ROCKWELL INTERNATIONAL
NORTH AMERICAN SPACE OPERATIONS
ROCKY FLATS PLANT

Seismic Reflection Modeling of the Arapahoe Formation at the Rocky Flats Plant

Final Draft Report

U.S. Department of Energy
Rocky Flats Plant
Golden, Colorado

11 January 1989

United States Department of Energy
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SEISMIC REFLECTION MODELING OF THE ARAPAHOE FORMATION AT THE ROCKY FLATS PLANT

FINAL DRAFT REPORT

January 1989

Prepared by:

EBASCO SERVICES INCORPORATED

Prepared for:

ROCKWELL INTERNATIONAL
NORTH AMERICAN SPACE OPERATIONS
ROCKY FLATS PLANT
GOLDEN, COLORADO

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EXECUTIVE SUMMARY

Rockwell International, North American Space Operations, is performing remedial investigations, feasibility studies, and remedial/corrective action projects at the Rocky Flats Plant near Golden, Colorado under the U.S. Department of Energy's Environmental Restoration Program. As part of that program, a seismic reflection modeling study was undertaken to determine if shallow high-resolution seismic reflection techniques could be utilized to map the three dimensional extent of Arapahoe Formation sandstones in the investigation area. These sandstone lens may influence the movement of potential groundwater contamination from the Rocky Flats Plant area eastward. In addition the use of the seismic reflection technique could provide data to optimize the monitor well network and future cleanup design efforts.

A geologic model was developed representing a 900 foot geologic cross section immediately east of the Plant in the vicinity of the Medium Priority Sites. To determine the resolution of the seismic reflection method acoustic properties were assigned to the model after review of available geophysical data. Seismic modeling results indicated that the method can detect Arapahoe Formation sandstones as thin as 3 feet up to a depth of a few hundred feet. Seismic field acquisition parameters for the collection of seismic data were developed from the modeling process. Potential data acquisition problems in the area of a known shallow caliche layer may exist; however, the burial of the seismic energy source may provide a solution. Recommendations for locations to collect actual field data for further evaluation are presented. A glossary of terms is included in the Appendix of this report.

1.0 INTRODUCTION

1.1 Scope of Work

Rockwell International, North American Space Operations, is performing remedial investigations, feasibility studies, and remedial/corrective action projects at the Rocky Flats Plant (Figure 1) under the Department of Energy's Environmental Restoration Program (ERP). Previous remedial investigations conducted at Rocky Flats have identified potential soil, surface water, and groundwater contamination in the vicinity of the Medium Priority Sites (see Figure 1 and 5). These investigations have also identified the presence of sandstone lens in the Arapahoe Formation which may be important pathways for groundwater flow.

The surficial geology in the area of the Medium Priority Sites is composed primarily of the Rocky Flats Alluvium, which is a poorly sorted Quaternary deposit of cobbles, pebbles, and gravel in a sandy clay matrix. The Rocky Flats Alluvium in this area ranges in thickness from 3 to 45 feet. The greater depths are located in bedrock channels. Bedrock in this area consists of the Cretaceous Arapahoe Formation (Weimer, 1973), comprised of stratigraphically complex fluvial claystones with interbedded lenticular sandstones and siltstones. Volatile organic contaminants are present in the bedrock in the investigation areas (Rockwell International, 1987). This contamination may have migrated from former waste storage sites at Rocky Flats. The stratigraphic and structural features of the Arapahoe Formation probably assist the potential movement of contamination from the Rocky Flats Plant area eastward.

Recent investigations (i.e. drilling) to date have not provided sufficient data to map in detail the lithology of the Arapahoe Formation because of the stratigraphic complexity. Therefore, the shallow high-resolution seismic reflection technique was selected to provide detailed data to map the Arapahoe Formation sandstones and to establish preferential groundwater flow routes in the bedrock. The scope of work consists of two tasks. Task 1 was to evaluate the shallow high-resolution seismic reflection technique using seismic modeling (described in this report). Task 2 will be a field testing program using the seismic computer modeling results as a basis for further evaluation of the seismic reflection technique. The objectives of the work are to determine the feasibility of the high-resolution shallow seismic reflection technique to: 1) answer detailed geologic questions; and 2) optimize groundwater monitoring and cleanup designs.

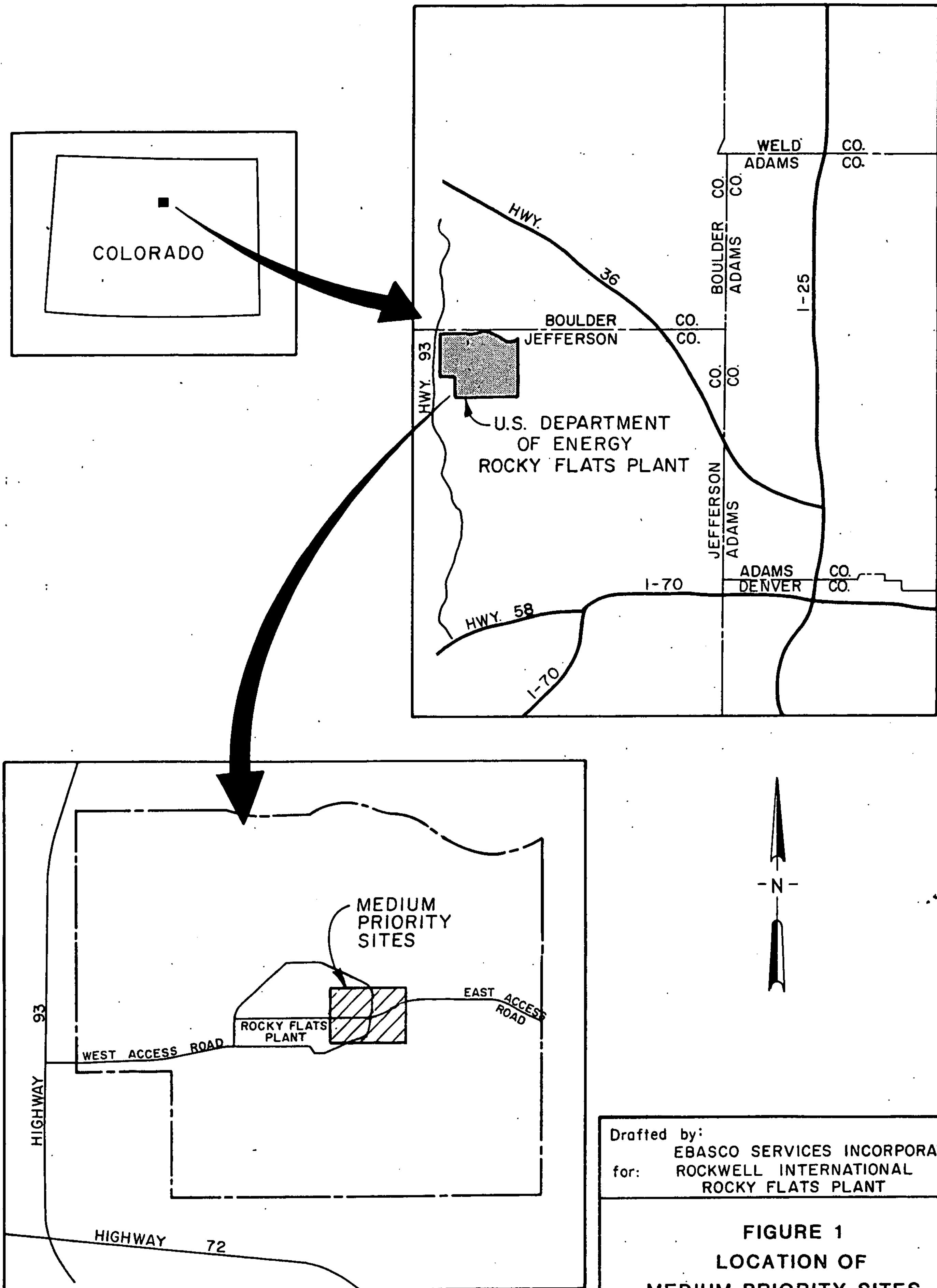

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FIGURE 1
LOCATION OF MEDIUM PRIORITY SITES

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The steps of the modeling process were to:

1) Construct a geologic cross section typical of the area proposed for seismic reflection work;

2) Estimate the geophysical properties of the lithology for the seismic modeling;

3) Simulate the collection of seismic reflection data across the geologic cross section using various seismic field parameters;

4) Determine the optimum set or sets of field parameters to collect seismic reflection data in the area of interest;

5) Identify potential problems for data acquisition and processing and offer possible solutions;

6) Estimate interpretation limitations of the seismic reflection technique and the potential vertical and horizontal resolution; and

7) Present one or more synthetic seismic reflection profiles derived from the geologic cross section.

1.2 Seismic Reflection Theory Overview

A glossary of geophysical terms relating to the seismic reflection technique is given in the appendix. A good text for review of seismic reflection theory is "Introduction to Geophysical Prospecting" by Milton B. Dobrin (1976).

A seismic source generates energy that manifests itself as seismic waves. Seismic waves propagate within solids as disturbances traveling through the materials with velocities that depend upon the elastic properties and densities of the materials. Typical commercial seismic sources are explosives and vibrating machinery. These sources generate two types of seismic waves - body and surface. Body waves consist of compressional (p) and shear (s) waves. Since most of the energy generated by a seismic source is in the form of compressional waves, these waves are of primary interest.

Seismic wave energy attenuates with distance. Part of this phenomenon is due to frictional heat loss through absorption of energy by the material. Absorption is dependent on the seismic medium; shales have the highest absorption rates, and granites have the least. Since seismic waves propagate as spherical wave fronts, the wave spreads out over a spherical area. Thus, the energy per unit area varies inversely as the square of the distance from the source.

A seismic wave will travel through a medium along a ray path until a discontinuity is encountered. A discontinuity can be caused by a change in lithology or fluid content of a porous medium. At a discontinuity, part of the wave will be reflected and another part refracted in accordance with Snell's Law as illustrated in Figure 2.

The relative amplitude of a reflected wave from the boundary of two layers, Layer 1 and Layer 2, can be expressed in the form

$$R = \frac{d_2 V_2 - d_1 V_1}{d_2 V_2 + d_1 V_1}$$

where

R = reflection coefficient.

d = density in grams per cubic centimeter of medium.

V = velocity of compressional wave through medium.

The product of the density and velocity is known as the acoustic impedance. If the acoustic impedance increases across an interface, then the reflected wave is positive in amplitude. Conversely, if the acoustic impedance decreases across an interface, the reflected wave has a negative amplitude.

The refracted compressional wave makes an angle, r, expressed by the relation

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

When $\sin i = V_1/V_2$, sin r becomes unity and r becomes 90°. The refracted wave does not penetrate the medium but travels along the interface between the two materials. Angles i and r are measured relative to the normal at the intersection of the interface and the incident wave.

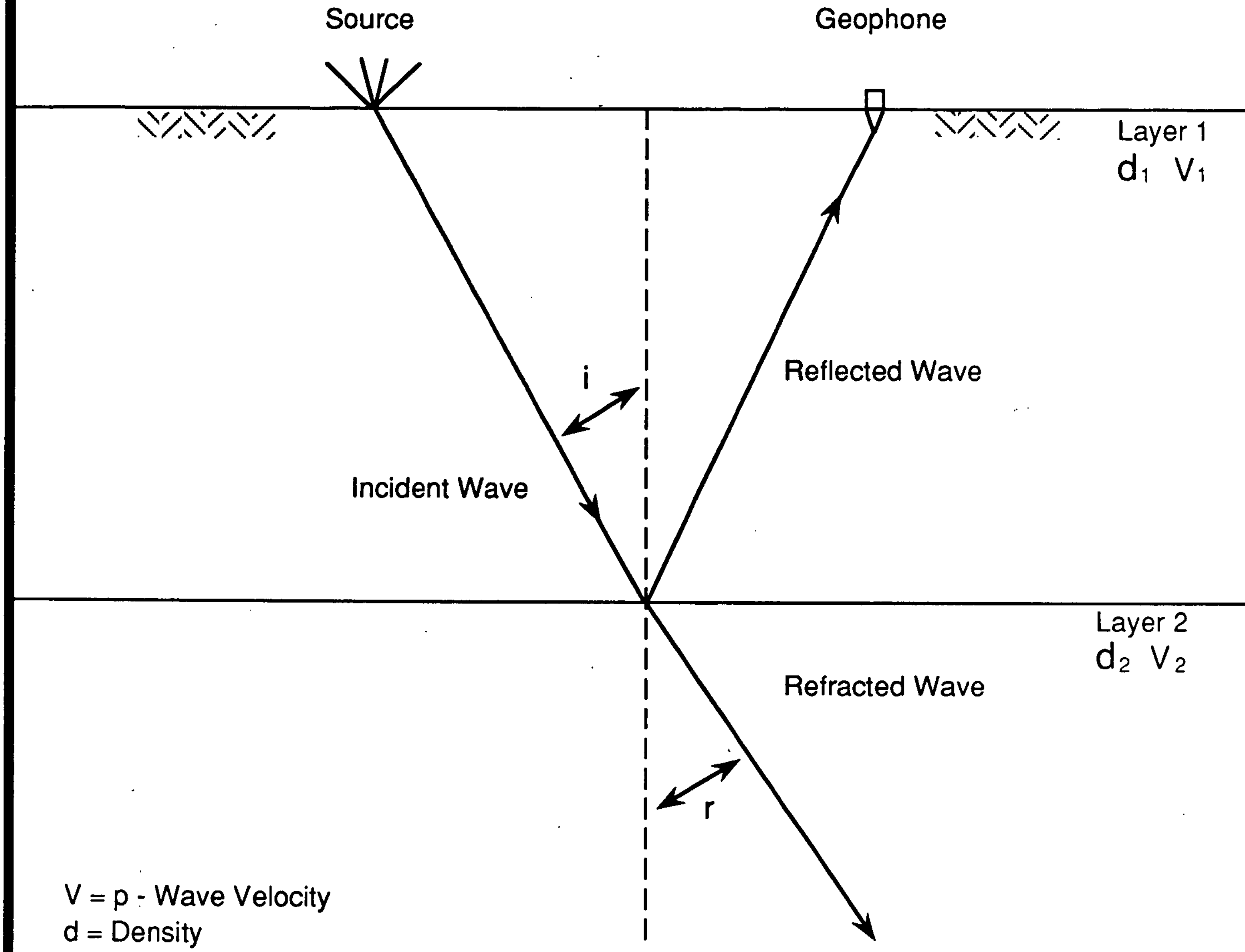

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FIGURE 2
GEOMETRY OF SNELL'S LAW

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Where seismic waves strike any irregularity along a surface such as a comer or a point where there is a sudden change of curvature, the irregular feature acts as a point source, radiating waves in all directions. Such radiation is known as diffraction. The amplitude of a diffracted wave falls off rapidly with distance away from the source.

Another seismic phenomenon is known as the interbed multiple reflection. Figure 3 illustrates a multiple reflection; a wave reflects upward from the interface between Layer 2 and Layer 3. Returning to the surface, the wave reflects downward from the Layer 1 - Layer 2 interface, because any change in acoustic impedance at an interface boundary can cause a reflection. The wave again reflects from the top of Layer 3 and successfully returns to the surface.

Figure 3 also shows the types of seismic waves generated by a surface source that will be detected by a geophone. The air wave travels at the speed of sound in air (approximately 1,100 feet per second). The direct wave travels from the source to the geophone within the uppermost medium. This wave is normally faster than the air wave but slower than the other illustrated waves. The refracted wave has the earliest arrival time. The reflected wave is slower than the refracted wave. A multiple reflected wave has a longer arrival time than the reflected wave because of the greater distance traveled. Because of the varying velocities of the different waves it is possible to design seismic field parameters to record the waves of primary interest.

According to signal theory, the amount of information present in a seismic reflection signal is proportional to the bandwidth. The bandwidth of a seismic signal is the range of frequencies contained within. The maximum frequency that can be recorded reliably is equal to one-half of the sampling frequency or rate. This is known as the Nyquist frequency. At 1/4 millisecond sampling rate, the Nyquist frequency is 2000 Hertz (Hz).

Seismic noise is any unwanted signal. Sometimes noise is random, other times it is coherent (e.g., a pumping water pump or a nearby powerline).

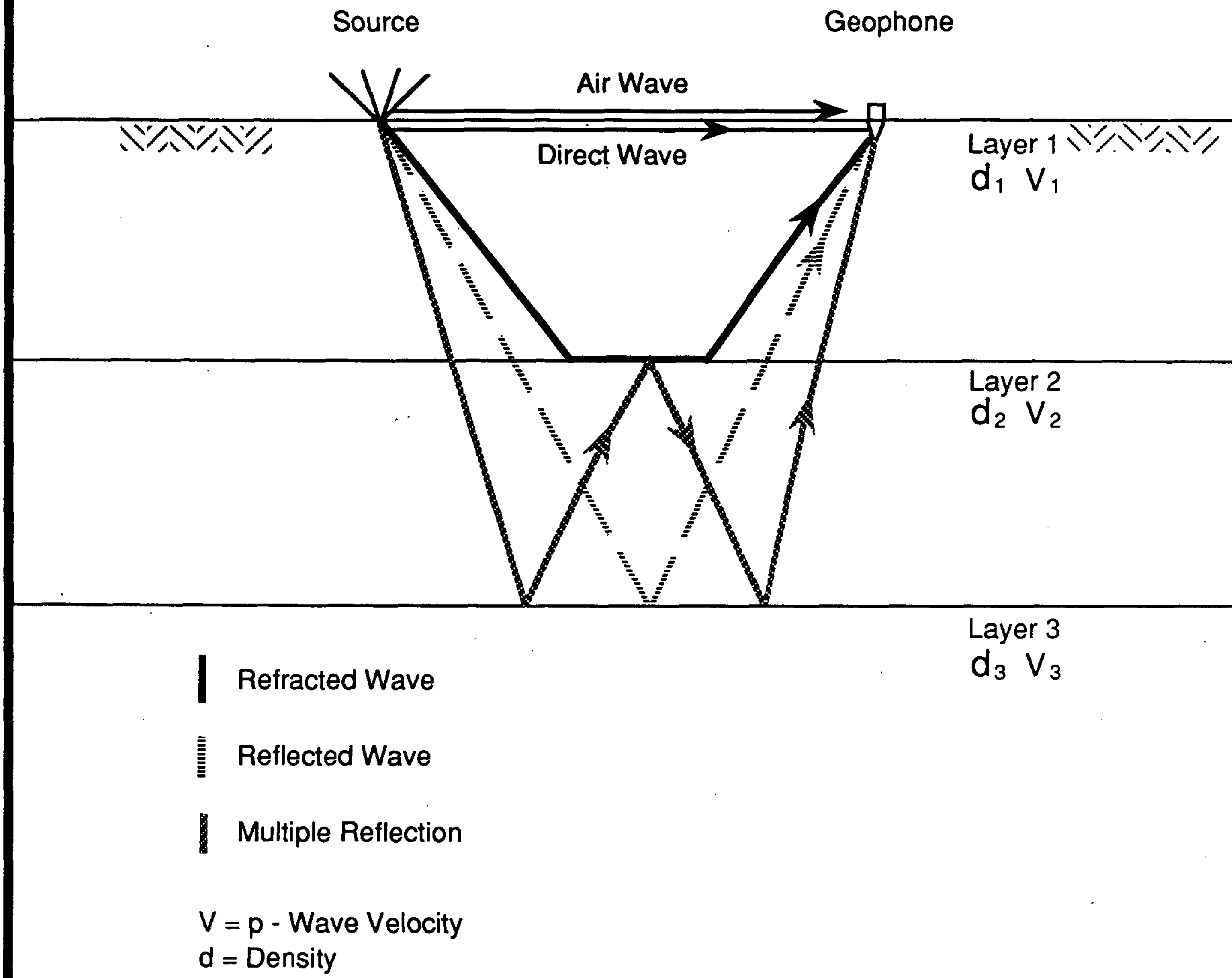

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FIGURE 3
TYPES OF SEISMIC WAVES

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1.3 Seismic Reflection Method

Seismic reflection techniques build on basic seismic principles. Development of digital recording techniques in the 1960s catalyzed great advances in seismic reflection acquisition, processing, and interpretation. To reliably interpret a seismic event, the signal-to-noise ratio must be at least 1:1. The common depth point (CDP) method has enabled the recording and display of reflection events that have signal to noise ratios less than unity. The CDP technique records reflections from multiple offsets at different source and receiver pairs as illustrated in Figure 4. For each CDP the number of source and receiver pairs recorded is called the fold. Six fold data has six source and receiver pairs. Another term for six fold data is 600 percent stack. The signal-to-noise ratio doubles for each quadruple increase in the CDP fold. The CDP fold can be calculated by:

$$\frac{\text{receiver spacing}}{2 \times \text{source spacing}} \times \text{number of recording channels} = \text{CDP fold}$$

The processing of seismic reflection data is a statistically intensive procedure and requires human guidance at each step. After acquisition, the seismic reflection data are processed from source record format into CDP record format. Each CDP record will have the same number of traces equal to its fold. Because the distance between source and receiver is greater for the longer offsets of a reflection event (source-receiver 1 as opposed to source-receiver 3, Figure 4), the recorded reflection event itself will record at a later time. The difference in time for a particular event on adjacent traces is termed normal moveout. Data are corrected for normal moveout during processing, and all traces in the CDP record are merged or summed summed together (stacked). This enhances the real events and cancels undesirable random noise, thus increasing the signal-to-noise ratio.

Before stacking, data are corrected for elevation variations, resulting in a static correction. After stacking, automatic statics are performed to correct for velocity variations in the near-surface weathered layer. Digital filters are applied at various steps in the processing to eliminate random noise and enhance the reflection events. Post-stack filtering may include enhancing individual reflection events to improve the interpretation by statistically comparing adjacent seismic traces for continous events versus random noise.

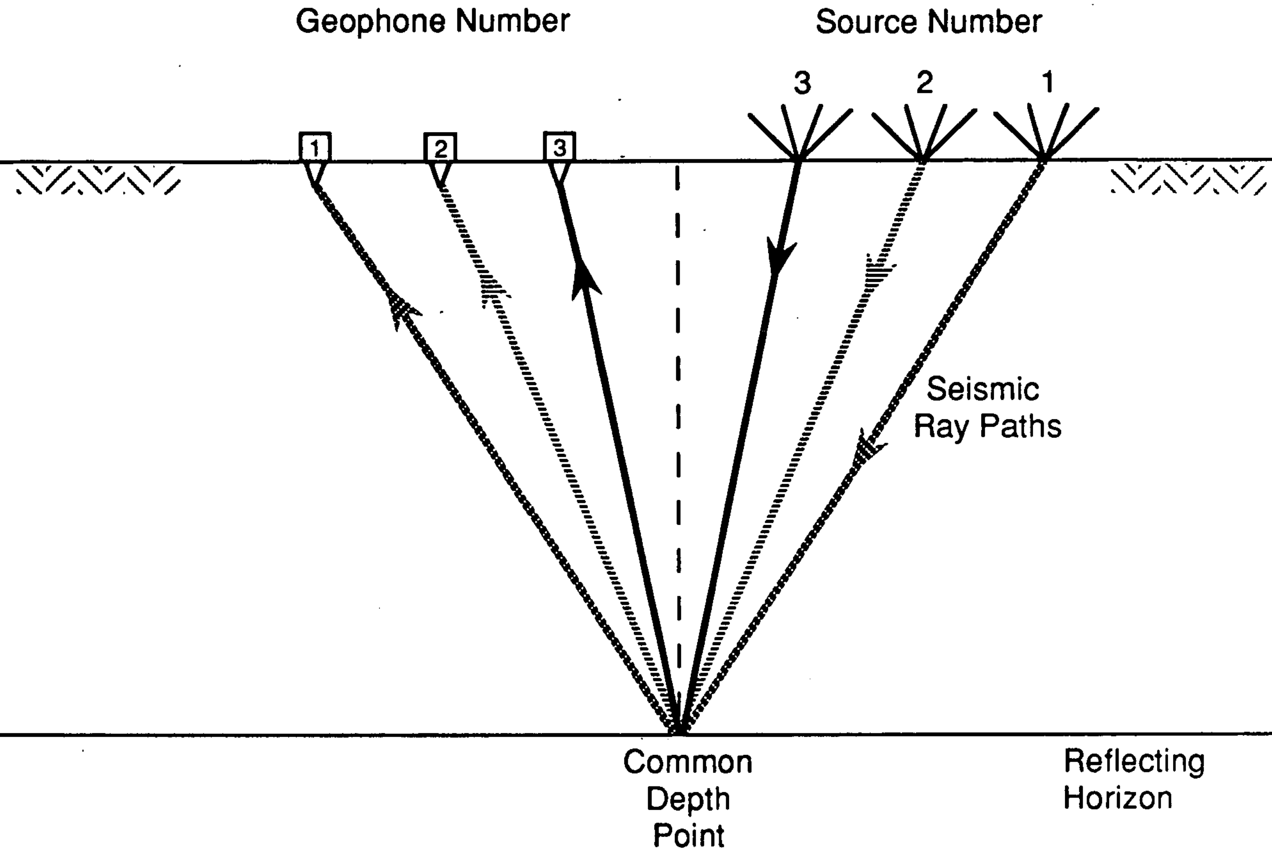

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FIGURE 4

COMMON DEPTH POINT TECHNIQUE

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Seismic events recorded from a geophone appear to arrive from directly beneath the geophone. Where the reflecting horizon is dipping, the position of the event is incorrect. Dipping events migrate downdip. If necessary, these events can be migrated back to their true location. Depending on the data and objectives of the interpreter, this process can be done either before or after stacking (pre-stack or post-stack migration).

1.4 Shallow High-Resolution Seismic Reflection Technique

Recording shallow reflection events requires modification of standard seismic reflection techniques. In standard seismic reflection techniques 12 or more geophones are grouped together as an array. Typical distances between groups are tens to hundreds of feet. In shallow high-resolution seismic reflection work geophone arrays are eliminated and individual geophones are used. Geophone spacings are reduced to a few feet, depending on the depth to the shallowest target. Shallower targets require closer geophone spacings. The number of recording channels needed is dependent on the depth to the deepest target of interest and the geophone and source spacing. Vertical resolution is limited by the bandwidth of the recorded signal and the sampling frequency. Horizontal resolution is limited by the bandwidth of the recorded signal and the geophone spacings.

1.5 Seismic Reflection Modeling

The purpose of seismic reflection modeling is to optimize field techniques by identifing possible acquisition, processing, or interpretation problems. Seismic data acquisition and processing are expensive operations in contrast to modeling, which is one or more orders of magnitude cheaper. During the interpretation of actual seismic reflection data, modeling is useful in analyzing seismic reflection responses to possible geological environments.

Seismic modeling involves the construction of a geologic cross section and subsequent generation of synthetic seismic data. The cross section is digitized, and velocity and density values are assigned to the lithologic layers after review of available geophysical data. Seismic field acquisition parameters such as source and geophone spacings and sampling rate are varied to determine the optimum arrangement.

Computer programs simulate the generation of seismic waves and their raypaths. The resultant synthetic seismic records are then processed into either final stacked sections or migrated sections.

2.0 BUILDING THE ROCKY FLATS GEOLOGIC MODEL

Lithologic logs from 28 monitoring wells and 39 boreholes that penetrated the bedrock located in the Rocky Flats Medium Priority areas were reviewed (see Figure 5). Seismic refraction data located approximately 1.4 miles southwest of the 903 pad (Ackerman, 1974) were reviewed to extract seismic velocity data for different materials. Borehole geophysical logs consisting of natural gamma ray and neutron were also reviewed from Well 22-74 located in the Medium Priority Sites area to interpret local lithology.

A geologic cross section was constructed through the Medium Priority Sites area (see Figure 5). Budgetary restrictions resulted in a reduction of the size of the geologic model to the western-most 900 feet of the geologic cross section between wells 9-87BR and 23-87BR. Sandstone lenses were postulated along trends inferred from the original cross section and based on the depositional environment of the Arapahoe Formation (Weimer, 1973). The various lithologies (sandstone, caliche, weathered claystone, and water table) that occur in the medium priority sites, were added to the shorter 900-foot cross section. In addition to this, combinations of sandstone were added to evaluate the vertical resolution of the seismic field parameters. Velocity and density values for each lithologic unit were assigned after examination of the available data. Because the amount of density and velocity data is limited for the site, data from a similar formation, the Denver Formation, were used to supplement the available site data.

Velocities and densities were assigned to the various units as shown in Table 1. Three classifications of Arapahoe sandstone units, called Types A, B, and C, were assigned for the modeling. Type A represents an uncemented sand or flowing sand. Type B represents a slightly cemented sandstone, and Type C represents a well cemented sandstone. These three classifications were selected to represent the typical sandstone units found in the Arapahoe Formation.

One sandstone body was assigned a varying velocity and density, being Type A at one end and gradually becoming Type C at the other. The purpose was to analyze the change in the character of the reflection event in the model. Sandstone lens thicknesses were varied from 3 feet to tens of feet. The approximate 7 degree dip of the sandstone lens was based on previous reports (Rockwell International, 1987).

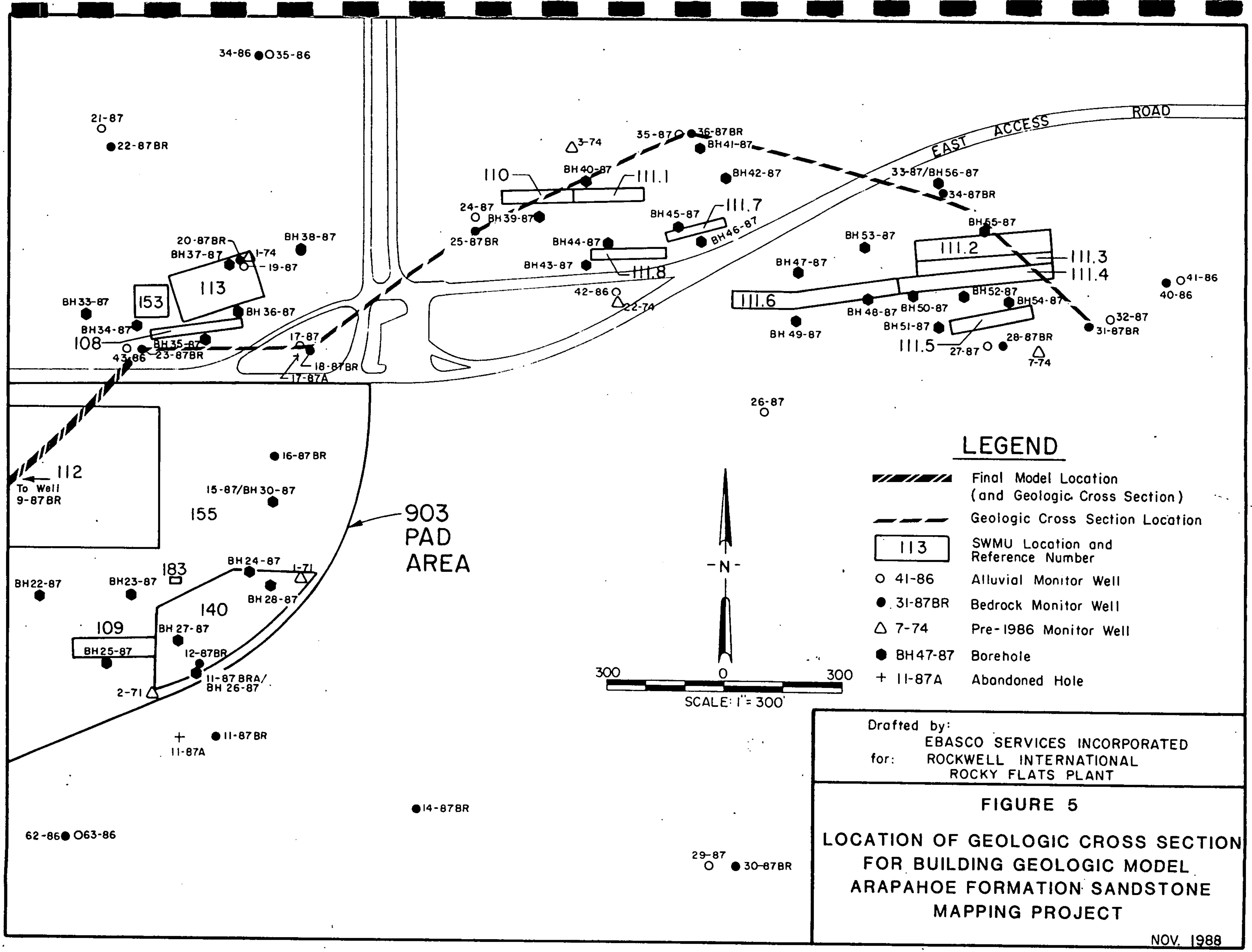

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FIGURE 5

LOCATION OF GEOLOGIC CROSS SECTION FOR BUILDING GEOLOGIC MODEL
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The velocities and densities used in the model are approximations based on available information. Variations within the units probably exist, however, the model is valid for determining relevant field parameters and limitations of the seismic reflection technique for the Rocky Flats Plant Area.

TABLE 1

Assignment of Seismic Velocity and Density Values

Lithologic Unit	Seismic (ft/sec) Velocity	(gm/cm^3) Density	Notes
Rocky Flats Alluvium	2,000a	1.7c	unsaturated
Caliche layer	8,000b	2.4b	
Rocky Flats Alluvium	4,000a	2.0b	saturated
Arapahoe Claystone	4,500a	2.1c	weathered
Arapahoe Claystone	6,000a	2.2c	unweathered
Arapahoe Sandstone	6,000c	2.1c	Type A (uncemented)
Arapahoe Sandstone	7,000c	2.3c	Type B (slightly cemented)
Arapahoe Sandstone	8,000c	2.4c	Type C (well cemented)

a - Source: Ackermann (1974).

b - estimated.

c - source: Rocky Mountain Arsenal data for similar lithology.

Initial results suggested that field data acquisition should start on the east and proceed westwards (See Section 3.1). The seismic modeling software was designed to simulate the seismic field acquisition starting at the left side of the model. It would have been cost and time prohibitive to redesign the modeling software to simulate seismic acquisition from right to left, since an easy mental reorientation will suffice. Therefore, the model is oriented with east on the left side.

3.0 SEISMIC MODELING

3.1 Preliminary Modeling Tests

To determine if the modeling results were reasonable, some simple modeling tests were made. Initially a sandstone body was defined at 800 feet depth within a claystone. To test vertical resolution the sandstone was given thicknesses of 2 to 20 feet on separate tests. To test the effect of the sample rate, both 1/2 and 1/4 millisecond sample rates were used.

These preliminary tests demonstrated the usefulness of the modeling results. The results also indicated that sandstone thicknesses less than 3 feet have a detectable response. The 1/4 millisecond sample rate was more accurate in defining the time thickness between the top and bottom events of a thin sandstone. The effect of 20 degrees dip was alarming; the reflection events were almost totally nondetected for an updip source.

The results of these preliminary tests demonstrated that model and field data acquisition should proceed from the downdip (east) to updip (west) direction. Model and field recording should be done at a 1/4 millisecond sample rate.

3.2 Final Modeling

The geologic model is shown in Plate 1. The caliche layer, a partial intra-alluvial water table and a weathered claystone area, were added to the model at arbitrary locations to analyze the synthetic seismic reflection responses with the other lithologic features. Model parameters were:

Geophone Spacing	2 feet
Source Spacing	4 feet
Number of Recording Channels	96
CDP Fold	24
Maximum Record length	200 milliseconds
Sample rate	0.25 (1/4) milliseconds

Two types of geophone geometries were tested. Balanced - split spread, with equal numbers of geophones on both sides of the seismic source, and off end, with the seismic source at one end of all the geophones. The split spread geometry yielded better results. Final display filters were trapezoidal bandpass filters with the following characteristics:

Report Plate	low cut (Hz)	low pass (Hz)	high pass (Hz)	high cut (Hz)
2	20	100	150	300
3	20	100	250	500
4	20	100	500	999
5	20	100	500	999

The frequencies between low pass and high pass were at the maximum amplitude. Frequencies less than low cut, or greater than high cut, were rejected (i.e., have an amplitude of zero). Frequencies between the low cut and low pass, and the high cut and high pass, had amplitudes almost at the maximum near the pass frequency and gradually attenuate to zero at frequencies near the cut frequency.

Each filter had 256 samples (length of 64 milliseconds). These filters simulated three probable recording bandwidths. The broadest bandwidth simulated the response of a 100-hertz geophone that was proposed for the field work (see Section 4 and Plate 4 and 5). The broadest bandwidth filter yielded the best synthetic resolution. If high frequencies above 500 Hertz could be recorded in the field, this would improve the interpretation of the data. It is possible to record these higher frequencies but seismic field tests are required to make a final analysis.

Each filter was applied to the processed model data and displayed. These displays are located in the pocket of this report as Plates 2, 3, 4, and 5. Each wiggle trace deviates to the right for a positive amplitude reflection event and deviates to the left for a negative amplitude reflection event. In addition the positive area associated with the positive event is blackened proportionally to the amplitude of the event. Flat events were stronger in amplitude than the dipping events, suggesting that automatic migration of the data may improve the amplitude. All dipping events had migrated downdip. To restore the seismic image for interpretation post-stack migration was performed (see Plate 5). Plate 5 is an improved image of the model in contrast to Plate 4. This suggests that automatic migration of the seismic data will be required. For enhancing the stratigraphic interpretation, pre-stack migration instead of post-stack, may be required.

3.3 Results

The top of the Arapahoe Formation was associated with a strong reflection event. However, the caliche layer located between stations 700 and 800 (Plates 2, 3, 4, and 5) prevented the transmission of almost all of the energy downward. This suggested that it will be necessary to place the seismic source below the top of a developed caliche layer.

The intra-alluvial water table was associated with a reflection event between stations 800 and 860, as shown on Plates 4 and 5. The interface between the weathered Arapahoe Formation claystone and the unweathered claystone exhibited a strong reflection event on all plates.

The Arapahoe Formation sandstone lenses had different responses, depending on their acoustic impedances. The Type A sandstones exhibited a positive reflection event at the base of the sandstone. The Types B and C sandstones exhibited positive reflection events at the top of the lens. The Type C sandstone exhibited a negative reflection event at the base of the sandstone. The Types B and C sandstones had higher amplitude events compared to the Type A sandstones. A Type A sandstone 3 feet thick located between stations 370 and 480 had a negative reflection event. This implied that 3 foot beds can be resolved on processed seismic data.

The Arapahoe sandstone between stations 370 and 500 (Plate 1) had a varying velocity and constant density of 2.4. At station 500 it had a seismic velocity of 8000 feet/second to grading a velocity of 6000 feet/second at station 370. The amplitude of the reflection event associated with the top of the sandstone decreased as the seismic velocity decreased (see Plate 5). The base of the sandstone had an associated negative reflection event, which also attenuated as the seismic velocity decreased.

4.0 CONCLUSIONS AND RECOMMENDATIONS

4.1 Seismic Data Acquisition Parameters

The recommended seismic acquisition parameters are shown in Table 2. The modeling results demonstrate the need to record frequencies in the 500 to 1000 hertz range. Knapp (1988) states that 100 Hertz geophones are necessary to record frequencies above 500 Hertz. No more than one geophone per group should be used because geophone arrays attenuate high frequencies (Knapp & Steeples, 1986).

A geophone spacing of 2 to 4 feet should yield adequate spatial sampling to record and process data as shallow as 20 feet with full fold. The overall distance covered by geophones on the ground (geophone spread length) should be at least equal to the depth to the target to be mapped, in the case of the proposed work approximately 300 feet. A 96-channel seismograph will provide a recording system that is adaptable to the approximate 300 foot spread length.

It is unknown whether the split spread geometry should be balanced or unbalanced. The modeling software did not have the capability to simulate an unbalanced split spread; therefore the two geometries should be tested in the field and analyzed to determine the optimum cable geometry.

One of the project goals is to detect sandstone lenses as thin as 3 feet. The recording sample rate of 1/4 millisecond gave a resolvable time separation for reflection events with as little as 3 feet thickness. The synthetic events occurred within the first 100 milliseconds (approximate depth of 200 feet). Real events as deep as 250 feet are of interest. Therefore, the total recording time should be at least 125 milliseconds. However, based on our experience, we believe a total recording time of 500 milliseconds should be used in actual field work. Later recorded events may be required for the seismic data processing sequences. The additional seismic field acquisition and processing costs are minimal.

The modeling results demonstrated that the presence of a caliche layer in the shallow subsurface degraded the data quality by severely limiting the amount of transmitted energy. A possible solution is to place the seismic source several feet beneath the top of the caliche layer. A model solution to the caliche layer problem was not sought due to limited resources.

TABLE 2

Recommended Seismic Reflection Acquisition Parameters

Geophone Spacing	2 to 4 feet
Geophone Frequency	100 Hertz
Geophones/station	One
Far Offset	approximately 150 feet
Cable geometry	Split spread, Unbalanced or balanced (to be determined in field)
Number of recording channels	96
Sample rate	0.25 millisecond
Record length	500 milliseconds
Filter - Low Pass	200 Hertz
Filter - High Pass	500 Hertz
Filter slope	24 decibels/octave
CDP Fold	24 to 48 (to be determined in the field)
Energy Source location	Surface (Subsurface in areas of caliche)

4.2 Recommended Location of Task 2 Seismic Reflection Lines

Task 2 will involve the collection of seismic data from five 300 foot lines in the Medium Priority Sites. The purpose is to demonstrate the high-resolution shallow reflection seismic technique and verify the modeling responses. The effect of noise generated by plant activities on the seismic data during acquisition will also be evaluated. Data from Task 2 will be used to determine the most cost-effective field acquisition parameters for further seismic work in the Medium Priority Areas. Some geologic problems will also be solved in the vicinity of the seismic reflection lines.

Figure 6 shows the locations of the proposed seismic reflection lines for the Task 2 seismic reflection tests. Each line will yield up to 300 CDPs per line for the most frequent source spacing. This amount of data will be sufficient to evaluate the survey results. Some data should be collected from an area within the plant perimeter to determine the effect of plant noise on data quality. The data from these lines should be acquired with a CDP fold of 48. During the processing stage, these data should be processed at 48 fold and have simulated processing of 24 fold (i.e., use every other shot record). The comparison of results will determine the field effort needed to obtain acceptable data quality for interpretation.

Some data should be collected in the eastern portion of the investigation area. These data can most likely be collected at 24 fold, since the distance to the plant should attenuate plant noise sufficiently. These data should be processed at a simulated 12 fold to determine if a reduced field effort will obtain acceptable data quality. Data should also be collected in the area between the plant and the eastern fringe of the investigation area. These data should be collected at 24 fold. By collecting data in these three characteristic noise areas (in the plant area, adjacent to the plant area, and 1,000 feet beyond the plant area), it can be determined what level of field effort will be needed to obtain acceptable data quality. The results of this work will be used to estimate the costs per linear foot in each area for further work.

All test lines should tie into existing borehole geological and geophysical data. The geophysical interpreter will be able to determine if there is a strong correlation between the seismic reflection data and the borehole data.

In addition, data from a vertical seismic profile (VSP) should be collected in an existing well or new drill hole near a seismic reflection line. VSP data provide, at a minimum, arrival times from the surface to a geophone's downhole position. From these arrival times and known source geometry, the interval velocities of the lithologic units can be calculated. The VSP data can be processed and displayed as a seismic profile. Seismic events associated with known lithologic units in the drill hole can then be identified on the nearby seismic profiles.

Other borehole geophysical data should be collected in the same drill hole, including a gamma-gamma (density) log, natural gamma log, and a neutron log. The density log can be used to determine in situ formation bulk density. The gamma ray log, in conjunction with the neutron log, will provide lithologic data. The neutron log will also provide in situ water saturation data. These data will provide the seismic intepreter comprehensive tools to determine if the objectives of the test survey have been met.

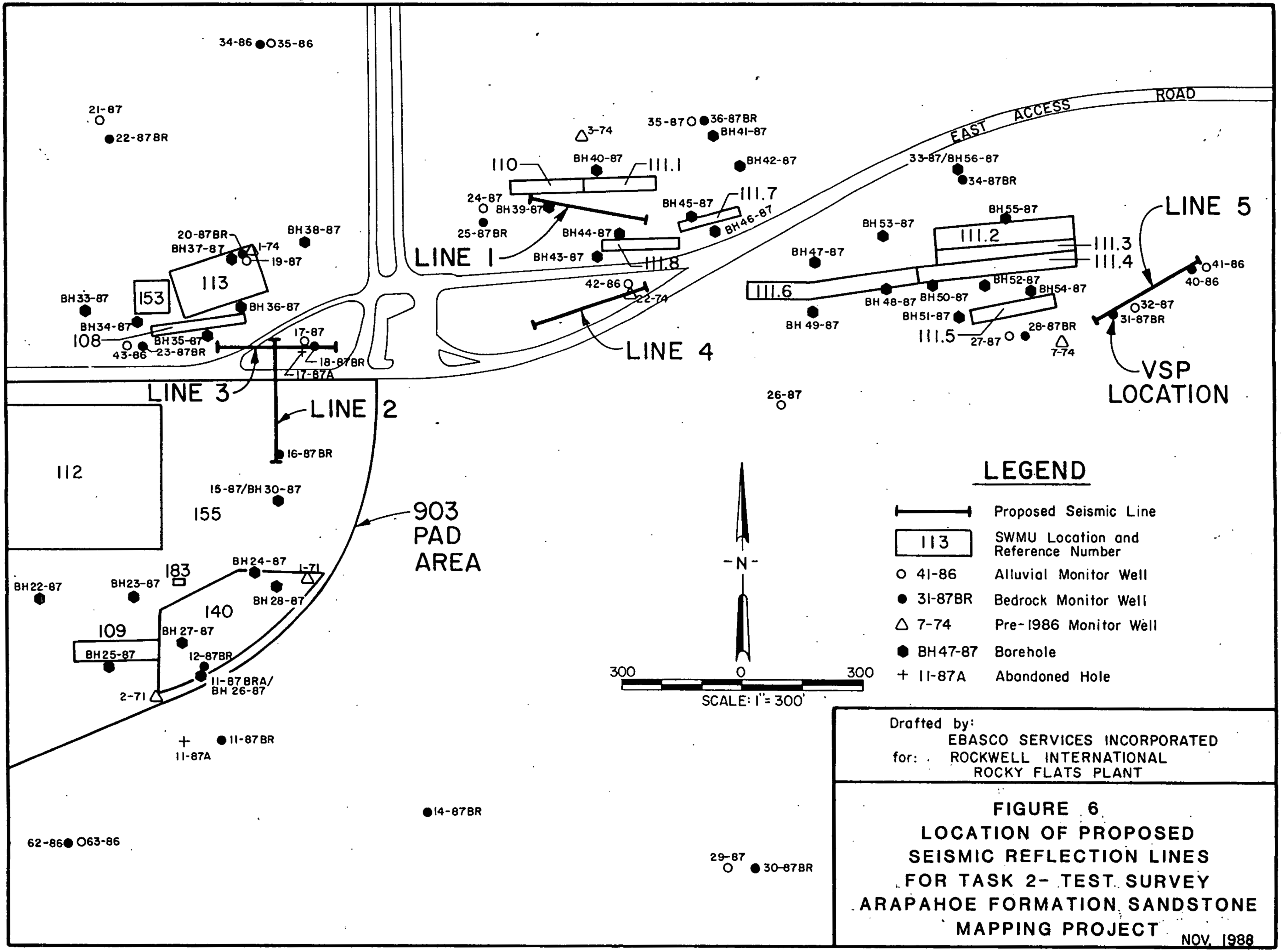

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FIGURE 6
LOCATION OF PROPOSED SEISMIC REFLECTION LINES FOR TASK 2- TEST SURVEY ARAPAHOE FORMATION SANDSTONE MAPPING PROJECT

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4.3 Proposed Line Locations for Field Tests

The proposed location for Line 1 (Figure 6) is located along cross section H-H' from the Remedial Investigation Report for the 903 Pad, Mound, and East Trenches Areas (Rockwell International, 1987). This line will tie into two boreholes, BH 39-87 and BH 44-87. The latter borehole appears to have an interpreted alluvial channel. Well 25-87BR is just east of a subcropping Arapahoe Formation sandstone and projects into the proposed seismic line.

The proposed location for Line 2 ties into Well 16-87BR which has a series of interbedded siltstones, sandstones, and claystones. This geologic series will be used to demonstrate the vertical resolution of the seismic reflection method. Line 2 also ties into the proposed location of Line 3. An Arapahoe Formation sandstone found in Well 16-87BR pinches out before reaching Well 18-87BR. Line 2 will be used to determine where the pinchout occurs.

The proposed location for Line 3 ties into Well 18-87BR. Arapahoe Formation sandstones found in Well 23-87BR project eastward into Well 18-87BR. Line 3 is positioned to detect these sandstones and tie into Line 2. Line 3 will also be used to determine the structural dip in this area.

The proposed location for Line 4 ties into existing borehole geophysical data (natural gamma and neutron logs) collected from Well 22-74.

The proposed location for Line 5 ties into Wells 31-87BR and 40-86. Arapahoe Formation sandstones found in Well 40-86 apparently become siltstones in Well 31-87BR. This line will be used to demonstrate the seismic response of sandstones grading into siltstones.

4.4 Additional Modeling

The area east of the plant has the potential for the occurrence of a caliche layer. Budgetary restrictions prevented the modeling of a subsurface seismic source to eliminate this potential problem. It is probable that a subsurface source in areas of a caliche layer will yield useable data. Automigration of dipping events was performed to determine the quality of the migrated data for interpretation. Plate 5 is the migrated seismic reflection profile. The image of the model has improved relative to Plate 4. Abrubt changes in dip of events in the near surface has caused some mismigration of events and data gaps. These problems can be addressed by pre-stack migration or additional iterations of processing in the post-stack migration step.

5.0 REFERENCES

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APPENDIX

GLOSSARY

A selection of relevent geophysical terms extracted from
Encyclopedic Dictionary of Exploration Geophysics, 1984,
Society of Exploration Geophysicists

ACCELEROMETER - A geophone whose output is proportional to acceleration. A moving coil geophone, for example, with a response proportional to frequency (as may be the case below the natural frequency) may operate as an accelerometer.

ACOUSTIC LOGGING - A borehole logging survey which will display any of several aspects of acoustic-wave propagation, i.e., a sonic, amplitude, character or 3-log.

AIR WAVE - Energy from the shot which travels in the air at the velocity of sound: 1051 (1 + 0.00217T) ft/sec, where T = Fahrenheit temperature, or 331.3 (1 + 0.00366C) m/sec, where C = Centigrade temperature.

ALIAS - Data in sampled form have an ambiguity where there are fewer than two samples per cycle. This creates a situation where an input signal at one frequency appears to have another frequency at the output of the system. Half of the frequency of sampling is called the folding or Nyquist frequency, f_N, and a frequency larger than this, $f_N + Y$, appears to have the smaller frequency $f_N - Y$. To avoid this ambiguity, frequencies above the Nyquist frequency must be removed by an anti-alias filter before the sampling. Otherwise the system will react as if the spectral characteristics were folded back at the Nyquist frequency. Thus, for a system sampled over 4 msec, or 250 times per second, the Nyquist frequency is 125 cps; if, for example, 50 cps is within the pass band, then 200 cps will also be passed if an anti-alias filter is not used, appearing upon output to have a 50 cps frequency. The pass bands obtained by folding about the Nyquist frequency are also called "alias bands," "side lobes," and "secondary lobes." Aliasing is an inherent property of all sampling systems and applies to digital seismic recording and also to the sampling which is done by the separate elements of geophone and shotpoint arrays.

ANALOG - (1) A continuous physical variable (such as voltage or rotation) which bears a direct linear relationship to another variable (such as earth motion) so that one is proportional to the other. (2) Continuous as opposed to discrete or digital.

ANOMALY -	A deviation from uniformity in physical properties, often of exploration interest. For example, a travel time anomaly, Bouguer anomaly, free-air anomaly.
APPARENT VELOCITY -	(1) The velocity with which a wavefront registers on a line of geophones. (2) The inverse slope of a time-distance curve.
AUTOMATIC GAIN CONTROL (AGC) -	A system in which the output amplitude is used for automatic control of the gain of a seismic amplifier, usually individual for each channel, although multi-channel devices are sometimes used.
BEDROCK -	Any solid rock exposed at the surface of the earth or overlain by unconsolidated material.
BODY WAVES -	The only waves which travel through the interior of a body consisting of P-waves and S-waves.
CABLE -	The assembly of electrical conductors used to connect the geophone groups to the recording instrument.
CHANNEL -	(1) A single series of interconnected devices through which geophysical data can flow from sources to recorder. Most seismic systems are 24 channel, allowing the simultaneous recording of energy from 24 groups of geophones. (2) A localized elongated geological feature resulting from present or past drainage or water action; often presents a weathering problems. (3) An allocated portion of the radio-frequency spectrum.
CHANNEL WAVE -	An elastic wave propagated in a layer of lower velocity than those on either side of it. Energy is largely prevented from escaping from the channel because of repeated total reflection at the channel boundaries or because rays which tend to escape are bent back toward the channel by the increasing velocity away from it in either direction.
CHARACTER -	(1) The recognizable aspect of a seismic event, usually in the waveform, which distinguishes it from other events. Usually a frequency or phasing effect, often not defined precisely and hence dependent upon subjective judgment. (2) A single letter, numeral, or special symbol in a processing system.

COMMON DEPTH POINT (CDP) - The situation where the same portion of subsurface produces reflections at different offset distances on several profiles.

COMPRESSIONAL WAVE - An elastic body wave in which particle motion is in the direction of propagation. (Same as P-waves, longitudinal wave, dilation wave).

CONVERTED WAVE - A wave which is converted from longitudinal to transverse, or vice versa, upon reflection or refraction at oblique incidence from an interface.

CRITICAL ANGLE - Angle of incidence, Θ_c, for which the refracted ray grazes the surface of contact between two media (of velocities V_1 and V_2):

$$\sin \Theta_c = V_1/V_2$$

CRITICAL DISTANCE - Used in either of two different meanings: (1) The offset at which a refracted event becomes the first break; cross-over distance. See Dobrin, p. 73. (2) The offset at which the reflection time equals the refraction time; that is, the offset for which the reflection occurs at the critical angle.

CROSSFEED - (Crosstalk) - Interference resulting from the unintentional pickup of information or noise on one channel from another channel.

CROSS-HOLE METHOD - Technique for measuring in situ compressional and shear wave velocities by recording transit times from a source within one borehole to receivers at the same elevation in one or more other boreholes. Sources may be explosive or directional to enhance either P- or S-wave generation.

CROSS SECTION - A plot of seismic events.

DATUM - (1) The arbitrary reference level to which measurements are corrected. (2) The surface from which seismic reflection times or depths are counted, corrections having been made for local topographic and/or weathering variations. (3) The reference level for elevation measurements, often sea level.

DELAY TIME - (1) In refraction work, the additional time taken for a wave to follow a trajectory to and along a buried marker over that which would have been taken to follow the same marker considered hypothetically to be at the ground surface or at a reference level. Normally, delay time exists separately under a source and under a detector; and is dependent upon the depth of the marker at wave incidence and emergence points. Shot delay time plus geophone delay time equals intercept time. See Dobrin, p. 83. (2) Delay producted by a filter.

DIFFRACTION - (1) Scattered energy which emanates from an abrupt irregularity of rock type, particularly common where faults cut reflecting interfaces. The diffracted energy shows greater curvature than a reflection (except in certain cases where there are buried foci), although not necessarily as much as the curve of maximum convexity. It frequently blends with a reflection and obscures the fault location or becomes confused with dip. (2) Interference produced by scattering at edges. (3) The phenomenon by which energy is transmitted laterally along a wave crest. When a portion of a wave train is interrupted by a barrier, diffraction allows waves to propagate into the region of the barrier's geometric shadow.

DIGITAL - Representation of quantities in discrete units. A digital system is one in which the information is represented as a continuous flow of the quantity constituting the signal.

DOWN-HOLE METHOD - Technique for measurement of in situ compressional and shear wave velocities utilizing a seismic source at ground surface and a clamped triaxial geophone at depth in a borehole. Shear wave energy is often enhanced by use of directional sources such as striking the ends of a weighted plank.

END LINE - Shotpoints that are shot near the end of the spread.

FIRST BREAK - (First arrival) The first recorded signal attributable to seismic wave travel from a known source. First breaks on reflection records are used for information about the weathering. Refraction work is based principally on the first breaks, although secondary (later) refraction arrivals are also used.

GALVANOMETER - A part of a seismic camera consisting of a coil suspended in a constant magnetic field. The coil rotates through an angle proportional to the electrical current flowing through the coil. A small mirror on the coil reflects a light beam, which exhibits a visual record of the galvanometer rotation.

GEOPHONE - (Seismometer) Instrument used to convert seismic energy into electrical energy.

GEOPHONE STATION - Point of location of a geophone on a spread, expressed in engineering notation as 1+75 taken from 0+00 at the beginning of the line.

GROUP VELOCITY - The velocity with which most of the energy in a wave train travels. In dispersive media where velocity varies with frequency, the wave train changes shape as it progresses so that individual wave crests appear to travel at a different velocity (the phase velocity) than the overall energy as approximately enclosed by the envelope of the wave train. The velocity of the envelope is the group velocity. Same as dispersion.

HYDROPHONE -	(Pressure detector) A detector sensitive to variations in pressure, as opposed to a geophone which is sensitive to motion. Used when the detector can be placed below a few feet of water as in marine or marsh work or in a well. The frequency response of the hydrophone depends on its depth beneath the surface.
IN-LINE OFFEST -	Shotpoints that are in line, but offset to, a spread.
LEADS -	An electrical conductor used to connect electrical devices. Geophones are connected to cables at the takeouts via leads on the geophones.
LINE -	A series of profiles shot in line.
LOVE WAVE -	A surface seismic wave associated with layering. This wave is characterized by horizontal motion perpendicular to the direction of propagation, with no vertical motion.
LOW-VELOCITY LAYER -	weathering.
MIS-TIE -	(1) The time difference obtained on carrying a phantom or reflection or some other measured quantity around a loop; or the difference of the values at identical points on intersecting lines or loops. (2) In refraction shooting, the time difference from reversed profiles which gives erroneous depth and dip calculations.
MULTIPLE -	Seismic energy which has been reflected more than once. Same as long-path multiple, short path multiple, peg-leg multiple, ghost.
NOISE -	(1) Any undesired signal; a disturbance which does not represent any part of a message from a specified source. (2) Sometimes restricted to energy which is random. (3) Seismic energy which is not resolvable as reflections. In this sense noise includes microseisms, shot-generated noise, tape-modulation noise, harmonic distortions, etc. Sometimes divided into coherent noise (including non-reflection coherent events) and random noise (including wind noise, instrument noise, and all other energy which is non-coherent). To the extent that noise is random, it can be attenuated by a factor of n by compositing n signals from independent measurements. (4) Sometimes restricted to seismic energy not derived from the shot explosion. (5) Disturbances in observed data due to more or less random inhomogeneities in surface and near suface material.
NOISE SURVEY -	(Ground noise survey); A mapping of ambient, continuous seismic noise levels within a given frequency band. As some geothermal reservoirs are a source of short-period seismic energy, this technique is a useful tool for detecting such reservoirs.
OBSERVER -	The geophysicist in charge of recording and overall field operations on a seismic crew.
ON-LINE -	Shotpoints that are shot at any point on a spread other than at the ends of the spread.

OSCILLOGRAPH -	Camera.
OSCILLOSCOPE -	A type of oscillograph that visually displays an electrical wave on a fluorescent screen as of the cathode ray tube type.
PHASE VELOCITY -	The velocity with which any given phase (such as a trough or a wave of single frequency) travels; may differ from group velocity because of dispersion.
PLANT -	The manner in which a geophone is placed on or in the earth; the coupling to the ground.
PROFILE -	The series of measurements made from several shotpoints into a recording spread from which a seismic data cross section or profile can be constructed.
RAYLEIGH WAVE -	A seismic wave propagated along a free surface. The particle motion is elliptical and retrograde.
RAYPATH -	A line everywhere perpendicular to wavefronts (in isotropic media). The path which a seismic wave takes.
REFLECTION SURVEY -	A survey of geologic structure using measurements made of arrival time of events attributed to seismic waves which have been reflected from interfaces where the acoustic impedance changes.
RESOLUTION -	The ability to separate two features which are very close together.
SEISMIC AMPLIFIER -	An electronic device used to increase the electrical amplitude of a seismic signal. (See geophone)
SEISMIC CAMERA -	A recording oscillograph used to produce a visible pattern of electrical signals to make a seismic record.
SEISMIC VELOCITY -	The rate of propagation of seismic wave through a medium.
SEISMOGRAM -	A seismic record.
SHEAR WAVE -	A body wave in which the particle motion is perpendicular to the direction of propagation. (Same as S-wave, equivoluminal, transverse wave).
SHOOTER -	The qualified, licensed individual (powderman) in charge of all shotpoint operations and explosives handling on a seismic crew.
SHOT DEPTH -	The distance down the hole from the surface to the explosive charge. With small charges the shot depth is measured to the center or bottom of the charge, but with large charges the distances to both the top and bottom of the column of explosives are usually given.
SHOT INSTANT -	(Time Break, TB, Zero Time) - The instant at which a shot is detonated.

SHOTPOINT - Point of location of the energy source used in generating a particular seismogram. Expressed either sequentially for a line (i.e. SP-3) or in engineering notation (i.e. SP 3+00).

SIGNAL ENHANCEMENT - A hardware development utilized in seismographs and resistivity systems to improve signal-to-noise ratio by real-time adding (stacking) successive waveforms from the same source point and thereby discriminating against random noise.

SPREAD - The layout of geophone groups from which data from a single shot are recorded simultaneously.

STONELEY WAVE - A type of seismic wave propagated along an interface.

SURFACE WAVE - Energy which travels along or near the surface (ground roll).

TAKEOUT - A pair of leads from a milticonductor cable to which geophones can be connected.

TIME BREAK - The mark on a seismic record which indicates the shot instant or the time at which the seismic wave was generated.

TOMOGRAPHY - The reconstruction of an object from a set of its projections. Tomographic techniques are utilized in medical physics as well as in cross-borehole electromagnetic and seismic transmission surveys.

TRACE - A record of one seismic channel. This channel may contain one or more geophones. A trace is made by a galvanometer.

UPHOLE - A method, also called the Meissner technique, of reconstructing wave front diagrams by shooting at several depths and recording on a full surface spread of geophones. Derived wavefront diagrams yield a true picture of wavepaths and, therefore, layering in the subsurface.

WAVE TRAIN - (1) The sum of a series of propagating wave fronts emanating from a single source. (2) The complex wave form observed in a siesmogram obtained from an explosive source.

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Nov. 1988

PLATE 1

GEOLOGIC MODEL
MEDIUM PRIORITY SITES AREA
ROCKY FLATS PLANT

HORIZONTAL SCALE 1 INCH = 16 FEET (Approx.)
NO VERTICAL EXAGGERATION

VIEW LOOKING SOUTH

HORIZONTAL POSITION (FEET)

LEGEND

ARAPAHOE SANDSTONE TYPE	VELOCITY (ft./sec.)	DENSITY (gm./cc.)
A	6000	2.1
B	7000	2.3
C	8000	2.4

V = Seismic p-wave velocity in feet per second

d = Bulk formation density in grams per cubic centimeter

PLATE 1

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PLATE 2

SYNTHETIC SEISMIC REFLECTION PROFILE
MEDIUM PRIORITY SITES AREA
ROCKY FLATS PLANT

HORIZONTAL SCALE 1 INCH = 16 FEET (Approx.)

VIEW LOOKING SOUTH

HORIZONTAL POSITION (FEET)

MODEL INFORMATION

FULL RAYTRACING ALGORITHM

FIRST SHOTPOINT	0
SHOTPOINT INTERVAL	4 FEET
NUMBER OF SHOTPOINTS	225
SHOTPOINT DEPTH	0 FEET
RECEIVER INTERVAL	2 FEET
RECEIVERS PER SHOT	96
NEAR OFFSET	4 FEET
RECEIVER SPREAD	SPLIT
CDP FOLD	24
FILTER TYPE	TRAPEZOIDAL
FILTER BANDPASS	20-100-150-300 Hz
DATUM PLANE	6000 FEET
DATUM CORRECTION VELOCITY	1100 FEET/SECOND (SEE TEXT FOR EXPLANATION)

PLATE 2

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PLATE 3

SYNTHETIC SEISMIC REFLECTION PROFILE
MEDIUM PRIORITY SITES AREA
ROCKY FLATS PLANT

HORIZONTAL SCALE 1 INCH = 16 FEET (Approx.)

VIEW LOOKING SOUTH

HORIZONTAL POSITION (FEET)

MODEL INFORMATION

FULL RAYTRACING ALGORITHM

FIRST SHOTPOINT	0
SHOTPOINT INTERVAL	4 FEET
NUMBER OF SHOTPOINTS	225
SHOTPOINT DEPTH	0 FEET
RECEIVER INTERVAL	2 FEET
RECEIVERS PER SHOT	96
NEAR OFFSET	4 FEET
RECEIVER SPREAD	SPLIT
CDP FOLD	24
FILTER TYPE	TRAPEZOIDAL
FILTER BANDPASS	20-100-250-500 Hz
DATUM PLANE	6000 FEET
DATUM CORRECTIONAL VELOCITY	1100 FEET/ SECOND (SEE TEXT FOR EXPLANATION)

PLATE 3

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PLATE 4

SYNTHETIC SEISMIC REFLECTION PROFILE
MEDIUM PRIORITY SITES AREA
ROCKY FLATS PLANT

HORIZONTAL SCALE 1 INCH =16 FEET (Approx.)

VIEW LOOKING SOUTH

HORIZONTAL POSITION (FEET)

MODEL INFORMATION

FULL RAYTRACING ALGORITHM

FIRST SHOTPOINT	0
SHOTPOINT INTERVAL	4 FEET
NUMBER OF SHOTPOINTS	225
SHOTPOINT DEPTH	0 FEET
RECEIVER INTERVAL	2 FEET
RECEIVERS PER SHOT	96
NEAR OFFSET	4 FEET
RECEIVER SPREAD	SPLIT
CDP FOLD	24
FILTER TYPE	TRAPEZOIDAL
FILTER BANDPASS	20-100-500-999 Hz
DATUM PLANE	6000 FEET
DATUM CORRECTION VELOCITY	1100 FEET/SECOND (SEE TEXT FOR EXPLANATION)

PLATE 4

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PLATE 5

SYNTHETIC SEISMIC REFLECTION PROFILE
IMAGE RAY MIGRATION
MEDIUM PRIORITY SITES AREA
ROCKY FLATS PLANT

HORIZONTAL SCALE 1 INCH 16 FEET (APPROX.)

VIEW LOOKING SOUTH

HORIZONTAL POSITION (FEET)

MODEL INFORMATION

IMAGE RAYTRACING ALGORITHM	
FIRST SHOTPOINT	0
SHOTPOINT INTERVAL	4 FEET
NUMBER OF SHOTPOINTS	225
SHOTPOINT DEPTH	0 FEET
RECEIVER INTERVAL	2 FEET
RECEIVERS PER SHOT	96
NEAR OFFSET	4 FEET
RECEIVER SPREAD	SPLIT
CDP FOLD	24
FILTER TYPE	TRAPEZOIDAL
FILTER BANDPASS	20-100-500-999 Hz
DATUM PLANE	6000 FEET
DATUM CORRECTION VELOCITY	1100 FEET/SECOND (SEE TEXT FOR EXPLANATION)

PLATE 5

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