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Interdisciplinary Study of Reservoir Compartments
Contract No. DE-AC22-93BC14891

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Subject: Quarterly Technical Progress Report

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Quarterly Technical Progress Report

INTERDISCIPLINARY STUDY OF RESERVOIR COMPARTMENTS

Contract No. DE-AC22-93BC14891

Colorado School of Mines

Contract Date: September 29, 1993

Completion Date: September 30, 1996

Award Amount $ 753,266

Robert S. Thompson, Program Manager
Colorado School of Mines

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Department of Energy

Reporting Period: July 1, 1994 - September 30, 1994

Contract No. DE-AC22-93BC14891

Project Scope:

This DOE research project was established to document the integrated team approach for solving reservoir engineering problems. A field study integrating the disciplines of geology, geophysics, and petroleum engineering will be the mechanism for documenting the integrated approach. This is an area of keen interest to the oil and gas industry. The goal will be to provide tools and approaches that can be used to detect reservoir compartments, reach a better reserve estimate, and improve profits early in the life of a field.

Progress During 3rd Quarter 1994:

Six tasks were ongoing during the third quarter of 1994. Where appropriate, reports by the research professors and the research assistants are included in the appendix. The following is a brief summary of the project status and the attached reports.

Theme 1: Reservoir/Outcrop Selection/Evaluation

Subdivision 1: Reservoir Selection and Evaluation

Task 1.1.1: Reservoir Selection and Data Gathering

During the 3rd quarter, the project team agreed on a tentative area for reservoir simulation. This area is shown on the figure at the end of this report.

Most of the data has been gathered, input into the data base, and checked for quality. Data will be added to the data base on an "as needed" basis. Some additional data will be needed now that the preliminary area for reservoir simulation has been selected.

Dwaine Edington in his report (Appendix A) discusses how the application of quality control data checking has helped identify correlation problems in some of the initial correlation work. Edington also points out the iterative nature of the integrated approach as more information is gathered and assimilated.

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Task 1.1.2: Outcrop/Core/Log Analysis/and Correlations
Task 1.1.3: Internal Architecture Description

The attached report (Appendix B) by Andrew Prestridge and Juli Mohd Jalaludin discuss the log analysis work. Important conclusions noted by Andrew Prestridge include:

1. Bulk Volume Water (BVW) is a better parameter for discriminating pay from non-pay than porosity, water saturation, or shale volume cutoffs. In addition, BVW helps to distinguish the thinly laminated sands that commonly occur above the basal sand.

2. 104 wells have been digitized and processed in the regional Aristocrat-Hambert Field area. "PLATES" have been printed for the above wells to check the quality of the digitization and graphically present data on a common set of scales along with results of the processing and a pay indicator.

3. Correlation is aided with these "PLATES" since all of the log traces are presented on a common format with common scales.

4. With the data analyzed to date, the clay mineralogy is still considered to be Illite with some Montmorillonite-Smectitie and possibly traces of Kaolinite. Again, all of these clays are hydrous and swell(to varying degrees) when in contact with fresh water.

The report by Dwaine Edington (Appendix A) and the Abstracts included in Appendix F discuss the internal architecture of the reservoir. During the quarter, a series of cross sections were constructed. Twelve NE-SW cross sections were constructed along with one NW-SW cross section. These cross sections coupled with a detailed analysis of the log "shapes", lend insight into the reservoir internal architecture. Slatt et al(Abstract, "Structural and Stratigraphic Compartmentalization of the Terry Sandstone and Effects on Reservoir Fluid Distributions: Part II, Hambert-Aristocrat Fields, Denver Basin, Colorado", Appendix F) have described the complex stratigraphic sequence:

> "In the western part of the area, the facies are arranged in a fining-upward or blocky sequence. By contrast, in the

> eastern part of the area they are arranged in a coarsing-upward sequence".
>
> "The complex pattern of sequences is interpreted to be a result of westward shingling (paleolandward) of three separate sandstone intervals --termed lower, middle, and upper "(see fig 2 in the Abstract).

Detailed structure and isopach mapping and log analysis indicates that the field area is also structurally complex. The evidence to date suggests that faults are common. A study of the GOR data and preliminary results of pressure build-up data suggests the faults are sealing.

Task 1.1.4: Seismic Analysis

The report included in Appendix C by Tom Davis and Bob Benson address the geophysical components of the integrated study. The seismic data is currently being interpreted using Landmark's SeisWorks software. Synthetic seismograms have been used to locate the Sussex, Niobrara, and "J" sandstone formations.

Figures 2 and 3 in their report show preliminary time structure maps on the Niobrara and Sussex formation. The current focus of the interpretation process is to map the faulting in the survey area. The results will be integrated with the geologic interpretation and engineering data.

Task 1.1.5: Detailed Reservoir Engineering Evaluation

The report in Appendix E by Clark Huffman summarizes the results of the detailed reservoir engineering which commenced during the 3rd quarter. As noted in the report, two wells have sufficient pressure build-up data to be analyzed. Preliminary analysis supports flow boundaries within the area of investigation. This information will be used in conjunction with the geologic and 3D seismic interpretations to better characterize the reservoir.

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Subdivision 2: Experimental Investigation

Task 1.2.1: Permeability Experimental Work

The attached report (Appendix D) by Ramona Graves and Hugo Araujo summarizes the permeability experimental work. Based on experimental work conducted during the quarter, Graves and Araujo note that the effect of increasing the net confining stress from 100 psig to 3500 psig and the temperature from 70 F to 140 F causes only a minor shift in the end points and the shape on the relative permeability curves. These variations could easily be within the limits of experimental procedures, the equipment, and data smoothing techniques. Figures 1 - 3 are examples included in Appendix D.

Other Information/Technology Transfer

Appendix F includes two detailed abstracts presented at the First Biennial Conference on Natural Gas in the Western United States, October 17-18, in Golden Colorado.

1. "Structural and Stratigraphic Compartmentalization of the Terry Sandstone and Effects on Reservoir Fluid Distributions: Part I, Latham Bar Trend, Denver Basin, Colorado", Al-Raisi, Slatt, Decker

Work done by Al-Raisi, Slatt, and Decker in the Lambert Bar Trend is being incorporated in the interpretation of the Hambert Field and is accordingly relevant for our project.

2. "Structural and Stratigraphic Compartmentalization of the Terry Sandstone and Effects on Reservoir Fluid Distributions: Part II, Hambert-Aristocrat Fields, Denver Basin, Colorado", Edington, Slatt, Araujo

Schedule for 4th Quarter 1994:

The following objectives are outlined for the 4th Quarter 1994:

1. Continue data gathering and data base management on as "as needed" basis.
   (Task 1.1.1)

2. Commence outcrop work. The outcrop work has been delayed until we were certain of the depositional environment. A suitable outcrop needs to be located. (Task 1.1.2 & 1.1.3)

3. Continue work on seismic analysis and integrate with the geologic and engineering data. (Task 1.1.4)

4. The relative permeability work will focus on simulation of the experimental work. (Task 1.2.1)

5. Detailed reservoir engineering work will continue during the 3rd quarter. This will consist of analysis of production data including decline curve analysis. (Task 1.1.5)

APPENDIX A

1. Data Gathering, Correlation, and Internal Architecture Description
   by Dwaine Edington

Colorado School of Mines
Interdisciplinary Study of Reservoir Compartments
DOE DE-AC22-93BC14891
3rd Quarter 1994 Technical Report

Hambert Field	
Task 1.1.1:	Reservoir Selection and **Data Gathering**
Task 1.1.2	Detailed Outcrop, Core, Log Analysis, and **Correlation**
Task 1.1.3	**Internal Architecture Description**
Research Assistant:	Dwaine Edington

Work completed during this period fell into five main categories: (1) constructing a dense grid of detailed, stratigraphic cross sections, (2) verifying the tops data, (3) collecting log shape and resistivity data, (4) creating structure and isopach maps, and (5) synthesis and analysis.

Cross Sections

A series of stratigraphic cross sections were constructed. Twelve cross sections oriented NE-SW and one oriented NW-SE were made (Figure 1). These cross sections were not constructed to scale horizontally to maximize the number of wells on each section. We tried to construct the sections such that the typical distance between wells was about 1/4 of a mile and that the maximum distance was no more than 3/4 of a mile. The distance between adjacent cross sections is about 1/2 of a mile. The high density of the cross sections enabled us to closely monitor the subtle changes in stratigraphy from one side of the study area to the other.

Tops Data Verification

The tops data that had been collected earlier was posted onto the cross sections. The correlations between wells on the cross sections were then drawn and verified. Non cross section wells were correlated into the nearest cross section. The tops in these wells were also verified. If any tops were found to be in error, they were corrected and entered into the EXCEL spreadsheet that serves as our tops database. This file also calculates the subsea value of each top and calculates the isopach between any two horizons.

These cross sections provided several new insights into our data. The histogram analysis of the raw data that had been done earlier (the "first pass") hinted that there were correlation problems with some of the data. For example, the histogram of the isopach between horizons "A" and "B" exhibited a distinct bimodality indicating that the correlation of either horizon "A" or "B" has not been consistent over the project area (Figure 2). The cross section analysis verified that there was indeed a correlation problem and that horizon "B" was frequently correlated erroneously with horizon "G" on the northeast side of the project area. Once all the tops had been verified (the second pass), a new set of histograms were constructed. The new histogram of the isopach between horizons "A" and "B" does not exhibit any bimodality (Figure 3).

Even after two passes through the database, there are still many wells with tops that are anomalous. In this case, *anomalous* is defined as those tops that are in the upper 1% and lower 1% of the histograms (the histogram tails). There are several reasons that a well may still exhibit anomalous data.

- We could only verify the wells for which we have prints. Many of the anomalous data points are from these wells.
- There may still be typographical and transcription errors.
- Bad kelly bushing elevations may be another reason. If a bad elevation is suspected, it was compared to a topographic map.

- Deviated wells cause both structure and isopach data to show up as anomalies on the histograms. If a well is known to be deviated in the Sussex interval, we threw the data out.
- Miscorrelations was mentioned above as one reason why the histograms exhibit anomalous data.
- Faulting is another process that creates anomalous data. This aspect will be discussed in greater detail below.

All the anomalous data was flagged in the database.

Further examination of the detailed cross sections revealed our second insight. The Sussex sandstone actually consists of three separate sand bodies. These sand bodies have a shingled or onlapping geometrical relationship (Figure 4). The youngest sand body (the upper sand) is present only on the southwest side of the area and the oldest sand body (the lower sand) is present on the northeast side of the area. The middle sand is present throughout the project area (Figure 5). Overall, the isopach of the entire Sussex sandstone package (Upper, Middle, and Lower Sands) is relatively consistent throughout the project area. The isopachs of the individual sand bodies however change dramatically from one side of the project area to the other.

Based on this analysis, the stratigraphic nomenclature was revised again. From top to bottom the horizons are:

"A"	Top of the Sussex Interval
"E"	Upper Marker
"H"	Top of the Upper Sand
"B"	Top of the Middle Sand
"G"	Top of Lower Sand
"C"	Base of the Sussex Interval
"D1"	Upper Bentonite
"D2"	Middle Bentonite
"F"	Lower Bentonite

The detailed correlations that were done during this phase also provided insights into the faulting in this area. Fault cuts were identified in 46 wells. It is very likely that there are more faults remaining to be discovered. The section cutout due to these faults ranged from 10 feet to 160 feet. Repeat sections were never observed indicating that all of these faults are normal faults rather than reverse faults.

Log Shape and Resistivity Data

During the second pass through the log database, two additional pieces of data were collected. These were log shape and resistivity threshold.

Each well was classified into one of six categories based on the general shape of the log curves in the Sussex sand interval (also known as log facies). These categories are shown in Figure 6. Please note that these log facies are not equivalent to lithofacies. An individual log facies contains information about the general sequence and trend of a set of depositional events that are related by space, time, and process. A single log facies may contain many lithofacies. A lithofacies is a rock characterized by a unique set of properties.

In general, the two fining upward sequences can be considered to belong to a single class, Likewise, the two coarsening upward sequences belong to another class. The remaining two shapes (blocky and triangular) are transitional between the two defined classes. When the log shape class was plotted on a map a definite pattern appeared. Wells with fining upward (or shaling upward) patterns were generally confined to the southwestern portion of the project area and those with a coarsening upward (or cleaning upward) patterns are present in the northeast side of the project area (Figure 7).

There also appears to be a relationship between the log shape and the distribution of the three sand bodies (compare Figures 5 and 7). The coarsening upward facies in generally confined to the lower sand body while the fining upward pattern is found in the upper and middle sand bodies. The line dividing the two log facies corresponds to a line that marks a major isopach change in the lower sand. To the northeast of this line, the lower sand thickens and approaches the thickness of the middle sand. To the southwest of this line, the lower sand is much thinner but it is still cleaner than the middle sand.

On an early map, we highlighted all known Sussex producing wells. There were two distinct trends of producing areas. One is the Hambert-Aristocrat trend running northwest through the center of the project area and the other is the Latham Bar trend located on the northeast corner of the project area. We began to wonder if the intervening area of non-production was truly non-productive and if so, why, and if not, why has it not been developed. We recognize that in sands such as these, many factors determine the productivity of a given location. Upon the completion of the petrophysical phase of this study, we anticipate that many of these questions may be answered. However, at this point of the project, we decided to see if a simple measure of producibility could be collected.

The factor that we chose to use is a resistivity threshold. This factor is a qualitative measurement and is based on an 8 ohm-m cutoff. "Conventional Oilpatch Wisdom" says that the 8 ohm-m value is a reasonable measure of Sussex producibility. If the resistivity of the Sussex sand is greater than 8 ohm-m, the well received a value of +1, if it is less, the well received a -1. If a resistivity log was unavailable or unreliable, the well receive a value of 0. No distinction of upper, middle or lower sands was made. Furthermore, we did not make a distinction between thick sections of Sussex sand with high resistivity and sections that were thin with low resistivity. For example, a well that has 100 feet of section with resistivity as high as 100 ohm-m received the same value (+1) as a well that has 2 feet of section with resistivity of 9 ohm-m.

This information was plotted on a map (Figure 8). On this map, we can see two main areas of low resistivity. The first is just northeast of the line that divides the area into the two main log facies. This area is the non-productive trend between the Hambert-Aristocrat and Latham Bar trends that we noted earlier. The second area of low resistivity is located on the southwest flank of the Hambert-Aristocrat trend.

STRUCTURE AND ISOPACH MAPS

Once the second pass of data verification and input was completed, a series of computer generated contour maps were made. The subsea and isopach data in the EXCEL tops spreadsheet was downloaded into an ASCII file. This file was read into the MCS (Mapping Contouring System) program. A total of 24 isopach, structure and other maps were made.

Computer generated contour maps are inherently unreliable because they cannot be contoured with a geologic concept in mind. Faults are especially troublesome, especially in this situation. At this point in time, we did not have any data that told us fault orientation. However, these maps do provide a basis for doing a preliminary interpretation. The computer generated isopach maps were especially useful in providing clues as to the fault trends (Figure 9 and compare to Figure 10). Figure 9 shows anomalous wells as "bullseyes". Many of these bullseyes correspond to wells with known faults.

A hand drawn structure map was drawn that covered a portion of the project area (Figure 10) The computer generated structure maps, isopach maps, the detailed correlations, and the fault information from the wells were used to make this map A simplified structural cross section was drawn through this area (Figure 11)

Synthesis and Analysis

The process that we use in a project such as this contains four main levels of activity In order of increasing complexity, they are

- **Compilation** Identifying the sources of data
- **Extraction** Gather the data, organize it, and store in a manner that allows easy access
- **Interpretation** The data is processed, described, translated, compared, contrasted, classified, correlated, and calculated
- **Analysis** Individual interpretations are brought together and synthesized into a general model that attempts to explain the facts

There are many tasks and sub tasks in this process Fundamentally however, it is nothing more than a series of information flows (Figure 12) In other words, the results of one task are used in the next This process is highly non-linear Information frequently flows in loops, frequently more than once

The identification of reservoir compartments requires that information and interpretations from many different types of data be brought together The fault interpretation appears to confirm that the Sussex reservoir is highly compartmentalized The initial gas to oil ratio (GOR) does not display a recognizable or consistent pattern when this data is plotted on a map (Figure 10) Wells with high GOR's (gassy production) are frequently found to be structurally lower than wells with lower GOR's (oily production) However, when this data is plotted on the structure map, certain patterns become visible (Figure 10) It appears that wells with higher GOR's are found generally on the structurally higher portions of each fault block This relationship is not perfect and work is underway to understand what other factors may be influencing this relationship

The degree of reservoir compartmentalization from stratigraphic sources is not yet known The three Sussex sand bodies certainly provide the potential for compartmentalization but hard information on the nature and extent of the barriers between these sand bodies has not been examined Further work is needed to understand the relationships between the various log facies, lithofacies, and gross sand body geometry The degree of reservoir heterogeneity within each of the three sand bodies has not been a focus of this investigator's assignment

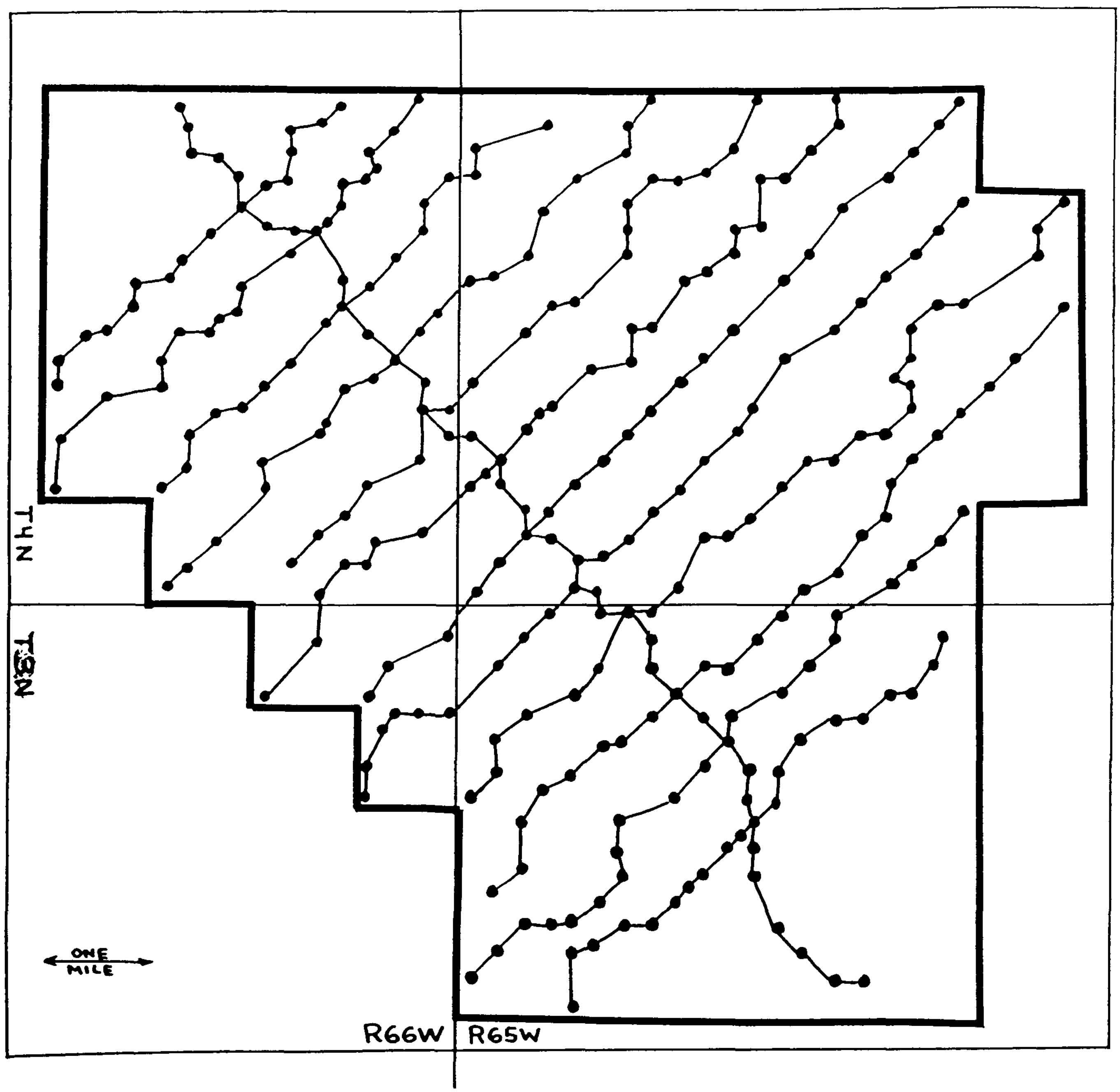
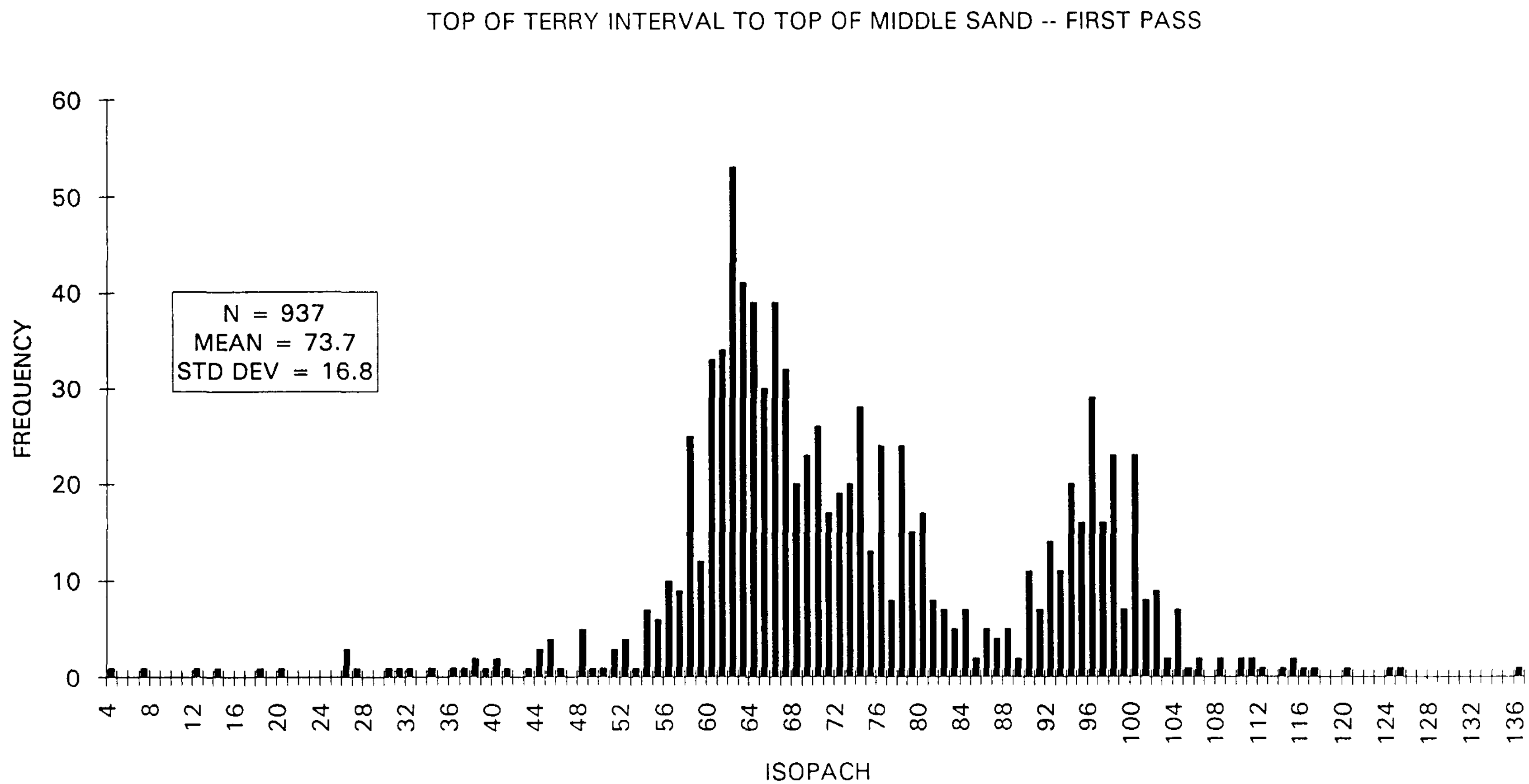


Fig. 1


TOP OF TERRY INTERVAL TO TOP OF MIDDLE SAND -- FIRST PASS
N = 937
MEAN = 73.7
STD DEV = 16.8
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0
10
20
30
40
50
60
ISOPACH
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
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84
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96
100
104
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112
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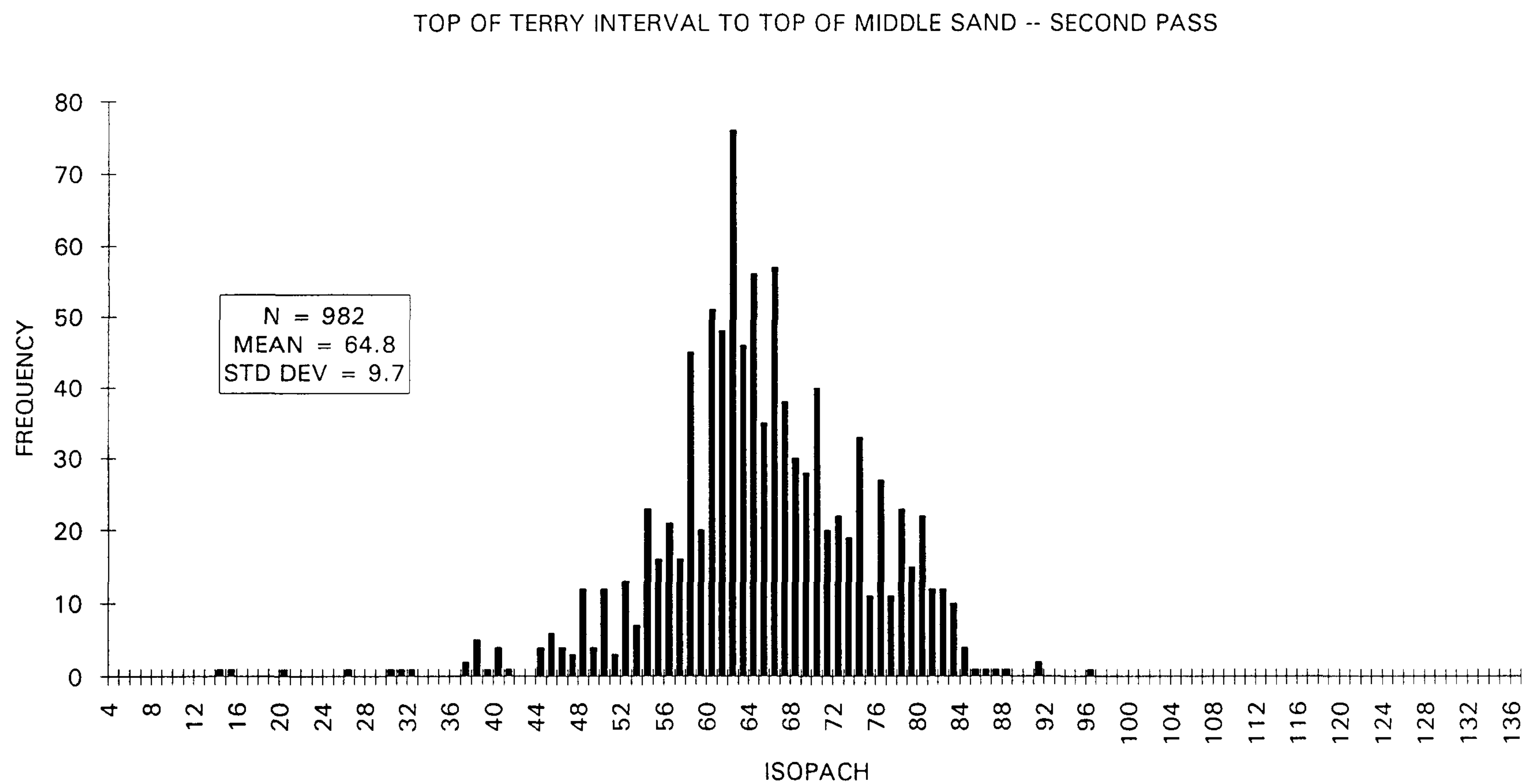
132
136

Fig. 2


TOP OF TERRY INTERVAL TO TOP OF MIDDLE SAND -- SECOND PASS
N = 982
MEAN = 64.8
STD DEV = 9.7
FREQUENCY
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10
20
30
40
50
60
70
80
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
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100
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116
120
124
128
132
136
ISOPACH

Fig. 3

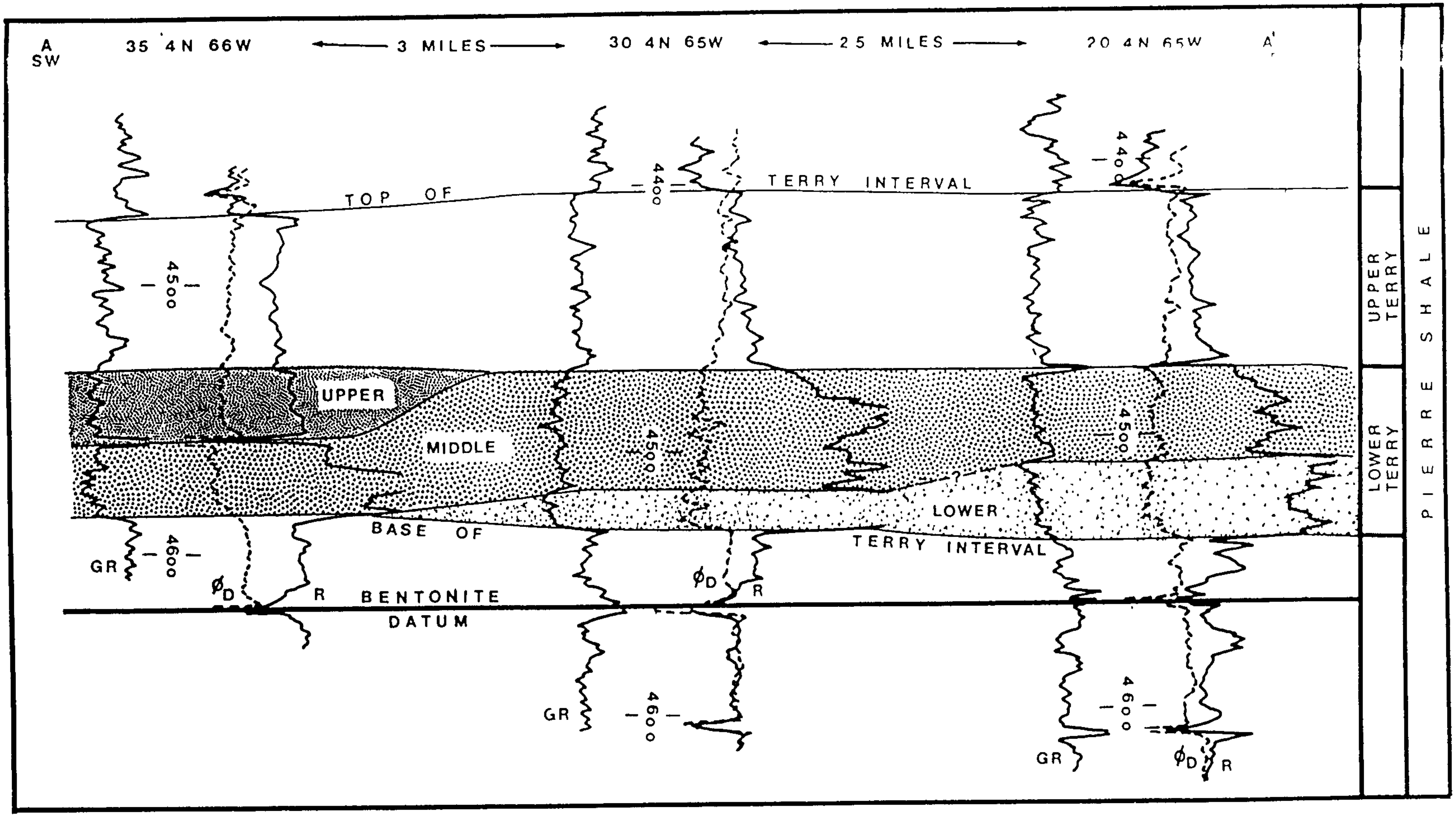

A
SW
35 4N 66W
3 MILES
30 4N 65W
2.5 MILES
20 4N 65W
A'
TOP OF TERRY INTERVAL
4400
4500
4600
UPPER
MIDDLE
LOWER
BASE OF TERRY INTERVAL
BENTONITE DATUM
GR
ϕ_D
R
UPPER TERRY
LOWER TERRY
PIERRE SHALE

Fig. 4

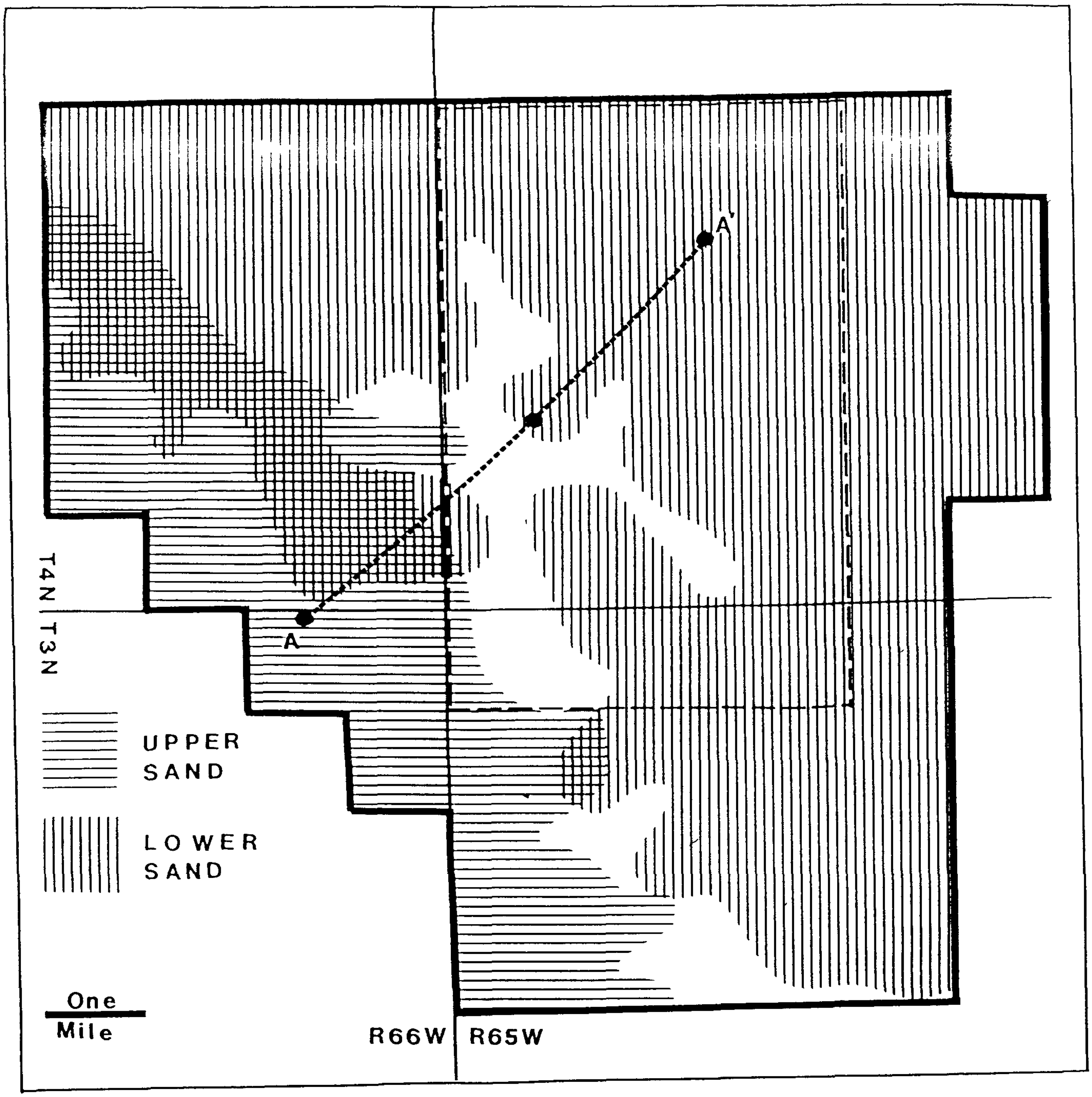


Fig. 5

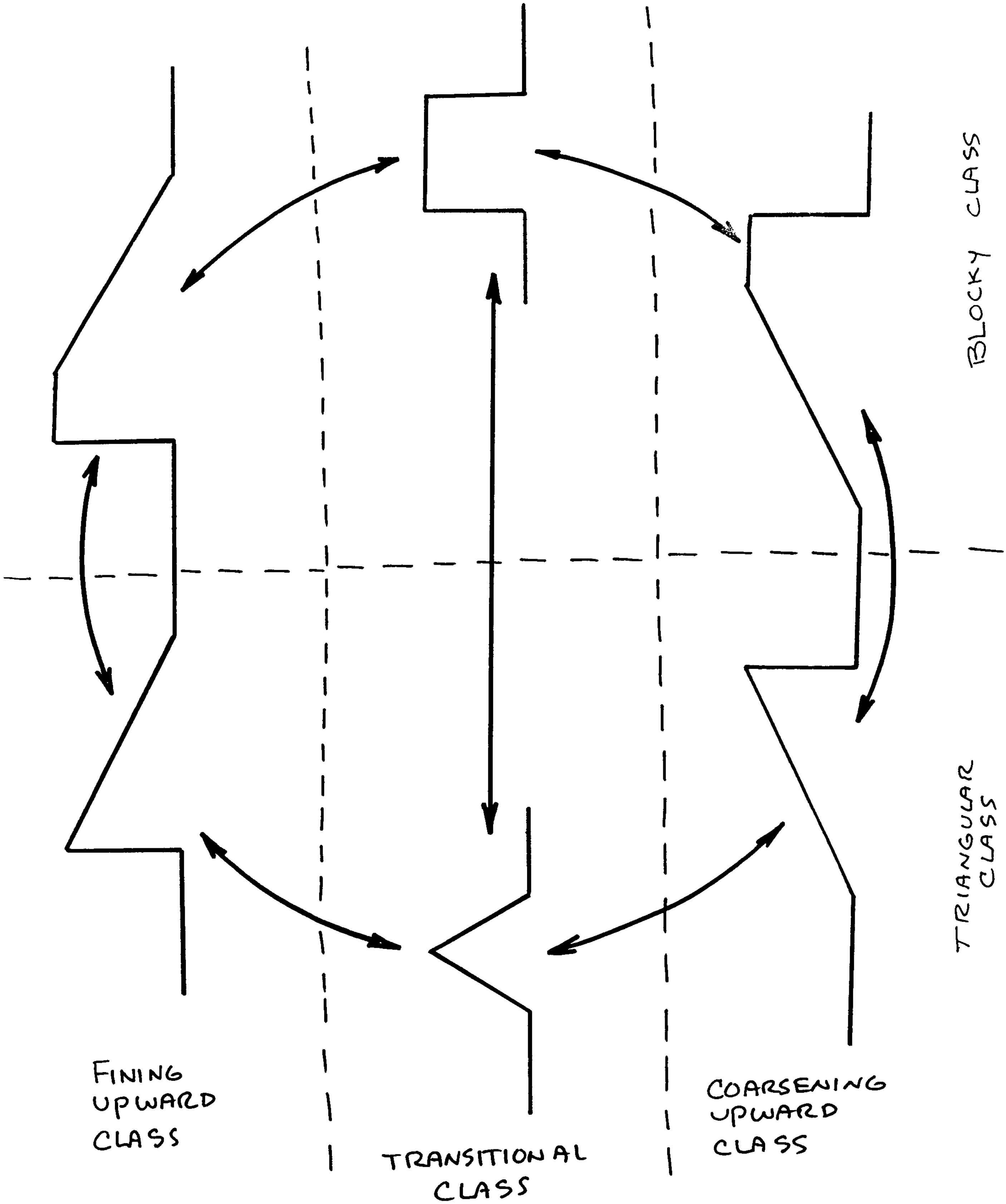

BLOCKY CLASS
TRIANGULAR CLASS
FINING UPWARD CLASS
TRANSITIONAL CLASS
COARSENING UPWARD CLASS

FIG6

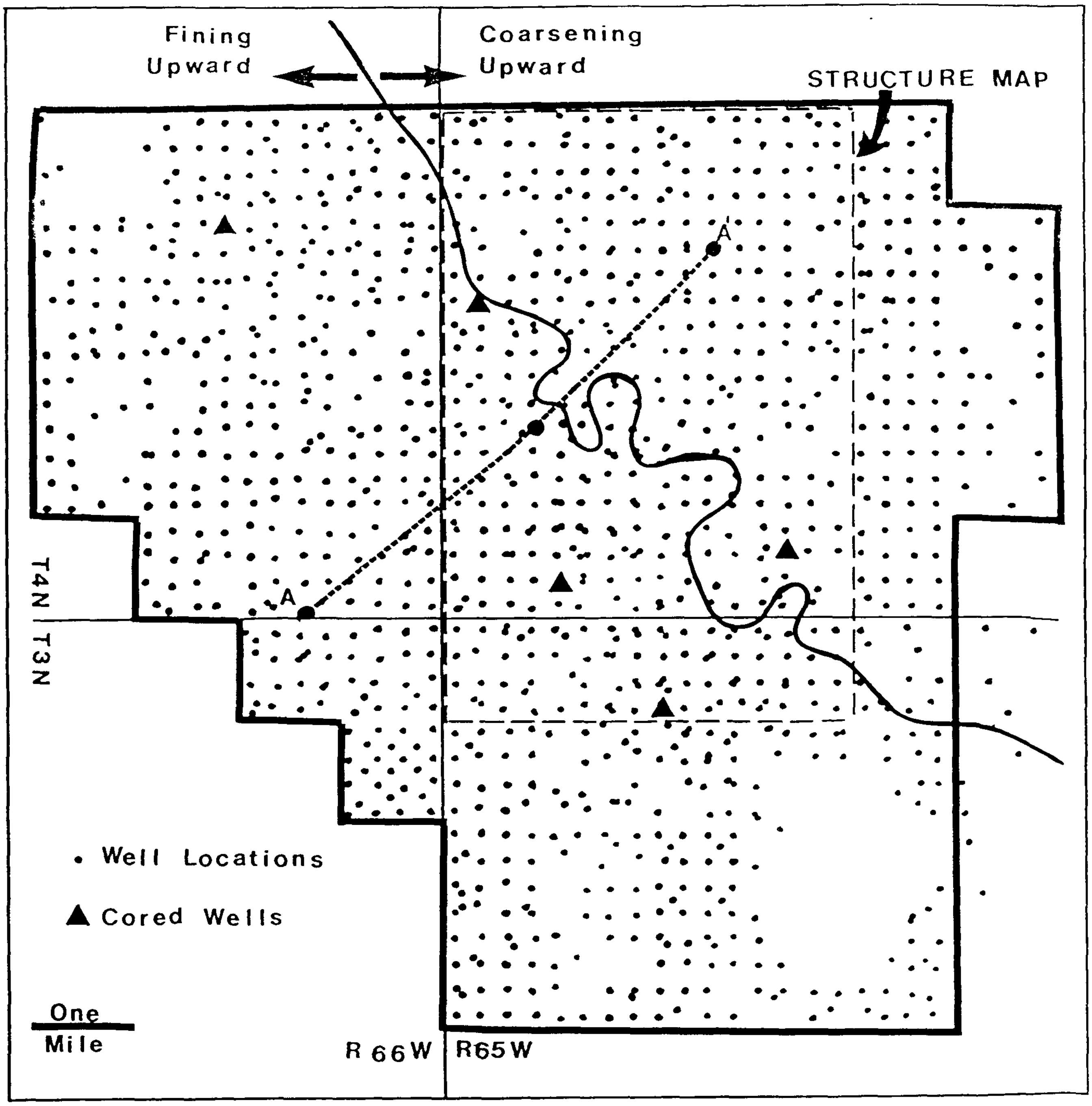

Fining
Upward
Coarsening
Upward
STRUCTURE MAP
A'
A
T4N
T3N
Well Locations
Cored Wells
One
Mile
R 66W
R65W

FIG.7

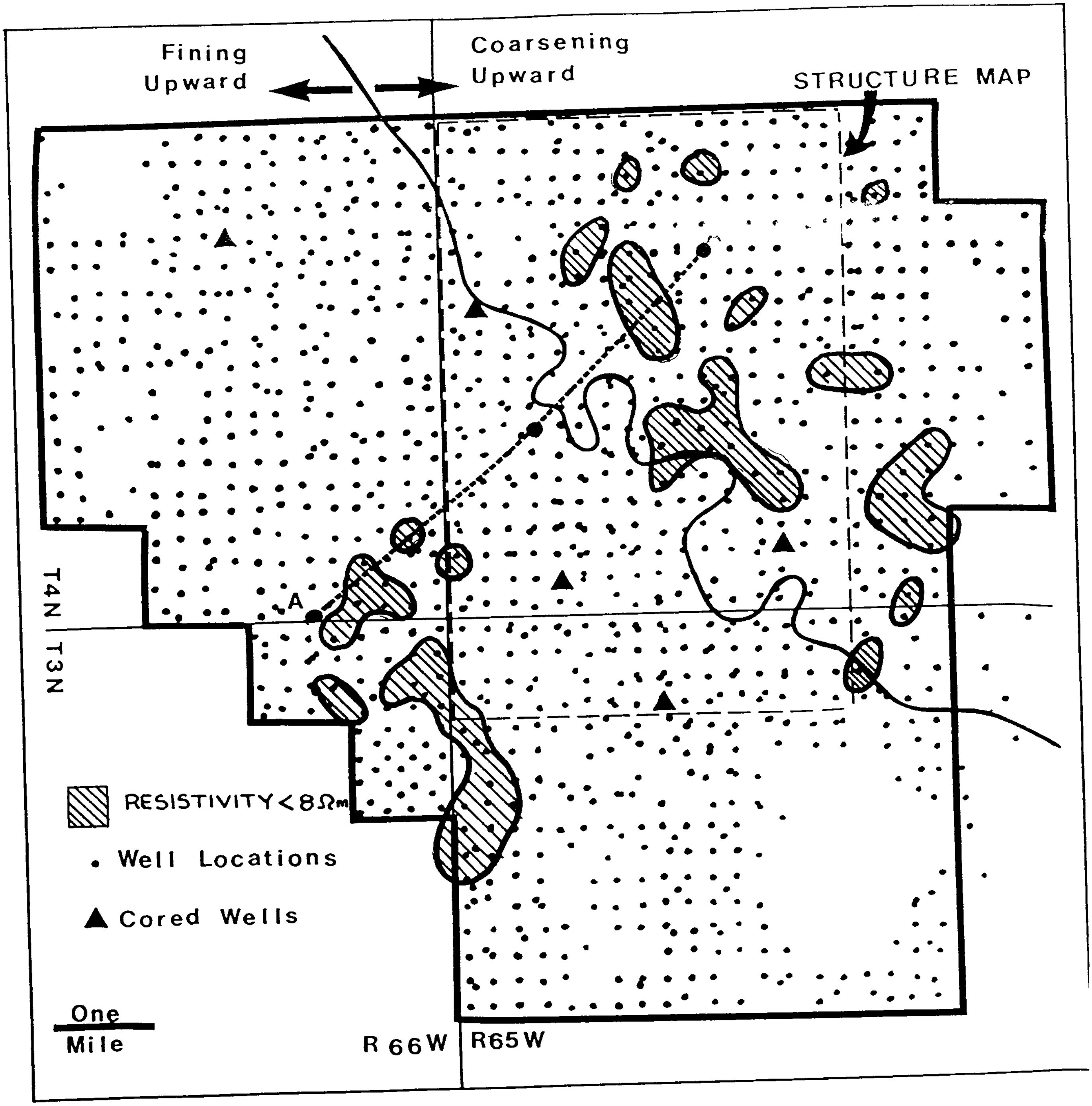

Fining
Upward
Coarsening
Upward
STRUCTURE MAP
A
T4N
T3N
RESISTIVITY < 8Ωm
Well Locations
Cored Wells
One
Mile
R 66W
R65W

Fig. 8

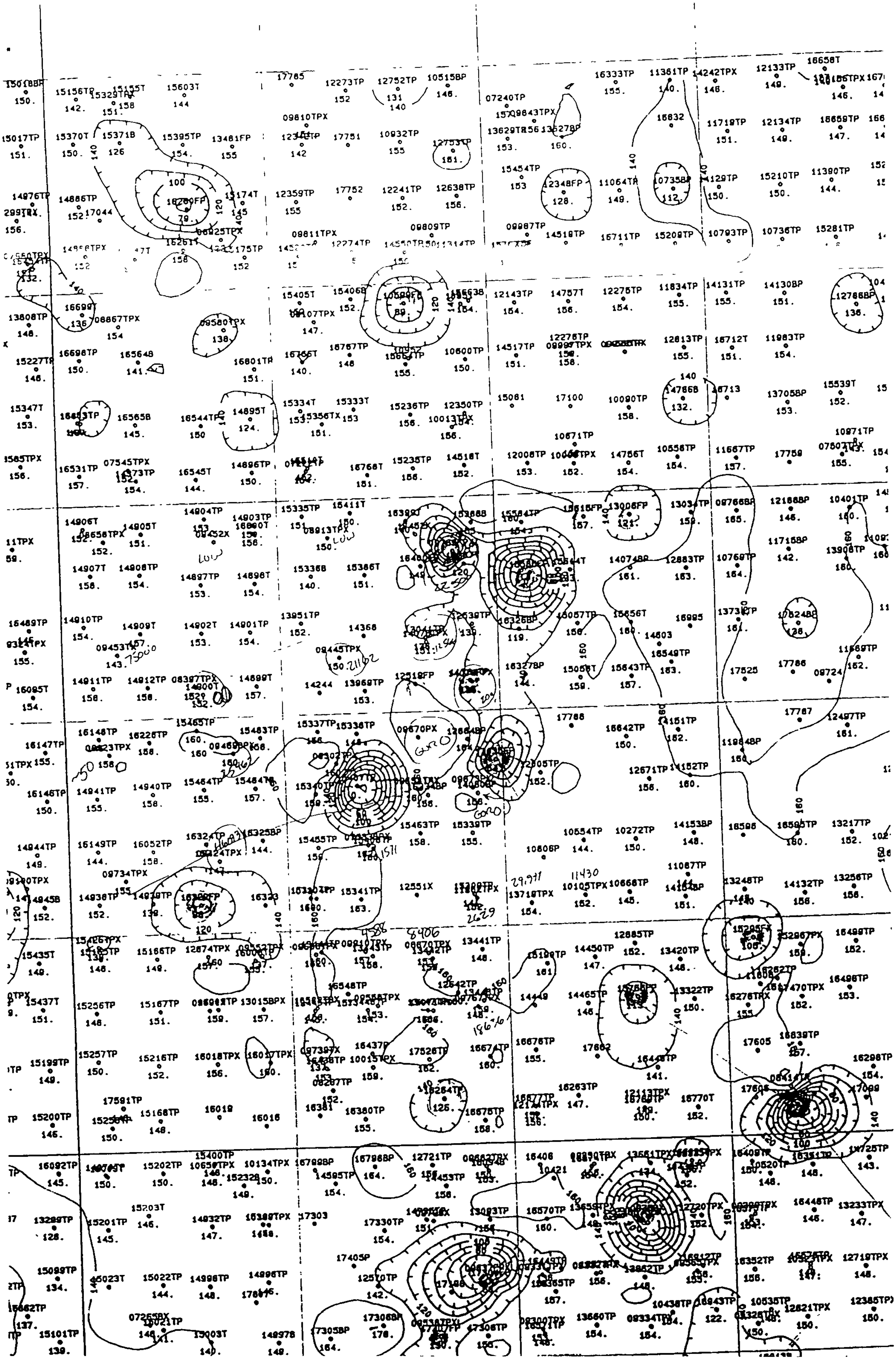


Fig. 9

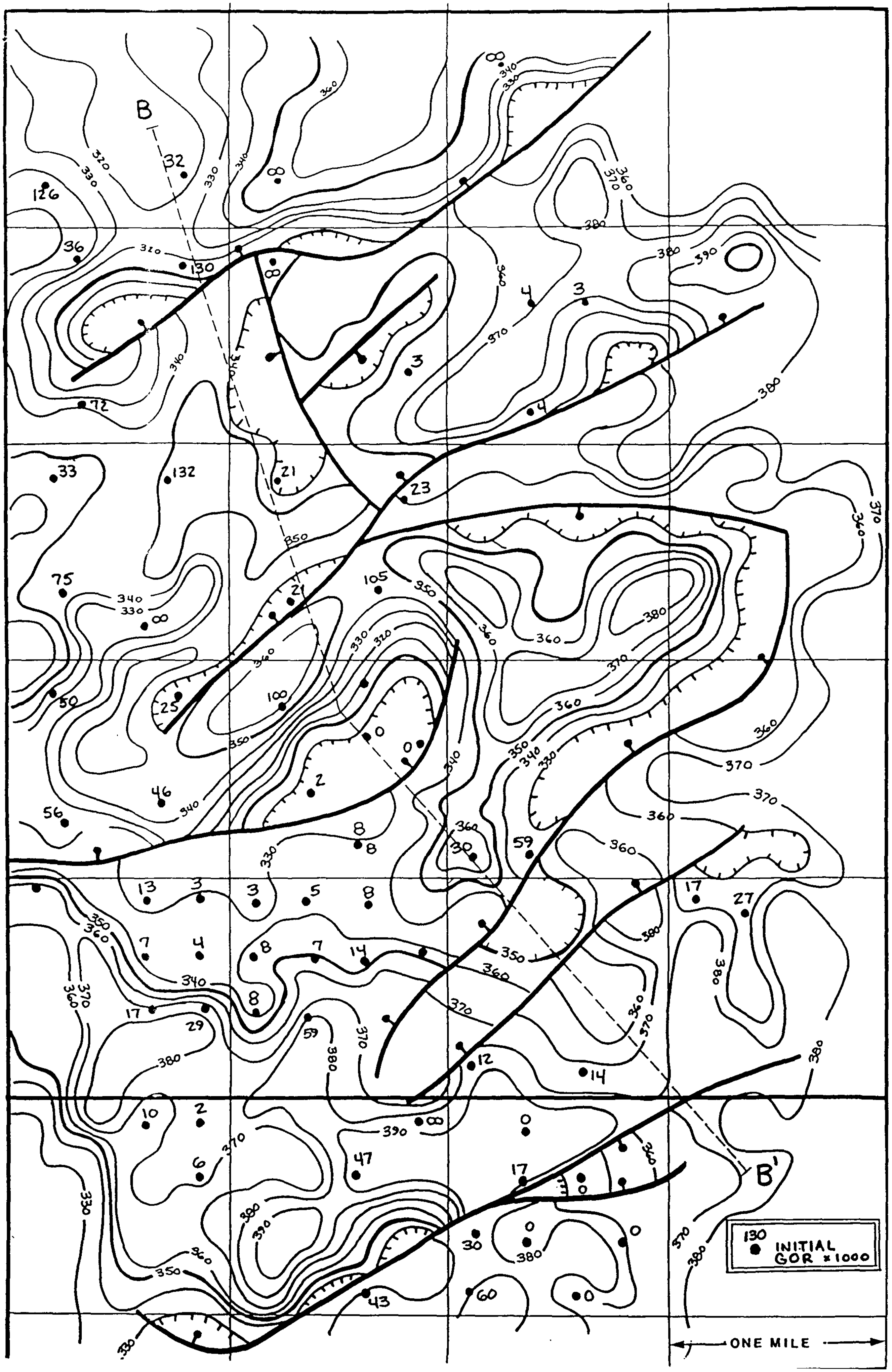


FIG 10

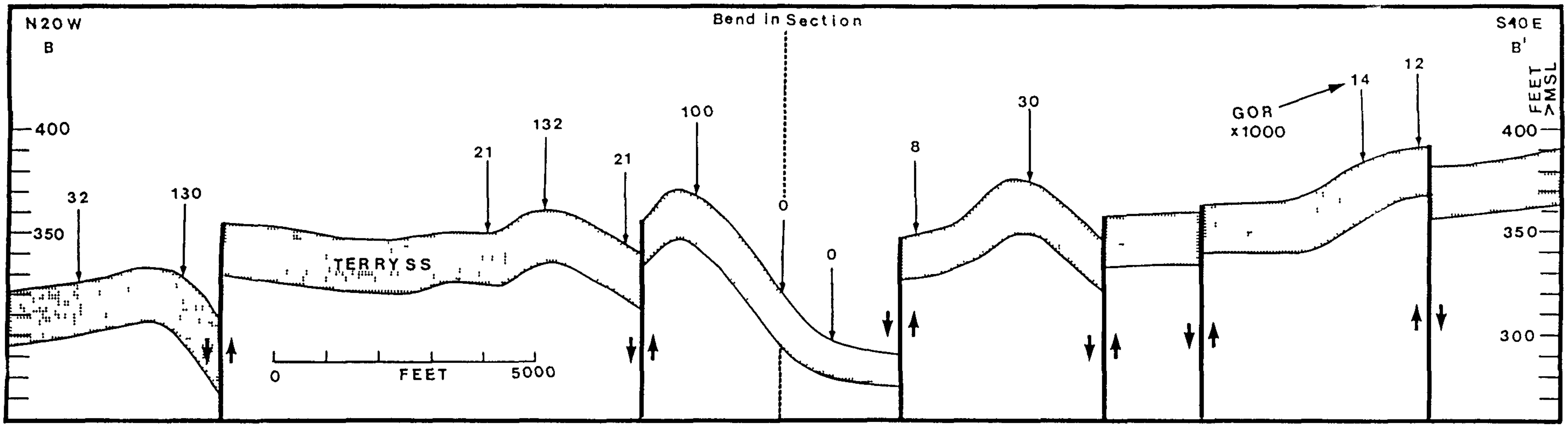

N20W
B
Bend In Section
S40E
B'
FEET >MSL
400
350
300
32
130
21
132
21
100
0
0
8
30
GOR x1000
14
12
TERRY SS
0
FEET
5000

Fig 11

DOE RESERVOIR CHARACTERIZATION PROJECT
GEOLOGIC PROCESS DIAGRAM

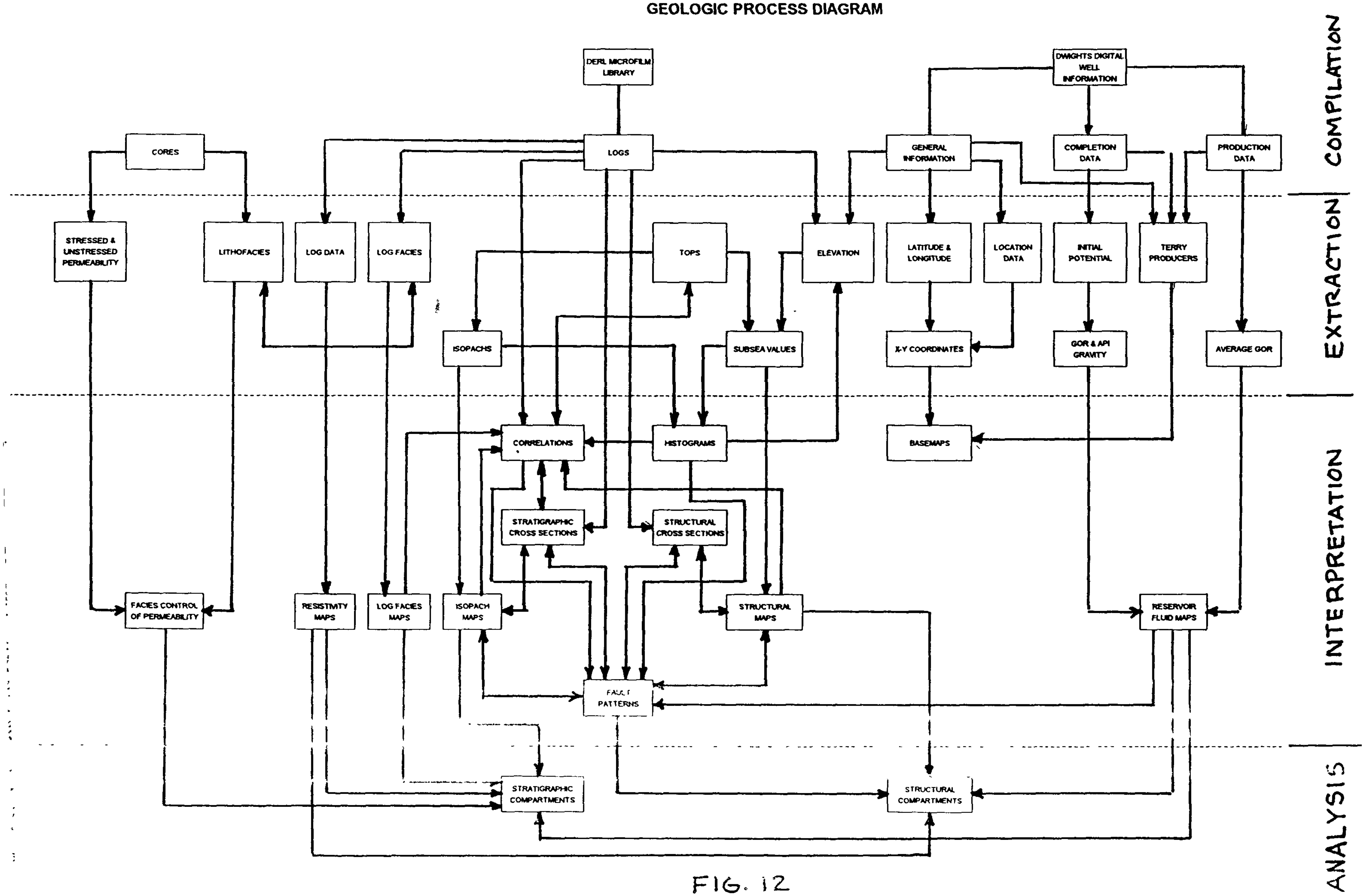


FIG. 12

APPENDIX B

1. Log Analysis and Correlations
   by Andrew Prestridge and Juli Mohd Jalaludin

Interdisciplinary Study of reservoir Compartments
DOE Contract No. DE-AC22-93BC14891
Quarterly Technical Report July - September 1994
Task 1.1.2 Detailed Outcrop, Core, **Log Analysis, and Correlation**
Aristocrat-Hambert Field Study
Research Associate: Andrew Prestridge
Research Assistant: Juli Mohd Jalaludin

Conclusions: Log Analysis

1. Bulk Volume Water (BVW) is a better parameter for discriminating pay from non-pay than porosity, water saturation, or shale volume cutoffs. In addition BVW helps to distinguish the thinly laminated sands that commonly occur above the basal sand.

2. 104 wells have been digitized and processed in the regional Aristocrat-Hambert Field area. "PLATES" have been printed for the above wells to quality control digitization and graphically present data on a common set of scales along with results of the processing and a pay indicator.

3. Correlation is aided with these "PLATES" since all of the log traces are presented on a common format with common scales.

4. With the data analyzed to date, the clay mineralogy is still considered to be Illite with some Montmorillonite-Smectitie and possibly traces of Kaolinite. Again, all of these clays are hydrous and swell(to varying degrees) when in contact with fresh water.

Discussion:

Regional log analysis work has helped to understand the characteristics of the Sussex sandstone and how to interpret this shaly sandstone reservoir. The Rz technique was crucial in the calculations of Bulk Volume Water. Rz is defined as the resistivity of the water in the flushed zone that is a mixture of Rmf and Rw. The relative amounts of each are calculated based on work done by Tixier (1949) in the Rocky Mountain area. Since the Sussex has very low permeabilities, the invasion process is one of slow diffusion of fresh drilling mud filtrate into the formation. The clays hold formation waters near their surfaces and are diluted somewhat by the mud filtrate, leaving a mixture of waters in the flushed zone. The common invasion profile for an induction log in a hydrocarbon formation is (from high to low resistivity) Shallow(SN or SFL), Medium(ILM), Deep(ILD or 6FF40). The shallow reading device will read a higher resistivity than Rt because of the waters in the flushed zone. Common logging convention places Rmf as the resistivity of the water in the flushed zone. Because of the invasion processes specific to the Sussex, Rz is the true nature of the water that is in the flushed zone. When this is not taken into account, invasion is very subtle to detect.

The BVW-Rz processing has also enhanced the ability to see the laminated sands in most wells. The technique does not enhance the vertical resolution of the logging tools, but does enhance the ability to see invasion. In early work, cutoffs such as porosity, water saturation and shale volume were used to define pay. Using the difference between BVW and BVXO as a pay indicator is a more realistic way to discriminate pay. The Amoco UPRR 36 Pan Am C #1 well is a good example of the pay indicator improvement(See Figures 1 and 2)

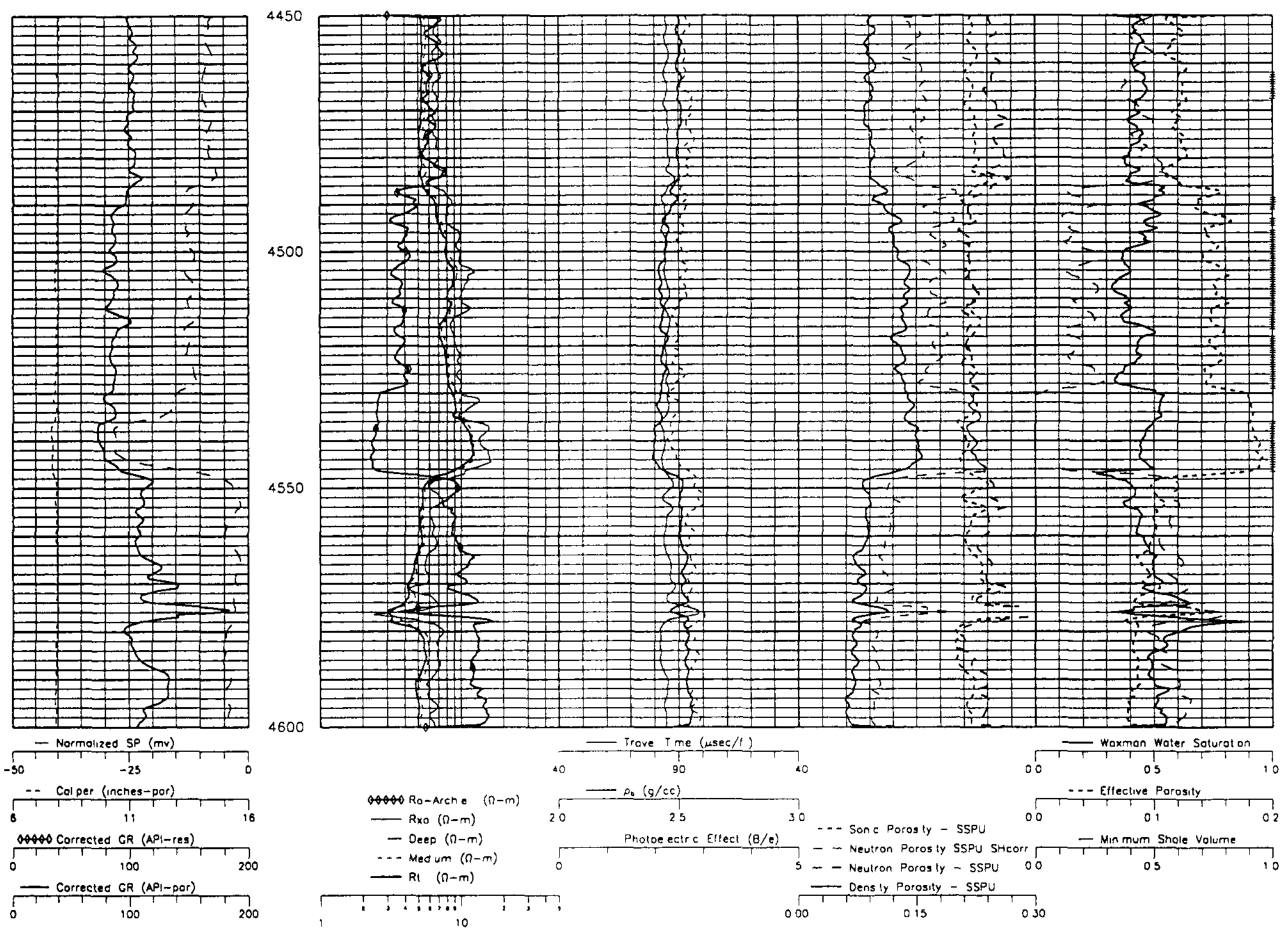
Parameter	Using Cutoffs Sw, ϕ, and Vsh	Using Cutoff BVW-BVXO
Net h (ft)	54.50	46.00
ϕ avg. (%)	15.41	16.38
Sw avg.(%)	42.12	46.04

From Figure 1 you can see pay indicated from 4462-4467 that is probably non-pay shale.(Pay is indicated by tics on the right hand side of the log). Almost the entire interval from 4490 - 4546 is marked as pay even when we know that the sands are typically laminated. A short interval of the better pay is not recognized by the early technique from 4529-4536.

Figure 2 shows a much more realistic indication of pay that is consistent with log signatures, our current geological model, and is much simpler to apply.

Tuning cutoffs to mimic the BVW-Rz technique may work on one well, but does not systematically apply to all wells. The BVW-Rz technique is a better universal pay discriminator.

Figure 1



CSM/DOE - SUSSEX

Preliminary Work Product

Contract No DE-AC22-93BC 4891

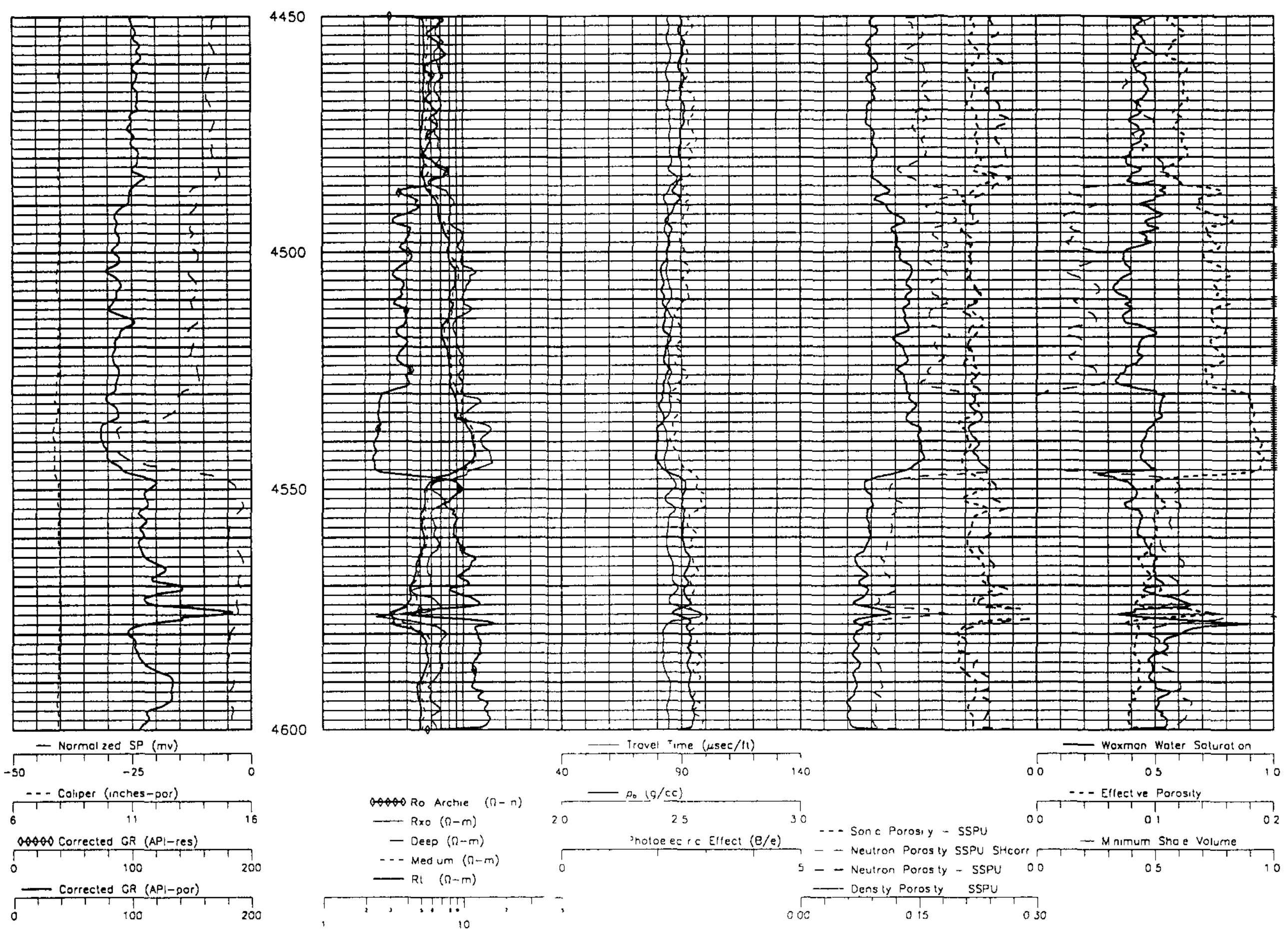
Task 1 1 2

OPERATOR	AMOCO PRODUCTION COMPANY
WELL	UPRR 36 PAN AM C #1
COUNTY	WELD
STATE	COLORADO
DEPTHS	4450 0 4600 0
Date Logged	19 NOV 1984
Api Number	0512312174
RKB	4867 0
PROCESS Date	07/26/1994 / 23 37

FAIRLY S_w ϕ V_{sh} Cutoff

LOG CODE	12174721	
NET THICKNESS	54 50	feet
AVE POROSITY	15 41	%
AVE SW	42 12	%
HC FT	4 86	feet
VSHALE from	Minimum	
Sw METHOD	Waxman Juhasz	

FIGURE 2



CSM/DOE – Sussex
Preliminary Work Product
Contract No DE-AC22-93BC14891
Task 1 1 2

OPERATOR	AMOCO PRODUCTION COMPANY
WELL	UPRR 36 PAN AM C #1
COUNTY	WELD
STATE	COLORADO
DEPTHS	4450 0 4600 0
Date Logged	19 NOV 1984
Api Number	0512312174
RKB	4867 0
PROCESS Date	10/23/1994 / 19 49

BVW CUTOFF

LOG CODE	12174721	
NET THICKNESS	46 00	feet
AVE. POROSITY	16 38	%
AVE SW	46 04	%
HC-FT	4 07	feet
VSHALE from	Minimum	
Sw METHOD	Waxman Juhasz	

APPENDIX C

1. Detailed Seismic Analysis
   by Tom Davis and Bob Benson

Colorado School of Mines
Interdisciplinary Study of Reservoir Compartments
DOE DE–AC22–93BC14891
3rd Quarter 1994 Technical Report

Hambert Field
Task 1.1.4 Detailed Seismic Analysis
Research Associates: Dr. Davis, Mr. Benson

Amoco was able to locate and provide all of their final processed 2–D and 3–D seismic data this past month. The 3–D seismic data volumes (P–wave and S–wave) have been loaded on the Landmark Graphics workstation. The seismic volumes were loaded using relative xy coordinates since Amoco has been unable to provide absolute xy coordinates at this time. Correct positioning of the seismic data should be possible by extracting xy coordinates from the trace headers of the unstacked seismic data provided by Amoco previously.

The seismic data is currently being interpreted using Landmark's SeisWorks[1] software. Data quality is excellent with an example N–S line extracted from the P–wave seismic volume shown in Figure 1. Synthetic seismograms were correlated to the data and the Sussex (Terry), Niobrara, and "J" sandstone formations were identified and picked through the entire 3–D volume. The Niobrara and "J" sandstone are excellent picks throughout the volume. The Sussex formation is more difficult pick due to the structural and stratigraphic variations in this interval. Figures 2 and 3 show preliminary time structure maps on the Niobrara and Sussex formations. The current focus of the interpretation process is to map the faulting in the survey area. There are a number of interpreted faults on the seismic data which cut the Sussex formation as well as the deeper Niobrara and "J" sandstone formations. Integration of the seismic interpretation with the geologic interpretation will continue in the 4th quarter.

[1] Registered Trademark of Landmark Graphics Corporation

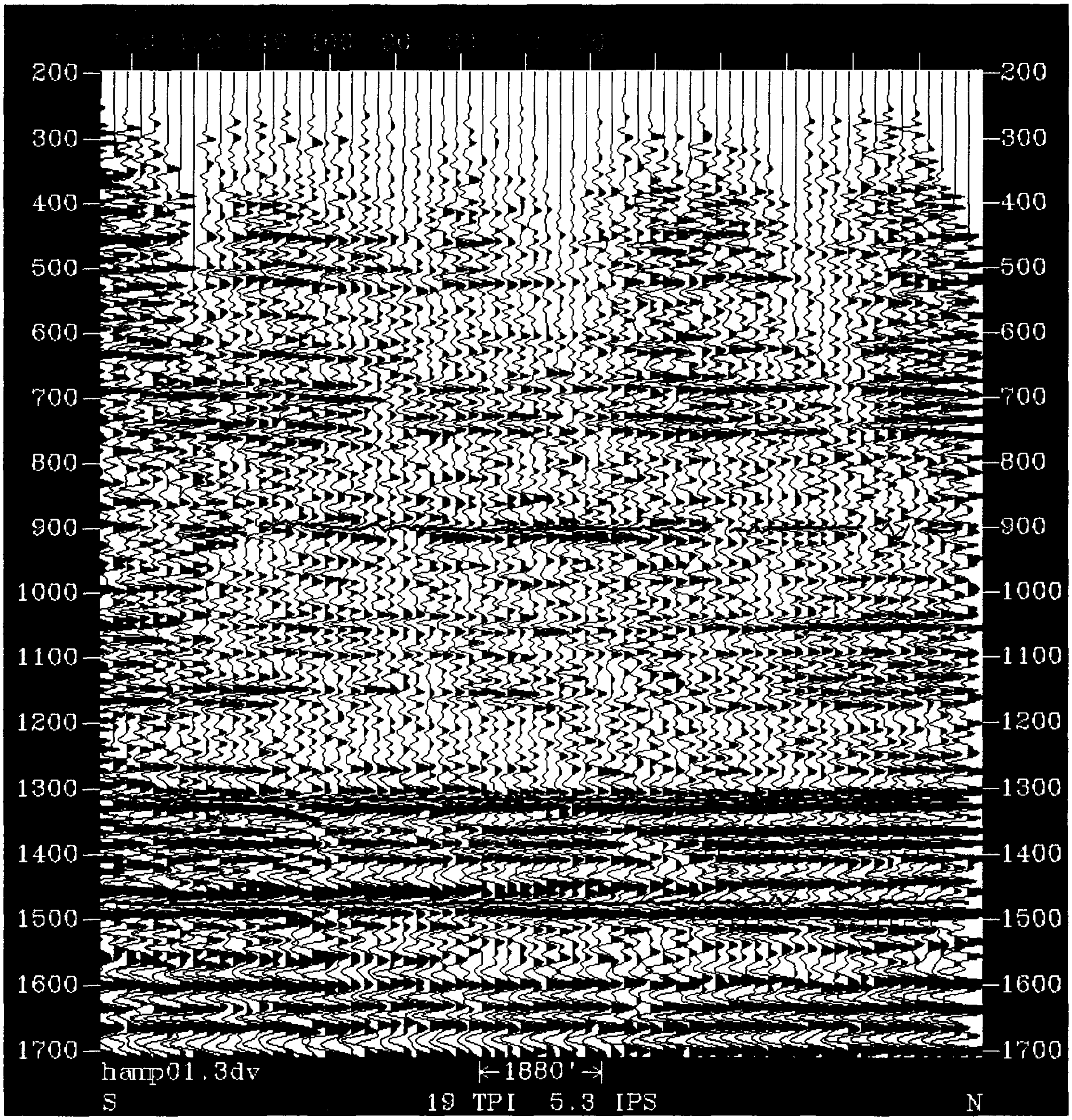


Figure 1: N–S Line #43 extracted from the 3-D P–wave seismic data. The Sussex (Terry) is located at 900ms, the Niobrara at 1310ms, and the "J" sandstone at 1480ms.

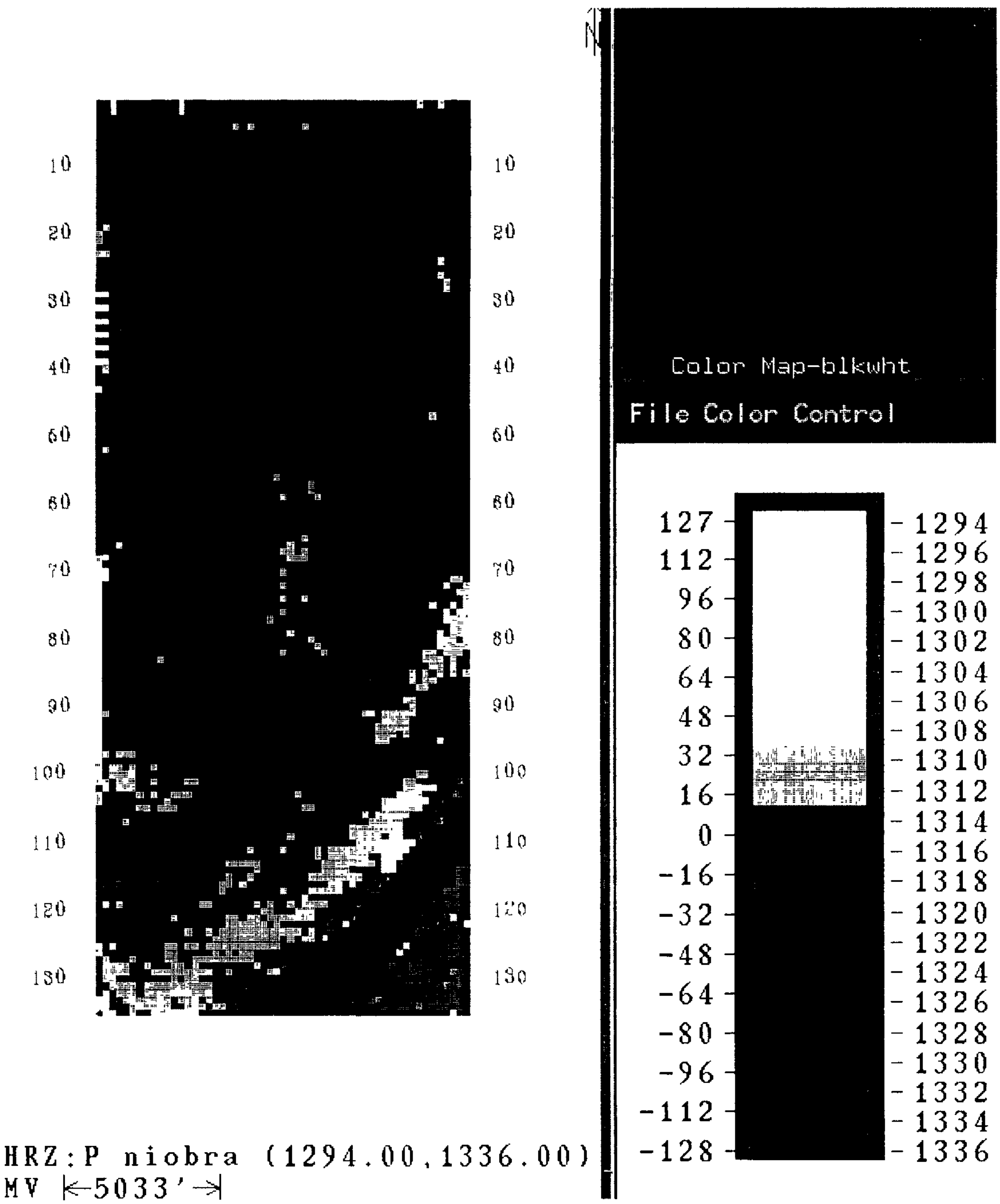


Figure 2: Niobrara formation time structure map. Note the SW–NE trending fault in the SE corner of the seismic survey.

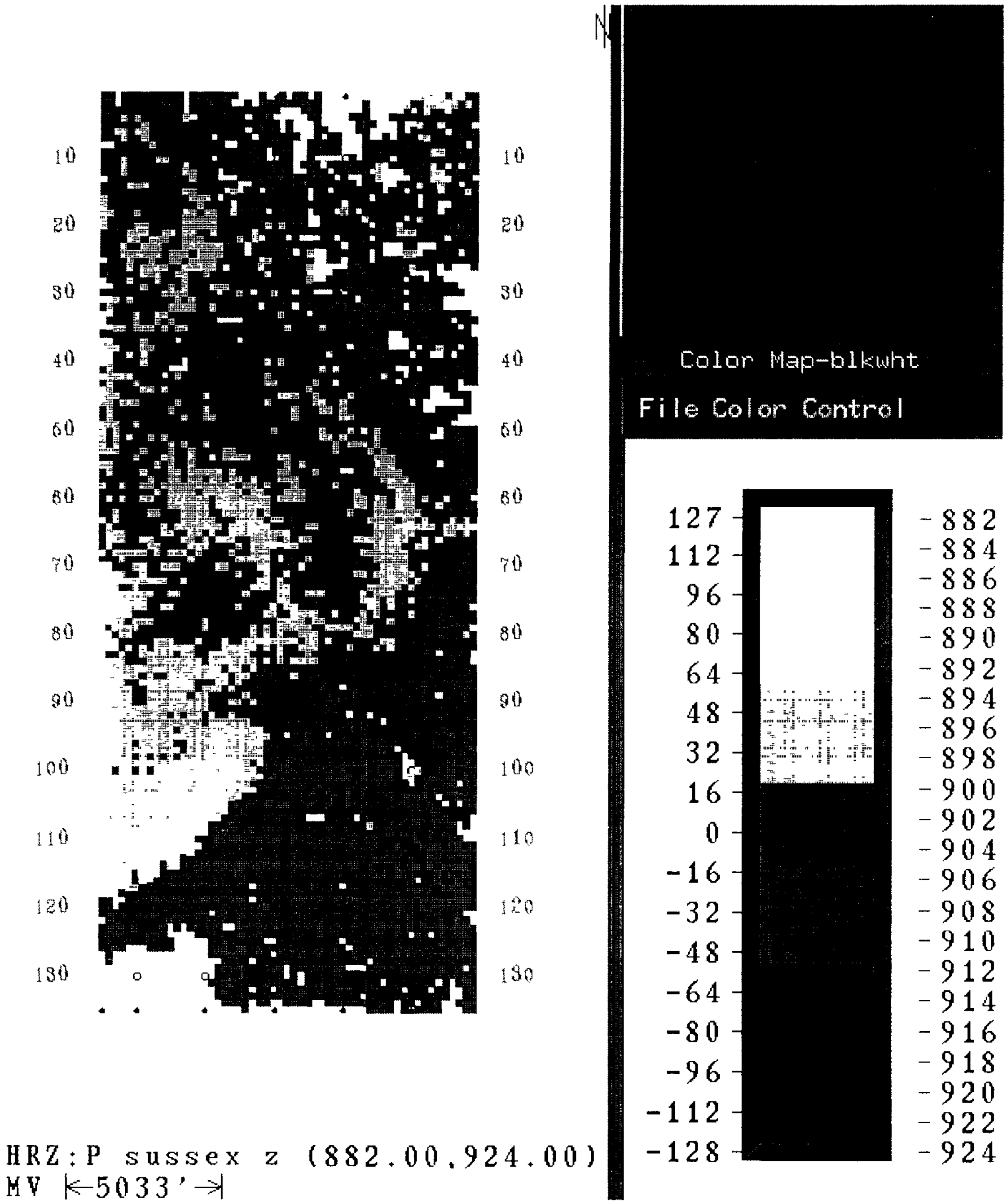


Figure 3: Sussex formation time structure map.

APPENDIX D

1. Permeability Experimental Work
   by Ramona Graves and Hugo Araujo

Colorado School of Mines
Interdisciplinary Study of Reservoir Compartments
DOE DE-AC22-92BC14891
3rd Quarter 1994 Technical Report

Hambert Field
Task 1.2.1 : Permeability Experimental Work
Research Associate: Ramona Graves
Research Assistant: Hugo Araujo

Following is a summary of the tasks accomplished as outlined in the first quarter report.

The effects of increasing the net confining stress from 100 psig to 3500 psig and the temperature from 70°F to 140°F are:

- Relative permeability curves shift slightly to the right.
- A minor shift of the end points was observed.
- These variations might be within the limits of experimental procedure/equipment and data smoothing techniques.
- The magnitude of these effects will be quantified in final report.

Table A

	σ = 100 psig T = 70 °F		σ = 3500 psig T = 70 °F		σ = 3500 psig T = 140 °F	
	S_{wir} %	S_{or} %	S_{wir} %	S_{or} %	S_{wir} %	S_{or} %
First Drainage	38.77		37.94		37.01	
First Imbibition		25.49		27.55		28.48
Second Drainage	37.46		35.35		35.02	
	35.78*		30.67*		33.18*	

* Based on Normalized JBN Procedure

Figures 1, 2, and 3 are attached for the three cases represented in Table A for Core Plug Berea 2.

1. Relative Permeability Measurements

In order to conduct unsteady-state relative permeability displacement experiments at confining stress conditions, a core holder capable of supporting axial confining stress up to 5000 psig was fabricated. The body consists of 316 stainless steel and the end caps of high strength bronze material to prevent galling between similar metals. This core holder can be used with cores of one inch diameter and up to five inches length.

Berea cores were used to establish an experimental procedure, set a base line standard, and will be used in the future to verify the simulation models.

The general procedure consisted in measuring the pressure drop and the fractional flow obtained :

1.1 At 100 psig net confining stress and 70°F temperature.

- a) drainage process, oil displacing water experiment.
- b) imbibition process, water displacing oil experiment.
- c) second drainage process, oil displacing water experiment.

1.2 At 3500 psig net confining stress and 70°F temperature.

- a) drainage process, oil displacing water experiment.
- b) imbibition process, water displacing oil experiment.
- c) second drainage process, oil displacing water experiment.

1.3 At 3500 psig net confining stress and 140°F temperature.

- a) drainage process, oil displacing water experiment.
- b) imbibition process, water displacing oil experiment.
- c) second drainage process, oil displacing water experiment.

The resulting data from the experiments was processed using the JBN (Ref.1) method to obtain relative permeability values. To apply this method, experiments must be run at a high rate so capillary pressure effects are overcome. It was found in a preliminary experiment for a Berea core that a rate of 2 cc/min can be valid to use this method. However, at the end of the second drainage experiment for each set of conditions, it was found that a little bit of water could still be displaced if the oil rate was increased. A normalized JBN procedure was used to adjust the experimental results. The volumes of displaced water were multiplied by the correction factor α :

$$\alpha = \left(\frac{1 - Sw_{ir}^{*}}{1 - Sw_{ir}} \right)$$

where:

Sw_{ir} is the irreducible water saturation at the end of the experiment at a flooding rate of 2 cc/min.

Sw_{ir}^{*} is the irreducible water saturation at the end of the experiment at the final flooding rate of 3.33 cc/min.

Results obtained from the experiments performed with the Berea core plug used, and analysis of the data reduction method applied, can be summarized in the following preliminary conclusions:

a) The effect of increasing the net confining stress, from 100 psig to 3500 psig, on the relative permeability-saturation relations are not very appreciable since the results from both conditions show the same tendency. Variations observed may be more from the use of derivatives on non smooth data than a real change on relative permeability.

b) The effect of increasing the net confining stress from 100 psig to 3500 psig and increasing the temperature from 70°F to 140°F, on the relative permeability-saturation relations are not appreciable since the results from both conditions show the same trend.

c) The effect of increasing the net confining stress from 100 psig to 3500 psig, on the end points, reduces the water saturation (wetting phase) very slightly. This effect could suggest that the net confining stress is acting over the wetting face as a force helping to expel this phase. It does not have the same effect for the non wetting phase. These changes can be considered to fall within limits of experimental procedure/equipment, data smoothing techniques.

d) The effect of increasing the net confining stress, from 100 psig to 3500 psig and increasing the temperature from 70°F to 140°F, on the end points, reduces the water saturation (wetting phase) but also in a smaller proportion. The residual oil saturation increases a little but not further than what was observed with only a confining stress effect. These changes are summarized in Table A.

Future Work

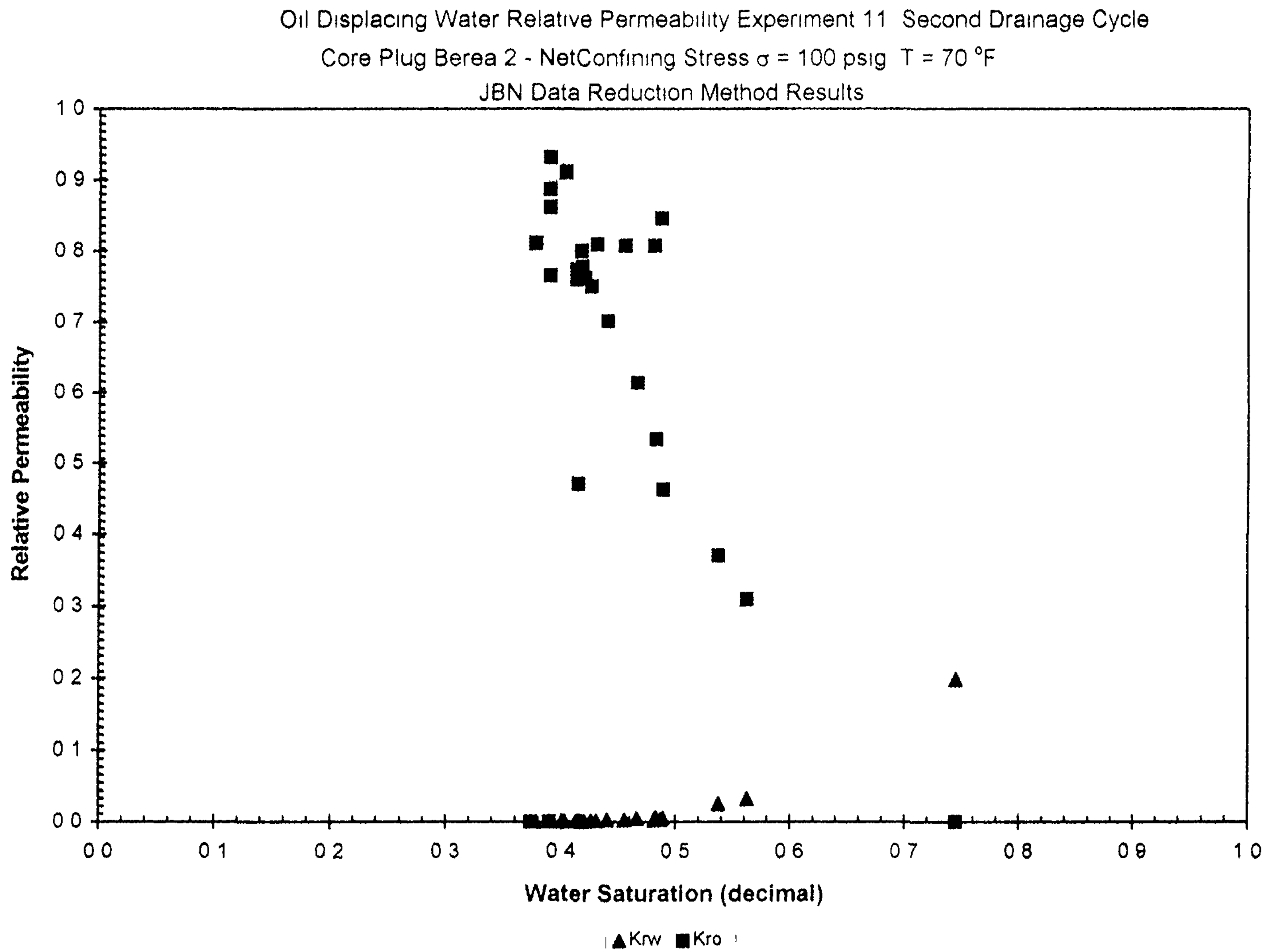
The next step will be to perform the experiments on core plug #4 from core Vern Marshall #1. Preliminary work indicated the experiments will be conducted at low rates and high pressure due to the low permeability conditions.

This will be followed by experimental capillary pressure data and numerical simulation of the core flooding process.

References

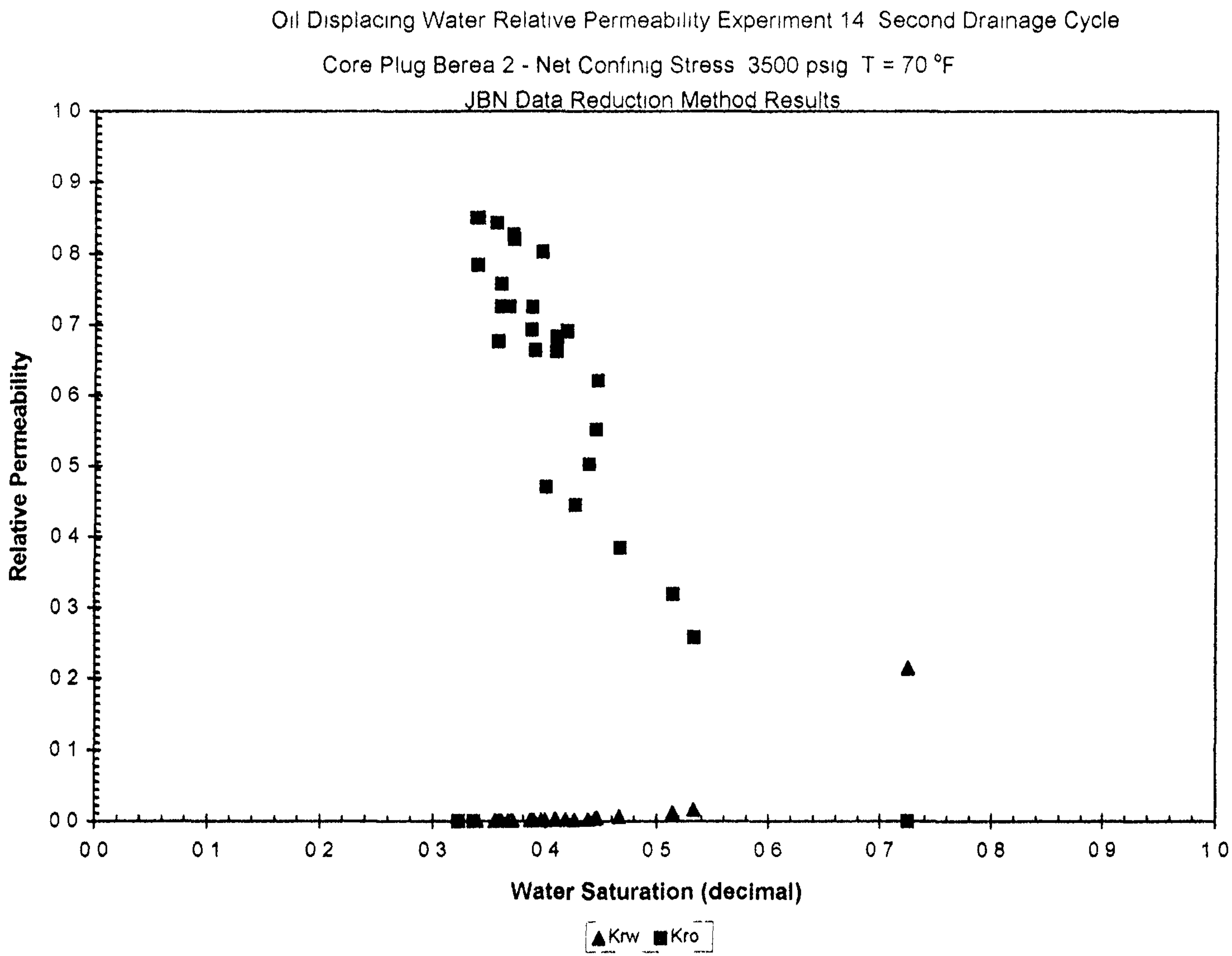
1. Johnson, E.F., Bossler, D.P. and Naumann, V.O.:"Calculation of Relative Permeability from Displacement Experiences," Trans., AIME (1959), 216, 370-2.

FIGURE 1



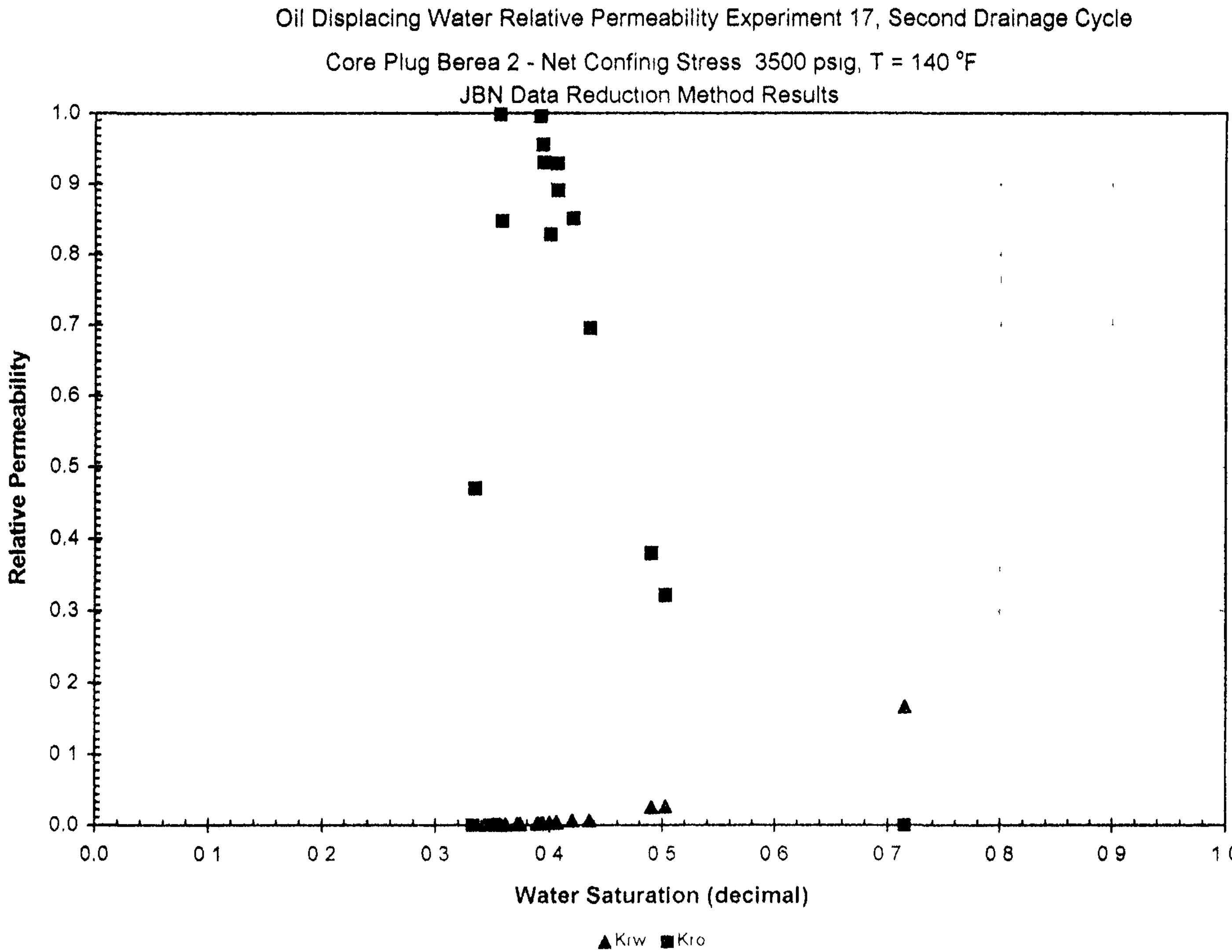
Oil Displacing Water Relative Permeability Experiment 11 Second Drainage Cycle
Core Plug Berea 2 - NetConfining Stress σ = 100 psig T = 70 °F
JBN Data Reduction Method Results
Relative Permeability
Water Saturation (decimal)
1 0
0 9
0 8
0 7
0 6
0 5
0 4
0 3
0 2
0 1
0 0
0 0
0 1
0 2
0 3
0 4
0 5
0 6
0 7
0 8
0 9
1 0
Krw
Kro

FIGURE 2



Oil Displacing Water Relative Permeability Experiment 14 Second Drainage Cycle
Core Plug Berea 2 - Net Confinig Stress 3500 psig T = 70 °F
JBN Data Reduction Method Results
Relative Permeability
Water Saturation (decimal)
0 0
0 1
0 2
0 3
0 4
0 5
0 6
0 7
0 8
0 9
1 0
Krw
Kro

FIGURE 3



Oil Displacing Water Relative Permeability Experiment 17, Second Drainage Cycle
Core Plug Berea 2 - Net Confinig Stress 3500 psig, T = 140 °F
JBN Data Reduction Method Results
Relative Permeability
1.0
0 9
0.8
0.7
0.6
0.5
0.4
0.3
0 2
0 1
0.0
0.0
0 1
0 2
0 3
0 4
0 5
0 6
0 7
0 8
0 9
1 0
Water Saturation (decimal)
Krw
Kro

APPENDIX E

1. Detailed Reservoir Engineering Evaluation
   by Clark Huffman

Colorado School of Mines
Interdisciplinary Study of Reservoir Compartments
DOE DE-AC22-93BC14891
3rd Quarter 1994 Technical Report

Hambert Field
Task 1.1.1: Reservoir Selection and Data Gathering
Research Assistant: Clark H. Huffman

Database

Initial data entry and quality checking completed. Production and completion data output queries implemented. Production data, in the form of decline curves, and completion data plotted on areal maps.

Hambert Field
Task 1.1.5: Detailed Reservoir Engineering Evaluation

Two wells have interpretable pressure build-up data, the Jack C. Noel #1, SW NE NE, Sec. 18, 4N, 65W, and the Warren McMillen #1, SE NW NW, Sec 19, 4N, 65W. Preliminary interpretations have been completed. Both well tests lack data at very early time ($\Delta t < 0.5$ hr) which hinders interpretation. Pressure build-up data is available on three other wells, but the tests were limited and this data is not considered interpretable at this time.

The Jack C. Noel #1 had the longest build-up, approximately 1,355 hrs, however the early time data was not reported. The preliminary interpretation indicates at least one and possibly several boundaries are within the area of investigation. Linearly constrained flow is also indicated by the build-up data. There is some evidence of dual porosity behavior early in the test, but there are not enough data points to be certain. The entire drainage area was possibly not investigated.

The Warren McMillen #1 was shut-in approximately 230 hrs. Again, early time data was not recorded adequately to interpret that portion of the test. The Horner plot indicates that reservoir behavior is seen, but that the entire drainage area was not investigated. The preliminary interpretation of the Bordet plot indicates the presence of a high conductivity fracture, linear flow during the entire shut-in period, and a possible boundary approximately 400 feet from the well.

APPENDIX F

Technology Transfer

1. "Structural and Stratigraphic Compartmentalization of the Terry Sandstone and Effects on Reservoir Fluid Distributions: Part I, Latham Bar Trend, Denver Basin, Colorado"
   by Muatasam H. Al-Raisi, Roger M. Slatt, and Michael K. Decker

2. "Structural and Stratigraphic Compartmentalization of the Terry Sandstone and Effects on Reservoir Fluid Distributions: Part II, Hambert-Aristocrat Fields, Denver Basin, Colorado"
   by Dwaine H. Edington, Roger M. Slatt, and Hugo Araujo

STRUCTURAL AND STRATIGRAPHIC COMPARTMENTALIZATION OF THE TERRY SANDSTONE AND EFFECTS ON RESERVOIR FLUID DISTRIBUTIONS: PART I, LATHAM BAR TREND, DENVER BASIN, COLORADO

[1]Al-Raisi, Muatasam H.
[1]Slatt, Roger M.
[2]Decker, Michael K.

[1]Department of Geology and Geological Engineering
Colorado School of Mines
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[2]Prima Oil and Gas Co.
1801 Broadway, Suite 500
Denver, Colorado 80202

Latham Bar Trend is located in the Denver Basin of Colorado about 15 mi. northeast of Spindle Field. The linear, elongate Trend extends in a northwest direction for more than 6 mi. and is up to 1-2 mi. wide. It is now under infill drilling on 40 acre spacing, with more than 65 wells producing from the Upper Cretaceous Terry Sandstone.

Detailed analysis of 4 cores indicates four sedimentary facies occur in the Trend: cross-bedded sandstone, burrowed muddy sandstone, interlaminated sandstone and mudstone, and muddy siltstone. Reservoir quality, particularly permeability, is primarily facies controlled (Fig. 1) and modified by diagenesis. The cross-bedded sandstone exhibits the best reservoir quality (Fig. 1). Estimated ultimate recovery (EUR) values in wells are related to thickness of this facies. The presence of clays and sericitized lithic grains can also reduce well log resistivity, giving rise to the potential for missed lower-resistivity pay sands.

Structural analysis in the Trend was completed by two methods: (1) identification of missing section within the entire Pierre Shale interval (1500ft.) of 73 wells, and (2) structure contour mapping on top of a prominent, continuous bentonite bed beneath the Terry Sandstone in 210 wells. Results indicate the Trend is dissected by a series of northeast-trending, northwest-dipping faults with vertical displacements of 30-100ft. (Fig. 2). The faults are interpreted to be sealing, separating the Terry Sandstone into isolated fault blocks, on the basis of the following criteria: (1) GOR values standardized to 13th month of production exhibit a non-systematic areal distribution across the trend (Fig. 3), but show systematic up-structure increases in GOR within individual fault blocks (Fig. 4); (2) initial API gravity values from different wells also are non-systematically distributed areally across the Trend, but show similar groupings within fault blocks; (3) EUR values within each fault block exhibit a positive correlation with thickness of cross-bedded sandstone facies (Fig. 5); (4) individual wells with specific standardized GOR values occur at lower structural elevations than wells in adjacent fault blocks with lower GOR's, giving rise to structural reversal of fluid distributions (Fig. 4).

These criteria have been successfully applied to identify reservoir compartments in Latham Bar Trend. Recognition of the stratigraphic and structural attributes which contribute to reservoir compartmentalization can help to explain complex distribution patterns of reservoir fluids in these and other strata in the Denver Basin (and possibly elsewhere), and to maximize reservoir producibility and exploration success.

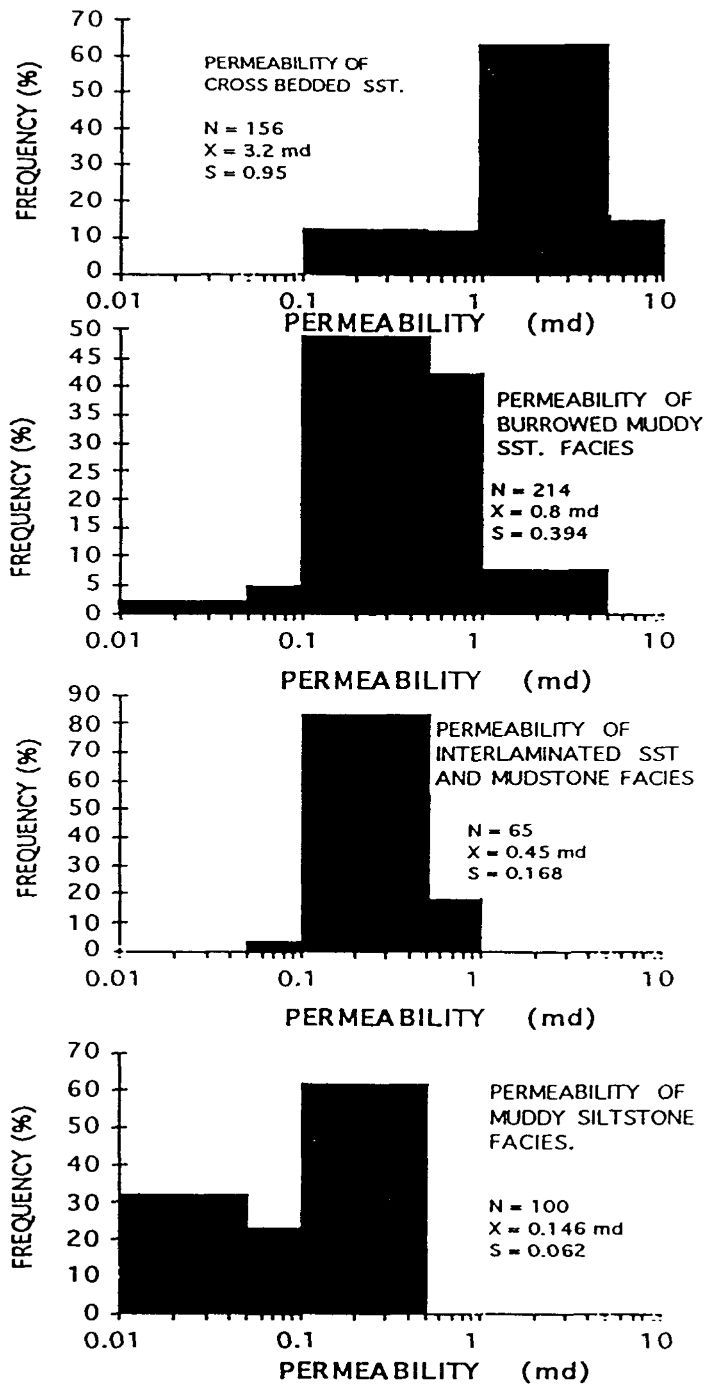

Figure 1. Permeability of distribution of Terry Sandstone facies.

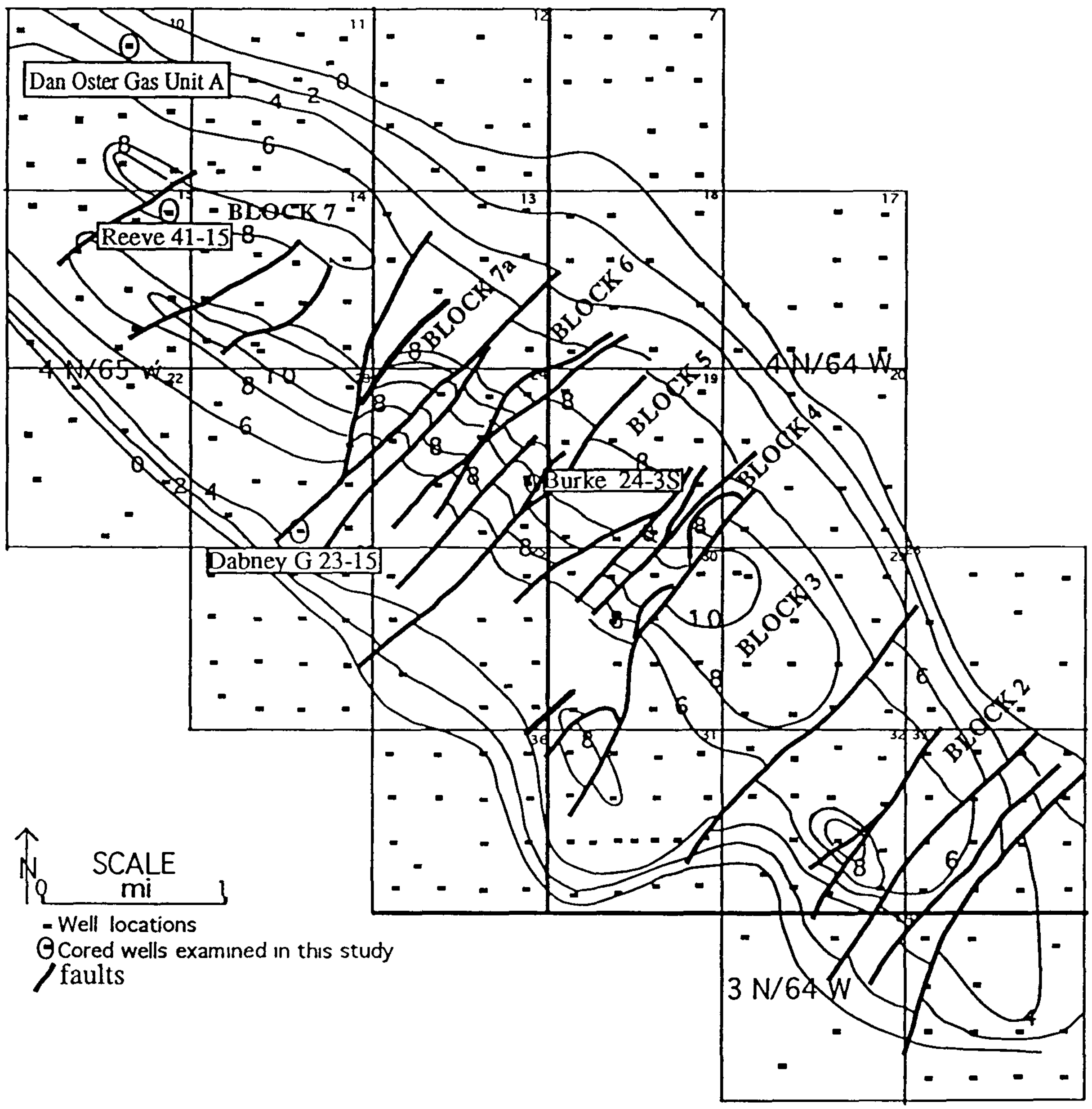

Figure 2. Isopach map of cross-bedded sandstone facies. Fault blocks are shown. C. I. = 2ft.

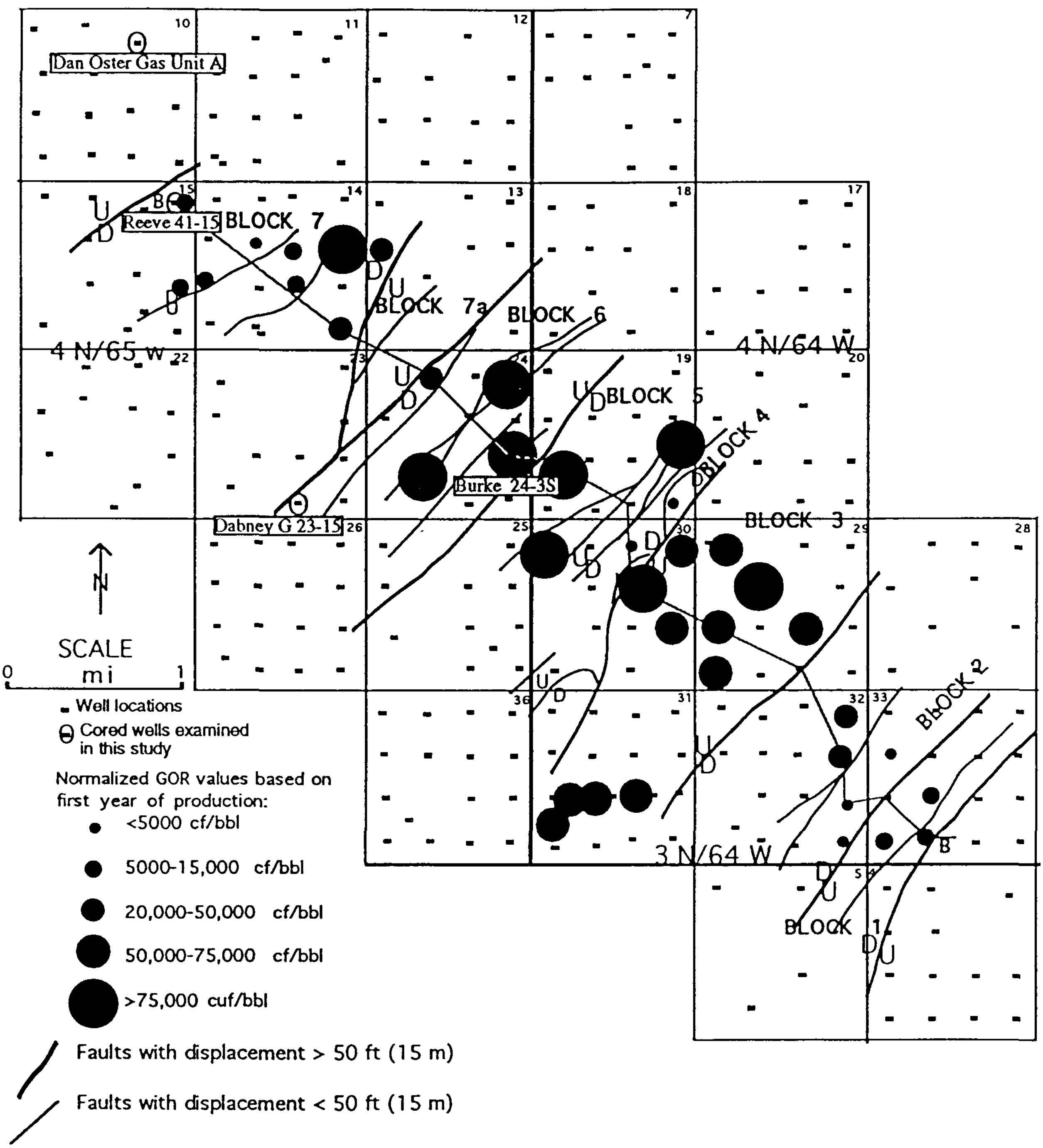

Figure 3. Distribution of normalized GOR values.

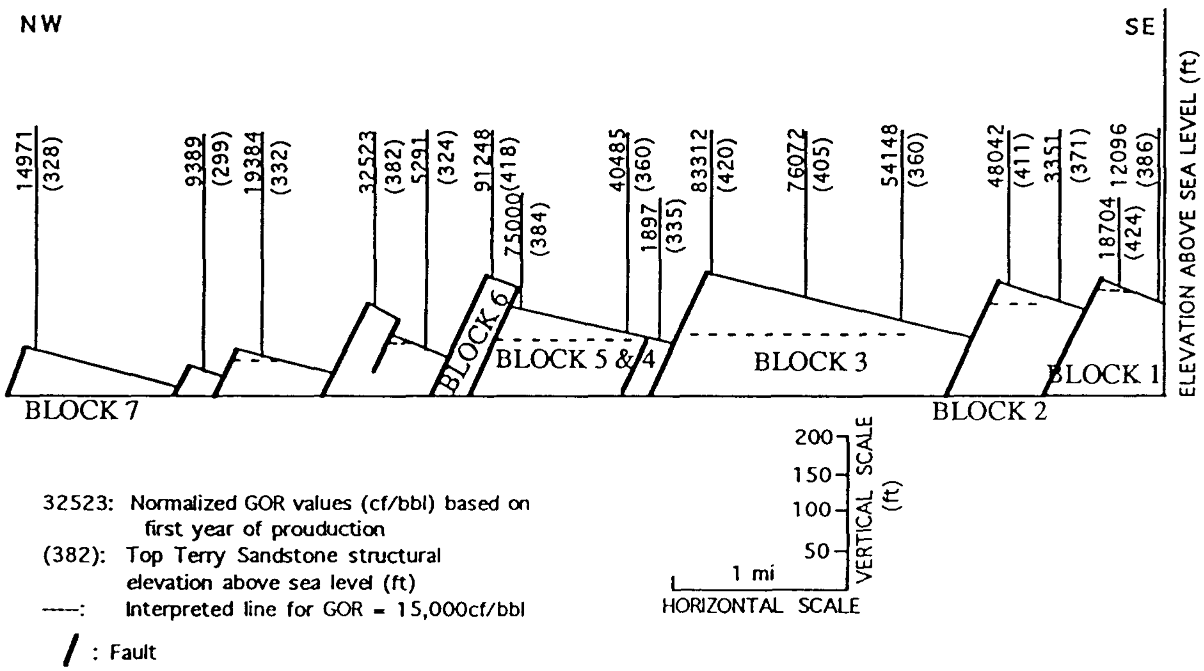

Figure 4. Schematic cross section showing fault blocks, normalized GOR values and elevations for wells. Location of cross section is shown in Figure 3.

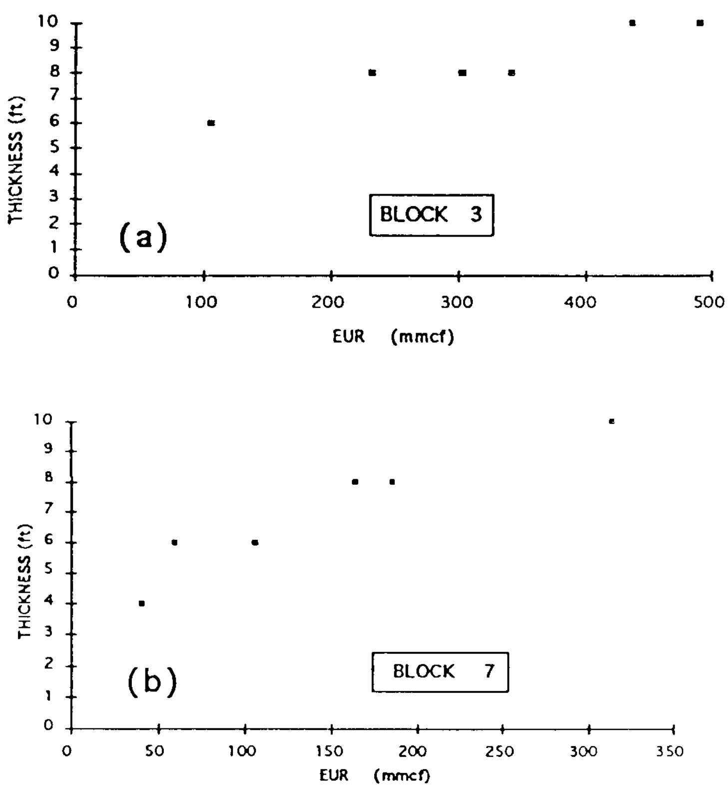

Figure 5. Estimated Ultimate Recovery (EUR) values vs. thickness of cross-bedded sandstone facies for two fault blocks.

STRUCTURAL AND STRATIGRAPHIC COMPARTMENTALIZATION OF THE TERRY SANDSTONE AND EFFECTS ON RESERVOIR FLUID DISTRIBUTIONS: PART II, HAMBERT-ARISTOCRAT FIELDS, DENVER BASIN, COLORADO

[1]Edington, Dwaine H.
[1]Slatt, Roger M.
[2]Araujo, Hugo

[1]Department of Geology and Geological Engineering
Colorado School of Mines

[2]Department of Petroleum Engineering
Colorado School of Mines

The mature Hambert-Aristocrat Fields are located in the Denver Basin of Colorado about 8 miles northeast of Spindle Field. The fields trend in a northwest direction for more than 9 miles, and are up to 3 miles wide. This study was designed to evaluate the detailed stratigraphic and structural architecture of the producing Upper Cretaceous Terry Sandstone in these fields, and the effects of architecture on reservoir fluid distributions. An 1100+ well database (Fig.1) was provided by Dwights Energydata Inc., thus allowing the opportunity to develop techniques for manipulating large databases for characterization studies. This study is being funded by DOE for the purpose of developing integrated geologic, engineering, and geophysical technologies for improved reservoir management. Preliminary results to date are provided in this abstract.

Analysis of five cores indicates five sedimentary facies occur in the fields, each with their own characteristic permeability and sand content:

- **bioturbated mudstone** (0.4md, 7% sand);
- **burrowed to bioturbated sandy mudstone** (0.71md, 37% sand);
- **burrowed to bioturbated muddy sandstone** (0.87md, 62% sand);
- **fine-very fine grained planar to low angle cross-bedded sandstone** (1.32md, 94% sand);
- **fine-very fine grained rippled cross-bedded sandstone** (2.31md, 93% sand).

Permeability measurements on core plugs made at several confining stresses indicate permeability values are on the order of 30-40% lower under reservoir conditions.

In the western part of the area, the facies are arranged in a fining-upward or blocky sequence. By contrast, in the eastern part of the area they are arranged in a coarsening-upward sequence (Figs. 1 and 2), as is the case in nearby Latham Bar Trend. This complex pattern of sequences is interpreted to be a result of westward shingling (paleolandward) of three separate sandstone intervals -- termed lower, middle, and upper (Fig. 2). Consequently, the lower sandstone occurs in the northeastern part of the area while the upper sandstone occupies the southwestern part (Fig. 3); the middle sandstone occurs throughout the area. The shingled stacking pattern suggests the sandstones are transgressive in origin. There is sedimentary evidence for common storm activity during the depositional interval represented in the cores. The boundary zone between the fining-upward and coarsening-upward trends is generally marked by relatively lower resistivity (<8 ohm-m) sandstones, unlike those sandstones on either side of the boundary zone (>8 ohm-m).

Detailed structure and isopach mapping, coupled with identification of missing sections interpreted on individual well logs, indicates the field area is structurally complex. Numerous northeast-trending, steeply-dipping faults with vertical offset on the order of 10-160 feet occur; Figures 4 and 5 show detailed structure over part of the area. Initial GOR values show a strong positive correlation with structural elevation, but only within individual fault blocks. Within each block, GOR increases with structural elevation (Fig. 5). However, initial GOR values vary among the different fault blocks. For example, in some blocks higher GOR's occur at structurally lower elevations than lower GOR's in other blocks (Fig. 5).

These results suggest that faults in the Hambert-Aristocrat Fields are common. They are sealing faults to the migration of reservoir fluids, thus the Terry Sandstone is highly compartmentalized. The presence of shingled, backsteping sandstones (Fig. 6) also provides opportunity for stratigraphic compartmentalization. In this complex geologic setting, reservoir fluids can be distributed in a complex manner, including gas structurally beneath oil. Current plans call for integrating a 3D seismic survey, donated by Amoco Production Co., and reservoir engineering information, donated by Amoco and Union Pacific Resources, to refine or modify the preliminary geologic model (Figs. 5 and 6) presented here.

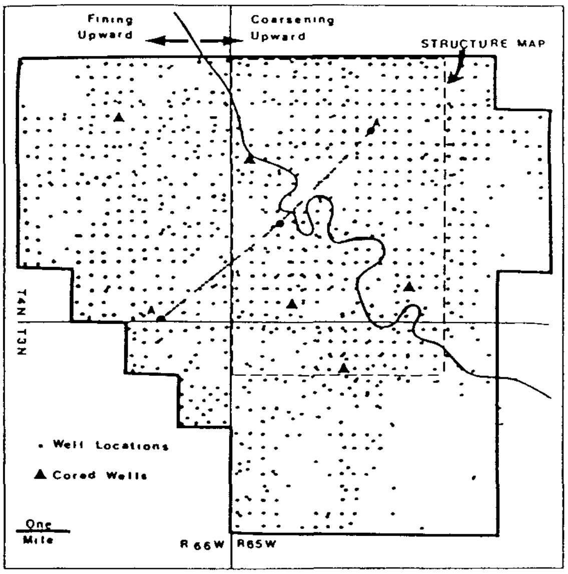

Figure 1. Map of Hambert-Aristocrat Field area showing wells and boundry between vertical sequences

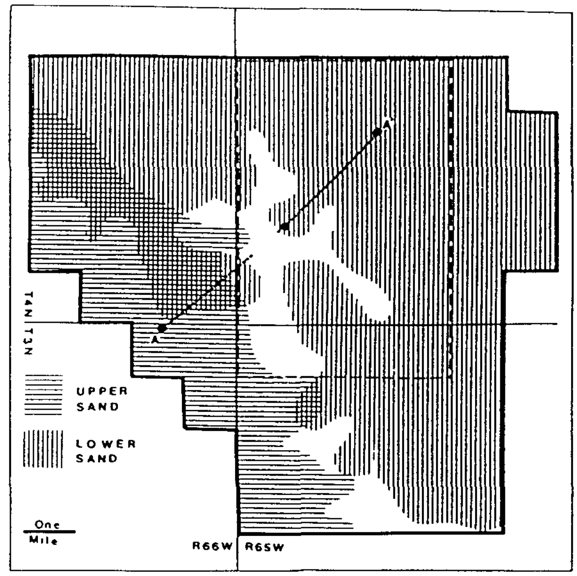

Figure 3. Map of areal distribution of lower and upper sandstones (see Fig. 2). Middle sandstone occurs throughout the area

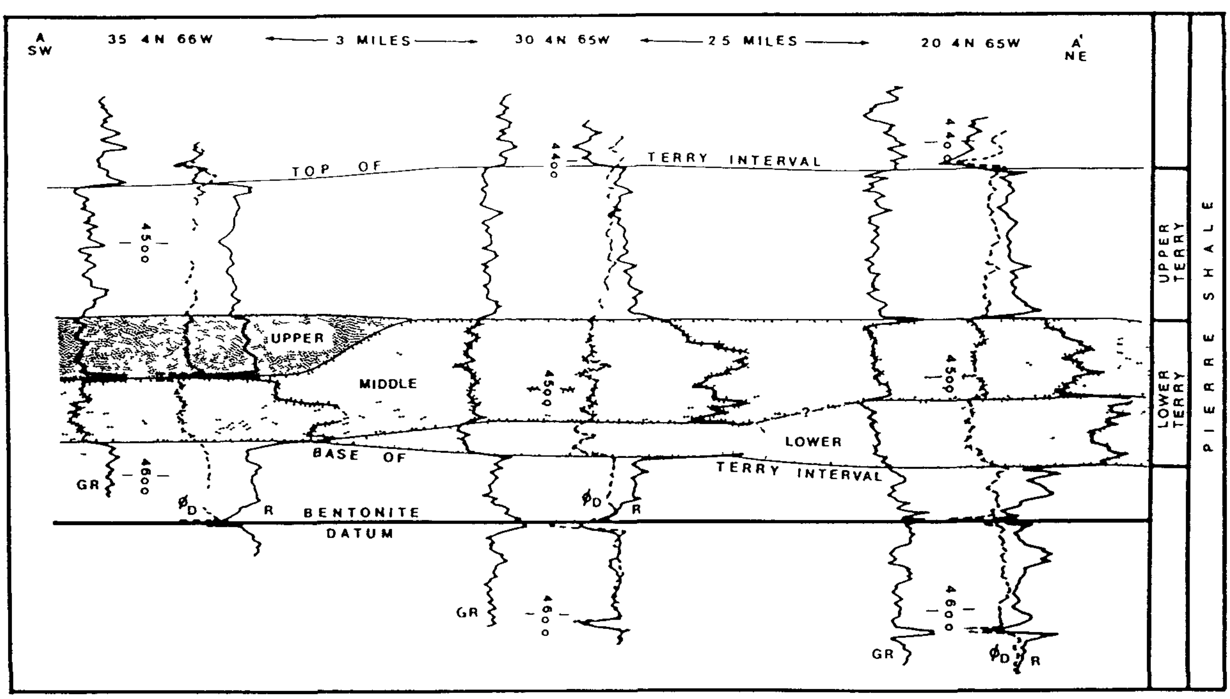

Figure 2. Southwest-northeast straigraphic cross-section (location in Fig. 1)

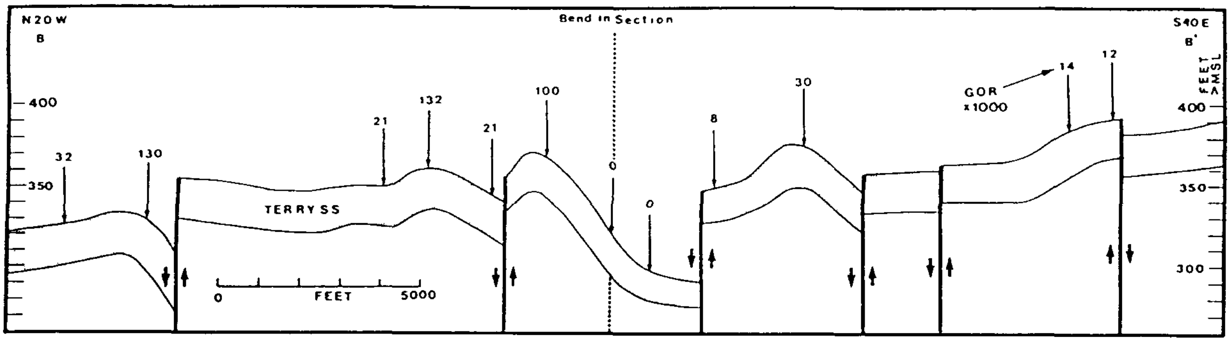

Figure 5. Structure cross-section (location in Fig. 4). Initial GOR values show well control.

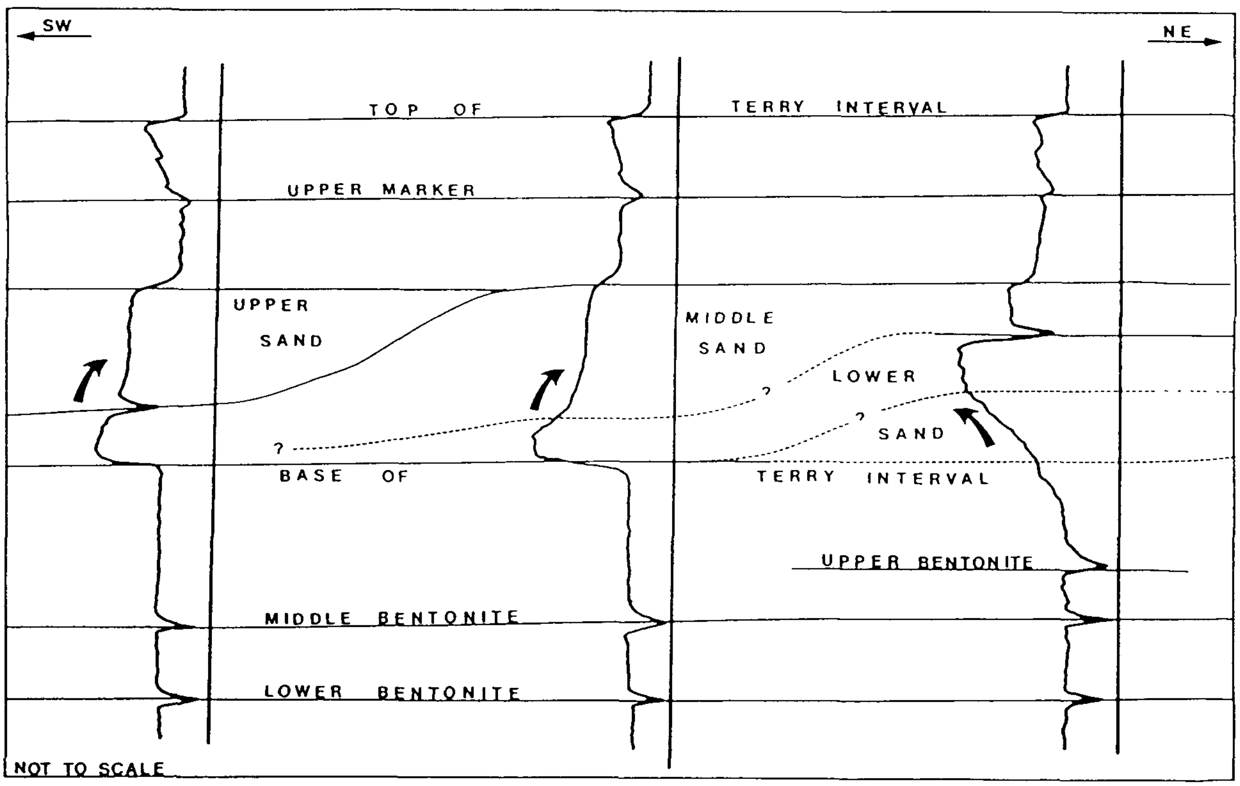

Figure 6. Schematic illustration of postulated stratigraphic relationships and correlation markers.

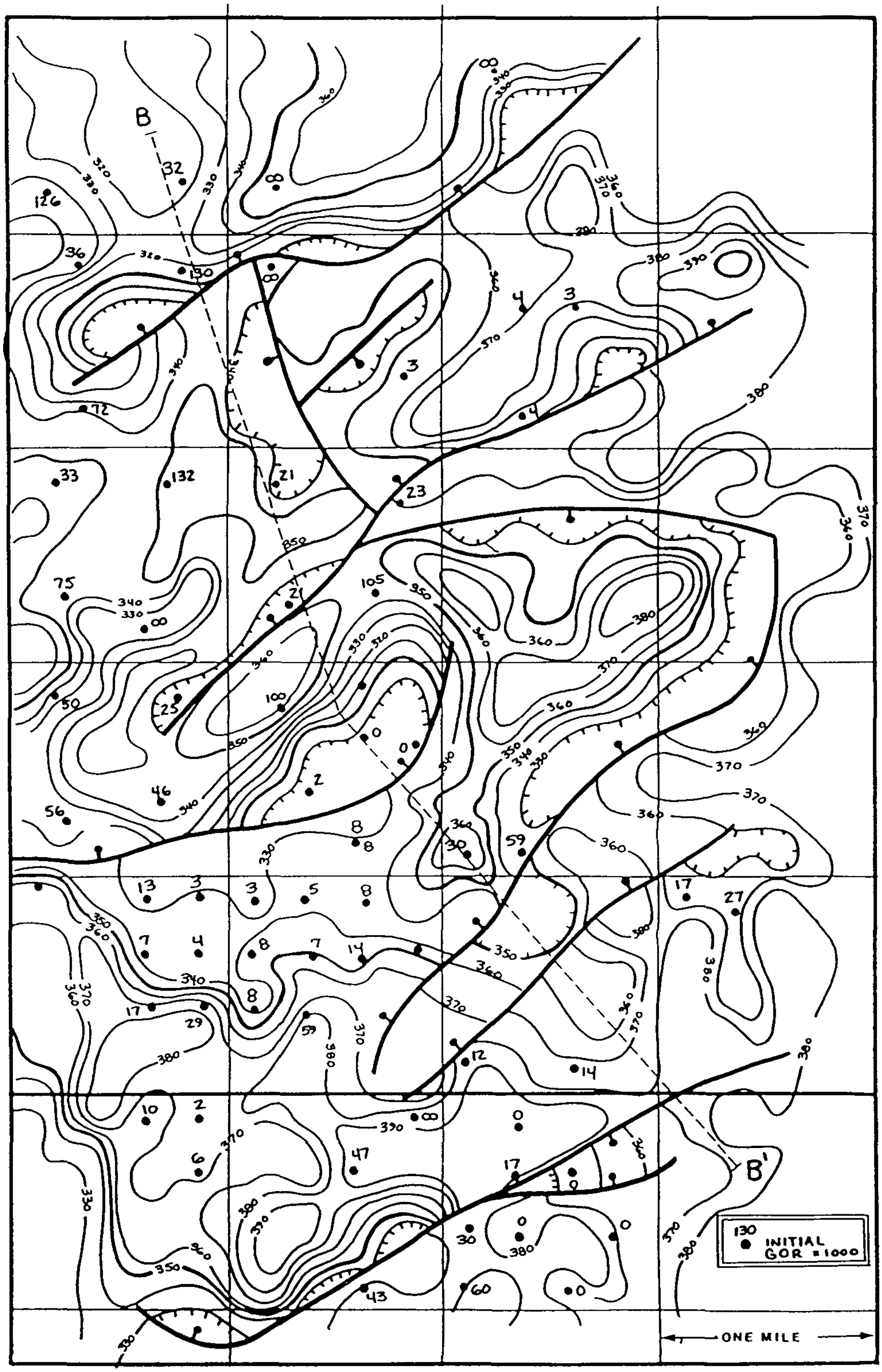

Figure 4. Structure map on top of middle sandstone (Fig. 2). CI = 10ft. Initial GOR's are posted alongside wells.

DOE RESERVOIR CHARACTERIZATION PROJECT
GEOLOGIC PROCESS DIAGRAM

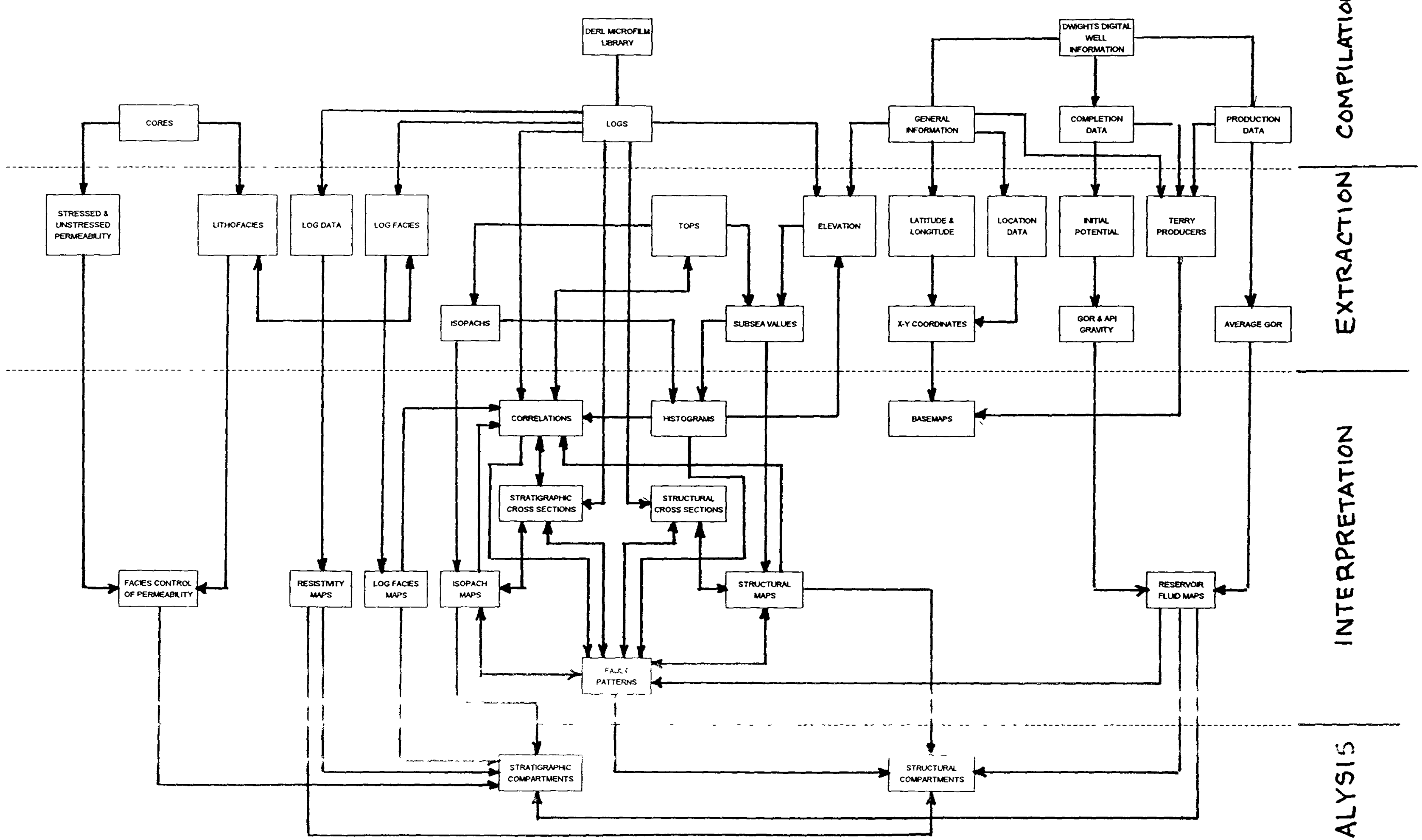

FIG. 12