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Imaging the Hydro-Geological Structure of the Limestone Aquifers of South Florida Using the Super Crosswell Tomography

A PILOT EXPERIMENT USING WELLS BF-1 AND BF-2

by

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prepared for

South Florida Water Management District

ABSTRACT

A pilot experiment of the Super Cross-Well Tomography (SCWT) system was conducted to evaluate its capability to image the hydro-geological properties of a deep limestone aquifer. The experiment used wells BF-1 and BF-2, at the test site of the South Florida Water Management District located at Ft. Lauderdale, Florida.

The velocity and attenuation within the limestone formations were measured by transmitting pseudo-random binary sequence (PRBS) pulses. The measured velocity and attenuation data were inverted for the porosity and permeability images. The porosity and permeability values measured by the patented SCWT method were compared with the porosity logs conducted earlier by Schulumberger, the porosity values measured from cores by SFWMD, and the permeability values measured from pumping tests by SFWMD.

The SCWT measurement produced a continuous porosity profile and a continuous permeability profile for a depth interval between 150 ft and 1,600 ft, and a two-dimensional (2-D) image of porosity and a 2-D image of permeability for a depth interval between 1,000 ft and 1,600 ft from a single frequency PRBS SCWT measurement. To complement the results, the permeability values at twenty depths were measured from a multiple frequency PRBS SCWT measurement.

The porosity profiles and images measured from the SCWT method agreed very well with the porosity values measured from core samples by SFWMD. The down-hole porosity log by Schlumberger overpredicted the porosity values measured by the SCWT and the core sample analyses by SFWMD. The Schlumberger porosity logs also contradicted to their density logs.

The permeability profiles and images measured by the SCWT agreed well with each other and the values measured from pumping tests by SFWMD.

The 1-D and 2-D images of porosity and permeability measured by the SCWT show that the hydro-geologic structure within the limestone aquifer is very heterogeneous in both vertical and horizontal direction.

The results from this SCWT experiment show that the SCWT method is accurate, powerful, and economical in imaging the hydro-geological structure within the limestone aquifers for exploration and management of underground water resources.

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INTRODUCTION

The South Florida is a part of the Florida-Bahamas Carbonate Platform whose sediment strata are dominated by porous limestone. Unlike sand stones, the hydraulic structure of limestone is complicated by diagenesis or chemical processes which alter rock structure. Imaging the hydro-geological structure of the South Florida is extremely important for managing the ground water resources and controlling ground water pollution.

Measurements of the aquifer characteristics such as porosity, permeability and spatial distribution have been very limited. Down-hole logging measures porosity and /or density with depth using the gamma ray, neutron, resistivity and sound speed loggers. This method has a serious limitation in that it only measures the porosity along an open hole. Furthermore, down hole porosity logging is known to be unreliable, especially for limestone (Telford et al., 1982). No permeability or lateral extent of the aquifer can be measured. The permeability and the transitivity (which is permeability multiplied by the thickness of the aquifer) are measured by pumping test. This is time consuming, requires open hole or perforations, yet does not measure the spatial variability of the permeability.

Imaging porosity and permeability in two dimensional and three dimensional space has been a challenge of oil and ground water geophysicists. The authors have developed an acoustic cross-well tomography measurement system called the Super Cross-Well Tomography (SCWT) to image 2-D and 3-D images of the aquifer and reservoir characteristics. The SCWT method has been used to image aquifers and oil reservoirs and verified by bore-hole logs and drilling and perforations. The SCWT method and its results have been published in Yamamoto et al. (1994, 1995) and patented (U.S. Patent Nos. 5,142,500 and 5,406,530). For this work, the authors were awarded the most significant accomplishment award by the Society of Exploration Geophysicists in 1995.

In order to verify the SCWT method for the South Florida Aquifers, a demonstration experiment was conducted using Wells BF-1 and BF-2 of the South Florida Water Management District (SFWMD) at Ft. Lauderdale, Florida during the period of March 3 through 12, 1997. Both wells are steel cased. The down-hole logging, core tests and pumping tests were performed prior to the casing, yielding some porosity and permeability information. This report presents the results of the SCWT demonstration experiment and comparisons of our acoustically imaged porosity and permeability with down-hole porosity logs, core and pump test results.

SUPER CROSS-WELL TOMOGRAPHY (SCWT) EXPERIMENT

A Super Cross-Well Tomography (SCWT) experiment was conducted across the wells BF-1 and BF-2, separated by a horizontal distance of 37 ft (11 m). An acoustic source ITC model no. 6121 was placed in well BF-2 while an 8-channel hydrophone array with a constant inter-element distance of 26 ft (8 m) was placed in well BF-1. A 40 feet high stand pipe was placed at the source well head to keep water from gushing out of the artesian well. Well head pulleys were placed at both wells to change the elevation of the source and the hydrophones. The deepest source depth was 1600 feet where the steel casing ended in the well BF-2. The hydrophone array was lowered down to 2100 feet at every 6 feet in the well BF-1. Above depth 1600 feet, both the source and the centroid of the hydrophone array were moved every 1.5 feet up to the depth of 1500 feet and then every 6 feet up to the depth of 150 feet. A 4095 cycles - 4 kHz pseudo-random binary sequence (PRBS) pulse was used as the source signal. An average of one hundred PRBS signals received by each hydrophone was recorded at each source depth by the SCWT digital signal processor (DSP) system. In addition to this depth sweep, five PRBS frequencies of 1, 2, 4, 6, and 12 kHz were used at 20 depths at 33 ft (10 m) intervals between depths 991 ft and 1600 ft.

MEASURED VELOCITY AND ATTENUATION

The 4kHz PRBS data was inverted for velocity and attenuation images. Only the first arrival wave energy was used in the inversion. An example wave field measured by the five hydrophones for a given source depth is shown in **Figure-1**. The quality of data was excellent; all of the attempted source-receiver ray paths were used in the inversion. It is very unusual to be able to use 100 % of the measured ray paths. Usually a 50 % usage of attempted ray paths would be considered very good. Therefore, we can place high confidence in the inverted images from this experiment.

The 4kHz data of velocity versus depth for 150 ft to 1600 ft is shown in **Figure-2.** The 4kHz data of attenuation versus depth for the same depth interval is shown in **Figure-3.** Only the first arrival waves direct across the two wells (the source and the receiver having same depths) were used to construct these figures. The pair of velocity and attenuation profile reveals three basic layers; a limestone layer between the depths 150 ft and 460 ft. a marl layer between depths 460 ft and 1,000 ft, and another limestone layer between depths 1,000 ft and 1,600 ft.

SCWT imaging was performed for the lower limestone layer using the entire source receiver ray paths taken at 4 kHz. The pair of velocity and attenuation images for the cross-section between the two wells, 37 feet wide for depths 1,000 to 1,600 ft is shown in **Figure-4**. The entire depth sections 600 feet long were imaged in seven subsections, each approximately 164 feet tall. Due to the ray paths used in the experiments, the top and bottom of each subsection, about 30 feet deep, have triangle-shaped shadows. These shadow areas should be ignored. The cross-section between depths 1,500 and 1,600 feet has a spatial resolution of 1.5 feet while the rest of the cross-section (between 1,500 ft and 1,000 ft) has a spatial resolution of 6 feet corresponding to the source and hydrophone spacing used during the SCWT experiment. The tomographic images show that the lower limestone layer has basically a horizontal layered structure and agree very well with the velocity profile in **Figure-2** and the attenuation profile in **Figure-3.** The velocity and attenuation images in **Figure-4** also show fine scale fluctuations in both horizontal and vertical directions, indicating that the limestone structure varies horizontally as well as vertically.

The open hole velocity log of well BF-3 by Schlumberger is reproduced in **Figure-5.** Well BF-3 is separated by horizontal distances of 77 ft and 90 ft from wells BF-2 and BF-1, respectively. It should be noted that the down-hole velocity logging is not very accurate because a smooth bore-hole of constant diameter is assumed in velocity log calculation when in reality bore-holes are rough and the diameter varies considerably (from 20 to 50 inches) as seen in the diameter log in **Figure-5**. Rough surfaces of borehole generate strong scattering which makes the first arrival pick difficult. Uneven borehole diameters also introduce errors in velocity estimation. Therefore, the reader is cautioned for these uncertainties when reading the down-hole velocity log in **Figure-5**.

The SCWT velocity profile in **Figure-2** and the SCWT velocity tomogram in **Figure-4** agree well with the velocity log in **Figure-5**. Slight differences between the SCWT velocity and the Schulumberger log velocity at some depths are noticeable wherever the bare hole diameter deviates considerably. This agreement confirms that the SCWT method accurately images the velocity structure within limestone aquifers. The velocity image shows that the velocity structure has a layered structure with some spatial variability in both horizontal and vertical directions.

The attenuation image shown in **Figure-4** is a direct indicator of permeable layers. As will be shown later in this report, higher permeability layers absorb more of the acoustic energy.

POROSITY

The porosity image can be transformed from a velocity image based on rock models. Depending on the rock minerals and degree of cementation, the rock models developed from theories and experiments can be used to extract porosity, density, shear modulus and permeability from measured velocity and attenuation (Yamamoto et al., 1994, 1995). These transformation procedures of Yamamoto et al. were used to transform the SCWT measured velocity and attenuation into images of porosity, density, shear modulus and permeability. Porous rock modeling is an area of active research. The Yamamoto et al. transformation procedure is ready to adapt improved future rock models for better imaging of porosity and permeability. Existing rock models in Yamamoto et al. (1994, and 1995) are used in this report.

The porosity versus depth profile obtained through the SCWT transformation is shown for depths between 150 ft and 1,600 ft in **Figure-6.** The limestone layers have relatively large porosity varying between 15 and 40 % while the marl layer between depths 460 ft and 1,000 ft has relatively small porosity varying from 10 and 20 %.

Figure-7 shows the porosity image for the lower limestone layer between depths 1,000 and 1,600 ft, obtained from the SCWT transformation. The continuous image of this 37 ft wide by 600 ft tall section is shown in seven subsections as inverted from the velocity data. As mentioned earlier, the readers should ignore the 30 feet border sections from the top and bottom edges of the seven subsections in **Figure-7** because of insufficient ray coverage for inversion calculations. The tomographically obtained porosity image basically agrees well with the velocity profile in **Figure-6** but also shows horizontal fluctuations as well as vertical.

The porosity depth log of well BF-3 by Schlumberger between depths 1,000 ft and 1,600 ft is reproduced in **Figure-8.** The horizontal distance from BF-3 to BF1 is 90 ft and 77 ft to BF-2. The Schlumberger porosity varies between 35 % and 50 %. These porosity values are not consistent with the density log ranging from 1.8 to 3.2 g/cc shown in the **Figure-8.** The porosity values calculated from the density log range from 53 % to -23 % (0 %). The porosity log values are very high compared to the porosity values of the lower limestone layer ranging between 15 and 35 % obtained from the SCWT measurements. The down hole porosity log measurements are known to produce poor results, especially for carbonate sediments (Telford et al., 1982).

The porosity values reported in the lithologic well log for the well BF-1(SFWMD internal report) are between 10 and 35 % for the section between 150 ft and 1,600 ft. These porosity values are in very good agreements with the SCWT measured porosity values.

PERMEABILITY

Permeability is the other important reservoir characteristic. The accurate measurement of permeability is limited to a laboratory hydraulic test using cores. Pumping tests are used to determine the transitivity of layers in the field. However, this method is based on the assumption that the permeability is homogeneous through out the layers and that no lateral or vertical variability exists. Except for the Super Cross-Well Tomography (SCWT) method there is no indirect measurement or imaging method of permeability.

The SCWT method measures the travel time and amplitude of a PRBS acoustic pulse across two wells. Then, the velocity and attenuation images are inverted from the travel time-amplitude data. The permeability is then extracted from the velocity-attenuation images based on the poro-elastic theories as described in Yamamoto et al. (1994, 1995). The original SCWT method required the velocity-attenuation data at more than one frequency, preferably five or six frequencies over a broad band. Recently, we have derived a method which requires measurement of the velocity-attenuation at only one frequency. We will present the permeability images extracted from the two SCWT methods. These images are compared with each other and also with the SFWMD pump test results.

Permeability Profile

The permeability versus depth profile shown in **Figure-9** was calculated from the measured velocity and attenuation profile data obtained from the 4 kHz PRBS transmission measurement of **Figures-2 and 3.** The modified Biot-BISQ poro-elastic rock model has been used in this inversion. As can be seen the upper and lower limestone layers have relatively high permeability ranging between one to hundreds of darcies while the marl layer between 460 and 1,000 ft has relatively low permeability, on the order of a tenth of a darcy. This layer is compacted by gravity due to its poorly cemented skeletal structure, resulting in small porosity and permeability. The permeability values from the SFWMD are 244 darcies for the depth interval between 1,000 and 1,031 ft and 37 darcies for the depth interval between 1,494 and 1540 ft. Comparisons between the two permeability measurements indicate that the average permeability values from the two methods agree well for the two depth intervals. The SCWT shows the vertical variability in permeability which the pumping test could not measure.

Two Dimensional Images of Permeability

The velocity and attenuation images given in **Figure-4** were inverted into the permeability image shown in **Figure-10** for the depth interval between 1,000 and 1,600 ft. by the new method of permeability extraction using only one PRBS frequency, 4 kHz. The 2-D permeability image shows that the limestone layer is generally very permeable ranging from a few darcies to a few hundred darcies. The SFWMD pumping test results at the two depth intervals are in general agreement with this 2-D permeability image. The detailed permeability structure of the limestone layer is , however, very complicated due to fine structures extending in both vertical and horizontal direction. Since the spatial variability is significant even for the well distance of only 37 ft between wells BF-1 and BF-2, one can expect a huge variability over larger horizontal distances.

Permeability Measured from Multiple-Frequency SCWT Test

Cross-well PRBS pulse transmission measurements were made using five PRBS frequencies, 1, 2, 4, 8, and 12 kHz for depths 991 ft to 1600 ft at 33 ft (10 m) intervals. The measured velocity values for the five frequencies are tabulated in **Table-1.** Using the multiple-frequency SCWT method, the average permeability values at the twenty depths were determined and plotted in **Figure-11.** The permeability profile agrees well with the permeability profile in **Figure-9** and the 2-D permeability image in **Figure-10** both of which are determined using the single frequency SCWT method. The SFWMD pumping test results at the two depth intervals agree well with the permeability values determined by the multiple-frequency SCWT method. These agreements support the credibility of the single frequency SCWT method as well as the multiple-frequency SCWT method for imaging the permeability structure. The fact that the single frequency SCWT method measures the permeability accurately is quite advantageous: in many cases, tomography is usually possible using only one PRBS frequency, especially when the cross-well distance becomes large.

SUMMARY AND CONCLUSIONS

A pilot experiment of the Super Cross-Well Tomography was successfully conducted using the South Florida Water Management District Test Wells BF-1 and BF-2. Porosity and permeability profiles and images were transformed from measured velocity and attenuation across the two wells. The transformation procedure and the rock models are presented in Yamamoto et al. (1994 and 1995). The results were compared with the Schlumberger down-hole porosity logs, the SFWMD porosity date from cores, and the permeability values from the SFWMD pumping tests. The following conclusions are made from this study:

1. The SCWT experiment accurately measured the velocity and attenuation profile versus depth profiles from 150 ft to 1,600 ft using 4 kHz PRBS pulses as shown in **Figures- 2** and **3**.
2. The SCWT experiment accurately measured the two-dimensional images of velocity and attenuation for the depth interval 1,000 ft to 1,600 ft using 4 kHz PRBS pulse as shown in **Figure-4.**
3. The single frequency SCWT method enables one to extract the porosity profile for the depth interval between 150 ft and 1,600 ft as shown in **Figure-6** and the 2-D porosity image for the depth interval between 1,000 ft and 1,600 ft as shown in **Figure-7**. These SCWT measured porosity values are in good agreements with the porosity values reported in the SFWMD lithologic well log for the well BF-1.
4. The Schlumberger down-hole porosity log shown in **Figure-8** for the well BF-3 shows significantly higher porosity values ranging from 35 to 50 % for the depth

interval 1,000 to 1,600 ft as compared to the porosity values from 15 to 35 % measured by the SCWT and the SFWMD coring. The Schlumberger porosity log is also contradicting to their density log ranging from 1.8 to 3.2 g/cc for the same depth interval as shown in **Figure-8.** This disagreements confirm the well known fact that the down-hole porosity logging is unreliable for measuring the porosity of limestone (Telford et al, 1982).

5. The single frequency SCWT method enables one to measure the permeability vs. depth profile for the depth interval from 150 ft to 1,600 ft as shown in **Figure-9** and the 2-D permeability image as shown in **Figure-10.** These single frequency SCWT measured permeability values agree well with the permeability values measured from the pumping tests by SFWMD. The SCWT permeability images show fine structures and strong spatial variability which can not be measured by pumping tests.
6. Permeability at twenty depths were measured by the SCWT using the measured velocity dispersion at five different PRBS frequencies as shown in **Table-1** and **Figure-11**. These permeability values agree well with the single frequency SCWT measured permeability profile in **Figure-9**, the 2-D permeability image in **Figure-10,** and the permeability values from the SFWMD pumping tests. The fact that the single frequency SCWT experiment enables one to measure permeability images accurately is advantageous for large cross-well distances, which often permit only a single PRBS frequency.
7. The pilot SCWT experiment shows that the SCWT method accurately measures porosity and permeability, and can image the spatial structure of these aquifer characteristics accurately. The SCWT method is shown to be an accurate, reliable, fast, and economical tool for exploration of underground water resources and their management.

ACKNOWLEGEMENTS

This pilot study of the SCWT method was totally sponsored by the South Florida Water Management District under Contract No. C8668. The site preparation for this experiment made by SFWMD is also appreciated. Dr. Tom Nye and Chris M. Day assisted in the field experiment. Dr. Tom Nye also assisted in the SCWT analysis.

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3. South Florida Water Management District, Lithologic Well Log Printout Source - FGS, 1993.
4. Telford, W. M., Geldart, L. P., Sheriff, R. E., and Keys, D. A., *Applied Geophysics*, Cambridge University Press, London, 1982.
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6. Yamamoto, T., Nye, T., and Kuru, M., "Imaging the Permeability Structure of a Limestone Aquifer by Crosswell Tomography," Geophysics, vol.60, no. 6, p.1634-1645, 1995.

Depth	Velocity (meters/sec)					Permeability
Ft.	1 kHz	2 kHz	4 kHz	8 kHz	12 kHz	(Darcies)
991	2740	2840	2805	2860	2850	17.8
1024		4960	5205	5325	5350	240
1056	2530	2550	2570	2570	2575	0.025
1089		2720	2750	2790	2800	0.558
1122		2775	2775	2800	2775	0.003
1155		2720	2815	2890	2860	0.028
1188	2780	2800	2825	2850	2850	89.1
1221		2720	2750	2800	2810	39.8
1253		2800	2825	2835	2850	4.46
1286		3040	3050	3075	3120	17.8
1319		2910	2940	2955	2970	0.316
1352	3040	3200	3150	3150	3180	39.8
1385		3100	3075	3100	3125	89.1
1417		3000	3060	3075	3225	1.56
1450		3320	3320	3355	3390	39.8
1483	2960	2980	3150	3150	3180	44.7
1516		3550	3585	3620	3700	44.7
1549		3600	3690	3830	3840	22.3
1581		3630	3820	3900	3990	10.1
1601		3360	3510	3615	3650	22.3

Table-1 Permeability Values from Multi Frequency Measurements

LIST OF FIGURES

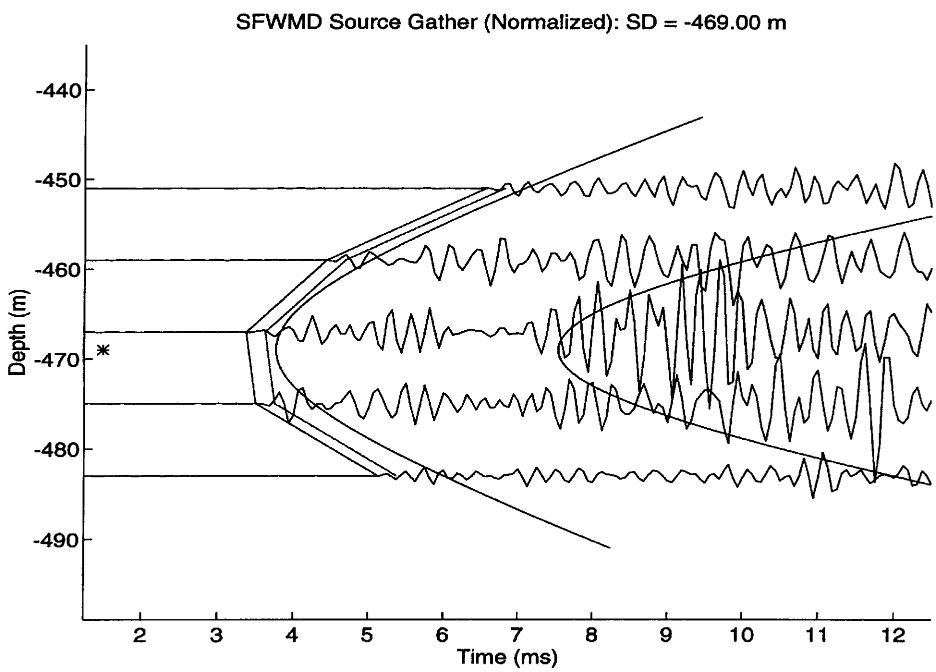


Figure-1: An example Source Gather (Source Depth: 1538 ft.)

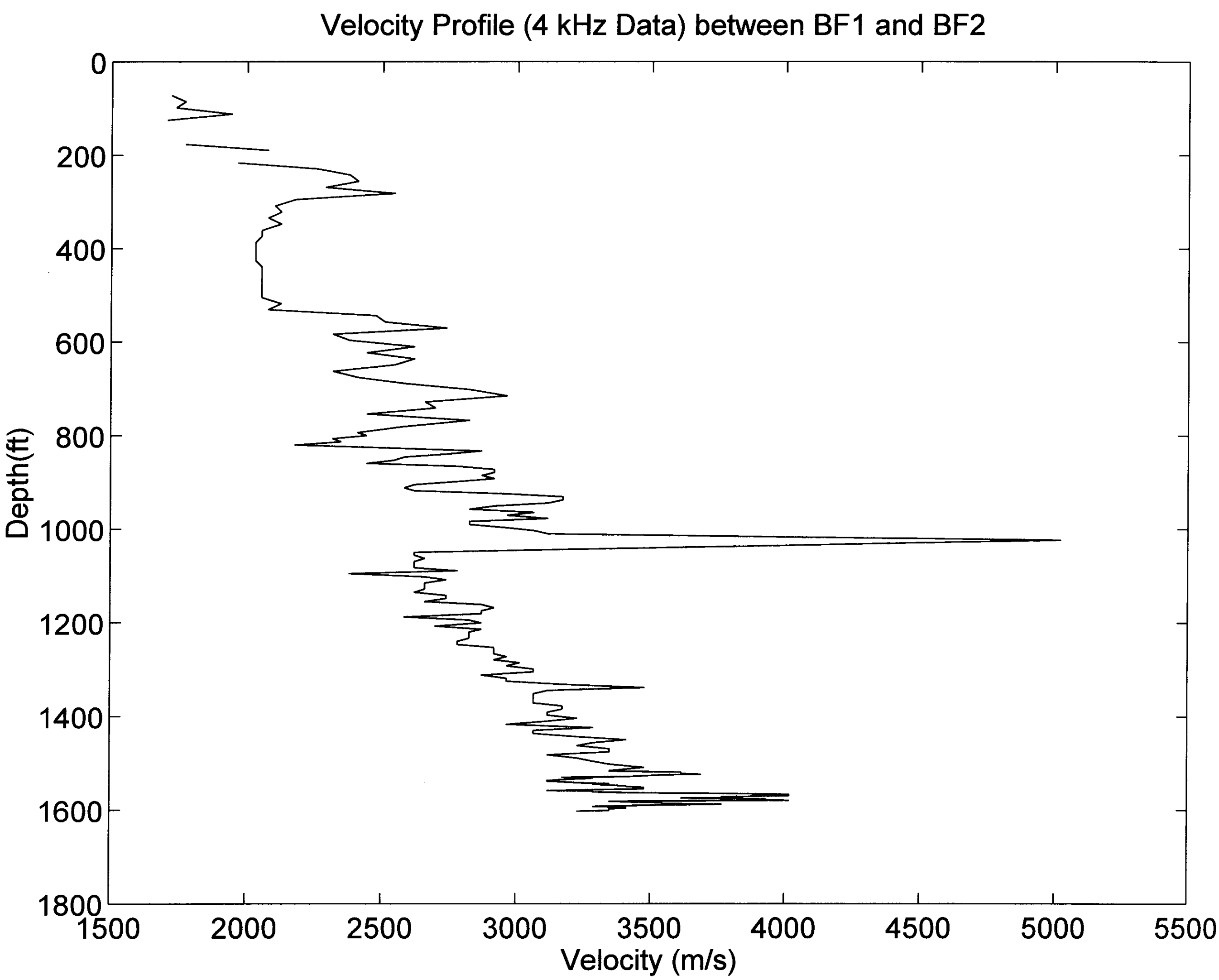


Figure 2: Velocity Profile

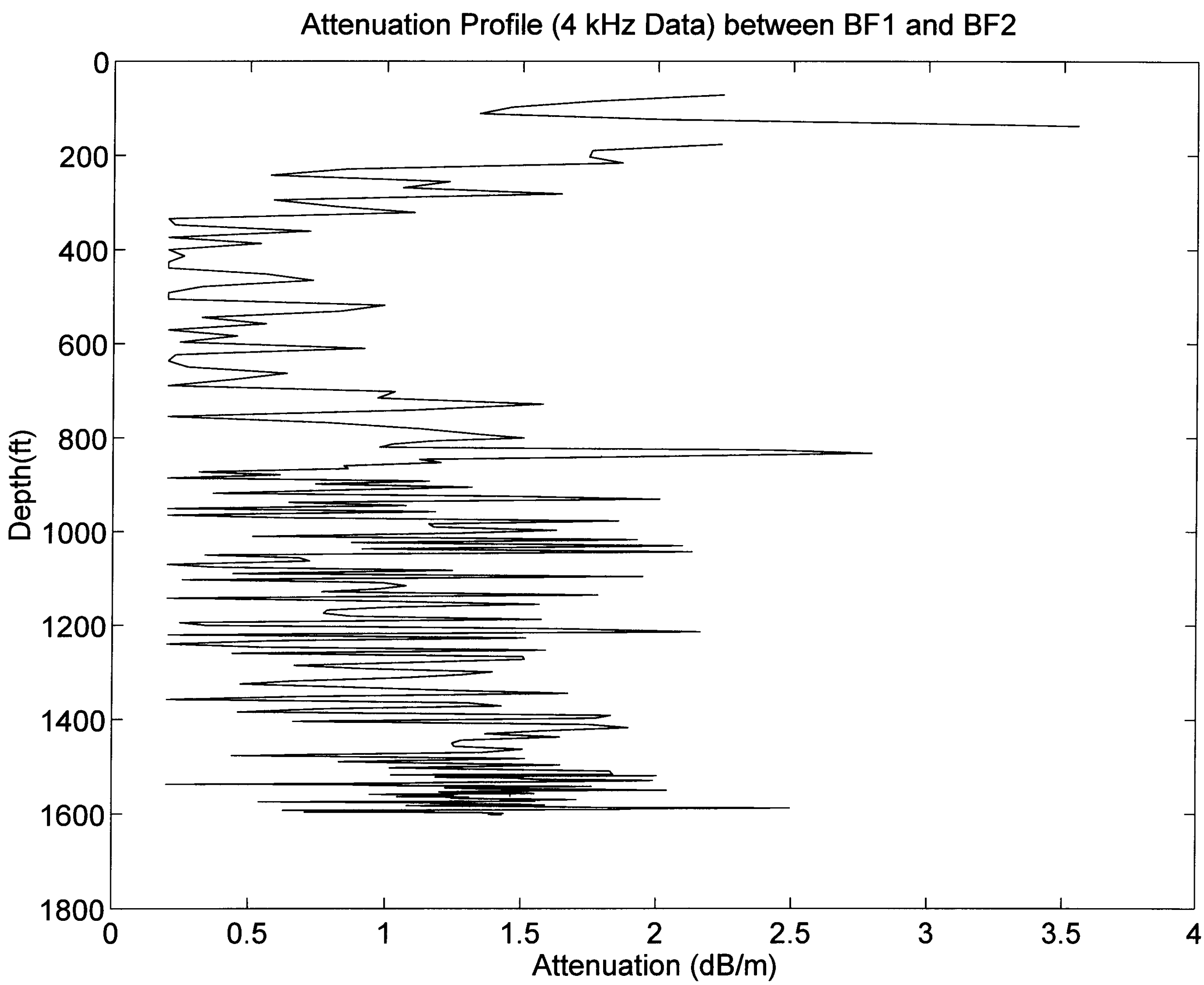


Figure 3: Attenuation Profile

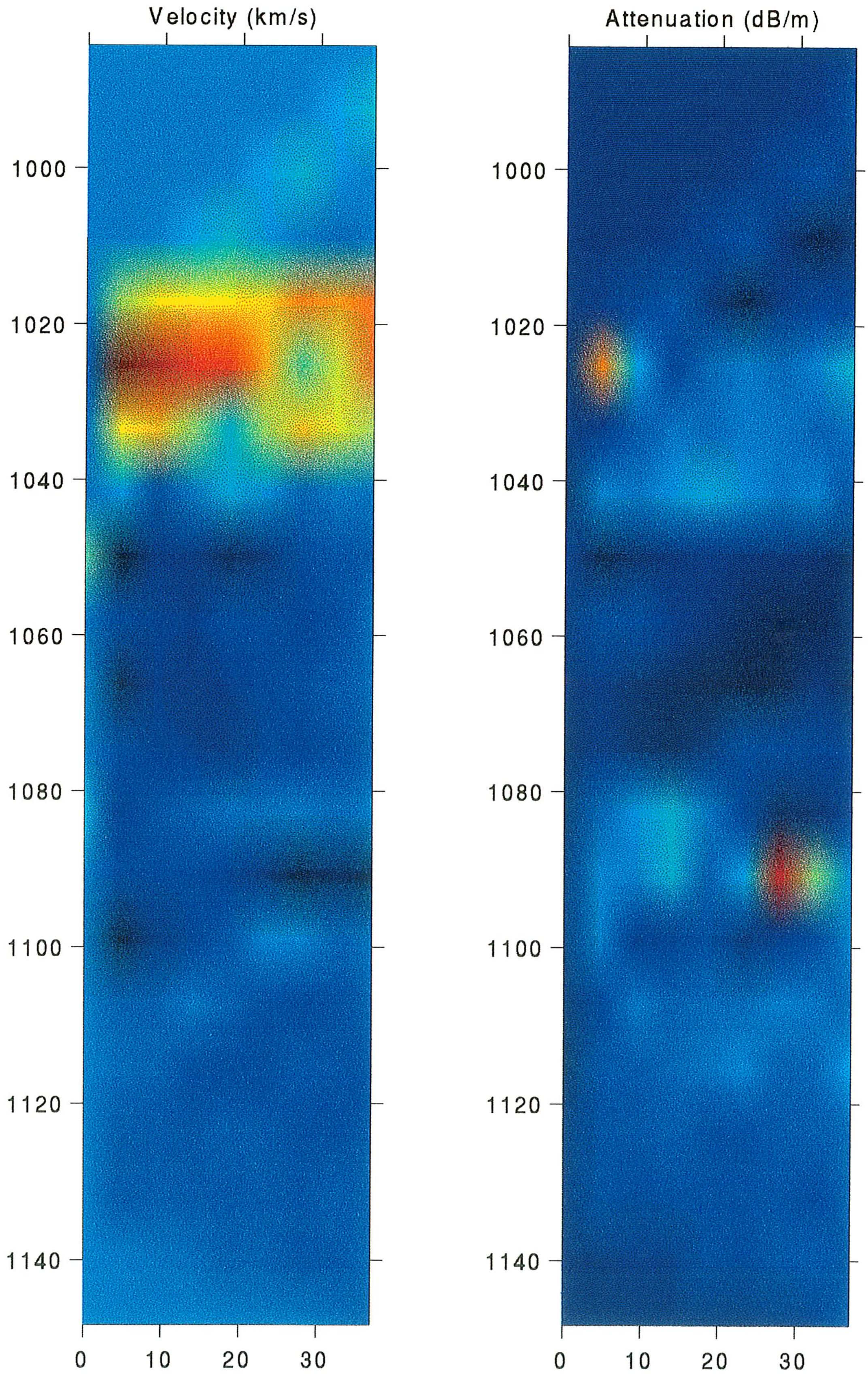


Figure 4: Velocity and Attenuation Images (984–1148 feet)

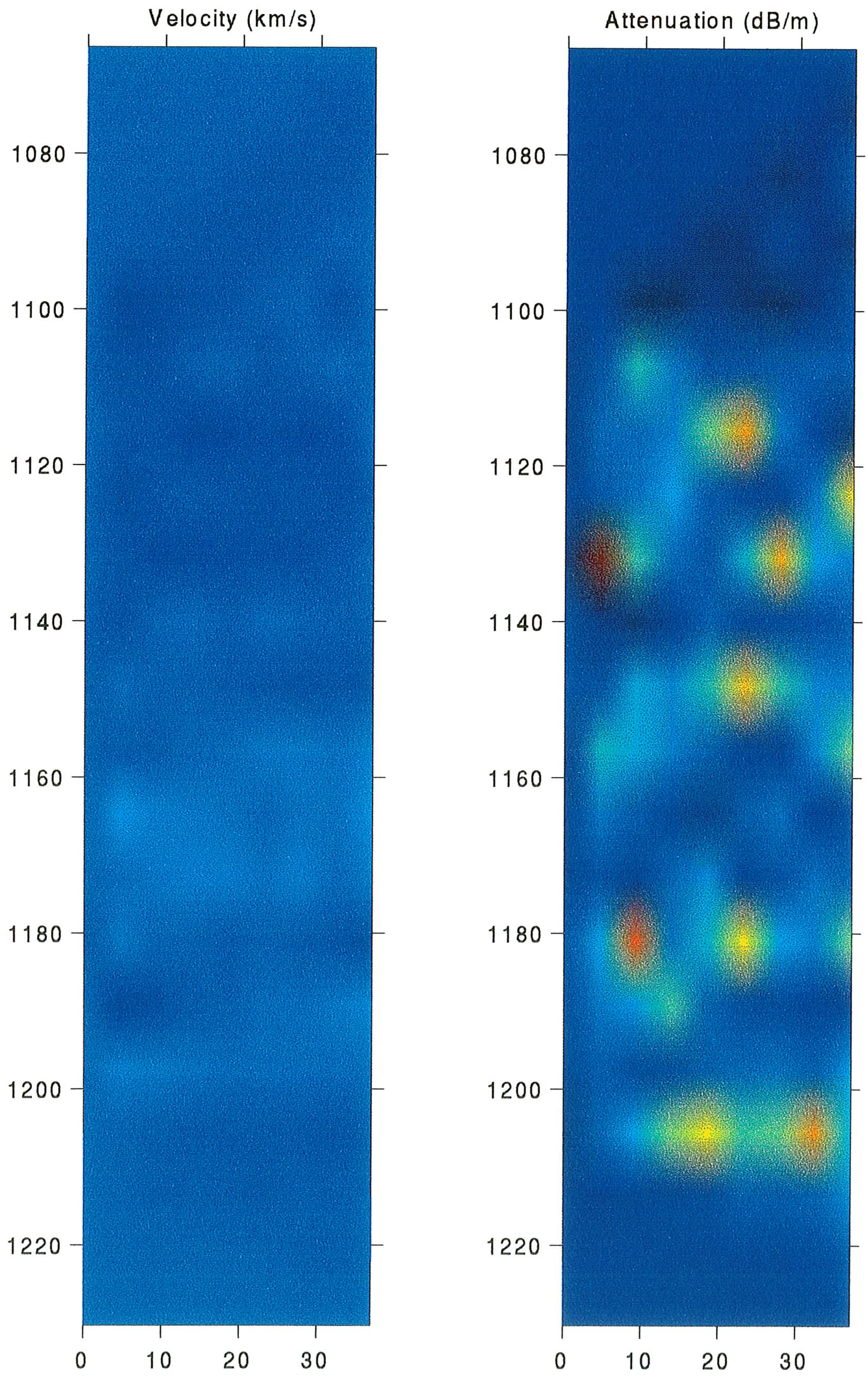


Figure 4 cntd. : Velocity and Attenuation Images (1066–1230 feet)

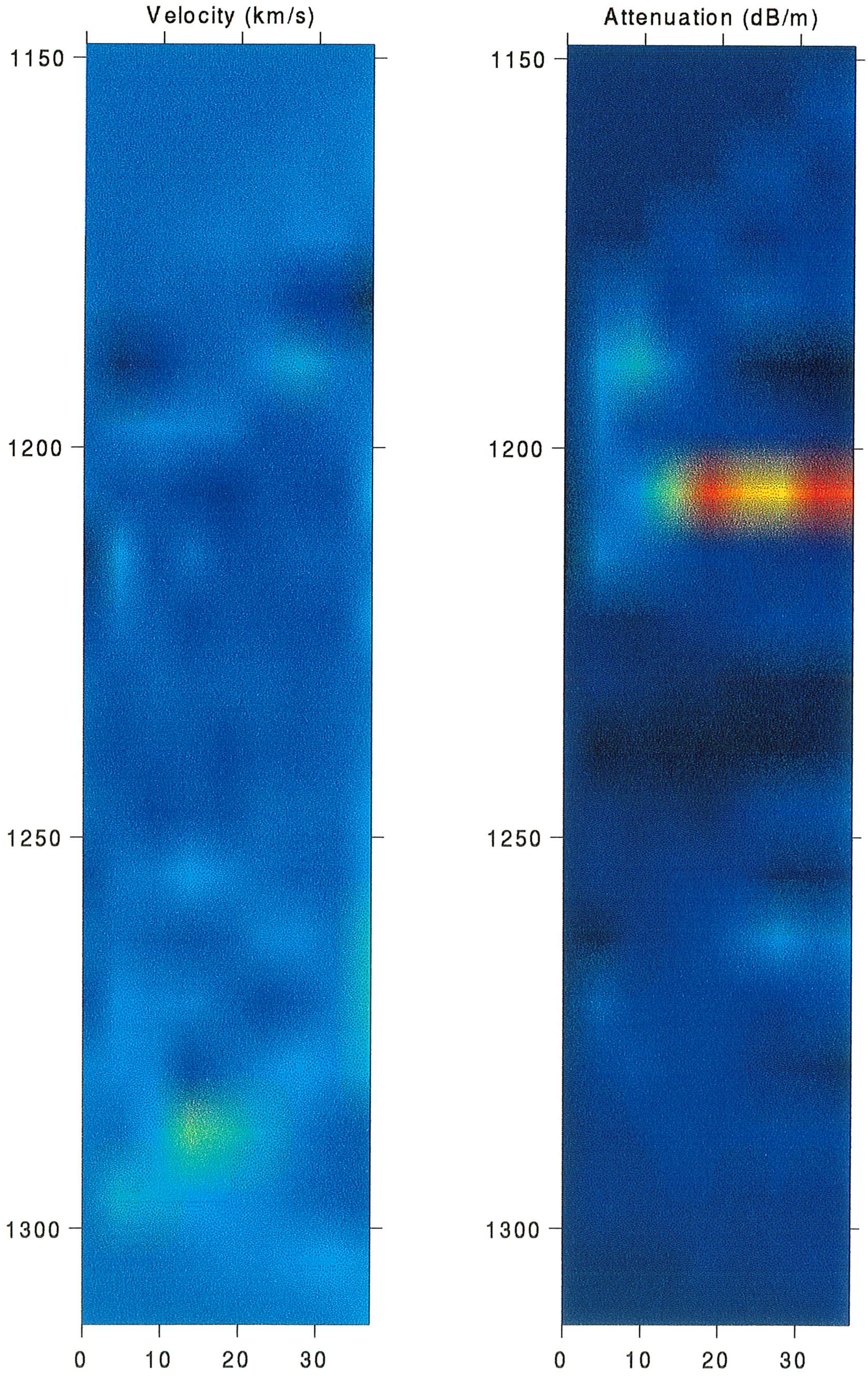


Figure 4 cntd. : Velocity and Attenuation Images (1148–1312 feet)

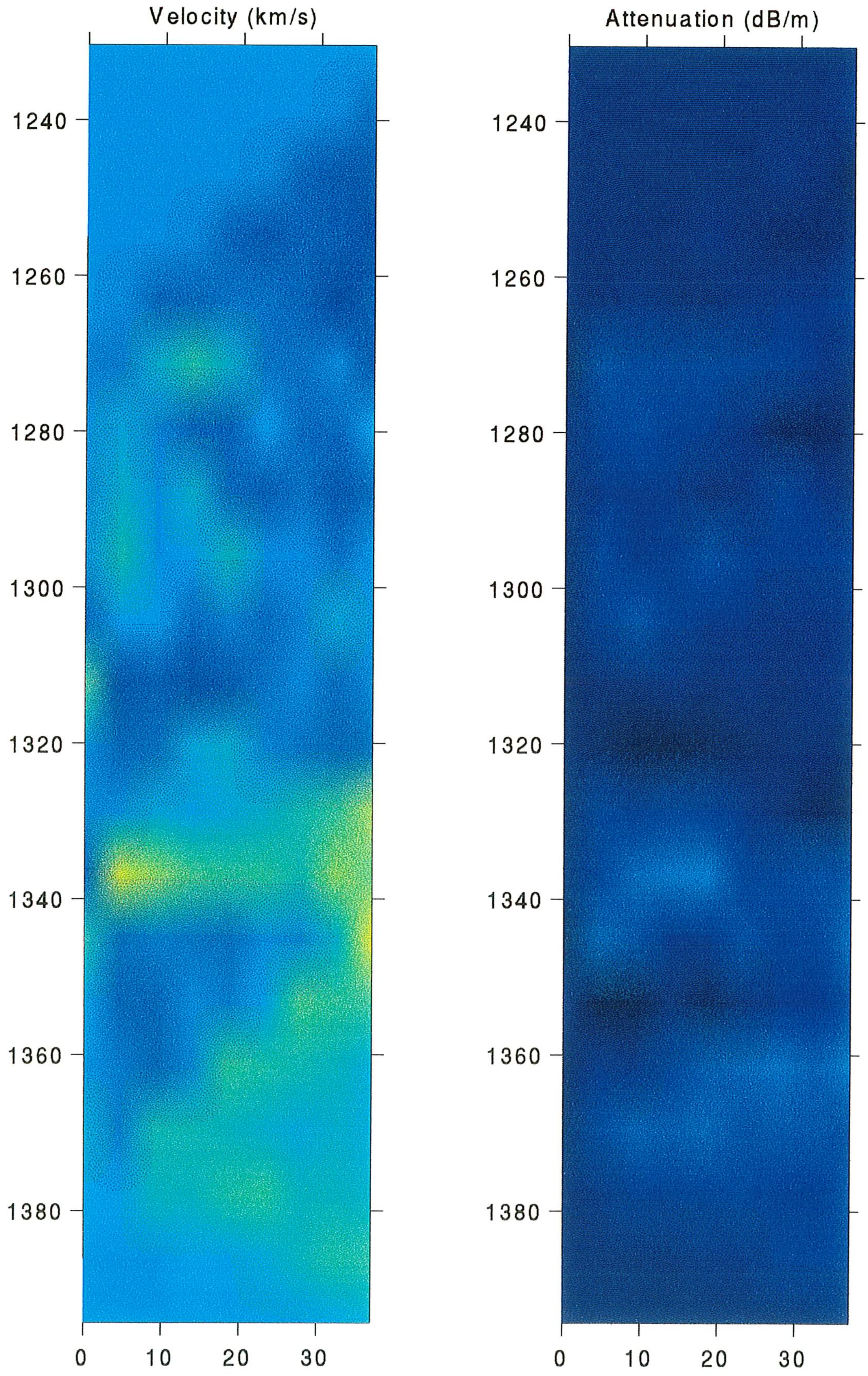


Figure 4 cntd. : Velocity and Attenuation Images (1230–1394 feet)

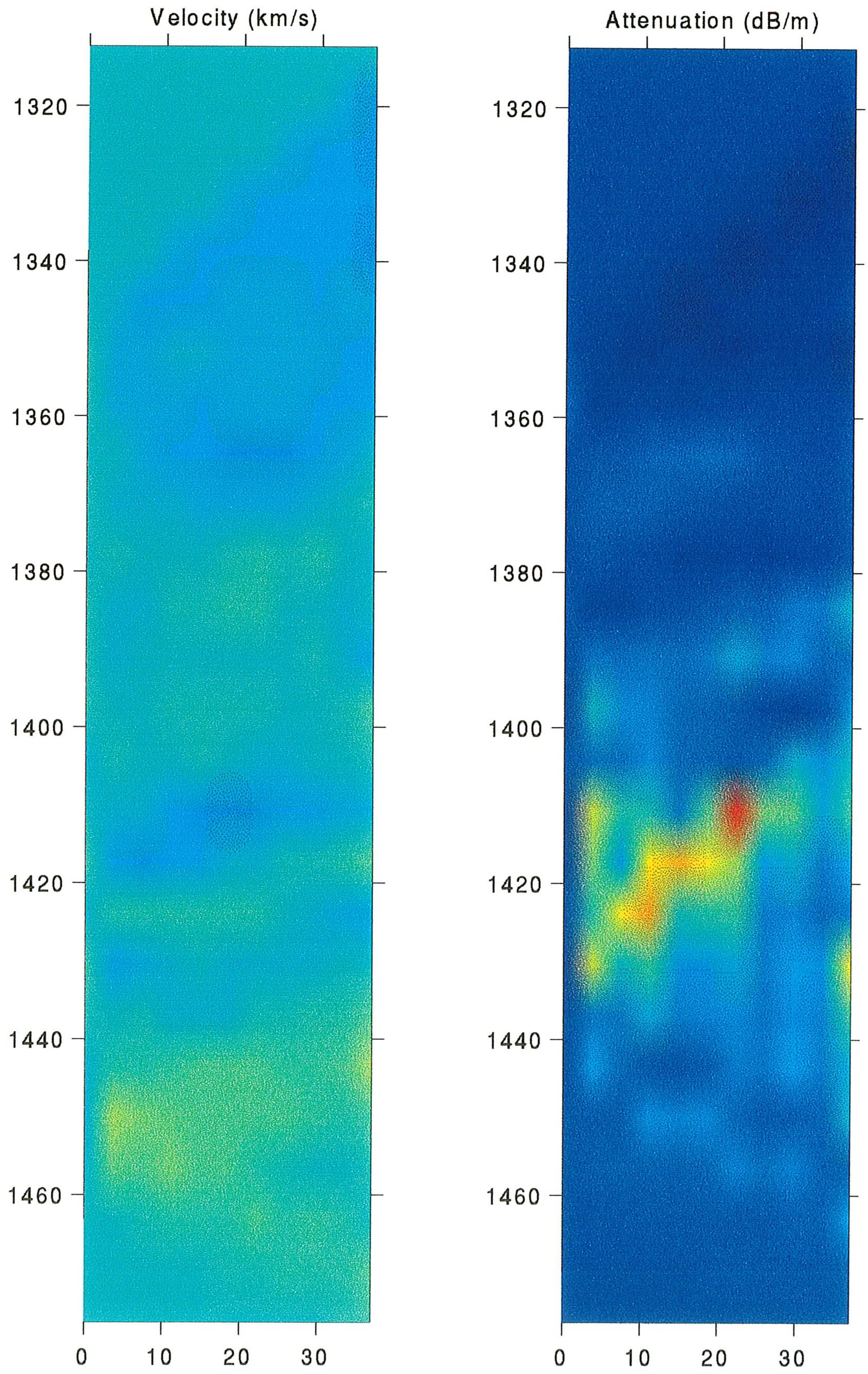


Figure 4 cntd. : Velocity and Attenuation Images (1312–1476 feet)

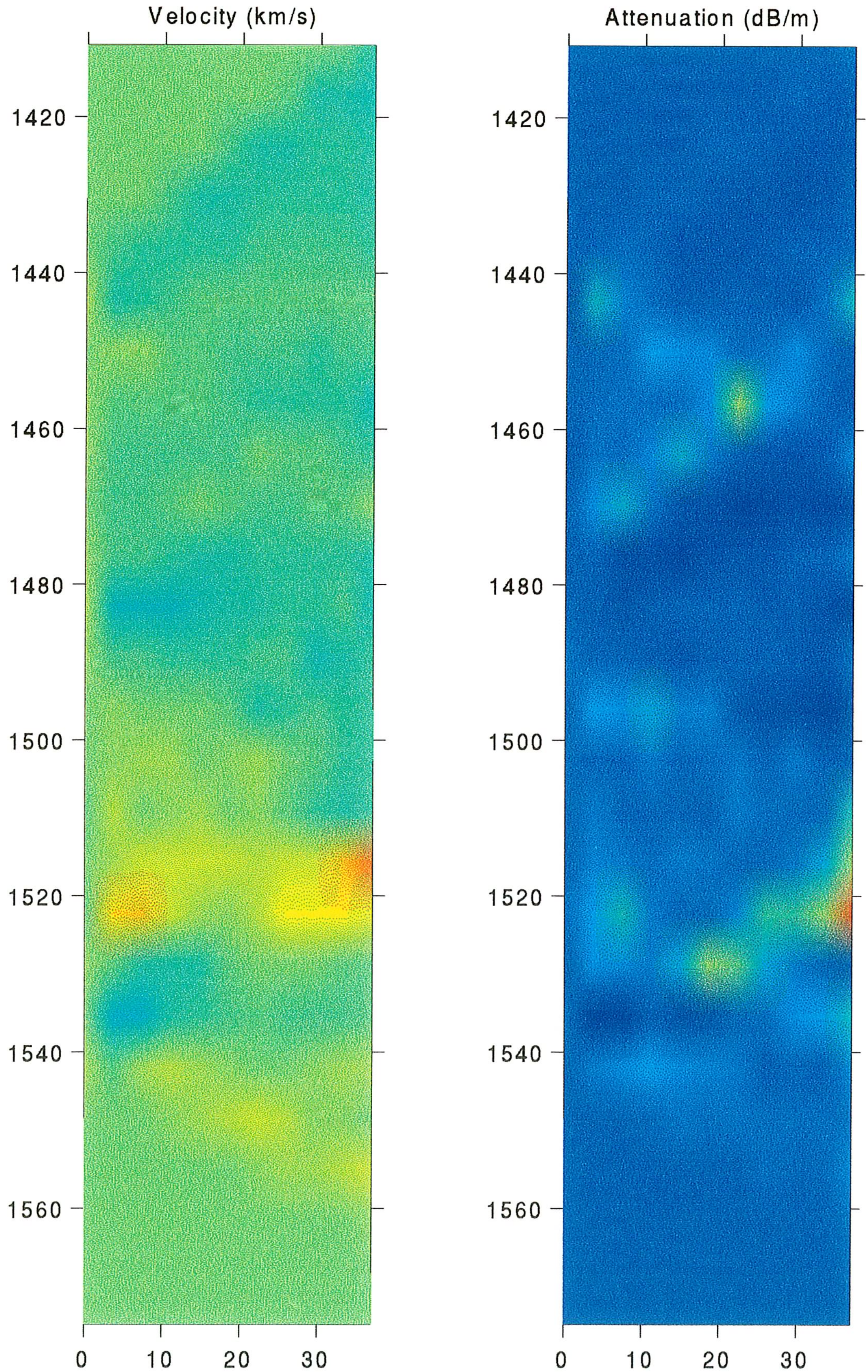


Figure 4 cntd. : Velocity and Attenuation Images (1411–1575 feet)

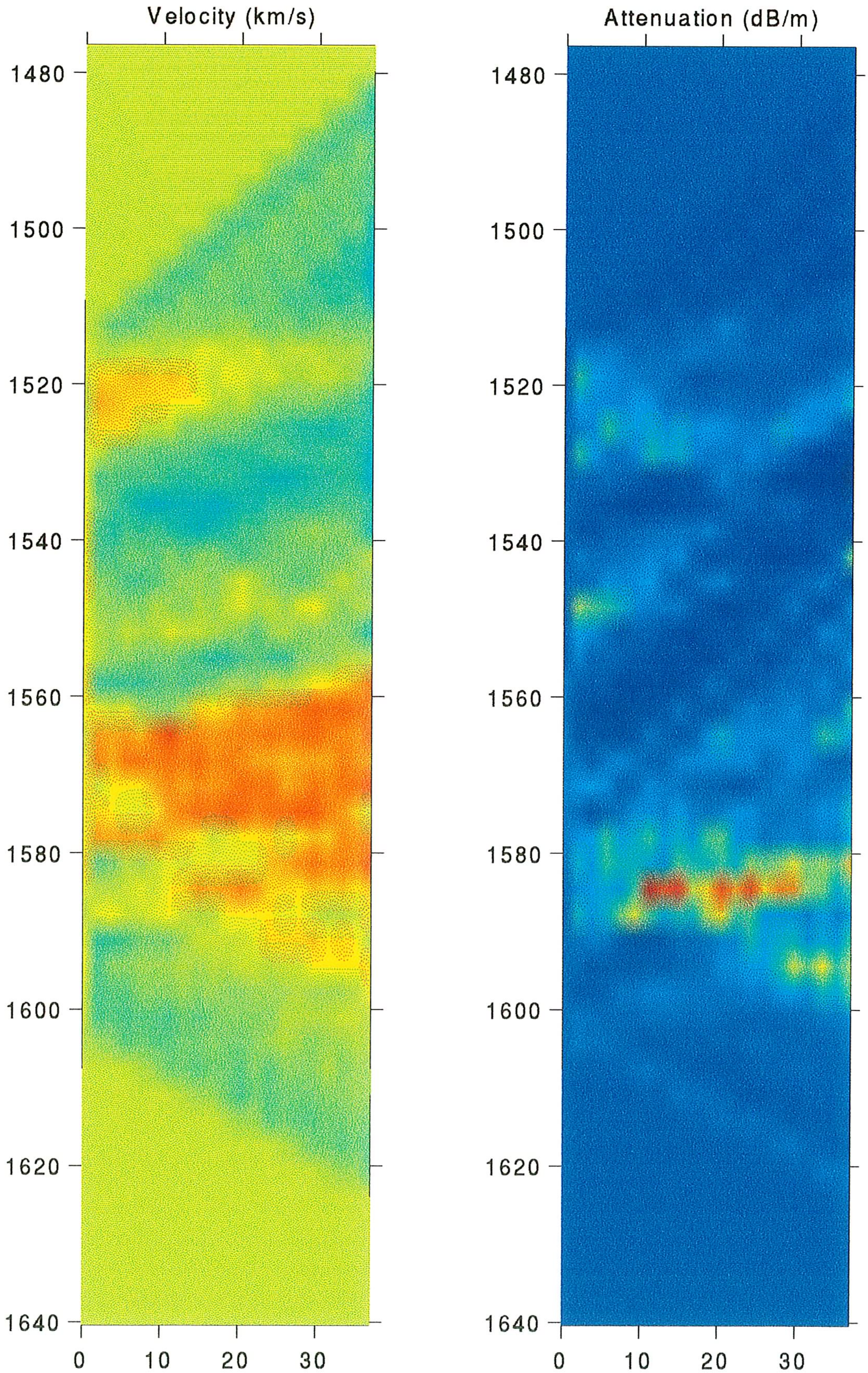


Figure 4 cntd. : Velocity and Attenuation Images (1476–1640 feet)

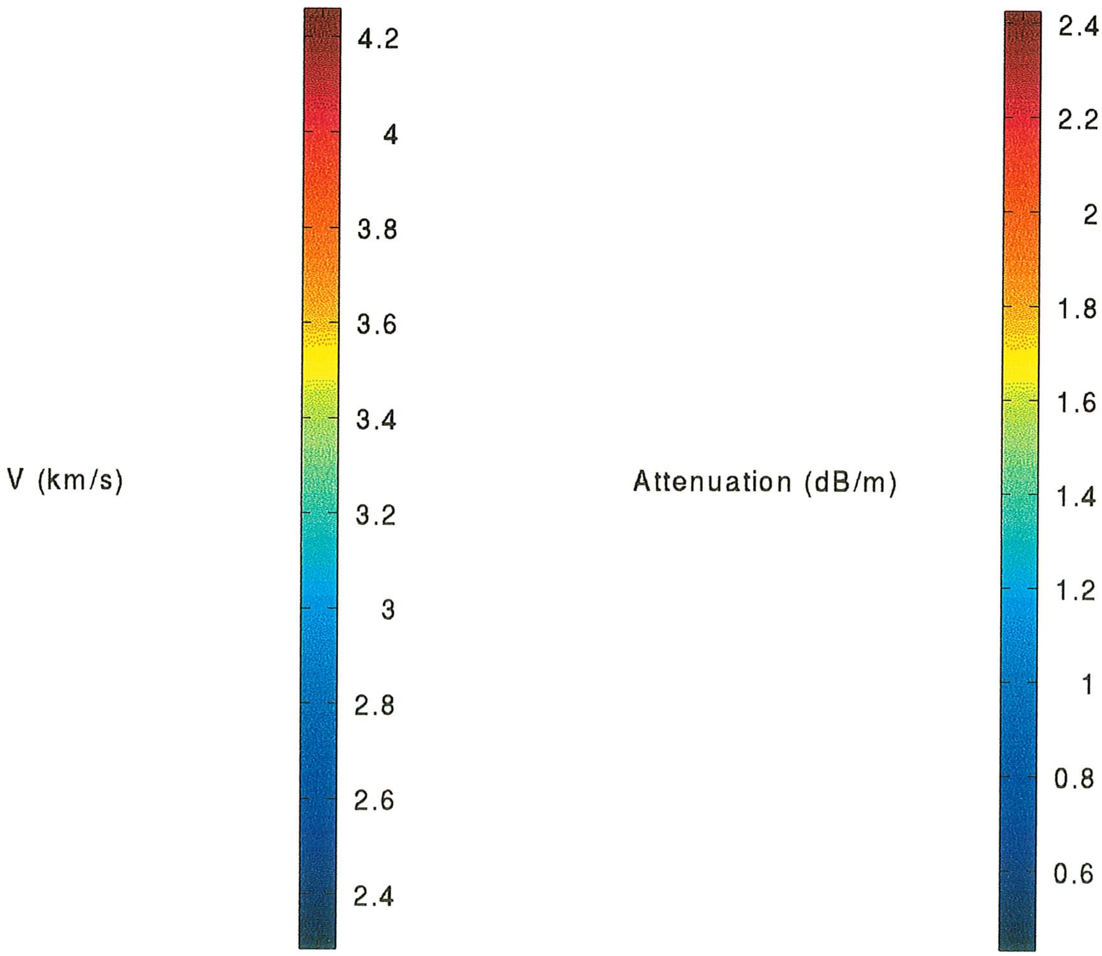


Figure 4 cntd: Velocity & Attenuation Image Colorbars

Schlumberger

DIGITAL BHC SONIC
CALIPER - GAMMA RAY

COUNTY	BROWARD
FIELD	OAKLAND PARK
LOCATION	ON C-13 CANAL AT
WELL	SFWMD BF-3
COMPANY	SOUTH FLORIDA WATER MANAGEMENT D

COMPANY SOUTH FLORIDA WATER MANAGEMENT DIST.

WELL SFWMD BF-3

FIELD OAKLAND PARK

COUNTY BROWARD **STATE** FLORIDA

LOCATION ON C-13 CANAL AT S-36 STRUCTURE

Other Services: DITE -- LDT/CNL CALIPER FLOWMETER TEMP

API SERIAL NO.	SECT.	TWP.	RANGE
N/A	20	49S	42E

Permanent Datum	GROUND LEVEL	Elev. 20.0 F		Elev.: K.B.30.5 F
Log Measured From	GROUND LEVEL	0.0 F	above Perm. Datum	D.F.29.5 F
Drilling Measured From	GROUND LEVEL			G.L.20.0 F

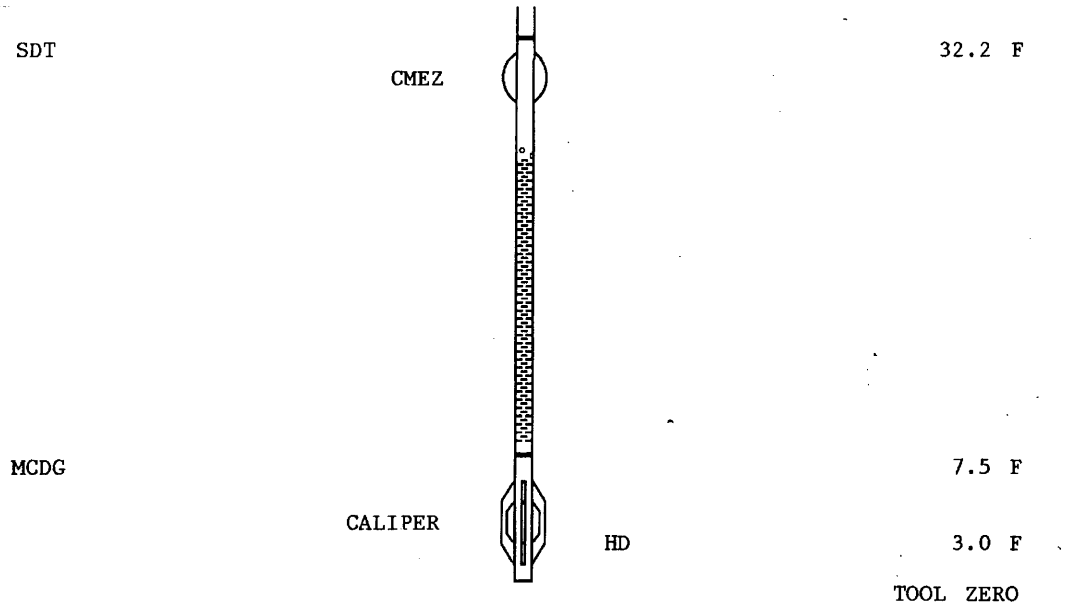
Date	11-FEB-1993		
Run No.	ONE		
Depth Driller	2217.0 F		
Depth Logger (Schl.)	2280.0 F		
Btm. Log Interval	2280.0 F		
Top Log Interval	1000.0 F		
Casing-Driller	12" @ 1006.0 F	@	@
Casing-Logger	1000.0 F		
Bit Size	10 3/4" @	@	@
Type Fluid in Hole	SALTWATER		
Dens. / Visc.	8.00 LB/G		
pH / Fld. Loss			
Source of Sample	CIRC. TANK		
Rm @ Meas. Temp.	.221 OHMM @ 72.0 DEGF	@	
Rmf @ Meas. Temp.	@	@	
Rmc @ Meas. Temp.	@	@	
Source: Rmf / Rmc			
Rm @ BHT	.242 OHMM @ 65.0 DEGF	@	
TIME Circulation Ended	2:00 02/11/93		
TIME Logger on Bottom	9:00 02/11/93		
Max. Rec. Temp.	65.0 DEGF		
Equip. / Location	8170	NATCHEZ, MS.	
Recorded By	BLIZNIK		
Witnessed By	JOHN LUKASIEWICZ		

The well name, location and borehole reference data were furnished by the customer.

All interpretations are opinions based on inferences from electrical or other measurements and we cannot, and do not guarantee the accuracy or correctness of any interpretations, and we shall not, except in the case of gross or willful negligence on our part, be liable or responsible for any loss, costs, damages or expenses incurred or sustained by anyone resulting from any interpretations made by any of our officers, agents or employees. These interpretations are also subject to Clause 4 of our General Terms and Conditions as set out in our current Price Schedule.

Run No.	ONE		
Service Order No.	607265		
Drilling Fluid Level			
Salinity	18000.0 PPM		
Rmf @ BHT		@ 65.0 DEGF	@
Rmc @ BHT		@ 65.0 DEGF	@
Logging Speed	4000.0 F/HR		
EQUIPMENT DATA			
Tool Number 1	SLS 1684		
Tool Number 2	SDC 622		
Tool Number 3	SGT		
Tool Number 4	MCD		
Tool Number 5	TCC		
Tool Number 6			
Tool Number 7			
Tool Number 8			
Tool Number 9			
Tool Number 10			
Tool Number 11			
Tool Number 12			

Figure-5: The Open Hole Velocity Log of Well BF-3 (reproduced from Schlumberger)



TOTAL TOOL STRING LENGTH IS 43.7 F.
TOTAL TOOL STRING WEIGHT IS 587. LB IN AIR.

FILES SPLICED	SPLICE DEPTH
2 TO 4	1999.0 F

ACCUMULATED INTEGRATION VALUES SUMMARY:

Integrated Hole Volume:	1519.35 F3	FROM 2280.00 F	TO 1000.00 F
Integrated Transit Time:	.130599 S	FROM 2280.00 F	TO 1000.00 F

EVENT MARK SUMMARY:

OUTPUT	INTERVAL BETWEEN PIPS	DEPTH TRACK EDGE
Integrated Hole Volume	10.0000 F3	LEFT EDGE
Integrated Transit Time	.00100000 S	RIGHT EDGE

Curve	Left scale	Right scale
BS(IN)	.0000	22.000
HD(IN)	.0000	22.000
GR(GAPI)	.0	150.00
TENS(LBF)	10000.	0.0
SPHI(V/V)	.45000	-.1500
DT(US/F)	140.00	40.000

WASHOUT

CP 32.6 FILE 6 11-FEB-1993 11:41

INPUT FILE(S) 4

CREATION DATE 11-FEB-1993 11:03

5"/100'

Figure-5 cntd.: The Open Hole Velocity Log of Well BF-3 (reproduced from Schlumberger)

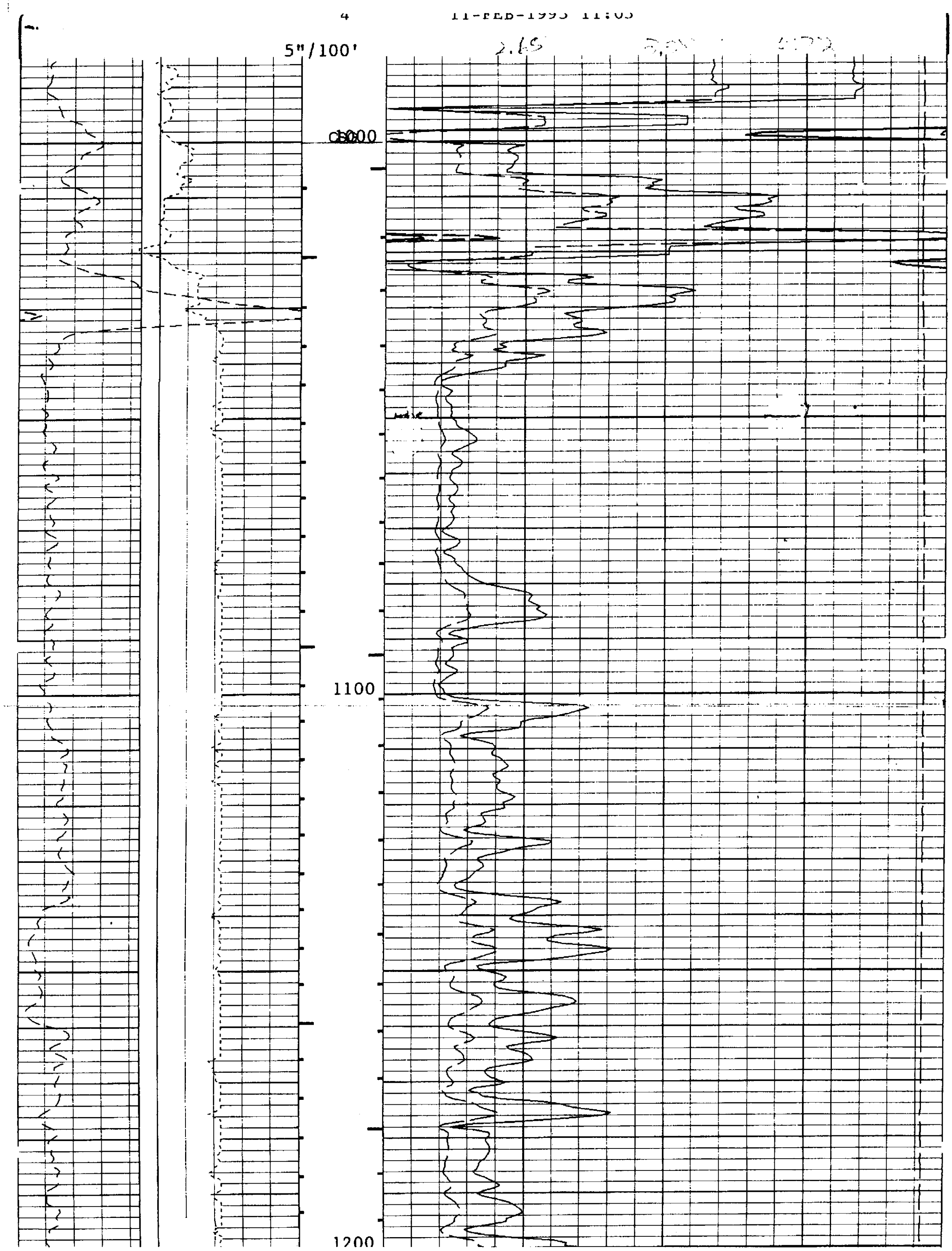


Figure-5 cntd.: The Open Hole Velocity Log of Well BF-3 (reproduced from Schlumberger)

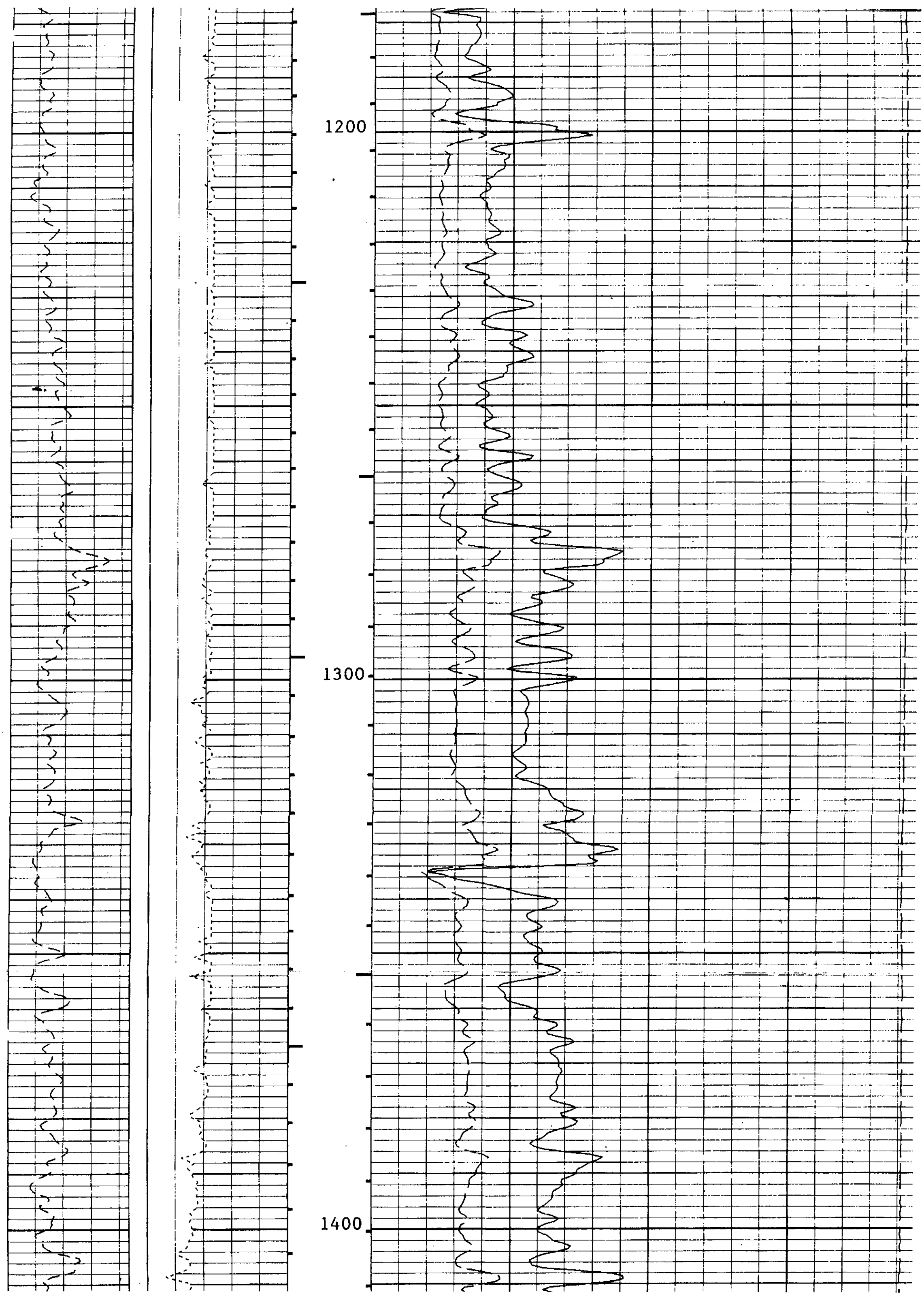


Figure-5 cntd.: The Open Hole Velocity Log of Well BF-3 (reproduced from Schlumberger)

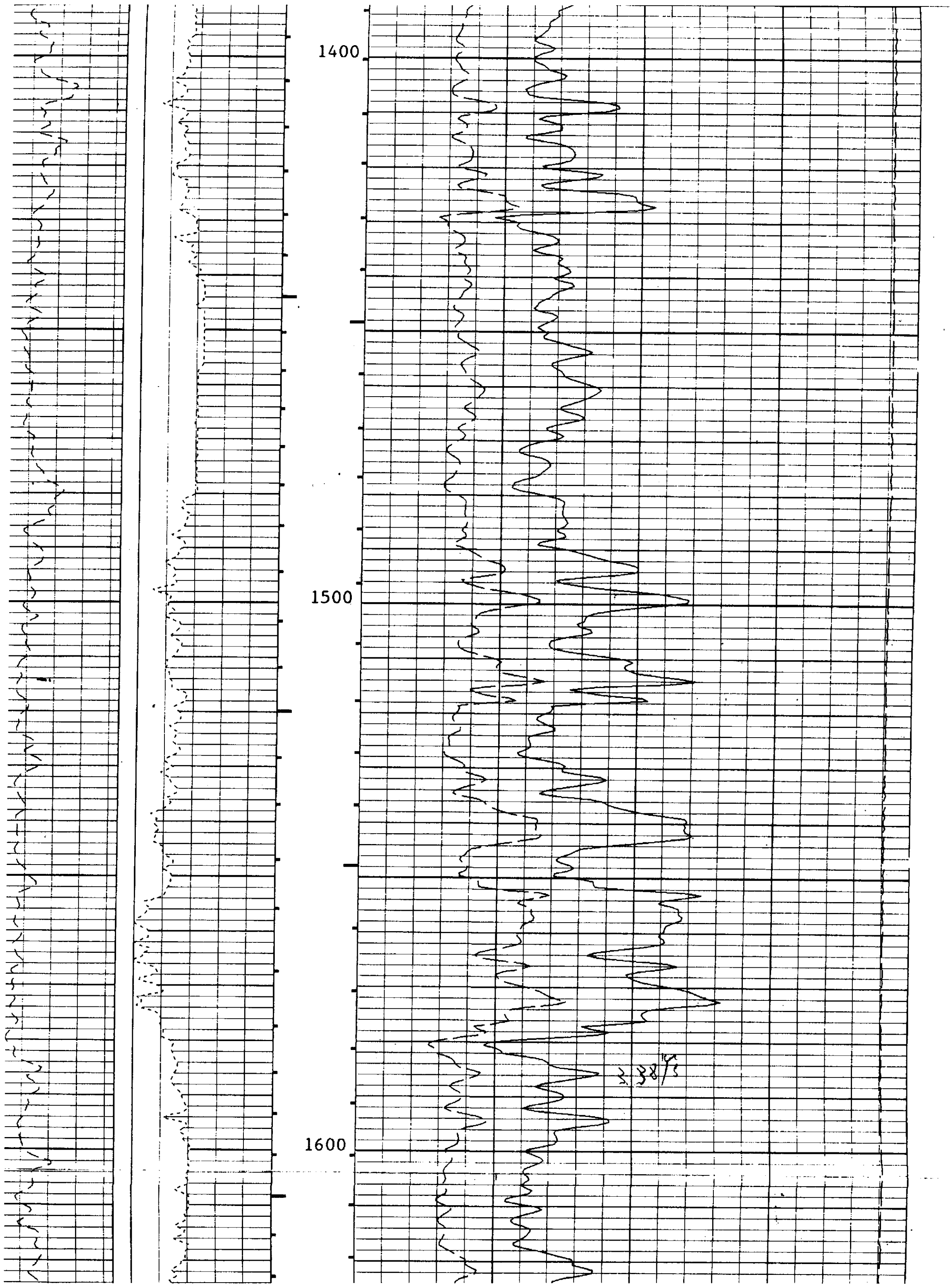


Figure-5 cntd.: The Open Hole Velocity Log of Well BF-3 (reproduced from Schlumberger

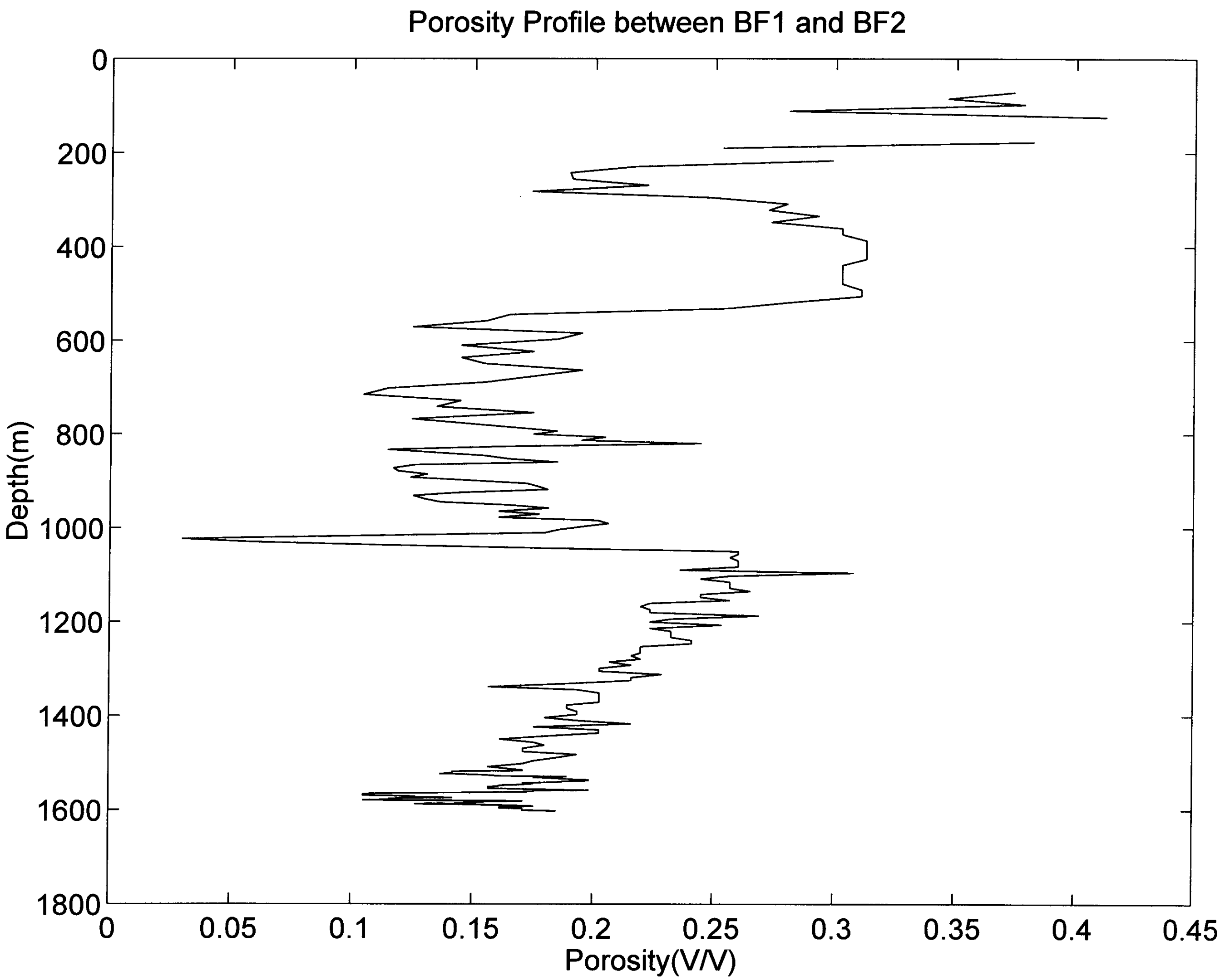


Figure 6: Porosity Profile

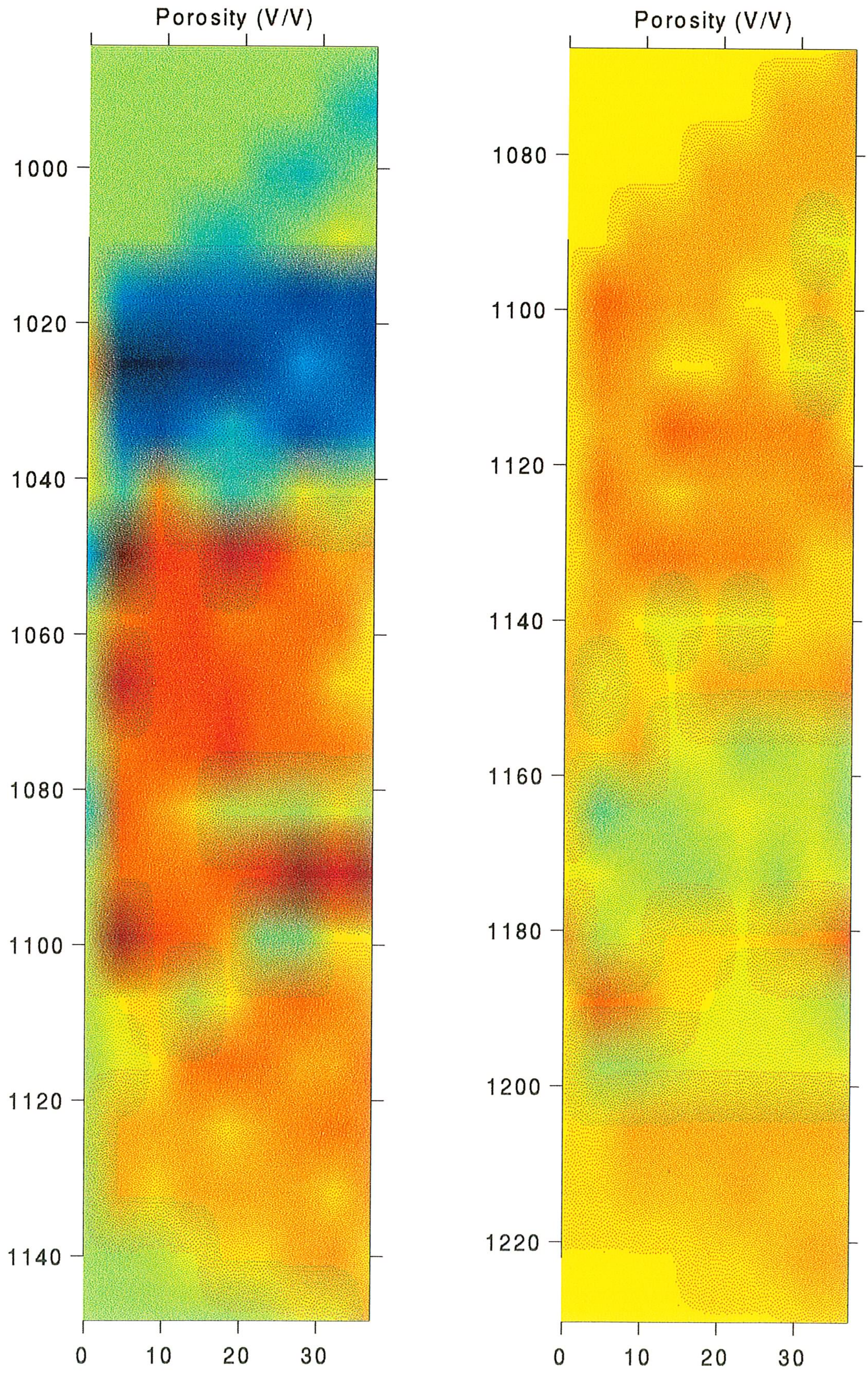


Figure 7: Porosity Images (984–1148 feet) and (1066–1230 feet)

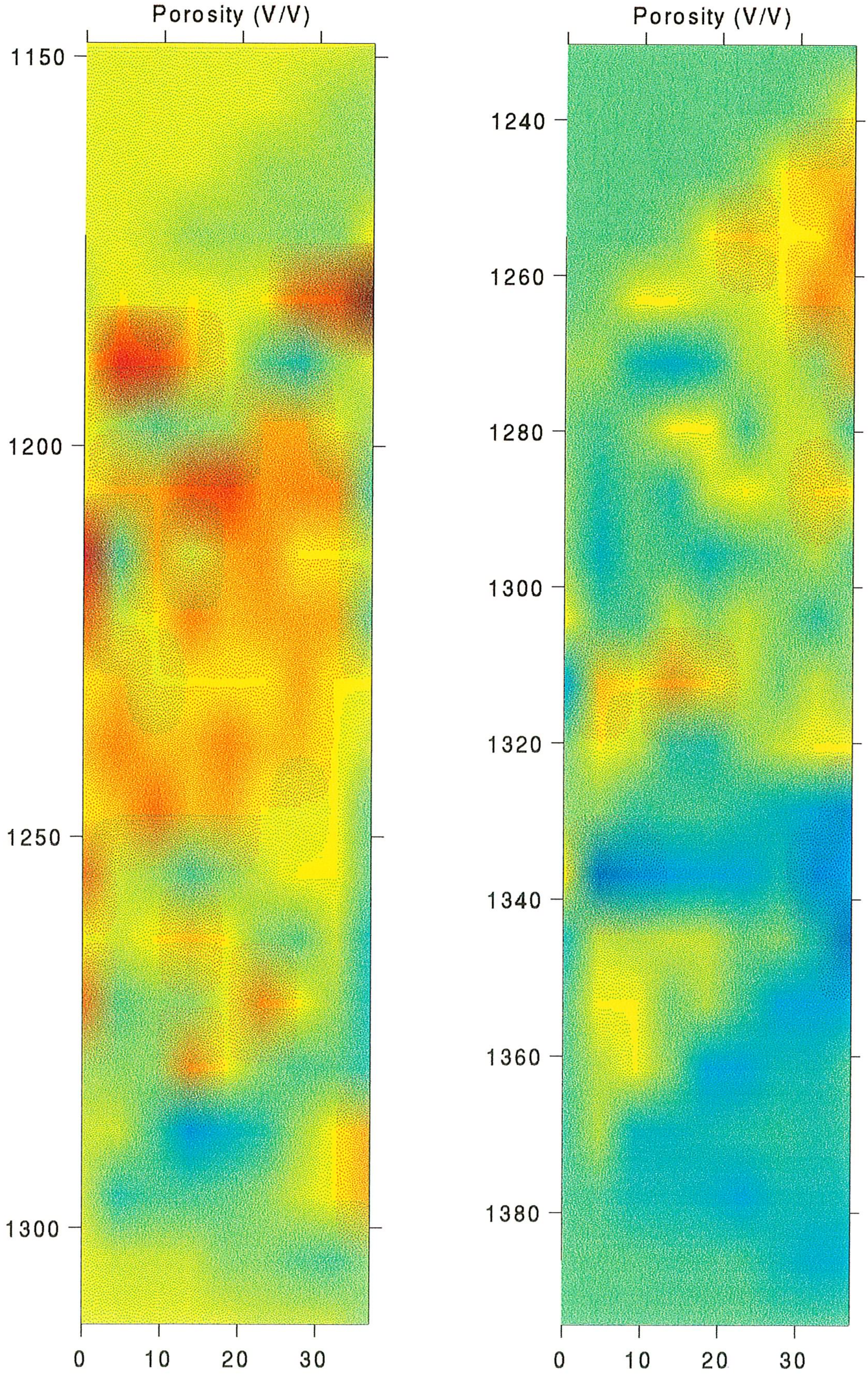


Figure 7 cntd. : Porosity Images (1148–1312 feet) and (1230–1394 feet)

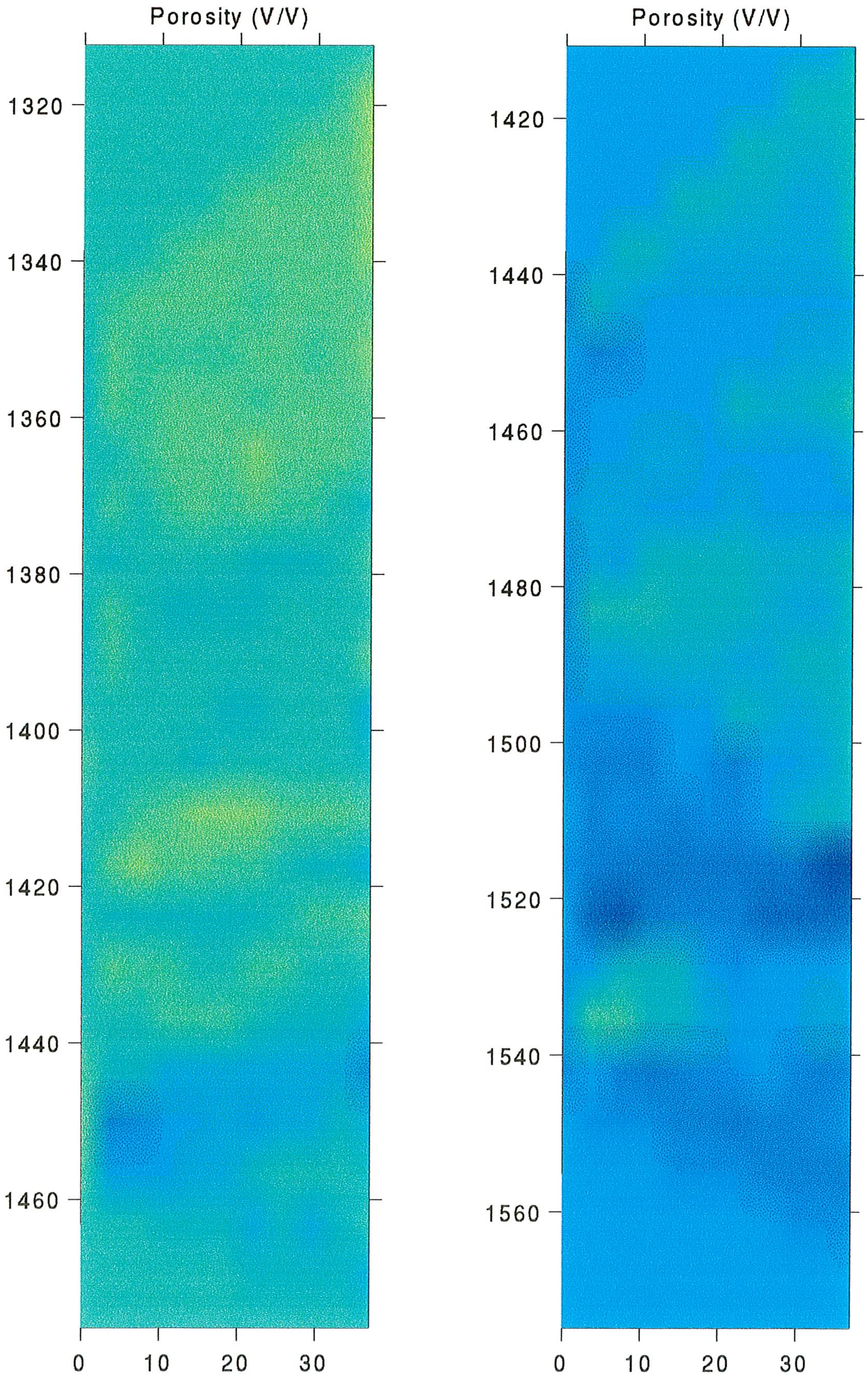


Figure 7 cntd. : Porosity Images (1312–1476 feet) and (1411–1575 feet)

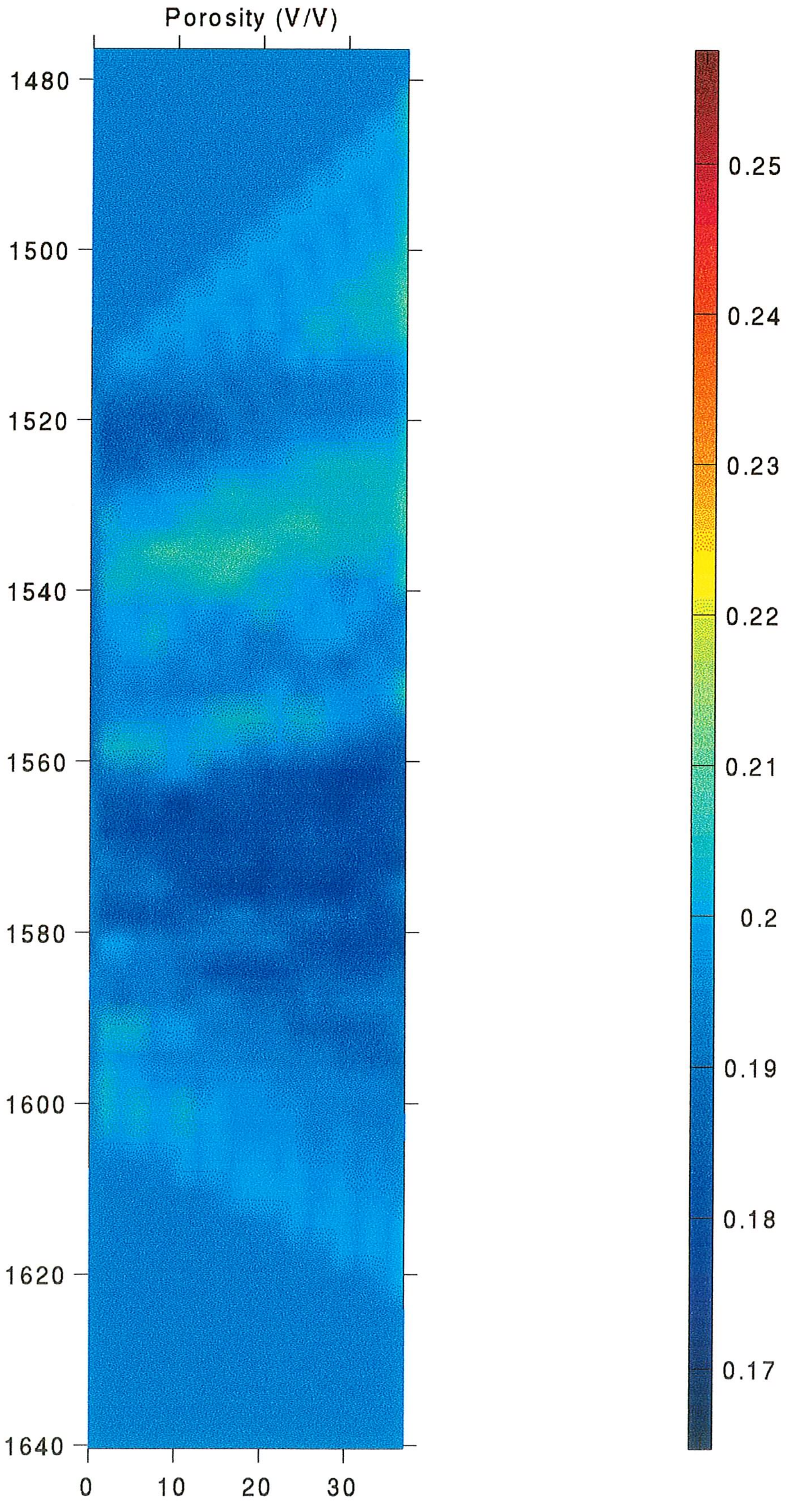


Figure 7 cntd. : Porosity Images (1476-1640 feet)

Schlumberger

LITHO DENSITY COMPENSATED NEUTRON

COMPANY	SOUTH FLORIDA WATER MANAGEMENT DIST.
WELL	SFWMD BF-3
FIELD	OAKLAND PARK
COUNTY	BROWARD
STATE	FLORIDA

COUNTY BROWARD / FIELD OAKLAND PARK / LOCATION ON C-13 CANAL AT / WELL SFWMD BF-3 / COMPANY SOUTH FLORIDA WATER MANAGEMENT DIST.

LOCATION: ON C-13 CANAL AT S-36 STRUCTURE

Other Services: AMS, BHC SONIC, DITE, CALIPER, FLOWMETER, TEMP

API SERIAL NO.	SECT.	TWP.	RANGE
N/A	20	49S	42E

Permanent Datum	GROUND LEVEL	Elev. 20.0 F	Elev.: K.B.30.5 F
Log Measured From	GROUND LEVEL	0.0 F above Perm. Datum	D.F.29.5 F
Drilling Measured From	GROUND LEVEL		G.L.20.0 F

Date	11-FEB-1993		
Run No.	ONE		
Depth Driller	2217.0 F		
Depth Logger (Schl.)	2280.0 F		
Btm. Log Interval	2280.0 F		
Top Log Interval	1000.0 F		
Casing-Driller	12" @ 1006.0 F	@	@
Casing-Logger	1000.0 F		
Bit Size	10 3/4" @	@	@
Type Fluid in Hole	SALTWATER		
Dens. / Visc.	8.00 LB/G		
pH / Fld. Loss			
Source of Sample	CIRC. TANK		
Rm @ Meas. Temp.	.221 OHMM @ 72.0 DEGF	@	
Rmf @ Meas. Temp.	@	@	
Rmc @ Meas. Temp.	@	@	
Source: Rmf / Rmc			
Rm @ BHT	.242 OHMM @ 65.0 DEGF	@	
Time: Circulation Ended	2:00 02/11/93		
Time: Logger on Bottom	9:00 02/11/93		
Max. Rec. Temp.	65.0 DEGF		
Equip. / Location	8170	NATCHEZ, MS.	
Recorded By	BLIZNIK		
Witnessed By	JOHN LUKASIEWICZ		

The well name, location and borehole reference data were furnished by the customer.

All interpretations are opinions based on inferences from electrical or other measurements and we cannot, and do not guarantee the accuracy or correctness of any interpretations, and we shall not, except in the case of gross or willful negligence on our part, be liable or responsible for any loss, costs, damages or expenses incurred or sustained by anyone resulting from any interpretations made by any of our officers, agents or employees. These interpretations are also subject to Clause 4 of our General Terms and Conditions as set out in our current Price Schedule.

Run No.	ONE	
Service Order No.	607265	
Drilling Fluid Level		
Salinity	18000.0 PPM	
Rmf @ BHT	@ 65.0 DEGF	@
Rmc @ BHT	@ 65.0 DEGF	@
Logging Speed	4000.0 F/HR	
EQUIPMENT DATA		
Tool Number 1	DRS 2993	
Tool Number 2	NSC 1771	
Tool Number 3	CNT 181	
Tool Number 4	SGT	
Tool Number 5	TCC	
Tool Number 6		
Tool Number 7		
Tool Number 8		
Tool Number 9		
Tool Number 10		
Tool Number 11		
Tool Number 12		
REMARKS:		

Figure-8: The Porosity Depth Log of Well BF-3 (reproduced from Schlumberger)

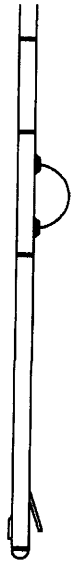
SGTL 30.1 F

GR 29.2 F

CNTH 24.6 F

BOWSPRING

LDTD 17.3 F



CALIPER

LDT DETECTOR SKID

CALI 2.7 F

TOOL ZERO

TOTAL TOOL STRING LENGTH IS 36.6 F.
TOTAL TOOL STRING WEIGHT IS 658. LB IN AIR.

BULK DENSITY/CROSSPLOT POROSITY LOG

ACCUMULATED INTEGRATION VALUES SUMMARY:

Integrated Hole Volume:	1562.89 F3	FROM 2151.50 F	TO 1000.00 F
Integrated Cement Volume:	1462.55 F3	FROM 2151.50 F	TO 1000.00 F

(ASSUMING 4.00000 IN O.D. CASING)

EVENT MARK SUMMARY:

OUTPUT	INTERVAL BETWEEN PIPS	DEPTH TRACK EDGE
Integrated Hole Volume	10.0000 F3	LEFT EDGE
Integrated Cement Volume	10.0000 F3	RIGHT EDGE

2.0000	CALI(IN)	22.000		
0.0	GR(GAPI)	150.00	.60000	PHIX(V/V)	0.0
2.0000	BS(IN)	22.000	2.0000	RHOB(G/C3)	3.0000

WASHOUT

CP 32.6 FILE 5 11-FEB-1993 13:02 (UP)

5"/100'

Figure-8 cntd.: The Porosity Depth Log of Well BF-3 (reproduced from Schlumberger)

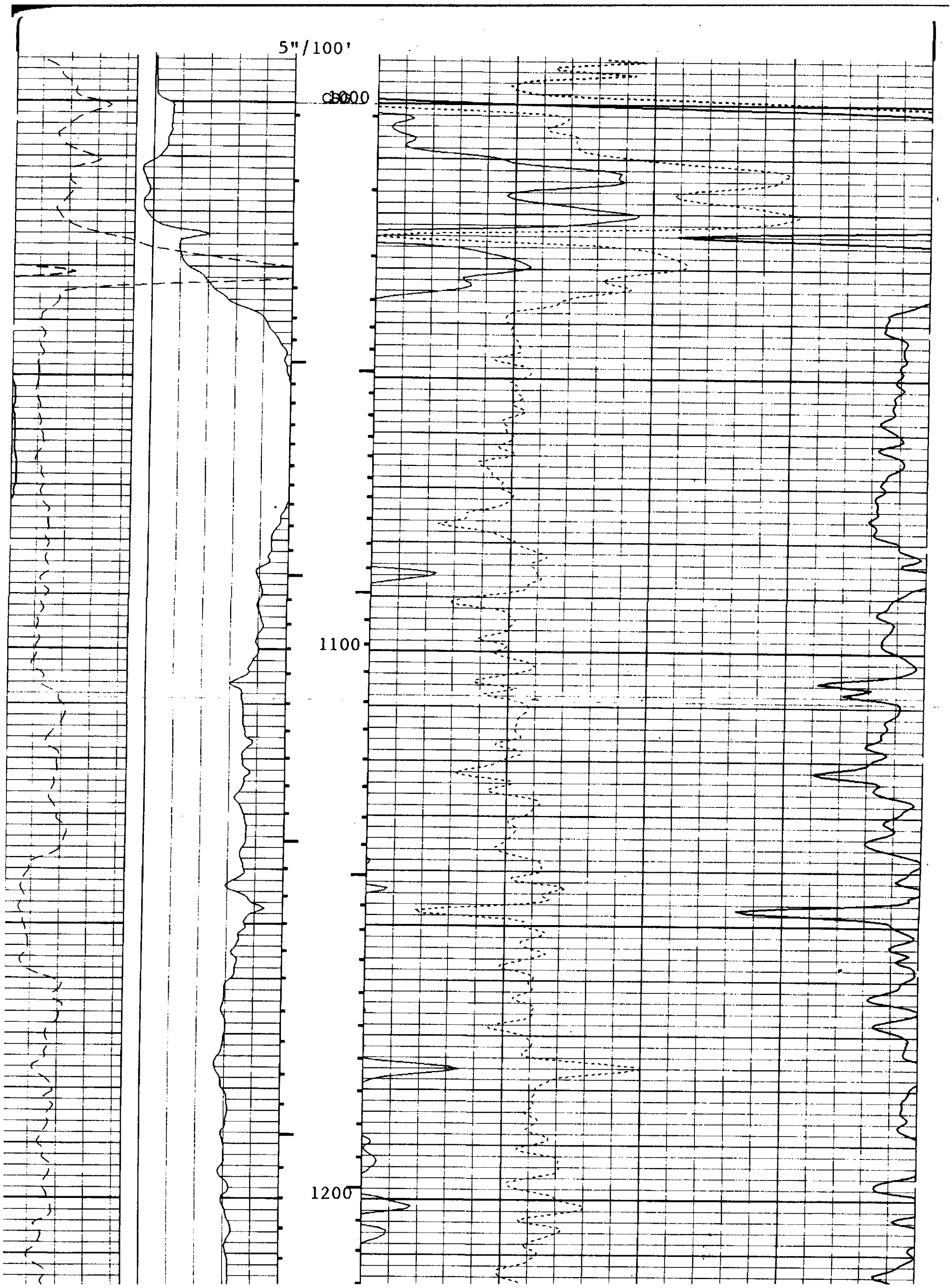


Figure-8 cntd.: The Porosity Depth Log of Well BF-3 (reproduced from Schlumberger)

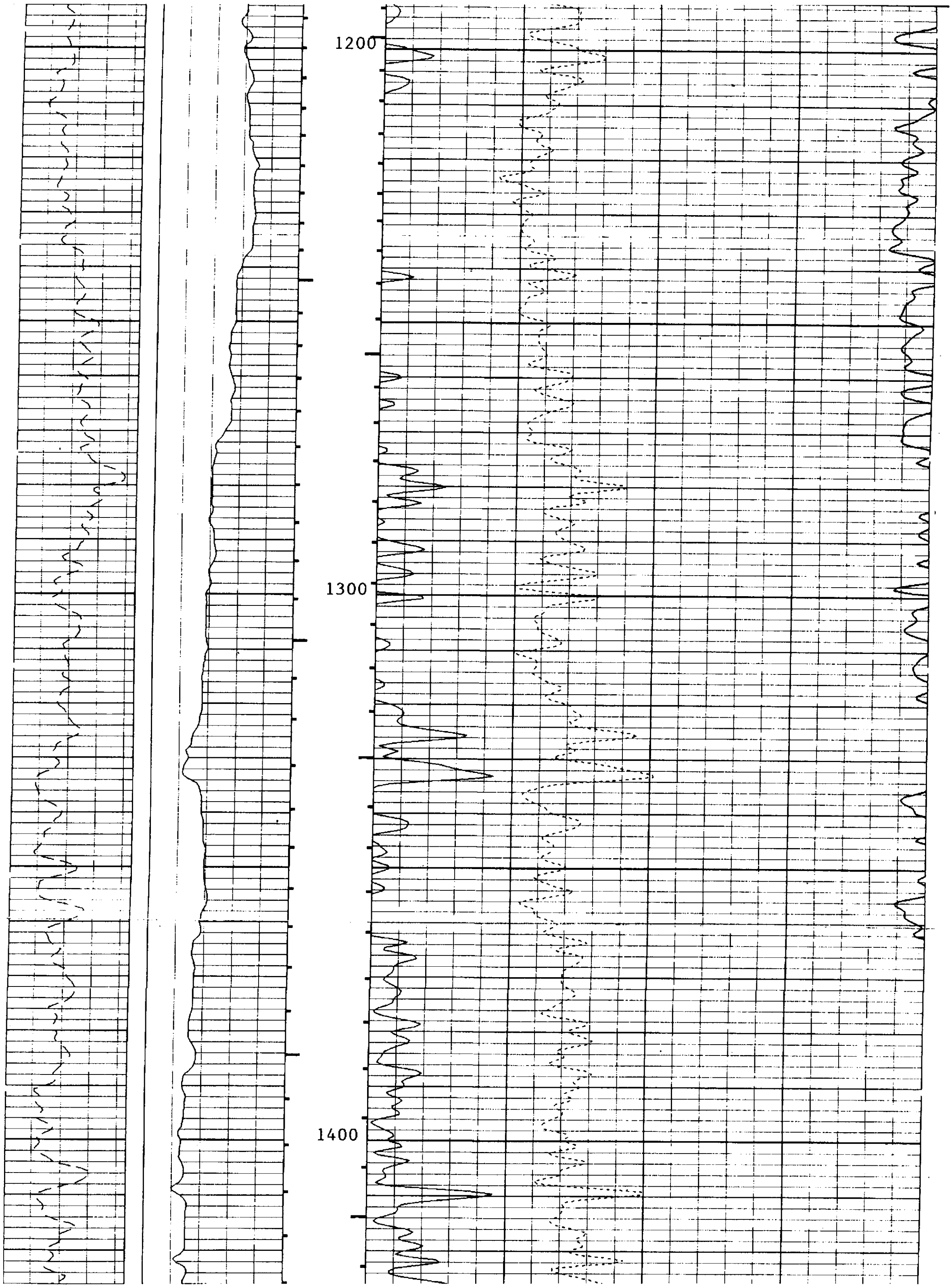


Figure-8 cntd.: The Porosity Depth Log of Well BF-3 (reproduced from Schlumberger)

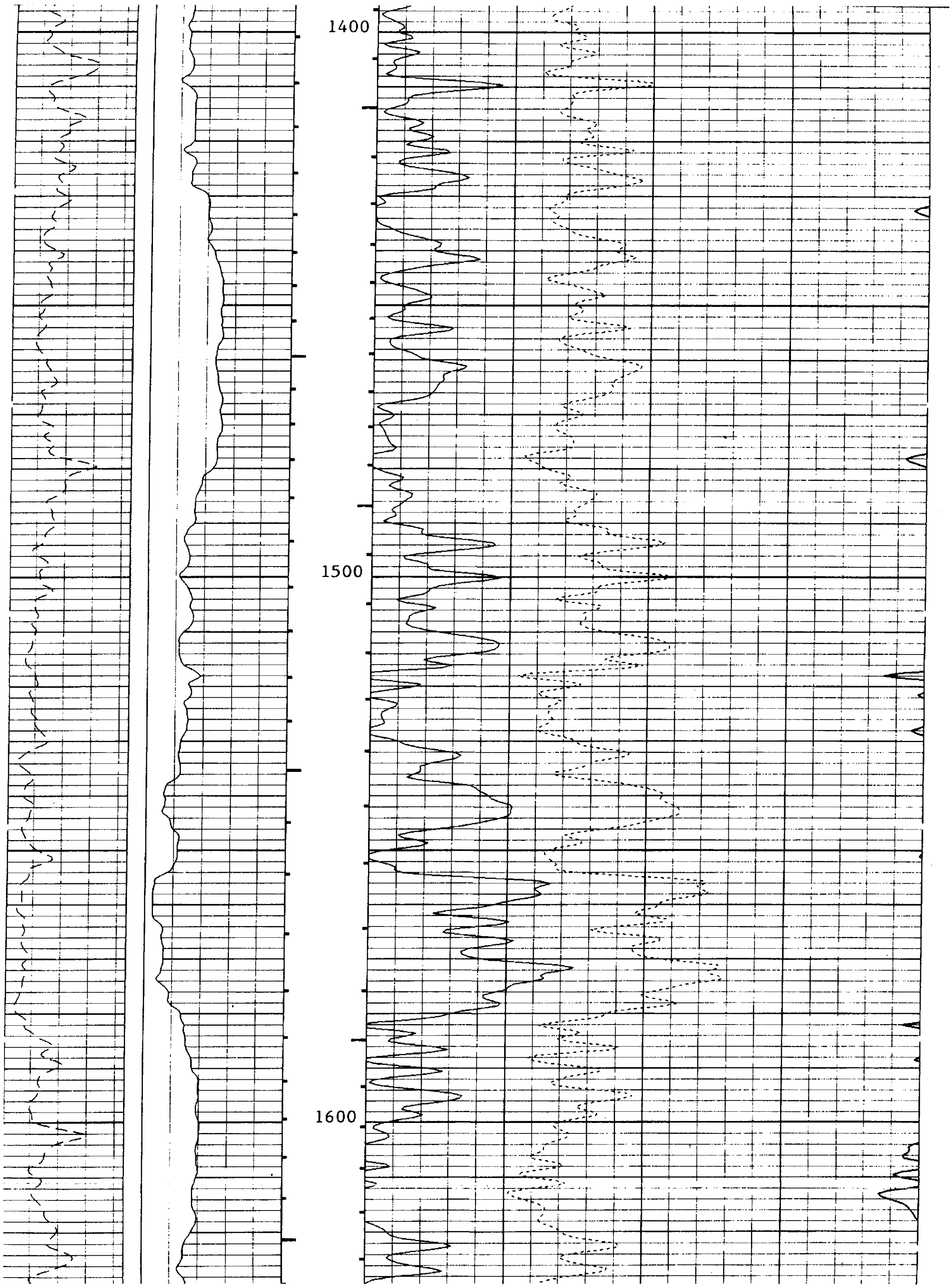


Figure-8 cntd.: The Porosity Depth Log of Well BF-3 (reproduced from Schlumberger)

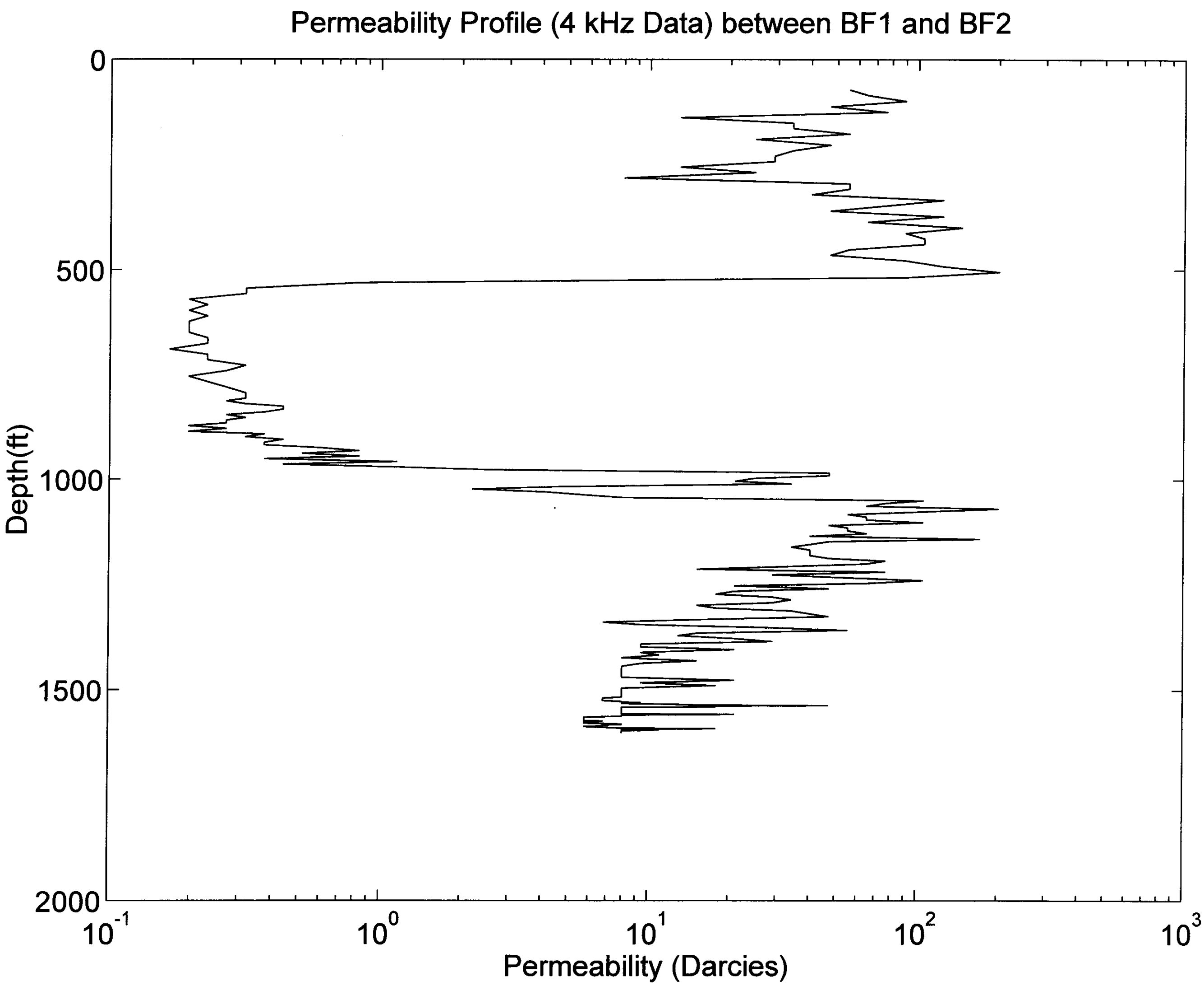


Figure 9: Permeability Profile

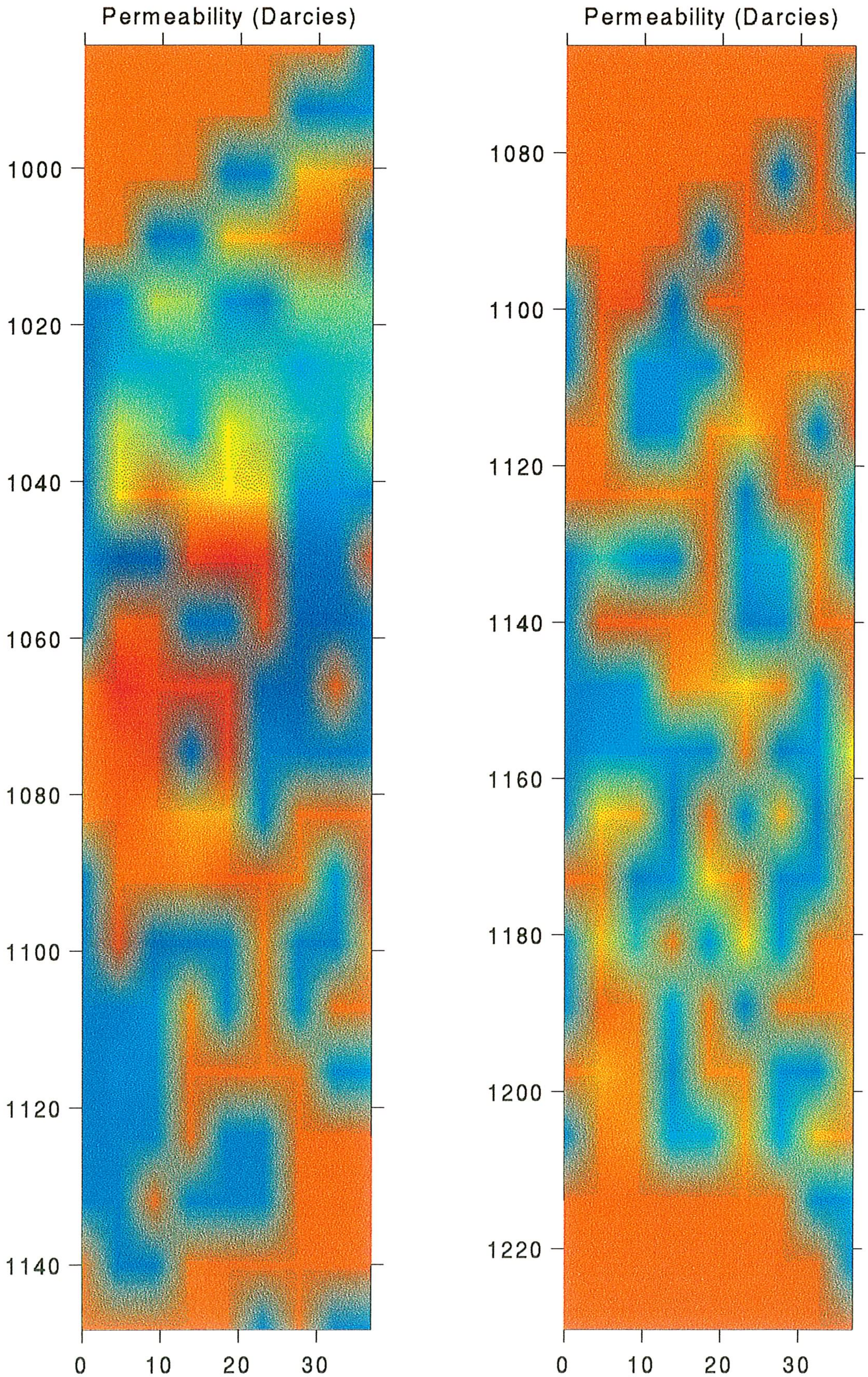


Figure 10: Permeability (984–1148 feet)

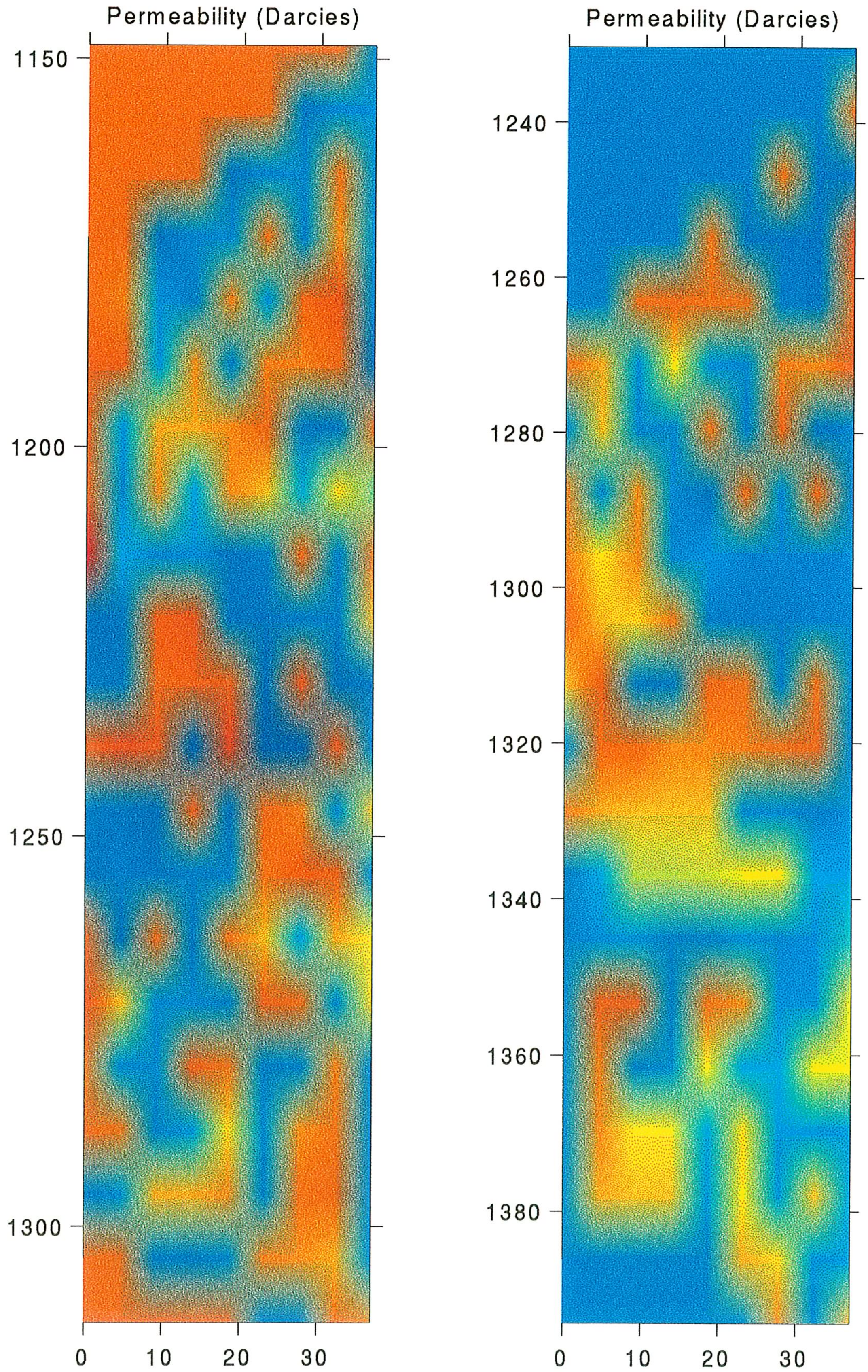


Figure 10 cntd.: Permeability (1148–1312 feet)

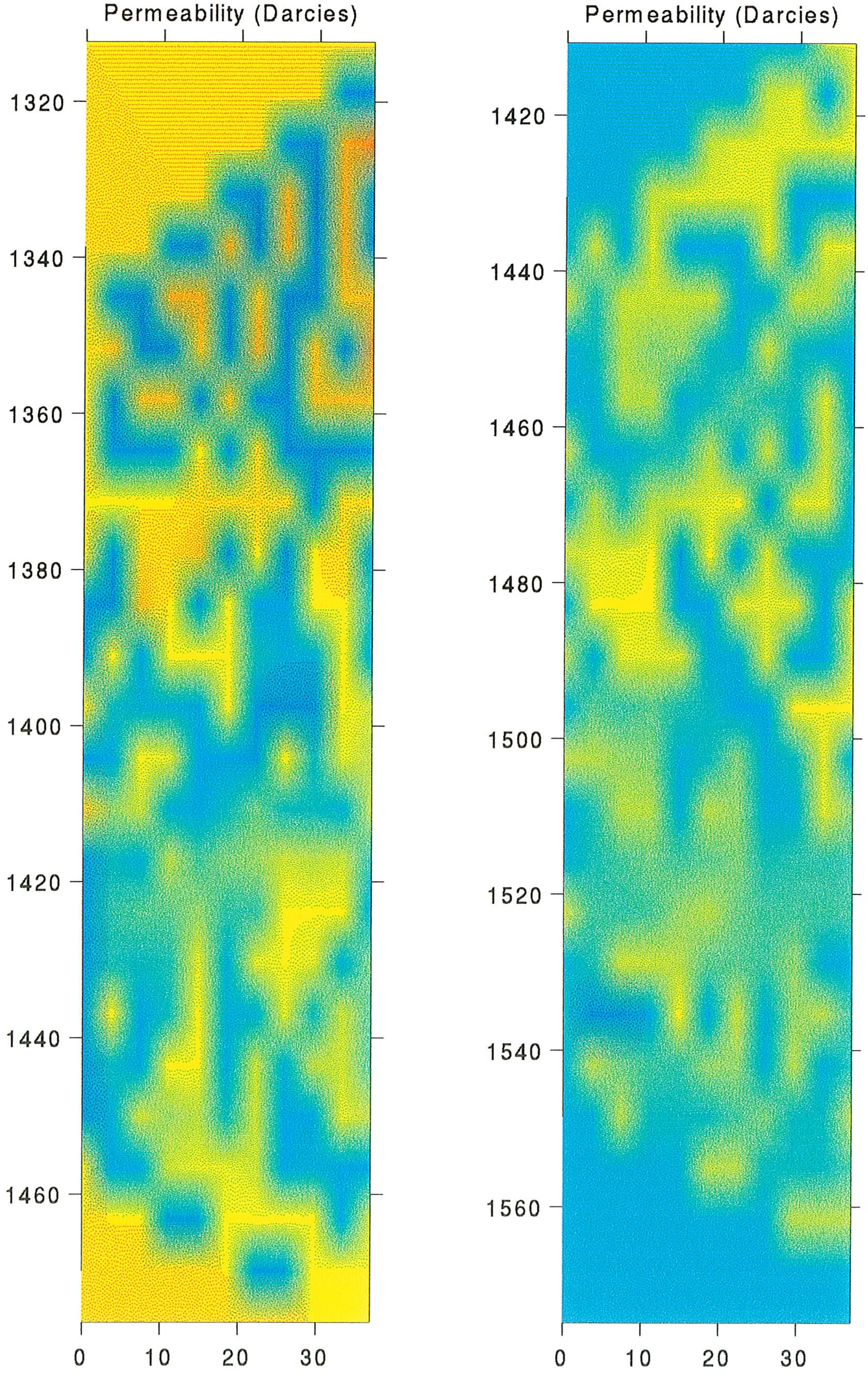


Figure 10 cntd.: Permeability (1312–1476 feet)

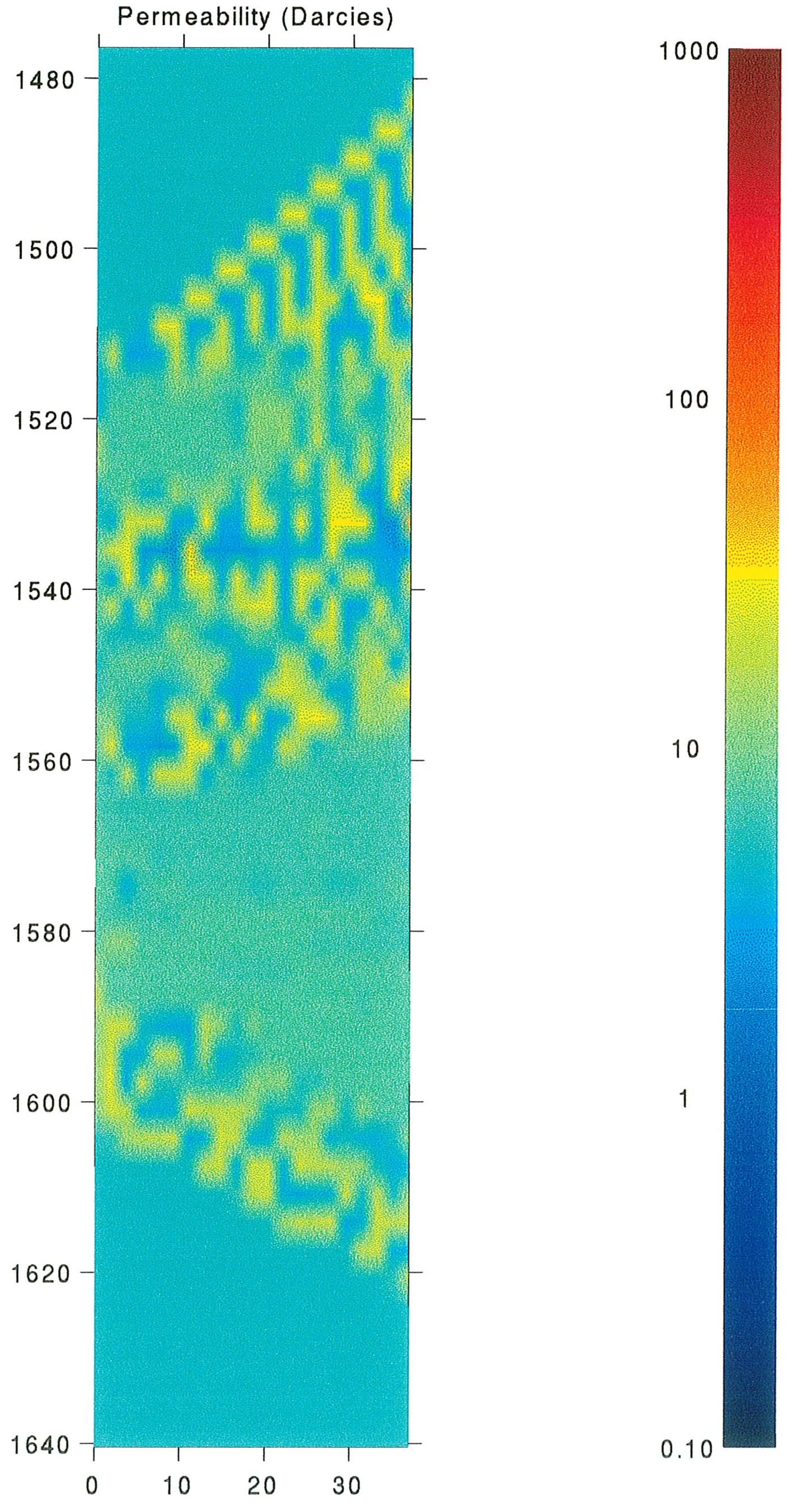


Figure 10 cntd.: Permeability Images (1476–1640 feet)

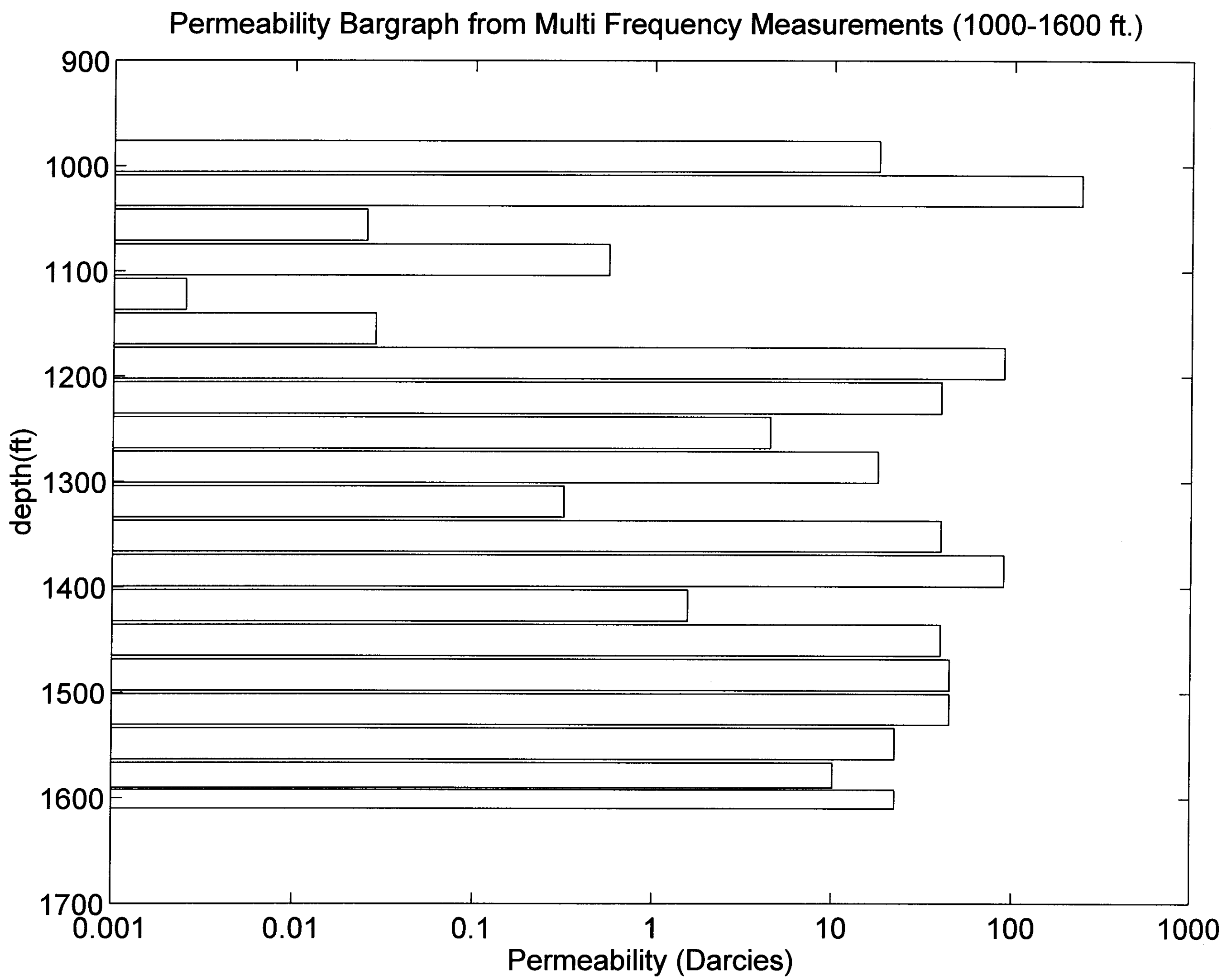


Figure 11: Permeability Bargraph