PRELIMINARY ASSESSMENT OF IMPULSE RADAR TO DETECT DECAY IN HARDWOOD

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DISCLAIMER

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Abstract

A simple, portable tool to detect decay in hardwoods non-destructively is required for forestry management. In this study a preliminary assessment of impulse radar was made for this application.

Twelve bolts of aspen from Alberta, with diameters of 10 to 20 cm, were profiled using an A-Cubed pulseEKKO I impulse radar system with a centre frequency of 700 MHz. The bolts were then cut, visually inspected for decay and sampled for moisture content and density.

The electrical characteristics of sound and decayed samples were sufficiently different to give differing radar responses. Sound samples usually gave a single, strong radar echo from the back of the bolt, and some even had a second back echo. Decayed samples gave increased ringing in the radar echo, due to reverberation within the bolts.

The relative dielectric constant of the wood as measured with the radar correlated well with volumetric moisture content. However, decay was not related to moisture content in these samples.

These results indicate that impulse radar is able to give useful information on wood properties. In order to utilize this technique a more complete understanding of the electrical/structural properties of sound on decayed aspen should be sought. More suitable antennas should be fabricated before additional laboratory or field tests are performed.

Acknowledgements

We are grateful for assistance from Mr. Ted Szabo and Mr. Brian Karaim of the Alberta Forest Service who collected the log samples tested here.

Density and moisture content measurements were made at the Forestry Department of the University of Toronto.

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1. Introduction

A cost-effective, reliable, portable instrument to detect decay or cull in hardwoods does not appear to be available for forestry management (Chow, 1987; Hailey and Morris, 1987). The authors of this report made some preliminary measurements in late 1985 which showed that impulse radar measurements were very sensitive to changes in moisture content of logs. The question remained whether this technique could detect decay in aspen. These preliminary measurements were made in the laboratory on a selection of aspen bolts provided by the Alberta Forest Service. The objective was to determine whether the technique showed enough promise for further consideration.

Impulse radar (or ground-penetrating radar) has been used in a number of remote areas for a variety of applications, including measurement of ice thickness, delineation of subsurface geology, detection of underground pipes and voids, etc. (e.g. Morey, 1974; Annan and Davis, 1976; Rossiter and Gustajtis, 1978; Ulriksen, 1982; Davis et al., 1987). There appears to have been little work done using this tool for measurement of the properties of wood.

In this study, twelve bolts of aspen were shipped to A-Cubed's Mississauga facility. They were marked and impulse radar profiles were made along the length of each bolt by A-Cubed personnel using one of their impulse radar systems. The bolts were then sampled for visual and laboratory examination under the supervision of Quaile Engineering. Data interpretation and project management were performed by Canpolar.

In section 2 of this report the impulse radar measurements are described; in section 3, the physical sampling results are given; in section 4, the discussion, conclusions and recommendations are presented. The actual radar and photographic data are in Appendix 1.

2. Impulse Radar Measurements

2.1 Impulse Radar Instrumentation

The impulse radar transmits a short burst of electromagnetic energy from the transmitter into the wood. This signal travels through the wood and is partly reflected whenever it encounters a change in the properties of the wood, such as a decayed section, and at the far side of the bolt. These reflected echoes are detected at the receiver where they are amplified and recorded. A schematic sketch of the radar system is shown in Figure 2.1.

The data are displayed on a grey-level paper recorder as shown in Figure 2.2. The radar signal is represented by three black bands along the top of the record. Position along the bolt is shown on the horizontal axis and the two-way travel time is shown on the vertical axis.

The speed of the signal in the wood is controlled by the electrical properties of the wood, particularly the moisture content. Increased moisture decreases the speed of the signal; voids and reduced moisture increase the speed. The strength of the echo (i.e. darkness of the signal on the record) is indicative of the attenuation through the wood and the contrast in electrical properties at the reflecting boundary. At the far side of the bolt the contrast is quite high and much of the transmitted energy is reflected back to the receiver.

The impulse radar used in this study was an A-Cubed pulseEKKO I system (which is a modified version of equipment manufactured by Geophysical Survey Systems Inc.), shown in Figure 2.3. This radar system, except for the graphic plotter, is quite portable and can operate on battery power. For remote applications data can be recorded on magnetic tape and plotted later. The radar parameters used are given in Table 2.1.

2.2 Radar Measurements

Each of the twelve bolts was mounted vertically in turn and profiled by moving the radar antennas slowly along the bolt (Figure 2.3(b)). Fiducial marks were put on the data records when the centre of the antenna package was at the assumed butt, at the one-quarter, one-half, three-quarters, and top points of each bolt. The bolts varied in size from 10 to 20 cm in diameter and from 75 to 90 cm in length. The data were recorded directly onto paper using the grey-level plotter.

The measurements were repeated once by re-mounting each bolt in turn. The differences between the two sets of data were not significant, but this test did confirm the repeatability of the results.

The measurements were made with the electrical field of the transmitted signal polarized perpendicular to the length of the bolt. Because of the arrangement of the antenna package it was not possible to examine the parallel polarized situation with bolts of this size.

Figure 2.1 Schematic sketch of the impulse radar system (after Morey, 1974). In this experiment a tape recorder was not used and received signals were displayed directly on the graphic recorder.

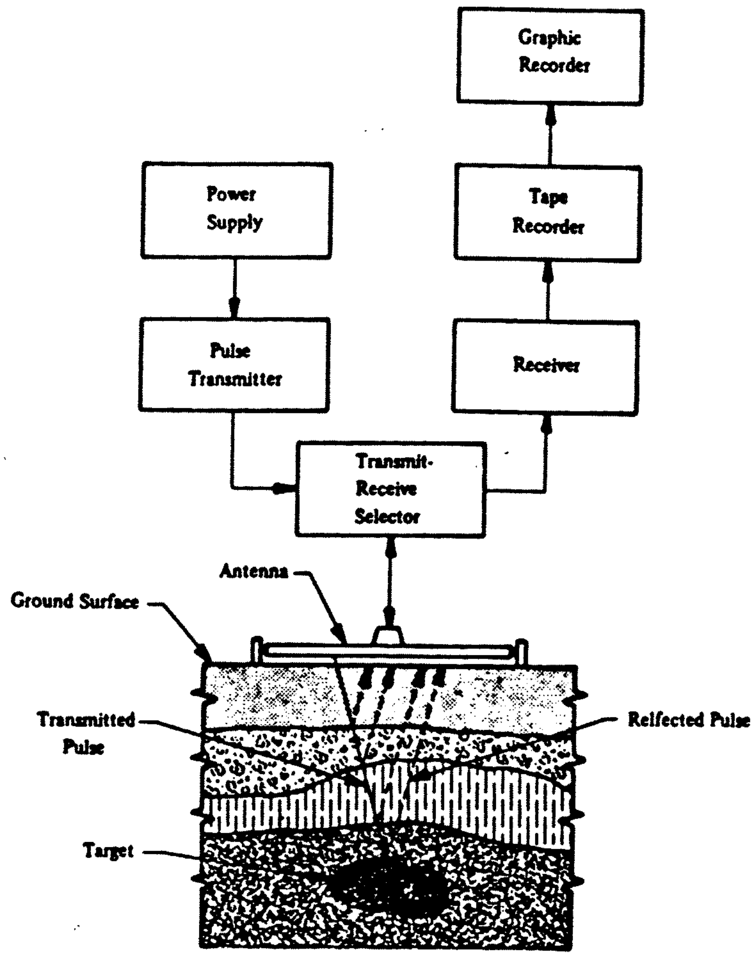


Figure 2.2 Explanation of the grey-level graphic record (after Morey, 1974). In this experiment bolts of wood were profiled rather than layers of ice.

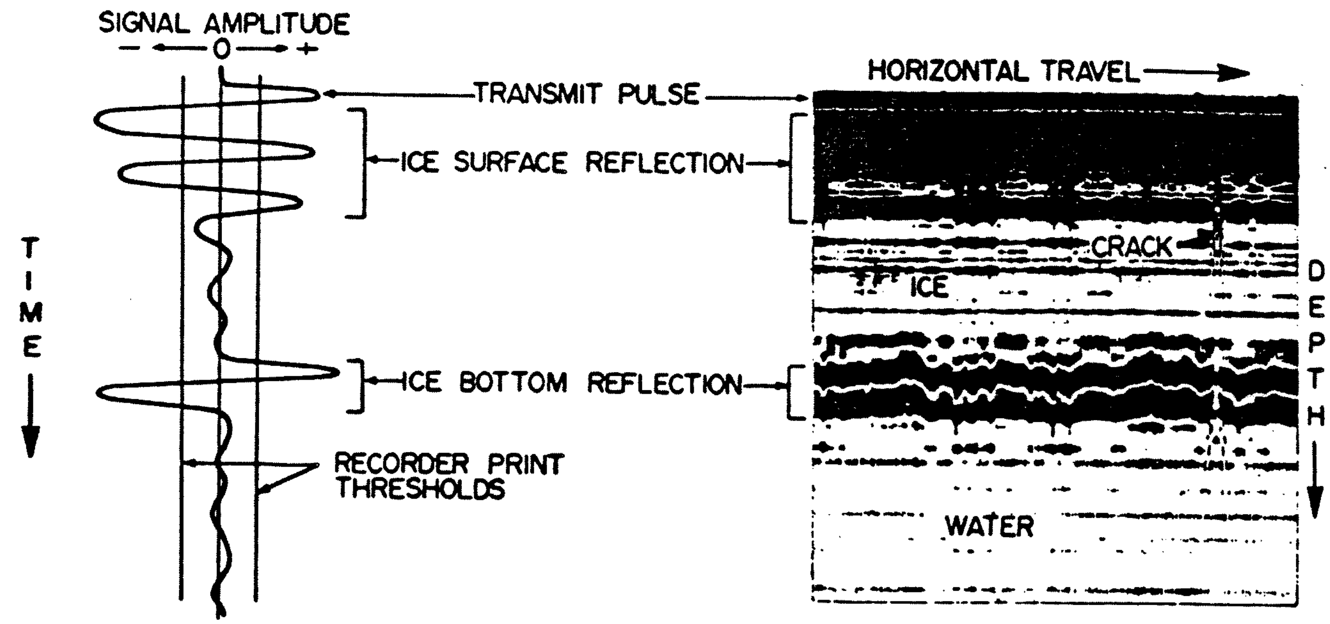


Figure 2.3(a) Photograph of the impulse radar graphic plotter and control unit.

Figure 2.3(b) Photograph of 700 MHz antennas as oriented on the bolts.

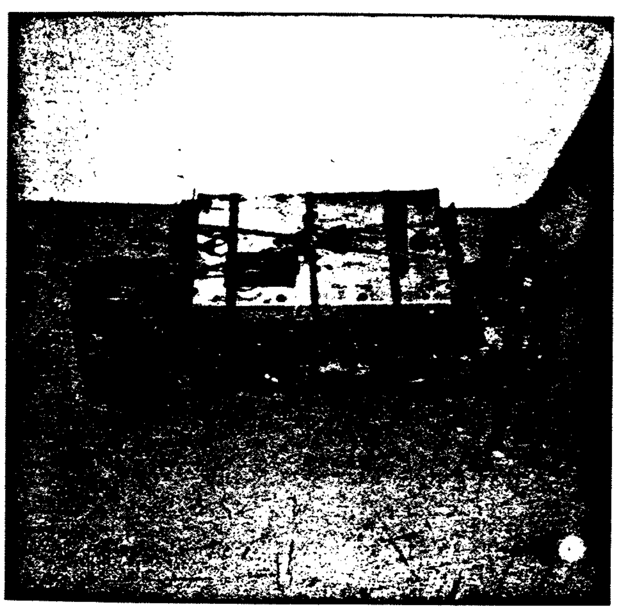


Table 2.1 Impulse Radar Parameters

Radar	
Pulse length	1.4 ns
Centre frequency	700 MHz
Antenna spacing	0.15 m
Range window	25 ns
Gain setting	100
Gain rate setting	minimum
Filter setting	medium
Scan rate	6.4 scans/second
Plotter	
Sweep time	0.125 s
Threshold setting	minimum
Contrast setting	maximum
Print polarity	+ and -

2.3 Data Compilation

The radar data records were mounted and the position and time scales were labelled. An approximate depth scale was added for reference purposes only. The signal speed used for this scale was 0.75 m/ns, which is approximately correct for bolts #1 and #2, but is about 20-40% slow for most of the other bolts.

An estimate of the travel speed was made for each of the bolts. From this estimate the dielectric constant of the wood can be calculated using the formula:

$$k = (0.3/s)^2 \quad [1]$$

where k is the average relative dielectric constant of the wood and s is the average one-way travel speed of the pulse in the wood in m/ns. The speed of light in air is 0.3 m/ns. The dielectric constant is one of electrical properties commonly used to describe materials, and it is often closely related to moisture content.

2.4 Radar Results

A complete set of radar profiles is given in Appendix 1. An example of bolt #1 is presented in Figure 2.4 (differences between radar runs can be seen by comparing Figure 2.4 with Figure A-1). The direct pulse travelling from the transmitter to the receiver gives the two-three dark bands at the top of the record. The reflection from the back side of the bolt is given by the three-four dark bands at about 5.5 ns. The lack of signal between these two echoes indicates there is little electrical structure within the bolt.

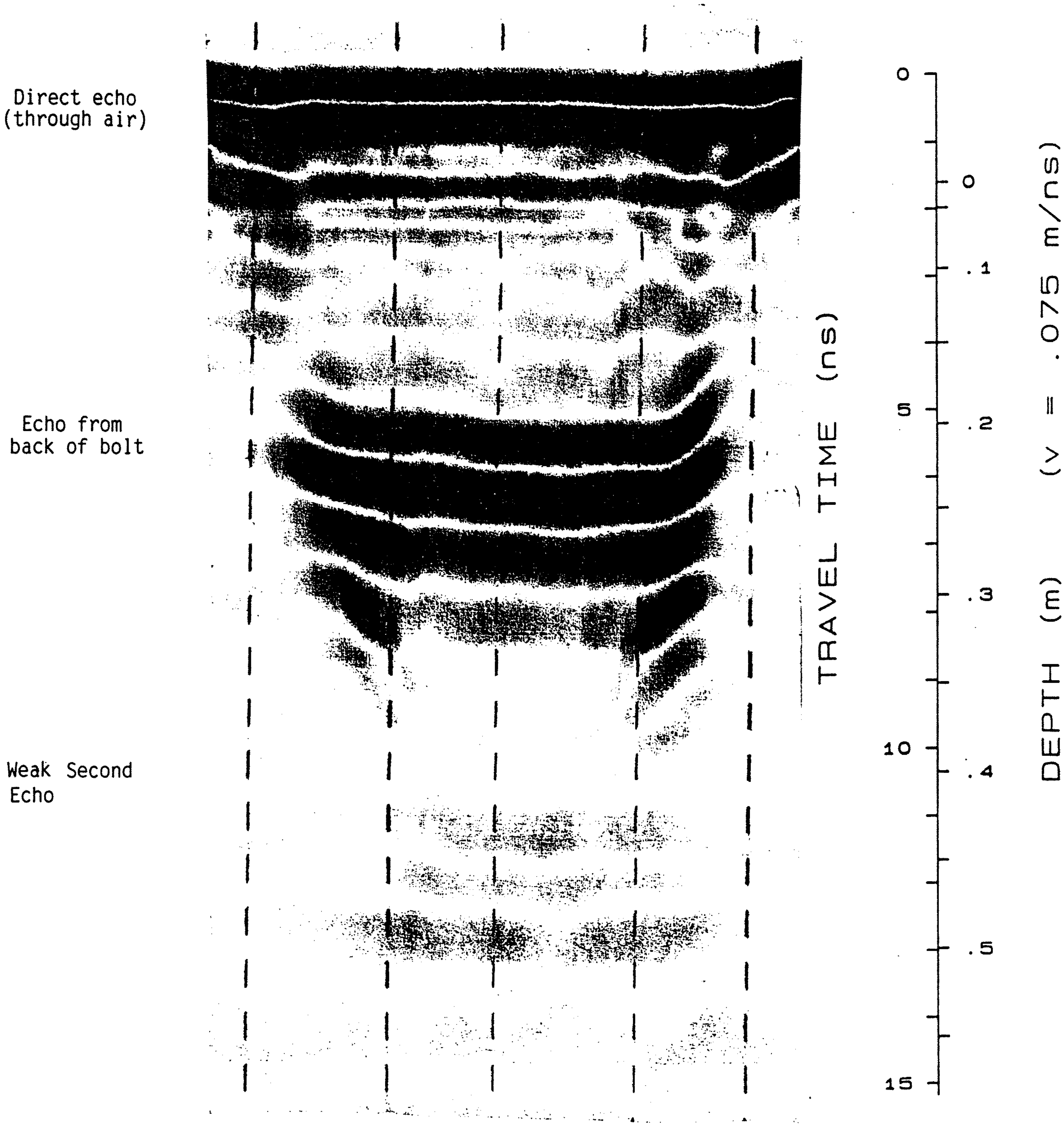
A second echo from the back of the bolt is seen at about 11 ns; i.e., an echo that travels to the far side of the bolt and back twice. This second echo is usually associated with little attenuation or reflection as the signal passes through the interior of the bolt, and hence is more likely to occur in sound samples.

Most of the bolts were are fairly uniform in diameter. However, bolt #12 varied in diameter from 10 to 12 cm. The increase in travel time is clearly seen in Figure A-12.

In some cases (e.g. Figure A-4) there is a second echo which arrives shortly after the direct signal. This is a signal which travels directly between the antennas, but in the wood. It takes longer to arrive than the direct pulse (in air), but less time than the reflected echoes, which of course travel much further in the wood. This signal is not always present because it depends on the exact nature of the coupling of the antennas to the wood, which can be easily altered by bark etc.

For many of the bolts the return echo "rings", giving more than the three dark bands (e.g. Figure A-6). This behaviour is indicative of the signal reverberating within the bolt, and usually occurs when there is a void within the wood, such as décay.

Figure 2.4 Impulse radar record from bolt #1



Many of the bolts studied here do not show direct and back echoes as clearly as those in Figure 2.4. In several of the records (e.g. Figures A-3, A-4, A-5) knots in the bolt appear as a distortion of the echoes. This is expected since the travel paths of the various signals are also distorted by the knot.

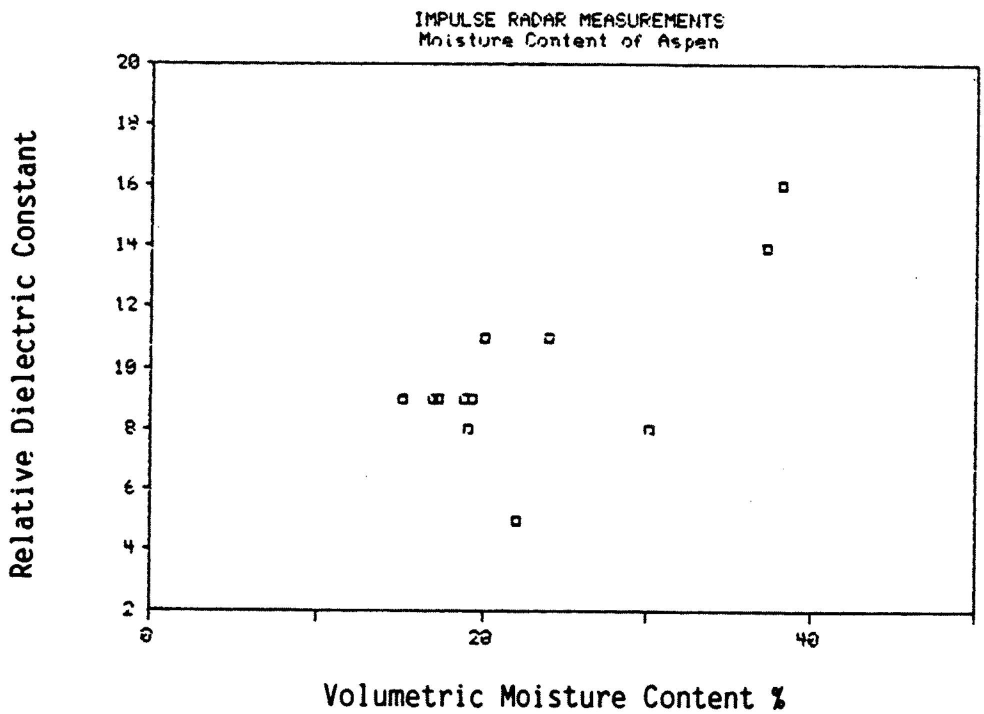
For many of these samples several of these phenomena occurred together. Distinguishing exactly which wave was which was difficult because of the small diameter of these bolts. For example, a reverberating echo (due to decay) could be similar to a second back echo (sound wood). A summary of the results, including comments on the radar returns is given in Table 2.2.

The travel speed of the signal through each bolt was calculated and the dielectric constant estimated using equation [1]. The average moisture content of each bolt was determined as described in Chapter 3. As shown in Figure 2.5, there was a strong correlation between dielectric constant and moisture. Although there was some scatter in the results, largely due to uncertainty in picking the correct echo from the back of the bolt, the radar is capable of resolving relatively small changes in average moisture. Unfortunately, the decay was not related to moisture content in these samples (for example, bolts 1 and 2).

Table 2.2 Summary of Radar Results

Bolt #	Average diameter (cm)	Dielectric constant	Comments
1.	20	16	Single back echo
2.	19	14	Single back echo Coupling
3.	20	9	Reverberation Knot; coupling
4.	19.5	5?	Single back echo Second back echo? Knot; coupling
5.	19	8	Single back echo Second back echo? Knot
6.	18	9	Strong reverberation Knot; coupling
7.	18	9	Reverberation Coupling
8.	16	9	Reverberation Coupling
9.	16	8	Reverberation Knot; coupling
10.	14	11	Reverberation? Second back echo? Coupling
11.	13	11	Reverberation Coupling
12.	10-12	9	Single back echo? Thickness variation apparent

Figure 2.5 Correlation between dielectric constant and moisture content.



3. Physical Assessments

3.1 General

After the impulse radar profiles were complete each of the twelve bolts were cut, inspected visually and destructively sampled for density and moisture content. All measurements were made within about a week of the trees being felled. As noted above, each bolt was numbered and identified with marks on the ends indicating an assumed butt or top. These ends were chosen arbitrarily and do not necessarily indicate the actual orientation of the bolt in the standing tree.

Each bolt was marked with three horizontal lines at 23 cm spacing corresponding to th the fiducial marks on the radar records and labelled A through C beginning near the end marked "butt". For each of the bolts, two 2.5 cm thick disks were cut at each reference line. One disk was used for visual observations of wood quality and the other for moisture content and density measurements. Bolts #4 and #5 were free of decay and stain, and so for these two bolts disks were cut only at the A location.

3.2 Visual Observations

The disks were used to obtain approximations of the percent sound wood, percent decay, and total area enclosed by the bark. Photographs were taken and are presented in Appendix 1. A summary of the visual survey is given in Table 3.1.

In most cases the decayed wood is well defined with front lines to indicate the delineation. The dark stained wood in bolt #1 was also well defined; however, the red or lighter colored stains in other specimens were quite difficult to delineate. For the purpose of this study only wood in advanced stages of decay was identified. Stained wood was noted but not measured.

3.3 Laboratory Tests

The disks designated for laboratory testing were wrapped in plastic at the time of cutting and delivered the following day to the University of Toronto. Each disk was cut to obtain four specimens: two for moisture content and two for density measurement. Of these pairs, one was taken from the pith area and one from the sapwood area.

Gravimetric moisture content was measured by the oven-drying method and density by the volume-by-immersion method. The results of these tests are given in Table 3.2. The variability in the results from sections of the same bolt was typically about $\pm 10\%$. The experimental errors are estimated to be less than $\pm 5\%$.

Table 3.1 Visual Observations

Bolt #		Area Gross	Area Decay	%	Comments
1	A	240	-	0	Black stained but sound heart occupies 50% of area within sound unstained perimeter.
	B	245	-	0	
	C	260	-	0	
2	A	260	50	20	Black and white rotted core enclosed by red-stained perimeter.
	B	285	55	20	
	C	295	60	20	
3	A	290	85	30	White rotted core surrounded by generally red-stained perimeter.
	B	335	80	25	
	C	315	85	25	
4	-	250	-	0	Sound specimen.
5	-	260	-	0	Sound specimen.
6	A	205	80	40	White heart rot with generally unstained wood around.
	B	250	125	50	
	C	225	70	30	
7	A	220	60	25	Similar to No.6 - white heart rot enclosed by sound wood.
	B	220	65	30	
	C	245	90	35	
8	A	180	50	25	White heart rot enclosed by sound wood.
	B	200	65	30	
	C	185	50	25	
9	A	165	40	20	White heart rot in poorly defined area with red-stained wood around.
	B	165	35	20	
	C	165	25	15	
10	-	140	-	0	Sound specimen (very light stain).
11	A	105	25	25	White rot, well defined within sound perimeter.
	B	95	30	30	
	C	90	30	35	
12	A	90	35	40	White rot, well defined within sound perimeter.
	B	70	25	35	
	C	65	15	25	

Note: Gross and decayed areas are given in square centimetres.

Table 3.2 Laboratory Tests

Bolt #		Volume cc	M.C. %	S.G.	Volumetric % Water
1	P	122	110	0.40	
	S	122	80	0.40	38
2	P	58	300	0.25	
	S	219	75	0.36	37
3	P	85	90	0.26	
	S	230	50	0.34	19
4	P	125	72	0.37	
	S	125	62	0.33	22
5	P	130	73	0.35	
	S	130	40	0.33	19
6	P	90	48	0.19	
	S	135	45	0.42	15
7	P	65	49	0.17	
	S	160	56	0.37	17
8	P	50	59	0.10	
	S	135	65	0.38	19
9	P	30	83	0.33	
	S	135	92	0.33	30
10	P	70	73	0.35	
	S	70	63	0.35	24
11	P	30	57	0.15	
	S	65	71	0.36	20
12	P	25	115	0.10	
	S	50	60	0.34	17

P - pith S - sapwood M.C. - gravimetric moisture content
S.G. - specific gravity

3.4 Volumetric Moisture Content

Since the radar is sensitive to volumetric (as opposed to gravimetric) moisture content, this parameter was calculated from the measurements described above using the following method:

a. For a 1 cm slice of bolt, calculate volume of decayed and volume of surrounding sapwood. For sound specimens, assume 50% pith and 50% sapwood.

b. Determine oven-dry mass of each: density x volume.

c. Determine mass of water in each: oven-dry mass (step b) x gravimetric moisture content.

d. Calculate equivalent water volume as percent of total wood volume.

The results of these calculations are also given in Table 3.2.

4. Discussion, Conclusions and Recommendations

4.1 Discussion

At least four parameters can be determined in principle from the radar echoes:

1. signal structure (e.g. reverberation)
2. signal speed
3. signal attenuation
4. polarization effects.

In this study, signal structure and speed were determined. As shown in Chapter 2, they were related to decay and moisture content respectively. Signal attenuation can be measured using post-processing techniques but was beyond the scope of this study. Similarly, only single polarization antennas were available.

The results from Chapters 2 and 3 were compared in order to evaluate the radar measurements and are summarized in Table 4.1. There was a correlation between the clarity of the back echo and the soundness of the bolt. In other words, as the amount of decay increased, the reverberation in the echo increased because of multiple echoing within the log.

In a few of the samples the results were not entirely unambiguous. For example, the back echoes for sound bolts 4 and 10 are not completely clean, and the echoes for decayed bolts 2 and 12 do not have a lot of reverberation. These discrepancies are accounted for by the small diameter of the bolts provided. Therefore, the various echoes arrive very closely together in time, and cannot separated with the pulse length used. If the diameter of the bolts were greater or the pulse length shorter (i.e. higher centre frequency), it is likely that echoes from the decayed region could be resolved separately.

This problem was further compounded by the presence of a direct echo through the wood for some samples. This echo is likely a function of the exact nature of antenna coupling (position, thickness of bark, etc.), and could probably be reduced by antennas that were designed to couple uniformly into the bolts.

Signal attenuation would likely provide corroboration of the effects detected using the signal structure. The attenuation through sound and decayed wood could be quite different, and therefore measurable by estimating the received signal strength of the various echoes.

Use of the other polarization (i.e. with the electric field parallel to the grain of the wood) would probably provide significant information on decay. Since sound wood is likely more anisotropic than decayed wood, comparison of the two polarizations could be highly diagnostic of decay.

Table 4.1 Summary of Echo Characteristics

Approximate decay	Bolt #	Echo character
Sound	1, (4), 5, (10)	Single back echo Second back echo?
15 - 30%	(2), 3, 7, 8, 9, 11	Reverberation
> 30%	6, (12)	Strong reverberation

Bolt numbers in parentheses gave ambiguous results.

4.2 Conclusions

The results indicate that impulse radar is able to give an estimate of moisture content and degree of decay of wood. The measurements can be made quickly and non-destructively. Although several portable impulse radars are commercially available, systems specifically suited to measurement of trees do not appear to be available.

Better information is required on the specific electrical properties of wood relevant to the radar measurements. Antennas designed to work more effectively on trees should operate at higher frequency, should address the coupling problem, and should be able to operate in both polarizations.

4.3 Recommendations

These results indicate that the technique is promising and warrants further investigation, particularly since relatively inexpensive, portable equipment could be produced. Based on experience with other equipment development projects, the following three recommendations are made.

1. A study to determine the relevant electrical properties of sound and decayed wood should be undertaken to guide further equipment development.

2. If the results of the first study indicate that the current type of impulse radar systems could be cost-effective for this problem, then much more satisfactory results could be obtained using antennas specifically designed for this application.

Antennas that operate at about 2 GHz centre frequency will have a pulse length about one-third as long as that used here, and commensurately better resolution. The attenuation of the radar signal at this frequency will also likely be greater, so that differences in attenuation for different types of wood will likely be more pronounced. This parameter could then be used more easily.

Antennas that can measure signals in both polarizations are strongly suggested by the nature of decayed wood. Antennas should also be designed to couple more uniformly to a variety of log diameters. It is possible that a bistatic antenna arrangement would be more useful, allowing use of tomographic signal processing techniques to resolve areas of decay within a tree.

3. Once a system configuration has been chosen and assembled, testing in the laboratory prior to field evaluation would likely be appropriate. In this way the system can be evaluated at minimum cost and improvements made easily. Of course the final evaluation will need to be made in the field, with adequate comparative measurements using standard techniques.

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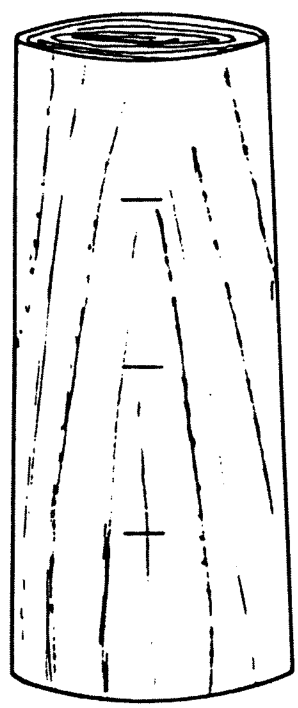
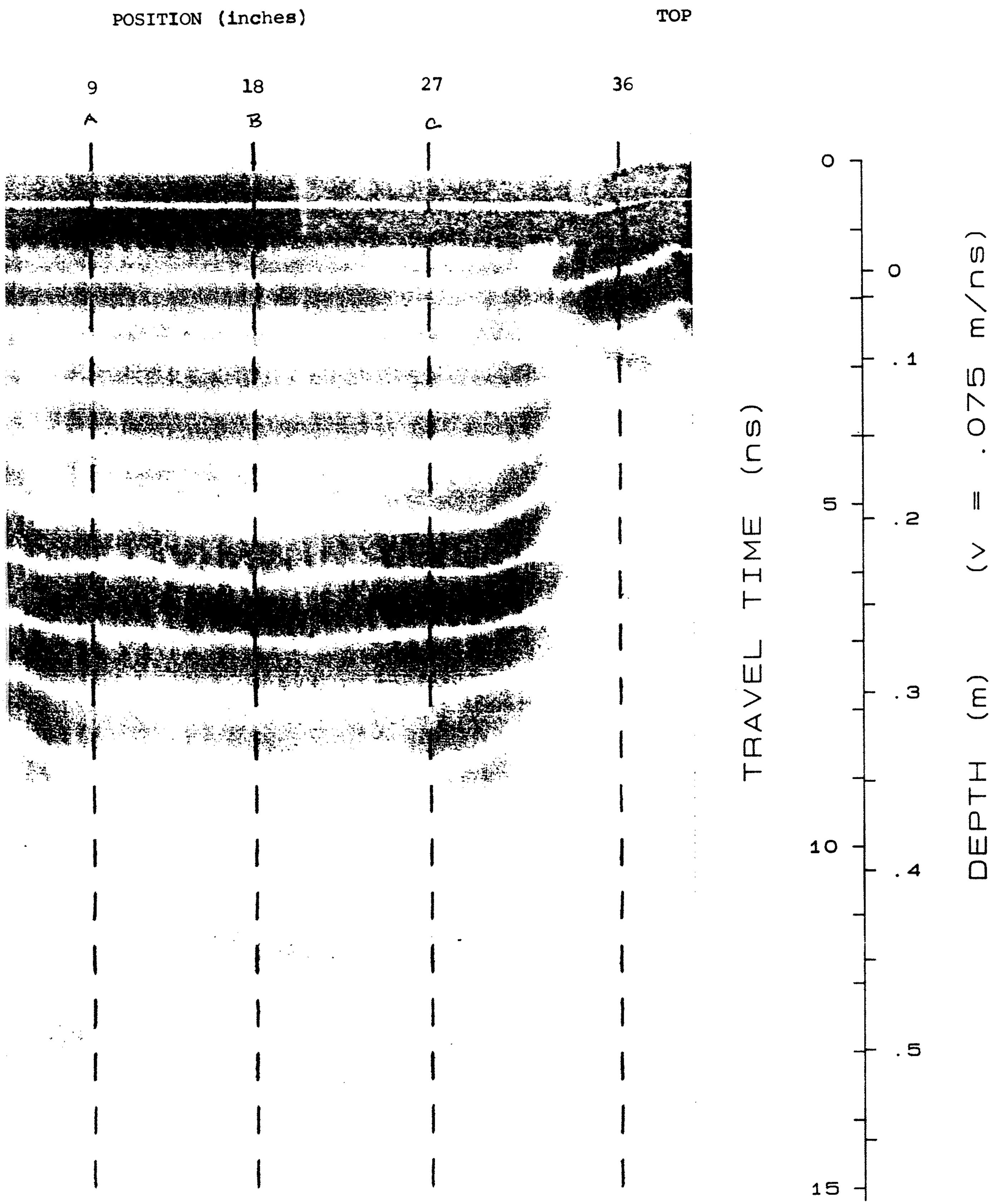
Appendix A. Radar and Photo Data Sets

A³ A-CUBED INC.

pulseEKKO I DATA LOG #1	
JOB 4068	FIGURE A - 1





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18
27
36
A
B
C
TRAVEL TIME (ns)
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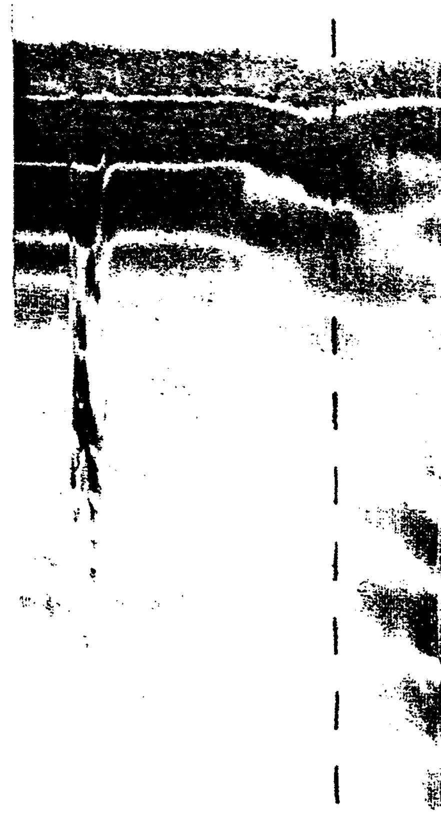
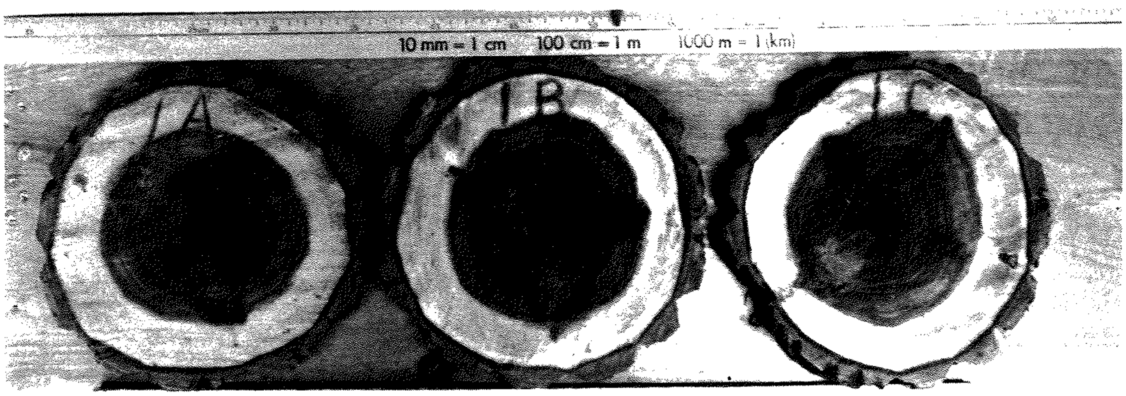
5
10
15
DEPTH (m) (v = .075 m/ns)
0
.1
.2
.3
.4
.5

BUTT

0



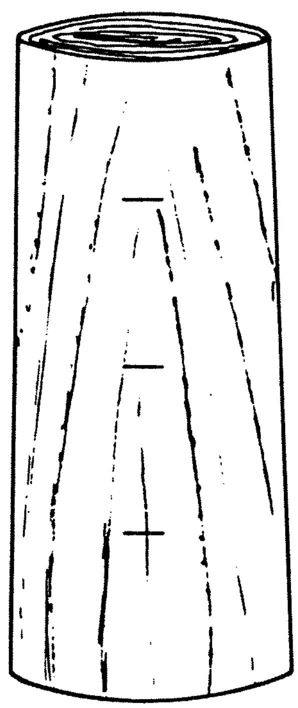


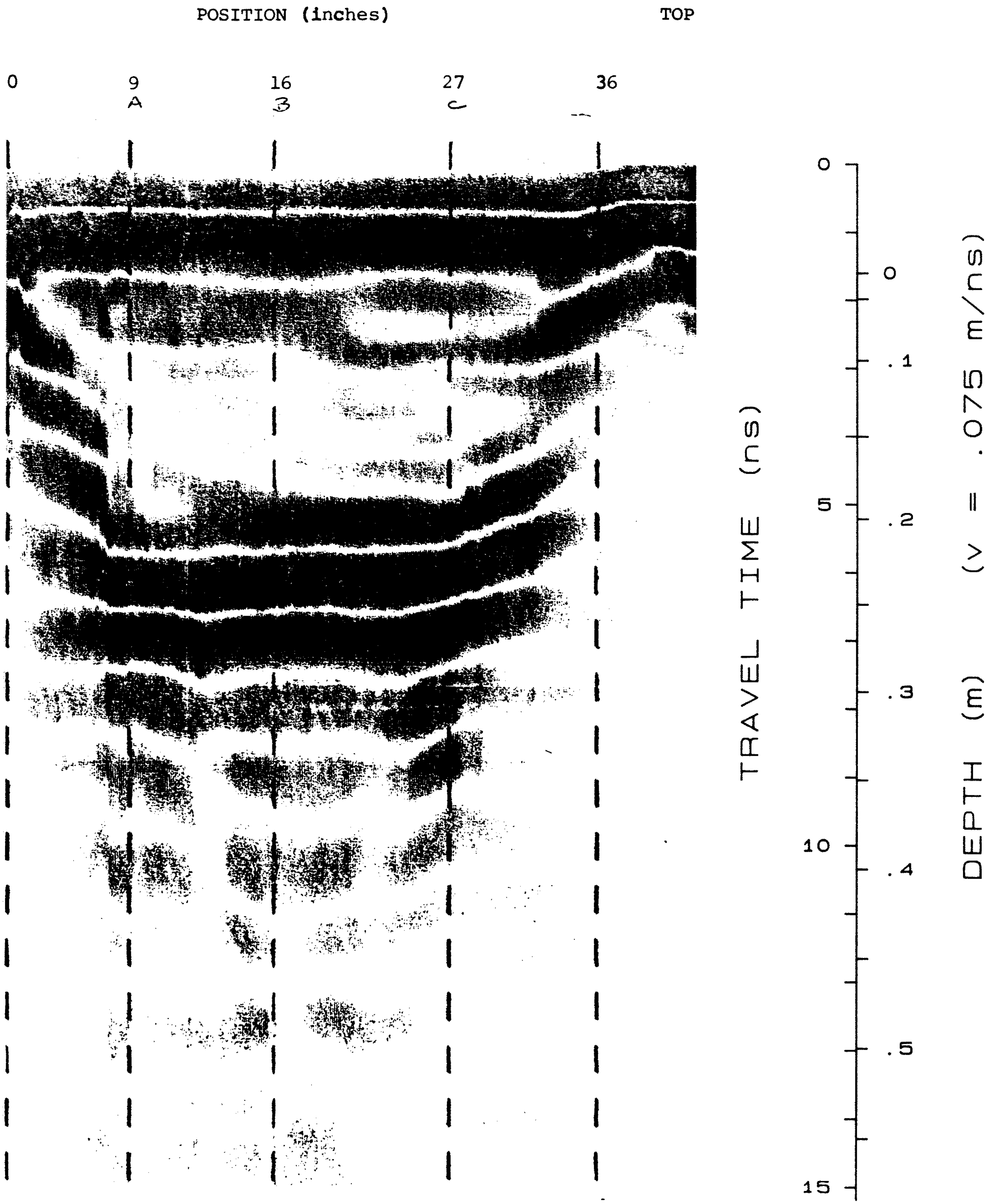
A-CUBED INC.

pulseEKKO I DATA

LOG #2

JOB	FIGURE
4068	A - 2

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A
16
27
c
36
TRAVEL TIME (ns)
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5
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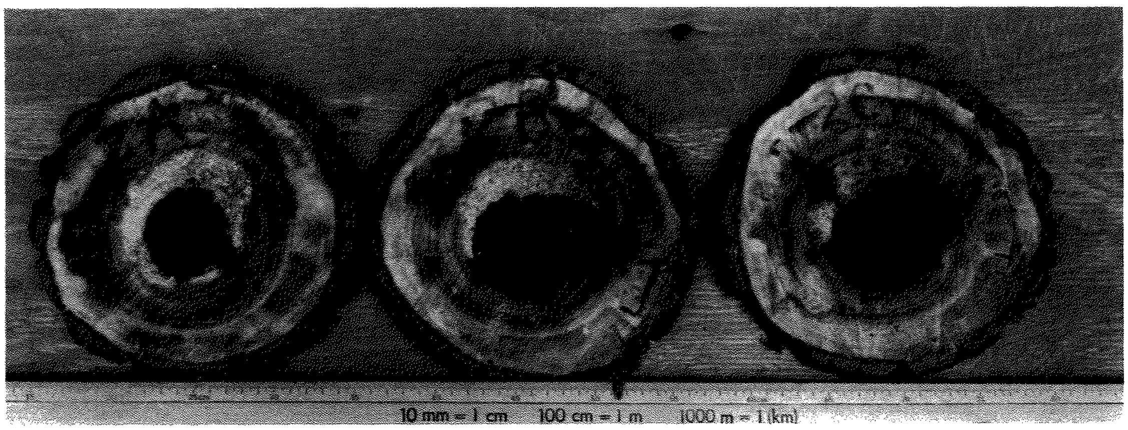
15
DEPTH (m)
(v = .075 m/ns)
0
.1
.2
.3
.4
.5

BUTT

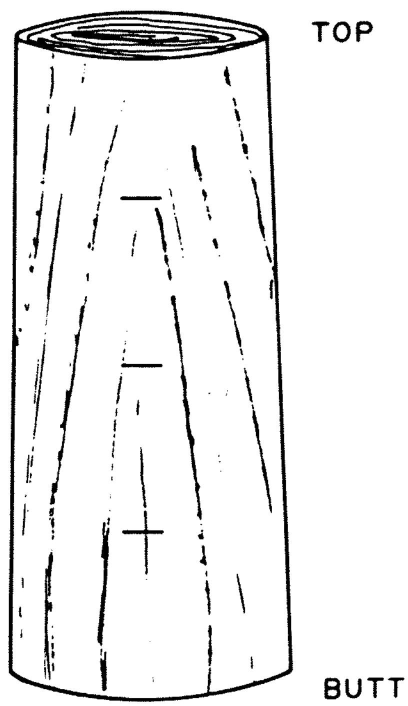


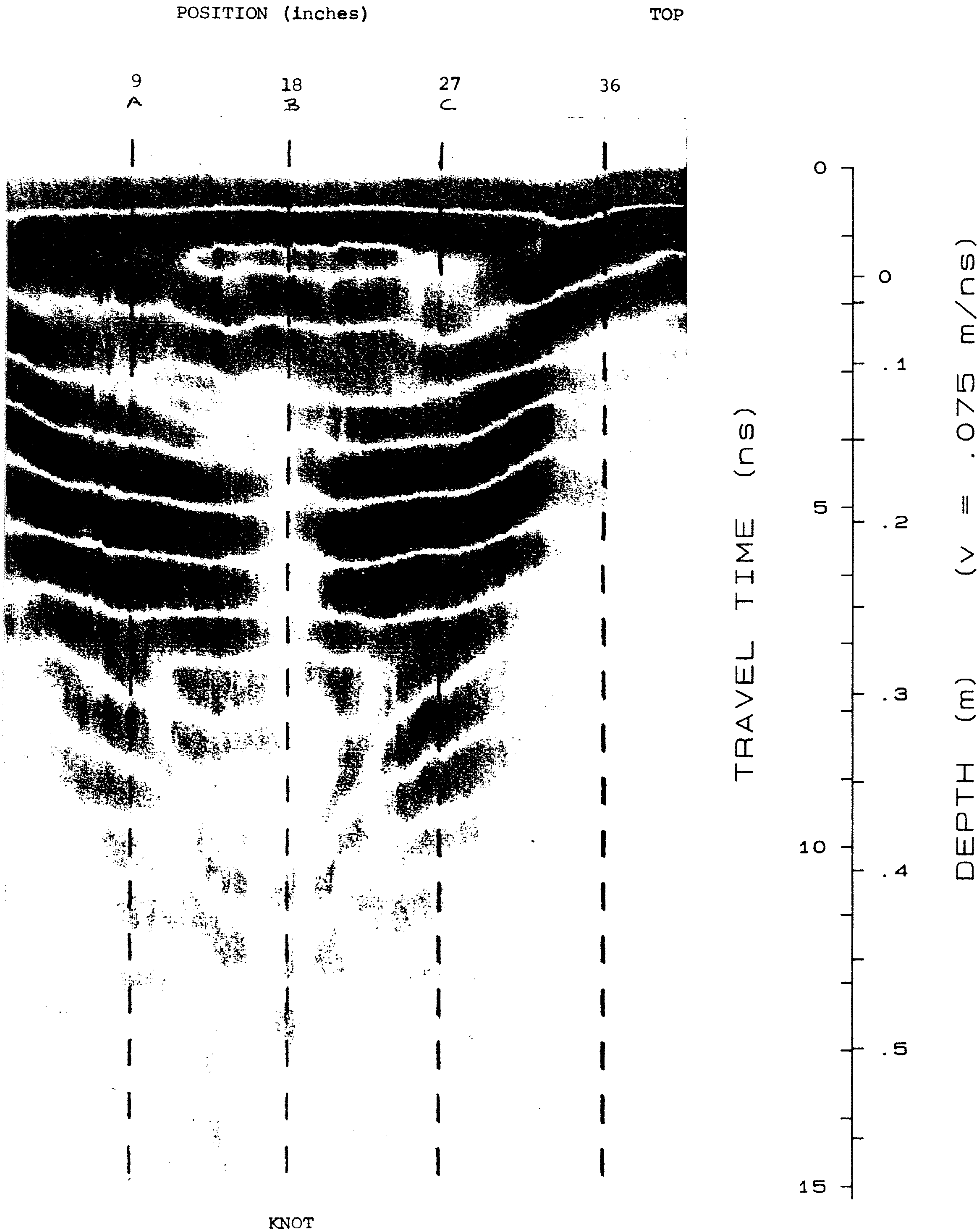
A³ A-CUBED INC.

pulseEKKO I DATA

LOG #3

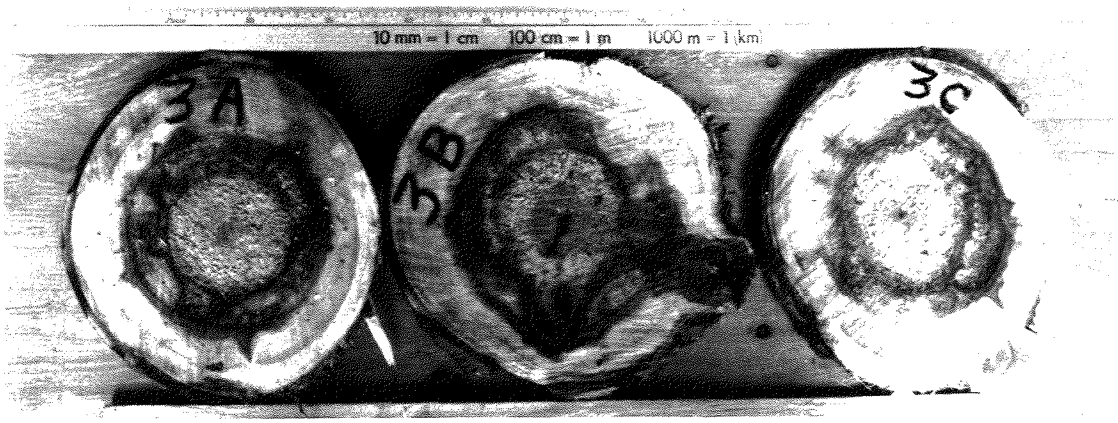
JOB	FIGURE
4068	A - 3




POSITION (inches)
TOP
9
A
18
B
27
C
36
0
5
10
15
TRAVEL TIME (ns)
0
.1
.2
.3
.4
.5
DEPTH (m) (V = .075 m/ns)
KNOT

BUTT

0

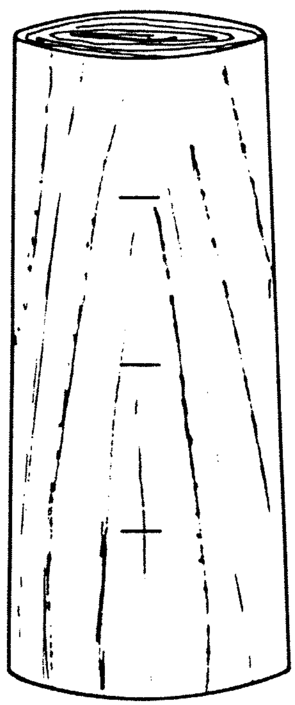


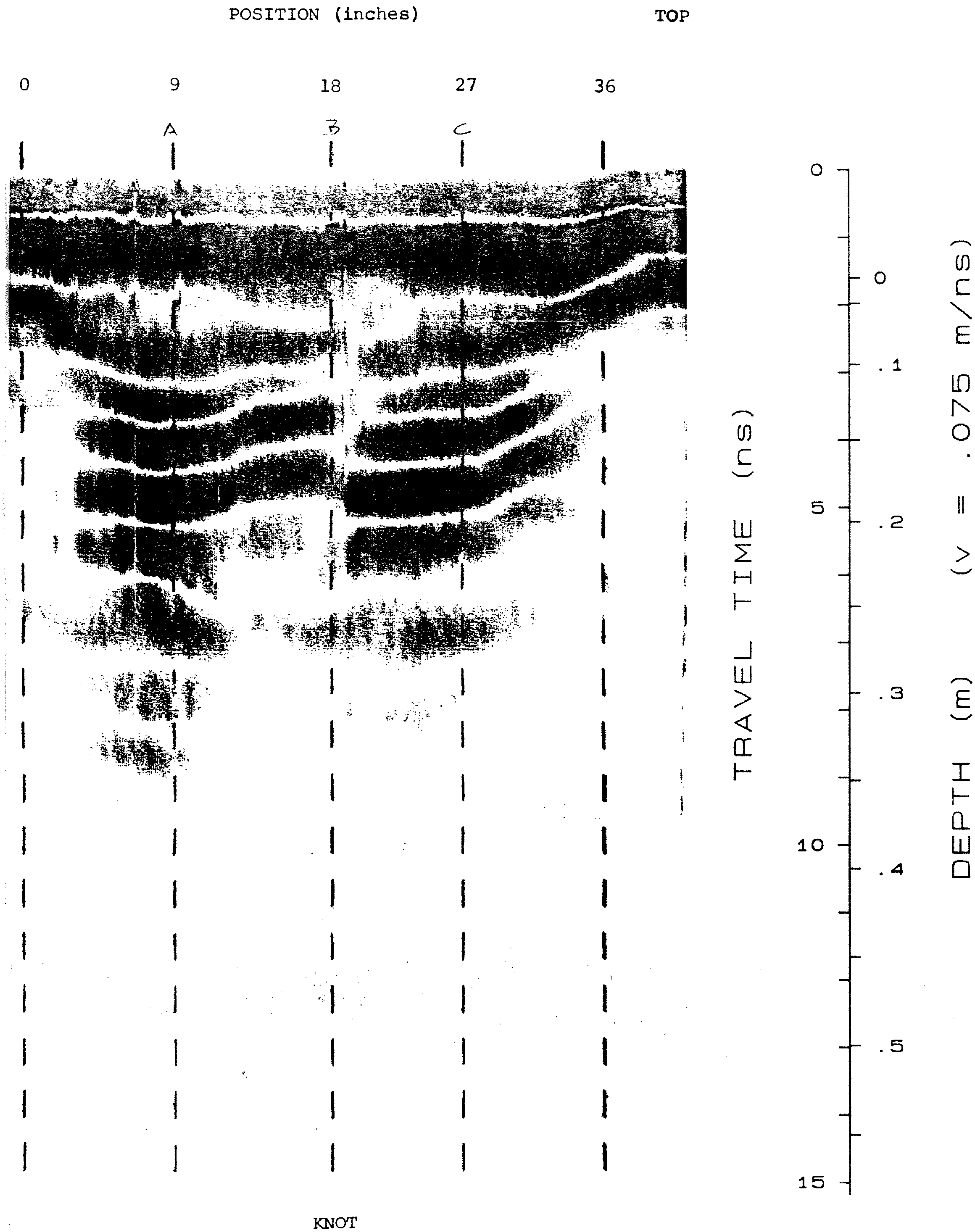
A-CUBED INC.

pulseEKKO I DATA

LOG #4

JOB	FIGURE
4068	A - 4





POSITION (inches)
TOP
0
9
18
27
36
A
B
C
TRAVEL TIME (ns)
0
5
10
15
DEPTH (m) (v = .075 m/ns)
0
.1
.2
.3
.4
.5
KNOT

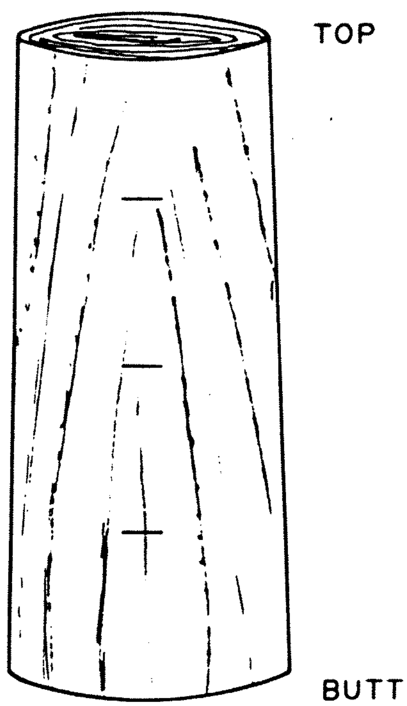
BUTT

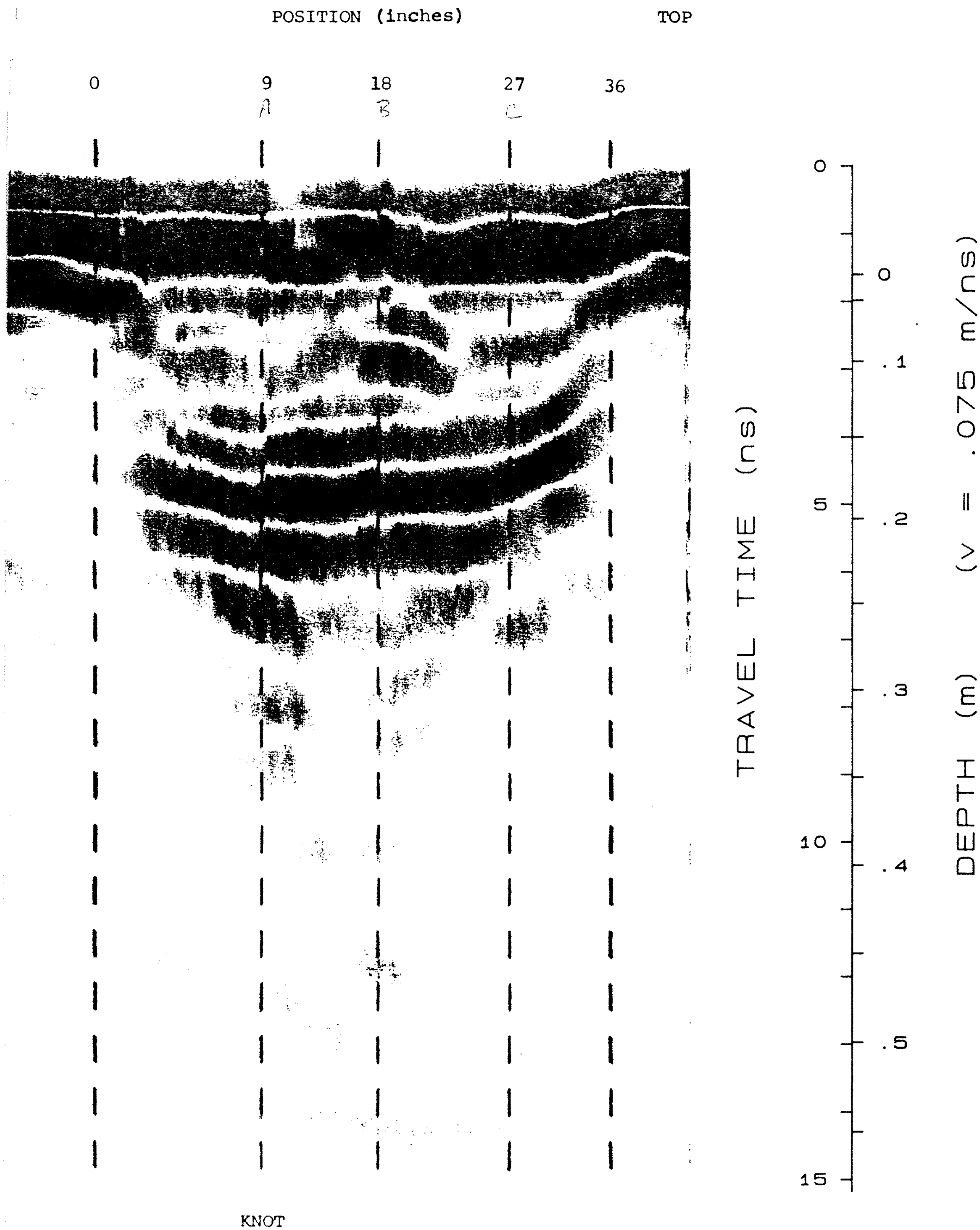
A-CUBED INC.

pulseEKKO I DATA

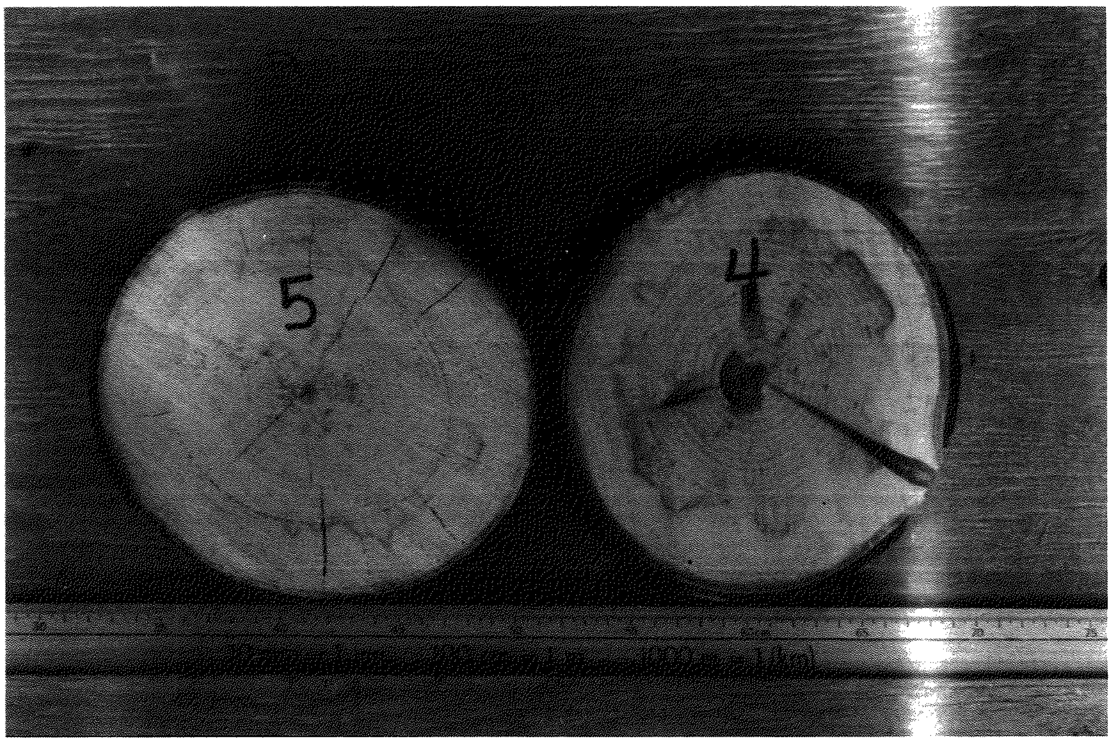
LOG #5

JOB	FIGURE
4068	A - 5




POSITION (inches)
TOP
0
9
18
27
36
A
B
C
TRAVEL TIME (ns)
0
5
10
15
DEPTH (m)
(v = .075 m/ns)
0
.1
.2
.3
.4
.5
KNOT

BUT

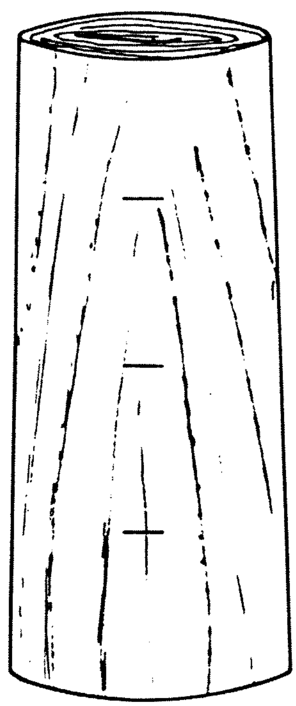


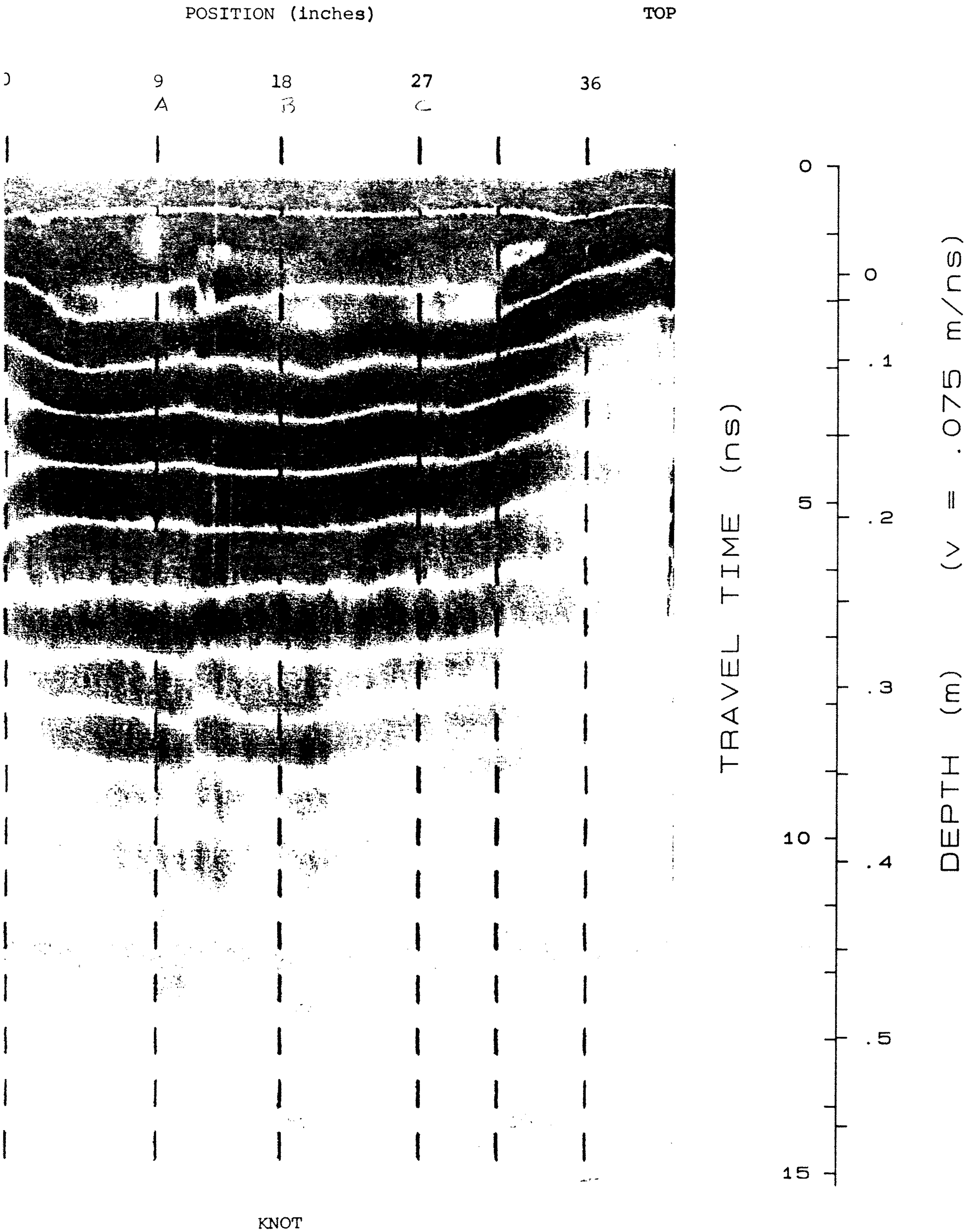
A-CUBED INC.

pulseEKKO I DATA

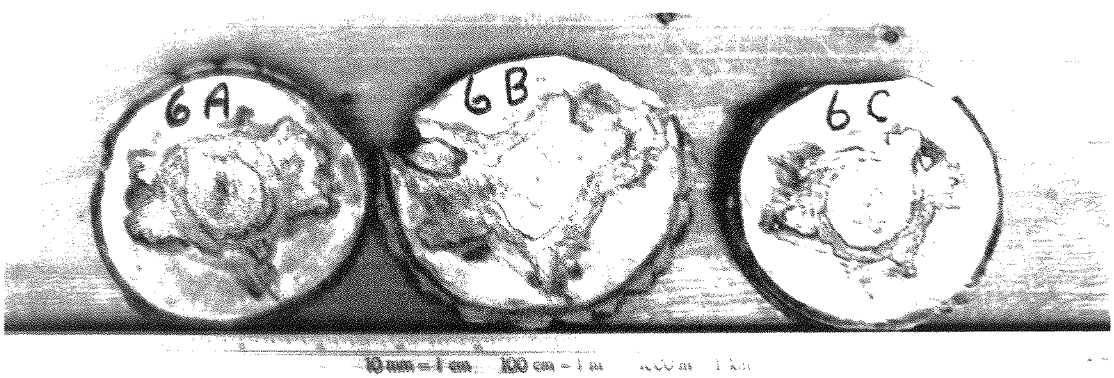
LOG #6

JOB	FIGURE
4068	A - 6




POSITION (inches)
TOP
0
9
A
18
B
27
C
36
KNOT
TRAVEL TIME (ns)
0
5
10
15
DEPTH (m) (v = .075 m/ns)
0
.1
.2
.3
.4
.5

BUTT

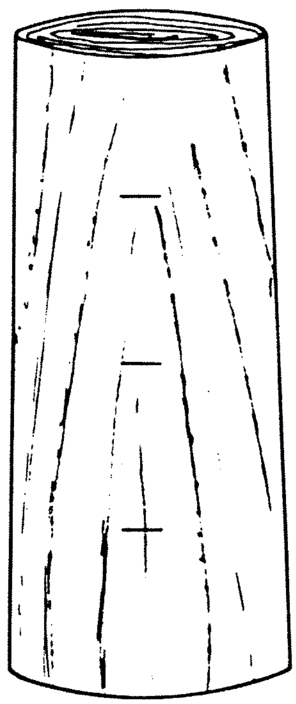


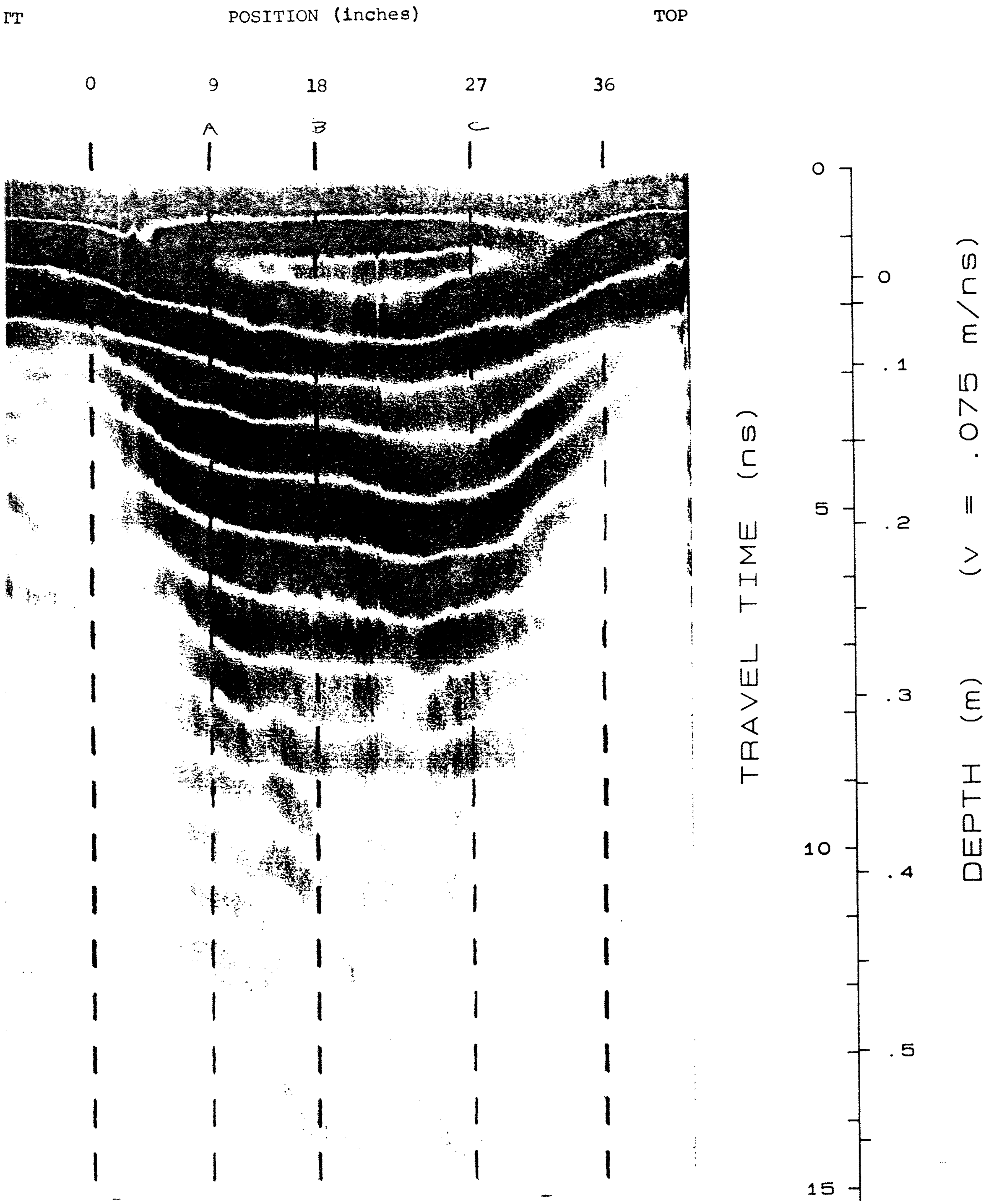
A-CUBED INC.

pulseEKKO I DATA

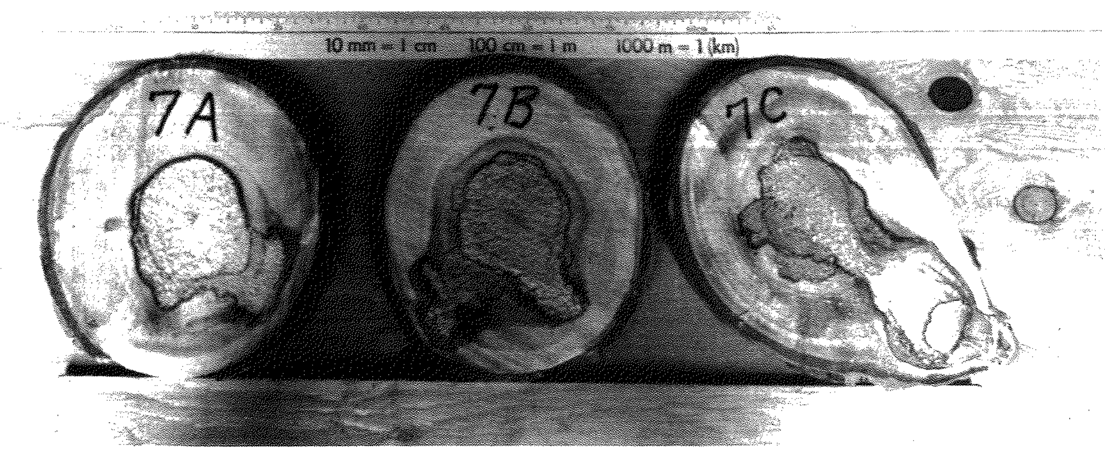
LOG #7

JOB	FIGURE
4068	A - 7





IT
POSITION (inches)
TOP
0
9
18
27
36
A
B
C
0
5
10
15
TRAVEL TIME (ns)
0
.1
.2
.3
.4
.5
DEPTH (m) (V = .075 m/ns)

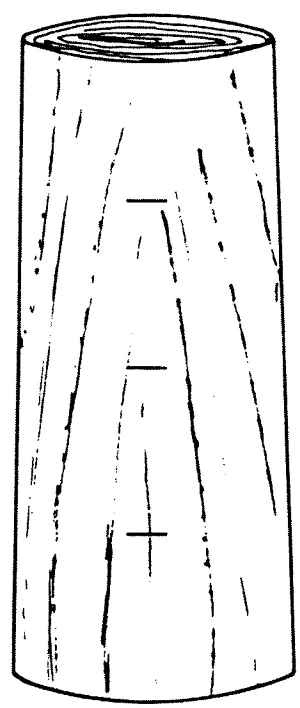

10 mm = 1 cm
100 cm = 1 m
1000 m = 1 (km)
7A
7B
7C

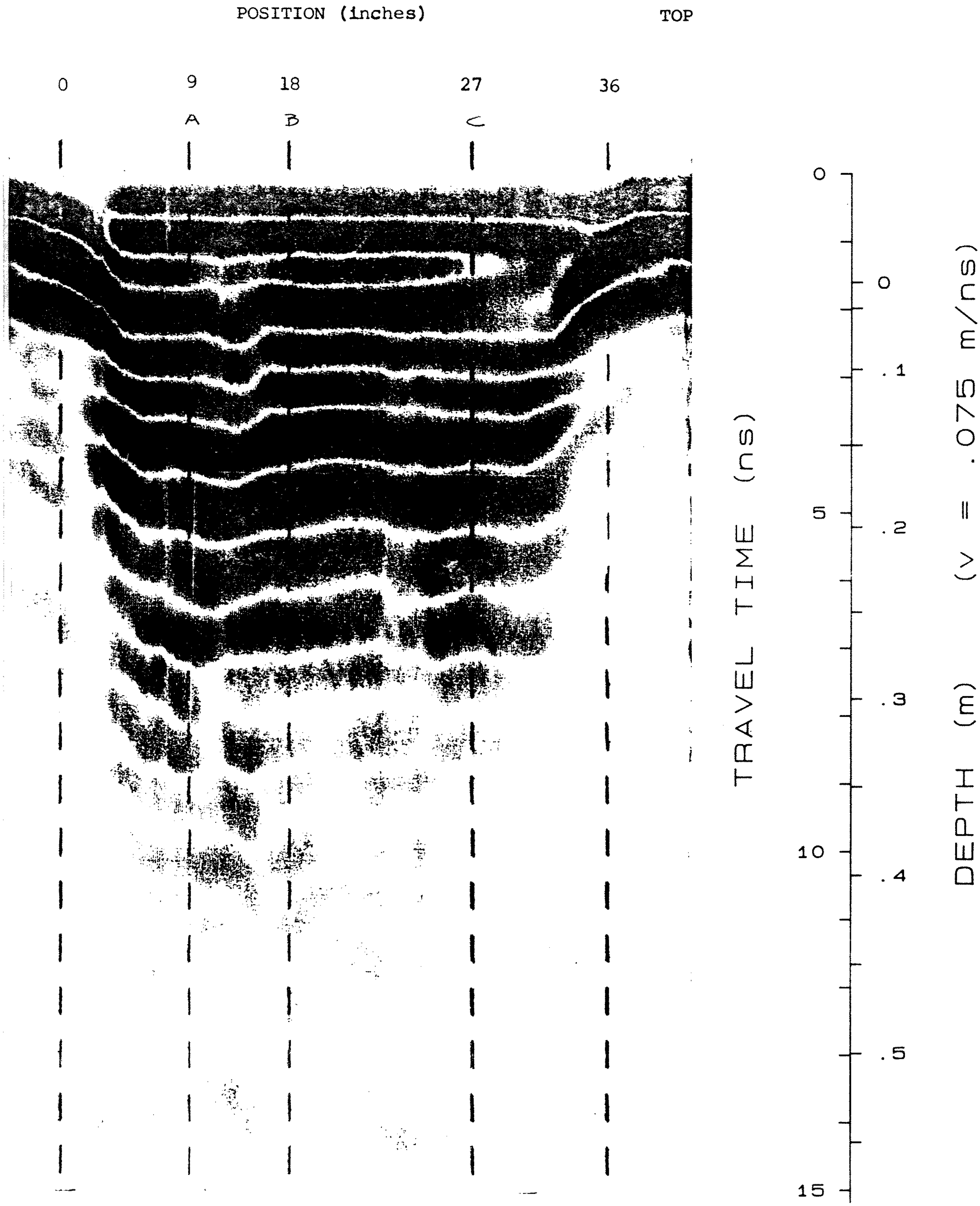
A-CUBED INC.

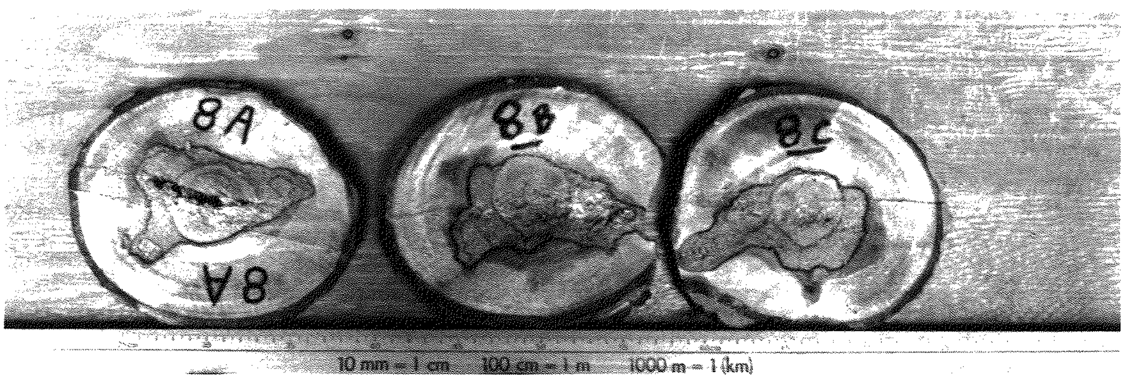
pulseEKKO I DATA

LOG #8

JOB	FIGURE
4068	A - 8




POSITION (inches)
TOP
0
9
18
27
36
A
B
C
TRAVEL TIME (ns)
0
5
10
15
DEPTH (m)
(v = .075 m/ns)
0
.1
.2
.3
.4
.5

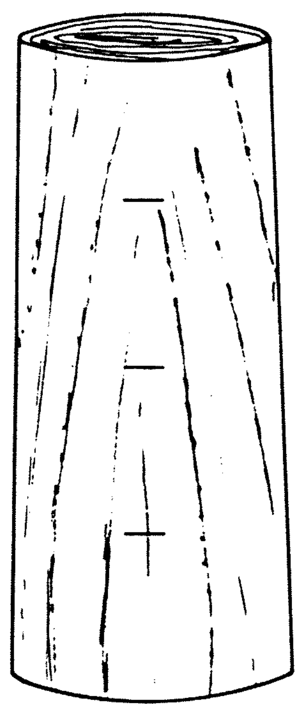

8A
8A
8B
8C
10 mm = 1 cm 100 cm = 1 m 1000 m = 1 (km)

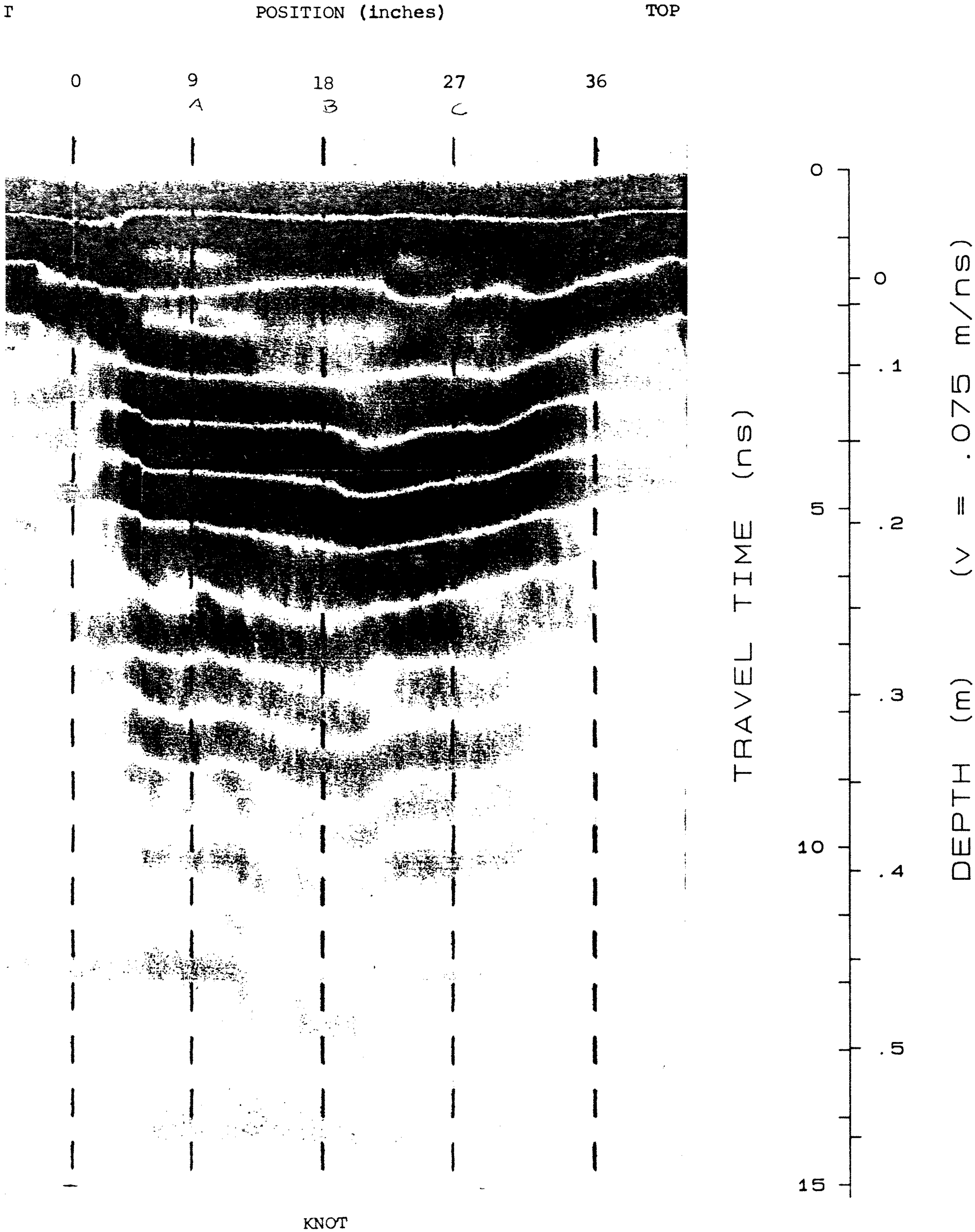
A³ A-CUBED INC.

pulseEKKO I DATA

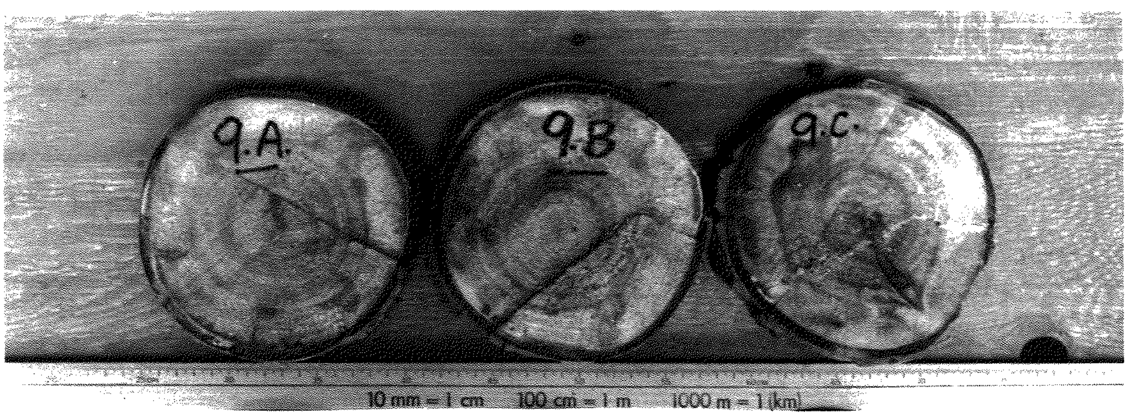
LOG #9

JOB	FIGURE
4068	A - 9




T
POSITION (inches)
TOP
0
9
18
27
36
A
B
C
KNOT
TRAVEL TIME (ns)
0
5
10
15
DEPTH (m) (v = .075 m/ns)
0
.1
.2
.3
.4
.5

BUT

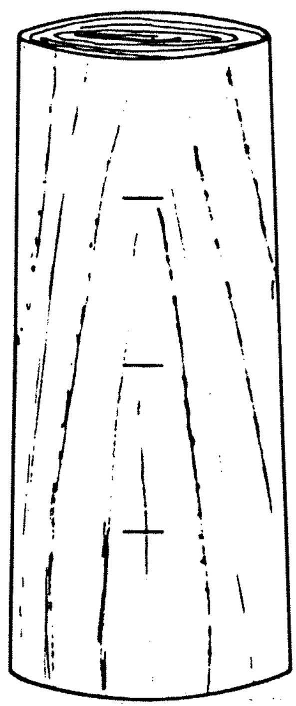


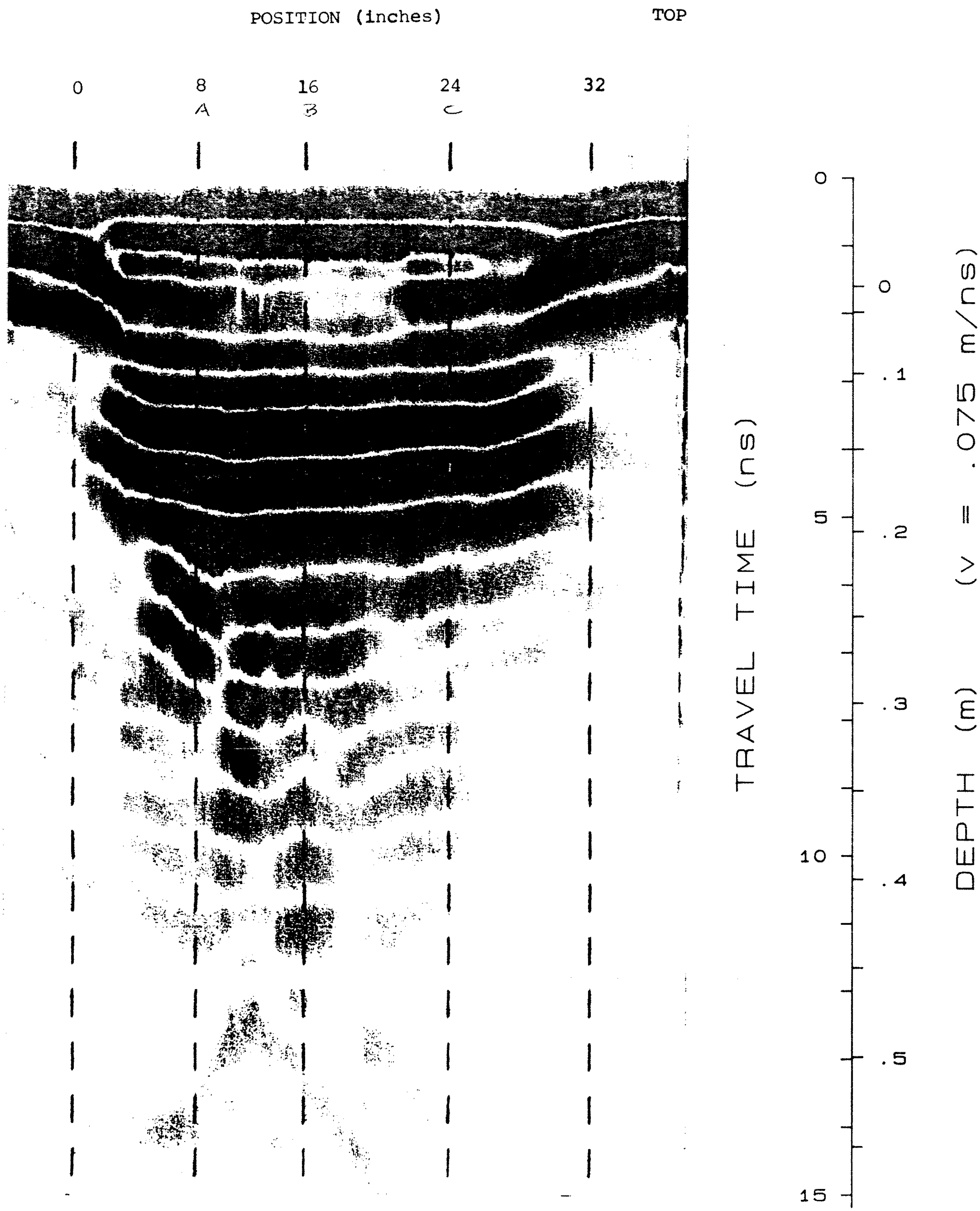
A-CUBED INC.

pulseEKKO I DATA

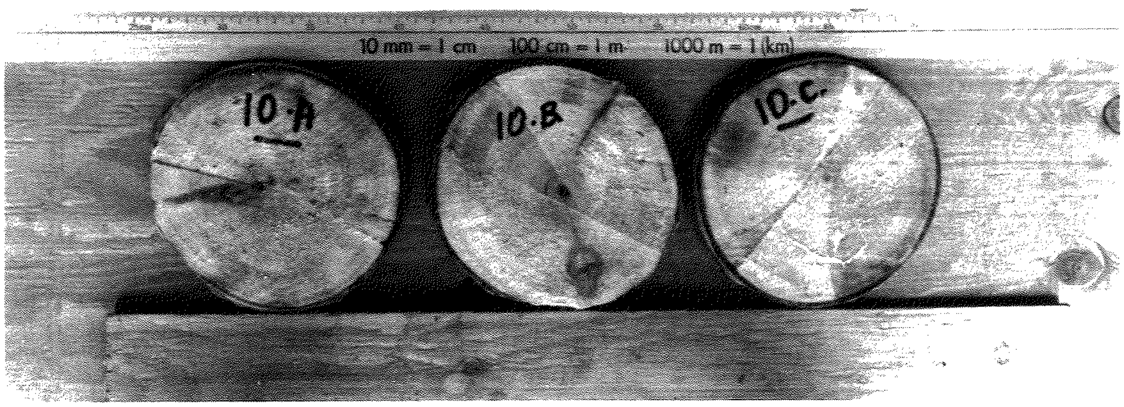
LOG #10

JOB	FIGURE
4068	A - 10





POSITION (inches)
TOP
0
8
A
16
B
24
C
32
TRAVEL TIME (ns)
0
5
10
15
DEPTH (m)
(v = .075 m/ns)
0
.1
.2
.3
.4
.5

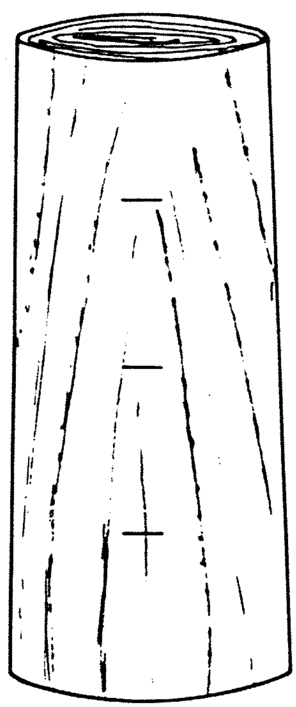

10 mm = 1 cm
100 cm = 1 m
1000 m = 1 (km)
10.A
10.B
10.C.

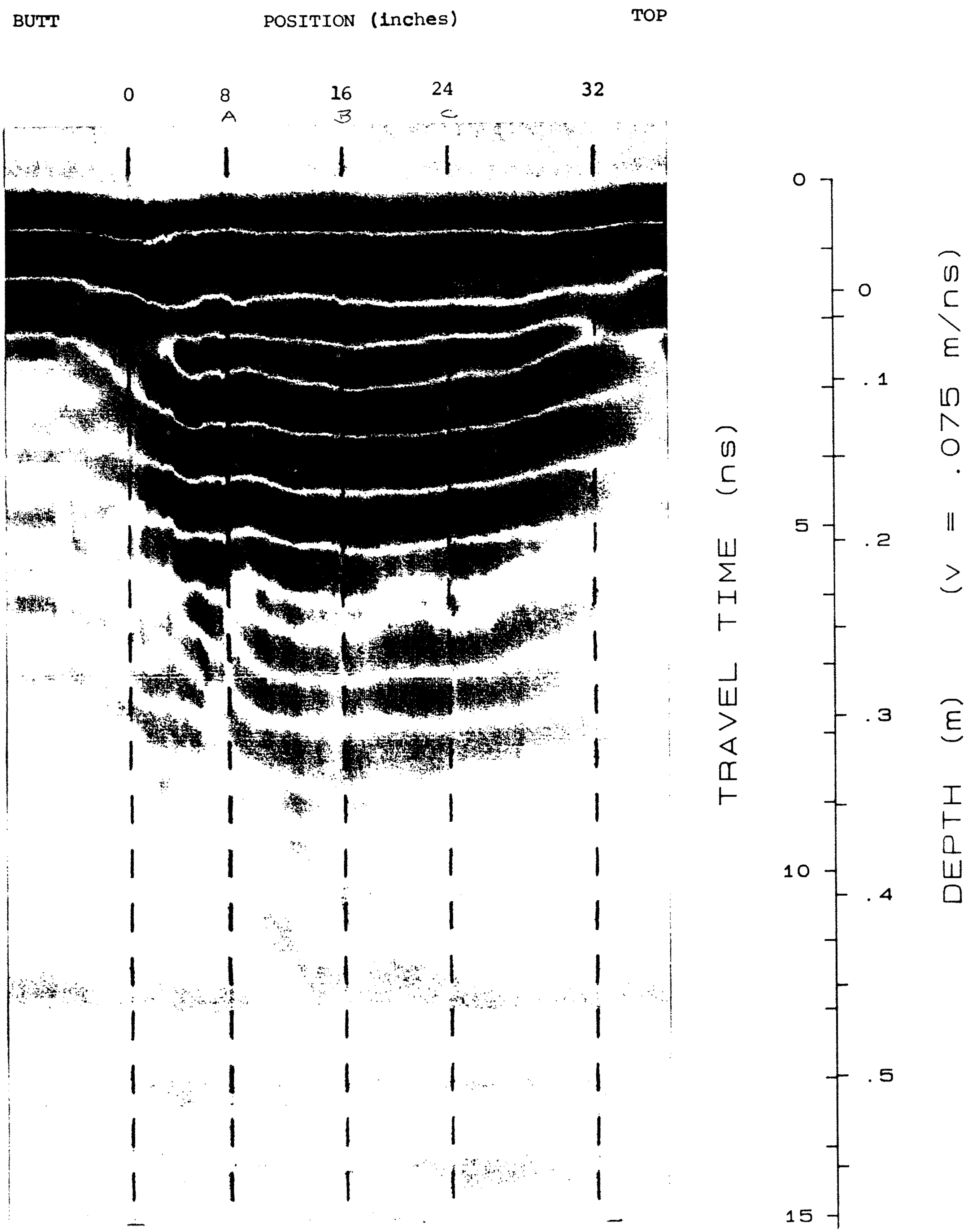
A³ A-CUBED INC.

pulseEKKO I DATA

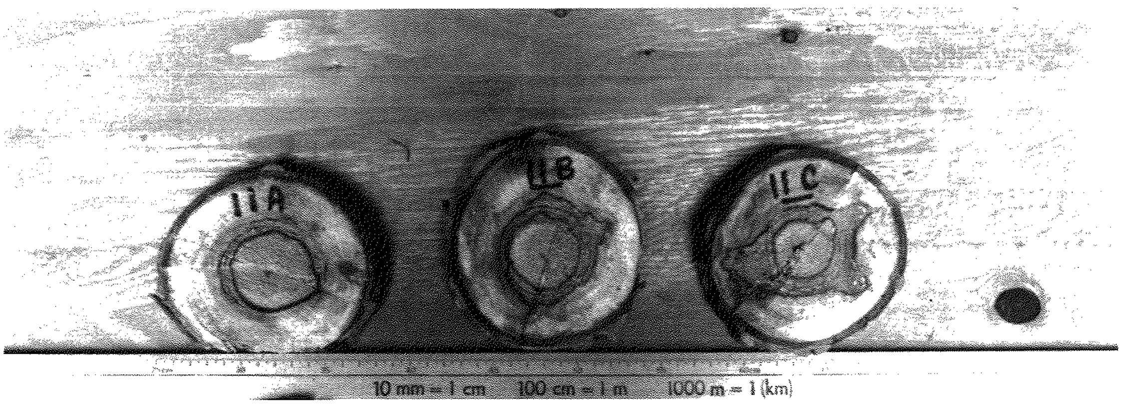
LOG #11

JOB	FIGURE
4068	A - 11





BUTT
POSITION (inches)
TOP
0
8
16
24
32
A
B
C
TRAVEL TIME (ns)
0
5
10
15
DEPTH (m) (v = .075 m/ns)
0
.1
.2
.3
.4
.5

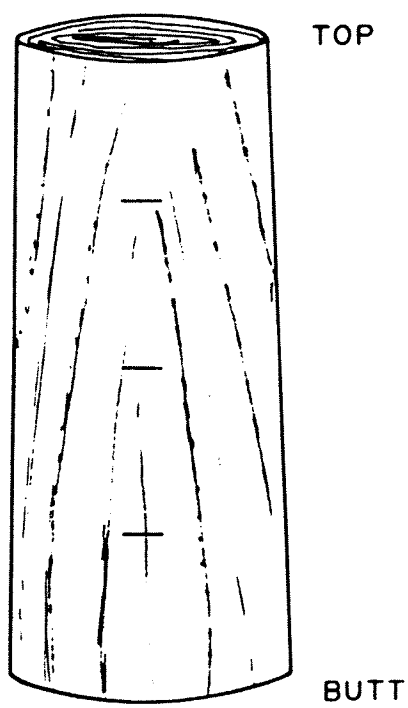

11A
11B
11C
10 mm = 1 cm 100 cm = 1 m 1000 m = 1 (km)

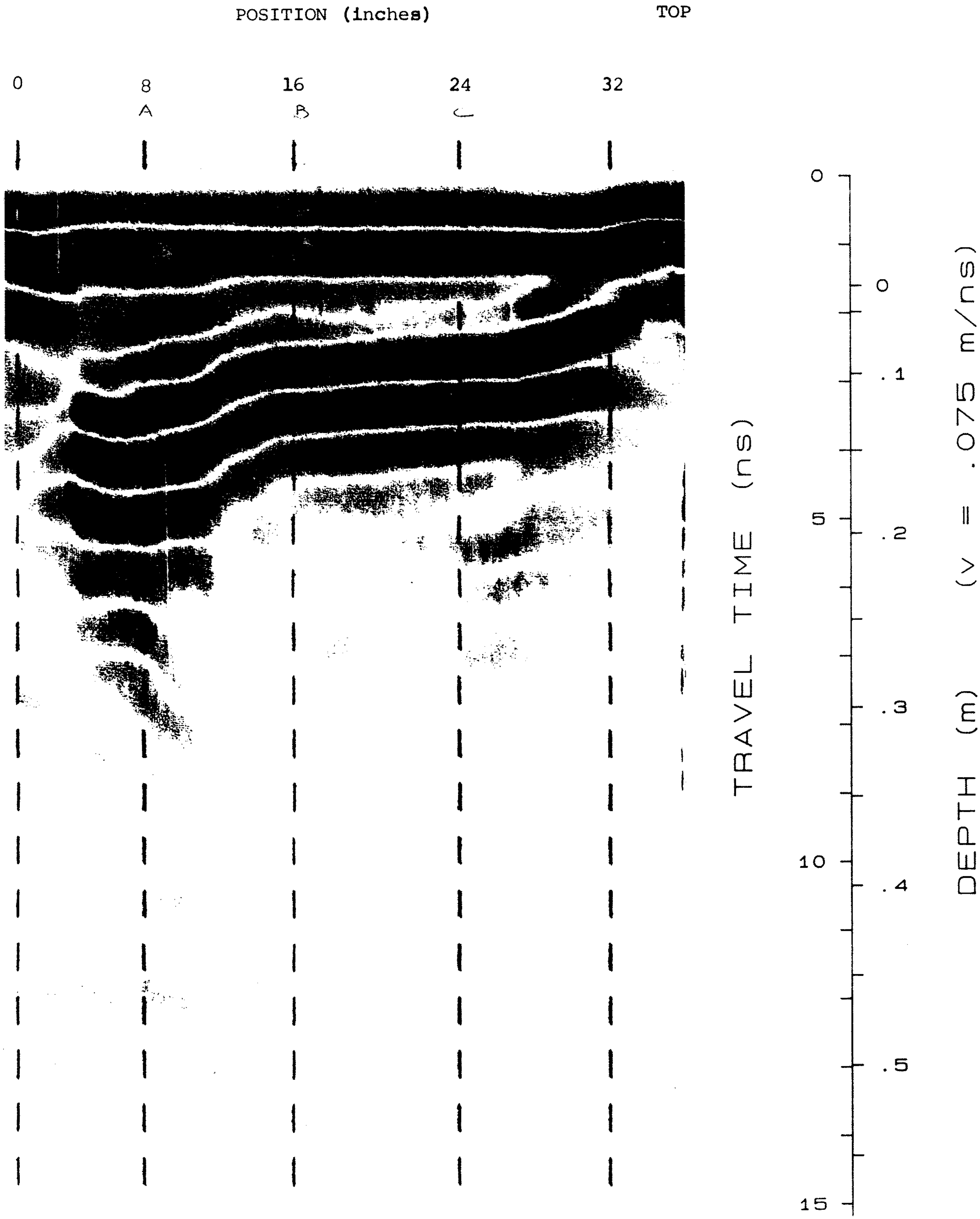
A-CUBED INC.

pulseEKKO I DATA

LOG #12

JOB	FIGURE
4068	A - 12





POSITION (inches)
TOP
0
8
16
24
32
A
B
C
TRAVEL TIME (ns)
0
5
10
15
DEPTH (m) (v = .075 m/ns)
0
.1
.2
.3
.4
.5

BUTT