

THE UNIVERSITY OF TULSA
THE GRADUATE SCHOOL

QUANTITATIVE CHARACTERIZATION OF VALLEY-FILL
DEPOSITS: APPLICATION TO MUDDY SANDSTONE
IN NEWCASTLE, WYOMING

by
Bayram Kara

A thesis submitted in partial fulfillment of
the requirements for the degree of Master of Science
in Discipline of Petroleum Engineering

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A THESIS

APPROVED FOR THE DISCIPLINE OF
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ABSTRACT

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Quantitative Characterization of Valley-Fill Deposits: Application to

Muddy Sandstone in Newcastle, Wyoming (6 Chapters - 149 pp)

Directed by Dr. Ekrem Kasap

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The objective of this study is to characterize Muddy Sandstone of Newcastle to be used for subsurface characterization. Valley-fill formations of Sun Ranch Field in Casper, Wyoming are studied for comparison.

A model is developed to estimate the errors in arithmetic mean and standard deviation as a function of number of measurements. The model shows a linear relationship between average error and inverse of square root of number of data. However, maximum error varies linearly with only inverse of number of data.

Flow units are identified from permeability derivative. The boundaries of computer and geologically generated flow units show excellent agreement.

The calculated bivariate statistical parameters (variograms, etc.) and measures of heterogeneity (Dykstra-Parsons, etc.) for subsurface and outcrop formations are similar. The heterogeneity measures and the variograms from valley-fill outcrop formations can be used for subsurface formations.

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TABLE OF CONTENTS

	Page
TITLE PAGE.....	i
APPROVAL PAGE.....	ii
ABSTRACT.....	iii
ACKNOWLEDGMENTS.....	iv
TABLE OF CONTENTS.....	v
LIST OF TABLES.....	viii
LIST OF FIGURES.....	ix
 CHAPTER I INTRODUCTION.....	 1
Literature Survey.....	4
Objectives.....	7
 CHAPTER II THE MECHANICAL FIELD PERMEAMETER.....	 8
Methodology.....	8
Restrictions.....	9
Calibration and Comparison.....	11
 CHAPTER III STATISTICAL ERROR RELATED TO NUMBER OF MEASUREMENTS.....	 18
Derivations.....	18
Average Error in Arithmetic Mean.....	19
Maximum Error in Arithmetic Mean.....	21
Average Error in Standard Deviation.....	22

Maximum Error in Standard Deviation.....	23
Procedure.....	24
Field Applications.....	25
Results and Discussion.....	25
CHAPTER IV AUTOMATED FLOW UNIT GENERATION.....	39
Background.....	39
Procedure.....	40
Comparison with Geological Descriptions.....	42
CHAPTER V GEOSTATISTICAL PARAMETERS OF VALLEY-FILL	
DEPOSITS.....	51
Location of Study Area.....	51
Permeability Measurements.....	51
Outcrop Measurements.....	51
Subsurface Measurements.....	53
Error Analysis.....	53
Vertical and Horizontal Variability.....	54
Permeability Distributions.....	56
Variogram Analysis.....	58
Outcrop Variograms.....	59
Variograms for Subsurface Data Sets.....	62
CHAPTER VI CONCLUSIONS AND RECOMMENDATIONS.....	95
Conclusions.....	95
Recommendations.....	97
NOMENCLATURE.....	98
REFERENCES.....	101

APPENDIX A.....	109
APPENDIX B.....	116
APPENDIX C.....	128

LIST OF TABLES

Table	Page
1 Measured grid locations and spacings on Outcrops 1, 2, and 3.....	65
2 Measured grid locations and spacings on core slabs of Wells A2, 2, and 7-22, Sun Ranch field	65
3 Geostatistical parameters for Outcrop 1, Sections A, B, and C.....	66
4 Geostatistical parameters for Outcrop 2 and 3.....	67
5 Geostatistical parameters for units of Well A2, Sun Ranch field.....	67
6 Geostatistical parameters for units of Well 2, Sun Ranch field.....	68
7 Geostatistical parameters for units of Well 7-22, Sun Ranch field.....	68

LIST OF FIGURES

Figure	Page
2.1 The effect of core sample length on geometrical factor, by Goggin et al. ³¹	13
2.2 The effect of core sample radius on geometrical factor, by Goggin et al. ³¹	14
2.3 The effect of core sample size on geometrical factor, by Goggin et al. ³¹	15
2.4 Comparison of MFP permeabilities with conventional Hessler-Sleeve permeabilities	16
2.5 Comparison of MFP permeabilities with conventional Hessler-Sleeve permeabilities measured on relatively homogenous Sun Ranch A2 core plugs.....	17
3.1a,b Average error in arithmetic mean of permeabilities as a function of $1/N^{1/2}$, (a) Well A2, (b) Well 2.....	28
3.2a,b Average error in arithmetic mean of permeabilities as a function of $1/N^{1/2}$, (a) Unit 15B, (b) Unit 16, Well A2.....	29
3.3a,b Average error in standard deviation of permeabilities as a function of $1/N^{1/2}$, (a) Well A2, (b) Well 2.....	30
3.4a,b Average error in standard deviation of permeabilities as a function of $1/N^{1/2}$, (a) Unit 15B, (b) Unit 16, Well A2.....	31
3.5a,b Maximum error in arithmetic mean of permeabilities for Well A2, (a) $1/N^{1/2}$, (b) $1/N$	32
3.6a,b Maximum error in arithmetic mean of permeabilities for Unit 16 of Well A2, (a) $1/N^{1/2}$, (b) $1/N$	33
3.7a,b Maximum error in standard deviation of permeabilities for Well A2,	

(a) $1/N^{1/2}$, (b) $1/N$	34
3.8a,b Maximum error in standard deviation of permeabilities for Unit 16 of Well A2, (a) $1/N^{1/2}$, (b) $1/N$	35
3.9a,b Error constants for arithmetic mean and standard deviation of permeabilities as a function of number of experiments, (a) average error constant, (b) maximum error constant.....	36
3.10a,b Comparison of calculated and model errors (a) average error, (b) maximum error, Well A2.....	37
3.11a,b Comparison of calculated and model errors (a) average error, (b) maximum error, Unit 16 of Well A2.....	38
4.1a-c There steps in the computer flow unit generation procedure (a) measured permeabilities, (b) permeability derivative, (c) flow units of well a2 and their average permeabilities.....	47
4.2 Comparison of geologically and computer generated flow units based on permeability data of Well A2.....	48
4.3a-c Comparison of computer defined various number of flow units of Well A2 with geologically defined 22 units, (a) 15 units, (b) 22 units, (c) 40 units.....	49
4.4a-c Comparison of geologically and computer defined flow units, for three well data, (a) Well 2, (b) Well A2, (c) Well 7-22.....	50
5.1 Geographic locations of study areas, Muddy sandstone outcrops 1, 2, and 3, Weston Co., and Sun Ranch Field Federal Well A2, 2, and 7-22, Natrona Co.,Wyoming	69
5.2 Geographic locations of Muddy sandstone outcrops 1, 2, and 3, Newcastle, Weston Co.,Wyoming.....	70
5.3 Geographic locations of Sun Ranch Field Wells, Federal Well A2, 2, and 7-22,Natrona, Co., Wyoming.....	71

5.4	Measured grid locations on Outcrop 1, Sections A, B, and C. The numbers are the number of data from that location.....	72
5.5	Frequencies and probability for Well A2, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.....	73
5.6	Frequencies and probability for Well 2, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.....	74
5.7	Frequencies and probability for Well 7-22, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.....	75
5.8	Frequencies and probability for Unit 16 of Well A2, (a) relative frequency distribution,(b) cumulative frequency distribution, (c) probability.....	76
5.9	Frequencies and probability for Unit 25 of Well 7-22, (a) relative frequency distribution,(b) cumulative frequency distribution, (c) probability.....	77
5.10	Frequencies and probability for Unit 5 of Section C, Outcrop 1, (a) relative frequency distribution,(b) cumulative frequency distribution, (c) probability.....	78
5.11	Frequencies and probability for Unit 11 of Section C, Outcrop 1, (a) relative frequency distribution,(b) cumulative frequency distribution, (c) probability.....	79
5.12	Frequencies and probability for vertical transect measurement on Outcrop 2, (a) relative frequency distribution,(b) cumulative frequency distribution, (c) probability.....	80
5.13	Frequencies and probability for vertical transect measurement on Outcrop 3, (a) relative frequency distribution,(b) cumulative frequency distribution, (c) probability.....	81
5.14	Frequencies and probability for Unit 6A of Well 2, (a) relative frequency distribution,(b) cumulative frequency distribution, (c) probability.....	82

5.15	Frequencies and probability for horizontal measurement on Outcrop 2, (a) relative frequency distribution,(b) cumulative frequency distribution, (c) probability.....	83
5.16.	Variogram for the data from Outcrop 1, Unit 11. (1 foot-grid).....	84
5.17.	Variogram for the data from Outcrop 1, Unit 11, (Horizontal 3 inch-grid).....	85
5.18.	Variogram for the data from Outcrop 2, (Horizontal 4 inch-Grid).....	86
5.19.	Variogram for the data from Outcrop 2, (Vertical 4 inch-Grid).....	87
5.20.	Variogram for the data from Outcrop 3, (Vertical 4 inch-Grid).....	88
5.21.	Variogram for the data from Well A2, (1 inch-grid).....	89
5.22.	Variogram for the data from Well 2, (1 inch-grid).....	90
5.23.	Variogram for the data from Well 7-22, (1 inch-grid).....	91
5.24.	Variogram for the data from Unit 16, Well A2, (1 inch-grid).....	92
5.25.	Variogram for the data from Unit 6A, Well 2, (1 inch-grid).....	93
5.26.	Variogram for the data from Unit 25A, Well 7-22, (1 inch-grid).....	94

CHAPTER I

INTRODUCTION

Reservoir characterization identifies reservoir compartments that are manifesting distinct properties in permeability, porosity, thickness, saturation etc.. Describing reservoir compartments in detail is a vital step in planning for advanced production practices, such as enhanced oil recovery (EOR). In numerous cases the completion, infill drilling, stimulation, and EOR operations were inefficient because of insufficient characterization of reservoirs, and the fact that the secondary and tertiary recovery predictions processes are very sensitive to inherent uncertainties in heterogeneities.

Heterogeneity, spatial variation in properties, is a widespread feature in all naturally-occurring permeable media and one of the most important factors governing fluid flow.¹ Reservoir heterogeneity, which is determined by variations in permeability, porosity, thickness, saturation, faults and fractures, and different facies/rock characteristics, is a result of complex geologic processes that vary in time and space.

Details of reservoir heterogeneity are required to identify compartments and flow units of a reservoir. These data can be obtained from well logs, well tests, direct core measurements, seismic data, geology and outcrop studies on analog formations.² Subsurface data - well logs, well tests, core data- may not be sufficient for two or three dimensional description of rock properties because of one dimensional character of sampling domain (a well). Certain bias is involved in taking core plugs from the reservoir facies toward high porosity and permeability facies. Therefore, in a highly heterogeneous reservoir, core plug data are less representative of actual reservoir heterogeneities.

An outcrop study is a useful tool for reservoir characterization because it allows studying the continuity of formations in second and third dimensions, and investigating in-situ vertical and horizontal variations in properties. A reservoir characterization study on outcrop formations allows a continuous sampling necessary for detailed reservoir description which is not possible on subsurface cores. This detail can be used to plan advance production processes applied to analogous subsurface reservoirs.³

Having permeability distribution data is one of the most important requirement for characterization of both subsurface and outcrop reservoirs due to direct relationship between permeability and fluid flow in porous media. In a characterization study detailed permeability measurements are required. Two common methods to measure permeability are conventional (Hessler-Sleeve 1-D), and MFP (Mechanical Field Permeameter) methods.

A core plug is required to measure permeability by conventional method. The core plug is placed in a special cell, a confining pressure difference is applied, and fluid is pushed through and across the length of the core plug. Darcy's law is used to calculate permeability by using measured flow rate and pressure drop between two ends of the core plug. Since this is such a time consuming process, it cannot be used for detailed outcrop studies. When detailed measurements are needed, the core plug taking procedure becomes impractical and environmentally destructive.

Unlike the conventional method, the MFP is portable and does not require drilling core plugs; therefore, it is advantageous to use MFP in detailed outcrop characterization studies. MFP allows us to take a large number of relatively inexpensive, non destructive and rapid permeability measurements in field conditions. Moreover, MFP has been successfully used for detailed studies on subsurface cores.

Similar to conventional method, MFP measures the flow rate and injection pressure of gas under steady state conditions to calculate permeability values. MFP method was first suggested by Dykstra and Persons in 1950. The MFP that was constructed by Chandler et al. is similar to the lab minipermeameter constructed by Eijpe and Weber (1971), but was designed for field measurements.⁴ The following points are vital for making accurate permeability measurements with MFP.

- 1) Good sealing between injection-tip and rock surface.
- 2) No measurement on and around the edge. When the measured point is close to a boundary, the accuracy of the measurement can be affected in two ways. First, especially in core slab measurements, because of formation damage during drilling, permeability may be lower than actual. Second, owing to gas escape through edges, the measured permeability may be higher than actual (more common in outcrop measurements).
- 3) No crack or fracture on the surface and on the plane normal to it.
- 4) No bending on injection tip (too much force).
- 5) No gas leak from MFP connections.

Although some surface chip-off is involved in MFP measurements to remove weathered rock surface, it is still considered to be non-destructive compared to conventional core plug drilling .

This study focuses on characterization of three Muddy Sandstone outcrops (Newcastle, Wyoming) through on-site MFP permeability measurements. Permeability measurements carried out on core slabs of three Sun Ranch Field wells, Well A2, 2 and 7-22 as well. The geostatistical parameters for outcrop and subsurface were calculated and the possibility of using outcrop parameters for subsurface studies was investigated.

Literature Survey

During the last three decades, numerous outcrop works have been reported. Nearly all studies focused on permeability characterization, because permeability readily describes fluid flow characteristics of formation. In the literature two methods are reported. The first one⁵⁻¹⁹ measures permeability with conventional method by taking core plugs from outcrop formations, while the second method²⁰⁻²⁹ uses minipermeameter for making the measurements in-situ.

Conventional approach has started in early 1960's and most of the work are geological based outcrop studies. The purpose was to find a relationship between permeability and stratification type of formation. Hutchinson et al.⁵ investigated the factors affecting permeability of a sediment. They concluded that grain size, which is characterized by the distribution and its geometric mean, has the most powerful effect on permeability distribution. They also concluded that compaction and cementation have some control on the permeability of a sediment. Dodge et al.⁹ worked in the same area and they observed that permeability decreases as the mean grain size decreases and permeability and porosity both decrease as the percent of cement in the rock increases. They concluded that permeability in a given sedimentary unit is correlated with vertical variation in sedimentology. Tillman et al.³⁰ studied heterogeneity of valley-fill sandstone reservoirs and drew conclusions that are different from the ones Hutchinson et al.⁵ and Dodge et al.⁹ reported. They stated that mean grain size has no effect on permeability or porosity. Jones et al.³ studied Mesaverde Meanderbelt sandstone and they concluded that permeability trends were related to stratification types but were not affected by varying grain size distribution.

Other investigators studied the possibility of using outcrop data for subsurface formations by comparing properties of outcrop and subsurface facies. Tomusta et al.¹⁵

worked on Shannon Shelf Sand Ridges. They indicated that if there is a strong similarity in permeability and porosity distribution between outcrop and subsurface, the outcrop data can be used to construct a reservoir simulation model for subsurface reservoirs.

MFP based studies are relatively new. Weber et al.'s²⁰ study is considerably important, because it is the first outcrop study in which MFP was used for in-situ permeability measurement. Their MFP was the first one built. Its basic principles were used by Goggin et al.²¹ to construct a Mechanical Field Permeameter for more precise permeability measurements, after modifying for outcrop studies. Most of the investigators^{4,21-24,31} have agreed that MFP is an efficient, economic, non-destructive and reliable device for measuring permeabilities directly on outcrop formations.

Goggin et al.²¹ and some other workers²³⁻²⁵ discussed accuracy of permeability values that are measured by MFP. They compared MFP and conventional method by plotting MFP verses Conventional Hessler-Sleeve measurements. They concluded that at very high permeabilities (in the order of a darcy) the minipermeameter displays smaller values and at low permeabilities (in the order of 1-10 md) the minipermeameter displays higher values, but in most permeability ranges both methods are in good agreement. The differences can be caused by turbulent flow effect at high permeabilities and leakage on low permeabilities.²⁶ The differences also come from the fact that in heterogeneous samples, minipermeameter and conventional method measure two different volumes of rock which may have two different permeabilities.²⁴

Well prepared rock surface is key to obtain best representative permeability values of a rock sample. Unprepared surface can affect the accuracy in two ways: 1) Without surface preparation, sealing between injection tip and rock is very difficult. 2) Weathered surface not removed decreases permeability. Lewis²⁹ discussed some surface preparation techniques such as, core-plug, angle grinding, chipping, and trowelling. Most common

techniques are coring, chipping and angle grinding. Coring is time consuming and more expensive than both chipping and angle grinding. Permeabilities measured on a surface prepared with a grinder are lower than the actual, due to pore plugging pores by fine particles generated by grinding.²² Chipping seems to be the most suitable technique for removing the weathered surface of the rock to make accurate permeability measurements.²⁵

The purpose of an outcrop study is to generate data to be used in subsurface reservoir modeling. Many minipermeameter studies focused on correlating outcrop and subsurface data. Kitredge and Lake²² compared properties of outcrop and subsurface San Andres formations to see if they correlate. They concluded that mean permeability agrees poorly, but other statistical measures, such as distribution type, coefficient of variation and variogram have much better agreement. Their explanation about mean permeability difference is that overburden pressure on the subsurface formation might have reduced the permeability. They suggested that their outcrop data can be used for subsurface reservoir modeling because of good statistical agreement between the two.

The main purpose of this study is to describe the Muddy sandstone outcrop in Newcastle, Wyoming. Although some geological work³²⁻³⁶ appeared in the literature previously, no work on statistical reservoir characterization of Muddy sandstone outcrops has been reported. The results of this study will be used to model valley-fill subsurface reservoirs. Tillman et al.³⁰ described valley-fill deposits as "The valleys in which the reservoirs occur were cut by rivers during drops in sea level and remained as conduits (narrow open valleys trending perpendicular to the regional shoreline). At a later time, as sea level rose, the valleys were filled from the landward side by rivers or from the seaward side by shoreline processes or alternatively by both processes."

Objectives

Determination of small scale spatial variation of permeability from subsurface core plugs is difficult and expensive. The variation obtained from the subsurface cores does not exactly represent the whole reservoir. Contrary to subsurface, continuity and cross-sectional exposure of outcrop facies allow us to study details of inter-well scale heterogeneities. These details can be used to characterize subsurface reservoir analog with similar depositional and sedimentological processes. The study area Muddy (Newcastle) sandstone outcrops are a few miles away from the valley-fill subsurface producing formations. The main purpose of this study is to describe Muddy sandstone outcrops by using geostatistical analysis methods, to investigate possibility of correlating Muddy outcrops with valley-fill reservoirs, since they are deposited by similar processes.

In the next five chapters, following subjects will be discussed. Chapter 2 gives general overview of the measurements with Mechanical Field Minipermeameter. Chapter 3 proposes an error model to predict average and possible maximum errors in arithmetic mean and standard deviation. Chapter 4 introduces a computer method for flow unit description based on permeability derivative. Chapter 5 is about geostatistical parameters of valley-fill deposits. In this chapter, three Muddy sandstone outcrops and three well deposits of Sun Ranch field were compared by means of univariate (histogram, means, standard deviation, etc.) and bivariate (variogram, correlation coefficient, etc.) statistics. The last chapter states the overall conclusions.

CHAPTER II

THE MECHANICAL FIELD PERMEAMETER

Methodology

The MFP, constructed by Chandler et al.⁴, is based on a gas permeameter used by Eijpe and Weber.²⁰ MFP is a mechanical and portable instrument that is mainly designed for field studies. MFP was also used for laboratory permeability measurements³¹⁻³⁸ and its practicality gives opportunities for variety of other applications. For example, Aasum et al.³⁹ described a method to quantify fine scale anisotropy and cross-bedding from MFP measurements. It measures steady state flow rate and pressure drop simultaneously when injection tip is pressed against a relatively smooth rock surface.⁴ After measuring flow rate and pressure drop, permeability value is calculated using a modified form of Darcy's equation.

$$K_G = \frac{2\mu Q P_i}{a G_o (P_i^2 - P_o^2)} \quad (2.1)$$

where

K_G = Air permeability (d)

Q = Flow rate (cc/sec)

P_i = Measured pressure (atm)

P_o = Atmospheric pressure (atm)

a = Internal radius of the tip seal (cm)

μ = Viscosity of the injection gas (cp)

G_o = Geometrical factor, based on the ratio between the outer and inner radii of the tip seal.

Restrictions

As indicated previously, MFP measures steady state gas flow rate and pressure drop on rock surface. MFP measured permeabilities may differ from the actual liquid permeabilities because of the following factors.

1. Viscosity of gas is pressure dependent.
2. Gas slippage affects measurements especially in low permeability samples.
3. Non-Darcy high velocity is effective in high permeability samples or high rate conditions.
4. Quality sealing between injection tip and measured sample is essential.
5. Gas flow geometry is not linear.

Theoretically all factors but sealing quality and flow geometry can be taken into account. Sealing quality can be improved by some additional efforts in surface preparation. Flow geometry, on the other hand, is a complex parameter and needs more attention.

Flow geometry is represented by a geometrical factor in Eq. (2.1) to calculate permeability from pressure difference and flow rate. Goggin et al.³¹ studied geometrical factor effects and introduced geometrical factors for both unconfined core-plug and confined half-space flow.

For unconfined flow geometry, which is used for core plug sample measurements, the assumption is such that the boundary normal to injection direction is open to flow. In other words when measurements take place on small samples, gas escape is allowed through the normal surfaces as well. This effect is taken into account by a geometric factor, G_0 . G_0 is function of b_D , R_D , and L_D , which are all dimensionless parameters. These dimensionless parameters are derived by using internal radius of tip-seal, as a

characteristic length.

a	internal radius of tip-seal
$b_D = b / a$	dimensionless tip seal thickness
$R_D = R_{core} / a$	dimensionless core-plug radius
$L_D = L_{core} / a$	dimensionless core-plug length.

The assumption for confined (half space) flow geometry is that the measured sample is so large that the flow is not affected by normal boundaries, and no flow is assumed through these boundaries. Since the measured sample is very large in the case of an outcrop, the confined flow geometry parameters are used for outcrop measurements. In confined flow geometry, the geometrical factor, $G_O(b_{D,inf})$, is determined assuming that R_D and L_D go to infinity.

Effects of core sample length and radius on geometrical factor, and general core plug dimensions are shown in Figs.2.1, 2, and 3 respectively. Geometrical factor (G_O) decreases as dimensionless tip seal size increases (b_D), for all cases. Figure 2.1 shows effect of core plug length on geometrical factor. If core plug length increases, geometrical factor decreases. Figure 2.2 indicates that, if core plug radius increases, geometrical factor decreases. Figure 2.3 shows smaller geometrical factors with decreasing core plug dimensions.

Gas slippage effect becomes important when measurements are conducted on low permeability samples, and with low pore pressures. This is also what we observed in comparisons involving on low permeability samples. Minipermeameter which measures at low pressures (0.1034 - 0.2068 MPa gauge) shows higher permeability values than the conventional method (1.379 MPa gauge).³¹ High velocity gas flow effect is more pronounced in measurements on samples having permeabilities greater than 1000 md, although some argue that it is present in any gas permeability measurement.³¹ A

FORTTRAN program by Goggin⁴⁰ is used to convert MFP measurements to permeability values. The program has corrections for all factors, which may affect MFP measurements.

Calibration and Comparison

Customarily MFP measurements are checked against conventional Hassler-Sleeve laboratory measurements. In this study, the core plugs from Sun Ranch Field, Well A2, are utilized for calibration and comparison. The permeabilities measured by MFP on both ends of forty four, one-inch diameter core plugs were compared with those measured by Core Laboratories using conventional method. Figure 2.4 compares the permeabilities from conventional method with the ones from MFP measurements taken on both ends of the core plugs. Figure 2.4 indicates a good agreement, although MFP permeabilities are slightly higher than the ones from the conventional method. For a better comparison, we selected some relatively homogeneous cores on which the top and bottom permeabilities differ no more than 10%. Figure 2.5 compares the geometric mean of the top and bottom permeabilities of the selected cores with the ones from Hassler-Sleeve method. Figure 2.5 indicates that the agreement has not improved when the cores are biasedly chosen for comparison. This might be because of the internal heterogeneities that may exist in those cores.

Various works^{24,26} involving calibration of MFP measurements concluded that at low permeabilities (less than 500 md) MFP measurements were higher, whereas at high permeabilities they were lower than the conventional method measurements. The same studies discussed reasons for the differences in permeability values between a conventional and a MFP measurement and reported that there can be three factors contributing to the discrepancy between two measurements.^{24,26} The permeabilities measured at two ends of the same sample is expected to differ, if the sample is not

homogenous (horizontal heterogeneity). The volume of investigation in a MFP measurement is only a portion of the sample, which is not the same volume in the conventional method (internal and vertical heterogeneity). It is more than likely to measure different permeabilities with MFP, if there exists any type of heterogeneity within the core plug. A perfect sealing between the sample and injection tip may not always be possible; therefore, any leak that is comparable to the amount of fluid going through the core will result in a higher MFP measurement. At high permeabilities, turbulent flow may affect accuracy of MFP measurements. In our calibrations it is believed that the small difference between MFP and conventionally measured permeabilities is caused by the internal core heterogeneities.

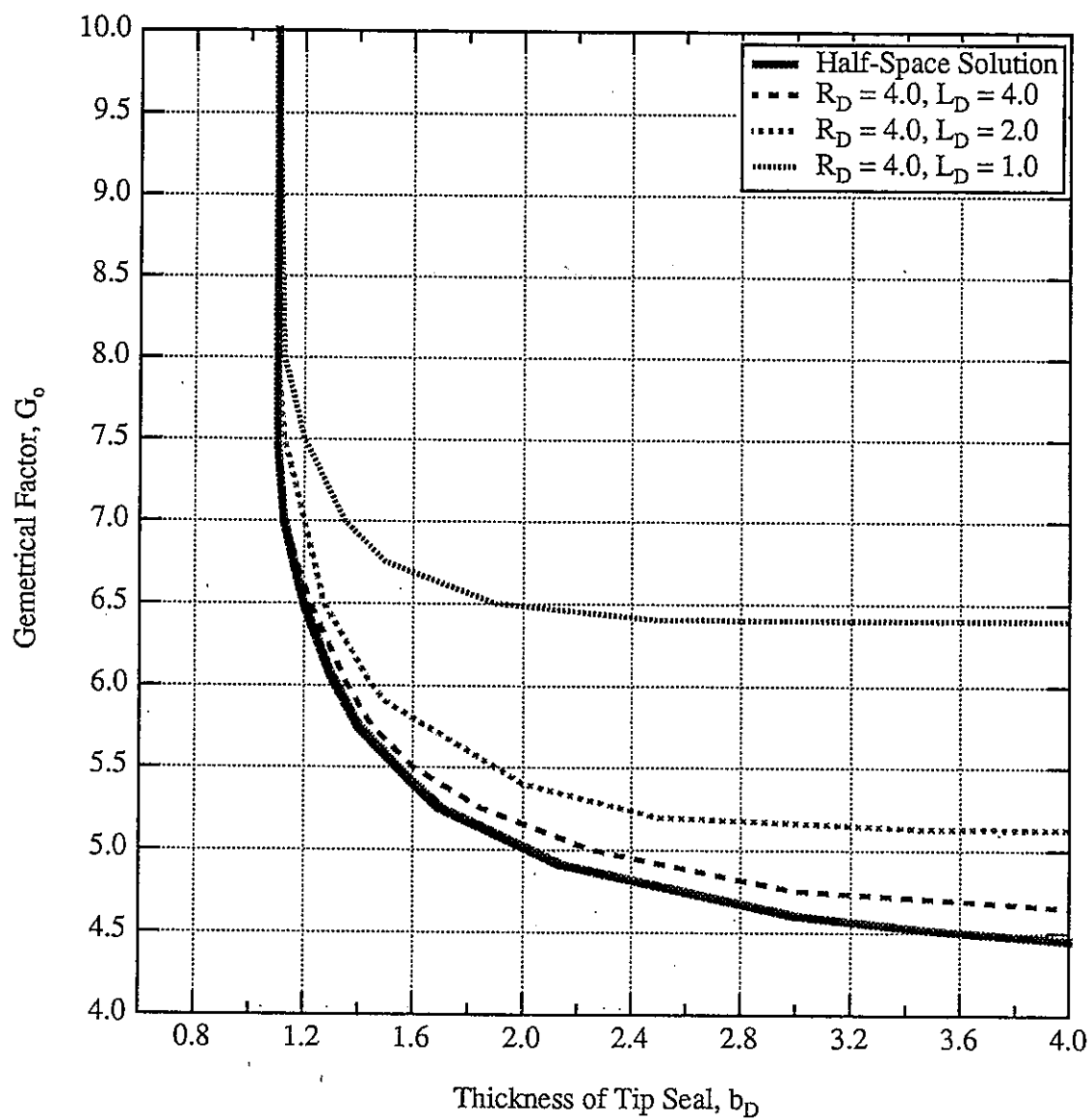


Figure 2.1. The effect of core sample length on geometrical factor, by Goggin et al.³¹

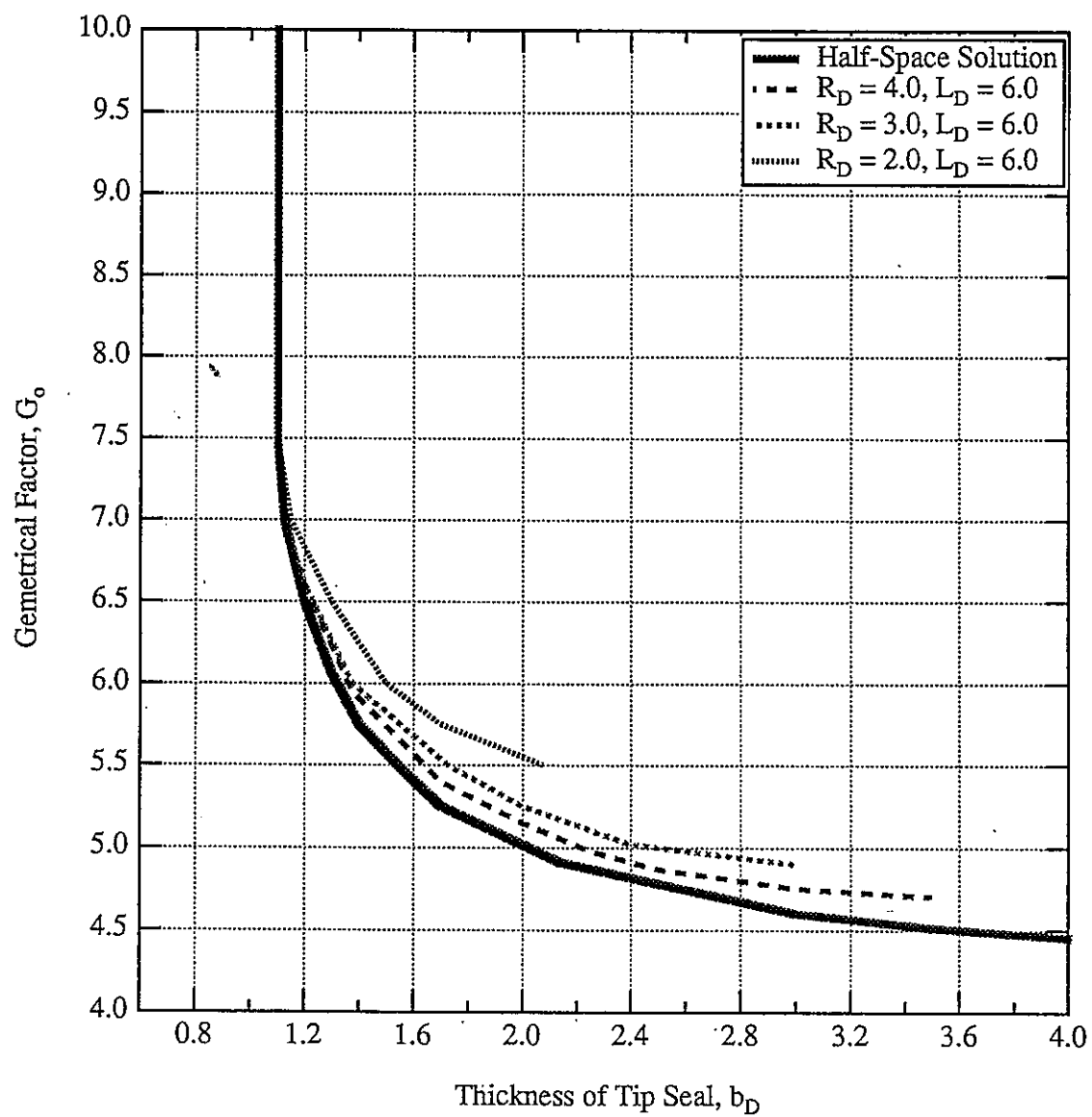


Figure 2.2. The effect of core sample radius on geometrical factor, by Goggin et al.³¹

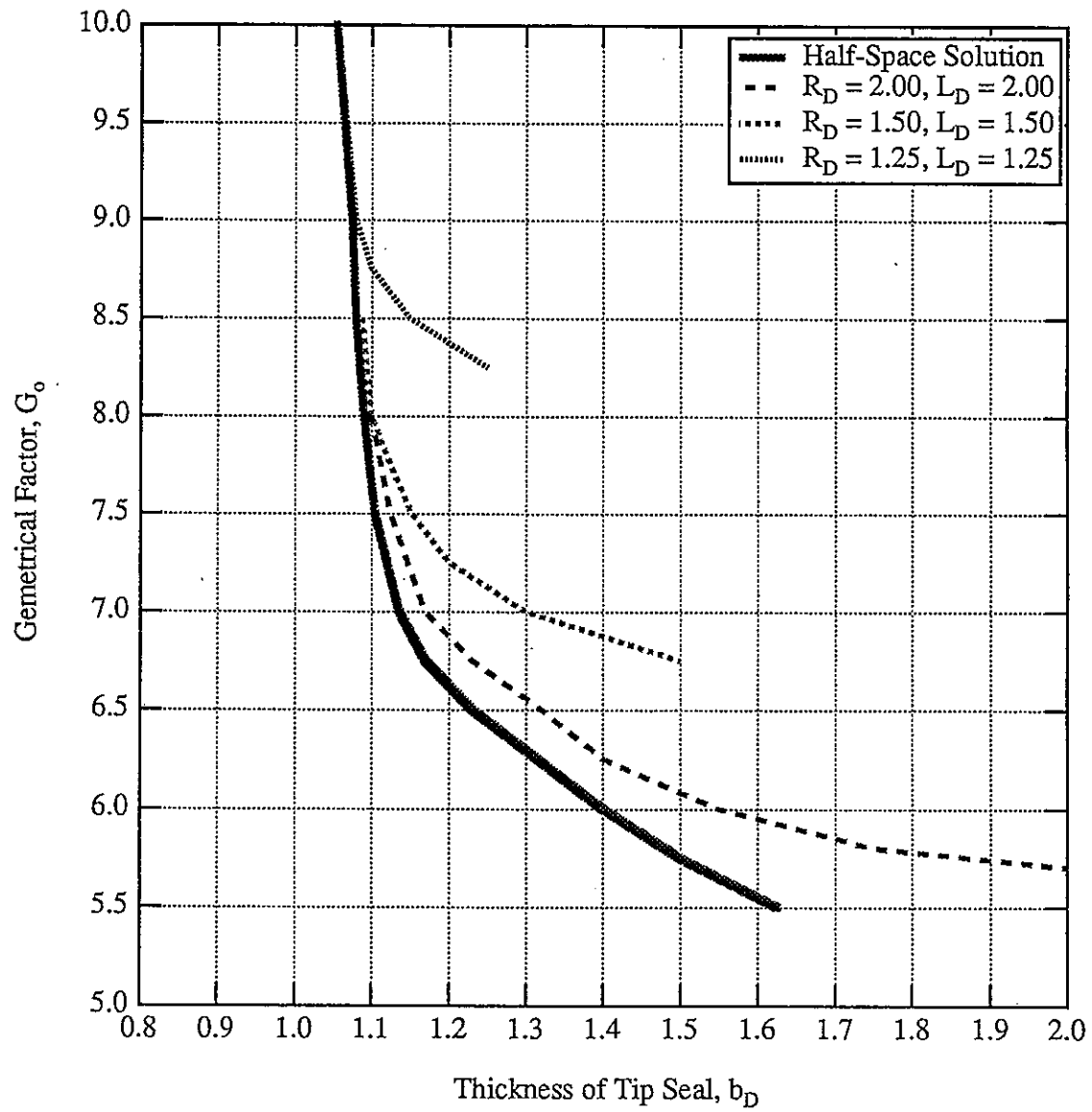


Figure 2.3. The effect of small sample size on geometrical factor,
by Goggin et al.³¹

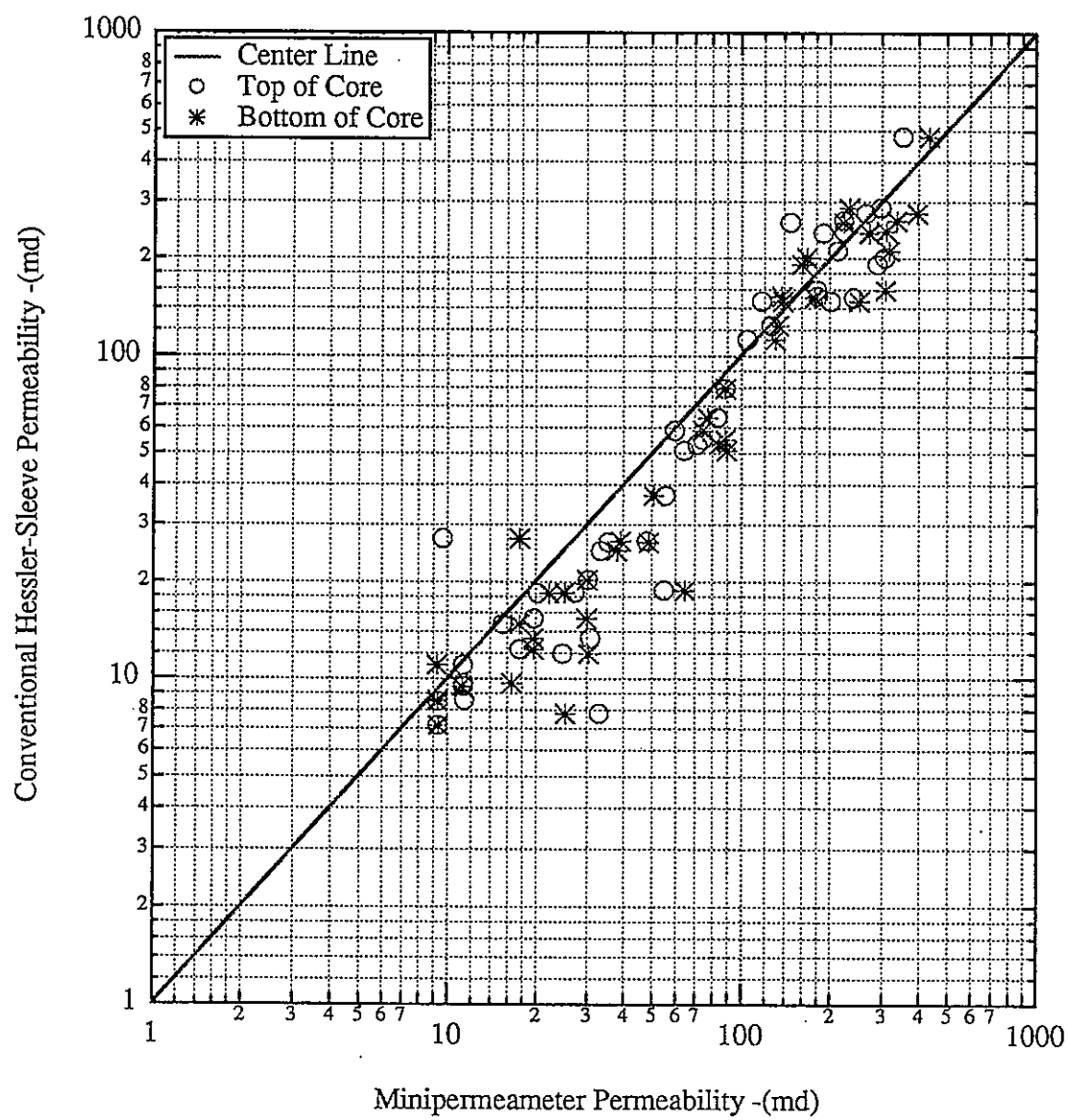


Figure 2.4. Comparison of MFP permeabilities with conventional Hessler-Sleeve permeabilities.

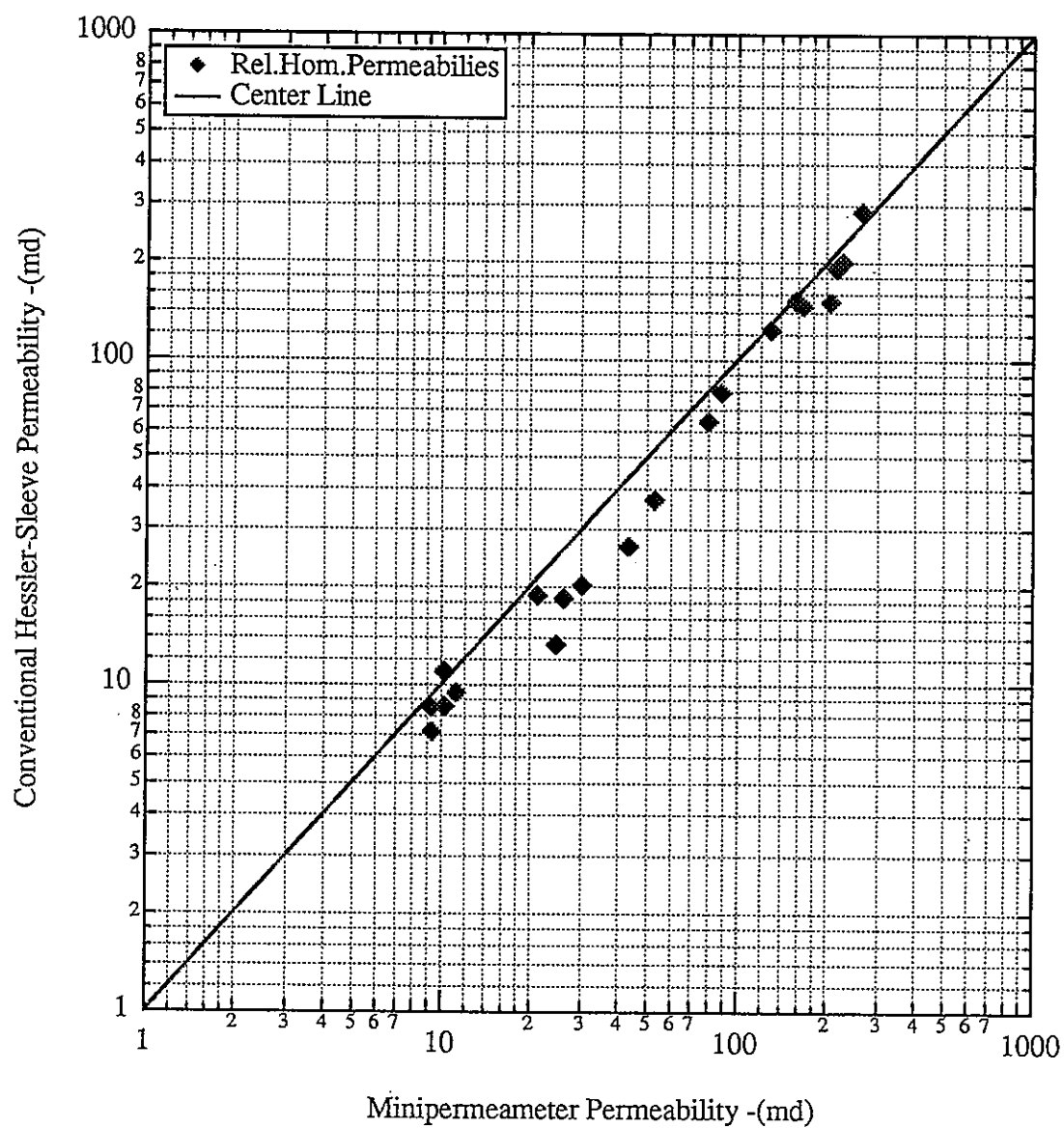


Figure 2.5. Comparison of MFP permeabilities with conventional Hessler-Sleeve permeabilities measured on relatively homogenous Sun Ranch A2 core plugs.

CHAPTER III

STATISTICAL ERROR RELATED TO NUMBER OF MEASUREMENTS

Calculated geostatistical parameters involve statistical error because of limited number of measurements. Neglecting the statistical error may result an improper characterization of a reservoir and may have an adverse effect on related reservoir studies (i.e. numerical simulation, production, etc.).

Sample data are the main tool for geostatistics. We expect that the larger the number of data is, the closer the estimated value of a parameter to its true value. The data collection is a costly process, thus the number of measurements needs to be optimized to minimize the statistical error. The optimum number of measurement will depend on heterogeneity and parameter type (e.g. arithmetic mean, standard deviation, etc.) to be calculated.

In this chapter a model is developed to estimate the magnitudes of errors in arithmetic mean and standard deviation. Two cases are considered: average and maximum errors in arithmetic mean and standard deviation.

Derivations

Errors in arithmetic mean and standard deviation are simply defined as the deviation from the true values that are calculated from an infinitely large data set. The error derivations for both arithmetic mean and standard deviation are simple and involve similar terms.

Average Error in Arithmetic Mean

Error in arithmetic mean is defined as,

$$E_{am} = \frac{|\bar{X} - \mu|}{\mu} \quad (3.1)$$

where E_{am} is error in arithmetic mean, $\bar{X}$ is sample mean, and μ is population mean.

Mean is defined as,

$$\bar{X} = \frac{1}{N} \sum_{i=1}^N X_i. \quad (3.2)$$

N is the number of data, X_i is the sample values.

Substituting Eq.(3.2) into Eq.(3.1) we get

$$E_{am} = \frac{1}{\mu} \left| \sum_{i=1}^N \frac{X_i}{N} - \mu \right|. \quad (3.3)$$

Absolute value can be written as the square root of a squared value.

$$E_{am} = \frac{1}{\mu} \sqrt{\left(\sum_{i=1}^N \frac{X_i}{N} - \mu \right)^2} \quad (3.4)$$

$$E_{am} = \frac{1}{\mu} \sqrt{\left(\sum_{i=1}^N \frac{X_i}{N} - \frac{N\mu}{N} \right)^2} \quad (3.5)$$

$$E_{am} = \frac{1}{\mu N} \sqrt{\left[\sum_{i=1}^N (X_i - \mu) \right]^2}. \quad (3.6)$$

Equation (3.6) can be rewritten as

$$E_{am} = \frac{1}{\mu N} \{[(X_1 - \mu) + (X_2 - \mu) + \dots + (X_N - \mu)] \\ \times [(X_1 - \mu) + (X_2 - \mu) + \dots + (X_N - \mu)]\}^{1/2}. \quad (3.7)$$

Equation (3.7) can be can be regrouped into two terms

$$E_{am} = \frac{1}{\mu N} \left[\sum_{i=1}^N (X_i - \mu)^2 + \sum_{i=1}^N \sum_{j=1, j \neq i}^N (X_i - \mu) \times (X_j - \mu) \right]^{1/2} \quad (3.8)$$

$$E_{am} = \frac{1}{\mu \sqrt{N}} \left\{ \frac{1}{N} \left[\sum_{i=1}^N (X_i - \mu)^2 \right] + \frac{1}{N} \left[\sum_{i=1}^N \sum_{j=1, j \neq i}^N (X_i - \mu) \times (X_j - \mu) \right] \right\}^{1/2}. \quad (3.9)$$

Equation (3.9) can be written in terms of population variances.

$$E_{am} = \frac{1}{\mu \sqrt{N}} (C_1 \sigma^2 + C_2 \sigma^2)^{1/2}. \quad (3.10)$$

Two terms, on the right hand side of Eq. (3.10), do not exactly correspond to sample variance, because the mean used is not the sample mean, but is a population mean, and the second term does not fit the definition of variance. Yet, those two terms can be assumed to be some fraction of the sample variance and can be represented as variance times a constant. Regrouping the constants

$$E_{am} = \frac{1}{\mu \sqrt{N}} [\sigma^2 (C_1 + C_2)]^{1/2}. \quad (3.11)$$

Summation of constants C_1 and C_2 can be replaced with a single constant C^2 .

$$E_{am} = \frac{1}{\mu \sqrt{N}} (C^2 \sigma^2)^{1/2}. \quad (3.12)$$

Using definition of standard deviation, (square root of variance) Eq.(3.12) is expressed,

$$E_{am} = \frac{C \sigma}{\mu \sqrt{N}}. \quad (3.13)$$

Expressing in terms of coefficient of variation,

$$E_{am} = C \frac{C_v}{\sqrt{N}}. \quad (3.14)$$

The first type of error we consider is average error. Average error is defined as the average of the errors obtained from various data sets with the same number of data. Equation (3.14) can be written in terms of average error.

$$EA_{am} = C_{AEA} \frac{C_V}{\sqrt{N}} \quad (3.15)$$

where EA_{am} and C_{AEA} are average errors in arithmetic mean and average error coefficient respectively. Equation (3.15) indicates that a straight line should be expected, when average error is plotted against square root of number of data. A straight line was observed in all experiments we conducted, and from the slope of this straight line an average error coefficient is calculated. The slope m is

$$m = C_{AEA} \times C_V. \quad (3.16)$$

Equation (3.16) can be solved for C_{AEA} .

$$C_{AEA} = m / C_V. \quad (3.17)$$

Maximum Error in Arithmetic Mean

For a maximum error, the largest error calculated among all data sets with the same number of data is picked. Equation (3.15) does not represent the error alone. When maximum error is plotted as a function of inverse of number of data, a straight line is obtained. Slope of this straight line is divided by coefficient of variation to get maximum error coefficient C_{MEA} . When Equation (3.15) is written for maximum error,

$$EM_{am} = C_V \frac{C_{MEA}}{N}. \quad (3.18)$$

This linear relationship corresponds to the data sets with relatively small number of data. When the number of data is large, maximum error and the average error should

converge to the same number, then the actual maximum error will be a combination of the linear and quadratic models.

$$EM_{am} = C_V \left(\frac{C_{AEA}}{\sqrt{N}} + \frac{C_{MEA}}{N} \right) \quad (3.19)$$

where EM_{am} is the maximum error in arithmetic mean, C_{AEA} and C_{MEA} are average error and maximum error coefficients respectively.

Average Error in Standard Deviation

The same principle is applied for error in standard deviation.

$$E_{sdv} = \frac{|\sigma_x - \sigma|}{\sigma} \quad (3.20)$$

where E_{sdv} is error in standard deviation, σ_x is sample standard deviation, and defined as

$$\sigma_x = \frac{1}{\sqrt{N}} \sqrt{\sum_{i=1}^N (X_i - \bar{X})^2} \quad (3.21)$$

and σ is population standard deviation.

$$\sigma = \frac{1}{\sqrt{N_P}} \sqrt{\sum_{i=1}^{N_P} (X_i - \mu)^2} \quad (3.22)$$

where N_P is the number of data that is large enough to represent the whole population.

Using Equations (3.21) and (3.22) in Equation (3.20), we get

$$E_{sdv} = \frac{\left| \frac{1}{\sqrt{N}} \left[\sum_{i=1}^N (X_i - \bar{X}) \right]^{1/2} - \frac{1}{\sqrt{N_P}} \left[\sum_{i=1}^{N_P} (X_i - \mu) \right]^{1/2} \right|}{\frac{1}{\sqrt{N_P}} \left[\sum_{i=1}^{N_P} (X_i - \mu) \right]^{1/2}} \quad (3.23)$$

Equation (3.23) can be written in slightly different form.

$$E_{sdv} = \frac{\left| \left[\sum_{i=1}^N (X_i - X_{am}) \right]^{1/2} - \sqrt{\frac{N}{N_P}} \left[\sum_{i=1}^{N_P} (X_i - \mu) \right]^{1/2} \right|}{\sqrt{\frac{N}{N_P}} \left[\sum_{i=1}^{N_P} (X_i - \mu) \right]^{1/2}} \quad (3.24)$$

$$E_{sdv} = \frac{1}{\sqrt{N}} \left| \sqrt{N_P} \frac{\left[\sum_{i=1}^N (X_i - \bar{X}) \right]^{1/2}}{\left[\sum_{i=1}^{N_P} (X_i - \mu) \right]^{1/2}} - \sqrt{N} \right| \quad (3.25)$$

By plotting error versus inverse of square root of number of data, slope m , which corresponds to all terms within the brackets, can be calculated. The slopes calculated from the eight data sets were very comparable to each other. Therefore, the terms included in the brackets can be replaced by a constant C .

$$E_{sdv} = \frac{C}{\sqrt{N}} \quad (3.26)$$

Equation (3.26) can be written in terms of average error by changing the notations

$$EA_{sdv} = \frac{C_{AES}}{\sqrt{N}} \quad (3.27)$$

where EA_{sdv} is the average error in standard deviation, and C_{AES} is average error coefficient.

Maximum Error in Standard Deviation

Maximum error in standard deviation can be represented with a combination of linear and quadratic relationships as it is in the arithmetic mean.

$$EM_{sdv} = \frac{C_{AEA}}{\sqrt{N}} + \frac{C_{MEA}}{N} \quad (3.28)$$

where EM_{sdv} is the maximum error in standard deviation, $CAES$ is the average error coefficient and C_{MES} is the maximum error coefficient. Procedures for calculation of the standard deviation error coefficients are the same with those in arithmetic mean.

Relation between the errors in the arithmetic mean and those in standard deviation can be derived by using Eqs. (3.15), (3.19), (3.27), and (3.28). Taking ratio of Eqs. (3.15) and (3.27), the relationship between average errors of arithmetic mean and standard deviation can be shown as

$$EA_{sdv} = EA_{am} / C_v. \quad (3.29)$$

The relationship in maximum errors is given by Eqs. (3.19) and (3.28).

$$EM_{sdv} = EM_{am} / C_v. \quad (3.30)$$

Any error, average or maximum, in standard deviation can be calculated by knowing error in arithmetic mean and coefficient variation. The relationship between any arithmetic mean and standard deviation errors is coefficient of variation.

Procedure

The objective is to investigate the necessary number of measurements for accurately estimating arithmetic means and standard deviations for permeability data sets. Several steps are involved. The first step is to calculate assumed true value of parameters, based on large number of measurements on representative scale length that gives satisfactory detail of heterogeneity. In our measurements, a one inch interval was assumed to be a good representative of the scale of heterogeneity. Hence, parameters based on one inch measurement interval assumed to be the true values. The second step is to reduce the number of measurements and calculate the parameters again. In practice, this is done by omitting some measurements for calculations. The last step is to calculate the errors based

on the difference from the true value calculated by the first step. The number of measurement is monotonically reduced down to two measurements. For a determined number of measurements, the starting point is changed and the parameters are recalculated. Two kinds of error are investigated, average error and maximum error. For an average error, the calculated errors from different data sets, but with the same number of data, are averaged. For a maximum error, the maximum of errors are picked among all possible data sets with the same number of data.

Field Application

The data used in this study is obtained with measurements on core slabs of Sun Ranch Field Wells A2, 2, and 7-22. Permeability is measured on one inch interval by using a MFP. The number of measurements on those core slabs are 857, 472, and 208, respectively. To investigate the effect of number of measurements within a geological unit, five sets of data belonging to three different units are used. Two units belong to Well A2, (Unit 16 and 15B) and have 278 and 187 data points respectively. Another two, from Well 2, (Unit 6A and 9B) have 83 and 67 number of measurements, and the last one, (Unit 25B) has 52 data points and belong to Well 7-22.

Results and Discussion

The effect of number of measurements on arithmetic mean and standard deviation of permeabilities are tested on eight data sets, which consist of combination of composite and single units. Error is investigated in two aspects; the average error which is the average of all errors with the same number of data and the maximum of all possible errors. The various possible errors are obtained by varying the starting point and maintaining the same number of measurements.

Figures 3.1a and b show the average error of arithmetic mean of permeabilities for

Well A2 and Well 2 respectively. The average errors as function of number of data for Unit 15B and 16 from Well A2, are shown in Figs 3.2a and b. The indication in those figures is that the average error is inversely proportional to the square root of number of data for all cases, irrespective of the measurement domain, (a single unit or a combination of several units). Behavior of the average error in standard deviation of permeabilities is the same as the one in the arithmetic mean. They are both inversely proportional to square root of the number of data, Figs. 3.3a and b and Figs.3.4a and b.

Unlike average error, possible maximum error for arithmetic mean and standard deviation is inversely proportional to the number of data, instead of square root of it. Figure 3.5a,b and 3.6a,b show the maximum error in arithmetic mean for Well A2 and Unit 16 of Well A2 as function of one with inverse of square root of number of data, and another one with the number of data only. Similar plots for the maximum errors in standard deviation for Well A2 and Unit 16 are shown in Figs.3.7a,b and 3.8a,b respectively.

Since there is a linear relationship between average error and inverse of square root of number of data and maximum error and inverse of number of data, the error coefficients (C_{AEA} , C_{AES} , C_{MEA} , and C_{MES}) for arithmetic mean and standard deviation can be calculated easily. After testing on eight sets of data, four constants C_{AEA} , C_{AES} , C_{MEA} , and C_{MES} for average and maximum errors of arithmetic mean and standard deviation were developed.

Figure 3.9a shows error coefficients (C_{AEA} , and C_{AES}) based on average errors in arithmetic mean and standard deviation as functions of number of experiments. The figure indicates that the variations in C_{AEA} , and C_{AES} are not very high (range 0.6-0.87), and average C_{AEA} , and C_{AES} are very close to each other 0.734, 0.747 respectively. Since there is not much difference, a general average error coefficient ,0.74, can be used to predict the average error that will be introduced in both arithmetic mean and standard deviation by

limited number of data.

Maximum error coefficients (C_{MEA} , and C_{MES}) for arithmetic mean and standard deviation are indicated in Fig.3.9b. Like in the case of average error, average of maximum error coefficients (C_{MEA} , and C_{MES}) for arithmetic mean and standard deviation are similar, 4.74 and 4.06 respectively. Again a general maximum error coefficient 4.4, can be used to predict possible maximum error in both arithmetic mean and standard deviation.

Figures 3.10a compares the calculated and model average errors in arithmetic mean for Well A2 data. For the same data set, maximum both calculated and model errors in arithmetic mean are shown in Fig. 3.10b. The figures show that there is a good agreement between estimated and model results in both average and maximum errors. The estimated and model, average and maximum errors for Unit 16 of Well A2 data, whose coefficient of variation is quite different from that of Well A2, compared in Fig. 3.11a and b. From those comparisons, it is seen that the model results are in good agreement with the calculated results.

As summary, two general error coefficients, average and maximum error coefficients, for arithmetic mean and standard deviation were generated. The average error coefficient is 0.74, and the possible maximum error coefficient is 4.4. Although the error in arithmetic mean is a strong function of number of data, it is function of coefficient of variation as well. It implies that heterogeneous regions need more data to get representative estimated parameter than relatively less heterogeneous regions. In standard deviation the error is a unique function of number of data. This result explicitly indicates that whatever the heterogeneity of the rock is, with the same number of data, the standard deviation error in the estimated parameters will be the same. The ratio of the errors (average and maximum), of arithmetic mean to the errors of standard deviation is coefficient of variation.

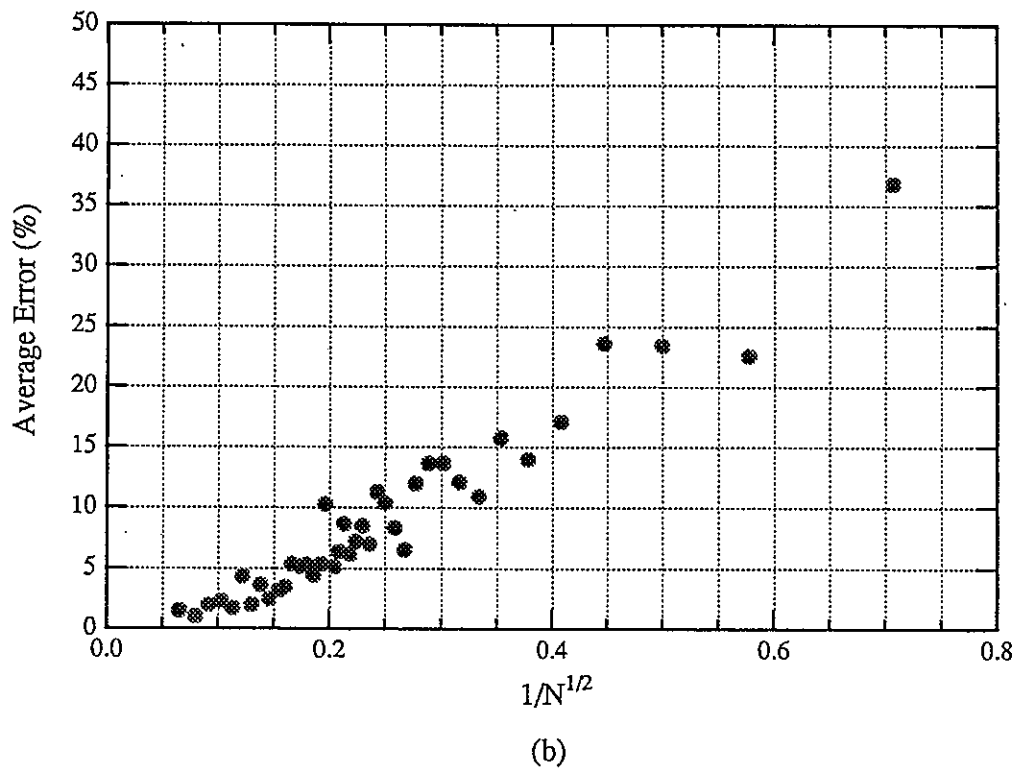
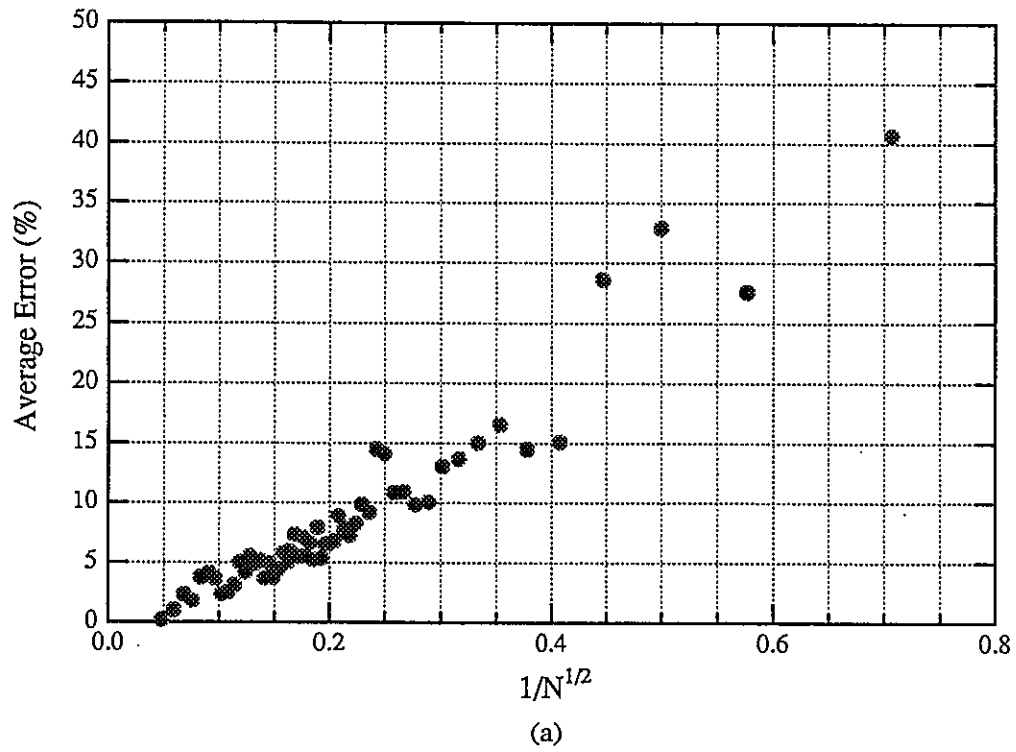
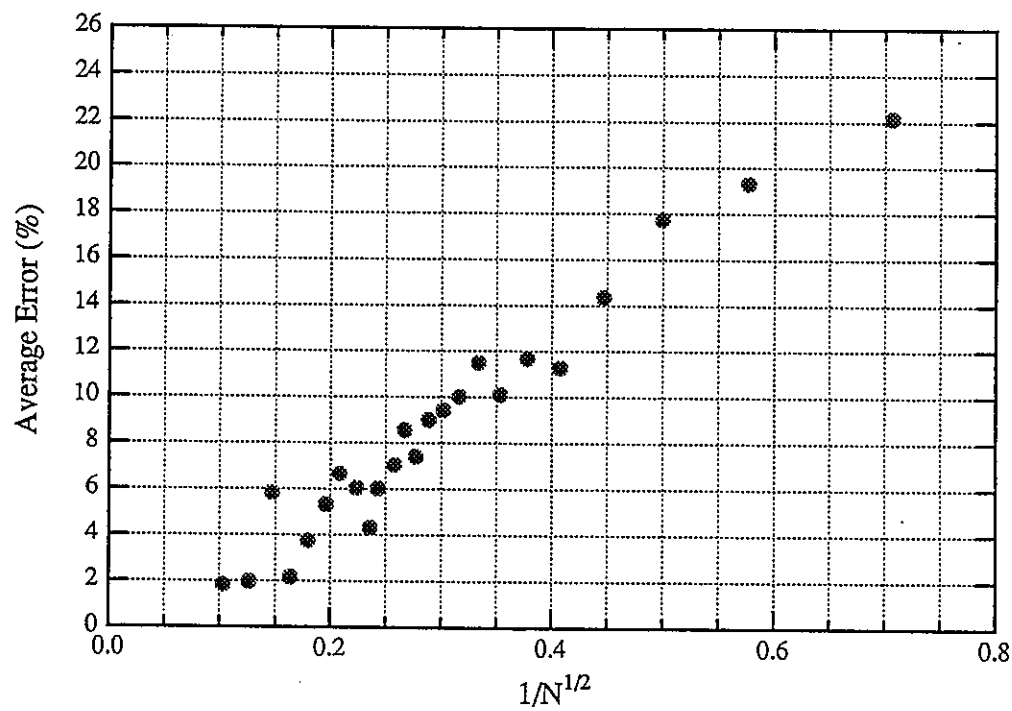
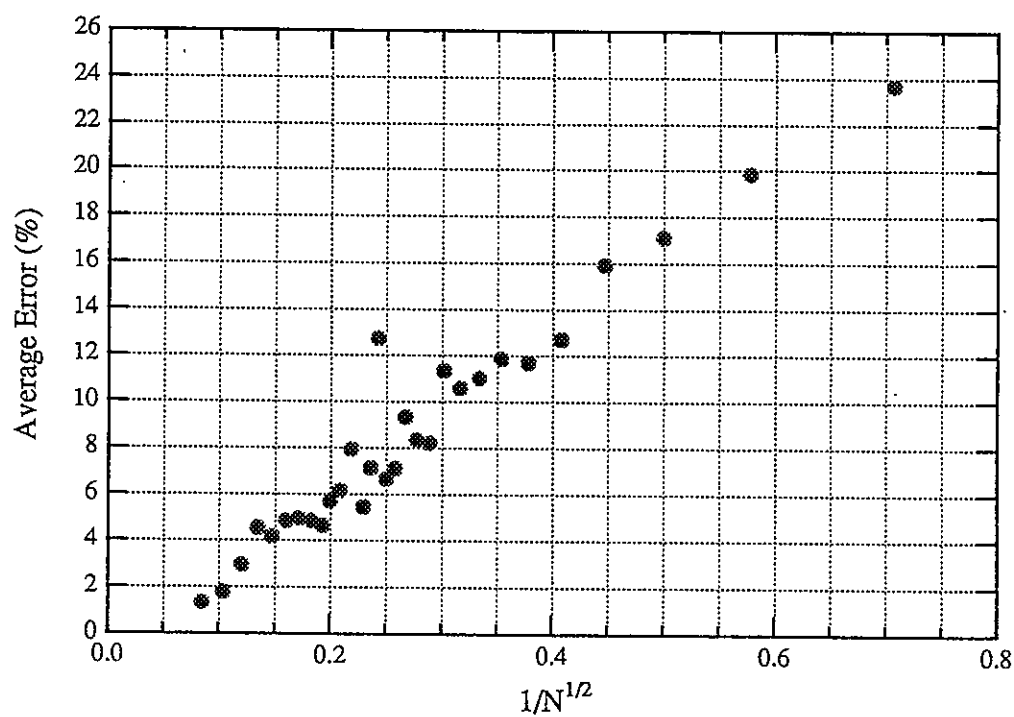


Figure 3.1a,b. Average error in arithmetic mean of permeabilities as a function of $1/N^{1/2}$, (a) Well A2, (b) Well 2.

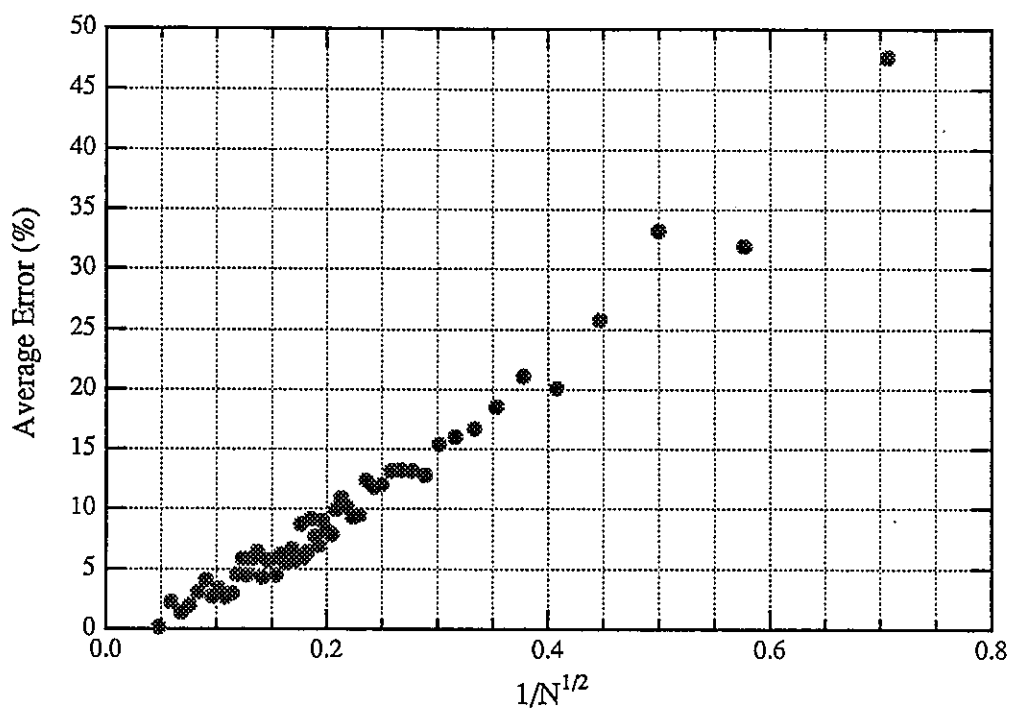


(a)

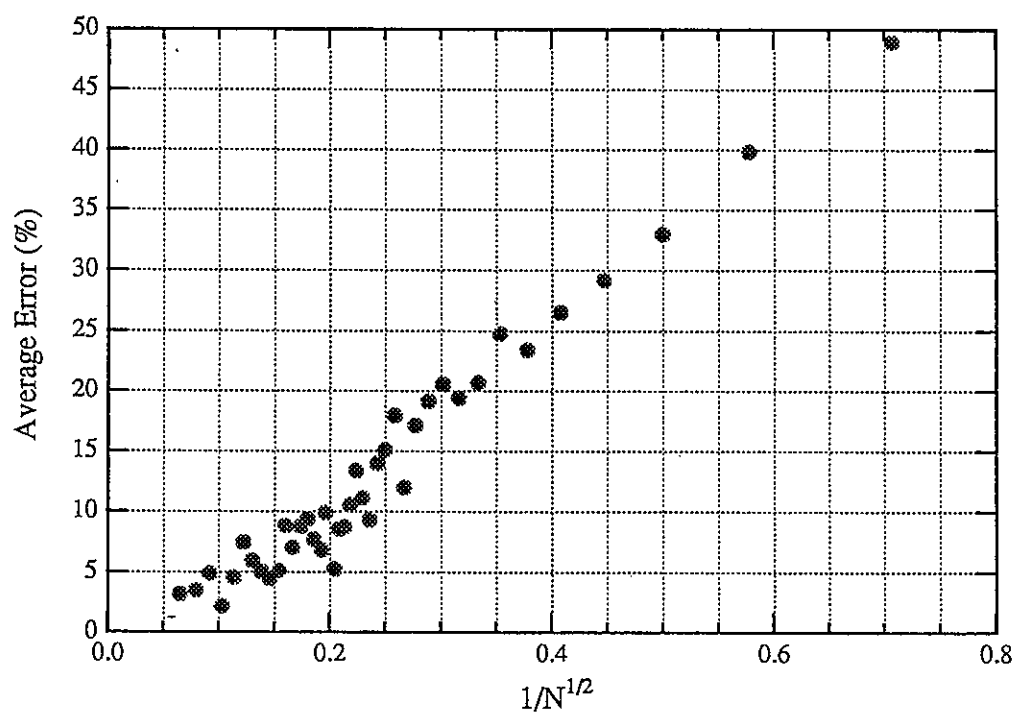


(b)

Figure 3.2a,b. Average error in arithmetic mean of permeabilities as a function of $1/N^{1/2}$ (a) Unit 15B (b) Unit 16, Well A2.

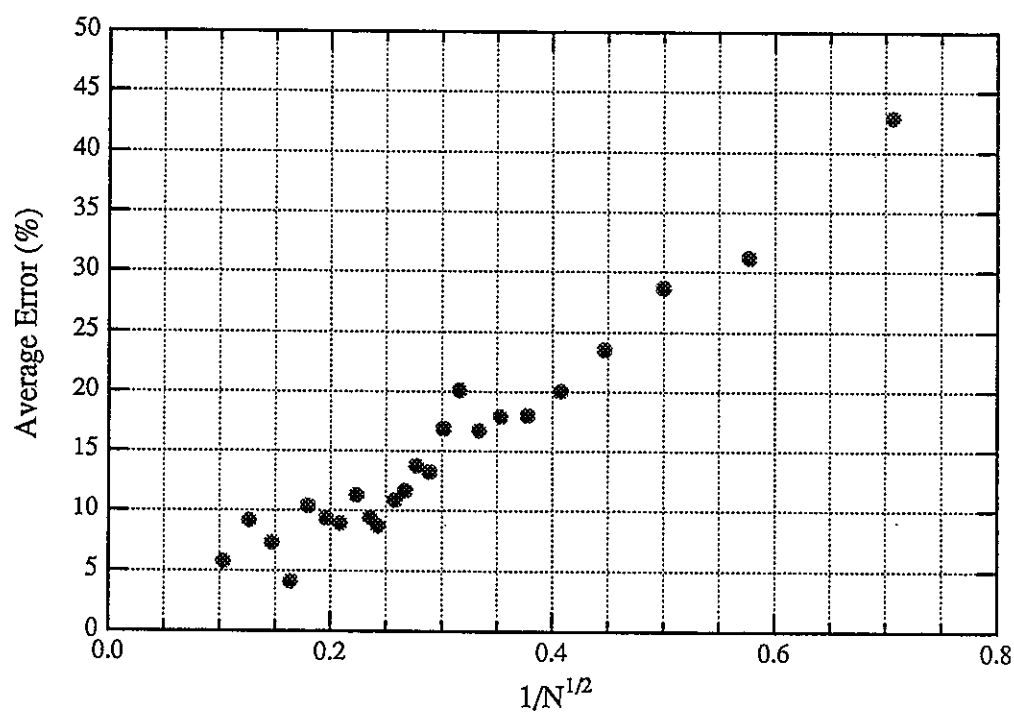


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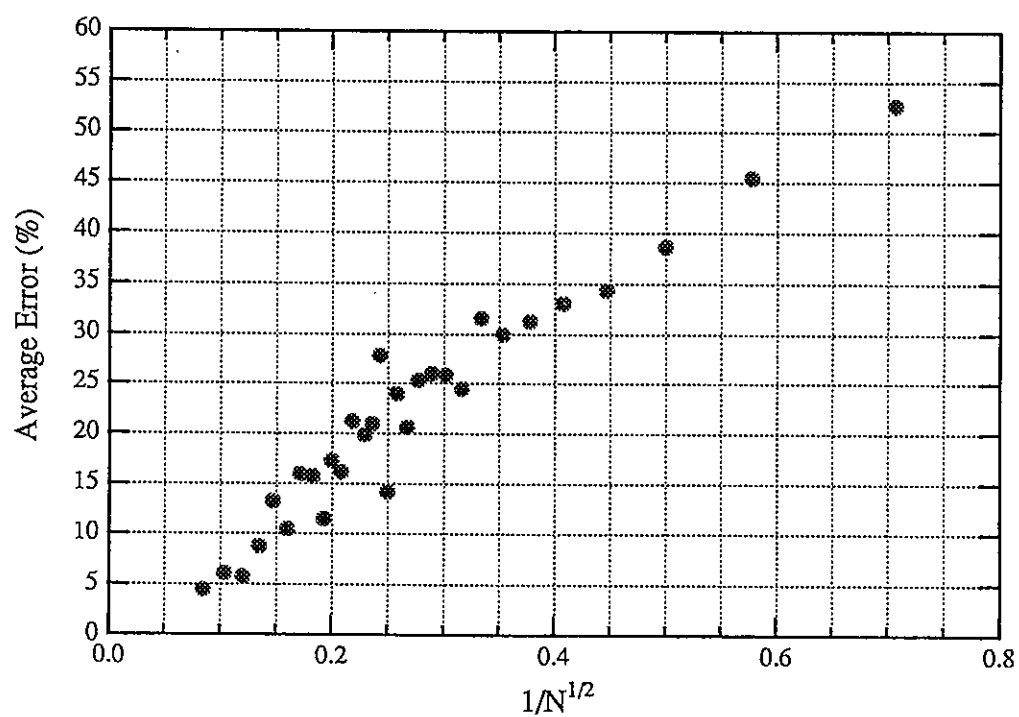


(b)

Figure 3.3a,b. Average error in standard deviation of permeabilities as a function of $1/N^{1/2}$, (a) Well A2, (b) Well 2.

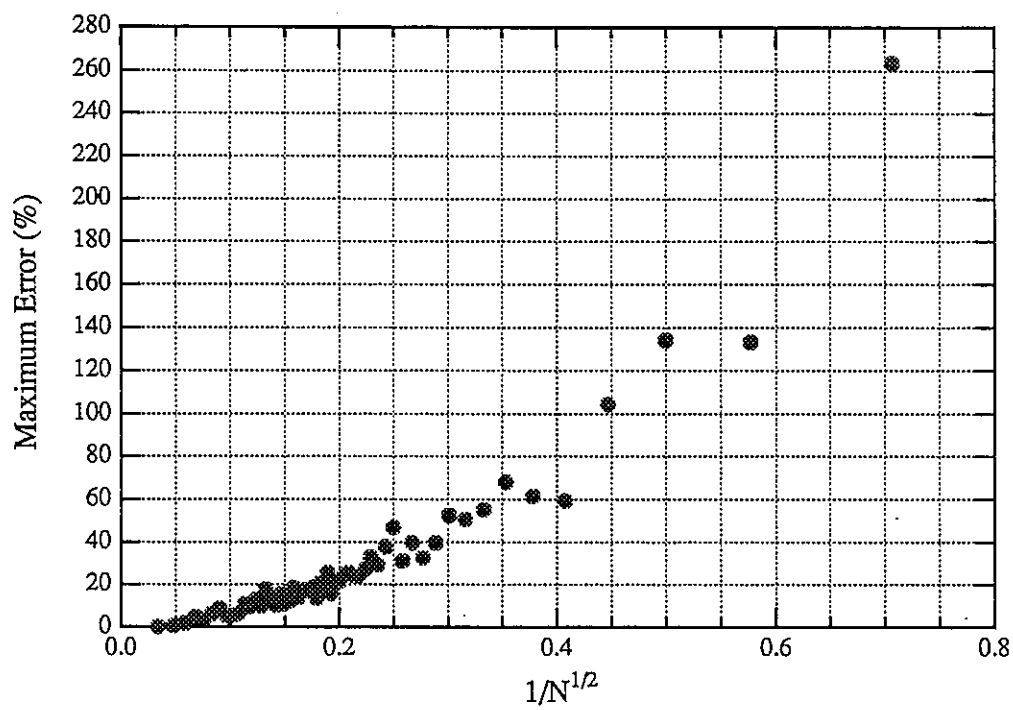


(a)

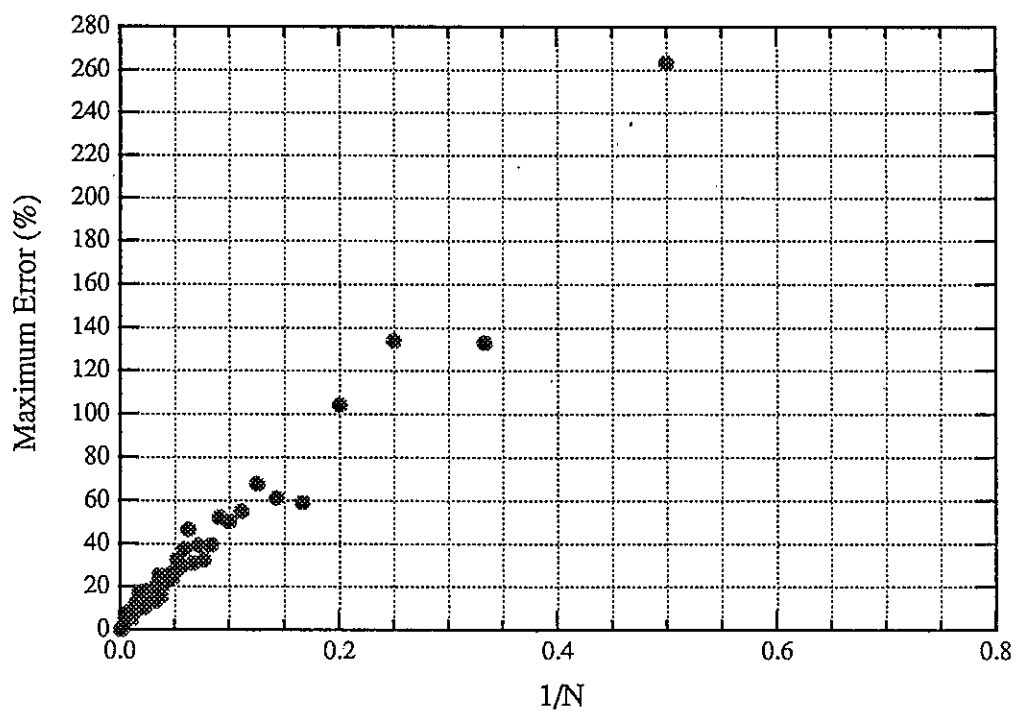


(b)

Figure 3.4a,b. Average error in standard deviation of permeabilities as a function of $1/N^{1/2}$, (a) Unit 15B, (b) Unit 16, Well A2.

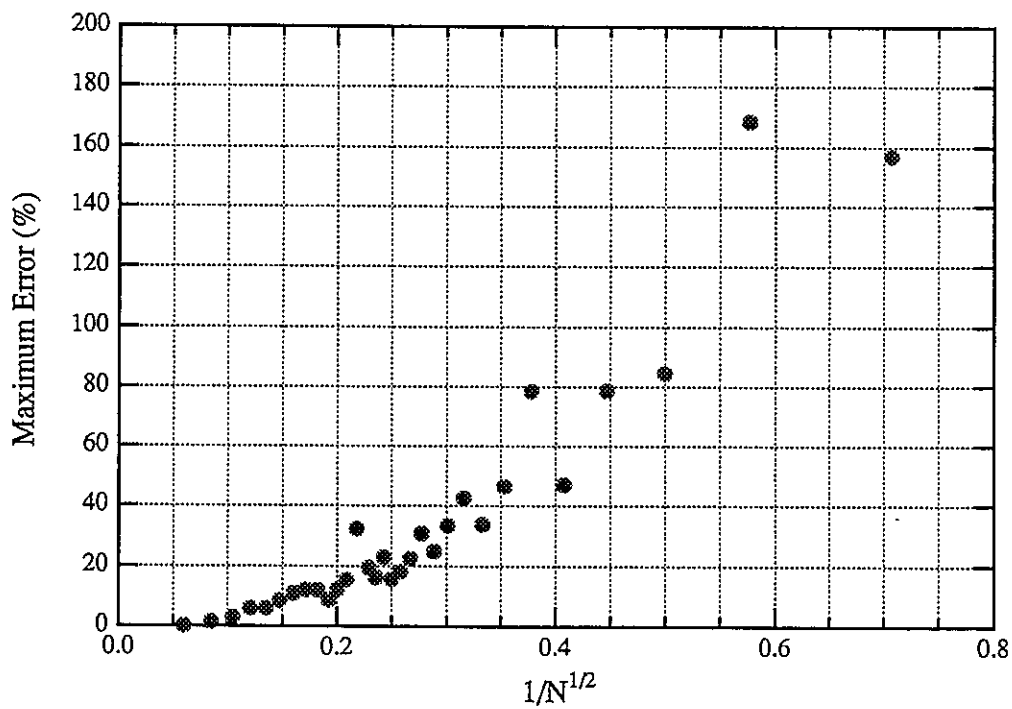


(a)

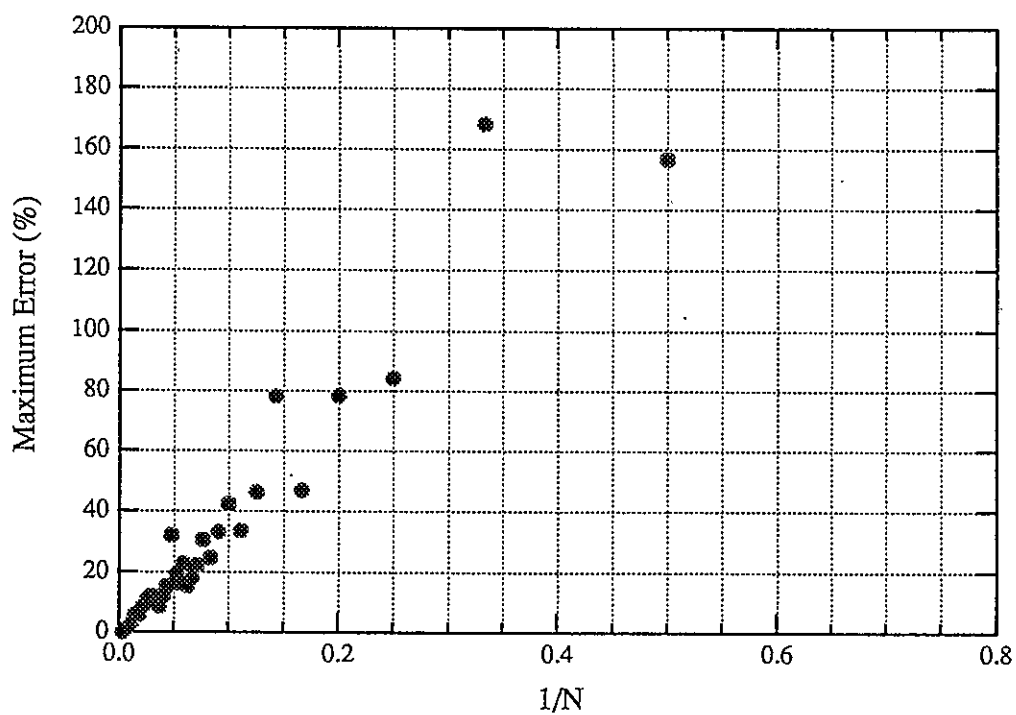


(b)

Figure 3.5a,b. Maximum error in arithmetic mean of permeabilities for Well A2, (a) $1/N^{1/2}$, (b) $1/N$.

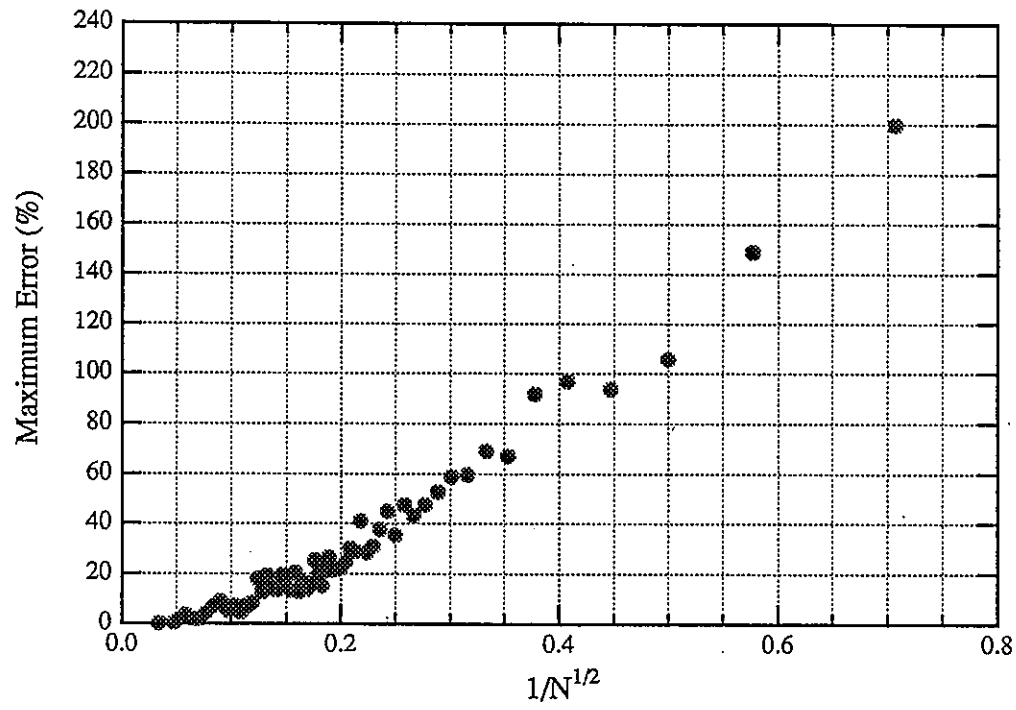


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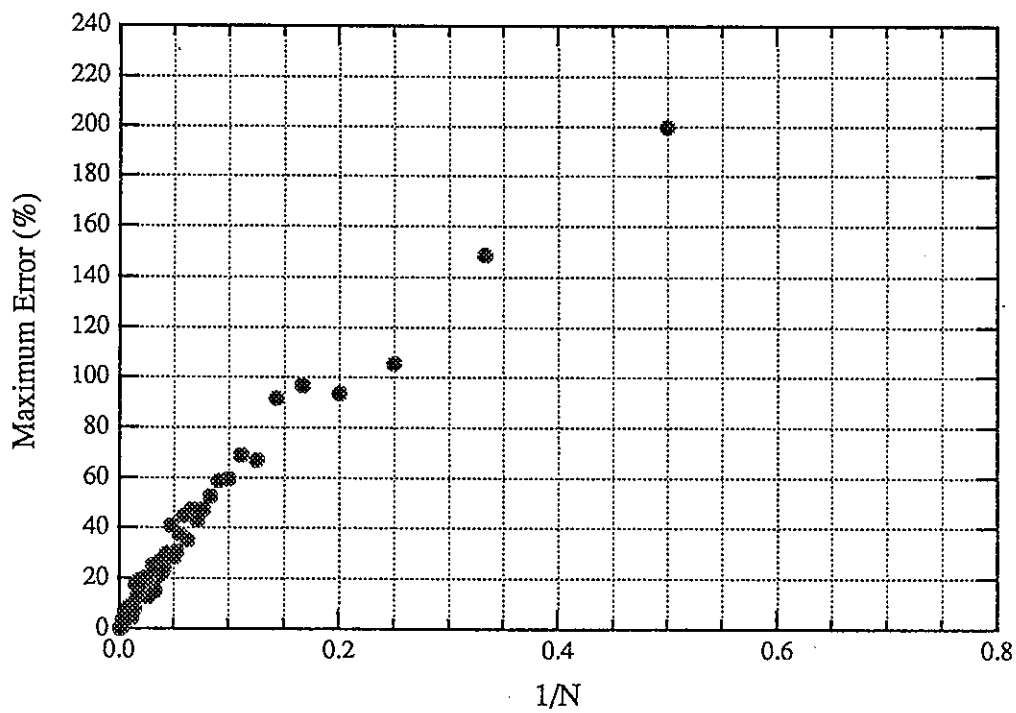


(b)

Figure 3.6a,b. Maximum error in arithmetic mean of permeabilities for Unit 16 of Well A2, (a) $1/N^{1/2}$, (b) $1/N$.

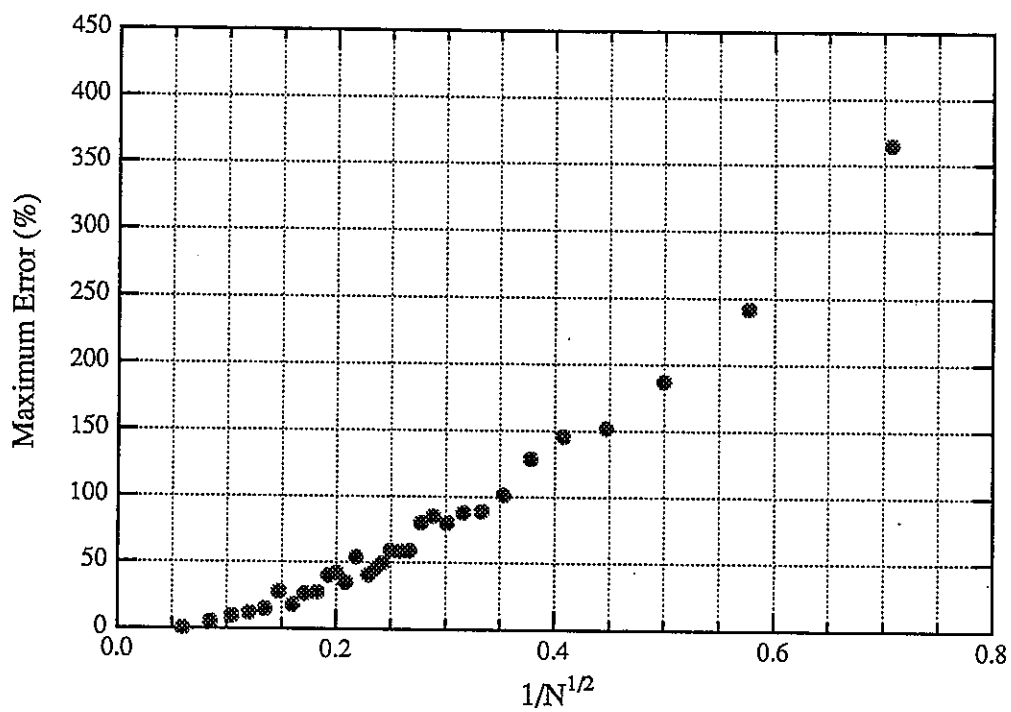


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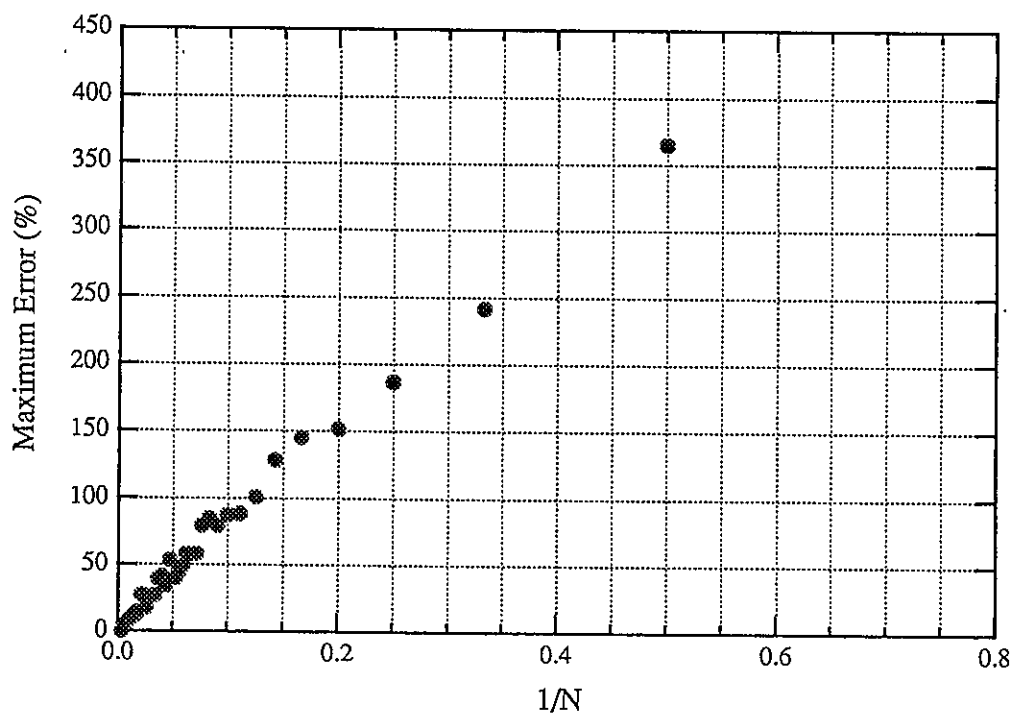


(b)

Figure 3.7a,b. Maximum error in standard deviation of permeabilities for Well A2, (a) $1/N^{1/2}$, (b) $1/N$.

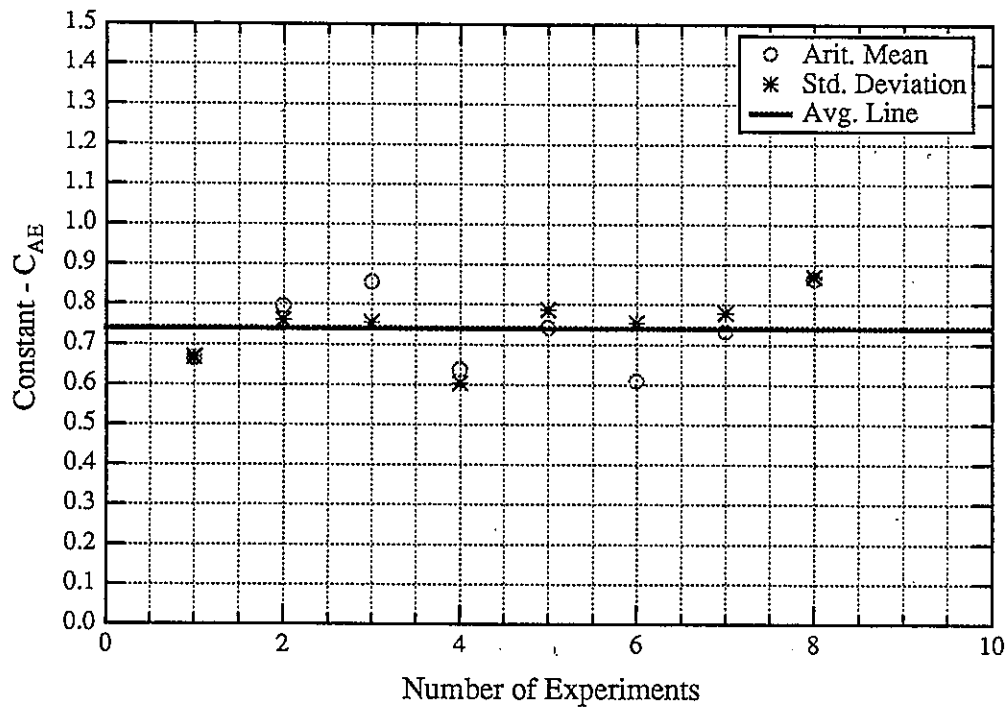


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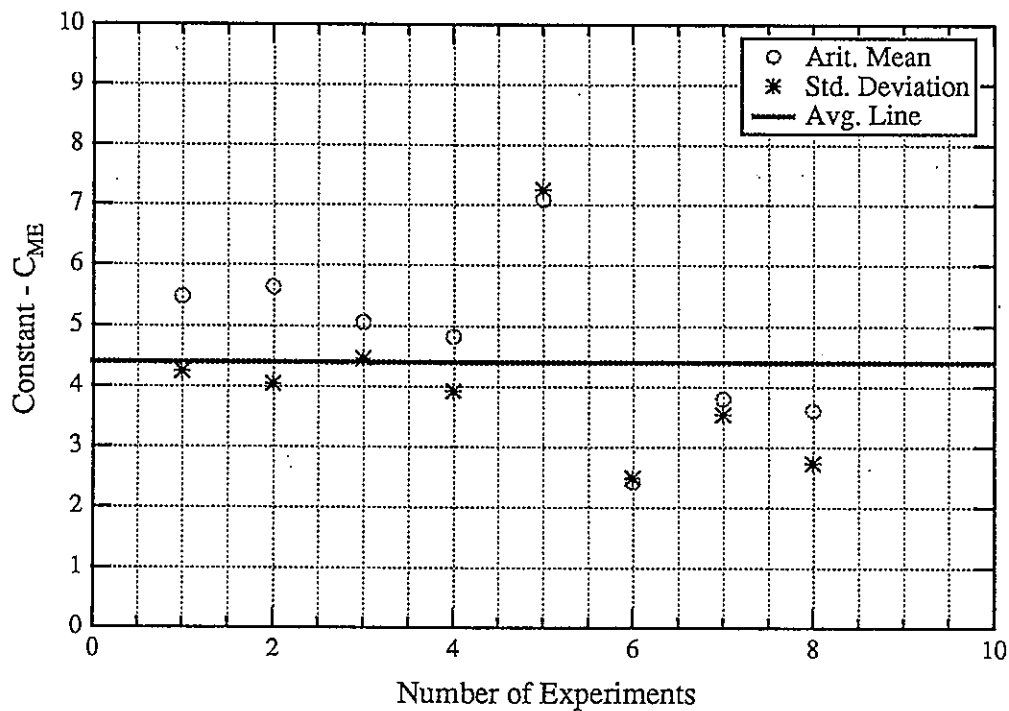


(b)

Figure 3.8a,b. Maximum error in standard deviation of permeabilities for Unit 16 of Well A2, (a) $1/N^{1/2}$, (b) $1/N$.



(a)



(b)

Figure 3.9a,b. Error constants for arithmetic mean and standard deviation of permeabilities as a function of number of experiments, (a) average error constant, (b) maximum error constant.

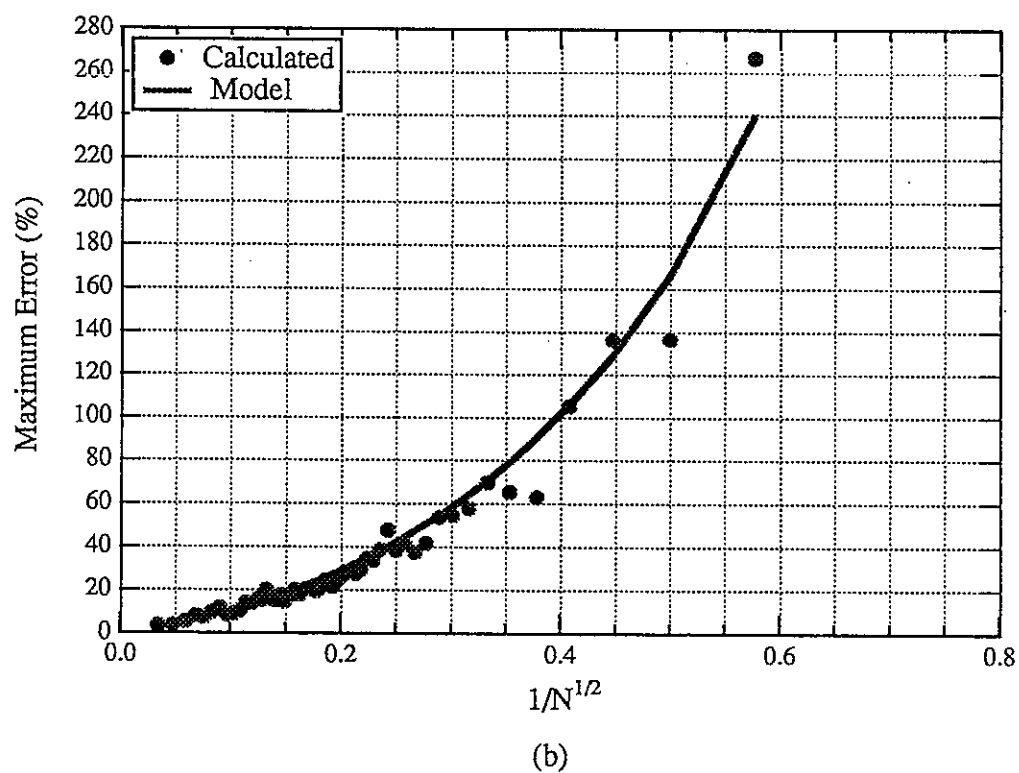
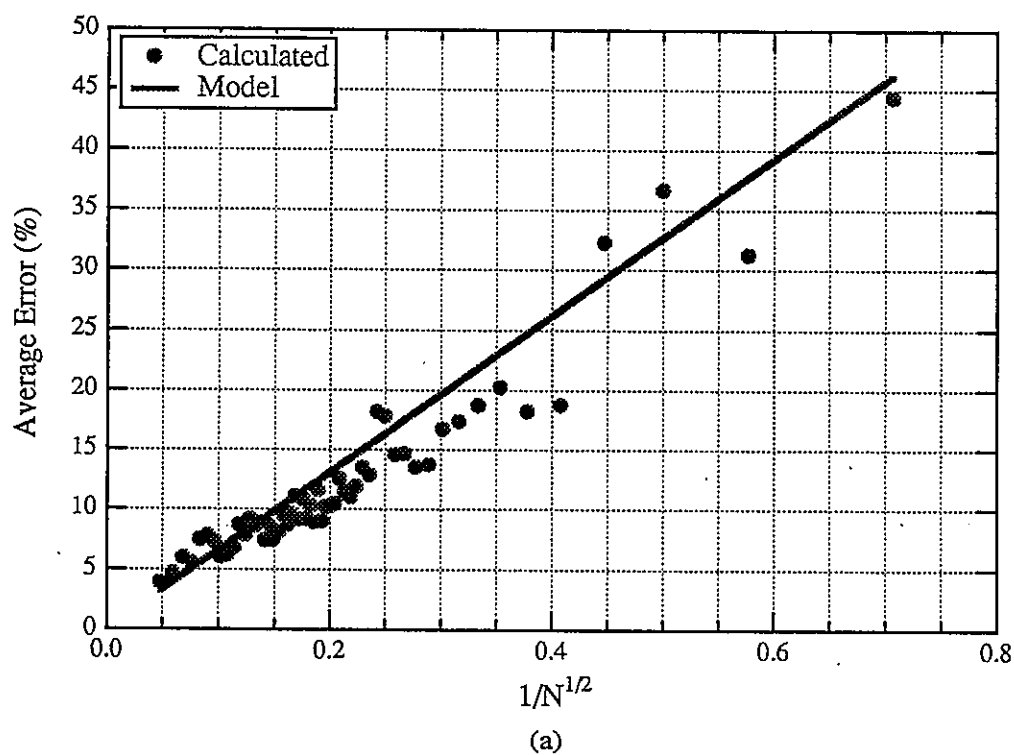


Figure 3.10a,b. Comparison of calculated and model errors,
(a) average error, (b) maximum error, Well A2.

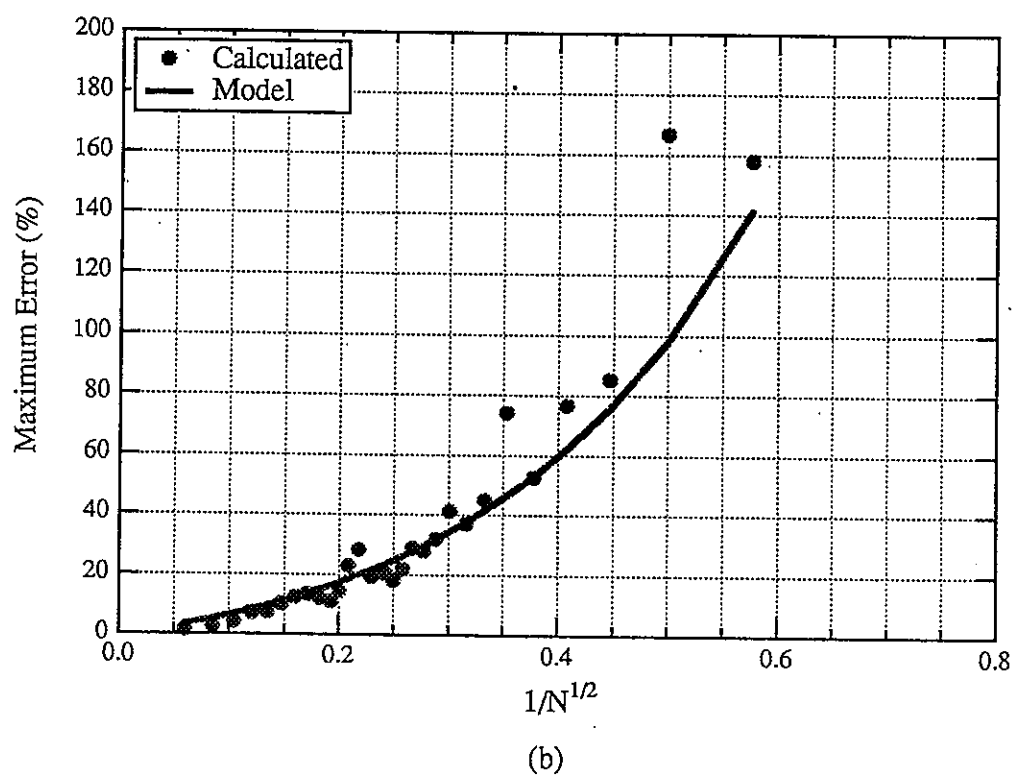
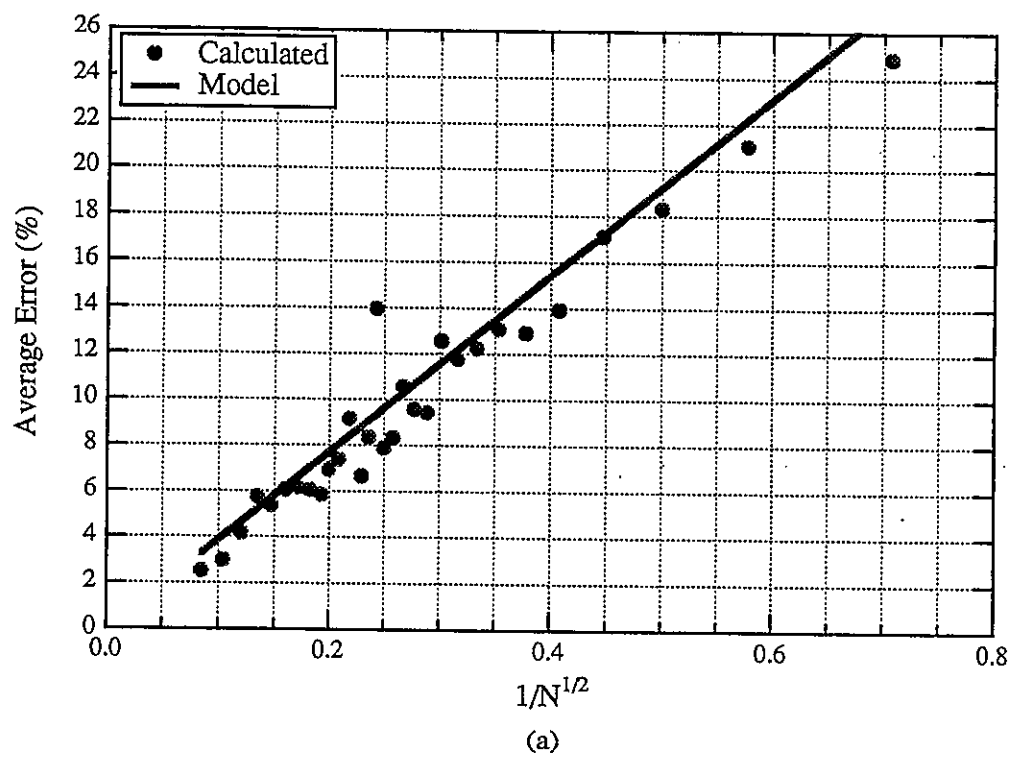


Figure 3.11a,b. Comparison of calculated and model errors, (a) average error, (b) maximum error, Unit 16 of Well A2.

CHAPTER IV

AUTOMATED FLOW UNIT GENERATION

Background

A flow unit is defined herein as a section of the reservoir rock body that has some distinct properties that are relatively homogeneous. A flow unit needed not necessarily have porosity and permeability. Shales, for example, have distinct rock and flow properties, will not allow any fluid to flow through, and constitute very distinct flow units.

Flow unit definitions are needed in numerical simulations for efficiency predictions and correlations in reservoir characterization studies. Typically, the definition of flow units utilizes, more or less, qualitative analysis and log shape of porosity logs, spontaneous potential log, gamma ray log, etc., and may not be very precise, because of its qualitative nature. In areas where no detailed geological study is available, geologic analysis may yield flow units but requires much time. Small independent companies may not choose to utilize a geological expert in field and regional descriptions. Furthermore, the techniques that are based solely on well-logging could be misleading. For example, well logs differentiate clean sand and shale formations, but they do not indicate the details of permeability variations in that particular region.

There is a need for semi-automated determination of flow units. In this study a flow unit generation method is generated based on formulas which yield a series of permeability derivatives. Detailed Mechanical Field Permeameter (MFP) measurements on core slabs can be used for that purpose. MFP measurements on core slabs are quick,

accurate, and clearly indicate pay zones (clean sand), shally zones and the permeability variations. Since the most representative flow units will be the ones that are defined on the basis of their flow properties, the objective should be to generate flow units based on variation in flow parameters between adjacent units. Since permeability is the most important flow parameter of a rock type, and directly related to flow, its derivative is used as the criterion here.

Procedure

The proposed automated flow unit generation method utilizes MFP measured permeabilities. For this purpose a FORTRAN code, which is given in Appendix A, was developed. The input parameters, in addition to the measured permeability values, are the number of units required by the user, and the bounding tolerances (two numbers between 0 and infinity). These bounding tolerances should be chosen such that the lower bound should result a number of units that is larger than the requested one, and similarly the upper bound tolerance should give a number of units that is smaller. Clearly with zero tolerance, every permeability value measured will be identified as a unit provided that it is different from its neighbors. On the other hand, with a large enough tolerance, one single unit may be generated for all measured.

After reading the bounding tolerances, the program iterates to identify the most proper unit boundaries for a given number of units. The iteration takes place as follows: two numbers of units with two bounding tolerances are compared with the requested number of units, and the bounding tolerance that results a closer number to the requested number is kept. The other bounding tolerance is replaced with an average of two prior bounding error tolerances, and the procedure repeated until the generated number of units matches with the requested one. This procedure is analogous to Bi-Section iterative root finding technique.

The inner loop of the iteration involves the generation of unit boundaries for a given tolerance. The determination of a unit boundary involves two screening steps. The first step is passed, only if the permeability deviation criterion at that point is larger than the current tolerance. The permeability deviation criterion is a dimensionless number, which is the ratio between the difference of average permeabilities of old unit and prospective new unit and the average of those two.

$$C_{Dx} = \frac{\bar{X}_{old} - \bar{X}_{new}}{0.5(\bar{X}_{old} + \bar{X}_{new})} \quad (4.1)$$

where $\bar{X}$ are arithmetic mean of permeabilities. The first step is an easy screening of the permeability change at a point, where the average permeability of the new unit is obtained with only one permeability. If C_{Dx} is greater than the current error tolerance, then the second screening step is applied, if not, it is decided that the measured x_i is within the working unit, and the next measured permeability value is checked for a unit boundary.

The second step is a test for the persistency of identified permeability change within the first step. For this purpose a toughness constant is defined, and multiplied by C_{Dx} . The purpose of the toughness constant is to make it harder to define a new unit if the permeability change is not persistent for a certain number of measurements (to make it harder to define small size units). In our studies, for example, we used 6 measurements that are required to justify a new unit definition. If any permeability change is not persistent for 6 measurements (in an average sense), there is still possibility of identifying a new unit boundary but the requirement is toughened (meaning permeability change has to be a lot sharper). For this purpose, C_{Dx} is multiplied by the toughness constant (a number that is less than 1), which is defined as

$$C_i = \exp\left(-\frac{n_L - n_i}{n_L - 1}\right) \quad i = 1, \dots, L \quad (4.2)$$

where n_i and n_L are the numbers of measurements within the new unit.

$$C_{D2} = C_{Dx} \times C_i. \quad (4.3)$$

C_i will reduce the effect of permeability change if the change is not continuous far beyond the point of change. But, the reduction itself diminishes (C_i converges to 1) if the average permeability beyond the new boundary is persistent within the new unit as many as pre-determined measurements. To pass the second test C_{D2} has to be greater than the current working tolerance. If the second test is not passed until n_i becomes n_L , (C_{Dx} , which is calculated by using n_L permeability measurements, is not greater than the current working tolerance), then the new unit boundary is not defined and the next measured point is taken for the screening (note that if n_i becomes n_L , then C_{D2} becomes C_{Dx}). The process is repeated for all measured points. Figure 4.1 shows three steps of flow unit generation procedure based on permeability derivatives obtained from MFP measurements on core slabs of Sun Ranch Field Federal Well A2.

Comparison with Geological Descriptions

We compared computer generated flow units with geologically generated facies to verify that the computer selected flow units are geologically reasonable. This comparison assumes that the variation in rock properties (permeability here) is strongly correlated with sedimentary structures and other depositional features. In other words, within a facies, rock properties should not change drastically since facies are generally relatively internally consistent, except for the distribution of very fine shale platelets and fractures.

Data was obtained from core slabs from three wells in Sun Ranch field; Sun Ranch Federal 2, A2, and 7-22 were used for flow unit generation and comparison. A MFP was used to measure permeabilities on core slabs from the three wells. The measurements were carried out on one inch intervals. This spacing was assumed to be a

fine enough grid for the scale of heterogeneity of interest. Measurements at every inch were not always possible, because some parts of the core slabs were missing (core plugs had been taken) and some portions of the slabs were fragmented shale platelets. A total of 1536 measurements were obtained from the core slabs from the three wells. The distribution was 856, 472 and 208 from wells A2, 2, and 7-22 respectively.

Detailed geological study and geological unit descriptions on those core slabs were done by Tillman et al.⁴³ as well. APPENDIX B shows geological description of Well A2, 2 and 7-22 respectively. The wells were divided into units according to their depositional environment. The geological study is done on the same core slabs with a detail of one tenth of a foot. For example APPENDIX B shows some units two or three tenths of a foot thick.

Figure 4.2 compares sedimentologically defined unit boundaries with computer defined ones for Well A2. The figure is a plot of depths versus mean permeabilities. Although Well A2 has 28 sedimentologically defined units, measurement could not be carried out on some parts of the core slabs because, as indicated above, those parts were either missing or were fragmented shale platelets. These units on which no permeability measurements were made include six sedimentologically defined units. In order to compare flow unit boundaries, 22 units, which is equal to the number of geological flow units in consideration, were generated with the computer method. As it is shown in Fig. 4.2, the major unit boundaries are very similarly defined by both methods. Some non-matched unit boundaries are expected because the computer method is much more sensitive to abrupt changes in permeability values.

The general trend and major unit boundaries are very similar in sedimentologic and computer flow units, although there are some differences in the location of flow unit boundaries. Those differences can be attributed to following: 1. Not every

sedimentologically defined unit is homogeneous. 2. Not all sedimentologically defined neighboring units have different properties. There may be some very large permeability fluctuations within a sedimentologic unit, if there exists a low permeability region such as a shale adjacent to a high permeability sandstone. These features may be in the same sedimentologic unit and yield significantly different flow characteristics. Some adjoining sedimentologically defined units may have very similar rock properties, which will result in low variation in permeability and might be combined into one single unit.

Most of the discrepancies between the unit boundaries generated by the computer method and those defined by geology are where there are thin streaks with extreme permeability. Identifying shale parts was important even if they are very thin, because they may form flow barriers. High permeability streaks may form preferential flow channels, which play an important role in the efficiency of an improved oil recovery process. In Fig. 4.2 we see that the computer method can identify these streaks properly. For example, only one sedimentologic unit is defined between 10054.0 and 10078.6 ft with a mean of 20.94 md, but the computer program generates five units for the same interval. The program generates one unit between 10054.00 and 10058.46 ft interval with a mean of 17.30 md, another one between 10058.46 and 10058.96 ft intervals with a mean of 26.42 md. Two more units are generated in the vicinity of 10058.96 ft, where they are one inch thick and have a high shale content with permeabilities of 1.73 and 5.50 md respectively. Following these two thin units, the program generates another unit between 10058.1 and 10059.1 feet with a mean of 20.501 md. However, when sedimentologic subunits are considered (see APPENDIX B), the variability generated with this sedimentologic unit is more similar, although the subunit boundaries vary some from the computer derived boundaries.

When the number of units is considered too high or the unit thicknesses are too

thin, several generated units with similar properties can be combined with computer method. The rearrangement of those units may be carried out according to the details needed. For example, those five units can be combined into two or three units, with shale barriers between them without losing flow characteristics of the zone. If the formation is considerably homogenous, and the transition between neighboring units are not gradual, boundaries of the sedimentologic and the generated flow units are identical. This can be seen in Fig. 4.2 at 10103.79 and 10078.13 ft interval, both methods give exactly same boundaries. The computer generation method has an option to automatically combine the several units with similar mean permeabilities into one unit. For example, between 10117.3 and 10128.1 feet there exists three sedimentologically defined units, including one two-inch thick shaly unit separating two thicker sandstone units, the computer method combines all of them into one unit, because the mean permeabilities of the thicker units are so similar.

Figures 4.3a-c compare mean permeability of sedimentologic flow units with those of various numbers of computer generated flow units. Figure 4.3a is the comparison of computer generated units with the sedimentologically defined units when the number of computer generated units is limited to 15. The figure indicates that when the number of computer generated flow units is somewhat less than the number of sedimentologically generated flow units, the computer method will miss some of the thin low and high permeability intervals where the permeability deviation is not very large. Where fewer generated units are specified, we can identify only units where the mean permeability is very different from the neighboring ones. Figure 4.3c similarly compares 40 computer generated flow units with the 22 sedimentologic units. The larger the number of flow units, the more the generation system becomes sensitive to smaller permeability fluctuations. However, having a very large number of units may be meaningless in terms of numerical simulation applications. In general, the best agreement

is obtained when the number of computer generated flow units is equal to or very close to the number of sedimentologic flow units.

Figures 4.4a-c indicates comparison of sedimentologic and computer generated flow units for the Sun Ranch field wells, 2, A2, and 7-22. The number of computer generated flow units and the number of sedimentologic units were intentionally similar for all three. The sedimentologic units and the computer generated units have similar boundaries and thicknesses for all three cores.

The computer based flow unit generation method may be useful in identifying similar formations in the two-well pairs. The computer generation method identifies the boundaries, mean permeabilities and the thicknesses of the units it generates. Where all of these parameters are similar, similarity of sedimentologic units may be inferred. Because the distance between any pair of wells in the Sun Ranch field is too great, unit by unit correlation was not possible among all three wells analyzed.

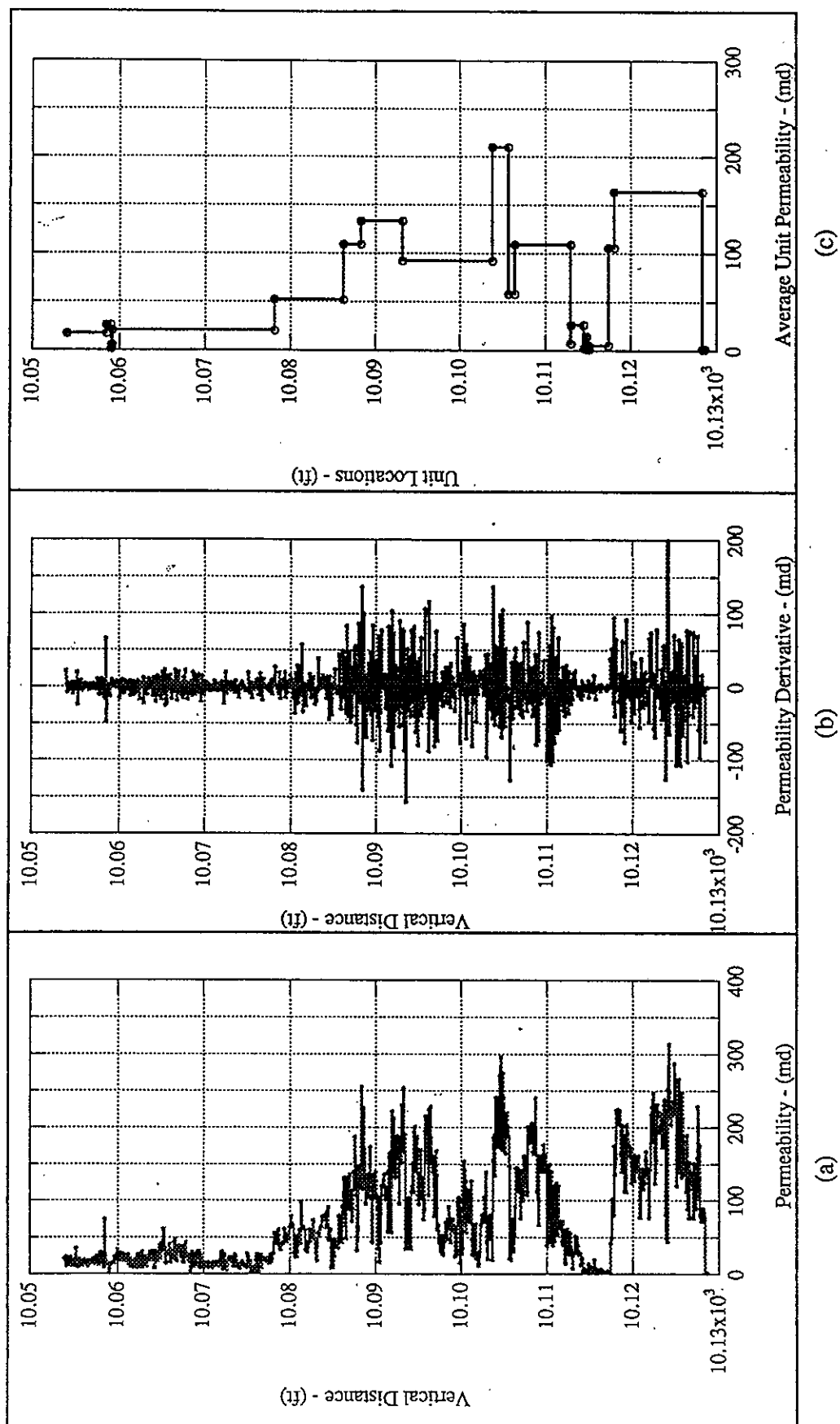


Figure 4.1a-c. Three steps in the computer flow unit generation procedure; (a) measured permeabilities (b) permeability derivative, (c) flow units of Well A2 and their average permeabilities.

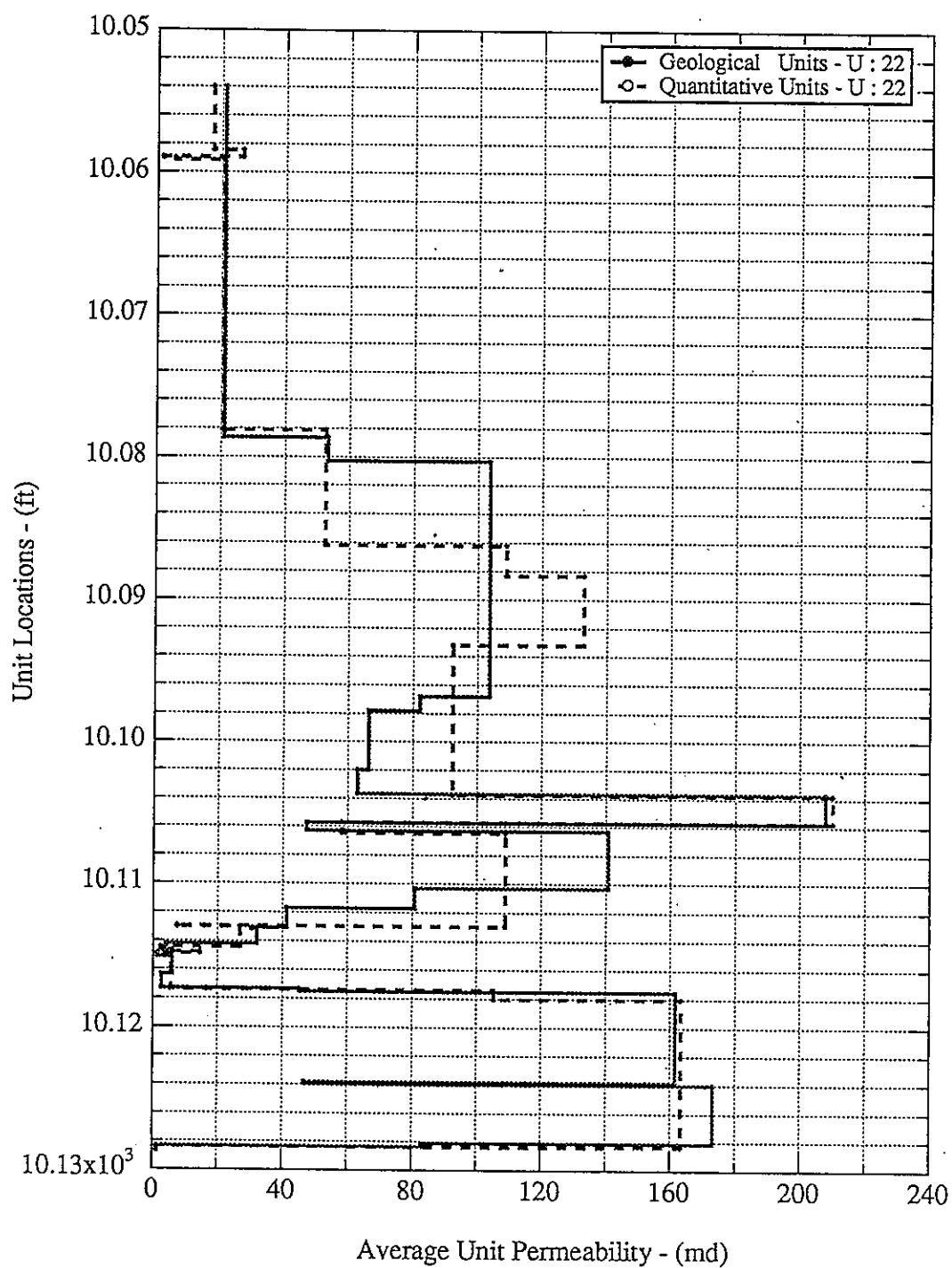


Figure 4.2. Comparison of geologically and computer generated flow units from permeability derivative, Well A2.

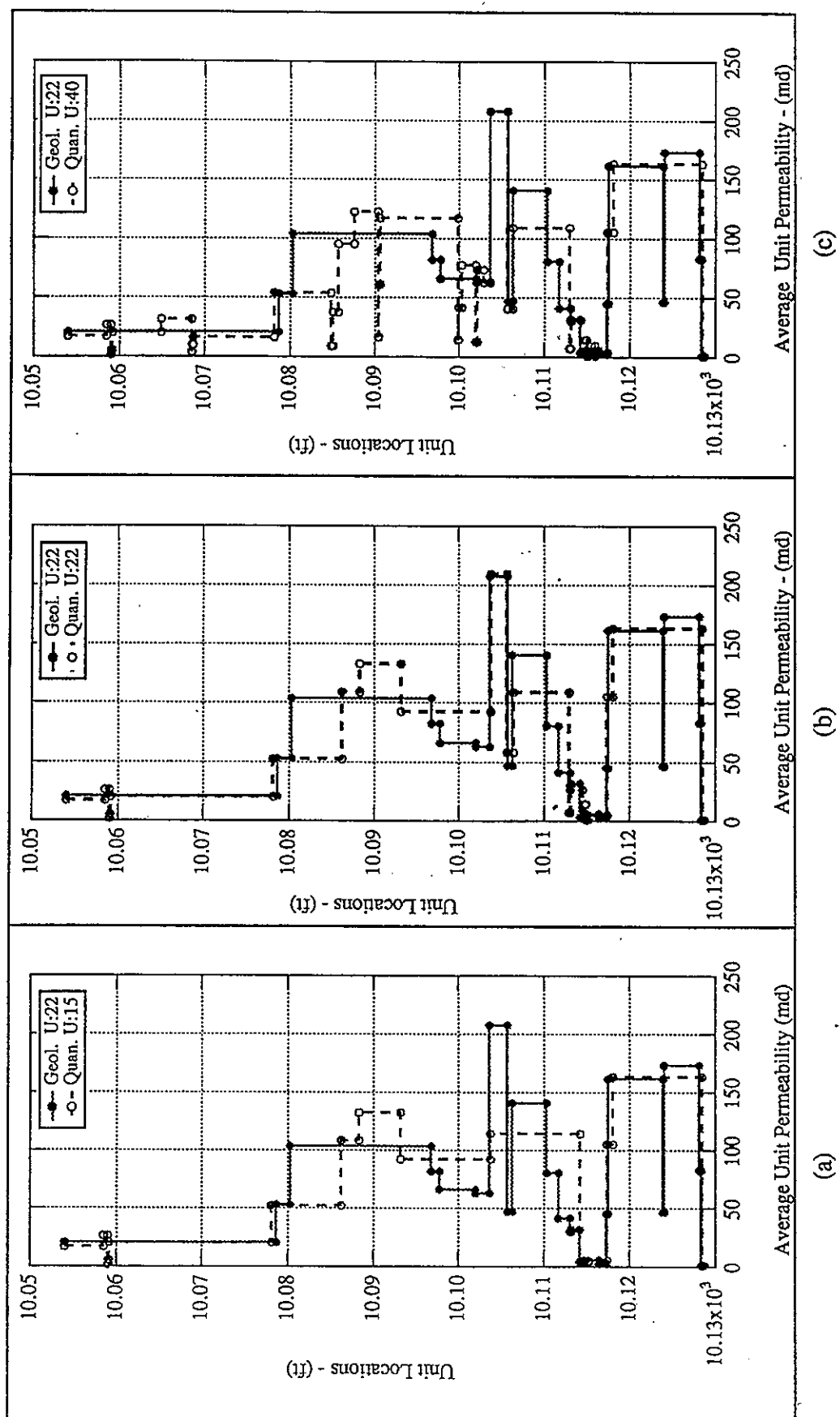


Figure 4.3a-c. Comparison of computer defined various number of flow units of Well A2 with 22 geologically defined units; computer defined; a) 15 units, b) 22 units, c) 40 units.

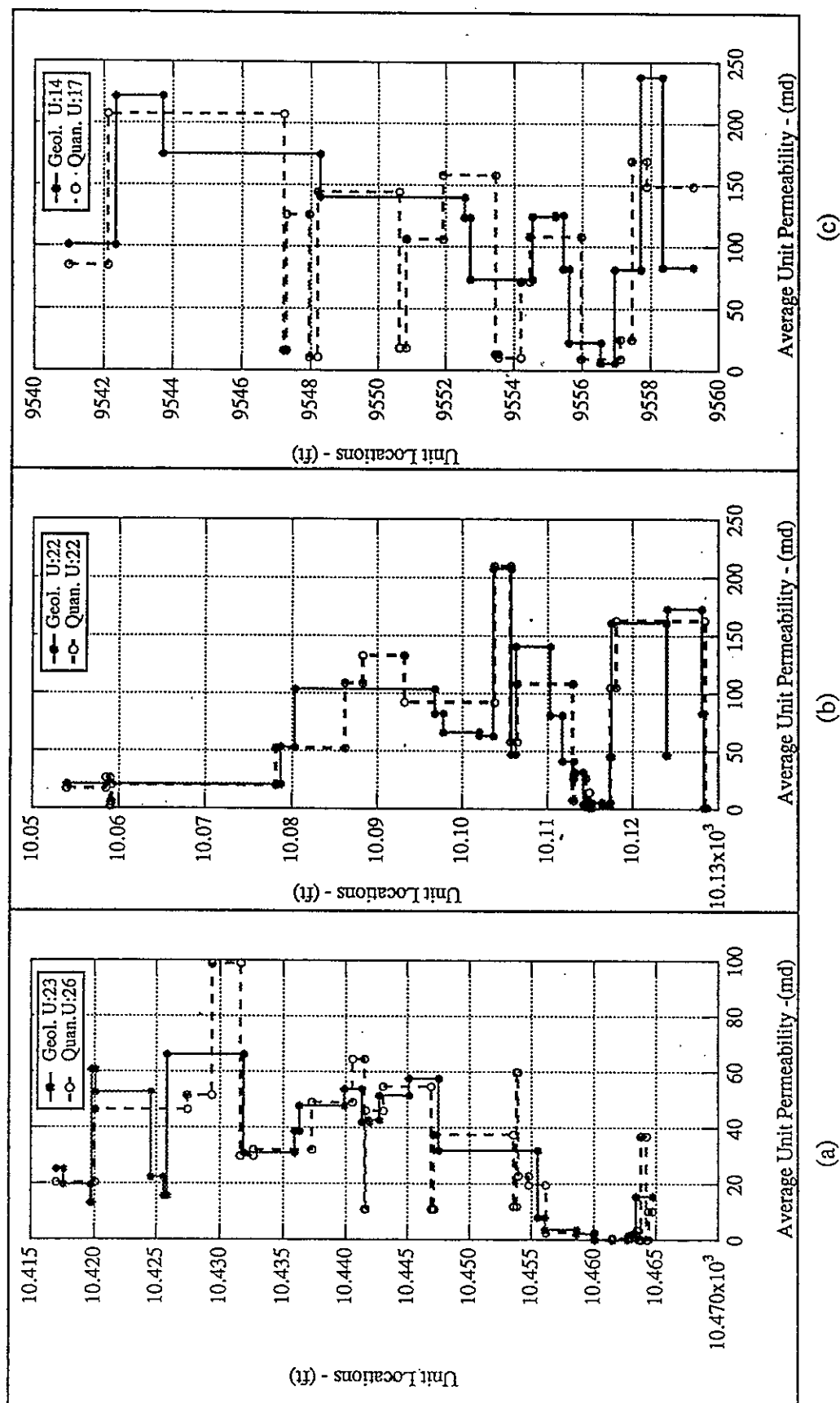


Figure 4.4a-c. Comparison of geologically and computer defined flow units for three wells; (a). Well 2, (b) Well A2, (c). Well 7-22.

CHAPTER V

GEOSTATISTICAL PARAMETERS OF VALLEY-FILL DEPOSITS

Location of Study Area

The study sites (outcrops and subsurface) are shown with a map in Fig. 5.1. The outcrops and subsurface are located 150 miles apart from each other. The outcrops are situated in Newcastle, Weston Co., while the producing field is in Natrona Co., both in Wyoming. Figure 5.2 shows outcrop study area, which includes three Muddy sandstone outcrops. Figure 5.3 indicates Sun Ranch Field Federal Wells A2, 2, and 7-22.

Permeability Measurements

All outcrop and subsurface data were measured with a MFP. Theory of MFP measurements and associated problems and the ways to circumvent those problems are included in the previous chapters. Permeability is measured on all three Muddy sandstone outcrops, as well as core slabs from three wells, Well A2, 2 and 7-22 in Sun Ranch Field.

Outcrop Measurements

Three Muddy sandstone outcrops are identified as Outcrop 1, 2, and 3. Although the major study area is Outcrop 1, it was not accessible for a several days after a rain. Outcrop 2 and 3 are more accessible since they are road cuts and located around the town Newcastle. All outcrops are Muddy sandstone formations in the same basin and

depositional system. Detailed geological description of these three outcrops were done by Tillman et al.⁴⁴, APPENDIX C.

Outcrop 1 is divided into three sections (Section A, B, and C). Because of the accessibility problems mentioned above the detailed measurements were focused on Section C only. On an average, 20 data were taken on the major units of Sections A and B. This number would not be enough to infer any geostatistical characterization, but to calculate mean permeabilities to be used in numerical simulations of a water flooding process.

The detailed measurements were carried on Section C, which consists of 14 main and subunits based on facies descriptions. The total of 632 permeability values are measured on those units with the exception of Units 3, 10, 12, where measurements were not possible because of their shale like nature, which results in very low permeability. In general, permeability was measured with one-foot grid spacing. The exceptions were special areal grid and two fine grids. The data were collected from every unit that had a reasonable exposure and permeability. In all cases, a special care is taken to stay within a flow unit.

Three special measurements were carried out with three detailed grids on Unit 11, which was chosen because of its largest length and thickness among all units of Section C. The first detailed grid, which is located between points A(125.00 ; 35.00) and B(126.00 ; 36.00), is an areal grid on 1 square foot area, where the measurements were on inch. The area was divided into 12x12 one inch interval adding up to 169 sampling points. The second special grid was verging on the areal grid and designed to investigate small scale permeability variation in the vertical direction of Unit 11. It was consisted of 33 measurements with 3 inch interval, between points C(132.50 ; 33.00) and D(132.50 ; 41.00). The third special grid was designed for the similar purpose in the horizontal

direction. It extends from point E(122.25 ; 34.50) to point F(131.00 ; 34.50) and consists of 36 measurements with 3 inch interval. The measured locations on Outcrop 1 are shown in Fig. 5.4.

Two sets of data, vertical with 300 data points and horizontal with 222, obtained from Outcrop 2. Four-inch grid spacing was used in both vertical and horizontal measurements. The horizontal data is to compare horizontal variations with vertical ones. Outcrop 3 has one set of measurements with 219 data points and 4 inch interval in the vertical direction, and is to compare the vertical variation in permeability with that of Outcrop 2. All measurement locations on the outcrop are given by Table 5.1.

Subsurface Measurements

A total of 1608 permeability measurements with one inch grid spacing were carried out on core slabs of three wells in Sun Ranch Field. Well A2 measurements are totaled to 856 and located at 10,054.1 - 10,138.00 ft depth. Well 2 has 472 data point at 10,416.00 - 10,464.70 ft interval. The measurements on Well 7-22 core slabs at 9541.30 - 9559.40 ft interval consist of 208 data point, Table 5.2.

Error Analysis

Reservoir characterization is based on sample data. A certain number of data is required to calculate true reservoir properties. Therefore, one would like to estimate the number of data required to calculate reservoir properties accurately, and the magnitude of the error involved in a certain number of data. Here, we have the data from the outcrop sites as well as subsurface core slabs, and would like to find out about the extent of the possible errors.

In Chapter III, an error model generated for arithmetic mean as a function of

number of data and coefficient of variation. Similar model was proposed for standard deviation as a function of number of data. Our experiments indicate that the average error is related to the square root of inverse of number of data. The maximum error, however, is a function of inverse of the number of data. Patrick et al⁴⁴ studied the minimum number of data required for correct estimation of mean permeability. They also concluded that the error is linearly related to inverse of square root of number of data. In this chapter average and possible maximum errors introduced to mean permeabilities and standard deviations were calculated for all data sets gathered from outcrop and subsurface core slabs. Error in standard deviation were not calculated because it was concluded in Chapter 3 that the error in standard deviation is related to error in arithmetic mean. Equations (3.15) and (3.19) were used to calculate the errors introduced to mean permeabilities.

Possible average and maximum errors because of insufficient number of data were calculated and tabulated in Tables 5.3-7. Tables 5.3-7 show that the majority of the data sets have enough number of data (with uncertainty limit of 25%). The exceptions are Unit 6 of Well A2 with an error of 34.92% (Table 5.5) and Unit 1 of Well 2 with 51.68% (Table 5.6).

Vertical and Horizontal Variability

Description of reservoir parameters by using subsurface data is restricted to the vertical direction only. In the case of outcrop studies, one can get horizontal measurements within scales ranging from an inch to inter-well, and use these data for analogous subsurface reservoirs. Daykstra-Parsons coefficient and coefficient of variation are calculated and used as criteria, since they are indicators of heterogeneity of porous media. The value of C_v below 0.5 represents homogenous, between 0.5 and 1 represents heterogeneity and greater than 1 represents very high heterogeneity.⁴² The

values of V_{DP} between 0 and 0.5 represent homogenous, between 0.5 and 0.7 represents heterogeneous, and between 0.7 and 1 represents extremely heterogeneous medium.²⁴ In this study V_{DP} was calculated by using a simple equation given by Warren and Cosgrove.⁴²

$$V_{DP} = 1 - \exp\left\{-\sqrt{\ln\left(\frac{\bar{X}}{H_m}\right)}\right\} \quad (5.1)$$

where

V_{DP} : Dykstra - Parsons Coefficient

$\bar{X}$: Arithmetic mean of the permeabilities

H_m : Harmonic mean of the permeabilities

This method is much more practical than the original Dykstra-Parsons procedure which involves sorting in descending order, plotting cumulative probabilities on a log-normal probability paper, and then reading 84 and 50 percentile values to calculate Dykstra-Parsons coefficient as,

$$V_{DP} = \frac{X_{0.50} - X_{0.84}}{X_{0.50}} \quad (5.2)$$

Above equation gives exactly the same result as the previous exponential form given by Eq. (5.1), but as Craig points out the correct form of the above equation is the form that utilizes the logarithms of the permeabilities.²⁴ Then it becomes,

$$V_{DP} = \frac{\log(X_{0.50}) - \log(X_{0.84})}{\log(X_{0.50})} \quad (5.3)$$

Since three whole sets of well data and vertically measured outcrop data includes various units with different properties, their V_{DP} 's and C_v 's indicate high heterogeneity. Tables

5.3-7 show the VDP 's and C_v 's of the data from wells and outcrops. We expect low degree of heterogeneity for the units. VDP 's and C_v 's show that the parameters in the horizontal or vertical direction do not change significantly. For example, Unit 11 of Section C has one vertical and one horizontal measurement with 33 and 36 number of data respectively, Table 5.3. The horizontal data have VDP of 0.321 and C_v of 0.334. The vertical ones have VDP and C_v of 0.451 and 0.423 respectively. Both horizontal and vertical data show low heterogeneity, although parameters of vertical data are slightly higher than horizontal. Since vertical data have higher uncertainty (higher error) than the horizontal ones, i.e. 11.09 vs 8.20, their values might have been much closer, had they had the same uncertainty level.

All outcrop and subsurface data collected within units indicate low VDP and C_v values, Table 5.3-7. This could be an indication of insensitivity of permeability variation to directions as long as a geological unit boundaries are not crossed. With 20% uncertainty limit, all the units of Outcrop 1 show VDP less than 0.5 and 90% of them show C_v 's less than 0.5 (Table 5.3). Under the same conditions, 95% of the units of three wells (Well A2, 2, and 7-22) indicate VDP less than 0.5 and 70% of them show C_v less than 0.5.

Permeability Distributions

Frequency distribution plots, which are also called histograms, are quite useful in presenting data sets. Histograms show how often observed values fall within certain interval or classes. Histograms, especially cumulative histograms, are indicators to the distribution type. There are two very commonly referred distribution types, normal (gaussian) distribution and log normal distribution. Both have mathematical expressions and a few parameters are needed to use them in statistical estimations.

To determine the distribution types of measured data, frequency histograms and cumulative frequency histograms are plotted for all units of three outcrops and three wells. Only a few are shown in Figs. 5.5-15 for practical purposes. Figures 5.5-7 show relative frequency, cumulative frequency, and probability plots of log of permeability for Wells A2, 2, and 7-22 respectively. Although it is not clear what type of distribution they have, the distributions look more like a log normal than normal distribution. Figures 5.8 and 5.9 show histograms of Unit 16 of Well A2, and Unit 25A of Well 7-22, which both indicate normal distribution. The same conclusion can be drawn from Figs. 5.10 and 5.11, which show histograms of Units 5 and 11 of Section C, Outcrop 1.

Vertical permeability distribution of Outcrop 2 is shown in Fig. 5.12. The figure indicates that 55% of the data fall between 0 and 0.15. That percentage represent the shaly parts in the measured section. These shale were assigned a permeability of 1 md, below which MFP measurements cannot be carried out accurately. Figure 5.13 shows the vertical permeability distribution of Outcrop 3. Similar to Outcrop 2 data, 24% of the data fall into the interval of 0 and 0.15. This case is also a result of shales through measured sections.

As a result of above findings highly heterogeneous (well) data show log normal distribution, and relatively homogenous (unit) data show normal distribution. Dykstra-Parsons Coefficient and coefficient of variation for all data sets, which show log normal distribution, are higher (Tables 5.5-7). But unit permeability distributions, for example Unit 5 and 11, have low V_{DP} 's and C_v 's, 0.28 - 0.32 and 0.311 - 0.331 respectively. Internally heterogeneous units, however, do exist with higher V_{DP} 's and do not show normal distribution. For example, Unit 6A of Well 2 with V_{DP} and C_v of 0.46 and 0.56 respectively and horizontal data of Outcrop 2 with V_{DP} and C_v of 0.59 and 0.57 do not show normal like distributions, Figs. 5.14, 15. Summarizing, the distributions of

permeability data will directly be related to the degree of heterogeneity of formation. Data from a relatively homogenous unit will show a normal distribution, otherwise, it will be closer to log-normal distribution.

Variogram Analysis

Variogram is a tool that quantifies the spatial relationship between spatially distributed variables. Variogram for the same variable measured on different locations is calculated by

$$\gamma(h) = \frac{1}{2n(h)} \sum_{i=1}^n (V(x_i) - V(x_i + h))^2 \quad (5.4)$$

$\gamma(h)$: Variogram at distance of h

$V(x_i)$: Measured value of variable at x_i

$V(x_i+h)$: Measured value of variable at x_i+h

n: Number of pairs

Simply, a variogram is an indicator of the relationship between two measurements as a function of distance. Since closer variables should be more similar to each other than the farther ones, the smaller the distance is, the smaller the value of the variogram will be. The variogram of the same variables is zero. The terminology used to describe the important features of the variogram is defined below.

Range

The variogram of two variables increases with increasing lag distance. However, there is a limit to this increase. The distance at which the variogram reaches a constant value is called range. Beyond the range, values are no longer related. Range gives the spatial continuity.

Sill

Value of the variogram at the range is called the sill, which is approximately equal to the variance of the data.

Nugget Effect

Some factors, such as error in sampling or small scale heterogeneity may cause two sample values to be dissimilar even if they are located very closely. Therefore, at the zero distance (origin), the variogram takes finite value instead of being zero. This deviation from the origin is called nugget effect which quantifies the uncertainty. For smaller lag distance nugget effect is supposed to be very small or zero. But in some instances even for small lag distances, it might be significant. For example, if measurement is taken from 1 cm lag distance and the variogram shows only nugget effect, that means there is no relationship among data and the variable is randomly distributed.

Hole Effect

In some instances the value of the variogram for particular lag distances is smaller than that of the previous one and the following lag distances; this situation is called hole effect. It implies that the samples are more similar for these particular lag distances than the rest. As it will be seen, hole effect happens quite often especially in the vertical transect data sets.

Outcrop Variograms

Spatial relationship in five data sets taken from Outcrops 1, 2 and 3 are investigated. Out of five, two sets belong to Unit 11 of Outcrop 1 at Section C. Both of them are horizontally measured with 1 foot and 3 inch grid spacing and consisting of 93 and 36 data points respectively. The other two data sets are from Outcrop 2 on horizontal

and vertical grids with 222 and 300 data points respectively. The fifth data set is vertically measured on Outcrop 3 and has 216 data points.

Figure 5.16 shows spatial relationship for Unit 11 of Outcrop 1. Data are taken on one foot interval. Variogram indicates totally sill with the value of 0.05. Data taken from the same unit, Unit 11, with smaller interval (3") yields to the same result, totally sill with a value of 0.03, Fig. 5.17. It can be concluded there is none or very small spatial relationship among permeabilities of Unit 11.

Figure 5.18 show the variogram of Outcrop 2 in horizontal direction. The variogram shows hole effect around 35-60 lag distances. The reason for the hole effect is permeability values between 35 and 60 ft interval are relatively low. To model this variogram we combined spherical and cosine models,

$$\gamma(h) = C_o + C_1 \text{Shp}_a(h) + C_2 (1 - \text{Cos}(kh)) \quad (5.5)$$

where $\text{Shp}_a(h)$ represents spherical model as

$$\gamma(h) = C_o + C_1 \left(\frac{3}{2} \left(\frac{h}{a} \right) - \frac{1}{2} \left(\frac{h}{a} \right)^3 \right) \quad h \leq a \quad (5.6)$$

$$\gamma(h) = C_o + C_1 \quad h \geq a \quad (5.7)$$

The last term on the right hand side of the Eq.(6.7) represents the cosine model;

$$\gamma(h) = C_2 (1 - \text{Cos}(kh)) \quad h > 0 \quad (5.8)$$

$$k = \frac{2\pi}{L} \quad (5.9)$$

C_o : Nugget

C_1 : Coefficient of Spherical Model (Sill)

C_2 : Coefficient of Cosine Model

L : Period,

h : Distance

The values of coefficients follow

a : 12	$h < L_1$	$h > L_1$
$C_0 : 0.003$	$C_2 : 0.007$	$C_2 : 0.014$
$C_1 : 0.022$	$L_1 : 45$	$L_2 : 75.$

The variogram for vertically measured permeabilities on Outcrop 2 is shown in Fig. 5.19. The variogram shows periodic behavior after certain lag distance. It implies that various sedimentologic units are encountered in the vertical direction. To imitiate this periodic behavior, again a combination of spherical and cosine model is used. Coefficients used are

a : 11.0	$h < L_1$	$L_1 < h < L_1 + L_2$	$h > L_1 + L_2$
$C_0 : 0.001$	$C_2 : 0.0035$	$C_2 : 0.0081$	$C_2 : 0.006$
$C_1 : 0.023$	$L_1 : 60$	$L_2 : 66$	$L_3 : 50.$

Figure 5.20 shows the vertical variogram in the vertical direction for Outcrop 3. Variogram indicates a relationship between permeability and measurement length. Sill does not reach to a constant value. There is a trend in permeability values, which is going from high to low values along the measurement length. Power law model is used to construct a spatial relationship.

Power Law model can be expressed with following equation.

$$\gamma(h) = C_0 + C_1 h^\omega \quad h > 0 \quad (5.10)$$

ω : takes value between 0 and 2 excluding limits. The feature of the variogram as follows

$$C_0 : 0.065$$

$$C_1 : 0.0007545$$

$$\omega : 1.$$

Variograms for Subsurface Data Sets

The variograms for three wells in Sun Ranch Field, Well A2, 2 and 7-22 and for three units having enough data, Unit 16 of Well A2, Unit 6A of Well 2, and Unit 25A of Well 7-22 were calculated. Figure 5.21 shows variogram of Well A2. The data suggest the existence of various sedimentologic units. In order to imitate the hole effect caused by existence of various sedimentologic units, a combination of spherical and cosine models is used.

Coefficients are

$a : 30$	$h < L_1$	$h > L_1 + L_2$
$C_0 : 0.0005$	$C_2 : 0.00075$	$C_2 : 0.00375$
$C_1 : 0.0023$	$L_1 : 170$	$L_2 : 430.$

Similar to some of the previous cases, the variogram for Well 2 data shows a periodic behavior, Fig. 5.22. The same combination model is used to build a spatial relationship. The related parameters are

$a : 30$	$h < L_1$	$L_1 < h < L_1 + L_2$	$h > L_1 + L_2$
$C_0 : 0.000125$	$C_2 : 0.0000875$	$C_2 : 0.000175$	$C_2 : 0.0001125$
$C_1 : 0.0005$	$L_1 : 87$	$L_2 = 100$	$L_3 : 100.$

Figure 5.23 shows the variogram for Well 7-22 data. It shows a stable periodic behavior with constant periodic length and coefficient C_2 . This result indicates that the well has consecutive symmetric sedimentologic units. Parameters of the variogram follow

$a : 8.5$

$C_0 : 0.001$

$C_1 : 0.005$

$C_2 : 0.0015$

$L_1 : 32.$

The variogram for the data from Unit 16 of Well A2 is shown in Fig. 5.24. When it is compared with the variogram for Well A2 data, this one shows more stable behavior. Since the data represents one geological depositional environment, hole effect is not seen. Yet another important point is that the data still show uncertainty (nugget effect). An exponential model with following features is used to get mathematical expression for spatial relationship.

$$\gamma(h) = C_0 + C_1(1 - \exp(-\frac{3h}{a})) \quad h \geq 0 \quad (5.11)$$

$C_0 : 0.000063$

$C_1 : 0.000077$

$a : 90.$

Figure 5.25 indicates that the variogram for the data from Well 2 Unit 6A has linear relationship. Power law model is used to get relationship with following features.

$C_0 : 0.00011$

$C_1 : 0.000008625$

$\omega : 1.$

The variogram for the data from Unit 25A of Well 7-22 does not show good stability, Fig. 5.26. One reason might be the number of data affecting the stability of variogram. A spherical model was a good fit for this variogram. The constants of the

variogram are

$a : 14$

$C_0 : 0.00175$

$C_1 : 0.00725.$

One can conclude from above discussion that the hole effect is observed when unit boundaries are crossed. This hole effect may result in stable or unstable periodic cyclic behavior in variograms depending on geological structure and the units. Variograms of individual units are more stable since we are in relatively homogenous domains. All variograms indicate uncertainties that result nuggets, even for the data measured on one inch interval.

Table 1

Measured Grid Locations and Spacings on Outcrops 1, 2, and 3.

Outcrop #	Location	# of Data	Spacing
Outcrop 1	Section A	7	One foot
Outcrop 1	Section B	248	One foot
Outcrop 1	Section C	632	One foot
Outcrop 2	Horizontal	222	Four inches
Outcrop 2	Vertical	300	Four inches
Outcrop 3	Vertical	219	Four inches

Table 2

Measured Grid Locations Spacings on Core Slabs of
Wells A2, 2, and 7-22, Sun Ranch Field.

Well #	Location	# of Data	Spacing
Well A2	10,054 - 10,136 ft	856	One inch
Well 2	10,416 - 10,465 ft	472	One inch
Well 7-22	9541 - 9600 ft	208	One inch

Table 3

Geostatistical Parameters for Units of Outcrop 1, Sections A, B (B-1,B-2), and C.

Section & Unit #	# of Data	$\bar{X}$ (Darcy)	H_m (Darcy)	Min. Perm. (Darcy)	Max. Perm. (Darcy)	σ_x^2	VDP	C_v	Avg. Err.in $\bar{X}$ (%)	Max. Err.in $\bar{X}$ (%)
A7& 9	7	0.194	0.095	0.024	0.293	0.009	0.570	0.509	14.24	46.23
B-2	21	0.532	0.430	0.145	1.012	0.043	0.370	0.386	6.23	14.31
B1-2A	21	1.020	0.969	0.497	1.261	0.041	0.203	0.198	3.20	7.35
B1-2B1	21	0.859	0.826	0.602	1.065	0.028	0.179	0.193	3.12	7.16
B1-2B2	21	0.967	0.949	0.597	1.083	0.014	0.128	0.123	2.00	4.56
B1-2C	18	0.483	0.408	0.156	0.693	0.026	0.337	0.337	5.87	14.12
B1-2D	23	0.319	0.088	0.010	0.628	0.032	0.678	0.563	8.69	19.46
B1-5A	20	0.563	0.548	0.393	0.667	0.008	0.149	0.161	2.66	6.20
B1-5C	20	0.348	0.298	0.114	0.559	0.015	0.341	0.347	5.74	13.37
B1-7	21	0.548	0.447	0.168	0.890	0.044	0.364	0.381	6.15	14.13
B2-3A	21	0.752	0.419	0.143	1.239	0.189	0.534	0.578	9.33	21.44
B2-3B	21	0.581	0.302	0.075	1.235	0.128	0.554	0.616	9.95	22.85
B2-3C	20	0.099	0.049	0.010	0.223	0.005	0.570	0.691	10.24	25.44
C-2	47	0.676	0.451	0.112	1.655	0.154	0.470	0.581	6.27	11.71
C-4	33	0.721	0.646	0.216	1.224	0.039	0.281	0.275	3.50	7.16
C-5	40	0.960	0.856	0.376	1.666	0.095	0.287	0.321	3.76	7.29
C-6A	18	0.749	0.604	0.225	1.391	0.126	0.371	0.474	8.26	19.85
C-6B1	23	0.638	0.371	0.074	1.331	0.147	0.521	0.600	9.26	20.74
C-6B2	20	0.520	0.444	0.271	0.933	0.047	0.327	0.417	6.90	16.07
C-6B3	14	0.449	0.382	0.163	0.648	0.021	0.330	0.329	6.50	16.88
C-7	11	0.597	0.480	0.226	0.999	0.069	0.372	0.442	9.86	27.54
C-9	49	0.150	0.113	0.041	0.359	0.006	0.412	0.539	5.70	10.54
C-11	93	0.607	0.528	0.190	1.275	0.051	0.311	0.371	2.85	4.60
C-11VG	33	0.604	0.421	0.096	0.999	0.065	0.451	0.423	5.45	11.09
C-11HG	36	0.518	0.446	0.163	0.815	0.030	0.321	0.334	4.12	8.20
C-11AG	169	0.514	0.490	0.140	1.126	0.026	0.271	0.298	1.70	2.47
C-13	27	0.436	0.190	0.239	1.044	0.066	0.597	0.591	8.42	18.05
C-14	19	0.481	0.385	0.151	1.022	0.051	0.375	0.469	7.96	18.82

Table 4

Geostatistical Parameters for Outcrops 2 and 3.

Ocrp. & Unit #	# of Data	$\bar{X}$ (Darcy)	H_m (Darcy)	Min. Perm. (Darcy)	Max. Perm. (Darcy)	σ_x^2	VDP	C_v	Avg. Err.in $\bar{X}$ (%)	Max. Err.in $\bar{X}$ (%)
2-Vert.	300	0.086	0.002	0.001	1.444	0.039	0.861	2.291	9.79	13.15
2-Hor.	222	0.443	0.218	0.012	1.270	0.064	0.569	0.570	2.83	3.96
3-Vert.	219	0.352	0.072	0.001	1.318	0.119	0.879	0.980	4.90	6.87

Table 5

Geostatistical Parameters for Units of Well A2, Sun Ranch Field.

Unit #	# of Data	$\bar{X}$ (Darcy)	H_m (Darcy)	Min. Perm. (Darcy)	Max. Perm. (Darcy)	σ_x^2	VDP	C_v	Avg. Err.in $\bar{X}$ (%)	Max. Err.in $\bar{X}$ (%)
WA2	856	0.078	0.022	0.0014	0.313	0.00476	0.677	0.882	2.23	2.68
3C-B	50	0.166	0.142	0.075	0.313	0.00405	0.325	0.383	4.01	7.38
3E	78	0.161	0.145	0.048	0.237	0.00212	0.273	0.285	2.39	3.40
6	20	0.006	0.003	0.001	0.019	0.00003	0.556	0.906	14.99	34.92
9	16	0.041	0.029	0.008	0.072	0.00035	0.447	0.453	8.38	20.84
10	16	0.081	0.067	0.039	0.149	0.00139	0.350	0.462	8.55	21.25
11A	46	0.140	0.125	0.039	0.205	0.00163	0.286	0.286	3.12	5.86
11C	24	0.207	0.199	0.134	0.295	0.00169	0.178	0.198	2.99	6.62
12	21	0.063	0.041	0.011	0.138	0.00103	0.481	0.509	8.22	18.88
14A	48	0.066	0.049	0.015	0.154	0.00118	0.427	0.519	5.54	10.30
15B	187	0.103	0.066	0.011	0.255	0.00321	0.486	0.546	2.95	4.24
15C	18	0.053	0.051	0.033	0.079	0.00014	0.194	0.219	3.82	9.17
16	278	0.021	0.015	0.017	0.0745	0.00011	0.420	0.519	2.30	3.12

Table 6

Geostatistical Parameters for Units of Well 2, Sun Ranch Field.

Unit #	# of Data	$\bar{X}$ (Darcy)	H_m (Darcy)	Min. Perm. (Darcy)	Max. Perm. (Darcy)	σ_x^2	VDP	C_v	Avg. Err.in $\bar{X}$ (%)	Max. Err.in $\bar{X}$ (%)
W2	472	0.0404	0.0006	0.001	0.1279	0.00074	0.660	0.672	2.28	2.92
1	15	0.0157	0.0029	0.001	0.0412	0.00028	0.726	1.067	20.39	51.68
3A-B	15	0.0027	0.0017	0.001	0.0064	0.00002	0.407	0.650	12.42	31.49
6A	83	0.0318	0.0217	0.0070	0.0807	0.00032	0.460	0.560	4.54	7.52
6B	28	0.0575	0.0418	0.0108	0.0994	0.00061	0.430	0.430	6.01	12.77
7A	26	0.0515	0.0330	0.0063	0.0931	0.00059	0.486	0.474	6.88	14.90
7B	16	0.0537	0.0428	0.0242	0.0907	0.00063	0.337	0.467	8.64	21.48
7C	39	0.0477	0.0393	0.0171	0.1112	0.00047	0.356	0.452	5.36	10.46
9A	44	0.0309	0.0267	0.0091	0.0584	0.00014	0.320	0.384	4.28	8.12
9B	67	0.0650	0.0490	0.0019	0.1279	0.00117	0.417	0.520	4.70	8.17
11B	52	0.0526	0.0468	0.0190	0.0953	0.00029	0.290	0.320	3.28	5.99
13A	24	0.0196	0.0169	0.0070	0.0316	0.00004	0.320	0.330	4.98	11.03

Table 7

Geostatistical Parameters for Units of Well 7-22, Sun Ranch Field.

Unit #	# of Data	$\bar{X}$ (Darcy)	H_m (Darcy)	Min. Perm. (Darcy)	Max. Perm. (Darcy)	σ_x^2	VDP	C_v	Avg. Err.in $\bar{X}$ (%)	Max. Err.in $\bar{X}$ (%)
W7.22	208	0.1328	0.0348	0.0023	0.4180	0.00830	0.685	0.685	3.52	4.96
23A-B	19	0.0737	0.0149	0.0727	0.2570	0.00702	0.717	1.136	19.29	45.59
24	46	0.1398	0.1020	0.0183	0.2830	0.00313	0.429	0.401	4.38	8.22
25A	52	0.1740	0.0250	0.0097	0.4180	0.00980	0.598	0.562	5.77	10.52
25B	16	0.2213	0.1920	0.0812	0.3822	0.00592	0.315	0.346	6.40	15.92
26	16	0.1008	0.0719	0.0252	0.1833	0.00252	0.440	0.498	8.14	20.24

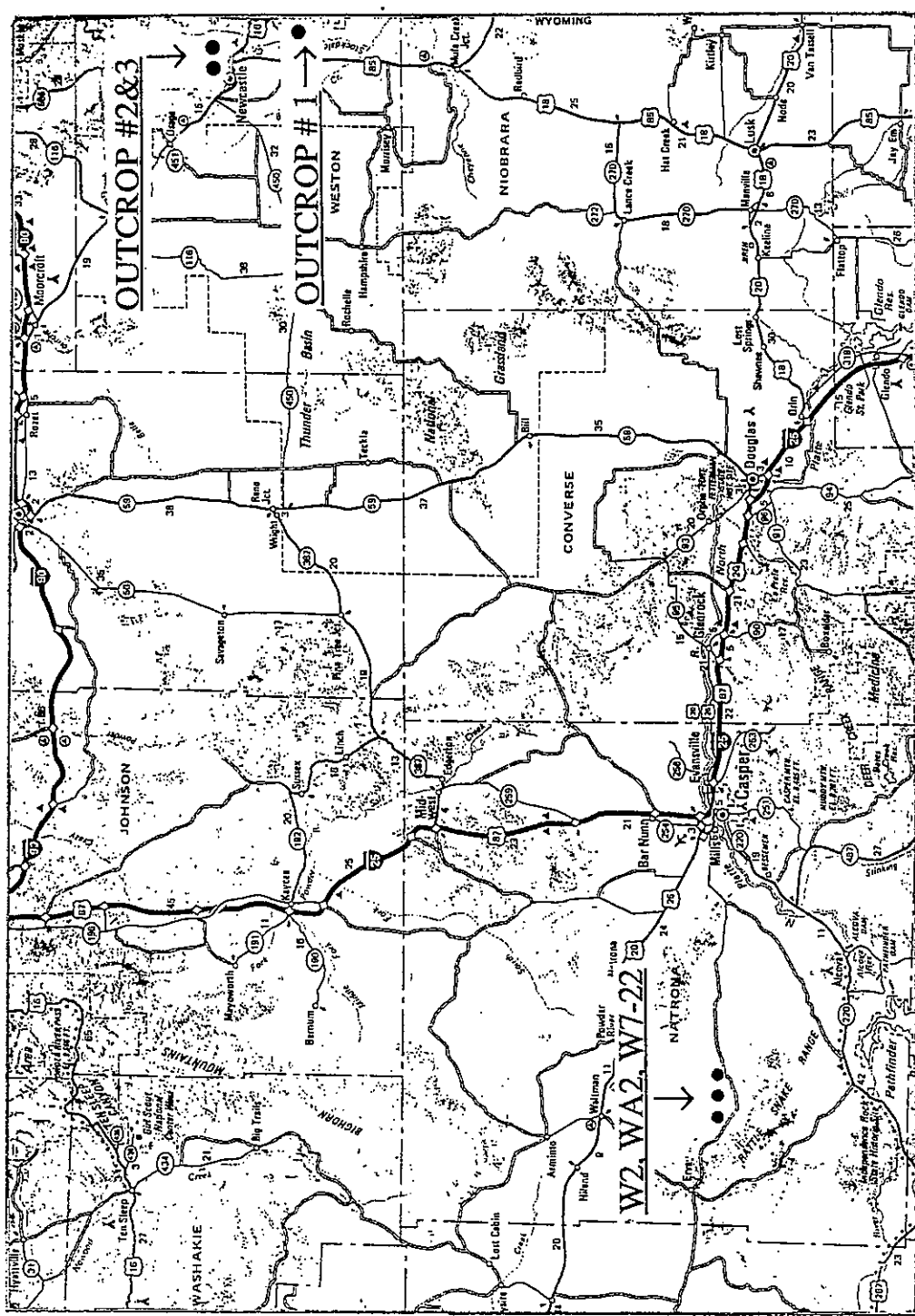


Figure 5.1. Geographic locations of study areas, Muddy sandstone outcrops 1, 2, and 3, Weston Co., and Sun Ranch Field Federal Well A2, 2, and 7-22, Natrona Co., Wyoming.

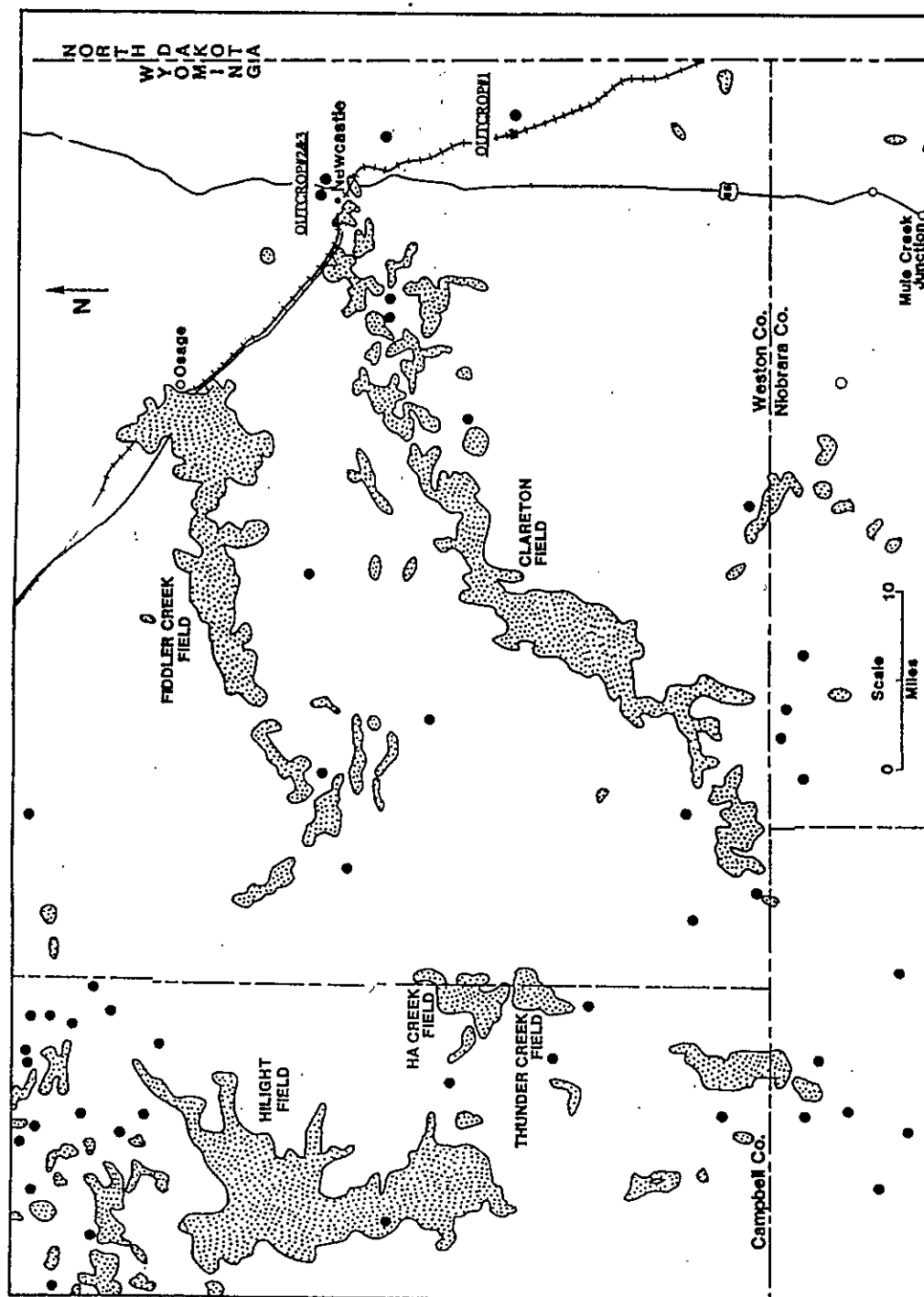


Figure 5.2. Geographic locations of Muddy sandstone outcrops 1, 2, and 3, Newcastle, Weston Co., Wyoming.

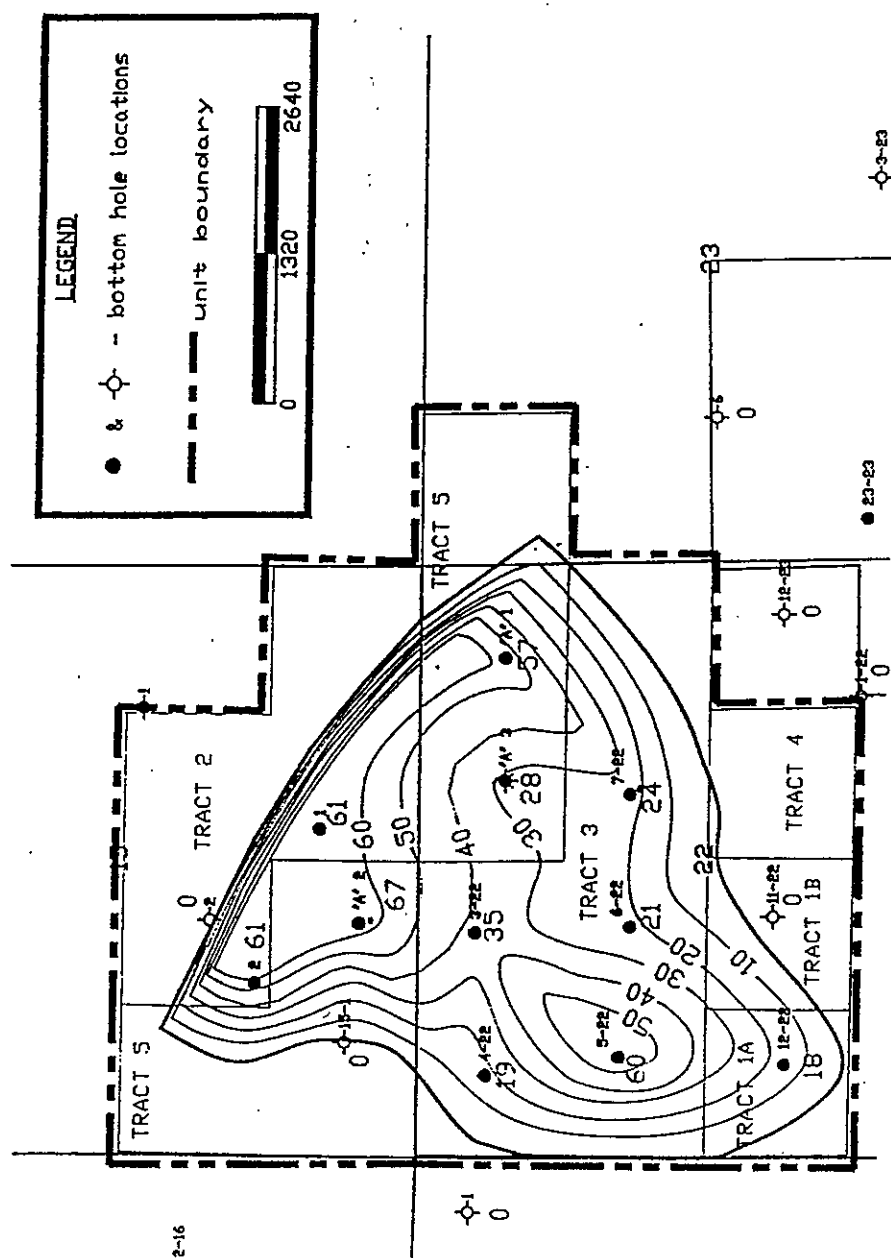


Figure 5.3. Geographic locations of Sun Ranch Field Wells, Federal Well A2, 2, and 7-22, Natrona, Co., Wyoming.

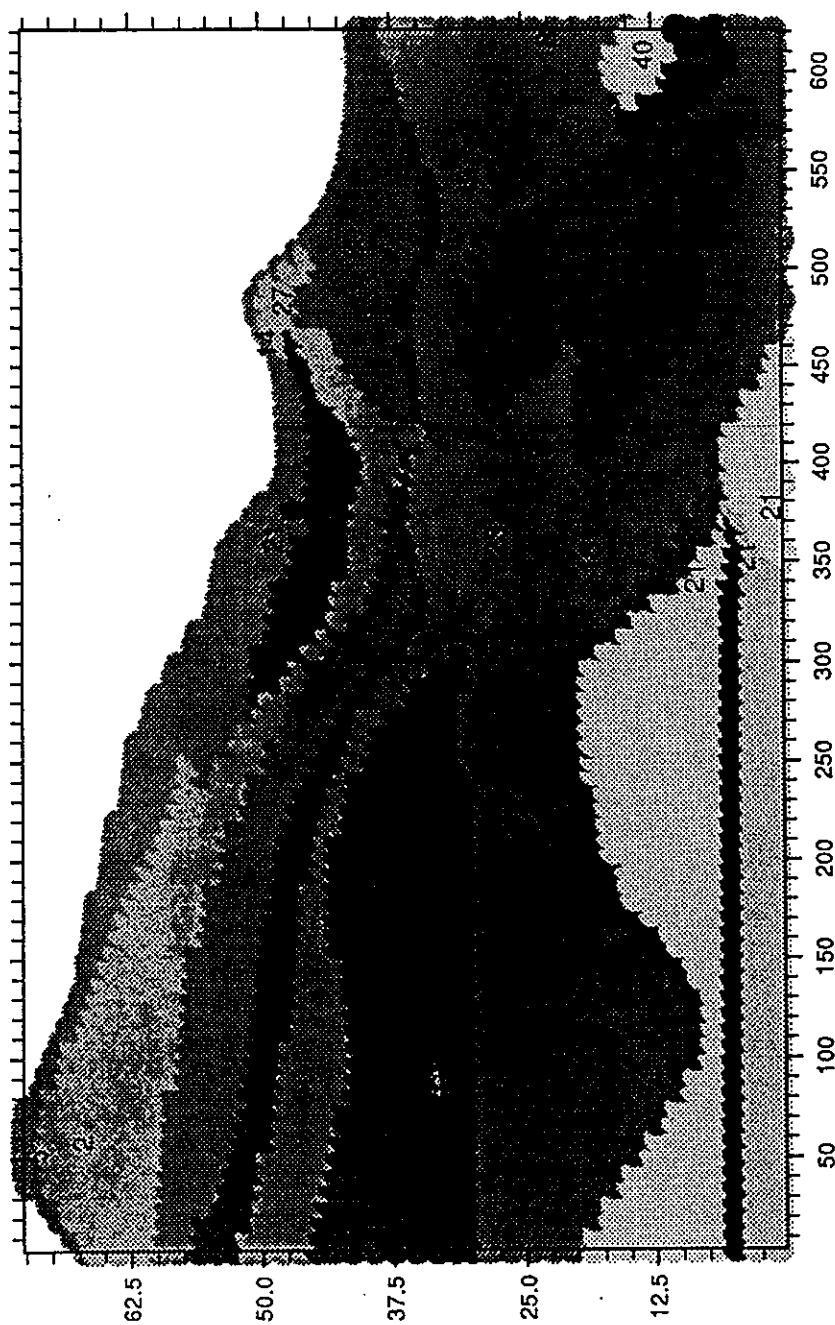
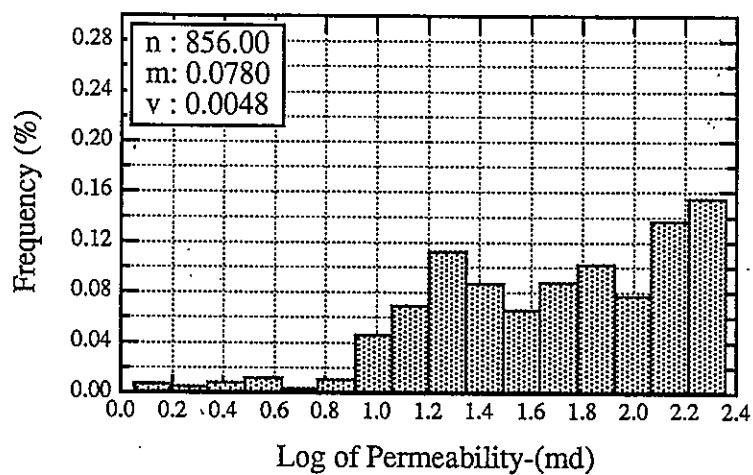
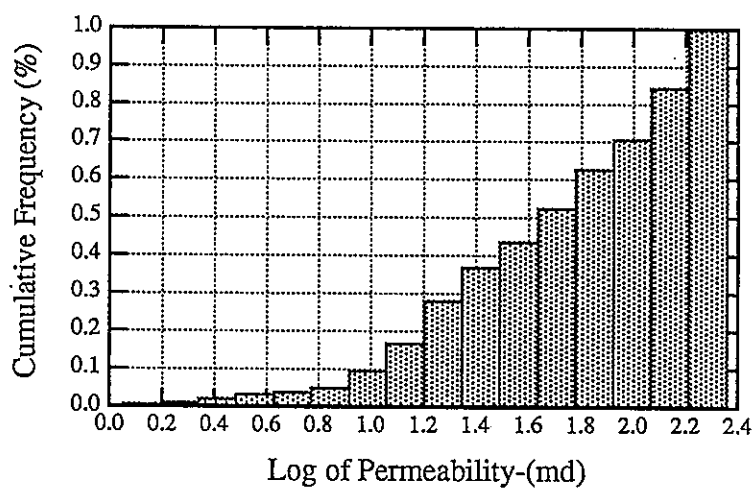


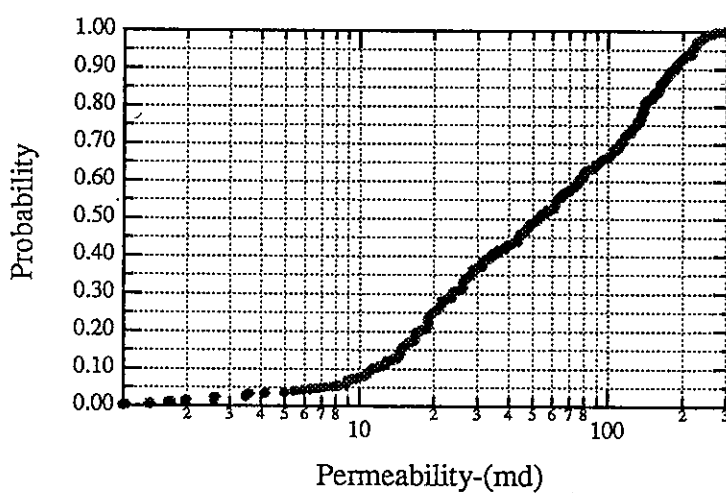
Figure 5.4. Measured grid locations on Outcrop 1, Sections A, B, and C. The numbers are the number of data from that location.



(a)

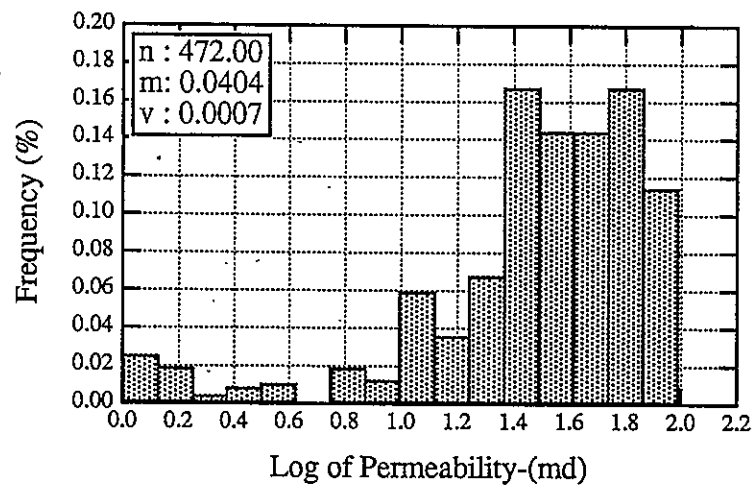


(b)

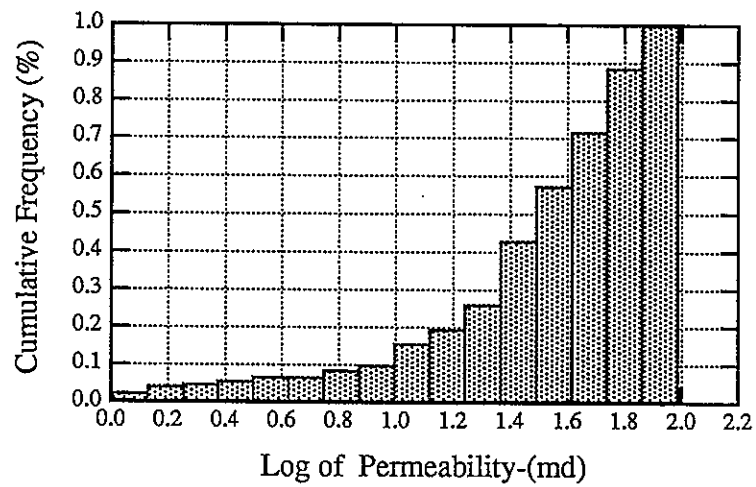


(c)

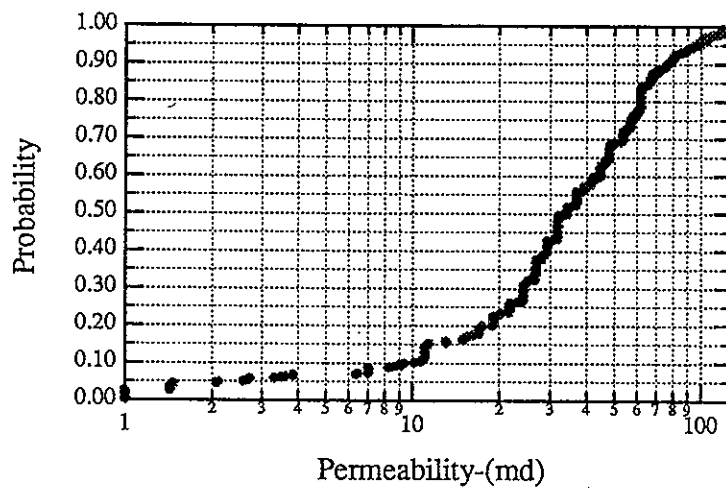
Figure 5.5. Frequencies and probability for Well A2, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.



(a)

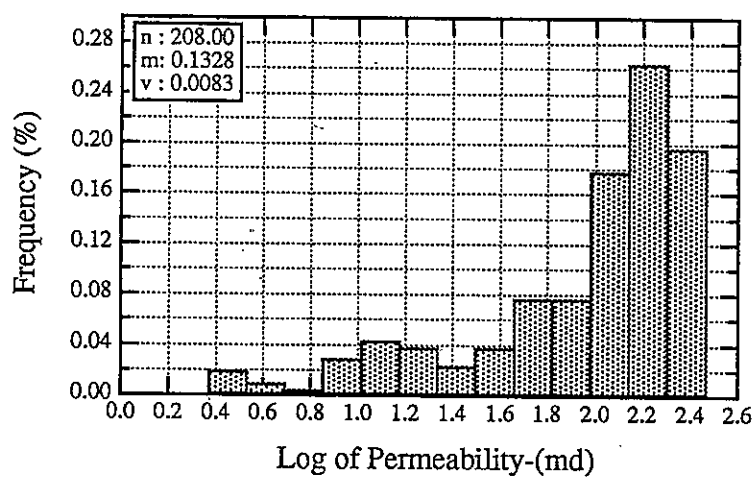


(b)

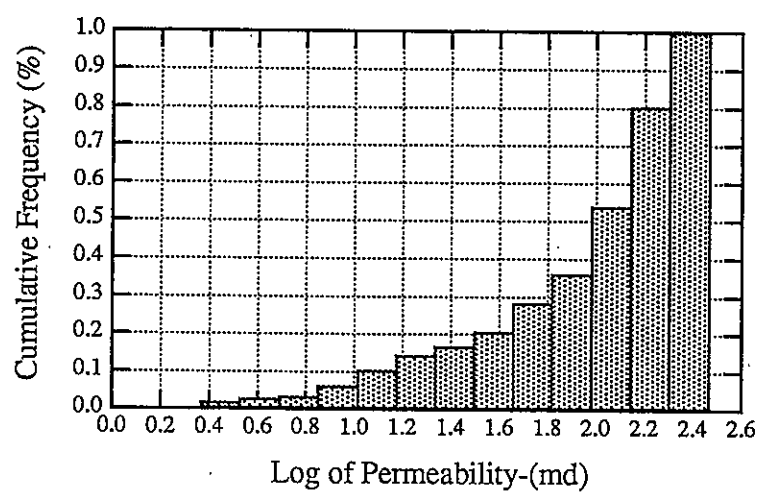


(c)

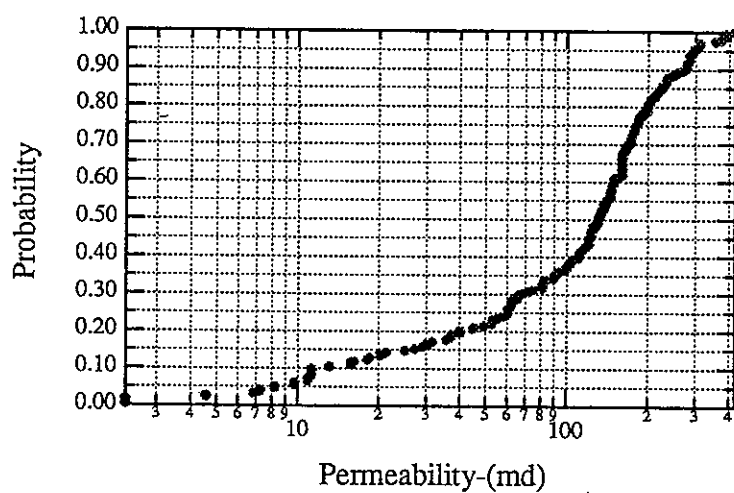
Figure 5.6. Frequencies and probability for Well 2, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.



(a)

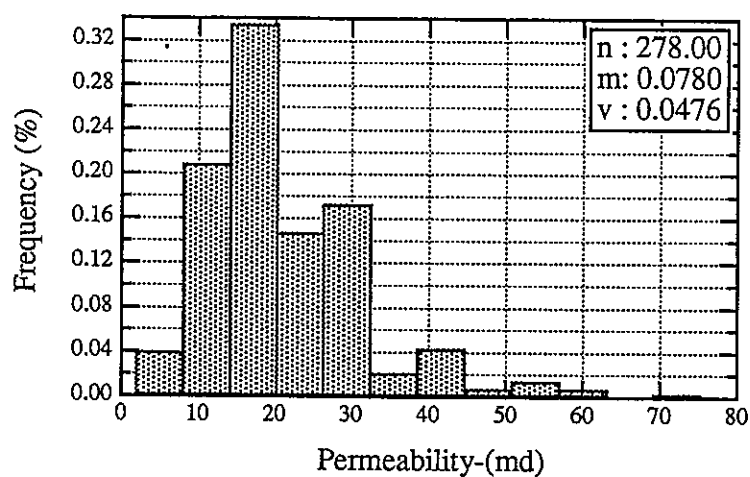


(b)

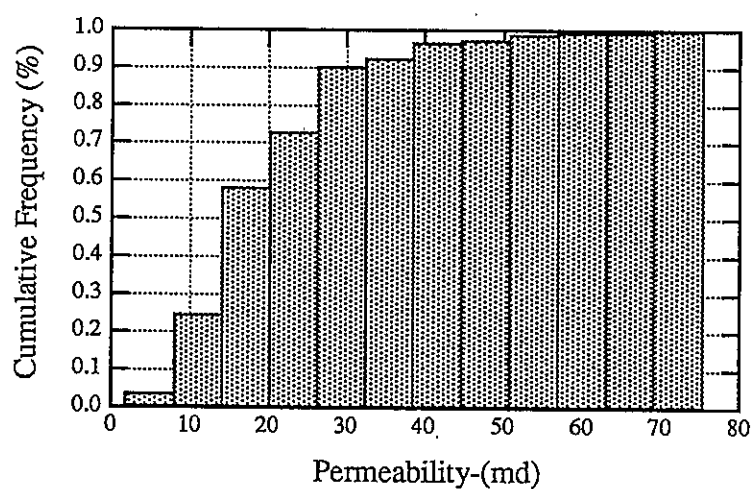


(c)

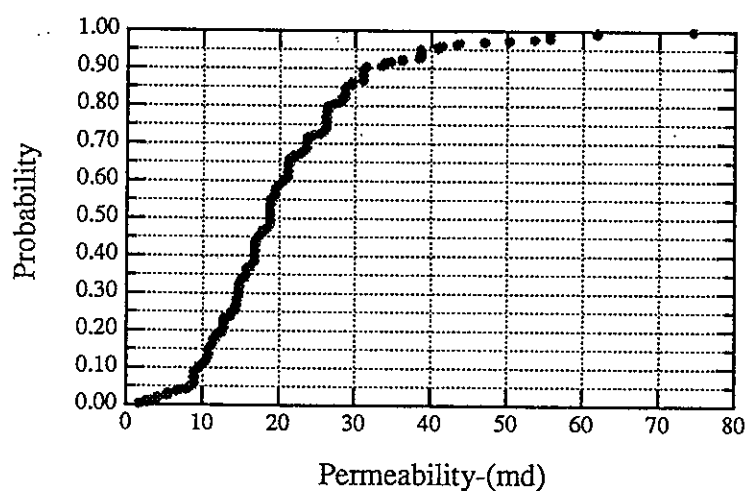
Figure 5.7. Frequencies and probability for Well 7-22, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.



(a)

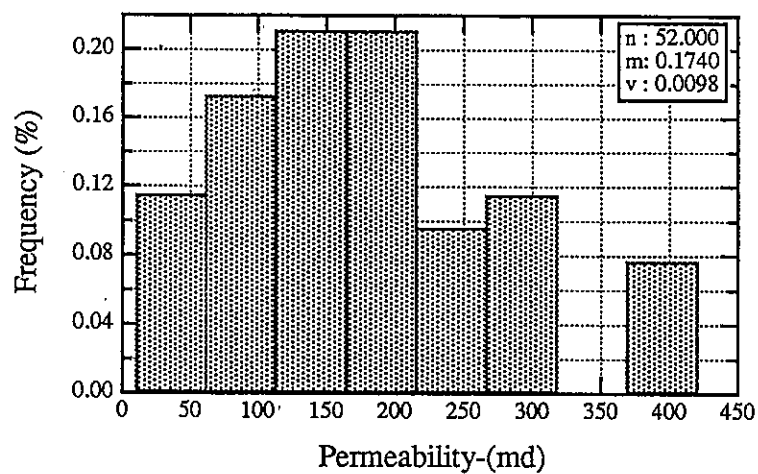


(b)

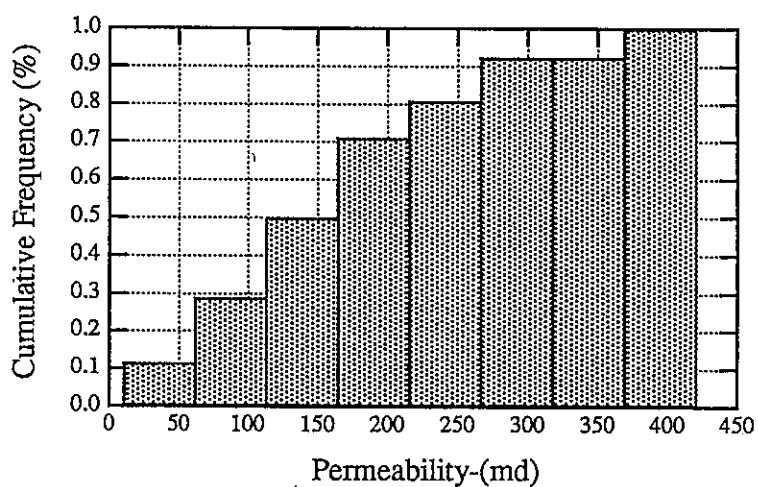


(c)

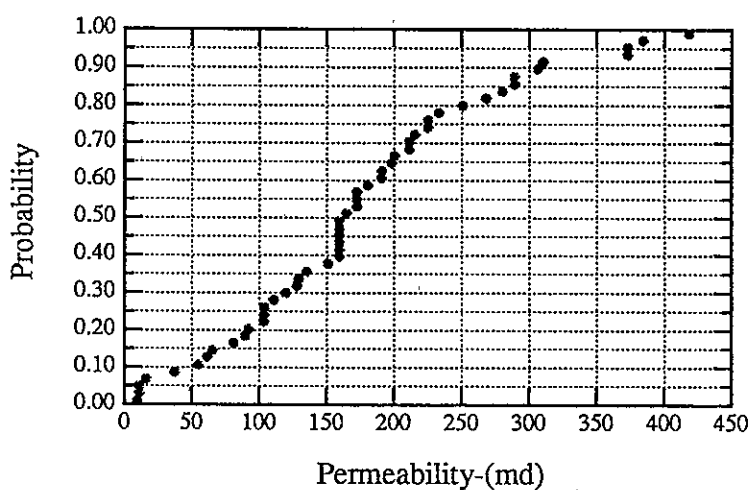
Figure 5.8. Frequencies and probability for Unit 16 of Well A2, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.



(a)

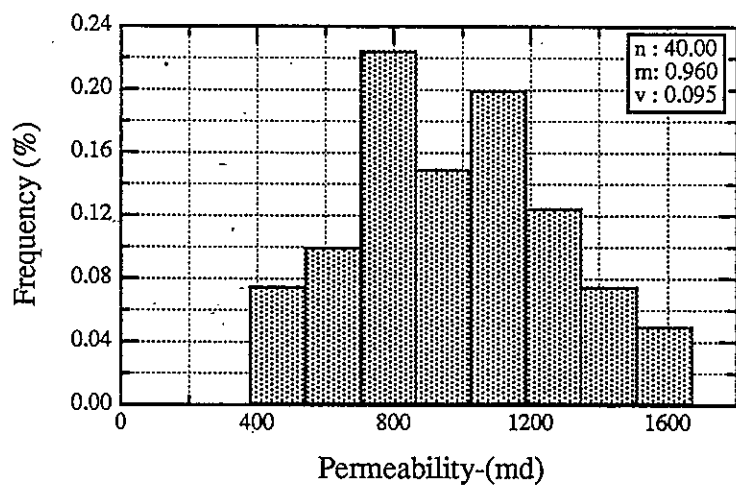


(b)

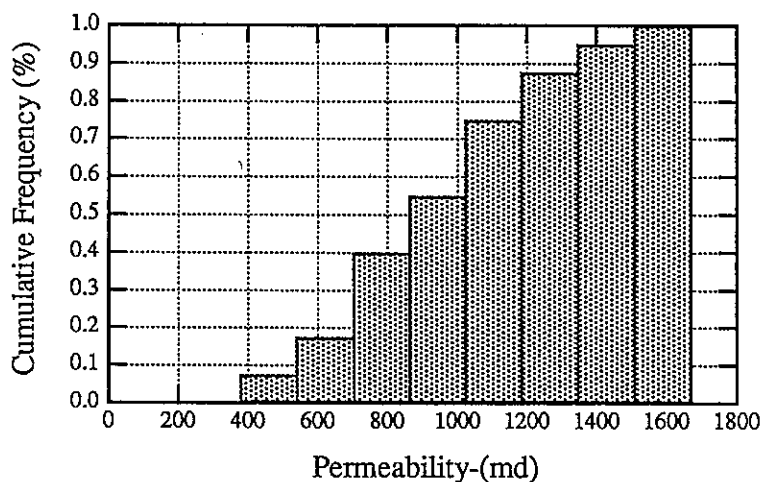


(c)

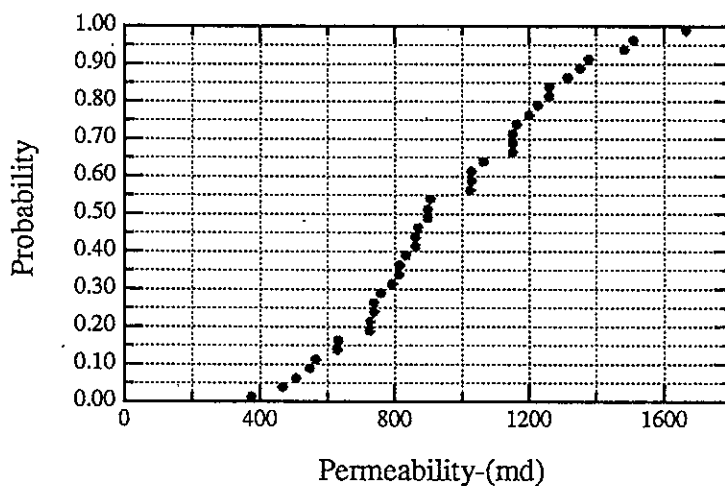
Figure 5.9. Frequencies and probability for Unit 25A of Well 7-22, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.



(a)

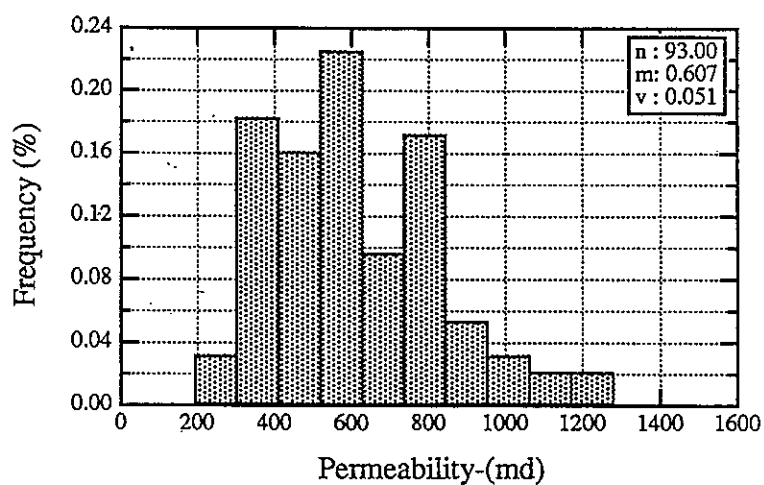


(b)

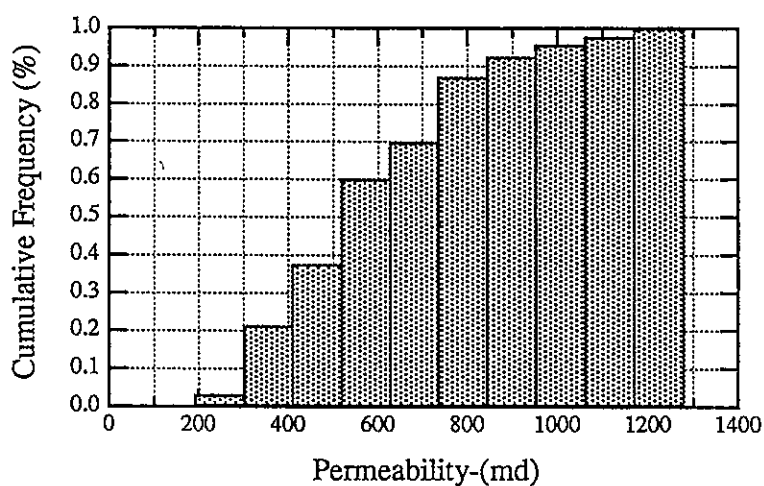


(c)

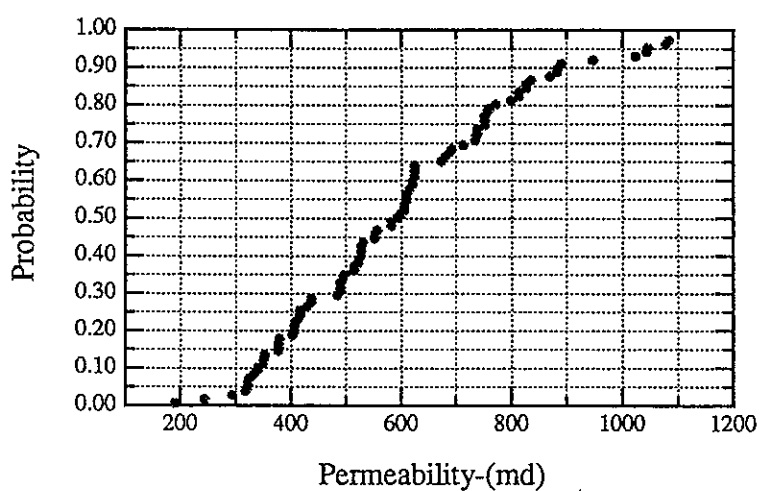
Figure 5.10. Frequencies and probabilities for Unit 5 of Section C, Outcrop 1, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.



(a)

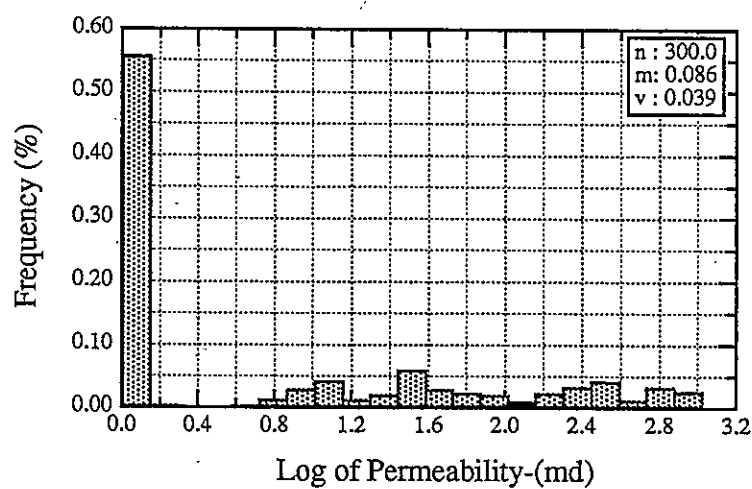


(b)

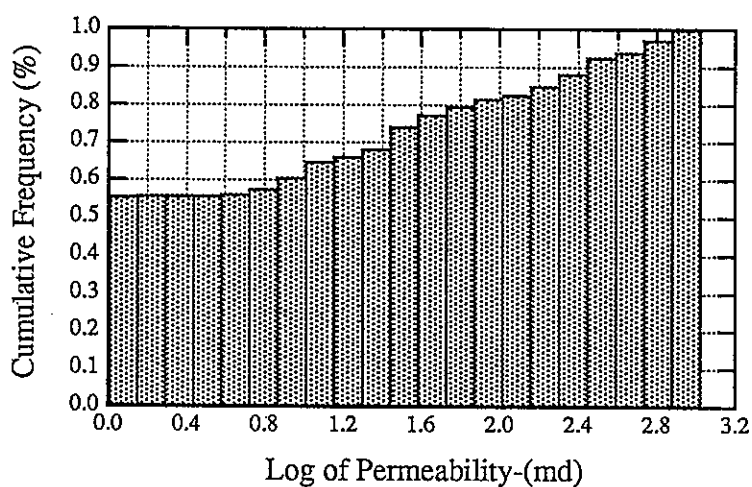


(c)

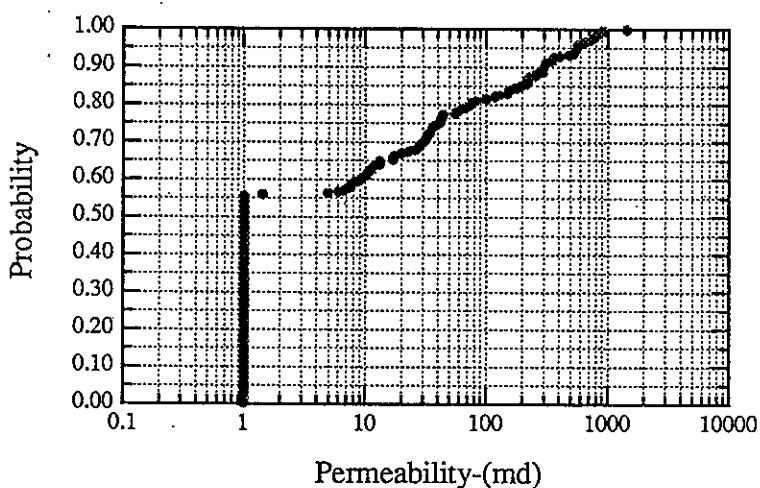
Figure 5.11. Frequencies and probability for Unit 11 of Section C, Outcrop 1, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.



(a)

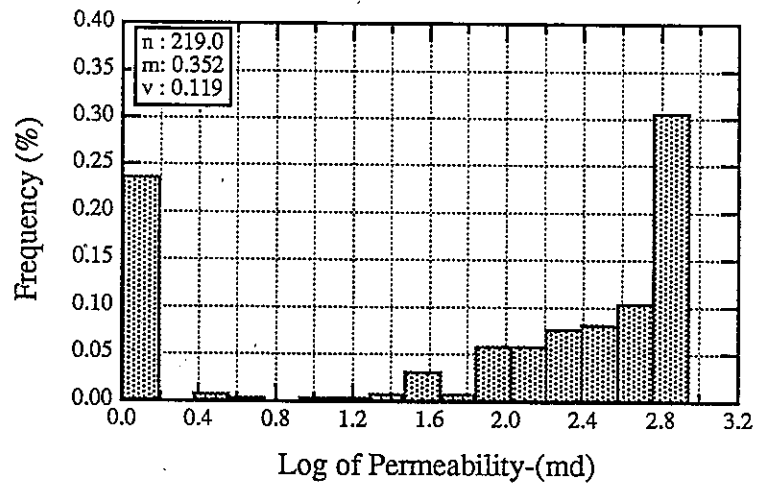


(b)

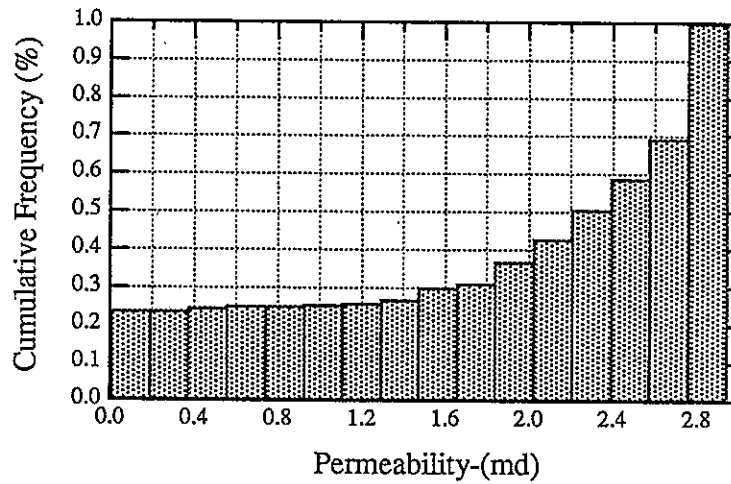


(c)

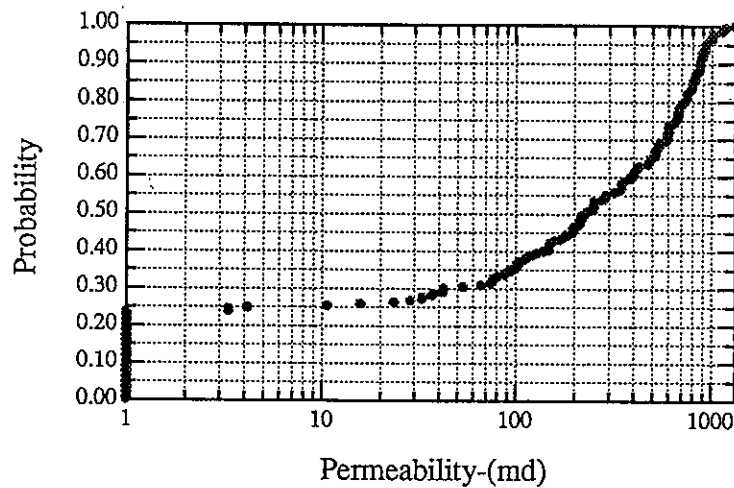
Figure 5.12. Frequencies and probability for vertical transect measurement on Outcrop 2, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.



(a)

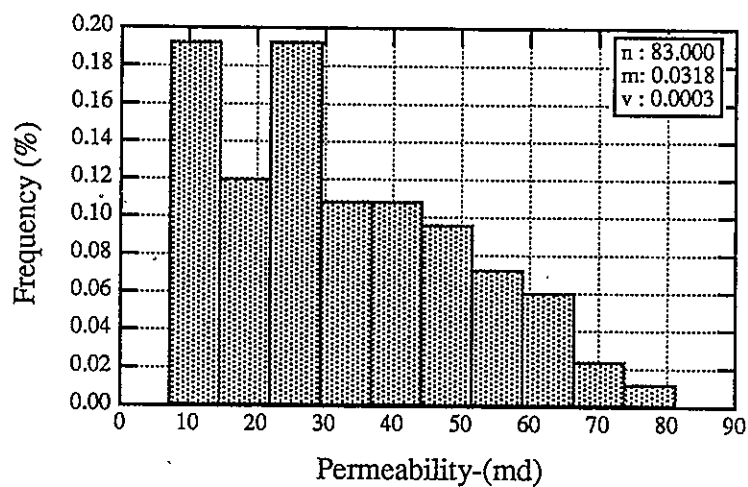


(b)

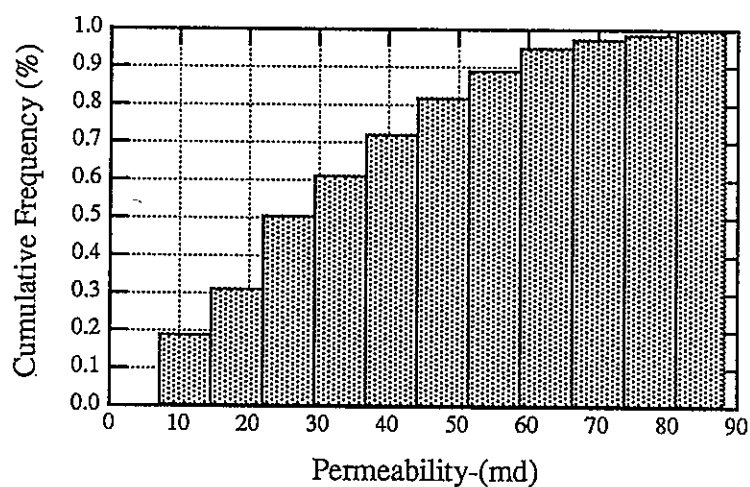


(c)

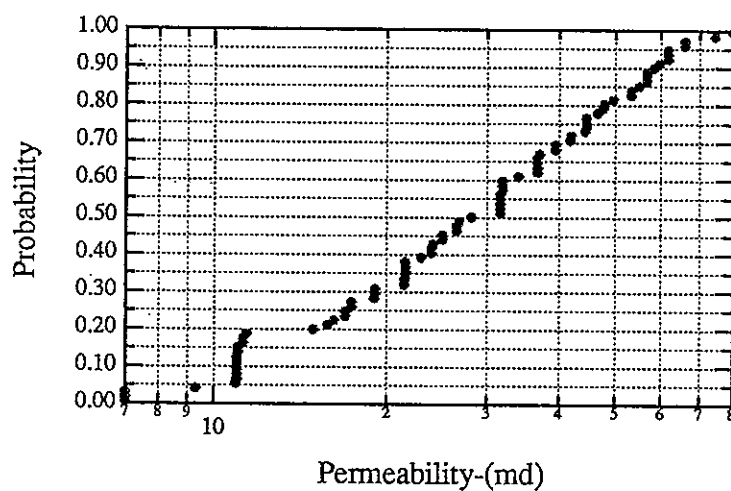
Figure 5.13. Frequencies and probability for vertical transect measurement on Outcrop 3, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.



(a)

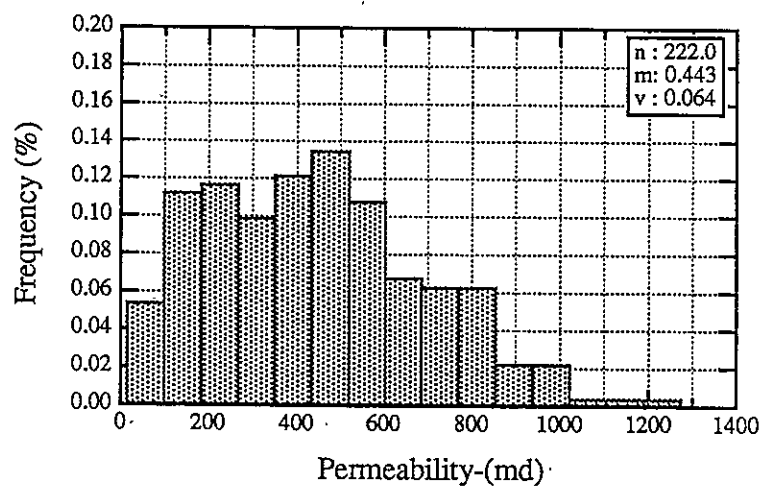


(b)

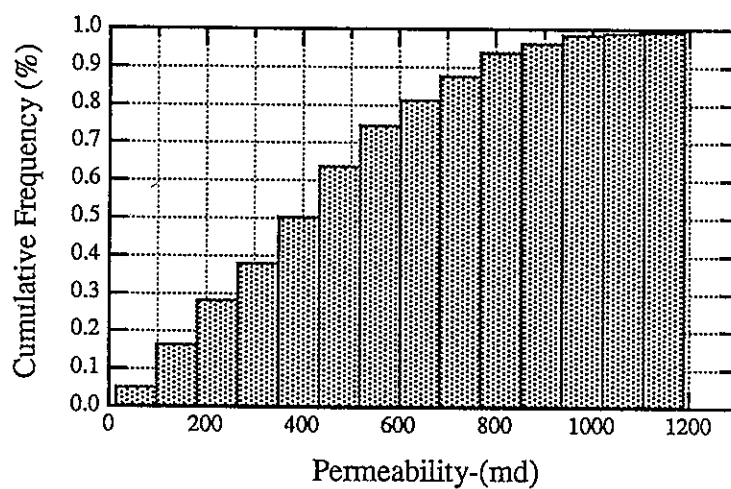


(c)

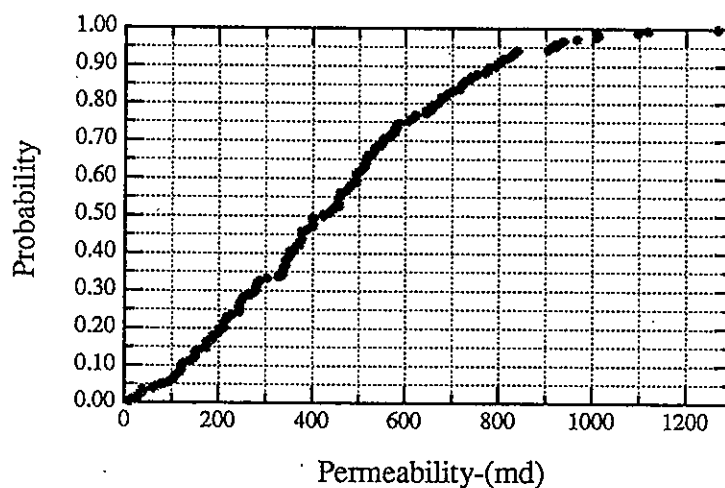
Figure 5.14. Frequencies and probability for Unit 6A of Well 2, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.



(a)



(b)



(c)

Figure 5.15. Frequencies and probabilities for horizontal transect measurement on Outcrop 2, (a) relative frequency distribution, (b) cumulative frequency distribution, (c) probability.

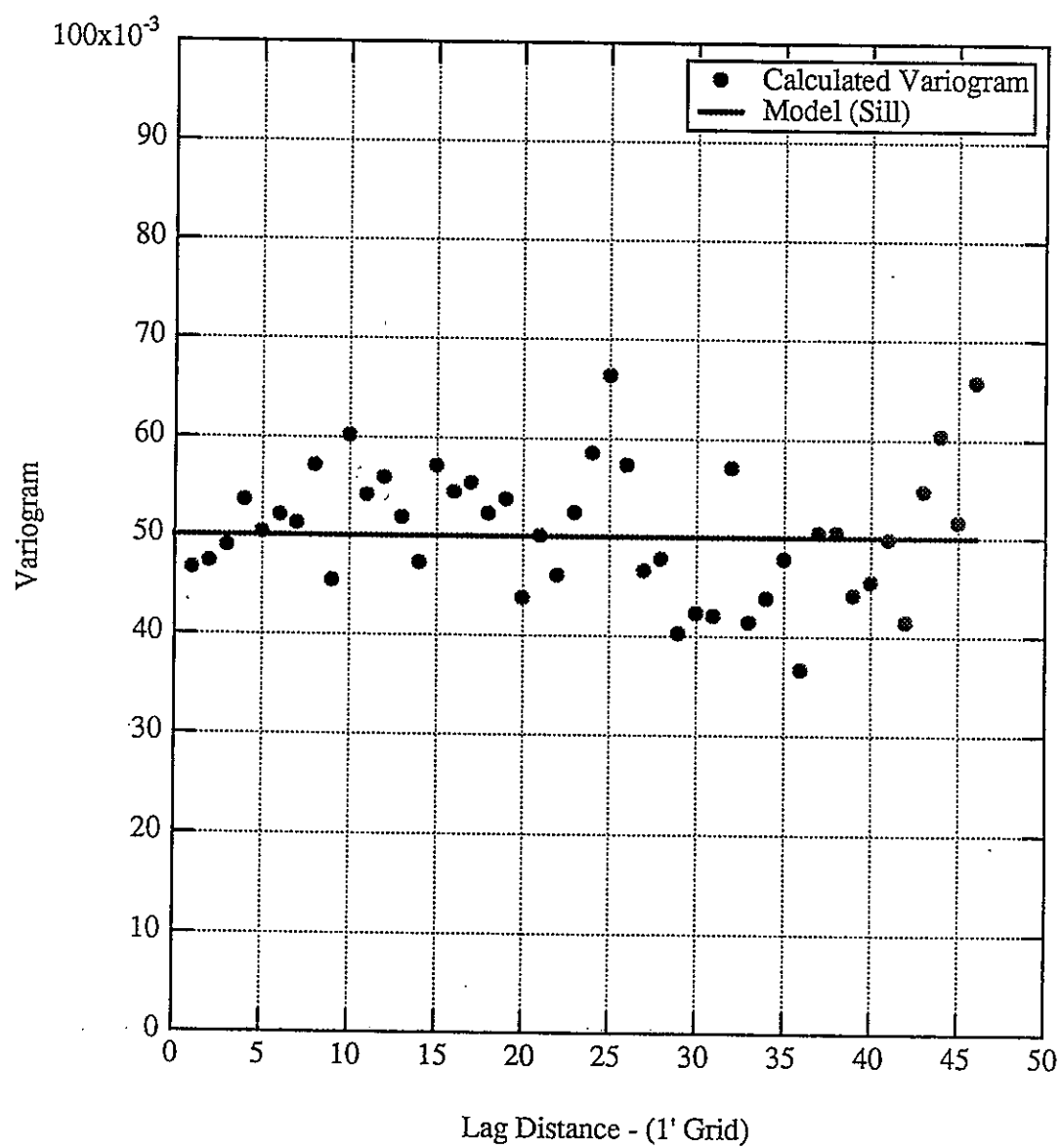


Figure 5.16. Variogram for the data from Outcrop 1, Unit 11, (1 foot-grid).

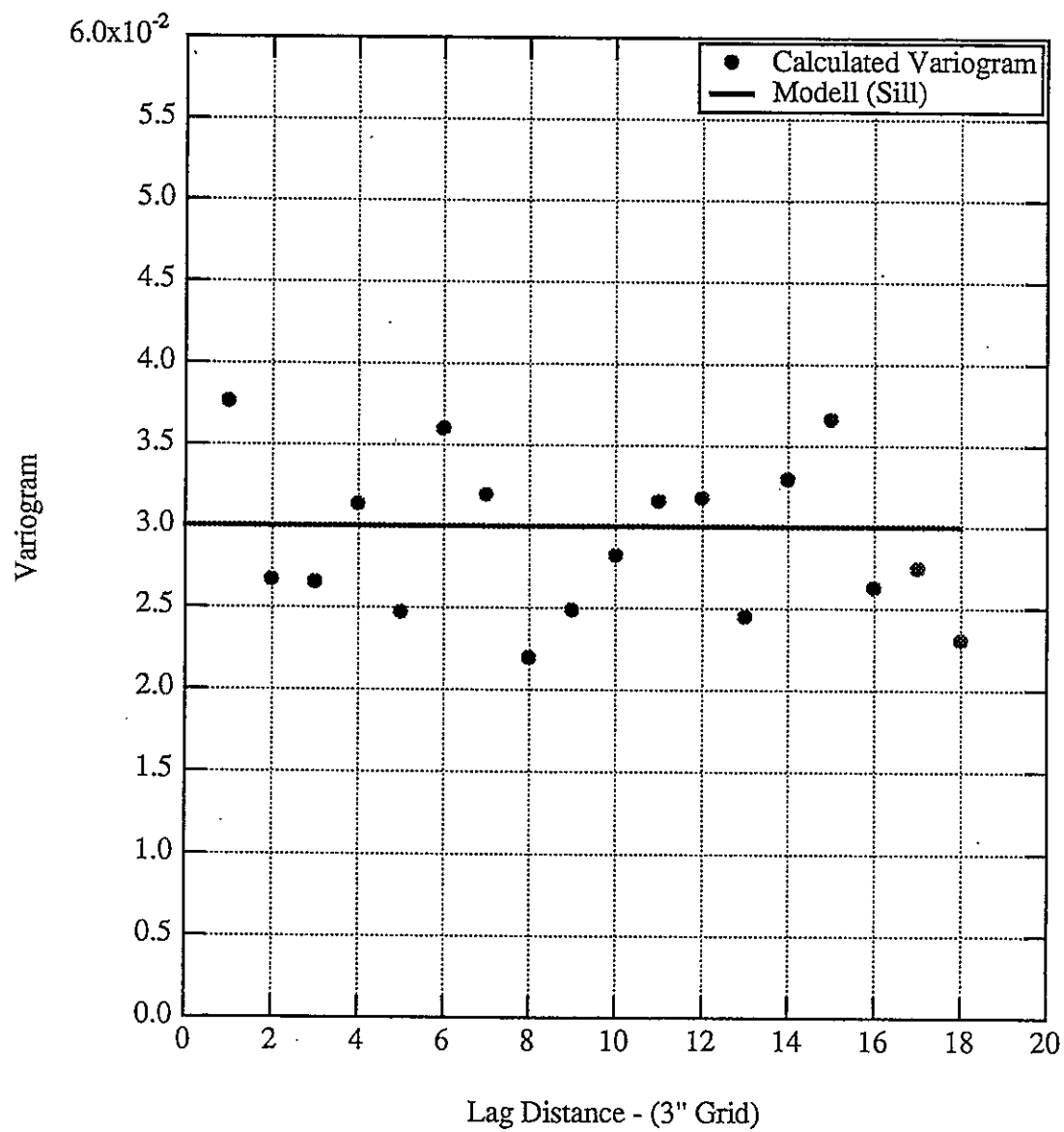


Figure 5.17. Variogram for the data from Outcrop 1, Unit 11, (Horizontal 3\"-grid).

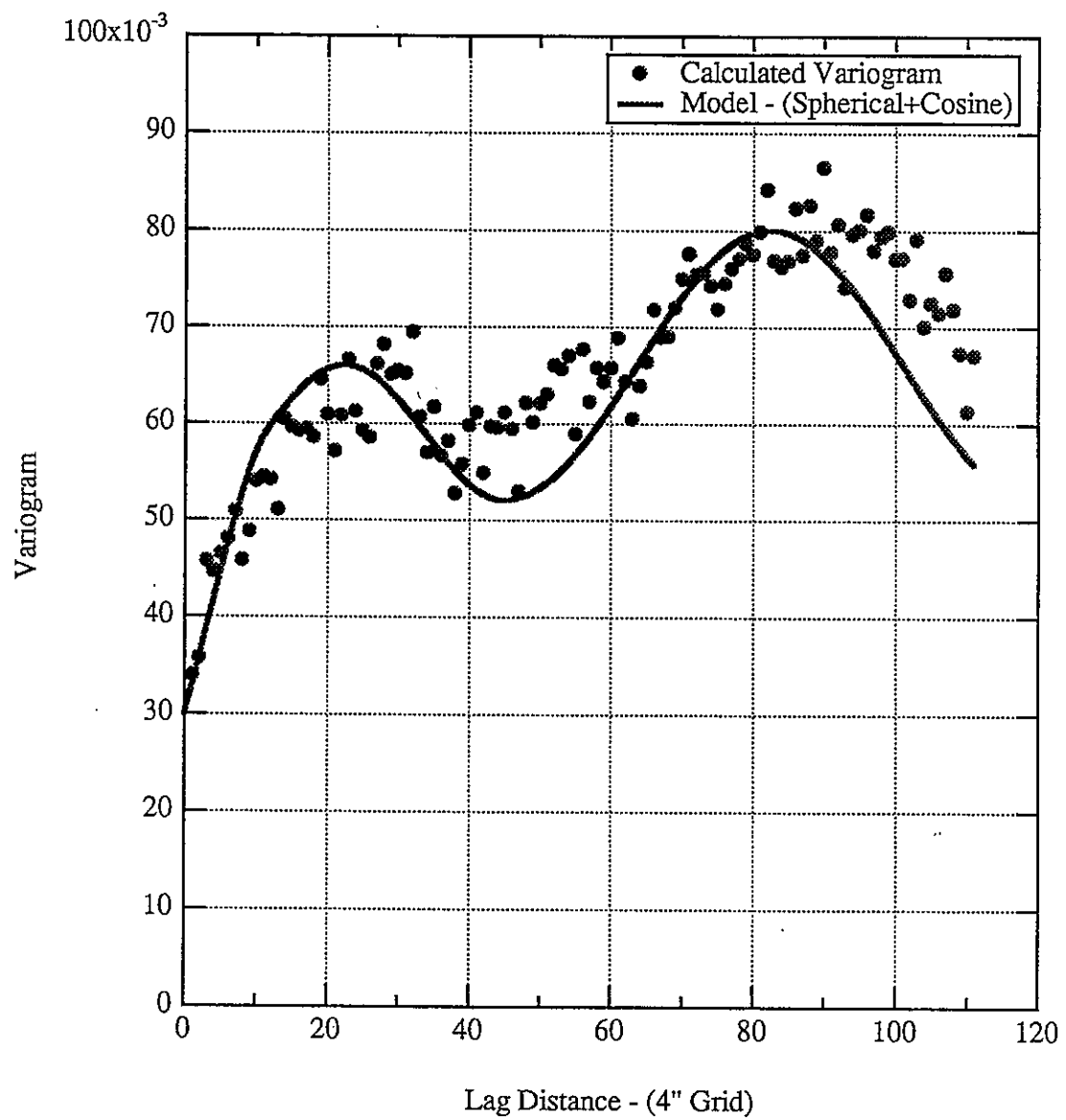


Figure 5.18. Variogram for data from Outcrop 2, (Horizontal 4"-grid).

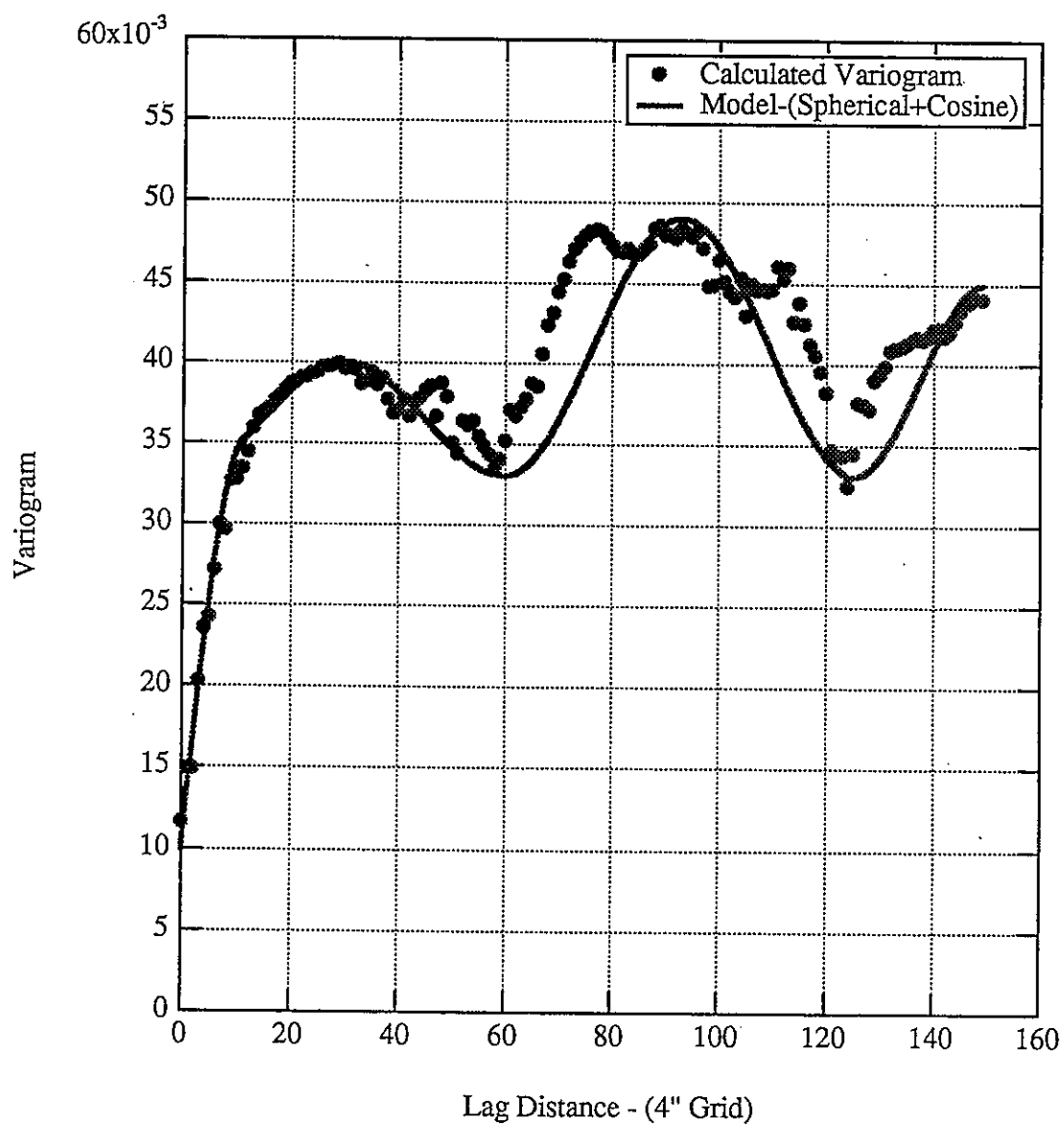


Figure 5.19. Variogram for the data from Outcrop 2, (Vertical 4"-grid).

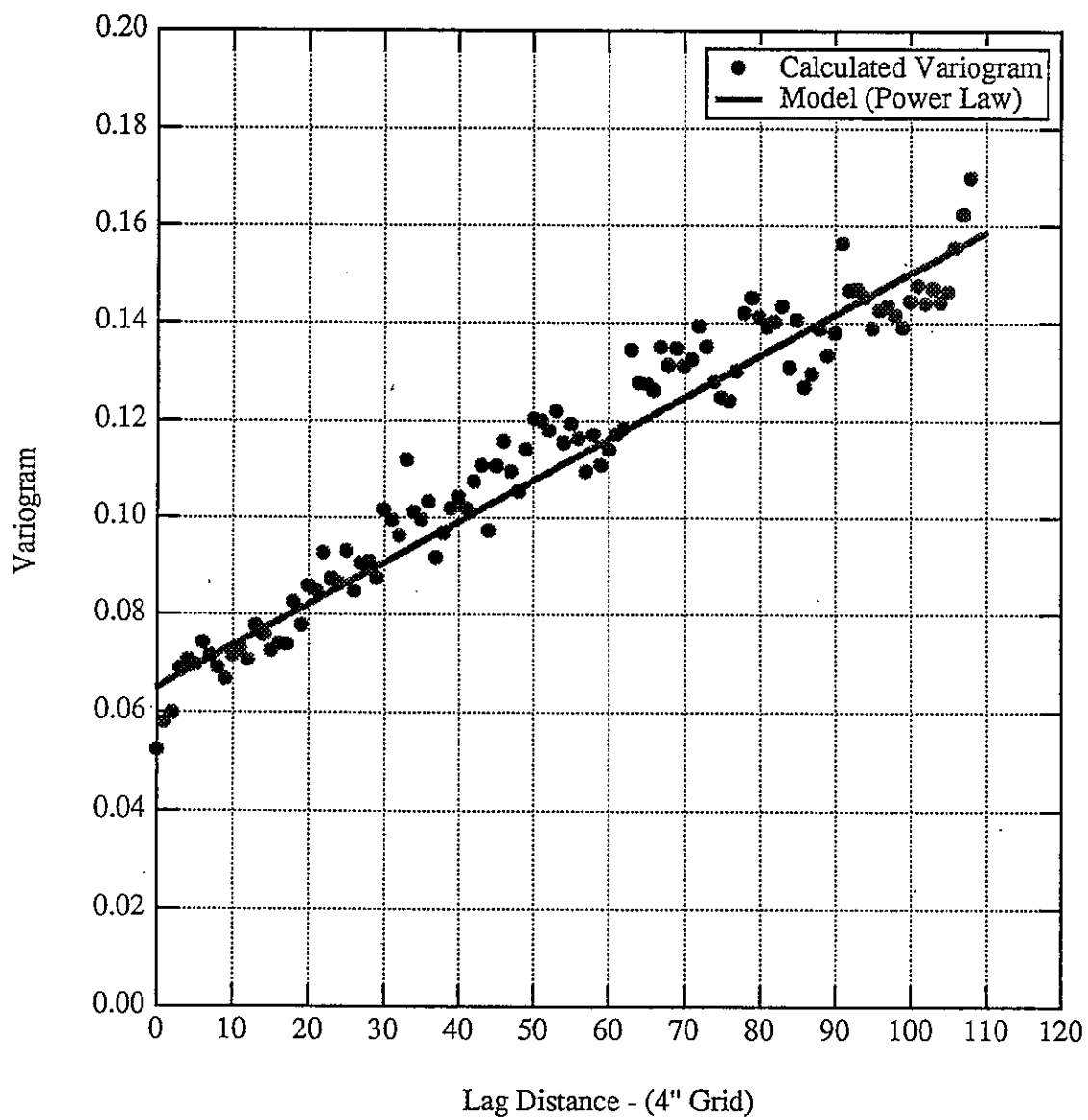


Figure 5.20. Variogram for the data from Outcrop 3, (Vertical 4"-grid).

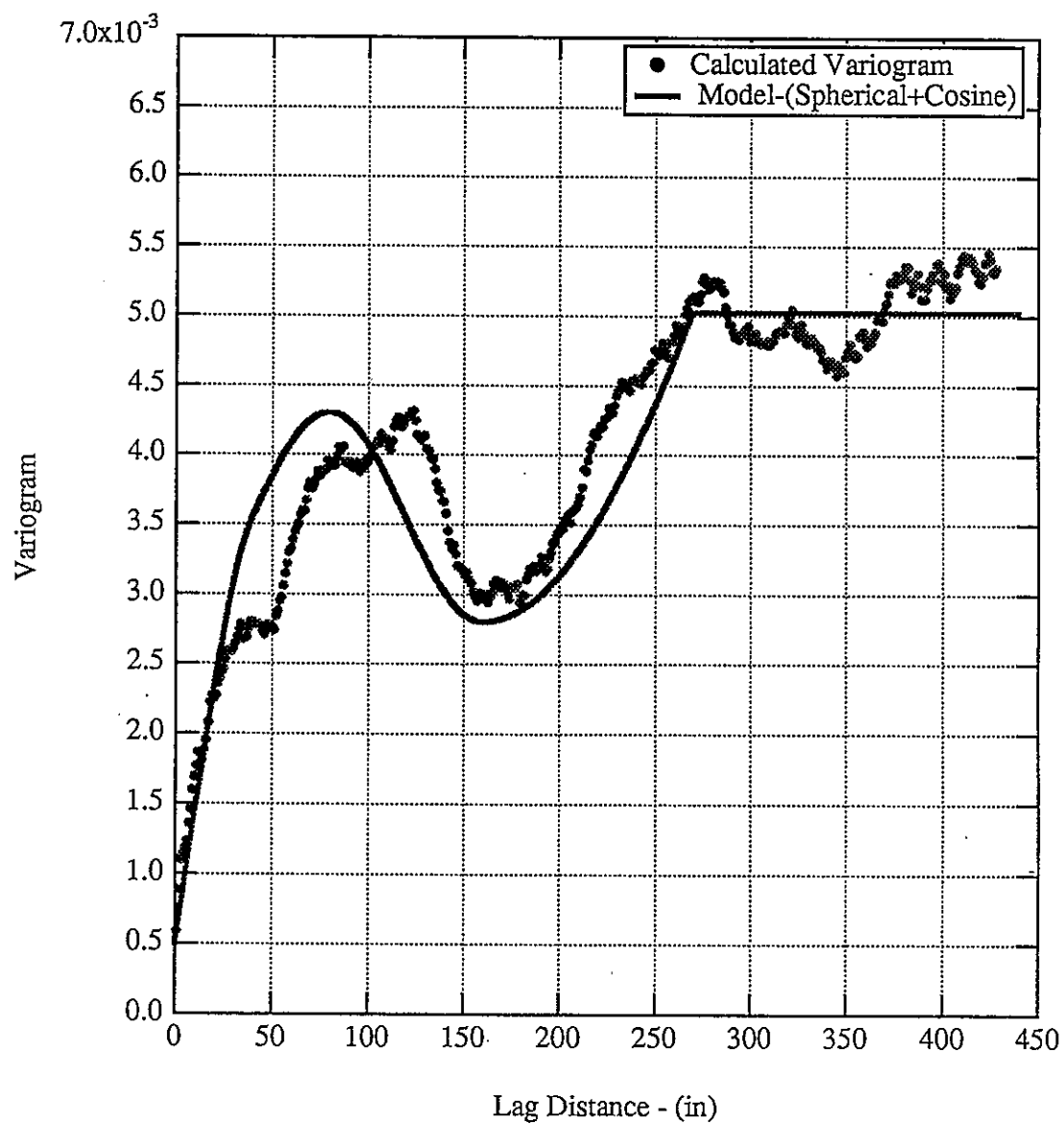


Figure 5.21. Variogram for the data from Well A2, (1"-grid).

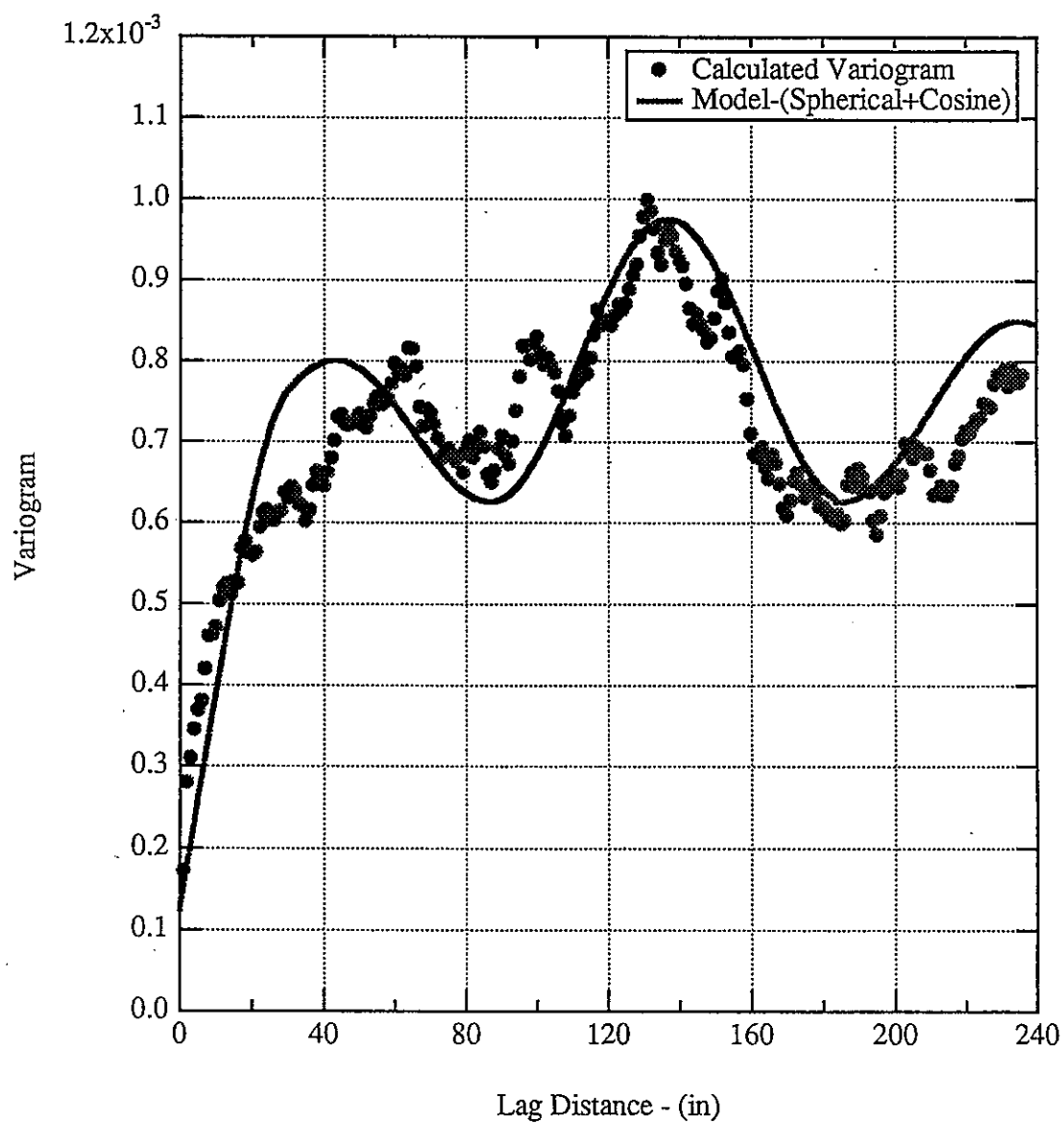


Figure 5.22. Variogram for the data from Well 2, (1"-grid).

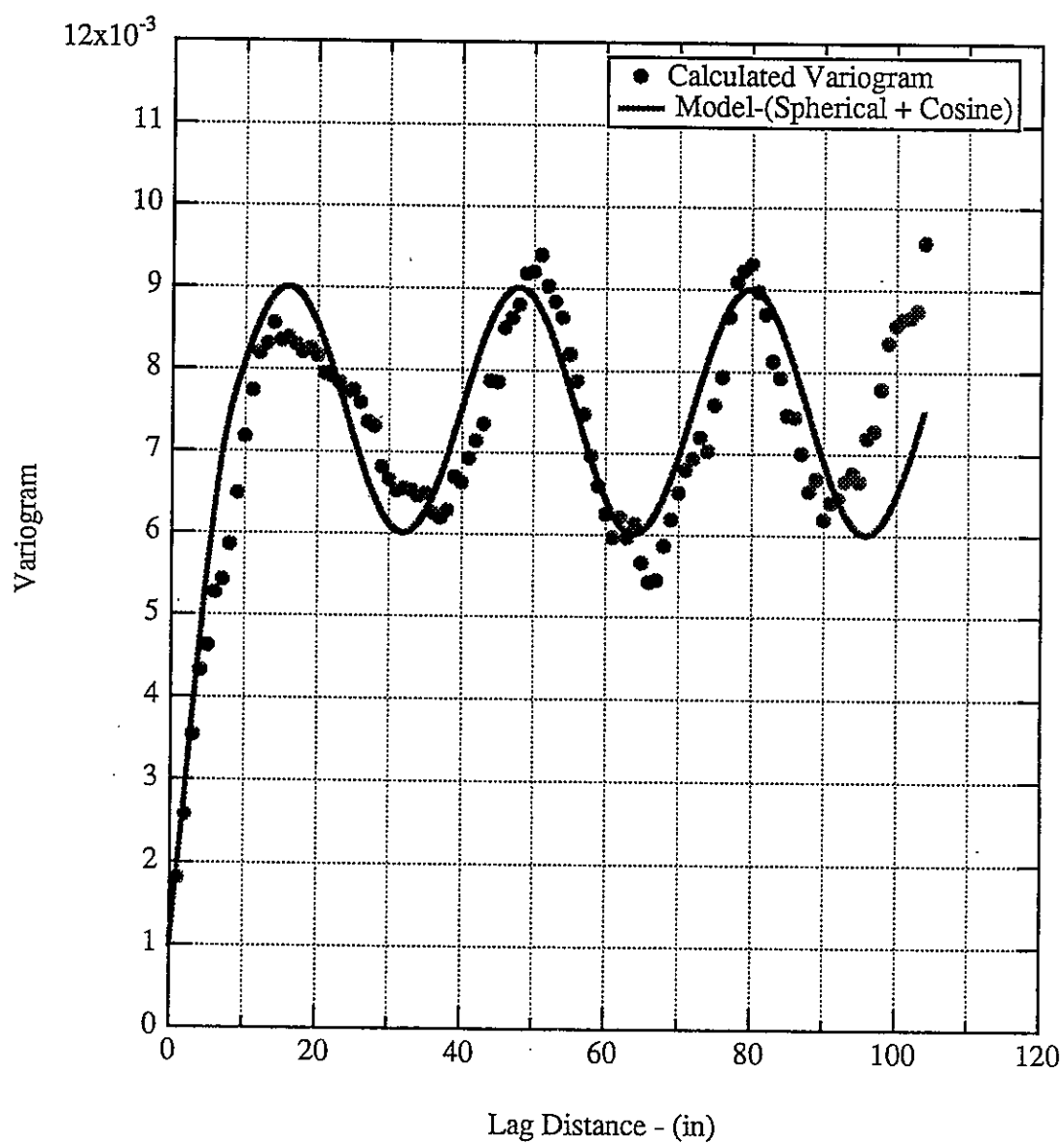


Figure 5.23. Variogram for the data from Well 7_22, (1"-grid).

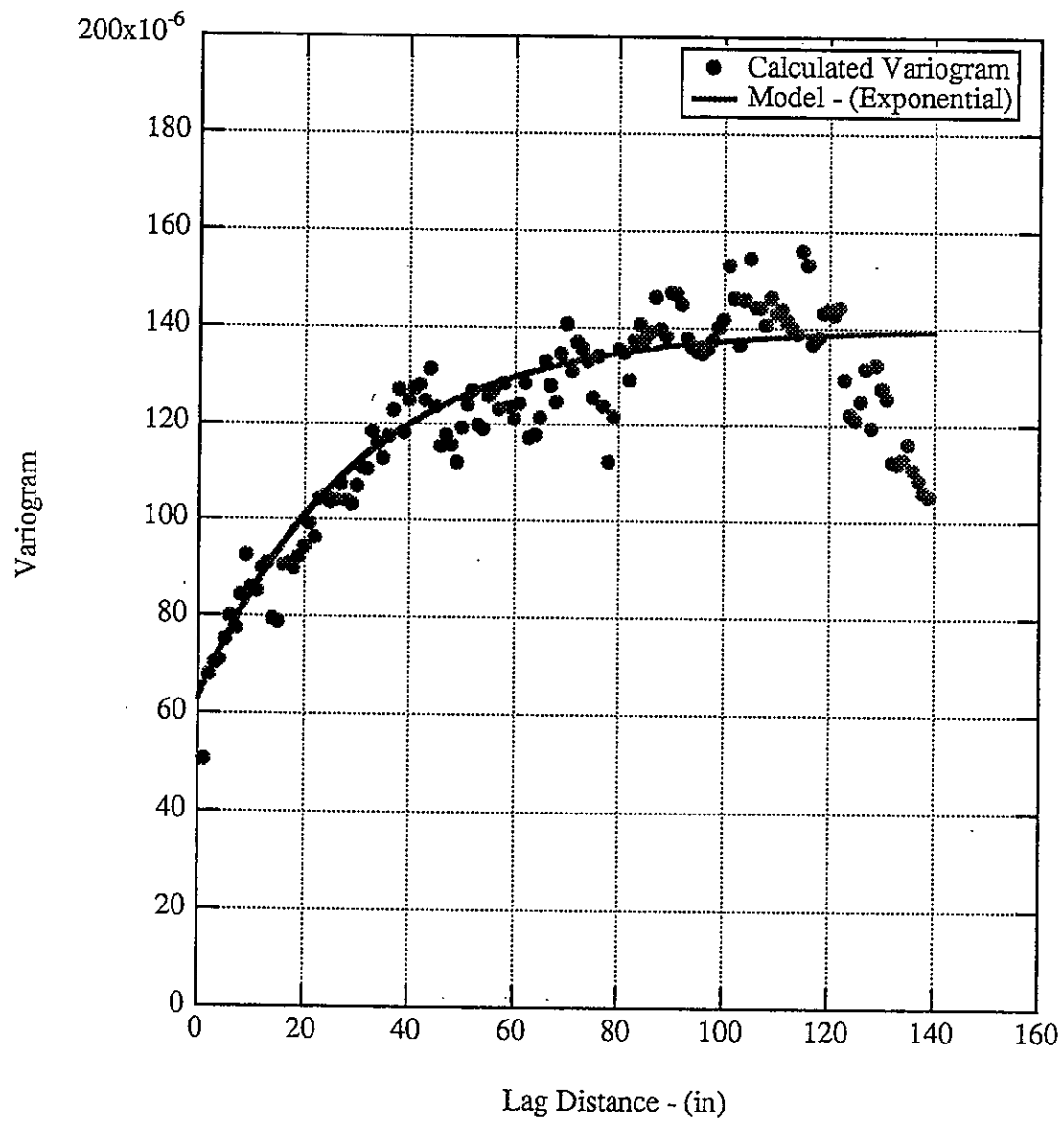


Figure 5.24. Variogram for the data from Unit 16, Well A2, (1"-grid).

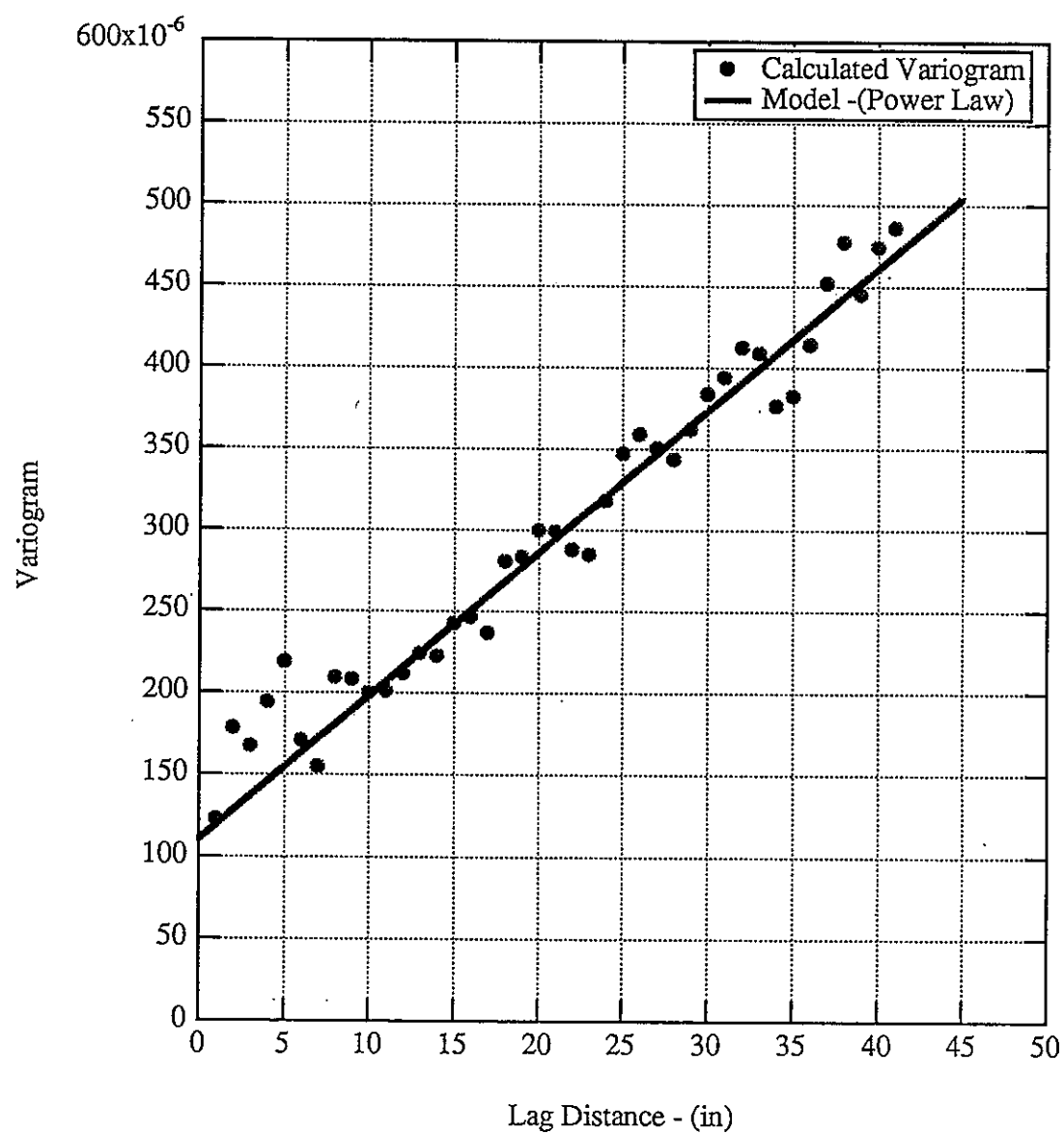


Figure 5.25. Variogram for the data from Unit 6A, Well 2, (1"-grid).

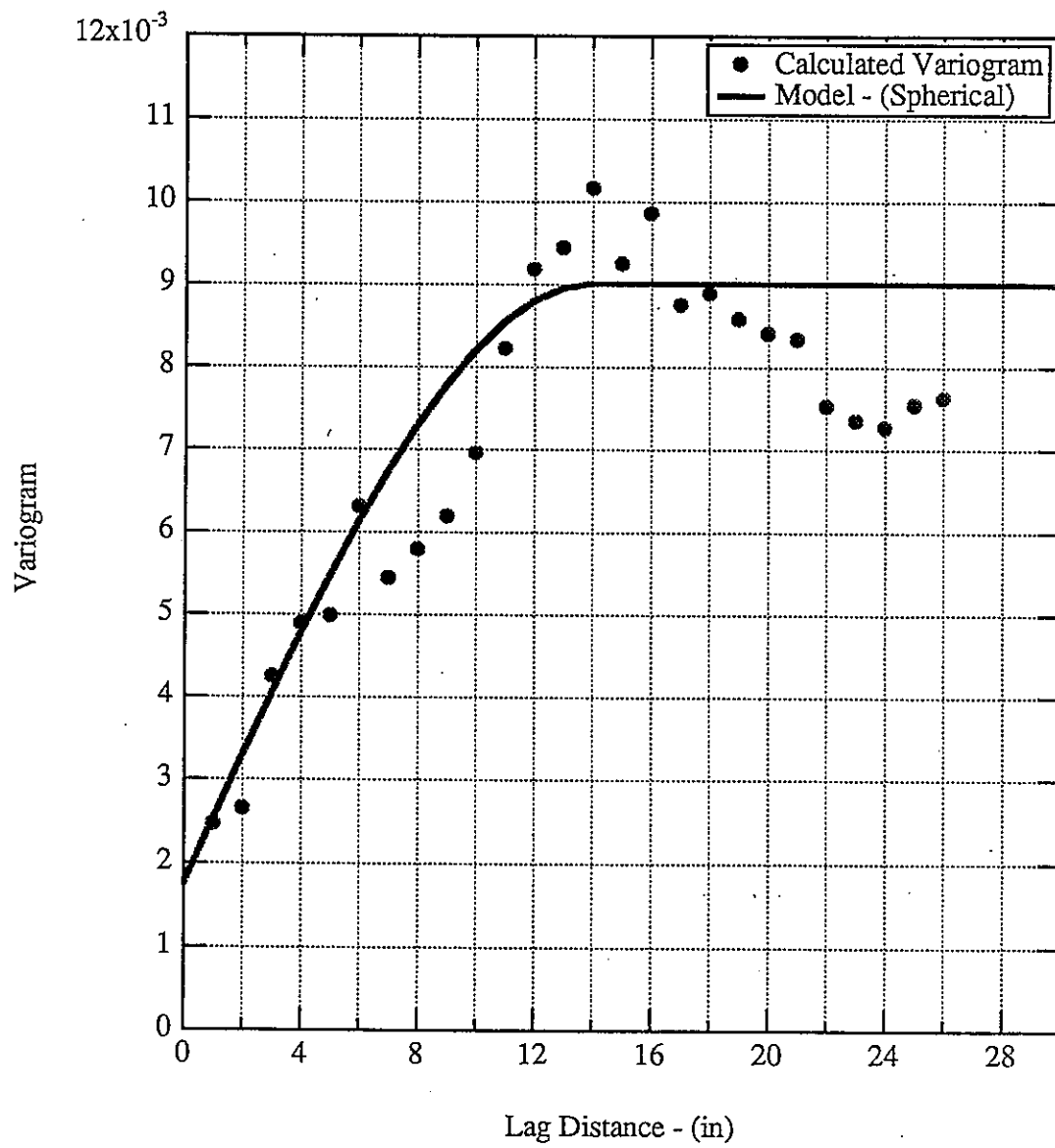


Figure 5.26. Variogram for the data from Unit 25A, Well 7-22, (1'-grid).

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The following conclusions can be drawn from the results of previous five chapters.

1. The Mechanical Field Permeameter (MFP) can be used to take large number of relatively inexpensive, non destructive, and rapid permeability measurements on outcrop formations. MFP has also been successfully used for detailed studies on subsurface cores.
2. To obtain the best representative permeability values of outcrop rock samples, a well prepared surface is needed. Chipping is found to be the most suitable surface preparation technique.
3. The average and maximum errors in arithmetic mean are functions of number of data and heterogeneity, while standard deviation errors are only functions of number of data. A linear relationship is derived between average error and inverse of square root of number of data, but a quadratic relationship is observed in maximum error. This is true for both arithmetic mean and standard deviation errors.
4. Average and maximum error coefficients are 0.74 and 4.4 respectively, which are the same for arithmetic mean and standard deviation.

5. Error in arithmetic mean is related to error in standard deviation with coefficient of variation.
6. Error analysis shows that the majority of the data sets gathered from the outcrop formations and the subsurface core slabs have enough number of data to calculate the mean permeability and standard deviation with an acceptable error of 25%. But some sets are not enough to generate variograms to quantify spatial relationship.
7. Unit generation from permeability derivative is a practical and inexpensive way to generate flow units for numerical simulations. With further development it may be used to supplement geological expertise required for defining flow units.
8. All outcrop and subsurface data collected within units indicate low heterogeneity, and insensitivity to direction, provided that unit boundaries are not crossed. Dykstra-Parsons coefficient for single units is around 0.3, but for multi-unit sets, it goes up to 0.6.
9. Relatively homogeneous single-unit data show normal distribution, while multi-unit heterogeneous data indicate log normal distribution.
10. The variograms for subsurface and outcrop data consistently indicate hole effect when unit boundaries are crossed. Stability of hole effect (wave length) is a function of geological structure within the measured sections.
11. In general, the variogram of an individual unit does not show hole effect. Variogram for some data sets indicate trend in permeability (Outcrop 3), while

some data show total sill (Unit 11 of Outcrop 1 Section C), implying no spatial correlation in permeability.

12. Some variograms both from outcrop formations and subsurface core slabs have nugget effect despite the measurement grid.

Recommendations

This is the first quantitative characterization study on Muddy Sandstone outcrop and subsurface formations. Because of (in addition to weather conditions) heterogeneity and volume of Outcrop 1, which was the main study area, enough number of measurement could not be carried out at every section of the outcrop. It might be worthy to get some detailed vertical measurements and some more detailed horizontal measurements to compare with each other. Unit size and shape distributions can be a future study that can be used in similar subsurface stochastic simulations. Errors can be investigated for other geostatistical parameters such as, harmonic mean, Daykstra-Parsons coefficient, correlation coefficient, etc.).

NOMENCLATURE

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>
a	internal radius of the tip-seal or range	[L]
b_D	dimensionless tip-seal thickness	[L]
$C_{1,2,3}$	constants	
C_{AEA}	average error coefficient for arithmetic mean	
C_{AES}	average error coefficient for standard deviation	
$C_{i,Dx,D2}$	dimensionless constants	
C_{MEA}	maximum error coefficient for arithmetic mean	
C_{MES}	maximum error coefficient for standard deviation	
C_o	nugget	
C_v	coefficient of variation	
E_{am}	error in arithmetic mean	
E_{sdv}	error in standard deviation	
EA_{am}	average error in arithmetic mean	
EA_{sdv}	average error in standard deviation	
EM_{am}	maximum error in arithmetic mean	
EM_{sdv}	maximum error in standard deviation	
G_o	geometrical factor	
h	lag distance	[L]
K_G	gas permeability	[L ²]
L	period	[L]
L_{core}	core-plug length	[L]

NOMENCLATURE (cont'd)

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>
L_D	dimensionless core-plug length	
m	slope	
N	number of data	
n	number of pairs for a given lag distance	
P_i	measured pressure	$[M/L^2]$
P_o	atmospheric pressure	$[M/L^2]$
Q	flow rate	$[L^3/T]$
R_{core}	core-plug radius	$[L]$
R_D	dimensionless core-plug radius	$[L]$
$\bar{X}$	sample arithmetic mean	
H_m	sample harmonic mean	
X_i	sample	
x_i	measured locations	$[L]$
V_{DP}	Dykstra-Parsons coefficient	
$V(x_i)$	measured value of variable at location of x_i	
$V(x_i+h)$	measured value of variable at location of x_i+h	
<u>Greek Letters</u>		
$\gamma(h)$	variogram for lag distance of h	
μ	population mean	
σ	population standard deviation	
σ_x	sample standard deviation	
σ^2	population variances	

NOMENCLATURE (cont'd)

<u>Symbol</u>	<u>Description</u>	<u>Unit</u>
<u>Subscripts</u>		
AEA	average error in arithmetic mean	
AES	average error in standard deviation	
am	arithmetic mean	
core	core-plug	
D	dimensionless	
DP	Dijkstra-Parsons	
G	gas	
m	mean	
MEA	maximum error in arithmetic mean	
MES	maximum error in standard deviation	
sdv	standard deviation	
v	variation	
<u>Superscript</u>		
ω	fractal dimension	

REFERENCES

1. Lake, L. W., Jensen L. J., " A Review of Heterogeneity Measures Used in Reservoir Characterization," In Situ (1991) 15, No.4, in press.
2. Kasap, E., " Analytical Methods To Calculate an Effective Permeability Tensor and Effective Relative Permeabilities for Cross-bedded Flow Units," Ph.D. Dissertation, The University of Texas, May 1990, 231 pages.
3. Jones, J.R, Jr. Scott, A.J., and Lake, L. W., " Reservoir Characterization for Numerical Simulation of Mesaverde Meanderbelt Sandstones, Northwestern Colorado," SPE Formation Evaluation (March 1987) 97-107.
4. Chandler, M. A., Goggin, D. J., and Lake, L. W." A Mechanical Field Permeameter For Making Rapid, Non-Destructive, Permeability Measurements," Journal of Sedimentary Petrology, Vol.59, No.4, July, 1989, P.613-635.
5. Hutchinson, C.A., Dodge, C.F., and Polasek, T.L., "Identification, Classification and Prediction of Reservoir Nonuniformities Affecting Production Operations," J. Pet. Tech., pp 223-230, March 1961.
6. Polasek, T.L., Hutchhinson, C.A., "Characterization of Nonuniformities Within A Sandstone Reservoir From A Fluid Mechanics Standpoint," Proc. 7th World Pet. Congr., Vol.2, pp 397-407, 1967.
7. Verrien, J.P., and Couraud, G., "Applications of Production Geology Methods to Reservoir Characteristic analysis From Outcrop Observations," Proc. 7th World Pet. Congr., Mexico, Vol.2, pp 397-407, 1967
8. Hrabar, S.V., and Potter, P.E., "Lower West Baden (Mississippian) Sandstone Body of Owen and Greene Countries, Indiana," Am. Assoc. Petrol. Geol. Bull., Vol.53, pp 210 - 216, 1969.

9. Dodge, C.F., Holler, D.P., and Meyer, R.L., "Reservoir Heterogeneities of Some Cretaceous Sandstone," Am. Assoc. Petrol. Geol. Bull., Vol.2, pp 1814 - 1827, 1971.
10. Robertson, R.W., and Caudle, B.H., "Permeability Continuity of Laminae in the Calvin Sandstone," J. Pet. Tech., pp 661-670, June 1971.
11. Pryor, W.H., "Permeability-Porosity Patterns and Variations in Some Holocene Sand Bodies," Am. Assoc. Petrol. Geol. Bull., Vol.57, No1 pp 162 - 189, 1973.
12. McLean, H., "Reservoir Properties of Submarine-fan Facies: Great Valley Sequence, California," J. Sed. Pet., Vol.51, No.3, pp 865-872, September, 1981.
13. Stalkup, F.I., "Permeability Variations Observed at the Faces of Crossbedded Sandstone Outcrops," In Lake, L.W., and Carrol, H.B., Reservoir Characterization, pp 141- 179, Academic Press, 1986.
14. Stalkup, F.I., and Ebanks, W.J., "Permeability Variation in a Sandstone Barrier Islands-Tidal Channel-Tidal Complex, Ferron Sandstone (Lower Cretaceous), Central Utah," SPE paper 15532 presented at the 61st Technical Conference held in New Orleans, 5-8 October, 1986.
15. Tomusta, L., Jackson, S.R., and Szpakiewicz, M., "Geostatistical Characterization and Comparison of Outcrop and Subsurface Facies. Shannon Shelf Sand Ridges," SPE paper 15127 presented at the 56th California Regional Meeting held in Oakland, 2-4 April 1986.
16. Lewis, J.J.M., "Studies of Reservoir Heterogeneity and Permeability Anisotropy in lithified Carbonate Sands From the Great Oolite Formation (Middle Jurassic) of Southern England," Unpubl. Ph.D. Thesis, University of Reading, 1987.
17. Lewis, J.J.M., "Outcrop-derived Quantitative Models of Permeability Heterogeneity For Genetically Different Sandbodies," SPE 18153 presented at

- the 63rd Annual Technical Conference held in Houston, TX, pp 449-463, 2-5 October, 1988.
18. Jackson, S.R., Tomusta, L., and Szpakiewicz, M., Chang, M.M., Honarpour, M.M., and Schatzinger, R.A., "Construction of Reservoir Model by Integrating and Engineering Information - Bell Creek Field, a Barrier/Sandplain Reservoir," presented at the Second International Reservoir Characterization Technical Conference, Dallas, Texas, 1989.
 19. Tomusta, L., Chang, M.M., and Jackson, S.R., "Application of Outcrop Data For Characterizing Reservoirs and Deriving Grid-block Scale Values For Numerical Simulation," presented at 3rd International Reservoir Characterization Technical Conference, November 3-5, 1991, Tulsa, Oklahoma, DOE/NIPER paper 3RC-08.
 20. Weber, K.J., Eijpe, R., Leijnse, D., and Moens, C., "Permeability Distribution in A Holocene Distributory Channel-fill Near Leerdam (the Netherlands)," *Geologie en Mijnbouw*, Vol.51, pp 53-62, 1972.
 21. Goggin, D. J., Chandler, M. A., Kocurek, G., and Lake, L. W., " Patterns of Permeability in Eolian Deposits: Page Sandstone (Jurassic), Northeastern Arizona," *SPE Formation Evaluation*, V.3, 297-306, 1988.
 22. Kittridge, M.G., Lake, L.W., Lucia, F.J., Fogg, G.E., " Outcrop-Subsurface Comparison of Heterogeneity in the San Andres Formation," paper SPE 19596 presented at the 1989 SPE Annual Technical Conference and Exhibition, San Antonio, Oct. 8-11.
 23. Drayer, T., Scheie, A., and Walderhaug, O., "Minipermeameter-based Study of Permeability Trends in Channel Sandbodies," *Am. Assoc. Petrol. Geol. Bull.*, Vol.74, pp 359 - 374, 1990
 24. Jacobsen, T., and Rendall, H., "Permeability Patterns in Some Fluvial Sandstones. An Outcrop Study From Yorkshire, North East England," Presented at Second

- International Reservoir Characterization Technical Conference, Dallas, Texas, 1989.
25. Senger, R.K., Lucia, F.J., Kerans, C., Ferris, M.A., and Fogg, G.E., "Dominant Control on Reservoir-Flow Behavior in Carbonate Reservoirs as Determined From Outcrop Studies, " presented at 3rd International Reservoir Characterization Technical Conference , November 3-5,1991, Tulsa. Oklahoma, DOE/NIPER paper 3RC-58.
 26. Lake, L.W., and Kocurek, G., "Geometrical Factors for unconfined core plugs using the field permeameter," In: 4th Annual Center for Enhanced Oil Recovery Resarch Report, Category A Resarch, University of Texas at Austin, 3-24, 1987.
 27. Jacobsen, T., Hoyer, T., Aasen, J.O., MacDonald, A., and Grindheim A., "Evaluation, Relevance, and Application of High Resolution Permeameter Data in Reservoir Modeling," presented at 3rd International Reservoir Characterization Technical Conference , November 3-5,1991, Tulsa. Oklahoma, DOE/NIPER paper 3RC-32.
 28. Lewis, J.J.M., Hurst, A., and Lowden, B., "Permeability Distribution and Measurement of Reservoir-Scale Sedimentary Heterogeneities in the Lochaline Sandstone (Cretaceous)," Field Guide, 13th International Sedimentological Congress, Nottingham, U.K., 26-31 August, 1990.
 29. Lewis, J.J.M., "A Methodology for the development of Spatial Reservoir Parameter Databases at Outcrop," In publish Heriot-Watt University, Riccarton, Edinburg.
 30. Tillman, R.W., "Reservoir Heterogeneities, Valley-Fill Sandstones Reservoirs, Southwest Stockholm Field, Kansas," presented at 3rd International Reservoir Characterization Technical Conference , November 3-5,1991, Tulsa. Oklahoma, DOE/NIPER paper 3RC-69.

31. Goggin, D. J., Threasher, R., and Lake, L. W., "A Theoretical and Experimental Analysis of Minipermeameter Response Including Gas Slippage and High Velocity Flow Effects," *In Situ*, V.12, No.1 and 2, (1988) 79-116
32. Baker, D.R., "The Newcastle Formation in Weston County, Wyoming: A Non-Marine (Alluvial) Plain Deposits" in 17th Annual Field Conference, Wyo.Geol. Assoc., p.148-162, 1962.
33. Emme, J.J., "Tectonic Influence on Sedimentation, Lower Cretaceous Strata Osage Newcastle area, Powder River Basin, Wyoming" Unpublished M.Sc. Thesis, Colorado School of Mines 173 Pages., 1981.
34. Farmer, C.L., "Tectonics and Sedimentation, Newcastle Formation (Lower Cretaceous) Southwestern Flank of Black Hills Uplift, Wyoming and South Dakota," Unpublished M.Sc. Thesis, Colorado School of Mines, 195 pages, 1981.
35. Tillman, R. W., and Dailey, D. H., "Evidence for Barrier Islands (vs Stand-plain) and Valley Fill Origins of Production Heterogeneities in Bell Creek Field, Montana," *Am. Assoc. Petrol. Geol. Bull.*, 1989, Vol.73, p.419-420.
36. Mayer, F.D., and Chapin, M.A., "A comparison of Outcrop and Subsurface Geologic Characteristic and Fluid-Flow Properties in the Lower Cretaceous Muddy J Sandstone," presented at 3rd International Reservoir Characterization Technical Conference , November 3-5,1991, Tulsa. Oklahoma, DOE/NIPER paper 3RC-23.
37. Jensen, J.L., Hinkley, D.V, and Lake, L.W., " A Statistical Study of Reservoir Permeability: Distributions, Correlations, and Averages," *SPE Formation Evaluation* (Dec. 1987) 461-468.
38. Jensen, J. L., Corbet, P.W.M., "A Stochastic Model for Comparing Probe Permeameter and Core Plug Measurements" presented at 3rd International

- Reservoir Characterization Technical Conference , November 3-5,1991, Tulsa. Oklahoma, DOE/NIPER paper 3RC-24.
39. Aasum, Y., Kasap, E., Kelkar, M., "Detecting Permeability Anisotropy and Cross-Bedding Patterns by Using Mini-Field-Permeameters", presented at 3rd International Reservoir Characterization Technical Conference , November 3-5,1991, Tulsa. Oklahoma, DOE/NIPER paper 3RC-25.
 40. Goggin, D. J., "Geologically Sensible Modeling of Permeability Patterens in Eolian Deposits: Page Sandstone (Jurassic) Outcrop, Northern Arizona," Ph. D. Dissertation, The University of Texas at Austin, (December 1988)
 41. Corbett, P. W. M., and Jensen, J. L., "Variation of Reservoir Statistics According to Sample Spacing and Measurement Type for Some Intervals in the Lower Brent Group.", presented at Science and Technology Institute Advences in Reservoir Technology Confrence, Edinburgh, Scatland, 21-22 February, 1991.
 42. Warren J. E. and Cosvarge, J. J., "Prediction of Waterflood Behavior in a Stratified System," Soc. Pet. Eng. J. (June, 1964), 149-157.
 43. Tillman, R. W., and Pittman, E. D., Schenewerk, P., Malik, M., Kara, B., Navarrete, N., Kasap, E., "Multiple Scale Valley-Fill Sandstone Heterogenities and Geologic and Engineering Reservoir Characterization Analysis", 1st Semi-Annual Report SBIR-DOE DE-FG05-90ER80976, (Phase II), June 1992.
 44. Tillman, R. W., and Pittman, E. D., Schenewerk, P., Malik, M., Kara, B., Navarrete, N., Kasap, E., "Sun Ranch Field and Muddy Sandstone Outcrops; Multiple Scale Valley-Fill Sandstone Heterogenities and Geologic and Engineering Reservoir Characterization Analysis", Annual Report SBIR-DOE DE-FG05-90ER80976, (Phase II), December 1992.

45. Corbett, P. W. M., and Jensen, J. L., "Estimating the Mean Permeability: How Many Measurements Do You Need?." presented at the 3rd EAPG Meeting, Florence, 1991.
46. Kelkar, M. "Applied Geostatistics for Reservoir Characterization," The University of Tulsa, Oklahoma, 1992.
47. Wright, F.M., and Weber, L.J., "Integrated Outcrop and Subsurface Reservoir Characterization: Carbonate Sequence Stratigraphy and Reservoir Behavior of the Giant Aneth Oil Field, SE UTAH," presented at 3rd International Reservoir Characterization Technical Conference , November 3-5,1991, Tulsa. Oklahoma, DOE/NIPER paper 3RC-94.
48. Law, J. "Statistical Approach to the Interstitial Heterogeneity of Sand Reservoirs," Trans., AIME (1944) 155, 202-222.
49. Kasap, E., and Lake, L. W., "Dynamic Effective Relative Permeabilities for Cross-Bedded Flow Units," SPE Paper 20179, Proceedings of SPE/DEO 7th Symposium on Enhanced Oil Recovery, (April, 1990) 71-82.
50. Honarpour, M. M., Szpakiewicz, M. J., Schatzinger, R. A., Tomusta, T., Carroll, Jr., H. B., "Integrated Geological/Engineering Model For Barrier Island Deposits in Bell Creek Field, Montana," Pres. at SPE/DOE Enhanced Oil Recovery Symposium, April 17-20,1988, Tulsa, OK.,SPE/DEO paper 19366.
51. Russell, T. L., Bradley, D. J., "Applied Geostatistical Analysis: Sage Spring Creek Unit "A", Natrona County, Wyoming " Pres. at SPE Rock Mountain Regional Meeting, Casper, WY, May 11-13, 1988, SPE paper 17507.
52. Chandler, M. A., Kocurek, G., Goggin, D. J., and Lake, L. W., "Effects of Stratigraphic Heterogeneity on Permeability in Eolion Sandstone Sequence, Page Sandstone Northern Arizona," The American Association of Petroleum Geologists Bulletin, V.73, No.5 (May 1989), P.658-668.

53. Jensen, J.L., Lake, L.W., "The Influence of Sample Size and Permeability Distribution Upon Heterogeneity Measures," Pres. at the 61st Annual Technical Conference and Exhibition of SPE, New Orleans, LA October 5-8 1986, SPE paper 15434.
54. Tillman, R. W., and Pittman, E. D., " Reservoir Heterogeneities, Valley-Fill Sandstone Reservoirs, Southwest Field, Kansas," Pres. at 3rd International Reservoir Characterization Technical Conference of DOE/NIPER, Tulsa, Oklahoma, November 3-5, 1991, Vol.1, paper 3RC-69.
55. Jhonson, H. D., Krol, D. E., " Geological Modeling of a Heterogeneous Sandstone Reservoir: Lower Jurassic Statfjort Formation, Brent Field," Pres. at 59th Annual Technical Conference and Exhibition of SPE, Houston, TX, September 16-19, 1984, SPE paper 13050.
56. Honarpour, M. M., Tomusta, L., "Injection/Production Monitoring: An Effective Method for Reservoir Characterization," Pres. at SPE/DOE Enhanced Oil Recovery Symposium, April 22-25, 1990, Tulsa, OK., SPE/DEO paper 2026.

APPENDIX A

Flow Unit Generation Program

```

c =====
c program flowunit
c This program defines flow units of a formation by utilizing
c permeability derivatives.
c =====

c ***** Description of some parameters *****
c -----
c n          : Number of data
c unit(i)    : Unit numbers
c per(i)     : Permeability values
c dist(i)    : Permeability measured locations
c perdif(i)  : Permeability difference (derivative)
c length(i)  : Length of an individual units
c tlength(i) : Location of units according to
c             measured domain
c -----

integer unit(1000)
real per(1000),perdif(1000),dist(1000)
real length(1000),tlength(1000),unavg(1000)
real right,left,avgk(1000),loc(1000),uz(1000),kdif(1000)
character*100 label

open(1,file='unit.in',status='old')
open(2,file='un1.out',status='unknown')
open(3,file='un2.out',status='unknown')
open(4,file='unit.out',status='unknown')
open(5,file='temp.out',status='unknown')
read(1,'(A)')label
read(1,*)igeoun,n
read(1,*)left,right

c read permeability values and locations
do 5 i=1,n
  read(1,*) dist(i),per(i)
5 continue

  k=0
  iter=0
6  k=k+1
  iter=iter+1
  if (k.eq.1) then
    error=left
  elseif(k.eq.2) then
    error=right
  endif

c -----
c call units(dist,per,error,unit,length,tlength,unavg,ij,n)
c -----

```

```

iestun=ij
if (k.eq.1) then
    maxun=ij
    ier=left*100
    print*, 'Maximum Unit Number is : ', maxun, ' Error : ', ier, '%'
    go to 6
elseif(k.eq.2) then
    minun=ij
    ier=right*100
    print*, 'Minimum Unit Number is : ', minun, ' Error : ', ier, '%'
    iavgun=(minun+maxun)/2.
    print*, iavgun, ' Can Be Optimum Number of Unit'
    print*, 'But Do Not Forget Geological # of Unit : ', igeoun
    print*, 'How Many Unit Do You Want to Have'
    print*, 'Please Enter # of Unit That You Want'
    read*, optun
    error=(left+right)/2.
    go to 6
endif
if (iestun.ne.optun.and.iter.le.1E3) then
    if (iestun.ge.optun) then
        left=error
        error=(left+right)/2.
    else
        right=error
        error=(left+right)/2.
    endif
    go to 6
endif

ierror=error*100

c -----
c Combine the similar flow units
print*, 'Do you want to combine similar units'
print*, 'If yes enter 1'
print*, 'Else enter 0'
read*, code
if (code.eq.0) go to 16
ic=0
id=0
err=0.125
15 ic=ic+1
undif=abs(unavg(ic)-unavg(ic-1))
hata=((unavg(ic)+unavg(ic-1))/2.)*err

if (undif.gt.hata) then
    id=id+1
    avgk(id)=unavg(ic)
    uz(id)=length(ic)
    loc(id)=tlength(ic)
else
    avgk(id)=(unavg(ic)+unavg(ic-1))/2.
    uz(id)=length(ic)+length(ic-1)

```

```

        loc(id)=tlength(ic)
    endif

    if (ic.lt.ij) go to 15
c -----
c
c =====
c                      write statement
c =====
16  write(2,*)'*****'
    write(2,*)'(A)' label
    write(2,*)'Number of Data      : ',n
    write(2,*)'Error                : ',ierror,'% '
    write(2,*)'Geo.# of Unit       : ',igeoun
    write(2,*)'Number of Unit      : ',id
    write(2,*)'*****'

    do 17 in=1,id
    write(2,*)'-----'
    write(2,*)'Unit Number      : ',unit(in)
    write(2,*)'Unit Average     : ',avgk(in)
    write(2,*)'Unit Length      : ',uz(in),'          in'
    if (in.eq.1) then
    write(2,*)'Unit Location : ',dist(1),' -',loc(in),' ft'
    else
    write(2,*)'Unit Location : ',loc(in-1),' -',loc(in),' ft'
    endif
c -----
    write(3,*)tlength(in),' ',unit(in)
c -----
    if (in.eq.1) then
        write(4,*)loc(1),' ',avgk(1)
    else
        do 7 im=1,2
        if (im.eq.1) then
            write(4,*)loc(in-1),' ',avgk(in)
        else
            write(4,*)loc(in),' ',avgk(in)
        endif
7        continue
    endif
17  continue

c -----
    if (code.eq.0) go to 18
    ielim=optun-id
    print*, 'You asked' ,optun, '# of unit'
    print*, ielim, ' # of unit combined'
    print*, id, ' # of unit generated'
c -----
18  stop
    end
c =====

```

```

      subroutine units(dist,per,error,unit,length,tlength,unavg,ij,n)
c =====
      integer unit(1000)
      real per(1000),perdif(1000),dist(1000)
      real length(1000),tlength(1000),unavg(1000),mul

      mul=6
      expconst=1.

c  calculate permeability derivatives (dx=1)
      dx=1.
      i=0
      j=0
      ll=0
      ii=0
      ij=0
      ik=0
      total=0.
      ifirst=0
      count=0.

10  i=i+1
      irank=0
      ifirst=ifirst+1
      if (i.eq.1) go to 10
      if (ifirst.eq.1.and.i.ne.1) then
          i=i-1
          go to 10
      endif
      j=j+1
      total=total+per(i-1)
      count=count+1
      avgper=total/count

      if (i.eq.n) then
          total=total+per(i)
          count=count+1
          avgper=total/count
      endif

      perdif(j)=(per(i)-avgper)/dx

c  Define a tolerance based on permeability derivative
c  and local means of permeabilities

      tol=abs(perdif(j)/avgper)

c  First creteria for defining a new unit
      if (tol.le.error.and.i.lt.n) go to 10

c  Second creteria for defining a new unit
      ameank1=per(i)
      avg1=abs(2.*(avgper-ameank1)/(avgper+ameank1))
      irank=irank+1

```

```

const1=exp((real(irank)-mul)/(mul-expconst))
avgdif=const1*avg1

if (avgdif.gt.error) then
  go to 15
else
  amean2=(amean1+per(i+irank))/2.
  avg2=abs(2.*(avgper-amean2)/(avgper+amean2))
  irank=irank+1
  const2=exp((real(irank)-mul)/(mul-expconst))
  avgdif=const2*avg2
  if (avgdif.gt.error) then
    go to 15
  else
    amean3=(amean2+per(i+irank))/2.
    avg3=abs(2.*(avgper-amean3)/(avgper+amean3))
    irank=irank+1
    const3=exp((real(irank)-mul)/(mul-expconst))
    avgdif=const3*avg3
    if (avgdif.gt.error) then
      go to 15
    else
      amean4=(amean3+per(i+irank))/2.
      avg4=abs(2.*(avgper-amean4)/(avgper+amean4))
      irank=irank+1
      const4=exp((real(irank)-mul)/(mul-expconst))
      avgdif=const4*avg4
      if (avgdif.gt.error) then
        go to 15
      else
        amean5=(amean4+per(i+irank))/2.
        avg5=abs(2.*(avgper-amean5)/(avgper+amean5))
        irank=irank+1
        const5=exp((real(irank)-mul)/(mul-expconst))
        avgdif=const5*avg5
        if (avgdif.gt.error) then
          go to 15
        else
          amean6=(amean5+per(i+irank))/2.
          avg6=abs(2.*(avgper-amean6)/(avgper+amean6))
          irank=irank+1
          const6=exp((real(irank)-mul)/(mul-expconst))
          avgdif=const6*avg6
          if (avgdif.le.error) then
            go to 15
          else
            go to 20
          endif
        endif
      endif
    endif
  endif
endif
endif
endif
endif

```

```

15  ii=ii+1
    ij=ij+1
    ik=ik+1
    ll=ll+1
    ifirst=0
    total=0.

    if (ii.eq.1)then
        unit(1)=ij
        length(1)=real(i-1)+(dx/2.)
        tlength(1)=(dist(i-1)+dist(i))/2.
    else
        unit(ij)=ij
        length(ii)=count
        if (i.eq.n) then
            tlength(ik)=dist(n)
        else
            tlength(ik)=(dist(i-1)+dist(i))/2.
        endif
    endif
    unavg(ll)=avgper
    count=0

20  if (i.lt.n) go to 10
    return
    end
c  -----end-----

```

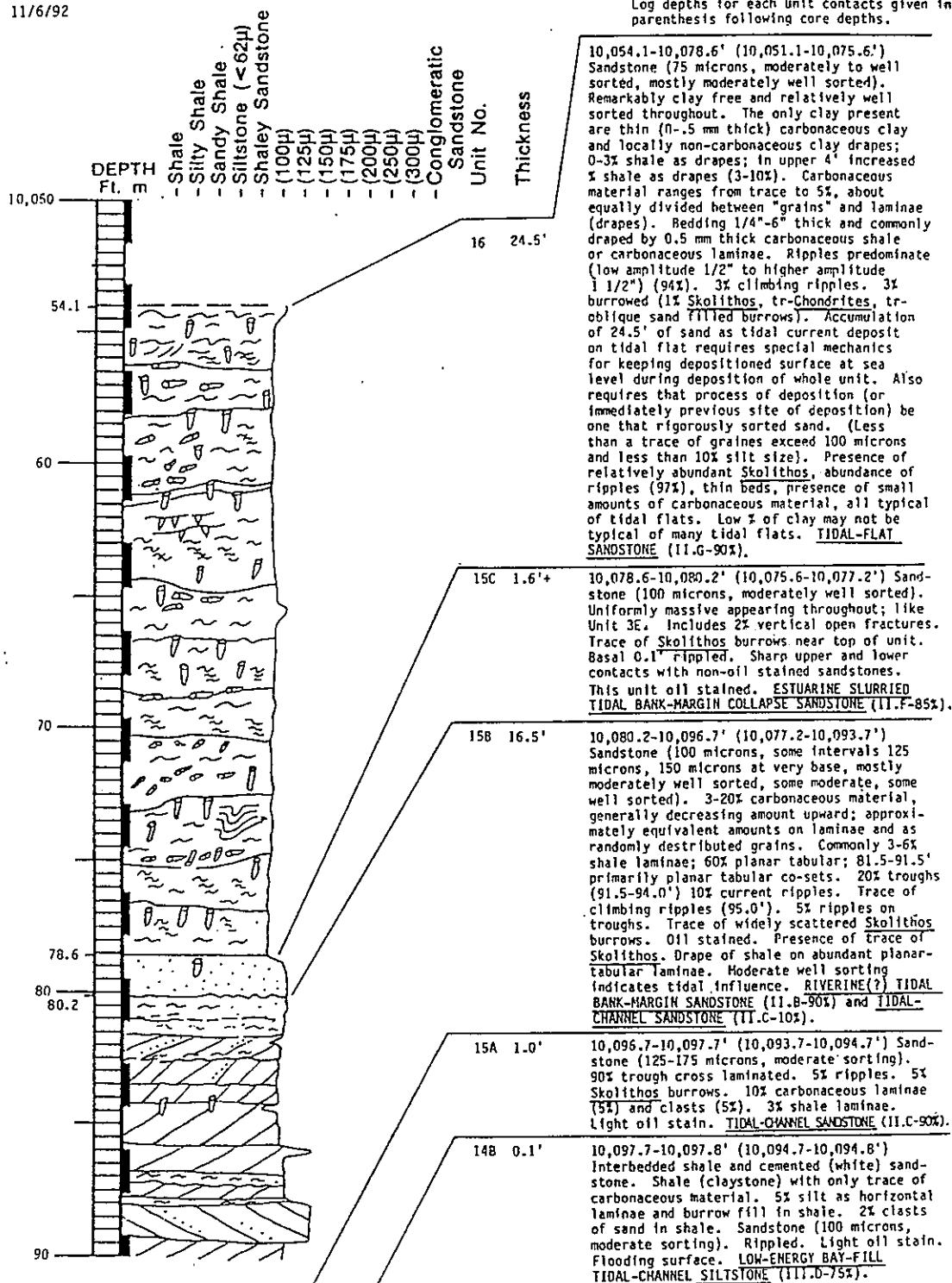
APPENDIX B

Geological Description for Units of Federal Well A2, 2, and 7-22,
Sun Ranch Field, by R. W. Tillman⁴³.

SUN EXPLORATION & PRODUCTION CO., SUN RANCH FEDERAL A-2
 MUDDY SANDSTONE, SUN RANCH FIELD
 SE SW SEC. 15 T33N R86W, NATRONA CO., WYOMING

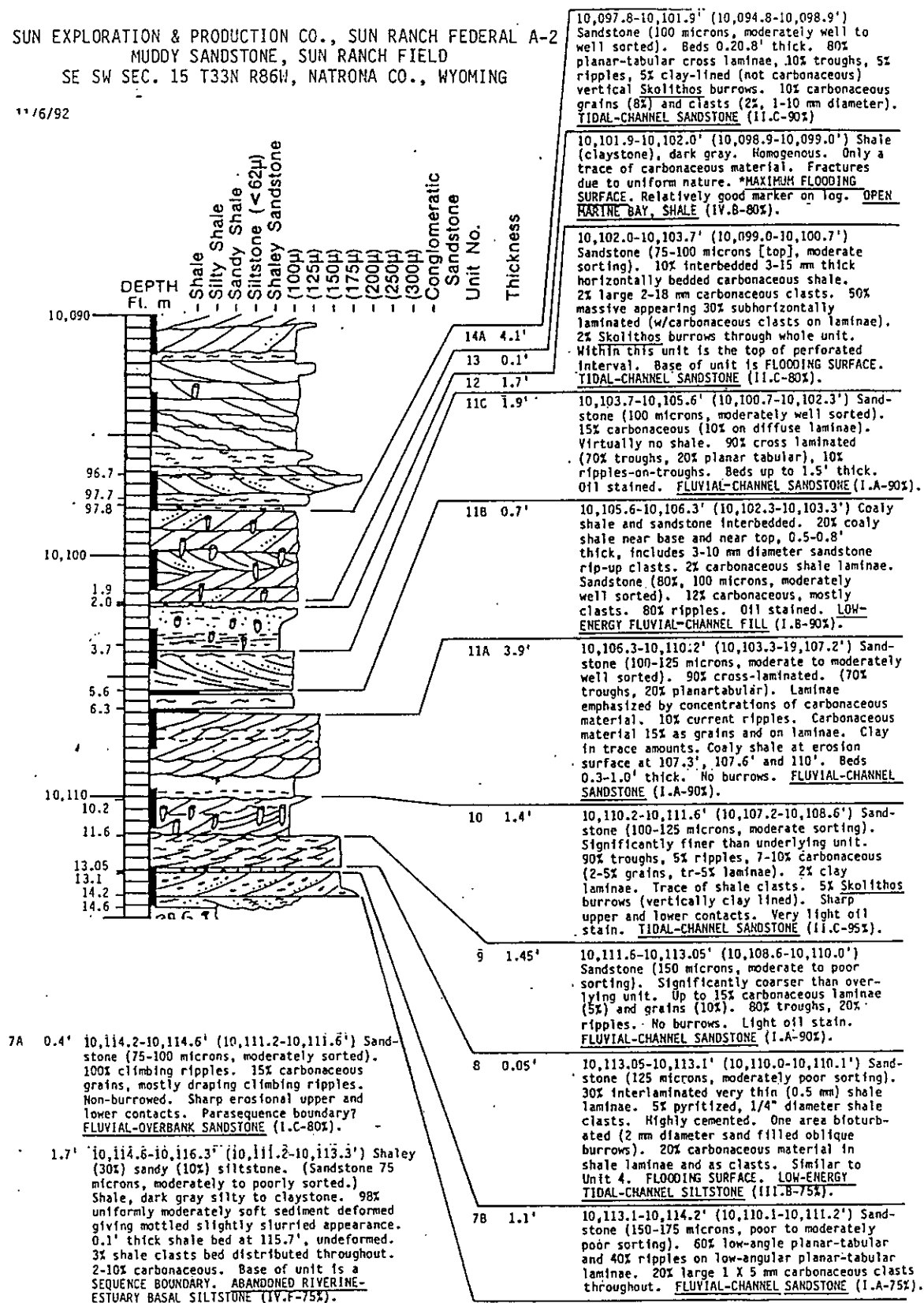
Described by: R. W. Tillman 7/91 and 10/91
 Cored interval 10,054.1-10,136.0' (82').
 Core to log correction (Gamma-ray Density
 Log) for cores 1; 2 and 3; subtract 3 feet.
 Log to core correction; add 3 feet.
 Log depths for each unit contacts given in
 parenthesis following core depths.

11/6/92

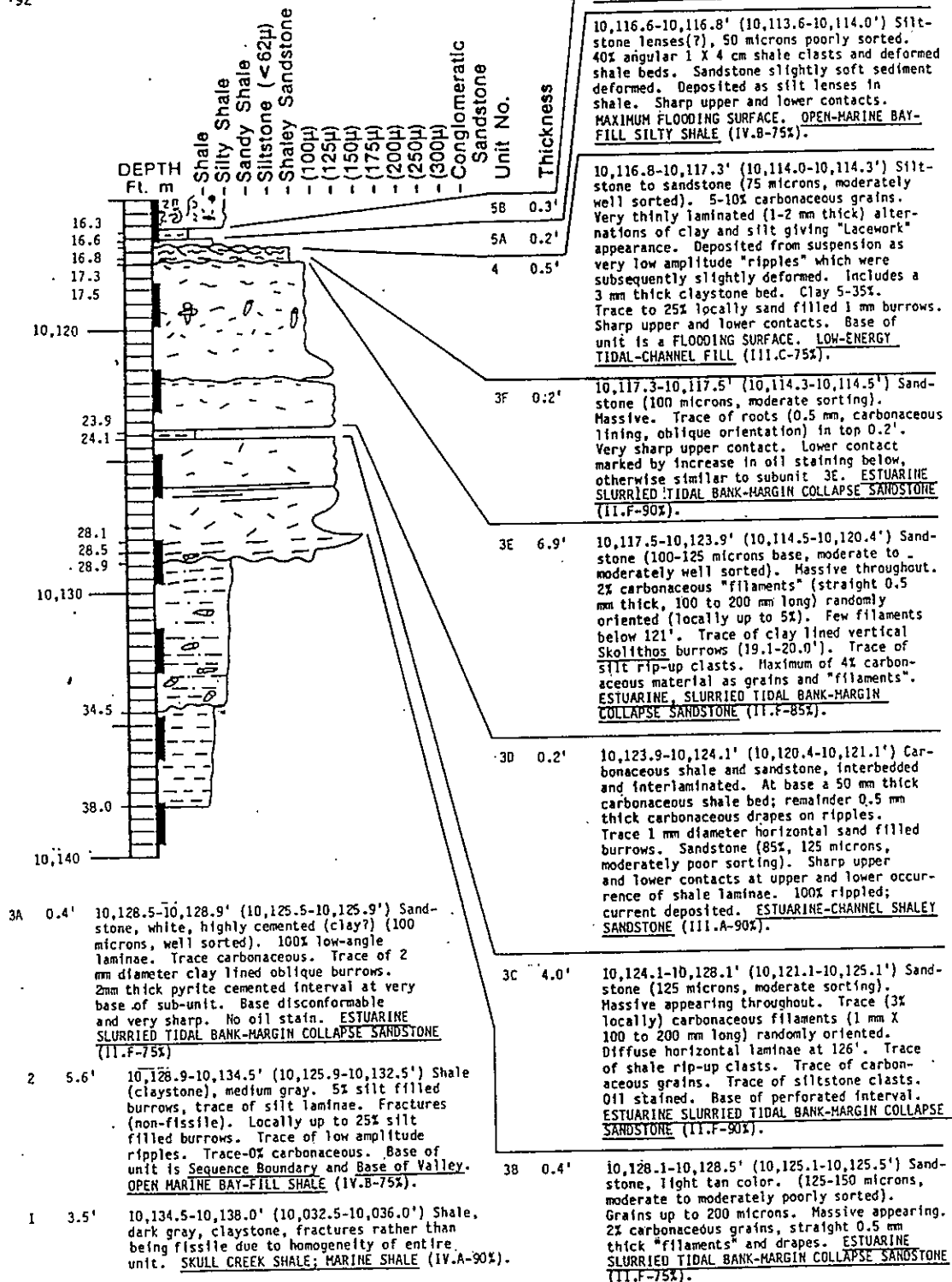


SUN EXPLORATION & PRODUCTION CO., SUN RANCH FEDERAL A-2
MUDDY SANDSTONE, SUN RANCH FIELD
SE SW SEC. 15 T33N R86W, NATRONA CO., WYOMING

11/6/92

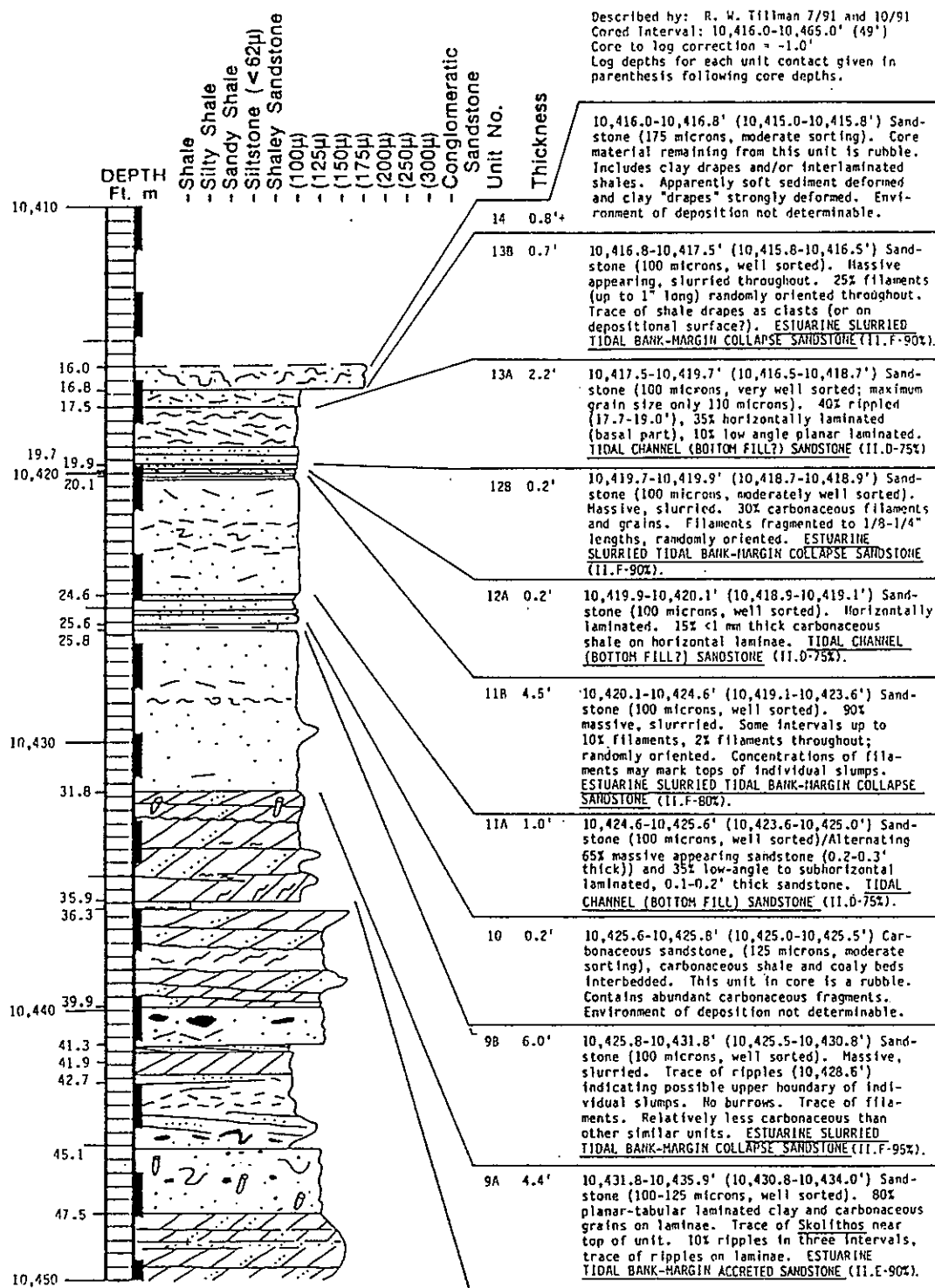


SUN EXPLORATION & PRODUCTION CO., SUN RANCH FEDERAL A-2
 MUDDY SANDSTONE, SUN RANCH FIELD
 SE SW SEC. 15 T33N R86W, NATRONA CO., WYOMING
 11/1/92

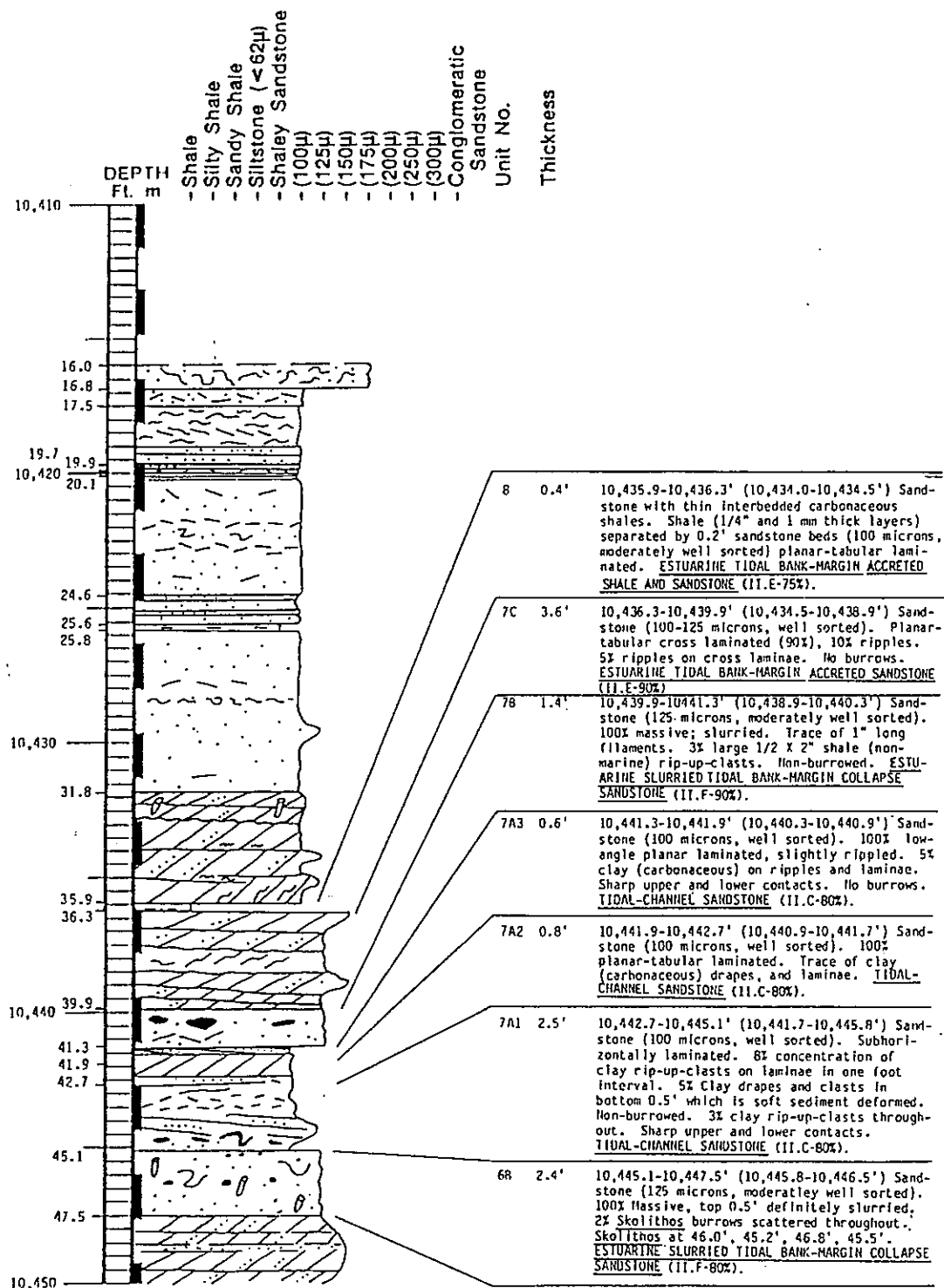


11/6/92

SUN EXPLORATION & PRODUCTION CO., SUN RANCH FEDERAL NO. 2
SUN RANCH FIELD, MUDDY SANDSTONE
SW NE SEC. 15 T33N R86W, NATRONA COUNTY, WYOMING

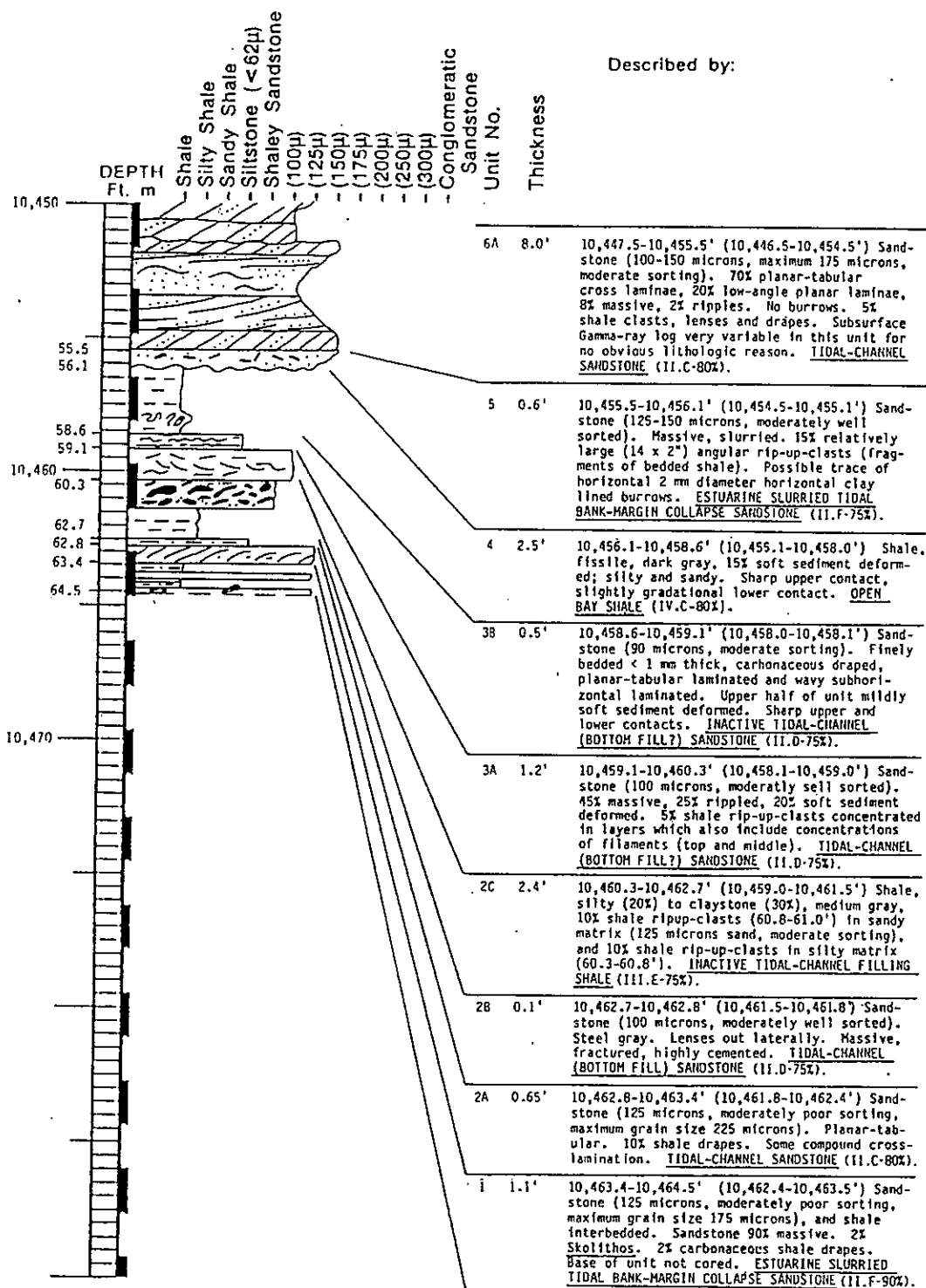


SUN EXPLORATION & PRODUCTION CO., SUN RANCH FEDERAL NO. 2
SUN RANCH FIELD, MUDDY SANDSTONE
SW NE SEC. 15 T33N R86W, NATRONA COUNTY, WYOMING



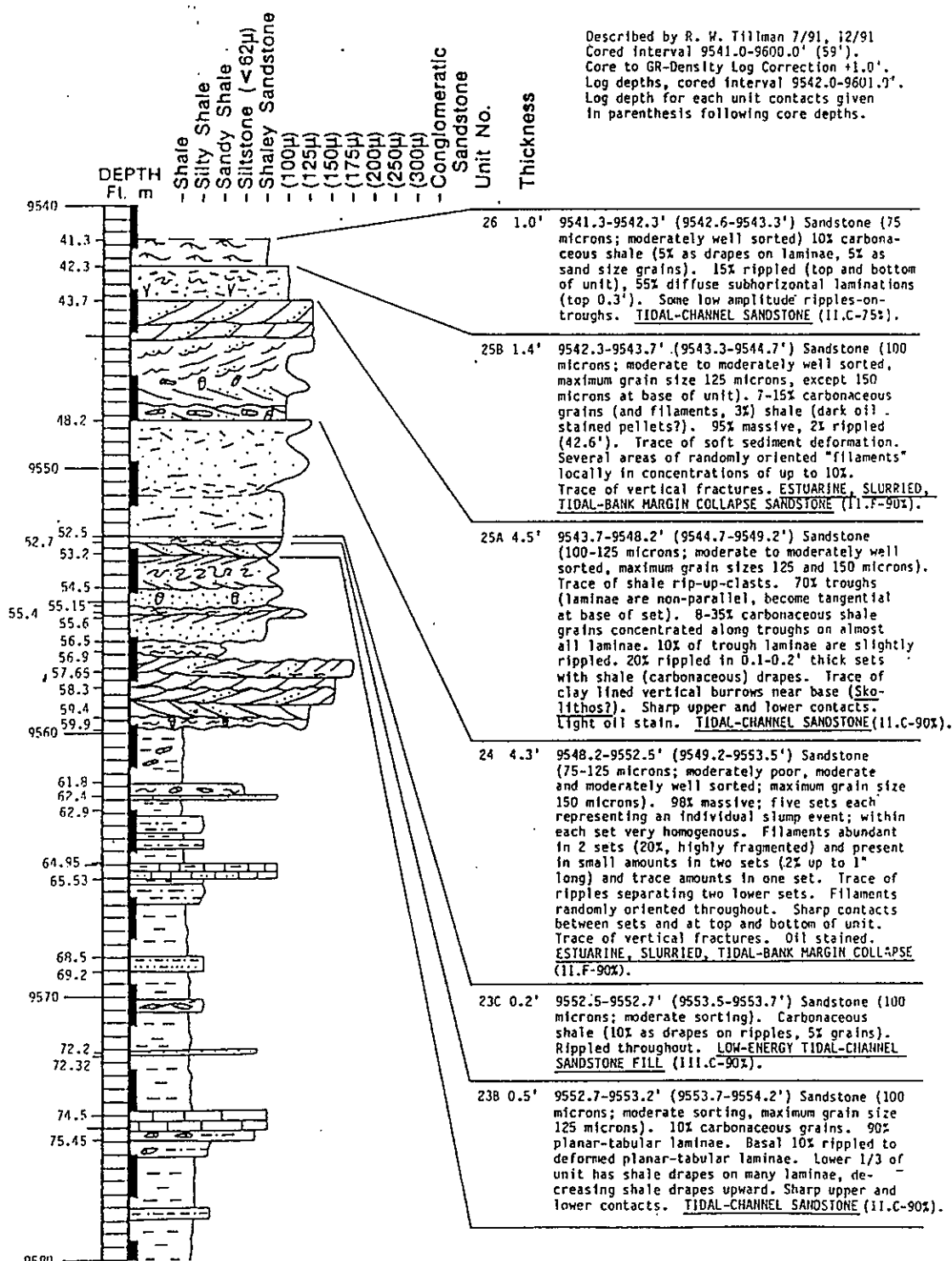
11/6/92

SUN EXPLORATION & PRODUCTION CO., SUN RANCH FEDERAL NO. 2
SUN RANCH FIELD, MUDDY SANDSTONE
SW NE SEC. 15 T33N R86W, NATRONA COUNTY, WYOMING



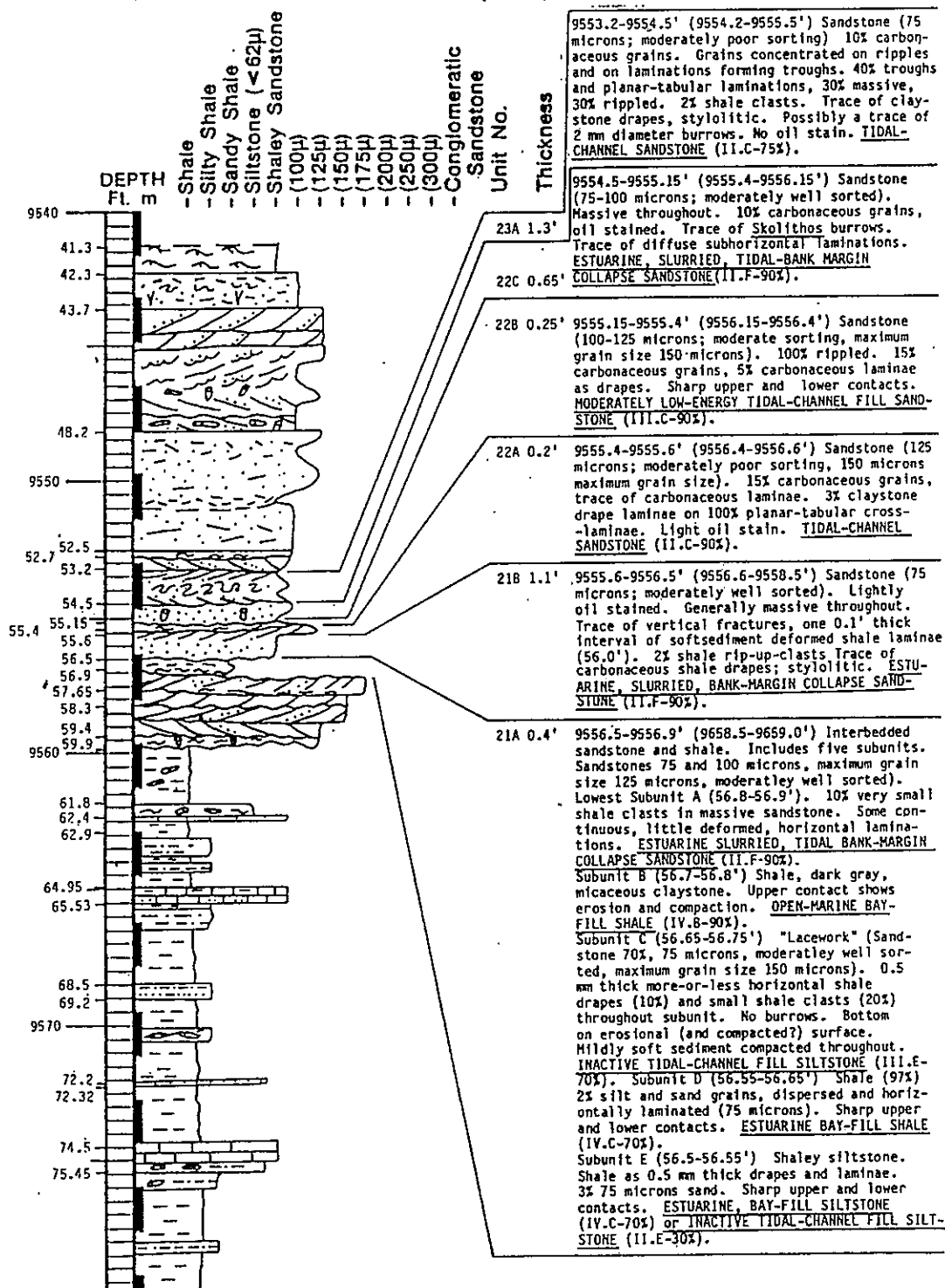
11/6/92

BHP PETROLEUM (AMERICAS), INC., SUN RANCH FEDERAL 7-22
SUN RANCH FIELD, MUDDY SANDSTONE
NE NE SEC. 22 T33N R86W, NATRONA COUNTY, WYOMING



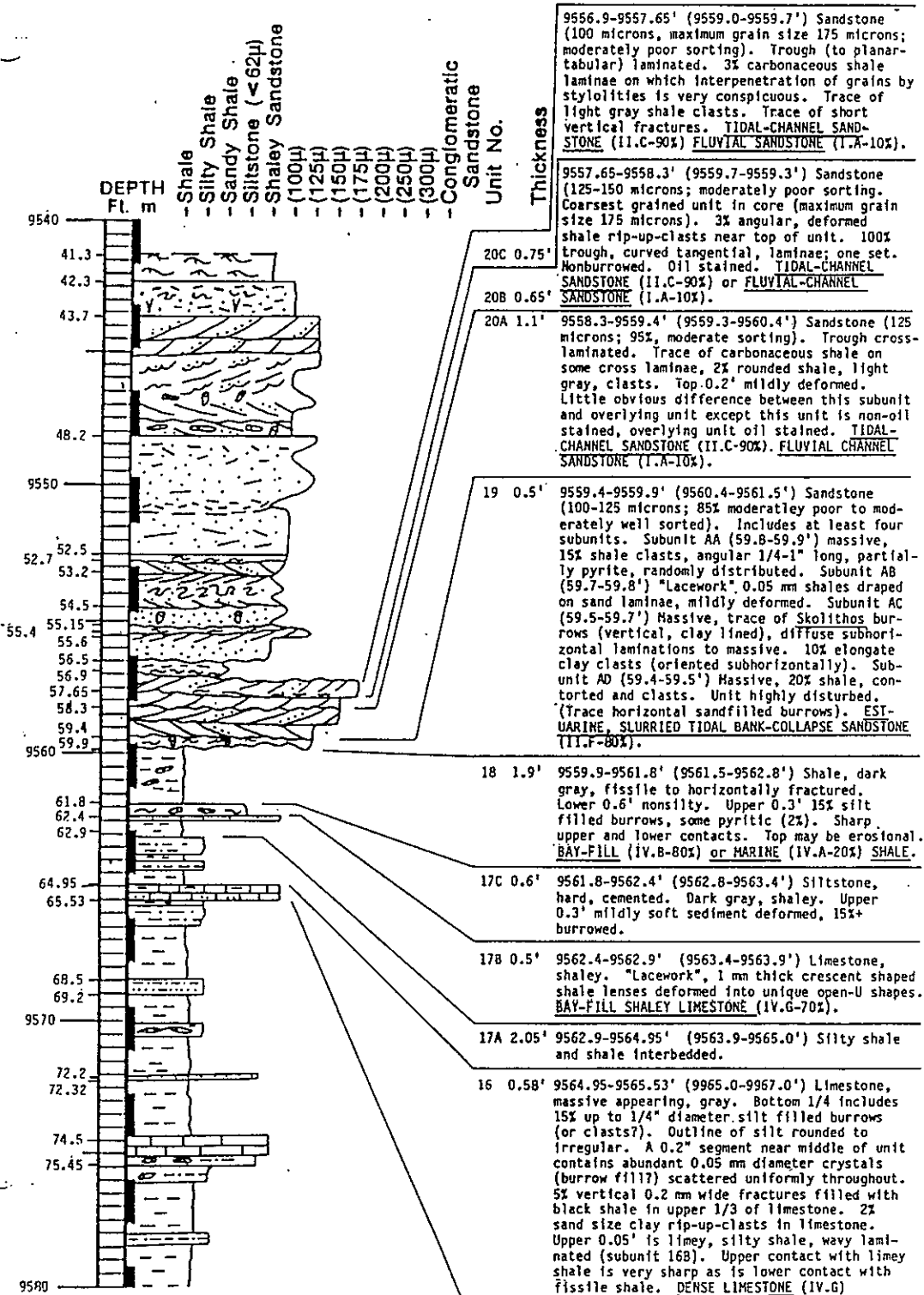
11/6/92

BHP PETROLEUM (AMERICAS), INC., SUN RANCH FEDERAL 7-22
SUN RANCH FIELD, MUDDY SANDSTONE
NE NE SEC. 22 T33N R86W, NATRONA COUNTY, WYOMING



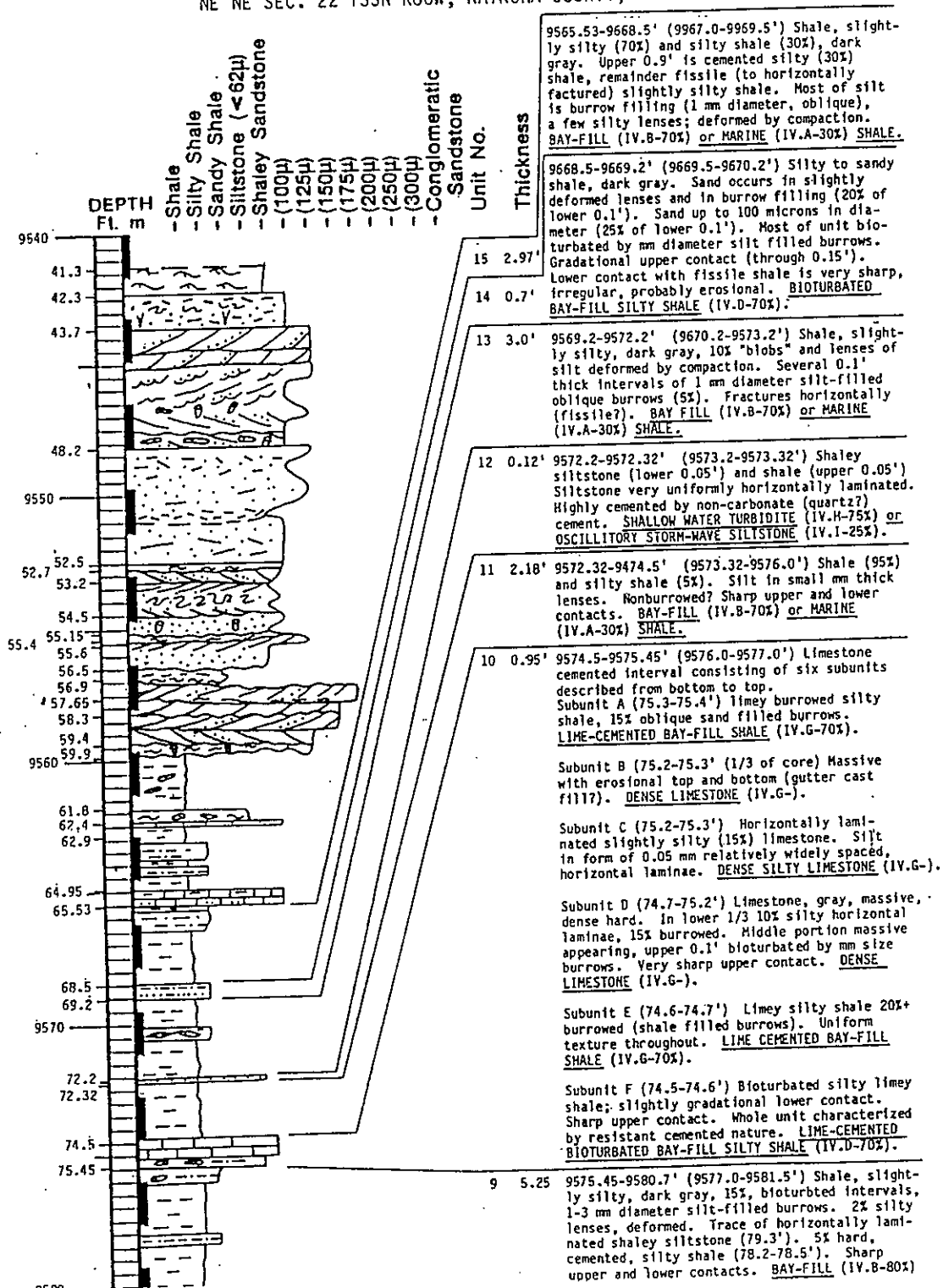
11/6/92

BHP PETROLEUM (AMERICAS), INC., SUN RANCH FEDERAL 7-22
SUN RANCH FIELD, MUDDY SANDSTONE
NE NE SEC. 22 T33N R86W, NATRONA COUNTY, WYOMING



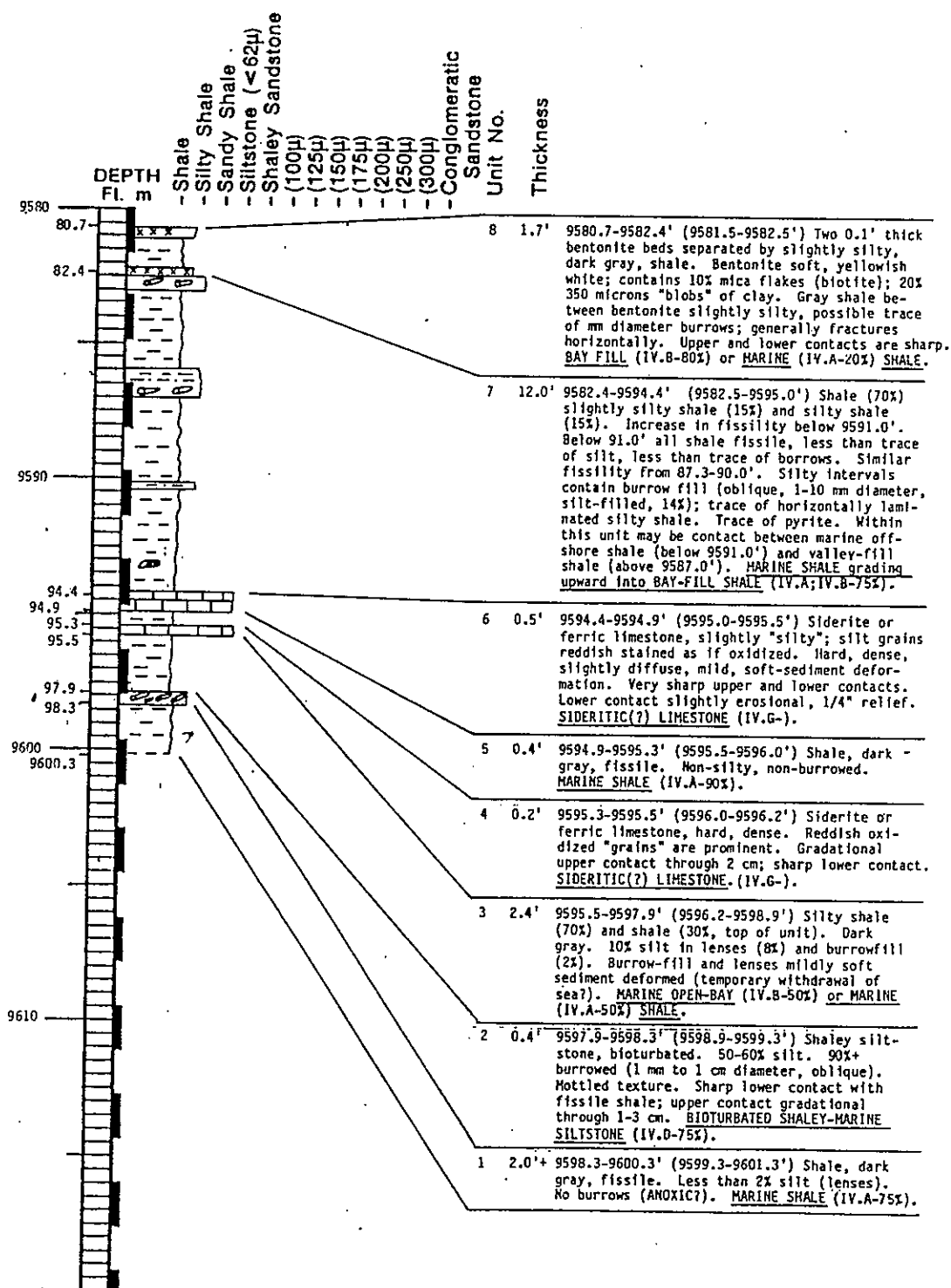
11/6/92

BHP PETROLEUM (AMERICAS), INC., SUN RANCH FEDERAL 7-22
SUN RANCH FIELD, MUDDY SANDSTONE
NE NE SEC. 22 T33N R86W, NATRONA COUNTY, WYOMING



11/6/92

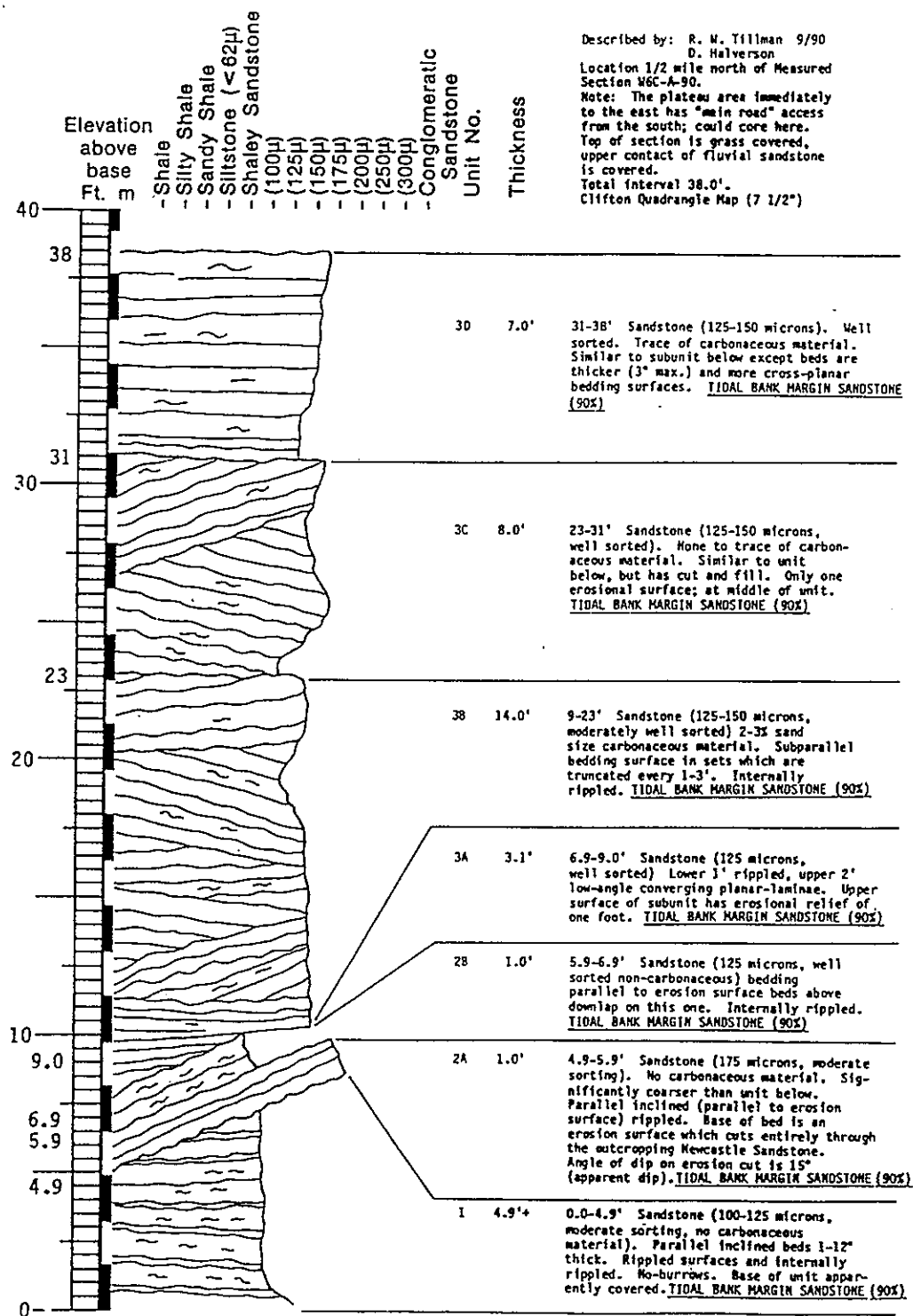
BHP PETROLEUM (AMERICAS), INC., SUN RANCH FEDERAL 7-22
 SUN RANCH FIELD, MUDDY SANDSTONE
 NE NE SEC. 22 T33N R86W, NATRONA COUNTY, WYOMING



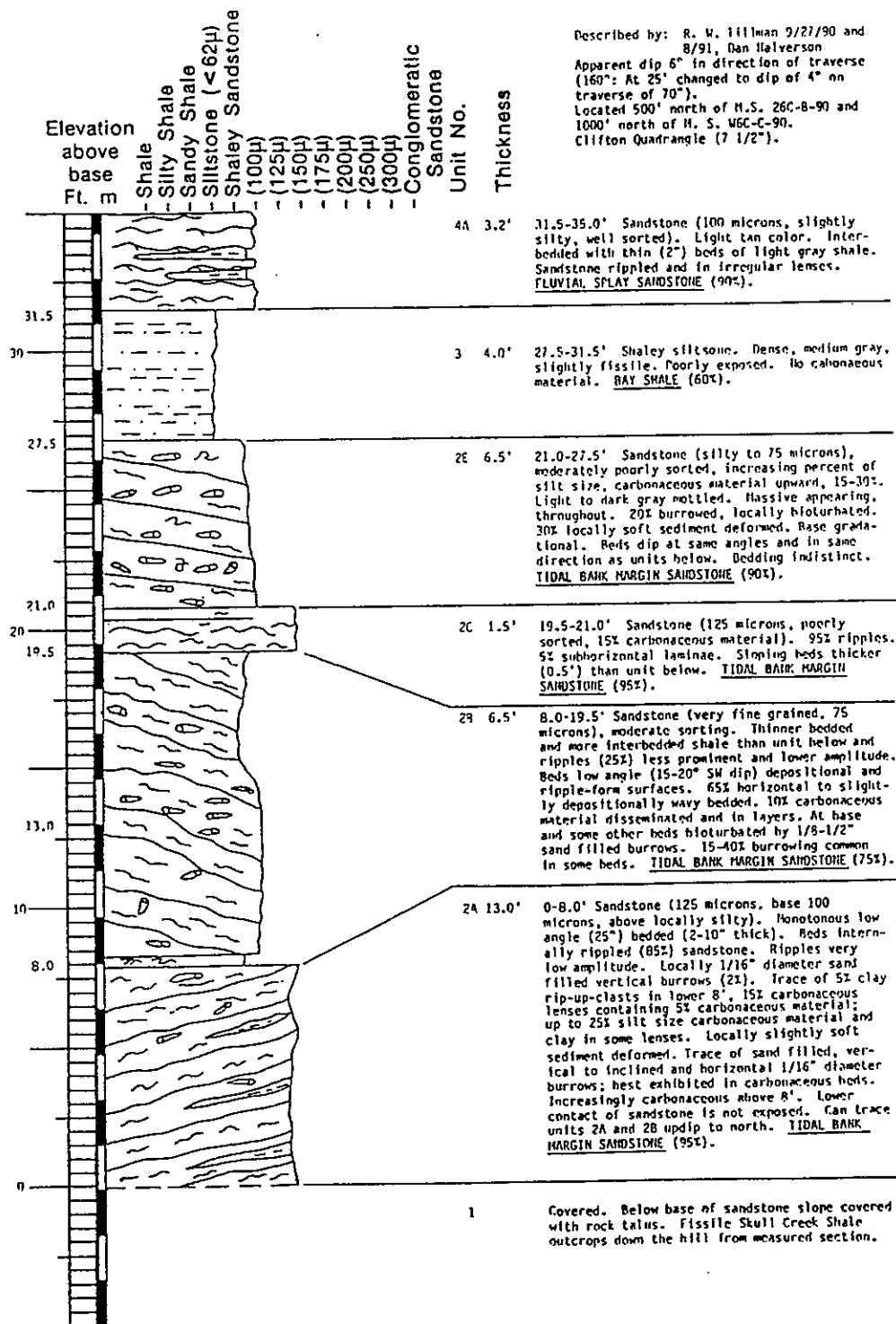
APPENDIX C

Geological Description for Units of Muddy Sandstone Outcrops 1, 2, and 3,
Newcastle, Wyoming, by R. W. Tillman⁴⁴.

MEASURED SECTION W6C-AA-90
NEWCASTLE (MUDDY) SANDSTONE
SENESE Sec. 7, T43N R60W, WYOMING

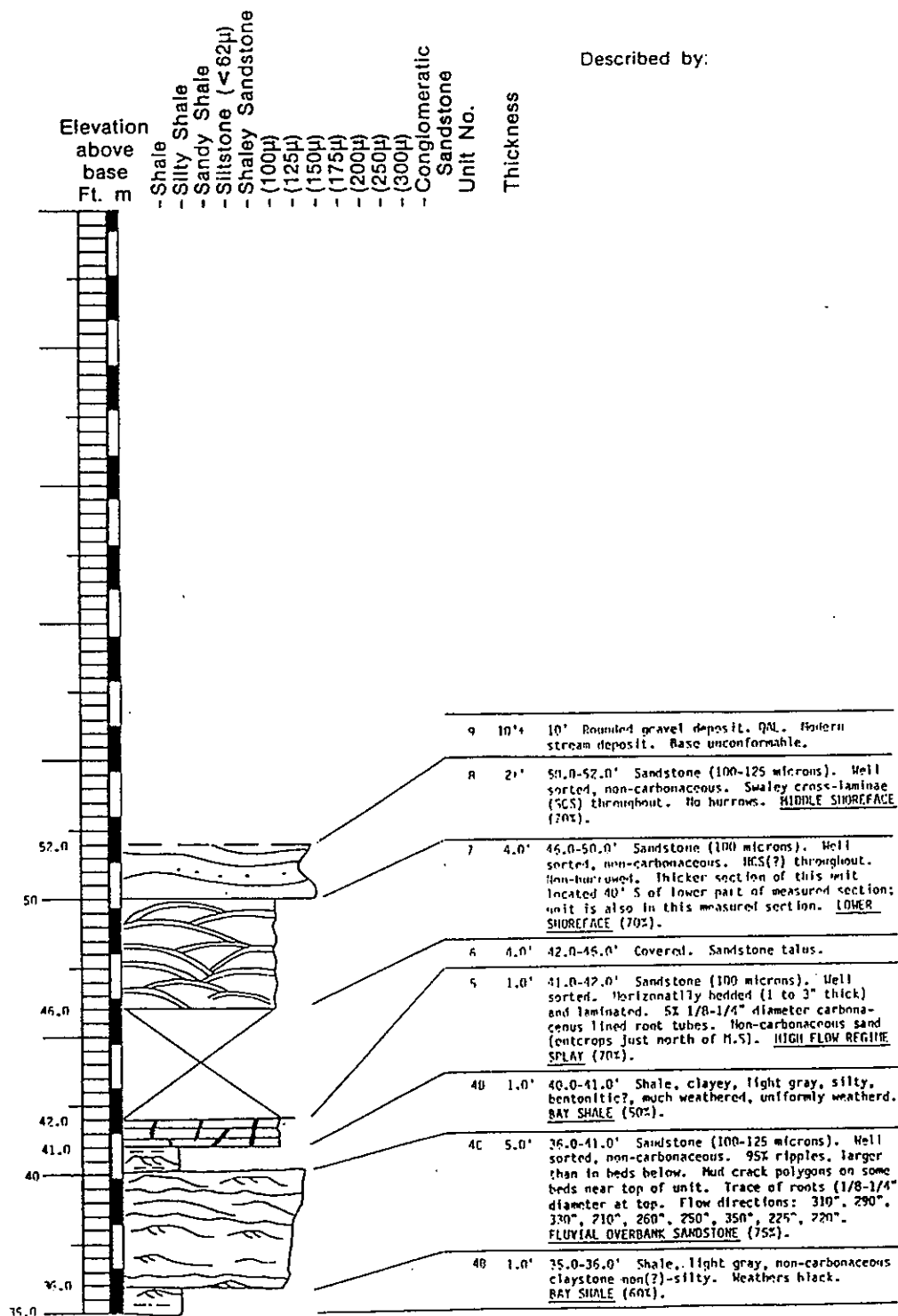


MEASURED SECTION W6C-A,
NEWCASTLE (MUDDY) SANDSTONE
N1/2 SE NW NE Sec. 18 T43N R6W, LAK RANCH, WESTON CO., WYOMING

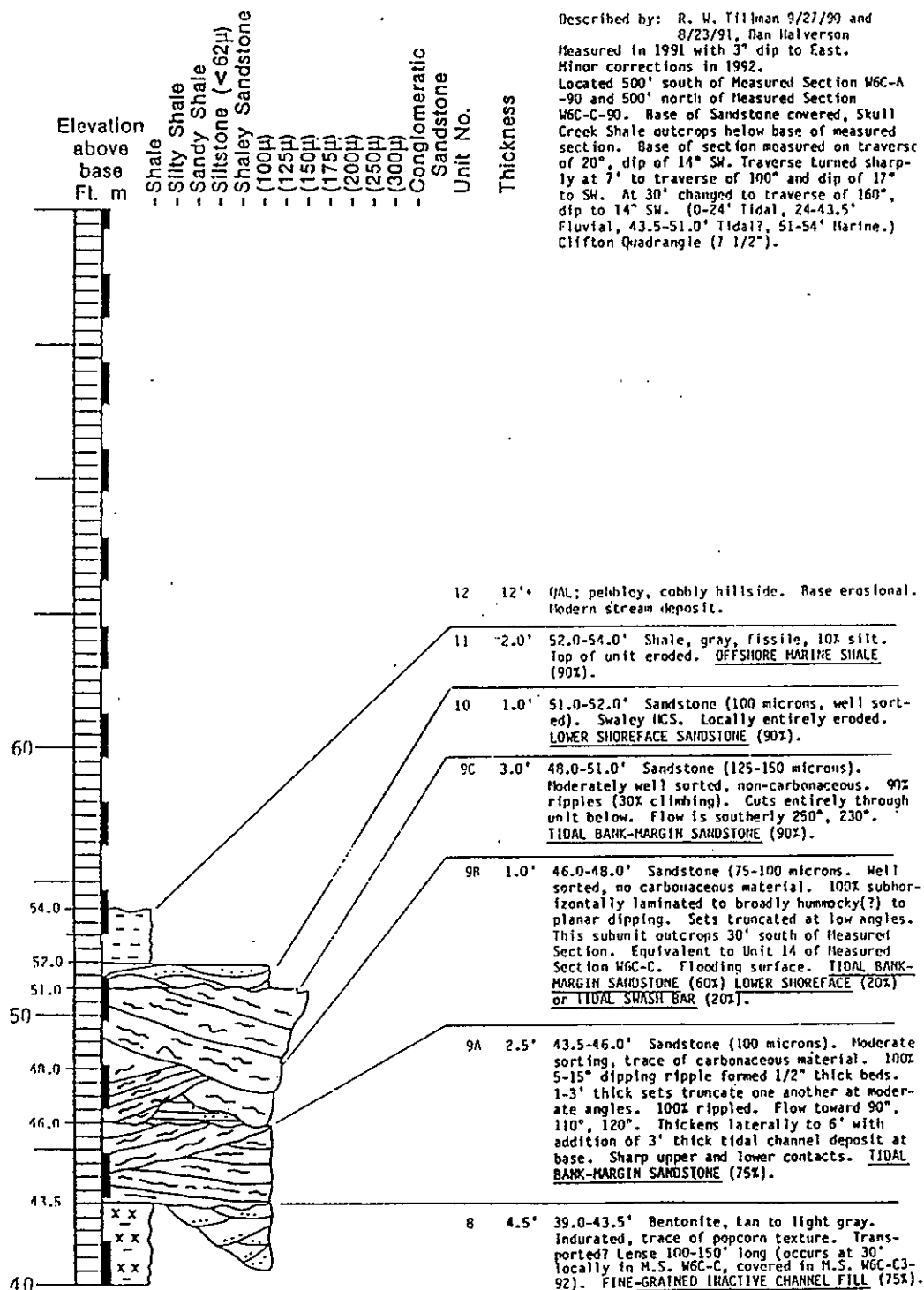


MEASURED SECTION W6C-A,
 NEWCASTLE (MUDDY) SANDSTONE
 N1/2 SE NW NE SEC. 18 T43N R60W, LAK RANCH, WESTON CO., WYOMING

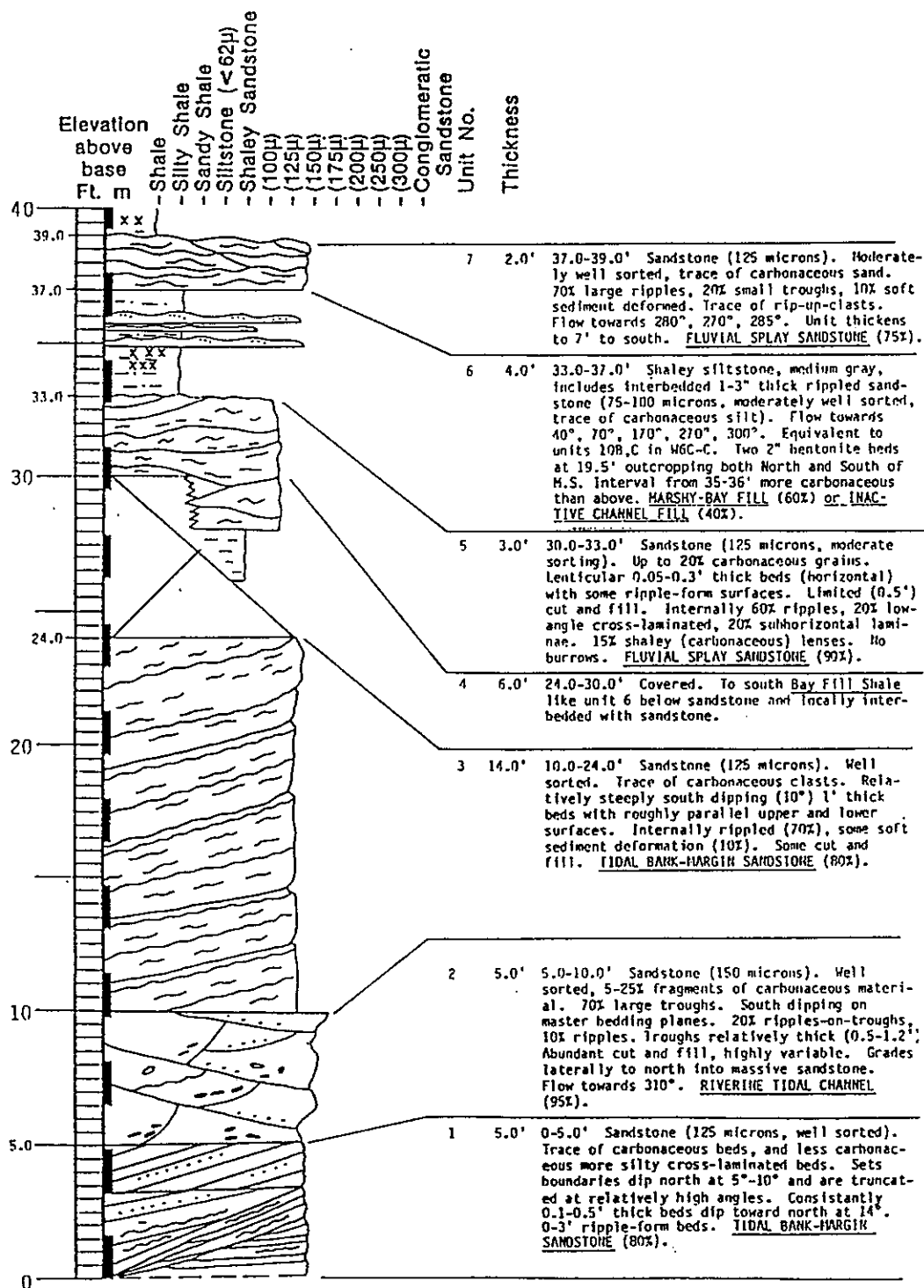
Described by:



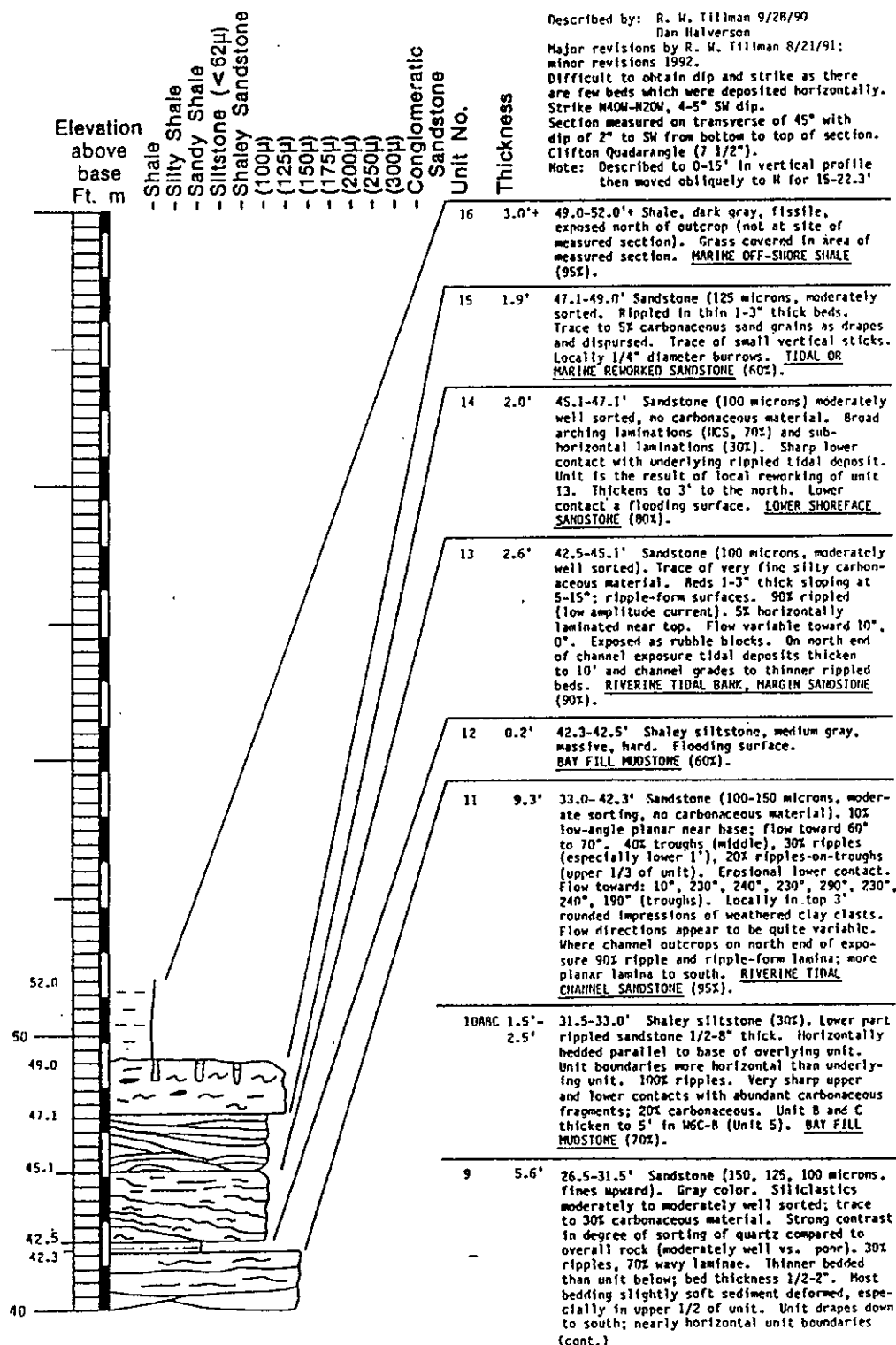
MEASURED SECTION W6C-R-90
 NEWCASTLE (MUDDY) SANDSTONE
 C SE NW NE Sec. 18 T43N R60W, LAK RANCH, WESTON CO., WYOMING



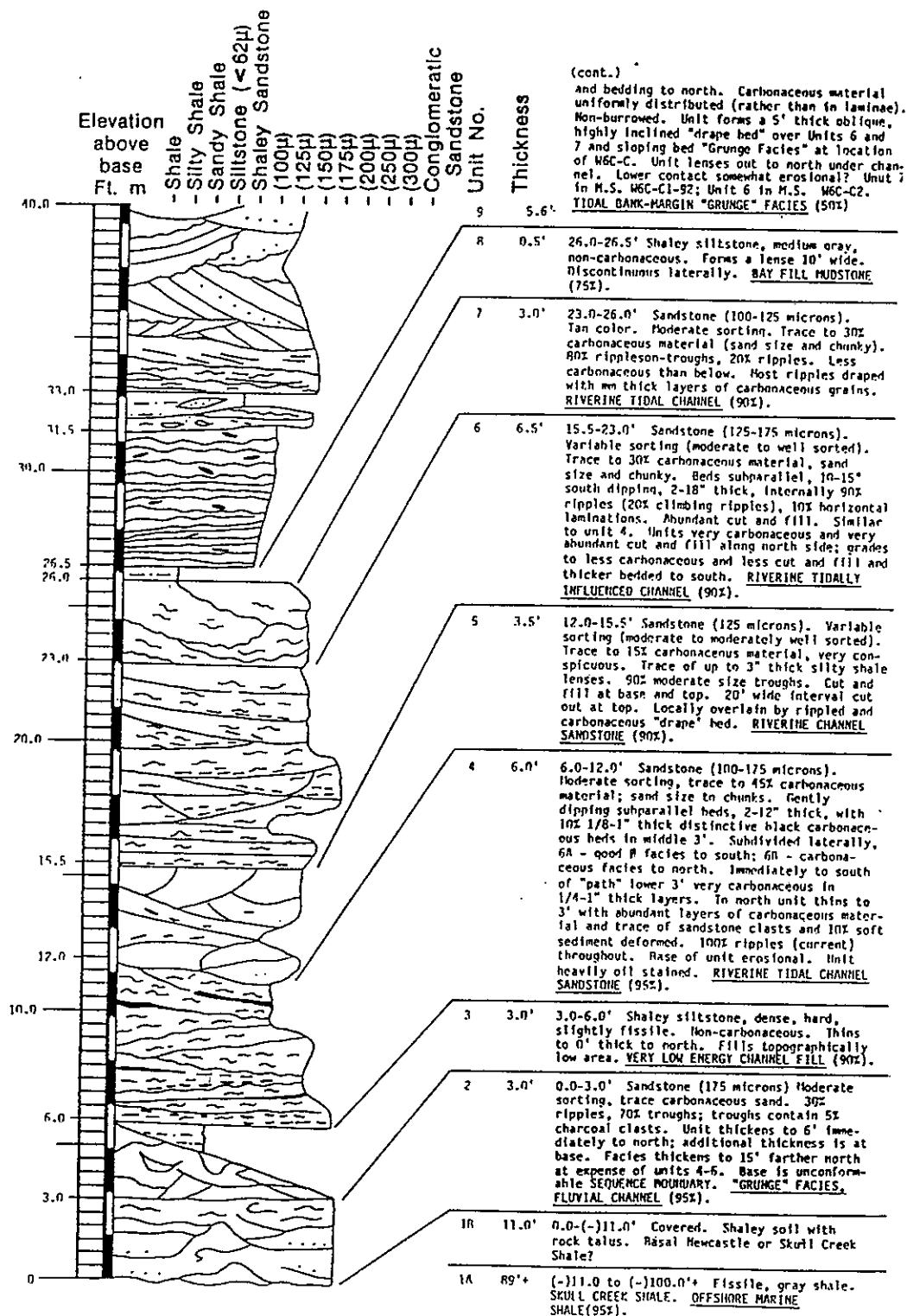
MEASURED SECTION W6C-B-90
NEWCASTLE (MUDDY) SANDSTONE
C SE NW NE Sec. 18 T43N R60W, LAK RANCH, HESTON CO., WYOMING



MEASURED SECTION W6C-C-90
NEWCASTLE (MUDDY) SANDSTONE
S1/2 SE NW NE Sec. 18 T43N R60W, LAK RANCH, WESTON CO., WYOMING



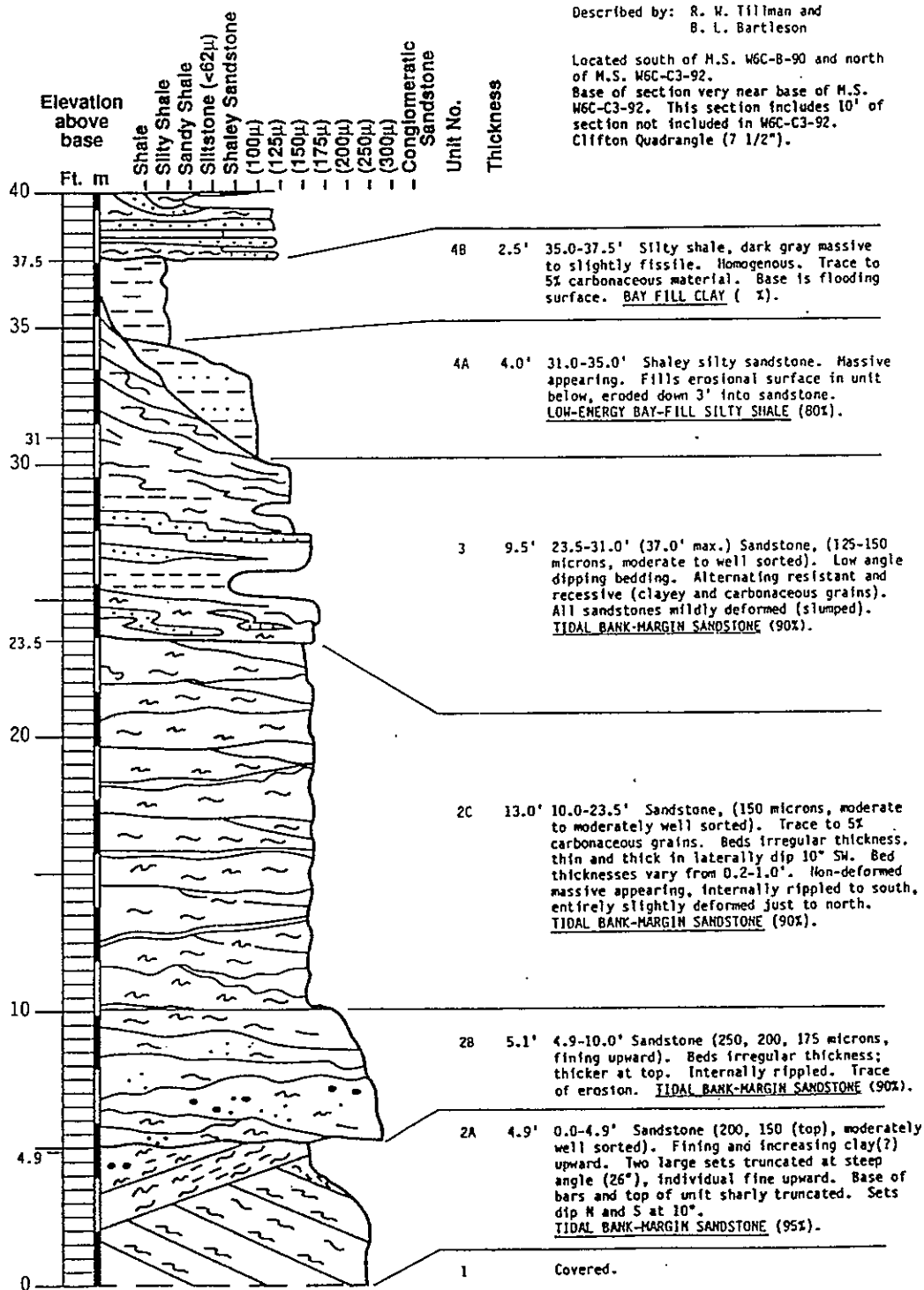
MEASURED SECTION W6C-C-90
NEWCASTLE (MUDDY) SANDSTONE
S1/2 SE NW NE Sec. 18 T43N R60W, LAK RANCH, WESTON CO., WYOMING



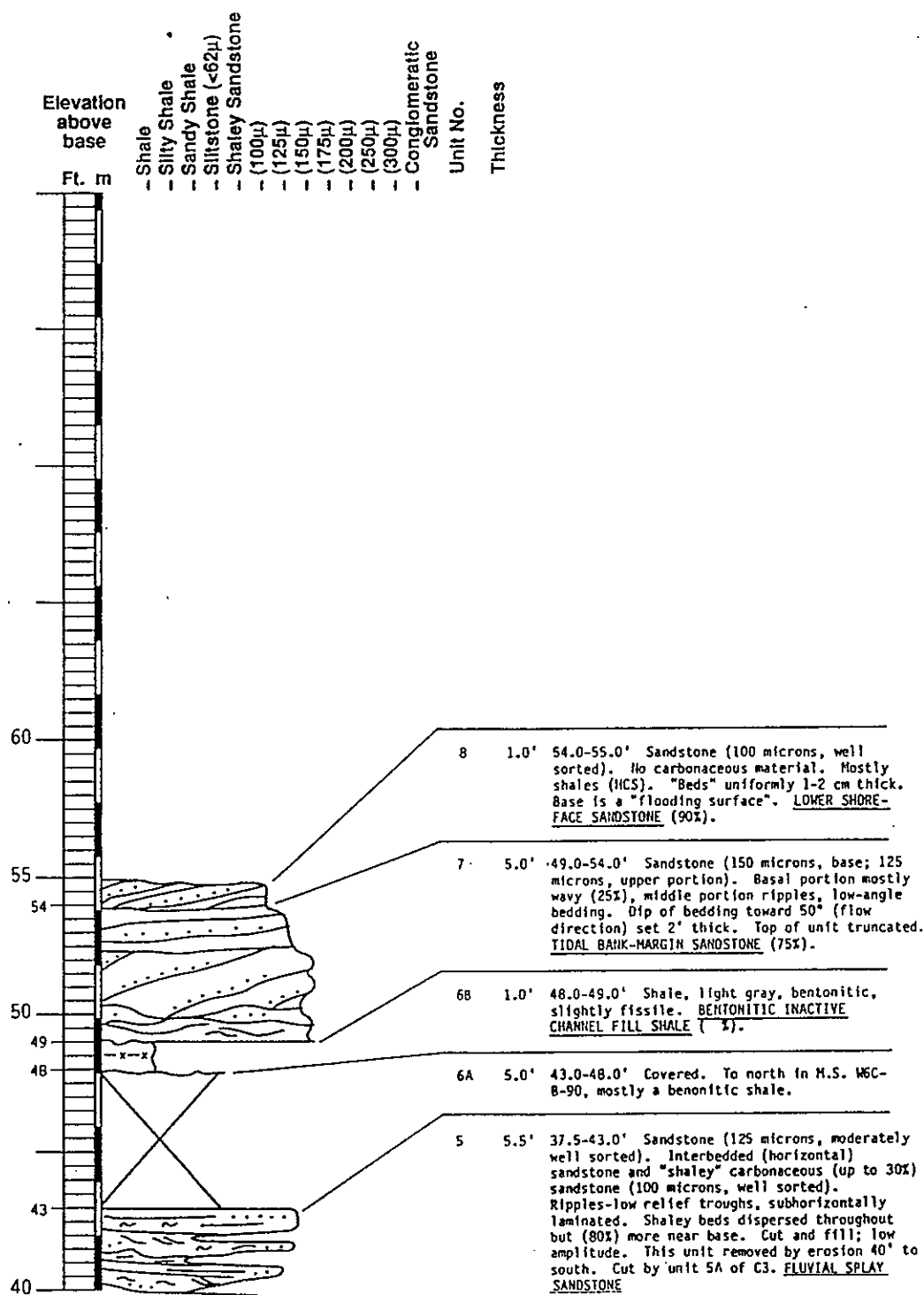
MEASURED SECTION W6C-B1-92
C SE NW Sec. 18 T43N R60W

Described by: R. W. Tillman and
B. L. Bartleson

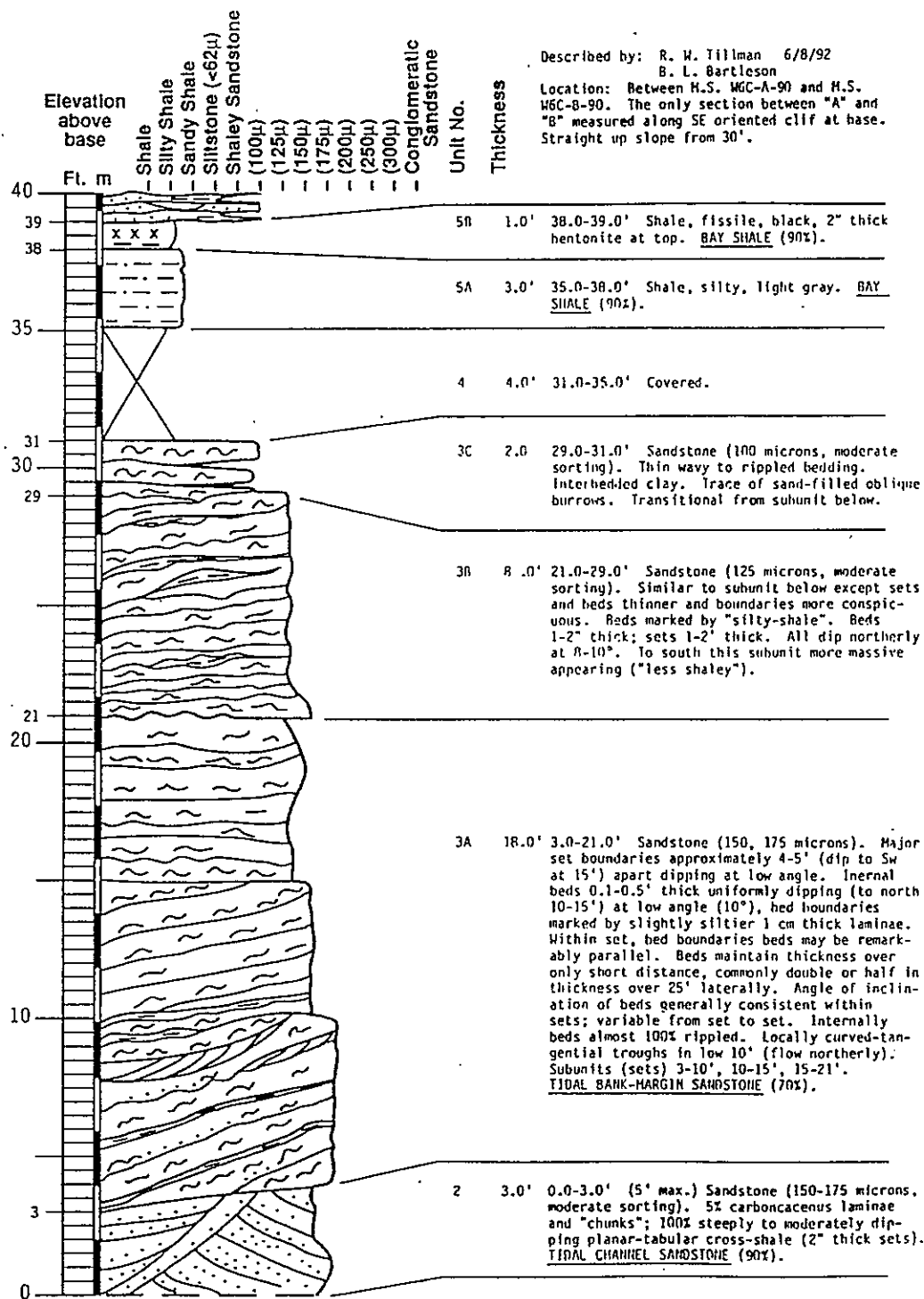
Located south of M.S. W6C-B-90 and north
of M.S. W6C-C3-92.
Base of section very near base of M.S.
W6C-C3-92. This section includes 10' of
section not included in W6C-C3-92.
Clifton Quadrangle (7 1/2").



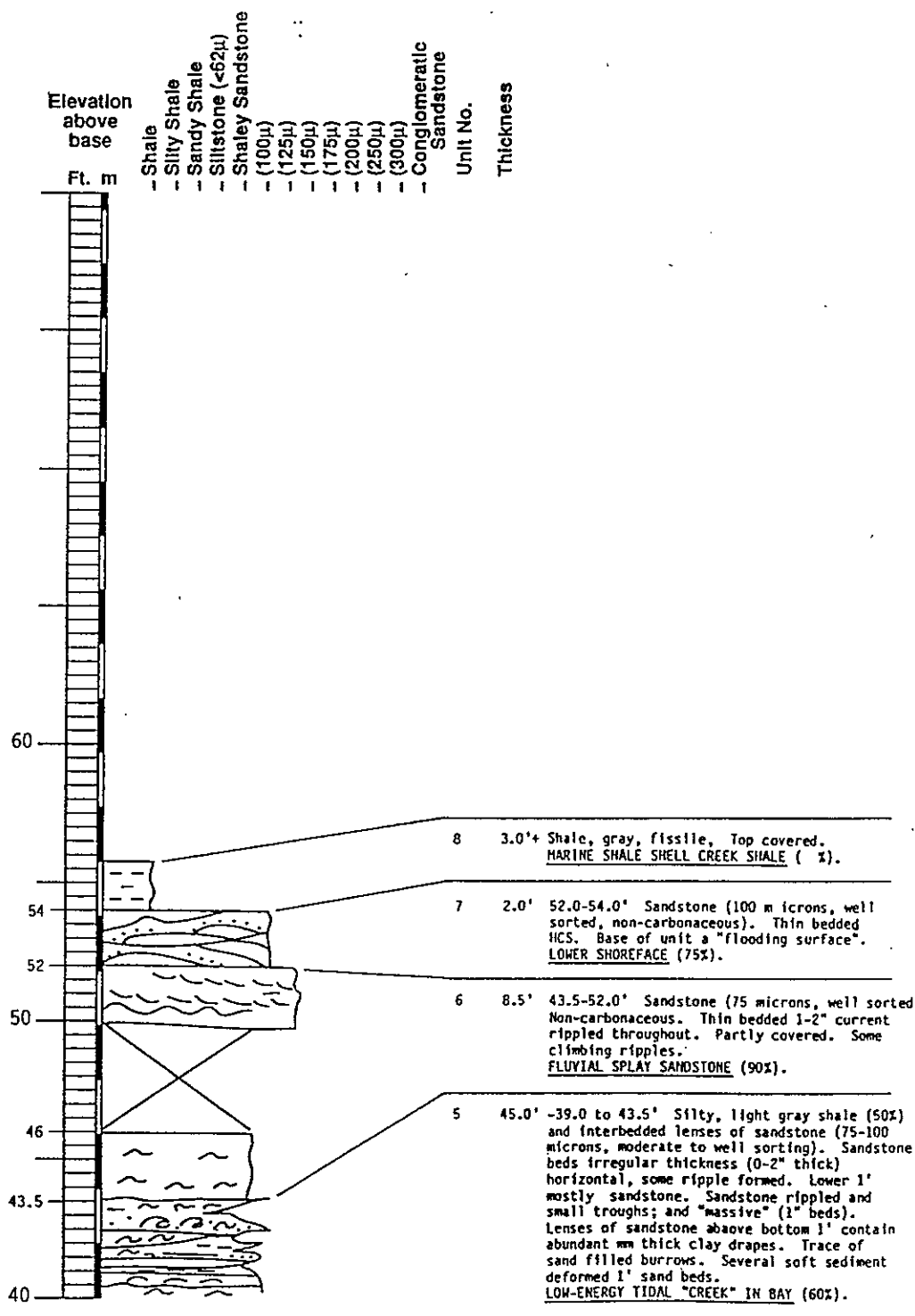
MEASURED SECTION W6C-B1-92
C SE NW Sec. 18 T43N R60W



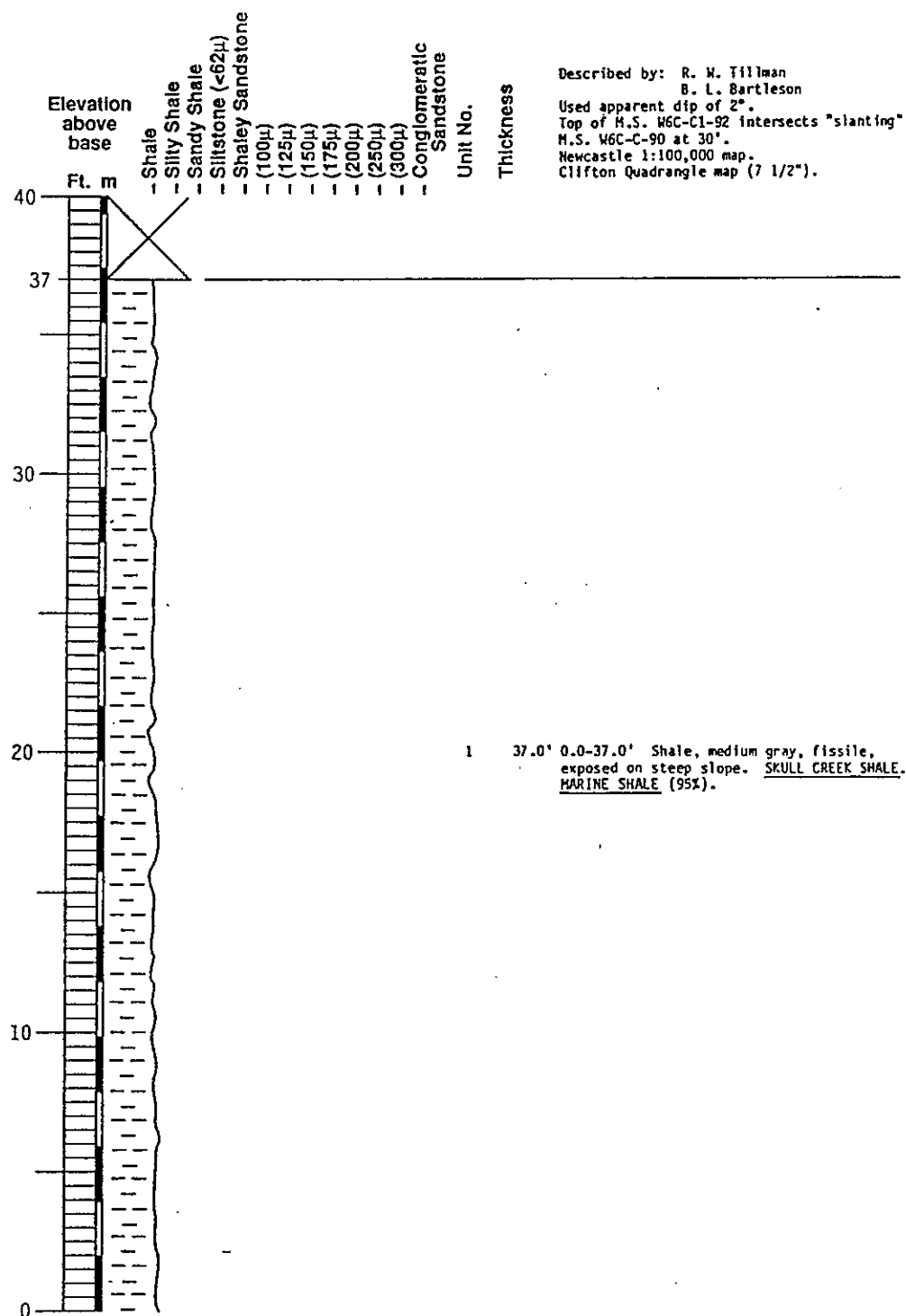
MEASURED SECTION W6C-B2-92
MUDDY (NEWCASTLE) SANDSTONE
C SE NW NE Sec. 18 T43N R60W



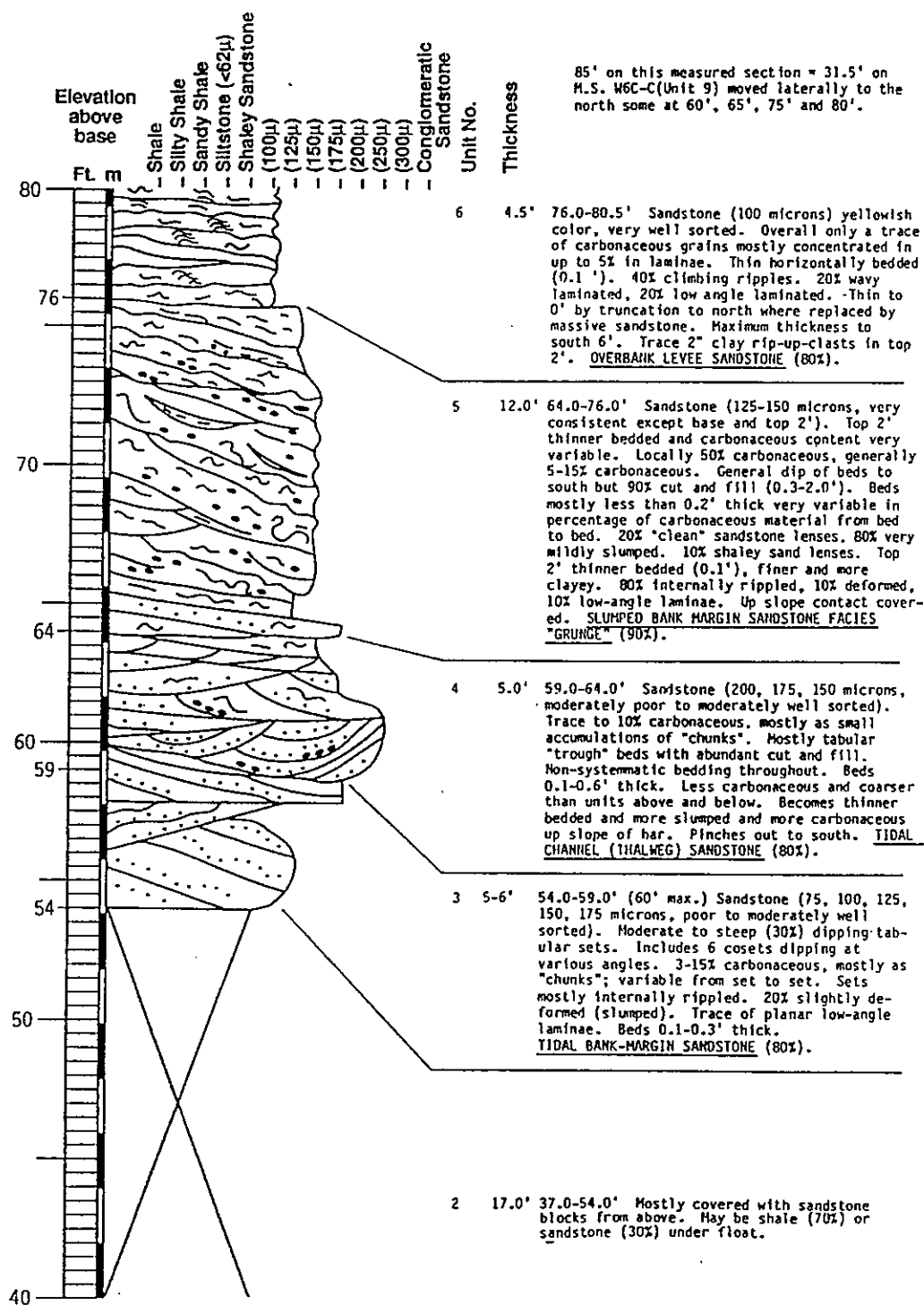
MEASURED SECTION W6C-82-92
 MUDDY (NEWCASTLE) SANDSTONE
 C SE NW NE Sec. 18 T43N R60W



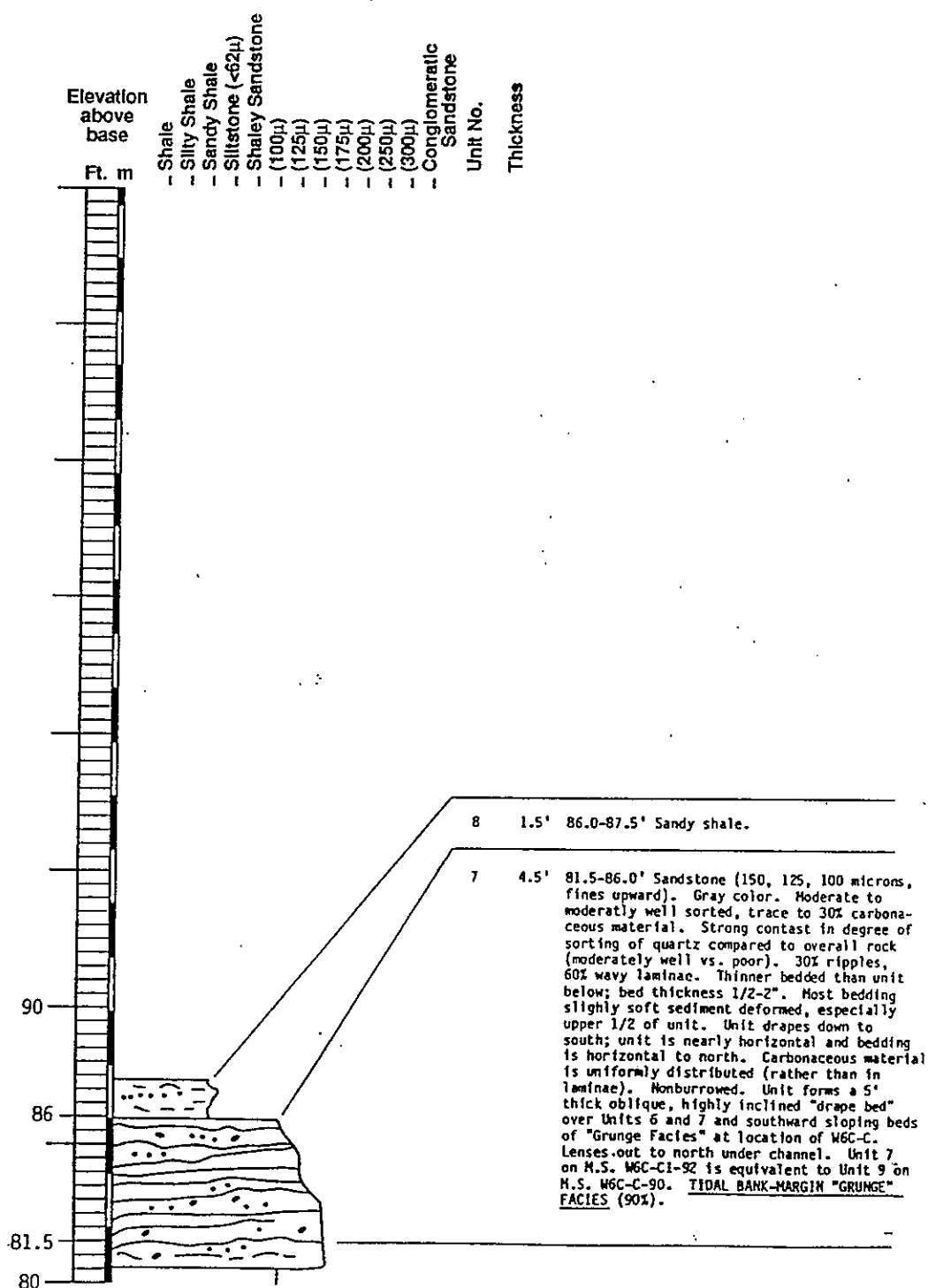
MEASURED SECTION W6C-C1-92
 NEWCASTLE (MUDDY) SANDSTONE, LAK RANCH,
 S1/2 SE NW NE Sec. 18 T43N R60W, WESTON CO., WYOMING



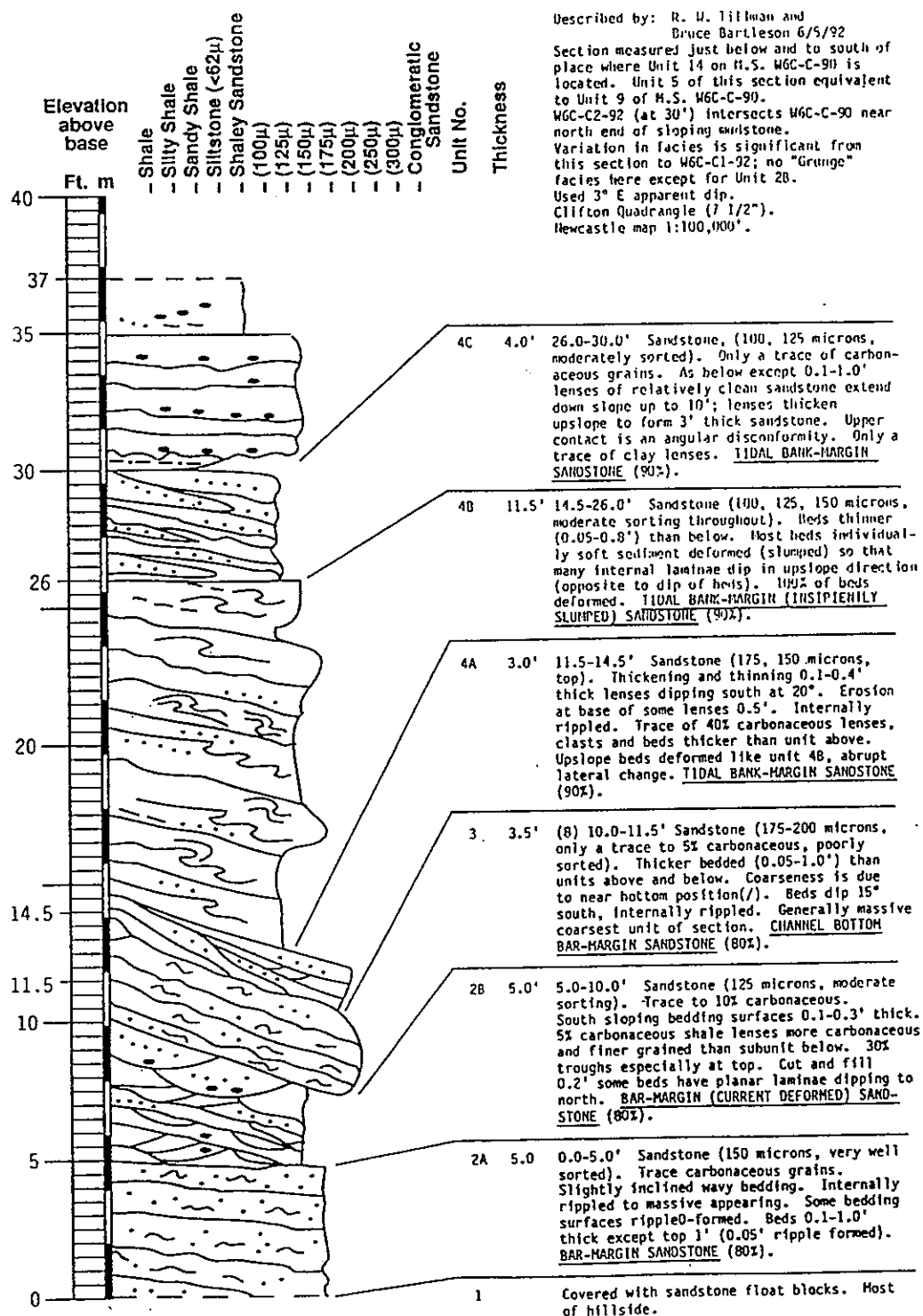
MEASURED SECTION W6C-C1-92
 HENCASTLE (MUDDY) SANDSTONE, LAK RANCH,
 S1/2 SE NW NE Sec. 18 T43N R60W, WESTON CO., WYOMING



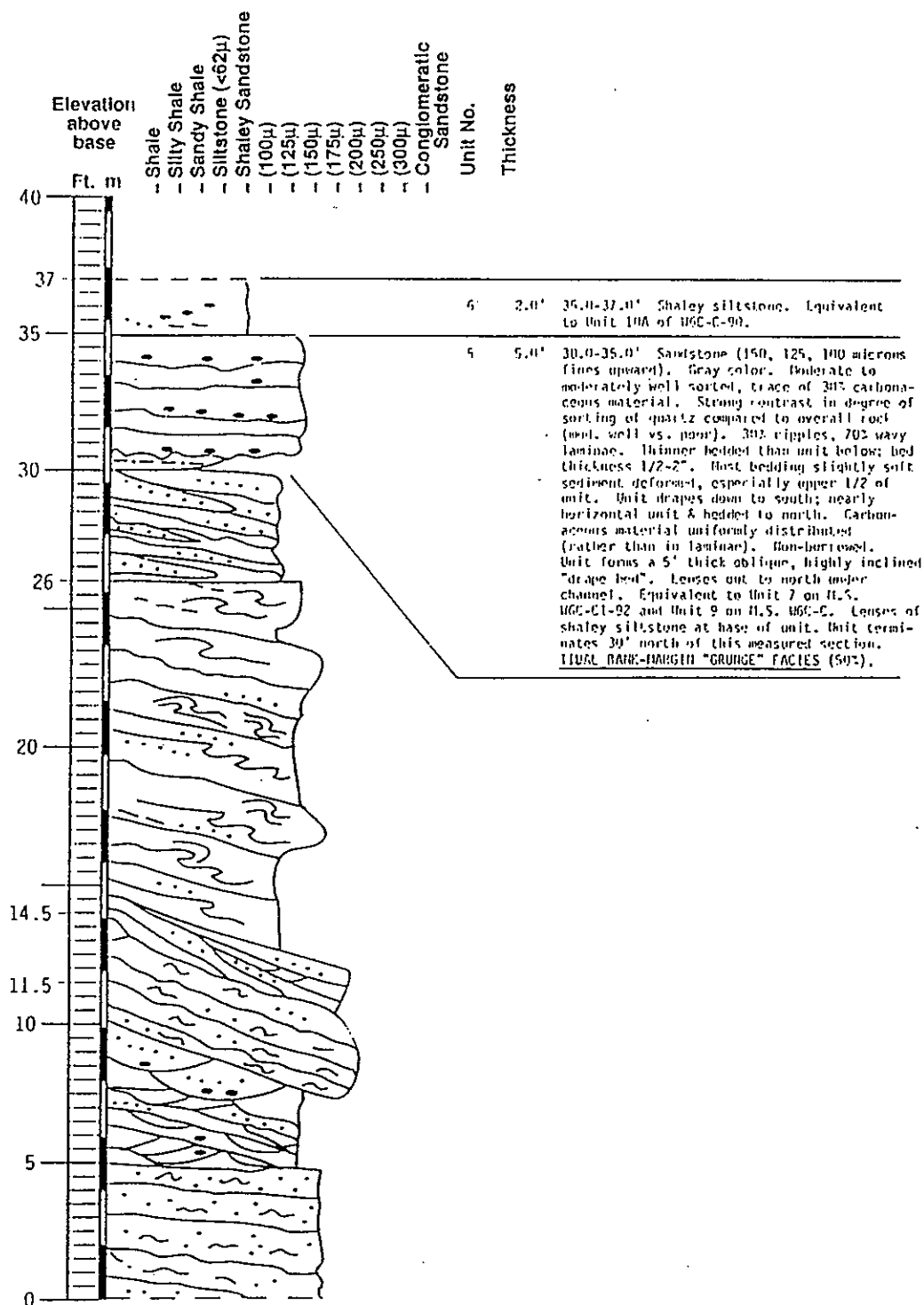
MEASURED SECTION W6C-C1-92
 NEWCASTLE (MUDDY) SANDSTONE, LAK RANCH,
 S1/2 SE NW NE Sec. 18 T43N R60W, WESTON CO., WYOMING



MEASURED SECTION W6C-C2-92
 NEWCASTLE (MUDDY) SANDSTONE
 S 1/2 SE NW NE Sec. 18 T43N R60W, LAK RANCH, WESTON CO., WYOMING



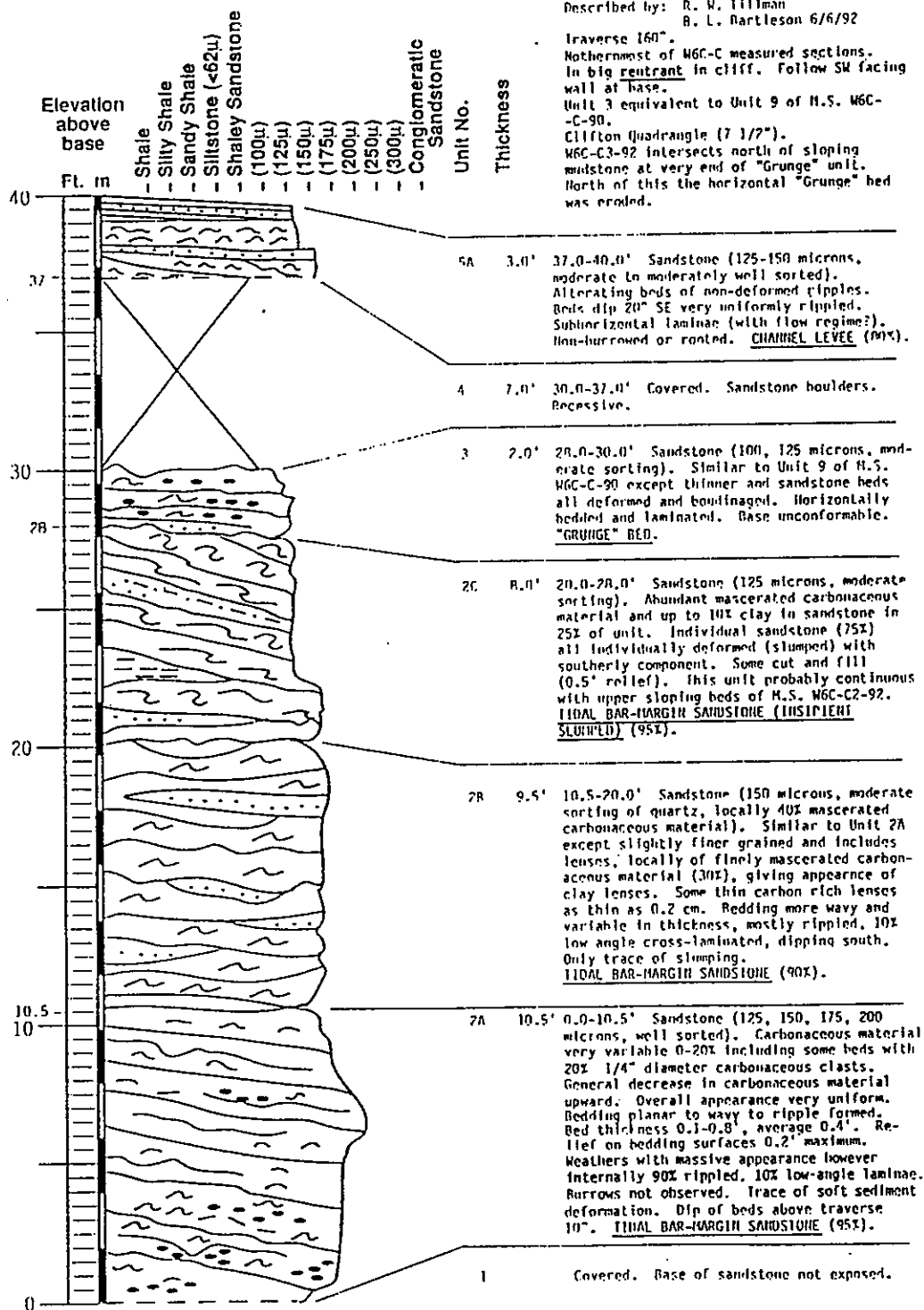
MEASURED SECTION W6C-C2-92
 NEWCASTLE (MUDDY) SANDSTONE
 S 1/2 SE HW NE Sec. 18 T43N R60W, LAK RANCH, WESTON CO., WYOMING



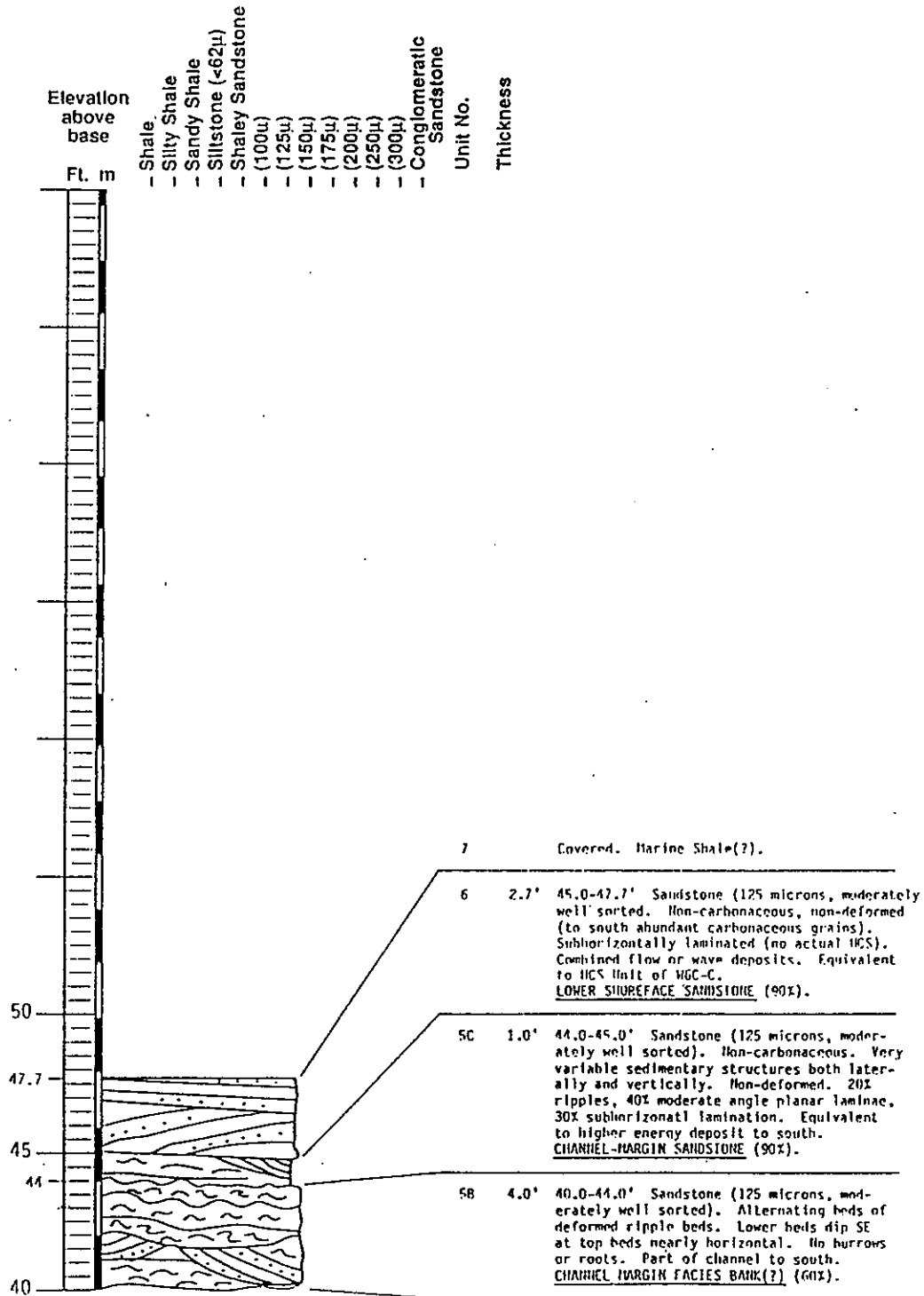
MEASURED SECTION W6C-C3-92
LAK RANCH,
S 1/2 SE 1/4 NE Sec. 18 T43N R6W, WESTON CO., WYOMING

Described by: R. W. Tillman
R. L. Hartleson 6/6/92

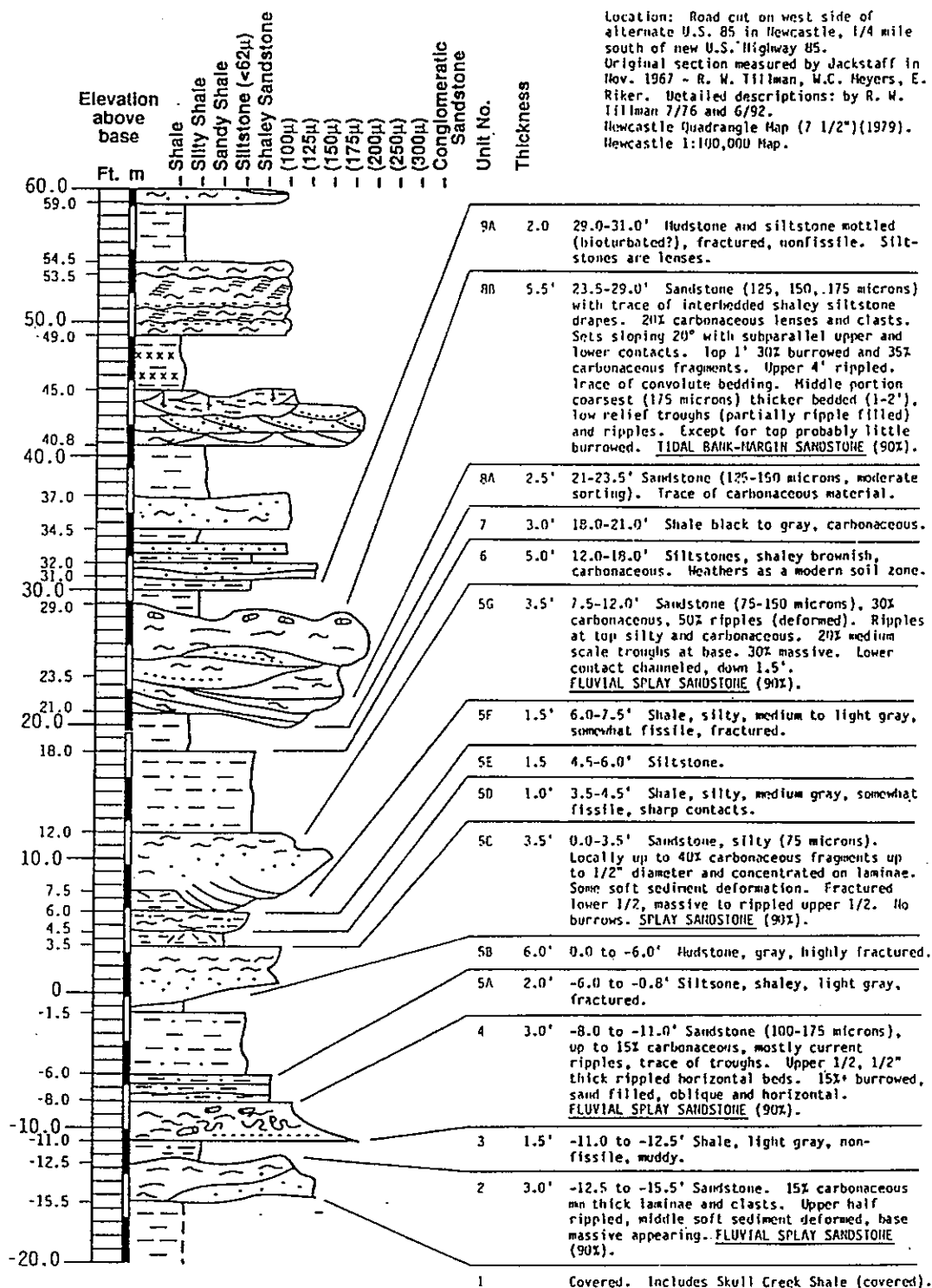
Traverse 160".
Northernmost of W6C-C measured sections.
In big reentrant in cliff. Follow SW facing
wall at base.
Unit 3 equivalent to Unit 9 of N.S. W6C-
C-90.
Clifton Quadrangle (7 1/2").
W6C-C3-92 intersects north of sloping
mudstone at very end of "Grunge" unit.
North of this the horizontal "Grunge" bed
was eroded.



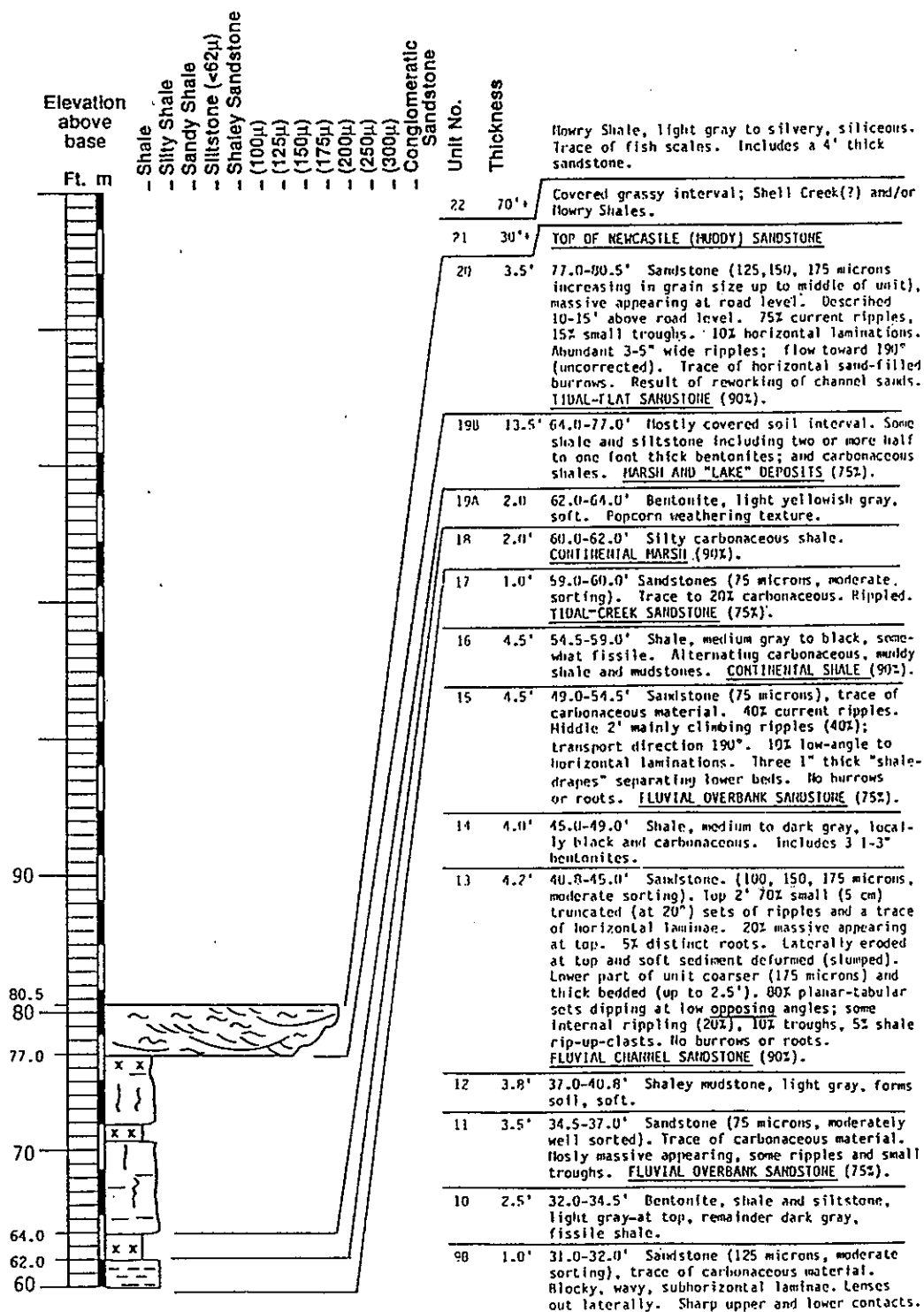
MEASURED SECTION W6C-C3-92
LAK RANCH,
S 1/2 SE NW NE Sec. 18 T43N R60W, WESTON CO., WYOMING



MEASURED SECTION W(9) NEWCASTLE MUDDY SANDSTONE FORMATION
NEWCASTLE TYPE SECTION, NEWCASTLE, WYOMING
SW SW SW Sec. 21 T45N R61W, WESTON CO., WYOMING



MEASURED SECTION W(9) NEWCASTLE MUDDY SANDSTONE FORMATION
 NEWCASTLE TYPE SECTION, NEWCASTLE, WYOMING
 SW SW SW Sec. 21 T45N R61W, WESTON CO., WYOMING



Preliminary
MEASURED SECTION W9B, NEWCASTLE (MUDDY) SANDSTONE
CITY OF NEWCASTLE, WESTON CO., WYOMING
NE NW Sec. 28 T45N R61W

