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CONODONT COLOR ALTERATION, ORGANIC METAMORPHISM, AND THERMAL HISTORY OF THE "TRENTON FORMATION," MICHIGAN BASIN

presented by

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Major professor
Duncan F. Sibley

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CONODONT COLOR ALTERATION, ORGANIC METAMORPHISM AND THERMAL HISTORY OF THE "TRENTON FORMATION," MICHIGAN BASIN

By

Craig G. Hogarth

AN ABSTRACT OF A THESIS

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ABSTRACT

CONODONT COLOR ALTERATION, ORGANIC METAMORPHISM, AND THERMAL HISTORY OF THE "TRENTON FORMATION," MICHIGAN BASIN

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The paleogeothermal gradient in the Michigan Basin has been found to closely resemble present day gradients. This conclusion is based on analysis of thermal maturation of conodonts in the "Trenton Formation" (Middle Ordovician), Michigan Basin.

In the northern and central portions of Michigan, a paleogeothermal gradient of 23 ^{o}C/km. best fits the maturity of the conodonts. In the southern portion of the basin, the observed maturity of the conodonts could not be accounted for with a geothermal gradient of 23 ^{o}C/km. Additional subsidence, between 600 and 700 meters, or an average geothermal gradient of 31 ^{o}C/km. had to exist to account for the maturity in southern Michigan.

From constraints provided by geothermal gradients, the 'oil generative window' was constructed for the burial history curves in the Michigan Basin. In the Central Michigan Burial History Curve, oil generation is presently beginning in the Lower Devonian section. In the Northern Michigan Burial History Curve, oil generation is beginning in the upper portion of the Upper Silurian section. In the Southern Michigan Burial History Curve, only rocks of Ordovician age and older are capable of hydrocarbon generation.

DEDICATION

In Memory of, Patricia Ellen Friedly Hogarth

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INTRODUCTION

The Michigan Basin is a stable, Paleozoic intracratonic basin which underwent subsidence from the Ordovician through the Pennsylvanian. Recently, two models for the thermal history of the basin have been proposed. Large discrepancies exist between the geophysical model of the basin (Nunn, Sleep, and Moore, 1984), and a model using the Time Temperature Index (TTI) of organic maturation (Cercone, 1984). The geophysical model proposes that geothermal gradients during the Paleozoic varied little from the average present day geothermal gradient of 22 ^{o}C/km. The Time Temperature Index model for the thermal history of the Michigan Basin proposes higher paleogeothermal gradients, between 35 ^{o}C/km. and 45 ^{o}C/km. for the Paleozoic section with a subsequent decrease in the geothermal gradient to present day values.

This study is concerned with the thermal history of the "Trenton Formation" (Middle Ordovician), Michigan Basin using conodonts as indicators of organic metamorphism. Conodonts are microfossils, which have been used as indicators of organic metamorphism in Paleozoic rocks, to estimate past thermal history and degree of organic maturity (Epstein, et al., 1977), (Harris, 1979)

(Legall, et al., 1981), and (Wardlaw and Harris, 1984). Conodonts were used in this study as indicators of organic metamorphism because, 1) they are present in the early Paleozoic rocks, unlike vitrinite; 2) they are common in carbonate rocks, unlike palynomorphs; and 3) they are stable under a wide range of thermal conditions, unlike palynomorphs. Using conodonts as indicators of organic metamorphism, estimates of a geothermal gradient in the Paleozoic were made. From the estimates of paleogeothermal gradients, inferences concerning the generation and preservation of oil and gas can be attempted for the Michigan Basin.

DESCRIPTION OF THE MICHIGAN BASIN AND "TRENTON FORMATION"

The Michigan Basin is composed of a sequence of predominantly marine, Paleozoic sediments which dip gently toward a depocenter in the north-central portion of the lower penninsula of Michigan. The sediments of the Michigan Basin are carbonates (47 %), clastics (41 %), and evaporites (12 %) (Ells, 1969).

The Michigan Basin is encircled by the Canadian Shield to the north, the Algonquin Arch to the east, the Findlay and Kankakee Arches to the south, and the Wisconsin Arch to the west (Ells, 1969). For the most part, the basin has had a relatively simple structural history with little evidence for post-subsidence structural deformation (Nunn, Sleep, and Moore, 1984).

The "Trenton Formation" is one of the first formations in the Michigan Basin to exhibit the present basin like geometry. It is a sequence of fossiliferous limestone with dolomite present in some portions of the basin. Near the base, and in the northern sectors of the basin, the "Trenton Formation" gradually becomes shalier. Thicknesses of the "Trenton Formation," in the southern penninsula of Michigan, range from 61 meters to 145 meters. From exposures in the Upper Penninsula, to the deepest portion in central, lower Michigan, there is about 3350 meters of relief on the top of the "Trenton Formation." Overlying the "Trenton Formation" in the southern penninsula, are sediment thicknesses ranging between 380 and 3000 meters (Lillienthal, 1978). Because the "Trenton Formation" is one of the earliest formations to exhibit the present basin geometry, it is ideal for examining the Paleozoic thermal history of the Michigan Basin with conodonts.

THERMAL HISTORY OF THE MICHIGAN BASIN

A preliminary study of the observed thermal maturity in the Michigan Basin was completed by Moyer (1982) using amorphous kerogen from selected formations. Moyer (1982) assumed that amorphous kerogen and terrestial spores undergo similar color changes as they mature. The coloration of organic matter was graded on the basis of a spore/pollen color chart. On the basis of one Saginaw Formation coal sample at Grand Ledge, Michigan (mean maximum reflectance R_o= .541%) and the amorphous kerogen coloration data, Moyer (1982) estimated that between 1.2 and 2.1 kilometers of overburden existed in the Michigan Basin. Moyer (1982) based the overburden estimate on a paleogeothermal gradient estimate of 46 ^{o}C/km. and a mean annual temperature of 8 ^{o}C. The paleogeothermal gradient was inferred from a least squares analysis of regression for amorphous kerogen coloration in the McClure Sparks well.

Cercone (1984), in order to infer the thermal history of the basin, utilized Moyer's (1982) data and constructed burial history curves, from stratigraphic data, for selected portions of the Michigan Basin. Using several lines of evidence, Cercone (1984) estimated that 1,000 meters of overburden had been eroded from the Michigan Basin between the Permian and the Jurassic. Her lines of evidence include:

1. The presence of immature Jurassic sediments unconformably lying on mature Pennsylvanian sediments.
2. Extrapolation of an early Paleozoic subsidence rate through the Carboniferous, posits 1,000 meters of additional subsidence.
3. The presence of 1,700 meters of Carboniferous sediment present in the Illinois Basin minus the 700 meters of Carboniferous sediment present in the Michigan Basin is about 1,000 meters.

4. Extrapolation of the regional dip in the Upper Mississippian Bayport Limestone to the northern hinge line of the basin reveals an estimate of about 1,000 meters of sediment eroded from the Michigan Basin (Cercone, 1984).

From these lines of evidence, and stratigraphic information, Cercone (1984) was able to construct burial history curves and apply Lopatin's method to estimate paleogeothermal gradients in the basin (Lopatin, 1971; Waples, 1980).

From the Time Temperature Index calculations and the maturity data from Moyer (1982), Cercone (1984) estimated that paleogeothermal gradients between 35 ^{o}C/km and 45 ^{o}C/km existed for the Paleozoic. Cercone (1984) postulates that a linear decrease in the geothermal gradient took place from the Permian to the present in order to account for present day geothermal gradients of around 22 ^{o}C/km. Moyer (1982) and Cercone (1984) have proposed higher geothermal gradients in the past, based on suspect organic maturity data, yet geophysical models of the basin propose paleogeothermal gradients which are the same as present day values.

Nunn (1981) and Nunn, Sleep, and Moore (1984) developed a 3-dimensional model for the isostatic subsidence of the Michigan Basin with subsidence beginning at the base of the Middle Ordovician (462 M.Y. b.p.). Excess temperatures due to uplift and subsequent thermal contraction of the lithosphere could produce an excess temperature anomaly of only 15 ^{o}C in the center of the basin for the Middle Ordovician rocks and degrade to 0 ^{o}C by the Pennsylvanian. Nunn, Sleep, and Moore (1984) conclude that the excess temperatures produced by a thermal event in the lithosphere would be insignificant compared to the deposition of overlying sediments and a corresponding increase in temperature due to burial. Based on the geophysical model, Nunn, Sleep, and Moore (1984) estimated that paleogeothermal gradients in the basin were similar to present day geothermal gradients of 22 ^{o}C/km.

The geophysical model rejects the model of higher geothermal gradients in the basin on two points. First, in order to account for paleogeothermal gradients of an additional 20 ^{o}C/km., heat flow would have to increase by an additional HFU. In order to perpetuate the additional heat flow during the Paleozoic history of the basin, an intrusion the size of a batholith must be present to account for geothermal gradients on the order of 42 ^{o}C/km. (Nunn, Sleep, and Moore, 1984). Secondly, if one was to assume, for a period from the Devonian through the Carboniferous, a gradient 20 ^{o}C/km. higher than the present day geothermal gradient, and apply the uniform extension model for total oceanization of continental lithosphere (McKenzie, 1978), then subsidence would be on the order of 10 kilometers for the Michigan Basin (Nunn, Sleep, and Moore, 1984). Obviously, these are strong arguments against higher paleogeothermal gradients in the Michigan Basin.

LOPATIN'S METHOD OR THE TIME TEMPERATURE INDEX

The Time Temperature Index is used to model the thermal conditions necessary for organic maturation (Lopatin, 1971; Waples, 1980). The model is based on the burial history of sediments through time, the thermal conditions encountered during burial, and the kinetics of organic maturation. Burial history can be constructed from knowledge of the geologic history and stratigraphic information available for the intervals of interest. The thermal conditions can be based on knowledge of present geothermal gradients in the area of interest. Paleogeothermal gradients can be estimated from the Time Temperature Index model using available organic maturity data within the area of interest and applying various geothermal gradients to best fit the burial history and observed organic maturity. In the model, the kinetics of organic maturation are based on the 'pseudo first-order reaction rate' which states that reaction rates in organic maturation will double with every 10 ^{o}C rise in temperature. Once the burial history, the geothermal gradient or observed maturity, and the kinetics of organic maturity are known then the Time Temperature Index can be calculated.

The Time Temperature Index (TTI) is a simple calculation used to infer the thermal conditions necessary for organic maturation. Figure 1. is a sample burial

Figure 1. Burial History Curve for Example Calculation of the Time Temperature Index.

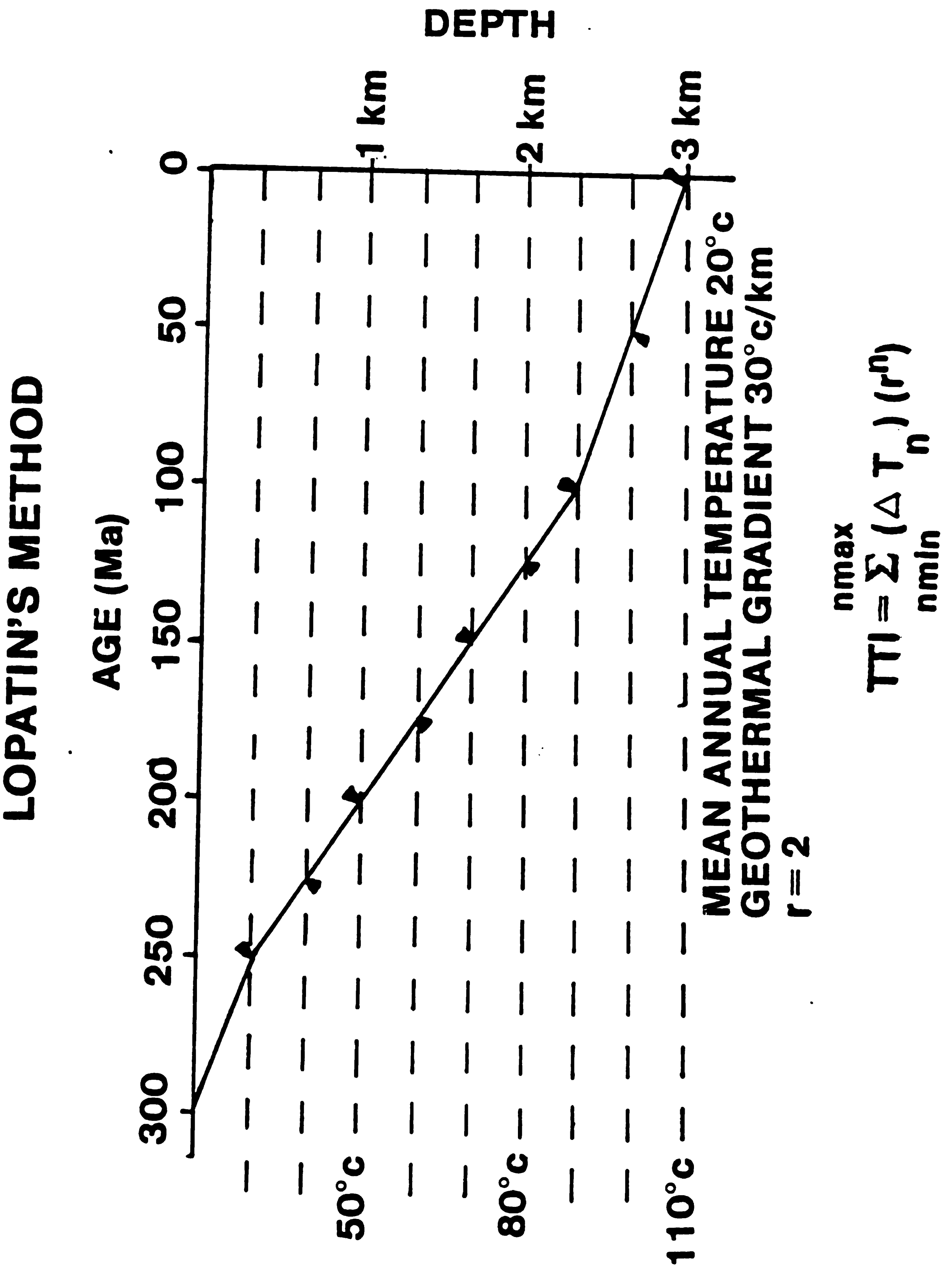

LOPATIN'S METHOD
AGE (Ma)
0
50
100
150
200
250
300
DEPTH
1 km
2 km
3 km
50°c
80°c
110°c
MEAN ANNUAL TEMPERATURE 20°c
GEOTHERMAL GRADIENT 30°c/km
r = 2
$TTI = \sum_{nmin}^{nmax} (\Delta T_n)(r^n)$

Figure 1.

history curve used for a simple calculation of the Time Temperature Index. The equation to calculate the Time Temperature Index is $TTI = \sum_{n_{min}}^{n_{max}} (\Delta T_n)(r^n)$. ΔT_n is the time in mega-annums which a sediment interface resides in a particular temperature interval. In the example the r value is equal to 2, or with every 10 °C increase in temperature the rate of reaction doubles. The superscript n, or the index value, is an arbitrary value which has been designated 0 for the temperature interval between 100 - 110 °C. Table 1. lists n values assigned to various temperature intervals. In the example, the geothermal gradient is 30 °C/km. and the mean annual temperature is 20 °C. From the geothermal gradient, the burial history curve, and the temperature factor the TTI can be calculated. For the example, a cumulative TTI of 87.5 was calculated (Table 2.).

Waples, (1980) has correlated the Time Temperature Index with various indicators of organic maturation, which are time and temperature dependent, such as vitrinite reflectance, the Thermal Alteration Index (TAI), and other organic indicators which define the 'oil generative window' and degrees of oil and gas preservation (Table 3.). Because vitrinite is correlative with the Color Alteration Index (CAI), the Time Temperature Index (TTI) can be applied and oil and gas generation can be estimated using conodonts as indicators of organic metamorphism. With Color Alteration Indices from the Trenton Formation and the

Table 1. Temperature Factors for Different Temperature Intervals

Temperature Interval °C	Index Value	Temperature Factor
30 - 40	-7	r^{-7}
40 - 50	-6	r^{-6}
50 - 60	-5	r^{-5}
60 - 70	-4	r^{-4}
70 - 80	-3	r^{-3}
80 - 90	-2	r^{-2}
90 - 100	-1	r^{-1}
100 - 110	0	r^{0}
110 - 120	1	r^{1}
120 - 130	2	r^{2}
130 - 140	3	r^{3}
140 - 150	4	r^{4}
.....,		

(After Waples, 1980)

Table 2. Calculation of Cumulative TTI for Example Burial History Curve

Time	Duration (Ma)	Temperature Factor	Interval TTI
1	50	2^{-8}	.195
2	25	2^{-7}	.195
3	25	2^{-6}	.390
4	25	2^{-5}	.781
5	25	2^{-4}	1.562
6	25	2^{-3}	3.125
7	25	2^{-2}	6.25
8	50	2^{-1}	25.0
9	50	2^{0}	50.0
		Cumulative TTI	87.5

Table 3. Correlation of TTI with Stages of Oil Generation and Preservation

	TTI	R_o
Onset of Oil Generation.....	15	.65
Peak of Oil Generation......	75	1.00
End of Oil Generation.......	160	1.3
Upper TTI Limit for Occurrence of Wet Gas.......	~1500	2.2

(From Waples, 1980)

Time Temperature Index (TTI) calculations, estimates of paleogeothermal gradients can be applied to estimate the thermal conditions necessary for the generation and preservation of oil and gas in the Michigan Basin.

BURIAL HISTORY CURVES

Analysis of the thermal history and evolution of hydrocarbons in the Michigan Basin necessitates the use of burial history curves. Burial history curves are reconstructions of various sediment units through time. The curves can be constructed to record subsidence, uplift, or other geologic conditions. The accuracy of the thermal history is dependent on the accuracy of the burial history curves (Waples, 1980). Cercone (1984) constructed three burial history curves in different sections of the Michigan Basin (Figure 2.). The curves are based on geologic evidence of subsidence, prexisting overburden in the basin, and stratigraphic data. Continuous subsidence of the Michigan Basin was inferred through the Carboniferous, and erosion events during the Paleozoic were combined into one major event beginning in the Permian. These assumptions were used to simplify the burial history models. The removal of 1,000 meters of preexisting overburden was also incorporated into the burial history curves (Cercone, 1984).

The curves represent three areas of oil production in the basin. The Central Michigan Burial History Curve is located in the central portion of the basin in the

Figure 2. Location of Burial History Curves Constructed in the Michigan Basin (From Cercone, 1984)

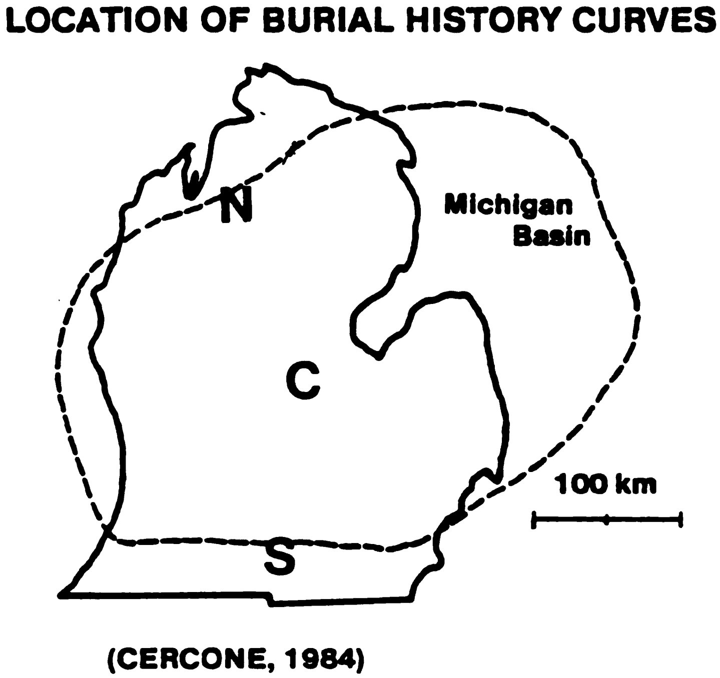

LOCATION OF BURIAL HISTORY CURVES
N
Michigan Basin
C
100 km
S
(CERCONE, 1984)

Figure 2.

Mississippian/ Devonian production areas of the basin. The Northern Burial History Curve represents the northern reef trend of the basin. The Southern Burial History Curve represents burial history in the Ordovician production zones of the Michigan Basin (Cercone, 1984). Finally, burial history curves were constructed in areas where changes in CAI are located. Burial history curves were used in the Lopatin modelling so paleogeothermal gradients could be estimated and compared with the observed maturity.

ORGANIC METAMORPHISM AND CONODONTS

Conodonts are a microfossil of debated biological affinity which were ubiquitous in Cambrian through Triassic seas. Numerous authors postulate that most conodonts were pelagic organisms, however, this interpretation is based solely on their global distribution and bilateral symmetry (Clark, 1981; Bergstrom, 1973; and Seddon and Sweet, 1971). Traditionally, conodonts have been used as biostratigraphic tools. Recently, interest has been focused on their use as indicators of organic metamorphism in Paleozoic rocks.

Diagenesis and catagenesis have long been studied in various types of organic matter. Temperature and time have been emphasized as the primary variables controlling the diagenetic and catagenetic processes occuring in organic matter (Teichmuller and Teichmuller, 1966; Lopatin and Bostick, 1973; Hood, Gutjahr, and Heacock, 1975). Conodont skeletons contain a small amount of organic matter, which accounts for their coloration. Upon heating, the organic matter present is progressively fixed within the conodont element. With progressive carbon fixation, darkening of the conodont element takes place. Maturation of conodonts, in the geologic environment, is considered to be additive and irreversible (Epstein, et al., 1977).

From experimental evidence, Epstein, et al., (1977) constructed the Color Alteration Index (CAI) to estimate the maturity of the conodonts, and then calculated an Ahrrenius plot to estimate the approximate paleo-temperatures conodonts have undergone during their burial history. Unaltered conodonts, from the Kope Formation (Upper Ordovician), were subjected to temperature ranges between 300 ^{o}C to 600 ^{o}C for 1 to 1000 hours in order to model the color changes observed in field collections of conodonts. In the presence of heat, conodonts gradually undergo color changes from amber at low temperatures to black at high temperatures. The color changes observed in the experiments were the same as the colors observed in the field collections. From the observed color changes, Epstein, et al., (1977) developed the Color Alteration Index (CAI). The Color Alteration Index is a numerical scale from 1 to 5 and is based on the color observed in the conodonts under reflected light (Figure 3.).

Based on the experimental evidence provided by the conodonts in open-air heating runs, Epstein, et al., (1977) extrapolated an Ahrrenius plot using the 'pseudo first

Figure 3. Color Alteration Indices, Paleotemperatures, and Percent Fixed Carbon. (From Epstein, et al., 1977)

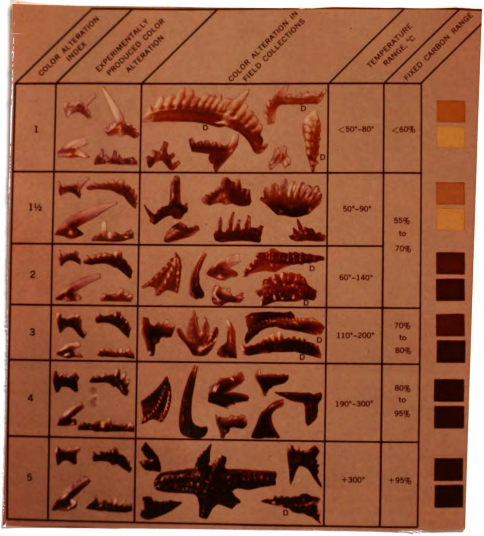

COLOR ALTERATION INDEX
EXPERIMENTALLY PRODUCED COLOR ALTERATION
COLOR ALTERATION IN FIELD COLLECTIONS
TEMPERATURE RANGE, °C
FIXED CARBON RANGE
1
1½
2
3
4
5
D
<50°-80°
50°-90°
60°-140°
110°-200°
190°-300°
+300°
<60%
55% to 70%
70% to 80%
80% to 95%
+95%

Figure 3.

order reaction rate' to geologic time and reasonable thermal conditions. From the Ahrrenius plot, estimates of paleotemperature can be made based on the observed Color Alteration Index (CAI) of the conodonts (Figure 4.).

In addition to developing the Color Alteration Index for conodonts, Epstein, et al., (1977) experimentally matured conodonts, under a variety of conditions, in order to determine whether the coloration process was contingent on variables other than the duration and magnitude of heating. Under high pressure (1 kbar), using inert Argon and reducing methane as media, the conodonts showed no variation in color from those heated at 1 atmosphere in open-air runs. Also, the effects of pressure have been addressed extensively in the coalification process. Lopatin and Bostick (1973), provide laboratory evidence showing that pressure has little or no effect on the increase in vitrinite reflectance during experimental heating at high temperatures and varying pressures. Field evidence from coal seams and conodonts demonstrates that pressure has little or no effect in the maturation of organic matter (Teichmuller and Teichmuller, 1966; Epstein, 1977).

Although pressure has no effect on the coloration process in conodonts, water pressure does affect the coloration of conodonts. Under high pressure (1 kbar), in a closed system, and in the presence of water the maturation of the conodonts is retarded. The presence of

Figure 4. Ahrennius Plot of Heat Induced, Open-Air, Conodont Color Alteration Data. (From Epstein, et al., 1977)

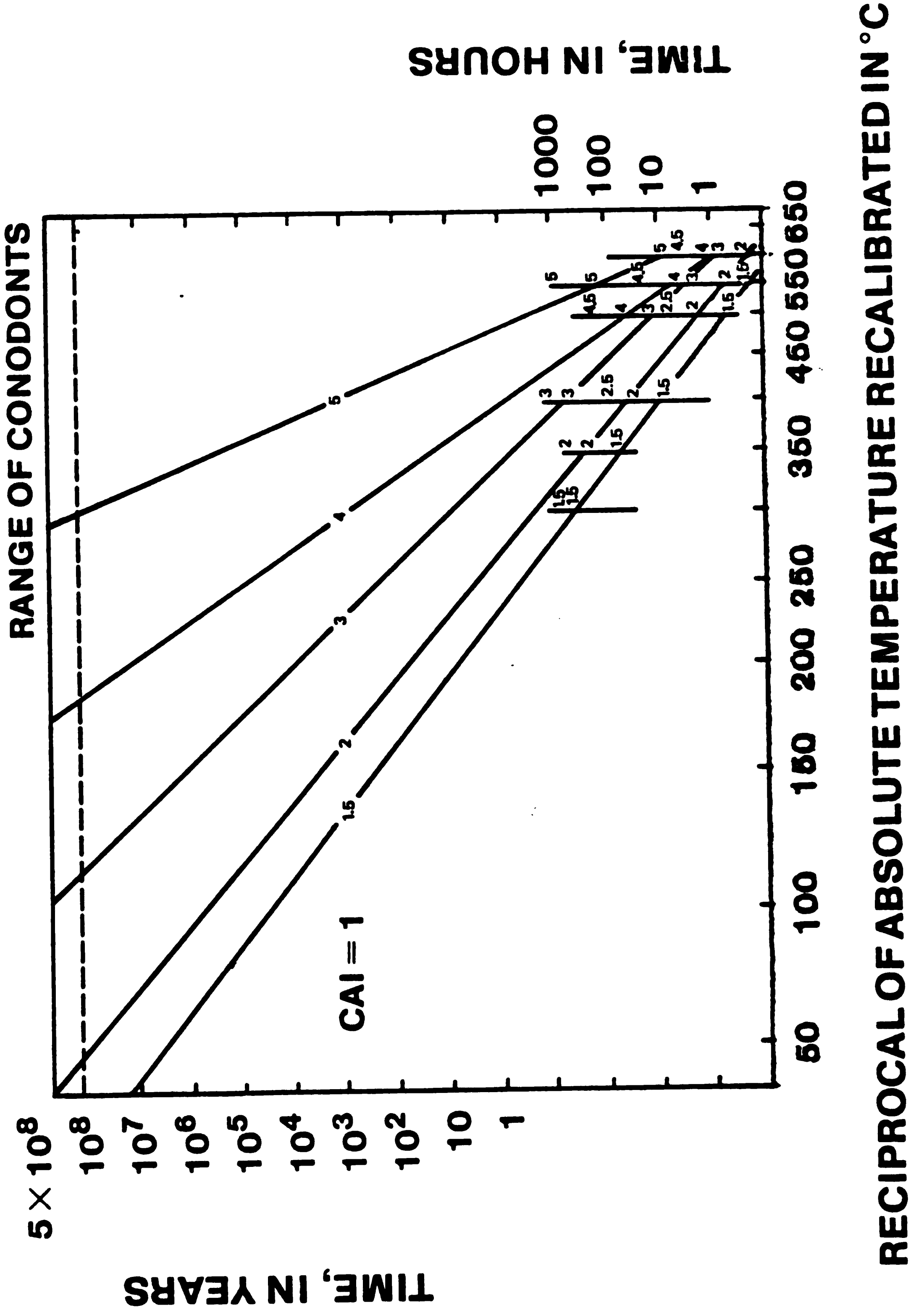

TIME, IN HOURS
RANGE OF CONODONTS
CAI = 1
TIME, IN YEARS
RECIPROCAL OF ABSOLUTE TEMPERATURE RECALIBRATED IN °C

Figure 4.

water in an open system has no effect on the coloration of conodonts. However, as a result of color retardation in a closed system, paleotemperature estimates from the Arrhenius plot could be underestimated. Epstein, et al., (1977) point out that these conditons may be present in overpressured rocks. Overpressured rocks, in the Michigan Basin, were not present due to low rates of sedimentation (Bethke, 1985), therefore paleotemperature estimates, from the Ahrrenius plot are probably correct. Based on the experimental and field evidence, conodonts appear to be good indicators of organic maturity and paleotemperature in carbonate rocks.

The Color Alteration Index (CAI) has been correlated with other scales of organic maturation in sediments. Epstein, et al., (1977), found a good correlation between vitrinite reflectance and the CAI observed in Devonian conodonts found in the Appalachian Basin. The range in vitrinite reflectance and CAI is less than 0.8 $\%R_o$ for a CAI of 1 to more than 3.6 $\%R_o$ for a CAI of 5. Color Alteration Indices (CAI) have also been correlated with percent fixed carbon. The fixed carbon percentages range from less than 60% to more than 95%. Other scales of organic maturity can be correlated with the Color Alteration Index based on the correlation with vitrinite reflectance. Some scales which can be correlated with the Color Alteration Index are the Level of Organic Metamorphism (Hood, Gutjahr, and Heacock, 1975), the

Thermal Alteration Index (TAI) (Staplin, 1969), and the Time Temperature Index (TTI) (Lopatin, 1971; Waples, 1980) (Figure 5.). All of the preceding are measures of organic maturation which can be correlated with the Time Temperature Index (TTI).

COLOR ALTERATION INDEX: DATA

Sample Preparation and Indexing:

Between 100 and 500 grams of limestone or dolomite was crushed in a coarse crusher. The size of the largest crushed chips was about 1/2 inch. The chips were then place in plastic buckets, and 10 percent acetic acid was added. The buckets were covered and placed under fume hoods for several days, until the carbonate matrix was dissolved. Once the matrix was dissolved, the remaining sediment was wet sieved to remove the coarse fragments and the fine particles from the conodont fraction. A 25 mesh sieve on top of 150 to 200 mesh sieves removed the remaining coarse fraction. The 150 to 200 mesh sieves caught the sediment fraction containing the conodonts. The sediment fraction containing the condonts was wet sieved to remove remaining fine particles. The fraction of the sediment containing the conodonts was allowed to dry overnight.

Once the remaining sediment is dry, conodonts can be further concentrated using heavy liquid separation. 1,1,2,2, Tetrabromoethane was used to complete the heavy liquid separation. Care must be taken when using heavy

Figure 5. Scales of Organic Metamorphism.
(LOM, TAI, and R_o: From Hood, Gutjahr, and Heacock, 1975)
(TTI: From Waples, 1980)
(CAI represent maximum estimated R_o: From Epstein, et al., 1977)

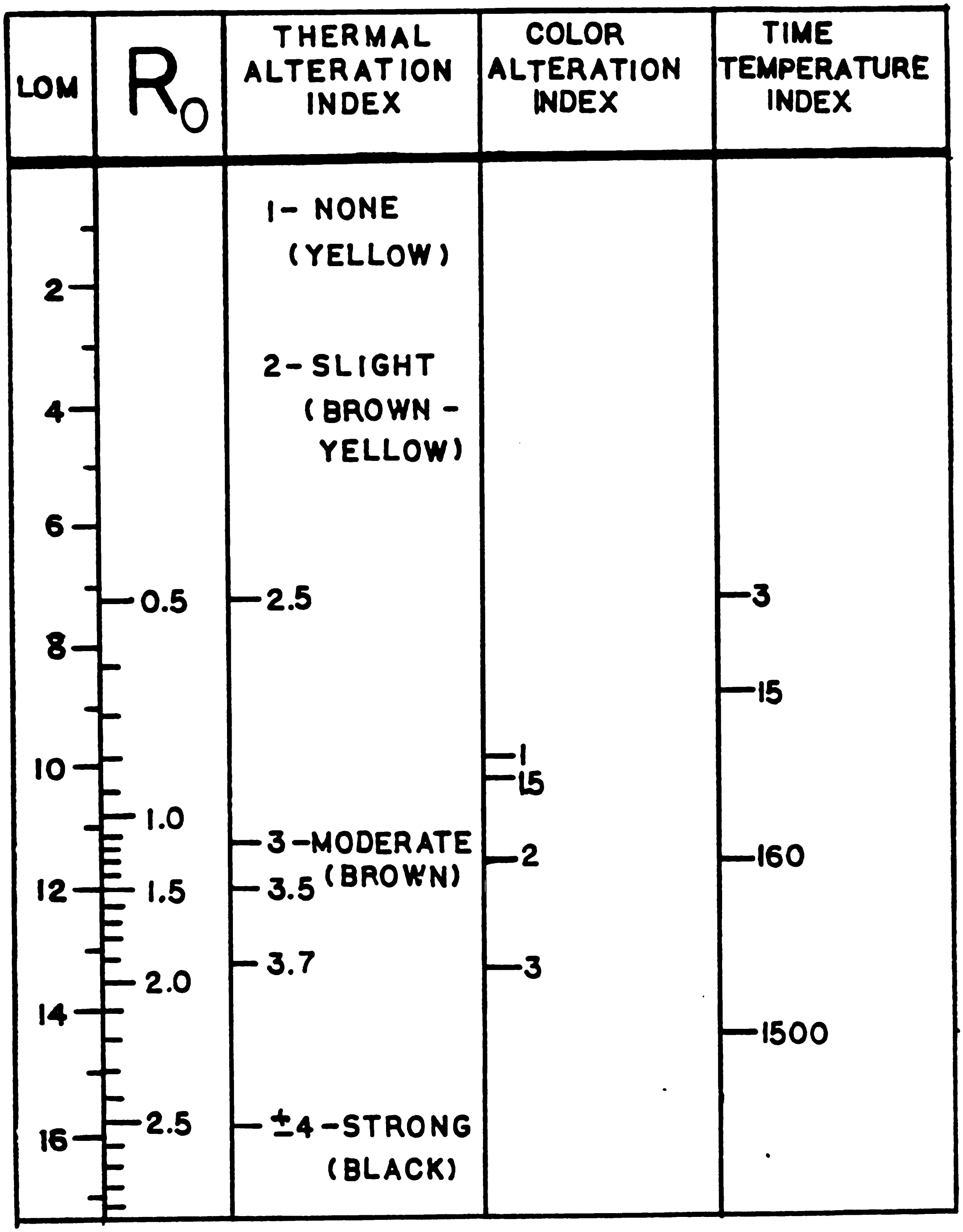

LOM
R_O
THERMAL ALTERATION INDEX
COLOR ALTERATION INDEX
TIME TEMPERATURE INDEX
2
4
6
8
10
12
14
16
0.5
1.0
1.5
2.0
2.5
1- NONE (YELLOW)
2- SLIGHT (BROWN - YELLOW)
2.5
3 -MODERATE (BROWN)
3.5
3.7
±4 -STRONG (BLACK)
1
1.5
2
3
3
15
160
1500

Figure 5.

liquids for they are carcinogenic (Hauff and Airey, 1978). A strong fume hood, a respirator, and Norton Viton gloves were used to handle the heavy liquid separation. The sediment containing the conodonts was placed in the 1,1,2,2, Tetrabromoethane and stirred. The slurry was then allowed to sit overnight with occasional stirring. Once the separation was complete the heavy portion is separated by filtering. The 1,1,2,2, Tetrabromoethane was filtered through and saved for future use. The heavy fraction was washed a few times, to remove the remaining heavy liquid, with methanol or acetone and allowed to dry. Once the sediment was dry, the conodonts were handpicked with a trimmed 00000 camel's hair brush. Conodonts were mounted on standard micropaleontologic slides and glued on with gum arabic.

Once the conodonts have been recovered, the Color Alteration Indices can be determined. From each core a number of individual samples were selected for indexing. Specimens were placed on a clean, white porcelain plate under reflected light. Using a CAI standard of Ordovician conodonts provided by Dr. Anita G. Harris, each sample was indexed by visual comparison with the standards and assigned a CAI. After initial indexing, representative samples from every core were tested to determine whether the assigned CAI value was consistent and reproducible.

Data:

Color Alteration Indices were determined for conodonts in 24 "Trenton" core locations, one Upper Penninsula surface exposure, and from data published on the Brazos-State Foster core in Ogemaw county (Repetski and Harris, 1981) (See Appendix A. for wells and exact locations). Color Alteration Indices, in the "Trenton Formation," range from 1.0 in the surface exposures of the Upper Penninsula and shallowly buried rocks in Southern Michigan, to 2.5 (at 3.02 km.) in the deepest central portion of the basin. At 3.84 km. the CAI is 3.0 in the Brazos State-Foster core (Repetski and Harris, 1981). From the CAI data collected in the "Trenton Formation," a CAI isograd map was constructed for the Southern Penninsula of Michigan. The isograd map is superimposed on a structure contour of the top of the "Trenton Group" (Figure 6.). The Ahrennius plot, constructed from experimental maturation of conodonts, indicates that temperatures in the basin ranged between 20 ^{o}C to 80 ^{o}C for a CAI of 1.0 and for a CAI of 3.0 paleotemperatures ranged between 110 and 200 ^{o}C. From the CAI estimates and the burial history curves, paleogeothermal gradients can be estimated for the Michigan Basin using Lopatin's Method.

PALEOGEOTHERMAL GRADIENT RECONSTRUCTION

Estimations of a paleogeothermal gradient in the Paleozoic is necessary to understand the thermal history of the Michigan Basin. The construction of a paleogeothermal

Figure 6. CAI Isograd Map Superimposed on Structure Contour of the Top of the "Trenton Group" (Structure Map: From Hinze and Merritt, 1969)

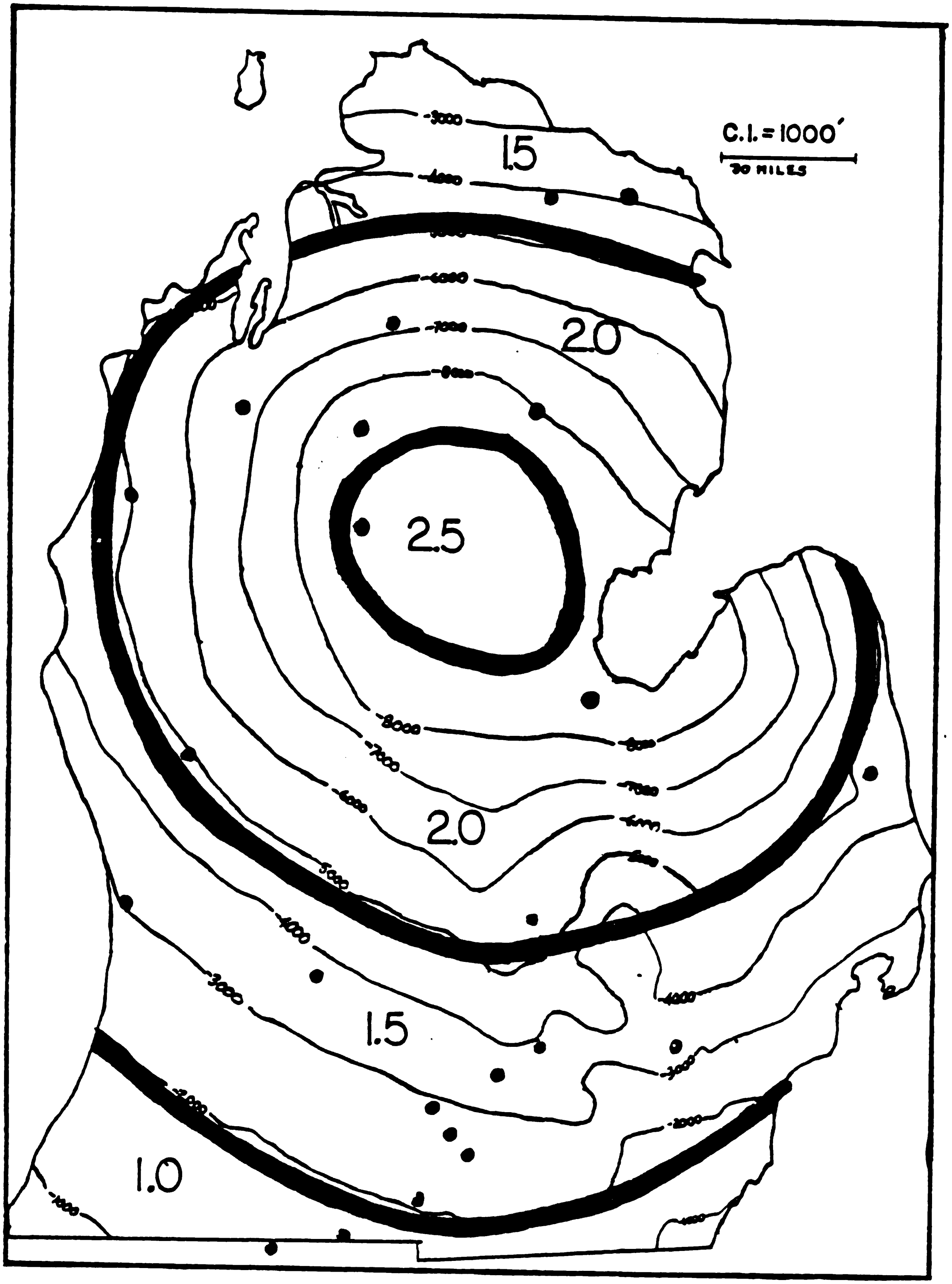

C.I. = 1000'
30 MILES
1.5
2.0
2.5
2.0
1.5
1.0
-3000
-4000
-6000
-7000
-8000
-8000
-7000
-6000
-5000
-4000
-3000
-2000
-1000

Figure 6.

gradient for the Ordovician rocks constrains geothermal gradients through most of the sedimentary history of the basin and provides constraints for the generation and preservation of oil and gas in the basin. Because conodonts provide an estimate of organic maturity in the early Paleozoic rocks, geothermal gradients can be applied to burial history curves in the Michigan Basin to estimate a gradient which fits the observed conodont maturity. In order to estimate paleogeothermal gradients, Lopatin's analysis was applied to the burial history curves, using a variety of geothermal gradients, to calculate maturities. A gradient was then picked which best fit the CAI observed in the conodonts.

Cercone (1984) has postulated geothermal gradients between 35 ^{o}C/km. and 45 ^{o}C/km. for much of the Paleozoic, with a subsequent linear decrease in the geothermal gradient from the Permian to the present day gradient of 22 ^{o}C/km. Using burial history curves constructed for portions of the Michigan Basin, the maturity of the Middle Ordovician section was calculated using Lopatin's analysis to determine whether the maturity of the conodonts concurred with the maturity calculated for a gradient of 35 ^{o}C/km. and a linear decrease to present day gradients of 22 ^{o}C/km. In most burial history curves, the maturity calculated by the published geothermal gradient of 35 ^{o}C/km. overestimated the observed maturity of the conodonts (Table 4.). For example, from an observed

Table 4. Calculation of the Cumulative TTI in the "Trenton Formation" Using a Paleogeothermal Gradient of 35 °C/km and a Linear Decrease to a Present Day Gradient of 22 °C/km. from the Permian to the Present.

	Present Burial	CAI Value	TTI Range	TTI Calc.
Southern Michigan....	.882 km.	1.0	1-30	21
Southern Michigan....	1.42 km.	1.5	20-40	68
S./Middle Michigan....	1.86 km.	1.5-2.0	~35-45	202
Northern Michigan....	2.26 km.	2.0	40-160	442
Central Michigan....	2.96 km.	2.0	40-160	2548
Central Michigan....	3.84 km.	3.0	200-900	24,392

CAI of 2 at 2.96 km., and a corresponding range in TTI of 40 to 160, the cumulative TTI calculated using a geothermal gradient of 35 ^{o}C/km and a subsequent decrease to present day values was 2,548. This corresponds to a CAI value of 4.0. From consistent overestimation of this magnitude, one can conclude that lower geothermal gradients must have been present in the Michigan Basin.

Since the observed maturity is overestimated by the published paleogeothermal gradient from amorphous kerogen coloration data, lower paleogeothermal gradients must have been present in the Michigan Basin. For the Northern and Central Michigan Burial History Curves a paleogeothermal gradient of 23 ^{o}C/km. (M.A.T. 20 ^{o}C) was found to be the best paleogeothermal gradient accounting for the observed Color Alteration Indices (Table 5.).

Paleogeothermal gradients of 23 ^{o}C/km. are consistent with the constraints provided by the geophysical model (Nunn, Sleep, and Moore, 1984). Other evidence supporting this gradient is paleomagnetic data, from the McClure-Sparks well in the basin, which estimates a maximum paleotemperature of 200 ^{o}C (van der Voo, and Watts, 1976). The paleotemperature estimate of 200 ^{o}C was measured at a depth of 5.3 kilometers. If 1,000 meters of overburden is added to the 5.3 km., and a paleo-geothermal gradient of 35 ^{o}C/km is used to estimate paleotemperature, then temperatures on the order of 240 ^{o}C would have been present in the basin. On the other

Table 5. Calculation of Cumulative TTI in the "Trenton Formation" Using a Geothermal Gradient of 23 $^{o}C/km$.

	Present Burial	CAI Value	TTI Range	TTI Calc.
Southern Michigan....	.882 Km.	1.0	1-30	8.5
Southern Michigan....	.97 Km.	1.5	20-40	9.0
Southern Michigan....	1.42 Km.	1.5	20-40	18
S./Middle Michigan....	1.86 Km.	2.0	40-160	37
Northern Michigan....	2.26 Km.	2.0	40-160	63
Central Michigan....	2.96 Km.	2.0	40-160	184
Central Michigan....	3.84 Km.	3.0	200-900	785

hand, applying a gradient of 23 °C/km. temperatures on the order of 165 °C would have been present during maximum burial. Sustained temperatures of 165 °C would be consistent with the paleomagnetic data and the Color Alteration Indices in the northern and central portions of the basin, however, the observed maturity in southern portion of the basin can not be accounted for with a paleogeothermal gradient of 23 °C/km.

With a geothermal gradient of 23 °C/km. and burial history curves of the southern portion of the basin, the observed maturity of the conodonts can not be explained. The maturity observed in the conodonts is higher than the calculated maturity. With CAI of 1.5 at 0.97 km., the calculated TTI from a gradient of 23 °C/km. would be around 9. The minimum TTI for a CAI of 1.5 is 20. Also, near the boundary where CAI changes from 1.0 to 1.5, the TTI calculated, using a gradient of 23°C/km., is around 8, yet the predicted maturity should be around 15 to 20. The discrepancy between the observed maturity and the 23 °C/km. gradient suggests that variables controlling the thermal maturity of the southern portion of the Michigan Basin were different from the northern and central sections of the basin. A number of explanations exist to account for the increased maturity of the southern portion of Michigan.

One explanation for the maturity observed in the southern portion of the basin could be to add additional overburden to the basin while maintaining a gradient of 23 ^{o}C/km.. The amount of cumulative overburden required to account for the observed maturity, from the Mississippian to the Pennsylvanian, is on the order of 1,600 to 1,700 meters rather than 1,000 meters suggested by Cercone (1984). Cercone (1984) has also observed heightened maturity in the southern portion of the basin and attributes it to error in the burial history curve underestimating the amount of burial due to the erosion of an unknown amount of pre-Devonian sediment during the Early to Middle Devonian. However, with a gradient of 23 ^{o}C/km., the amount of pre-Devonian sediment removed during the Early to Middle Devonian (~15-20 Ma) would have to exceed 3,000 meters in order to account for the maturity observed in the Ordovician rocks of the southern basin. Sediment accumulation and erosion of this magnitude seems unlikely.

Another possible explanation for the higher observed maturity in the southern portion of the basin could be regional variation in the conductivity of rocks from the southern sector to other sectors of the basin. Generally, carbonates and sandstones have higher conductivities than shales, hence the geothermal gradient would be higher in sections containing more shale units. Hitchon (1984) points out that variation in conductivity is also related to permeability, the type of cementation, and the magnitude of compaction, as well as lithology. Pollack and Watts (1976) addressed the variation in conductivity of rocks from samples in the McClure Sparks well of the Michigan Basin. Their findings indicate that geothermal gradients in shale units of the Michigan Basin are around 25 °C/km, slightly higher than the average gradient of 22 °C/km. (Pollack and Watts, 1976). This variation is due to lower conductivity of shale units. Accounting for higher geothermal gradients in the southern portion of the basin by changing the conductivity would be difficult, for the conodonts were all selected from a carbonate matrix. Also, the shale content of the "Trenton Formation" increases to the north and the effects of decreased conductivity would probably be expressed in the rocks of the northern section of the basin (Lillienthal, 1978).

Although the addition of more cumulative overburden and changing rock conductivities are possible explanations for the increased maturity of the southern basin, the most plausible explanation would be an increase in heat flow on the southern flank of the basin. Based on the burial history curves, average geothermal gradients of 31 °C/km. had to exist in the southern portion of the basin to account for the maturity observed in the conodonts. Two possible models exist for increasing the heat flow in the southern portion of the basin. The most obvious method to increase heat flow in the sedimentary section would be to increase the heat flow contribution from basement rocks. Increased heat flow in the basement could be the result of an increased amount of radioactive decay on the southern edge of the basin. Another model accounting for higher heat flow, hence higher geothermal gradients is gravity-driven, ascending basin waters in the southern portion of the basin.

The paleohydrology of the Michigan Basin has not been studied. However, Bethke (1985) modelled the paleo-hydrology of the Illinois basin and concluded gravity driven groundwaters moved in a south to north direction through the Illinois Basin. With gravity drive, heat flow is increased significantly in the north due to warm ascending fluids. Hitchon (1984) associates hydrocarbon accumulations and variation in paleogeothermal gradients to gravity-driven paleohydrologic conditions operating in the Alberta Basin of Canada. Bethke (1985) points out that the Michigan Basin could also be considered for the development of a gravity drive model because it is tectonically similar to the Illinois Basin. The fact that large bodies of hydrothermal dolomites occur in the "Trenton Formation" in the southern portion of the basin (e.g. Albion-Scipio and Northville Fields (Taylor, 1982) is consistent with the idea that basinal brines were ascending in this region. Of course, much more work needs to be done in order to determine the paleohydrology of the Michigan Basin.

The regional movement of warm fluids through time could account for the maturity observed in the southern portion of the Michigan Basin, however, determining the duration and timing of such an event would be difficult. A geothermal gradient of 31 $^{o}C/km$. represents an average geothermal gradient for the entire post-depositional history of the Middle Ordovician section. Basin water movement of this nature would not span the entire post-depositional history of the Middle Ordovician section. Obviously, geothermal gradients would have fluctuated significantly during an event of this nature. However, if one assumes a duration from the Devonian through the Jurassic (~250 Ma) for the movement of basin waters in this manner, and a geothermal gradient of 23 $^{o}C/km$. for the remaining post-depostional history, the geothermal gradient would only have to increase to 32 $^{o}C/km$. in order to account for the observed maturity.

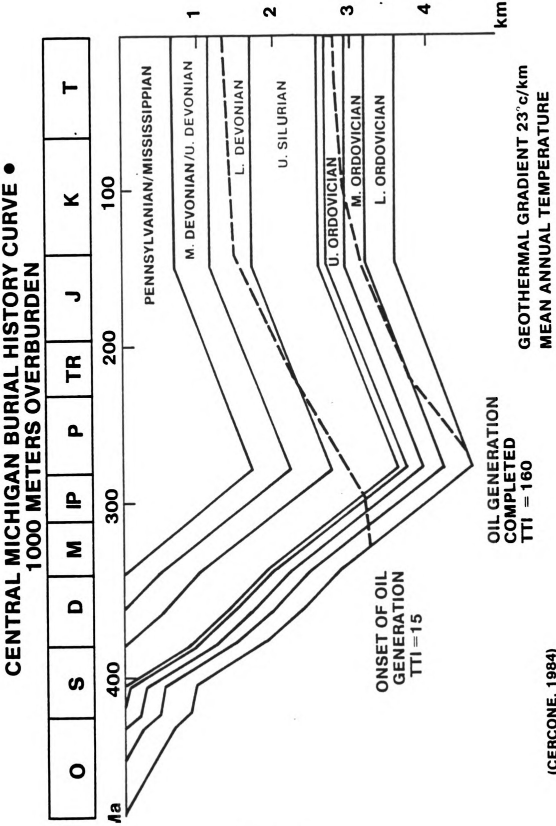
In summation, a paleogeothermal gradient of 23 $^{o}C/km$. is the best fit for the observed maturity in the northern and central sections of the basin, but in the southern portion of the basin additional overburden or an average gradient of 31 $^{o}C/km$ had to exist to account for the observed maturity of the conodonts.

GENERATION OF OIL AND GAS IN THE MICHIGAN BASIN

Once thermal conditions are established for the Michigan Basin, the generation and preservation potential for hydrocarbons can be estimated. Based on the constraints provided by the paleogeothermal gradient and burial history curves constructed for the Michigan Basin, the 'oil generative window' was constructed for each burial history curve. In the Central Michigan Burial History Curve (Figure 7.) the initial generation of oil (TTI=15) began in the Lower Ordovician section during the Mississippian and currently oil generation is beginning in the Lower Devonian section at just over 1 km. from the surface. The Lower Devonian section probably began generating oil about 200 million years ago. Oil generation has been completed (TTI=160) for all of the Lower and Middle Ordovician sections and portions of the Upper Ordovician section. Presently, the base of the oil generative window is about 2.85 km. from the surface in the Central Michigan Burial History Curve.

The Northern Michigan Burial History Curve represents the Silurian production zones of the Michigan Basin. In the Northern Michigan Burial History Curve, initial oil generation began in the Lower Ordovician section during the Mississippian and generation is presently occuring in the uppermost section of the Upper Silurian. Oil generation is completed for a small portion of the Lower Ordovician section in the Northern Michigan Burial History Curve. Presently, the boundary of the 'oil generative window' is from 1.30 to 2.75 kilometers below the surface (Figure 8.). The 'oil generative window' for the Central and Northern Michigan Burial History Curves was calculated using a

Figure 7. Central Michigan Burial History Curve
1,000 Meters Cumulative Overburden.
(Burial Curve: From Cercone, 1984)


CENTRAL MICHIGAN BURIAL HISTORY CURVE ●
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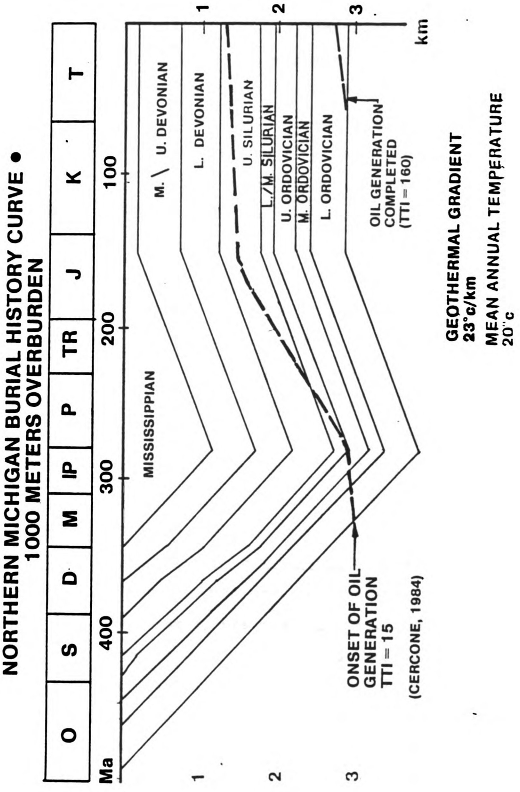
M. DEVONIAN/U. DEVONIAN
L. DEVONIAN
U. SILURIAN
U. ORDOVICIAN
M. ORDOVICIAN
L. ORDOVICIAN
ONSET OF OIL GENERATION TTI =15
OIL GENERATION COMPLETED TTI = 160
GEOTHERMAL GRADIENT 23°c/km
MEAN ANNUAL TEMPERATURE 20°c
(CERCONE, 1984)

Figure 7.

Figure 8. Northern Michigan Burial History Curve 1,000 Meters Cumulative Overburden. (Burial Curve: From Cercone, 1984)


NORTHERN MICHIGAN BURIAL HISTORY CURVE ●
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L. DEVONIAN
U. SILURIAN
L./M. SILURIAN
U. ORDOVICIAN
M. ORDOVICIAN
L. ORDOVICIAN
ONSET OF OIL GENERATION TTI = 15
OIL GENERATION COMPLETED (TTI = 160)
(CERCONE, 1984)
GEOTHERMAL GRADIENT
23°c/km
MEAN ANNUAL TEMPERATURE
20°c

Figure 8.

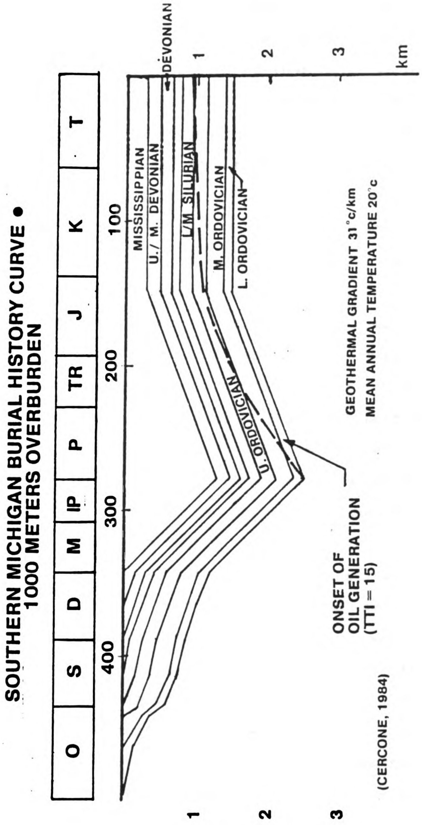
geothermal gradient of 23 $^{o}C/km$, however, in the Southern Michigan Burial History Curve a higher geothermal gradient was used to estimate the commencement of oil generation.

In the Southern Michigan Burial History Curve, a geothermal gradient of 31 $^{o}C/km$. was used to calculate the onset of oil generation. As a result of thinner units in the southern portion of the basin, the magnitude of cumulative burial was not as great as in other sections of the basin. With a geothermal gradient of 31 $^{o}C/km$., only rocks of Ordovician age and older are capable of oil generation. Presently, the top of the 'oil generative window' is at about 1 kilometer from the surface. The base of the 'oil generative window' (TTI=160) is not present in the sedimentary section of the southern basin due to shallow burial (Figure 9.). Under the assumption that burial was greater and a gradient of 23 $^{o}C/km$. was present in the southern portion of the basin, the location of the 'oil generative window' would be similar.

DISCUSSION OF HYDROCARBON GENERATION

From data presented in previous sections, the Michigan Basin's thermal history has changed little since its inception. A model using conodonts as indicators of organic metamorphism, differs significantly from the thermal model proposed by Cercone (1984) and concurs with the geophysical model of the basin constructed by Nunn, Sleep, and Moore (1984). One of the problems associated with the geophysical model is the generation of

Figure 9. Southern Michigan Burial History Curve
1,000 Meters Cumulative Overburden.
(Burial Curve: From Cercone, 1984)


SOUTHERN MICHIGAN BURIAL HISTORY CURVE •
1000 METERS OVERBURDEN
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M. ORDOVICIAN
L. ORDOVICIAN
U. ORDOVICIAN
ONSET OF
OIL GENERATION
(TTI = 15)
GEOTHERMAL GRADIENT 31°c/km
MEAN ANNUAL TEMPERATURE 20°c
(CERCONE, 1984)
1
2
3
km

Figure 9.

hydrocarbons in the Devonian aged rocks of the central portion of the basin. Nunn, Sleep, and Moore (1984), and Vogler, et al., (1981) postulate that Devonian oils have an Ordovician source, and have migrated through the Silurian section to Devonian resovoirs. Illich and Grizzle (1983), Powell, et al., (1984), and Pruitt (1983) suggest three genetic groupings of oil in the Michigan Basin. They propose that the Devonian rocks are mature enough to have generated hydrocarbons in situ. Much of the Devonian production is in the central portion of the basin and the onset of oil generation is presently in the uppermost Lower Devonian of the Central Michigan Burial History Curve.

Cercone (1984) points out that the Central Michigan Burial History curve is not in the deepest portion of the basin. As a result, oil generation may be beginning in the Middle and Upper Devonian section in the deepest portion of the basin. Nunn, Sleep, and Moore (1984) and Powell et al., (1984) point out that oils in the Devonian section are immature. Construction of the 'oil generative window' from the burial history curves and the conodont maturity data suggests that Devonian oils in the central portion of the basin would be immature. Additional burial in the central portion of the basin or variation in the conductivity of source rocks may account for the presence of the oil window in Middle and Upper Devonian sections. A geothermal gradient of 23 ^{o}C/km. is capable of accounting for Devonian oils.

Ordovician oils are located in reservoirs associated with hydrothermal dolomitization events (e.g. Albion-Scipio and Northville Fields) on the southern flanks of the basin. From previous sections, additional overburden or an average geothermal gradient of 31 $^{o}C/km$. had to exist to account for the observed maturity. When the 'oil generative window' is calculated, the maturity of the oils generated in southern Michigan would probably be immature. Geochemical evidence from southern Canada indicates that Ordovician oils are at a point where oil is being intensely generated (Powell, et al., 1984). A discrepancy exists between the maturity observed in conodonts and the oil geochemistry. This discrepancy could be explained by higher than predicted geothermal gradients on the southern flanks of the basin or migration of Ordovician oils updip from central portions of the basin in response to a gravity driven paleohydrologic system operating in the basin.

CONCLUSION

From the conodonts observed in the "Trenton Formation" of the Michigan Basin:

1. Color Alteration Indices, in the "Trenton Formation," range from 1.0 in the shallowly buried and surface exposures of the basin to 2.5 in the deepest samples from the basin.

2. With a geothermal gradient of 35 $^{o}C/km$. during the Paleozoic and a subsequent linear decrease to a present day geothermal gradient of 22 $^{o}C/km$. from the Permian to

the present, the observed maturity of the conodonts was consistently overestimated.

3. From Color Alteration Indices and burial history curves constructed in the Michigan Basin, a geothermal gradient of 23 $^{O}C/km$. best fit the observed maturity in northern and central Michigan.

4. In southern Michigan observed maturity could not be accounted for with a gradient of 23 $^{O}C/km$. Additional subsidence of 600 to 700 meters had to occur in the southern basin or an average geothermal gradient of 31 $^{O}C/km$. had to exist to account for observed maturity.

5. Higher geothermal gradients could be attributable to gravity driven fluid flow of warm basin waters onto the southern flanks of the basin.

6. Calculation of the 'oil generative window' for the burial history curves in the Michigan Basin reveals that oils generated in the basin are probably immature in the Devonian section and marginally mature in other areas of the basin.

7. The model constructed from the Color Alteration Index concurs with geophysical models of the basin, however, detailed studies of probable source rocks and rock conductivities should be considered for a comprehensive study of the Michigan Basin thermal history.

APPENDICES

Appendix A.

Core sampled for conodonts in the "Trenton Formation"

Location	API Number	Operator	Farm Name
30-20N-06W	21-039-33680	Hunt Energy	Wnterfld Dp. A-1
01-06N-15W	21-139-34268	Omni Pet.	Hirde #1-1
25-23N-15W	21-101-34277	Shell	Maidens #5-25
07-24N-06W	21-113-34078	Dart Oil	Brugger #3-7
11-12N-13W	21-123-13816	Sun/Turner	Bradley #4-11
14-25N-02E	21-135-34070	Hunt U.S.A.	Big Creek #14
01-01S-01W	21-075-33129	Total Pet.	Harmon Luck #1-1
26-03S-04W	21-025-23039	Humble	J. Riley #2
05-05N-02E	21-155-27907	Mobil	Jelinek-Ferris #1
02-01S-07E	21-161-18940	Torosian	Nerreter #1
07-04S-03W	21-075-22213	Humble	Kryst/Comm. #1
29-07S-04W	21-059-28407	Andersn Oil	Whitaker #2
03-05S-03W	21-059-22168	Mammoth Pet.	Wooden #4
10-08S-07W	21-023-37704	Shell	Bidwell #1-10
15-02S-02W	21-075-26541	Texaco	S. Konkol #1
24-38N-10E	Indiana	Shell	R & L Mat. #1-24
13-33N-05E	21-141-29372	Shell	Taratuta #1-13
24-26N-11W	21-055-34319	Shell	Blair #2-24
23-28N-05W	21-079-34673	Shell	Blue Lake #3-24
30-33N-02E	21-141-34957	Shell	Allis #3-30
09-25N-11W	21-055-34132	Shell	Weber-Schrn. #6-9
14-03N-08W	21-015-30137	Shell	Timm-Kenndy #1-1

Location	API Number	Operator	Farm Name
16-09N-15E	21-151-25357	Humble	Hoppinthal #1
11-14N-04E	21-017-37779	Shell	Prevost #1-11
28-24N-02E	21-129-25099	Sun@	Brzos St. Fstr. 1
05-38N-24W	Outcrop	Bark River	22.0*

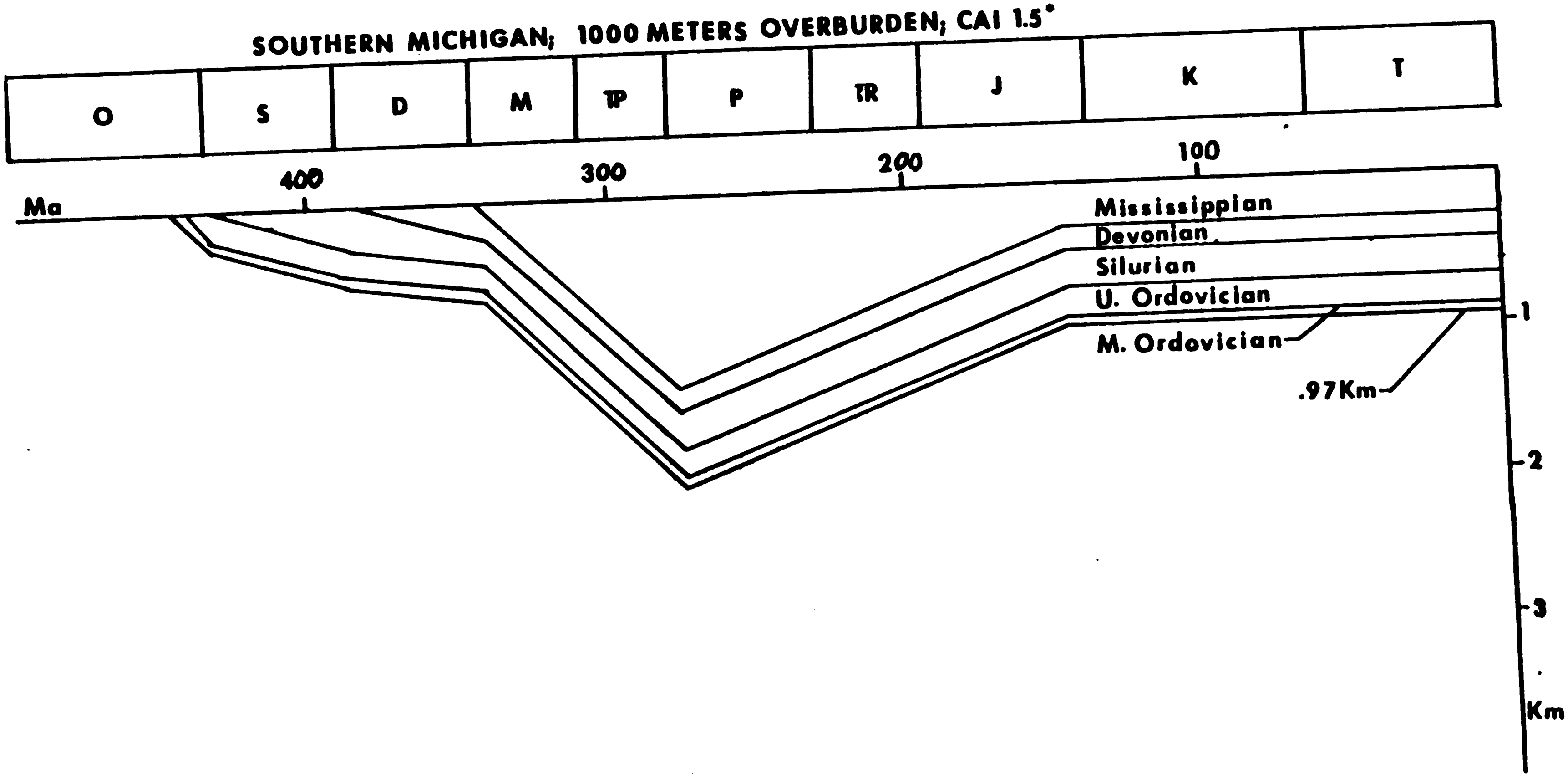
@ CAI provided by Repetski and Harris, 1981, U.S.G.S. Rept.

* Specimens from outcrops provided by Dr. Robert Votaw, Indiana University at Gary

Appendix B.

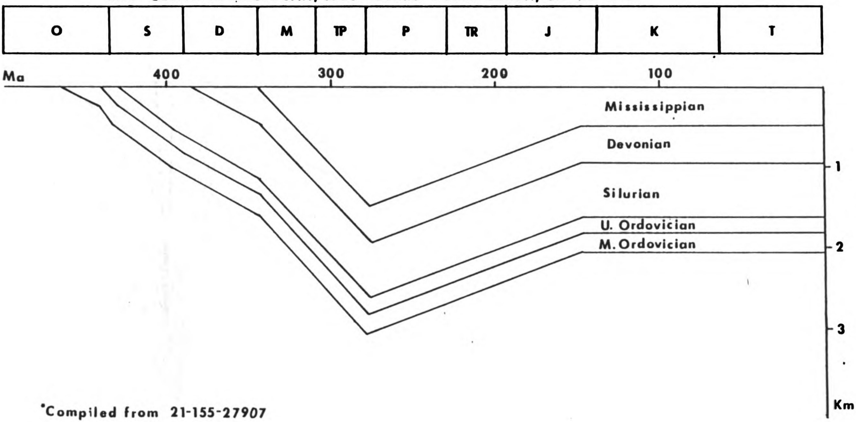
Burial History Curves Constructed in the Michigan Basin

SOUTHERN MICHIGAN; 1000 METERS OVERBURDEN; CAI 1.5*



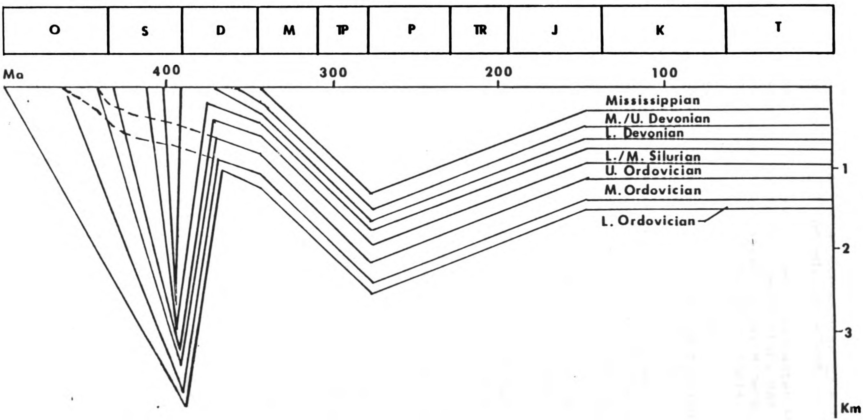
*Compiled from 21-059-28407

MID-CENTRAL MICHIGAN; 1000 METERS OVERBURDEN; CAI 1.5 – 2.0*



*Compiled from 21-155-27907

SOUTHERN MICHIGAN BURIAL HISTORY CURVE •
1000 METERS OVERBURDEN



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