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11

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Classification/Unclassified Controlled Nuclear Information		☐ Yes ☒ No		} SW BERGLIN <i>[Signature]</i> 6/30/93	
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RL Program/Project		☒ Yes ☐ No		M.J. Furman <i>[Signature]</i> 7/21/93	
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Information conforms to all applicable requirements. The above information is certified to be correct.					
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SUPPORTING DOCUMENT		1. Total Pages 45
2. Title Feasibility of the Shallow High-Resolution Seismic Reflection Technique for Use at the Hanford Site	3. Number WHC-SD-EN-TI-120	4. Rev No. 0
5. Key Words seismic recorders, receivers, seismic sources, nonreflecting, A/D conversion APPROVED FOR PUBLIC RELEASE	6. Author Name: S. M. Narbutovskih <i>S. M. Narbutovskih</i> Signature Organization/Charge Code 81231/PL3NA	
7. Abstract <i>7/29/93 D. Solis</i> Narbutovskih, S. M., 1993, Feasibility of the Shallow High-Resolution Seismic Reflection Technique for Use at the Hanford Site, WHC-SD-EN-TI-120, Westinghouse Hanford Company, Richland, Washington.		
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GLOSSARY

This section gives general information on pertinent terminology used throughout the text. Terms are listed with basic definitions to allow the reader a quick referral.

Seismic source--The method/equipment used at the surface to generate acoustic energy propagation in the subsurface. Each source is characterized by a unique amplitude range and frequency content that varies from site to site. Choice of the best source to image a specific target or depth horizon is crucial to achieving successful results for a shallow high resolution seismic survey.

Receiver--Geophones set at or near the surface or clamped into a borehole that sense acoustic energy. Geophones have a low end frequency below which they are damped. This means that to a certain extent geophones may be selected to remove unwanted low frequency energy. In the high frequency range, geophones can register parasitic frequencies in excess of 500 Hz caused by stimulating the instruments natural resonance. This will degrade the data and should be filtered out.

Channel--The electrical signal from one geophone or from several geophones connected together is sent as one input to the recorder. For shallow high resolution reflection surveys each geophone is sent to a separate channel. Consequently the number of channels on the recorder will limit the number of geophones that are active at any given time.

Trace--Referred to as a wiggle trace, this the data recorded from one channel displayed as a line. Each wavelet is associated with an acoustic event.

Seismic record--The data obtained when the seismic source generates one shot. A raw unprocessed record is displayed in the field showing the response of the nearby recording geophones.

Amplitude/frequency spectrum--The amplitude of acoustical energy plotted against the various frequencies contained in a seismic event. This plot may be generated for a signal recorded close to a seismic source called a near-field spectrum. It will provide information on source frequencies since most of the energy is still at the surface. A spectrum may also be generated from data recorded far from the source, called a far-field spectrum, and will provide information about the frequencies generated at depth. Knowledge of far-field spectra allow determination of the maximum resolution for a specific survey depth.

Geophone array--The pattern of geophones in a survey or the distribution of seismic sources fired at the same time. The most common array for shallow high resolution seismic reflection surveys is linear.

Spreads--Geometrical relationships between lines of geophones and shot locations. Usually a split-spread is used with the shot point in the center of a linear array with equal number of active geophones of either side.

Common mid-point recording technique (CMP)--Redundant coverage where each sampled point on a reflector is sampled multiple times.

Fold--By moving the shot point along a linear array of geophones, the same point on a reflector can be sampled many times producing redundancy in the data set. These redundant traces are combined to strengthen the reflected signal and to reduce random wavelets. The number of traces sampling the same point is referred to as the fold of the data.

Stacking--The process of combining traces sampling the same point of a reflector.

Receiver spacing--Distance between individual geophones. This parameter controls how often spatially a reflector is sampled. Setting the optimal spacing can also assist in reducing noise in the data.

Continuous profiling--Geophones and shots or sources are arranged to obtain continuous sampling of a reflector with no spatial gaps other than that due to the receiver spacing.

Signal--Any event on a seismic record from which information is to be obtained.

Noise--Any event on a seismic record that interferes with the detecting the desired signal. Coherent noise has a characteristic frequency and appears on adjacent traces. Some sources of coherent noise consist of groundroll, which is a surface wave emanating from the seismic source, shock waves traveling through the air and direct seismic arrivals. Incoherent noise is random. A common source for random noise is wind blowing plants and trees which vibrates their roots causing acoustic events.

Analog filter--Series of resistors/capacitors used on recording system to remove unwanted events with specific frequency bands. For shallow high resolution reflection surveys, low pass filters of 60 to 110 Hz are frequently used.

In situ velocity control--The quality of the data processing is improved if knowledge exists of the subsurface velocity structure. This information is obtained by directly measuring the distance and time for acoustic propagation at or in a borehole.

Sonic logs--Travel time data collected in a borehole that determines the acoustic velocity of a short interval of a formation. This method gives the most detailed information of velocity as a function of depth.

Vertical seismic profiling (VSP)--A technique to locate lateral velocity changes and to obtain in situ velocity control by using a seismic source at the surface and measuring arrival times at geophones located in a nearby borehole. Reverse vertical seismic profiling (RVSP) reverses the position of the geophones and the source placing the source in the borehole and the geophones at the surface.

CONTENTS

1.0	INTRODUCTION	1
2.0	CONCLUSIONS AND RECOMMENDATIONS	3
3.0	THEORY AND RESOLUTION REQUIREMENTS	9
4.0	PREVIOUS STUDIES	13
5.0	VELOCITY/DEPTH CONTROL	15
6.0	HIGH-FREQUENCY SEISMIC ACQUISITION EQUIPMENT	18
6.1	SHALLOW SEISMIC SOURCES	19
6.2	SEISMIC RECORDERS	21
6.3	RECEIVERS/CABLES	23
7.0	REFERENCES	23

FIGURES:

1	Structure contour map of the top of basalt surface at the 200 East Aggregate Area	28
2	Stratigraphic pinchout modeled with three different dominant frequencies, 20, 30 and 40 Hz	29
3	Discontinuities in a reflector due to vertical offsets such as a fault or erosional scarp	30
4	An earth model that consists of four reflectors with four nonreflecting segments A, C, C, and D	31
5	200 East Area Geologic Cross Section extending in a north-south direction	32
6a	Raw data section with time (s) on the vertical axis and distance (f) on the horizon axis	33
6b	The data are shown after part of the signal has been removed based on velocity content	34
7	This noise walkaway has distance in feet along the horizontal axis and time in milliseconds along the vertical axis	35
8	Vertical seismic profiling geometry with the shot or acoustic source at the surface	36
9	Simplified block diagram of a reflection acquisition system	37
10	Time/distance plot with arrival times for various coherent events indicated at the appropriate source-to-receiver offset	38
11	Schematic examples of 8-bit (left) and 12-bit (right) digital words	39
12	The effect of sampling rate on A/D conversion	40

TABLE:

1	Acoustic Resolution.	10
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1.0 INTRODUCTION

Data obtained during site characterization should be useful to assess the need for remediation, to evaluate and design effective remedial plans, and to allow long-term monitoring to discern remediation effectiveness. A valuable environmental tool that incorporates this data is a model that describes groundwater and vadose zone flow and transport characteristics. Data on geology and hydrology combined with information on contaminant sources are incorporated into these conceptual models that delineate the relative significance of the various fluid migration pathways. Downstream these same models also support risk assessment, remediation design, and long-term assessment of remediation effectiveness. Consequently, the building of coherent, accurate vadose zone and groundwater models is fundamental to a successful remediation. Among the important requirements for these models is accurate knowledge of flow domain boundaries and soil characteristics. At the Hanford Site, this knowledge is obtained primarily from borehole data, which provides information only at a point.

In the high energy flood and fluvial deposits found at the Hanford Site, it can, at times, be difficult to correlate lithologic horizons between boreholes. Where there is no borehole control, our understanding of the geometry of hydrogeologic boundaries and thus of fluid migration paths is limited. Surface geophysical techniques are generally used to provide a measure of geologic control between boreholes. In particular, the seismic reflection method has the potential to provide the greatest resolution of the subsurface hydrogeology between and beyond boreholes.

When properly integrated with well histories, geophysical logs and at least one other spatial geophysical data set, deep seismic reflection surveys have become the standard exploration technique to define stratigraphy and structure in the deep subsurface for 40 yr in the petroleum industry. In 1980, work began to adapt this deep imaging technique to shallow environmental and engineering problems with increasing success as appropriate acquisition equipment and processing was designed and our experience base broadened. Today this technique has been used successfully at numerous U.S. Department of Energy (DOE) sites requiring major clean-up efforts with the exception of the Hanford Site (Irons and Lewis, 1990; Irons and Lewis, 1989; Keller et al. 1990; Johnson and Clark, 1991; Bainer, B. per. comm. 1992; Majors, E. per. comm. 1992; Miller and Steeples, 1990; Miller et al. 1988).

One of the reasons for this report is to review the shallow high resolution seismic technique's applicability to site-wide investigations at the Hanford Site. Questions that could potentially be addressed with this technique range from the extension of lithologic control between boreholes such as resolving pinchouts in the Ringold lower mud, mapping structural lows in the caliche facies of the Plio-Pleistocene to using ultra high resolution techniques such as 3-D surveys and tomography to monitor water table changes during remediation pumping (Birkelo et al. 1987; Devaney 1984; Merrey et al. 1991; Lines et al. 1993; Burns et al. 1988; Cheruvier and Winkler, 1987). Considering the average drilling costs of \$850/ft per well, the cost savings associated with reducing the need for borehole control warrants close examination of this rapidly advancing technology.

Another purpose for this study is to evaluate this seismic technique's ability to map the erosional windows extending through the Elephant Mountain Basalt north of the 200 East Aggregate Area (Figure 1). Several monitoring wells mark the location of a region where the uppermost Elephant Mountain Basalt is missing allowing direct communication between the unconfined and confined Rattlesnake Ridge aquifer (Graham et al. 1984; Trent 1992). Also, this area is down gradient from contamination plumes in the 200 East Area. With the present well control and our current knowledge of the local hydrologic velocity gradients, it is not possible to determine if mass from the BY-Crib contamination plume is traveling into the confined aquifer through this gap in the Elephant Mountain Basalt.

This report documents an in-depth investigation of the shallow high resolution reflection technique to evaluate its potential usefulness for future work at the Hanford Site (Steeple 1990; Ward et al., 1990). The work scope included a semi-quantitative evaluation of the frequency requirements to resolve the boundaries of the basalt erosional window. These results were then used to evaluate acquisition equipment and field parameters and to set initial criteria for future characterization of the window. In addition, state-of-the-art technology advancements were studied to gain a better understanding of optimal acquisition equipment specifications, critical field parameters and procedures (Stephenson et al. 1992; Miller et al. 1992; Rector 1992; Miller et al. 1986; Miller et al. 1992; Miller and Steeple, 1991; Johnson and Clark, 1992; Hasbrouck 1991; Miller et al. 1989; Treadway et al. 1988; Michelsen et al. 1992; Christensen 1992; Rohay 1992; Chen et al. 1990). Special attention was given to problems associated with obtaining in situ acoustic velocity information, which has been lacking to date due to the absence of uncased boreholes (Chen et al. 1990; Rector 1992; Rector and Hardage, 1992; Zimmerman and Chen, 1993). Recommendations are made to guide future work in three consecutive phases that allow for interim assessments to evaluate continuing work on a project.

It was specifically out of the scope of this study to evaluate advanced processing techniques or to investigate the powerful, innovative methods for ultra high resolution of subsurface lithology. These methods include the use of shear wave analyses to discern the location and lateral extent of thin clay beds a few feet thick and local perched water zones, fullwave form analysis to allow in situ estimation of hydraulic permeability and acoustic tomography to estimate seismic velocities, lateral structural changes and hydraulic porosity (Johnson and Clark, 1991; Hasbrouck 1991; Burns et al. 1988; Cheruvier and Winkler, 1987; Hornby 1989; Justice et al. 1989; Woodward 1992; Phillips and Fehler, 1991; Devaney 1984).

Furthermore other geophysical techniques such as high resolution refraction methods, advanced transient electromagnetic methods (TEM), very low frequency (VLF) electromagnetic techniques and ground magnetics were not evaluated in this study by request. However, it should be noted that integrating two or more geophysical data sets with borehole geology frequently results in a superior interpretation (Lines et al. 1993; Dickson et al. 1992).

This report presents the conclusions and recommendations from this study then discusses resolution theory and frequency specifications. A review of previous site studies is given followed by a presentation of current methods to obtain velocity control. Finally an evaluation of data acquisition

equipment was done incorporating new advances in the industry and highlighting a "systems" approach philosophy.

2.0 CONCLUSIONS AND RECOMMENDATIONS

After reviewing the high resolution seismic technique and analyzing results from preliminary studies, it is concluded that shallow reflection surveys have the potential to significantly contribute to our understanding of fluid migration paths between and beyond borehole control. In fact, current drilling programs could be reduced while increasing areal and depth coverage. Evidence for this conclusion comes from four sources:

- (1) A recent survey conducted at the 300-FF-5 Operable Unit resulted in data that was encouraging but inconclusive in evaluating the limits of the reflection technique. The raw records were recently analyzed by an offsite contractor and it was concluded that a persistent reflection existed at 40 ms with hints of other reflectors at 60 ms and 110 ms (Steeple, D. per. comm. 1993). These are the reflectors that were stacked and mapped by Kunk (1993). However, these reflectors were low amplitude events and were obscured with low-frequency, high-amplitude noise. Since these data were collected with low to medium energy sources, the potential exists to improve on these results.
- (2) A higher energy source was employed at the 200 West Carbon Tetrachloride Site and the results were significantly better. This survey was designed to image only the caliche layer of the Plio-pleistocene at a depth of 140 ft, and consequently, no data were collected at other time horizons. In general, the reflector that correlates with the caliche was strong and well defined. This indicates that deeper horizons could have been sensed with a longer receiver spread. Problems occurred with the shallow time data because very high-amplitude, low-frequency groundroll signals obscured the reflected energy. The source used in this survey has a demonstrated history of causing this type of interference (Miller et al. 1992).
- (3) The above surveys suffered from the lack of borehole velocity surveys that allow the acoustic material properties to be correlated to the borehole geology and that increase processing capabilities. During the acquisition phase of the 200 West Area survey, field logistics impeded collection of the borehole data while the high energy source was on site. A high energy source is necessary to collect this type of data in steel-cased holes, as a later attempt with a low energy sources was not successful. During the Basalt Waste Isolation Project (BWIP), it was demonstrated that acoustic events can be detected and recorded through steel casing in the suprabasalt sediments provided a mobile surface source with sufficient energy is used (DOE 1988). The energy must be enough to allow the source to be moved away from the borehole to avoid interference of the first direct arrival event with signals transmitted down the casing (i.e., casing ring). Actually it is preferable to have the source in the hole and a receiver array at the surface since interfering events are then avoided. A preliminary test was conducted using the cable bit as the source and initial results are very

encouraging displaying distinct first arrival events. In addition, the cone penetrometer offers a viable alternative for the collection of densely spaced velocity data for statics control since an acoustic receiver can be emplaced with the cone head.

- (4) Finally, newly developed acquisition equipment will greatly increase the signal to noise ratio of future high resolution reflection surveys by reducing or eliminating the interfering noise, increasing the signal response of the high resolution frequencies and increasing the recording capabilities of low-amplitude, high-frequency signals. The best proven seismic land source used for deep oil and gas exploration is the swept or vibroseis system. Use of this source revolutionized seismic land acquisition in the mid 1960's, and now several swept sources have been developed for use in the shallow environmental and engineering arena. The ability to control the frequency content of the input signal while imparting maximum energy over time has several advantages. The low-frequency noise that obscured the reflected signal in previous surveys can be reduced or eliminated. Also, by increasing the frequency range and concentrating more power at these higher frequencies, the earth's natural low-pass tendencies can be offset. This feature greatly enhances detection of smaller features at deeper horizons.

Another important advance has been made in recording capabilities to detect very weak, exceptionally high-frequency signals and to significantly reduce systems noise. Until recently, the seismograph used to acquire data was of less importance to high resolution acquisition than the source characteristics. An innovative seismic recorder developed for the petroleum industry has significantly increased signal to noise ratios for acoustic acquisition. This system utilizes 24-bit resolution and 120 Db instantaneous dynamic range, which effectively captures even very low amplitude signals in high noise environments. The easiest way to understand the significance of this type of acoustic recording is by comparing the audible signal from a standard record player with a compact disk system. The technology that allows for the dramatic increase in audible resolution is the sigma/delta analog to digital (A/D) recording capabilities. The petroleum industry seismograph, although the recognized leader in this area, is too expensive to mobilize for use in the environmental arena. However, seismographs have become available utilizing these advanced techniques that are designed and priced specifically for environmental and engineering applications. One of these new systems will be field tested in early July 1993 at the Hanford Site to record borehole velocity data in the 200 West Area. It should be noted that by recording the complete acoustic signal, distorting analog filters currently used to reduce the effects of coherent high-frequency noise can be avoided while nondistorting digital velocity filters can be more effectively applied to separate noise from the desired signal.

Results from geophysical surveys are seldom definitive and always require subjective interpretation. The hydrologist and engineer deal with data that directly samples the subsurface and thus expect a definite answer since results are less subjective; however, this answer is only for the point location at the borehole and will be less representative away from the borehole. On the other hand, geophysical data is collected remotely between, beyond, and in place of borehole data by sensing a response related to the

medium's material properties. This observed data is then interpreted to predict changes in lithology, structures, or fluid migration paths. Consequently, the answers are not as precise or as accurate as the hydrologist and engineer may desire. The upshot is that the geophysicist must strive to improve his product by paying close attention to detail through all aspects of a project and staying cognizant with front line advances in development. Likewise, the hydrologist/engineer should recognize even though it is not as accurate as borehole information, geophysical data can provide control to guide interpretation between and beyond boreholes, especially seismic reflection data.

The application of any geophysical technique to a particular geology has a learning curve, as does the adaptation of any remedial technique to a specific subsurface environment. As more experience is gained in the use of shallow seismic techniques at the Hanford Site, the results can be expected to improve, provided continuity of management is provided.

Although the following recommendation is specific to defining the boundaries of erosional basalt windows, the general scheme can be adapted to work plans for any area onsite. Since proper acquisition of seismic data is more important than downstream processing or interpretation, a "systems" approach is recommended to optimize data collection. To implement this "systems" approach, each element of the acquisition system and procedure is chosen to provide the greatest amplitude, high-frequency signal with the lowest possible noise. If the data are acquired to optimize the signal to noise ratio, processing should be straight forward with minimal variations in the processing stream. The plan is implemented in three separate phases with a simple evaluation at the completion of each step to determine if the next phase is feasible. This allows work to be terminated before expensive production and processing steps are enacted. For each phase, goals and procedures are described, time requirements are estimated, and initial criteria to evaluate success is stated.

PHASE I:

Description--Acquisition of borehole velocity control.

Purpose--(1) Verify that current technology exists to obtain adequate velocity control to constrain seismic processing and interpretation of surface data and (2) Acquire necessary data for Phase II (feasibility forward modeling) and Phase III (acquisition field tests).

Procedure--Shallow velocity control to depths of 30 to 50 ft is necessary to perform static control. It could be obtained in a cost effective manner with a cone penetrometer (Rohay 1992). For deeper control, two scenarios are suggested. First, detailed measurements should be made with the cable drill bit used as the acoustic source during drilling of wells near the area of interest. As discussed in Section 5.0, this can be done inexpensively and without significant impact on the drilling procedure. All data should be collected with a 24-bit seismograph and 40-Hz two- or three-component geophones on a 96-channel system with receivers initially at 5 ft spacing. Use of the 24-bit seismograph throughout the study will ensure quality data and eliminate changes in data character based on variable recording capabilities. By using multi-component receivers, shear wave propagation can be monitored. Since data of this nature can be collected only once during the

drilling of a well and there is no additional cost, any true shear wave velocities should be obtained. These data may prove useful to discern unsaturated from saturated sediments such as perched water tables. Although fewer channels could result in adequate coverage, increased coverage allows the distance between geophones to be adjusted to study factors such as lateral changes in acoustic velocity and to estimate the earth's natural attenuation factor. This information can then be included in Phase II.

The second scenario is to obtain borehole control from existing wells using a standard Vertical Seismic Profiling (VSP) configuration (refer to Section 5.0). The BWIP demonstrated that acoustic impulses from the suprabasalt sediments can be sensed through steel casing. This procedure requires a high energy surface source, a three-component, clamping, oriented geophone that can accommodate variable hole size, a very sensitive seismic recorder to detect low amplitude arrivals and experienced field personnel. Careful field procedure and waveform analysis is critical. Well construction is another important factor in obtaining this data and after reviewing possible wells in the area, three have been selected as potential candidates (699-53-55B, 699-55-57, 699-59-55). Two other wells strategically located are 699-52-54 and 699-55-55, which have 5- to 7-in. bentonite-filled annuli that may attenuate the signal. Other wells are either double cased or house permanent piezometers.

The procedural steps are as follows:

- From cone penetrometer surveys or drilling data, the very shallow velocity structure should be determined and rough, vertical arrival times calculated for P-waves (compressional waves).
- By adjusting source offset distance with receiver 5 to 10 ft in the hole, locate arrivals close to expected arrival time. Record arrivals on both vertical and horizontal transducers. Stimulate casing and record signal to allow continued recognition of this signal.
- Move receiver down in 5 to 10 ft increments and record on the next channel. Plot data as collected to detect any velocity changes.
- Keep moving receiver down the hole. When the casing wave is recognized, carefully monitor its arrival on the record, and when it is close to the P-wave arrival, move source further from hole until the first arrival is again clearly a P-wave. The source may have to be placed far enough from the hole at a very shallow depth causing the P-wave to impact the casing with a greater horizontal than vertical component. The P-wave arrival can then be monitored with the horizontal transducer. However, since the sonde can rotate in the hole, the pulse polarity may switch with depth and this should be recognized. A horizontal arrival may actually be desirable since the casing is stiffer vertically than horizontally and a horizontal signal would propagate more easily through the casing.
- Carefully track the P-wave arrival, plotting the data in the field before lowering receiver to the next horizon.

Duration--Two man-months, since data collection is tied to a drilling schedule. The three studies can run concurrently.

Evaluation Criteria--The ability to recognize a distinct P-wave arrival will determine the success of the study. The quality of the calculated velocities can be evaluated by the agreement between the results of the three surveys. If results are not satisfactory, Phase II and III should not be continued.

PHASE II

Description--Construction of a quantitative velocity/depth model utilizing the results of Phase I.

Purpose--There are three objectives for Phase II:

- Evaluate if the target horizon has sufficient impedance contrast to reflect acoustic energy. This is unlikely to be a problem since the Elephant Mountain and Pomona Basalts are fast formations overlain by significantly lower velocity sediments.
- Determine resolution and source energy requirements to design the production survey. These results will set the criteria to evaluate source characteristics and determine initial acquisition parameters.
- Produce average and interval velocities as a function of depth to support processing and to correlate borehole geology with seismic reflectors.

Procedure--Conduct computer modeling of velocity structure using arrival times collected in Phase I.

Duration--One man-month.

Evaluation Criteria--The interface between the basalt and Hanford lower gravels is unlikely to have insufficient impedance contrast; however, for general studies with other targets, this is the place to determine if a geologic horizon can generate an acoustic reflection. Also, a qualitative comparison should be made to ensure that candidate sources have the potential to generate sufficient energy at required frequencies to image the target. This document contains preliminary calculations that indicate required resolution frequencies can be generated with existing sources (Sections 3.0 and 5.0). Whether or not the earth will return those frequencies is the question.

PHASE III

Description--Conduct preliminary field tests of multiple surface sources and conduct noise walkaway experiments.

Purpose--Determine the best source and field parameters with initial configuration set by the results of Phase II and obtain raw records displaying reflections from the basalt/sediment interface.

Procedure--It is recommended that a recognized expert in the area of shallow seismic reflection acquisition oversee work pertaining to these field studies. This allows an experienced, unbiased opinion to ensure data quality and to troubleshoot. Based on the energy/frequency results predicted in Phase II, identify all qualifying acoustic sources and eliminate those that may produce similar results. Although a further discussion of appropriate shallow, high-resolution sources is given in Section 6.0, particular attention should be given to the new swept sources. With the ability to control the input frequency range, it is possible to put a high-frequency signal up to 500-Hz into the earth while not exciting lower frequencies. The problem with groundroll may be significantly reduced by eliminating this natural frequency from the input bandwidth. More importantly, swept source technology has the greatest potential to return high-frequency signals from the earth because the input energy can be concentrated at higher frequencies to offset the earth's natural low-pass filtering effect. To increase the maximum input energy, the use of multiple vibrators is recommended.

Each source should be tested onsite using a 24-bit recorder and 40-Hz geophones. Although the data is not currently available to compare 16-bit to 24-bit recorders, a field survey by the Kansas State Geologic Survey is being conducted and results will soon be available. Although it is common to use 100-Hz geophones to damp high-amplitude, lower-frequency noise such as groundroll, this bandlimits the frequency content of the received signal and decreases resolution. If 24-bit sigma/delta seismographs perform as expected, there should be less signal distortion and increased resolution by recording a wider frequency band and digitally filtering out unwanted coherent signals during processing. Previously, this was not possible because high-amplitude, low-frequency signals saturated the limited 16-bit dynamic range leaving no space to record the low-amplitude, high-frequency signals. This reasoning suggests that low-frequency, signal-distorting analog filters used for spectral shaping and reducing amplitude error may not be necessary. The value of high-pass analog filters could be tested during the noise walkaway tests. Furthermore, the sample rate should be high to preserve very low-amplitude, high-frequency signals and to increase the nyquist frequency well above the required resolution frequency. Since the whole earth response is recorded, it may be necessary to process a few raw data records in the field to sufficiently evaluate the data and optimize the noise walkaway studies.

The maximum depth of the target horizon is over 300 ft from the surface, and thus a 144-channel system should be used. It may not be necessary to use all 144 channels; however, the increased flexibility could prove advantageous to modify array parameters during testing. Finally, the field test location could affect the results. The water table is only 5 ft above the Elephant Mountain Basalt outside the erosional window and 127 ft above the Pomona Basalt within the window. Therefore, the walkaway tests should be conducted in areas with both situations.

Duration--Two months of crew time.

Evaluation Criteria--The quality control expert should evaluate the raw records, recommend any preliminary processing such as initial F/K filtering to increase the signal to noise ratio and identify reflectors. These should then be matched to the borehole geology via the results of Phase I and Phase II to assure imaging the target. The amplitude and frequency content of the

basalt/sediment reflector can then be calculated to determine if resolution requirements are achieved.

This report only investigated the shallow reflection technique; however, it is recommended that multiple geophysical methods be used. Experience has shown that a synergistic approach frequently leads to a more constrained geologic model (Lines 1991; Lines et al. 1993). To supplement the reflection data, a high resolution refraction method and a low altitude or ground magnetic survey might be considered.

3.0 THEORY AND RESOLUTION REQUIREMENTS

This section provides basic theory and explains the importance of resolution to detect a specific subsurface target. The seismic reflection technique is briefly defined with an explanation of wave propagation, wave types, the relationship of acoustic velocity to wavelength and frequency, and resolution of subsurface features. For an in-depth treatment of these subjects refer to Telford et al. (1985) and Yilmaz (1987).

Acoustic waves are generated by pounding the earth's surface or causing an explosion at or below the surface. The resulting energy propagates through the subsurface and is modified by the various layers defined by acoustic impedance changes. At each point of acoustic variation, some of the energy is reflected according to Snell's law. The modified energy that is able to return to the earth's surface is detected by a series of receivers spread across the ground, usually in linear arrays. The characteristics of amplitude, frequency, and phase are monitored. Amplitude reflects the amount of energy returning to the surface, and frequency is the number of wavelengths passing a fixed point per second. The phase of an acoustic compressional wave is related to whether a cycle begins with a "push" or a "pull". This can be useful information since a change in phase may occur when a wave is reflected at an acoustic boundary depending on the nature of the velocity contrast. All three characteristics of wave propagation are considered during analysis of the data.

Elastic waves propagate in two basic ways. Body waves travel through the interior of an elastic body as either a series of compressions and expansions (i.e., compressional waves) or as slices moving perpendicularly to the direction of travel (i.e., shear waves). Although analyses of shear wave propagation can increase the level of confidence in interpretations, discussions in this study are directed towards compressional propagation only since there is more industry experience with compressional wave techniques. The second basic wave type is a surface wave that travels along an interface between layers with different elastic moduli and hence different velocities; however, the interface must be a free moving surface. A well known surface wave is generated by earthquakes and causes the destruction we see at the surface.

Although the acoustic velocity of a formation depends on the material properties of elastic moduli and density, the wavelength and frequency of the harmonic motion vary with velocity. As the velocity increases with depth in the earth, the wavelength increases and the frequency decreases. To detect or

resolve a subsurface feature, a propagating wave must be modified by this feature. The most critical wave property to allow this interaction is the wavelength. If the feature is physically much smaller than the wavelength, it is not possible to detect it. To determine whether a target has the potential to be detected by the seismic reflection method, an analysis of the required wavelengths and frequencies prior to designing the survey is advisable. For example, there is a limit how close two reflectors can be for a given wavelength before the seismic signal appears as one wavelet. The thickness of a layer can be measured only if the reflected signal from the top surface is separate from the bottom surface wavelet. An example of when this resolving ability is necessary would be detecting and mapping where the Lower Ringold Mud pinches out against the basalt basement. Pertinent to this study is "seeing" the basalt surface separate from the water table north of well 52-55 as the basalt drops into the erosional window.

The theoretical limit in vertical resolution is equal to one fourth the dominant wavelength (Yilmaz 1987). No seismic source induces a single frequency or a single wavelength wave. Instead a range of wavelengths is transmitted with more of the energy concentrated in a narrow band of wavelengths. This band is referred to as the "dominant wavelength" or the "dominant frequency".

Since the dominant wavelength increases with depth, a deeper feature must be thicker to be detected. This can be seen by comparing the results from calculations made on some representative Hanford velocities shown in Table 1 (DOE 1988). Note that as the velocity increases with depth from dry sediments to wet Ringold Formation to basalt, the size of a feature that can interact with the wave must be greater for a given dominant frequency. The magnitude of the dominant frequency and hence, the corresponding wavelength that reaches the sediment/basalt interface, depends in part on the dominant frequency put into the ground at the surface. Also, the noise level of the data will degrade the resolving ability of the seismic signal. Consequently, the quarter wavelength rule may be too generous, and in actual planning for a specific target, setting the resolution equal to the wavelength might be more appropriate. Using this conservative criterion, the resolution for a wave traveling at 11,000 fps with a dominant frequency of 50 Hz is 220 ft, a significant decrease in resolving potential.

Table 1. Acoustic Resolution.

Velocity (fps)	Frequency (Hz)	Resolution (ft)
3,000 (dry sediments)	50	15
11,000 (saturated L. Ringold)	50	55
16,000 (basalt)	50	80
3,000	100	8
11,000	100	28
16,000	100	40

Figure 2 shows a stratigraphic pinchout modeled with three different dominant frequencies, 20, 30 and 40 Hz. The actual edge of the wedge is beneath location A. Although the vertical axis is in milliseconds, the true thickness is given by the numbers across the top of Figure 2(a). The horizontal axis is distance across the surface. As the dominant frequency of the propagating wave is increased going from a to b, the wavelength is decreased and the point of resolving from one high amplitude wavelet to two distinct wavelets is moved towards the true termination point. In Figure 2(c), the point of resolution is even closer to the "pinchout" since the dominant frequency is greater at 40 Hz. Figure 2(d) is the same as Figure 2(b) except the true wedge geometry is shown on top of the seismic signature. The interpreter looks for this type of pattern displaying a bifurcation of one wavelet into two.

The degree of vertical resolution should also be considered when attempting to locate a fault with vertical throw or a sharp erosional dropoff. An example of a seismic signature illustrating this geologic situation is shown in Figure 3. The parabola shapes are caused by diffractions from the sharp edge of the offset and usually are processed out of the final records. The amounts of vertical relief are shown as fractions of the dominant propagating wavelength, λ . Notice that for offsets less than a quarter of a wavelength, it is not possible to detect the "faults." However, for greater relief the feature can be clearly imaged.

If a feature consists of two separate points situated relatively close together, the ability to discern these points as separate features is a function of the lateral resolution. This is governed by the size of the fresnel zone, which is controlled again by the dominant frequency. An explanation of this derivation is not necessary for the purposes of this discussion; a detailed description can be found in Yilmaz (1987). Essentially the analysis calculates the region in which the total energy arriving will interfere constructively. Two reflecting points within the region or zone are generally not discernable; that is, one reflecting point cannot be distinguished from the other.

This situation is illustrated in Figure 4 and is applicable to mapping channels, either small fluvial features or larger erosional channelways. Figure 4 shows the effect on the seismic record of increasing the size of a nonreflecting section corresponding to a channel as indicated by the solid bars at A, B, C, and D. Each reflector represents a deeper subsurface horizon with the vertical scale in seconds. This means that the Fresnel zone and the dominant wavelength increases with depth and thus resolving power decreases. Note that the smallest "channel" at A is barely recognizable at any depth while the largest discontinuity at D is recognizable at all depths. A more complete understanding of the relationship between the required dominant frequency at depth necessary to image a given target and the source frequency at the surface can be obtained by preliminary, quantitative modeling of this nature.

Ability to detect a feature can be improved by increasing the dominant frequency (i.e., decreasing the wavelength) of the propagating wave. This dominant frequency is a function of the seismic source, subsurface material properties, processing quality, and the recording capabilities). Of these variables, we have control over the acquisition abilities and the processing train. This leaves us with the question of what dominant frequency range is

needed at depth to resolve the erosional window north of BP1 Pond. However, the nature of the structural change between the control wells is at present unknown. The distances between these wells is roughly half a mile with no control to the northwest. The basalt/sediment interface may be gently sloping over this distance so that a wedge model (as shown in Figure 2) is most appropriate with the basalt gently dipping and separating from the water table reflector. The opposite situation is shown in Figure 5, which is an interpreted north-south cross section through wells 50-53 and 52-54 (after DOE-RL 1992) and shows a sharp change of relief in the basalt. This end member model corresponds to the vertical offsets displayed in Figure 3.

The request from engineering was to discern the basalt dropoff to within a few hundred feet. Calculations have been made to bracket the desired dominant frequencies to determine initial feasibility of the seismic project. Assumptions were made about local velocities based on velocity data collected during the BWIP project. Two end member velocities of 11,000 fps and 15,000 fps were used with the theoretical resolution set at a quarter of a wavelength. Resulting frequencies range from 14 to 19 Hz. These values are low for high resolution work since frequencies reported in the literature are routinely greater than 100 Hz (Merey et al. 1992; Miller et al. 1988; Miller et al. 1986; Miller and Steeples, 1990; Miller et al. 1992). However, this is using the theoretical resolution with no noise interference and assuming an excellent acoustic impedance contrast, a material property that determines how much energy will be reflected from an interface. A conservative value equal to the wavelength might be more representative. This results in a frequency range from 55 to 75 Hz. This estimate applies to the resolution of a wedge geometry. The actual vertical relief in the basalt is 130 ft. Using this value for the resolution, a conservative range for allowable dominant frequencies ranges from 85 to 130 Hz. Thus, care should be taken in planning any future surveys to optimize results by increasing the initial source frequencies.

This same analysis can be applied to determine the resolution of features in the upper sediments where formations terminate in the subsurface. An example are the suspected pinchouts of the Ringold Lower Mud against the basement, the verification of interfingering between the middle Ringold overbank muds and the discontinuous nature of the caliche horizon in the 200 West Area. In these areas velocities are much slower ranging from 2,000 to 5,000 fps. Once again a conservative estimate sets dominant frequencies from 20 to 50 Hz. Quantitative modeling of the specific environment appropriate to a specified target will tighten these frequency values.

This analysis did not account for the loss of signal strength or amplitude as the acoustic energy travels through the subsurface. This is a problem better addressed by forward modeling once direct velocity control and attenuation information have been obtained.

The cost of a shallow high resolution seismic survey across the entire region of the known basalt erosional window located at well 53-55 and 55-55 (Figure 1) would be much less than the cost of drilling one well to a 180 ft depth at a drilling cost of \$850/ft. The maximum number of wells required to define a sharp dropoff from the top of the Elephant Mountain Basalt to the Rattlesnake Interbed with a 200-ft resolution is nine while the minimum is one. This locates the boundary in only one direction while a well planned

reflection survey gives mappable coverage. The cost savings combined with the additional areal coverage warrants that consideration be given to developing the shallow high resolution seismic reflection technique for use at the Hanford Site.

4.0 PREVIOUS STUDIES

By reviewing previous reflection studies conducted on the Hanford Site, it is possible to estimate the appropriateness of the shallow high-resolution reflection technique for future applications on the Hanford Site. Previous seismic work can be placed into three categories: (1) data gathered to support BWIP, (2) surveys performed for risk evaluation of man-made structures for the nuclear industry, and (3) recent shallow high resolution surveys for environmental site characterization. Except for the nuclear risk studies, which involve very shallow work, each category has been reviewed to learn what equipment, field techniques and field specifications were employed and to evaluate the success of each.

Although there were numerous refraction surveys conducted for BWIP, there were only a few attempts at reflection work. The surveys and the results are discussed in DOE (1988). For a more detailed evaluation, the reader is referred to Kunk (1993). The goal of these surveys was to image the basalt/sediment interface and any faults extending through the basalt pile. The data were acquired prior to the development of the high resolution shallow reflection technique and used petroleum industry acquisition equipment and procedures. This equates to coarsely spaced receiver and shot spacings, low-frequency sources and low resolution seismic recorders. The data are of poor quality by today's standards and show very little reflection energy from the sediment pile, which was purposely not imaged.

The most important information from these surveys was the acquisition of borehole velocity control through steel-cased holes from vertical seismic profiling surveys. Although the actual data are not readily available, the results indicate that first arrivals can be obtained through the casing in the suprabasalt sediments. Two surface sources were used, a high energy air gun and a quarter pound of dynamite. According to the offsite contractor that acquired the data, it was difficult to obtain sufficient coupling of the source to the subsurface until the air gun was submerged in a 10 ft, water-filled pit (Walker, C. per. comm. 1992). Also several very cumbersome walkaway tests had to be performed to determine the optimal distance between the borehole and the source to avoid casing ring and to identify first compressional wave arrivals. Although the land air gun and dynamite are not the ideal source from the view of logistics, economics and the environment, this study is useful since it illustrates that velocity data can be acquired through steel casing in these unconsolidated sediments if the surface source has sufficient energy.

Many of the surveys conducted to support the nuclear industry were refraction or very shallow reflection studies, and consequently are not discussed here. Since there are numerous, diverse organizations collecting data at Hanford to assist in both engineering, risk assessment and environmental efforts, locating reliable sources of information can be

logistically difficult. It has recently been suggested that gross cross borehole surveys have been attempted at shallow depths with very close hole spacing of less than 40 ft. These reports are being investigated since they may delineate additional ways to acquire very shallow velocity control. If the work can be documented and proves useful, results will be reported separately.

Finally there have been two recent shallow reflection surveys aimed at high resolution. The first was conducted in the 300-FF-5 Operable Unit in 1991. For a complete discussion of the survey goals, specifications, and results, the reader is referred to Kunk (1993). Two main targets were the water table at roughly 40 ft depth and the Ringold Lower mud at about 180 ft. The water table is within 10 ft of the Hanford/Ringold contact while the top of the lower mud sequence is 30 ft from the basalt bedrock surface. The survey was conducted during the summer months when the top soil is dry and impedes acoustic coupling. After attempts to acquire the data by implanting the 40-Hz geophones in a normal fashion, they were buried up to 1.5 ft to allow adequate coupling. Two impact sources and one gun-type source were tested. While careful work was done to acquire the data, the results were nebulous for two reasons. First, the strength or amplitude of reflectors was very low with respect to high amplitude coherent noise. This made identification of the reflected signal less than clear. Second, it was not possible to obtain borehole velocity control and thus, processing was difficult. In these low velocity sediments, the uncertainty in velocity becomes amplified since small changes in velocity equate to large changes in time. Consequently, small errors in the assumed velocity can cause erroneous small structures to appear in the stacked sections. In addition, the lateral velocity variations can be enough to cause periodic stacking and static problems.

For the purpose of this study, the primary interest was to determine if the low-amplitude high-frequency signals apparent on the raw record were indeed reflectors. Consequently, a series of raw sections with and without a mild velocity filter applied were evaluated by a recognized expert in the area of shallow seismic reflection work. Examples of these sections are shown in Figure 6. After careful study of numerous records, it was concluded that a persistent reflector exists at a time of 40 ms with hints of deeper events at approximately 60 ms and 110 ms. These reflectors are located with red lines in Figure 6. Note the increase in amplitude of the wavelets from Figure 6a to Figure 6b after the velocity filter was applied. The dominant frequency of the reflected energy is about 70 to 80 Hz while the interfering noise has a dominant frequency range of 30 to 60 Hz. These three reflectors were the events that were mapped and interpreted in Kunk (1993) as the Hanford/Ringold-water table contact, the interfingering middle muds and the top of the lower mud. By applying the quarter wavelength rule, the theoretical vertical resolution of the data is about 6 ft at 80 Hz and a 2,000 f/s velocity. It was recommended that the lower frequency noise be separated from the reflectors by applying several simple lowcut frequency filters. Furthermore, it was suggested that more useful data could be obtained by conducting a seismic source study tailored to match the best source to a particular target and depth for the Hanford sediments.

The goal of the second survey at the Volatile Organic Compound (VOC) Arid Integrated Demonstration Site at the 200 West Area was to collect surface geophysical data to support a demonstration of a developing integration

technology. The reflection survey targeted the Plio-Pleistocene caliche horizon located approximately 140 ft from the surface. A very high energy source was employed with closely spaced shot points and receivers. The receivers were 100-Hz geophones while the seismic recorder had 16-bit resolution, the same used for the 300 Areas survey. Extensive noise walkaway tests were conducted prior to acquiring production data to study the coherent noise characteristics and to set the survey parameters to delineate only the caliche surface. As with the survey from the 300 Areas, high-amplitude groundroll noise interfered with the arrival of early events. A series of lowcut analog filters were used to reduce the effects of the noise. An example of a raw record collected with a 100-Hz lowcut filter is shown in Figure 7.

These data were collected during melting and freezing after an unusual amount of snowfall and this moisture may have helped acoustic coupling. Notice the strong, relatively high-amplitude high-frequency reflector marked with the arrow. From about 164 ft to the end of the line, it is well defined. However, as the data approach the source at the right of the figure, there is strong interference from high-amplitude low-frequency coherent noise. The noise is identified on the figure with a label at 332 ms. Since the target was solely the caliche, source to first receiver distance was extended for the final survey to eliminate this early time data. Although a comparison of the same test with no filters applied vs a 100-Hz filter demonstrate the reduction in the interfering noise, it was not reduced enough to allow defining the shallow subsurface reflectors that are there. The solution to this problem for future work involves the use of a new 24-bit recorder, which is discussed in Section 6.0.

Although there are definite reflectors that do correlate with the caliche horizon when an appropriate assumed velocity is used, the lack of direct velocity measurements hampered processing and interpretation of this data set also. Due to the lack of adequate field support, the contractors were not able to collect borehole velocity data while the high energy surface source was onsite and as a result, the stacked sections may contain spurious structures or do not stack as well as expected if velocity control had been obtained.

The results of this survey are very encouraging. It has been clearly demonstrated that good quality, strong, obvious reflectors can be obtained from depths close to 150 ft. There may indeed have been deeper reflectors; however, the initial testing and production survey lines were not long enough to answer this question. These results are even more encouraging in light of recent major advances in acquisition equipment designed specifically to obtain shallow, high resolution data with frequency contents up to 500 Hz and with increased dynamic recording range. These equipment advances are discussed in Section 6.0.

5.0 VELOCITY/DEPTH CONTROL

For standard petroleum reflection surveys, any processor, interpreter, researcher or manager will agree that understanding acoustic velocity as a function of horizontal coordinates and depth can be key to the success of a

survey. This data set has three primary functions that allow maximum utility of the surface survey. One use is for static adjustments, which correct for topographic relief between receiver elevations. This difference in elevation must be equated to a time difference by knowing the near surface velocity and is removed from the data such that all the records are referenced to a common datum. Generally this is not a problem for most deep reflection surveys; however, for shallow applications, the choice of the best datum can be critical since near surface velocities are very slow and heterogeneous. Small changes in velocity equate to large time shifts in the travel time data and thus, small velocity errors are large time errors.

An even more important application of the velocity/depth information is to constrain the normal moveout (NMO) correction. The NMO removes the additional time required for a reflected signal to reach a receiver far from the acoustic source. If not well constrained with a priori velocity information, spurious structures can be introduced into the stacked time section. The final need for velocity control involves interpretation of the processed data. During this step, the acoustic impedance contrasts detected by the reflection data are correlated with geologic/hydrologic boundaries such as the water table or formation boundaries. The standard procedure requires detailed borehole velocity values from which a single wiggle trace can be calculated called a synthetic seismogram. A comparison between the synthetic seismogram and the borehole geology allows a direct correlation between the two data sets. This wiggle trace is then correlated to the time section where the seismic line intersects the borehole. If the velocities are known and the surface data is properly processed, the correlation should be very close for major reflectors. This allows an unambiguous assignment of geology/hydrology to acoustic reflectors that can then be mapped and integrated with other subsurface information.

In this section current standard technologies are described and evaluated for use at the Hanford Site. Also there has been one previous checkshot survey to support BWIP, which is briefly discussed, and finally, some suggestions are made concerning nonstandard techniques that may be applicable for use at the Hanford Site.

Although not usually a problem, acquisition of borehole velocity control has been complicated at the Hanford Site due to the borehole environment and the highly attenuative sediments. When the geologic medium is consolidated with velocities greater than 6,000 or 7,000 fps and the steel casing is well coupled to the medium, sonic logging tools are used to collect velocity data in liquid filled holes. No documentation has been found of attempts to measure formation travel times below the water table using acoustic logging techniques until the well encountered hard basalts. Although not applicable to the 600 Area, the Ringold Formation may be consolidated well enough that acoustic logging could be achieved in this unit. The limiting factor will be the degree to which the casing is coupled to the formation via the backfill material. The bentonite seal may not couple adequately causing attenuation. However, a field technique that could improve acoustic coupling is pressurization of the borehole to close any microannular cracks between the casing and bentonite seal. For the cost involved, it is worthwhile to field check this technique in the faster Ringold Formation when conducting a survey in the 200 West Area.

Two other techniques used to gain velocity control are vertical seismic profiling (VSP) and Reverse VSP (RVSP). For VSP measurements, an acoustic source is placed at the surface while one or more receivers are in a borehole (Figure 8). For RVSP, the source is placed in the borehole with receivers at the surface. Velocities are frequency dependent and since the VSP data have a frequency bandwidth closer to the seismic data than the sonic logs, VSP data often provide a more reliable correlation of well control to seismic reflectors. In addition, VSP can provide detailed information on structural, stratigraphic and lithologic interpretations. Since the energy travels only one way through the earth, higher frequency data can be recorded providing greater resolution than surface seismic surveys.

Generally VSP measurements are made in open or cased holes with a repeatable land source while one or more receivers are in the hole. For work in dry holes, borehole geophones are clamped against the wall while hydrophones are suspended in liquid filled holes. A successful demonstration of this technique has been documented in DOE (1988) to support BWIP and the results are discussed in Section 4.0. For the BWIP, both a downhole air-gun and 1/4 lb dynamite sources were submerged in a water-filled pit 10 ft deep to enable adequate coupling of the energy. Although the air-gun source could be used again, there are several sources now available that have should have sufficient energy and allow increased mobility for walkaway tests. An accelerated weight drop and a small vibrator are repeatable, mobile sources that do not require the construction of a water-filled pit (see Section 6.0). The accelerated weight drop is the high energy source used for the 200 West survey. It is easily employed and has a reasonably broad bandwidth in most environments (Miller et al. 1992). The vibratory source, however, has the flexibility of concentrating the input energy in a higher frequency range achieving greater resolution but requires cross correlation techniques that complicates acquisition and processing. Regardless of which source is used, the expertise of the field quality control personnel will be critical to the success of the survey:

The more recently developed RVSP method places the acoustic source in the hole, which is shot into a surface array of geophones. This method is preferred to the VSP since the receivers remain at fixed locations on the surface and can be buried to improve ground coupling and noise reduction. In addition, problems associated with borehole washouts in open holes and casing ring arrivals in steel-cased holes are eliminated. Although tube wave generation can obscure signals, these waves are not generated in dry wells. The challenge is to find a source that can generate enough energy downhole to produce a detectable signal at the surface and yet not damage the borehole. Possible sources for existing boreholes include the borehole air-gun, a water gun, a light explosive charge, and several downhole vibratory sources. Field experiments that compare the air-gun, a water gun, a perforating gun, and a small explosive charge of 23 g concluded that the air-gun and explosive charge can be viable direct sources in open or cased wells even with free casing (Chen et al. 1990). The explosive charge actually gave the best results producing a higher amplitude, cleaner signal with no visible tube wave while the air-gun signature displayed tube waves and tube wave conversions that confused the signals. Furthermore, it was concluded that no damage was done to either the casing or borehole wall even after repeated firings of the explosive charge up to 95 g in new casing. In a 50-yr old production well, the casing was damaged with a 60 g charge. In the bentonite backfilled wells

at the Hanford Site, this may be a viable source in younger wells away from tanks or cribs to increase velocity control.

Since RVSP surveys and crosswell tomography are very powerful imaging techniques, new borehole sources are being developed. A high energy vibrator borehole source is preferable to other sources since the frequency content of the input signal can be controlled and because of the generally nondestructive nature of swept sources. Two such sources are now available, one developed by Conoco, Inc., that requires a fluid-filled hole and can sweep from 70 to 450 Hz and another developed by Sandia National Laboratory. These are mentioned for completeness since these sources have potential for future use.

It is also possible to use the drill bit as a seismic source and collect data while drilling (Rector 1992; Rector and Hardage, 1992). Recently Western Atlas International, Inc., a large seismic acquisition and processing firm, offered a service to collect RVSP data utilizing a rotary drill bit as the source for the oil and gas industry. Recently, a feasibility test was conducted at the Hanford Site using the drill bit of the cable rig as a downhole source. Data collected from a depth of 140 ft during the drilling of well 299-W15-218 displayed clear first arrivals while the impact to drilling operations was minimal. Although the maximum depth at which signals from the bit can be detected is not presently known, this technique is simple and may produce useful data to constrain surface surveys and help to interpret data collected in cased wells.

After reviewing the literature and previous work conducted at the Hanford Site, it is concluded that acquisition of the borehole velocity control necessary to process and interpret high resolution data collected at the Hanford Site should be possible with existing technology without resorting to plastic cased wells. The RVSP method is preferred using the drill bit as the source to collect data during drilling and/or using either a light explosive charge or borehole air-gun in existing wells. However, initially a simple VSP survey with a high energy surface source and a borehole geophone should be tried since this system is the simplest and least expensive. Solution of this problem not only supports future surface surveys but allows the powerful imaging techniques of VSP and acoustic tomography to address problems such as detecting fractures in grout barriers, monitoring the vertical efficiency of pump and treat scenarios or, if combined with electrical resistivity tomography, for detailed leak detection in the vadose zone.

6.0 HIGH-FREQUENCY SEISMIC ACQUISITION EQUIPMENT

Since the requirements of environmental and engineering applications are different from that of the oil industry, there has developed a different suite of acquisition equipment. In fact recent advances in shallow sources and recording capabilities may significantly increase the quality and resolution of future surface surveys. The goal of shallow high resolution surveys is to reduce the noise and enhance the signal to generate and record high-frequency acoustic signal from depths up to 1000 feet. Goals for delineating the basalt window are to record 85 Hz to 130 Hz signals that have traveled through 600 ft (two ways) of Hanford sediments. Therefore, the challenge is to input much

greater frequencies at the source and be able to detect a weak signal with the receivers and recorder. A "systems" approach is adopted such that each component of the acquisition system is chosen to maximize the signal to noise ratio. The main components of the acquisition system (see Figure 9) are described and current 'state of the art' equipment is compared to ensure that each part of the system contributes to the success of the method. Initial suggestions are made for the best acquisition system to delineate the edges of the basalt window.

However, before equipment is discussed, the types and sources of noise are defined to better understand how equipment causes or interacts with noise. Simply explained, noise can be either coherent or noncoherent. If noise is coherent, to the novice it will appear like a reflector on the raw record. Examples of coherent noise include the high amplitude groundroll, which is a surface wave excited by the source at the surface and the low amplitude air blast, which travels through the air from the source to the receivers. Another example is the signal interference from power lines. Also included in this category are early arriving refracted events and direct waves. A schematic of how all these signals appear on a time/distance plot is shown in Figure 10. The velocity/depth model used to generate the plot is displayed to the right. Body-wave arrivals are correlated to ray paths through the geologic model by number. Note the interference of the various events on the left side of the plot closer to the seismic source. It is easy to see that high amplitude events can mask lower amplitude signals in this region of the plot. Coherent noise from nearby drilling operations can also obscure the reflected signal. Although refracted energy can be a problem interfering with reflected signals at the Hanford Site, groundroll appears to be the most significant problem with coherent noise. Noncoherent noise is a random signal that can usually be deleted if enough records are stacked since these random events will add destructively. When the wind shakes cables or tree roots, a random signal can be detected at the geophones. Fortunately, random noise is not a severe problem at the Hanford Site (Kunk 1993).

The above examples of spurious signals are due to recording or site specific conditions and are not directly caused by the acquisition equipment. Noise from the seismic source, receivers/cables or recorder can be either coherent or random, and for the most part is inherent in the equipment. Thus equipment performance is important. Examples are noise introduced when multiple shots are stacked from a nonrepeatable source or amplifier noise in the seismograph. To allow detection of very small amplitude reflectors, it is important to consider all sources of noise and to realize that even if an individual noise source is very small, the effects are cumulative. Thus all efforts should be made to reduce it as much as possible.

6.1 SHALLOW SEISMIC SOURCES

The choice of a seismic source can be a key decision in the design of a high resolution study. Since the behavior of shallow reflections is site dependent, one particular source will produce better quality, more useful results than another source at a given location. Consequently, without a priori knowledge of the acoustic properties of the subsurface, it is difficult to choose a "best" source without executing field tests. The input signal of the ideal shallow seismic source would contain a broad band of frequencies with more energy concentrated at the higher frequencies. The wide bandwidth

increases the information carrying capabilities of the system allowing greater resolving power. Since the earth acts as a low-pass filter differentially attenuating the higher frequencies, the source should have an output energy that can be controlled as a function of frequency. Furthermore, to allow separate shots to be stacked, the source must be repeatable. Also the energy should be well coupled to the ground and yet be nondestructive. Finally air-coupled waves and groundroll should be minimal to avoid interfering with reflected waves. No source has all these properties; however, results are available of comparative source studies that allow an initial evaluation of various sources' characteristics (Miller et al. 1992a; Miller et al. 1992b; Miller et al. 1986). For these tests the characteristics of total energy or amplitude, frequency content and signal-to-noise ratio were compared for eleven basic sources. At one site where comparisons were made the water table depth is in excess of 100 ft in dry, unconsolidated sediments with very low velocities of 600 fps. Source evaluations for this report were based on data from this test.

Most shallow sources fall into two main categories. Impact sources have an elevated weight that is either dropped or forced unto the ground while explosive sources involve firing a gun or rifle into the ground with or without a projectile. For perspective an accelerated weight drop was used to collect the data from the 200 West Area while a modified impact source, a sledgehammer and a gun source were tested at the 300 Area. By comparing relative amplitudes, frequency content and the quality of the raw records, it appears that three sources selected from these studies may be useful for Hanford applications. Note that the new swept source was not available at the time of testing and, as shown later, this one has the most potential for use at Hanford. The accelerated weight drop produced the most energy even when analog lowcut filters were set at 110 Hz and 220 Hz. Both the weight drop and a Buffalo gun produced wide bandwidth spectra with frequencies as great as 200 Hz and with considerable energy when analog filters were not employed. The main different in characteristics of these two sources is repeatability. The weight drop was designed to stack records to enhance the signal to noise ratio while the gun does not produce a repeatable signal to allow stacking. A 20-lb sledgehammer and the Buffalo gun gave the best quality data and hence the best signal to noise ratio allowing identification of reflection information. It should be noted that these reflectors were very shallow at 25 ft and the sledgehammer will not generate sufficient energy to image deep targets at the Hanford Site. Experience with the accelerated weight drop at the Hanford Site has shown that stacking multiple shots does increase the signal to noise ratio to allow reflected energy to be identified. However, as stated by the authors, multiple sources should be field tested at any site without previous experience particularly when the water table is deep. Consequently, it is suggested that prior to any future seismic reflection surveys, each of these three sources be field tested with the swept source described in the following paragraphs.

The earth acts as low pass filter preferentially allowing certain frequencies to typically propagate while attenuating the higher desired frequencies. For the sources discussed previously, no control on input energies or frequencies are available. When it became necessary to explore for and develop stratigraphic reservoirs, the petroleum industry developed a high-frequency land source that allowed varying the input energy while sweeping from low to high frequencies called a vibrator. This vibrioses system rapidly became the standard for land acquisition surveys because it

produced a superior signal to noise ratio at higher frequencies. Although designed to produce a 200-Hz signal, generally the highest input signals are around 90 Hz. The earth and vibrator define a mass-spring system with a natural resonance frequency typically between 15 and 30 Hz. The generation and coupling of energy to the earth will be less difficult within this limited frequency range. As the vibrator is operated farther from the resonance frequencies, it must provide higher drive forces to generate sufficient energy, especially at higher frequencies necessary for high resolution work. Consequently there is a difference between the peak design frequency and the peak operating frequency. This lack of ability to get 100 Hz + signal into the ground and the cost to deploy and maintain the large vibroseis trucks eliminated its use for shallow applications.

Recently a source was developed that vibrates up to 550 Hz with variable hold-down force while still maintaining mobility and reasonable costs. It was designed by a leading manufacturer of the larger vibrators but specifically for use as a shallow high resolution source. This source has most of the ideal characteristics discussed previously, specifically a broad bandwidth from 20 to 550 Hz, output energy controlled as a function of frequency concentrating energy at the higher end, repeatability, and nondestructive. If the frequency sweep begins above that at which groundroll propagates, then this high amplitude interfering noise may be eliminated. Furthermore to assure sufficient energy, more than one vibrator can be used together, which is routinely done with the large vibroseis trucks. The degree to which this source can successfully couple with the earth and the practical limits of the frequency range have not been determined since the supporting software and recording capabilities are just now emerging from development. The results of testing planned for the summer of FY93 will allow further evaluation.

6.2 SEISMIC RECORDERS

Generally, the success of any high-frequency reflection survey is directly related to the attention given to details of all aspects of the survey. Any compromises or mistakes that are made first degrade the high-frequency content of the signal. Selection of the best recorder requires attention be paid to details. At present there are two types of portable seismographs available for environmental and engineering applications. Performance parameters of interest are listed below.

- Analog/Digital resolution-dynamic range
- Type of A/D conversion
- Effects of amplifiers
- Available memory
- Number of channels
- Software/hardware to support the vibrator source

In Figure 11, the importance of dynamic range is schematically illustrated comparing an 8-bit to a 12-bit digital word. For the 8-bit digital word, high amplitude groundroll set the first 7 bits almost saturating the dynamic recording range. Reflection information is contained only in the least significant bit which seriously limits the reflection amplitude that can be recorded since one bit equates to 6 dB of amplitude. As the number of bits is increased in the digital word, the amplitude of the groundroll remains the same allowing more recording range for reflected events as shown for the

16-bit word. Now 5 bits are set by a reflector and in the absence of system noise, 30 dB of amplitude is available. As the goal to detect high frequencies began, successive seismographs have increased this range to 96 dB for 16-bit seismographs which, until recently, was the best available in a portable model. Now 24-bit recorders are available pushing the theoretical dynamic range to 144 dB, which is the best available even in the petroleum industry. With an extra 28 dB of amplitude, this seismograph can detect very weak signal provided the system's noise level is low.

Another important feature of a seismograph is the manner in which the A/D conversion takes place. Standard recorders use a technique termed instantaneous floating point (IFP) amplifiers while the new 24-bit recorders use Sigma-Delta A/D technology. Without getting into the functional details, these techniques can be evaluated by comparing three specifications. First, the equivalent input noise effectively sets the lower limit of the recording amplitude range. In other words, this is the lowest noise level for the system below which a signal is lost in noise. For IFP converters, this value is typically 0.5 microvolts while systems using Sigma-Delta A/D conversion list 0.1 microvolts for noise, a five-fold decrease in noise. Next the frequency distortion caused by the conversion process is specified by the total harmonic distortion. For IFP recorders, a value of 0.1% is obtained versus 0.005% for Sigma-Delta systems. Thus, the 24-bit recorders have exceptionally low distortion values.

Finally Sigma-Delta A/D technology enables increasing the sampling rate to allow complete conversion of the analog signal. The sampling interval is from 31.25 microseconds to 4 milliseconds. The importance of fine sampling is illustrated in Figure 12. Both plots display the same analog signal and compare the effect of sampling rate. The coarser sampling rate results in a digital signal that does not contain the lower amplitude, higher frequency signal that was returned by the earth. However, with a sufficient sampling rate, nearly all the signal is converted maintaining the high-frequency information. Since attention to detail is important, all acquisition, whether VSP, RVSP or surface surveys should require the use of the 24-bit seismic system.

Two final parameters that should be compared are the available computer memory and the number of recording channel. The capacity to collect vibrator data requires increased acquisition memory. For the 24-bit systems, the acquisition memory can be as great as 16 MB with 32 MB of system memory. These systems are designed specifically to acquire either impulse or vibroseis data. In addition, the increase from 120 (standard) to 144 channels enables collection of data over a wider time interval to sample deeper reflectors or to collect shear wave data simultaneously with compression arrivals. This type of reflection data is used to detect saturated zones from surrounding unsaturated zones.

The implications of Sigma-Delta A/D technology are far reaching when combined with a vibratory energy source and less distorting digital frequency and velocity filters. For example, lowcut analog frequency filters are currently used to reduce the effects of high-amplitude low-frequency noise. This band limits the total signal, which reduces the overall resolution of the data and analog filters cause subtle phase distortions. On the other hand, digital filters are less distorting and the effects can be controlled and evaluated. Since the entire signal is converted, groundroll can be removed

digitally with either a frequency or velocity filter preserving any low-amplitude high-frequency information. Also by beginning a vibroseis sweep above the characteristic frequency of the groundroll, this noise source is not generated. Another advantage of full A/D conversion relates to the highest frequency these recorder can detect which is well above 2,000 Hz. Based on the above discussion, the combination of a 24-bit Sigma-Delta seismic acquisition recorder and a high resolution vibratory energy source is recommended for testing at the Hanford Site.

6.3 RECEIVERS/CABLES

Generally for shallow reflection surveys, cables that connect the geophone to the seismograph are not long enough to attenuate signal or introduce spurious noise. Certain quality control field procedures should be checked such as clean, solid connections to the geophones. If weather conditions such as wind vibrate the cables there may be some distortion; however, generally cable do not present a problem provided they are maintained.

Surface receivers for shallow reflection surveys are either 40- or 100-Hz geophones. Although the quality of manufacturing and the condition of geophones should be considered, the industry has not considered advancing current technology. The question of whether to use 40 or 100 Hz geophones can be answered once again with a "system" approach. If using an impact or impulsive source with a standard 16-bit recorder, the 100-Hz geophones should be used to damp low-frequency noise. However, for a 24-bit system with or without a vibratory source, 40 Hz-geophones will preserve a greater bandwidth since low-frequency noise can be filtered out. Probably more important is the degree to the geophones couple to the earth. Because the very near surface at the Hanford Site appears to be highly attenuative especially over the eolian sand dunes, it is recommended that geophones be buried and coupling be increased by wetting the surrounding soil. Also when possible, geophones should be relatively new and in excellent condition.

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Legend:

- Borehole
- Borehole where Rattlesnake Ridge Interbed encountered before Basalt
- 123 Elevation (in meters) of the Upper Surface of Basalt
- 200- Contour on Upper Surface of Basalt

Contour Interval = 25 meters

0 1000 2000 Meters

Figure 1. Structure contour map of the top of basalt surface at the 200 East Aggregate Area.

Figure 2. Stratigraphic pinchout modeled with three different dominant frequencies, 20, 30 and 40 Hz. The horizontal axis represents distance along the seismic line while the vertical axis is in time (ms). The true wedge edge is beneath location A and the true thickness of the wedge is indicated by the numbers on top; (b) same as (a) except the dominant frequency is 30 Hz; (c) same as (a) except the dominant frequency is 40 Hz; (d) same as (b) with the actual wedge geometry superimposed on top of the seismic signature (After Yilmaz 1987).

Figure 3. Discontinuities in a reflector due to vertical offsets such as a fault or erosional scarp. Offsets are expressed in fractions of the dominant wavelength. Only for reliefs greater the a quarter of a wavelength is the feature detectable. (After Yilmaz 1987)

Figure 4. An earth model that consists of four reflectors with four nonreflecting segments A, B, C, and D. The vertical is measured in seconds. The lateral extent of each "channel" is indicated by the solid bars on top. Note that A is barely recognizable at any depth since the dominant wavelength is too long but that as the size of the nonreflecting gap increases, the depth at which the feature is discernable also increases. Even though the wavelength increases with depth, the gap at D can still be resolved at 3 seconds. (After Yilmaz 1987)

Figure 5. 200 East Area Geologic Cross Section extending in a north-south direction.
(After DOE/RL-92-19)

Figure 6a. Raw data sections with time (s) on the vertical axis and distance (f) on the horizon axis. One phone was located at each trace. Two possible reflectors are indicated with the upper red lines. Notice the low amplitude on the upper reflector with respect to the interfering high amplitude coherent noise.

Figure 6b. The data are shown after part of the signal has been removed based on velocity content. The shallower event at 40 ms can be seen clearly while a third lower reflector can now be identified at about 110 ms.

GEOSCIW062993-B

Figure 7. This noise walkaway has distance in feet along the horizontal axis and time in milliseconds along the vertical axis. The source is at the origin and the geophones are two and one half feet apart. The arrows with the labels indicate the possible caliche reflector and the high amplitude interfering noise. The data were collected with an analog 100 Hz lowcut filter.

Figure 8. Vertical seismic profiling geometry with the shot or acoustic source at the surface. Receiver locations mark the borehole location. Direct and reflected raypaths are shown with the arrows.

H9306020.1

Figure 9. Simplified block diagram of a reflection seismic acquisition system.

H9306020.2

Figure 10. Time/distance plot with arrival times for various coherent events indicated at the appropriate source-to-receiver offset. The refraction path labeled 2 does not appear on the plot for this source/receiver geometry (after Miller et al, 1992).

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Figure 11. Schematic examples of 8-bit (left) and 12-bit (right) digital words (modified from Steeples, 1990).

H9306020.3

Figure 12. The effect of sampling rate on A/D conversion.

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