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TECTONIC DOLOMITIZATION IN THE GAVILAN MANCOS OIL POOL, RIO ARRIBA COUNTY, NEW MEXICO

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Abstract—The Gavilan Mancos Oil Pool is one of several naturally fractured oil reservoirs producing from the Mancos Formation on the eastern side of the San Juan Basin. Commercial production is the result of the concentration, on structure, of natural fractures within carbonate-cemented sandstone and calcareous shale intervals of the Mancos Formation. Fracturing of the rock column resulted from the formation of the Gavilan dome by compressional forces associated with right lateral movement along the Nacimiento fault zone. Accompanying the fracturing process was the metasomatic formation of ankerite within calcareous portions of the rock column by tectonic dolomitization. Sulfide mineralization also formed by this mechanism. Detailed sample examination and thin section analysis of drill cuttings enabled recognition of the correct relationship between fracturing and the dolomite content of the rock. An understanding of the influence of tectonic dolomitization on the Gavilan Mancos Oil Pool will aid in additional exploration efforts on the eastern side of the San Juan Basin.

INTRODUCTION

The Gavilan Mancos Oil Pool is a naturally fractured reservoir located on the eastern side of the San Juan Basin, approximately 70 mi east of Farmington, New Mexico (Fig. 1). Discovered in 1982, it is one of several oil fields on the eastern side of the basin that rely on the occurrence of natural fractures in the Mancos Formation for all or most of the reservoir productivity. Centered in T25N, R2W, the Gavilan Mancos Oil Pool (Fig. 2) consists of approximately 80 wells with a cumulative productive total in excess of 5.2 MMBO and 18.7 BCFG. The field is contiguous with the West Lindrith Gallup–Dakota, Northeast Ojito Gallup–Dakota and West Puerto Chiquito Mancos Oil Pools. The nearby East Puerto Chiquito Mancos and Boulder Mancos Oil Pools are additional fractured reservoirs in the area.

There has been much controversy concerning the reservoir characteristics of the Gavilan Mancos Oil Pool. Between 1986 and 1988 a series of New Mexico Oil Conservation Division hearings was held to determine, among other things, permanent pool rules. In light of and in addition to these hearings, field operator cooperation in the form of study committee meetings to exchange and analyze data were held. One result of this cooperative effort was the cutting and subsequent independent study of 338 ft of Mancos core obtained from Mallon Oil's Davis #3-15 well (Fig. 2). This core and additional data aided in the study of the stratigraphy, mineralogy and reservoir characteristics of the field.

London (1972) published a study that related fracture production to dolomite-cemented sandstones of the Mancos Formation within the West Puerto Chiquito Mancos Pool. He contended that the fractures were developed in the dolomitic sandstone layers within the reservoir, owing to the more brittle nature of dolomite compared to calcite. This relationship between dolomite and fractures is applicable to the Gavilan area as well. Emmendorfer (1989), however, has recently shown that the dolomite content of the sandstones is a direct result of tectonic dolomitization associated with the fracturing process.

Current exploration efforts continue on the eastern side of the basin. Operators are utilizing both vertical and horizontal drilling techniques in an attempt to gain additional oil production within known field limits and in wildcat areas. This paper outlines the geology of the Gavilan Mancos Oil Pool, with particular attention given to the occurrence of tectonic dolomite, in an effort to aid others in their exploratory efforts.

GEOLOGY

Stratigraphy

The gross vertical limits of the Gavilan Mancos Oil Pool include approximately 1000 ft of the Mancos Formation (Fig. 3). This interval consists of the upper Mancos and El Vado Sandstone units, both of

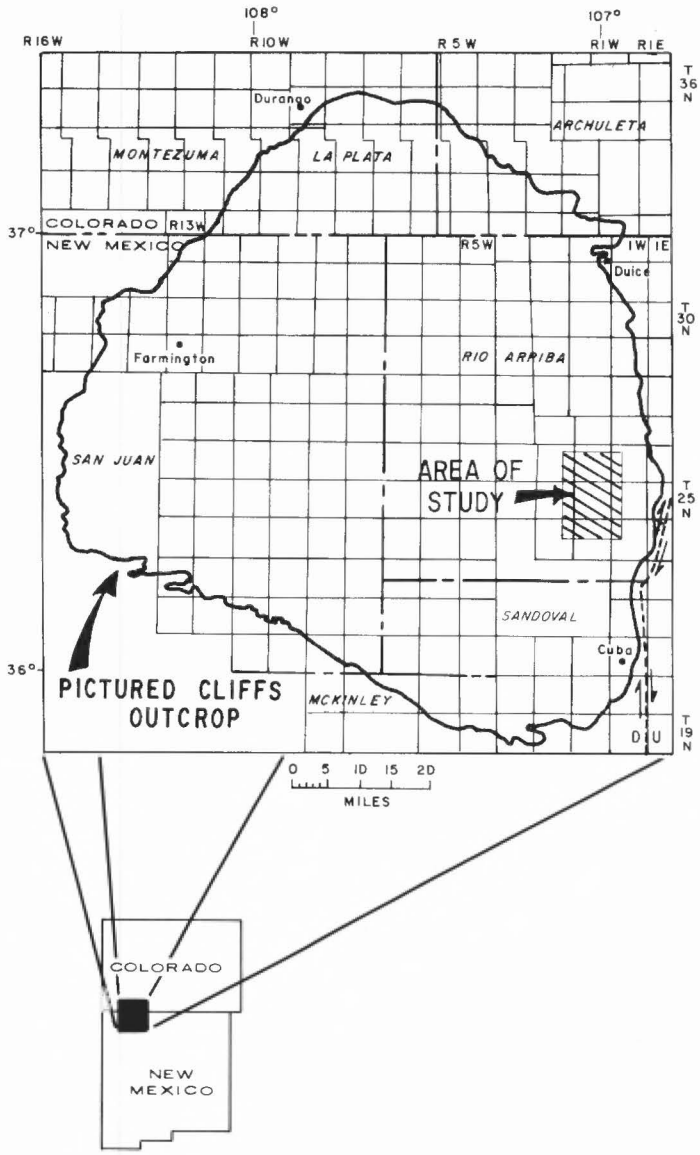


FIGURE 1. Location map of the San Juan Basin as defined by the Pictured Cliffs outcrop. The Gavilan Mancos Oil Pool lies within the area of study. The Nacimiento fault forms the southeastern edge of the basin.

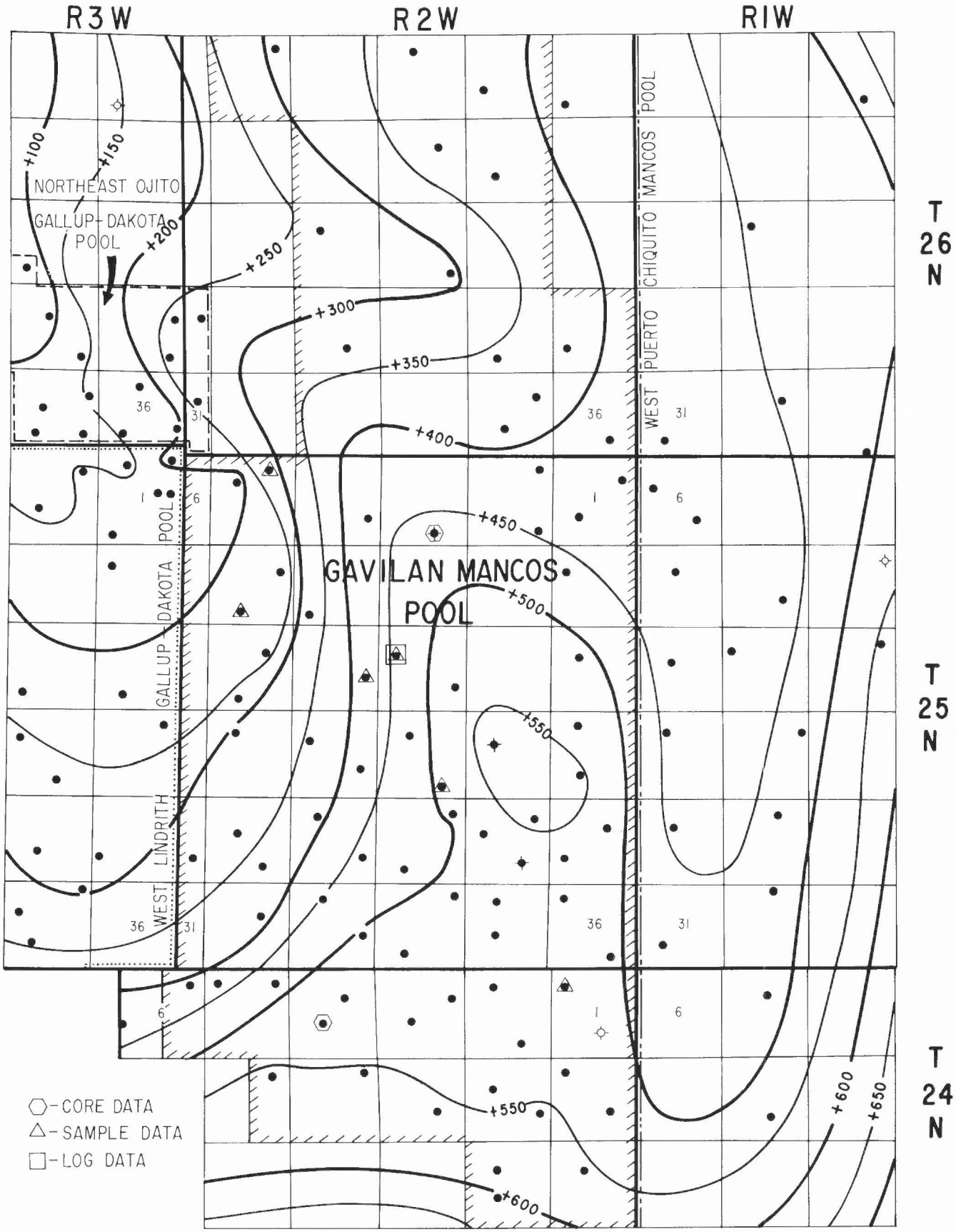


FIGURE 2. Structure map of the top of the Niobrara "A" zone within and surrounding the Gavilan Mancos Oil Pool. Contour interval is 50 ft. Only wells penetrating the Mancos Formation are shown. The wells that were examined utilizing thin section sample analysis, core examination and computer log analysis are highlighted.

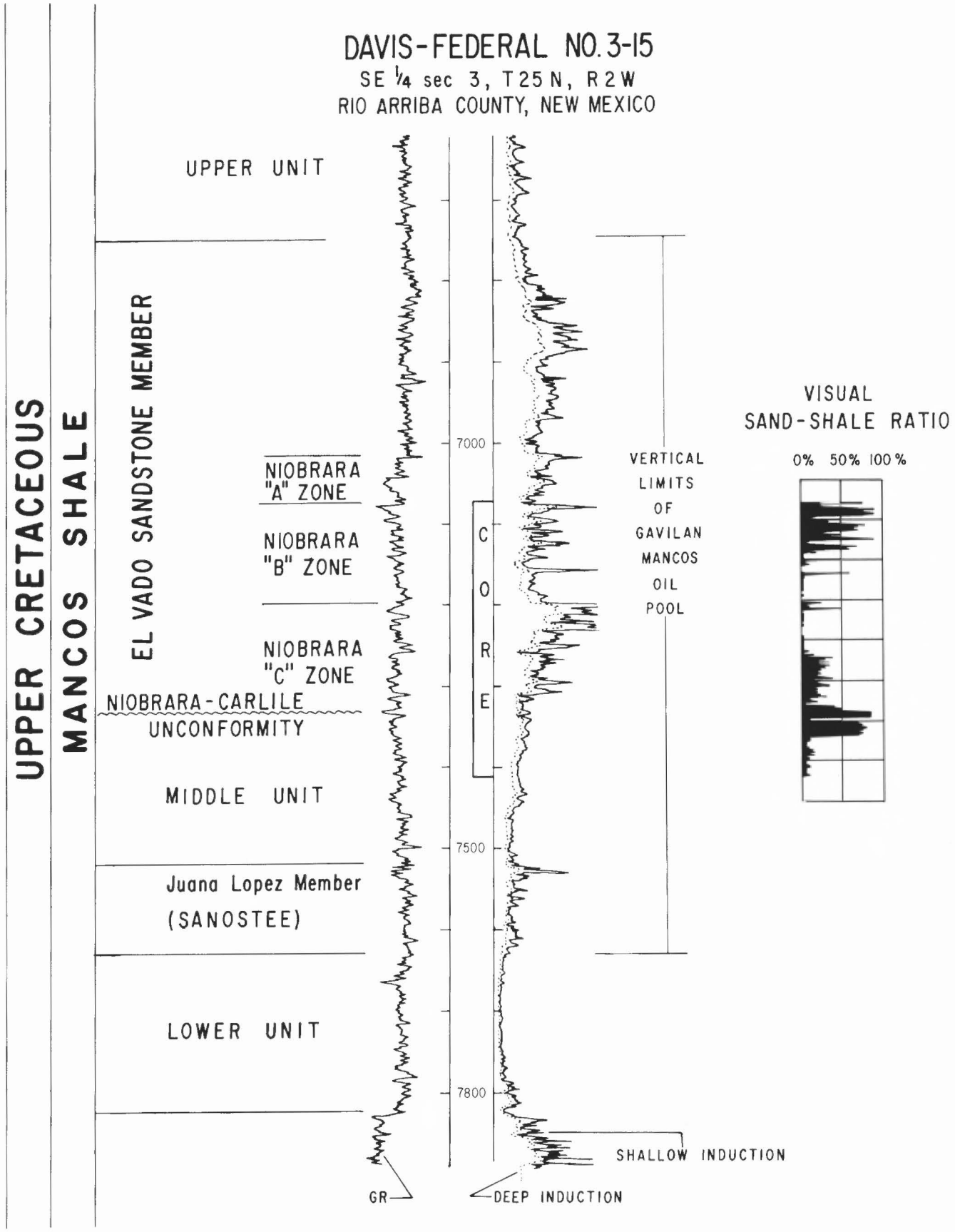


FIGURE 3. Gamma Ray-Induction log and stratigraphic nomenclature of the Mancos Formation in Mallon Oil's Davis-Federal #3-15. Also shown are the vertical limits of the Gavilan Mancos Oil Pool as defined by the New Mexico Oil and Gas Commission. On the right is the visual sand-shale ratio plot corresponding to the 338 ft of cored interval taken from the well.

Niobrara age, and the middle Mancos unit and the Juana Lopez Member, both of Carlile age. A complete discussion of the stratigraphic nomenclature of the Mancos was presented by Fassett and Jentgen (1978).

To date, the majority of fractured Mancos oil production on the eastern side of the basin is from the El Vado Sandstone unit. In the Gavilan Mancos Oil Pool and the surrounding pools, the El Vado has locally been divided into mappable units called the Niobrara A, B and C zones. The rocks consist of interbedded sandstones, siltstones, shales and marly shales. These zones are remarkably consistent in thickness and lithology over many miles, and wireline log signatures in offset wells can be very similar.

Fig. 3 documents the distribution of sandstone and shale within the rock column as recorded from visual examination of 338 ft of core taken from the Davis-Federal #3-15 (SE¼ sec. 3, T25N, R2W). Sandstones are prominent in the Niobrara A and B zones (Fig. 4), which are the intervals that are most commonly productive in the Gavilan Mancos Oil Pool. The Niobrara C zone is a highly bioturbated shale section, which may also contain thin, discontinuous sandstone stringers that characteristically display high resistivity readings on wireline logs. The middle Mancos unit is predominately black shale with thin interbedded sandstones and siltstones. Separating the El Vado Sandstone from the middle Mancos unit is the Carlile-Niobrara unconformity, which reflects uplift of the northeast portion of the San Juan Basin (Fassett and Jentgen, 1978). This unconformity is represented by a sharp contact in the Mallon well at a core depth of 7344 ft (Fig. 5). Identifying this unconformity on wireline logs can prove difficult due to the shaly nature of the middle Mancos, but has been observed to thin approximately 20 ft over the 6 mi distance represented by the north-south boundaries of T25N, R2W.

The matrix rock within the fractured intervals is characteristically of low porosity and permeability. Extensive testing utilizing standard perm-plug analysis was conducted separately on cores from two wells in the field located 6 mi apart (Fig. 2). Sixty-two samples taken from the core of the El Vado Sandstone and middle Mancos units in Mallon's Davis-Federal #3-15 well yielded an average porosity of 2.14%. Porosity data measured from Mobil's Lindrith B Unit #38 well (SW¼ sec. 4, T24N, R2W) averaged 1.59% from 65 samples taken from the cored interval in the El Vado Sandstone. In both wells the permeability readings from these samples were around 0.1 md. Core compressibility tests conducted on samples from the Mallon well demonstrated that the matrix, although low in porosity and permeability, was capable of production when connected to a natural fracture system. Hueni et al. (1990) discussed in detail the tight but productive nature of the matrix and described the logic behind the characterization of the Gavilan Mancos Oil Pool as producing from a dual-porosity system.

Structure

Commercial hydrocarbon production in the Gavilan Mancos Oil Pool is a result of the concentration of natural fractures within the Mancos Formation caused by the formation of the Gavilan dome. The Gavilan dome is a northwest-trending anticline centered in T25N, R2W (Fig. 2). This structure is evident at all regional mapping horizons (Baltz, 1967; Bowman, 1983) down to and including the Dakota Formation, the present common drilling horizon, at a depth of more than 8000 ft. Fig. 2 demonstrates that over 60 ft of closure exists at Niobrara A zone depth in the central portion of the field.

Formation of the Gavilan dome occurred during the Eocene tectonism responsible for the present structural configuration of the San Juan Basin. The eastern boundary of the structural basin is the north-trending



FIGURE 4. Core photograph of interbedded sandstones and shales in the Niobrara "B" zone from the Davis-Federal #3-15 well. Numerous fractures can be seen, including parallel fractures spaced approximately two inches apart at the core depth marked 7096 ft. The 4-inch-diameter core is marked at foot intervals as measured from the drilling depth below the kelly bushing. Top of core is at upper right of photo.



FIGURE 5. Core photograph of the unconformity between the El Vado Sandstone Member and middle unit of the Mancos Formation in the Davis-Federal #3-15 well. The unconformity can be seen at the sharp contact present at a core depth of 7344 ft. The base of the El Vado is a zone of highly bioturbated coarse-grained glauconitic sandstone 4 ft thick. The middle unit of the Mancos consists of interbedded fine-grained sandstones and black shales. Note the concretion at a core depth of 7349 ft. The 4-inch-diameter core is marked at foot intervals as measured from the drilling depth below the kelly bushing. Top of core is at upper right of photo.

Nacimiento fault. Work by Baltz (1967), consisting of both field mapping and modeling of the Tertiary sedimentation and tectonics on the eastern side of the basin, showed evidence of sufficient right-lateral transcurrent movement along the Nacimiento Fault to produce a series of northwest-trending anticlines and synclines.

Fracturing of the rock column in the Gavilan Mancos Oil Pool developed as a result of the shear deformation associated with the formation of Gavilan dome. Methods used for detection of these natural fractures include wireline fracture identification logs, core data, well cuttings, drilling characteristics and reservoir performance. Harris et al. (1960) and other workers, utilizing field studies from around the world, have shown that both fracture orientation and concentration are related to structural position, and that variation in trend and concentration of the dominant fracture sets reflects local irregularities in the fold structure. A second-derivative interpretation of structure at the level of fracture study duplicates the areas of maximum curvature and deformation and can be used for exploration (Harris, 1991). Surface exposures on the eastern side of the San Juan Basin show local variation in fracture concentrations. At reservoir level, second-derivative maps of the Gavilan Mancos Oil Pool (Emmendorfer, unpubl. testimony in New Mexico Oil Conservation Case Nos. 7980, 8946, 8950, 9113 and 9114, March 1987; and Hueni et al., 1990), tend to confirm the relationship between high productive rates and areas of maximum structural curvature. Application of this second-derivative technique has also recently proven effective in coal seam gas exploration in the San Juan Basin (McBane and Mavor, 1989).

Mineralogy

The matrix portion of the Gavilan Mancos Oil Pool reservoir consists of interbedded sandstones, siltstones, shales and marly shales. Table 1 illustrates the bulk mineralogy, as analyzed by x-ray diffraction, for six core samples taken from the Davis-Federal #3-15 well (Terra Tek Core Services, unpubl. report, 1986). Mineralogy is consistent with values reported by London (1972) and Cole (1989) for Mancos Formation samples from other boreholes on the eastern side of the basin.

Carbonate minerals, principally calcite and ankerite, are the predominant cementing material in the sandstone and siltstone intervals. Drill cutting analysis from several wells in the Gavilan Mancos Oil Pool (Fig. 2) reveals that the percentage of calcite versus dolomite cement within the sandstones can vary both vertically within the wellbore and

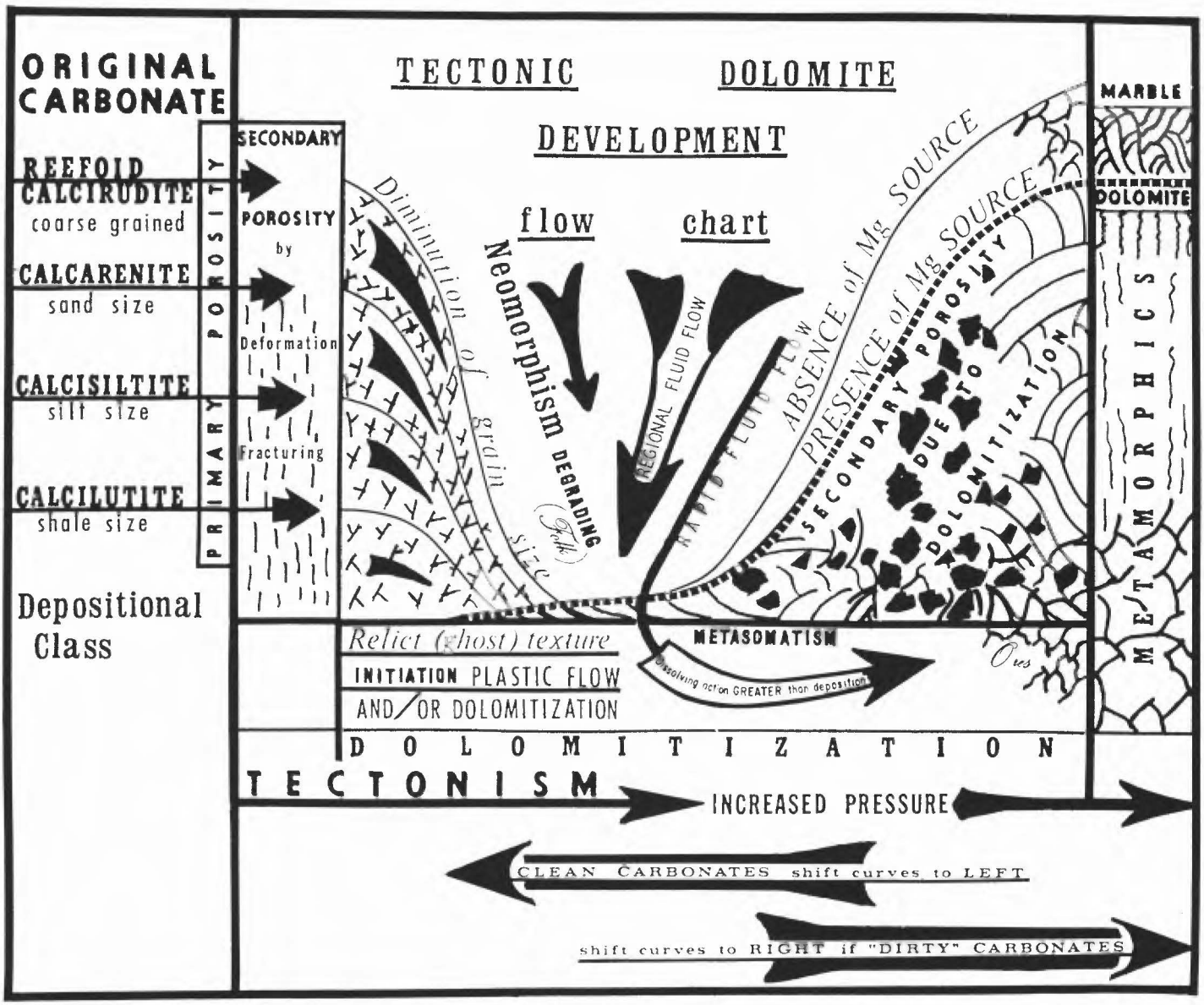


FIGURE 6. Flow chart showing tectonic influence on fabric alteration and ultimate result of metasomatic replacement or nonreplacement of original sediment types (after Harris, 1991).

TABLE 1. Bulk mineralogy as determined by x-ray analysis of six samples taken from representative intervals of the Davis-Federal #3-15 well (modified from Terra Tek, unpubl. report, 1986).

Core Depth (ft.)	7109.02	7167	7209.7	7294.8	7273	7341.8
Quartz	36	23	29	41	42	52
Plagioclase	7	5	6	5	9	7
K-Feldspars	2		1		1	1
Calcite	26	49	42	25	16	14
Dolomite	9	5	7	8	10	4
Ankerite		3	3	3	2	8
Pyrite	3	3	2	3	4	2
Mixed Layer						
Illite-Smectite	7	5	4	6	6	6
Illite	5	5	4	6	7	5
Chlorite	1	1	1	1	1	1
Kaolin	2		1	2	2	

horizontally from well to well. Variations in carbonate cements of the sandstone of the Mancos Formation have also been reported in similar studies by London (1972) and Cole et al. (1989).

London (1972) used x-ray analysis of drill cuttings and sidewall cores from the West Puerto Chiquito Pool, and noted that the productive wells contained a higher dolomite to calcite cement ratio than the nonproductive wells that contained predominantly calcite-cemented sandstones. From this, he concluded that the rocks with a higher dolomite content were selectively fractured due to the difference in the brittleness of calcite and dolomite. However, thin section analysis of drill cuttings from the Gavilan Mancos Oil Pool suggests that the ankerite within the rock column is a result of structural influences and was preceded by tectonic fracturing (Emmendorfer, 1989). This process is known as tectonic dolomitization.

TECTONIC DOLOMITIZATION

Tectonic dolomite is a term given to rocks that have undergone metasomatic replacement of calcite by dolomite due to structural influences. Similarities between tectonic dolomite deposits and areas of intense fracturing related to structural curvature have been documented by field and subsurface study (Harris, 1966, 1991).

Fig. 6 outlines the process leading to tectonic dolomitization. Under tectonic stress, the original rock is fractured and then undergoes a sequence of diminution of grain size accompanied by dilatancy. If a magnesium source is available, the metasomatic replacement of calcite by dolomite occurs. This sequence of events can be observed both in outcrop (Fig. 7) and in the subsurface by careful sample examination.

In the past, most recognized tectonic dolomites have been associated with carbonate rocks, with many of the examples from prolific oil productive zones and fields. The Garrard Formation, a calcite-cemented siltstone in central Kentucky, is locally dolomitized and was shown to be associated with other tectonic dolomites by Black et al. (1981). More examples of tectonically dolomitized sandstones, siltstones and shales are being recognized in producing fields of the Midcontinent region (John F. Harris, personal comm. 1991). Evidence from the Gavilan Mancos Oil Pool, stemming from sample examination and petrographic analysis, suggests that tectonic dolomitization associated with the fracturing of the rock column is the result of structural formation of the Gavilan dome (Emmendorfer, 1989).

DISCUSSION

As noted by London (1972), there is a relationship between fracturing and dolomite content of the rock column in the Mancos Formation. Thin sections from the Davis-Federal #3-15 core (Fig. 3) contain two types of dolomite occurrences. In the sandstone intervals a small amount of detrital dolomite grains are found. These detrital grains are iron-free but contain overgrowths of ankerite resulting in a rhombic form. The most abundant type of dolomite in the rock is ankerite, consisting of cement material in the sandstone and siltstone intervals and as individual ankerite crystals found predominately in the marly shale sections. As previously mentioned, the ankeritic dolomite found in the Mancos on

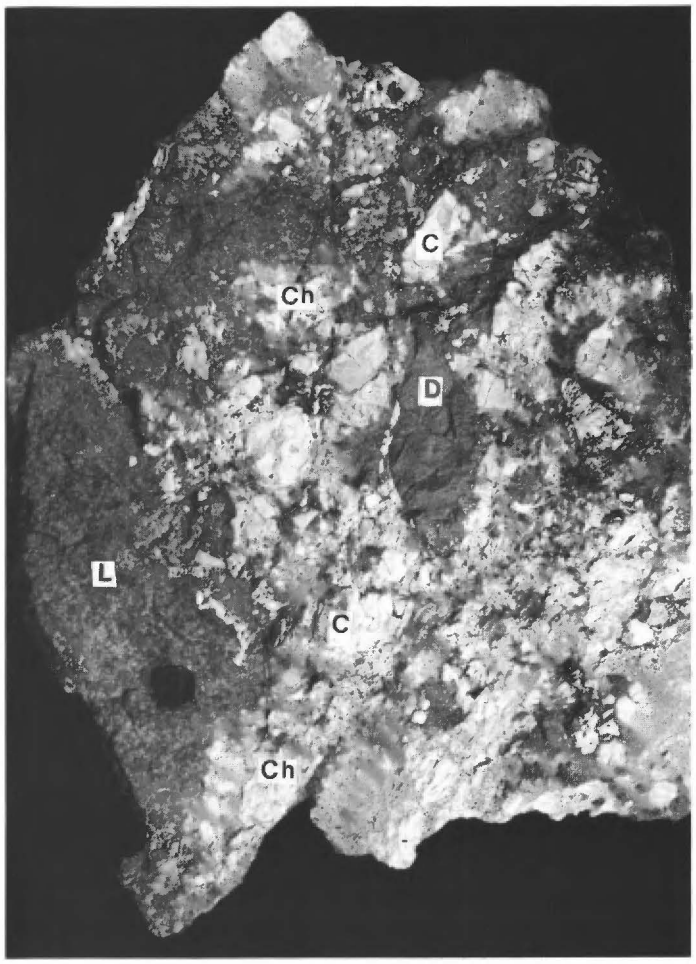


FIGURE 7. Example of the stages of tectonic dolomitization as seen from a slab collected from a roadcut on I-44 of the Kimswick Limestone (Ordovician), 7.5 mi east of Springfield, Missouri. The original limestone (L) undergoes fracturing and reduction of grain size into a chalky limestone phase (Ch) before the metasomatic replacement of dolomite (D) takes place. The fact that the chert (C) within the transition area, containing both chalky limestone and partially dolomitized limestone, is fractured gives evidence that the chert was already in place before tectonic dolomitization occurred. The top of the photo is stratigraphically in the upward position. Note penny for scale.

the eastern side of the San Juan Basin is a direct result of the tectonic fracturing process, and is clearly documented from detailed sample and petrographic analysis of drill cuttings from the Gavilan Mancos Oil Pool.

Drill cuttings from six wells in the Gavilan Mancos Oil Pool were examined in detail and cuttings containing fracture traces were selected for thin sectioning and further analysis. Before thin sectioning, care was taken to orient the cuttings so that the fracture traces were normal to the plane of the glass slides.

From sample examination the progressive stages of tectonic dolomite alteration were directly observed. Drill cuttings in the fractured sandstone intervals showed the complete range of carbonate cements, progressing from calcite to chalky calcite to calcite-dolomite to ankeritic dolomite. Recognition of the chalky calcite cemented sandstone cuttings, representing the diminution of grain size stage of tectonic dolomitization, provided the subtle clue (Harris, 1970) necessary for the proper interpretation.

Thin section analysis of the cuttings exhibiting fracture traces provides further evidence of tectonic dolomitization of the rock column. The most dramatic evidence exists in the shale sections (Fig. 8A–C), where the boundaries of the dolomitized portion of the shale are quite distinct and often parallel the fracture surface of the cuttings. These

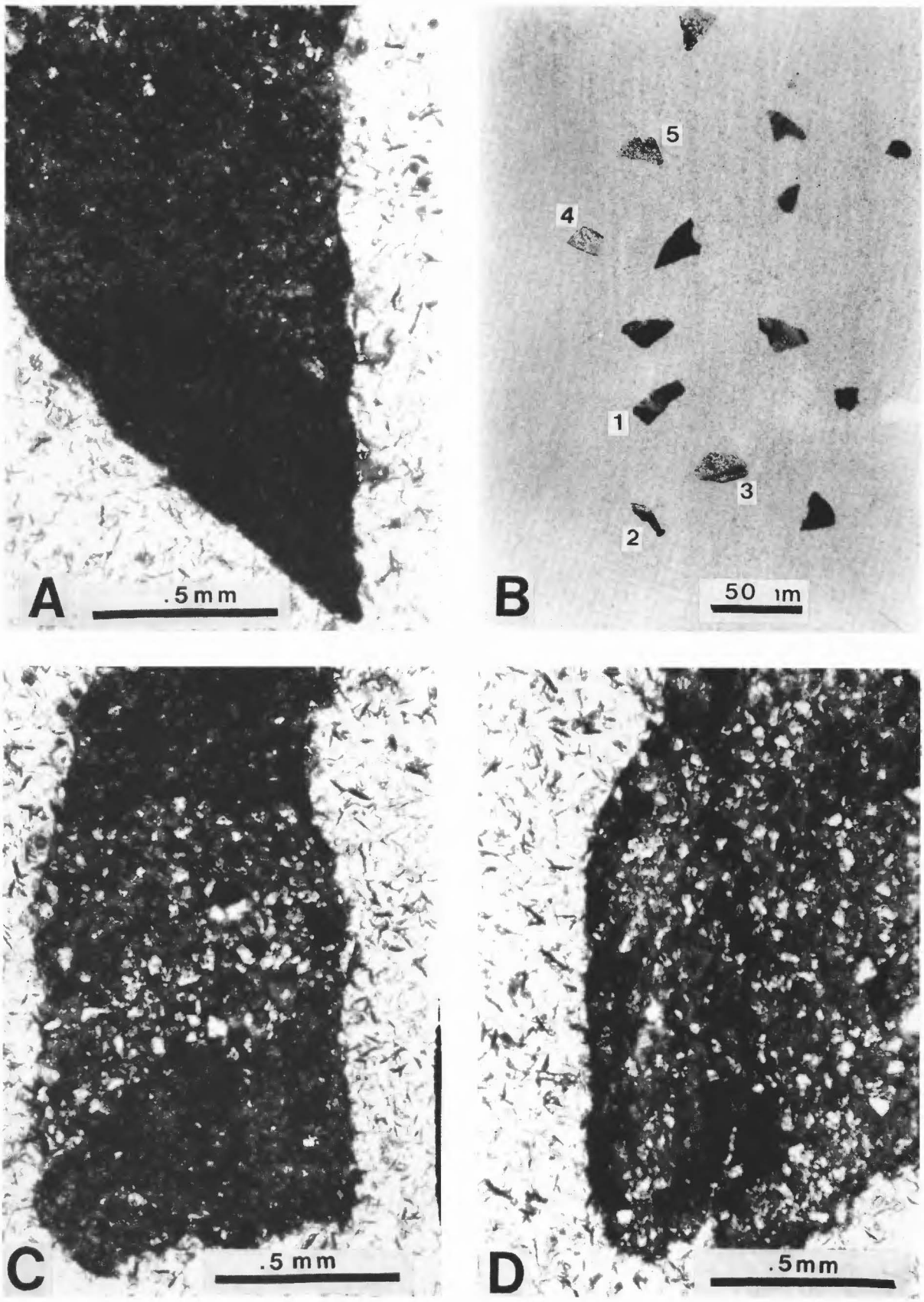


FIGURE 8. Photomicrographs showing evidence of tectonic dolomite in drill cuttings from the Gavilan Mancos Oil Pool. A. A distinct boundary exists between the calcareous shale and the dolomitized shale section. The boundary parallels the fracture edge of the cutting (plane polarized light). B. Drill cuttings displaying multiple fracture sets (plane polarized light) and dolomitized shale sections (1, 2) and sulfide mineralization along fracture trends (3, 4, 5). C. Close-up of shale drill cutting (1) in (B), displaying sharp contact with the shale that has been dolomitized (plane polarized light). D. Close-up of sandstone drill cutting (3) in (B) with euhedral pyrite and marcasite crystals in fracture traces paralleling the two fracture sets that define the edges of cutting (refracted light).

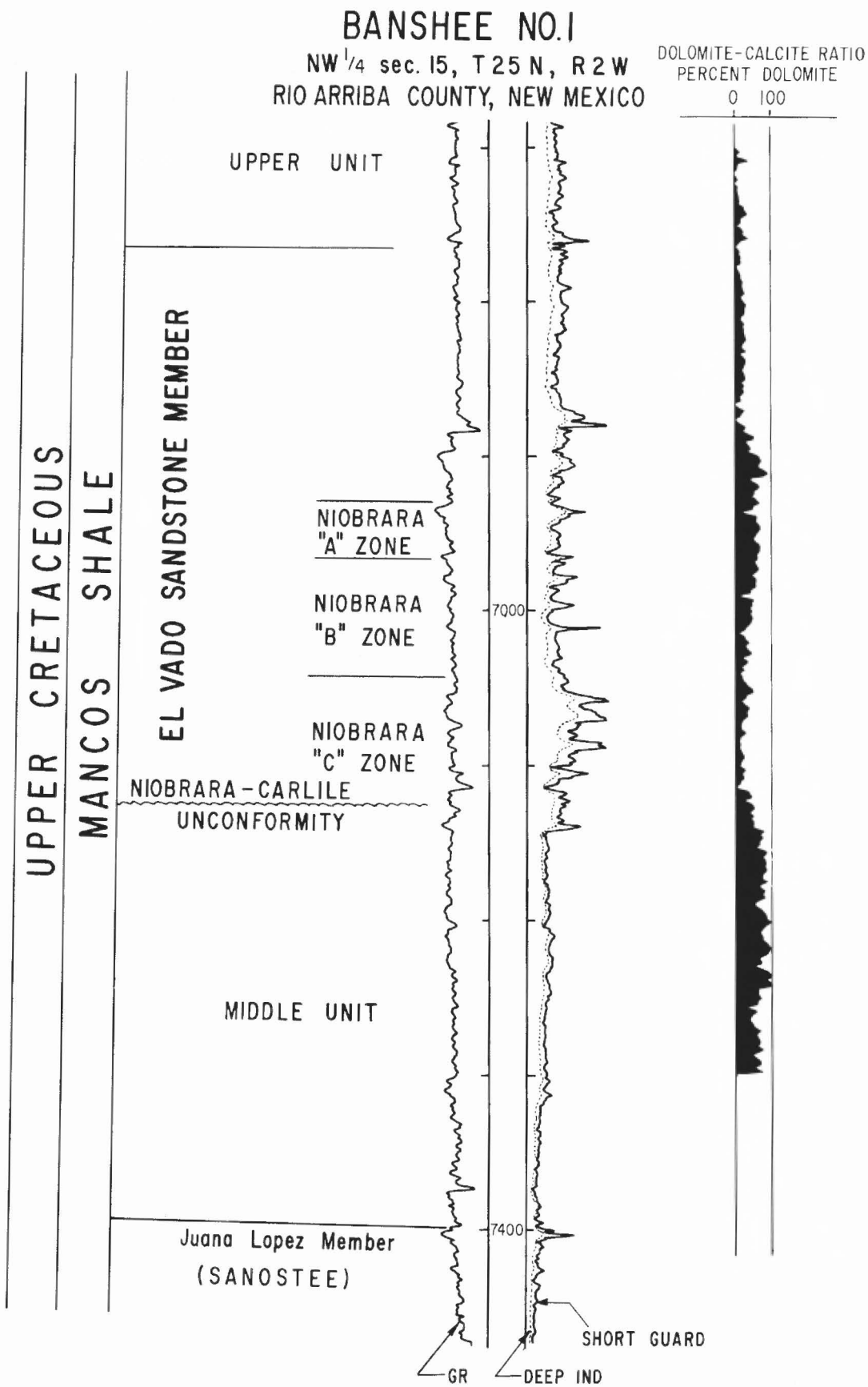


FIGURE 9. A portion of the Gamma Ray-Induction log through the Mancos interval of the Banshee No. 1 well. Also indicated is the dolomite-calcite ratio for this portion of the well as determined from computer-generated, three-mineral cross plots of the bulk density and neutron curves from the Spectral DSNII log. Compare stratigraphy and log responses with the Davis-Federal #3-15 well in Fig. 3.

boundaries also change direction in angles consistent with theoretical shear angles (Moody and Hill, 1956).

During the tectonic dolomitization process, sulfide mineralization accompanied the metasomatic replacement of calcite by dolomite. Euhedral crystals of pyrite and marcasite formed adjacent to fracture planes and in the matrix near the intersection of multiple fracture sets (Fig. 8B, D).

Although London (1972) utilized x-ray diffraction techniques to correlate zones of fracturing to high dolomite content, computerized wireline log analysis may prove to be a more practical exploratory tool in narrowing the search for fractured intervals in wellbores where tectonic dolomite is common with fracture production. Fig. 9 is the Induction-Electric log for the Banshee #1 (NW¼ sec. 15, T25N, R2W) and a graph showing the ratio of calcite to dolomite as determined utilizing wireline log crossplot analysis. High dolomite content is present in the Niobrara A and B zones (historically the interval of major production in the Gavilan Mancos Oil Pool), in the lower portion of the Niobrara C zone and in the middle unit of the Mancos shale. Drill cuttings from the lower interval include large volumes of dolomitized black shale showing the evidence of fracturing. In addition, major drilling problems, typical of fractured intervals, were encountered between 7150 ft and 7250 ft.

CONCLUSIONS

The Mancos Formation of the San Juan Basin is characteristically of low porosity and permeability. Commercial oil production has been established in fractured reservoirs that are found in a favorable structural position on the eastern side of the basin. Production from the Gavilan Mancos Oil Pool, a dual-porosity reservoir, is the result of the concentration of natural fractures on the Gavilan dome within the calcareous sandstones, siltstones and shales of the Mancos Formation.

Natural fractures were formed from shear deformation associated with the formation of the Gavilan dome. The fractures originally formed preferentially in the carbonate-cemented sandstones and siltstones, and calcareous shales in the Mancos Formation. As a result of the fracturing process, portions of the rock column were tectonically dolomitized. A portion of the carbonate component of the matrix was metasomatically replaced by ankerite. As a result, both calcite and ankerite are found in varying amounts both in the sandstones and in the shales.

The varying stages leading to tectonic dolomitization have been personally observed by the author utilizing standard drill cutting evaluation. Thin section analysis of the drill cuttings from wells in the Gavilan Mancos Oil Pool graphically illustrate the relationship between the dolomite content of the rock and the fractures. In addition, sulfide mineralization, principally pyrite and marcasite, are also structurally controlled by the fracturing process, thereby giving additional evidence of tectonic dolomitization.

The relationship between fractures and dolomite content of the Mancos Formation was identified by London (1972) on the adjacent West Puerto Chiquito Mancos Pool. It was thought previously that the sandstones were dolomitized earlier and then preferentially fractured due to tectonic movement on the eastern side of the San Juan Basin. However, this study gives convincing evidence that the fracturing of the rock caused the formation of tectonic dolomite.

An understanding of the formation of fractured reservoirs is important when exploring for additional reserves in an area. The knowledge that tectonic dolomitization is the result of fracturing in the Gavilan Mancos Oil Pool and adjoining fields should lead to additional exploratory successes in the San Juan Basin. An additional exploratory tool, where sample examination is not practical, is the crossplotting of density-neutron wireline logs for identification of the dolomitic content of the rock. Identifying zones of high dolomite content may be useful in narrowing the search for fractured intervals.

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