T-2748

REGIONAL VELOCITY STUDY OF THE MIDDLE CRETACEOUS STRATIGRAPHIC INTERVAL, NORTHERN DENVER BASIN, COLORADO

by

Belgasim M. Saiti

T-2748

A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the Degree of Master of Science in Geophysics.

Golden, Colorado

July 20, 1983.

Signed: Saiti B. M.
Belgasim M. Saiti

Approved: Thomas L. Davis
Thomas L. Davis
Thesis Advisor

Golden, Colorado

November 23, 1983.

P R Romig
Phillip R. Romig, Head
Geophysics Department

ABSTRACT

Regional velocity study of the middle Cretaceous stratigraphic interval in the northern Denver basin of Colorado indicates anomalous variations. The stratigraphic section of interest in this study is the interval from the top of the Dakota J-sandstone to the top of the Niobrara formation. Velocity increase coincide with axes of isopach thinning of the stratigraphic intervals along northeast-southwest trends. Greatest interval velocity anomaly increase of 6% exists in the area of the Wattenberg gas field which was located on an ancient paleohigh named the Wattenberg paleohigh. Positive velocity anomalies of six percent occur along other northeast-southwest paleostructural trends. The velocity anomalies may be due to the influence of the Transcontinental arch on the Cretaceous strata by allowing more compaction, uplifting the strata in a significant magnitude, or controlling sedimentation patterns thereby creating lateral lithologic variations. Whatever the cause of variation, velocity patterns appear to reflect paleostructural trends in the basin. These trends should be of significance to the petroleum explorationist.

TABLE OF CONTENTS

LIST OF FIGURES

Page

Page

LIST OF TABLES

ACKNOWLEDGEMENTS

I wish to thank my thesis advisor, Dr. Thomas L. Davis for suggesting the subject for this thesis and for the consistent guidance and encouragement given thoughout the phases of this study.

I also express my thanks to Dr. James K. Applegate, Dr. James E. White and Dr. Maurice W. Major for serving on my thesis committee.

I express my appreciation to the following oil companies in the Denver area for releasing some of the data used in this study: Monsanto Oil Company, Amoco Production, and Chevron U.S.A.

I would like to express my appreciation to the Geology Department, Gar-Younis University, Libya, for giving me the opportunity to attend graduate school.

Finally, I would like to express my deepest appreciation to my wife, Ashmiasa, for her patience and encouragement throughout the course of the study.

INTRODUCTION

Most of the geologic investigations in the Denver basin related tectonics and sedimentation, defined facies, and thickness changes on a regional basis; for example: Hoyt (1963); Martin (1974); Clark (1978); Land (1972); MacMillan (1974); Volk (1971); Suryanto (1979); and others. Tweto (1980) and Tweto and Sims (1963) and Weimer (1978) reported that most of the fault systems and shear zones in Colorado originated during the Precambrian time. When the crust in later times was subjected to stresses, movement occurred along the pre-existing zones of weakness (Weimer, 1980). Major fault systems and shear zones in Colorado fall into four trends: north-northwest, northeast, west-northwest, and east-west (Sonnenberg, 1981). In the northern Denver basin, recurrent movement occurred primarily along northeast trends during the Phanerozic time, where the Cambrian, Ordovician, and Silurian rocks are not widely distributed in this area (Sonnenberg, 1981). Absence of Cambrian, Ordovician, and Silurian rocks across the northeast trend, which forms a portion of Colorado lineament (Warner, 1980) have been related to a major structural feature extending from the State of Minnesota to the Grand Canyon region, and named the Transcontinental arch (Fig. 1)

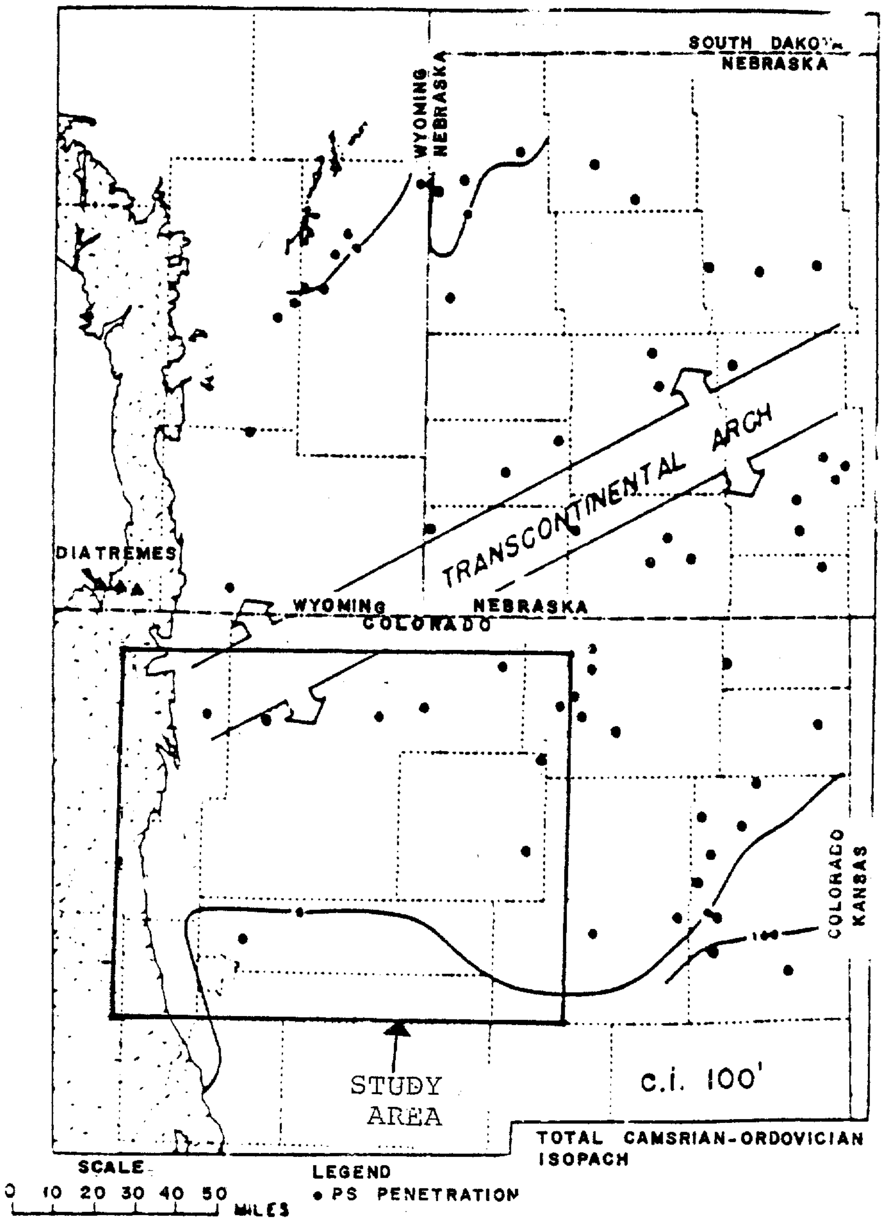

FIGURE 1. DIAGRAM OF NORTHEAST-SOUTHWEST TRENDING PALEO-STRUCTURE - "TRANSCONTINENTAL ARCH AXIS DURING CAMBRIAN-ORDOVICIAN TIME" (AFTER SONNENBERG, 1981)

(Weimer, 1980). The arch was positive throughout much of the Paleozoic time.

In the Denver basin Weimer (1978, 1982), documented that the Transcontinental arch influenced Cretaceous strata, where unconformities, thickness changes, and facies changes occured across the flank of the paleo-structures. Weimer (1978, 1980, 1982) and Sonnenberg (1981), mapped an isopach of the Niobrara formation (Fig. 2) in the Denver basin and related a northeast-thinning trend on the isopach to the influence of the arch. The arch was active during early Cretaceous Dakota J-sandstone deposition, controlling distribution of the J-sandstone, Weimer (1978). Weimer suggested that the Wattenberg J-sandstone gas field is located on a paleo-structural element named the Wattenberg paleohigh (Fig. 3). The paleohigh subsequently was downwarped into the present low setting. Weimer (1980) suggested that the arch influenced unconformity presence at the top of the J-sandstone and at the top and the base of the Niobrara formation (Figs. 8 and 9).

In this study, velocity data was derived from about 80 sonic logs and 25 check-shot velocity surveys in order to examine the effect of the paleostructure on the velocity of the middle Cretaceous stratigraphic interval from

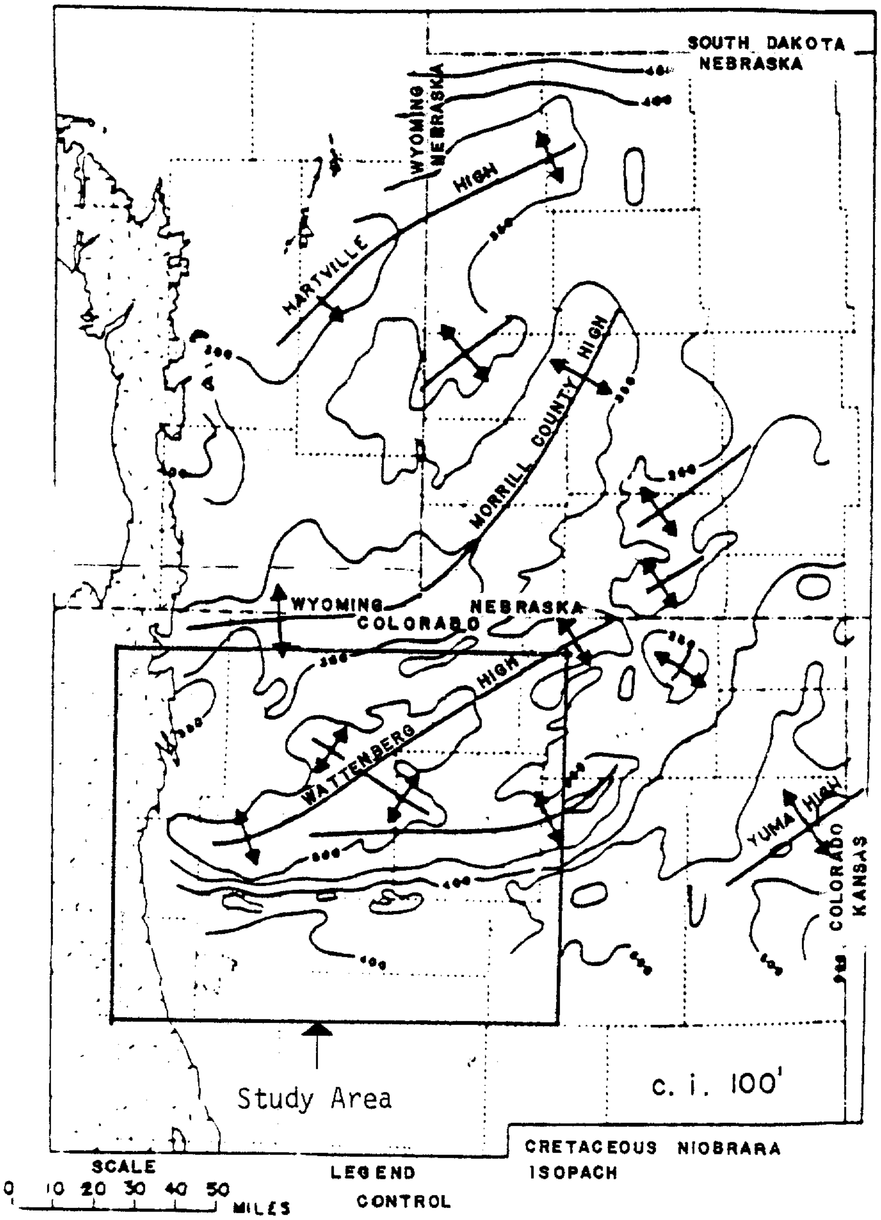

FIGURE 2. ISOPACH MAP OF NIOBRARA FORMATION (AFTER WEIMER AND SONNENBERG 1982)

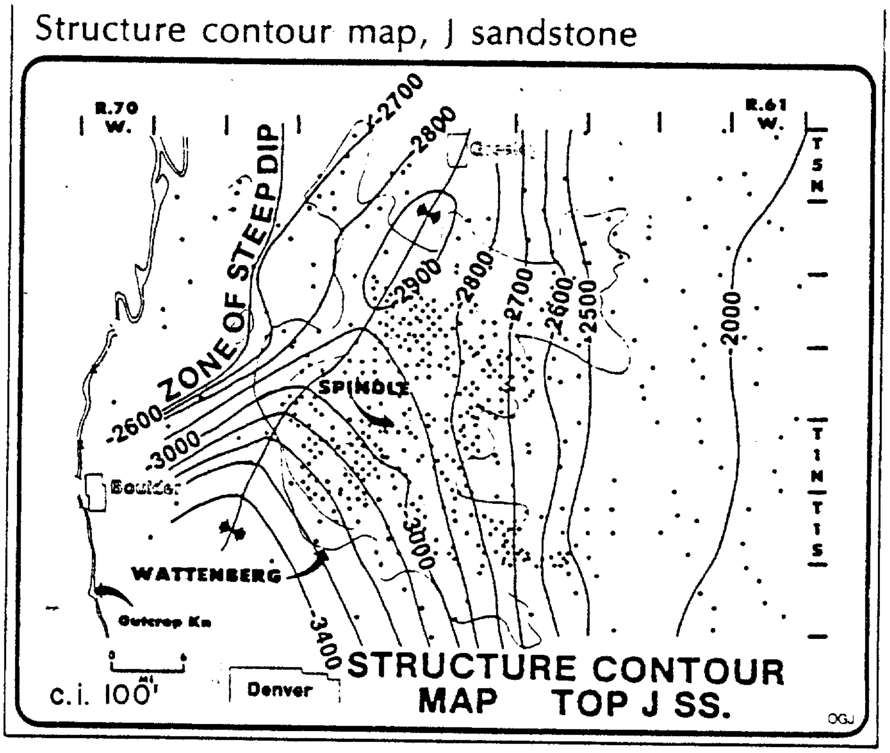

FIGURE 3. STRUCTURE CONTOUR MAP TOP J SS. (AFTER WEIMER AND SONNENBERG 1982)

the top of the Dakota J-sandstone to the top of the Niobrara formation, and to depict the velocity anomaly present within the stratigraphic interval. Velocity-depth relations were used to calculate and map regional velocity anomalies throughout the study area in the northern Denver basin and to examine these anomalies with respect to known paleostructure trends within the study area. Velocity-depth relations used in this study conform to those used by others; for example: Faust (1951, 1953); Acheson (1959, 1963, 1981); Hosking (1966); Lask (1967); Janowsky (1970); and Sarmiento (1961).

Faust (1951) proposed that the p-wave velocity of the sedimentary rocks is proportional to the one-sixth power of the product of the depth of burial (Z) in feet and the geologic age (T) in years: $V = 125.3\ (ZT)^{1/6}$. In 1953, Faust included the lithological factor (L), derived from the resistivity logs in the above relation: $V = 1948\ (ZTL)^{1/6}$. Acheson (1959) proposed general velocity depth relation for Cretaceous rocks in South-Central Alberta: $t = b + c\ Z^{1-n}$, where t = time in millisecond and Z = depth in feet, (1); $V = aZ^n$, where V = velocity in ft/sec. Acheson (1963, 1981) reported that p-wave velocities in both the Western Canada basin and the Arctic Islands obey the same velocity-depth relation, but differ in some specifications depending on the lithological variation and basin position. For example, in the Artic Islands, the value n approaches the theoretical value 1/6, and it is found to be close to 0.1 in the western part of the western Canada basin. Acheson suggested that the deviation in the value of n from the theoretical value in the western Canada basin is due to the fact that the effective stress (Δp) at certain depths (Z) is a function not only of present overburden, but also of the other forces of orogenic movements, and suggested in computing the value n, it is logical to use information gathered at an old surface some distance d above the present datum, so the effective stress is proportional to the depth (Z + d), and therefore: $V = a(Z + d)^{1/6}$.

Davis (1972) used the velocity depth relation proposed by Acheson (1963), in studying velocity variations around Leduc reefs in Alberta. Wyrobeck (1959) investigated seismic velocity of Triassic and Permian sedimentary rocks in England and reported the same relation proposed by Acheson (1963), but concluded the value n varies from 1/6 to 1/4. Jankowsky (1970) studied velicities of carbonate rocks in west Germany, and related the scattering in the velocity values on the velocity-depth plot to lithological variations, where he derived a lithological factor for the shale-carbonate ratio from the velocity logs. Velocity of sedimentary rocks depends on many factors in addition to depth of burial, such as: geologic age, effective pressure (overburden pressure-fluid pressure) and lithology. Statistical relation between the velocity (v) and the porosity ($\emptyset$) as proposed by Pickett (1970). According to Pickett $\frac{1}{V} = A + B\emptyset$ where A and B are constants depending on the lithology, effective stress and grain structure. It is difficult to assess the variation in the velocity for single factors but since all those factors are closely related, the investigation of the velocity in terms of the depth of burial will include the effect of some of the others.

PURPOSE OF STUDY

The main purpose of this investigation is to examine the velocity as a function of depth in Cretaceous stratigraphic interval from the top of the Dakota J-sandstone to the top of the Niobrara formation in the northern Denver basin, and to map velocity anomalies which may exist due to the effect of the Transcontinental arch.

AREA OF STUDY

The study area in the Denver basin in northeastern Colorado involves subsurface velocity data covering an area of approximately 9000 square miles (Fig. 4). The study area extends from T5S to T10N, and from R54W to R72W (Fig. 5). The well-control map of the study area (Fig. 5) shows the locations of wells selected for this study. Circles represent those wells having continuous velocity logs; open squares represent the wells having check-shot velocities; and closed squares represent those wells having both the check-shot survey and the continuous velocity logs. (Fig. 6) is a structure contour map on the top of the Niobrara formation.

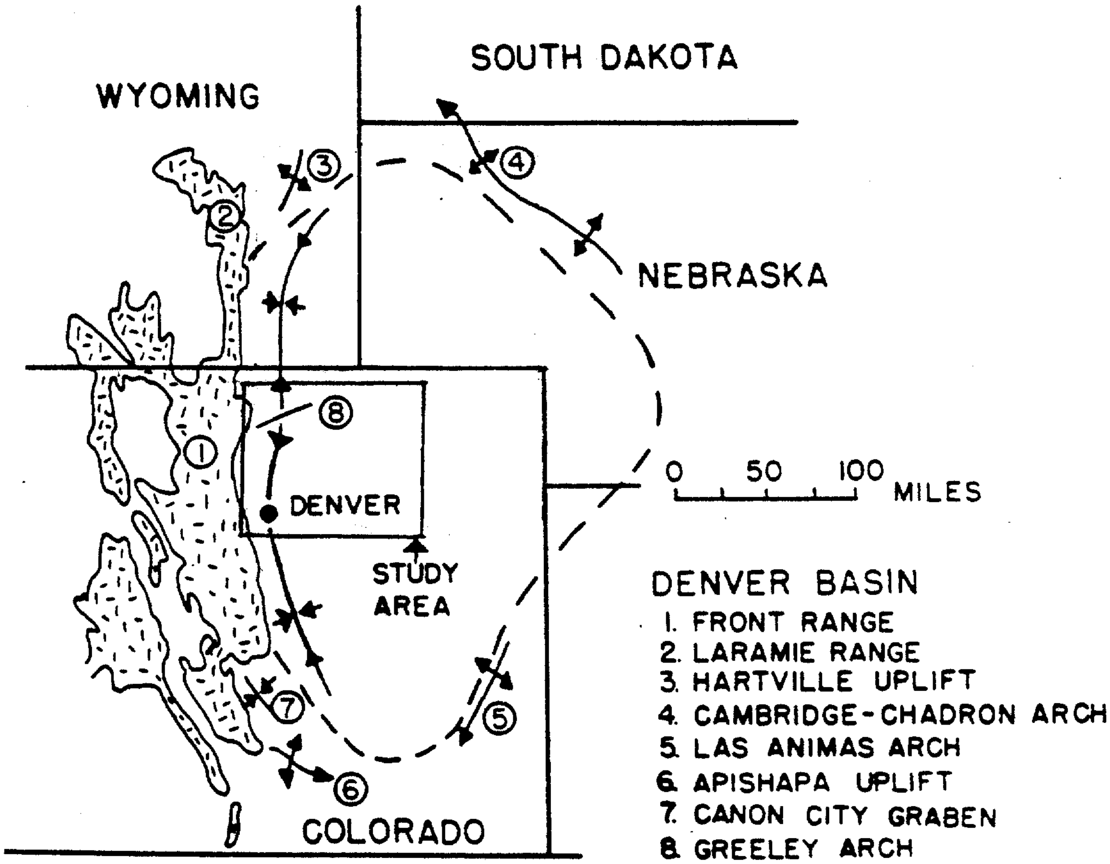

FIGURE 4. INDEX MAP SHOWING DENVER BASIN AND STUDY AREA (AFTER SONNENBERG, 1981)

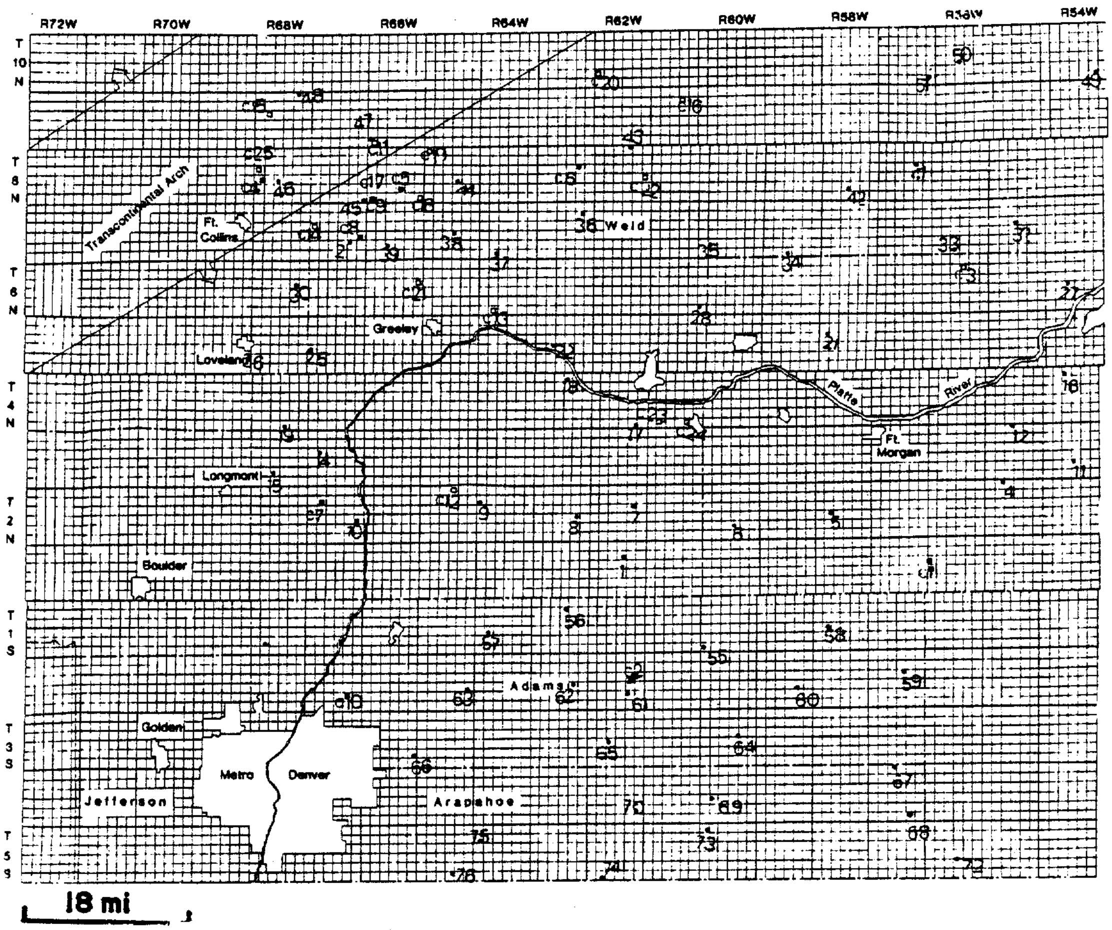

FIGURE 5. WELL CONTROL MAP OF THE STUDY AREA, WELL LOCATIONS LISTED IN APPENDIX 1.

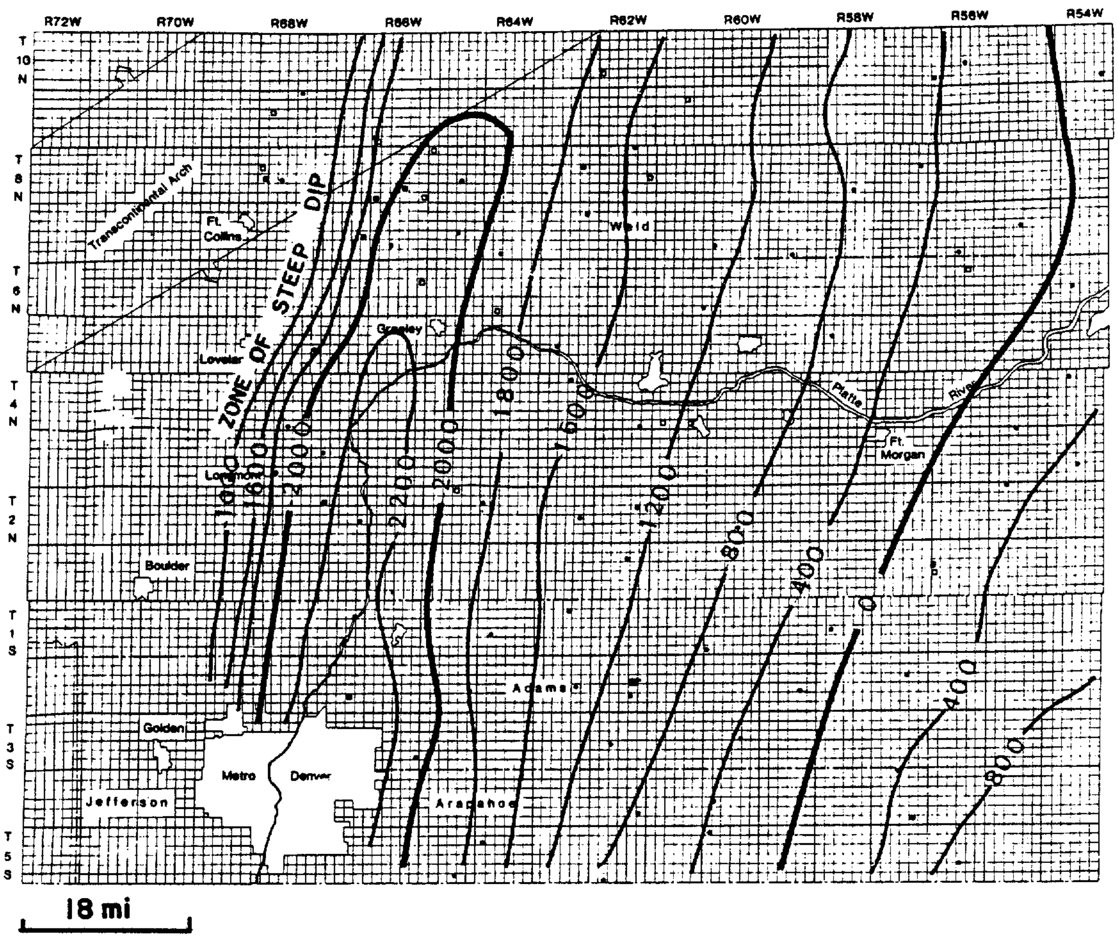

FIGURE 6. TOP OF NIOBRARA STRUCTURE CONTOUR MAP, DATUM SEA LEVEL.

STRATIGRAPHIC DESCRIPTION

Stratigraphic section of study is from the top of the Niobrara formation of "early time of late Cretaceous" to the top of the Dakota J-sandstone of "late time of early Cretaceous" (Fig. 7). Average thickness of the section in the study area is approximately 850 feet. In an ascending order, the strata described in this study are: Dakota D-sandstone and/or Mowry shale; Graneros; Greenhorn; Carlile; and Niobrara.

I. Dakota Group

1) Dakota-J: J-sandstone is the top of the Dakota group (Fig. 8). Isopach map of this member (Fig. 10), mapped by Haun (1963), shows thinning trends in areas where the Niobrara formation is thin, and it is thick where the Niobrara is thick in the area of the Morgon County low, Colorado. The J-sandstone is recognized on the velocity logs by its high velocity (Fig. 7). Because of few penetration of wells for this member no complete velocity study has been done.

2) D-sandstone and/or Mowry shale: In the study area, both the D-sandstone and the Mowry shale vary in the thickness from wedge-edge to about 40 feet thick (Fig. 11 and 12). The southern desposition limit of the organic

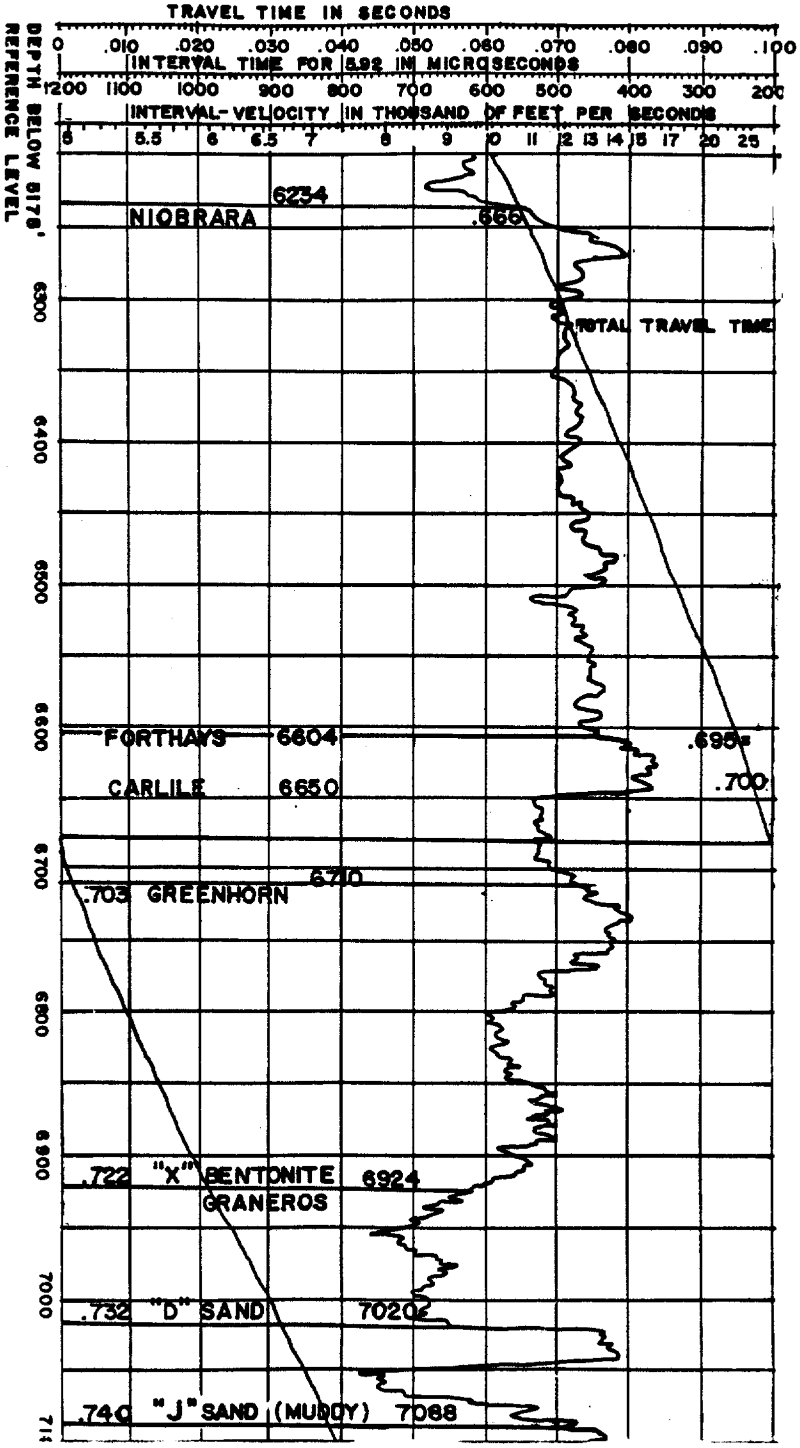

FIGURE 7. VELOCITY LOG ILLUSTRATES THE INTERVAL OF STUDY
TOPS OF FORMATIONS ARE LABELLED

siliceous Mowry shale (Fig. 12) is in Central Colorado (Haun, 1959).

II. <u>Benton Group</u> -- This group consists of Graneros, Greenhorn, and Carlile (Fig. 8). These units are considered as formations since each one of them consists of a distinctive lithology. This group is regarded as the source for the oil accumulation in the lower Cretaceous rock in the Denver basin (Clayton and Swetland, 1980).

1) Graneros: Graneros is a black, marine shale of rather uniform lithology (McGooky, 1972), and is recognized on the logs by its low velocity nature (Fig. 7). The top of this formation is the X-Bentonite, a wide-spread bentonite member (Weimer, 1972). The base of this interval is the top of the D-sandstone or the Mowry shale (Fig. 8).

2) Greenhorn: This formation is easily distinguished on the velocity logs from the underlying and the overlying units by its high-velocity values (Fig. 7). The base of the Greenhorn is placed at the top of the X-Bentonite and the upper boundary is placed at the top of the first limestone member below the Carlile formation (Fig. 8).

3) Carlile: The base of the Carlile formation is on the top of the Greenhorn formation and the top boundary of the Carlile is placed at the top of the Codell sandstone.

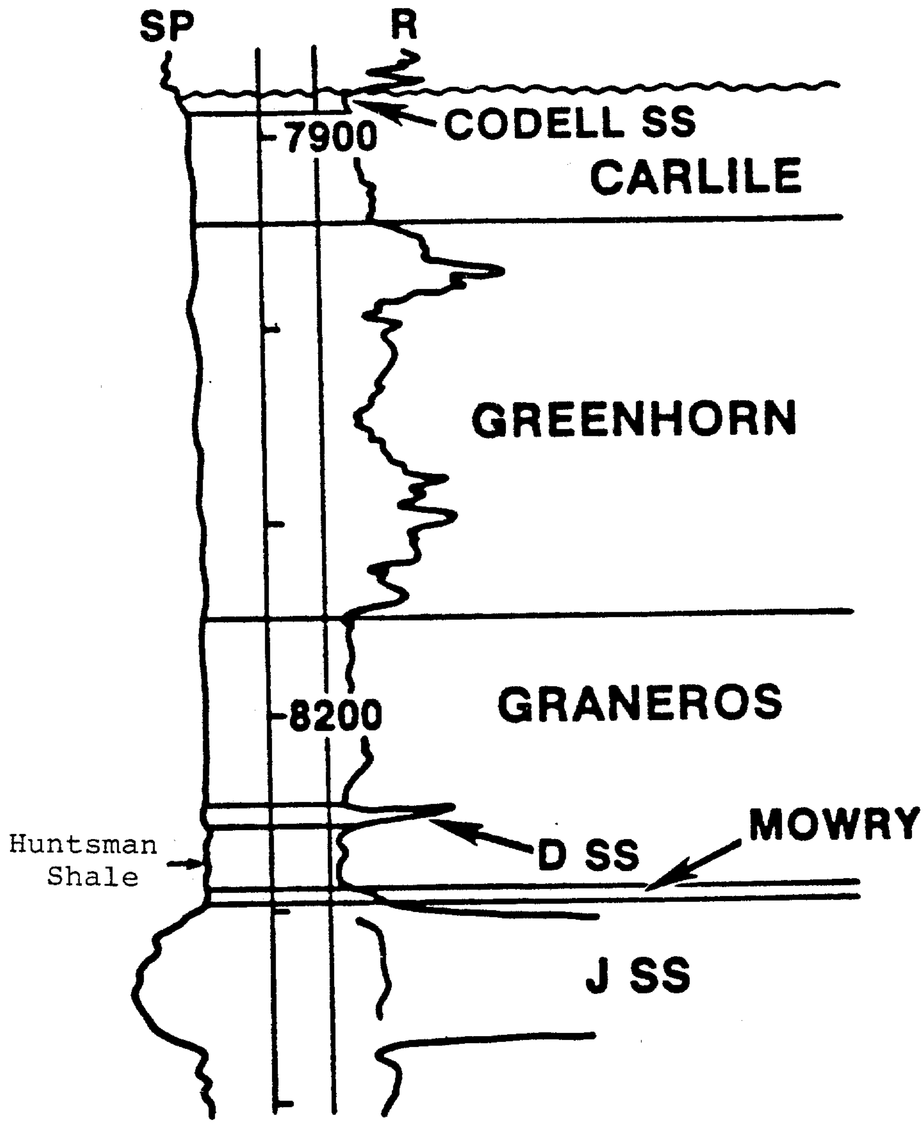

FIGURE 8. TYPICAL ELECTRIC LOG ILLUSTRATING UPPER DAKOTA GROUP AND BENTON GROUP (JOHNSON #1 UPPR-AUSTIN, SEC. 17, T2S, R65W) (AFTER SONNENBERG, 1981)

This formation is easily recognized on the logs from the overlying and the underlying limestones (Fig. 8).

Niobrara: The dominant lithologies of the Niobrara formation are limestones "chalks" and interbedded shales (Weimer, 1978). The formation consists of four limstone intervals and three intervening shale intervals (Fig. 9). These seven intervals are easily recognized on velocity logs (Fig. 7). The lower limestone is named the Fort Hays member, the six overlying units are grouped together and named the Smoky Hill member (Fig. 9). The lower boundary of the Niobrara formation is placed at the base of the Fort Hays member or the top of the Carlile formation. The upper boundary of the Niobrara formation is the contact of the Niobrara upper chalk and the overlying noncalcareous black shales of the Pierre formation (Fig. 9).

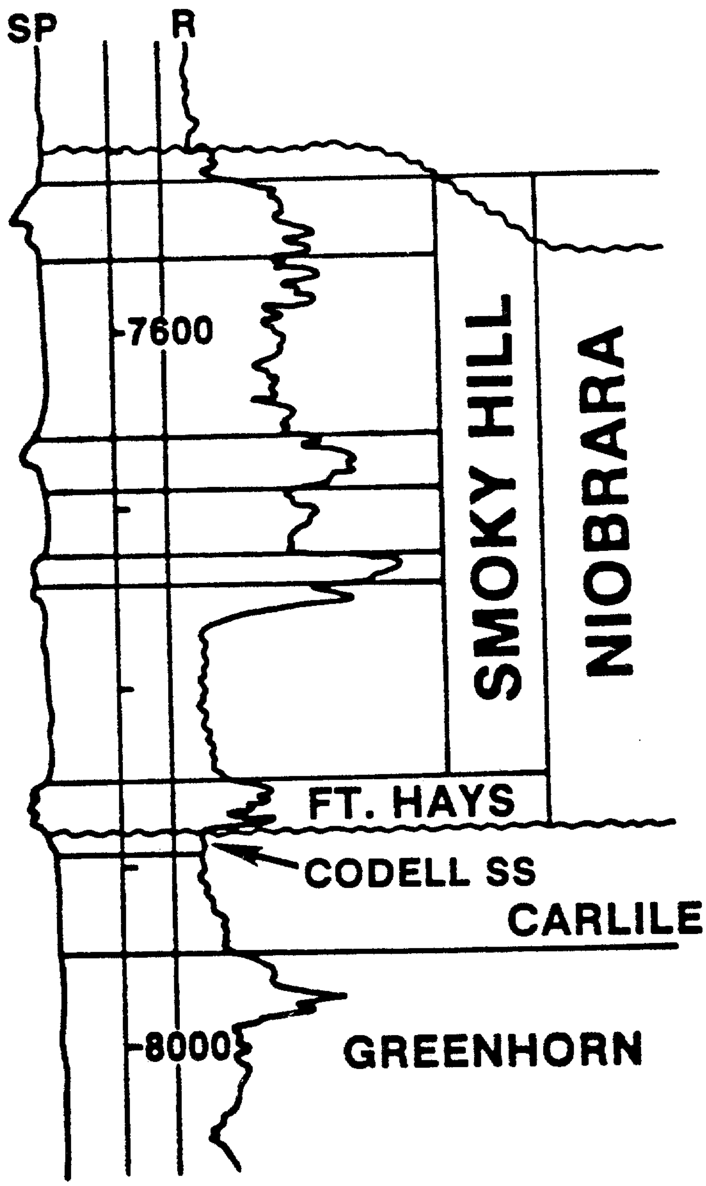

FIGURE 9. TYPICAL ELECTRIC LOG ILLUSTRATING NIOBRARA FORMATION (JOHNSON #1 UPRR-AUSTIN SEC. 17, T2S, R65W) (AFTER SONNENBERG, 1981)

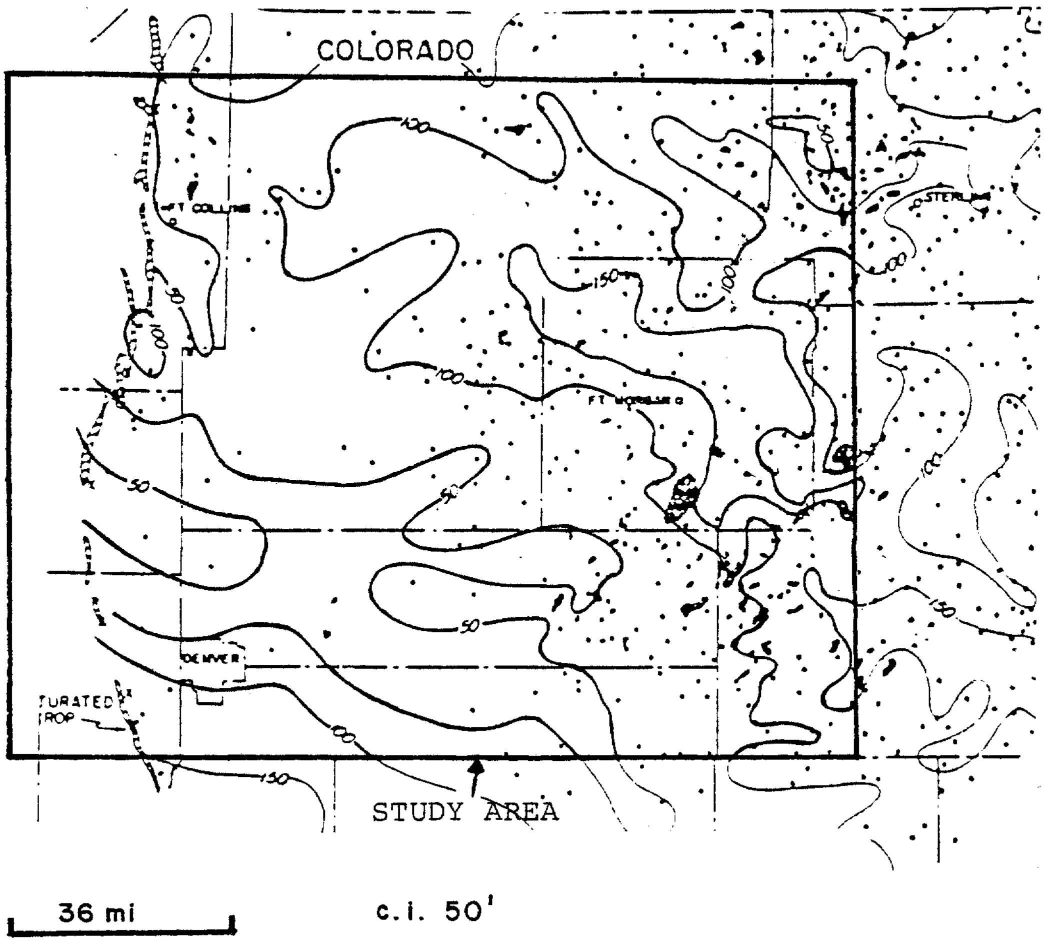

FIGURE 10. J-SANDSTONE ISOPACH MAP (AFTER HAUN, 1963)

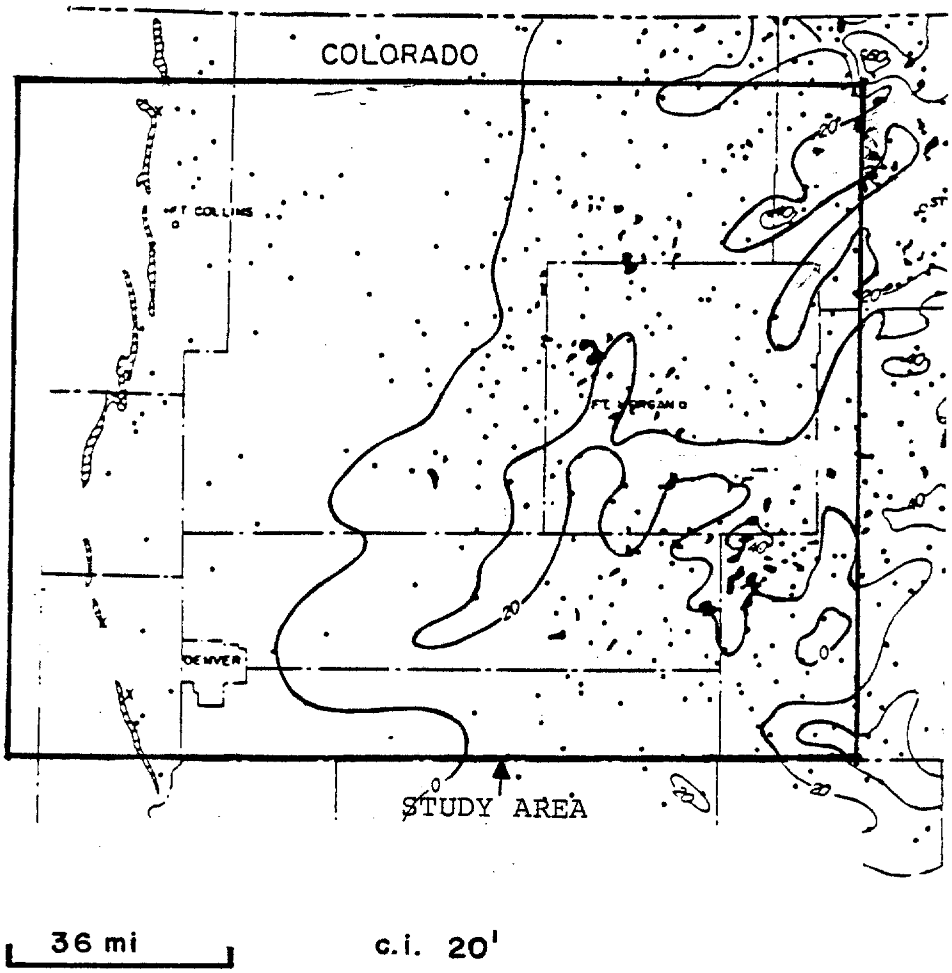

FIGURE 11. D-SANDSTONE ISOPACH MAP (AFTER HAUN, 1963)

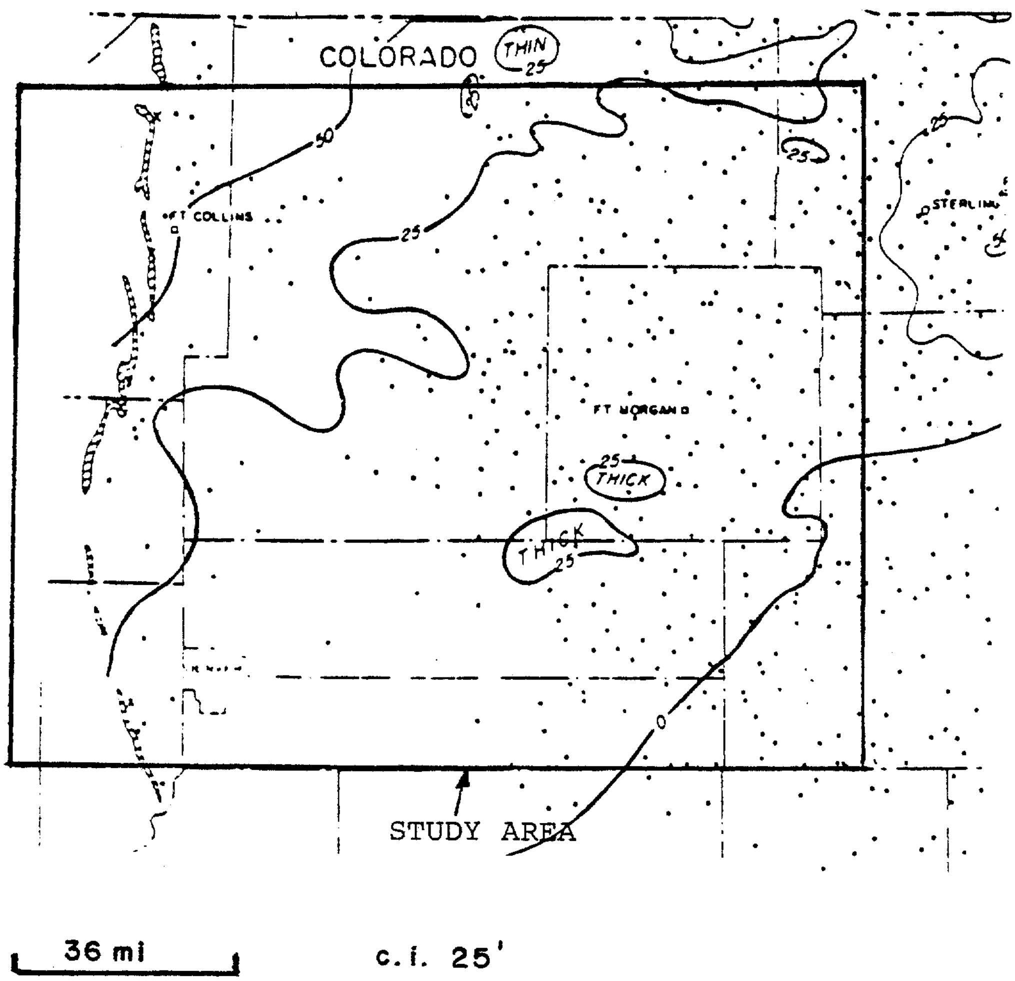

FIGURE 12. MOWRY SHALE ISOPACH MAP (AFTER HAUN, 1963)

INVESTIGATION PROCEDURE

Data

The data used in this study has been derived from 80 sonic logs and 25 check-shot velocity surveys. The data is derived from wells scattered throughout the wide area within and off the trends of the paleostructures reported by Weimer (1978, 1982). Due to the quantity of the data involved with this study, a file containing all the sonic logs and check-shot velocity surveys used in this study has been established in the Geophysics Department in addition to the velocity and depth data derived from those logs listed in Appendix II, page 93.

Stratigraphic Interval of Study

The stratigraphic interval of study is from the top of the Dakota J-sandstone to the top of the Niobrara and distinct lithologic formations within this interval, are mapped based on the well log character on some regional logs available at the Geology Department (well-log library). The stratigraphic interval is divided into stratigraphic components and the interval velocity and the vertical travel time are computed for each of the stratigraphic intervals selected.

Conventional and Continuous Velocity Surveys

Interval velocities derived from the continous velocity survey are found to be higher than the velocities derived from the conventional check-shot survey in the same well. By examining these discrepancies in nine wells, where both velocity surveys exist, the magnitude of the discrepancies varied from 1% to about 6% of the continuous log velocity values (Table 1). The average magnitude was found to be approximately 4% of the velocity values. Gretener (1961) related the discrepancy between both surveys to the anisotropy and the ray path curvature associated with the conventional check-shot survey. Gretner concluded that the amount of discrepancy decreased with the depth, where he reported a systematic deviation between the two surveys for shallow depths (below 4,000 feet) of 2 msec/1,000' and for depths greater than 4,000' of 1.5 msec/1,000'. In this investigation the velocity data derived from the continuous velocity logs are adjusted to the velocity data from the check-shot survey by subtracting the average amount of discrepancy from the interval velocities of all the sonic logs involved. The argument for this procedure is that the conventional velocity survey simulates more closely the conditions encountered in the

TABLE 1. THE DISCREPANCY BETWEEN THE CONVENTIONAL AND CONTINUOUS VELOCITY SURVEY OF THE STRATIGRAPHIC INTERVAL (TOP NIOBRARA TO TOP J-SANDSTONE)

Well #	Conventional Velocity Survey Ft/Sec	Continuous Velocity Survey Ft/Sec	Discrepancy $\Delta V/V$ cont%
C1	10560	10983	3.85
C2	11232	11855	5.26
C3	10944	11583	5.52
C5	12096	12392	2.38
C6	12000	12326	2.64
C7	12096	12400	2.45
C8	12048	12351	2.45
C9	11856	12150	2.42
C10	11796	12010	1.78

The average magnitude of discrepancy between the continuous and the conventional velocity surveys based on the above results is estimated to be approximately 4% of the continuous velocity value.

seismic velocity shooting (Gretener, 1961). The data derived from the velocity surveys are presented in the form of maps, plots, and tables. In addition all the well names, locations, and the information derived from them have been tabulated in the appendix.

Velocity Function

In order to examine the effect of the depth of burial on siesmic velocity, a logarithmic relationship has been used to relate the interval velocity and the mean depth of burial. The logarithmic relation chosen for this statistical investigation has been proposed by many workers worldwide; for example: Faust (1951, 1953); Wybrobek (1959); Acheson (1959, 1963, 1981); Fennebak (1968); Jankowsky (1970); and others. The logarithmic relationship between the velocity and the mean depth of burial is: $V = aZ^n$ (1). The parameters a and n depend mainly on the lithology and the basin position (the state of rock compaction). By taking the logarithm of both sides, the relation becomes: $\log V = \log a + n \log Z$ (2); a relationship between the log of the inteval velocity and the log of the mean depth, where the velocity distribution with the depth of burial in the study area can be examined. Faust (1953) and Acheson (1963) suggest thickness of the studied section should be not less than 1,500 feet to obtain a reliable values of the slope and the intercept of the above relation, since the average thickness of the stratigraphic interval of study is about 850 feet, a and n values can't be mapped for each individual well used in this study, but an average value for a and n can be established regionally for the stratigraphic interval and for each one of the formations within the interval. Empirical relationships established "as an average velocity-depth relation" represent the whole area for those intervals.

Residual Velocity

Values of velocity deviation (velocity anomalies) were computed and mapped throughout the study area on a percentage basis. These are computed by dividing the value of the velocity deviation (Δv) by the interval velocity value from the empirical relationship at the same depth.

$$\text{Residual Velocity \%} = \frac{\Delta v}{V_{emp.}} \; 100\%$$

RESULTS AND DISCUSSION

The data derived from the velocity surveys are presented in the form of six isopach maps, six interval velocity maps, ten velocity-depth plots, and six residual velocity maps.

1. Top J-Sandstone to Top Niobrara

1.1) Isopach Map:

An isopach map of the top J-sandstone to top Niobrara stratigraphic interval (Fig. 13) shows major northeast-southwest thinning trends along the Wattenberg paleohigh. Another northeast-southwest thinning trend in the south-west part of the area of study has been dipicted in this investigation. The thickness of the interval varies from less than 700 feet to more than 950 feet in the study area. The thinning and thickening trends are explained by Weimer (1978) as a result of peleohighs and paleolows respectively.

1.2) Interval Velocity Map:

After the velocity data of the compensated sonic logs has been adjusted to the seismic velocity data derived from the conventional check-shot survey, interval velocity map has been compiled and mapped for the stratigraphic section of study from the top of the Niobrara formation

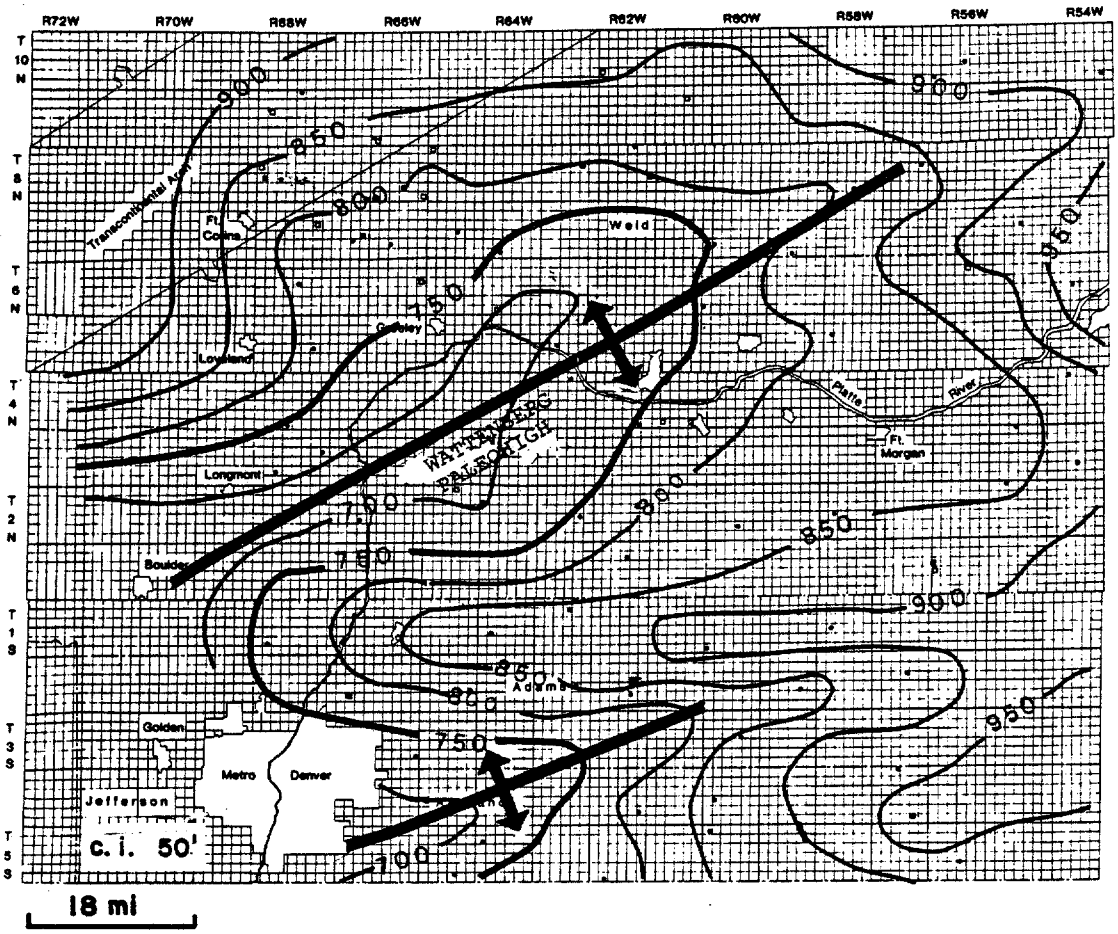

FIGURE 13. TOP NIOBRARA TO TOP J-SANDSTONE ISOPACH MAP

to the top of the Dakota J-sandstone. Interval velocity map (Fig. 14) shows northeast-southwest trends of increasing velocity values. These trends of increased velocity coincide with the thin trends on the isopach map of this interval (Fig. 13). The velocity value of the stratigraphic interval varies from 10,000'/sec (in the areas of thickening on the isopach map) to about 12,500'/sec (in the areas of thinning on the isopach). This correspondence may reveal that paleostructures influenced the seismic velocity of the Cretaceous stratigraphic intervals in the study area. The increase in the velocity value from 10,000'/sec to 12,500'/sec (Fig. 14) is considered to be abnormally high if compared with the increase of the mean depth from 4,000' to 8,000' in the study area (Fig. 6). Since the velocity is subjected to other factors, such as the lithologic variation (shale, carbonate, and sandstone) with different matrix velocity values and may be predominantly to the state of compaction of the rock, obviously it is illogical to relate any increase in the velocity value to the paleostructure without correction of the lithologic factor. By examining the degree of radiation of gamma ray logs the shale carbonate ratio is variable over the study area. From the logs involved in the study, the lithology of this stratigraphic interval along

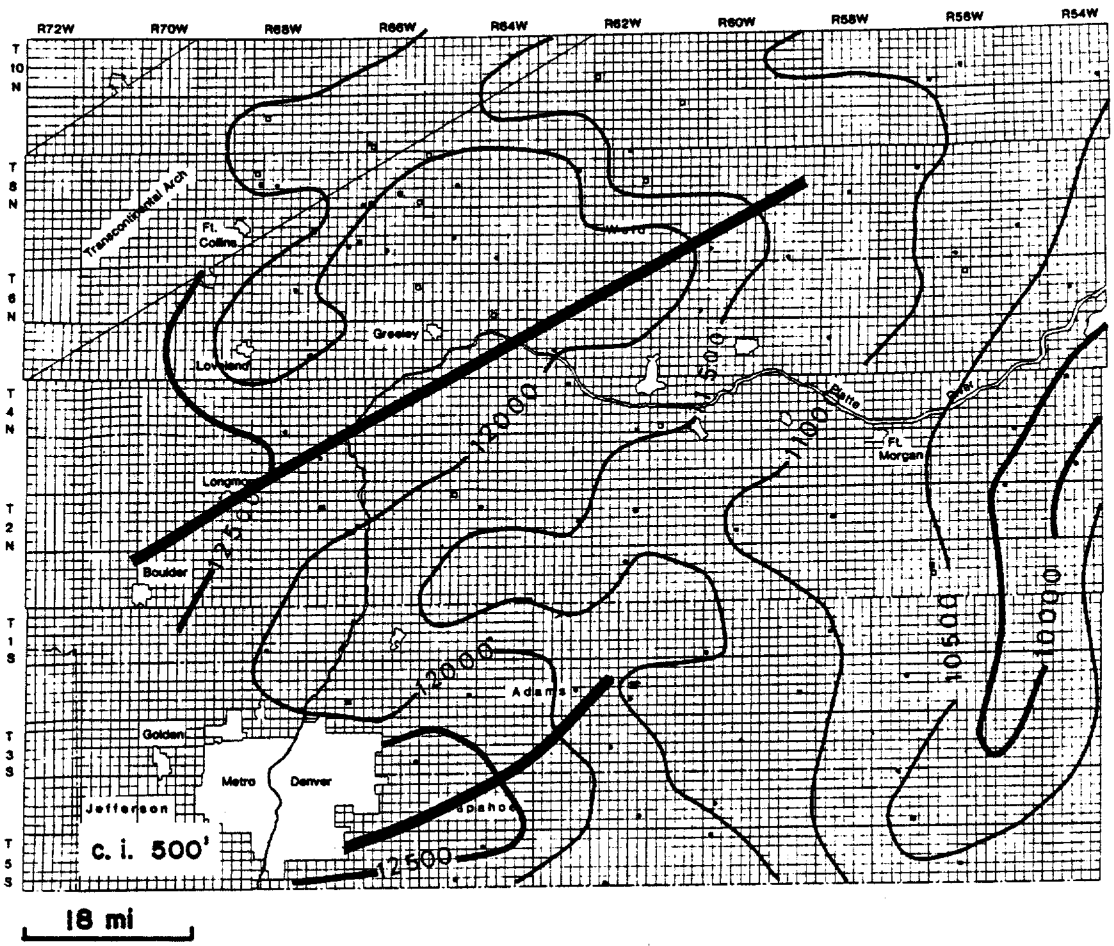

FIGURE 14. TOP NIOBRARA TO TOP J-SANDSTONE INTERVAL VELOCITY MAP

east-west cross section (Fig. 15) is found to be non-uniform through the area of study (Fig. 16). So the increase in the velocity values is not attributable to the effect of the paleostructures only, but to the lithologic variation too, which may be associated with the paleostructural elements as well. In the eastern part of the mapped area "low velocity region" (Fig. 14), the Niobrara formation which represents about 50% of the thickness of the whole stratigraphic interval, is predominantly shale (Fig. 16). This variation in the lithology of the studied interval requires a systematic correction throughout the area of study.

1.3) Velocity-Depth Relationship

In terms of normal lithology and depth associated with basin deposition, velocity may be expected to vary systematically in the region. From the previous discussion of the interval velocity map, a significant increase in the velocity exists along northeast-southwest trends coinciding with paleostructures. To examine the effect of depth of burial on the seismic velocity, the interval velocity is plotted against the mean depth according to logarithmic relationship: $\log V = \log a + n \log Z$. (1) The plot of the log of the interval velocity against the log

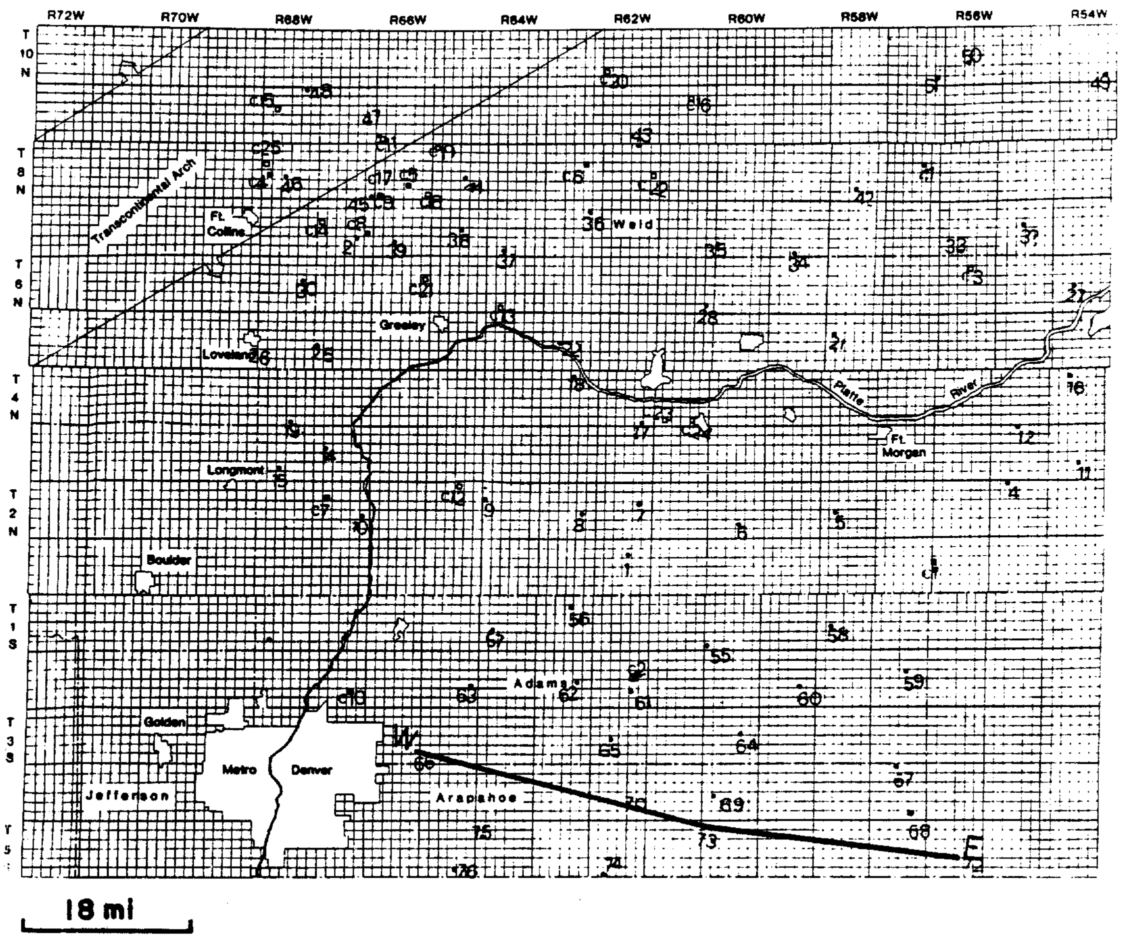

FIGURE 15. EAST-WEST CROSS SECTION.

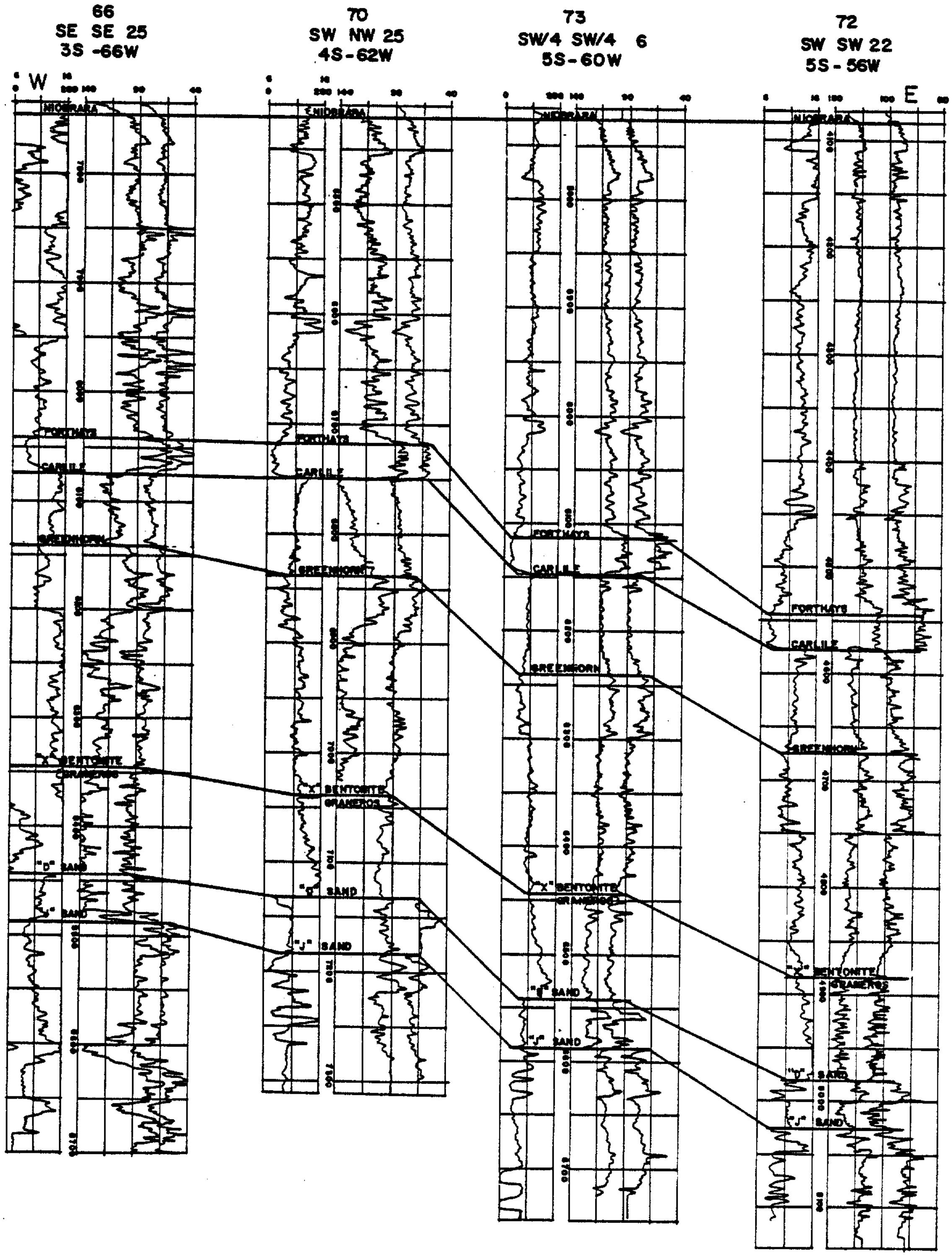

FIGURE 16. EAST-WEST CROSS SECTION ILLUSTRATES THE LITHOLOGIC VARIATION IN THE STUDY AREA (TOPS OF FORMATIONS ARE LABELLED)

of the mean depth of the stratigraphic interval of study from Top J-sandstone to Top Niobrara (Fig. 17) shows a general increase in the velocity with depth. As discussed the lithology of this stratigraphic interval is not uniform throughout the study area which tends to obscure the true relationship of the velocity to depth for the whole area. The study area can be divided into three regions based on the shale-carbonate ratio (Fig. 18) of a considerable uniform lithology by examining the log character, where a velocity-depth line-segment for each region has been established. The low-velocity region (in the eastern part of the study area) line-segment (Fig. 19); the medium-velocity region (in the central part of the study area) line-segment (Fig. 20); and the high velocity region (in the western part of the study area) line-segment (Fig. 21). The parameters log a and n "the intercept and the slope respectively" of the power-law relationship are computed for each line-segment, where the slopes of the best fit line segments are found to be approximately .181, .172, .134 for the low velocity, medium velocity and high velocity region respectively (Figs. 19, 20, 21), and the intercept values are: 2591, 2677, and 2765, respectively. By examining the basic relation the quantity n is more directly related to the pressure applied in the case of uniform lithology. From the basic relation $V = aZ^n$,

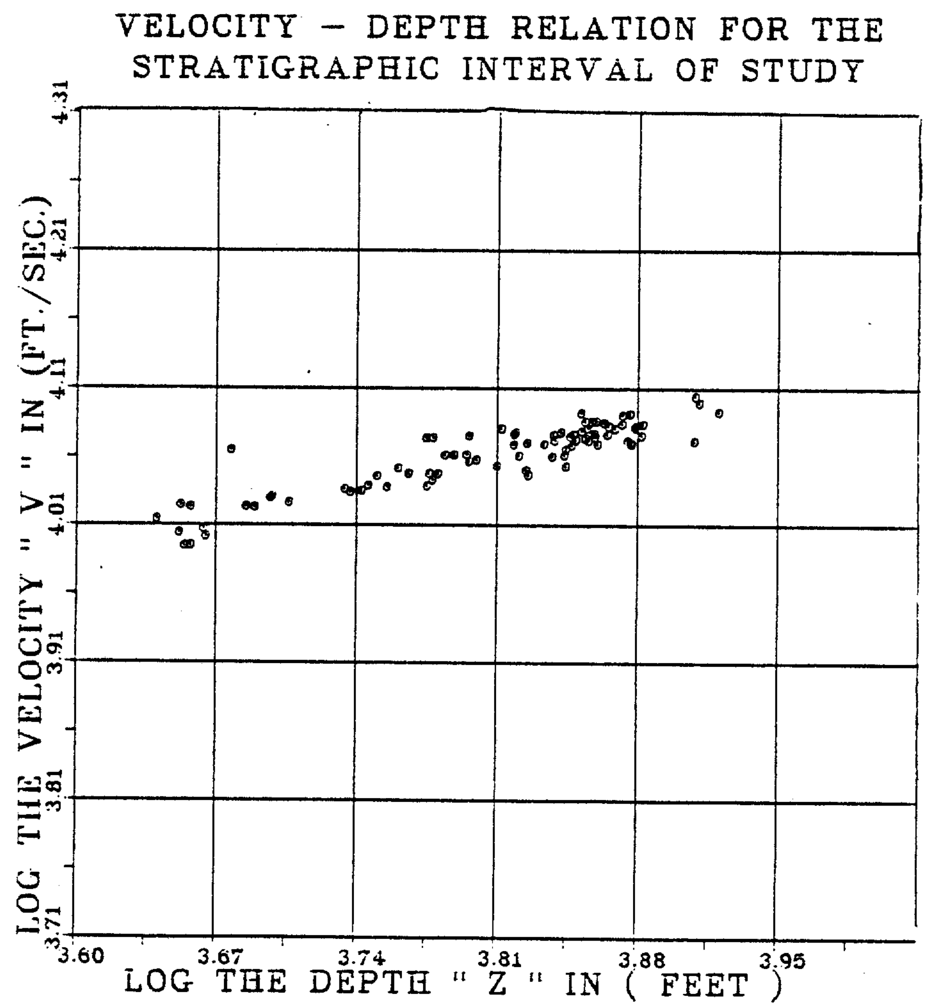

FIGURE 17. VELOCITY-DEPTH RELATION FOR THE STRATIGRAPHIC INTERVAL OF STUDY

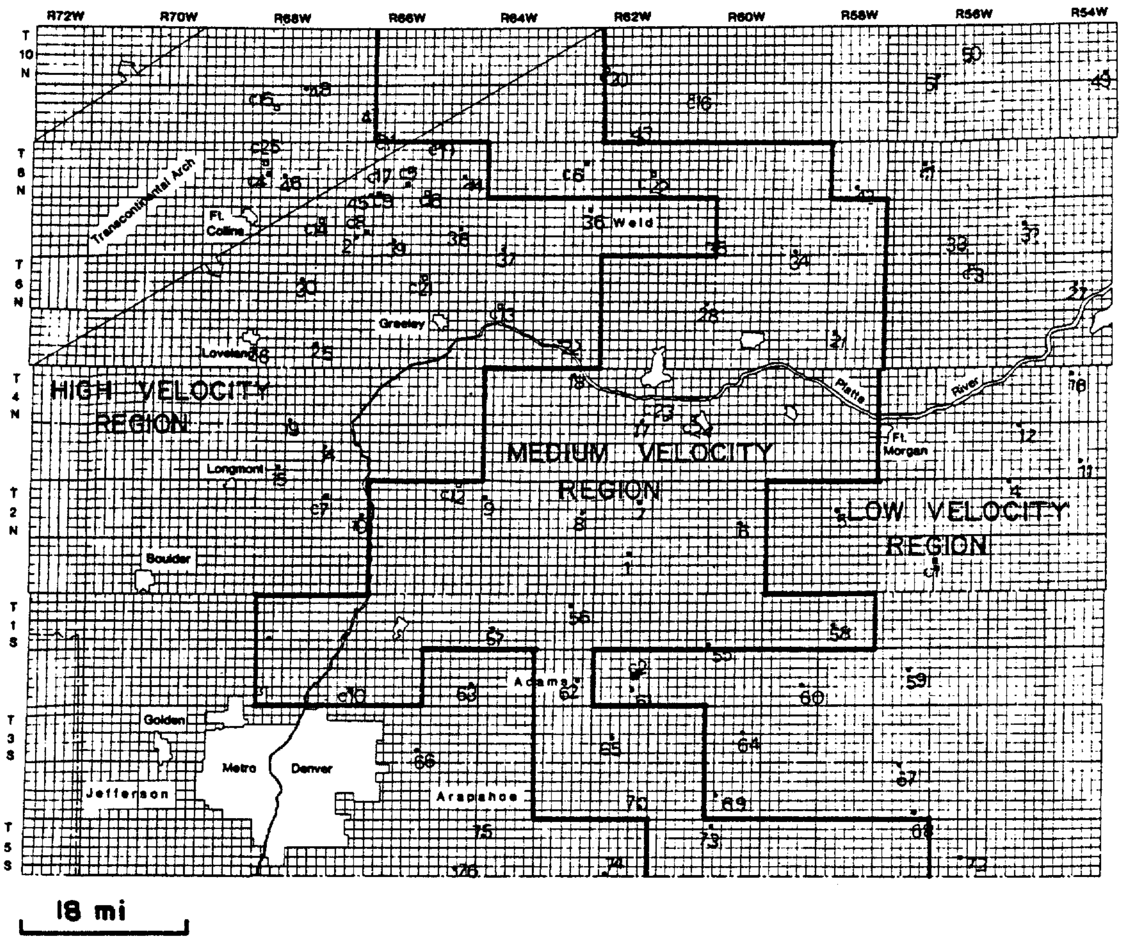

FIGURE 18. STUDY AREA DIVIDED INTO THREE VELOCITY REGIONS

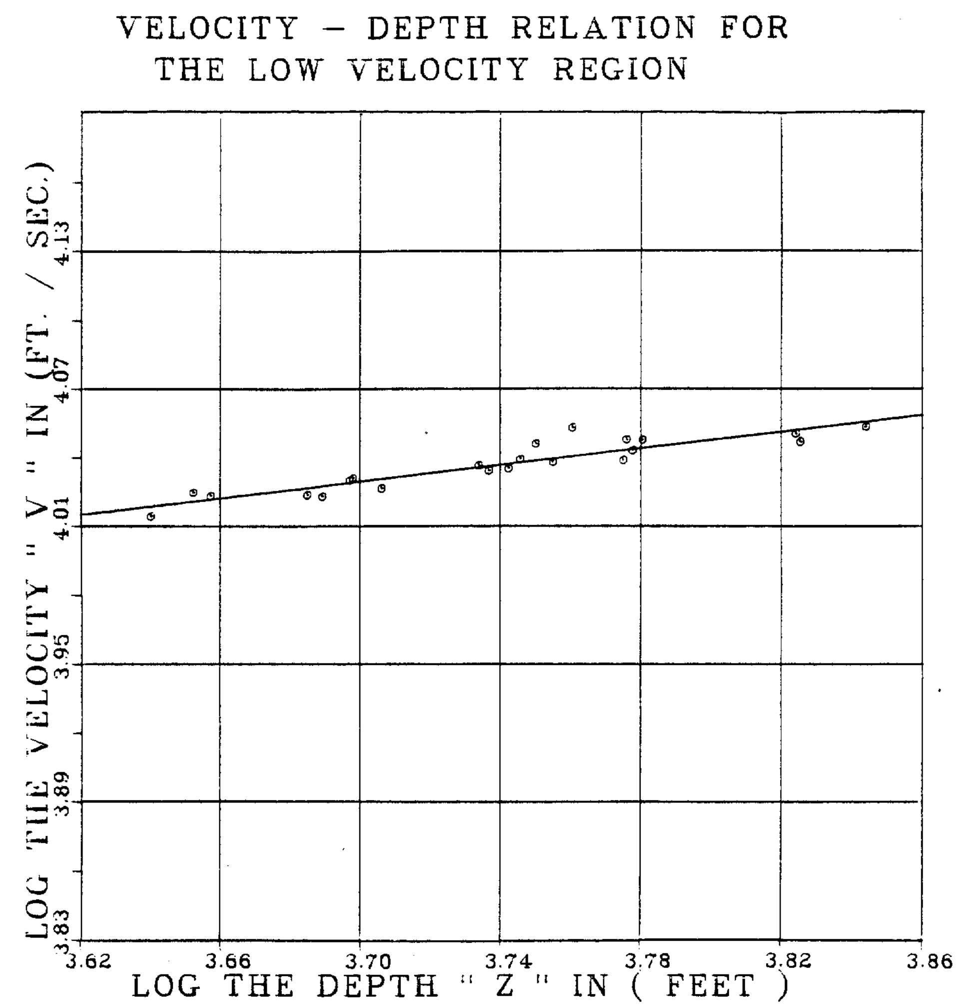

FIGURE 19. VELOCITY-DEPTH RELATION FOR THE LOW VELOCITY REGION

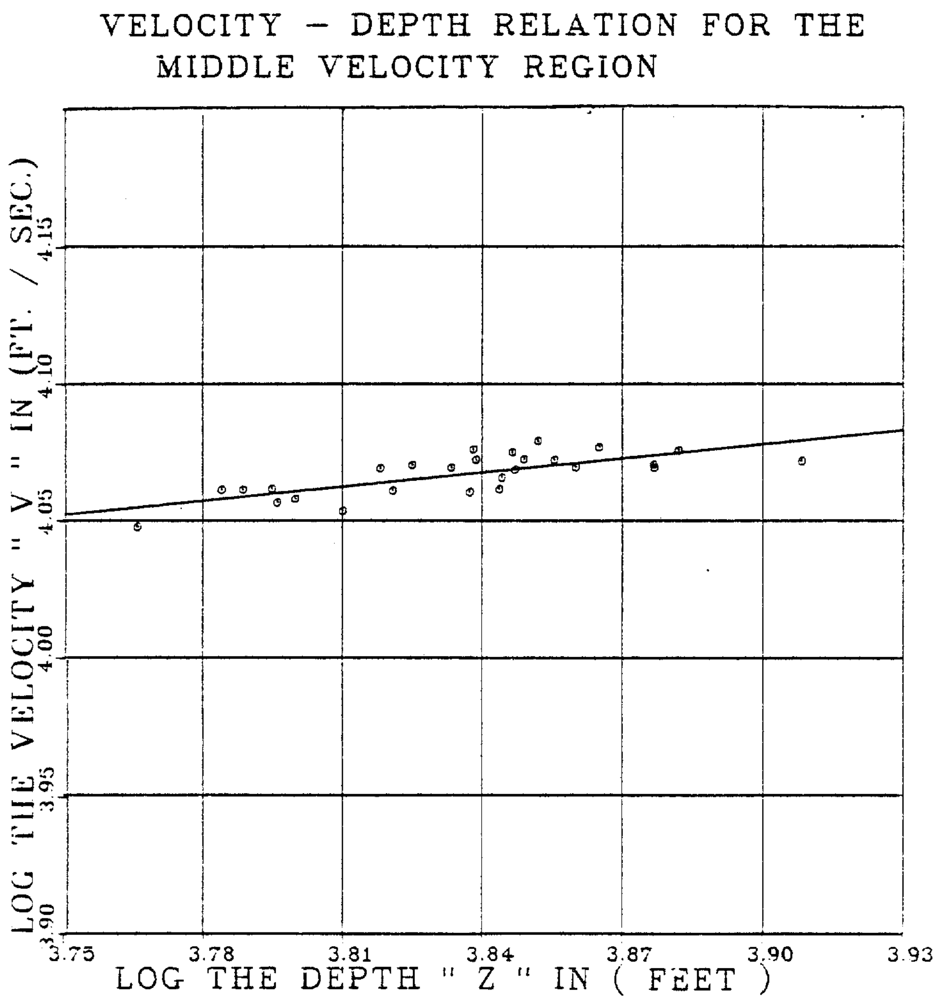

FIGURE 20. VELOCITY-DEPTH RELATION FOR THE MEDIUM VELOCITY REGION

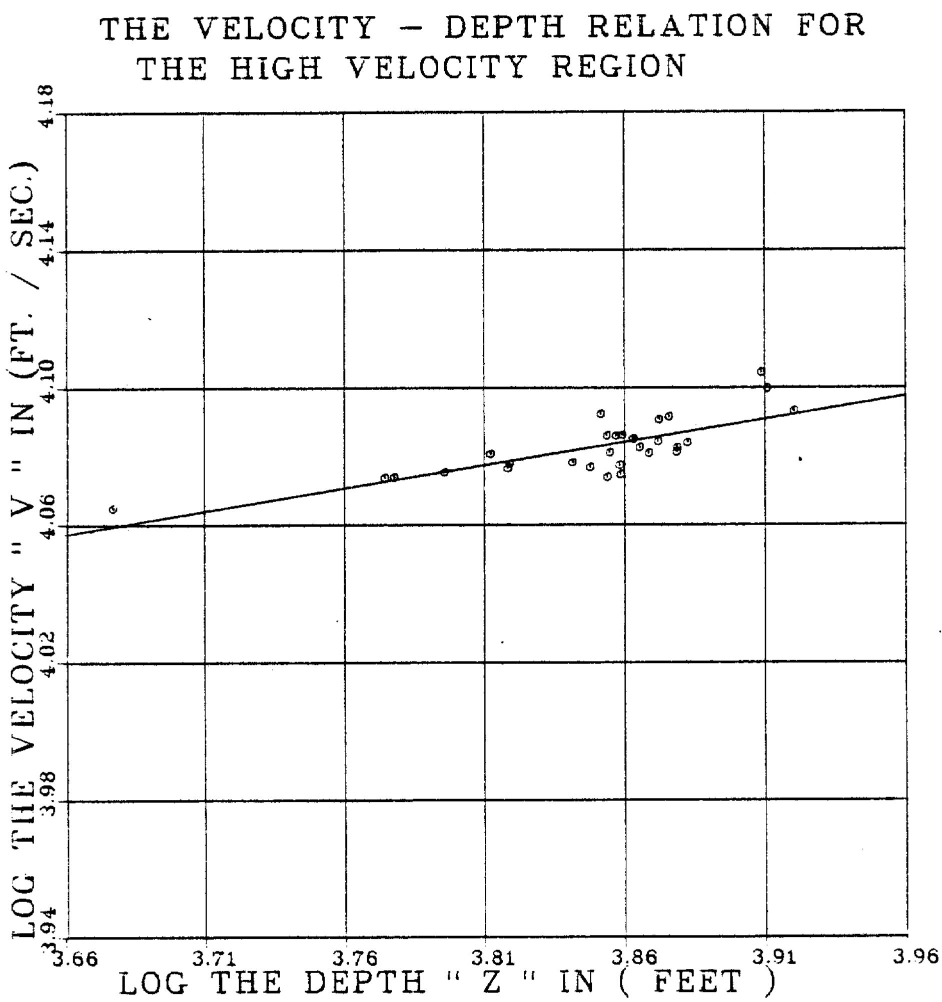

FIGURE 21. THE VELOCITY-DEPTH RELATION FOR THE HIGH VELOCITY REGION

$t = cZ^{1-n} + b$ or $t - b = cZ^{1-n}$, where t is time in m.sec, by differentiating with respect to Z and setting $\frac{\partial Z}{\partial t} = V$ (interval velocity) and $\frac{Z}{T} = \bar{V}$ (average velocity)
$\frac{\bar{V}}{V} = (1 - n)\ (1 - \frac{b}{t})$, as first approximation $b = 0$;
$\bar{V} = (1 - n)\ V$, as n decreases average velocity ($\bar{V}$) approaches interval velocity (V), where in the more compacted section the interval velocity should be nearly equal the average velocity (Acheson, 1981). One-sixth power of the depth is found to be proportional to the interval velocity Faust (1951, 1953) and Acheson (1981), but strictly under two restrictive conditions:

1) The rock comes from a normally compacting sequence in shich all fluids have always been free to escape (Anstey, 1977, p. 2.19).
2) There has been neither uplift, erosion nor structural movement, so deposition has been continous since the beginning and the present depth 'Z' is the greatest depth at which the rock has ever been buried (Acheson, 1981).

From the slope values of the three velocity regions, it is clear that they have subtle variations around the theoretical 1/6 value and the average slope value representing the whole study area is approximately 1/6. The change in the slope value (n) reveals change in lithology or as a result of compaction. Therefore, to establish an average velocity-depth relationship for the whole study area, the relationship can be written in the form: $V = az^{1/6}$ (3) or: $\log V = \log a + 1/6 \log Z$ (4). Since the intercept value of this relation "log a" which usually indicates change in gross lithology is found to vary greatly for each region, the value of "log a" is computed for each individual well involved in this study by using the above relationship and an average value of the parameter a is computed regionally for the stratigraphic interval of study from the top of Niobrara formation to the top of J-sandstone representing the whole area of study. Velocity-depth plot for the interval from the top of the Niobrara formation to the top of the Dakota J-sandstone (Fig. 22) with average velocity depth relationship for depths from 4370-8830 feet.

$$V = 2670.2\ Z^{1/6} \qquad (5)$$

From the plot (Fig. 22), a negative velocity anomalies exist at shallow depths in the eastern part of the study area (Fig. 18), are contributed to the higher percent of shale within the interval of study (Fig. 16), and may be also due to possible presence of fracturing "in the carbonate rocks". Positive velocity anamalies exist in the

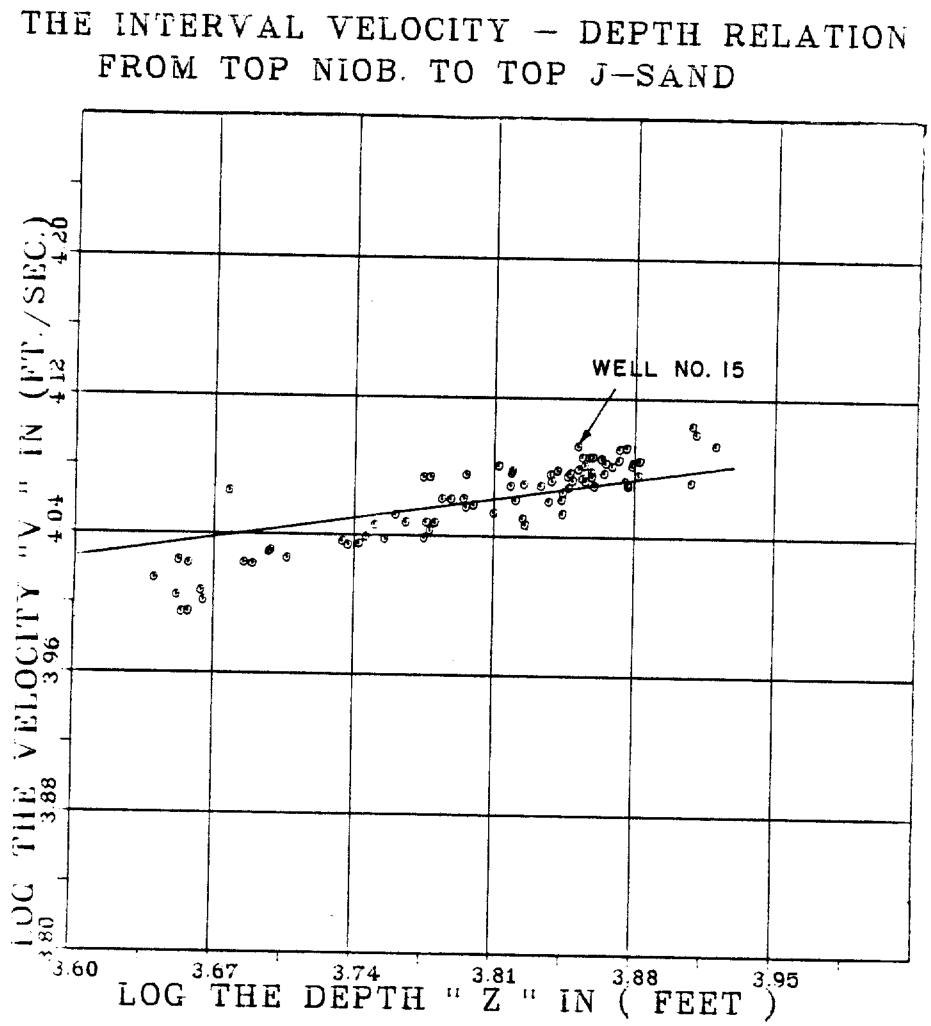

FIGURE 22. THE INTERVAL VELOCITY-DEPTH RELATION FROM TOP NIOB. TO TOP J-SAND

western part of the study area (Fig. 18). Since the velocity of sedimentary rocks corresponds to their maximum depth of burial rather than by present depth (Jankowsky, 1970) the increase in velocity values in these areas coincide with paleostructural trends (Fig. 1) may result from large magnitude of compaction, uplift, and/or erosion where at that time the top of the stratigraphic interval of study was in different position from that which is in now. The approximate amount of uplift or eroded strata d in feet "which depends on the basin position" between the maximum depth of burial and the present depth, is the amount necessary to make the interval velocity to fit the average approximation curve of the velocity-depth relation, as an example the approximate amount of uplift and/or eroded strata of the stratigraphic interval from top Niobrara to the J-sandstone at well #15 (Fig. 23) found to be approximately equal to 2780 feet. Therefore, the interval velocity is porportional to (Z + d) to the power of 1/6.

1.4) Residual Velocity Maps

By using the empirical relationship of the stratigraphic interval of study $V = 2670.2\ Z^{1/6}$, the values of the velocity deviations from the average velocity function are measured and mapped for the stratigraphic interval of

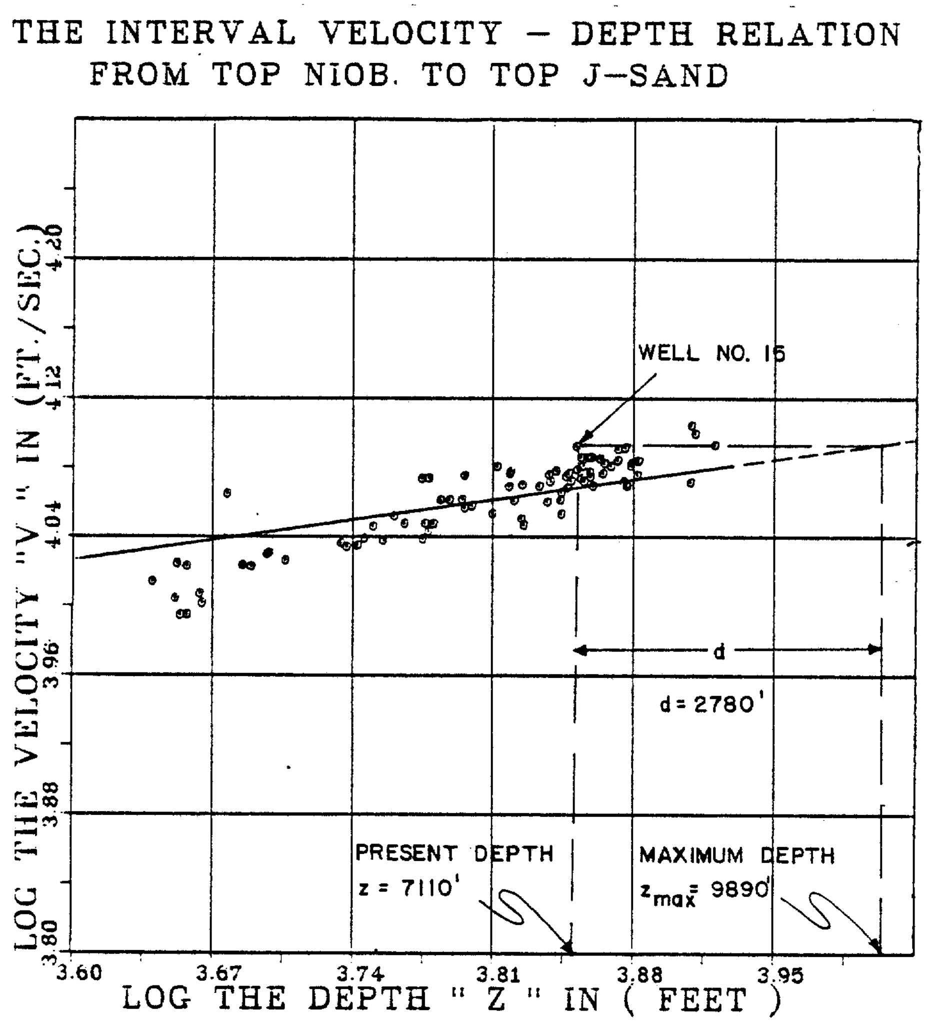

FIGURE 23. UPLIFT AND/OR ERODED STRATA OF THE STRATIGRAPHIC INTERVAL OF STUDY AT WELL #15

study. The residual velocity values are mapped on a percentage basis, by dividing the amount of the velocity deviation (Δv) by the corresponding velocity value from the average velocity-depth curve at the same depth. The residual velocity map of this interval (Fig. 24) shows a percentage of anomalies in ranges from less than -6% to about +6% of the average velocity value. The anomaly map shows that a positive anomaly trend coincides with the northeast-southwest trend of velocity increase (Fig. 14) and of the isopach thinning (Fig. 13) of this interval. Because depth effect has been excluded, this positive anomaly increase maybe related to the lithologic variations and perhaps to the effect of abnormal compaction, uplift, and/or erosion due to paleostructural influence in the region of the anomaly increase. The negative anomaly values in the eastern part of the area of study may be related to the predominantly shale occurrence and/or related to fracturing in the section. To minimize the effect of the lithologic variation in the study area the stratigraphic interval of study is divided into district stratigraphic formations, to examine the velocity behavior with each formation. These units discussed in an ascending order.

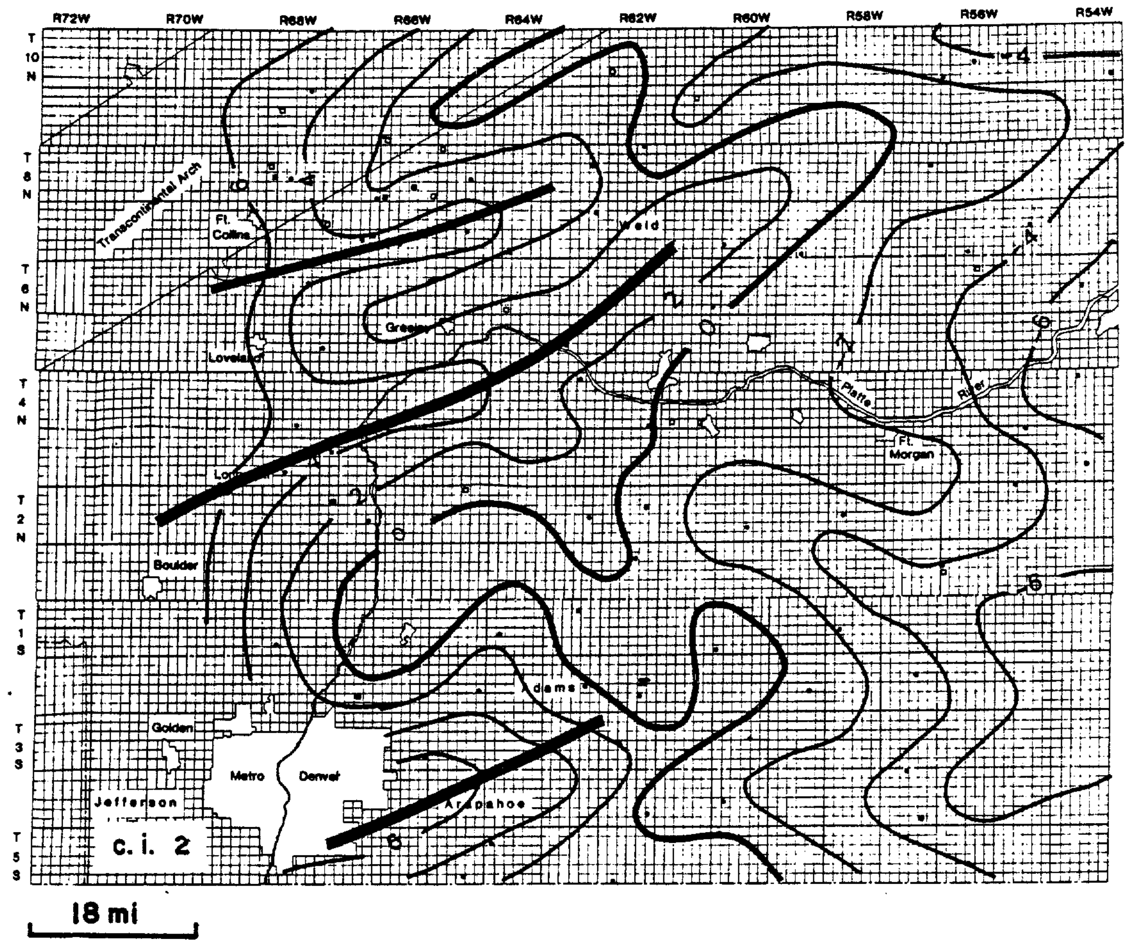

FIGURE 24. TOP NIOBRARA TO TOP J-SANDSTONE RESIDUAL VELOCITY MAP IN PERCENTAGES

2. D-sandstone and/or Mowry Shale Interval

2.1) Isopach Map:

The isopach map of the D-sandstone and/or Mowry shale (Fig. 25) in the study area shows the thickness varies from less than 50 feet in the western part of the area, where the predominant unit is the Mowry shale, to more than 80 feet toward the eastern part, where both Mowry shale and D-sandstone exist.

2.2) Interval Velocity Map:

The interval velocity of the D-sandstone and/or Mowry shale (Fig. 26) shows an increase in the velocity along the northeast-southwest trends in the west part of the mapped area. The velocity of this unit varies from less than 10,000'/sec in the northeast and southeast part of the study area to more than 11,500'/sec in the western part of the area. The isopach map for the D-sandstone (Fig. 11), mapped by Haun (1963), shows that the D-sandstone thickness varies from a wedge edge near the center to about 40' thick toward the eastern part of the study area. Isopach map of the Mowry shale in the study area (Fig. 12) has been mapped by Haun (1963) and shows that the thickness varies from zero in the southeast to about 50' thick in the northwest corner of the area. Highest velocity values of D-sandstone

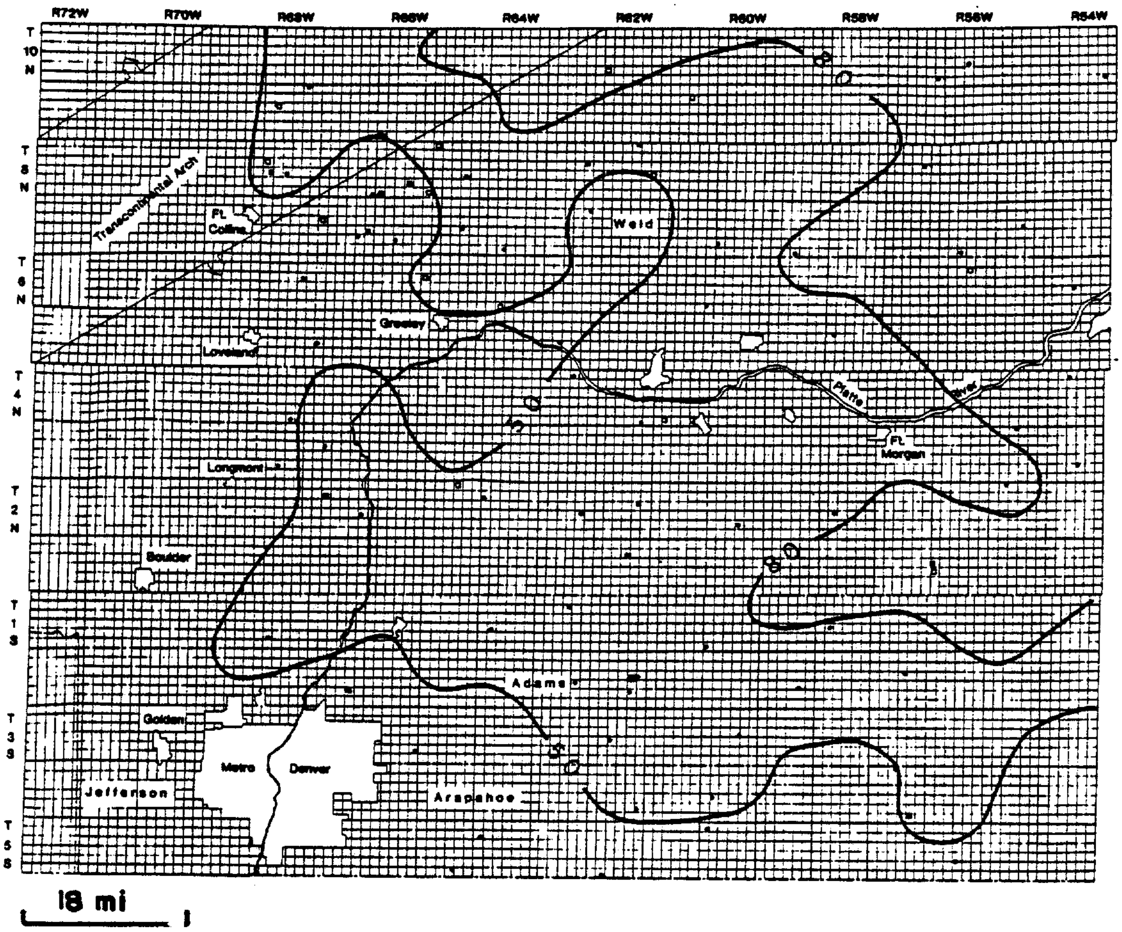

FIGURE 25. D-SANDSTONE AND/OR MOWRY SHALE ISOPACH MAP

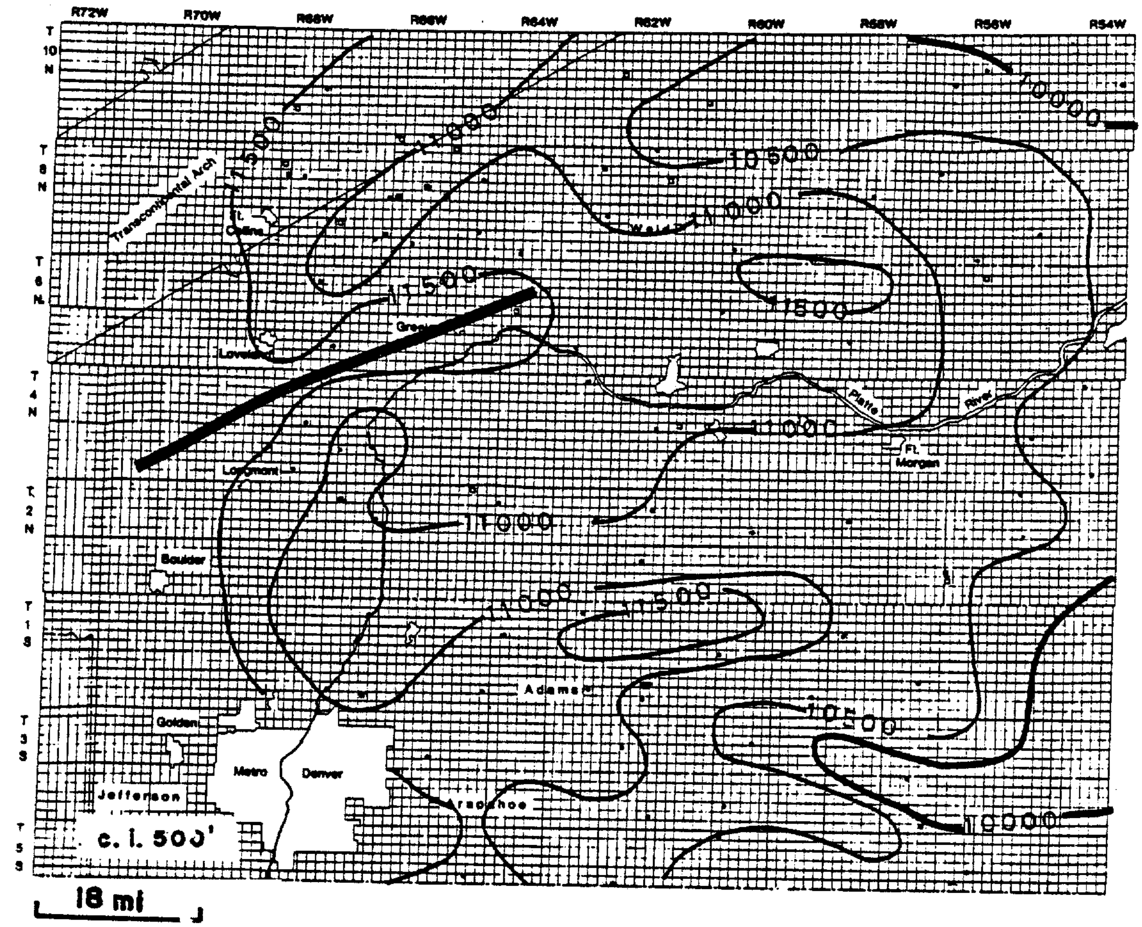

FIGURE 26. D-SANDSTONE AND/OR MOWRY SHALE INTERVAL VELOCITY MAP

and/or Mowry interval are mapped along the northeast-southwest trends in the west part of the study area (Fig. 26). As the interval is mainly shale, the increase in the velocity values is due to the effect of the overburden, and may be to the influence of the paleo-structures.

2.3) Interval Velocity - Depth Relation:

From relation (4) a numerical value for the parameter (a) is computed. Average velocity function of the D-sandstone and/or Mowry shale interval in the area of study (Fig. 27) for depths from 4735 to 8655 feet is:

$V = 2511.6\ Z^{1/6}$ (6)

2.4) Residual Velocity Map:

The residual velocity map (Fig. 28) shows that the velocity anomaly varies from less than -6% to about +6% of the velocity value. The negative anomaly in the south and in the north part of the mapped area is associated with the regions where the unit mainly consists of Mowry shale. The positive anomaly in the northeastern part of the study area are associated with the deposition of a thick D-sandstone unit which has higher matrix velocity than the Mowry shale. The highest positive anomaly values in the northwestern part of the area may be related to the

THE INTERVAL VELOCITY – DEPTH RELATION
FOR D–SANDSTONE INTERVAL

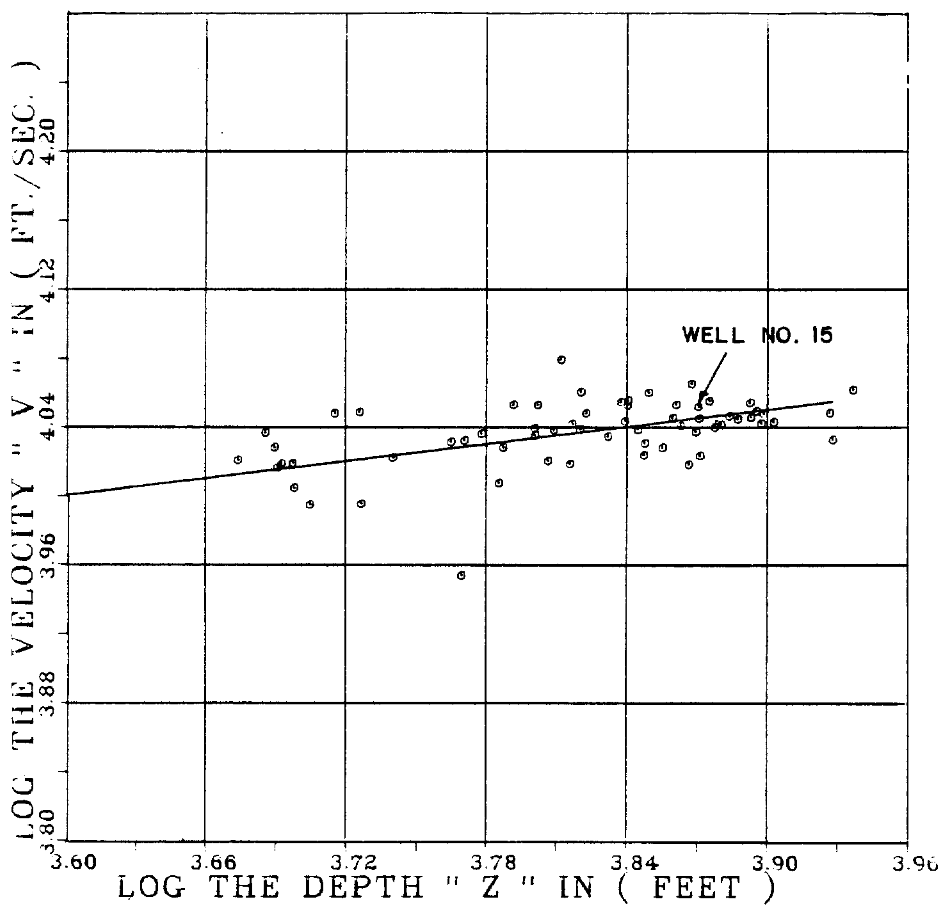

FIGURE 27. THE INTERVAL VELOCITY-DEPTH RELATION FOR D-SANDSTONE INTERVAL

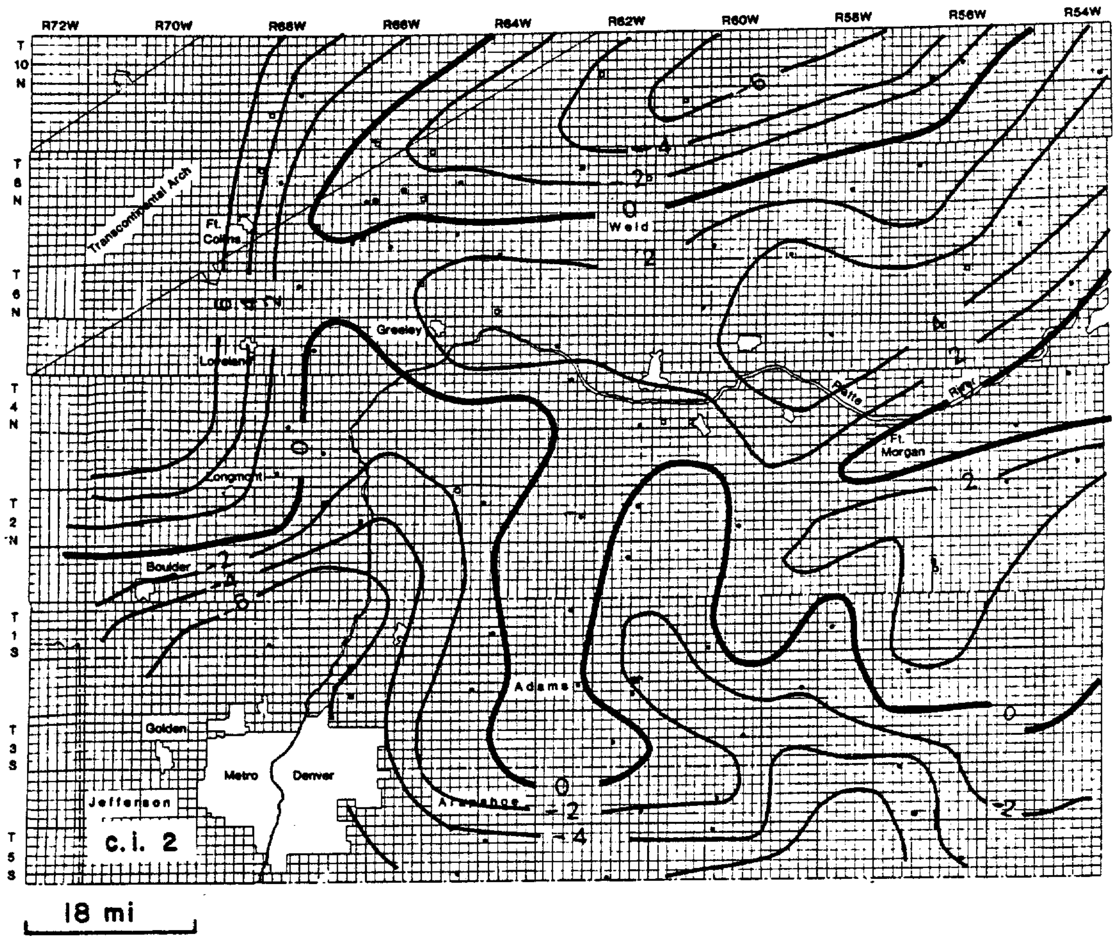

FIGURE 28. D-SANDSTONE AND/OR MOWRY SHALE RESIDUAL VELOCITY MAP IN PERCENTAGES

effect of the paleostructure, since in this area, the interval is mainly shale.

3. Graneros "Bentonite" Formation

3.1) Isopach Map:

The isopach map of the Graneros formation (Fig. 29) shows general northwest thickening in the study area. Weimer (1978) explained the thickening toward the northwest as a result of a higher rate of deposition. The thickness ranges from 80 feet to more than 160 feet toward the northwest.

3.2) Interval Velocity Map:

The interval velocity map of Graneros formation (Fig. 30) shows that the velocity varies from less than 8,500'/sec in the eastern part of the mapped area to more than 10,500'/sec in the western part. The highest increase in the velocity is found along the northeast-southwest trends. Since the lithology of the formation is extremely uniform throughout the study area "organic marine shale" the velocity anomaly map of this formation will be considered as the key map in the interpretation of the effect of the paleostructures on the velocity of the Cretaceous formations.

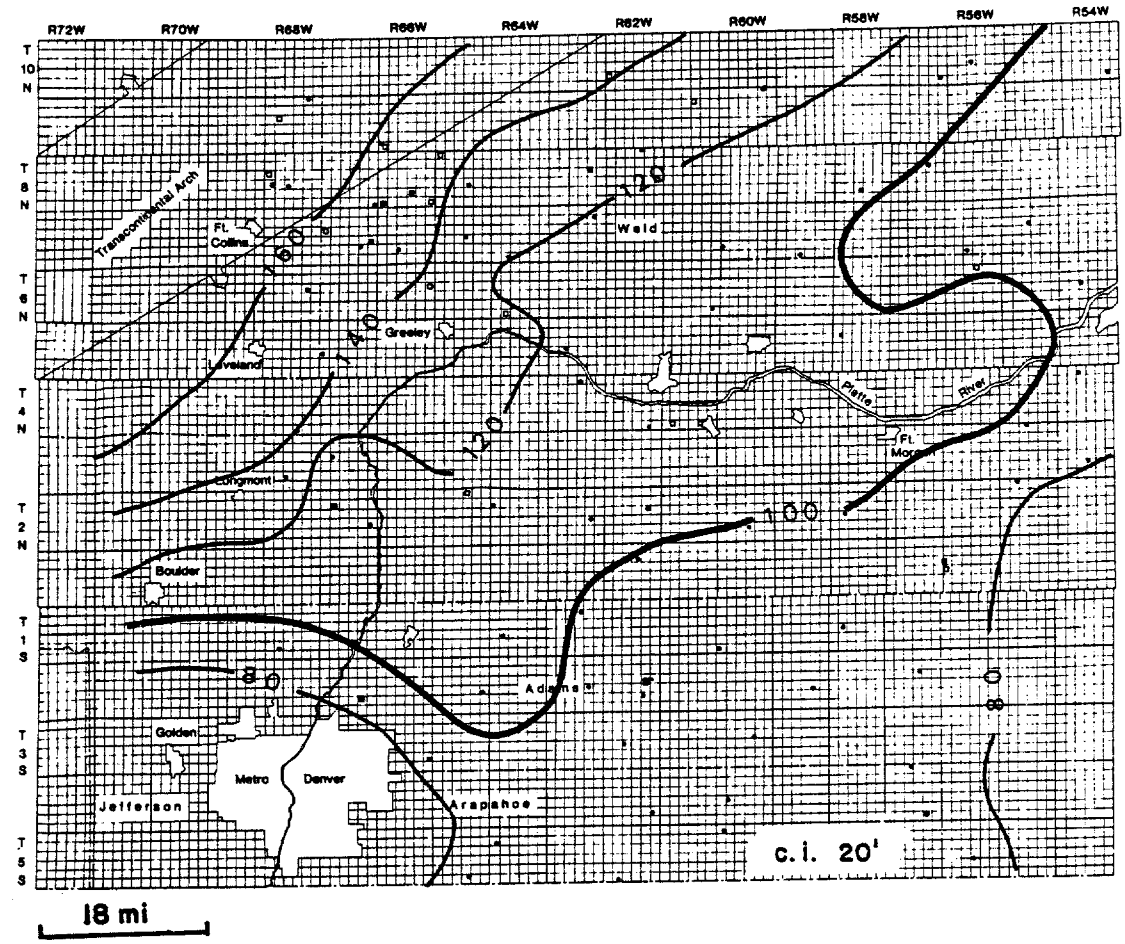

FIGURE 29. GRANEROS "BENTONITE" ISOPACH MAP

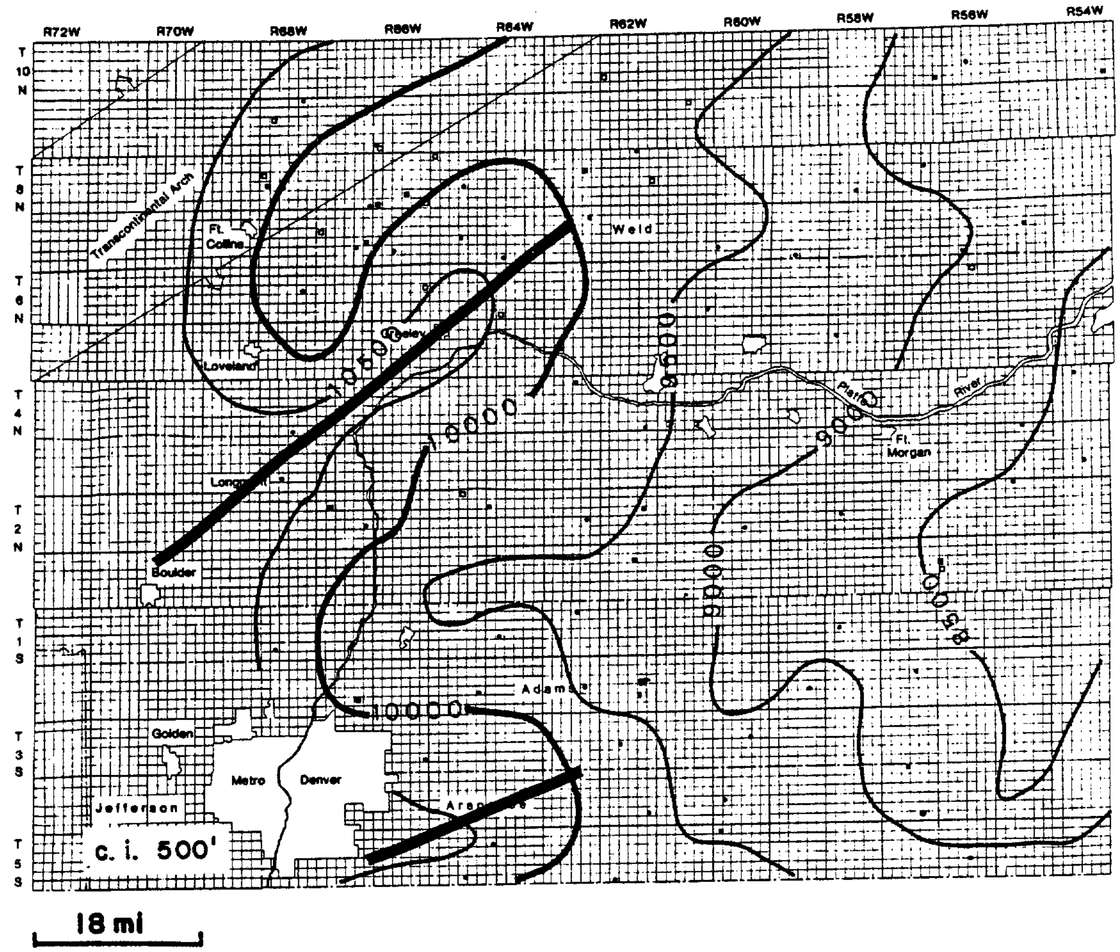

FIGURE 30. GRANEROS "BENTONITE" INTERVAL VELOCITY MAP

3.3) Velocity-Depth Relationship:

The average velocity function of Graneros interval (Fig. 31) for depths from 4650 to 8590 feet is:

$$V = 2185.9\ Z^{1/6} \qquad (7)$$

3.4) Residual Velocity:

The residual velocity map of the Graneros "Bentonite" formation (Fig. 32) shows positive anomaly values increase along the paleostructure trends. Since the lithology of this formation is extremely uniform throughout the study area "by examining the gamma-log curve," the possible interpretation of positive anomaly values along these trends is that the formation has been subjected to more compaction, uplifting, and/or erosion of pre-existing load therefore decreasing of the porosity values and increasing both density and velocity values and may be subjected to significant magnitude of uplifting from the maximum depth of burial. Therefore, this stratigraphic unit may be used as a key unit in the interpretation of the effect of the paleostructure on the velocity of the Cretaceous marine sediments in the study area.

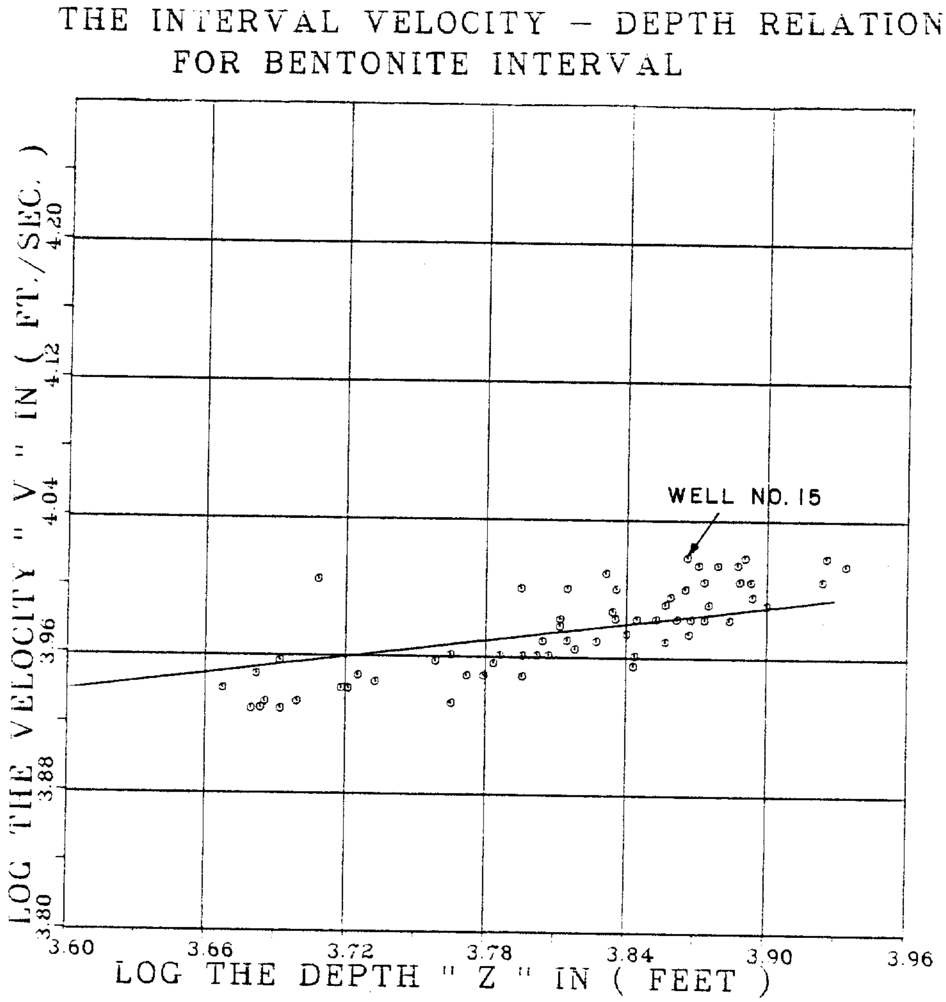

FIGURE 31. THE INTERVAL VELOCITY-DEPTH RELATION FOR BENTONITE INTERVAL

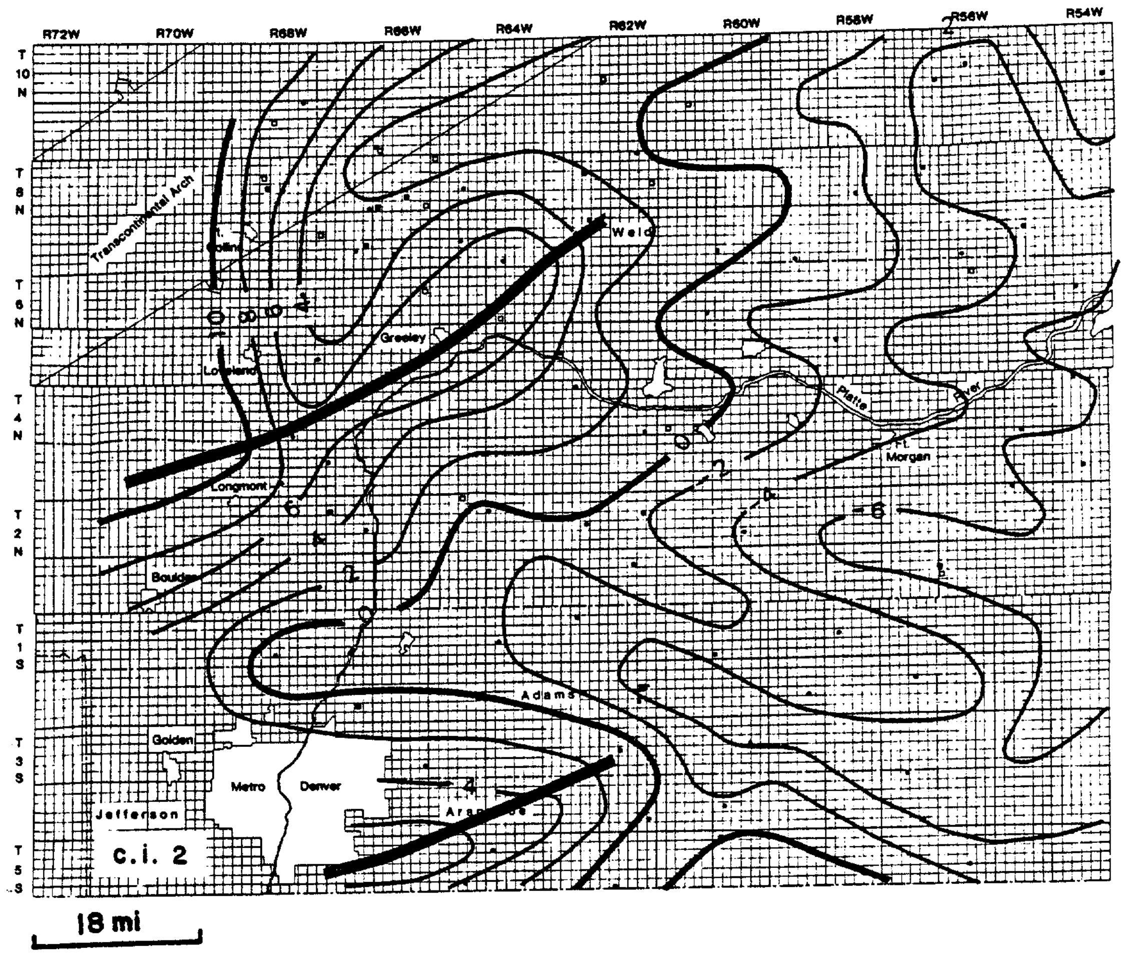

FIGURE 32. GRANEROS "BENTONITE" RESIDUAL VELOCITY MAP IN PERCENTAGES

4. Greenhorn Formation

4.1) Isopach Map:

The isopach map of the Greenhorn formation (Fig. 33) shows general northward thickening, where the thickness ranges from less than 200 feet to more than 260 feet toward the north. Sonnenberg (1981) reported that the thickening trend toward the north coincides with an axes of a paleo-structure feature in Colorado named the Morgan County low. In the surface cross section in the west part of the study area (in Golden, Boulder, and Fort Collins) Sonnenberg reported a thickness of about 150 feet for the Greenhorn formation.

4.2) Interval Velocity Map:

The interval velocity of the Greenhorn formation (Fig. 34) shows that the velocity varies from less than 10,000'/sec to more than 12,000'/sec in the study area. Lithology of this formation consists of shales, and carbonates with different ratios within the formation throughout the study area. General patterns of the interval velocity map of the Greenhorn formation are similar to the general patterns of the other formations discussed earlier.

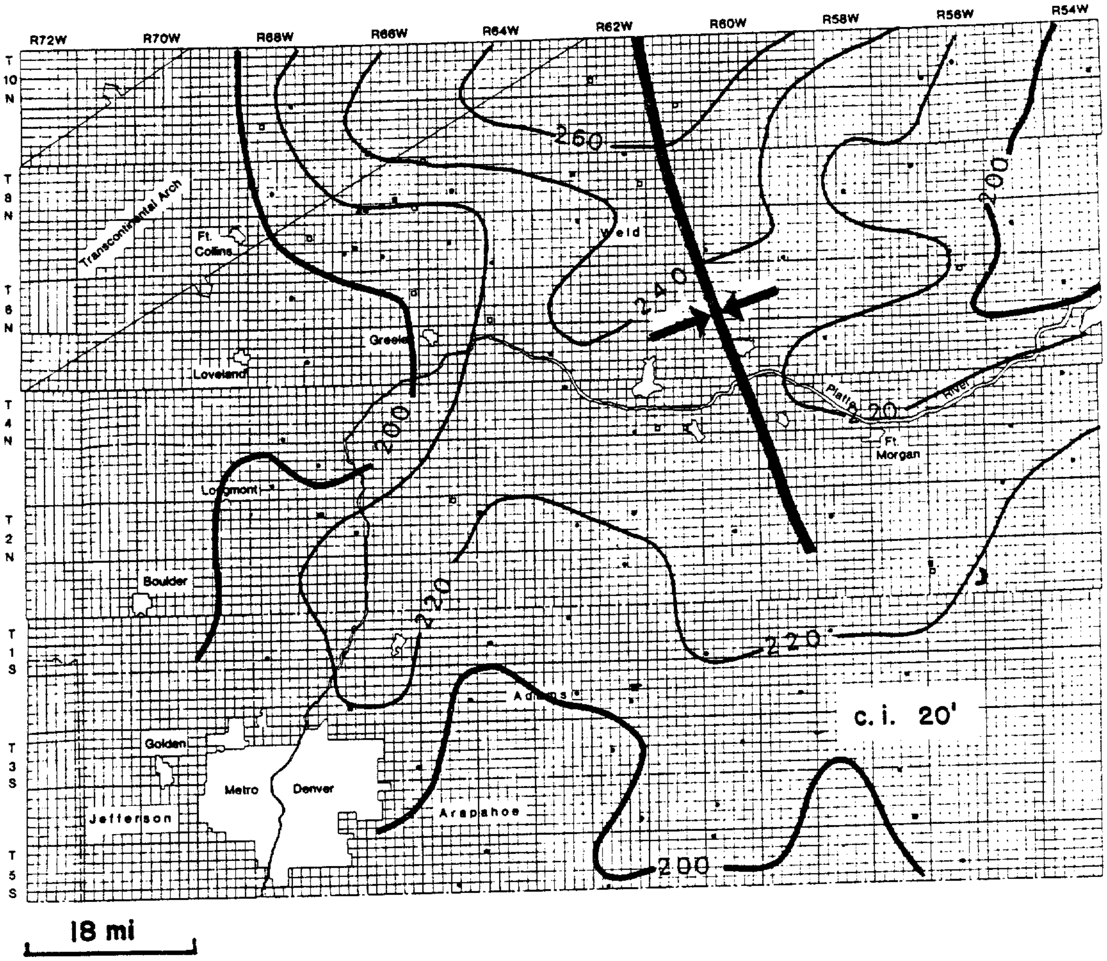

FIGURE 33. GREENHORN ISOPACH MAP

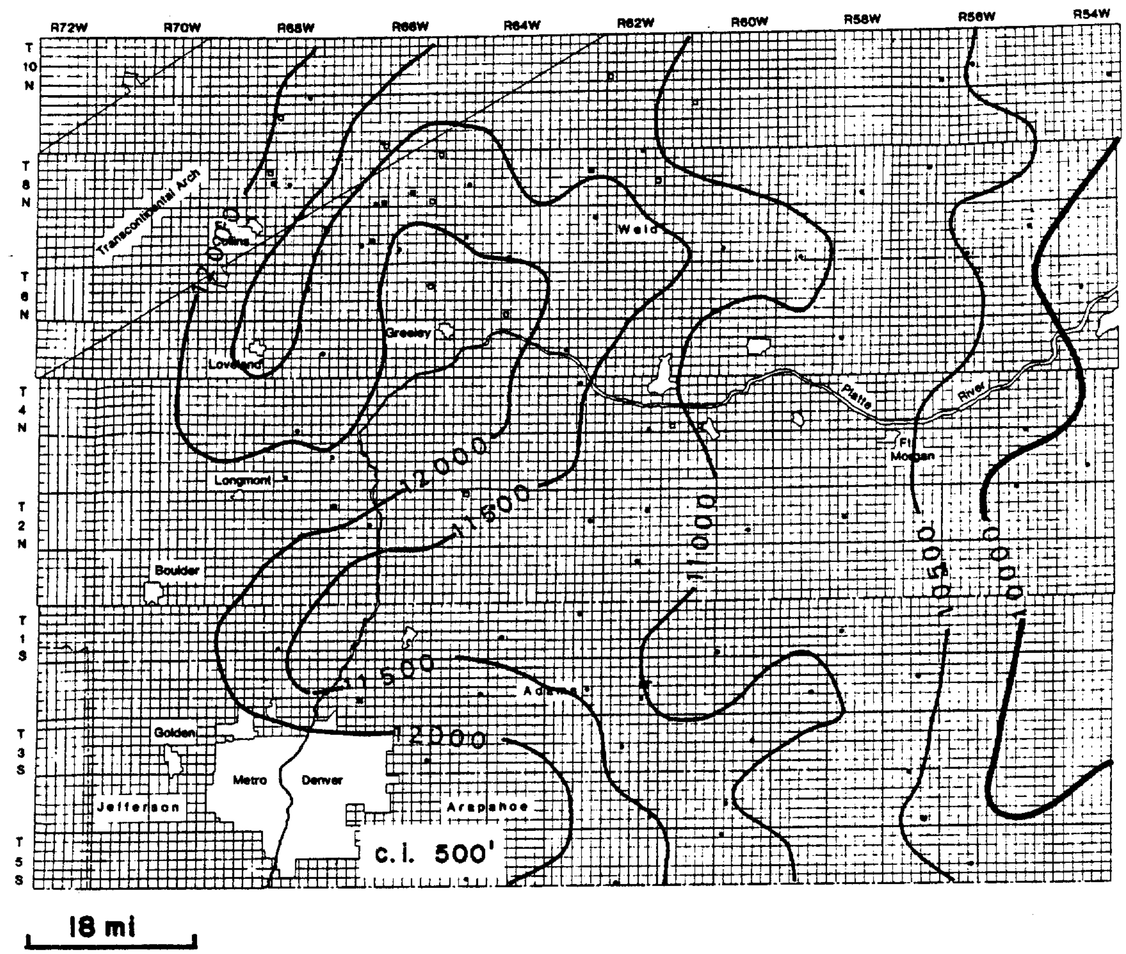

FIGURE 34. GREENHORN INTERVAL VELOCITY MAP

4.3) Interval Velocity-Depth Relationship:

The empirical relationship of Greenhorn formation (Fig. 35) for depths from 4505 to 8450 feet is:

$$V = 2590.5\ Z^{1/6}$$

4.4) Residual Velocity Map:

The residual velocity map (Fig. 36) of this interval shows velocity anomaly varies from less than -8% to about +6% of the velocity value in the study area. In general the residual map follows the same patterns of the anomaly distribution noticed on the previous residual maps.

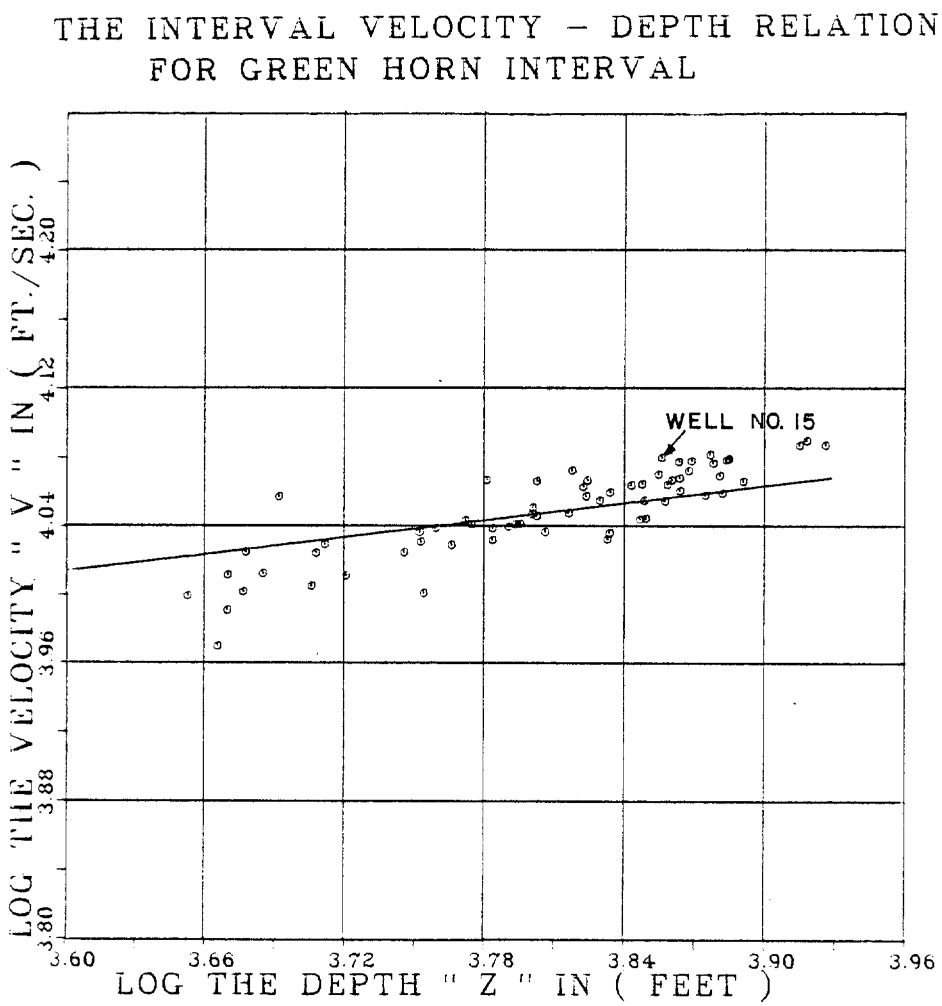

FIGURE 35. THE INTERVAL VELOCITY-DEPTH RELATION FOR GREENHORN INTERVAL

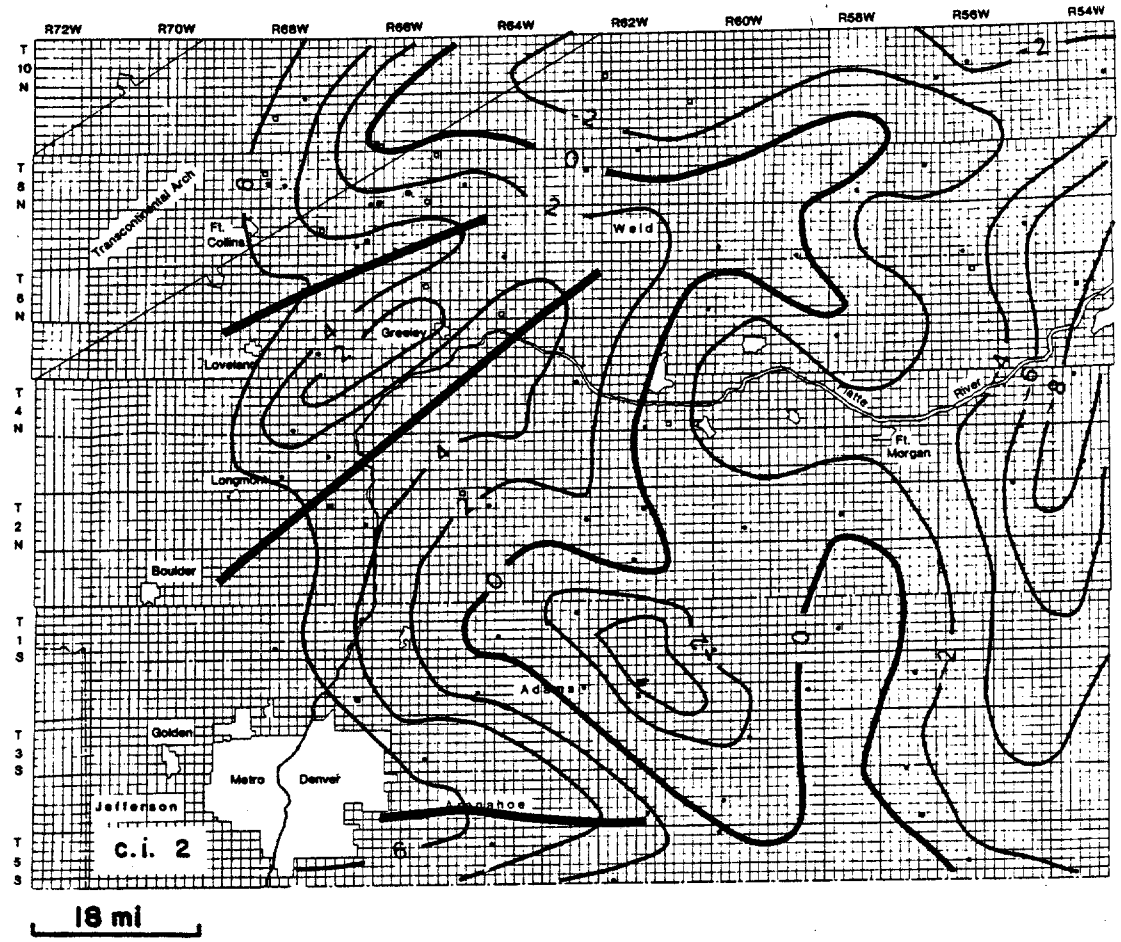

FIGURE 36. GREENHORN RESIDUAL VELOCITY MAP IN PERCENTAGES

5. Carlile Formation

5.1) Isopach Map:

The isopach map of the Carlile formation (Fig. 37) shows reverse patterns of thickening and thinning from the underlaying Greenhorn formation along the Morgan County low. In the western part of the mapped area two thinning northeast-southwest trends are mapped. Weimer (1978) related the thinning in the Carlile to the Laramie Range uplift, where apparently strata were uplifted and eroded during and/or after Carlile deposition. Thickness of the Carlile in the mapped area ranges from less than 40 feet thick in the Wattenberg gasfield area, to more than 200 feet thick in the northeastern part of the area. Two thinning trends of the Carlile formation mapped in the area seem to coincide with the thinning northeast-southwest thinning trends of the Niobrara formation, which Weimer (1978) related that to the Transcontinental arch uplift. From the isopach of this interval, it is reasonable to believe that second-order fault blocks superimposed on the top of the Transcontinental arch have been active after the deposition of the Carlile formation.

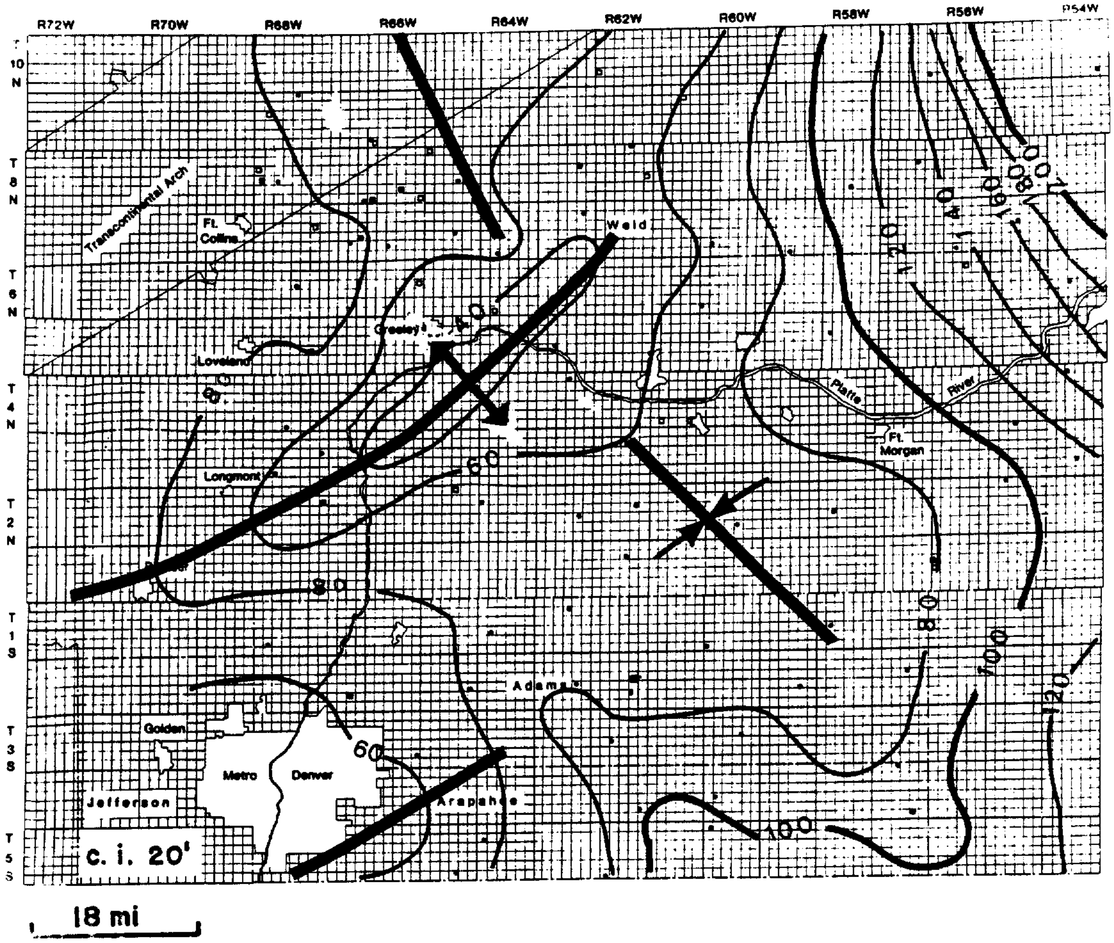

FIGURE 37. CARLILE ISOPACH MAP

5.2) Interval Velocity Map:

The interval velocity map of the Carlile formation (Fig. 38) shows that the velocity varies from less than 10,000'/sec to more than 13,000'/sec in the mapped area. The velocity map shows similar patterns to the other formations. Velocity increases along the axes of thinning on the isopach map of this interval (Fig. 37). By examining the character of the gamma logs used, the lithology of the Carlile formation (mainly shale) is considered to be uniform throughout the study area. Increase in the velocity along the northeast-southwest trends is interpreted to result from the effect of the overburden and maybe to associated forces, due to block movements along these trends.

5.3) Interval Velocity-Depth Relationship:

The average velocity function of the Carlile (Fig. 39) for depths from 4340 to 8315 feet is:

$$V = 2643\ Z^{1/6} \qquad (9)$$

5.4) Residual Velocity Map:

The residual velocity map (Fig. 40) of the Carlile shows velocity anomaly varies from -8% to about +10% of the velocity value. The positive anomaly values increase along a major northeast-southwest trend. The Carlile is

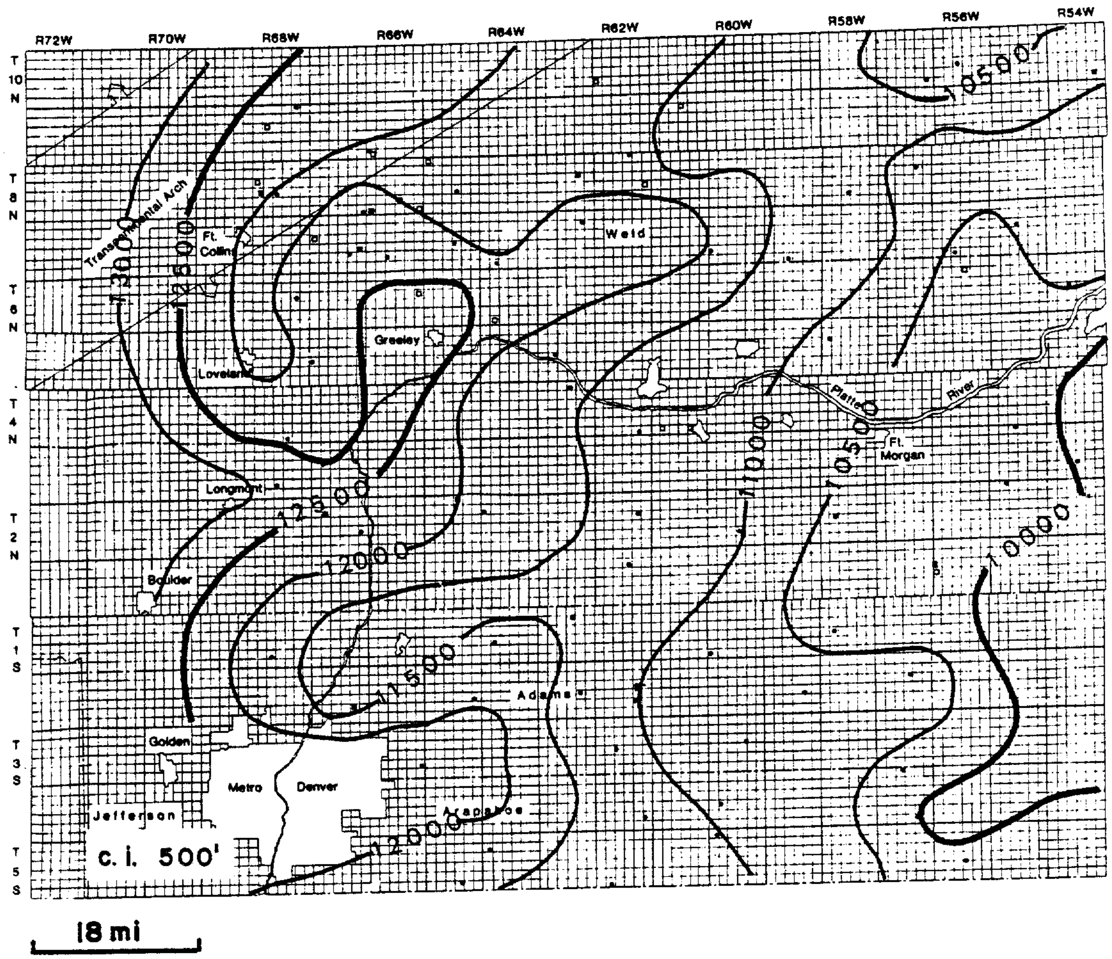

FIGURE 38. CARLILE INTERVAL VELOCITY MAP

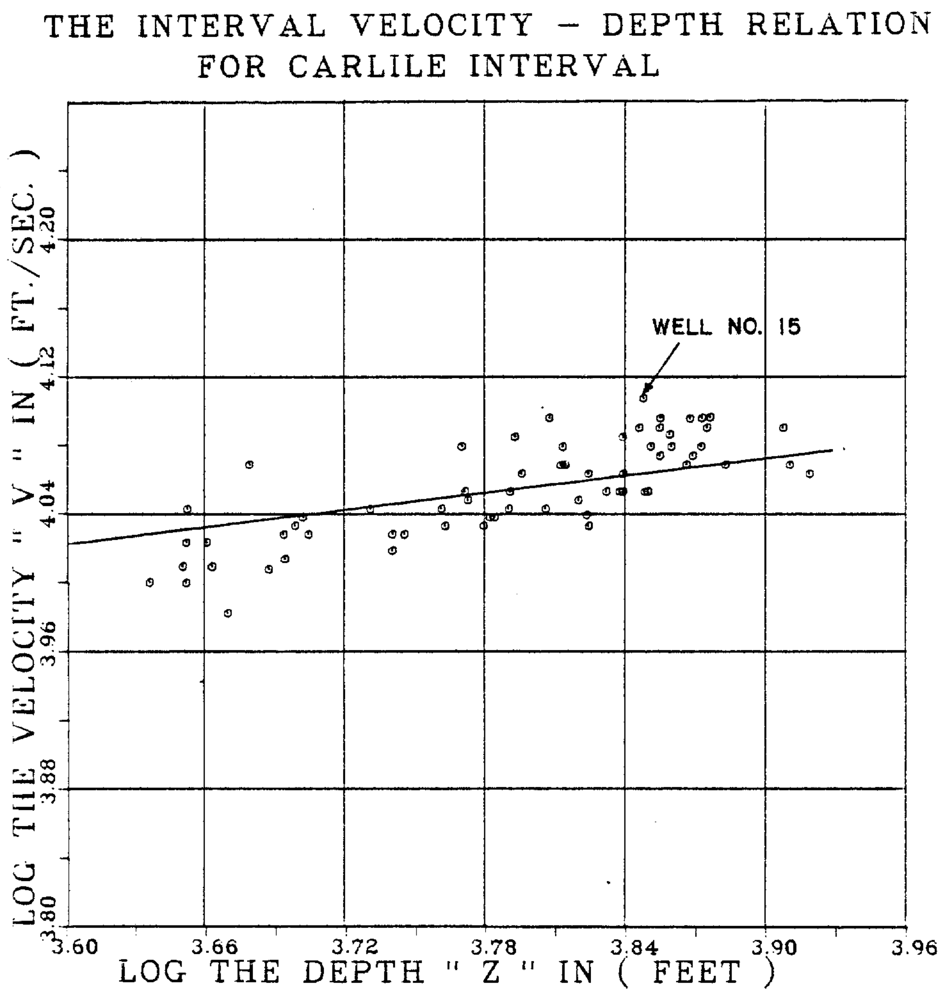

FIGURE 39. THE INTERVAL VELOCITY-DEPTH RELATION FOR CARLILE INTERVAL

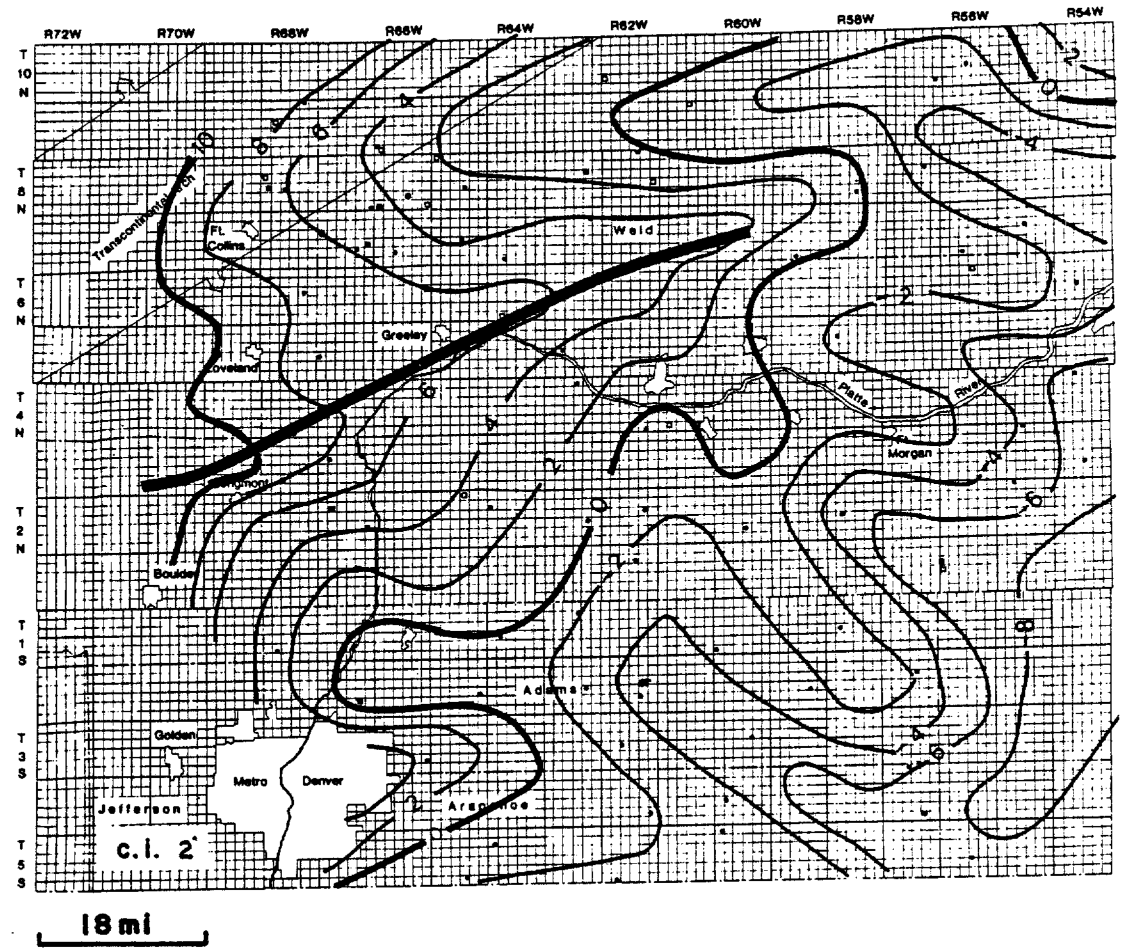

FIGURE 40. CARLILE RESIDUAL VELOCITY MAP IN PERCENTAGES

considered to be of uniform lithology to a certain degree, "mainly shale," considering the amount of the gamma-log radiation of the well logs involved in this study. Therefore, the increase in the velocity anomaly along the northeast-southwest trend which coincides with the paleostructure trend may be explained that the Transcontinental arch uplift influenced the Cretaceous formations by increasing the velocity of these formations.

6. Niobrara Formation

6.1) Isopach Map:

The isopach map of the Niobrara formation shows areas of thinning and thickening (Fig. 41). The thickness in the study area varies from less than 250 feet thick to more than 500 feet thick. A major trend of thinning is a northeast-southwest trend "Wattenberg paleohigh". Another thinning northeast-southwest trend is depicted in the southwest part of the mapped area. An unconformity at the Niobrara-Pierre shale contact was reported by Leroy and Schieltz (1958). In the west-central part of the study area, Weimer (1980) reported that the upper chalk member of the Niobrara formation and part of the underlying shale unit was removed by erosion or bevelling due to the unconformity event. Weimer (1978, 1980), mapped the paleo-structure trends in the area, where he concluded that the thinning in the Niobrara is related to the Transcontinental arch. This thinning is also believed to be a result of convergence and onlap onto the broad structure, Weimer (1982).

6.2) Interval Map:

The interval velocity of this formation (Fig. 42) shows an increase of the velocity values along the

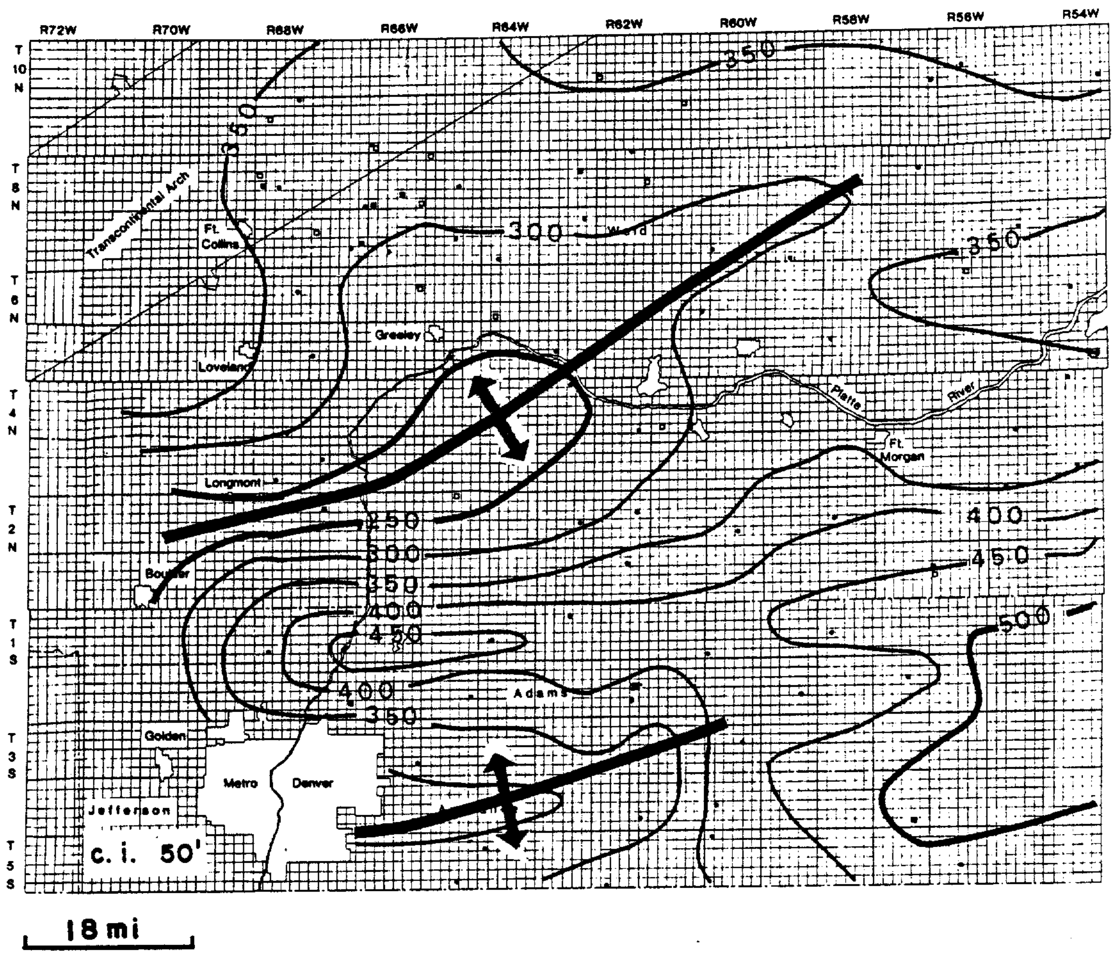

FIGURE 41. NIOBRARA ISOPACH MAP

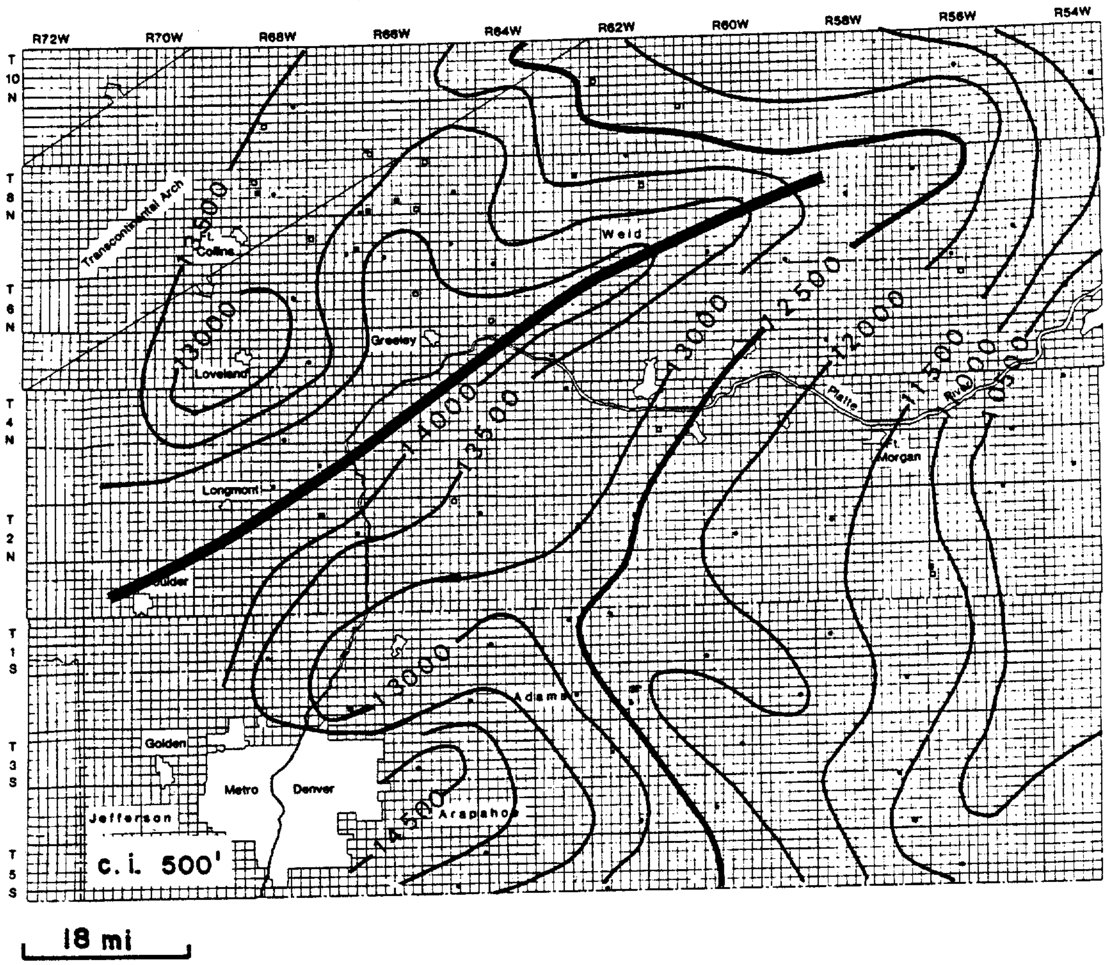

FIGURE 42. NIOBRARA INTERVAL VELOCITY MAP

northeast-southwest trends, which coincide with the axes of thinning on the isopach map of this formation (Fig. 41). Velocity values vary from less than 10,000'/sec in the eastern part of the map area, where the Niobrara formation is predominantly shale (Fig. 16), to more than 14,500'/sec in the western part. Upon examining the interval velocity maps of each individual formation within the stratigraphic interval of study (Figs. 14, 26, 30, 34, 38, 42), it is concluded that all these maps show the same basic pattern of interval velocity variation as that of the whole stratigraphic interval. The interval velocity maps of the stratigraphic interval, Niobrara formation, and Carlile formation, show that the trends of the velocity increase coincide with the trends of thinning in the isopachs of these intervals. Since the lithology of the Carlile formation is uniform to a certain degree throughout the area of study, velocity anomalies may be a result of the paleostructure effect.

6.3) Interval Velocity-Depth Relationship

The average velocity function of Niobrara formation in the study area (Fig. 43) for depths from 4110 to 8115 feet is:

$$V = 2950.3\ Z^{1/6} \qquad (10)$$

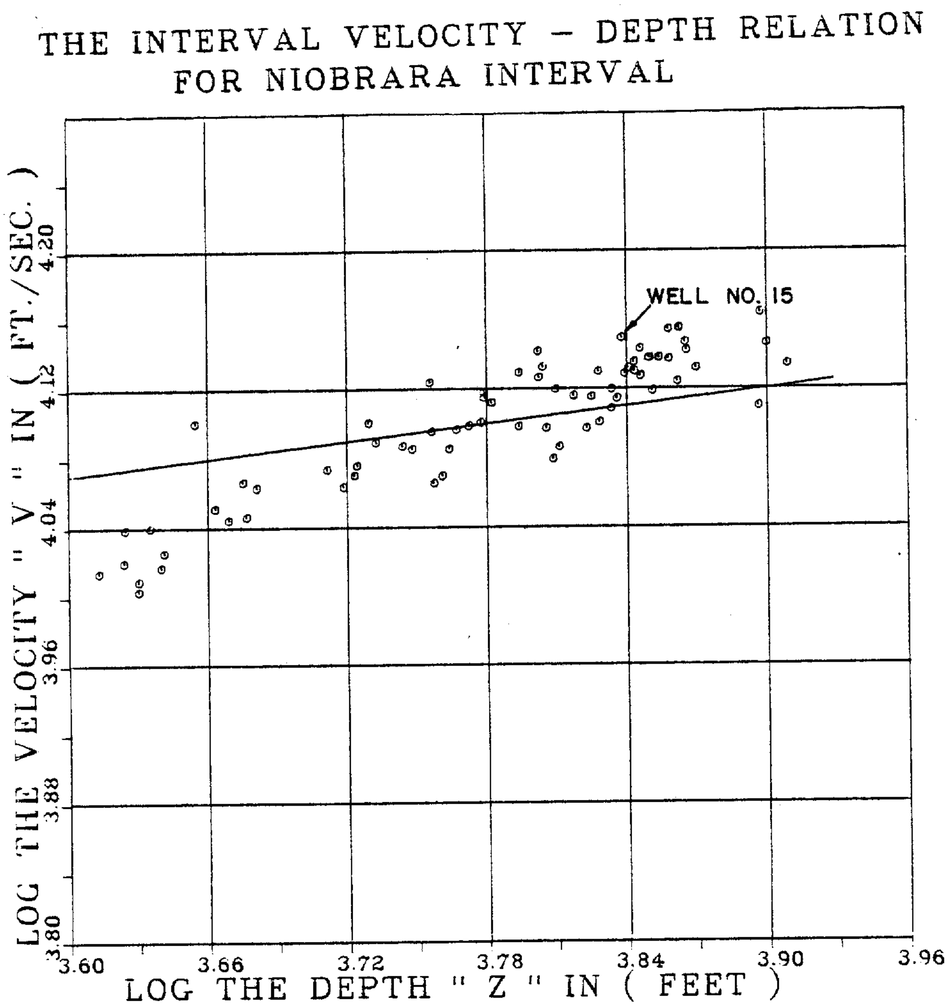

FIGURE 43. THE INTERVAL VELOCITY-DEPTH RELATION FOR NIOBRARA INTERVAL

6.4) Residual Velocity Map:

The residual velocity map of this interval (Fig. 44) shows that a percentage velocity anomaly varies from less than -16% in the east part of the mapped area where the formation is predominantly shale "about 75%" (Fig. 16) to about 10% in the west part of the study area. The positive anomaly values increase along the northeast-southwest trends and coincide with the axes of thinning in the isopach map of the Niobrara formation (Fig. 41).

From the discussion of the residual velocity maps, one may conclude that the increase in the velocity anomaly values along northeast-southwest trends in the study area, which coincide with the trends of paleostructures documented by Weimer (1982), reflect the effect of these paleostructures on the velocity of Cretaceous marine sediments in the study area. Porosity is one of the most dominant factors controlling velocity, since the velocity depends on rock porosity for an uniform lithology, uplift may cause more compaction, less porosity and therefore more density. Regional density studies may be warranted. Velocity variations may also be caused by lateral variations in lithoogy. These lithologic variations may in term be caused by paleostructural features in the basin during time of deposition or subsequent erosion.

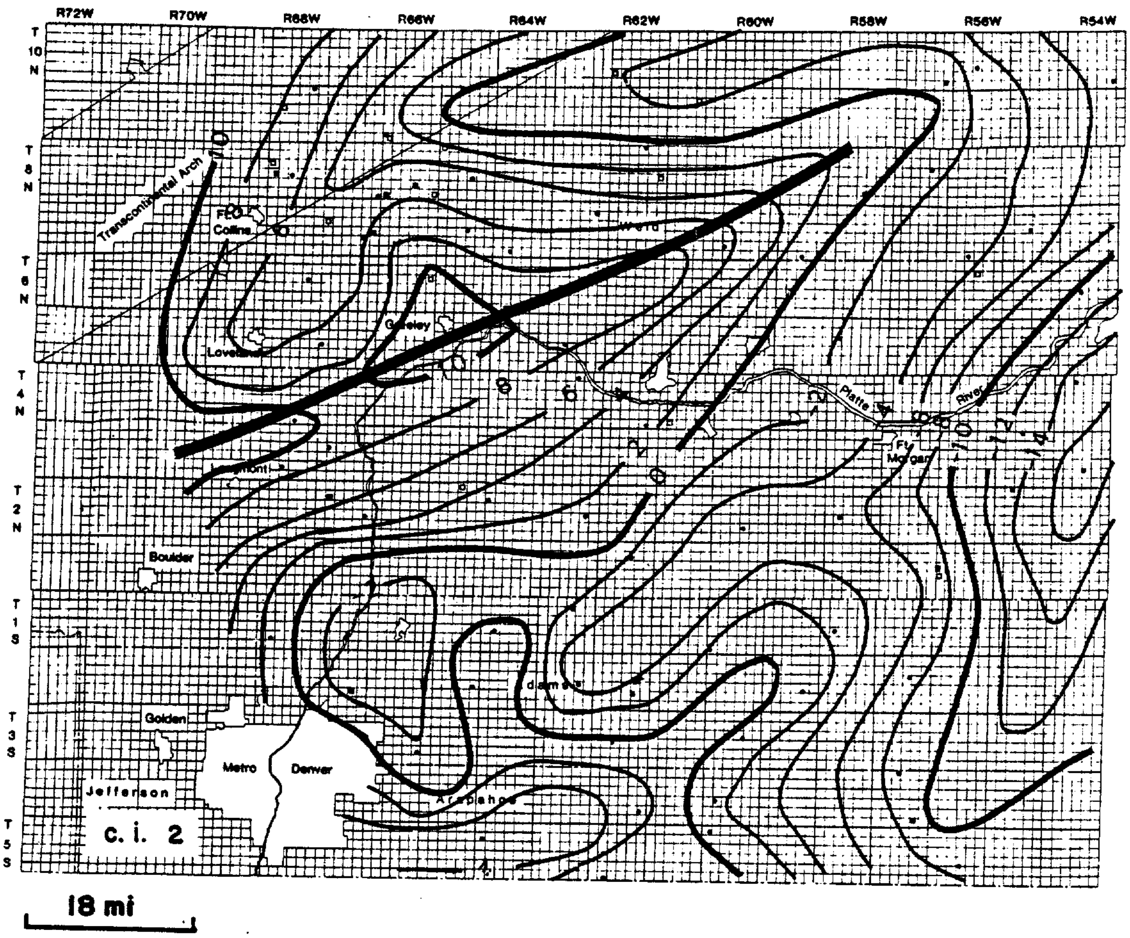

FIGURE 44. NIOBRARA RESIDUAL VELOCITY MAP IN PERCENTAGES

CONCLUSIONS

From this study the following conclusions may be drawn:

1. Analysis of well velocity surveys in the northern Denver basin has demonstrated the presence of lateral velocity variations in the middle Cretaceous stratigraphic interval. These variations may be due to the lithology variations or differential compaction or differential uplift and erosion of the stratigraphic interval of study due to the influence of the Transcontinental arch on Cretaceous strata.

2. Positive interval velocity anomalies occur along northeast-southwest paleostructure trends. Largest deviation in the velocity values found in the Niobrara formation; ranging from -16% to +10% of the average velocity value (Fig. 44). This large deviation is related to a significant change in lithology by depositional and erosional processes controlled by the paleostructure features in the basin.

RECOMMENDATION FOR FUTURE STUDIES

1) Regional porosity and density study of the stratigraphic interval from top Dakota J-sandstone to top Niobrara formation to examine the effect of the paleostructure on the porosity and density. Velocity-depth relation will be more meaningful if we include a variable such as porosity.
2) Regional velocity study of the noncalcareous black shales of the Pierre formation.
3) Study into derivation of a lithological factor for the different constituents (shale, sand, and carbonate) based on their existence ratio within the studied interval. This study would have to be conducted by using a combination of more reliable lithological identification tools; for example: resistivity logs, s.p. logs, formation density logs, etc.

REFERENCES

Acheson, C.H., 1959, "The Correlation of Seismic Time Maps for Lateral Variation in Velocity Beneath the Low Velocity Layer": Geophysics, V. 24, pp. 706-724.

Acheson, C.H., 1963, "Time/Depth and Velocity/Depth Relation in Western Canada": Geophysics, V. 28, pp. 894-909.

Acheson, C.H., 1981, "Time/Depth and Velocity/Depth Relations in Sedimentary Basins: A Study Based on Current Investigation in the Arctic Islands and Interpretation of Experience Elsewhere": Geophysics, V. 46, pp. 707-716.

Anstey, N.A., 1977, "Seismic Interpretation: The Physical Aspects": International Human Reso. Develop. Corp., Boston, pp. 51-100.

Berman, A.E., Poleschook, D., Jr., and Dimelow, T.E., 1980, "Jurassic and Cretaceous Systems of Colorado": in Kent, H.C., and Proter, K.W. eds.: Colorado Geology: Rocky Mountain Association of Geologists, pp. 111-128.

Boos, C.M., and M.F. Boos, 1957, "Tectonics of Eastern Flank and Foothills of Front Range": Colorado: American Association of Petroleum Geologists, Bulletin, V. 45, no. 12, pp. 2603-2676.

Carloss, J.C., 1974, "Depositional Environments From Bore-Hole Measurements, Lower Cretaceous Peoria Field, Arapahoe County": Colorado: Colorado School of Mines Thesis, T 1623, p. 335.

Clark, B.R., 1978, "Stratigraphy of the Lower Cretaceous J-Sandstone, Boulder County, Colorado: A Deltaic Model" in Pruit, J.D., and P.E. Coffin, eds, Energy Resources of the Denver Basin: Rocky Mountain Association of Geologists, pp. 237-246.

Clayton, J.L. and P.S. Swetland, 1980, "Petroleum Generation and Migration in Denver Basin": American Association of Petroleum Geologists, Bulletin, v. 64, pp. 1613-1634.

Cobban, W.A., and J.B. Resside, 1952, "Correlation of the Cretaceous Formations of the Western Interior of the United States": Geol. Soc. Am. Bulletin, V. 63, no. 10, pp. 1011-1044.

Davis, T.L., 1972, "Velocity Variations Around Leduc Reefs," Alberta, Canada: Geophysics, V. 37, pp. 584-604.

Davis, T.L., and R.J. Weimer, 1976, "Late Cretaceous Growing Faulting, Denver Basin": Colorado, in Epis, R.C., and R.J. Weimer ed." Prof. Contrib. of Colorado School of Mines, No. 8, pp. 280-300.

Dobrin, M.B., and W.G. Rimmer, 1964, "Regionals and Residuals in Seismic Prospecting for Stratigraphic Features Geophysics, V. 29, pp. 38-53.

Faust, L.Y., 1951, "Seismic Velocity as a Function of Depth and Geologic Time": Geophysics, V. 16, pp. 192-206.

Faust, L.Y., 1953, "A Velocity Function Including Lithologic Variation": Geophysics, V. 28, pp. 271-278.

Gardner, G.H.F., Gardner, L.W., and A.R. Gregory, 1974, "Formation Velocity -- The Diagnostic Basis for Stratigraphic Traps": Geophysics, V. 39, pp. 770-780.

Gassmann, F., 1951, "Elastic Waves Through A Packing of Spheres": Geophysics, V. 16, pp. 673-686.

Gretener, P.E., 1961, "An Analysis of the Observed Time Discrepancies Between Continuous and Conventional Well Velocity Surveys": Geophysics, V. 26, pp. 1-11.

Haskell, N.A., 1941, "The Relation Between Depth, Lithology and Seimic Wave Velocity in Tertiary Sandstone and Shales": Geophysics, V. 6, pp. 318-326.

Haun, J.D., 1959, "Lower Cretaceous Strata of Colorado" in Haun, J.D., and R.J. Weimer, eds. Symposium on Cretaceous Rocks of Colorado and Adjacent Areas, 11th Field Conf. Guidebook: Rocky Mountain Association of Geologists, pp. 1-8.

Haun, J.D., 1963, "Stratigraphy of Dakota Group and Relationship to Petroleum Occurrence, Northern Denver Basin": in Bolyard, D.W. and P.E. Katisch eds, Geology of Northern Denver Basin and Adjacent Uplifts, 14th Field Conf. Guidebook: Rocky Mountain Association of Geologists, pp. 119-134.

Haun, J.D., and H.C. Kent, 1965, "Geologic History of Rocky Mountains Region": American Association of Petroleum Geologists, Bulletin, V. 49, pp. 1781-1800.

Hicks, W.G., and J.E. Berry, 1956, "Application of Continuous Velocity Logs to the Determination of Fluid Saturation of Reservoir Rocks": Geophysics, V. 21, pp. 739-754.

Hicks, W.G., 1959, "Lateral Velocity Variations Near Bore Holes": Geophysics, V. 24, pp. 451-464.

Hughes, D.E., and J.L. Kelly, 1952, "Variation of Elastic Wave Velocity with Saturation in Sandstone": Geophysics V. 17, pp. 739-752.

Jankowsky, W., 1970, "Empirical Investigation of Some Factors Effecting Wave Velocities in Carbonate Rocks": Geophysical Prosp., V. 18, pp. 103-118.

King, M.S., 1966, "Wave Velocities in Rocks as Function of Changes in Overburden Pressure and Pore Fluid Saturants": Geophysics, V. 31, pp. 50-73.

Kline, M.A., Jr., 1956, "The Structure and Stratigraphy of Cretaceous Rocks in Northeastern Larimer County": Colorado School of Mines Thesis T1843.

Kokesh, F.P. and R.B. Blizard, 1959, "Geometrical Factors in Sonic Lagging": Geophysics, V. 24, pp. 64-76.

Leroy, L.W., and N.C. Schieltz, 1958, "Niobrara Pierre Boundary Along Front Range", Colorado American Association of Petroleum Geologists, V. 42, pp. 2442-2464.

MacKenzie, D.B., 1963, "Dakota Group on West Denver Basin", in Bolyard, D.W., and P.E. Kutisch, eds., Denver Basin and Adjacent Uplifts: Rocky Mountain Association of Geologists, V. 8, no. 3, pp. 91-131.

MacKenzie, D.B., 1965, "Depositional Environments of Muddy Sandstone, Western Denver Basin": Colorado: American Association of Petroleum Geologists, Bulletin, V. 49, pp. 186-206.

Matthews, Vicent III, and D.F. Work, 1978, "Laramide Folding Associated with Basement Block-Faulting Along the Northeastern Flank of the Front Range," Colorado: Geologic Soc. Am. Memoir 151, p. 370.

Matusczak, R.A., 1976, "Wattenberg Field: A Review of Epis, R.C., and R.J. Weimer, eds, Studies in Colorado Field Geology": Colorado School of Mines Prof. Contrib. no. 8, pp. 275-279.

Melemore, E.W., 1963, "Probability in Three Variants: Seismic Velocity, Depth, and Lithology": Geophysics, V. 28, pp. 46-86.

Paterson, N.R., 1956, "Seismic Wave Propagation in Porous Granular Media": Geophysics, V. 21, pp. 691-714.

Peterson, W.L., and S.D. Janes, 1978, "A Refined Interpretation of the Depositional Environments of Wattenberg Field", Colorado: in Pruit, J.D., and P.E. Coffin, eds. Energy Resources of the Denver Basin: Rocky Mountain Association of Geologists (1978) Symposium, pp. 141-147.

Pickett, G.R., 1960, "The Use of Acoustic Logs in the Evaluation of Sandstone Reservoirs": Geophysics, V. 25, pp. 250-274.

Pickett, G.R., 1970, "Application for Borehole Geophysics in Geophysical Exploration": Geophysics, V. 35, pp. 81-92.

Pinel, M.J., 1977, "Stratigraphy of the Upper Carlile and Lower Niobrara Formations 'Upper Cretaceous', Fermont and Pueblo Counties, Colorado": Unpublished M.S. Thesis Colorado School of Mines, Golden, p. 111.

Ross, R.J., Jr., and O. Tweto, 1980, "Lower Paleozoic Sediment and Tectonic in Colorado", in Kent, H.C., and K.W., Porter eds., Colorado Geology: Rocky Mountain Association of Geologists, pp. 47-56.

Scheidegger, A.E., and P.L. Willmore, 1957, "The Use of Least Squares Method for the Interpretation of Data From Seismic Surveys": Geophysics, V. 22, pp. 9-22.

Schwaetzer, T., 1960, "Well surveys and the calibration of velocity logs": Geophysics Prosp., V. 8, pp. 85-97.

Stulken, E.J., 1941, "Seismic Velocities in the Southeastern San Joaquin Valley of California": Geophysics, V. 6, pp. 327-355.

Suryanto, U., 1979, "Stratigraphy and Petroleum Geology of the J-Sandstone in Portions of Boulder, Larimer, and Weld Counties, Colorado" Unpublished Thesis, Colorado School of Mines, Golden, p. 173.

Tweto, O., 1980, "Tectonic History of Colorado"; in Kent, H.C., and K.W., Proter, eds., Colorado Geology: Rocky Mountain Association of Geologists, pp. 5-10.

Tweto, O., 1980, "Summary of Laramide Orogeny", in Kent, H.C., and K.W. Proter, eds., Colorado Geology, Rocky Mountain Association of Geologists, pp. 129-134.

Vaderstoep, D.M., 1966, "Anisotropic Variation of Velocity With Direction of Propagation": Geophysics, V. 31, pp. 900-916.

Vogel, C.B., 1952, "A Seismic Velocity Logging Method" Geophysics, V. 17, pp. 586-597.

Walsh, J.B., 1965, "Effect of Cracks on the Compressibility of Rock": Geophysical Research, V. 70, pp. 381-388.

Warner, L.A., "The Colorado Lineament," in Kent, H.C., and K.W., Porter eds., Colorado Geology: Rocky Mountain Association of Geologists, pp. 11-22.

Weatherby, B.B., and L.Y. Faust, 1935, "Influence of Geological Factors on Longitudinal Seismic Velocity": American Association of Petroleum Geologists, Bulletin, V. 19, pp. 1-8.

Weimer, R.J., 1959, "Upper Cretaceous Strata, Colorado": in Haun, J.D., and R.J. Weimer, eds., Symposium on Cretaceous Rocks of Colorado and Adjacent Uplifts, 11th Field Conf. Guidebook: Rocky Mountain Association of Geologists, pp. 9-16.

Weimer, R.J., 1978, "Influence of Transcontinental Arch on Cretaceous Marine Sedimentation: A Preliminary Report": in Pruit, J.D., and P.E. Coffin, eds., Energy Resources of the Denver Basin: Rocky Mountain Association of Geologists, 1978, Symposium, pp. 211-221.

Weimer, R.J. and S.A. Sonnenberg, 1982, "Wattenberg Paleo-Structure -- Stratigraphic Trap, Denver Basin, Colorado": Oil and Gas Journal, pp. 204-210.

West, S.S., 1950, "Dependence of Seismic Velocity Upon Depth and Lithology": Geophysics, V. 15, pp. 653-662.

White, J.E., and R.L. Sengbush, 1953, "Velocity Measurement in Near Surface Formations": Geophysics, V. 18, pp. 54-69.

Wyllie, M.R., Gregory, A.R., and L.W. Gardner, 1956, "Elastic Wave in Hetrogeneous and Porous Media": Geophysics, V. 21, pp. 41-70.

Wyrobeck, S.M., 1959, "Well Velocity Determination in English, Triassic, Precambrian and Carboniferous": Geophysical Prospects, V. 7, pp. 218-230.

Wyrobeck, S.M., 1974, "Abnormal Subsurface Pressure: Selected Papers Printed From the American Association of Petroleum Geologists, Bulletin, Series No. 11, Tulsa, Oklahoma, 1974.

APPENDIX I

LIST OF WELLS USED IN THE STUDY

LIST OF WELLS

WELL #	WELL NAME	WELL LOCATION	COUNTY	SURVEY DATE	K.B. IN FT.	DEPTH TO TOP NIOBRARA BELOW K.B. FT.
11	W.A. Rolland #1	NW NW 27 3 N., 54 W.	Washington	6/25/71	4383	3940
27	State #1	C NW NW 22 6 N., 54 W.	Logan	12/20/67	4161	4016
49	Sanders-Cedar Creek #1	NE/4 NE/4 35 10N., 54 W.	Logan	6/18/77	4106	4042
4	Fedral #1-5	NE NE 5 2 N., 55 W.	Morgan	12/21/80	4463	4114
16	Higbe #1	C NW SW 4 4 N., 54 W.	Washington	4/7/63	4499	4120
72	Fraizar #1-A	SW SW 22 5 S., 56 W.	Washington	5/25/70	5070	4082
68	UPRR-Frasier Farms #1	SE NW 35 4 S., 57 W.	Arapahoe	4/22/67	4832	4135
12	Fedral #1-4	NW NE 4 3 N., 55 W.	Morgan	6/18/71	4351	4210
26	Henry Weber #1	NE NE 25 5 N., 69 W.	Larimer	5/21/65	4926.5	4350
C1	Kauffman #1	SW SW SW 18 1 N., 56 W.	Morgan	6/29/55	4516	4363
67	Union Pacific #7	NE NE 9 4 S., 57 W.	Arapahoe	3/20/67	4975	4430
32	State #15-1	SE SE 15 7 N., 55 W.	Logan	9/23/81	4398	4582
59	Causey #1-A	SW SW 15 2 S., 57 W.	Adams	11/4/72	4707	4558
50	J.E.Kester #1	C SW SE 21 10 N., 56 W.	Logan	11/24/65	4341	4634
33	Hoozee Bjolin #3	SW NE 33 7 N., 56 W.	Weld	2/22/82	4646	4980
58	Downing #1	NW SE 20 1 S., 58 W.	Adams	4/22/82	5116	5008
5	Orth Jimerson #1	SE NE 20 2 N., 58 W.	Morgan	5/4/67	4606	5114
C3	Nicklas #1	10 6 N., 56W.	Morgan	1/13/54	4616	5129
41	State #1-14	SW/4 NW/4 14 8 N., 57 W.	Weld	1/15/81	4609	5208
51	Hopsetail Creek #1-36	C NW NW 36 10 N., 57 W.	Weld	2/3/80	4710	5264
60	Flader #1	SW SW 26 2 S., 59 W.	Adams	6/6/70	5056	5366
21	Christensen #1	SW NE 18 5 N., 58 W.	Morgan	5/19/81	4732	5440
46	Wadleigh #34-21	C SW SE 21 8 N., 68 W.	Larimer	11/20/77	5073	5544
6	Midcap #1	C SW NW 27 2 N., 60 W.	Morgan	6/6/78	4672	5554
42	Dixonetal #128	SE SE 28 8 N., 58 W.	Weld	9/11/81	4778	5578
64	Kroh #1-A	C NE NE 22 3 S., 60 W.	Adams	3/15/70	5113	5564
C15		17 9 N., 68W.		12/2/56	5298	5565
69	M.L. Gerstenberger B. #1	SW NW 20 4 S., 60 W.	Arapahoe	2/28/71	5166	5606

LIST OF WELLS (CONT'D.)

WELL #	WELL NAME	WELL LOCATION	COUNTY	SURVEY DATE	K.B. IN FT.	DEPTH TO TOP NIOBRARA BELOW K.B. FT.
55	Amoco UPRR Kalceoic #1	W/2 W/2 31	Adams	10/2/77	4891	5642
73	J.A. Bennett #5	SW/4 SE/4 6 5 S., 60 W.	Arapahoe	12/29/70	5337	5726
17	Litter #1	SE SE SW 35 4 N., 62 W.		11/8/79	4562	5890
34	Lundock #3	NE SW 33 7 N., 59 W.	Weld	2/8/82	4836	5854
30	Suedman #1	C NW/4 SE/4 14 6 N., 68 W.	Larimer	4/21/78	4821	5866
28	Hendershot State #1	SW NW 36 6 N., 61 W.	Weld	9/13/81	4665	5920
7	Lottie Ferguson State #1	NE NE 14 2 N., 62 W.	Weld	9/21/81	4820	6082
48	Copeland #7-2	SW NE 2 9 N., 68 W.	Larimer	3/6/75	5450	6069
18	Ronald #1-B	E/2 SE/2 3 4 N., 63 W.	Weld	2/3/81	4567	6233
35	Weitzel #30-1	30 7 N., 60 W.	Weld	5/19/78	4897	6210
22	Peterson #1	NE SE 20 5 N., 63 W.	Weld	3/7/70	4567	6242
1	Reid Cooksey #1	SE SE 10 1 N., 62 W.	Weld	3/3/78	4952	6210
C2	Roloc #1	C NE SE 14 2 S., 62 W.	Adams	6/6/56	5175	6248
8	Cuykendall #1-F	SE NE 23 2 N., 63 W.	Weld	6/7/75	4777	6312
61	Habelfee "C" #1	SW NW NW 26 2 S., 62 W.	Adams	2/24/78	5155	6318
70	Champlin 353 Amoco C #1	SW NW 25 4 S., 62 W.	Arapahoe	12/21/77	5439	6420
56	Beltz #1A	NE NE 10 1 S., 63 W.	Adams	5/20/70	5017	6458
65	Champlin 287 Amoco #2	NW NW 21 3 S., 62 W.	Adams	3/10/80	5317	6514
C22		24 8 N., 62 W.		8/2/56	5003	6500
36	Henry Bender #1	NW NE 11 7 N., 63 W.	Weld	1/30/67	4849	6586
C24		35 4 N., 61 W.		11/4/52	5539	6579
43	Grace Marathon Dalton #31	NE/4 NW/4 3 8 N., 62 W.	Weld	4/5/81	4991	6594
C23		32 4 N., 61 W.		7/27/54	5561	6588
C13		32 6 N., 64 W.		6/27/55	4660	6691
62	Antelope Frams #32-28	SW NE 23 2 S., 63 W.	Adams	12/19/80	5256	6610
25	Koening #1-19	SW SW 19 5 N., 67 W.	Weld	4/7/81	4814	6664
74	Roth #32-9	NE SW 32 5 S., 62 W.	Arapahoe	7/18/80	5725	6680
15	Elmer Hergenreder #1	C NW SW 28 3 N., 68 W.	Weld	1/23/73	4960	6770
C6	Ball #16-14	SW NW SW 14 8 N., 63 W.	Weld	9/27/55	4960	6715

LIST OF WELLS (CONT'D.)

WELL #	WELL NAME	WELL LOCATION	COUNTY	SURVEY DATE	K.B. IN FT.	DEPTH TO TOP NIOBRARA BELOW K.B. FT.
C14		18 7 N., 67 W.		11/13/57	5057	6750
C9	UPRR #1	31 8 N., 66 W.	Weld	12/25/53	5117.5	6752
37	McCrory #1	SE NE 32 7 N., 64 W.	Weld	4/18/70	4828	6798
C12		3 2 N., 65 W.		6/5/55	4829	6828
C21		13 6 N., 66 W.		4/13/57	4864	6815
2	Burnner #2	26 7 N., 67 W.			4928	6818
45	State #4	NE NE 36 8 N., 67 W.	Weld	11/18/68	5137	6836
14	Nick Sekich #2	NE SW SW 17 3 N., 67 W.	Weld	7/7/73	4874	6892
9	UPRR 53 PanAm #1	NE SW SW 7 2 N., 64 W.	Weld	11/9/73	4949	6908
C18		36 8 N., 66 W.			5035	6904
38	Calue #1 Wells 12-22	SW NW 22 7 N., 65 W.	Weld	5/6/81	4843	6928
57	Thomas C. #1	C SW SE 20 1 S., 64 W.	Adams	1/27/79	5140	6900
C5	UPRR #1 Frech	SE SE NE 27 8 N., 66 W.	Weld	9/28/56	5050	6935
C8	Nashland #1	C SW SW 24 7 N., 67 W.	Weld	12/1/75	4993	7000
44	UPRR #27-1	SW SE 22 8 N., 65 W.	Weld	2/5/81	4941	7060
39	Severin and Company	28 7 N., 66 W.	Weld	1/8/82	4894	7090
C17		31 8 N., 66 W.		8/25/53	5096	7090
19	Nelson #1-X	NW SW 34 4 N., 68 W.		10/12/66	5156	7156
C11	Amoco Champlin	SE NW 31 9 N., 66 W.	Weld	6/30/77	5230	7103
47	Amoco Champlin	SE NW 31 9 N., 66 W.	Weld	6/30/77	5230	7120
10	Roy Dutcher #1	NE SW SW 24 2 N., 67 W.	Weld	10/27/73	4924	7216
C7	Osmund Dir. #1	C NE SE 8 2 N., 67 W.	Weld	4/2/55	4951	7242
C19		6 8 N., 65 W.			5055	7221
63	Box Elder #2-G	N NE SW 24 2 S., 65 W.	Adams	3/13/73	5300	7232
C10	R.M. AR. #1	C NW NW 26 2 S., 67 W.	Adams	9/4/61	5203	7710
66	Grimm #16-25	SE SE 25 3 S., 66 W.	Adams		5497	7746
75	State AB #2	C NE NE 7 5 S., 65 W.	Arapahoe	4/12/74	5996	7800
76	Coal Butte State	NE NE 34 #1-34	Arapahoe	2/6/73	6050	7958
C4	Meyer #1	C SE SW 19 8 N., 68 W.	Larimer	3/7/53	5133	3625
C16		10 9 N., 61 W.		3/30/53	5006	6460
C20		30 10 N., 62 W.		2/28/56	5069	6785
C25		18 8 N., 68 W.	Larimer	3/7/53	5136	3631

APPENDIX II

VELOCITY AND DEPTH DATA

THE STRATIGRAPHIC INTERVAL FROM THE TOP
OF THE NIOBRARA TO THE TOP OF THE DAKOTA J-SANDSTONE

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS △Z (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
11	4369	870	10334	10796	-462	-4.28
27	4483	952	10103	10843	-740	-6.82
49	4492	922	10583	10846	-263	-2.43
4	4510	810	9881	10853	-972	-8.96
16	4544	868	9885	10867	-982	-9.04
72	4544	942	10548	10867	-319	-2.94
68	4611	970	10164	10893	-729	-6.69
12	4624	840	10037	10899	-862	-7.91
26	4760	840	11613	10951	662	6.04
C1	4843	887	10560	10953	-423	-3.85
67	4891	940	10543	11002	-459	-4.17
32	4980	814	10713	11035	-322	-2.92
59	4991	882	10739	11039	-300	-2.72
50	5087	928	10626	11073	-447	-4.04
33	5422	904	10875	11192	-317	-2.83
58	5459	924	10818	11204	-386	-3.45
5	5529.5	847	10840	11228	-388	-3.46
C3	5572	885	10944	11233	-299	-2.66
41	5628	842	11116	11262	-146	-1.29
51	5693	914	10911	11283	-372	-3.30
60	5766	818	11296	11334	- 38	-0.33
21	5835	804	11159	11335	-176	-1.51
46	5953	840	11852	11367	485	4.26
6	5961	834	10931	11371	-440	-3.87
42	5974	812	11162	11374	-212	-1.87
64	5998	888	11040	11382	-342	-3.00
C15	6000	870	11856	11382	474	4.16
69	6036	872	11158	11394	-236	-2.07
55	6083	902	11515	11408	107	0.94
73	6148	860	11516	11429	87	0.76
17	6237	716	11525	11456	69	0.60
34	6253	818	11392	11461	- 69	-0.60
30	6254	790	11897	11461	436	3.80
28	6309	7980	11427	11478	- 51	-0.45
7	6458	764	11309	11523	-214	-1.86
48	6494	871	12043	11533	510	4.42
18	6580.5	727	11725	11559	166	1.44
35	6586	768	11927	11561	366	3.17
22	6596	730	11966	11563	403	3.48
1	6621	826	11505	11571	- 66	-0.57
C2	6676	851	11232	11587	-355	-3.06
8	6685	758	11757	11589	168	1.45

THE STRATIGRAPHIC INTERVAL FROM THE TOP
OF THE NIOBRARA TO THE TOP OF THE DAKOTA J-SANDSTONE
(CONT'D.)

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS △ Z (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
61	6696	778	11137	11593	-456	-3.93
70	6816	812	11731	11627	104	0.90
56	6879	862	11491	11645	-154	-1.32
65	6891	776	11914	11649	265	2.28
C22	6900	800	11808	11651	157	1.35
36	6946	742	11974	11664	310	2.66
C24	6980	802	11520	11673	-153	-1.31
43	6988	812	11304	11675	-371	-3.18
C23	6990	806	11635	11676	- 41	-0.35
C13	7026	691	11886	11686	200	1.71
62	7035	854	11710	11688	22	0.19
25	7049	794	11935	11693	242	2.07
74	7066.5	795	11815	11697	118	1.01
15	7110	702	12371	11709	662	5.65
C6	7115	799	12000	11710	290	0.47
C14	7146	791	12192	11718	473	4.04
C9	7149	814	11856	11720	136	1.16
37	7163	756	12054	11724	330	2.82
C12	7173	685	11808	11726	82	0.70
C21	7200	765	12192	11734	458	3.91
2	7221	786	11952	11739	213	1.81
45	7227	814	11879	11741	138	1.18
14	7234	704	12196	11743	453	3.86
9	7247.5	699	11733	11746	- 13	-0.11
C18	7300	795	12162	11760	402	3.41
38	7303	770	12167	11761	406	3.45
57	7330	880	11932	11769	163	1.39
C5	7340	810	12096	11771	325	2.76
C8	7396	792	12048	11786	262	2.22
44	7452	805	12145	11801	344	2.91
39	7457	758	12324	11802	522	4.42
C17	7500	810	11808	11814	- 6	-0.05
19	7519	748	12348	11818	530	4.48
C11	7527	847	11760	11821	- 61	-0.51
47	7531	843	11731	11822	- 91	-0.77
10	7566	724	12057	11831	226	1.91
C7	7568	652	12096	11832	264	2.24
C19	7622	802	11904	11846	58	0.49
63	7633	822	12136	11848	288	2.43
C10	8099	775	11796	11966	-170	-1.42
66	8108	742	12720	11968	752	6.28
75	8146	714	12583	11978	605	5.05
76	8330	726	12396	12023	373	3.11

NIOBRARA STRATIGRAPHIC INTERVAL.

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS Δ Z (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
11	4108	348	10319	11808	-1489	-12.6
27	4208	402	10466	11854	-1388	-11.7
49	4213.5	365	10938	11857	- 919	- 7.75
16	4270	320	10072	11883	-1811	-15.2
4	4272	336	10207	11885	-1678	-14.12
72	4321	496	10963	11907	- 944	- 7.93
12	4371	334	10392	11930	-1538	-12.89
68	4380.5	507	10604	11934	-1330	-11.14
26	4520	360	12602	11997	605	5.05
C1	4613	490	11246	12037	- 791	- 6.57
67	4671	500	11077	12062	- 985	- 8.17
32	4738	330	11655	12091	- 436	- 3.6
59	4761	422	11120	12101	- 981	- 8.11
50	4799	352	11561	12117	- 556	- 4.59
33	5150	360	11848	12260	- 412	- 3.36
58	5234	474	11578	12294	- 716	- 5.82
5	5292.5	373	11756	12316	- 560	- 4.55
C3	5311	364	11904	12323	- 419	- 3.40
41	5363	312	12601	12343	258	2.09
51	5404	336	12276	12360	- 84	- 0.68
60	5554	394	12211	12415	- 204	- 1.65
21	5598	330	12166	12432	- 266	- 2.14
46	5698	330	13296	12469	827	6.64
42	5717	298	12448	12475	- 27	- 0.22
6	5726	364	11631	12479	- 848	- 6.79
64	5773	438	11744	12496	- 752	- 6.02
69	5812	424	12172	12510	- 338	- 2.70
55	5849	434	12485	12524	- 39	- 0.31
73	5928.5	421	12548	12551	- 3	- 0.03
34	5997	306	12607	12575	32	0.25
17	6019	280	13027	12583	444	3.53
30	6019.5	321	13118	12583	535	4.25
28	6070	320	12931	12601	330	2.62
7	6228	304	12533	12655	- 122	- 0.96
48	6230.5	345	13471	12656	815	6.44
35	6345	286	13858	12695	1163	9.16
18	6348	262	13380	12696	684	5.39
22	6370	278	13565	12703	862	6.79
1	6398	380	12508	12712	- 204	- 1.60
C2	6446	396	12000	12728	- 728	- 5.72
8	6455	298	13175	12731	444	3.49
61	6480	346	12198	12739	- 541	- 4.25
70	6575	330	13055	12770	285	2.23

NIOBRARA STRATIGRAPHIC INTERVAL (CONT'D.)

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS Δz (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
56	6655	414	12502	12795	- 293	- 2.29
65	6690	374	13039	12807	232	1.81
36	6733	316	13488	12820	668	5.21
43	6737	310	12605	12822	- 217	- 1.69
62	6817	418	12840	12847	- 7	- 0.05
25	6821.5	339	13171	12848	323	2.51
74	6859	380	13007	12860	147	1.14
15	6891.5	265	14105	12870	1235	9.60
C9	6919		13440	12879	561	4.36
37	6929	288	13541	12882	659	5.12
45	6979	318	13490	12897	593	4.59
2	6446	312	13646	12898	748	5.80
14	7018	272	13904	12910	994	7.70
9	7020	244	13400	12910	490	3.79
38	7067	298	13725	12924	801	6.20
C5	7090	310	13723	12931	792	6.12
57	7108	436	13134	12937	197	1.52
C8	7157	313	13728	12952	776	5.99
44	7212	326	13706	12968	738	5.69
39	7214	272	14266	12969	1297	10.0
47	7272	324	13298	12986	312	2.40
19	7292	294	14289	12992	1297	9.98
C7	7344	203	14016	13007	1009	7.75
10	7346	284	13867	13008	859	6.61
63	7419	394	13535	13029	506	3.88
C10	7895	268	12864	13165	- 301	- 2.29
66	7901	328	14582	13166	1416	10.75
75	7951.5	325	13998	13181	817	6.20
76	8113	328	13611	13225	386	2.92

CARLILE STRATIGRAPHIC INTERVAL

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS Δ Z (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
11	4340	117	10000	10675	-675	-6.33
4	4485	90	10214	10734	-520	-4.84
27	4500	182	10552	10740	-188	-1.75
16	4501	142	9998	10740	-742	-6.91
49	4504.5	217	11035	10742	293	2.73
12	4592	108	10550	10776	-226	-2.10
72	4617	96	10214	10786	-572	-5.30
68	4688	96	9600	10814	-1214	-11.23
26	4790	80	11707	10853	854	7.87
C1	4883	50	10176	10888	-712	-6.54
32	4954.5	103	10666	10914	-248	-2.28
67	4961	80	10325	10917	-592	-5.42
59	5012	80	10786	10935	-149	-1.37
51	5049	154	10910	10948	- 38	-0.35
50	5076	202	10666	10959	-293	-2.67
33	5398	136	11035	11071	- 36	- .32
5	5515.5	73	10435	11111	-676	-6.08
58	5516	91	10666	11111	-445	-4.01
41	5581	124	10666	11133	-467	-4.20
60	5790	78	11035	11201	-166	-1.48
21	5808	90	10788	11209	-421	-3.76
46	5904	82	12000	11238	762	6.78
42	5925	118	11294	11244	50	0.46
6	5942	68	11165	11250	- 85	-0.75
64	6035	86	10786	11279	-493	-4.37
69	6073	98	10910	11290	-380	-3.37
55	6100	68	10910	11299	-389	-3.44
73	6185.5	93	11035	11325	-290	-2.56
17	6189	60	11294	11326	- 32	-0.28
34	6194	88	11294	11327	- 33	-0.29
30	6222.5	85	12154	11337	817	7.21
28	6266	72	11568	11350	218	1.92
7	6415	70	11035	11394	-359	-3.15
48	6438	70	12470	11401	1069	9.38
18	6506.5	55	11707	11421	286	2.5
35	6521	66	12000	11425	575	5.03
22	6534	50	11707	11429	278	2.43
1	6621	66	11165	11450	-290	2.53
C2	6678	68	10944	11471	-527	-4.59
8	6689	70	11568	11474	94	.82
61	6691	76	10786	11475	-689	-6.00
70	6809	138	11294	11508	-214	-1.86

CARLILE STRATIGRAPHIC INTERVAL (CONT'D.)

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS Δ Z (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
56	6898	72	11294	11532	-238	-2.07
36	6913	44	12152	11537	615	5.33
43	6918	52	11568	11538	30	0.26
65	6921.5	89	11294	11539	-245	-2.12
25	7031.5	81	12307	11570	737	6.37
15	7058.5	69	12802	11578	1224	10.58
62	7066	80	11294	11579	-285	-2.46
74	7086.5	75	11294	11584	-290	-2.51
37	7107	68	12000	11590	410	3.53
45	7174	72	12307	11608	699	6.02
9	7176	72	11851	11609	242	2.09
14	7178	48	12466	11610	856	7.37
2	7245		12192	11678	564	4.85
38	7252	72	12000	11629	371	3.19
57	7366	80	11707	11660	47	0.41
39	7389	78	12466	11666	800	6.86
44	7407	64	11851	11670	181	1.55
47	7470	72	12000	11687	313	2.68
19	7477	76	12466	11689	777	6.65
10	7516	56	12307	11699	608	5.20
C7	7540		12480	11705	775	6.62
63	7655	78	11707	11735	-28	-0.23
66	8099	68	12307	11845	462	3.90
75	8154	80	11707	11859	-152	-1.28
76	8312	70	11568	11897	-329	-2.76

GREENHORN STRATIGRAPHIC INTERVAL

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS △ Z (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
11	4504.5	211	9974	10527	-553	-5.26
4	4642	224	9322	10581	-1259	-11.9
27	4685	188	9780	10597	-817	-7.71
49	4687	148	10254	10598	-344	-3.24
12	4761	230	10036	10625	-589	-5.55
72	4770	210	10575	10628	- 53	-0.50
68	4848	244	10272	10657	-385	-3.62
26	4930	200	11397	10687	710	6.64
32	5093	175	10104	10745	-641	-5.97
67	5109	216	10563	10751	-188	-1.75
59	5161	218	10692	10769	- 77	-0.71
50	5264	174	10243	10804	-561	-5.20
33	5576	220	10570	10909	-339	-3.11
5	5666	228	10865	10938	- 73	-0.66
58	5670.5	217	10726	10939	-213	-1.95
16	5685	226	10010	10944	-934	-8.54
41	5752	218	1092[illegible]	10966	- 44	-0.40
51	5840	228	10675	10993	-318	-2.90
60	5930	202	11046	11022	24	.22
21	5956.5	207	10979	11030	- 51	-0.46
46	6046	202	11651	11057	594	5.37
6	6090	228	10921	11070	-149	-1.35
42	6091	214	10756	11070	-314	-2.83
64	6186	216	10947	11099	-152	-1.37
69	6226	208	10982	11111	-129	-1.16
55	6248	228	10981	11117	-136	-1.23
17	6324	192	11131	11140	- 9	-0.08
73	6334	204	11226	11143	83	0.75
34	6357	238	11100	11150	- 50	-0.45
30	6360.5	191	11640	11151	489	4.39
28	6416	228	10874	11167	-293	-2.62
7	6561	222	11151	11208	- 57	-0.51
48	6585	224	11808	11215	593	5.28
18	6651.5	235	11548	11234	314	2.79
35	6673	238	11402	11240	162	1.44
22	6675	232	11647	11241	406	3.61
1	6762	216	11339	11266	73	0.65
C2	6819	214	10771	11281	-510	-4.52
61	6832	206	10857	11285	-428	-3.79
8	6833	218	11468	11283	183	1.63
70	6979	202	11572	11325	247	2.18

GREENHORN STRATIGRAPHIC INTERVAL (CONT'D.)

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS Δ Z (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
56	7039	210	11059	11341	-282	-2.48
36	7048	226	11592	11343	249	2.19
65	7064	197	11337	11348	- 11	-0.10
43	7074	260	11063	11350	-287	-2.53
25	7168	192	11748	11376	372	3.27
15	7187	188	12015	11380	635	5.58
62	7207	202	11329	11385	- 56	-0.50
74	7224	200	11580	11389	191	1.67
37	7252	222	11653	11398	255	2.24
14	7308	212	11943	11412	531	4.66
9	7319	210	11491	11415	76	.67
45	7320	220	11686	11415	271	2.37
2	7386		11808	11432	376	3.29
38	7394	212	11955	11434	521	2.24
57	7508	204	11419	11463	- 44	-0.39
39	7535	214	12057	11471	586	5.11
44	7555	228	11914	11476	438	3.82
19	7612	194	11726	11489	237	2.06
47	7627	242	11448	11493	- 45	-0.40
10	7658	228	11969	11501	468	4.07
C7	7680		12000	11507	493	4.29
63	7793	198	11638	11535	103	0.90
66	8236	206	12209	11641	568	4.88
75	8291.5	195	12285	11654	631	5.41
76	8446	198	12213	11690	523	4.47

GRANROS STRATIGRAPHIC INTERVAL

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS ΔZ (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
11	4654	88	8726	8931	-205	-2.3
4	4787	66	8496	8974	-478	-5.32
49	4805	88	8890	8980	- 90	-1.0
27	4826	94	8496	8986	-490	-5.45
16	4846	96	8563	8992	-429	-4.77
72	4923	96	9058	9016	42	0.47
12	4924	96	8496	9016	-520	-5.77
68	5004	88	8572	9039	-467	-5.17
26	5108	156	10104	9071	1033	11.38
32	5226	90	8726	9105	-379	-4.17
67	5264	94	8726	9116	-390	-4.28
59	5316	92	8890	9132	-242	-2.65
50	5402	106	8808	9156	-348	-3.80
33	5735	98	9057	9248	-191	-2.07
58	5824	90	9144	9272	-128	-1.39
5	5829.5	99	8573	9237	-700	-7.55
41	5913	104	8890	9296	-406	-4.36
51	6012	116	8890	9321	-431	-4.63
60	6075	88	9048	9337	-289	-3.10
21	6109.5	99	9144	9346	-202	-2.16
46	6234	174	9998	9377	621	6.62
42	6249	102	9144	9381	-237	-2.53
6	6253	98	8890	9383	-493	-5.25
64	6341	94	9144	9404	-260	-2.77
69	6377	94	9322	9411	- 91	-1.0
55	6409	94	9144	9421	-277	-2.94
17	6481	104	9600	9438	162	1.71
73	6485	98	9504	9439	65	0.68
34	6528	104	9321	9449	-128	-1.36
30	6531	150	10003	9450	553	5.85
28	6582	104	9230	9462	-232	-2.46
7	6724	104	9322	9497	-175	-1.84
48	6784	174	10214	9510	704	7.40
18	6824.5	111	9696	9520	176	1.85
35	6845	106	9600	9525	75	.79
22	6846	110	9998	9525	473	4.97
1	6919	98	9413	9542	-129	-1.35
C2	6974	95	9024	9554	-530	-5.55
61	6981	92	9144	9556	-412	-4.31
8	6995	106	9600	9559	41	0.43
70	7126	92	9600	9589	11	0.12

GRANROS STRATIGRAPHIC INTERVAL

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS ΔZ (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
56	7193	98	9321	9604	-283	-2.95
65	7194	62	9797	9604	193	2.01
36	7222	122	9898	9611	287	2.99
43	7266	124	9600	9620	- 20	-0.21
25	7335	142	10003	9635	368	3.82
15	7348	134	10435	9638	797	8.27
62	7357	98	9413	9640	-227	-2.36
74	7371.5	95	9600	9643	- 43	-0.45
37	7423	120	10325	9655	670	6.94
14	7472	112	10104	9665	439	4.54
9	7479.5	111	9600	9667	- 67	-0.69
45	7508	156	9797	9673	124	1.28
38	7566	132	10325	9685	640	6.61
57	7661	102	9600	9705	-105	-1.08
39	7718	152	10325	9717	608	6.25
44	7732	126	10104	9720	384	3.95
19	7780	142	10435	9730	705	7.25
47	7825	154	9898	9740	158	1.62
10	7827	110	10104	9740	364	3.74
63	7943	102	9797	9764	33	0.34
66	8387	96	10104	9853	251	2.55
75	8429	80	10435	9861	574	5.82
76	8591	92	10325	9893	432	4.37

D-SANDSTONE AND/OR MOWRY SHALE STRATIGRAPHIC INTERVAL

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS Δ Z (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
11	4736	76	10483	10292	191	1.35
4	4867	94	10876	10340	536	5.19
49	4901	104	10666	10352	314	3.03
27	4916	86	10381	10356	25	.24
16	4936	84	10435	10364	71	.69
72	4993	44	10440	10384	56	0.54
12	5008	72	10104	10389	-285	-2.74
68	5074.5	53	9879	10411	-532	-5.11
26	5208	44	11163	10457	706	6.75
32	5329	116	11181	10497	684	6.52
67	5336	50	9893	10499	-606	-5.78
50	5504	94	10526	10553	- 27	-0.26
33	5829	90	10745	10655	90	.85
58	5895	52	8986	10675	-1689	-15.83
5	5916	74	10763	10682	81	0.76
41	6007	84	10867	10708	159	1.48
51	6110	80	10175	10739	-564	-5.25
60	6147	56	10666	10750	- 84	-0.78
21	6198	78	11294	10764	530	4.92
6	6340	76	10841	10805	36	0.33
42	6340	80	10941	10805	136	1.26
46	6347	52	11294	10807	487	4.51
64	6415	54	10477	10826	-349	-3.22
69	6453	58	10917	10837	80	0.74
55	6495	78	12000	10849	1151	10.61
73	6556	44	10435	10866	-431	-3.96
17	6564	62	11006	10868	138	1.27
34	6621	82	11486	10883	603	5.54
30	6627.5	43	10927	10886	41	0.38
28	6671	74	11165	10898	267	2.45
7	6808	64	10824	10934	-110	-1.01
48	6900	58	11337	10959	378	3.45
18	6912	64	11050	10962	88	.80
22	6931	60	11292	10967	325	2.97
35	6934	72	11362	10968	394	3.59
1	7001	66	10923	10985	- 62	-0.57

D-SANDSTONE AND/OR MOWRY SHALE STRATIGRAPHIC INTERVAL

WELL #	MEAN DEPTH (FEET)	INTERVAL THICKNESS ΔZ (FEET)	INTERVAL VELOCITY (FEET/SEC)	REGIONAL INTERVAL VELOCITY (FEET/SEC)	VELOCITY DEVIATION (FEET/SEC)	RESIDUAL VELOCITY PERCENTAGE
61	7056	58	10728	11000	-272	-2.47
C2	7062	82	10560	11001	-441	-4.01
8	7081	66	11479	11004	473	4.29
70	7179	50	10666	11032	-366	-3.32
65	7252	54	11097	11050	47	0.42
56	7276	68	11294	11056	238	2.16
36	7300	34	10982	11062	- 80	-0.72
43	7361	66	10433	11077	-644	-5.82
59	7397	70	11610	11086	524	4.72
25	7425	40	10891	11094	-203	-1.83
62	7434	56	11088	11096	- 8	-0.07
15	7438	46	11265	11097	168	1.51
74	7441	45	10550	11097	-547	-4.93
37	7512	58	11358	11115	243	2.18
14	7560	60	10958	11124	-169	-1.51
9	7565	60	11002	11129	-127	-1.14
45	7610	48	10998	11139	-141	-1.27
38	7660	56	11129	11151	- 22	- .20
57	7741	58	11078	11170	- 92	-0.83
39	7815	42	11325	11188	137	1.22
44	7825.5	61	11111	11191	- 80	-0.72
19	7872	42	11199	11202	- 3	-0.03
10	7910	56	11015	11211	-196	-1.75
47	7927	50	11168	11215	- 47	-0.42
63	8019	50	11035	11236	-201	-1.79
66	8457	44	11174	11336	-162	-1.43
75	8486	34	10780	11343	-563	-4.97
76	8656	38	11522	11381	141	1.24