearly indicate that the unconformity is of regional extent, with the deepest incision occurring in the northwest and northeast parts of the basin. Thus, any sandstone that is correlative to the Tocito and thus, above the unconformity, should be older to the north and younger to the south, as transgression and back-filling of the incised surface occurred. In the Guadalupe area, there is no indication of any local topography or structural setting that would cause capture and retention of sediment close to the shoreline like that proposed in the northwest part of the basin with the uplift of the Waterflow anticline (Nummedal and Riley, 1999). Thus, it is unlikely that the Tocito-like sandstone containing *C. erectus* is above the unconformity at the Guadalupe locality if sediment by-pass conditions occurred.

METHODS OF STUDY

Several lines of study were implemented in order to define the facies, sequence stratigraphy, structural geology, hydrocarbon potential, and hydrocarbon-producing areas of the Mancos Shale ("Gallup" sandstone or El Vado Sandstone) between the Juana Lopez Member of the Mancos Shale and the Point Lookout Sandstone of the Mesaverde Group. Eight available cores in this interval near the Reservation were logged for facies and sampled for Rock-Eval analysis.

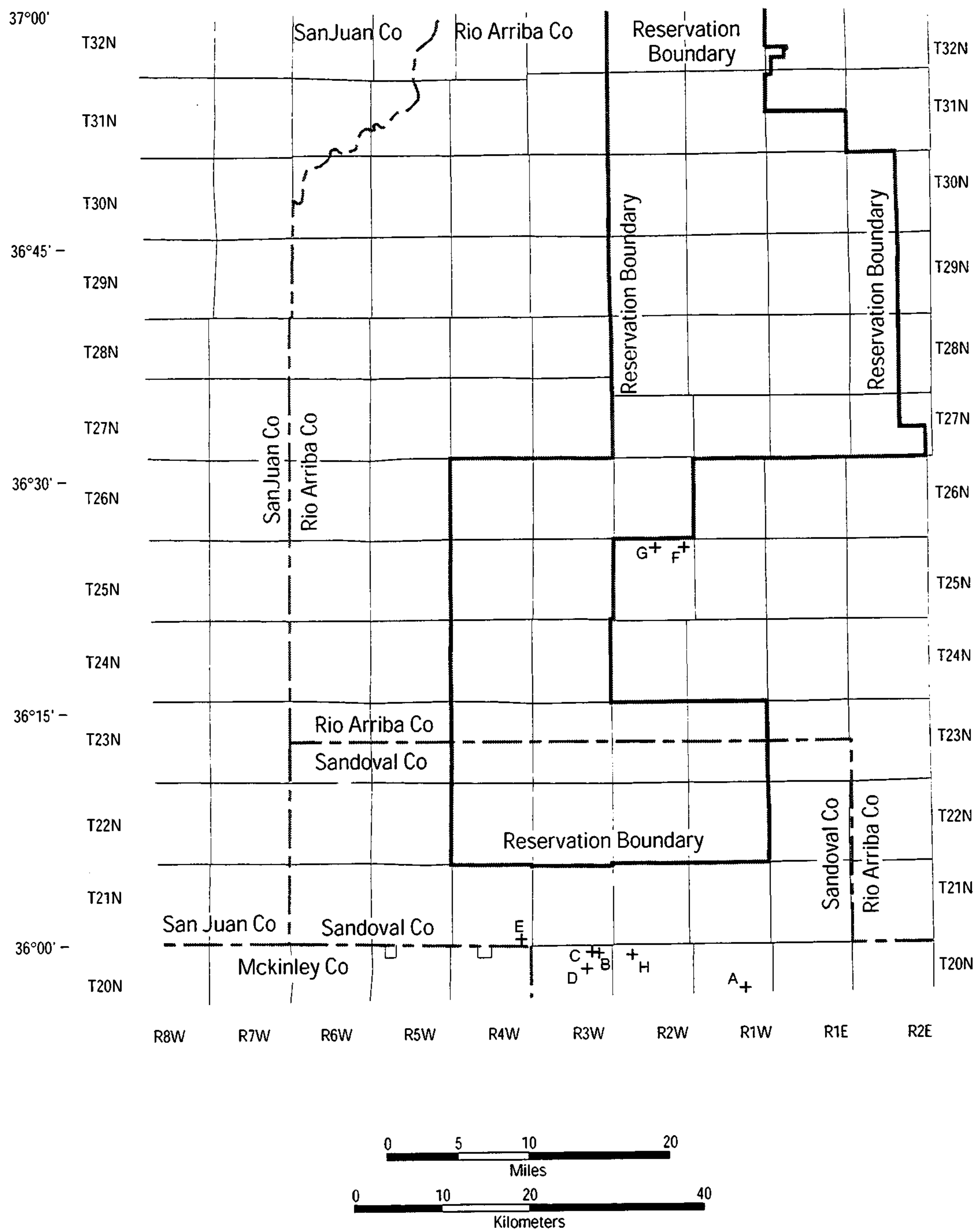


Figure 5. Map showing location of core (A -H) from which Rock - Eval analyses were obtained and for which descriptions and photographs of core (A- G) are shown in Appendix A.

Their locations are shown in figure 5. Descriptions and photographs of seven of the cores are found in appendix A. Numerous wireline logs were examined to determine tops of the geologic units within the interval. Five cross sections (2 south to north and 3 west to east) across the Reservation were constructed to show the stratigraphic relationships between the geologic formations (fig. 6; plates 1-5). These cross sections also show more detailed stratigraphic relationships within the interval commonly assigned to the "Gallup" or El Vado Sandstone by drillers. The top of the Juana Lopez, considered to be nearly isochronous in the study area, was used as a datum.

A large digital tops database leased from IHS Energy Group was initially used to create a structure contour map on the base of the Bridge Creek Limestone Member of the Mancos Shale. The base of the Bridge Creek or top of the Graneros Shale, which represents either a bentonite bed or low-resistivity shale bed of undetermined composition, is considered to be a nearly isochronous unit throughout the area of the Jicarilla Reservation. However, there were too many spurious values for this datum in the database, because the same horizon was not consistently picked by drillers. Therefore, over 2550 wells on and near the Reservation were reexamined and the top of the Graneros Shale was manually picked and entered into a new database. From this database a new structure contour map was created (plate 6).

Production data from the Mancos Shale interval between the Juana Lopez and the base of the Point Lookout were extracted from the IHS Energy Group database. Data were obtained for both oil- and gas-producing fields. These data were evaluated for assignment to the correct producing formation and where necessary producing wells were reassigned to the correct formation after evaluation of producing and perforated intervals. The data were then plotted to show their spatial distribution with respect to structure and to each other (fig. 7). API oil gravities from formations in the same stratigraphic interval of the Mancos were also extracted from this database and their distribution plotted (fig. 8) to determine any regional trends.

Boundaries of 17 individual oil and five gas fields in the Mancos interval between the Juana Lopez and the base of the Point Lookout Sandstone (data from individual fields in Fassett, 1978; 1983) on and near the Reservation were compiled onto a base map (figs. 9 and 10). The spatial distributions of these fields were then used to evaluate the position of productive intervals, by field, within a sequence stratigraphic context. In looking at producing intervals this way, it was hoped that areas and intervals in the Mancos that might contain by-passed resources would be highlighted.

STRUCTURAL GEOLOGY

The San Juan Basin is semi-circular basin in northwest New Mexico and southwest Colorado that is bounded mostly by monoclinal uplifts. The basin has had a complex structural history; the final configuration of the basin was achieved during the Laramide orogeny in the Paleocene and Eocene (Woodward and Callender, 1977). The structural configuration of the northeast part of the basin in the vicinity of the Jicarilla Apache Indian Reservation basin is shown in plate 6. The deepest part of the San Juan Basin is often referred to as the central basin (plate 6). It is roughly elliptical in shape with the longest dimension oriented northwest-southeast and it straddles the Colorado New Mexico border. The southwest part of the central basin is bordered by a northwest-southeast structural platform that dips gently to the northeast. This structural platform, known as the Chaco slope, is a regional structure upon which is superimposed a series of broad, low-amplitude folds that gently plunge to the northeast (plate 6). The northeast side of the basin is

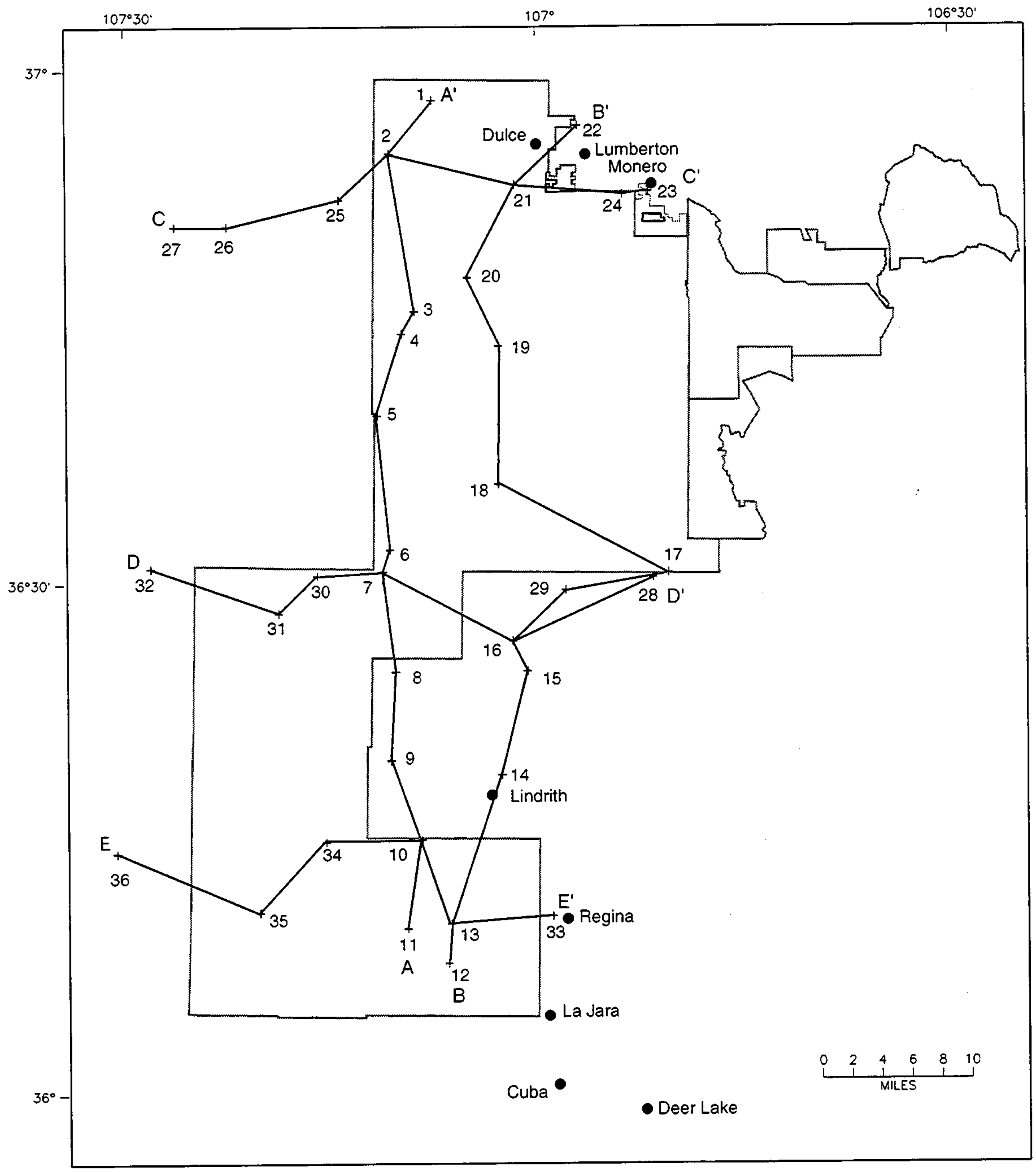


Figure 6. Map showing location of cross sections A-A', B-B', C-C', D'D', and E-E' with respect to the Jicarilla Apache Indian Reservation.

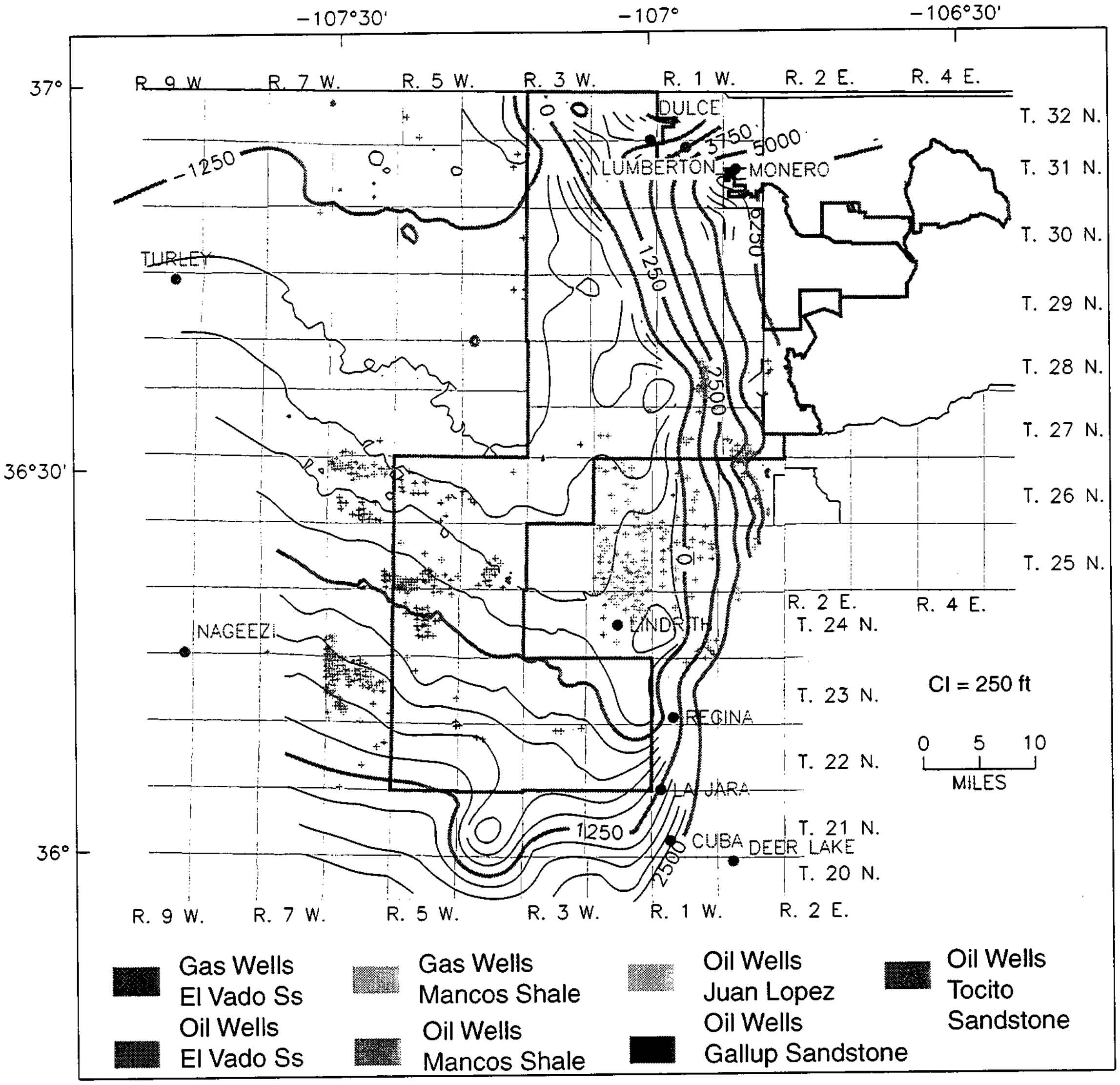


Figure 7. Map showing distribution of Mancos Shale oil and gas producing fields on and adjacent to the Jicarilla Apache Indian Reservation superimposed on the regional structure. Structure contours on the base of the Bridge Creek Limestone.

defined by a west-dipping monocline. This north-south monocline is defined by a set of west-verging and east-verging thrust or reverse faults (Taylor and Huffman, 2000).

The location of Mancos oil and gas fields on and near the Reservation with respect to structure is shown on figure 7. All of the Mancos, distal Gallup equivalents, and Juana Lopez oil fields are located along the Chaco slope or on the west-dipping monocline that bounds the northeast side of the basin. Many of these oil fields have associated gas, which generally is found in the structurally highest part of the field. Where the Chaco slope passes to the northeast into the central basin, hydrocarbon production is predominantly gas. Between the oil and gas production is a narrow zone where condensate is produced in conjunction with either oil or gas.

SEQUENCE STRATIGRAPHY

A principal focus of this study was to subdivide the Mancos Shale interval between the Juana Lopez Member and the Point Lookout Sandstone into intervals that reflect periods of transgression and regression. These intervals would then be used to identify currently productive oil and gas facies as well as define potentially productive facies that have been overlooked by past drilling. Two south-north cross sections A-A' and B-B' (fig. 6; plates 1 and 2) and three west-east cross sections E-E', D-D', and C-C' (fig 6; plates 3-5) through the Reservation show the results of the subdivision of the Mancos and the oil and gas producing intervals in the control wells.

The Mancos Shale above the Juana Lopez and below the Point Lookout Sandstone on the east side of the San Juan Basin is about 1600 ft (487.8 m) thick; the basal 700 ft (213.4 m) is the potentially oil and gas productive part of the Mancos. On the regional cross sections, the Mancos above the Juana Lopez is divided into a middle unit, the El Vado Sandstone Member, and an upper unit. The middle unit of the Mancos is split by a regional unconformity that juxtaposes genetically unrelated strata (although they are similar in appearance) across the unconformity. The unconformity is based on convergence of marker beds in the Mancos Shale in the subsurface (Molenaar, 1974) and on fossil assemblages (see discussion above). The unconformity is commonly thought to reflect uplift of the northeast part of the basin with subsequent submarine erosion of sediments below the unconformity (Molenaar, 1974; Fassett and Jentgen, 1978). The cause of the uplift has not been documented, although it may be related to movement on basement fault blocks (Nummedal and Riley, 1999). It is not known if this uplift was accompanied by a tilt in the basin axis to the southwest. It is possible that uplift in the northeastern part of the basin did not occur or that it was not the sole cause of loss of strata below the unconformity. Rather the loss of rock below the unconformity may be related to incision as a result of a pronounced fall in sea level (possibly concurrent with tectonic movement on basement fault blocks). Newer interpretations of controls on deposition of the Gallup Sandstone suggest that the Gallup was deposited as a progradational wedge during sea level fall. The depositional pattern suggests deposition during a forced regression (Posamentier and others, 1992; Nummedal and Riley, 1999). During a sea level fall, water depths would be reduced in offshore regions and those regions within the active wave base would be subjected to submarine erosion (Plint, 1988). Thus, submarine erosion during a sea level fall should be considered as a possible, if not contributory, mechanism for loss of strata below the unconformity.

Prior studies of the Gallup-Mancos interval commonly use the unconformity as a datum (Molenaar, 1974; Molenaar and Nummedal, 1995), the maximum flooding surface of the Mulatto Tongue (Jennette and Jones, 1995), or bentonite beds within the Mancos Shale (Pentilla, 1964). The datum for the cross sections used in this study is the top of the Juana Lopez. The

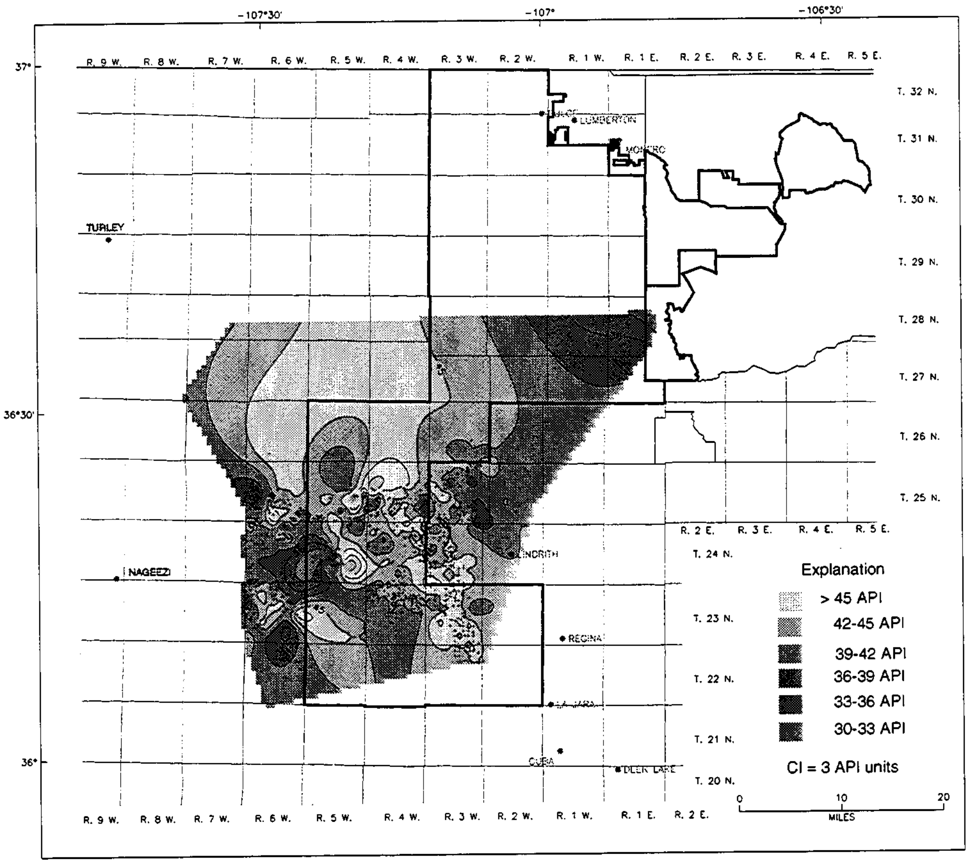


Figure 8. Contour map of API gravities from the Mancos Shale in the northeastern part of the San Juan Basin.

23

stratigraphic relationships shown on cross sections A-A' and B-B' (plates 1 and 2) are similar to those shown by Pentilla (1964) for the same stratigraphic interval on the west side of the basin This study and that of Pentilla demonstrate the diachronous relationships of the rock units that comprise the transgressive wedge above the unconformity and their overstepping relationships from north to south.

The middle unit of the Mancos Shale below the regional unconformity is time correlative to the Gallup Sandstone. Deposition of the middle unit was in shelf or basinal environments. The top 15 ft (4.6 m) of the distal Gallup equivalents in core from the Mallon 3-15 Federal Com well (Appendix A, core G; fig. 5) in T. 25 N., R. 2 W. consists mostly of black shale with scattered thin siltstone and sandstone laminae. Rocks of the middle unit below the unconformity are the distal offshore facies in part laterally equivalent to shoreface sandstones that define the Gallup. These distal Gallup equivalents are thickest in the southern parts of cross section A-A', B-B', and E-E' (plates 1-3) where up to 450 ft (137.2 m) of shale and interbedded sandstone and shale comprise the middle unit below the unconformity. The distal Gallup equivalents thin to the north beneath the regional unconformity to a thickness of 10 to 20 ft (3 to 6 m) (plates 1 and 2). Fossils for this interval are generally lacking and thus age equivalency is based on lithostratigraphic correlation. The only reported fossils from the Mancos below the unconformity in the study area are from shale below the late lower Coniacian Cooper Arroyo Sandstone near El Vado Reservoir (fig. 1; King, 1974). However, the fragments of the Scaphites ammonite collected did not permit accurate age determination of the strata. The Mancos Shale at the El Vado Reservoir locality between the Juana Lopez and the unconformity is projected to be about 60 ft (18.3 m) thick (B-B', well 17). Thus, the nearly 400 ft (121.6 m) of section truncated between townships 22 and 27 north represents loss of strata time equivalent to at least the Gallup B and A sandstones (late Turonian and early Coniacian in age).

The middle unit of the Mancos Shale above the unconformity in this study ranges from about 70 ft (21.3 m) in the southern part of the study area to about 260 ft (79.3 m) in the northern part. It is divided into two principal subunits: 1) basal sandstones that appear to be correlative to Tocito Sandstones on the west side of the basin, and 2) an unnamed transgressive wedge of rocks between the Tocito Sandstones (or the top of the unconformity where the Tocito is absent) and the El Vado Sandstone Member. The transgressive wedge is further divided into several genetic units based on their wireline log responses. The lower principal subunit of the middle unit of the Mancos Shale is equivalent to the lower part of the "Gallup sandstone" of drillers, basal Niobrara sandstone interval (Molenaar, 1974; 1977), Tocito and lower part of the El Vado Sandstone Member interval, (Fassett and Jentgen, 1978), part of the lower shale unit of the Mancos (King, 1974, 1975), or the middle shale unit of the Mancos (Landis and Dane, 1967). At the south end of the study area, the middle unit consists of two subdivisions and at the north end it consists of five subdivisions (plates 1 and 2). The increase in the number of subdivisions from south to north reflects increased deposition of rock strata within the more deeply incised surface of the unconformity.

The units within the transgressive wedge were deposited during an overall sea level rise. Although the stratal relationships of the rocks in the transgressive wedge reflect deposition during transgression, the individual genetic packages were deposited during periods of regression as fluivally-derived sediment from the south was deposited and redistributed in the marine environment. The overall rise in sea level that accompanied transgression appeared to have been punctuated by periodic stillstands during which greater concentrations of sandstone or sandstone mixed with shale accumulated in neritic environments closer to the shoreline. These stillstands thus, can be used to define areas of greater sandstone concentration and thus better reservoir characteristics. In the northeastern part of the San Juan Basin these sandstone trends would be

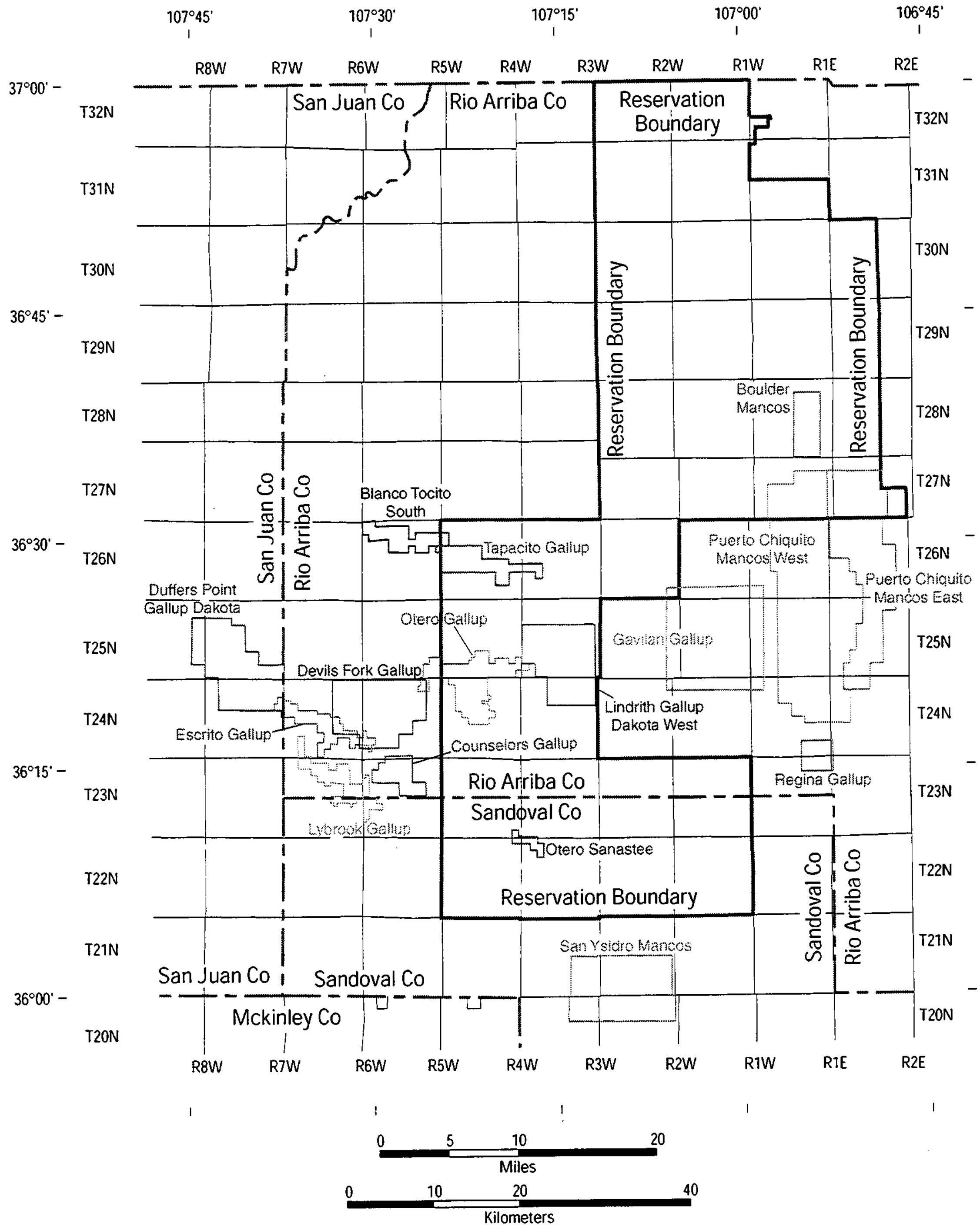


Figure 9. Map showing distribution of oil fields in the Mancos Shale on and adjacent to the Jicarilla Apache Indian Reservation (data from Fassett, 1978, 1983).

elongate northwest-southeast, subparallel to the inferred paleo shorelines. These intermediate shorelines overstepped each other to the south. This overstepping results in a thicker wedge of transgressive sediments in the northern part of the study area and a thinner wedge of transgressive sediments in the southern part of the study area. These relationships are shown on cross section A-A' and B-B' (plates 1 and 2).

The sandstone lenses referred to as the Tocito sandstone on the regional cross sections (plates 1- 5) are most prominent north of township 25, although Tocito-like sandstones are locally present in township 23 north (plate 3) where they occur lateral to slightly thicker sand build ups. The Tocito-like sandstone lenses either rest directly on the unconformity or from 10 to 40 ft (3 to 12.2 m) above the unconformity. The sandstone lenses may occur singly or doubly stacked and are interbedded with shale. The interval assigned to the Tocito in this report consists of 50 to 70 ft (15.2 to 21.3 m) of interbedded sandstone and shale lenses. In cross sections C-C', D-D', and E-E', the sandstone lenses appear to be more elongate and laterally persistent in a west-east direction (plates 3-5) than in a south-north direction. The Tocito-like sandstones were deposited during the early stage of transgression over the unconformity that was associated with an overall rise in sea level. The sandstone lenses with respect to the top of the Juana Lopez step up stratigraphically to the south, although they maintain the same depositional position with respect to the unconformity. Based on the age of the Tocito-like sandstone at Guadalupe and the Cooper Arroyo near El Vado Reservoir (fig.1), the lowermost Tocito Sandstones along the unconformity on the east side of the basin are late early Coniacian (*C. deformis* zone) in age.

The unnamed transgressive wedge of rocks above the Tocito and below the El Vado has been subdivided into one to four units from south to north. From north to south, the stratigraphically lower (older) units are shown to wedge out; they are overstepped to the south by successively stratigraphically higher (younger) units. At its southern terminus, a unit often is more sand-rich (interpretation of wireline log responses) suggesting that the terminus marks a stillstand position of a shoreline within an overall transgressive setting. The unnamed transgressive wedge ranges from 20 ft (6 m) thick at the south end of the study area to as much as 190 ft (57.9 m) thick at the north end (plates 1 and 2). Based on inoceramids recovered from rocks of the transgressive wedge near Guadalupe and El Vado Reservoir, at least the middle and upper part of the transgressive wedge (80 to 100 ft (24.4 to 30.5 m) above the unconformity) is middle to early-late Coniacian in age (see discussion above). This interval would correspond to the distal part of the Mulatto Tongue (near maximum flooding) where it intertongues with the lower part (A-B) of the Dalton Sandstone (fig. 3).

Cores from the transgressive wedge of sediment were examined in three wells (Appendix A, cores C, F, and G; fig. 5). The southernmost core from the Champlin 2 Federal 24-2 (Appendix A, core C; fig. 5) well in T. 20 N., R. 3 W. is in the lower part of the transgressive wedge in the position of the Tocito Sandstone. The wireline log for this well (Appendix A, core C) shows a sharp gamma ray and resistivity peak that corresponds (when core is adjusted to the log) to about four feet (1.2 m) of fine-grained, carbonaceous, very bioturbated, fossiliferous sandstone. The remainder of the transgressive sediment consists of silty mudstone and black shale. In the Mallon 1-11 Howard Federal well (Appendix A, core F; fig. 5) in T. 25 N., R. 2 W., the top of the transgressive wedge of rock about 20 ft (6 m) below the base of the El Vado Sandstone Member consists of about 30 ft (9.1 m) of black shale with thin sandstone laminae. The shale overlies a sequence of interbedded thin sandstone and shale. Sandstone from the interbedded sequence is carbonaceous, fine grained, wavy-bedded, and locally bioturbated; "dead" oil coats fossil fragments. Core from the Mallon 3-15 Federal Com well (Appendix A, core G; fig. 5) in T. 25 N., R. 2W. was cut continuously through the entire transgressive wedge. The top 45 ft below the base of the El Vado sandstone consists predominantly of black shale. Below the shale interval,

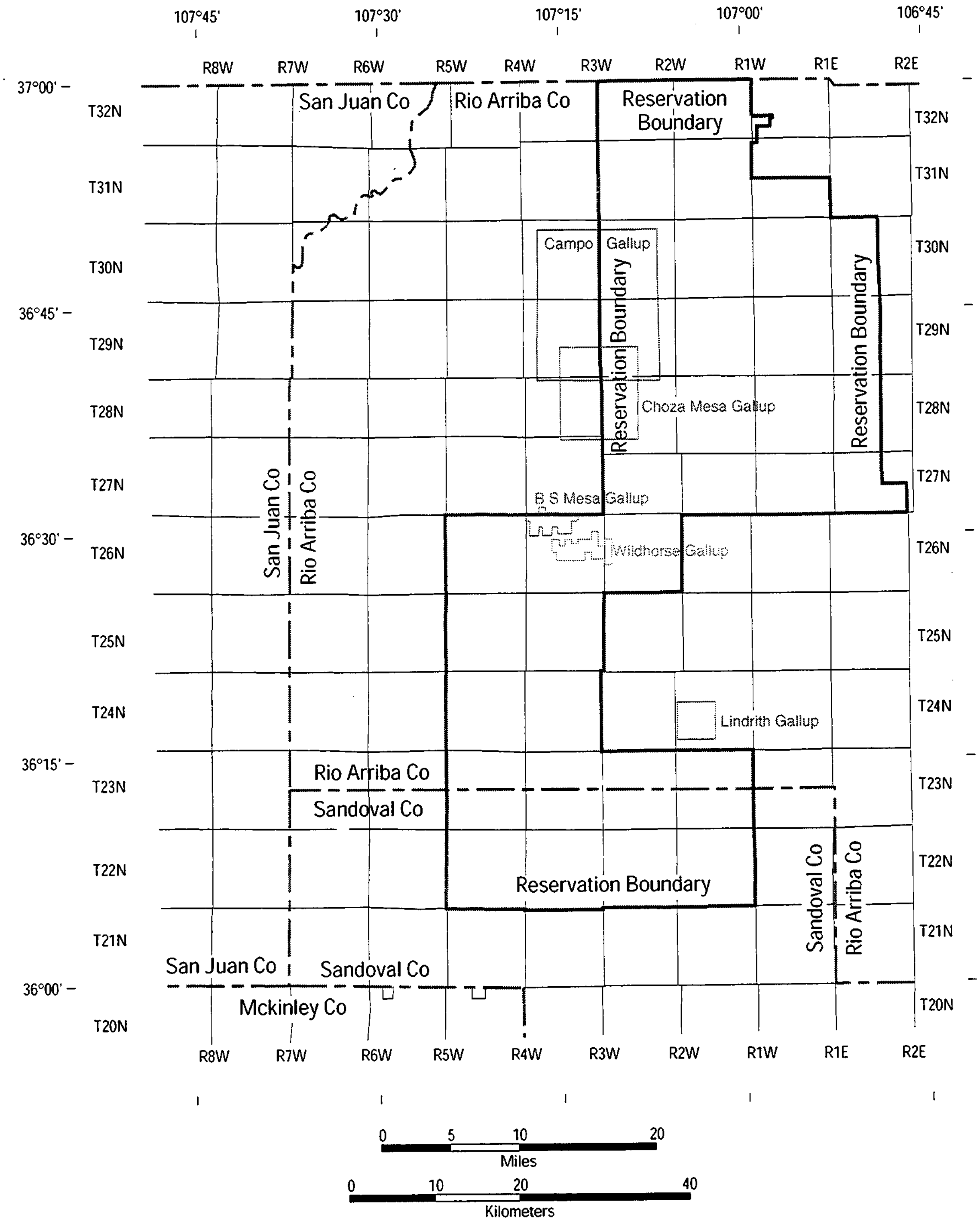


Figure 10. Map showing distribution of gas fields in the Mancos Shale on and adjacent to the Jicarilla Apache Indian Reservation (data from Fassett, 1978, 1983).

the transgressive wedge consists of thin parasequences of shale and sandstone. The top 50 ft (15.2 m) of the sandstone and shale parasequences is laterally equivalent to the cored interval in the Mallon 1-11 Howard Federal well, although in the 3-15 Federal Com well the sandstone appears to be better developed. Sedimentary structures in core from the three wells in the transgressive wedge indicate deposition in inner shelf, neritic environments, possibly associated with tidal or deltaic processes.

The El Vado Sandstone Member separates the middle unit of the Mancos Shale from the upper unit. The El Vado as used in this report follows the definition of Landis and Dane (1967). As such, it is more narrowly restricted in the subsurface than the subsurface definition of the El Vado proposed by Fassett and Jentgen (1978). As defined by Fassett and Jentgen, the El Vado in the subsurface encompassed the entire interval from the top of the Tocito Sandstone to the base of the upper unit of the Mancos Shale (where the resistivity of the wireline log response is much reduced). This subsurface definition would include the transgressive wedge, El Vado Sandstone Member, and the regressive-transgressive wedge of silty and sandy rocks above the El Vado in this report. At the type locality, the El Vado consists of 90 to 100 ft (27.4 to 30.5 m) of interbedded crossbedded sandstone, siltstone, and shale. In the subsurface, the El Vado ranges from 120 to 150 ft (36.6 to 45.7 m) in thickness. The base of the El Vado is picked at a prominent shale break (see core descriptions above for the upper part of the transgressive wedge) and the top was picked to match that defined at the type locality. The top generally coincides with a decrease in sandstone beds and a corresponding decrease in resistivity on the wireline logs.

Core from the El Vado, as restricted in this report, was examined in 4 wells (Appendix A, cores A, B, D, and G; fig. 5). In these wells, the El Vado consists of interbedded sandstone and shale. However, the sandstone beds tend to be thicker (compare El Vado sandstone to the sandstone of the underlying sandstone in the transgressive wedge in the various cores), more carbonaceous, and the sedimentary structures are better developed. The increase sand content in the El Vado suggests a closer proximity to sediment source than for the underlying transgressive wedge. The El Vado was deposited during regression associated with progradation of the B-lower C part of the Dalton Sandstone (fig. 3). King (1975) also suggested an equivalency of the El Vado to the Dalton Sandstone. However, Molenaar (1974) suggested that the El Vado was equivalent to only the lower part of the Dalton (A and possibly lower part of B on fig. 3). The Dalton crops out south of the study area near Cabezon and west of Bernalillo, New Mexico (Hunt, 1936; Sears and others, 1941). The fossil assemblage from the El Vado indicates a late Coniacian age (see discussion above), however, because so many of the inoceramids originally collected (King, 1974) were from float or represented fragments, it is recommended that the type El Vado section be recollected.

The upper unit of the Mancos Shale ranges in thickness from 900 ft (274.4 m) at the south end of the study area to over 1100 ft (335.3 m) at the north (plates 1-5). The increase in thickness is related to the stratigraphic rise of the base of the Point Lookout Sandstone of the Mesaverde Group. Some attempt was made to subdivide the lower 300 to 400 ft (91.4 to 121.6 m) of the lower Mancos, because this part of the upper unit is both oil and gas productive. However, while some of the log responses can be correlated for some distance before they lose their character through facies changes, others can only be correlated a short distance, possibly because of low-contrast log response. The lower part of the upper unit in core from the Samuel Gary 36-D State well (Appendix A, core E; fig. 5) in T. 21 N., R. 4 W., consists of 50 ft (15.2 m) of carbonaceous, wavy to hummocky crossbedded sandstone that is interbedded with thin black shale. This sandstone sequence is similar to the sandstones found in the underlying El Vado Sandstone Member. Oil is produced from this sandstone interval (plate 3, well 36) as well as from the immediately overlying sandy interval (plate 3, well 35). The pattern of deposition of the lower sandstone interval (plate 3) suggests deposition in a deltaic setting. At least the lower part of the basal 300 to 400 ft (91.4 to 121.9 m) of the upper unit of the Mancos appears to have been deposited during continued regression of the Dalton Sandstone. The upper part of the basal 300 to 400 ft (91.4 to 121.9 m) of the upper unit contains less sandstone and proportionally more shale. This change from greater sand to less sand probably marks the turn around point between the regressive Dalton Sandstone and the transgressive Hosta Tongue of the Point Lookout Sandstone. More definitive studies of this interval of the Mancos within a sequence stratigraphic context are warranted, particularly because there is no biostratigraphic control on this part of the section in the northeast part of the San Juan Basin.

THERMAL MATURITY

Thermal maturity studies and time temperature modeling of Cretaceous rocks in the San Juan Basin document high levels of thermal maturity in the deep northern part of the basin (central basin) (Law, 1992). In their mapping of coal beds in the Fruitland Formation, Fassett and Hinds (1971) noted that the rank of these coals increased from southwest to northeast across the basin. The increase in coal rank was attributed to greater depth of burial in the northeast part of the basin. Heat from emplacement of the San Juan volcanics in the San Juan volcanic field in southern Colorado has also been suggested to be the principal cause for the higher thermal maturity of the coals in the northern part of the basin (Choate and Rightmire, 1982; Reiter and Clarkson, 1983a, 1983b; Reiter and Mansure, 1983; Bond, 1984; Meissner, 1984). Subsequent thermal maturity studies of coals from the Fruitland and Dakota Sandstone by Rice (1983) resulted in a basin thermal maturity pattern similar to that presented by Fassett and Hinds (1971). However, Rice attributed the higher thermal maturity of the coals in the northern part of the basin to a combined effect of greater depth of burial and higher geothermal gradient due to emplacement of the volcanics.

In a study using mean vitrinite reflectance (R_m) on coals and carbonaceous shales from core and cutttings from wells, Law (1992) found a similar thermal maturity pattern in the basin, except that he noted a small area of very high thermal maturity in the northeastern part of the basin (fig. 11). This area of higher thermal maturity was attributed to proximity to a series of northeast-trending dikes. Law's study not only focused on examining the lateral variation in thermal maturity but also looked at the change in thermal maturity in vertical profiles through 15 wells. Data from these profiles should permit a better interpretation of the effects of heat transfer process as well as examining the temporal changes in thermal regimes. Vertical vitrinite reflectance profiles from wells near the Reservation (Superior Sealy 1-7, sec. 7, T. 25 N., R. 6 W. and Sohio, Southern Ute 15-16, sec. 16, T. 32 N., R. 7 W.) are nonlinear and are composed of two or more linear segments having different slopes. The changes in slope suggest different processes acting on different sections of the rock column or to contrasting thermal conductivities. The steeper slopes were attributed either to pressure-induced vertically flowing fluids that formed in response to thermogenic hydrocarbon generation and generally coincided with a Rm of about 0.5 %, which is near the onset of catagenic hydrocarbon generation or to convective heat transfer associated with vertically flowing water. Time-temperature modeling (Law, 1992) suggested that if a major buried intrusion (source of heat) in the northern San Juan basin was responsible for the heat, the heating event took place about 20 to 40 m.y. ago (during Oligocene and Miocene). This is the time during which maximum burial was achieved and during which hydrocarbons would have been generated.

The past thermal maturity studies provide the framework for understanding the optimal time for hydrocarbon generation in the basin and where in the basin source rocks would be mature enough to generate hydrocarbons. Within and near the Reservation, few studies have examined the thermal maturity of the Mancos Shale, the rock unit believed to be the source of most of the oil in Cretaceous reservoirs. Vitrinite reflectance data from the Mancos shale (probably on carbonaceous material in cuttings) in Law (1992, fig. 8) indicate that most of the shale at least as far south as T. 22 N. and as far west as R. 6. W. are near or above a R_m of 0.5%, indicating the rock is mature enough to have started to produce oil (fig. 11). The R_m values in the Mancos increase to the north where they are well within the oil-generation window.

Although most of the thermal maturity studies focused on interpreting the vitrinite reflectance of the coals as a means to understand the thermal history of the basin and individual rock units, Rock-Eval data may also be used to interpret the thermal history of shale units which lack coal material. Rock-Eval pyrolysis measures the quantity, quality (type), and level of thermal maturation of organic matter contained in a rock. This technique alone is by no means the only way to evaluate a source rock, but, if used with an understanding of the limitations, it can be useful as a first screening tool and can yield a general characterization of the organic matter in a rock. In this study, representative chips of medium-gray to black shale from available cores in the Mancos were evaluated by Rock-Eval pyrolysis (Espitalie and others, 1977). The cores (fig.5, table 1) are in the Mancos Shale just south of and just east of the central part of the Reservation and thus, provide some boundaries to thermal maturity levels that might be expected on the Reservation.

Rock-Eval analyses of samples from the Mancos Shale are summarized in table 1. The total organic carbon (TOC) reported is the sum of the carbon in the pyrolyzate plus the carbon from the residual oxidized organic matter. Although the TOC is relatively low (< 3.0 percent, however most samples contain >1.5 percent), it appears to be well within the range of 1-3 percent required for oil generation and expulsion (Gries and others, 1997). The TOC range of 0.86 to 2.68 is similar to that obtained for samples of the Mancos Shale in the nearby San Juan sag (Gries and other, 1997). Hydrocarbon generation potential is estimated by the total pyrolytic hydrocarbon yield (sum of the S_1 and S_2 components). S_1 is the quantity of free hydrocarbons (HC) liberated by volatilization at 250° C and S_2 is the quantity of HC produced by further laboratory heating of kerogen. Both S_1 and S_2 are reported in mg HC/g rock. Several generative potential schemes using Rock-Eval analyses have been proposed (table 2). Mostly commonly used is the sum of the S_1 and S_2 components (Tissot and Welte; 1984). As shown in table 2, the generative potential of Mancos Shale samples collected is commonly between 2 and 6 mg HC/g indicating a fair to moderate potential to generate liquid hydrocarbons. In five samples, the generative potential exceeded 6 mg HC/g, indicating the samples represented good to excellent source rocks.

Another measure related to the quantity of pyrolyzable organic matter or hydrocarbons is the hydrogen index (HI), defined as the S_2 yield (remaining hydrocarbon-generating capacity of the organic matter) normalized by total organic carbon. The hydrogen index is also useful in describing the type of organic matter present in a rock and the type of hydrocarbons that will be ultimately generated. Hydrogen index values (in mg HC/g $C_{organic}$) of 0-150 yield mostly gas, of 150-300 yield gas and oil, and greater than 300 yield mostly oil (Peters, 1986). The most widely used graphical tool for defining the type of organic matter contained in a source rock is the modified van Krevelen diagram. This diagram is a plot of the hydrogen index (HI) and the oxygen index (OI) (S_2 and S_3 normalized by total organic carbon respectively), and gives an indication of the type of organic matter (types I, II, III) and the degree of thermal evolution. Type I organic matter is hydrogen rich (sapropelic or lipid rich), is present primarily in marine and

Table 1. Rock-Eval data from selected core in the Mancos Shale, San Juan Basin. [Locations of core are shown in figure 5. TOC, total organic carbon (in weight percent); S_1, integral of first peak (existing hydrocarbons volatilized at 250°C for 5 minutes) (in milligrams per gram); S_2, integral of second peak (hydrocarbons produced by pyrolysis of solid matter (kerogen) between 250°C and 550°C) (in milligrams per gram); S_3, integral of third peak (CO_2 produced by pyrolysis of kerogen between 250°C and 390°C) (in milligrams per gram); T_{max}, temperature (°C) at which maximum yield of hydrocarbons occurs during pyrolysis of organic matter; PI, production index (S_1/S_1+S_2); HI, hydrogen index (S_2/TOC); OI, oxygen index (S_3/TOC).]

Well Name	Location	Depth/ft	TOC	S_1	S_2	S_3	S_1+S_2	T_{max}	HI	OI	PI
San Ysidro 11-16[D]	Sec. 11, T. 20 N., R. 3 W.	4038.4	2.05	0.68	6.71	0.48	7.19	433	327	23	0.09
		4081.2	1.68	0.48	5.63	0.22	5.85	429	335	13	0.08
State 36-D[E]	Sec. 36, T. 21 N., R.4 W.	4390.2	1.53	0.47	2.71	0.20	2.91	436	177	13	0.15
		4433	1.7	0.38	3.22	0.19	3.41	436	189	11	0.11
San Ysidro 5-2[H]	Sec. 5, T. 20 N., R. 2 W.	4421.9	2.12	0.66	6.45	0.14	6.59	433	304	7	0.09
		5102	2.16	0.82	8.11	0.15	8.26	437	375	7	0.09
		5132	2.68	1.00	10.27	0.18	10.45	435	383	7	0.09
Shelby 41-22[A]	Sec. 22, T. 20 N., R. 1 W.	2423	1.00	0.35	1.97	0.34	2.31	428	197	7	0.15
Howard Federal 1-11[F]	Sec. 1, T. 25 N., R. 2 W	7282	1.85	1.60	3.70	0.23	3.93	446	200	12	0.3
2 Federal 24-2[C]	Sec. 2, T. 20 N., R. 3 W.	4582.6	2.39	0.90	9.17	0.27	9.44	433	384	11	0.09
		4612.6	0.86	0.22	0.97	0.12	1.09	439	113	14	0.18
1Federal 44-2[B]	Sec. 2, T. 20 N., R. 3 W.	4408	1.61	0.67	3.38	0.15	3.53	435	210	9	0.17
Davis Federal 3-15[G]	Sec. 3, T. 25 N., R. 2 W.	7114.1	1.70	1.31	3.08	0.18	3.26	439	181	11	0.3
		7266.2	2.32	1.59	4.59	0.26	4.85	448	198	11	0.26

Table 2. Pyrolysis parameters used to define source rock generative potential. [Parameters are defined in table 1.]

Quality	TOC (wt. %)[1]	S_1 (wt. %)[1]	S_2 (mg/g)[1]	S_2 (mg/g)[2]	S_2 S_1+S_2 (mg/g)[3]
Poor	0-0.5	0-0.5	0-2.5	0-2.2	<2
Fair	0.5-1	0.5-1	2.5-5	2.2-5.5	2-6
Good	1-2	1-2	5-10	>5.5	>6
Excellent	2+	2+	10+	>5.5	>6

[1] Peters (1986).
[2] Humble Laboratory (J. Espitalie, written commun., 1982).
[3] Tissot and Welte (1984).

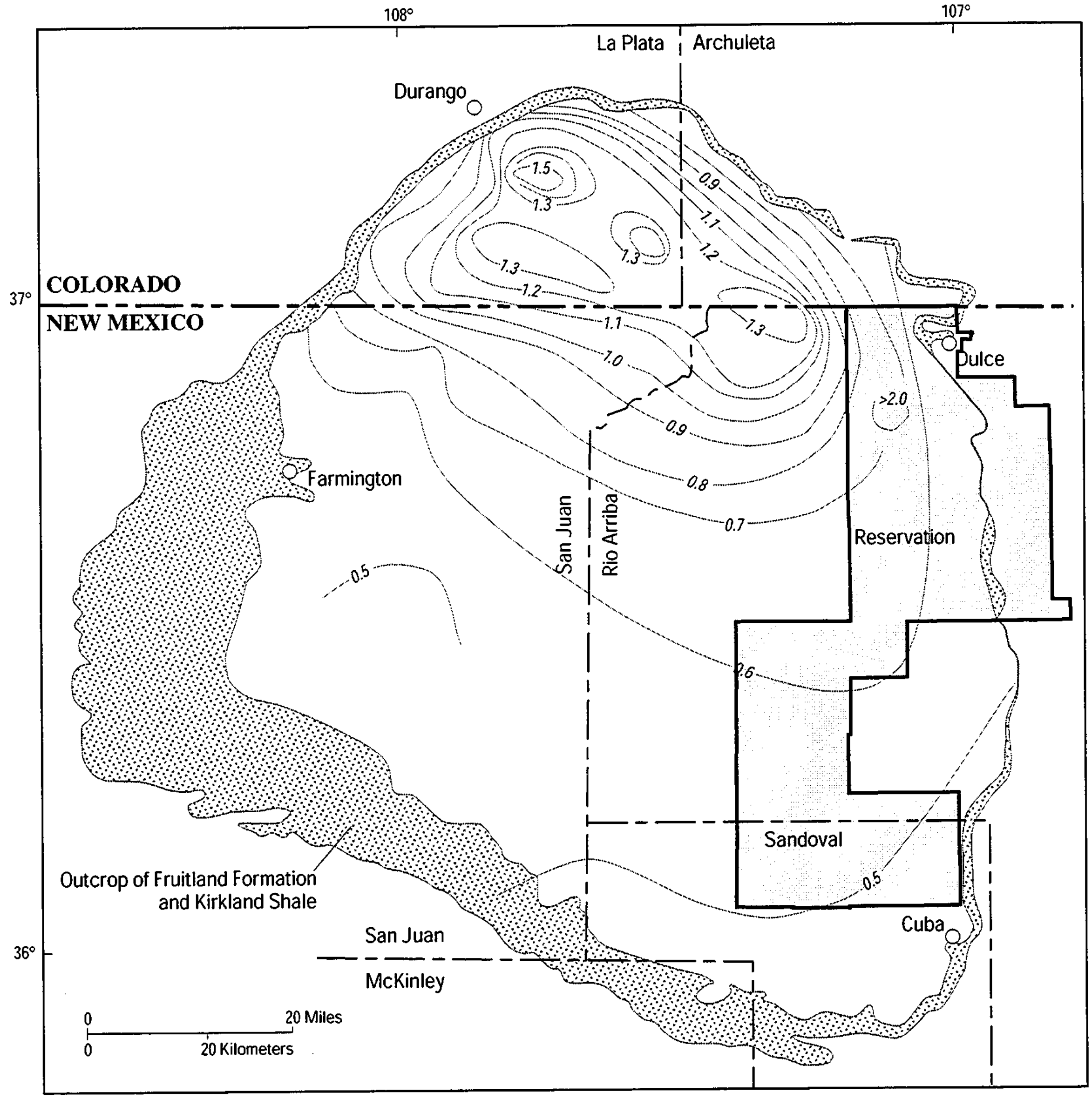


Figure 11. Thermal maturity map of the coal -bearing Fruitland Formation (modified from Law, 1992) showing relative position of the isoreflectance contours to the Jicarilla Apache Indian Reservation. Contour interval, 0.1% R_m.

lacustrine rocks, and generates mainly oil during catagenesis. Type II organic matter is generally present in marine rocks, and generates oil and gas during catagenesis. Type III kerogen is oxygen rich and hydrogen poor (huminite and vitrinite), is present mainly in terrestrial, marginal-lacustrine, or marginal-marine rocks, and generates mostly gas during catagenesis.

Figure 12 is a modified van Krevelen diagram comparing the HI to OI of the samples (table 1) from the Rock-Eval pyrolysis assay. Using the criteria set forth above, there appear to be two populations of organic matter type. Six of the 14 samples have HI greater than 300. This is indicative of type I organic matter and these rocks would be expected to produce oil. Seven of the remaining eight samples have HI between 150 and 300 which is indicative of mixed type I and type II organic matter. These rocks would be expected to produce a mixture of oil and gas. Only one sample had a HI less than 150 indicative of type III organic matter; this rock would be expected to produce gas. This sample also had the least amount of TOC and the lowest (poor) generative potential to produce hydrocarbons. The very sandy nature of the sample (Appendix A, 2 Federal 24-2 well) would most likely be the cause of the poor potential. The distribution of HI in figure 12 is similar to that observed for the Mancos in other studies from the San Juan Basin (Clayton and others, 1991) and San Juan sag (Gries and others, 1997).

Rock-Eval data can also be used as evidence of thermal maturity. One thermal maturity indicator is the production index (PI) or transformation ratio. Production index is defined as the ratio of volatile hydrocarbon yield to total hydrocarbon yield $S_1/(S_1 + S_2)$. The transition from immature to mature, or beginning of the oil window, is about PI=0.10, and the end of the oil window is about PI=0.50 (Tissot and Welte, 1984). Several samples (table 2) have PI less than 0.1 although not much less than this value, which suggests that they are immature to marginally mature with respect to hydrocarbon generation. The remaining samples have PI greater than 0.1 and 3 samples have PI of 0.3, indicating maturity well within the oil window.

One other thermal maturity indicator obtained from Rock-Eval data is T_{max} which is the temperature at which maximum yield of hydrocarbons occurs during pyrolysis or, in other words, the temperature at which the S_2 peak occurs. The onset of oil generation (transition from immature to mature) is considered to occur at a T_{max} of 430°C (Humble Laboratory, 1993, based on written communication from J. Espitalie, 1982) or 435°C (Tissot and Welte, 1984). The upper limit of oil generation occurs at about 460°C (Tissot and Welte, 1984). Peters (1986) suggested that the analytical error of a measured T_{max} is commonly from 1° - 3° C. As shown in table 1, the T_{max} for most samples is at or above 435° C, placing the samples within the oil generation window. Most of the samples with a PI slightly less than 0.1 have a T_{max} slightly less than 435° C. The thermal maturity data suggest that near the southern part of the Reservation there are intervals within the Mancos Shale, that may have generated oil or had the capacity to generate oil or oil and gas. These samples are well away from areas in the northern part of the San Juan Basin (and thus the northern part of the Reservation) in which high thermal values have been observed in coals. This has implication for migration of oil. While oil undoubtedly migrated from the deeper part of the San Juan Basin south into structural and stratigraphic traps in the Mancos, the thermal maturity data presented herein suggests that some of the oil could have been locally sourced and migrated into nearby reservoirs.

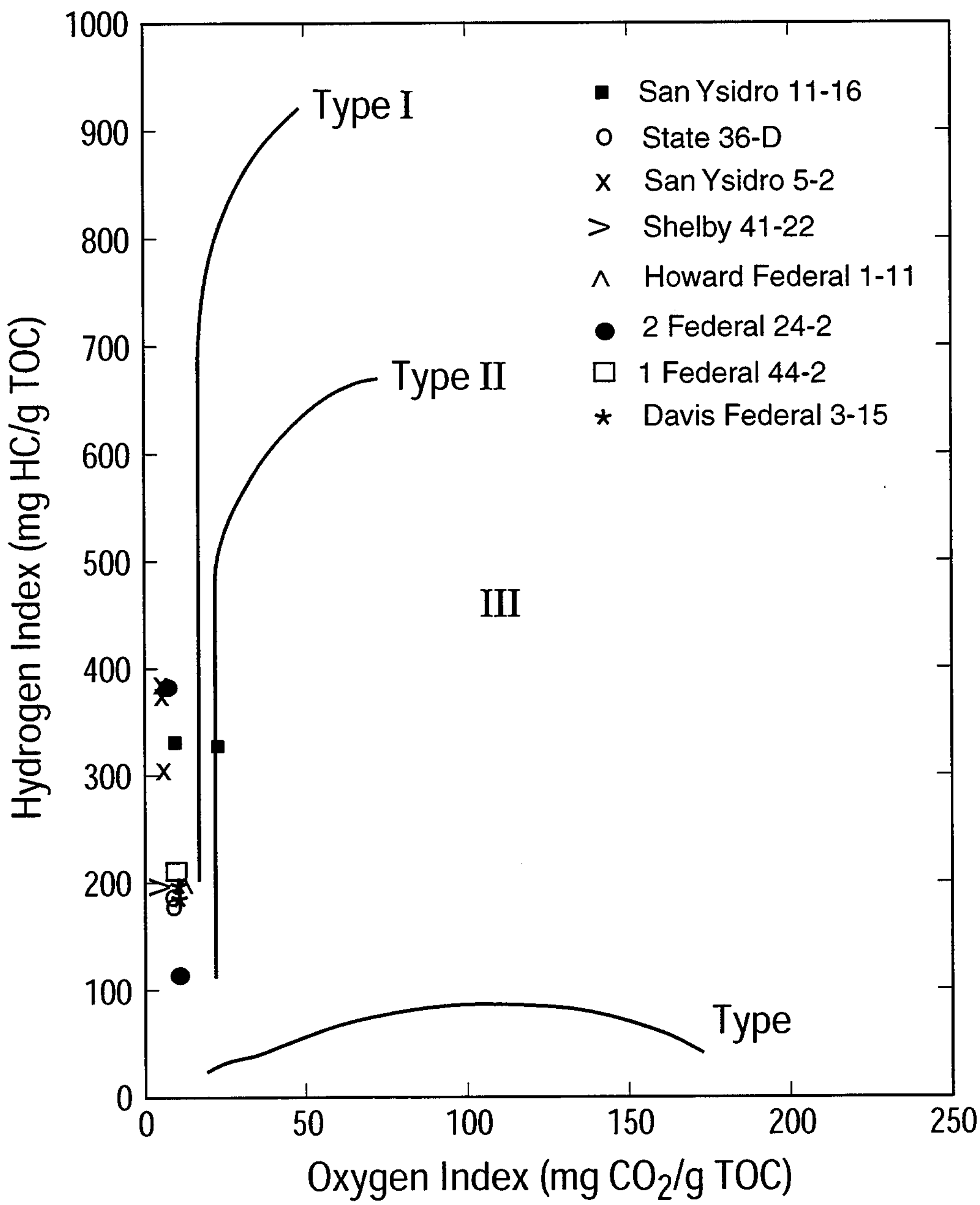


Figure 12. Plot of hydrogen index (HI) versus oxygen index (OI) on a modified Van Krevelan diagram from Rock - Eval pyrolysis of rock chips from the Mancos Shale. Samples are separated by core. Two populations are shown. Samples with HI > 300 are more shale rich; those with HI <300 tend to contain more silt and sand or to be shale layers interspersed between sandier layers.

OIL AND GAS FIELDS

Seventeen oil and five gas fields (figs. 9 and 10; table 3) in the Mancos Shale (including the driller's "Gallup sandstone" or El Vado Sandstone) on and adjacent to the Reservation were evaluated with respect to the sequence stratigraphic model that has been constructed for the lower Mancos Shale. The principal reason for this evaluation was to determine currently producing facies and the areal extent of production from these facies within existing field boundaries. This spatial distribution could then be used to highlight areas where similar facies are present but from which there is no current production. The field name, location, type of hydrocarbon production, type of drive, field API gravity, producing interval, and structural setting for each oil and gas field are listed in table 3. Data for the fields were taken from individual field descriptions in Fassett (1978; 1983); references for individual field descriptions are also in table 3 and will not be repeated below. Observations as to producing intervals and field boundaries are from field descriptions in Fassett (1978, 1983); these have not been updated since the original descriptions. However, the contacts as shown on the cross sections (plates 1-5) between the various productive intervals discussed below can be used in conjunction with data available for individual wells drilled since the original descriptions to expand our knowledge of currently productive units.

Oil-producing intervals from the Mancos Shale were evaluated in 17 oil fields on and near the Reservation. Oil and associated gas produced from various intervals in the Mancos are reported as combined production and thus, cannot be ascribed to the various depositional sequences defined in this report. For this report, combined production by field or for several fields is reported according to the predominant producing facies. Characteristics of these producing intervals will be discussed briefly from oldest to youngest. Of these fields, oil production occurs in the Semilla Sandstone (not the Juana Lopez) in the Otero Sanastee field (table 3; fig 9). This field has produced about 72 thousand barrels of oil and over 91mmcf of associated gas. The Semilla Sandstone occurs stratigraphically below the Gallup Sandstone to the southwest in the basin. It was deposited as an offshore bar. In the subsurface, the formation appears to be more elongate in a northwest-southeast direction and pinches out to the north between townships 25 and 26 (plates 1 and 2). The Otero Sanastee field occurs within the broad northwest-southeast trending, northeast-dipping regional structure of the Chaco slope; there appears to be no structural closure to the field (fig. 13). Production from the Juana Lopez occurs in the Gavilan Gallup field (table 3; 9). The Gavilan field is located on a northwest-plunging anticline (fig. 13).

The distal Gallup equivalents (lower Mancos Shale) between the Juana Lopez and the overlying regional unconformity consists of thin a shale and interbedded thin sandstone and shale sequence genetically unrelated to the transgressive wedge of rocks that overlie the regional unconformity. Oil production from distal Gallup equivalents occurs in the nearly contiguous Counselors Gallup and Lybrook Gallup fields (table 3; fig. 9). Production is in the upper part of distal Gallup equivalents which contain more interbeds of fine-grained sandstone. This somewhat sandier interval is time equivalent to the last regressive Gallup sandstone (A). This part of the distal Gallup equivalents is cut out north of township 24. The Counselors Gallup field is located on a flexural bend in the broad northeast-dipping regional structure of the Chaco slope (fig. 13). Similarly, the Lybrook Gallup field is located on the same structural trend to the west (fig. 13). At the Lybrook Gallup field a small low-amplitude northeast-plunging anticline superimposed on the regional structure might have some closure along the crest.

Of the 17 fields evaluated, three produce oil from Tocito-like sandstones (Blanco Tocito south, Lybrook Gallup, and Tapicito Gallup; table 3; fig. 9). The Tocito-like sandstones in both

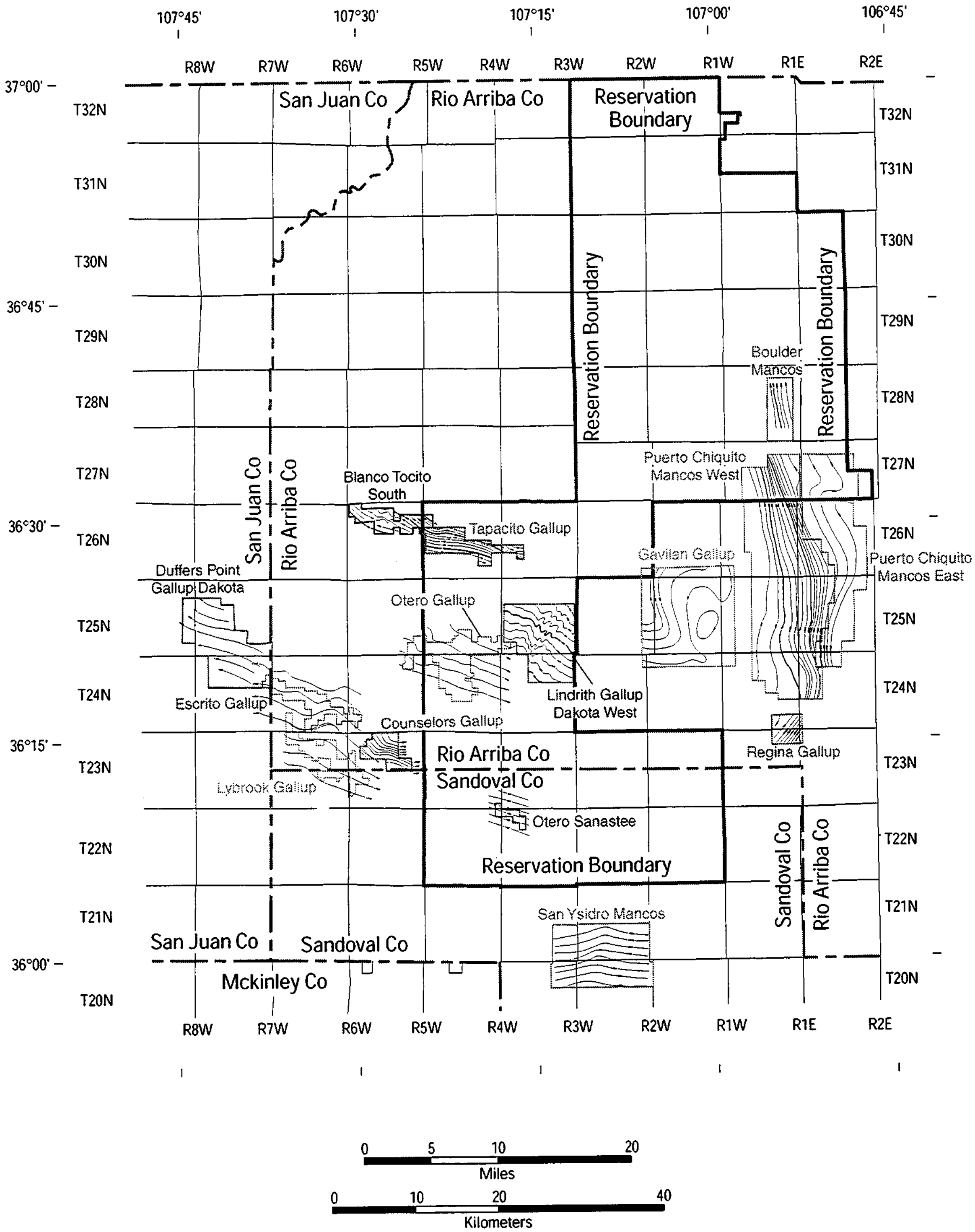


Figure13. Map showing structure within select oil fields in the Mancos Shale on and near the Jicarilla Apache Indian Reservation (data from Fassett, 1978, 1983).

the Blanco Tocito south and Tapicito Gallup fields are part of a trend of northwest-southeast elongate, vertically stacked or isolated sandstone lenses (plates 1, 2, and 3). The sandstone lenses either rest on the regional unconformity or occur as much as 50 feet above the unconformity. The sandstones are fine- to coarse-grained which distinguishes them from the generally fine-grained sandstones in the overlying units. The generally coarser-grained sandstone lenses were deposited during transgression and are stratigraphically higher in the section (and thus, somewhat younger) than similar Tocito-like sandstones found to the north (plates 1, 2, and 5). The Blanco Tocito south and Tapicito fields are contiguous and occur along the same broad northeast-dipping regional structure of the Chaco slope (fig. 13). There are small flexural bends in the regional structure across the fields that could provide some structural closure and development of natural fractures. Combined, these two fields have have produced 4.6 mbl oil and 37.7 bcf associated gas. The Tocito-like sandstone in the Lybrook Gallup field (often called the Marye sandstone) occupies a similar position with respect to the regional unconformity, but is stratigraphically younger and higher in the section than the Tocito-like sandstones found to the north (plates 1, 2, 4, and 5). This Tocito-like sandstone is at the same stratigraphic level as the productive sandstone interval found in the Devils Fork Gallup field. It may represent a local sand buildup lateral to the site of a major sand accumulation deposited during a stillstand that occurred within an overall transgression. The Lybrook field has produced about 4.3 mbl oil and 38.4 bcf associated gas; production is from Tocito-like sandstone as well as from distal Gallup equivalents and the El Vado Sandstone (table 3.)

As defined in the 5 regional cross sections (plates 1-5), the wedge of transgressive rocks below the El Vado Sandstone and above the regional unconformity thins from north to south. Oil production from various sandstones and interbedded sandstone and shale beds in the transgressive interval occurs in seven fields (Devils Fork Gallup, Duffers Point Gallup, Escrito Gallup, Gavilan Gallup, Ojito Gallup, Puerto Chiquito East, and Puerto Chiquito West; table 3; fig. 9). Oil production from the Devils Fork Gallup is exclusively from the top transgressive interbedded sandstone and shale which is about 50 ft thick. A net sandstone map of this unit in the Devils Fork field (fig. 14) does not have a northwest-southeast trend. Rather it shows a multilobate configuration suggestive of deltaic deposition. This transgressive unit was deposited close to a shoreline established during a still stand that occurred within an overall transgression. The Devil's Fork Gallup field has produced over 4.6 mbl oil and about 59 bcf of associated gas. Oil in the Duffers Point Gallup, Gavilan Gallup, and Ojito Gallup is also from the same stratigraphic interval. Combined these three fields have produced 9.6 mbl oil and 44.2 bcf associated gas from all units. Additional oil production at the Ojito Gallup field is from an underlying, genetically older, interbedded sandstone and shale interval, about 50 ft thick. This older sandy interval is also present at the Gavilan field, where it may be marginally productive (Emmendorfer, 1992), and is poorly developed at the Duffers Point Gallup field. Oil production in the Puerto Chiquito Mancos East and West fields is also from the top transgressive unit. However, it is generally noncommercial in the East field, possibly due to a change to a more shaly facies as shown in cross section D-D' (plate 4). In the West field, oil production from the transgressive unit is confined to the south end of the field. Combined, the Puerto Chiquito East and West fields have produced 8.1 mbl oil and 46.3 bcf associated gas from all units. Oil production is split nearly equal between the two fields. However, all but 2 bcf of gas is produced from the Puerto Chiquito East field.

Most of the oil productive facies for the 17 fields evaluated are within the El Vado Sandstone as defined in this report. Twelve fields (Boulder Mancos, Counselors Gallup, Duffers Point Gallup, Escrito Gallup, Gavilan Gallup, Lindrith Gallup West, Lybrook Gallup, Ojito Gallup, Otero Gallup, Puerto Chiquito East and West, and Regina Gallup; table 3; fig. 9) produce from thin sandstone lenses or interbedded sandstone and shale in the El Vado. Low porosity and

Table 3. Location and producing characteristics of oil and gas fields in the Mancos Shale on and near the Jicarilla Apache Indian Reservation.

Field Name	Location	Type of Hydrocarbon Production	Type of Drive	Field API Gravity	Producing Formation	Structural Setting
BS Mesa Gallup[1]	T. 26-27 N., R. 4 W.	Gas/minor oil	Gas expansion	65°	Lower Tocito Sandstone	Broad, low-amplitude folds on E-W regional structure
Campo Gallup[2]	T. 29-30 N., R. 3-4 W.	Gas/condensate	Gas expansion	40°	El Vado Sandstone	Limbs of synclinal bend; fractured
Chozo Mesa Gallup[3]	T. 28, R. 3-4 W.	Gas	Gas expansion	No data	Regressive and transgressive units above El Vado Sandstone; El Vado Sandstone, transgressive unit	Down-dip end of NE-SW-trending monocline
Lindrith Gallup[4]	T. 24 N., R. 2 W.	Gas/minor oil	Solution gas	38°-40°	Minor gas in El Vado Sandstone; distal Gallup equivalents	Nose of NE-plunging anticline
Wildhorse Gallup[5]	T. 26 N., R. 3-4 W.	Gas/condensate	Gas expansion	65°	Lower Tocito Sandstone	Broad, low-amplitude folds on E-W regional structure
Blanco Tocito, South[6]	T. 26 N., R. 5-6 W.	Oil	Solution gas	43°-44°	Tocito Sandstones	Low-amplitude folds on broad NW-SE-trending regional structure
Boulder Mancos[7]	T. 28 N., R. 1 W.	Oil	Gravity drainage/solution gas	37°	Regressive and transgressive units above El Vado Sandstone; top El Vado Sandstone	West-dipping monocline cut by faults

Counselors Gallup[8]	T. 23 N., R. 6 W.	Oil	Solution gas	40°-45°	El Vado Sandstone, Tocito-like sandstone, distal Gallup equivalents	NW-SE flexural bend of broad regional structure
Devil's Fork Gallup[9]	T. 24 N., R. 6-7 W.	Oil	Dissolved gas/gas expansion	40°	Upper transgressive unit	Broad regional NW-SE structure with northeast-plunging anticline
Duffers Point Gallup[10]	T. 24-25 N., R. 8 W.	Oil	Solution gas	40°	El Vado Sandstone, transgressive unit	NW-SE regional structure
Escrito Gallup[11]	T. 24 N., R. 6-8 W.	Oil	Solution gas	40°	El Vado Sandstone, transgressive unit	NW-SE regional structure with northeast-plunging anticline
Gavilan Gallup[12]	T. 25 N., R. 2 W.	Oil	Solution gas/fluid expansion	41.2°	El Vado Sandstone, trangressive unit, Juana Lopez	Crest and limbs of N-NW plunging anticline
Lindrith Gallup West[13]	T. 24-25 N., R. 4 W.	Oil	Solution gas/fluid expansion	43.7°	El Vado Sandstone, top transgressive unit	Small anticlines and synclines on broad NW-SE regional structure
Lybrook Gallup[14]	T. 23-24 N., R. 6-7 W.	Oil	Solution gas	40°	El Vado Sandstone, Tocito-like sandstone, distal Gallup equivalents	NW-SE regional structure with northeast-plunging anticline
Ojito Gallup[15]	T. 25 N., R. 3 W.	Oil	No data	43°	El Vado Sandstone, trangressive unit	NW-SE regional structure with small northeast-plunging anticline
Otero Gallup[16]	T. 24-25 N., R. 4-6 W.	Oil	Gas	40.7°	El Vado Sandstone	Broad, low-amplitude folds on NW-SE regional structure
Puerto Chiquito East[17]	T. 25-27 N., R. 1 E.	Oil	Gravity drainage/solution gas	34°	Mostly in El Vado; noncommercial in transgressive unit	NW-trending anticline on west-dipping monocline

Puerto Chiquito West[18]	T. 25-27, R. 1 E, 1 W.	Oil	Gravity drainage	39°-40°	North end in El Vado; south end in transgressive unit	West-dipping monocline
Regina Gallup[19]	T. 24 N., R. 1 W.	Oil	Gas expansion	46°	El Vado Sandstone, transgressive unit	NE-SW flexural bend of regional monocline
San Ysidro Mancos[20]	T. 21 N., R. 3 W.	Oil	Solution gas/gravity drainage	38°	Regressive and transgressive units above El Vado Sandstone	Broad regional E-W structure with north-plunging anticline
Tapicito Gallup[21]	T. 26 N., R. 4-6 W.	Oil	Gas expansion	43°-44°	Tocito Sandstone	Flexure on broad NW-SE regional structure
Otero Sanastee[22]	T. 22-23 N., R. 4-5 W.	Oil	Gas expansion	40.1°	Semilla Sandstone	Broad NW-SE-trending regional structure

1 Matheny, M.L., and Matheny, J.P., BS Mesa Gallup, in Fassett (1978), p. 251-253.
2 Middleman, A.A., Campo Gallup, in Fassett (1983), p. 941-943.
3 Roe, J.D., Choza Mesa Gallup, in Fassett (1983), p. 944-945.
4 Hornbeck, J.M., Lindrith Gallup, in Fassett (1983), p. 978-981.
5 Matheny, M.L., Wildhorse Gallup, in Fassett (1978), p. 564-567.
6 Fassett, J.E., and Jentgen, R.W., Blanco Tocito South, in Fassett (1978), p. 233-240.
7 Needham, C.N, Boulder Mancos, in Fassett (1978), p. 248-250.
8 Folk, K. F., Counselors Gallup, in Fassett (1983), p. 948-950.
9 Dunn, S.S., Devils Fork Gallup, in Fassett (1978), p. 276-278.
10 Dunn, S.S., Duffers Point Gallup-Dakota, in Fassett (1978), p. 282-284.
11 Reese, V.R., Escrito Gallup, in Fassett (1978), p. 287-289.
12 Bowman, K.C., Gavilan Gallup, in Fassett (1983), p. 959-962.
13 Attebery, R.T., Lindrith Gallup-Dakota West, in Fassett (1978), p. 381-384.
14 Reese, V.R., Lybrook Gallup, in Fassett (1978), p. 395-397.
15 Matheny, M.L., Ojito Gallup, in Fassett (1978), p. 433-434.
16 Brown, H.H., Otero Gallup, in Fassett (1978), p. 444-446.
17 Greer, A.R., Puerto Chiquito East, in Fassett (1978), p. 464-467.
18 Greer, A.R., Puerto Chiquito West, in Fassett (1978), p. 468-471.
19 Davies, M.L., Regina Gallup, in Fassett (1983), p. 1011-1013.
20 Chittum, W.E., San Ysidro Mancos, in Fassett (1983), p. 1026-1028.
21 Fassett, J.E., and Jentgen, R.W., Tapicito Gallup, in Fassett (1978), p. 510-515.
22 Hawks, R.L, Otero Sanastee, in Fassett (1983), p. 995-997.

low permeability characterize the sandstones. Production is aided by natural and induced fractures (see discussion of fracture development in the Gavilan Gallup field in Emmendorfer, 1992 and in the Puerto Chiquito East and West fields in Gorham Jr. and others, 1977; Greer and Ellis, 1991). Along the Chaco slope, on which most of the oil fields are located, natural fractures formed during the Laramide orogeny in conjunction with the formation of broad low-folds superimposed in the generally northwest-southeast regional structure (plate 6; fig. 13; Gorham Jr. and others, 1977). Additional fractures may have formed as a result of post-Eocene extensional tectonics. Fracture development in the Boulder Mancos, and Puerto Chiquito East and West fields is related to development of the monocline (fig. 13; Gorham Jr. and others, 1977; Greer and Ellis, 1991) and its associated reverse and normal faulting. Oil production from fractures associated with major folds occurs only in the Gavilan Gallup and part of the Puerto Chiquito East fields (fig. 13). Together the Boulder Mancos, Counselors Gallup, Escrito Gallup, Lindrith Gallup West, Otero Gallup, and Regina Gallup fields have produced 35.4 mbl oil and 357 bcf associated gas from all productive facies.

The interval overlying the El Vado Sandstone as defined in this report consists of interbedded thin sandstone and shale deposited during continued regression associated with deposition of the Dalton Sandstone and during the intial stages of transgression associated with deposition of the Hosta Tongue of the Point Lookout Sandstone. Oil production from this combined interval occurs only in the Boulder Mancos and San Ysidro Mancos fields (table 3; fig. 9). Production is enhanced by natural and induced fractures. The San Ysidro field is located on a broad, north-dipping anticline that is superimposed on the generally east-west structure of the Chaco slope (table 3; fig. 13).

Oil production in the various subdivisions of the Mancos Shale discussed above appears to be both stratigraphically (fracture) and structurally controlled (Fassett, 1991). Natural fracture permeability is important especially in fields located on major structures or on the west-dipping monocline (Gorham Jr. and others, 1977; DuChene, 1989; Fassett, 1991). All of the oil fields are located along the Chaco slope between the deep part of the San Juan Basin to the north and the shallow part of the basin to the south or in steeply west-dipping rocks along the east margin of the basin. Most of the oil fields on the Chaco slope occur in sandstone lenses or in interbedded sandstone and shale; natural fractures may be locally important. The sandstones generally have low porosities and permeabilities (except perhaps the Tocito-like sandstones). As a result, fractures serve as both storage and as conduits through which hydrocarbons move. Because most of the sandstone is of low permeability, long distance migration of oil from the deep part of the San Juan Basin on to the more shallow-buried Chaco slope may not have occurred, except through fractures or faults. The oil in the Mancos reservoirs was probably sourced from shales within the Mancos. Most API gravities of the oil range from 39 to 48 (fig. 8; table 3); although there are a few oils with API gravities above 50 and less than 39. There are no real trends to the distribution of API gravities that might indicate regional migration pathways for the oil, although the oils tend to be somewhat heavier to the northeast and southwest (fig. 8). In the Puerto Chiquito field API gravities are heavier, less than 35 (fig.8; table 3). The cause of the heavier API gravities is not known. API gravities of 65 in the BS Mesa and Wildhorse Gallup gas fields (fig. 10) are well within the condensate range.

As discussed above, the area encompassed by the Chaco slope is well within the oil-generation window but not within the gas-generation window. The gas window lies to the north in the deep central basin (> R_m 0.9 % on fig. 11), where gas is the only hydrocarbon produced from the Mancos. Thus, it is possible that some oil was locally sourced from the interbedded shale and simply migrated into sandstone that had some porosity or into associated fractures. If

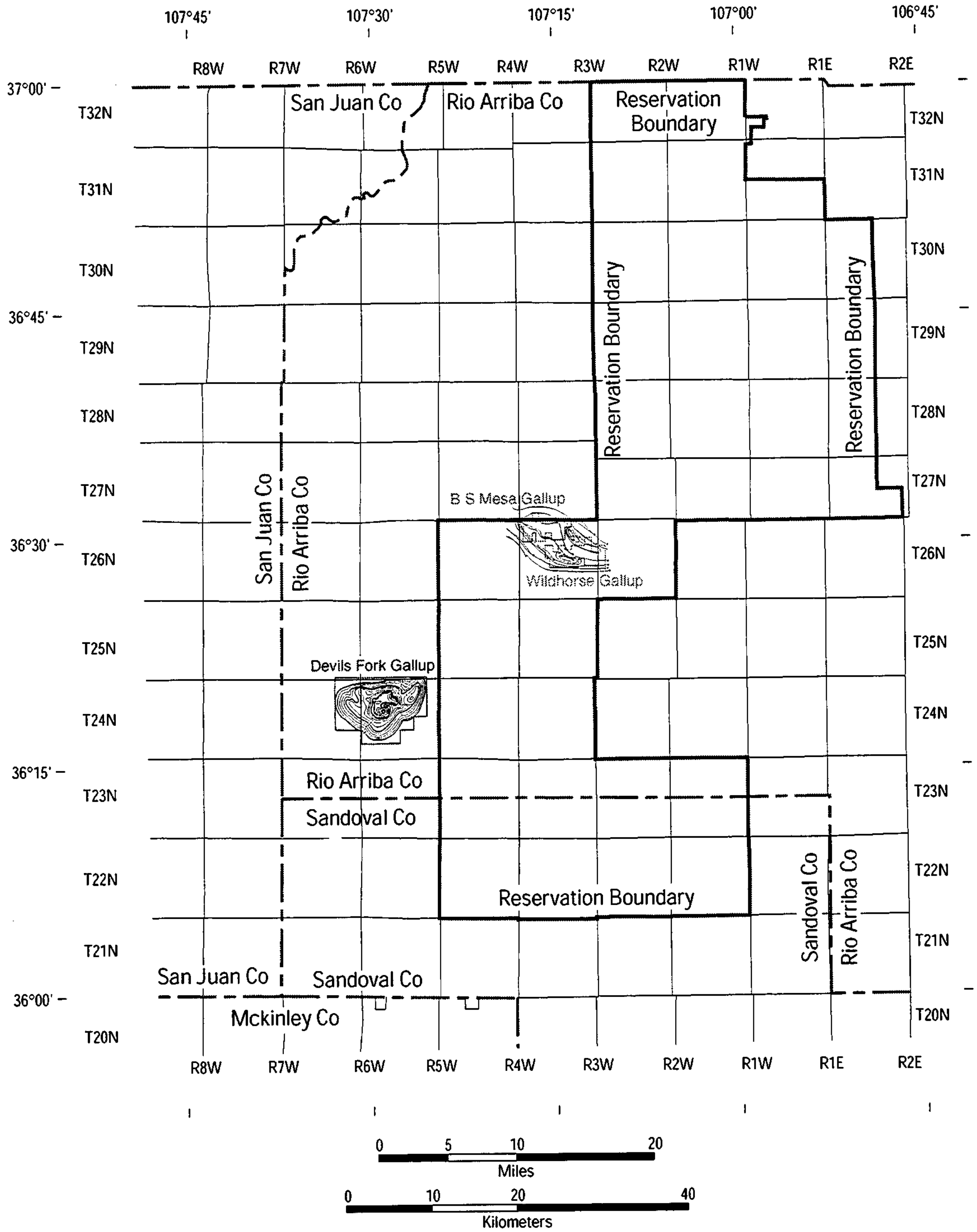


Figure 14. Map showing net sandstone in the oil-producing interval of the Mancos Shale at the Devils Fork Gallup field and in the gas-producing interval of the Mancos Shale at the BS Mesa and Wildhorse Gallup fields (data from Fassett, 1978).

this scenario is the case, then the oil accumulations might be considered as a type of continuous accumulation (see discussion below). Most of the oil fields lack a downdip water contact that is common in a conventional reservoir. In some fields, a thick interval of Mancos contains several oil-productive horizons none of which are structurally controlled (no structural closure) but rather oil production appears to be controlled by a combination of sandier facies, possibly cemented with dolomite (Gorham Jr and others, 1977; Emmendorfer, 1992), with associated fractures. Most of the oil fields produce associated gas which may form a cap in the structurally updip parts of the fields. The location of the gas cap accounts for the fact that some parts of a field are totally gas productive while other parts produce oil or oil with some quantity of gas. Gas compositions (as reported in Fassett, 1978; 1983) indicate a thermogenic origin, i.e. have several percent of ethane, propane, and higher hydrocarbons. Because much of the oil in the Mancos in this part of the basin (and on the Reservation) is not conventionally reservoired, exploration and development strategies that recognize the unconventional nature (and possible local sourcing) of the oil accumulations should be considered.

Gas production from the five Mancos fields (table 3; fig. 10) evaluated is from lenticular Tocito-type sandstones (BS Mesa Gallup field and Wildhorse) or from thinly interbedded sandstone and shale in the El Vado Sandstone (Campo Gallup, Chozo Mesa Gallup, and Lindrith Gallup). It is also found in distal Gallup equivalent rocks (Lindrith Gallup), and from regressive and transgressive rocks above and transgressive rocks below the El Vado (Chorzo Mesa Gallup). The lenticular Tocito-type sandstones occur in the lower part of the Mancos (below the El Vado Sandstone, as defined in this study) and about 50 ft above the top of the Juana Lopez. These sandstones were deposited during the early stages of transgression above the unconformity that separates regressive sediments of generally Carlile age from those of generally Niobrara age. The sandstone bodies have limited regional distribution, and are areally more extensive in a northwest-southeast direction than in a northeast-southwest direction as shown on a net sandstone map through the BS Mesa and Wildhorse Gallup fields (fig. 14). The sandstones are in a similar position relative to the unconformity as the lowermost oil-producing Tocito sandstone lentils farther to the west and south. The BS Mesa and Wildhorse Gallup fields are located on the northeast side of the broad east-west regional structure of the Chaco slope. In the area of these fields, the regional structure dips gently to the north; broad low-amplitude, north-dipping folds are superimposed on the regional structure (fig. 15). These two fields have combined production of about 44.5 bcf of gas; the majority of the gas is from the Wildhorse Gallup field.

Gas production from the El Vado Sandstone in the Campo Gallup, Chorzo Mesa Gallup, and Lindrith Gallup fields (table 3; fig. 10) is in fractured interbedded thin sandstone and shale deposited in a shelf setting. Combined gas production from these fields is about 928 mmcf; most of the gas production is from the Lindrith Gallup field. The Lindrith Gallup filed has also produced over 68 thousand barrels of oil. The thin sandstone and shale sequence have low permeability and production is generally from natural or enhanced fractures. Structurally, the Campo Gallup field is located on a generally north- to northwest-plunging syncline (fig. 16); the Chorzo Mesa Gallup field, which is contiguous with the Campo Gallup field (fig. 10), occurs on the southeast part of the syncline (fig. 15). At the Lindrith Gallup field (table 3; fig. 10), gas is mostly produced from the top part of distal Gallup equivalents. These distal equivalents were deposited in a shelf to basinal setting. At this locality, the top of the distal Gallup equivalents contains proportionally more interbedded sand layers than the underlying rocks, because it is more proximal to the last regressive tongue (A) of the Gallup Sandstone. Production is from low-permeability interbedded sandstone and shale layers. Fracturing enhances permeability. The field is located on a northeast-dipping flexural bend in the broad regional structure of the Chaco slope (fig. 15).

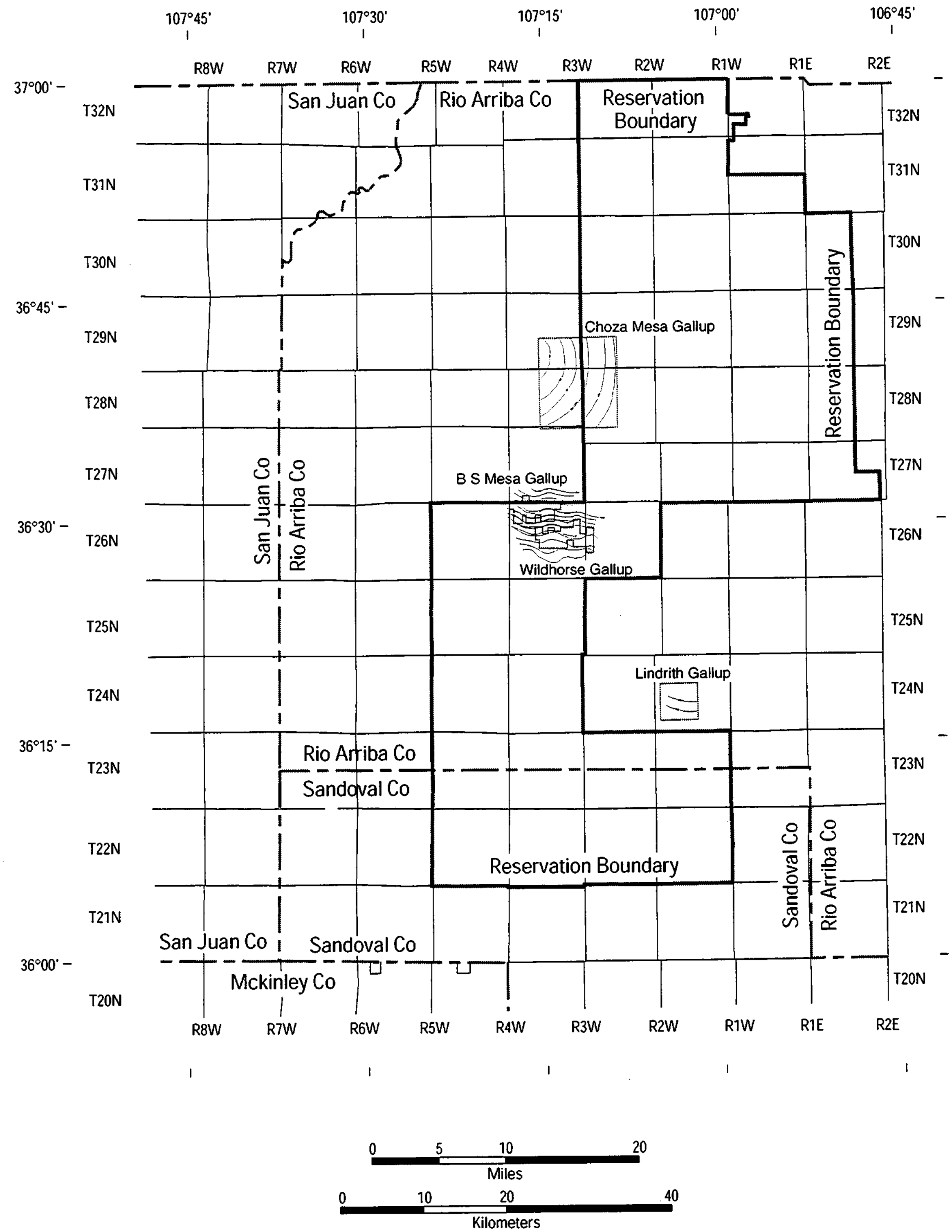


Figure15. Map showing structure within select gas fields in the Mancos Shale on and near the Jicarilla Apache Indian Reservation. Data from Fassett (1978, 1983).

Only the Chozo Mesa Gallup field produces gas from the transgressive sequence below the El Vado and from the regressive-transgressive units above the El Vado (table 3). As shown on cross section A-A' (plate 1), in this part of the basin, these transgressive and regressive-transgressive units consist of thinly interbedded sandstone and shale. Deposition of these units was probably in shelf environments. Permeabilities are low and production is enhanced by natural and induced fractures.

Gas production from the five gas fields that were evaluated is neither stratigraphically nor structurally controlled, although the fields are found in a variety of structural settings. It appears that natural fracturing enhances recoverability and better sandstone reservoir character concentrates local accumulations. The gas fields lack a water drive; no water production has been reported (see discussions in Fassett, 1978). The shaly nature of the units coupled with low-contrast wireline log responses make it difficult to detect the presence of hydrocarbons onthe logs. Because of the difficulty in evaluating the presence of hydrocarbons on the logs, there are probably many potential gas-bearing (and oil-bearing) zones in the Mancos that have been by-passed. In the discussion above, producing intervals were shown to vary between fields and within specific fields all potentially productive intervals may not have been tested. Additionally, many wells drilled in this part of the basin have only tested higher or lower formations, thus, by passing this part of the Mancos altogether.

The sandstones in many Cretaceous rock units in this part of the San Juan Basin (away from the structural east margin) are gas saturated. This is a characteristic of basin-centered gas accumulations. This type of accumulation fits the "continuous-type" gas accumulation category that was first defined and used in the 1995 USGS national assessment (Schmoker, 1995). Continuous-type accumulations are considered to be large, low grade (initial volumes), unconventionally reservoired (i.e. no downdip water contact) accumulations that crosscut lithologic boundaries. They might require different development strategies from those used in conventionally reservoired gas accumulations (Schmoker, 1995). Where they occur, continuous-type gas accumulations are thought to be everywhere gas-charged in the gas-bearing interval, although the gas may not always be economic. Other characteristics of continuous-type gas accumulations include an updip water contact (i.e. the gas accumulation is located downdip from water-saturated rocks), the insignificance of conventional traps and seals, a close association of reservoir with source rock, and low reservoir permeability in facies that have large areal extent. Reservoirs include sandstone, siltstone, shale, chalk, and coal. Although characterized by large in-place hydrocarbon volumes, production is characterized by low recovery; however, individual wells may produce for a long time. Production rates are heterogeneous (Schmoker, 1995). Because the gas in the Mancos in this part of the basin (and on the Reservation) is not found in conventional reservoirs, exploration and development strategies that recognize the unconventional nature of the gas accumulations should be considered.

SUMMARY

Oil distribution in the lower part of the Mancos Shale seems to be mainly controlled by fractures and by sandier facies that are dolomite-cemented. Thus, it is critical to have an understanding of the detailed structure of the area (as a control on distribution of fractures) and of the facies distribution within the lower Mancos. The detailed structure map (plate 6) shows not only the large-scale regional structures, but also delineates the location of broad low-amplitude folds superimposed on the regional grain. Fractures seem best developed in the areas of these folds. To better understand the facies distribution and their relation to hydrocarbon production, the lower part of the Mancos Shale has been subdivided into four main regressive and transgressive components as shown on five regional cross sections (plates 1-5; fig. 6). The

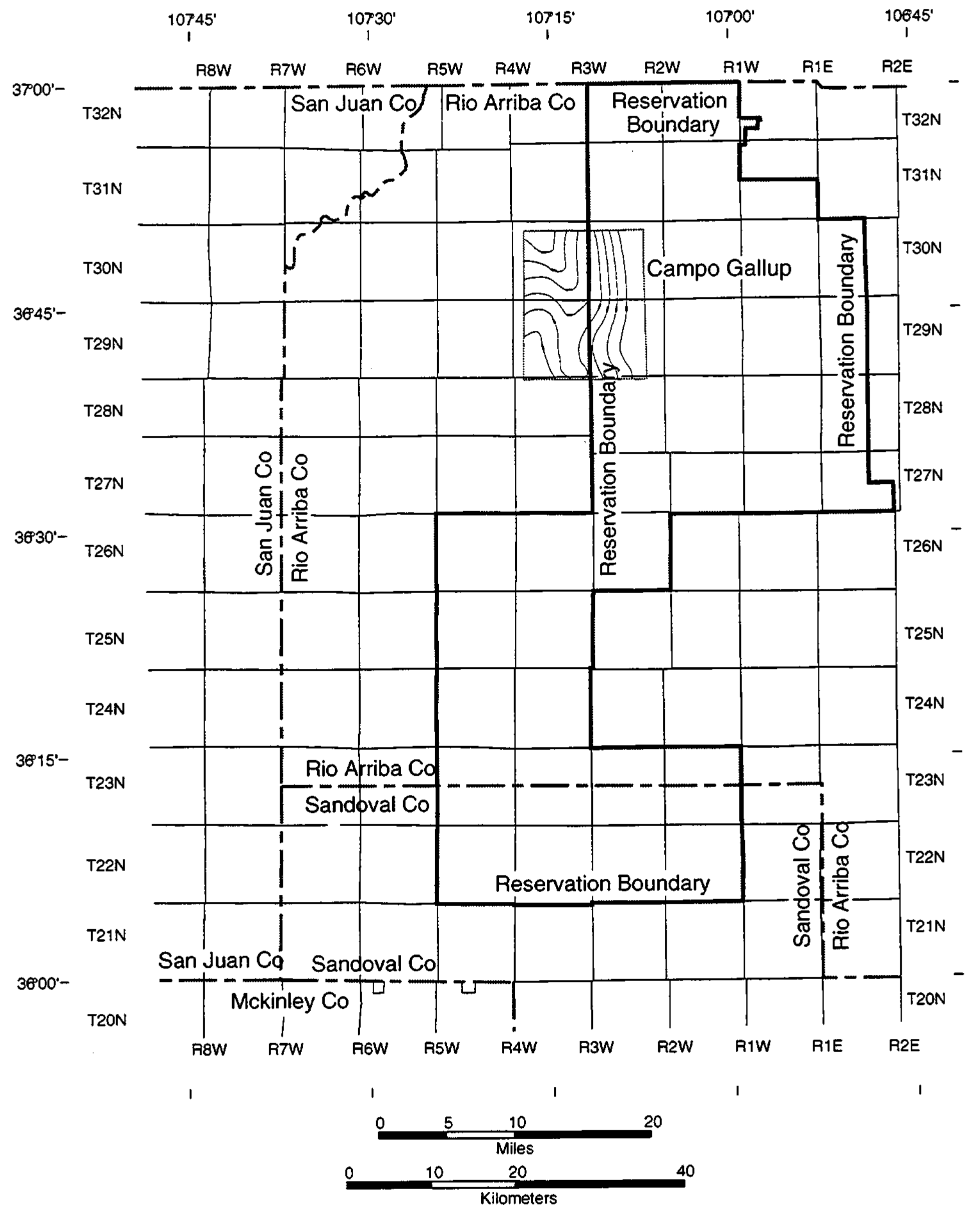


Figure16. Map showing structure within the Campo Gallup gas field on and adjacent to the Jicarilla Apache Indian Reservation (data from Fassett, 1983).

middle unit of the Mancos Shale is split by an unconformity of regional extent. Rocks below the unconformity are distal (basinal) equivalents of the sandy shoreface sandstones of the Gallup Sandstone. These units locally produce oil from fields in and adjacent to the southern part of the Reservation. These distal Gallup equivalents are gradually truncated to the north below the regional unconformity. The best areas for possible additional production from this unit are in the southern part of the Reservation south of Township 25 North where the upper, more sandy part of the distal Gallup equivalents are preserved. The middle unit above the unconformity and below the El Vado Sandstone Member of the Mancos Shale consists of a wedge of rock deposited during transgression. In the basal part of the transgressive sequence, sandstone lenses considered to be equivalent to the Tocito Sandstone produce both oil and gas. This hydrocarbon reservoir is the easiest to determine on logs and its distribution is probably the best known. Additional hydrocarbon production from these sandstone lenses would require delineation of areas where the sandstone lenses have not been identified or tested. The overlying unnamed transgressive sequence of interbedded sandstone and shale is productive in a few fields. It is hoped that correlation of genetically-equivalent rocks in this interval on the cross sections (plates 1-5) can be used to delineate trends of these potentially productive facies that warrant further testing.

The El Vado Sandstone Member of the Mancos Shale, as defined in this report, was deposited as facies basinward of the lower part of the regressive Dalton Sandstone. This member produces most of the oil and gas from the Mancos. In the central and southern part of the Reservation, large areas, currently not productive or not tested, have the potential to contain oil in the El Vado simply based on the trend of the facies and structure as shown in the five regional cross sections (plates 1-5) and structure map (plate 6). The wedge of rocks overlying the El Vado Sandstone were laid down during continued regression of the Dalton Sandstone followed by transgression of the Hosta Tongue of the Point Lookout Sandstone. There has been little oil or gas production in these rocks and much of this interval is largely untested. Thus, large areas of the Reservation could contain hydrocarbon resources in these strata.

Most of the Reservation lies within the oil generation window based on new Rock-Eval data from the Mancos Shale just south of the southern part of the Reservation. If these observations are valid then oil could have been generated locally and would only have needed to migrate short distances in to sandy reservoirs and fractures. This would not rule out long distance migration of oil from the deeper, more thermally mature part of the basin to the north. However, low porosity and permeability characterize sandier rocks in the Mancos, with the exception of Tocito-like sandstones. These factors could retard long distance oil migration through the sediment package, except through fracture or fault conduits. Thus, it is suggested that future oil and gas explorations in the Mancos treat the accumulations and reservoirs as unconventional and consider whether the source and reservoir are in closer proximity than has previously been assumed.

REFERENCES

Bond, W.A., 1984, Application of Lopatin's method to determine burial history, evolution of the geothermal gradient, and timing of hydrocarbon generation in Cretaceous source rocks in the San Juan Basin, northwestern New Mexico and southwestern Colorado, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists Guidebook, p. 433-448.

Campbell, C.V., 1979, Model for beach shoreline of Gallup Sandstone (Upper Cretaceous) of northwestern New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 164, 32 p.

Choate, R., and Rightmire, C.T., 1982, Influence of the San Juan Mountain geothermal anomaly and other Tertiary igneous events on the coalbed methane potential in the Piceance, San Juan, and Raton basins, Colorado and New Mexico; Proceedings of the Unconventional Gas Recovery Symposium, May 16-18, Pittsburgh, Pennsylvania: Society of Petroleum Engineers/U.S. Department of Energy 10805, p. 151-164.

Clayton, J.L., Rice, D.D., and Michael, G.E., 1991, Oil-generating coals of the San Juan Basin, New Mexico and Colorado, U.S.A.: Organic Geochemistry, v. 17, n. 6, p. 735-742.

Dane, C.H., 1960, The boundary between rocks of Carlile and Niobrara age in the San Juan Basin, New Mexico and Colorado: American Journal of Science, v. 258-A, p. 46-56.

Dane, C.H., Cobban, W.A., and Kauffman, E.G., 1966, Stratigraphy and regional relationships of a reference section for the Juana Lopez Member, Mancos Shale, in the San Juan Basin: U.S. Geological Survey B Bulletin, 1224-H, 15 p.

Dane, C.H., Kauffman, E.G., and Cobban, W.A., 1968, Semilla Sandstone, a new member of the Mancos Shale in the southeastern part of the San Juan Basin, New Mexico: U.S. Geological Survey Bulletin 1254-F, 21 p.

DuChene, H.R., 1989, Fracture reservoirs in the San Juan Basin, Colorado and New Mexico, in Lorenz, J.C., and Lucas, S.G., Energy Frontiers in the Rockies; Albuquerque Geological Society, p. 101-109.

Espitalie, J., Madec, M., Tissot, J., Mennig, J., and Leplat, P., 1977, Source rock characterization method for petroleum exploration: Offshore Technology Conference, v. 3, no. 9, p. 439-444.

Emmendorfer, A.P., 1992, Tectonic dolomitization in the Gavilan Mancos oil pool, Rio Arriba County, New Mexico, *in* Lucas, S.G., Kues, B.S., Williamson, T.E., Hunt, A.P., eds., Sand Juan Basin IV; New Mexico Geological Society Guidebook, 43rd Annual Field Conference, p. 123-132.

Fassett, J.E., 1974, Cretaceous and tertiary rocks of the eastern San Juan basin, New Mexico and Colorado, *in* New Mexico Geological Society Guidebook, 25th Field Conference, Ghost Ranch, Central-Northern New Mexico, p. 225-230.

Fassett, J.E, 1978, ed., Oil and gas fields of the Four Corners area; Four Corners Geological Society, v. 1 and 2, p. 177-568.

Fassett, J.E, 1983, ed., Oil and gas fields of the Four Corners area; Four Corners Geological Society, v. 3, p. 915-1060.

Fassett, J.E., 1991, Oil and gas resources of the San Juan basin, New Mexico and Colorado, in Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., Economic Geology, U.S., Geological Society of America, The Geology of North America, v. P-2, p. 357-372.

Fassett, J.E., and Hinds, J.S., 1971, Geology and fuel resources of the Fruitland Formation and Kirtland Shale of the San Juan Basin, New Mexico: U.S. Geological Survey Professional Paper 676, 76 p.

Fassett, J.E., and Jentgen, R.W., 1978, Blanco Tocito, South, in Fassett, ed., Oil and gas fields of the Four Corners area; Four Corners Geological Society, v. 1, p 233-240.

Gorham, Jr., F.D., Woodward, L.A., Callendar, J.F., and Greer, A.R., 1977, Fracture permeability in Cretaceous rocks of the San Juan basin, *in* New Mexico Geological Society Guidebook, 28th Field Conference, San Juan Basin III, p. 235-241.

Greer, A.R., and Ellis, R.K., 1991, West Puerto Chiquito— U.S.A., *in* Foster, N.H., and Beaumont, E.A., comp., Structural Traps V; American Association of Petroleum Geologists Treatise of Petroleum Geology, Atlas of Oil and Gas Fields, p. 59-102.

Gries, RR., Clayton, J.L., and Leonard, China, 1997, Geology, thermal maturation, and source rock geochemistry in a volcanic covered basin: San Juan sag, south-central Colorado: American Association of Petroleum Geologists Bulletin, v. 81, n. 7, p. 1133-1160.

Hunt, C.B., 1936, The Mount Taylor coal field, part 2, of Geology and fuel resources of the southern San Juan Basin , New Mexico: U.S. Geological Survey Bulletin 860-B, p. 31-80.

Jennette, D.C., and Jones, C.R., 1995, Sequence stratigraphy of the Upper Cretaceous Tocito Sandstone: a model for tidally influenced incised valleys, San Juan Basin, New Mexico, *in* Van Wagoner, J.C., and Bertram, G.T., eds., Sequence Stratigraphy of Foreland Basin Deposits: American Association of Petroleum Geologists Memoir 64, p. 311-348.

Jennette, D.C., Jones, C.R., Van Wagoner, J.C., and Larsen, J.E., 1991, High-resolution sequence stratigraphy of the Upper Cretaceous Tocito Sandstone: The relationship between incised valleys and hydrocarbon accumulation, San Juan Basin, New Mexico, *in* Van Wagoner, J.C., Nummedal, D., Jones, C.R., Taylor, D.R., Jennette, D.C., and Riley, G.W., eds., Sequence Applications to Shelf Sandstone Reservoirs- outcrop to subsurface examples: American Association of Petroleum Geologists Field Conference Guidebook. Not consecutively paginated.

King, N.R., 1974, The Carlile-Niobrara contact and lower Niobrara strata near El Vado, New Mexico, *in* New Mexico Geological Society Guidebook, 25th Field Conference, Ghost Ranch, Central-Northern New Mexico, p. 259-266.

____, 1975, The Mancos Group along the eastern margin of the San Juan Basin--a summary, *in* Field trips to Central New Mexico: American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists Rocky Mountain Section Meeting, p. 57-66

Landis, E.R., and Dane, C.H., 1967, Description, geologic map of the Tierra Amarilla Quadrangle, Rio Arriba County, New Mexico: New Mexico Bureau of Mines and Mineral Resources Geologic Map 19.

Landis, E.R., Dane, C.H. and Cobban, W.A., 1974, Cretaceous rocks of the Tierra Amarilla Coal Field and adjacent areas, Rio Arriba County, New Mexico, *in* New Mexico Geological

Society Guidebook, 25th Field Conference, Ghost Ranch, Central-Northern New Mexico, p. 231-238.

Law, B.E., 1992, Thermal maturity patterns of Cretaceous and Tertiary rocks, San Juan Basin, Colorado and New Mexico: Geological Society of America Bulletin, v. 104, p. 192-207.

Meissner, F., 1984, Cretaceous and lower Tertiary coals as sources for gas accumulation in the Rocky Mountain area, *in* Woodward, J., Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Rocky Mountain Association of Geologists Guidebook, p. 401-431.

Molenaar, C.M., 1973, Sedimentary facies and correlation of the Gallup Sandstone and associated formations, northwestern New Mexico, *in* Fassett, J.E., ed., Cretaceous and Tertiary rocks of the Colorado Plateau; Four Corners Geological Society Memoir, p. 85-110.

____, 1974, Correlation of the Gallup Sandstone and associated formations, upper Cretaceous, eastern San Juan and Acoma Basins, New Mexico, *in* New Mexico Geological Society Guidebook, 25th Field Conference, Ghost Ranch, Central-Northern New Mexico, p. 251-258.

____, 1977, Stratigraphy and depositional history of upper Cretaceous rocks of the San Juan Basin area, New Mexico and Colorado, with a note on economic resources, *in* New Mexico Geological Society Guidebook, 28th Field Conference, San Juan Basin III, p. 159-166.

____, 1983, Principal reference section and correlation of Gallup Sandstone, northwestern New Mexico, in Hook, S.C., compiler, Contributions to mid-Cretaceous paleontology and stratigraphy of New Mexico: New Mexico Bureau of Mines and Mineral Resources Circular 185, p. 29-40.

Molenaar, C.M., Nummedal, D., and Cobban, W.A., 1996, Regional stratigraphic cross sections of the Gallup Sandstone and associated strata around the San Juan Basin, New Mexico and parts of adjoining Arizona and Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC-143.

Nummedal, D., and Molenaar, C.M., 1995, Sequence stratigraphy of ramp-setting strand plain successions: the Gallup Sandstone, New Mexico, *in* Van Wagoner, J.C., and Bertram, G.T., eds., Sequence Stratigraphy of Foreland Basin Deposits: American Association of Petroleum Geologists Memoir 64 p. 277-310.

Nummedal, D., and Riley, G.W., 1999, The origin of the Tocito Sandstone and its sequence stratigraphic lessons, *in* Bergman, K. and Snedden, Isolated Shallow Marine Sand Bodies: Sequence Stratigraphic Analysis and Sedimentologic Interpretation: Society for Sedimentary Geology, no. 64, p. 227-254.

Nummedal, D., Wright, R., Swift, D.J.P., Tillman, R.W., and Wolter, R.W., 1989, Depositional systems architecture of shallow marine sequences, in Nummedal, D. and Wright, R., eds., Cretaceous shelf sandstones and shelf depositional sequences: International Geological Congress 28th Field Trip, p. 35-73.

Pentilla, W.C., 1964, Evidence for the pre-Niobrara unconformity in the northwestern part of the San Juan Basin: The Mountain Geologist, v. 1, no. 1, p. 3-14.

Peters, K.E., 1986, Guidelines for evaluating petroleum source rock using programmed pyrolysis: American Association of Petroleum Geologists Bulletin, v. 70, no. 3, p. 318-329.

Plint, A.G., 1988, Sharp-based shoreface sequences and "offshore" bars in the Cardium Formation of Alberta: their relationship to relative changes in sea level, in Wilgus, C.K., hastings, B.S., Kendall. C.G.St.C, Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea-level changes: an integrated approach: SEPM Special Publication 42, p. 357-370.

Posamentier, H.W., Allen, G.P., James, D.P., and Tesson, M., 1992, Forced regressions in a sequence stratigraphic framework; concepts, examples, and exploration significance: American Association of Petroleum Geologists Bulletin, v. 76, p. 1687-1709.

Reiter, M., and Clarkson, G., 1983a, Geothermal studies in the San Juan Basin and the Four Corners area of the Colorado Plateau, I. Steady-state methods of thermal source of the San Juan volcanic field: Tectonophysics, v. 91, p. p. 253-269.

_____, 1983b, Relationships between heat flow, paleotemperatures, coalification, and petroleum maturation in the San Juan Basin, northwestern New Mexico and southwestern Colorado: Geothermics, v. 12, p. 323- 339.

Reiter, M., and Mansure, A.J., 1983, Geothermal studies in the San Juan Basin and the Four Corners area of the Colorado Plateau, I. Terrestrial heat flow measurements: Tectonophysics, v. 91, p. 233- 251.

Rice, D.D., 1983, Relation of natural gas composition to thermal maturity and source rock type in San Juan Basin, northwestern New Mexico and southwestern Colorado: American Association of Petroleum Geologists Bulletin, v. 67, p. 1199-1218.

Riley, G.W., 1993, Origin of a coarse-grained shallow marine sandstone complex: the Coniacian Tocito sandstone, northwestern New Mexico: unpublished Ph. D. Dissertation, Baton Rouge, Louisiana State University, 251 p.

Sabins, Jr., F.F., 1964, Symmetry, stratigraphy, and petrography of cyclic Cretaceous deposits in San Juan basin: American Association of Petroleum Geologists Bulletin, v. 48, no. 3, pt. 1, p. 292-316.

Schmoker, J.W., 1995, Methodology for assessing continuous-type (unconventional) hydrocarbon accumulations; *in* Gautier, D.L., Dolton, G.L., Takahashi, K.I., and Varnes, K.L. (eds.), 1995 National Assessment of United States Oil and Gas Resources - Results, Methodology, and Supporting Data: U.S. Geological Survey, Digital Data Series DDS-30, release 2.

Sears, J.D., Hunt, C.B., and Hendricks, T.A., 1941, Transgressive and regressive Cretaceous deposits in southern San Juan Basin, Mew Mexico: U.S. Geological Survey Professional Paper 193-F, 101-

Taylor, D.J., and Huffman, Jr., A.C., 2000, Location, reprocessing, and analysis of two-dimensional seismic reflection data on the Jicarilla Apache Indian Reservation; Report to Department of Energy DE-AI26-98BC-15026, p.

Tillman, R.W., 1985, The Tocito and Gallup Sandstones, New Mexico, a comparison, *in* Tillman, R.W., Swift, D.W.J., and Walker, R.G., eds., Shelf Sands and Sandstone Reservoirs: Society for Sedimentary Geology Short Course Notes 13, p. 403-464.

Tissot, B.P., and.D.H. Welte, 1984, Petroleum formation and occurrence (2nd ed.): Berlin, Springer-Verlag, 699 p.

Williamson, T.E., and Lucas, S.G., 1992, Selachian fauna from the upper Cretaceous (Coniacian) El Vado Sandstone Member of the Mancos Shale, San Juan Basin, New Mexico, *in* Lucas, S.G, Kues, B.S., Williamson, T.E., and Hunt, A.P., New Mexico Geological Society 43rd Field Conference, San Juan Basin IV, p. 17-19.

Woodward, L.A., Callender, J.F., 1977, Tectonic framework of the San Juan Basin, *in* New Mexico Geological Society Guidebook, 28th Field Conference, San Juan Basin III, p. 209-212.

Appendix A. Generalized core descriptions and photographs of cored intervals in the Mancos Shale. Cored interval bracketed by solid black lines. Top and base of El Vado Sandstone Member of the Mancos Shale as defined in this report shown in solid blue lines. Unconformity separating regressive distal Gallup equivalents of the Mancos Shale from overlying transgressive units in the Mancos Shale shown by solid red line.

A. 'Cotton Petroleum Corporation Shelby 44-22, sec. 22, T. 20 N., R. 1 W. (no photographs)

B. Champlin Oil 1 Federal 44-2, sec. 2, T. 20 N., R. 3 W.

C. Champlin Oil 2 Federal 24-2, sec. 2, T. 20 N., R. 3 W.

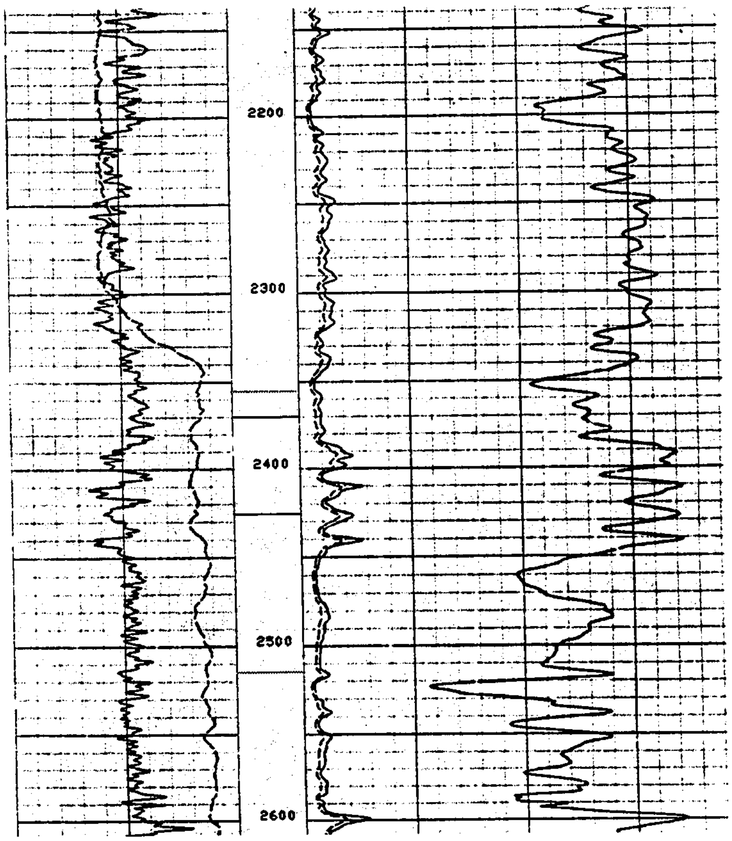
D. Samuel Gary 11-16 San Ysidro, sec. 11, T. 20 N., R. 3 W.

E. Samuel Gary State 36-D, sec. 36, T. 21 N., R. 4 W.

F. Mallon Oil 1-11 Howard, sec. 1, T. 25 N., R. 2 W.

G. Mallon Oil Fed Com 3-15, sec. 3, T. 25 N., R. 2 W.

A. Lithologic description of cored interval 2370 -2428 ft, Cotton Petroleum Corporation Shelby 44-22, Sec. 22, T. 20 N., R. 1 W.



Top and base of El Vado Sandstone of Mancos Shale shown by solid blue lines; cored interval shown by solid black lines.

2370 - 2384 ft Interbedded black, silty shale and thin very-fine-grained sandstone beds and laminae. The shale and sandstone form a parasequence. The base of the parasequence is black shale, the middle part of the parasequence is interbedded black shale and sandstone, and the upper part where present is dominantly sandstone that has thin interbeds of black shale. Shale from 2370-2372 forms the base of the overlying parasequence which was not cored. Sandstones are burrowed. Soft-sediment deformation

2384 - 2408 ft Interbedded black, silty shale and thin very-fine-grained sandstone beds and laminae. The shale and sandstone form a thick parasequence dominated by sandstone. Sandstone is prominent from 2384 to 2400. The sandstone is locally intensely bioturbated and compacted. Sedimentary structures include wavy and flaser laminations. Microstylolites. The sandstone grades downward into interbedded thin sandstone and black shale with sandstone laminae decreasing in proportion downwards. The basal part of the parasequence is silty black shale.

2408 - 2419 ft Like above. The thicker sandstone is from 2408 to 2417 with the amount of sandstone decreasing and the amount of black shale laminae increasing in the lower 2 feet. The basal part of the parasequence is silty black shale with rare thin sandstone laminae.

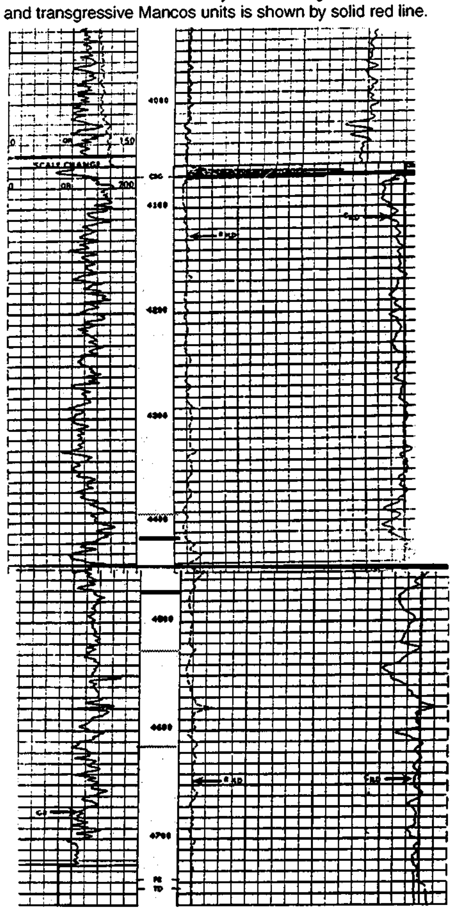
2419 - 2428 Dominantly very-fine grained gray to tan sandstone. Sandstone is bioturbated and burrowed especially in the upper part. Sedimentary structures include parallel and wavy laminations and flaser bedding.

Drill stem Test 2384 - 2466 ft Recovered 5 ft water

No initial production. Well D & A.

B. Lithologic description of cored interval 4405-4464.75 ft, Champlin Oil 1 Federal 44-2, Sec. 2, T. 20 N., R. 3W.

Top and base of El Vado Sandstone of Mancos Shale shown by solid blue lines; cored interval shown by solid black lines. Unconformity between regressive distal Gallup and transgressive Mancos units is shown by solid red line.



Perforated 4550 - 4630 ft

4405 - 4416.1 ft Interbedded black, silty shale and thin very-fine-grained sandstone beds and laminae. The shale and sandstone form multiple, stacked parasequences. The base of the parasequence is black shale, the middle part of the parasequence is interbedded black shale and sandstone, and the upper part where present is dominantly sandstone that has thin interbeds of black shale. The proportion of sandstone laminae and beds increases upwards. Within the parasequence sets the proportion of sandstone is greater between 4405-4407 and 4412-4416. Sandstones are horizontal to wavy bedded. Low angle hummocky cross bedding is evident. Cut and fill structures are locally present. Scattered Inoceramus prisms and shell fragments are common and burrowing and bioturbation of the sandstones is minor.

4416.1 - 4423 ft Dominantly very-fine grained gray carbonaceous sandstone with black shale laminae and partings. Some intervals of thicker, better sorted and cleaner (less shale partings) sandstone. Sedimentary structures include wavy, flaser, and locally low angle hummocky cross beds and local cut and fill. Microstylolites are common. Burrowing and bioturbation are locally prominent; burrows are especially prominent in the shalier beds.

4423 - 4426 Like interval 4416.1 - 4423 ft but sandstones are siltier. Sandstones are intensely bioturbated imparting a disrupted fabric to the rock. Black shale layers are more common.

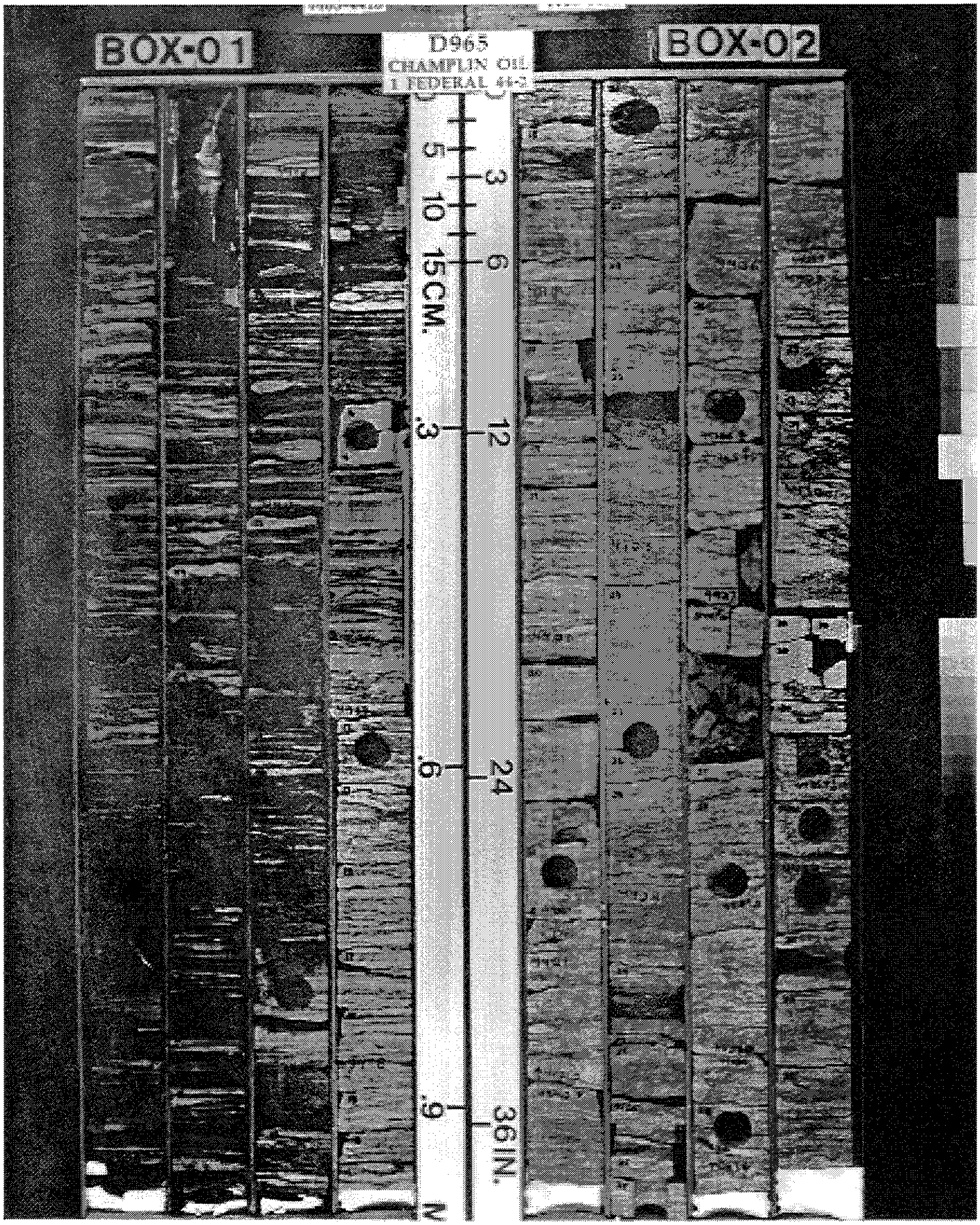
4426 - 4436.6 ft Dominantly very-fine grained gray carbonaceous sandstone with black shale laminae and partings. Some intervals of thicker, better sorted and cleaner (less shale partings) sandstone. Sedimentary structures include wavy, flaser, and locally low angle hummocky cross beds and local cut and fill. Local soft-sediment deformation. Microstylolites are common. Burrowing and bioturbation are locally prominent; burrows are especially prominent in the shalier beds.

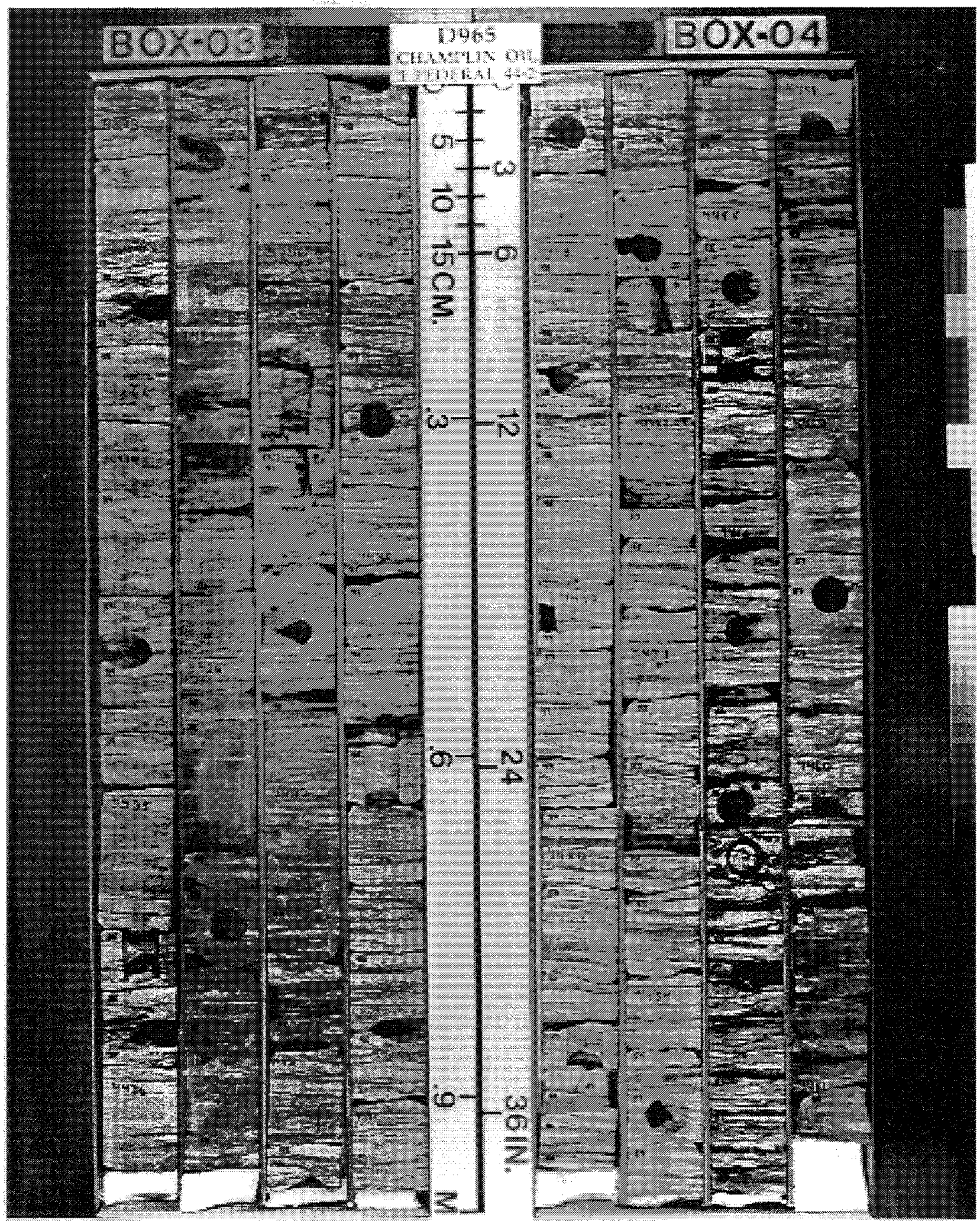
4436.6 - 4443 Interbedded black, silty shale and thin very-fine-grained sandstone beds and laminae. The shale and sandstone form multiple, stacked parasequences like in the interval 4405 - 4416.1 ft. However, the sandstones are more intensely bioturbated.

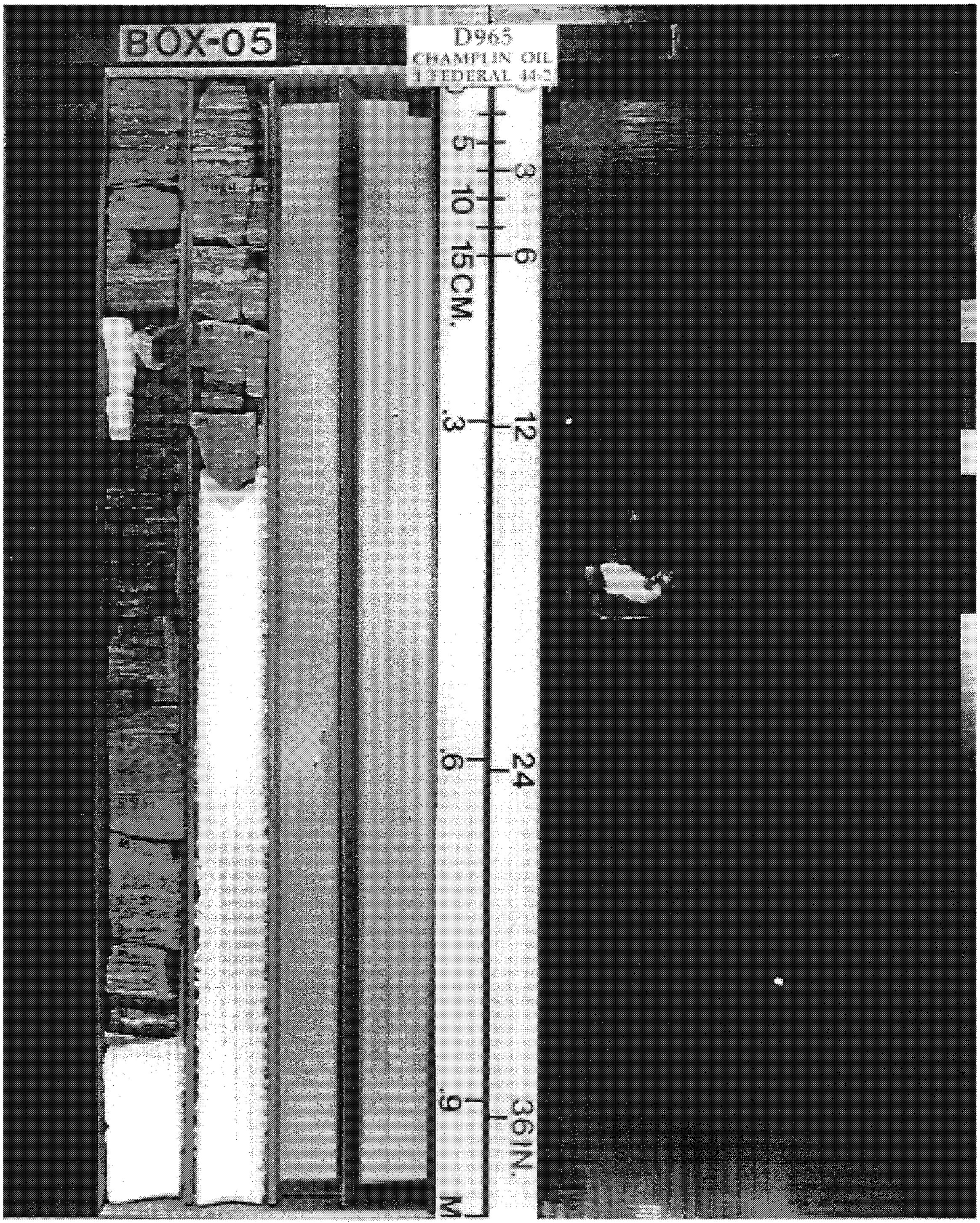
4443 - 4458 Like 4416.1 - 4423 ft. Dominantly sandstone with black shale laminae. Bioturbation less than in interval above. Microstylolites are common.

4458 - 4464.75 Interbedded black, silty shale and thin very-fine-grained sandstone beds and laminae. The shale and sandstone form multiple, stacked parasequences. Shale beds are thicker than in the overlying interval. Sedimentary structures in the sandstone include wavy bedding. Low angle hummocky cross stratification, and flaser bedding. Bioturbation is locally intense imparting a disrupted fabric. Shell fragments are locally common

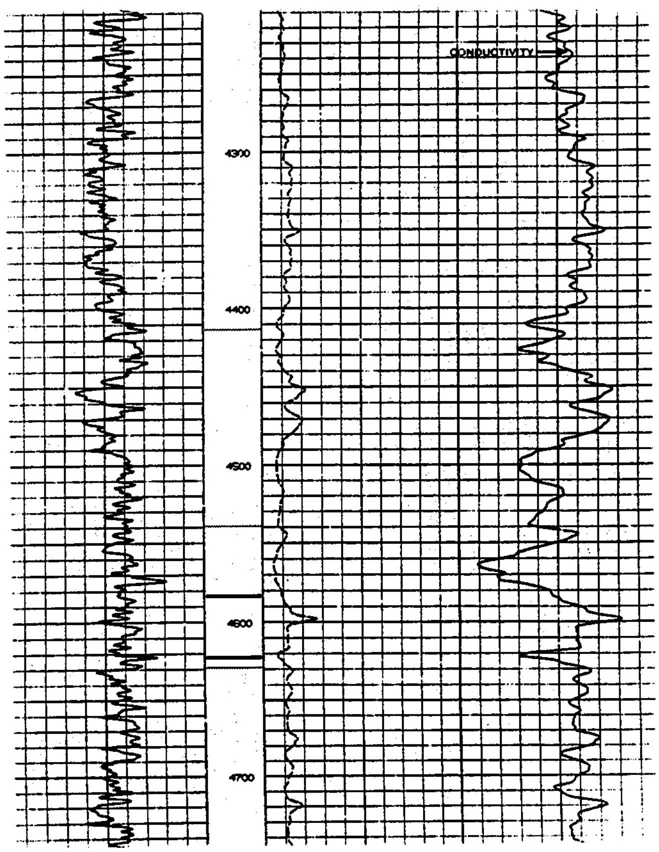
Initial Production 128 BOPD, 37 API gravity, GOR 164


BOX-01
D965
CHAMPLIN OIL
1 FEDERAL 44-2
BOX-02
5
10
15CM.
3
6
.3
12
.6
24
.9
36IN.


BOX-03
D965
CHAMPLIN OIL
BOX-04


BOX-05
D965
CHAMPLIN OIL
1 FEDERAL 44-2

C. Lithologic description of cored interval 4586-4621 ft, Champlin Oil 2 Federal 24-2, Sec. 2, T. 20 N., R. 3W.



Top and base of El Vado Sandstone of Mancos Shale shown by solid blue lines; cored interval shown by solid black lines. Unconformitybetween regressive distal Gallup and transgressive Mancos units is shown by solid red line.

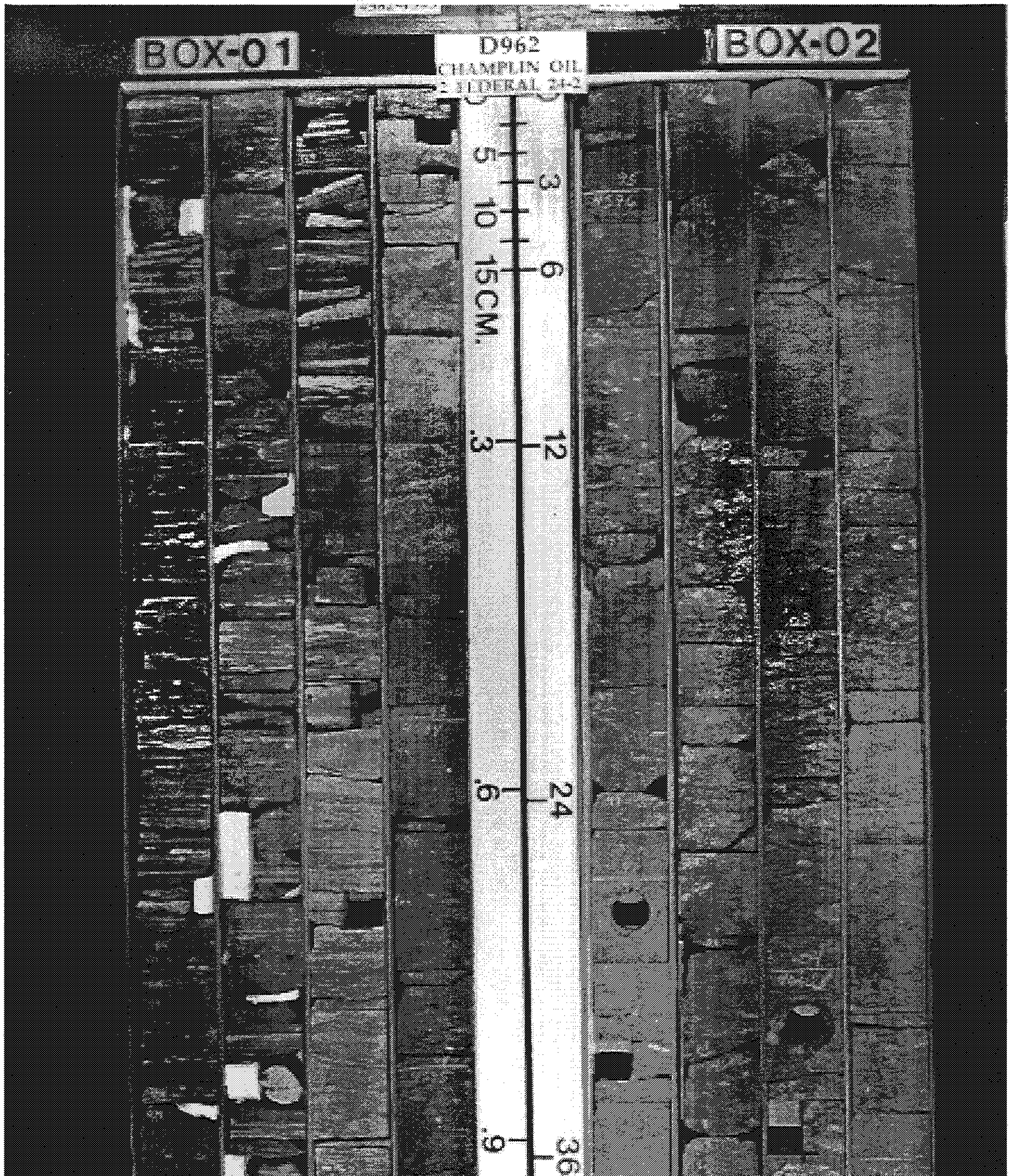
4582 - 4589 ft Light to dark silty mudstone interbedded with thin very-fine grained light gray sandstone beds and laminae. Sandstones have a dominantly subhorizontal fabric. Current ripples and flaser bedding are dominant sedimentary structures. Bioturbation is locally prominent. Fossil fragments are common in the black shale. The black shale and thin sandstone beds form stacked, multiple small parasequences of variable thickness. These parasequences are defined by a basal black shale (a flooding surface), a middle interval of interlaminated black shale and thin sandstone, and an upper interval of dominantly sandstone with mud drapes, shale partings, and thin interbeds of black shale. In the middle interval the proportion of sandstone laminae/beds increases upwards.

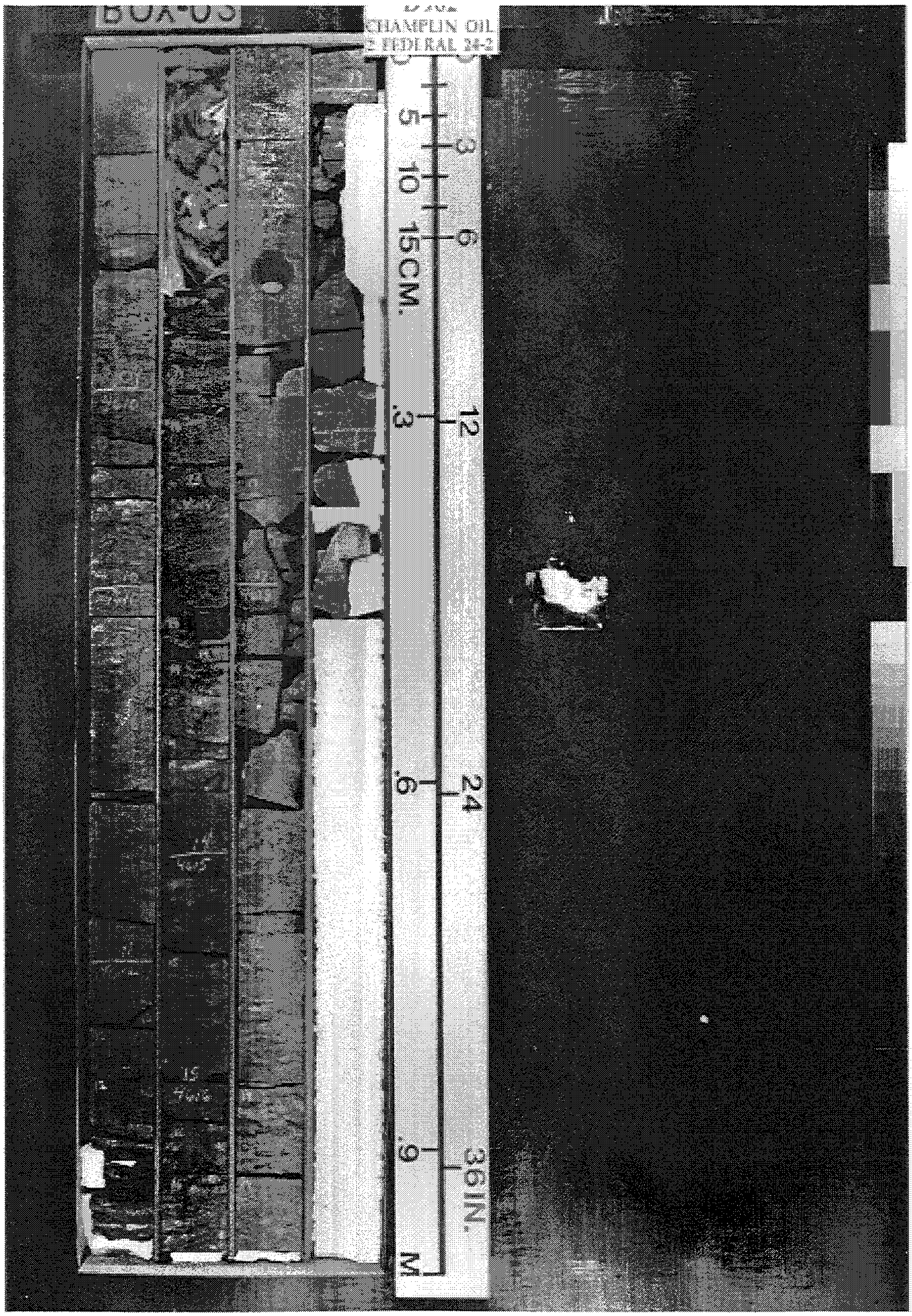
4589-4593.6 ft Light gray very-fine grained very carbonaceous sandstone. Contains minor amounts of black shale partings. Sandstone is bioturbated and contains abundant fossil fragments. Soft sediment deformation is locally prominent. Elsewhere the sandstone is characterized by subhorizontal wavy laminations. Sandstone locally contains abundant microstylolites.

4593.6-4621 ft Light to dark silty mudstone interbedded with thin very-fine grained light gray sandstone lenses. The black shale and sandy intervals form stacked, multiple small parasequences of variable thickness. The base of the parasequence is silty black shale which is overlain by very silty sandstone. The sand occurs as lenses that are heavily bioturbated, destroying most of the sedimentary fabric, and burrowed. The proportion of sandy lenses increases upwards and the sand lenses are most bioturbated and burrowed in the upper part of the parasequence. Fossil fragments are found throughout. Carbonaceous material is found throughout and pyrite is locally prominent, especially as replacements of shell material. There is an increase in porosity in the sandier parts. Microstylolites and healed vertical fractures are locally prominent.

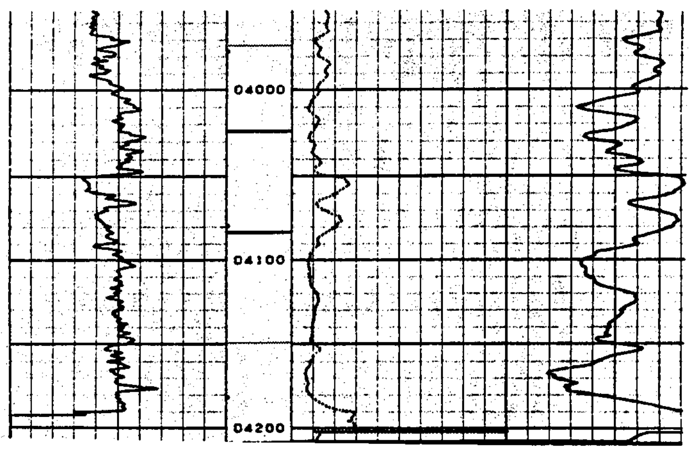
Perforated intervals 4444-4494, 4580-4610 ft

Initial Production 33 BOPD, 41.0 API Gravity, GOR 546


BOX-01
BOX-02
D962
CHAMPLIN OIL
FEDERAL 24-2
15CM.
36 IN.


CHAMPLIN OIL
2 FEDERAL 24-2

D. Lithologic description of cored interval 4023 -4082.2 ft, Samuel Gary 11-16 SanYsidro, Sec. 11, T. 20 N., R. 3 W.



Top and base of El Vado Sandstone of Mancos Shale shown by solid blue lines; cored interval shown by solid black lines.

May need to adjust core down 10 feet to match thick sandstone sequences to log response.

4023- 4040 ft Interbedded black, silty shale and thin very-fine-grained carbonaceous sandstone beds and laminae. The shale and sandstone form a parasequence. The base of the parasequence is black shale, the middle part of the parasequence is interbedded black shale and sandstone, and the upper part where present is dominantly sandstone that has thin interbeds of black shale. Maximum thickness of the top sandstone is 5 inches in the interval from 4037.6 - 4038 ft. Sedimentary structures include wavy and parallel laminations, low angle hummocky cross stratification, minor cut and fill, and rare soft-sediment deformation. Burrowing and bioturbation are localized and are more prominent in the shale and silty shale layers

4040 - 4059 ft Thick parasequence dominated by sandstone from 4040 to 4057.5 ft. Sandstone is vary fine grained, gray and tan, carbonaceous and intensely bioturbated and burrowed. Microstylolites are common as are black shale partings and laminae. Some cut and fill and soft-sediment deformation features are evident. Black shale with fewer sandstone laminae characterize the basal 2 ft of the parasequence.

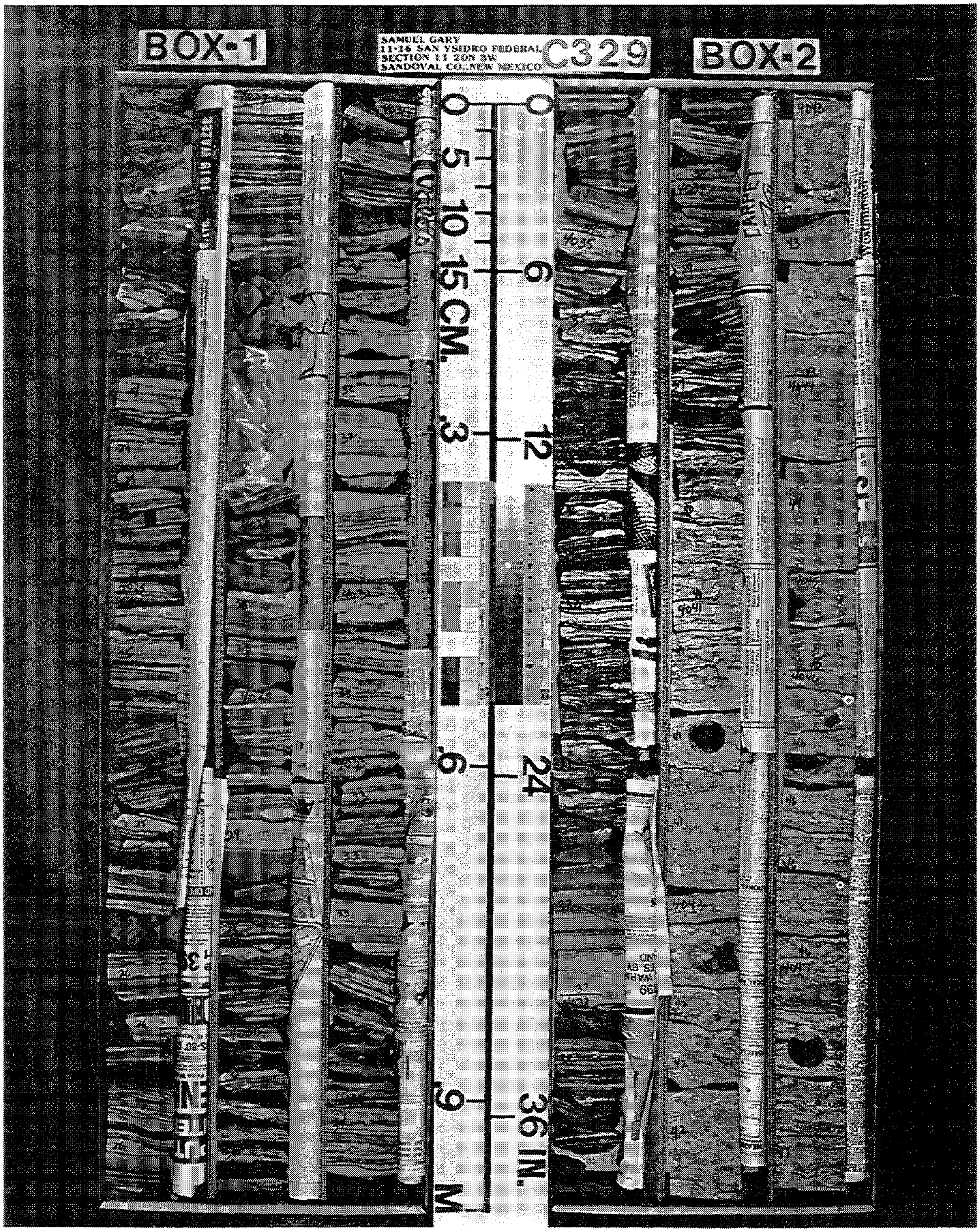
4059 - 4065.2 Mutliple, stacked parasquences consisting of interbedded black, silty shale and thin very-fine-grained carbonaceous sandstone beds and laminae. The proportion of sandstone laminae increases upwards in the parasequence. The sandstone layers are intensely bioturbated imparting a disrupted fabric to the rock. Organic matter is abundant. Burrowing is more common in the silty and shale layers.

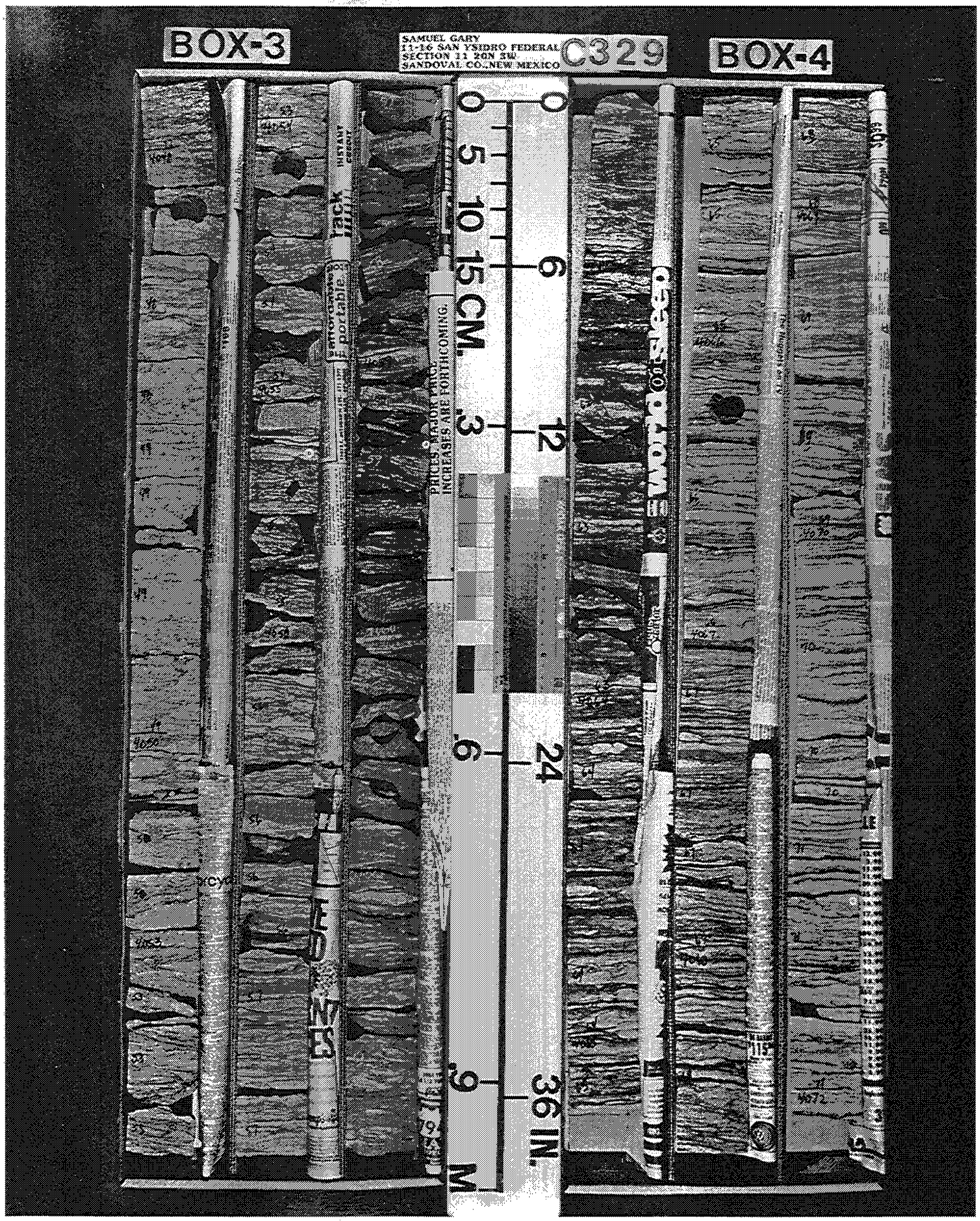
4065.2 - 4079 Like interval 4040 - 4059 ft

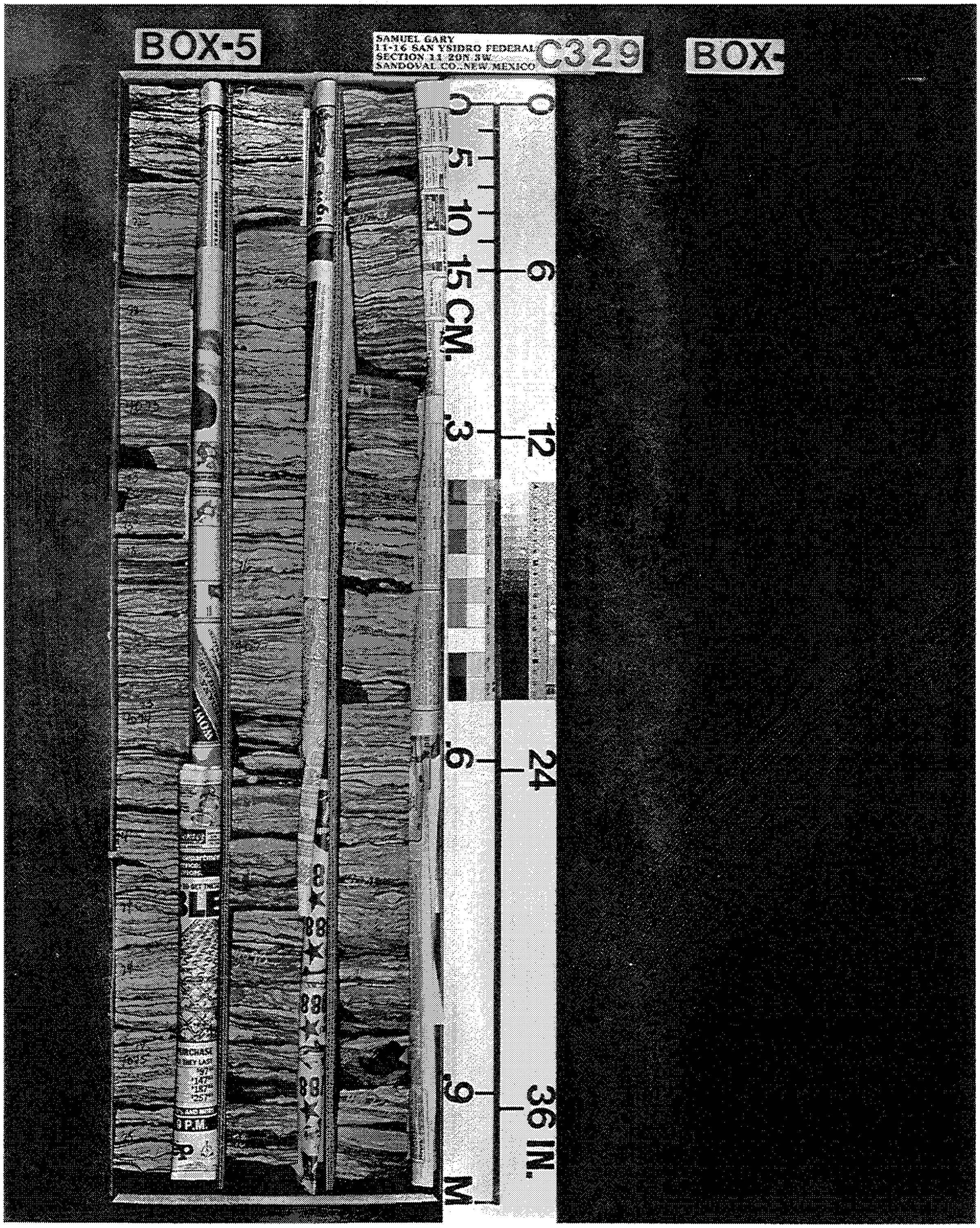
4079 -4082.2 ft Interbedded black, silty shale and thin very-fine-grained carbonaceous sandstone beds and laminae. The shale and sandstone form a parasequence. The base of the parasequence is black shale, the middle part of the parasequence is interbedded black shale and sandstone, and the upper part where present is dominantly sandstone that has thin interbeds of black shale. Sedimentary structures include wavy and parallel laminations, low-angle hummocky cross stratification, minor cut and fill, rare soft-sediment deformation, and load casts. Burrowing and bioturbation are localized and are more prominent in the shale and silty shale layers.

No perforations. Open hole 3793 - 4188 ft.

Initial Production 500 BOPD, 277 MCFPD, 39 API gravity

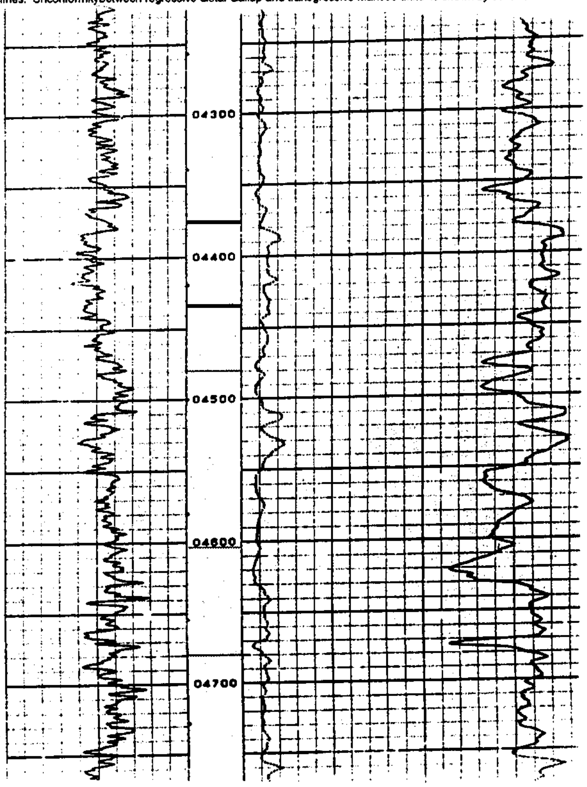

BOX-1
SAMUEL GARY
11-16 SAN YSIDRO FEDERAL
SECTION 11 20N 3W
SANDOVAL CO., NEW MEXICO
C329
BOX-2
0 5 10 15 CM.
3
6
9
M.
6
12
24
36 IN.


BOX-3
SAMUEL GARY
11-16 SAN YSIDRO FEDERAL
SECTION 11 20N 3W
SANDOVAL CO., NEW MEXICO
C329
BOX-4


BOX-5
SAMUEL GARY
11-16 SAN YSIDRO FEDERAL
SECTION 11 20N 3W
SANDOVAL CO. NEW MEXICO
C329
BOX-

E. Lithologic description of cored interval 4374-4434 ft, Samuel Gary Oil State 36-D, Sec. 36, T. 21 N., R. 4W.

Top and base of El Vado Sandstone of Mancos Shale shown by solid blue lines; cored interval shown by solid black lines. Unconformitybetween regressive distal Gallup and transgressive Mancos units is shown by solid red line.



Perforated intervals 4734- 4742, 4744-4748, 4758-4764

Initial production 20 BOPD

4374 - 4375 Interbedded black shale and thin very-fine-grained sandstone beds and laminae. The shale and sandstone form multiple, stacked parasequences. The base of the parasequence is black shale, the middle part of the parasequence is interbedded black shale and sandstone, and the upper part where present is dominantly sandstone that has thin interbeds of black shale. The proportion of sandstone laminae and beds increases upwards. Sandstones are horizontal to wavy bedded. Low angle hummocky cross bedding is evident. Scattered Inoceramus prisms are common and burrowing and bioturbation of the sandstones is minor. Microstylolites are common.

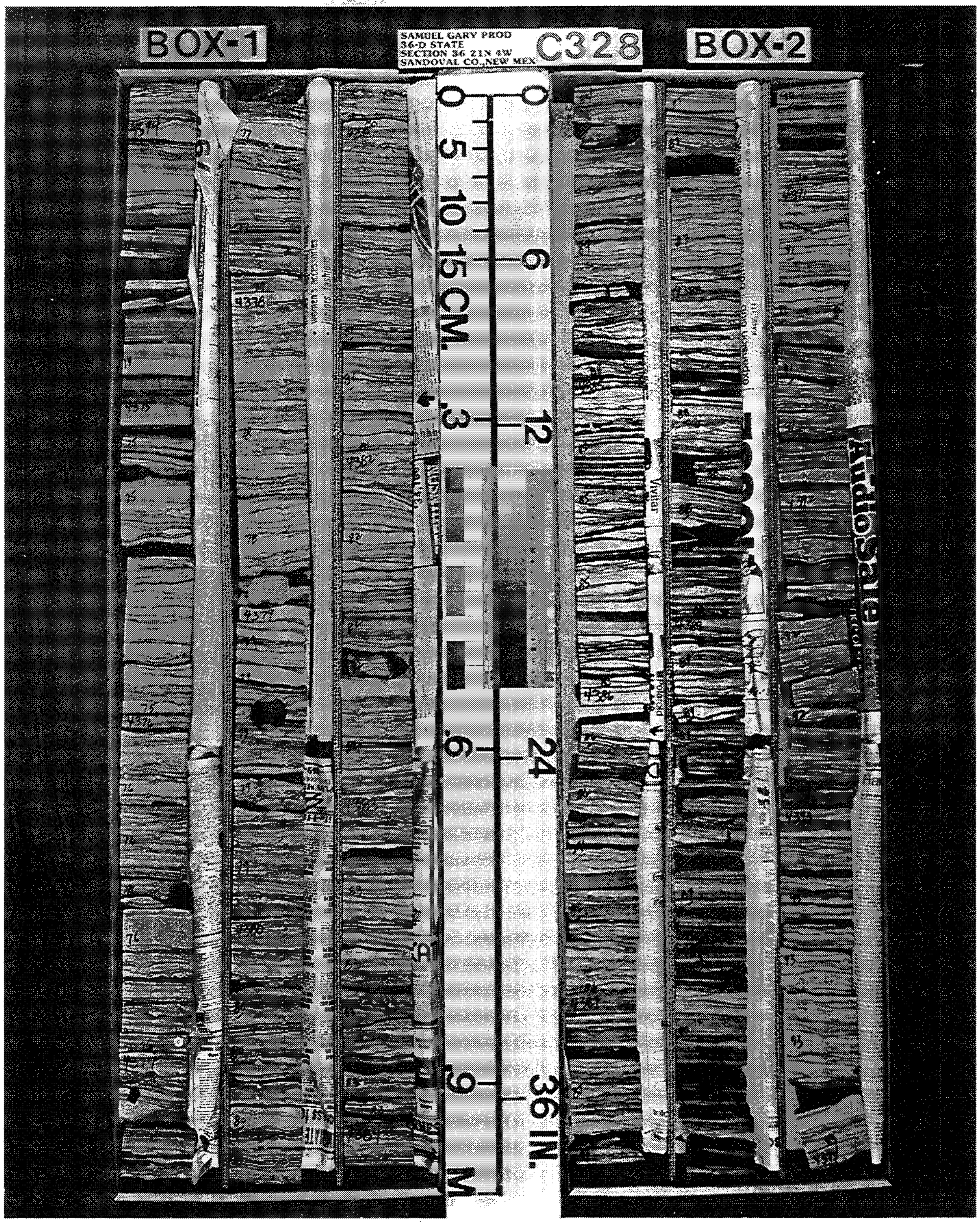
4375 4388.4 Interbedded black shale and thin very-fine-grained carbonaceous sandstone beds and laminae. The shale and sandstone form multiple, stacked parasequences. The base of the parasequence is black shale, the middle part of the parasequence is interbedded sandstone and black shale, and the upper part is dominantly sandstone that has thin interbeds of black shale. This interval is more sand rich than the underlying interval. The proportion of sandstone laminae and beds increases upwards. Sandstones are horizontal, wavy and flaser bedded. Low-angle hummocky cross bedding is evident. Scattered Inoceramus prisms are common and burrowing and bioturbation, especially in the shaly beds, is evident. Most burrows are horizontal. Microstylolites are common. Soft-sediment deformation of both the sandstone and shale intervals is locally prominent.

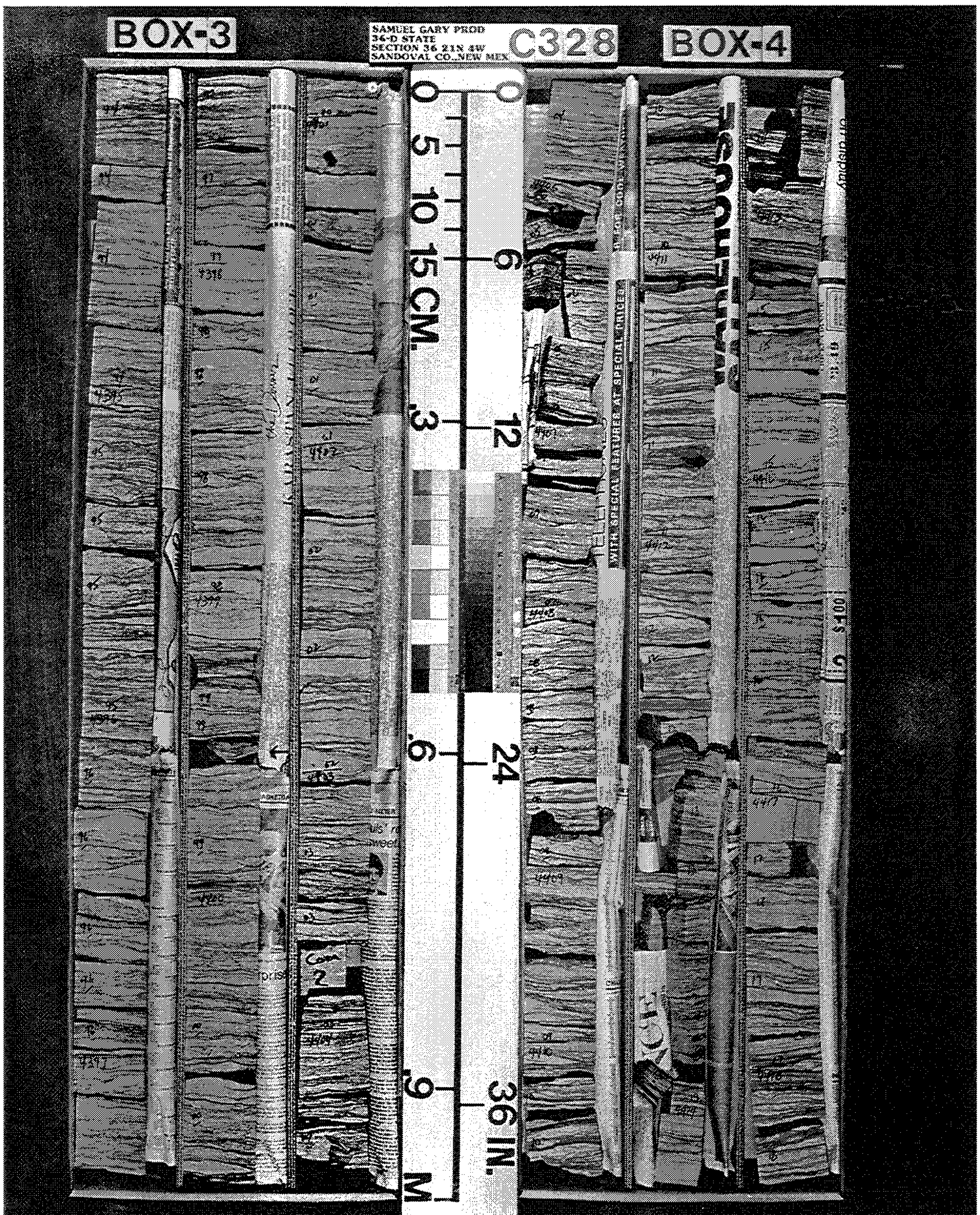
4388.4 - 4493.1 Like 4374 - 4375 in that more black shale is present. However, overall, the parasequences are still dominated by sandstone. Burrowing is common in the shales. Soft sediment deformation is generally lacking.

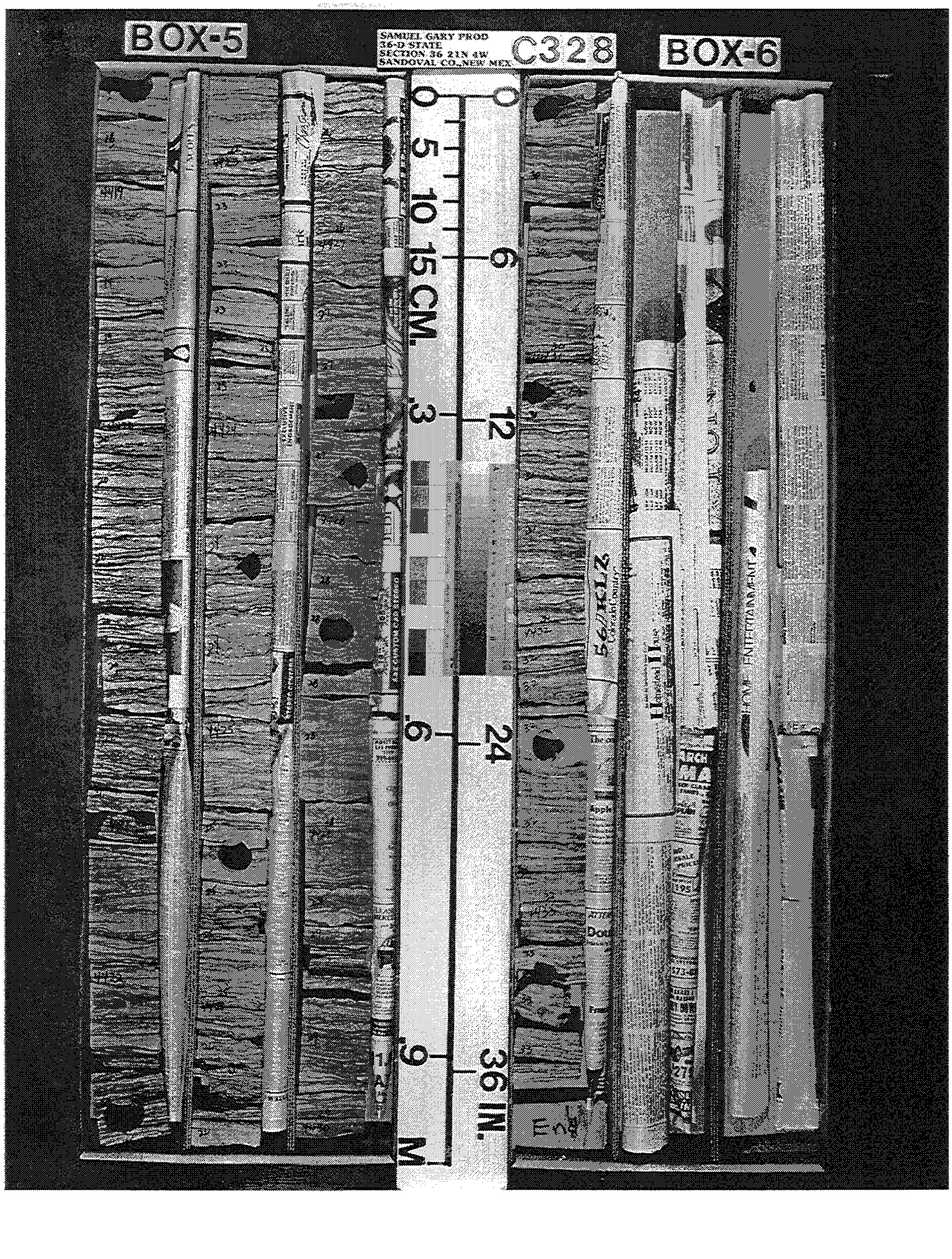
4493.1 - 4428 Dominantly very-fine grained gray carbonaceous sandstone with black shale laminae and partings. Some intervals of thicker, better sorted and cleaner (less shale partings) sandstone. Sedimentary structures include wavy, flaser, and locally low angle hummocky cross beds and local cut and fill. Microstylolites are common. Burrowing and bioturbation are locally prominent; burrows are especially prominent in the shalier beds.

4428 - 4429.25 Bioturbated very-fine grained sandstone that is better sorted. Microstylolites are common.

4429.25- 4433.8 ft Like 4388.4 - 4493.1

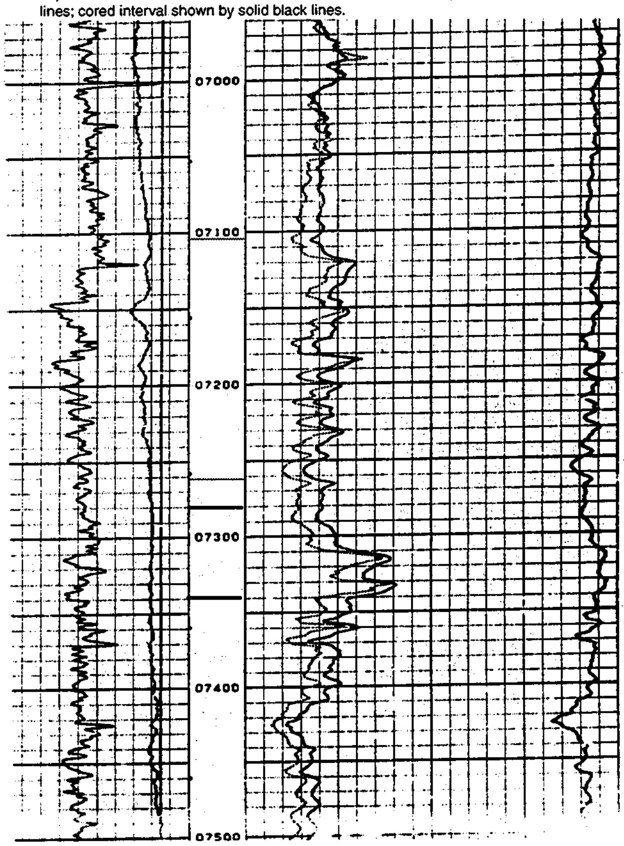

BOX-1
SAMUEL GARY PROD
36-D STATE
SECTION 36 21N 4W
SANDOVAL CO., NEW MEX
C328
BOX-2


BOX-3
SAMUEL GARY PROD
36-D STATE
SECTION 36 21N 4W
SANDOVAL CO., NEW MEX
C328
BOX-4


BOX-5
SAMUEL GARY PROD
36-D STATE
SECTION 36 21N 4W
SANDOVAL CO.,NEW MEX
C328
BOX-6
0 5 10 15 CM.
.3
.6
.9
M
0
6
12
24
36 IN.

F. Lithologic description of cored interval 7280-7340 ft, Mallon Oil 1-11 Howard, Sec. 1, T. 25 N., R. 2W.

Top and base of El Vado Sandstone of Mancos Shale shown by solid blue lines; cored interval shown by solid black lines.



7280 - 7313 ft Interbedded black to gray silty mudstone, siltstone and rare thin very fine- grained sandstone. Shale is predominant. Thin bioturbated very fine to fine- grained sandstone from 7280.3-7280.6 ft. This sandstone has a horizontal permeability of 0.74 md and a helium porosity of 1.2 percent. At 7296.4 ft there is a layer of fossil shell hash and a horizontal calcite-filled fracture. This layer is also a bit sandier. At 7306.75ft there is another fossil shell hash layer.

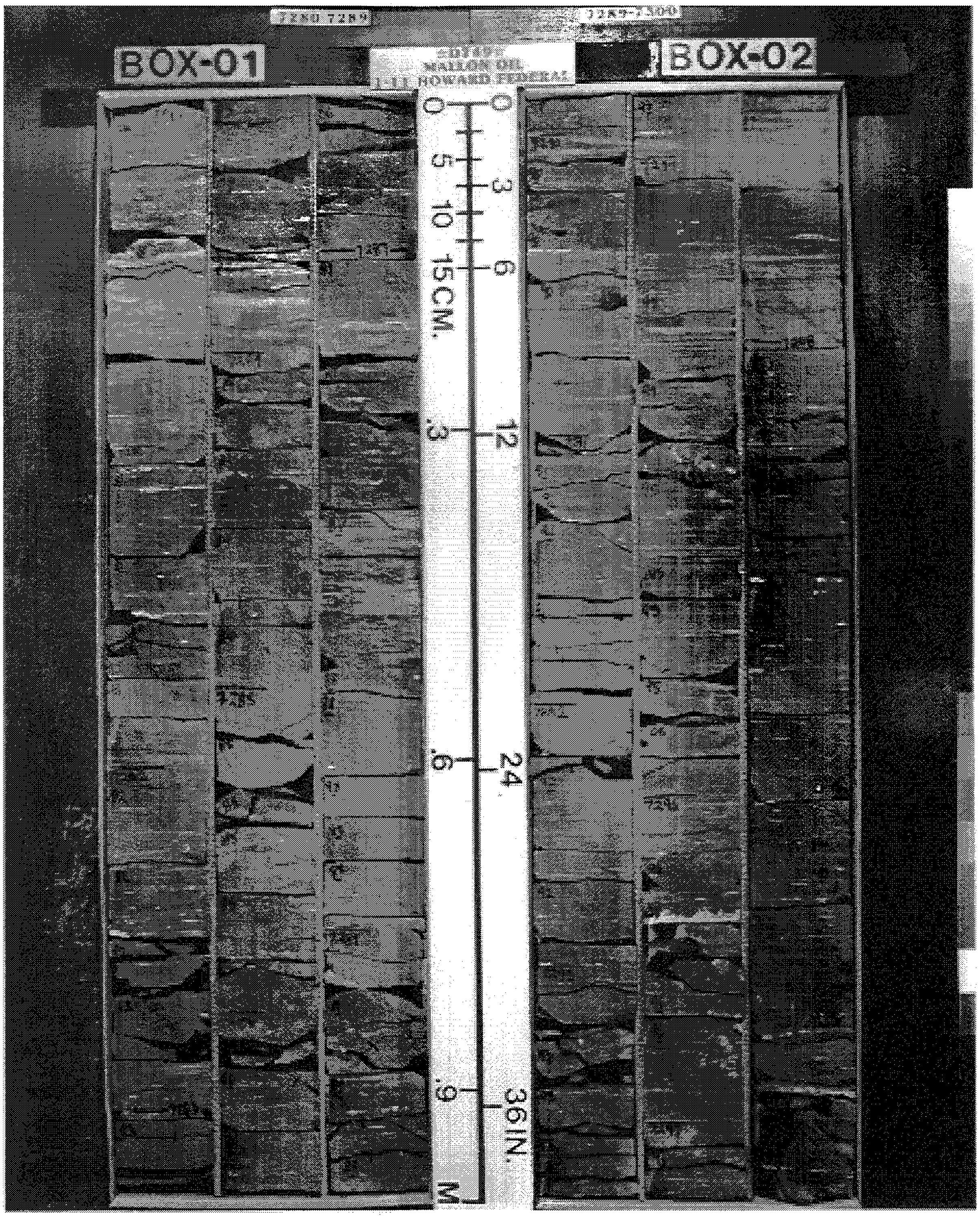
7313 - 7314 ft Interbedded black, silty shale and thin very-fine-grained sandstone beds and laminae. The shale and sandstone form multiple, stacked parasequences. The base of the parasequence is black shale, the middle part of the parasequence is interbedded black shale and sandstone, and the upper part where present is dominantly sandstone that has thin interbeds of black shale. The proportion of sandstone laminae and beds increases upwards. Sandstone at 7313.3 ft has a helium porosity of 1.0. Organic matter is abundant.

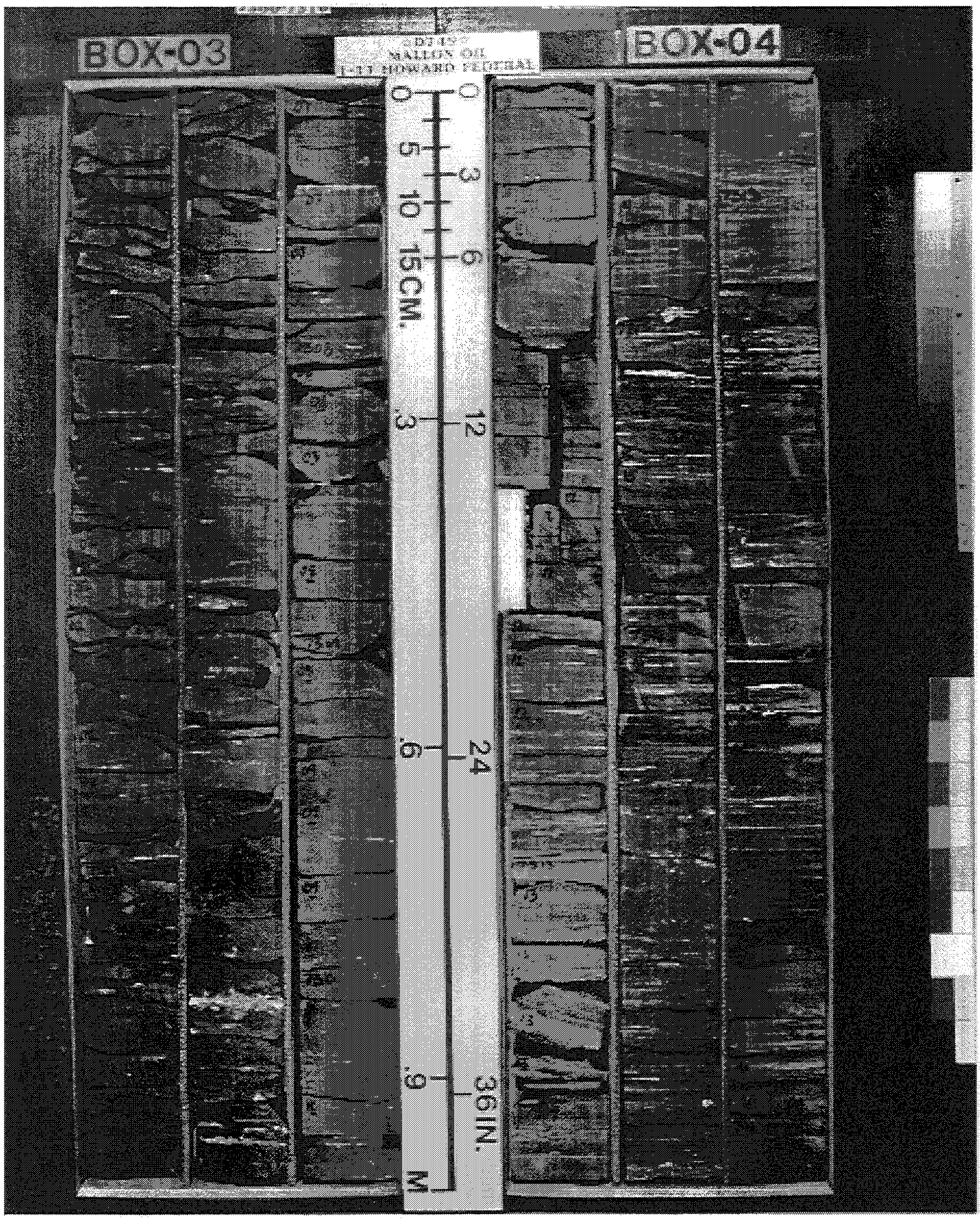
7314- 7326.1 ft Interbedded black, silty shale and thin very-fine-grained sandstone beds and laminae. The shale and sandstone form multiple, stacked parasequences like above. Organic matter is common. Pyrite and dead oil coat fossil shell fragments. Sedimentary structures include flaser and wavy bedding, minor cut and fill, and load casts. Sandstones are more bioturbated; bioturbation imparts a disrupted fabric. Sandstone at 7317.2 ft has a horizontal permeability of 0.09 md and a helium porosity of 0.7 percent. Sandstone at 7322.8 ft has a horizontal permeability of 0.04 md and a helium porosity of 0.9 percent. Sandstone at 7325.8 ft has a horizontal permeability of 0.42 md and a helium porosity of 1.3 percent. Sandstone at 7327.5 ft has a horizontal permeability of 0.02 md and a helium porosity of 3.0 percent.

7326.1 - 7340 ft Interbedded black to gray silty mudstone, siltstone and rare thin very fine-grained sandstone. Shale is predominant. Sandstone mostly parallel laminated. Isolated fossil pelecypod fragments and thin shell hash layers.

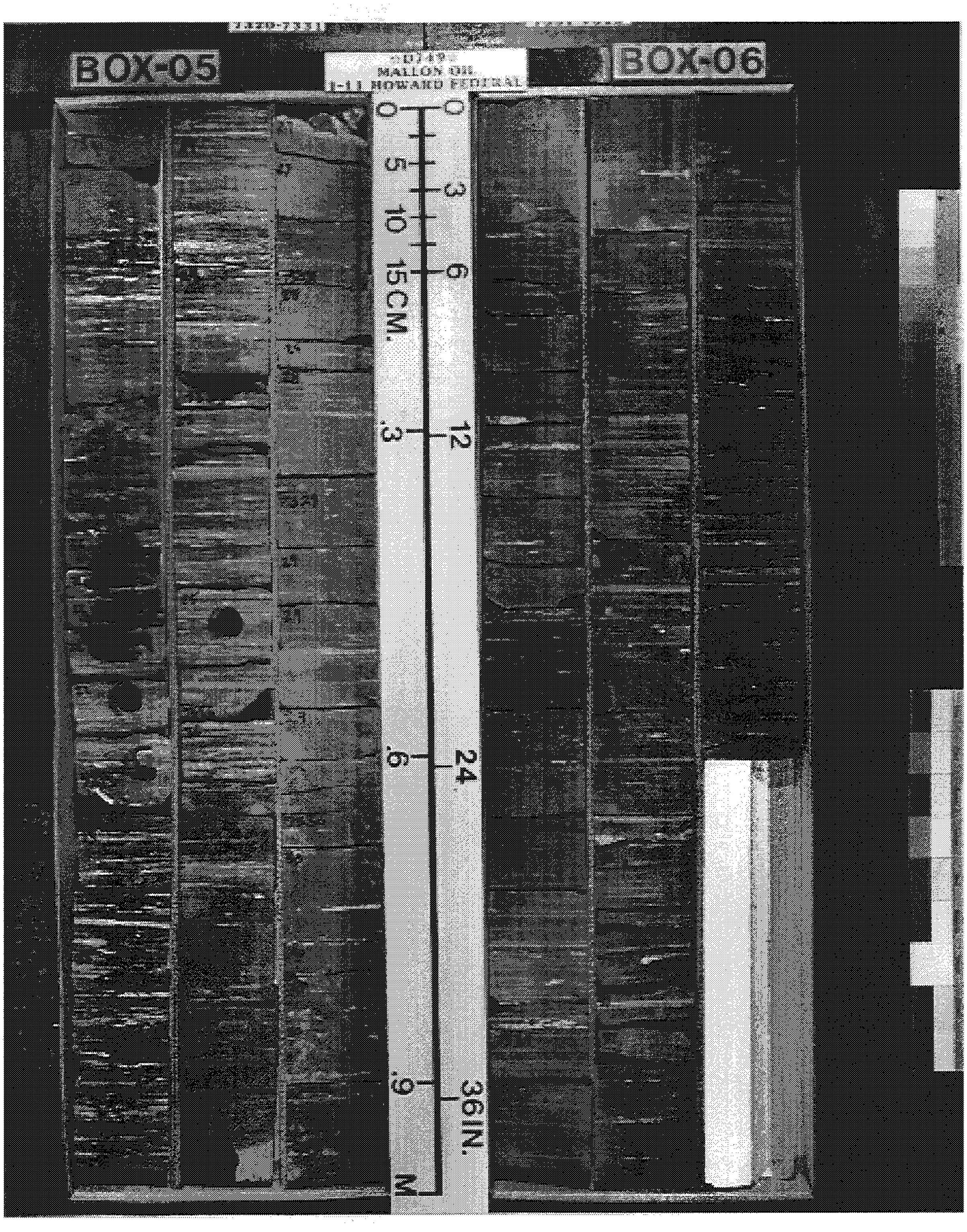
Producing zone 6931 - 7754 (multiple perforated intervals)
Perforated intervals within cored interval at 7282, 7296, 7313, 7318, 7333, 7339

Initial Production 43 BOPD, 101 BWPD


BOX-01
BOX-02
MALLON OIL
HOWARD FEDERAL
0
5
10
15CM.
.3
.6
.9
M
0
3
6
12
24
36IN.

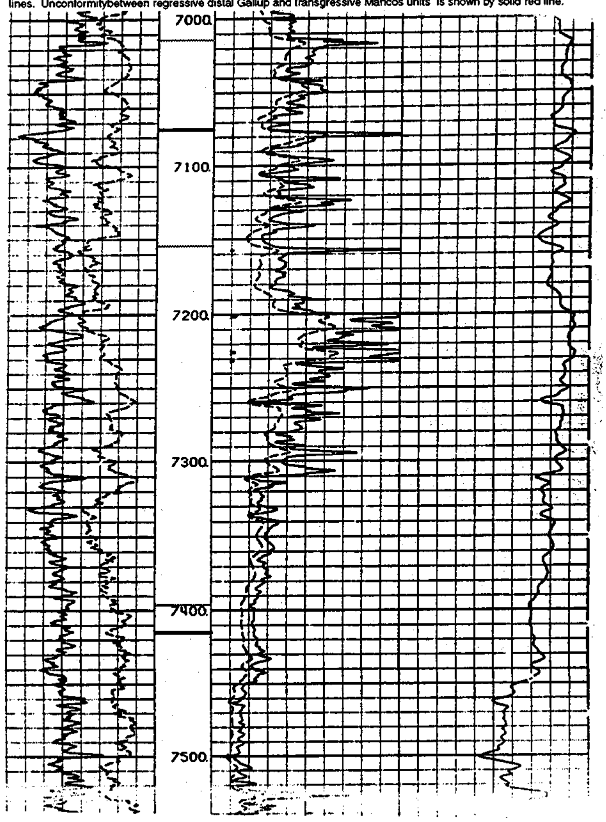


BOX-03
MALLON OIL
1-11 HOWARD FEDERAL
BOX-04


BOX-05
MALLON OIL
1-11 HOWARD FEDERAL
BOX-06
15CM.
36IN.

G. Lithologic description of cored interval 7076 - 7415 ft, Mallon Oil Fed Com 3-15, Sec. 3, T. 25 N., R. 2 W.

Top and base of El Vado Sandstone of Mancos Shale shown by solid blue lines; cored interval shown by solid black lines. Unconformitybetween regressive distal Gallup and transgressive Mancos units is shown by solid red line.



Perforated multiple intervals from 7195-7390 ft.

7076-7084 ft Thin, multiple, stacked parasequences consisting of intebedded black shale and laminated gray sandstone. The base of the parasequence is black shale, the middle part of the parasequence is interbedded black shale and sandstone, and the upper part where present is dominantly sandstone that has thin interbeds of black shale. Sandstone are wavy to parallel laminated and are carbonaceous. Burrowing and bioturbation are more Prevalent in the shale and silty layers. Microstylolites are common.

7084 - 7138.75 ft Like 7076- 7084 except that the parasequence sets are thicker and the sandstone portion within each set is thicker. Sandstone shows evidence of compaction, soft-sediment deformation, local cut and fill. Bioturbation and burrowing are locally intense imparting a disrupted fabric to the rock.

7138.75 - 7165.25 ft Like 7076 - 7084 except that black shale forms a greater proportion of the parasequence, especially below 7156 ft.

7165.25 - 7197.25 ft Mostly black shale with thin sandstone stringers, except for sandstone interval at the top from 7165.25 to 7167.5 ft.

7197.25 - 7208.75 ft Like 7138.75 to 7165.25 ft.

7208.75 - 7270.6 ft Mostly black shale with thin sandstone stringers, except for sandstone interval at the top from 7208.75 to 7211 ft. Thin sandy intervals increase in proportion in the lower 8 feet.

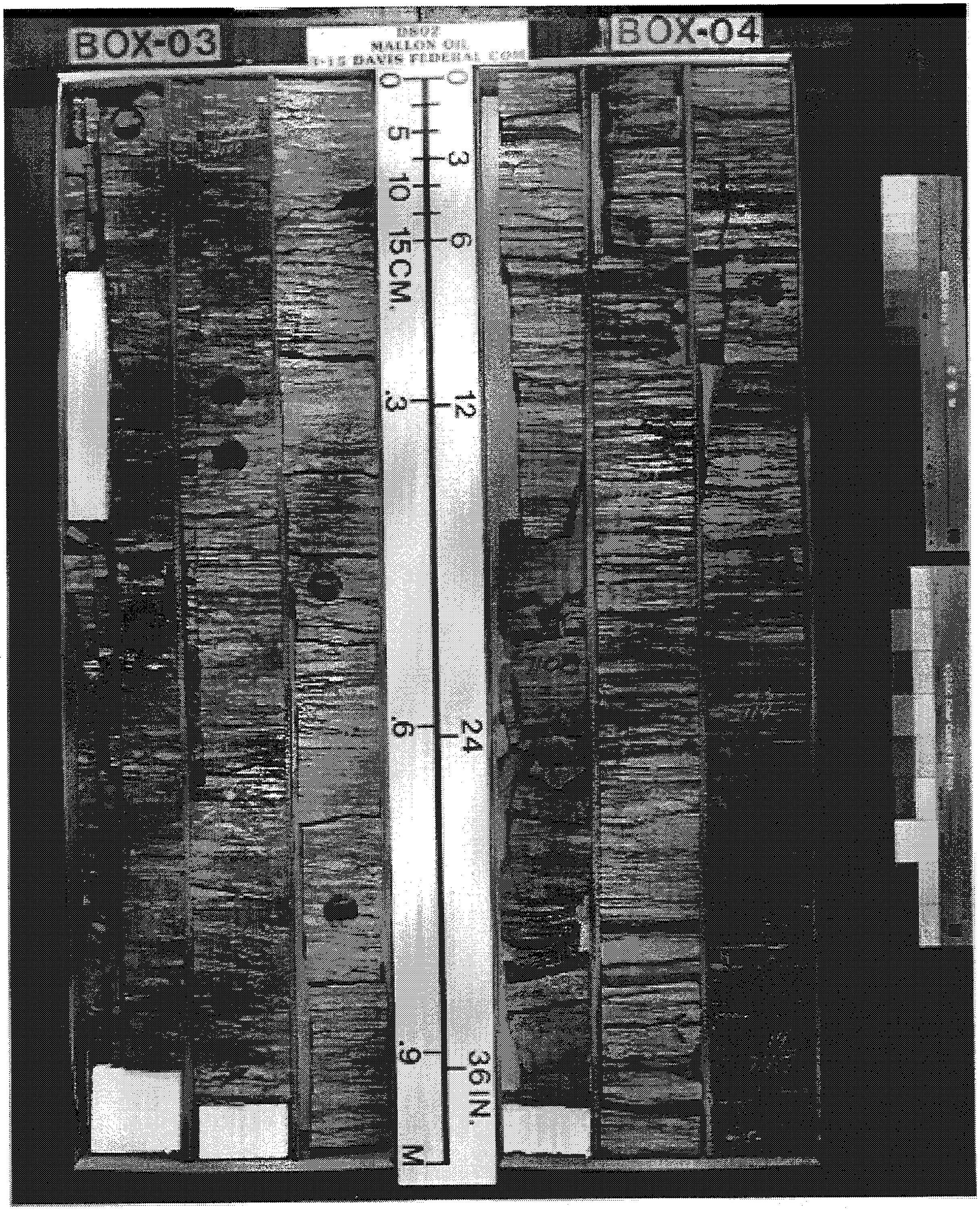
7270.6 - 7329 ft Thin, multiple, stacked parasequences consisting of intebedded black shale and laminated gray sandstone. Sandstone is a dominant portion of the parasequence set. Burrowing and bioturbation are extensive imparting a disrupted fabric to the rock. In the lowermost set very black shale is prominent.

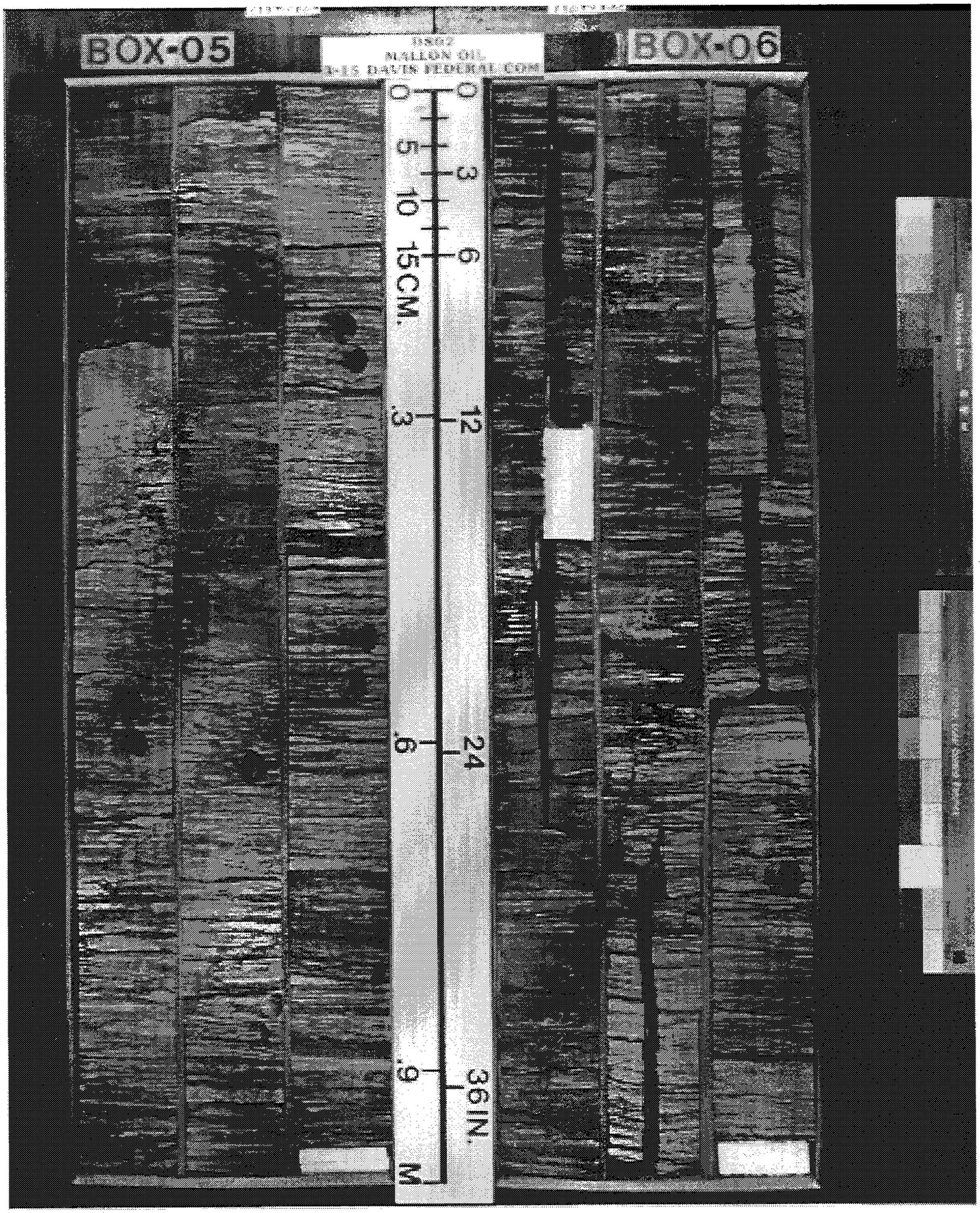
7329 - 7349 ft Mostly sandstone from 7329 to 7344 at the top underlain by black shale with thin sandstone stringers. Large concretion near base.

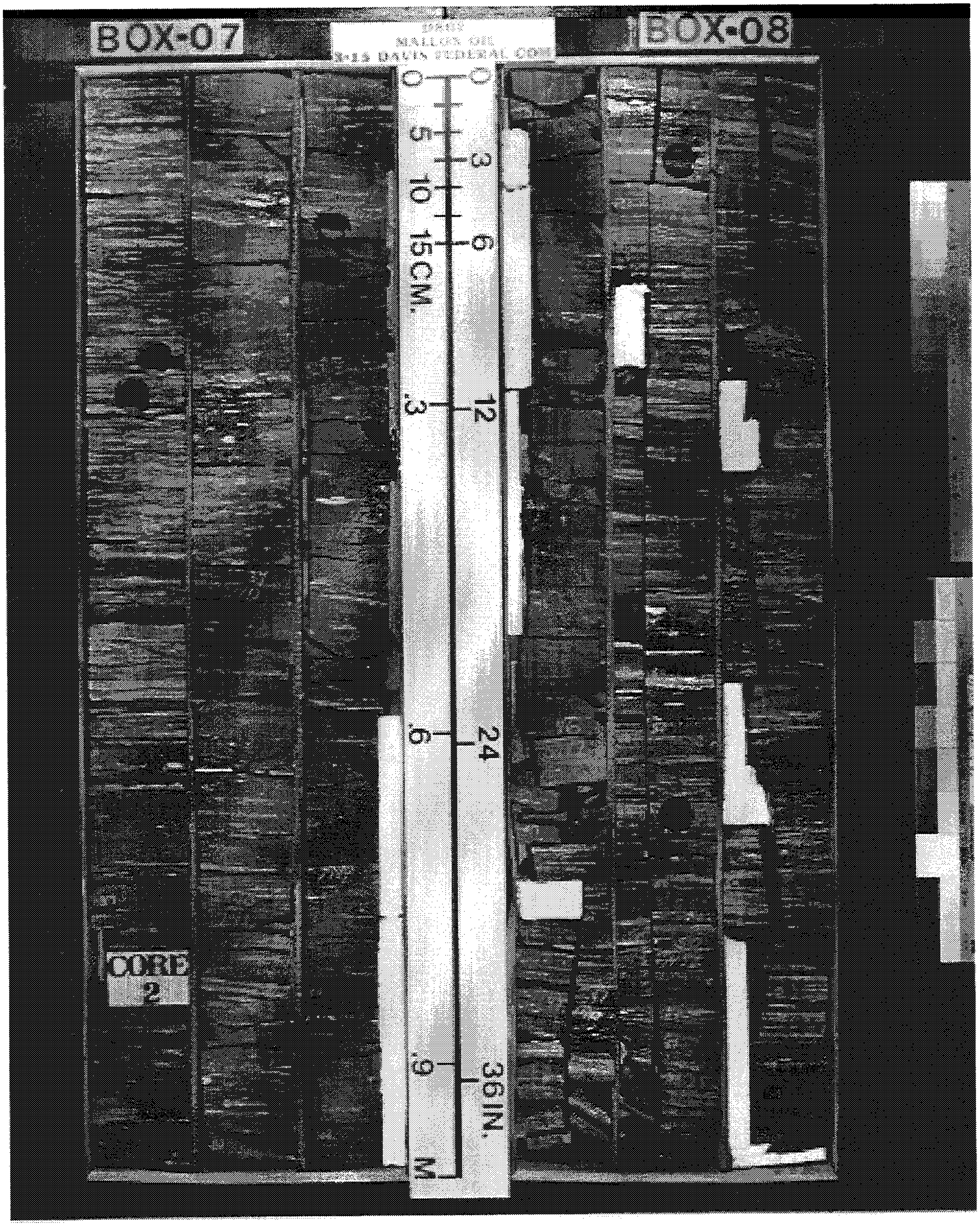
7349 - 7383.6 ft Like 7270.6 to 7329 feet

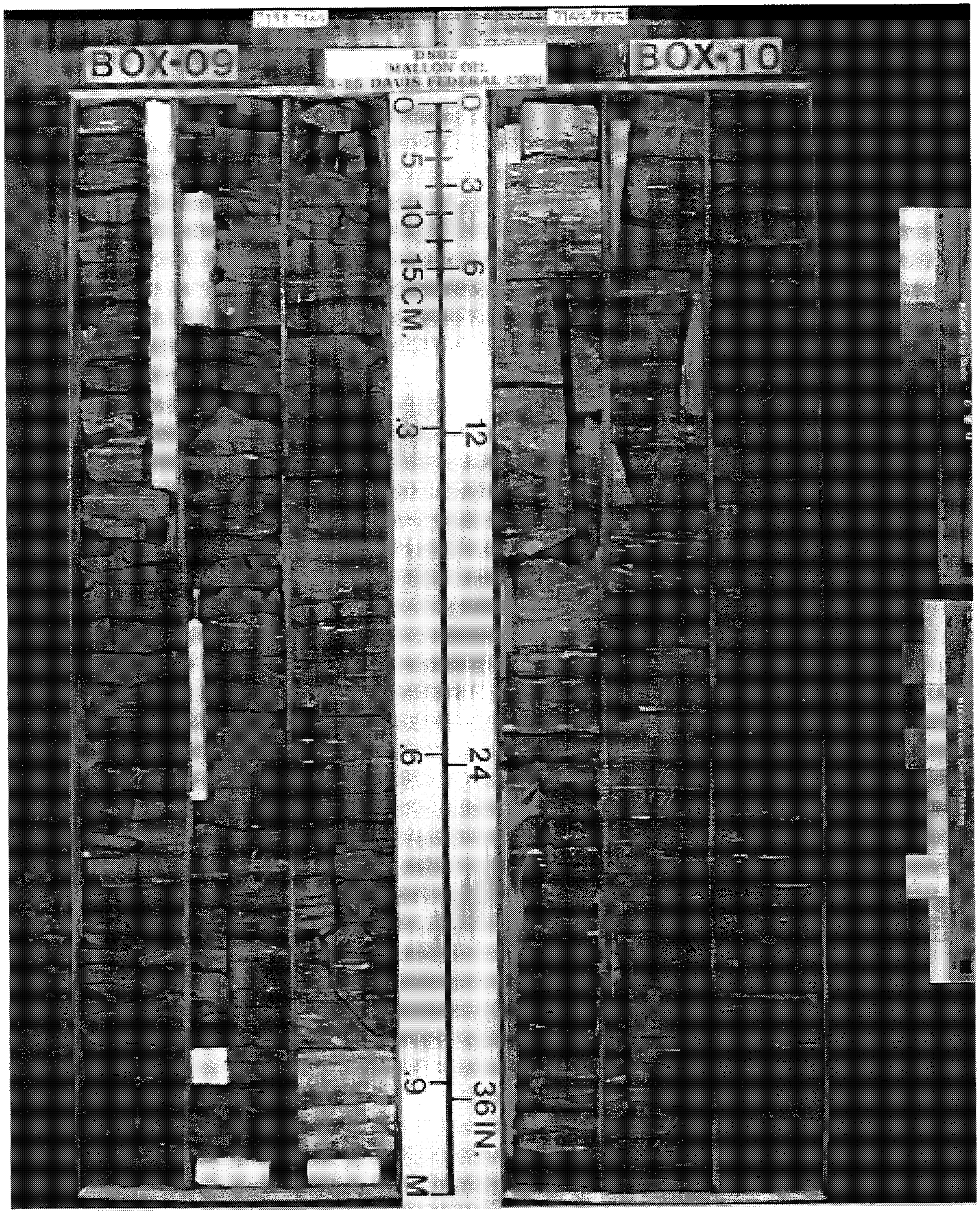
7383.6 - 7415 ft Like 7076-7084 feet. Black shale is dominant.

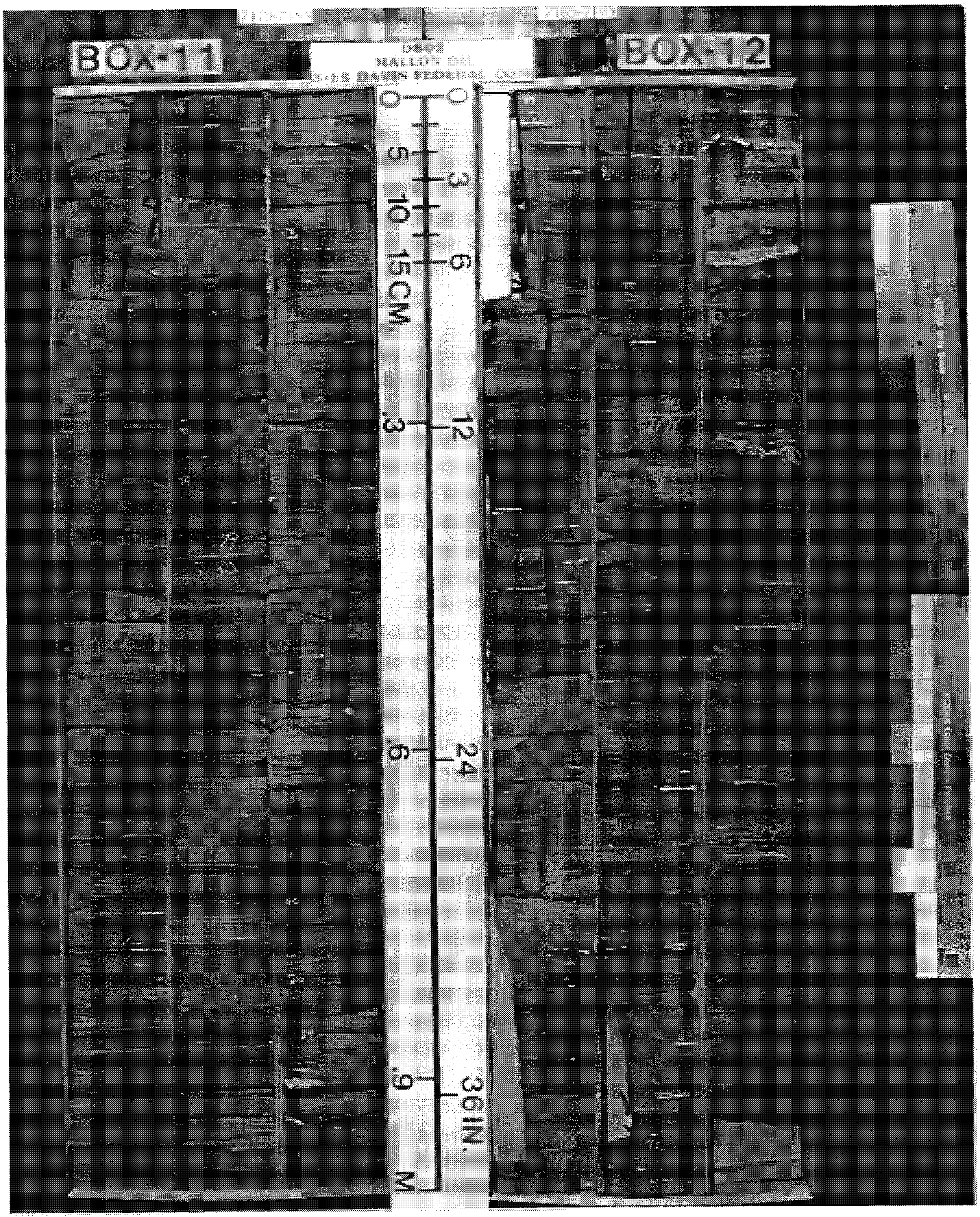

BOX-01
BOX-02
MALLON OIL
15CM.
36IN.

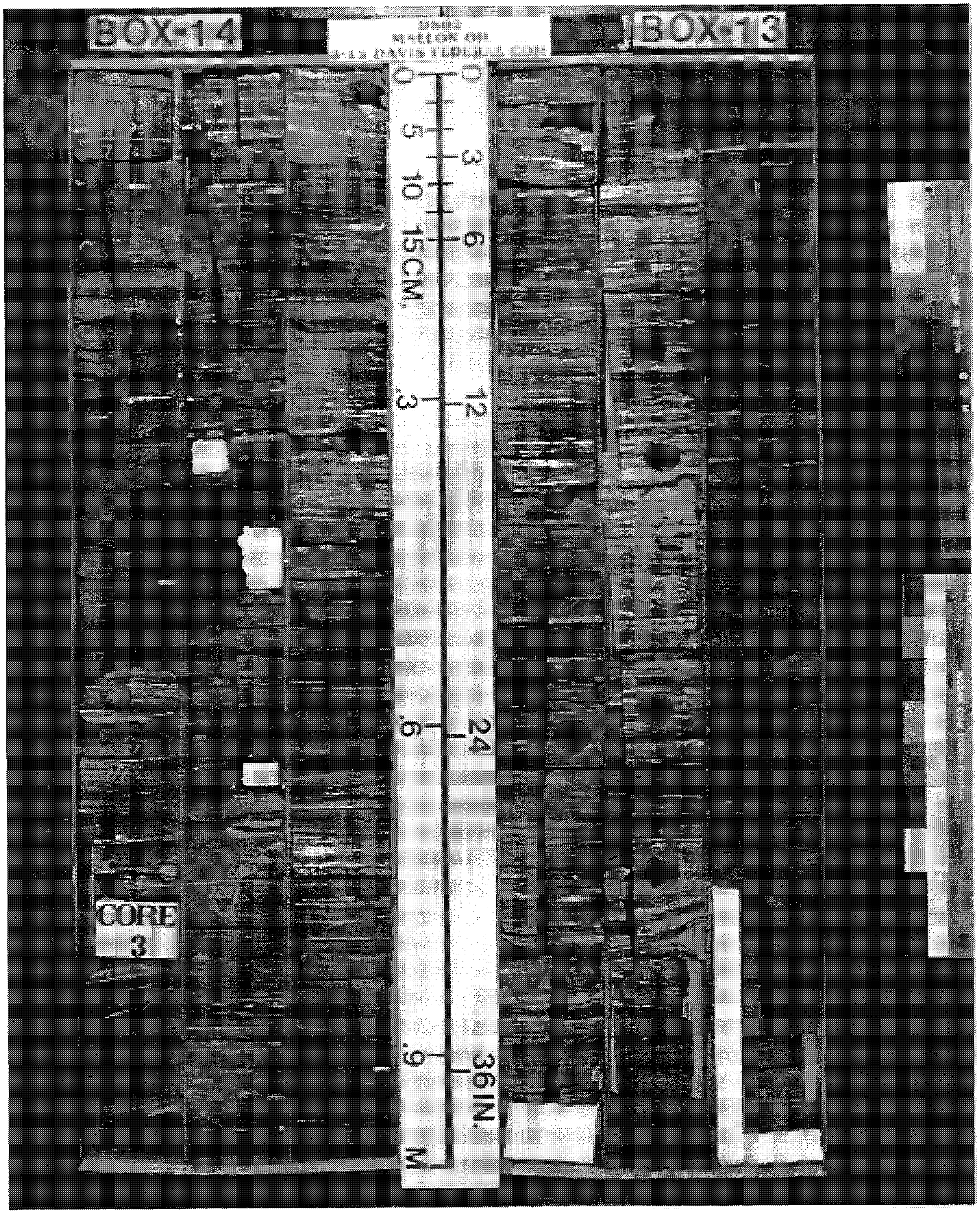

BOX-03
DB07
MALLON OIL
3-15 DAVIS FEDERAL COM
BOX-04
0 5 10 15CM. .3 .6 .9 M
0 3 6 12 24 36IN.

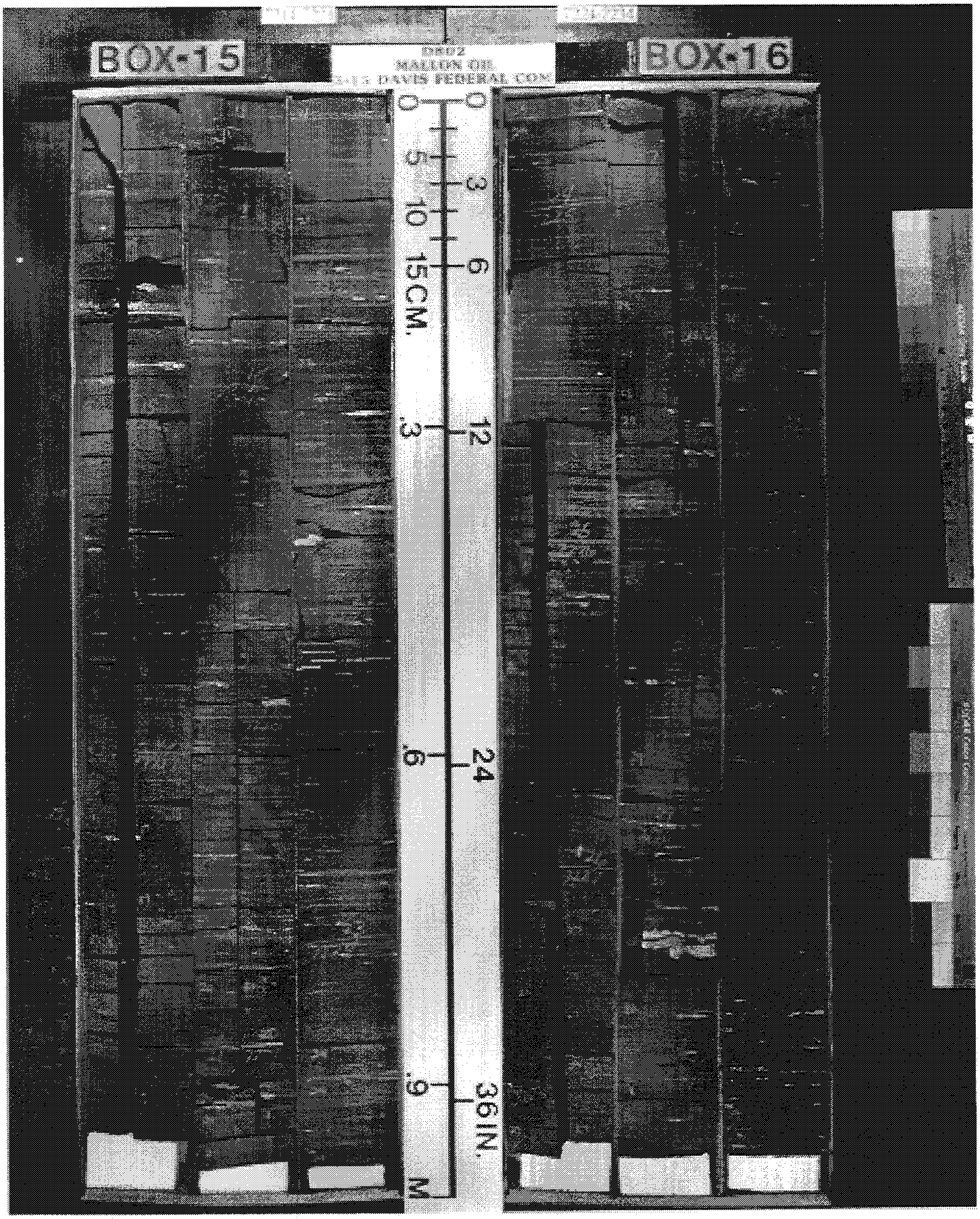

BOX-05
MALLON OIL
3-15 DAVIS FEDERAL COM
BOX-06

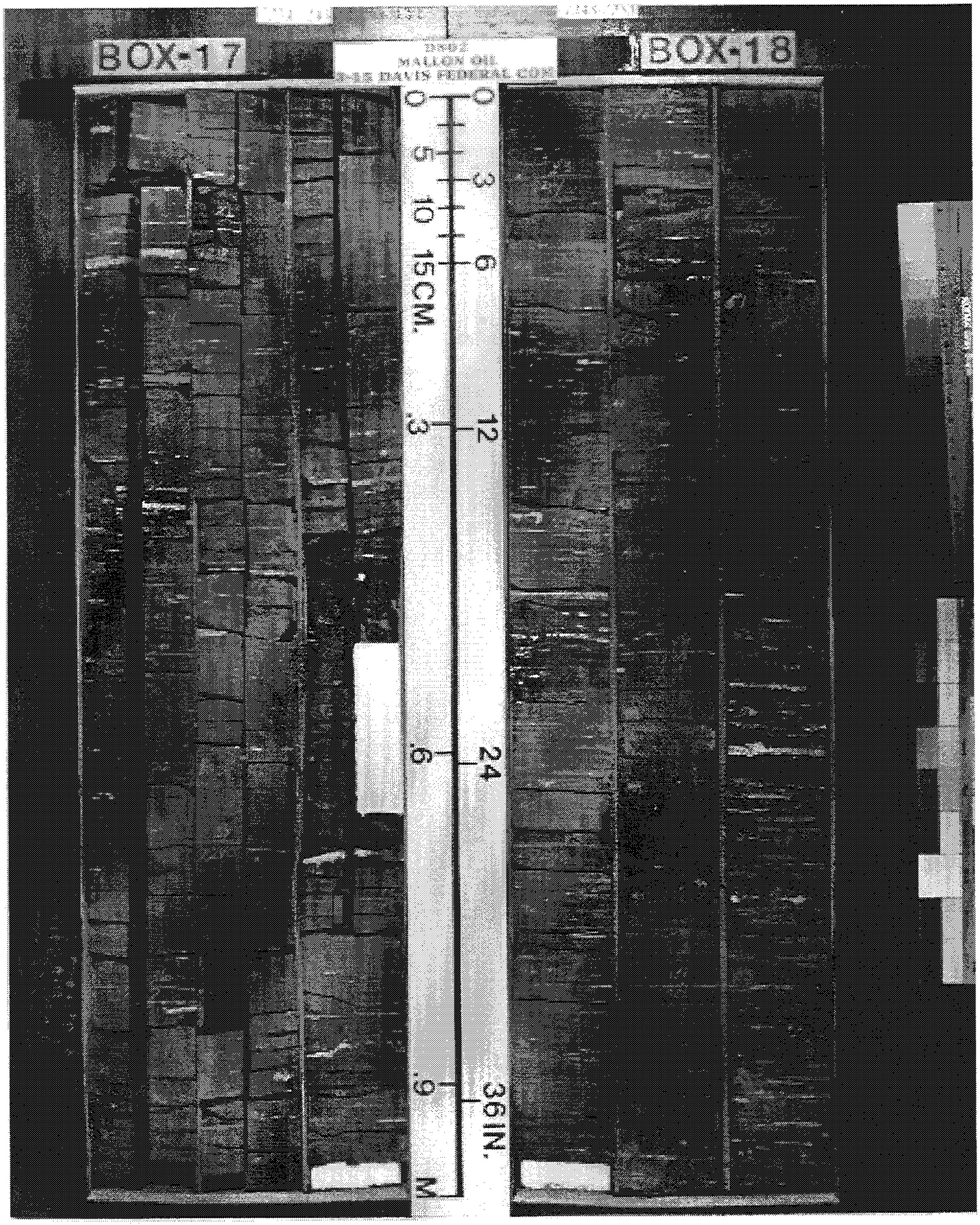

BOX-07
MALLON OIL
3-15 DAVIS FEDERAL COM
BOX-08
0 5 10 15CM.
.3
.6
.9
M.
0 3 6
12
24
36 IN.
CORE
2

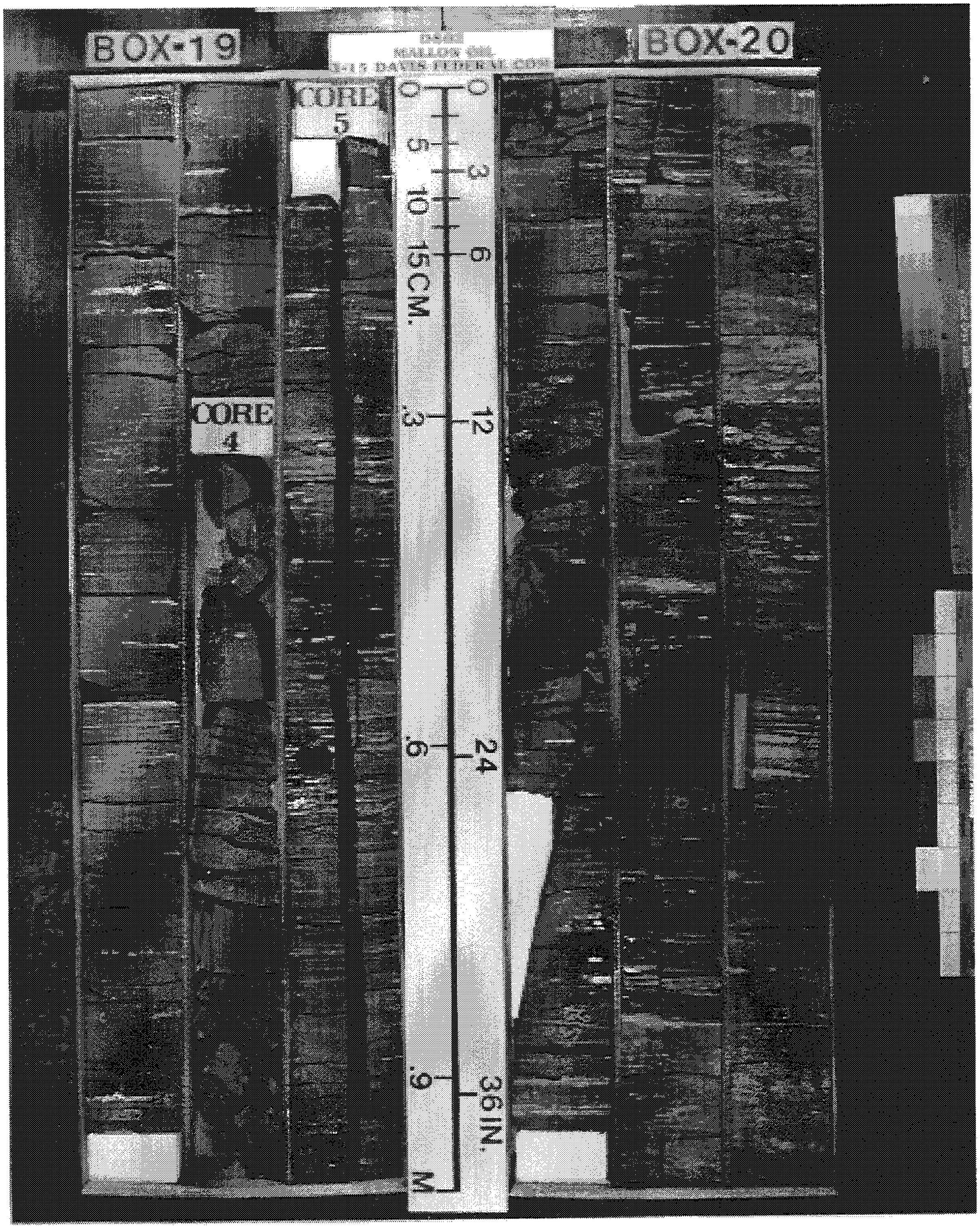

BOX-09
MALLON OIL
BOX-10

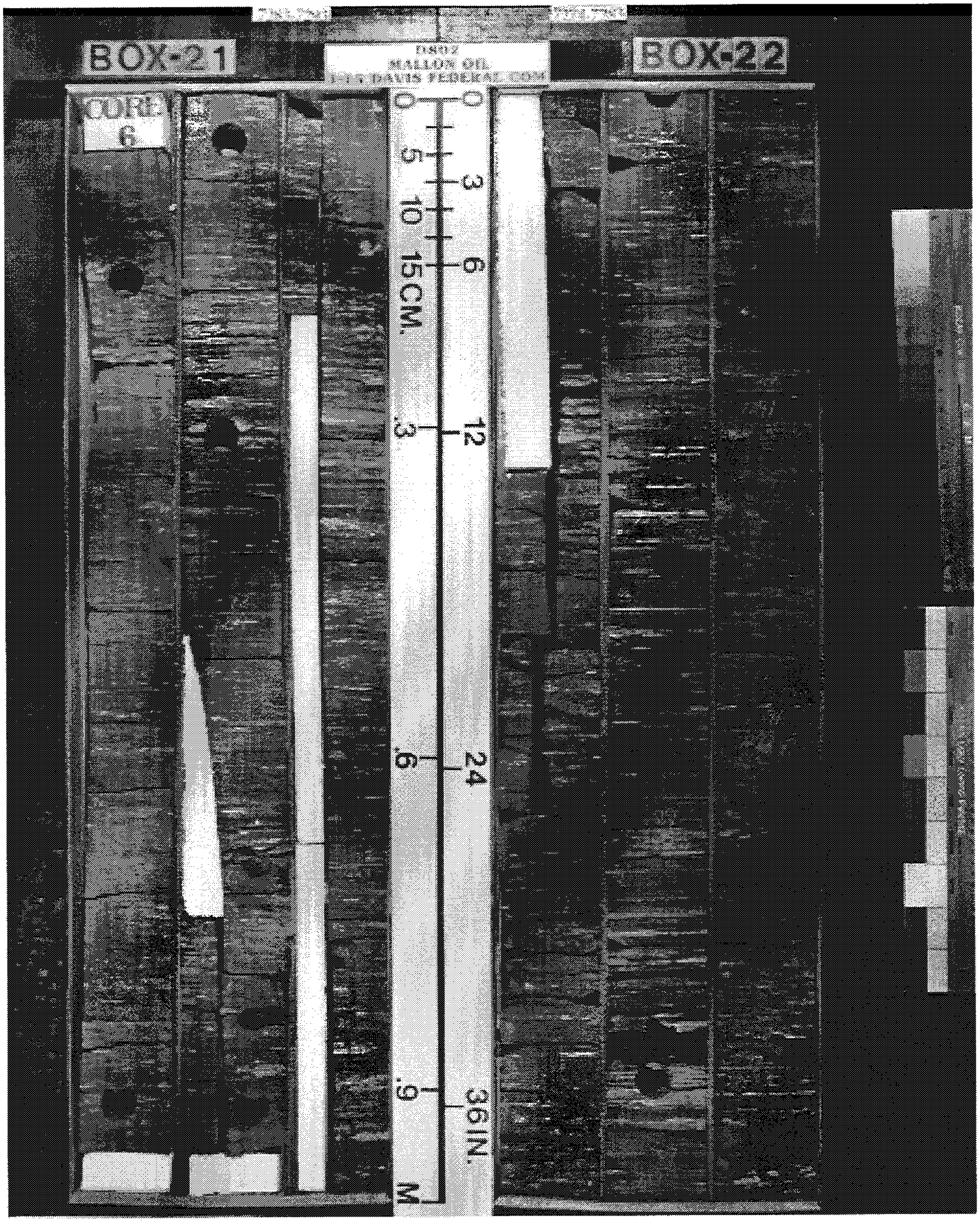

BOX-11
BOX-12
MALLON OIL

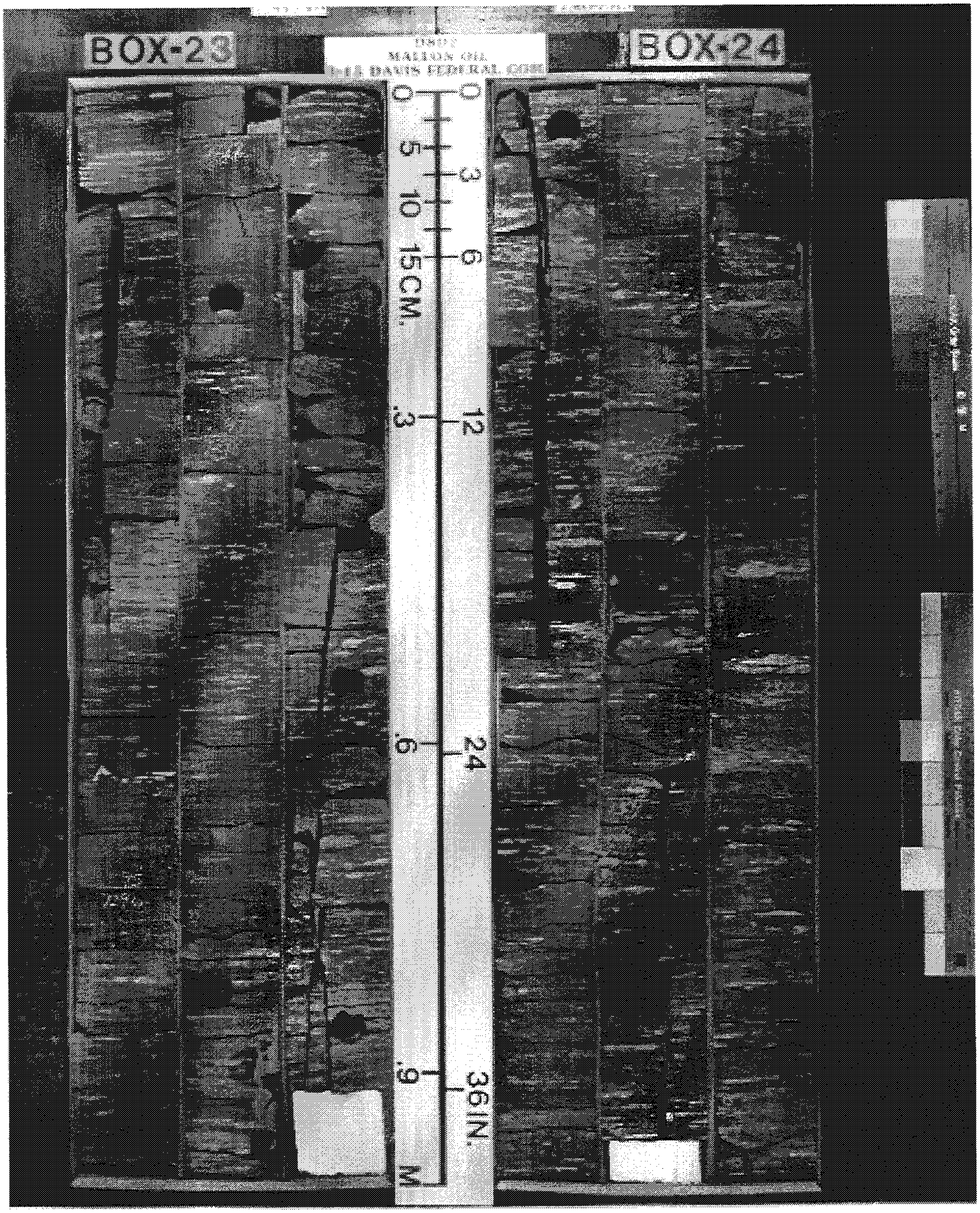

BOX-14
D802
MALLON OIL
3-15 DAVIS FEDERAL COM
BOX-13
0
5
10
15CM.
.3
.6
.9
M.
0
3
6
12
24
36IN.
CORE
3

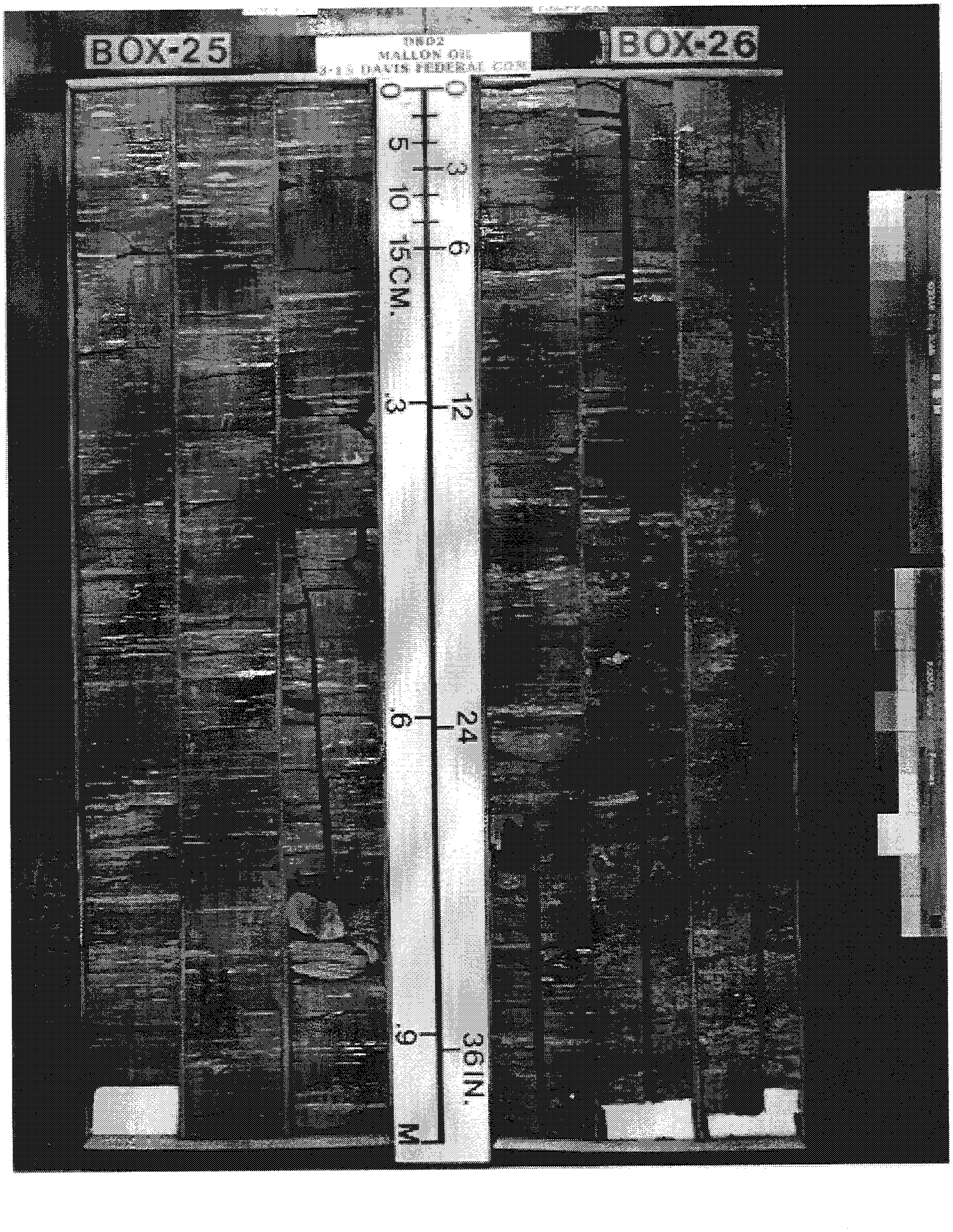

BOX-15
MALLON OIL
DAVIS FEDERAL COM
BOX-16
0 5 10 15CM.
.3
.6
.9
M
0 3 6 12 24 36IN.

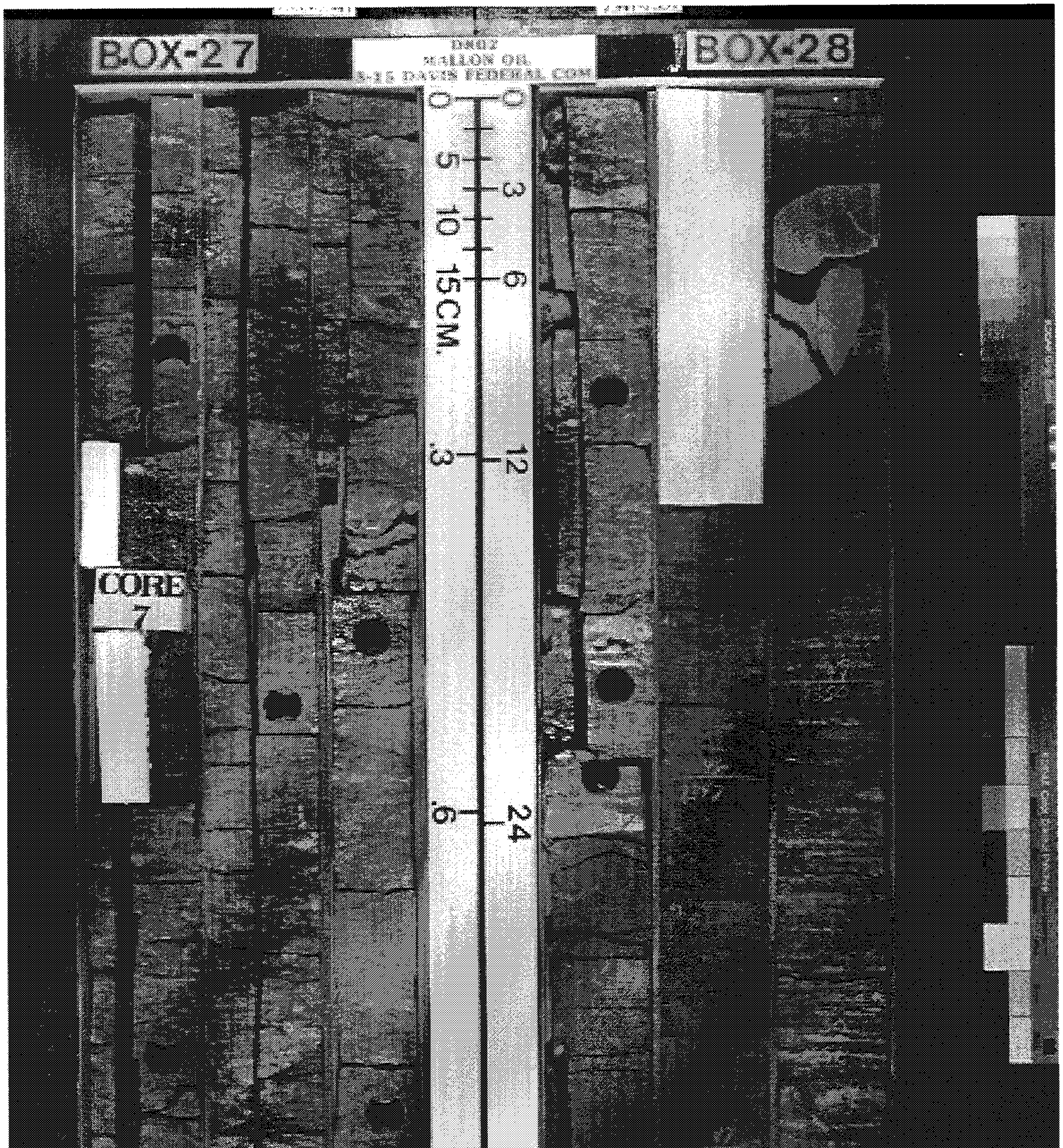

BOX-17
MALLON OIL
BOX-18
36IN.

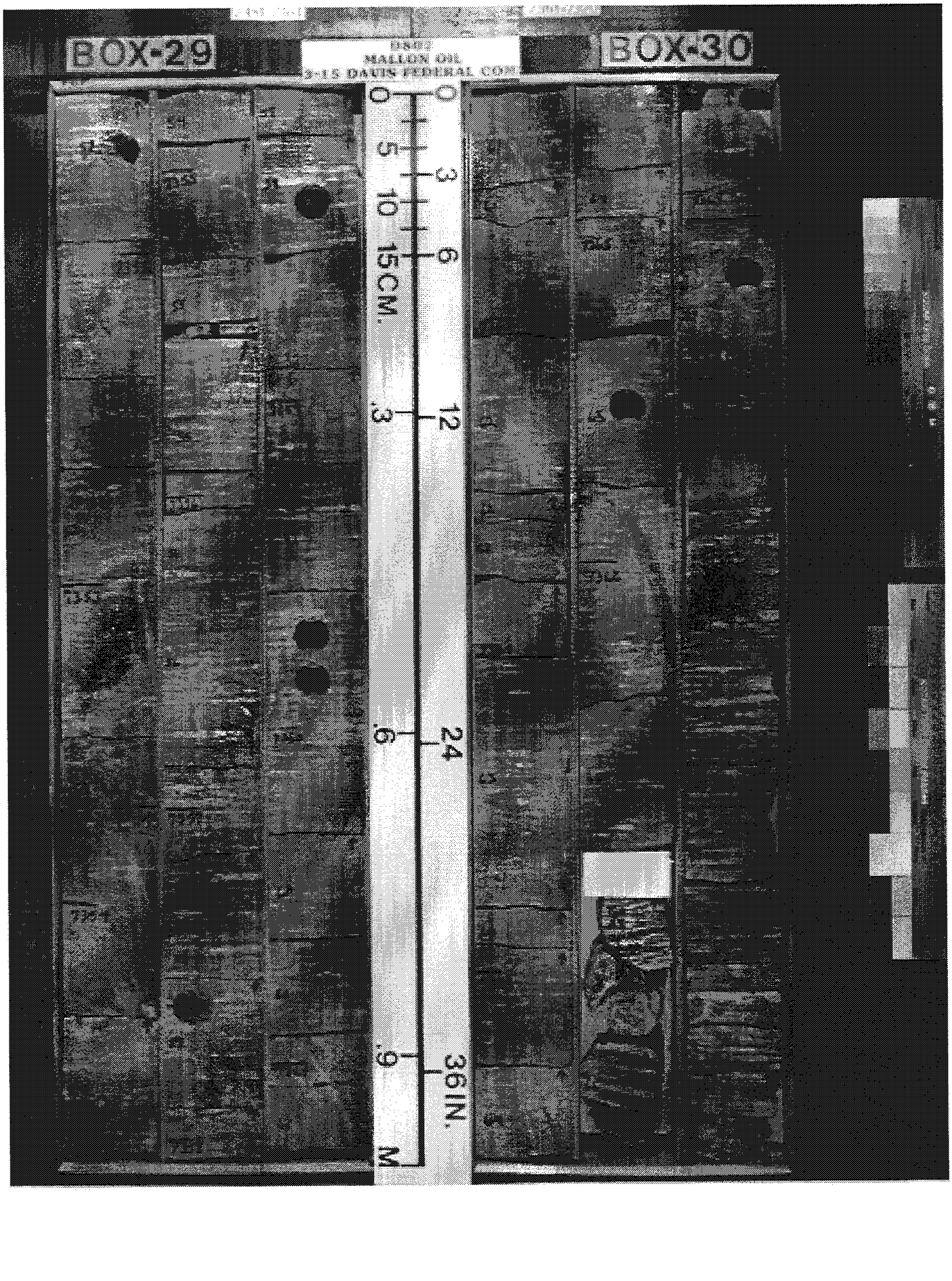

BOX-19
BOX-20
CORE
5
CORE
4
15CM.
36IN.
M.

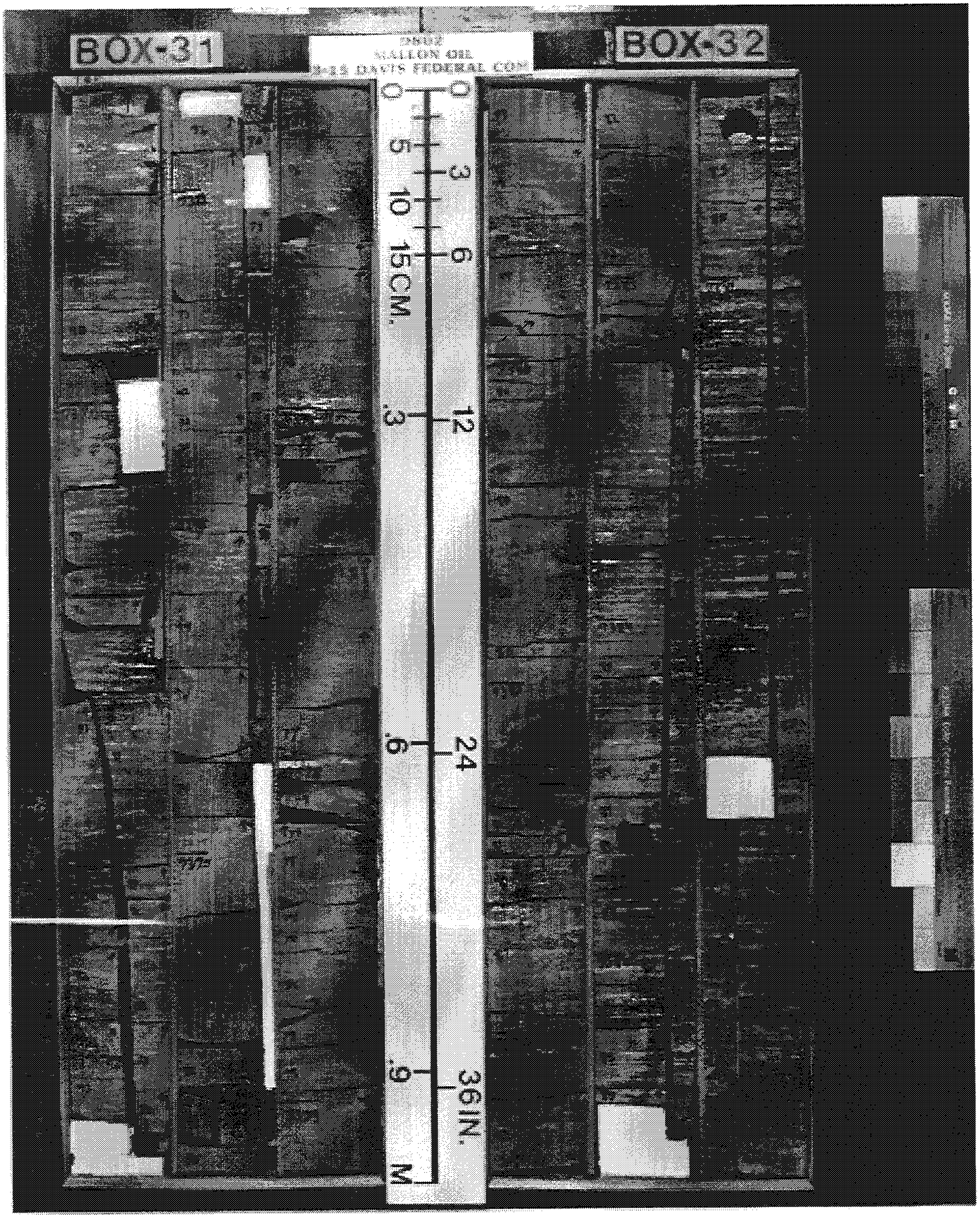

BOX-21
BOX-22
CORE 6
D802
MALLON OIL
1-15 DAVIS FEDERAL COM
15CM.
36IN.

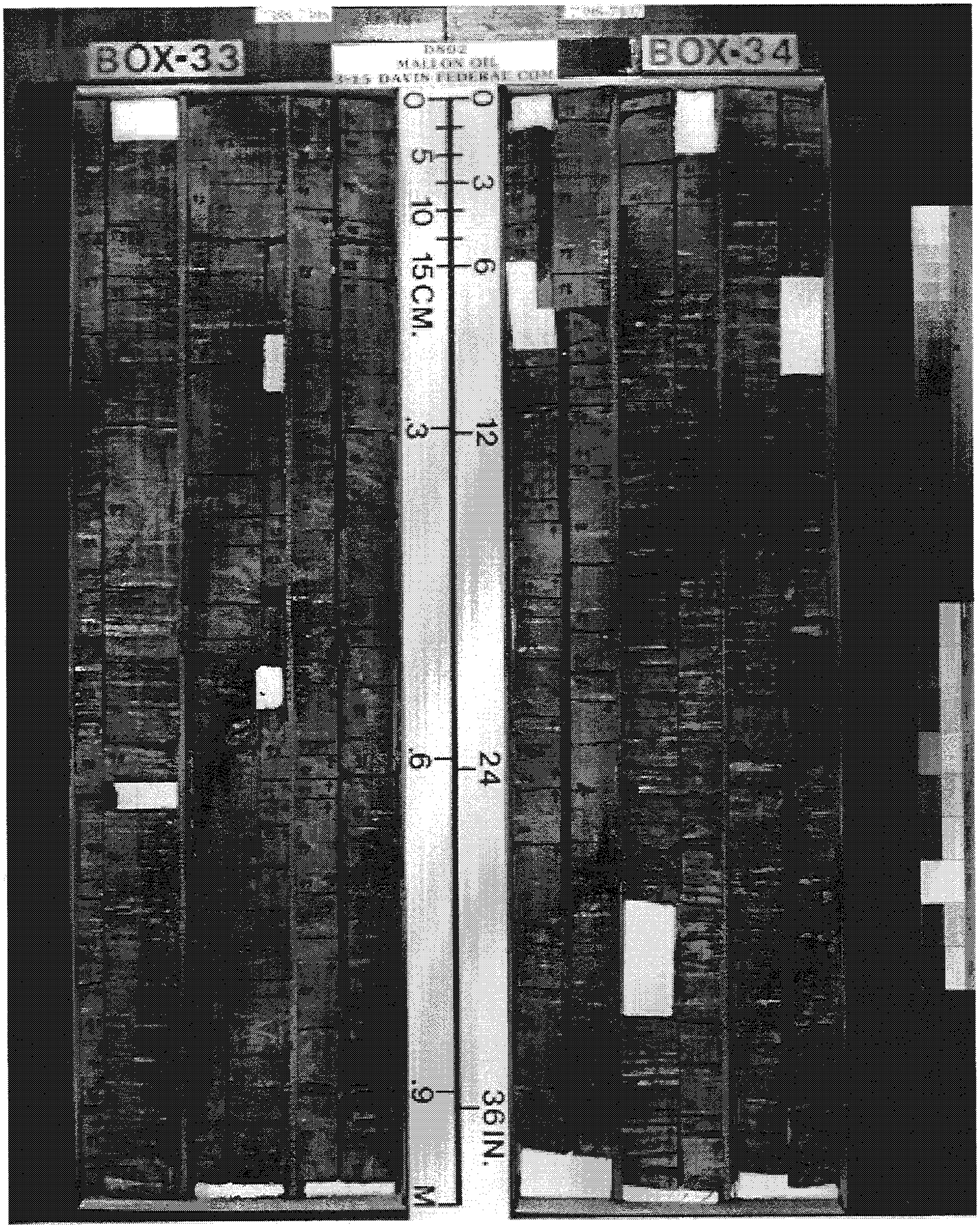

BOX-23
MALLON OIL
DAVIS FEDERAL COM
BOX-24
0
5
10
15CM.
.3
.6
.9
M
0
3
6
12
24
36IN.

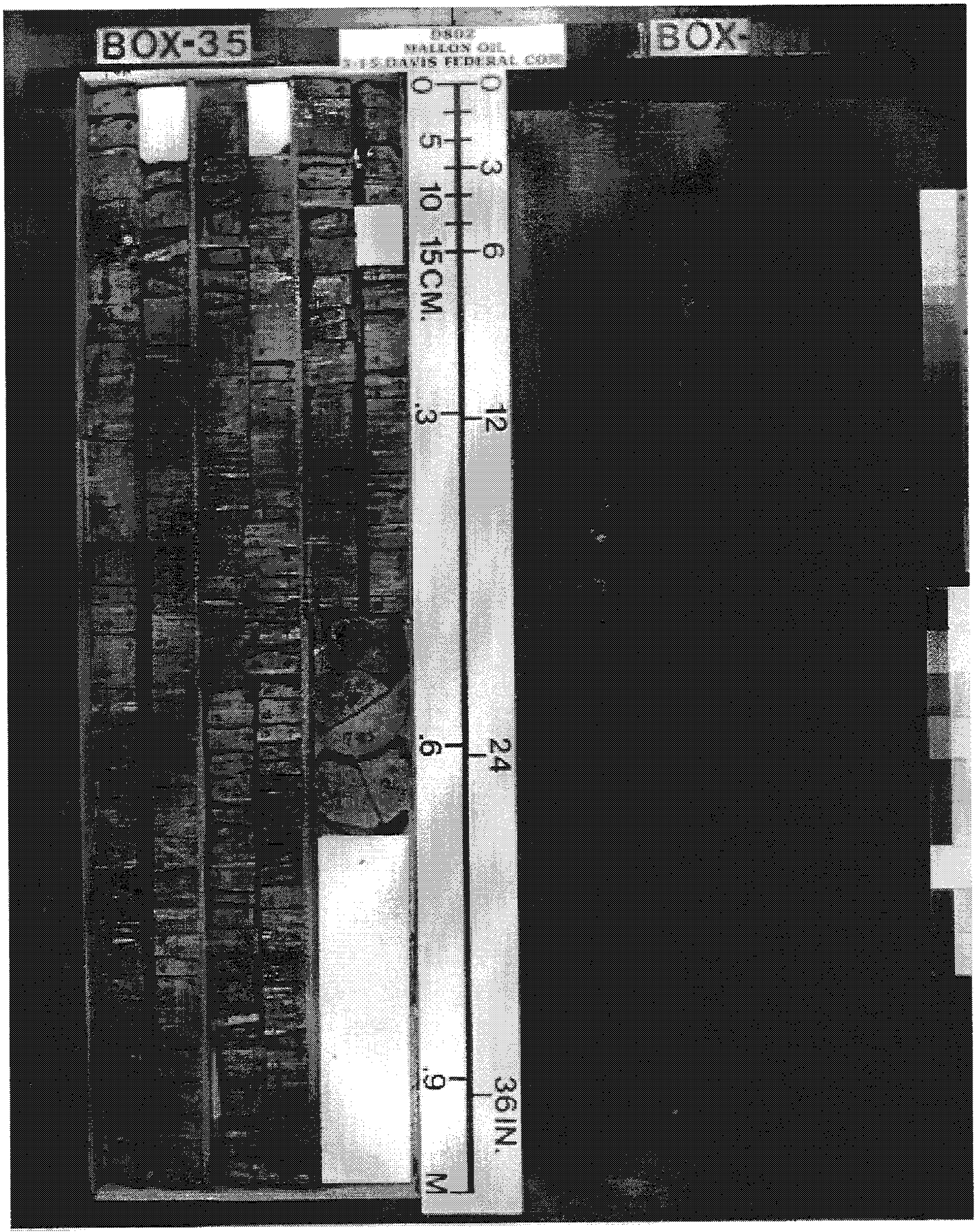

BOX-25
BOX-26
MALLON OIL
15CM.
36IN.

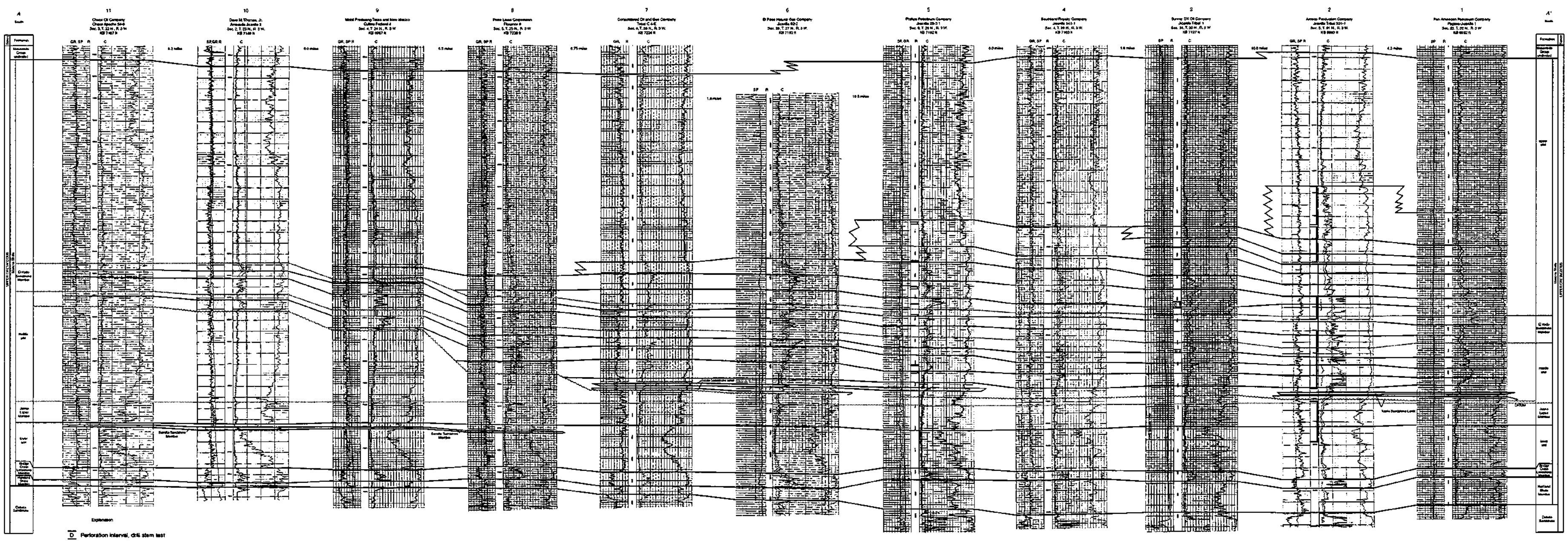

BOX-27
MALLON OIL
BOX-28
CORE
7
15CM.
36IN.


BOX-29
MALLON OIL
3-15 DAVIS FEDERAL COM
BOX-30
0 5 10 15CM.
0 3 6 12 24 36IN.
.3 .6 .9 M.


BOX-31
MALLON OIL
DAVIS FEDERAL COM
BOX-32


BOX-33
BOX-34
MALLON OIL
0 5 10 15CM.
.3
.6
.9
M.
0 3 6 12 24 36IN.


BOX-35
D802
MALLON OIL
3-15 DAVIS FEDERAL COM
BOX-



Explanation

Perforation interval, drill stem test

Perforation interval, gas production

Unconformity

PLATE 1. SOUTH-NORTH CROSS SECTION SHOWING CORRELATION OF UNITS IN THE MANCOS SHALE ON THE WEST SIDE OF THE JICARILLA APACHE INDIAN RESERVATION, NEW MEXICO.

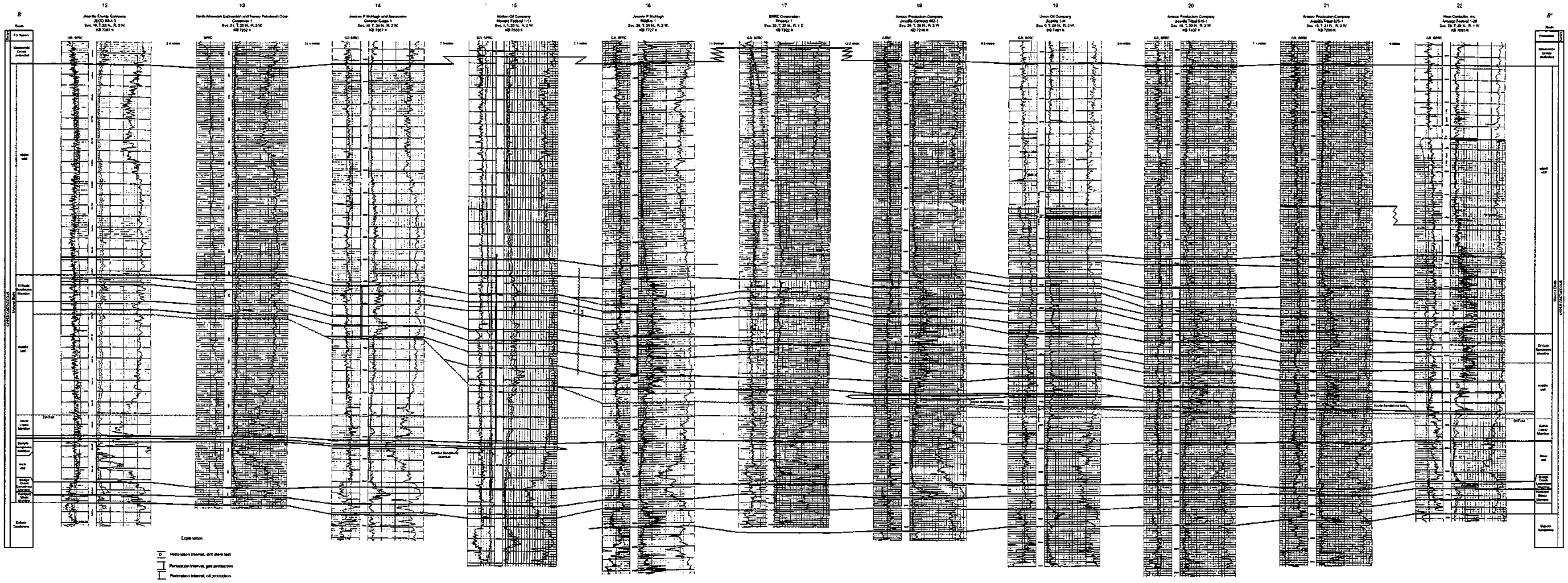


PLATE 2. SOUTH-NORTH CROSS SECTION SHOWING CORRELATION OF UNITS IN THE MANCOS SHALE ON THE EAST SIDE OF THE JICARILLA APACHE INDIAN RESERVATION, NEW MEXICO.

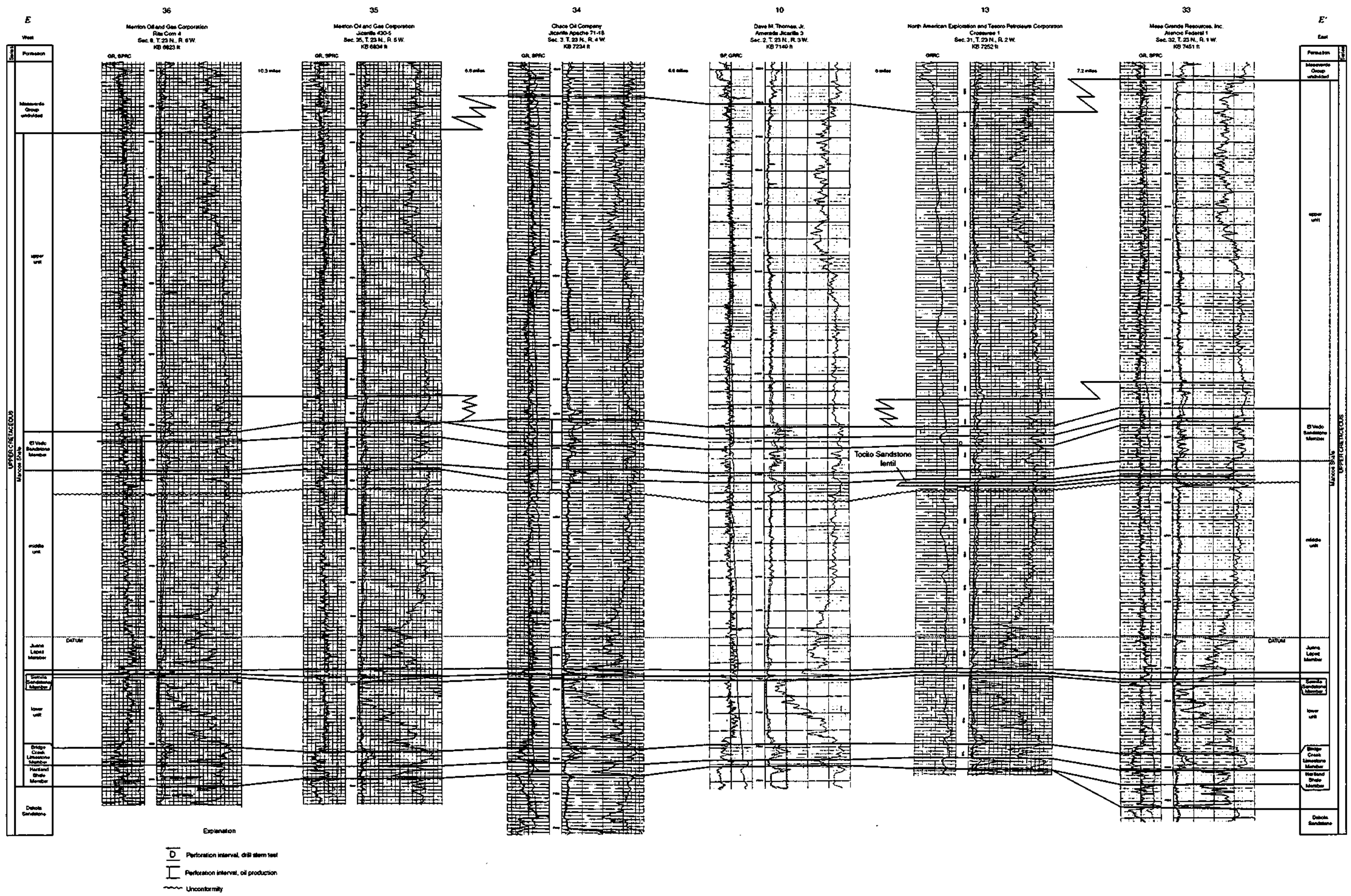


PLATE 3. WEST-EAST CROSS SECTION SHOWING CORRELATION OF UNITS IN THE MANCOS SHALE THROUGH THE CENTRAL PART OF THE JICARILLA APACHE INDIAN RESERVATION, NEW MEXICO.

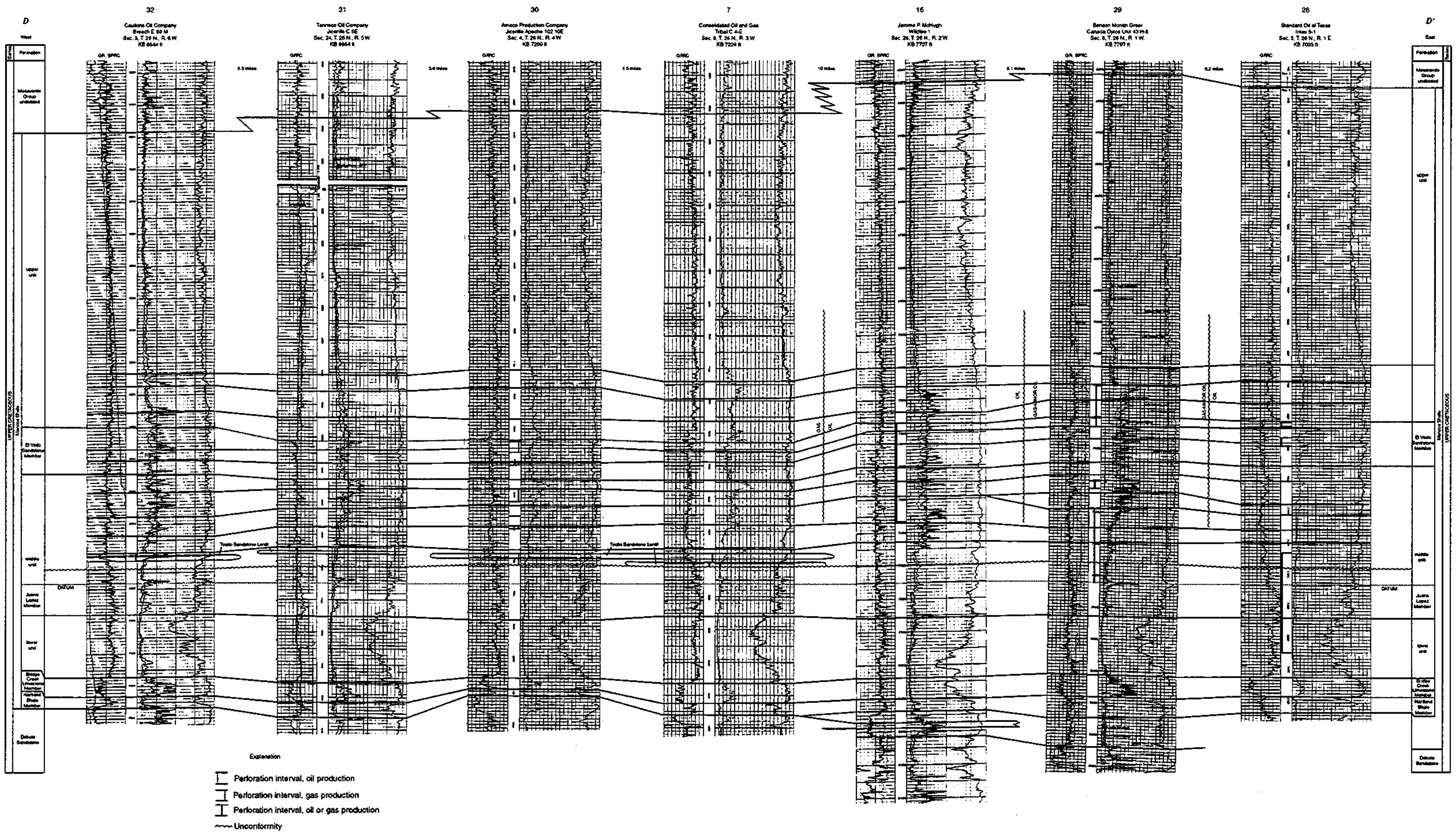


PLATE 4. WEST-EAST CROSS SECTION SHOWING CORRELATION OF UNITS IN THE MANCOS SHALE THROUGH THE MIDDLE PART OF THE JICARILLA APACHE INDIAN RESERVATION, NEW MEXICO.

PLATE 5

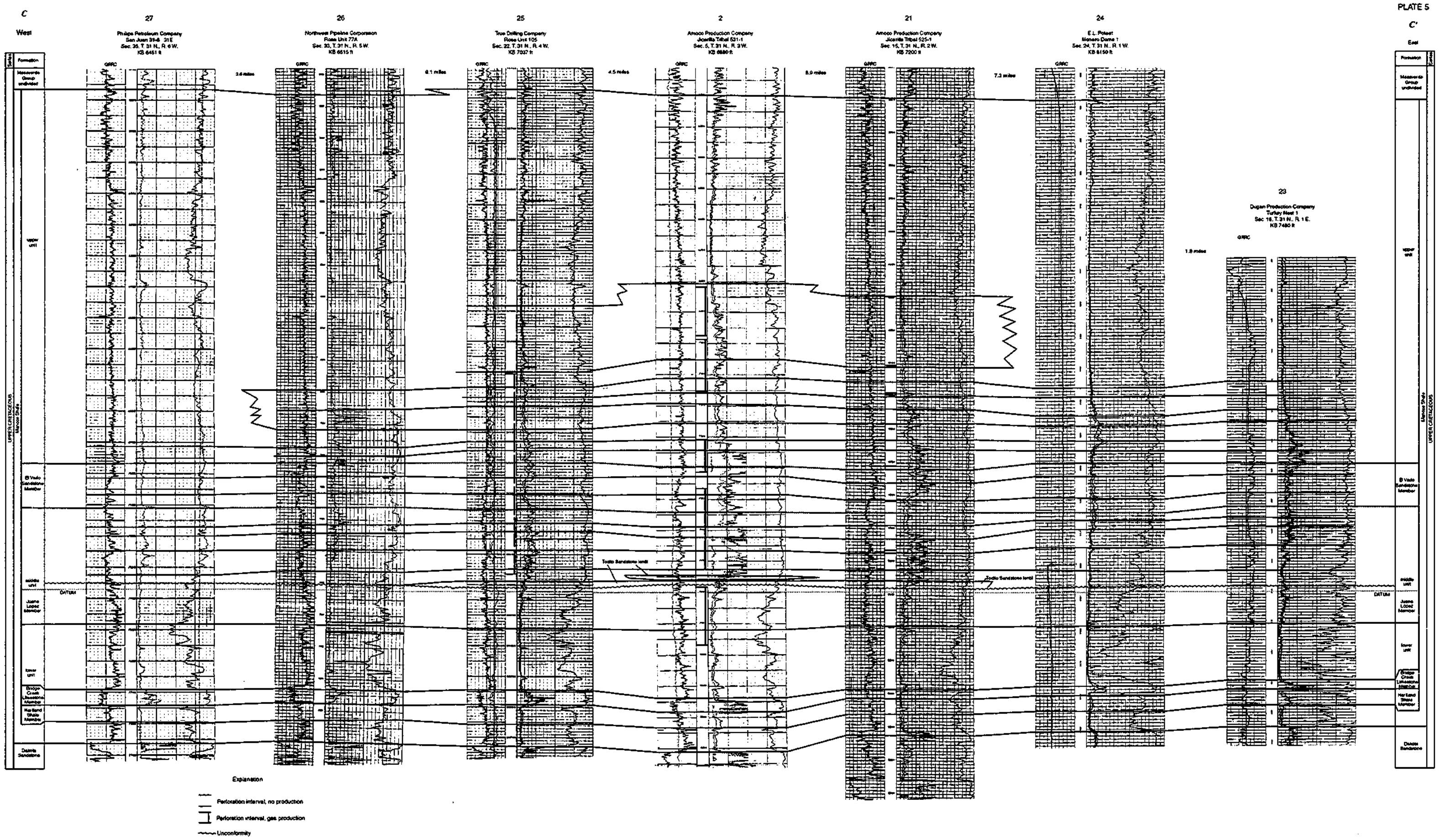


PLATE 5. WEST-EAST CROSS SECTION SHOWING CORRELATION OF UNITS IN THE MANCOS SHALE ON THE NORTH PART OF THE JICARILLA APACHE INDIAN RESERVATION, NEW MEXICO.

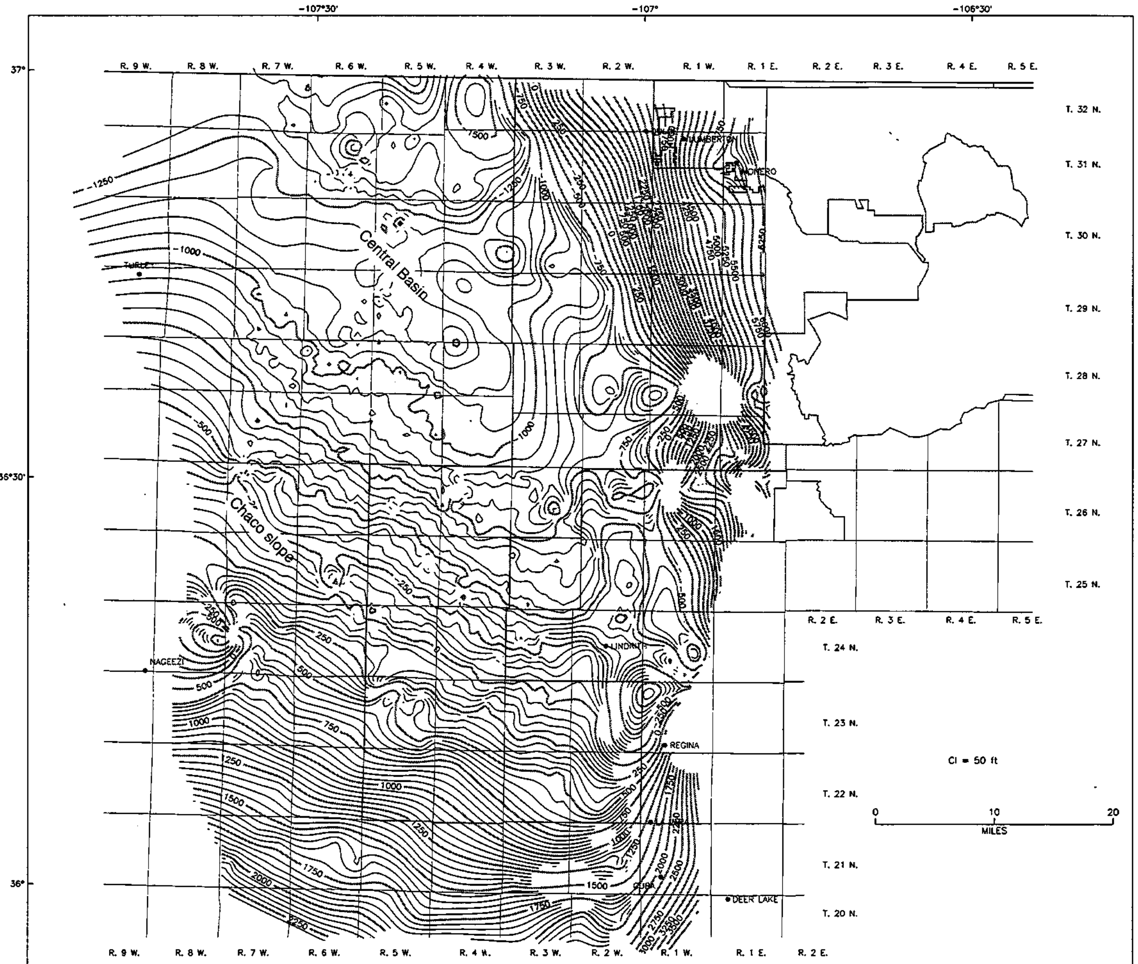


PLATE 6. COMPUTER-GENERATED STRUCTURE MAP DRAWN ON THE BASE OF THE BRIDGE CREEK LIMESTONE MEMBER OF THE MANCOS SHALE