A PROPOSED SEISMIC REFRACTION EXPERIMENT

TO EXPLORE FOR GEOTHERMAL ENERGY AT MT. PRINCETON

HOT SPRINGS, COLORADO

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INTRODUCTION

Refraction, both in-line shooting and fan-shooting, can be used to explore for geothermal energy. The purpose of this paper is to outline the geometries and rock properties which can be measured by application of refraction seismic methods. Geothermal models were selected for analysis, but it should be carefully noted that the method is measuring the seismic properties of the rock; direct correlation with geothermal energy will depend on the geologic environment in a specific area.

This discussion will focus on the techniques which are available and on the velocity parameters which can be detected by these techniques.

The sample analysis used in this discussion came from an attempt to model large mining blasts as the source of energy for a refraction survey. Local, controlled explosions can be used if the source-receiver distance is sufficient to achieve the required depth penetration. This critical distance is a function of the depth and the velocity contrast between geologic layers and is approximately twice the depth to the refracting horizon.

The velocity model assumed is two dimensional with two layers over a basement half-space. At a specified location in the model, an anomalous vertical zone extending from layer 2 into the half space is inserted. In this analysis, the anomalous zone was modeled as a low velocity anomaly and calculations were made to investigate the effect of this zone on arrival times and amplitudes from a combination refraction and fan-shooting spread.

Table 1 lists the parameters used in the sample model. A twenty per cent reduction in velocity was used for the low velocity zone. Velocity increases downward but the S-wave velocity increases more slowly than the P-wave velocity. Thus the Vp/Vs ratio increases as a function of depth.

Table 1

Parameters of The Velocity Model

Layer 1	P velocity = 4.5 km/sec S velocity = 2.7 km/sec Attenuation constant = 100 Thickness of layer = 2 km Velocity ratio = 1.67
Layer 2	P velocity = 5.5 km/sec S velocity = 3.4 km/sec Attenuation constant = 130 Thickness of layer = 10 km Velocity ratio = 1.62
Half Space	P velocity = 6.5 km/sec S velocity = 3.75 km/sec Attenuation constant = 175 Velocity ratio = 1.73
Velocity Anomaly in Layer 2	P velocity = 4.5 km/sec S velocity = 2.4 km/sec Attenuation constant = 100 Velocity ratio = 1.88
Velocity Anomaly in Half Space	P velocity = 5.2 km/sec S velocity = 2.6 km/sec Attenuation constant = 150 Velocity ratio = 2.00

Arrival times were calculated assuming source to receiver distance ranging from 80 to 150 kilometers with the vertical velocity anomaly beginning 100 kilometers from the source. The width of the anomaly was assumed to be 10 km along the refraction line and to range between 0 and 15 km for the fan-shooting ray paths.

To obtain as much information as possible, a computer program was developed to calculate P and S travel times from three separate paths (direct, refraction from first and second interface), relative amplitudes for each of these paths and the Vp/Vs ratio for the total travel path. Thus any anomalous factor would be detected in the course of the model study.

In preparing this analysis, the limitations and possible sources of errors involved have been identified. The following is a brief discussion of these points with regard to their possible significance in the experiment and techniques that may minimize their effect.

Velocity Model - Careful consideration should be placed in choosing the velocity structure and the parameters of the model. Although relative amplitude and travel time are used rather than any absolute measurements, one independent variable must be estimated in order to describe the anomaly. For example, if you chose the velocity contrast, the model can predict the size of the anomaly, or vice versa.

Table 2

Arrival Time and Amplitude Data from Test Case

In-Line Refraction

	No Anomaly		Anomaly		Changes*	
Distance	P-Wave Arrival	Relative Amplitude	P-Wave Arrival	Relative Amplitude	Δt	% Attenuation
80	14.887	24.2%	14.887	24.2%	0.000	0.00%
90	16.426	21.1	16.426	21.1	0.000	0.00
100	17.964	18.4	17.964	18.4	0.000	0.00
110	19.502	16.0	19.767	09.4	0.265	41.25
115	20.272	14.9	20.464	13.1	0.192	12.10
120	21.041	13.9	22.233	12.2	0.192	12.10
130	22.579	12.1	22.772	10.6	0.192	12.10

*due to Anomaly

Arrival Time and Amplitude Data from Test Case

In-Line Refraction

	No Anomaly		Anomaly		Changes**	
Distance	S-Wave Arrival	Relative Amplitude	S-Wave Arrival*	Relative Amplitude*	Δt	% Attenuation
80	24.430*	12.8	24.430*	12.8	0.000	0.00%
90	27.371*	10.1	27.371*	10.1	0.000	0.00
100	30.176	05.9	30.176	05.9	0.000	0.00
110	32.843	04.6	33.866*	03.7	1.772	67.40
115	34.176	03.6	34.695	03.1	0.519	24.40
120	35.510	03.6	36.021	02.9	0.511	19.40
130	38.176	02.9	38.695	02.2	0.519	24.10

*first arrivals were from the refraction path from the first interface
**due to Anomaly

Table 3

Fan Shooting

P Wave

Distance	Normal Section	1 x 10* Anomaly	5 x 10* Anomaly	10 x 10* Anomaly	15 x 10* Anomaly	Δt Max.
110	19.502	19.541	19.767	19.959	20.151	0.649
115	20.272	20.310	20.464	21.426	21.279	1.007
120	21.041	21.079	21.233	21.426	22.049	1.008
130	22.579		22.772	22.964	23.156	0.579

S Wave

Distance	Normal Section	1 x 10* Anomaly	5 x 10* Anomaly	10 x 10* Anomaly	15 x 10* Anomaly	Δt Max.
110	32.843	33.376**	33.866**	34.479	35.092	2.249
115	34.176	34.280	34.695	35.949	36.562	2.386
120	35.510	35.613	36.021	36.547	38.033	2.523
130	38.176		38.695	39.213	39.732	1.556

*km
**first arrivals were from the refraction path from the first interface

Table 4

P Wave Attenuation

Distance	Normal	1 x 10 Anomaly	5 x 10 Anomaly	10 x 10 Anomaly	15 x 10 Anomaly	Max.
110	16.0	15.6	09.4	08.3	07.2	55.0%
115	14.9	14.5	13.1	06.9	06.0	59.7
120	13.9	13.6	12.2	10.7	05.6	59.7
130	12.1		10.6	09.3	08.2	32.2

S Wave Attenuation

Distance	Normal	1 x 10 Anomaly	5 x 10 Anomaly	10 x 10 Anomaly	15 x 10 Anomaly	Max.
110	04.6	05.6	03.7	02.1	01.3	71.7%
115	04.1	03.9	03.1	01.1	00.8	80.5
120	03.6	03.5	02.9	02.1	00.7	80.6
130	02.9		02.2	01.7	01.3	55.2

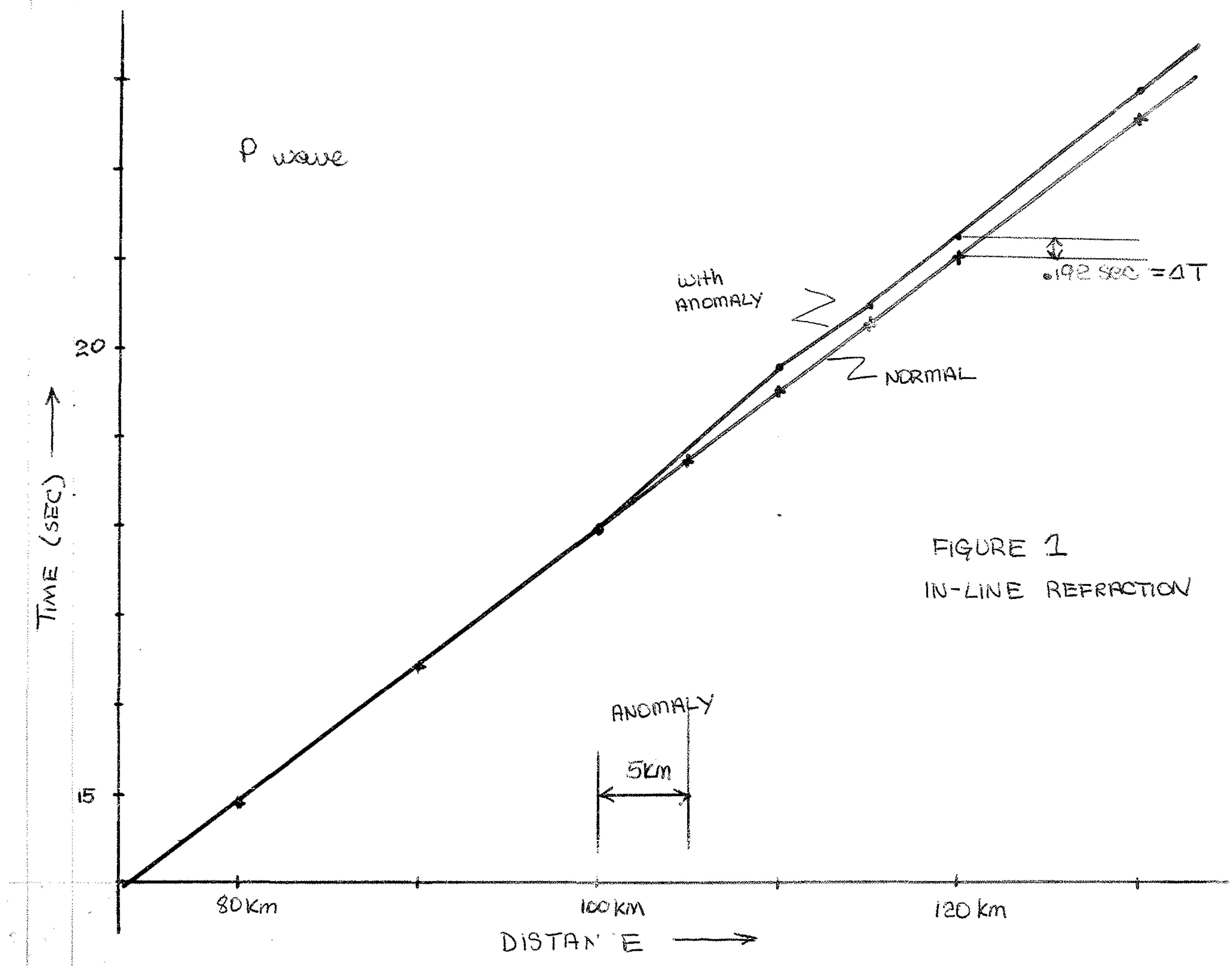


FIGURE 1
IN-LINE REFRACTION

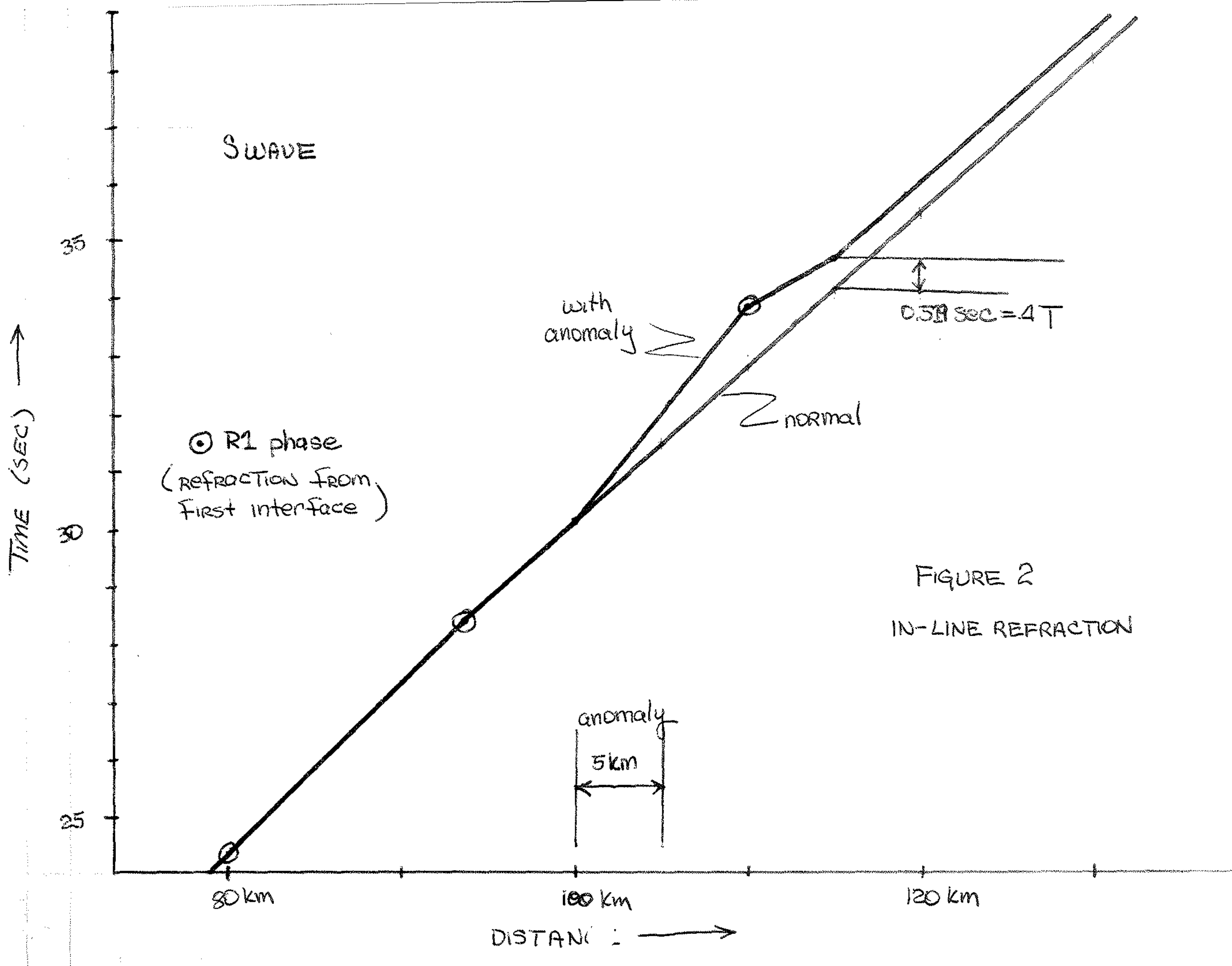


FIGURE 2

IN-LINE REFRACTION

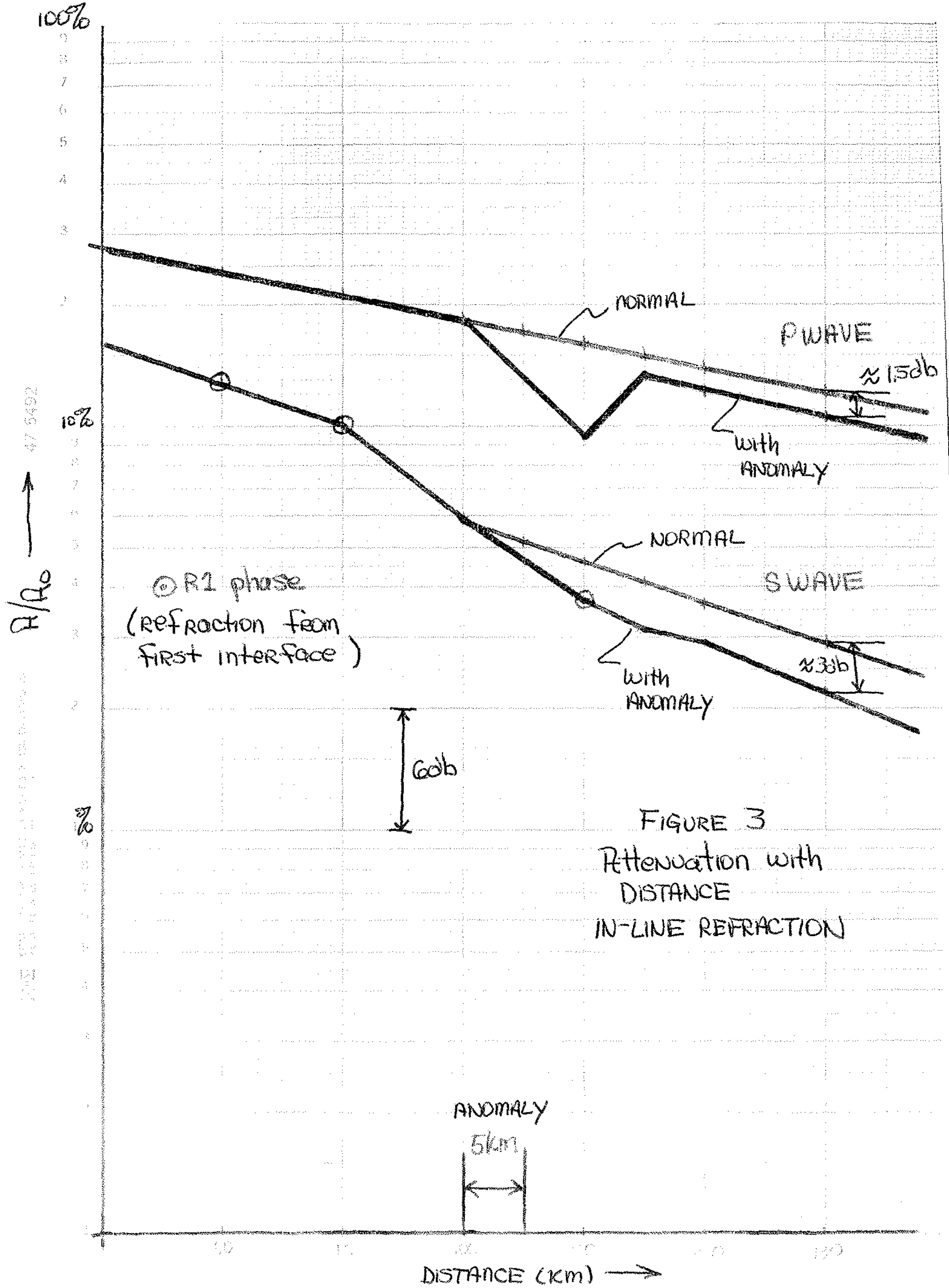


FIGURE 3
Attenuation with DISTANCE
IN-LINE REFRACTION

FIGURE 4
FAN-SHOOTING

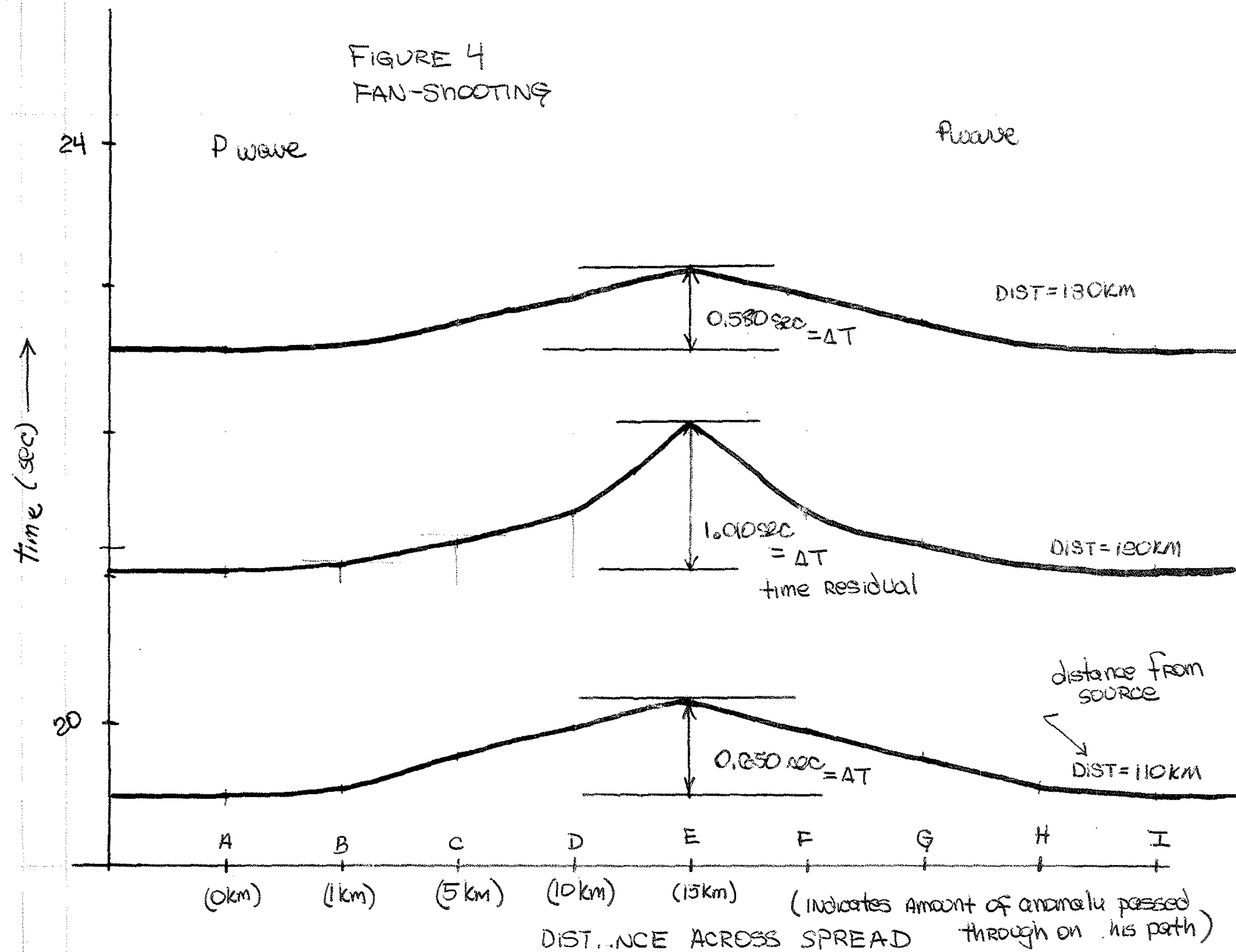
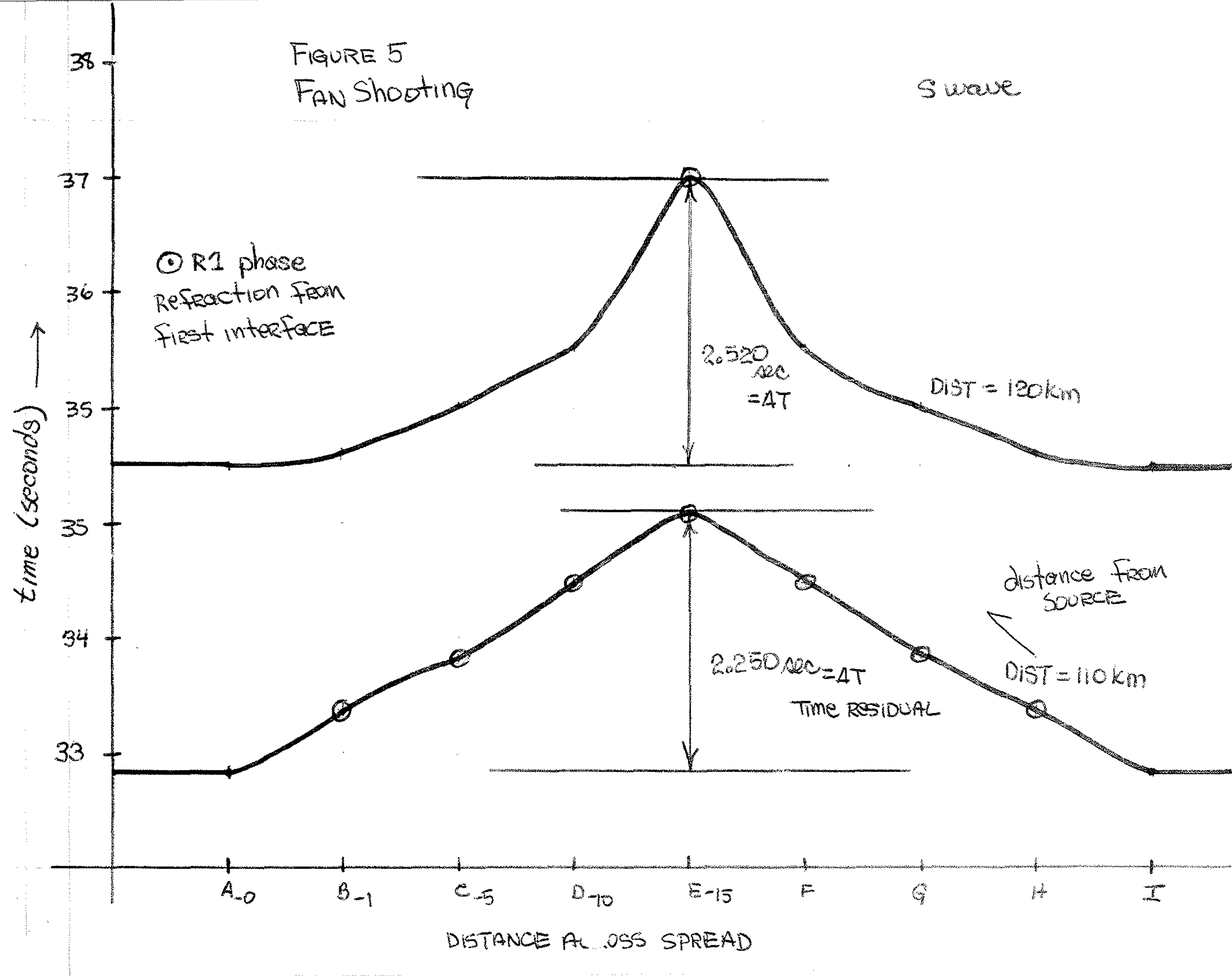
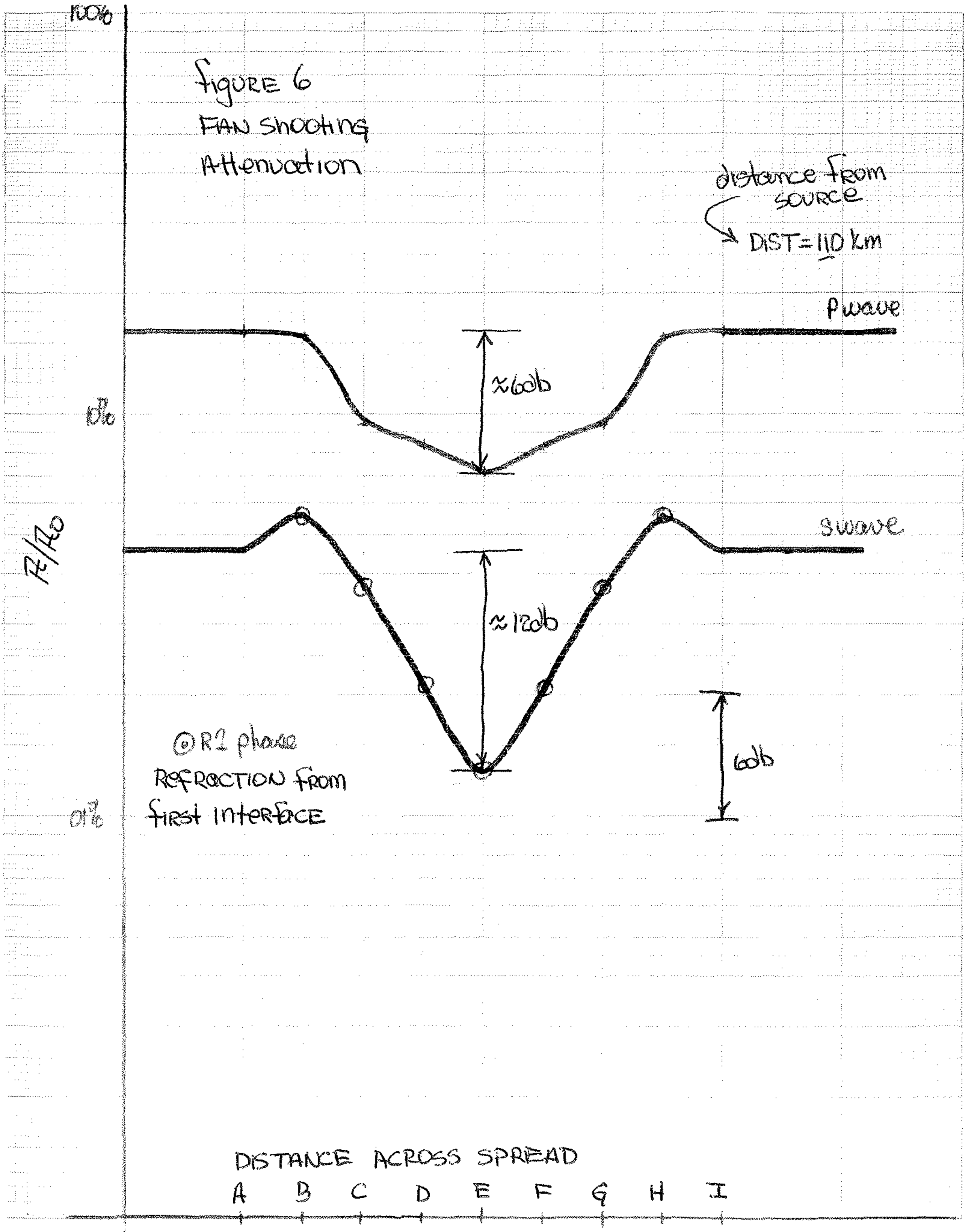


FIGURE 5
FAN Shooting





100%
figure 6
FAN Shooting
Attenuation
distance from source
DIST = 110 km
P wave
≈60db
10%
S wave
≈120db
60db
R/Ro
⊙ R2 phase
Refraction from first interface
01%
DISTANCE ACROSS SPREAD
A B C D E F G H I

Any two dimensional velocity model in basin and range geology is bound to be limited in accuracy over any large distance. Horizontal refractions from boundary blocks may or may not be significant but should be investigated. The computer model used can be modified to look perpendicular to as well as parallel to the regional structure. The horizontal refractions can be approximated to model sideswipe effects.

Amplitude - The attenuation model of the computer program assumed the relationship $A/A_o = e^{-dr}$ where A/A_o = amplitude observed at a given location divided by the initial amplitude, R = distance traveled, $d = {}^{\pi f}/_{aQ}$, f = frequency of the wave energy, here chosen to be a constant but is a function of distance, a = velocity of the elastic energy and Q = attenuation constant. As only relative amplitude is considered, effects such as internal reflection and scattering and energy loss at boundaries are ignored. As variations in station site response due to local geologic conditions are on the order of the expected anamolous behavior, great care must be taken in selecting station locations. One of the questions that this experiment must deal with is whether or not the effect of increased attenuation can be attributed to an anamolous section of the travel path or falls within the uncertainty due to local site conditions.

We propose to use two specific recording techniques to enhance the data recovery. The use of magnetic tape will allow us to more carefully examine an event and pick secondary P wave arrivals to further define the velocity structure. The possibility also exists for frequency analysis of the data when good digital records are available. We also plan to use a three component recording, vector magnitude trace display recording system. The technique should enhance coherent signals, thus improving the signal to noise ratio and should significantly improve the recording of the shear wave arrival.

Assuming a 20% decrease in velocity in a 5 km anomaly, time residuals of approximately 200 ms for P and 500 ms for S were calculated. Amplitude variations of 12% for P and 25% for S were observed. These results are larger if a station can be located where the energy path must travel upwards through the anomaly.

Figures 4-6 illustrate the result of fan shooting over an anomaly 15 km wide at station E decreasing to 1 km wide at stations B and H. Travel paths to stations A & I are in the normal section. Assuming the anomaly begins at 100 km from the source, stations 110 km from the source would record time residuals of approximately 1 sec for P and 2.5 sec for S. Amplitude variations of 55% for P and 72% for S were observed.

Although many questions remain to be answered, this analysis indicates that a survey combining refractions and fan-shooting rechniques designed to monitor amplitude variations and travel time residuals will provide valuable information about the seismic parameters of anomalies which may correlate with geothermal systems.

If the questions concerning the magnitude of the velocity contrast and the attenuation characteristics and the uniformity of site characteristics can be answered in such a way as to support the use of this technique in searching for velocity anomalies, this method will add valuable information if used as a detailing tool once a target has been located by other methods. Uncertainties in the velocity model should make refraction a poor choice as a reconnaissance tool but valuable in determining the areal extent of any velocity anomaly suspected to correspond to a geothermal system.

SCOPE OF THE WORK

Application of this experiment to the Mount Princeton prospect involves the examination of several questions. Before detailing of small scale anomalies can be designed, the gross geologic structure must be defined. Three dimensional data will contribute valuable constraints into the velocity model and into the selection of shot and spread locations to maximize coverage of areas of interest.

Specifically referring to the Mt. Princeton prospect, there are two targets for detail analysis, the extension of the Cottonwood Creek feature into the valley and the resistivity anomaly near the airport. Before this work can be done we need to know the general gross structure of the basement to design spread lengths and recover station intervals. We propose to obtain this data by first shooting long interval, 1/2 mile station spacing, reversed refraction spreads both parallel and perpendicular to the axis of the valley.

The geologic model we propose is a source of hot water somewhere at the alluvium-basement contact on the valley. The boundary features of the Cottonwood Creek fault and the Mt. Princeton batholith channel the hot water into the surface manifestation of the system at the Cottonwood hot spring. If the gross structure from the initial refraction lines supports this model then small station spacing in-line and fan-shooting lines can be shot to investigate both the depth, location and areal extent of the two targets.

In order to evaluate the refraction detailing method in the most cost effective manner, MGC proposes to run the experiment in the format of work on a Masters' thesis in Geophysics at the Colorado School of Mines by Jim Crompton. In this form the equipment and the data analyzing potential of the Geophysics Department and the school will become available at little or no cost to you. To further specify the experiment, we propose to run the refraction spread using a 24-channel recording truck (8 stations times 3 components per station). One station using the field vector display recording technique will be run with a standard vertical seismometer microearthquake set-up to evaluate the operation of the new electronics. By recording each component individually in the recording truck and using the enhanced shear wave manipulations numerically rather than electronically in the field, the experiment can evaluate the refraction detailing technique independent of the restriction of the success of the new electronics.

In this format we can use the drill truck, recording truck and the blasting capabilities of the School of Mines. Assumed in this proposal is the right of publication of the data. Also assumed is that your company will secure whatever permission or tresspass permits are needed to operate the equipment and blast in the area. We have envisioned as a source of energy, small to medium size dynamite explosions in shallow holes, several miles from the prospect area.

Specific goals of the experiment are to:

1. Determine the gross structure of the basement of the Arkansas Valley near Buena Vista,
2. Find any seismic expression of resistivity anomaly and Cottonwood Creek feature,
3. Collect data on time residuals and attenuation (relative) to test velocity model and estimates of physical parameters of the geothermal model,
4. Test new electronics involved in VDR technique,
5. Compare VDR with vertical recording with regard to frequency response, noise reduction and enhance time resolution in S wave pick,
6. Test uniformity of seismometer plants to minimize amplitude contrasts due to site contrasts,
7. Use of magnetic tape recording (digital) in examining coda of arrival wave, and
8. Examine problem of generation of shear energy from shallow explosions.

BUDGET ESTIMATE

TASK		COST
Design experiment, obtain permits and access	4 man days at $75.00	$ 300.00
Field work to drill holes shoot, and collect data	16 man days at $75.00	$1,200.00
Data analysis -- office report preparation	15 man days at $50.00	$ 750.00
Build and design VDR equipment	Subcontracted	$ 600.00
Equipment rental from CSM Geophysics Fund, Inc. (includes expendables)	4 days at $200 per day	$ 800.00
Equipment rental from CSM	Trucks and MEQ-800's	$ - 0 -
Computer time and data analysis	Phoenix and PDP-10	$ - 0 -
Total Estimated Budget		$3,650.00
Not to Exceed		$4,000.00