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**Acid-Insoluble Residue/Carbonate Content of the Upper Cretaceous Niobrara
Formation, Berthoud Field, Denver basin, Colorado--A Key Factor for
Understanding Natural Fracturing in Chalks?**

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Acid-insoluble residue/carbonate content of the Upper Cretaceous Niobrara Formation, Berthoud field, Denver basin, Colorado--A key factor in understanding natural fracturing in chalks?

Abstract

The acid-insoluble residue content and corresponding acid-soluble carbonate content of 148 samples from core representing the entire section of the Niobrara Formation was studied in the Berthoud State No. 3 well, Berthoud field, Larimer County, Colorado. The Smoky Hill Chalk Member is comprised of mostly impure chalks that, on average, contain about 30 wt % insoluble residue; basal Smoky Hill Chalk, however, contains purer chalk beds. The Fort Hays Limestone Member contains the purest chalk beds, some containing as little as 5 wt % insoluble residue. The data suggest that natural fracturing in the Berthoud State 3 well is related to basic bulk composition; contrast in bed composition and thickness of interbedded chalk and shale beds may be important in understanding natural fracturing within the Niobrara Formation.

Acid-insoluble residue and carbonate contents of the Niobrara Formation in the Berthoud State 3 well identify cyclic variations that correspond to large- and small-scale alternations of chalk and shale. Large-scale cyclicity that produced the major chalk and shale zones in the Niobrara Formation is related to second-order eustatic changes within an overall major transgressive event. Similar large-scale cyclicity of organic matter content in a nearby well generally correlates with insoluble residue content. Smaller third-order cyclicity of beds, superimposed on the large-scale cycles, is related to climatic changes due to Milankovich-type variations in the earth's orbital patterns.

Five natural fracture zones, four relatively minor in intensity, are identified in core of the Berthoud State 3 well. Each of the fracture zones occurs in the upper half of a thick chalk unit that is immediately overlain by a thick shale and each corresponds to the second order eustatic changes that define the main lithologic units of the Niobrara Formation. Fractures do not extend much into overlying shale sequences.

The major and most intense zone of fracturing, showing evidence for extensive solution, fluid movement, displacement, and related deformation, occurs in the lower midportion of the formation. This 35-40 ft interval, informally referred to as fracture zone 3, contains several beds of chalk with relatively low (<20 wt %) acid-insoluble content interbedded with shale having high (>50 wt %) acid insoluble content. The second-order cycle curve for the Niobrara, as defined by the data, is shortened (thinner units) within this interval. This interval of major fracturing is also characterized by high resistivity. Fracture zone 3 is bounded by two large spikes on the gamma log at about 3,060 ft and 3,140 ft. Fracture zone 3, however, corresponds to a cyclic low in the organic matter profile for the nearby Berthoud State 4 well.

The occurrence of natural fractures in Niobrara strata of the Berthoud State 3 well appear to be related to composition, as defined by acid-insoluble residue and carbonate contents, and correspond to intervals where strata have insoluble residue content in excess of 50 wt %, and where composition differences among the alternating strata over the interval approach 50 wt %. These differences or contrast in bulk composition, as defined basically by insoluble residue and carbonate contents, probably produce differences in thermal and mechanical behavior of interbedded units during deep burial and stress that result in fractures; open, tensile fractures that are formed in extremely tight, deeply-buried, organic-rich chalks can create the porosity and permeability necessary for economic oil production.

Introduction

Since the mid 1970's, the Upper Cretaceous Niobrara Formation in the Denver basin and adjacent areas has been a major hydrocarbon play in the Rocky Mountain region. Although much of the activity in hydrocarbon exploration and development has subsided substantially within the Rockies since the mid 1980's, the development and success of horizontal drilling in the Upper Cretaceous Austin Chalk and Devonian-Mississippian Bakken Shale plays have generated a renewed interest in understanding fractured oil reservoirs in chalks and chalky shales of the Niobrara Formation. In response to this renewed interest and activity with respect to horizontal drilling technology, there has been a recent

surge of geologic and engineering studies, workshops, and short courses by commercial and academic groups to better understand the cause, timing, and patterns of fracturing within the Niobrara Formation relative to oil generation.

The bulk composition of sedimentary rocks has a critical affect on physical and chemical properties during progressive burial. In particular, numerous studies have shown that chalks and shales undergo considerable physical and chemical (diagenetic) changes during progressive burial (Hower and others, 1976; Hower, 1981; Neugebauer, 1973; 1974; Schlanger and Douglas, 1974; Scholle, 1977a, b; Pollastro and Scholle, 1986a, b). The amount and composition of acid insoluble residues and related organic matter from the Niobrara Formation has been described in several reports (Arthur and others, 1985; Scholle, 1977a, b; Pollastro, 1981; Pollastro and Scholle, 1986; Pollastro and Martinez, 1985a, b; Precht and Pollastro, 1985). No studies, however, have described the composition of the entire Niobrara Formation in detail from a fractured, oil-producing reservoir.

The insoluble residue in the Niobrara Formation of the Denver basin consists mainly of clay minerals, quartz, organic matter, pyrite, and some feldspar (Scholle, 1977b; Pollastro, 1981; Pollastro and Martinez, 1985a, b; Pollastro and Scholle, 1986; Precht and Pollastro, 1985). The clay minerals are mainly mixed-layer illite/smectite, discrete illite, and kaolinite (Pollastro, 1981, 1985; Pollastro and Scholle, 1986). In the Berthoud State 3 well, all I/S clay is of the ordered variety with an average illite/smectite ratio of 70/30 (Pollastro and Scholle, 1986). Organic matter content in thermally mature Niobrara beds commonly ranges from about 0.5 to 5.0 wt % (Pollastro and Martinez, 1985a,b; Precht and Pollastro, 1985; Dean and Arthur, 1989).

Although much is known about the composition of insoluble residues and the relation of insoluble residue content to porosity, permeability, compaction, and solution of chalks (Schlanger and Douglas, 1974; Arthur, 1979; Arthur and others, 1984; Pollastro and Martinez, 1985a; Pollastro and Scholle, 1986), little is known about the relations between composition and fracturing in oil producing, chalk reservoirs. The Niobrara Formation consists of cyclic beds of chalk and chalky shale of variable composition and thickness. The plastic, mechanical, and thermal properties of rocks are important for understanding fracturing. Since differences in bulk composition directly affect the mechanical and thermal properties of rocks, it is likely that bulk composition is an important factor in controlling fracturing within the cyclic-bedded Niobrara Formation.

It is the purpose of this report to provide a better understanding of the relation between fracturing and composition in the Niobrara Formation by documenting a detailed, vertical profile of the basic bulk composition--the acid insoluble residue and carbonate contents--of the Niobrara Formation from a known oil-producing, fractured reservoir in the Berthoud field, western Denver basin.

Methodology

152 samples of chalk, shaley chalk, and calcareous shale were taken from core of the Coquina Oil Corporation, Berthoud State No. 3 well (sec. 16, T.4N, R.69W), Berthoud field, Larimer County, Colorado (figure 1). The core included a virtually complete, but thin (about 290 ft), section of the Niobrara Formation from an area once covered by overburden estimated at about 10,000 ft (Scholle and Pollastro, 1985; Crysedale and Barker, 1990; Elliott and others, 1991). The core was recovered at depths ranging from about 2,900 to 3,210 ft and included the entire Niobrara Formation (Smoky Hill Chalk and Fort Hays Limestone members), a small portion of the lowermost Upper Cretaceous Pierre Shale, and about 5 feet of the uppermost Cretaceous Codell Sandstone Member of the Carlile Shale (figure 2). Three samples (2911.0; 2914.4; 2917.4; table 1) were taken from the lowermost Pierre Shale and one sample (3211.5) from the Codell Sandstone; the remaining 148 samples at intermediate depths were of the Niobrara Formation. Numerous bentonite beds were also found throughout the Berthoud State 3 core. Although the Niobrara had good oil shows in the Berthoud State 3 well, production in the well is from the Cretaceous Dakota and Permian Lyons Formations. A similar section of core from the Niobrara Formation was also taken from the nearby Coquina Oil Corporation, Berthoud State No. 4 well (sec.16, T.4N, R.69W, Larimer County, Colorado), which produces from the Niobrara Formation. Organic carbon data from the Berthoud State 4 well published by Dean and Arthur (1989) are also used to supplement data from this report.

Samples were taken to include any visible heterogeneity and homogeneity that may relate to composition and (or) lithology. Samples were washed and scrubbed to remove surficial contaminants, dried, and then ground to <35 mesh. Each sample was then split into 10 g portions using a Jones-type splitter.

Carbonate was dissolved in 1N HCl and the residue filtered and washed immediately after effervescence stopped, so as to minimize the solution of noncarbonate minerals (Pollastro, 1977). The insoluble residue was dried overnight at 65 °C; the weight percent (wt %) of the residue was then determined. A small portion of the residue was spot-checked for undissolved carbonate with 6N HCl.

Lithology and fractures were logged by visual inspection of core from the Berthoud State 3 well and correlated to insoluble residue/carbonate analyses and geophysical log profiles. In addition, data on total organic matter content (TOC) reported by Dean and Arthur (1989) and Pratt and others (in press) from the Berthoud State 4 well is used in this report to relate rock composition to oil generation, fracturing, and lithology of the Niobrara Formation in the Berthoud field. However, the Niobrara Formation in the Berthoud State 4 well occurs at slightly shallower depths (about 30 ft) than in the Berthoud State 3 well. TOC plotted in figure 2 was, therefore, correlated to Pierre Shale and Carlile Shale formation boundaries.

Results and Interpretation

Lithology and stratigraphy

Figure 2 shows the gamma-ray and resistivity logs from the Berthoud State 3 well correlated to the point-to-point log and area graph of insoluble residue and carbonate. Location of fractures in core, formation and member boundaries, interpreted lithologies for the Niobrara Formation, and the TOC data from the nearby Berthoud State 4 well (Dean and Arthur, 1989; Pratt and others, in press) is also shown. The Niobrara Formation is about 290 ft thick in the Berthoud State No. 3 well. Measured sections of outcrop reported by Hann (1981) indicate that the Niobrara Formation is up to 370 ft thick northwest of Fort Collins, Colorado, about four townships north of the Berthoud field (figure 1).

Lithologic and member and formation boundaries of figure 2 differ from those reported by Scholle and Pollastro (1985) for the Berthoud State 3 well. The interpretations from logs and core of the Berthoud State 3 well reported by Scholle and Pollastro (1985) are incorrect when compared to the interpretations of the same core and logs in this study; those shown in figure 2 represent more accurate log-to-core interpretations, particularly for the Smoky Hill/Fort Hays and Fort Hays/Codell boundaries. The Fort Hays Limestone is about 18-20 ft thick in the Berthoud State 3 well and occurs at depths between about 3,190 to 3,210 ft (figure 2). This thickness is in agreement with isopach maps of the Fort Hays Limestone published by Laferriere and Hattin (1989).

Fractures and related features

Natural fractures and fault-related features are found in several zones of the Berthoud State 3 core and within the Niobrara Formation; however, only one interval contains major and open fractures, evidence for extensive solution and fluid movement, and some displacement. Five natural fracture zones are identified on the basis of core examination in the Berthoud State 3 well. These five fracture zones are located and numbered progressively with increasing depth in figures 2, 4, and 5.

Vertical, inclined, and nearly horizontal natural fractures occur in the core; many of the fractures are filled with calcite (figure 3). Fracture zones 1, 2, 4, & 5 are considered minor in intensity and contain fine (<1 mm wide), mainly vertical, calcite-filled fractures. The major zone of fracturing, defined here as zone 3 (figures 2, 4, 5), spans an interval about 35 ft and occurs between depths of about 3,070 to 3,105 ft. Zone 3 occurs in the lower half of the "middle chalk and shale" interval within the Smoky Hill Chalk Member. Many of the fractures from this zone are open and are oil stained or contain residual bitumen (figure 3c). Extensive evidence for solution is indicated by floating clasts in calcite cement (figure 3a). Other deformation features include minor bed displacement (figure 3a), changes in bed orientation (figure 3b); and bed-parallel slickensides in shaley and bentonite beds. Some brecciation is evident within zone 3 from the Berthoud State 3 well but is better displayed in core

of the Berthoud State 4 well. Many fractures are also associated with stylolitic solution seams both parallel and perpendicular to bedding (figure 3b).

Composition

Acid insoluble residue/soluble carbonate contents

The result of insoluble residue/soluble carbonate analyses for the Berthoud State 3 well are given in table 1: a vertical distribution of the data is also presented graphically in the point-to-point logs and area graphs of figures 2, 4 and 5. Insoluble residue content of the Niobrara Formation ranges from about 5 to 95 wt %; corresponding carbonate content ranges from 95 to 5 wt %, respectively. The mean weight percent insoluble residue/carbonate ratio of the Smoky Hill Chalk Member of the Niobrara is about 70/30. Thus, the data demonstrate that most chalk beds of Smoky Hill Chalk Member are relatively impure. The purest chalk beds, i.e., chalk with the lowest insoluble residue content, are in the Fort Hays Limestone Member.

Cyclic variations in composition are found throughout the Niobrara Formation and on several scales. Although sampling of the core was biased relative to color, sedimentary structure, and lithology, among other criteria, the data suggest large- and small-scale cyclicity in carbonate and noncarbonate (mostly terrigenous) components. Note both large- (figure 4) and small-scale chalk/shale cycles within the Niobrara Formation; small-scale cycles are particularly evident in the lowest part of the Smoky Hill Chalk and throughout the Fort Hays Limestone (figures 2, 4, 5). Small scale cycles in basal Niobrara strata were described in outcrop by Hann (1981) and Arthur and others (1985), and in the Berthoud State 3 core by Scholle and Pollastro (1985). In particular, the Fort Hays Limestone contains numerous alternations of thicker (1-2 ft), light-colored, bioturbated, low acid-insoluble-residue chalk, with very thin (2-4 in), dark, wavy-laminated, shale beds (Scholle and Pollastro, 1985; Laferriere and Hattin, 1989). Dean and Arthur (1989) and Pratt and others (in press) found similar patterns of cyclicity in the Niobrara Formation from geochemical analyses of core samples from the nearby Berthoud State 4 well.

Large-scale cyclicity of chalk/shale and chalk/marl is particularly evident in the Smoky Hill Chalk Member as shown from the geophysical logs and insoluble residue/carbonate data (figures 2 and 4). Large-scale cycles of alternating chalk and shale are outlined by the dashed curve in figure 4. These large-scale cycles represent second order eustatic changes superimposed upon the overall major transgressive event represented by Niobrara time (Kauffman, 1977). The large-scale, second order eustatic cycles can be further divided into smaller, third order cycles of chalk and shale, shown superimposed on the large scale cycles that are represented by the dashed curve of figure 4. These third order cycles represent changes in climate induced by Milankovich-type variations in the earth's orbitals (Arthur and others, 1985; Fischer and others, 1985; Dean and Arthur, 1989).

Organic matter content

TOC from the nearby Berthoud State 4 well, as reported by Dean and Arthur (1989) and Pratt and others (in press), is also shown in figure 2. Because faulting may occur in the Berthoud State 3 and 4 wells, and the TOC data are derived from core of the Berthoud State 4 wells, correlation of the data between wells is somewhat speculative.

TOC for the Niobrara Formation in the Berthoud State 4 well ranges from 0.5 to 5.7 wt % (Dean and Arthur, 1989) and shows a distinct cyclic pattern throughout Niobrara deposition. These cyclic variations in TOC are also attributed to second order eustatic changes and Milankovitch cyclicity (Arthur and others 1985; Dean and Arthur, 1989). In general, high concentrations of organic matter correlate to intervals of high acid-insoluble residue in figure 2. The lowest TOC in the Berthoud State 4 well is in the purer, bioturbated chalk beds of the Fort Hays Limestone and lowermost Smoky Hill Chalk in the Berthoud State 3 well. Similar relations in TOC and basal Niobrara Formation are shown by Arthur and others (1985; figure 6) in data from the Ideal Cement Quarry, Larimer County, Colorado.

Relation of composition to fracturing

There are some consistent relations between fracture occurrence and composition (as related to lithology) in the Berthoud State 3 well. All fracture zones in the Niobrara occur near the top of thick, second-order-cycle chinks and immediately below thick, second-order-cycle shales. The upper extent of fracturing appears to be limited by overlying shales. These areas are located by the large arrows opposite each of the fracture zones in figure 4. Zones of fracturing correspond closely to specific portions of the dashed "second-order-cycle curve" in figure 4. Fractures occur where the dashed cycle curve in figure 4 shifts toward lower insoluble content (higher carbonate content), as shown by the location of small arrows to the left of the curve.

The relation between fracturing and composition is also demonstrated in figure 5. When peak maxima are connected for both insoluble residue (bold line A) and carbonate (bold line B) contents in the log profile of figure 5, all but fracture zone 2 correspond to areas where differences in composition between chalk and shale beds is at or near maximum (about 50 wt %). In particular, fracture zone 3 (the major zone of fracturing) correlates with a long interval (about 40 ft) where maximum compositional difference between peak insoluble residue and peak carbonate contents is about 50 wt %. This major fracture zone also contains many alternations of thicker chalk and shale beds relative to beds in the other fracture zones. Fracture zones 1, 3, and 5, also occur where insoluble residue content of interbedded shale exceeds 50 wt % of the whole rock, as indicated where portions of the composition log cross the dashed 50 wt % line (figure 5). Thus, fracture zones in Niobrara strata of the Berthoud State 3 well are most common in upper half of a major chalk unit immediately below thick shale or marl zones, and in intervals where strata have 1) insoluble residue content in excess of 50 wt %, and 2) composition differences among the alternating strata over that interval approach about 50 wt %. Additionally, the major fracture zone (zone 3, figure 4) in the Berthoud State 3 well corresponds to an interval where several cycles of thicker chalk and shale beds have compositional difference near or at maximum, generally about 50 wt %. These relations suggest that bed thickness, and perhaps thickness of the interval containing beds with these characteristics, are important in promoting fracturing.

Composition and log response

High gamma ray intensity is correlated to zones of high insoluble residue and high organic matter content (figure 2). The total gamma ray reflects the sum of the response from potassium, uranium, and thorium. Spectral gamma logs, which separate these three components, have shown that potassium is commonly related to potassium feldspar and illitic clay minerals, whereas uranium is commonly related to organic matter and, sometimes, fractures (Fertl and others, 1982). Uranium is commonly precipitated from subsurface waters due to flow along highly permeable fractures (Fertl and others, 1980). Pollastro and Martinez (1985a) showed that there is a direct relation between TOC and insoluble residue content in the Niobrara Formation. This relation is also shown in figure 2 by the good correlation between insoluble residue content from the Berthoud State 3 well and organic matter content from the Berthoud State 4 well. Gamma ray intensity is particularly high in zones where both insoluble and organic contents are high. This is shown in the two shale or marl sections of the Smoky Hill Chalk (figure 2). The two gamma ray spikes at depths of about 3,060 ft and 3,140 ft, however, may reflect bentonite beds.

The microresistivity log is commonly used to identify fractures because it generally indicates fluid content; high resistivities often indicate oil-filled fractures. The resistivity log has also been used as an indicator of organic matter maturity within the Niobrara Formation (Smagala and others, 1984), Austin Chalk. (Hinds and Berg, 1990) and Woodford Shale (Schmoker and Hester, 1989). The major fracture zone in the Berthoud State 3 well occurs at the log resistivity maximum (figure 2); in this zone, resistivities exceed 100 ohm-meters. This zone is probably saturated with oil because many of the fractures in the core were oil stained or contain bitumen-like residues. Drilling reports also show high oil saturations within this interval. High resistivity elsewhere in the Berthoud State 3 well is inversely related to the gamma ray response and correspond to relatively purer chalk beds that correspond to second-order cycles. These purer chinks commonly have relatively higher porosity and permeability.

Although these chalks do not appear to be fractured, the relatively higher resistivities in these chalks may indicate oil-saturated matrix porosity. High resistivities do not necessarily correspond to high TOC (figure 2), however, the log-to-data comparison is for the Berthoud State 3 to Berthoud State 4 wells, respectively.

Brief Discussion

Mechanical behavior of the Niobrara Formation determined by the brittle-elastic, ductile, and thermal expansion properties of individual beds, and as expressed by fractures, can be related to basic bulk composition. Mechanical stratigraphy studies of the Austin Chalk have shown that high fracture intensity represents more brittle response in chalk units highest in carbonate and porosity (Corbett and others, 1987). Those units containing relatively less carbonate and porosity, described as chalk-marl in their study, are thus more ductile. Although the units studied by Corbett and others (1987) are purer and more massive than the chalk, marl, and shale beds that comprise the Niobrara Formation in the Berthoud field, similar relations between mechanical behavior and composition can be applied. Because less pure chalks contain higher insoluble residue content, and the insoluble residue of the Niobrara is comprised mostly of clay, mechanical behavior may be affected to a greater degree.

The extensive cyclicity and differences in bulk composition among chalk, marl, and shale beds in the Niobrara Formation may produce differences in mechanical behavior that result in fractures. Contrast in basic bed composition, expressed here as insoluble residue and carbonate contents, can directly affect the mechanical properties of the rock. The properties that are considered here are ductile, elastic (plastic), and thermal expansion. Differences in bed composition of chalk, marl, and shale may produce bed contrast in elasticity, ductility, and thermal expansion during stress that result in mechanical failure. The mechanical failure due to bed contrast can result in tensile fractures during bed bending and stretching (Meissner, 1991); tensile fractures are fractures that create porosity and permeability and are most favorable for oil production in deeply buried chalks.

The correspondence of fractures in core of the Berthoud State 3 well to 1) intervals where differences in bulk composition are greatest (~50 wt %) between chalk and shale, 2) intervals where insoluble residue content of beds exceeds 50 wt %, 3) intervals where there are multiple cycles of beds having characteristics of 1) and 2), and 4) alternating beds of chalk and shale are at a critical thickness, suggest that bed composition and bed contrast plays an important role in fracturing within the Niobrara Formation in the Berthoud field, Colorado, and may be an important consideration for understanding fractured chalk reservoirs.

Summary

Acid-insoluble residue and carbonate contents of the Niobrara Formation in the Berthoud State 3 well show cyclic variations that correspond to large- and small-scale alternations of chalk and shale. Large-scale cyclicity that produced the major chalk and shale zones in the Niobrara Formation is related to second-order eustatic changes within an overall major transgressive event. Smaller, third-order cyclicity is related to climatic changes due to Milankovich-type variations in the earth's orbit.

The Smoky Hill Chalk Member contains mostly impure chalks that, on average, contain about 30 wt % insoluble residue; basal Smoky Hill Chalk, however, contains purer chalk beds. The Fort Hays Limestone Member contains the purest chalk beds, some containing as little as 5 wt % insoluble residue.

Five natural fracture zones, four relatively minor in intensity, are identified in core of the Berthoud State 3 well. Each of the natural fracture zones occur in the upper half of a thick chalk unit that is immediately overlain by a thick shale. Fractures do not extend much into overlying shale sequences. The major and most intense zone of natural fracturing, showing evidence for extensive solution, fluid movement, displacement, and related deformation, occurs in the lower midportion of the formation. This 35-40 ft interval, informally referred to as fracture zone 3, contains several beds of chalk with relatively low (<20 wt %) acid-insoluble content interbedded with shale having high (>50 wt %) acid insoluble content. This interval is also characterized by high resistivity. Fracture zone 3 is bounded by

two large spikes on the gamma log at about 3,060 ft and 3,140 ft. Fracture zone 3, however, corresponds to a cyclic low in the organic matter profile for the Berthoud State 4 well.

Natural fractures in Niobrara strata of the Berthoud State 3 well appear to be related to composition, as defined by acid-insoluble residue/carbonate contents, and correspond to intervals where strata have insoluble residue content in excess of 50 wt %, and where composition differences among the alternating strata over the interval approach 50 wt %. These differences or contrast in bulk composition, as defined basically by insoluble residue and carbonate contents, probably produce differences in thermal and mechanical behavior of interbedded units that result in natural fractures during stress and deep burial.

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Figure Captions

- Figure 1.**--Map showing location of Berthoud field, Larimer County, Colorado and surrounding counties, states, major cities, and Front Range uplift (granitic pattern).
- Figure 2.**--Gamma-ray and resistivity logs, acid-insoluble residue and carbonate content, number and location of fractured intervals, and lithology and stratigraphy of the Coquina Oil Corporation, Berthoud State No. 3 well. Total organic matter data is from core of the nearby Coquina Oil Corporation, Berthoud State no. 4 well reported by Dean and Arthur (1989), and Pratt and others (in press).
- Figure 3.**--Fractures in core of the Smoky Hill Chalk Member, Niobrara Formation, Coquina Oil Corporation, Berthoud State No. 3 well. Orientation of core samples is indicated by arrows. *A*) Large, oil-stained fracture in zone 3 at 3,074 ft containing calcite cement, clasts, and showing some displacement in bedding across fracture; *B*) Inclined bedding with calcite filled fractures parallel, near-perpendicular, and inclined to bedding in zone 3; note dark stylolitic seams parallel and perpendicular to bedding (3,096 ft); *C*) Large, open, oil-stained fractures containing coarse calcite crystals and bitumen on fracture face in fracture zone 3 (3,101 ft).
- Figure 4.**--Area graph of acid-insoluble residue and carbonate content of core samples from the Niobrara Formation, Berthoud State 3 well, and location of fractured intervals with assigned numbers. Dashed curve shows large-scale cyclicity of chalk and shale intervals. Large arrows indicate correspondence of fractures to upper portions of chalk facies; small arrows indicate correspondence of fracture zones to cyclicity.
- Figure 5.**--Insoluble residue and carbonate content of Niobrara Formation and numbered intervals of fractures in the Coquina Oil Corporation, Berthoud State No. 3 well. Bold line A connects insoluble residue maxima and bold line B connects carbonate content maxima. Note the correlation between intervals of fractures and intervals of maximum difference in insoluble/carbonate composition (greatest separation of lines).

Table 1.--Acid-insoluble residue (I.R.) and acid-soluble carbonate (S.C.) content of 151 core samples from the Niobrara Formation and adjacent units, Coquina Oil, Berthoud State No. 3 well, Larimer County, Colorado. Data reported in weight percent of whole rock. Sample depth in feet as measured from reference footages on core.

| Sample depth | I.R. | S.C. | Total | Sample depth | I.R. | S.C. | Total | Sample depth | I.R. | S.C. | Total |
|--------------|------|------|-------|--------------|------|------|-------|--------------|------|------|-------|
| 2911.0 | 54 | 46 | 100 | 3050.8 | 30 | 70 | 100 | 3116.9 | 50 | 50 | 100 |
| 2914.4 | 51 | 49 | 100 | 3051.4 | 46 | 54 | 100 | 3120.3 | 44 | 56 | 100 |
| 2917.4 | 45 | 55 | 100 | 3055.1 | 44 | 56 | 100 | 3125.4 | 35 | 65 | 100 |
| 2920.2 | 30 | 70 | 100 | 3055.6 | 18 | 82 | 100 | 3126.0 | 40 | 60 | 100 |
| 2922.2 | 15 | 85 | 100 | 3056.3 | 48 | 52 | 100 | 3134.6 | 21 | 79 | 100 |
| 2923.5 | 16 | 84 | 100 | 3057.2 | 40 | 69 | 100 | 3136.8 | 39 | 61 | 100 |
| 2923.9 | 73 | 27 | 100 | 3058.2 | 13 | 87 | 100 | 3139.6 | 46 | 54 | 100 |
| 2927.2 | 49 | 51 | 100 | 3058.3 | 11 | 89 | 100 | 3142.3 | 18 | 82 | 100 |
| 2929.0 | 13 | 87 | 100 | 3058.4 | 22 | 78 | 100 | 3143.4 | 43 | 57 | 100 |
| 2932.0 | 14 | 86 | 100 | 3059.4 | 21 | 79 | 100 | 3147.9 | 46 | 54 | 100 |
| 2933.8 | 14 | 86 | 100 | 3061.0 | 36 | 64 | 100 | 3148.2 | 32 | 68 | 100 |
| 2935.5 | 27 | 73 | 100 | 3061.9 | 57 | 43 | 100 | 3149.9 | 45 | 55 | 100 |
| 2939.7 | 12 | 88 | 100 | 3063.4 | 51 | 49 | 100 | 3153.1 | 49 | 51 | 100 |
| 2940.2 | 47 | 53 | 100 | 3064.8 | 24 | 76 | 100 | 3153.9 | 36 | 64 | 100 |
| 2940.7 | 13 | 87 | 100 | 3065.2 | 49 | 51 | 100 | 3156.7 | 49 | 51 | 100 |
| 2941.7 | 9 | 91 | 100 | 3065.8 | 36 | 64 | 100 | 3168.8 | 30 | 70 | 100 |
| 2945.9 | 10 | 90 | 100 | 3065.9 | 18 | 82 | 100 | 3174.7 | 30 | 70 | 100 |
| 2947.4 | 19 | 81 | 100 | 3066.3 | 40 | 60 | 100 | 3176.9 | 41 | 59 | 100 |
| 2948.9 | 21 | 79 | 100 | 3066.7 | 27 | 73 | 100 | 3182.0 | 42 | 58 | 100 |
| 2950.3 | 19 | 81 | 100 | 3067.3 | 43 | 57 | 100 | 3183.1 | 20 | 80 | 100 |
| 2953.7 | 39 | 61 | 100 | 3068.3 | 28 | 72 | 100 | 3185.5 | 40 | 60 | 100 |
| 2956.7 | 23 | 77 | 100 | 3068.8 | 11 | 89 | 100 | 3186.5 | 27 | 73 | 100 |
| 2957.7 | 17 | 83 | 100 | 3069.0 | 28 | 72 | 100 | 3187.1 | 71 | 29 | 100 |
| 2958.9 | 33 | 67 | 100 | 3069.4 | 18 | 82 | 100 | 3187.2 | 34 | 66 | 100 |
| 2963.2 | 47 | 53 | 100 | 3069.9 | 28 | 72 | 100 | 3187.6 | 18 | 82 | 100 |
| 2963.6 | 20 | 80 | 100 | 3070.0 | 47 | 53 | 100 | 3190.5 | 52 | 48 | 100 |
| 2967.1 | 28 | 72 | 100 | 3070.3 | 28 | 72 | 100 | 3191.3 | 8 | 92 | 100 |
| 2972.8 | 43 | 57 | 100 | 3071.9 | 37 | 63 | 100 | 3191.9 | 38 | 62 | 100 |
| 2976.1 | 38 | 62 | 100 | 3073.2 | 22 | 78 | 100 | 3192.5 | 9 | 91 | 100 |
| 2977.1 | 50 | 50 | 100 | 3078.0 | 12 | 88 | 100 | 3193.5 | 11 | 89 | 100 |
| 2979.9 | 47 | 53 | 100 | 3079.0 | 33 | 67 | 100 | 3195.3 | 14 | 86 | 100 |
| 2985.3 | 33 | 67 | 100 | 3081.4 | 29 | 71 | 100 | 3195.5 | 33 | 67 | 100 |
| 2987.9 | 32 | 68 | 100 | 3084.1 | 63 | 37 | 100 | 3197.5 | 49 | 51 | 100 |
| 2989.0 | 51 | 49 | 100 | 3084.6 | 17 | 83 | 100 | 3198.5 | 5 | 95 | 100 |
| 2989.2 | 34 | 66 | 100 | 3087.6 | 53 | 47 | 100 | 3199.5 | 10 | 90 | 100 |
| 2991.7 | 31 | 69 | 100 | 3092.8 | 64 | 36 | 100 | 3200.1 | 7 | 93 | 100 |
| 2995.9 | 49 | 51 | 100 | 3093.6 | 11 | 89 | 100 | 3200.2 | 21 | 79 | 100 |
| 2997.4 | 36 | 64 | 100 | 3097.7 | 13 | 87 | 100 | 3201.5 | 12 | 88 | 100 |
| 3000.7 | 40 | 60 | 100 | 3099.0 | 30 | 70 | 100 | 3203.5 | 36 | 64 | 100 |
| 3005.3 | 23 | 77 | 100 | 3100.0 | 36 | 64 | 100 | 3204.5 | 10 | 90 | 100 |
| 3010.5 | 29 | 71 | 100 | 3102.9 | 41 | 59 | 100 | 3205.0 | 14 | 86 | 100 |
| 3012.9 | 29 | 71 | 100 | 3103.0 | 47 | 53 | 100 | 3205.5 | 6 | 94 | 100 |
| 3015.6 | 35 | 65 | 100 | 3104.0 | 29 | 71 | 100 | 3206.5 | 6 | 94 | 100 |
| 3017.5 | 15 | 85 | 100 | 3104.1 | 34 | 66 | 100 | 3208.0 | 36 | 64 | 100 |
| 3017.6 | 31 | 69 | 100 | 3104.8 | 29 | 71 | 100 | 3208.1 | 6 | 94 | 100 |
| 3023.4 | 10 | 90 | 100 | 3104.9 | 34 | 66 | 100 | 3208.5 | 24 | 76 | 100 |
| 3024.4 | 14 | 86 | 100 | 3109.1 | 41 | 59 | 100 | 3209.5 | 57 | 43 | 100 |
| 3029.8 | 16 | 84 | 100 | 3109.2 | 40 | 60 | 100 | 3210.5 | 39 | 61 | 100 |
| 3043.8 | 17 | 83 | 100 | 3110.1 | 25 | 75 | 100 | 3211.5 | 90 | 10 | 100 |
| 3045.4 | 28 | 72 | 100 | 3110.8 | 38 | 62 | 100 | | | | |
| 3048.5 | 24 | 76 | 100 | 3116.5 | 46 | 54 | 100 | | | | |

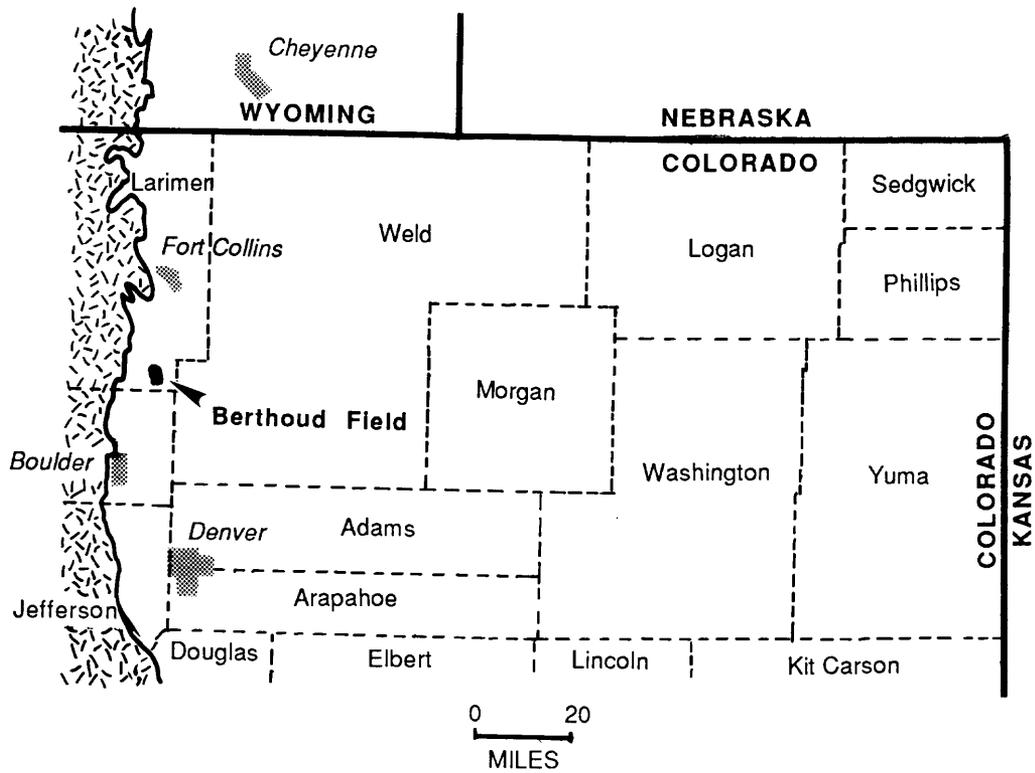


Figure 1.

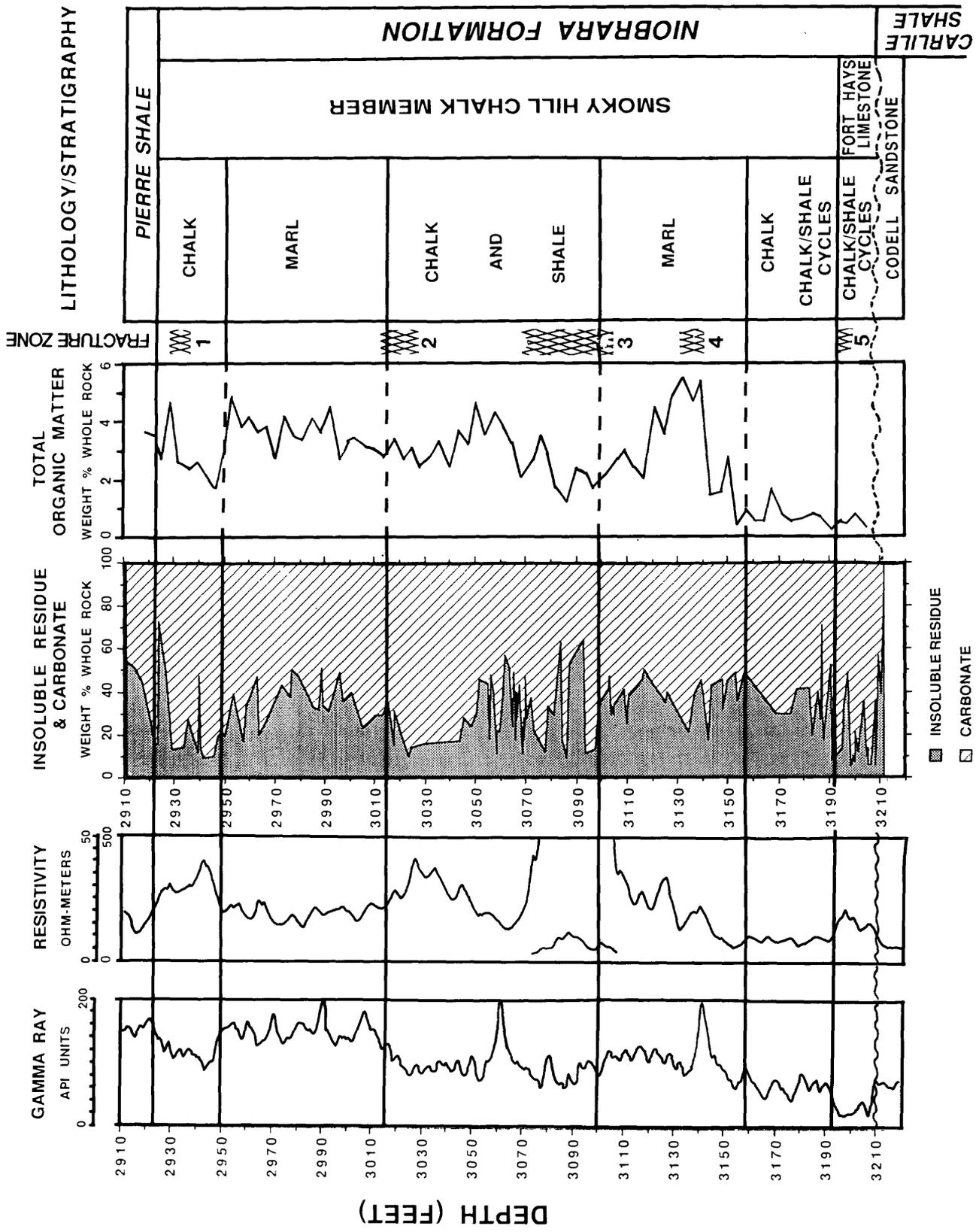
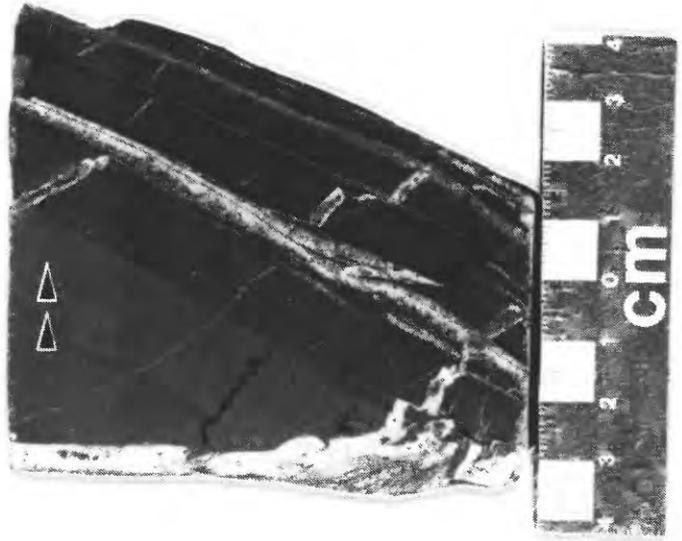


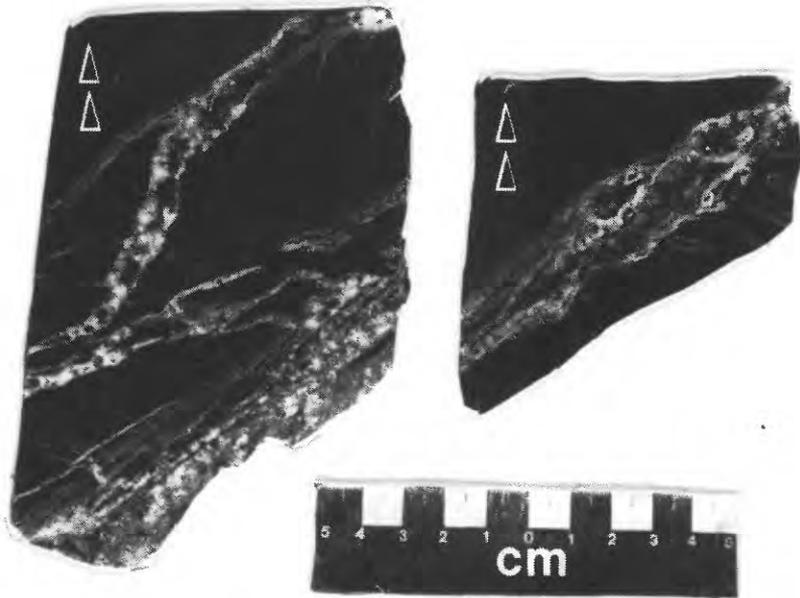
Figure 2.



A



B



C

Figure 3.

WT % WHOLE ROCK

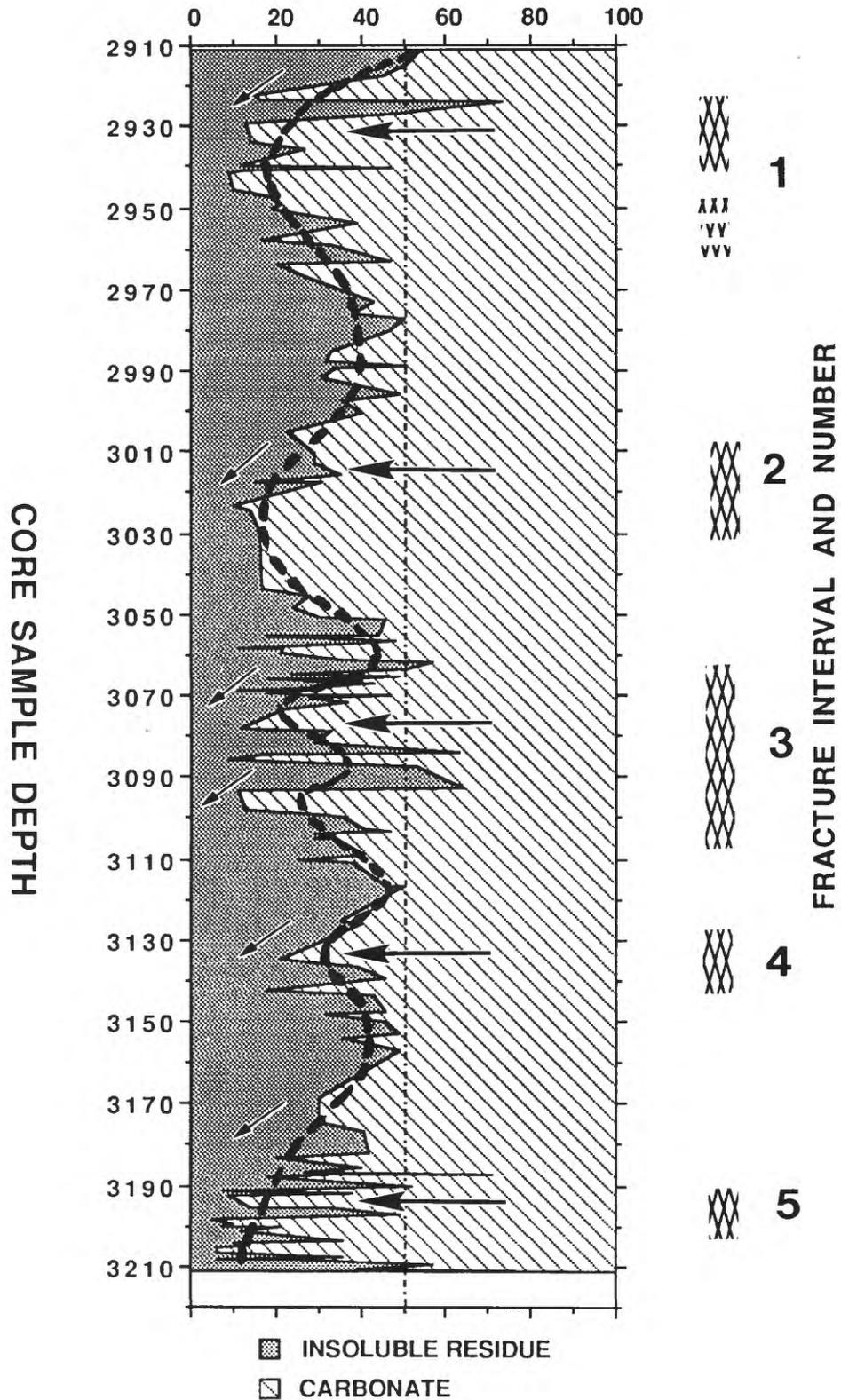


Figure 4.

WT % WHOLE ROCK

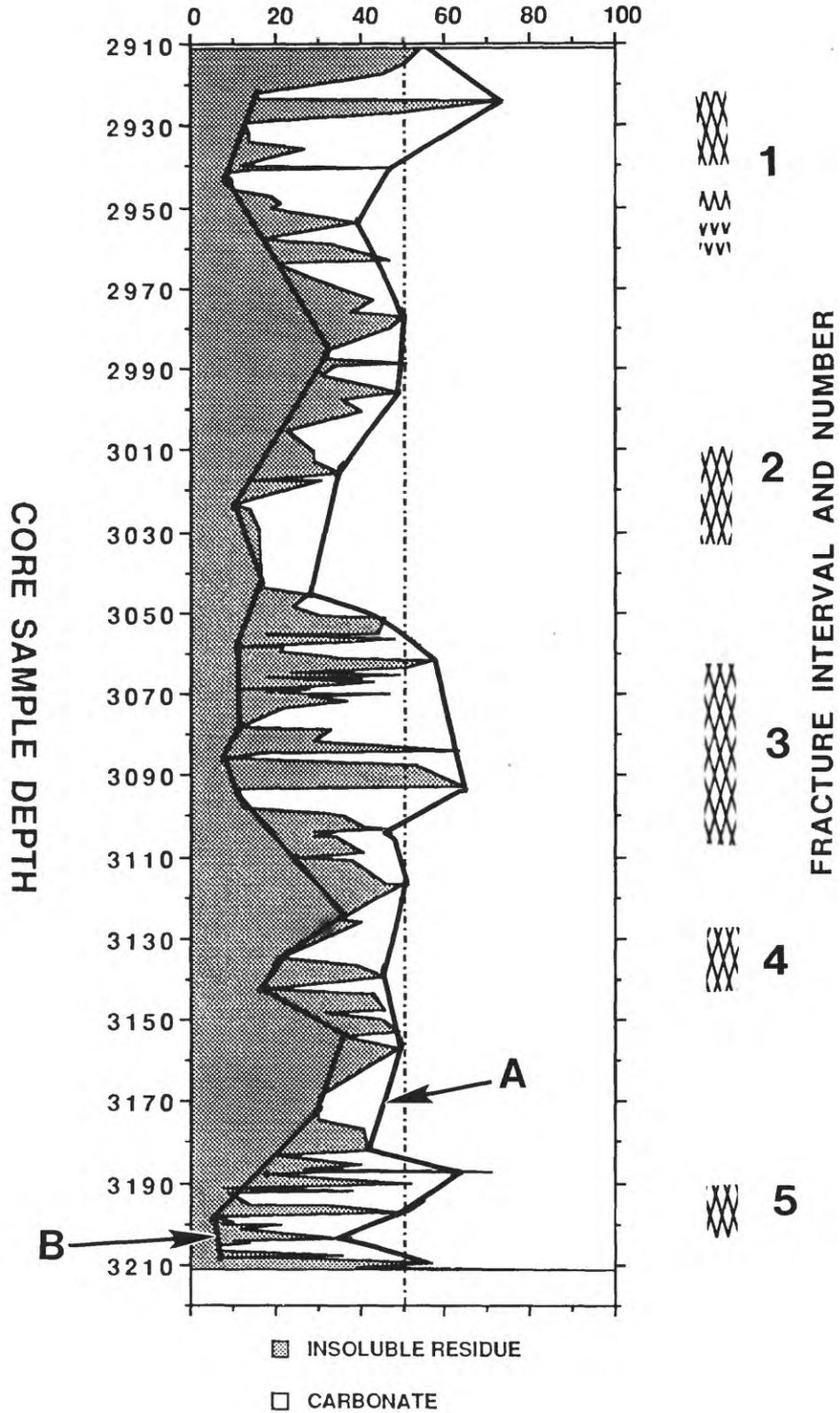


Figure 5.