GENERAL PROBLEM:

Spatial Statistics are Calculated From a Small Fraction of the Outcrop Area

GOAL:

Evaluate Accuracy of Sampling Patterns Used to Determine Variograms from Outcrops

METHODS:

1. Generate Synthetic Outcrops of Known Variograms
2. Sample Outcrops with Typical Sample Patterns.
3. Sample Outcrops using a Simulated-Annealing Approach to Move Samples into Better Positions.

Basic Approach to Geostatistical Re

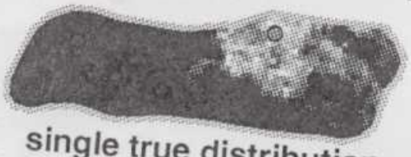
The
Va

Data is sparse so Many Stochastic Models (Realizations) are Generated

Reality

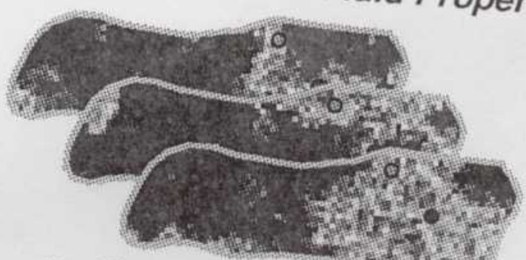
Model

Distribution of Rock/Fluid Properties



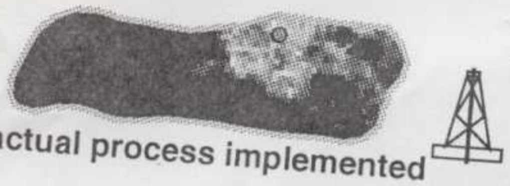
single true distribution

Distribution of Rock/Fluid Properties



multiple stochastic models

Recovery Process



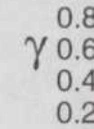
actual process implemented

Recovery Process

numerical model of process

Field Response

Field Response



Vertical

statistical Reservoir Modeling

els

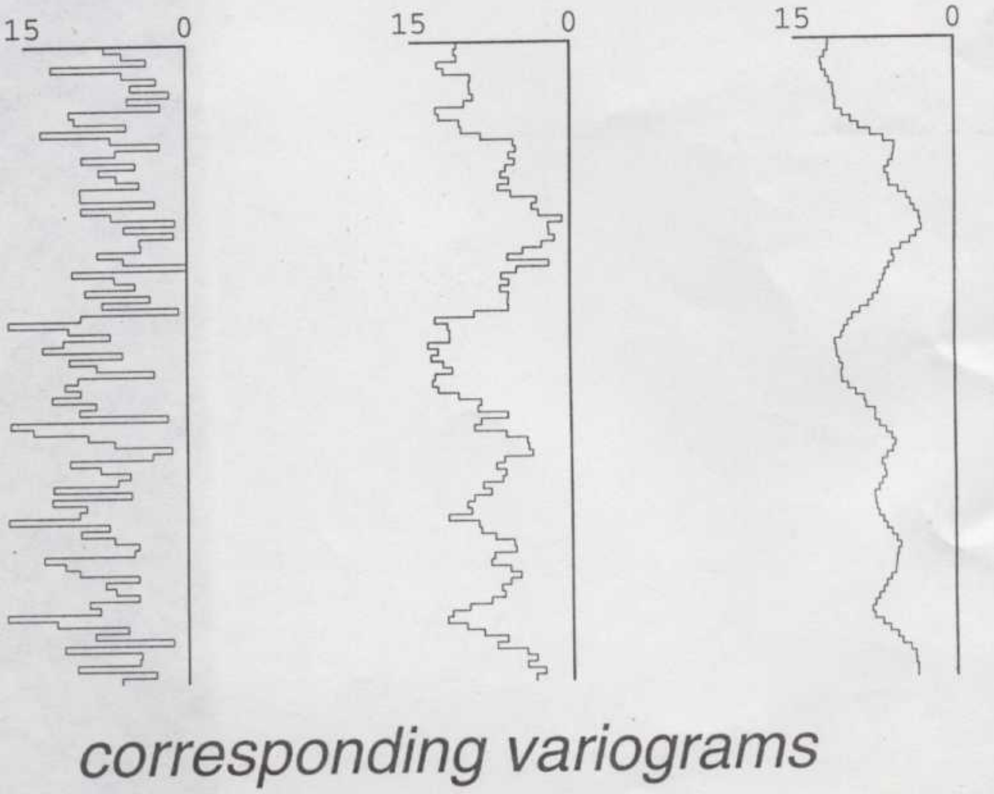
Properties

lels

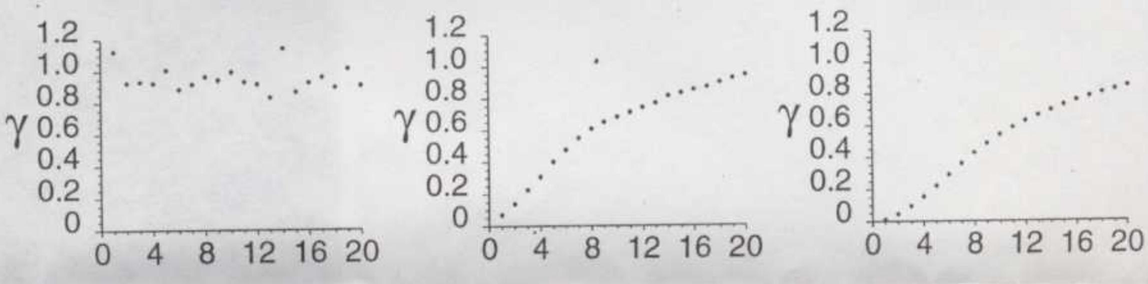
ss

The Variogram is a Measure of Spatial Variability that is commonly used in Reservoir Modeling

Example: 3 synthetic well logs



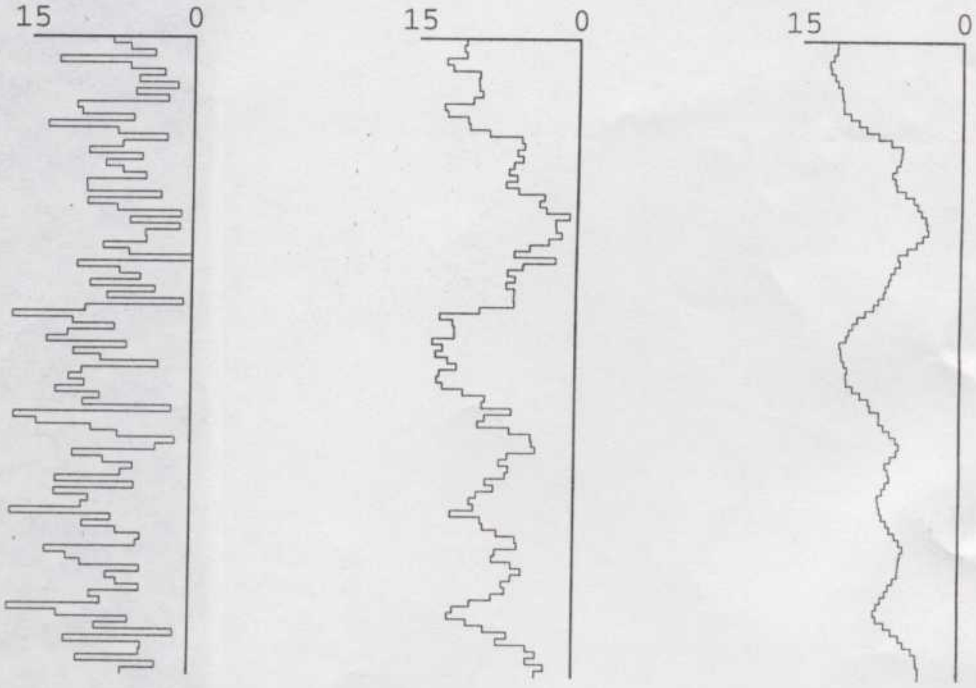
corresponding variograms



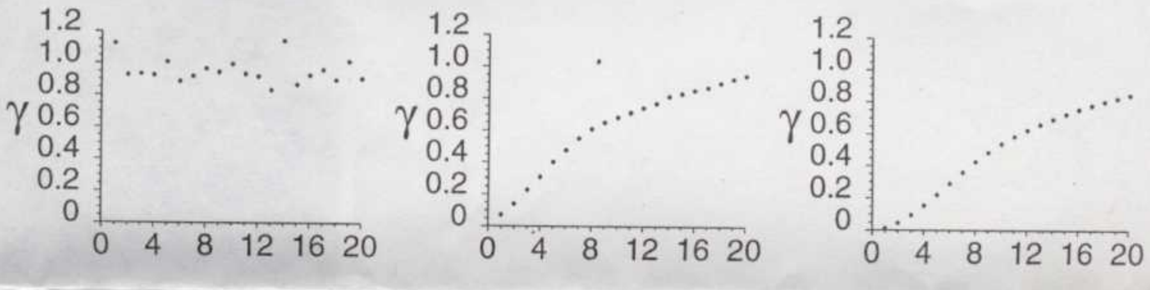
Vertical axis indicates variability; Horizontal axis is distan

Reservoir Modeling

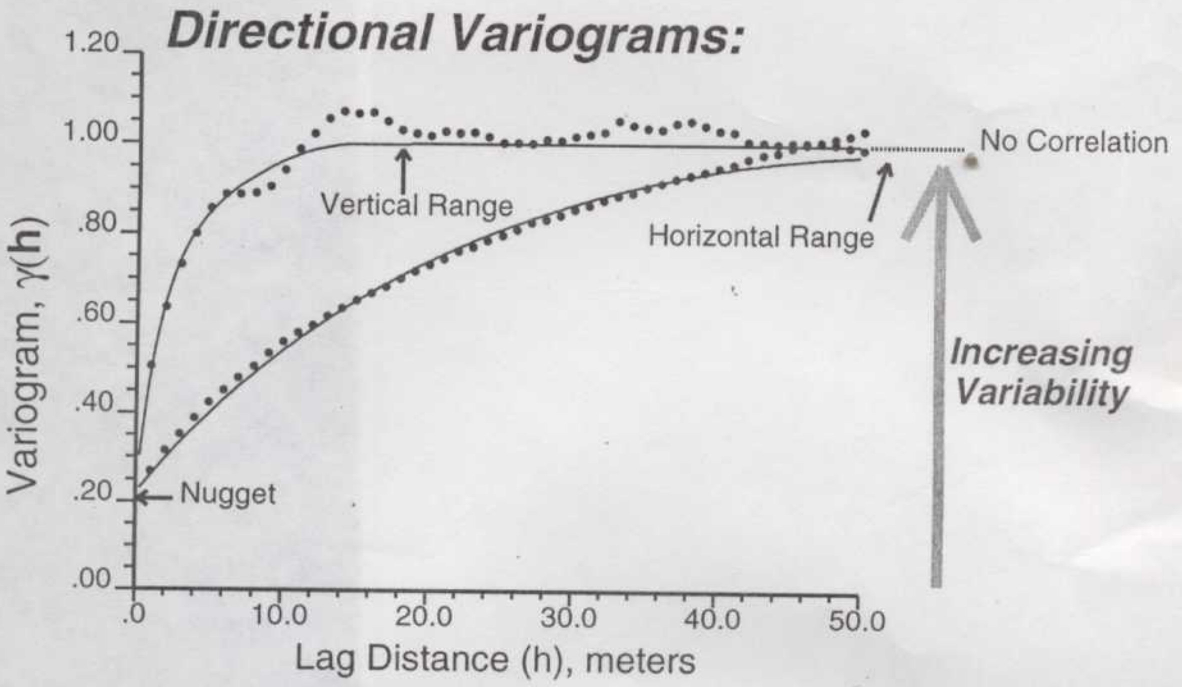
Example: 3 synthetic well logs



corresponding variograms



Vertical axis indicates variability; Horizontal axis is distanc



Data is sparse so Many Stochastic Models (Realizations) are Generated

Reality	Model

Reality

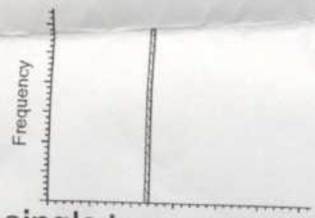
Distribution of Rock/Fluid Properties

single true distribution

Recovery Process

actual process implemented

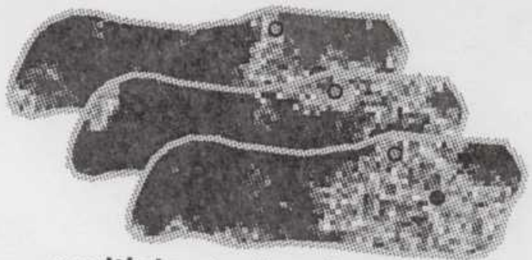
Field Response



single true response

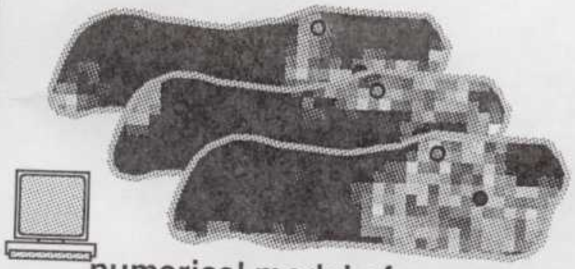
Model

Distribution of Rock/Fluid Properties



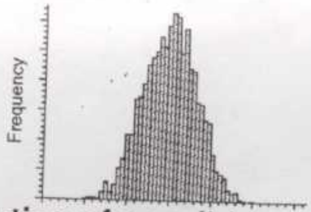
multiple stochastic models

Recovery Process



numerical model of process

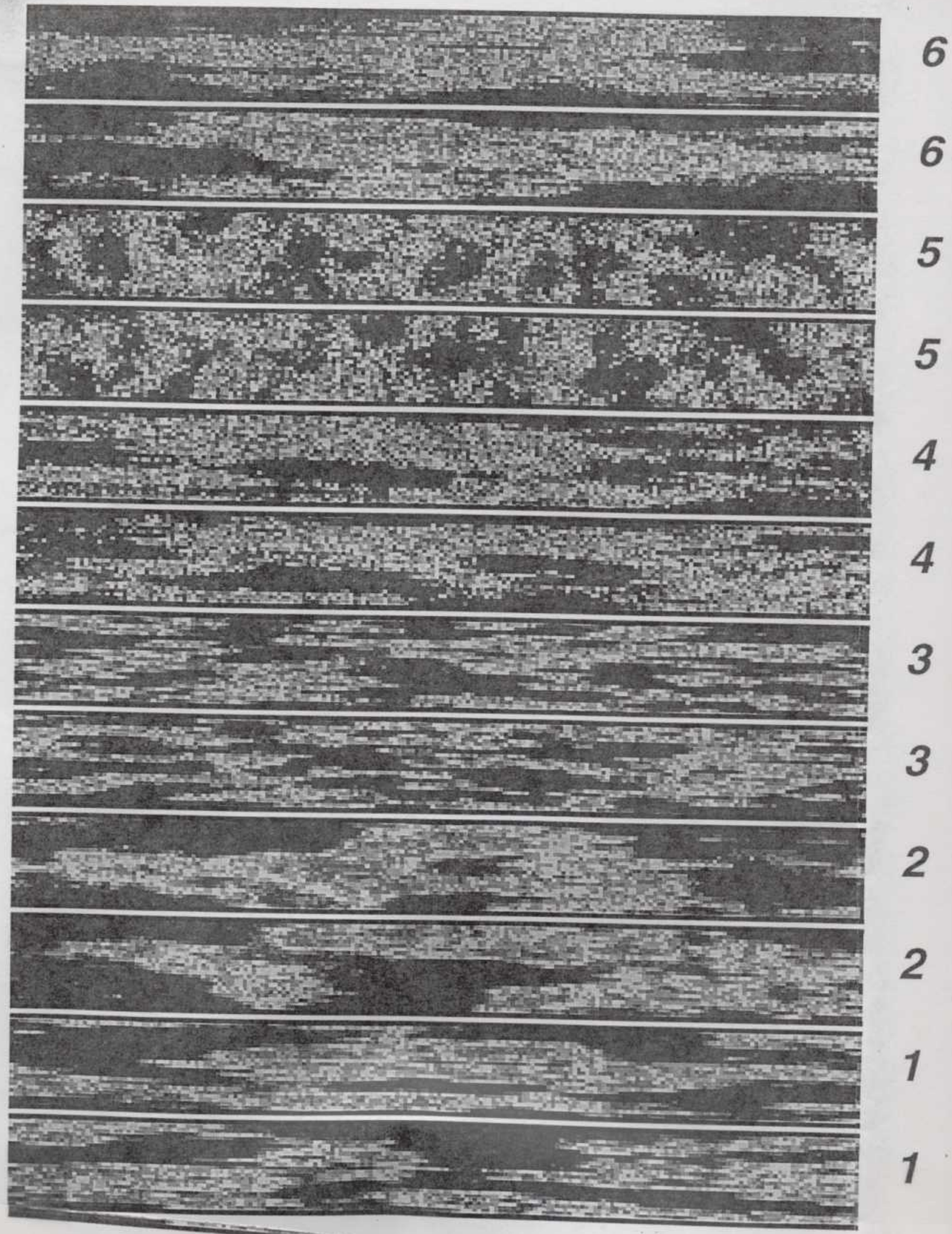
Field Response



distribution of possible responses

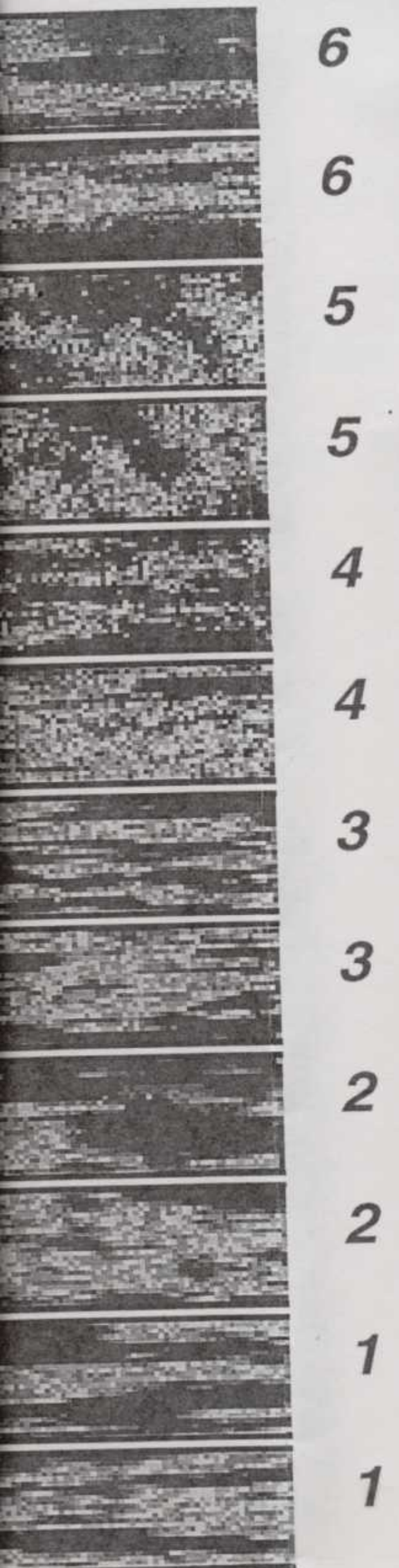
Vertical

6 Synthetic Permeability Outc



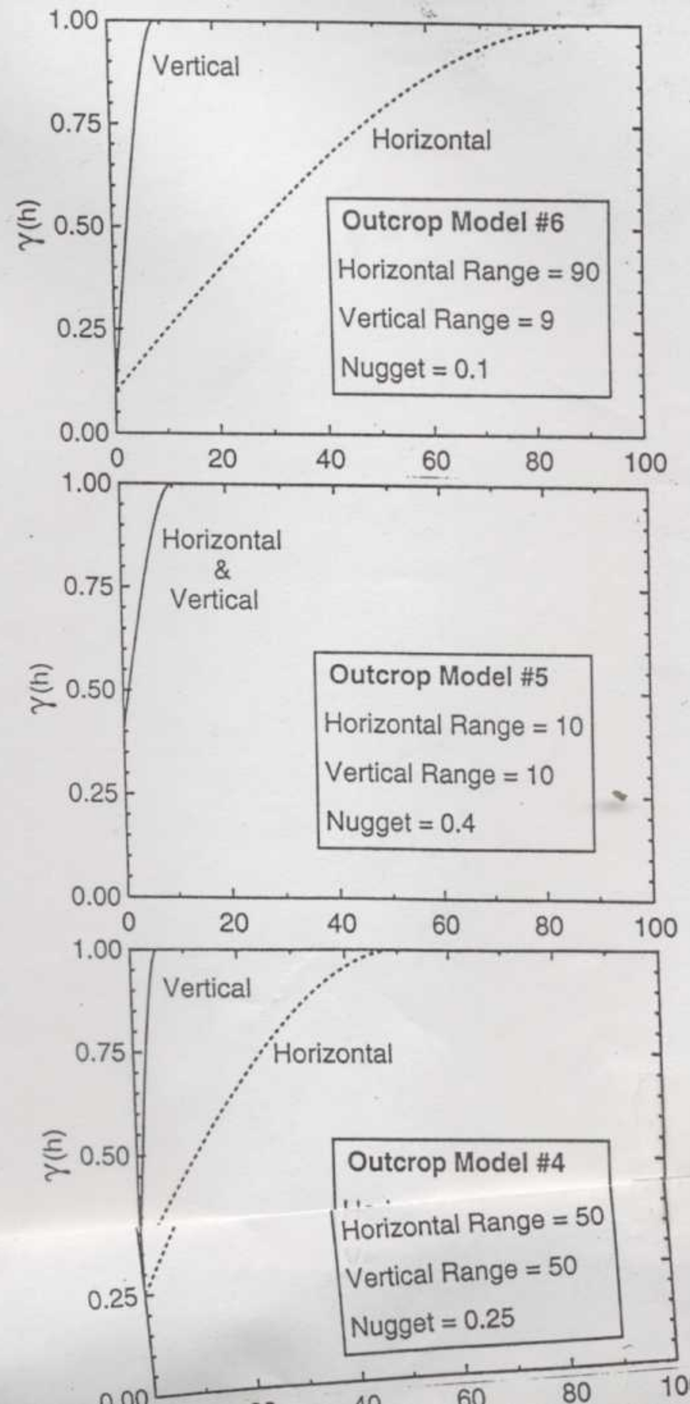
Colors range from blue (low log permeability) to red (high log permeability).

eability Outcrop Models



log permeability).

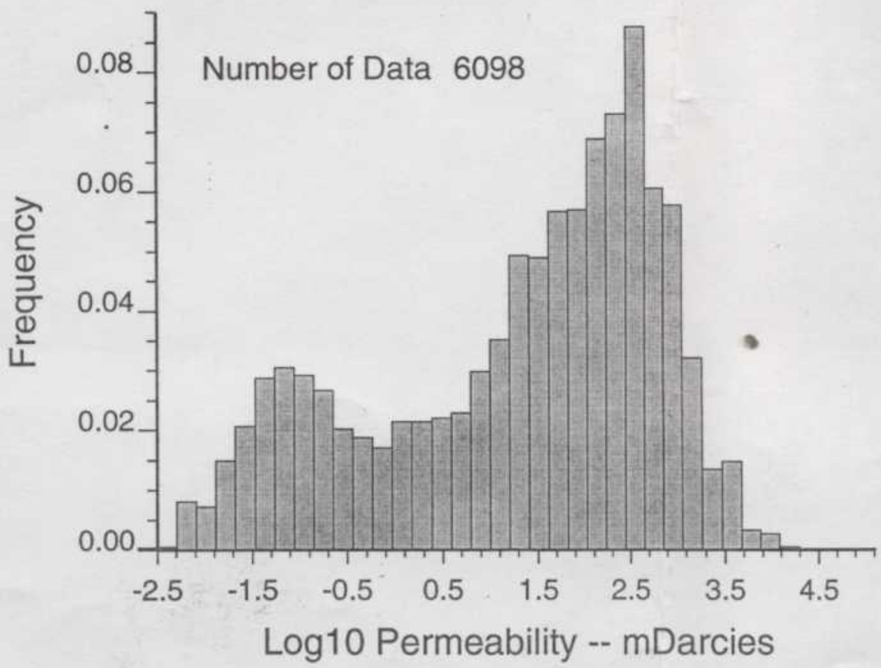
Model Variograms



Colors range from blue (low log permeability) to red (high log permeability).

- 6 Corresponding Variogram Models Used.
- 2 Realizations (different random seeds) Shown for E
- 53 Realizations Generated for Each Model.
- Outcrop Dimensions are 201 x 25 Cells.
- Generated using Annealing Cosimulation
  - ⋆ Deutsch & Cockerham, 69th Annual SPE Meeting, SP
    28413,1994.
  - ⋆ Constrained by Permeability Distribution & Variograms

Input Distribution of Log Permeability Data



high log permeability).

ls Used.

eeds) Shown for Each.

ch Model.

Cells.

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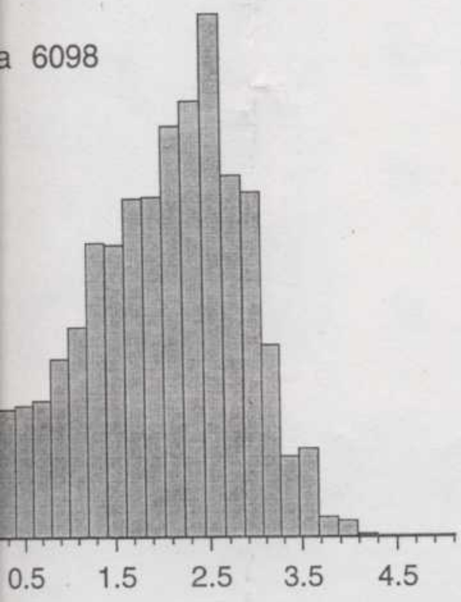
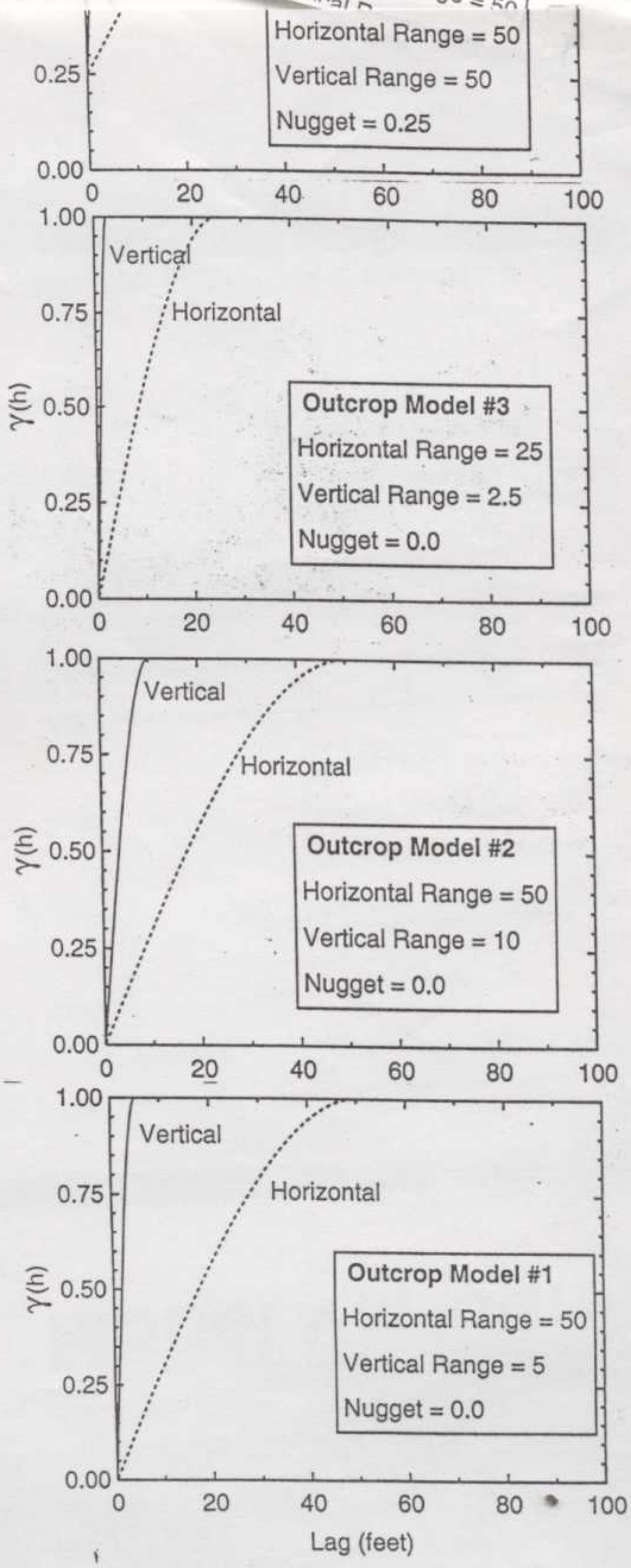
al SPE Meeting, SPE

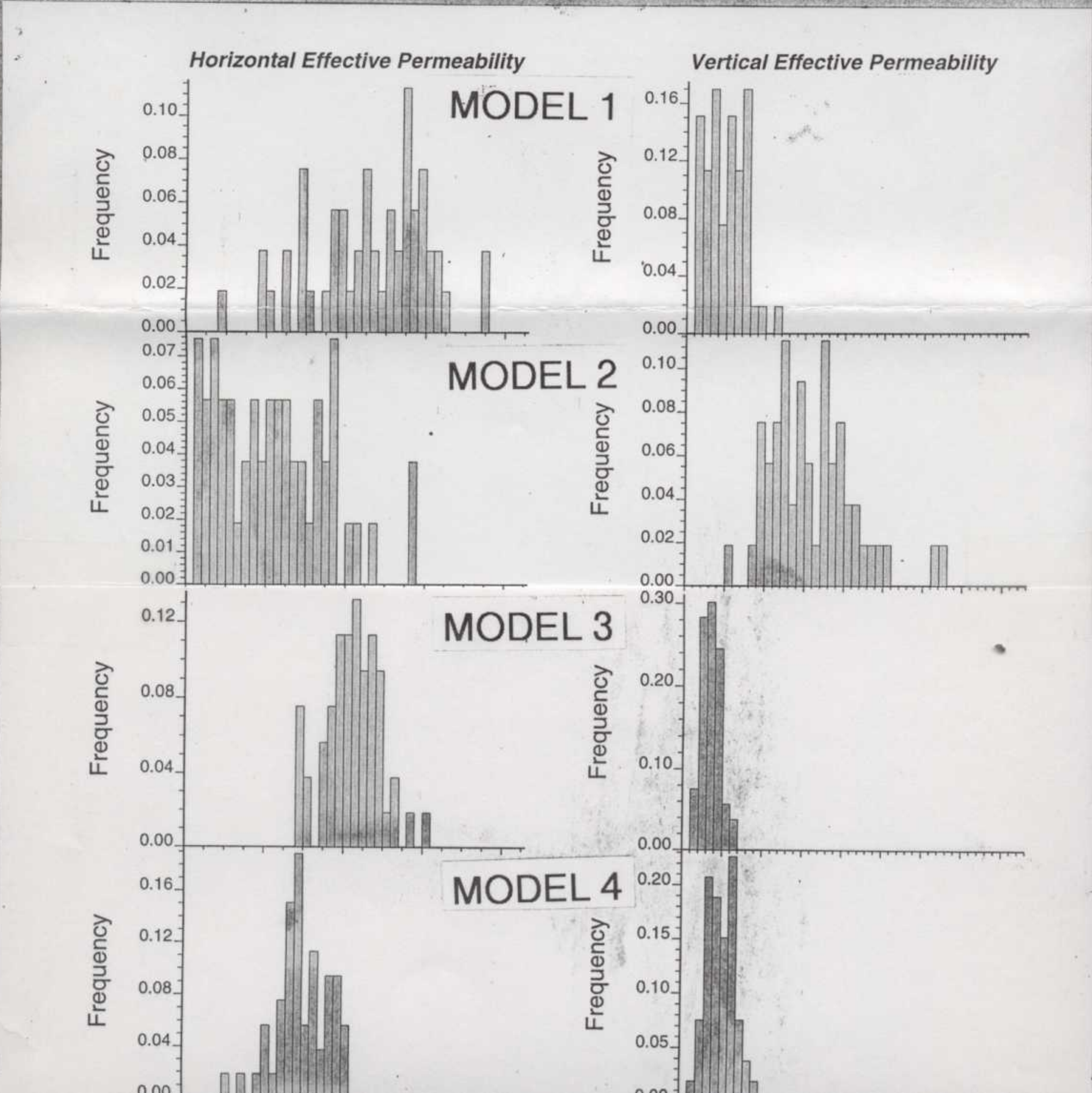
bution & Variograms.

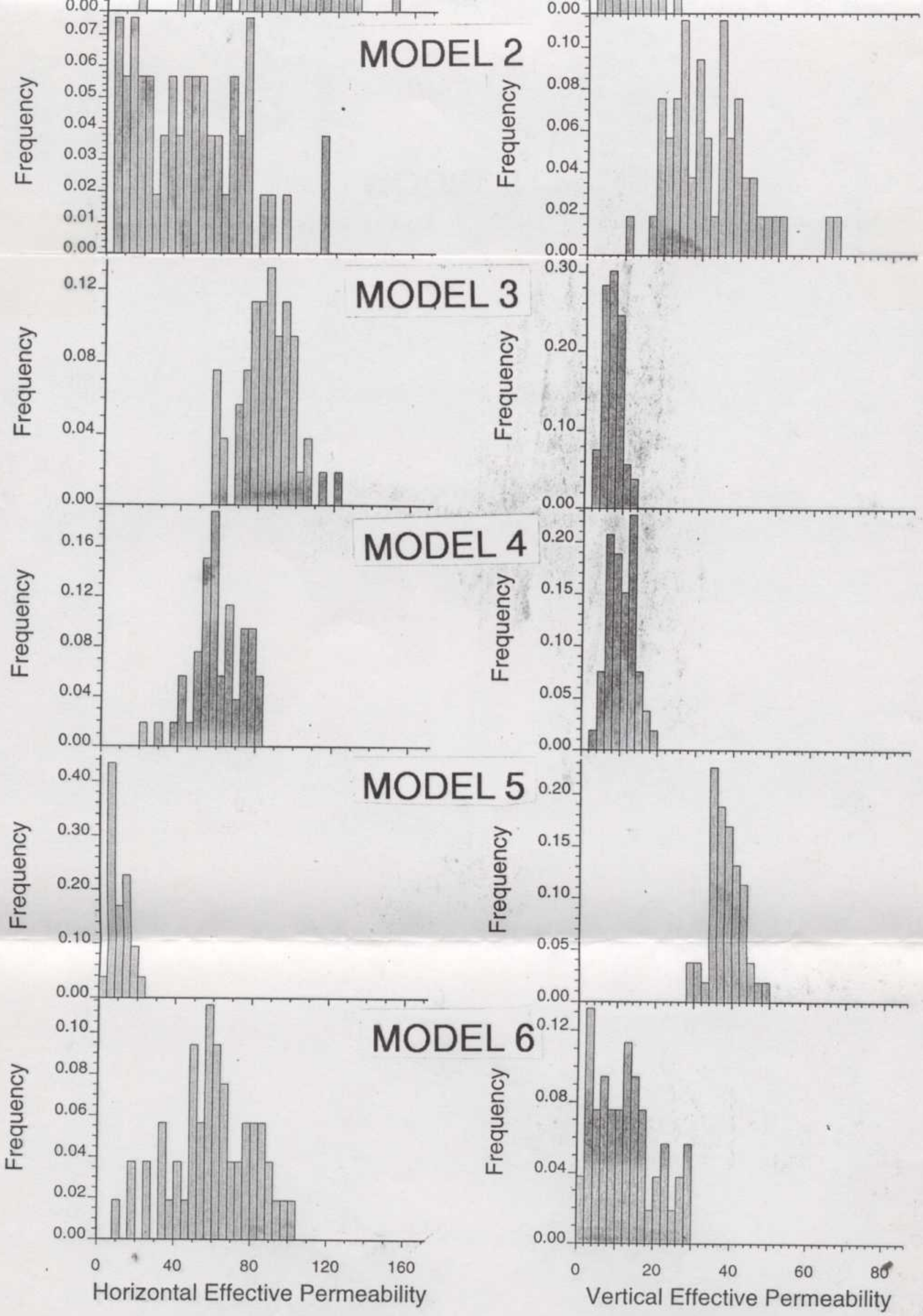
f Log Permeability Data



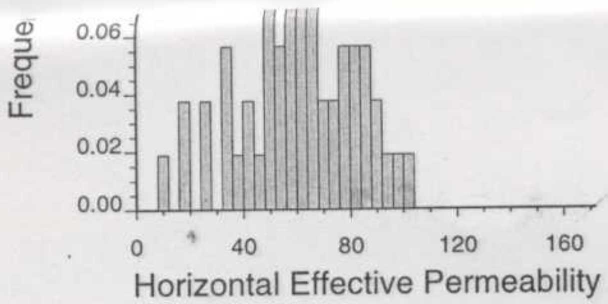


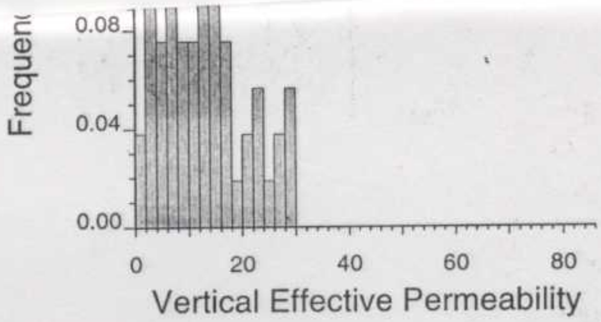
Anticipated Variability in Flow Behavior Among Realizations when Variograms Known





A goal of sampling is not merely a variogram model that yields the correct average flow behavior, but one that also accurately represents the variation in flow behavior





A goal of sampling is not merely a variogram model that yields the correct average flow behavior, but one that also accurately represents the variation in flow behavior from different realizations created from the original, known variogram.

Thus, we desire outcrop sampling methods to yield variogram model parameters for each outcrop within about 50% of their true values.

Effective Permeability is the Permeability that, when Multiplied by the Mean Fluid Pressure Gradient, Produces the Specific Discharge Through the Outcrop.

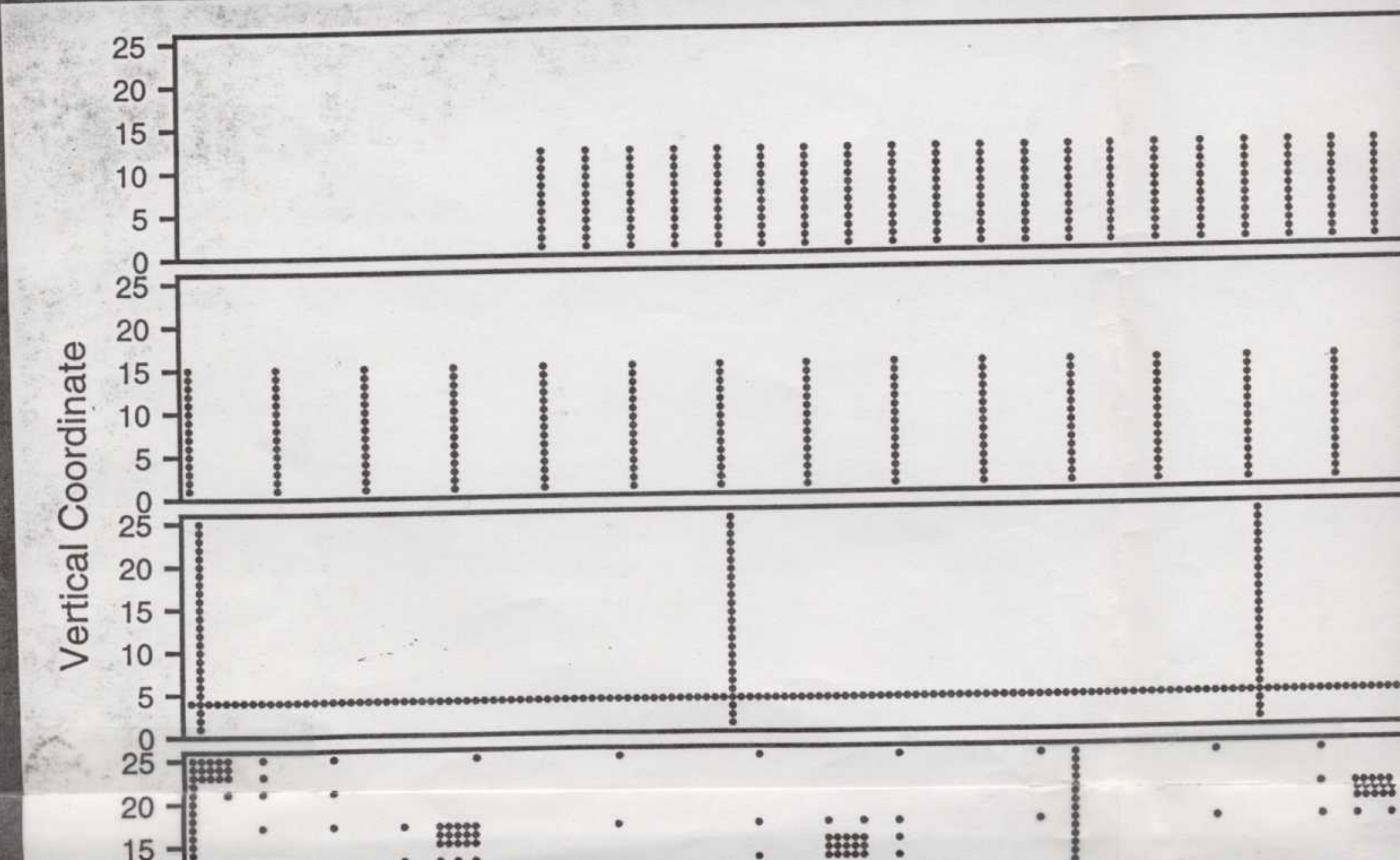
- Horizontal Effective Permeability Calculated Assuming Constant Pressure at Right & Left Ends Of the Outcrop & No Flow Through Top & Bottom Edges.
- Vertical Permeability Is Determined Correspondingly.

Approach 1:

Test Typical Sampling Patterns or

10 Common Outcrop Sample

- Patterns 1–5 confinded to low

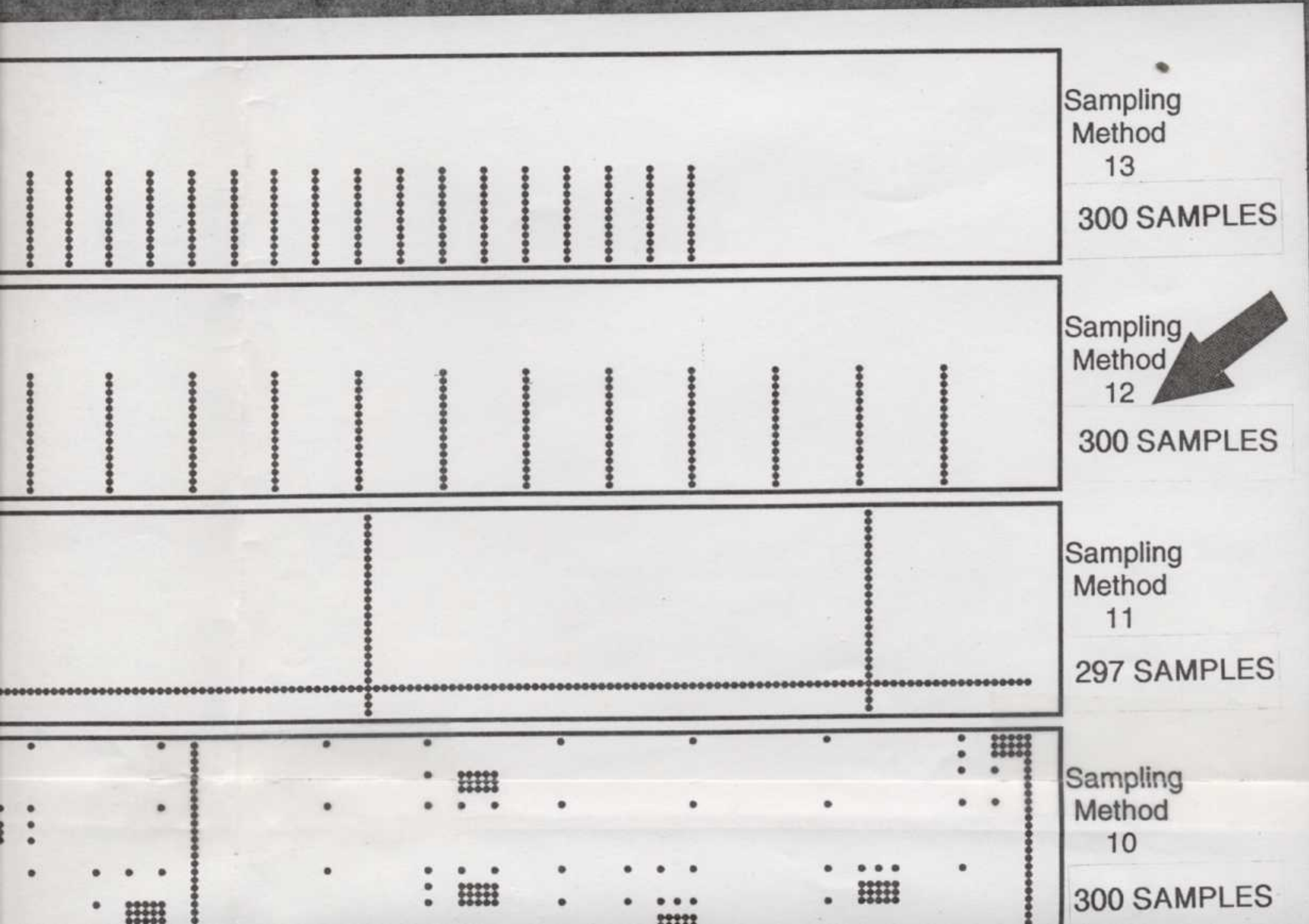


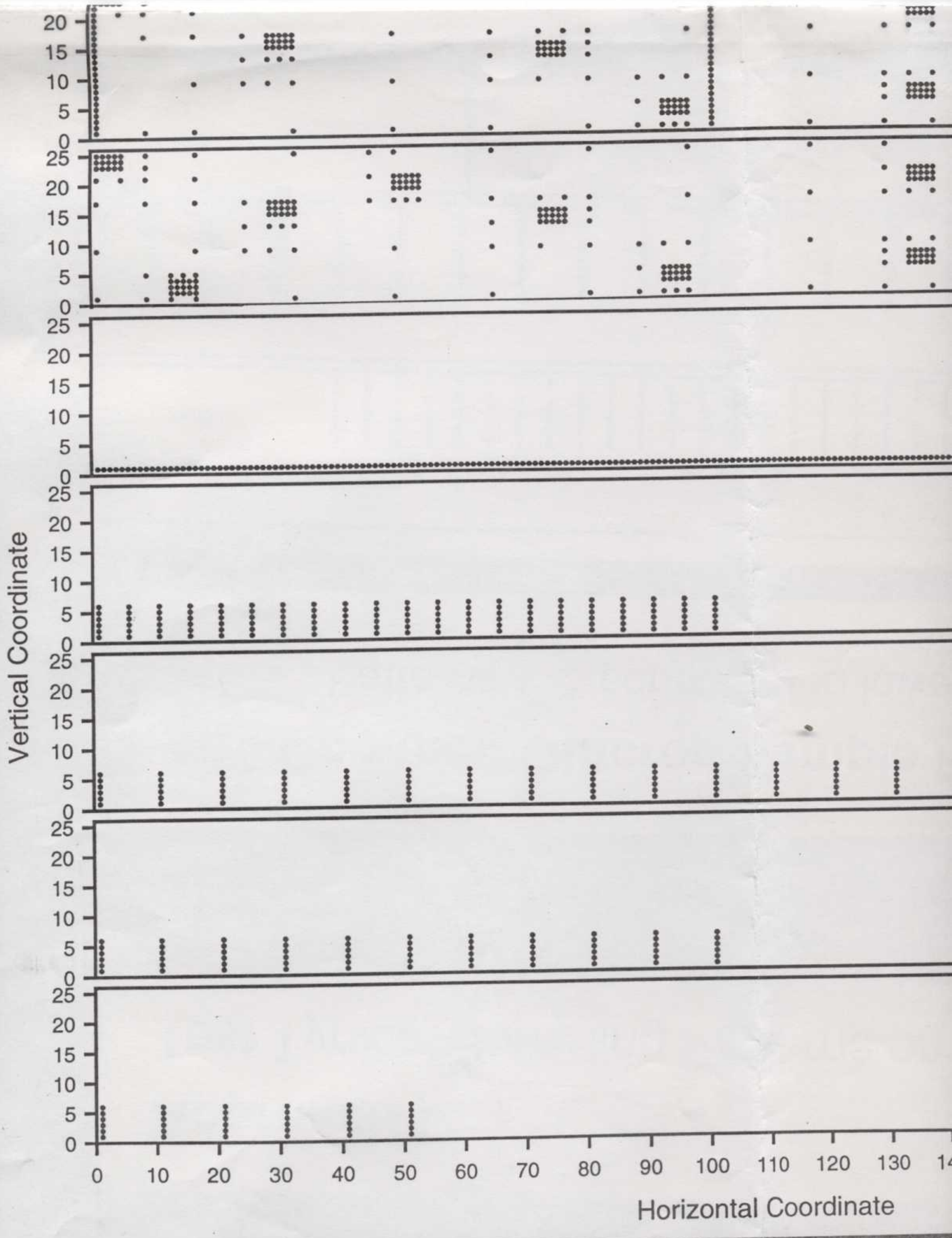
5

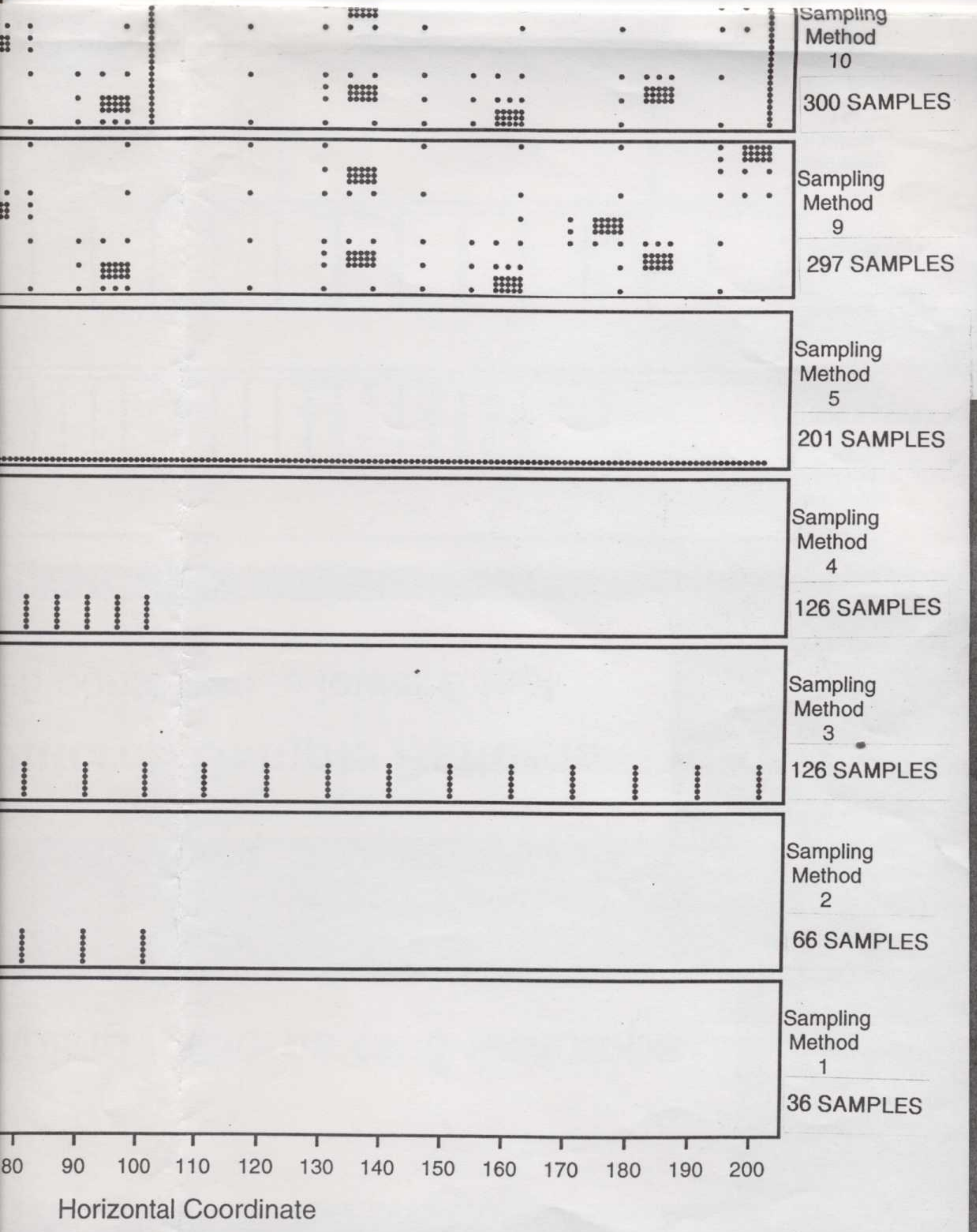
pling Patterns on 6 Outcrops

utcrop Sample Patterns

-5 confinded to lower 6 feet.



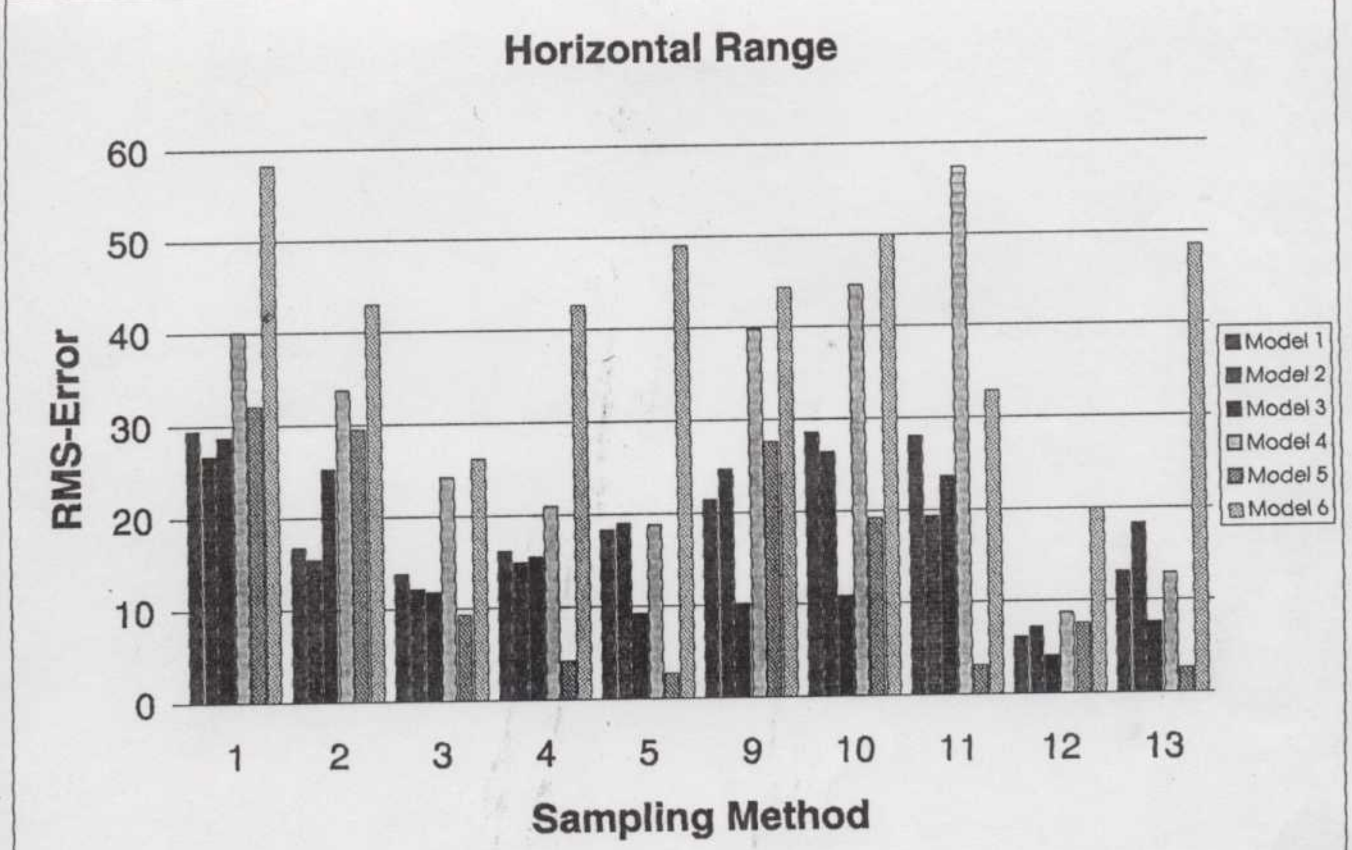

Vertical Coordinate
Horizontal Coordinate

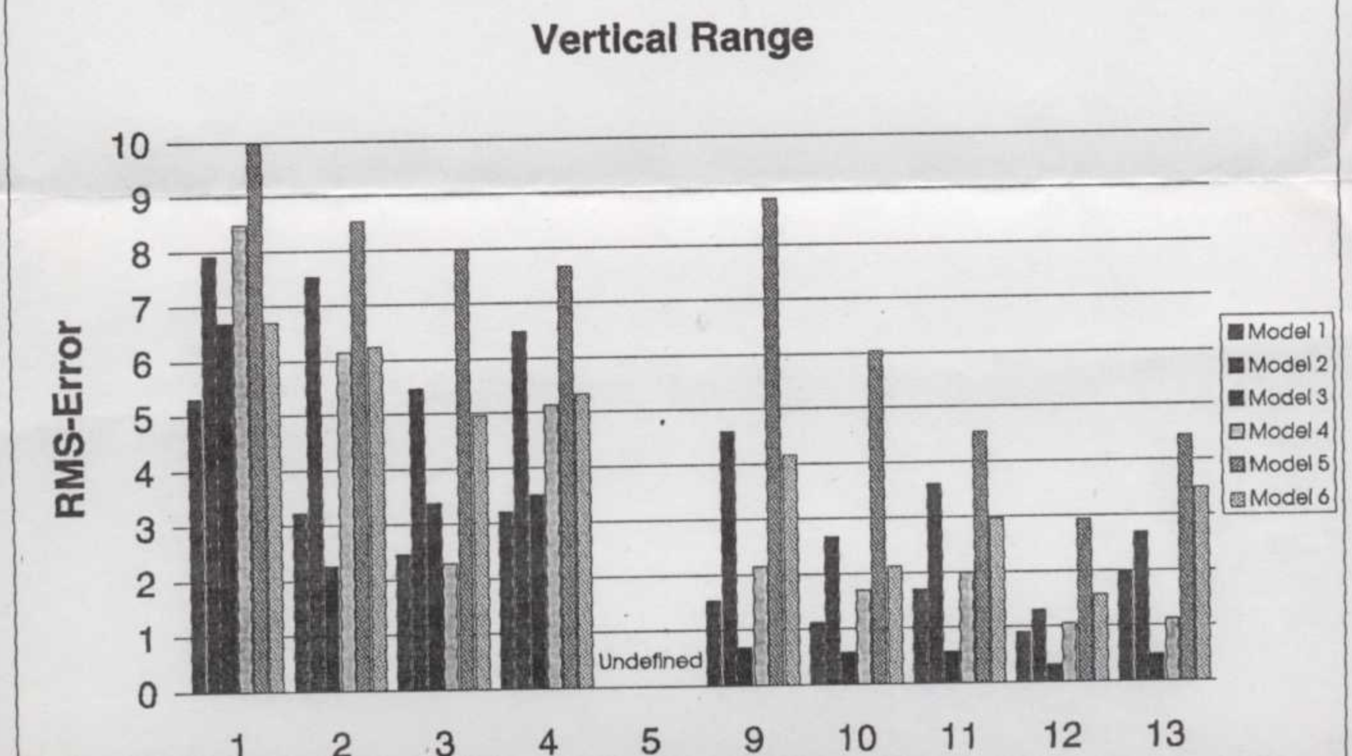

Sampling Method 10
300 SAMPLES
Sampling Method 9
297 SAMPLES
Sampling Method 5
201 SAMPLES
Sampling Method 4
126 SAMPLES
Sampling Method 3
126 SAMPLES
Sampling Method 2
66 SAMPLES
Sampling Method 1
36 SAMPLES
80 90 100 110 120 130 140 150 160 170 180 190 200
Horizontal Coordinate

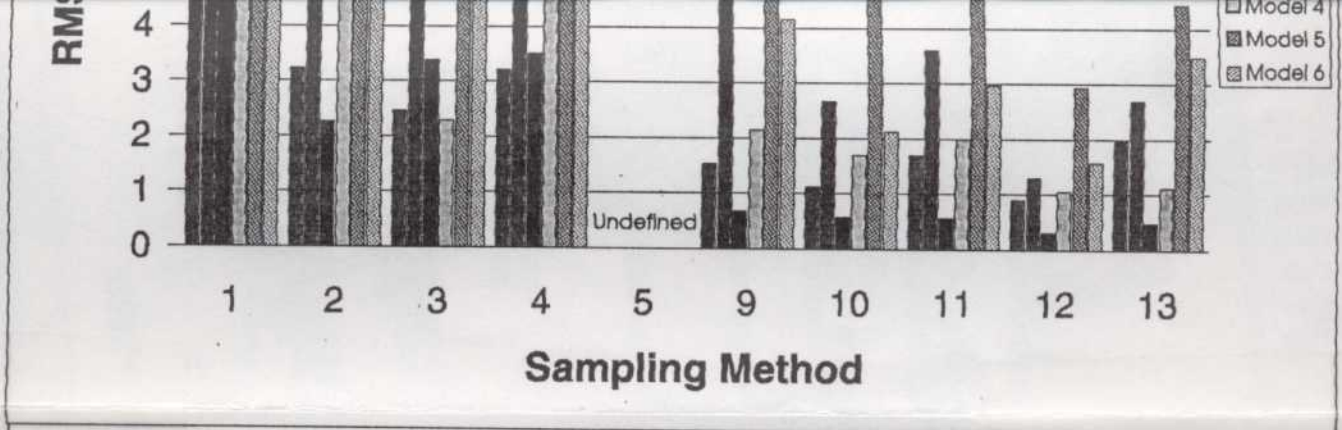
Root-Mean-Square Errors of Variogram Model Parameters Calculated From Samples:

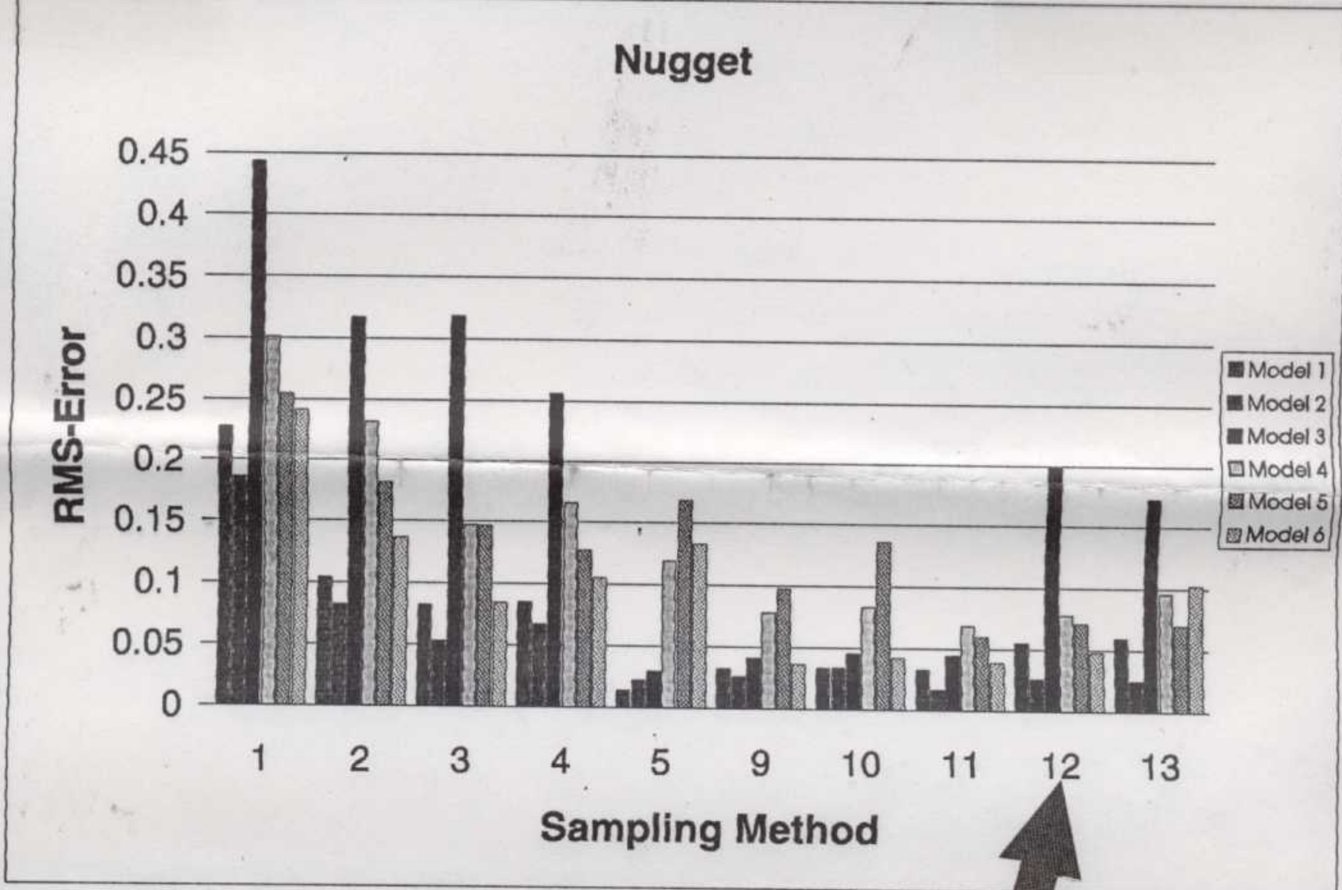
Fixed Samples

(6)





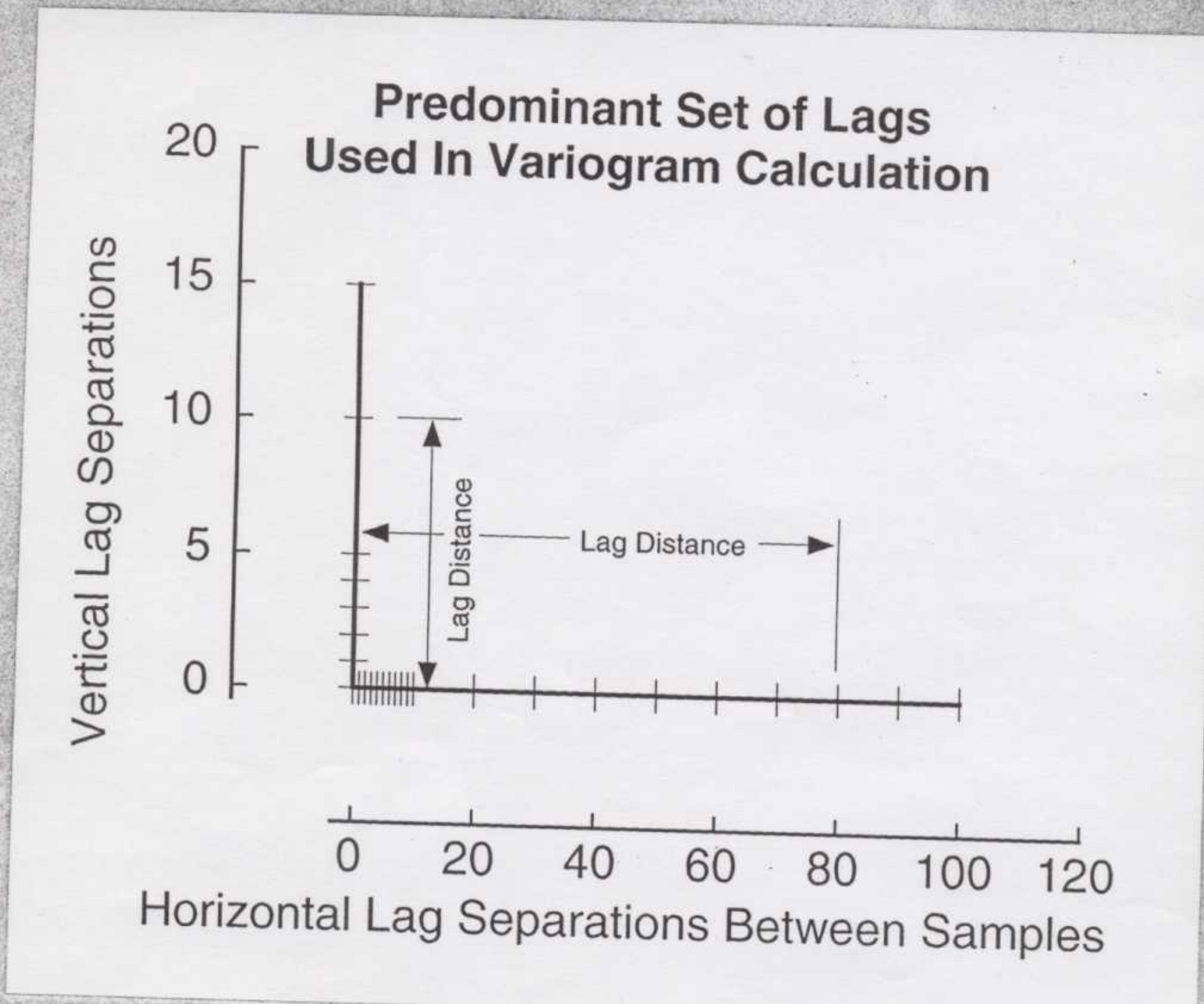




☛ Overall Best Method 12.

Strategy 12 is poor at predicting the nugget.

✖ Accurate prediction of the nugget is especially important with regard to flow behavior
⇨ strategy C300b is preferred.



Predominant Set of Lags
Used In Variogram Calculation
Vertical Lag Separations
20
15
10
5
0
Lag Distance
Lag Distance
0
20
40
60
80
100
120
Horizontal Lag Separations Between Samples

Number of Samples Used for Each Lag According to Sampling Method

		Sampling Method									
	Lag #	1	2	3	4	5	9	10	11	12	13
Vertical	1	30	55	105	105	0	125	158	96	280	275
	2	24	44	84	84	0	102	140	92	260	250
	3	18	33	63	63	0	32	86	88	240	225
	4	12	22	42	42	0	73	116	84	220	200
	5	6	11	21	21	0	7	64	80	200	175
	6	0	0	0	0	0	10	52	60	100	50
	7	0	0	0	0	0	14	42	40	0	0
Horizontal Lags	8	0	0	0	0	200	144	108	200	0	0
	9	0	0	0	0	199	120	89	199	0	0
	10	0	0	0	0	198	72	54	198	0	0
	11	0	0	0	0	197	87	73	197	0	0
	12	0	0	0	120	196	16	16	196	0	0
	13	0	0	0	0	195	22	21	195	0	0
	14	0	0	0	0	194	16	16	194	0	0
	15	0	0	0	0	193	58	56	193	0	288
	16	0	0	0	0	192	2	2	192	0	0
	17	30	60	120	114	191	4	3	191	285	276
	18	24	54	114	102	181	33	34	181	270	252
	19	18	48	108	90	171	8	10	171	255	228
	20	12	42	102	78	161	42	42	161	240	204
	21	6	36	96	66	151	18	16	151	225	180
	22	0	30	90	54	141	24	31	213	210	156
	23	0	24	84	42	131	3	7	131	195	132
	24	0	18	78	30	121	52	35	121	180	108
	25	0	12	72	18	111	5	4	111	165	84
	26	0	6	66	6	101	22	64	101	150	60
	Total # samples	36	66	126	126	201	297	300	297	300	300

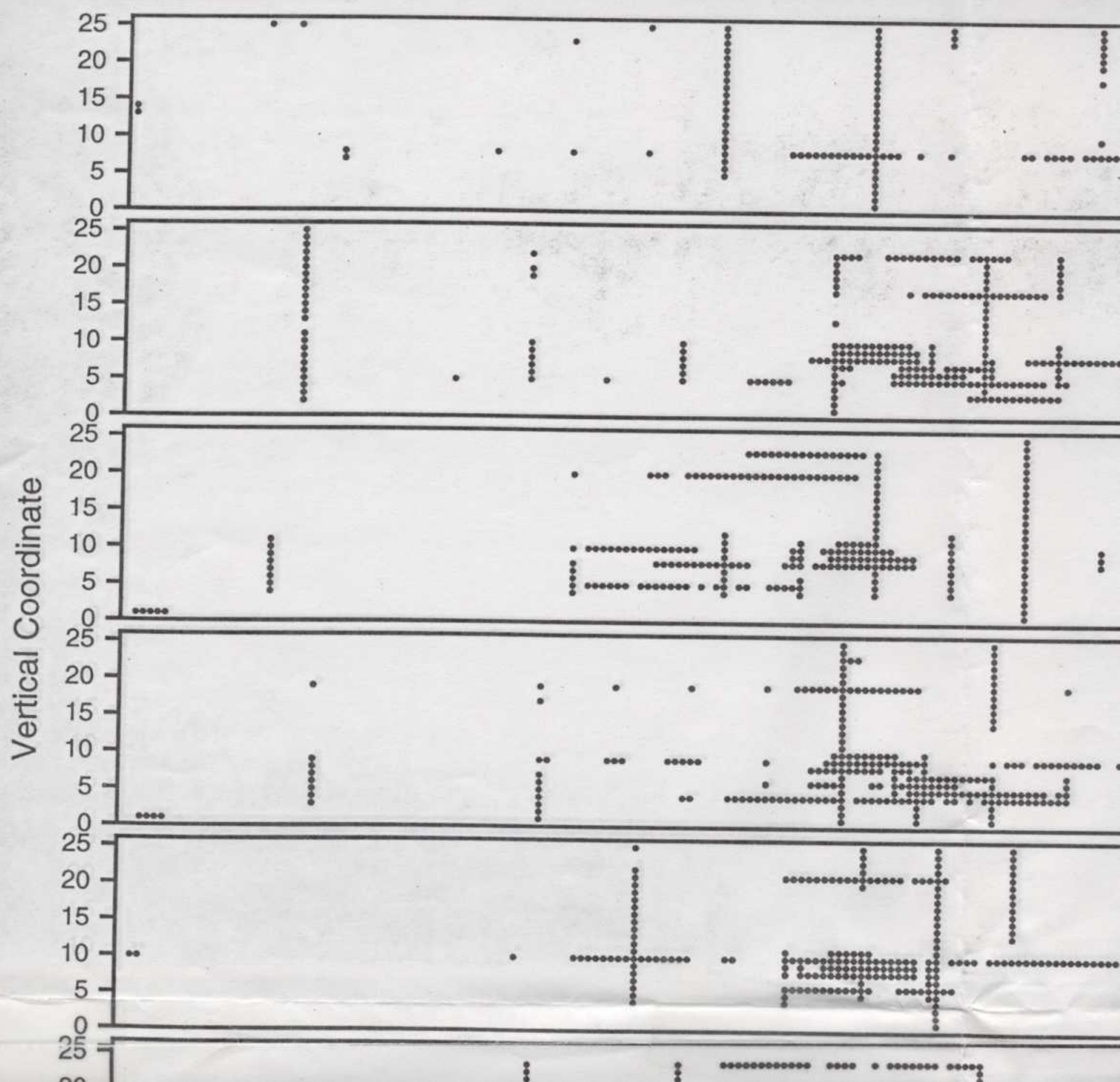
Approach 2:

Use Simulated-Annealing to Move Samples Into More Favorable Pattern

- Anneal Using Models 1–4
- Test On Models 5 & 6

12 Outcrop Sample Patterns From I

- Combined Set of 53 Realizations of Outcrop
- 300 Samples.
- Different sampling patterns result from differe initial random patterns.
- Outcrop models 5 and 6 reserved for testing



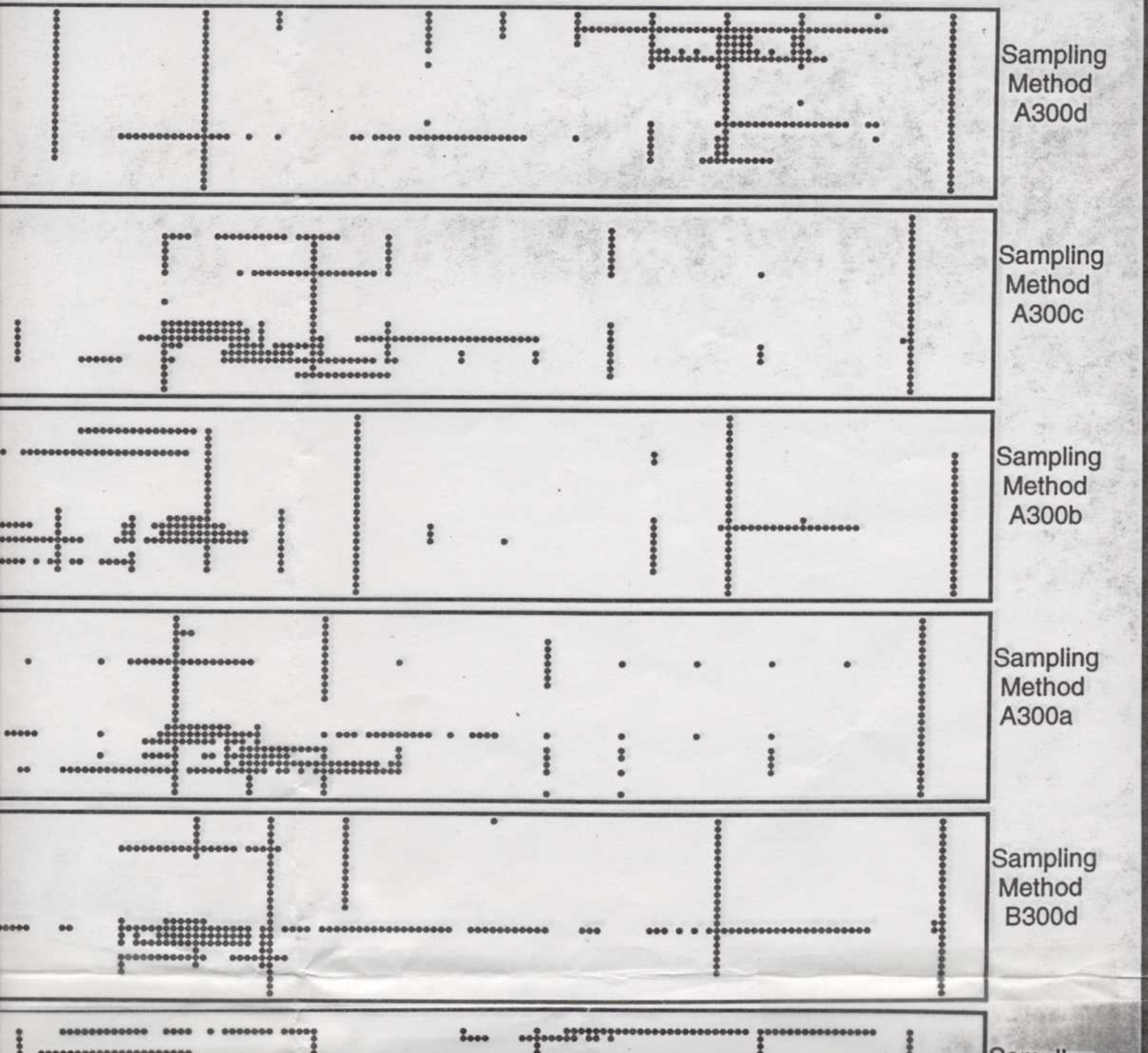
Patterns From Different Annealing Runs

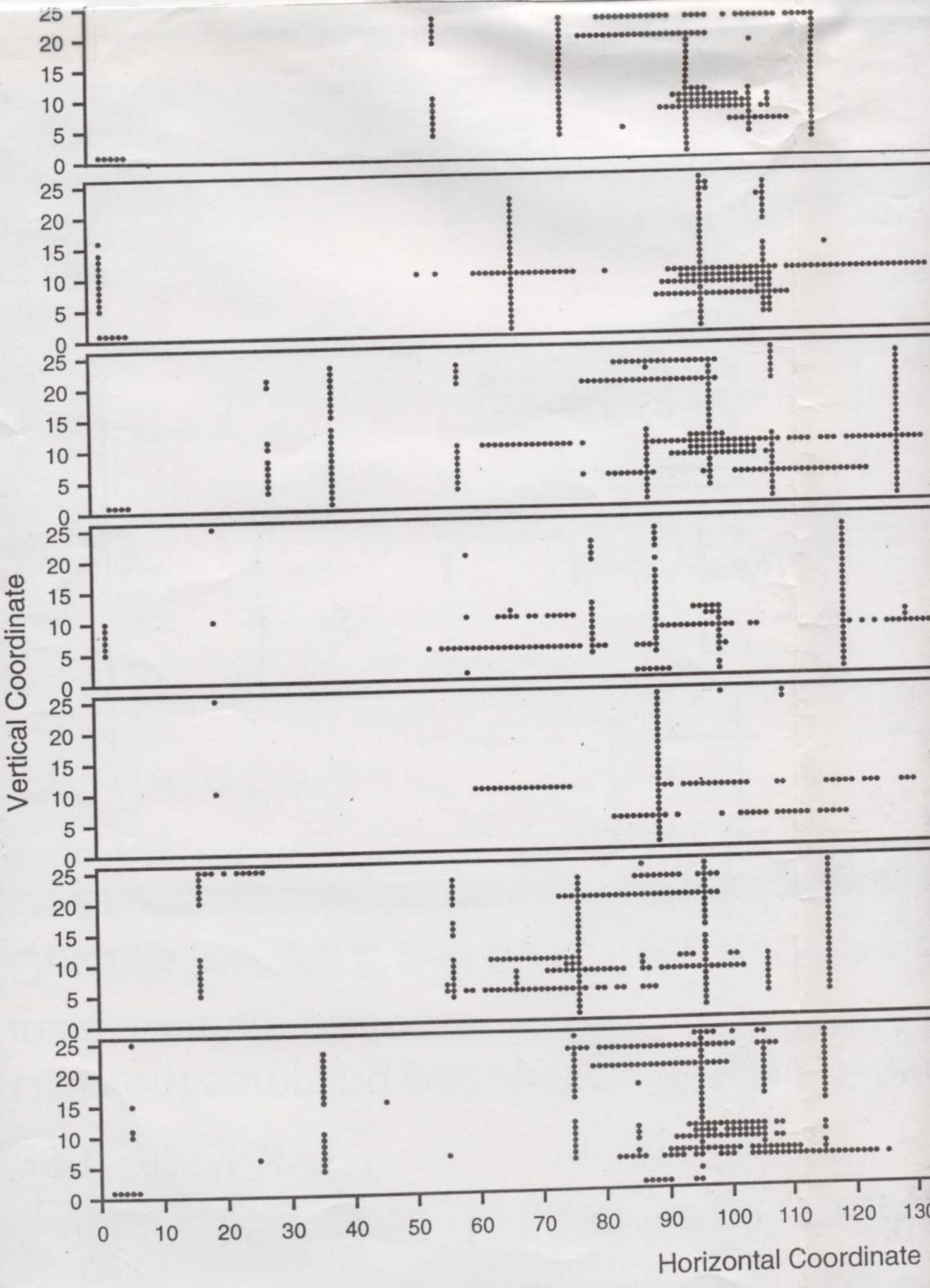
(10)

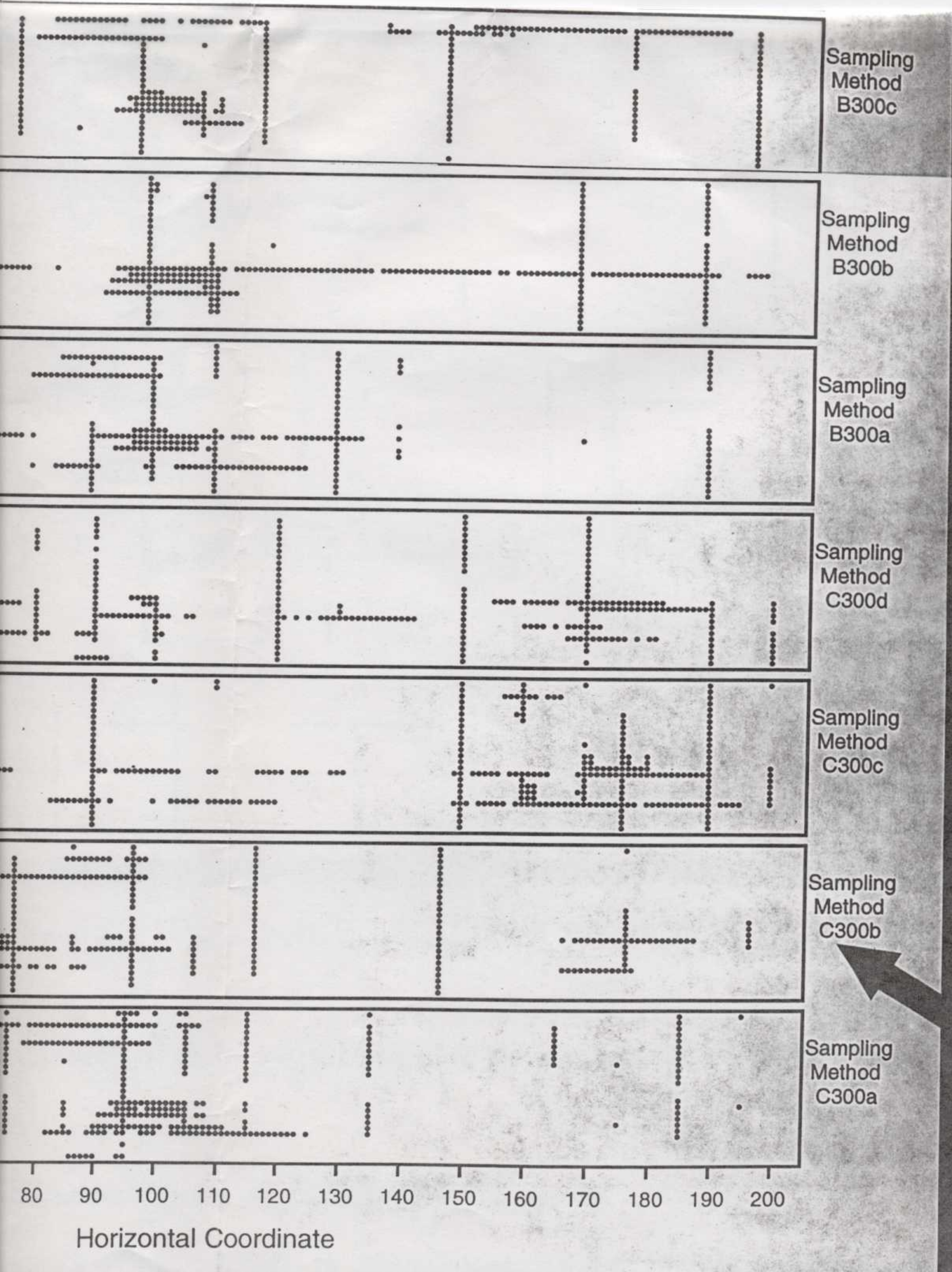
zations of Outcrop Models 1–4.

s result from differences in annealing rates and

served for testing resultant sampling patterns.

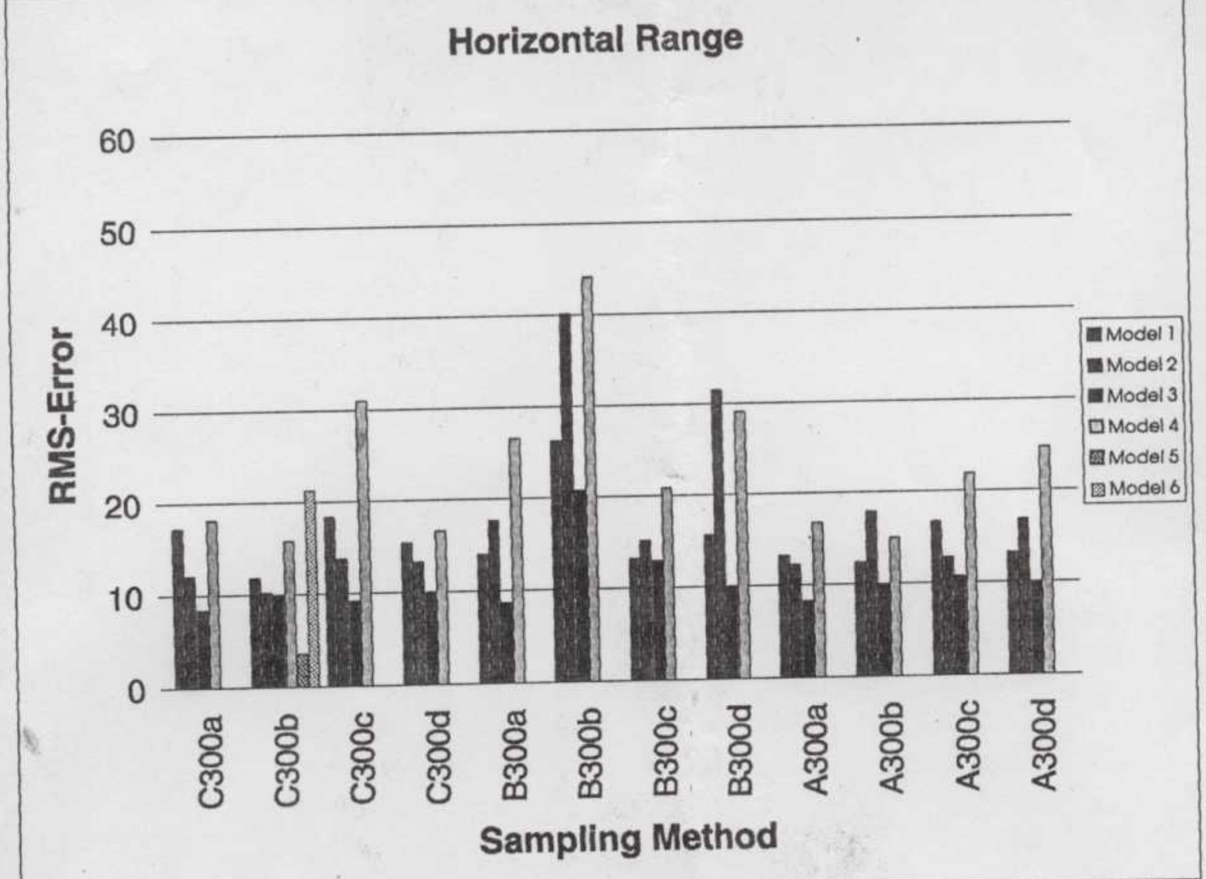


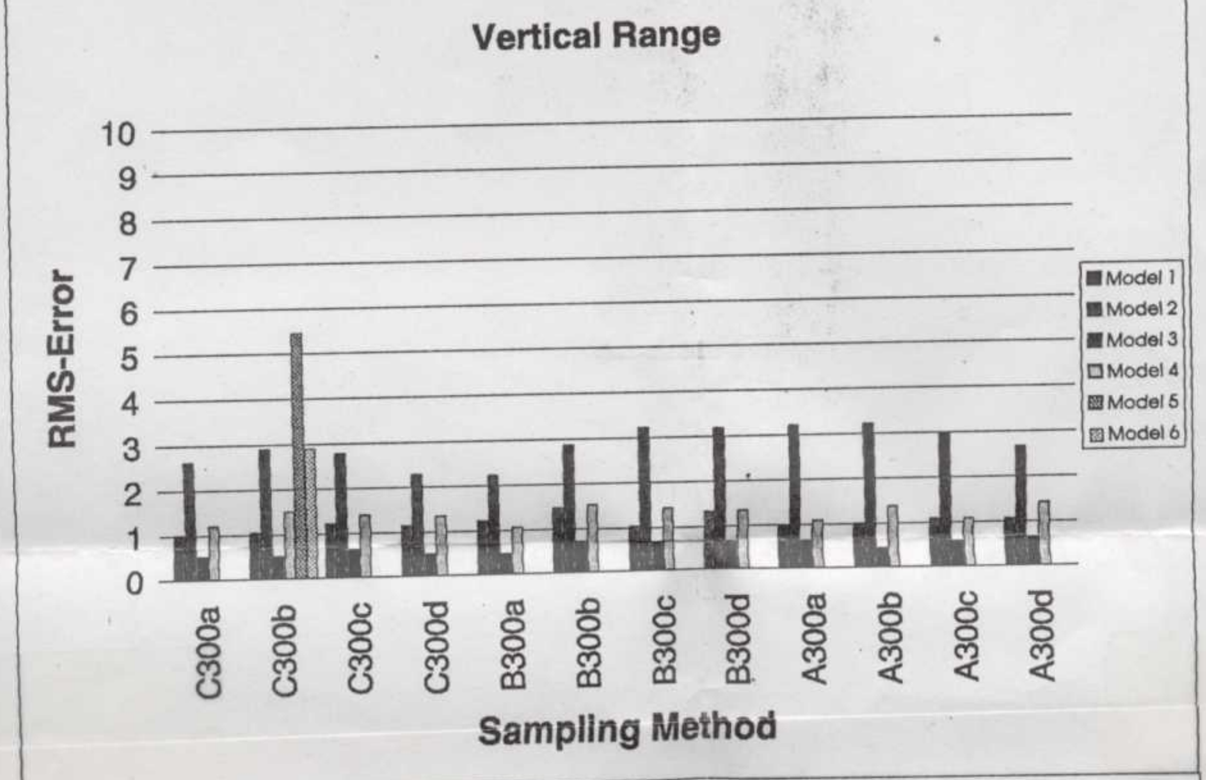

Vertical Coordinate
Horizontal Coordinate
0
10
20
30
40
50
60
70
80
90
100
110
120
130
0
5
10
15
20
25

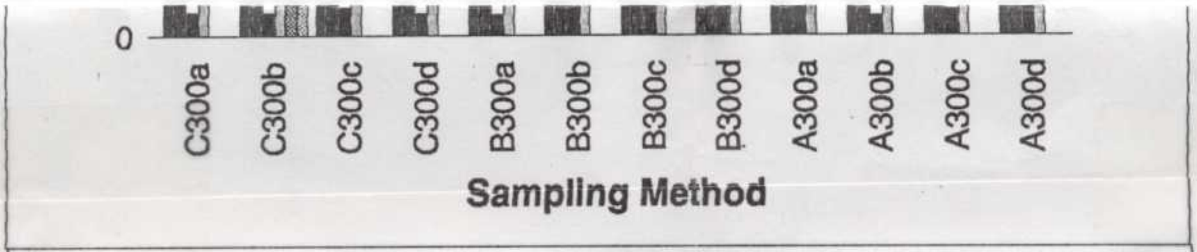

Sampling Method B300c
Sampling Method B300b
Sampling Method B300a
Sampling Method C300d
Sampling Method C300c
Sampling Method C300b
Sampling Method C300a
80
90
100
110
120
130
140
150
160
170
180
190
200
Horizontal Coordinate

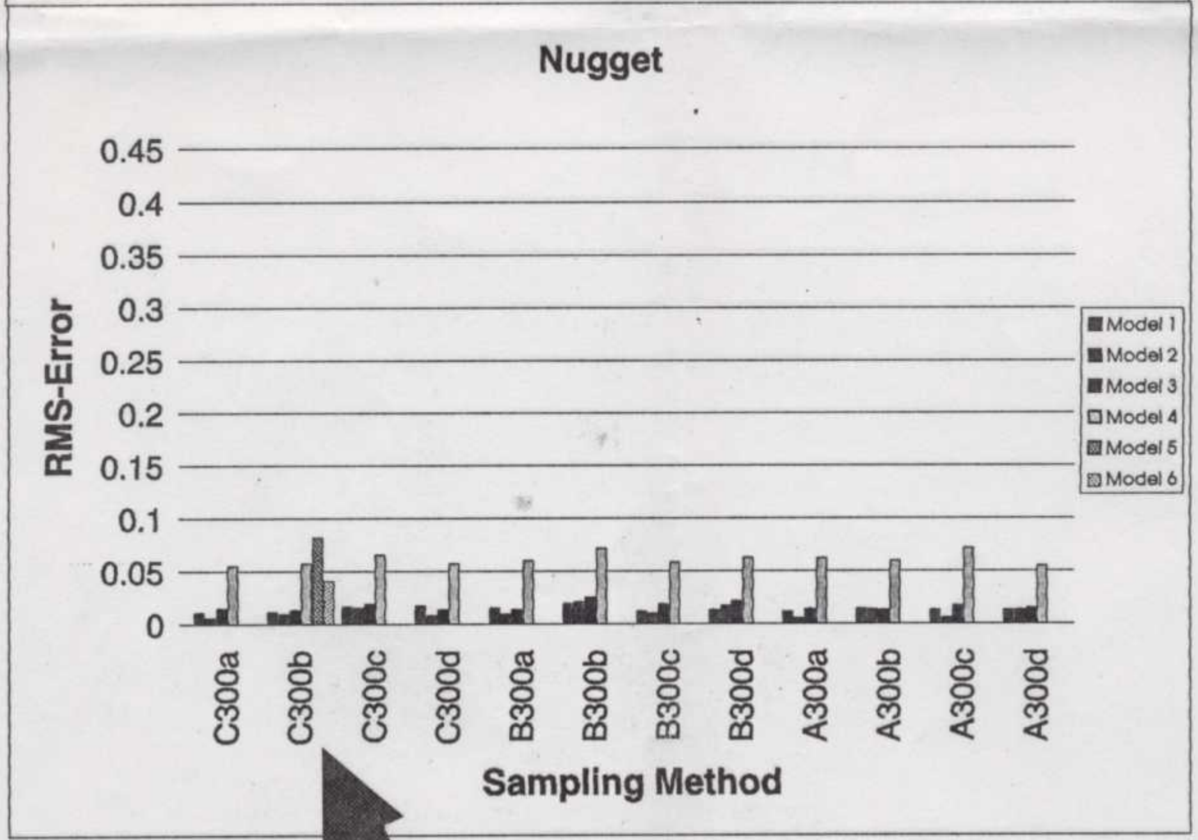
Root-Mean-Square Errors of Variogram Model Parameters Calculated From Samples:

300 Annealed Samples







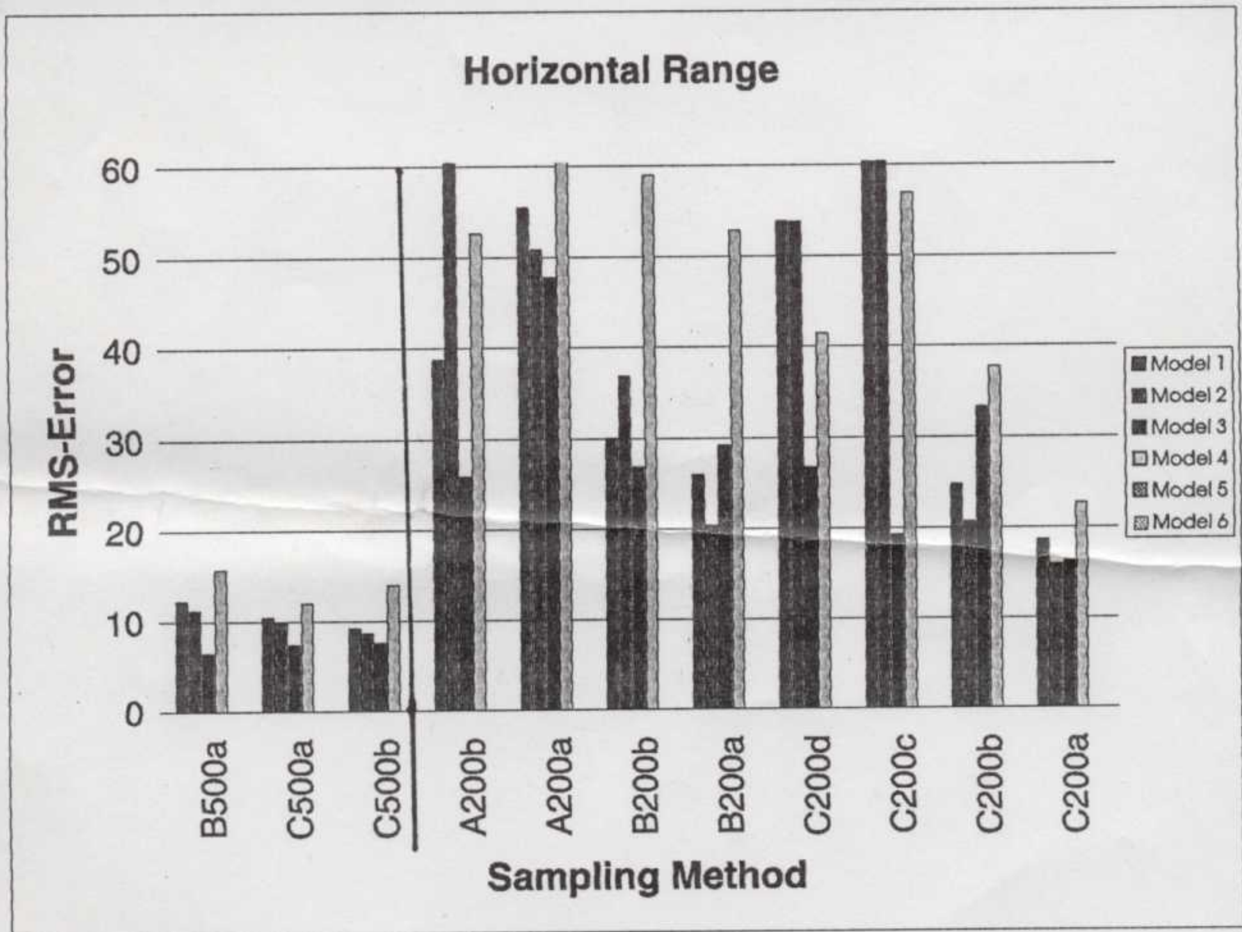


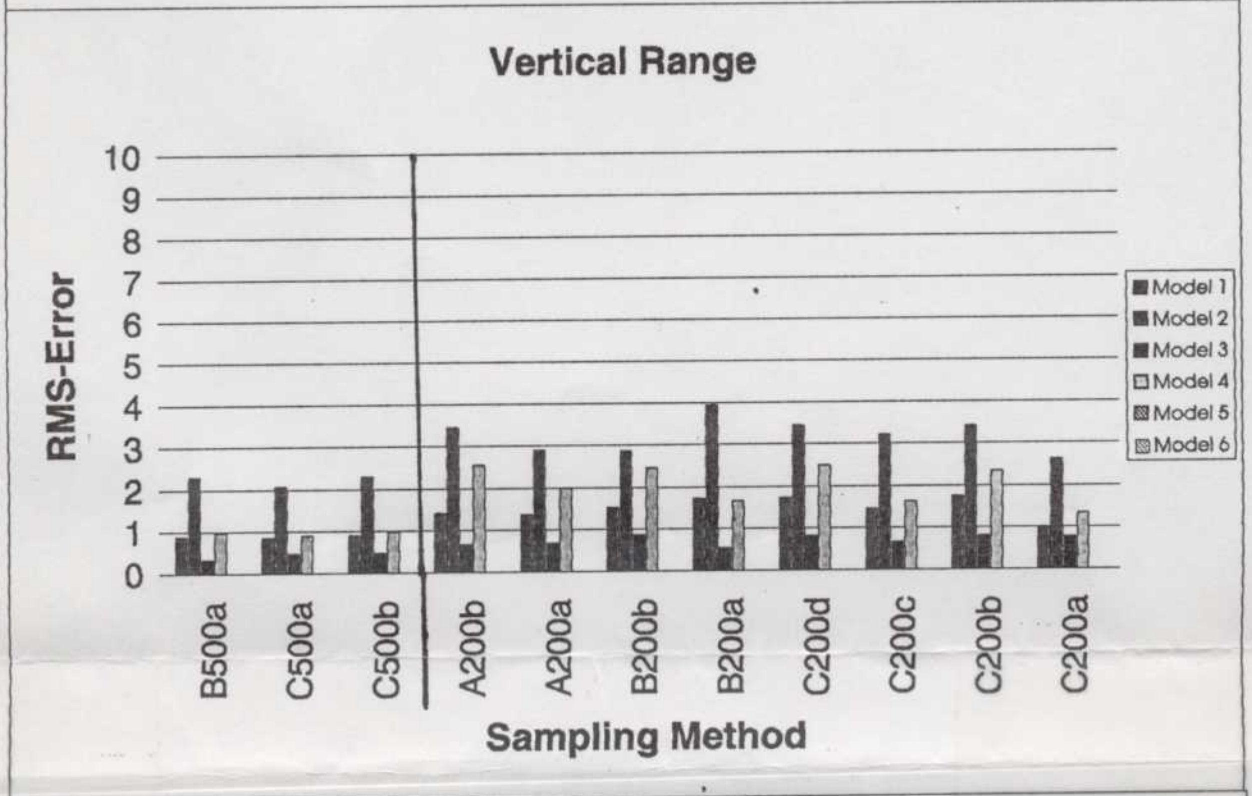
☛ Overall Best Method C300b.

This Method Was Tested on Outcrop Models 5 & 6, and Produced Results Better Than Most of Other Invariable Sampling Methods.

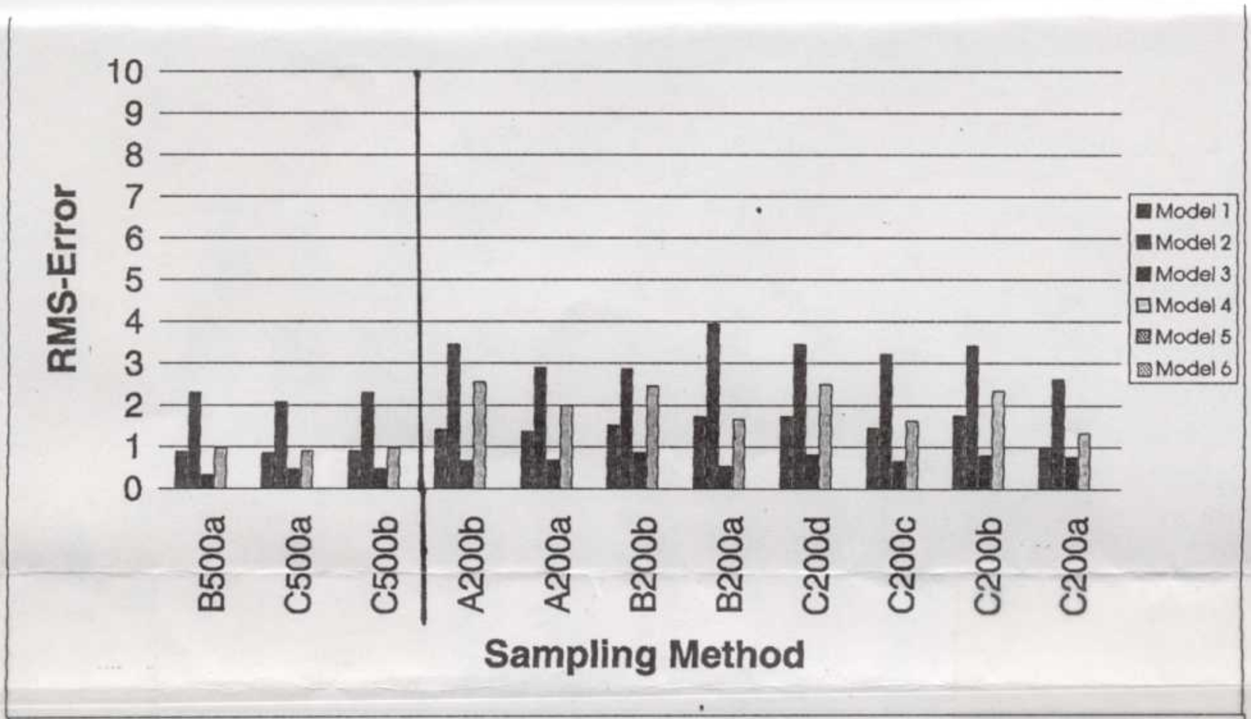
Root-Mean-Square Errors of Variogram Model Parameters Calculated From Samples:

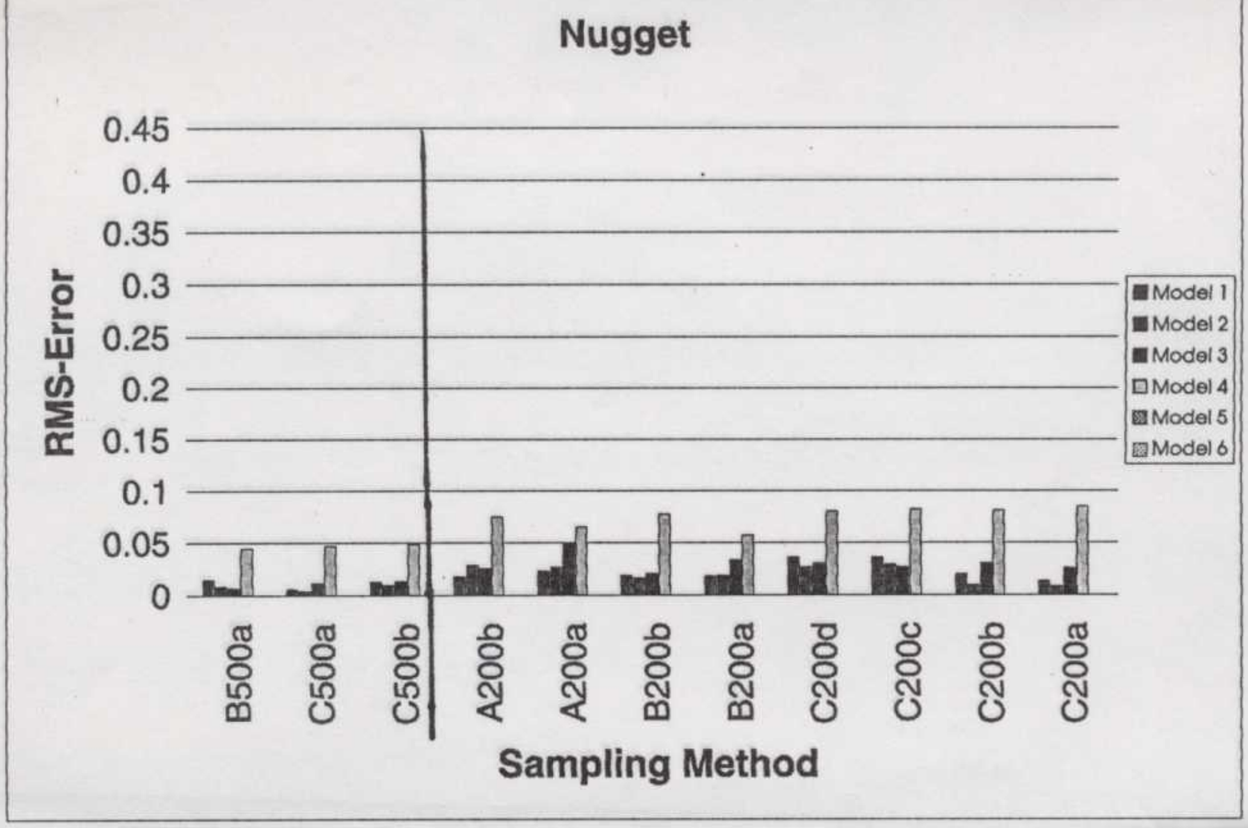
200 & 500 Annealed Samples





Nugget





Annealing Results Greatly Improve From 200 to 300 Samples; Small Improvement From 300 to 500 Samples. (500 Samples are three at left; 200 Samples are right 8.)

Simulated-Annealing

- For selected outcrops, number of samples, & set of variogram lag distances, optimize the sample locations.
- Initially random sample pattern perturbed to minimize objective function.

$$\text{objective} = \sum_i \frac{\left\{\left[\frac{\gamma_{true}(i) - \gamma_{sample}(i)}{N(i)}\right]\right\}^2}{h(i)}$$

Factors in Objective:

(1) minimize the difference between the sample-derived variogram and the true underlying variogram.

(2) maintaining a large and relatively uniform number of pairs of samples *N*(*i*) that contribute to each lag.

(3) normalized by separation distance *h*(*i*) to better model the variogram nugget ⇨ important for flow modeling.

Sampling Approach & Considerations

. General:
   a) Define stratigraphic coordinate space.
   b) Establish sampling strategy for each stratigraph zone (items 2-7).
   c) Translate sampling strategy to real coordinate space
   d) Sample outcrop.

. Form several continuous, tightly-spaced horizontal strin of samples to capture the nugget. Total lengths of thes strings relatively short.

A few horizontal strings can be grouped together to for clusters of moderate length. Horizontal gaps between th substrings, and staggering of these gaps verticall reduces the relative importance of any sing measurement — protects against anomalous samples.

A couple of horizontal strings aligned with, and at larg vertical separation from, the dominant clusters a required.

Clusters should generally be separated horizontally distances comparable to their horizontal extent.

Vertical strings of tightly-spaced samples should b separated horizontally at irregular intervals. Only a few these strings need span the entire outcrop and sever strings should be short to reduce the relative importanc

d) Sample outcrop.

2. Form several continuous, tightly-spaced horizontal strin of samples to capture the nugget. Total lengths of the strings relatively short.

3. A few horizontal strings can be grouped together to fo clusters of moderate length. Horizontal gaps between substrings, and staggering of these gaps vertica reduces the relative importance of any sin measurement — protects against anomalous samples.

4. A couple of horizontal strings aligned with, and at la vertical separation from, the dominant clusters required.

5. Clusters should generally be separated horizontally distances comparable to their horizontal extent.

6. Vertical strings of tightly-spaced samples should separated horizontally at irregular intervals. Only a few these strings need span the entire outcrop and seve strings should be short to reduce the relative importan of any single measurement.

7. The number of lags to which a sample contributes sho be relatively uniform for all samples. Prior to sampli this condition should be verified.

DISCUSSION

- Many fixed sampling methods yield poor variograms.
- Simulated annealing of sample locations generally yields sample patterns with characteristics that lead to better variograms.
- For sampling methods studied, the general characteristics of C300b are preferred.
- A poor sampling strategy yields variograms that result in inferior geologic models & poor flow-simulation predictions.
- When main goal of sampling is for variogram inference:
  - ☞ Limit the importance of anomalous samples by limiting the redundancy of information at different lags
  - ☞ Maximize the number of different samples contributing to each lag.

16

Some Additional Considerations

- Cost of Sampling
  - ⇨ irregular vs. simple patterns
  - ⇨ sampling more costly at tall heights
- Trends in Permeability Across Outcrop
- Rock-Face Inaccessibility or Damage
- Mulitple Lithologies & Facies

Many of these factors could be explored using a simulated-annealing approach.