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THE UNIVERSITY OF ALBERTA

THE EFFECTS OF SEISMIC BLASTING ON WATER WELLS

by

(C) DOUGLAS THOMAS SNEDDON

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

IN

WATER RESOURCES

DEPARTMENT OF CIVIL ENGINEERING

EDMONTON, ALBERTA

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FACULTY OF GRADUATE STUDIES AND RESEARCH

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THE EFFECTS OF SEISMIC BLASTING ON WATER WELLS

submitted by Douglas Thomas Sneddon in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

Complaints of water well damage related to seismic petroleum exploration blasting in Alberta are common. The most common allegations are complete loss of production or suspended sediment in produced water.

Field experimentation showed no significant changes in water yield or quality over the range of distances and charge weights commonl associated with seismic exploration blasting, although small permanen changes to aquifer transmissivity and temporary increases in suspend sediment were observed.

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Kevin Goble, formerly of Alberta Energy and Natural Resources, provided professional, logistic and moral support throughout the project, as did his Director, George Fulford. The Exploration Inspector corps was magnificent in the field as were the Environment technical staff from both the Groundwater Branch and the Survey Branch. These people carried out their tasks under the harshest environmental conditions our province could provide. Surveyors, drillers and pumping test teams worked at all hours of the day in temperatures ranging from +42°C (at Gem on August 29, 1979) to -20°C (also at Gem, on January 15, 1980).

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Three farm families put up with a yard full of strange equipment and people. I would like to thank Mr. and Mrs. William Wycenko of Hoselaw; Mr. and Mrs. Norman Newstad of New Norway and Mr. and Mrs. Ralph Jarvis of Eckville for the use of their property and hospitality.

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DTS

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SUMMARY

The relationship between shock waves generated by blasting and water well performance is complicated. It is not easily explained in each specific case by simple observation and common sense reasoning. As a result, Exploration Inspectors have experienced a high degree of frustration in attempts to mediate disputes between seismic exploration companies and well owners who allege serious reductions in water yield or quality following blasting operations near the well. An analysis of a representative sample of complaint files showed the most common complaint was a drastic yield reduction or a complete loss of production.

While a profile of a "typical" blasting-related complaint can be produced from the files, the number of variables and the high degree of variability in each seriously limits the generality of any conclusions that could be drawn from such a profile.

Very little experimental work has been reported on blasting damage to water wells. What is available in the literature suggests that there is little or no demonstrable effect on either water yield or quality from blasts generated by 50 Kg of dynamite or less, detonated at distances from 8 to 300 metres away from the well tested. Improvement in well performance has been reported by detonating several kilograms of high explosive in the bottom of a well. This procedure, which is occasionally applied to old wells, fractures the producing formation and thus increases the effective intake area. It also breaks up and dislodges precipitates that have built up in the zone adjacent to the intake.

The blasting mechanics literature suggests that beyond the immediate vicinity of the burst, structural damage is largely probabilistic. It is a function of a number of random variables, the most important of which are the mechanical properties of the propagating medium. Of equal importance is the dynamic properties and condition of the structure exposed to blasting vibrations.

No experimental work has been reported on either the structural response of water wells to impulsive loading, or the elastic response of aquifers to impulsive loading. Some recent information is available on well bore deformation in response to continuous loading which suggests that significant casing deflections may occur at the interface between two beds that exhibit different mechanical properties. The net difference in stress is in the order of 5 MPa pressure.

Changes to permeability in granular media subjected to continuous loading have been reported in the geotechnical literature. Significant changes in permeability appear to occur in the 2 to 12 MPa range. Such changes were permanent and thus represent consolidation phenomena.

To obtain objective field data concerning the behaviour of water wells subjected to blasting, a series of experiments were carried out which compared the magnitude of peak impulsive stresses to changes in aquifer transmissivity. The magnitude of applied stress was controlled by varying charge size and shot-to-well separation distances.

Small changes in transmissivity were observed following blasting at most of the test sites. No clear correlation was observed between the magnitude of the stress pulse and changes to transmissivity, although small but statistically significant changes correlate with the number of episodes of blasting.

It was also found that the magnitude of the stress pulse is influenced most strongly by the geology of the site and does not attenuate in a simple, linear fashion with distance. Further, over the range of charge weights commonly used in seismic exploration, the magnitude of the stress pulse peak is relatively constant.

Following treatment by blasting, it was concluded that no dramatic changes to water yields or water quality were observed at any of the test sites, although small permanant changes were observed at some sites.

I. INTRODUCTION

A. MOTIVATION

Petroleum exploration activity in the populated areas of Alberta is usually carried on without a great deal of conflict between private citizens and exploration crews. However, one important category of conflict that does arise relates to alleged changes in domestic water wells following seismic geophysical surveys in a rural area.

The Exploration Review Branch, Alberta Energy and Natural Resources, has the responsibility for mediating these conflicts through authority of the Exploration Regulation (Alberta Regulation 423/78) under the Mines and Minerals Act (RSA 1970, Chapter 238). Approximately 500 complaints arising from geophysical exploration activities were investigated by the Branch in 1978. Of the 500 complaints about one half alleged interference with domestic water wells.

A second body of legislation, the Groundwater Control Act (RSA 1970, Chapter 162) and regulations thereunder, is administered by the Earth Sciences Division of Alberta Environment. Under this act, any problems relating to water well performance or changes to aquifer characteristics resulting from man's activities are of concern to the Division.

Government complaint files represent only a portion of the total number of conflicts that actually do arise. Informal discussions with geophysical contractors and field personnel suggest the number may be as high as two cases per crew-month. This would produce an industry-wide figure of approximately 1,200 cases for 1979. Statistics are not presently collected, however, and the true situation remains speculative.

The cost associated with each case is significant. Compensation payments made through the Water Well Recovery Program, which is administered jointly by the provincial Departments of Energy and Natural Resources, Agriculture and Environment, averaged $2,634 per case in fiscal year 1979/80. Assuming this figure applies equally to private settlements, a rough direct cost for compensation costs from all sources would be in the order of $3,100,000. In addition, Exploration Inspectors spent about 45% of their time investigating water well complaints, which amounted to 847 man-days of effort in 1979. This translates into an additional cost to the public of about $56,000.

Individual damage complaints are usually difficult to assess objectively as there are many elements in the problem. Exploration Inspectors lack a well-defined technology for assessing the relative importance of each element and the synergistic effect of the sum of elements. The goal of this study is to provide information that can be used in the development of such an investigation technology.

B. <u>REGULATIONS</u>

At present, the Exploration Regulations establish 180 m as the minimum safe distance between a shot point and a domestic water well (Section 24, Schedule B). Informal discussions with field personnel indicate that most contractors maintain a policy of a 250 m minimum distance to further reduce the risk of damage.

There are no references to blasting damage in the Groundwater Control Act for the Groundwater Control Regulations (Alberta Regulation 168/77) but there are references to control of flowing holes drilled for any purpose (section 10) and to prevention of aquifer contamination (sections 12 and 13).

C. BACKGROUND

Despite over 35 years of seismic exploration activity and its parallel history of conflict with water well owners, very little has been learned about the relationship between blasting and its probable effects on water wells. In part, this might be due to the relative lack of knowledge about seismic phenomena on the part of groundwater engineers and hydrogeologists and an equal lack of awareness of groundwater phenomena by geophysicists.

In order to partially bridge this gap, a brief outline of the key phenomena from both fields follows. Detailed explanations of hydrogeological phenomena may be found in such standard texts as Walton (1970), Bear (1972) and Johnson Inc. (1972). The equivalent geophysical texts would be Heiland (1946), Dobrin (1976) and Telford et al (1976). Glossaries of hydrogeological and geophysical terms are presented in Appendix 2.

1. Groundwater

Groundwater refers to all naturally occuring waters found below the ground surface and includes both soil moisture in the near surface and formation fluids found at depth. For present purposes, only those waters between the water table (the phreatic surface) and the lowest commonly used aquifer in the stratigraphic section will be considered when the term "groundwater" is used.

Two zones are defined by the water table: the zone of Aeration above it, and the zone of Saturation below it. "Saturation" refers to the air-to-water ratio in the interstices of the host medium, with the water table being defined as the uppermost extremity of 100% water saturation. The nearly saturated zone immediately above the water table is referred to as the "capillary fringe". These relationships are illustrated in Figure 1.

Porous zones within the host rock or unconsolidated deposits are called "aquifers" when it is possible for significant volumes of water to pass through them under ordinary field conditions. Formations that do not allow significant quantities of water to flow through them are "aquicludes", or "aquitards" even if they contain large volumes of immobile water. They are essentially impervious to water.

Aquifers may be classified as "confined" if the overlying beds are aquitards or aquicludes and the water column in a well penetrating it rises above the base of the confining layer; or unconfined, if its upper surface is defined by the water table. This latter kind of aquifer is also called a "water table", or "phreatic" aquifer.

Water flows through aquifers from zones of high piezometric head to zones of lower piezometric head. The properties of the formation that determines the rate at which water travels down the piezometric gradient are described quantitatively by its "permeability conductivity", and its "storage coefficient".

Permeability is a combined property of the geologic matrix and the groundwater flowing through it. The product of aquifer permeability and thickness produces its "transmissivity" value.

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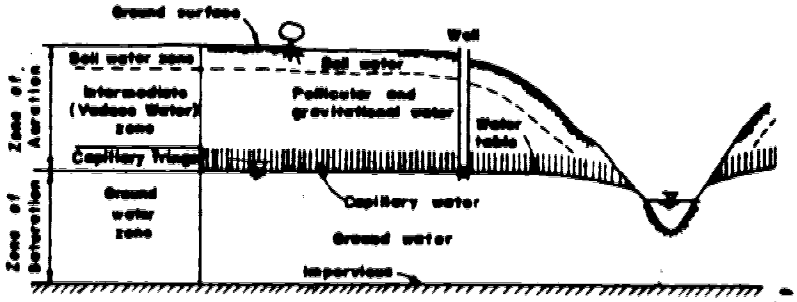

FIG. 1a. SUBSURFACE WATER DISTRIBUTION

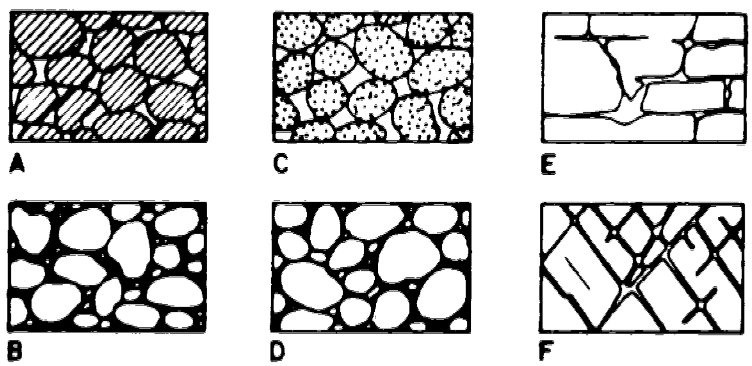

FIG. 1b. HOST ROCK VOID SPACE TYPES

(from Bear, 1972)

A. Well-sorted sedimentary deposit having high porosity.

B. Poorly sorted sedimentary deposit having low porosity.

C. Well-sorted sedimentary deposit consisting of pebbles that are themselves porous, so that the deposit as a whole has a very high porosity.

D. Well-sorted sedimentary deposit whose porosity has been diminished by the deposition of mineral matter in the interstices.

E. Rock rendered porous by solution.

F. Fracture porosity.

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Alberta ENVIRONMENT		SUBSURFACE WATER DISTRIBUTION HOST ROCK VOID SPACE TYPES	
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The "storage coefficient" is a measure of the changes in quantity of water stored in an aquifer for a given change in elevation of the piezometric surface or water table.

Unconfined aquifers are replenished ("recharged") by the direct infiltration of precipitation to the water table through the overlying soil. Confined aquifers obtain water from their outcrop area or where they subcrop beneath permeable formations. The outcrop or subcrop region is called the "recharge area".

"Discharge areas" are topographically and hydraulically low areas that receive effluent from one or more aquifers. Typical surface expressions of discharge areas are lakes, perennial surface streams and swamps.

Aquifers are said to be elastic if storage capacity and transmissivity remain unaffected by a major cycle of discharge and recharge. In general, compaction of the aquifer (i.e. a permanent reduction in porosity) will occur when discharge greatly exceeds recharge, or where mechanical loads produce subsidence of the ground.

In summary, a simple groundwater system consists of an aquifer or stacked set of aquifers, each of which has a recharge area in a hydraulically and (usually) topographically high region, and a discharge area that is hydraulically lower than the corresponding recharge area. The hydraulic properties of an aquifer are evaluated by measuring its transmissivity and storage coefficient. Aquifers behave in an elastic fashion when subjected to a mechanical loading/unloading cycle or hydraulically when discharged and recharged, to some maximum threshold value of mechanical or hydraulic stress. Beyond this stress threshold, consolidation begins and the aquifer transmissivity and storage capacity change permanently.

2. Water Well Construction and Hydraulics

a. Well Types

There are as many ways of building a water well as there are people who construct them. Only general categories of construction style will therefore be discussed, together with a description of the variables involved with each style. Details of standard practices may be found in Johnson, Inc. (1972).

(i) Hand-dug Wells and Springs:

In discharge areas or places near discharge areas, the water table is sometimes at or near the ground surface. In the case of springs, the water flows out of the ground and into surface water courses without human intervention and may be captured easily for domestic use by diversion into a pipe and cistern system or a simple surface dam and reservoir. The method of capture depends largely on the local topography, user needs and user ingenuity.

Where water does not flow out of the ground naturally, a shallow pit or shaft can be dug down to the lowest known level of the water table. Water is allowed to seep into the pit or shaft and is lifted by a simple sump pump or by bucket. Pits or shafts are usually lined with concrete or masonry to the water table and timbered below that to total depth. It is normally impractical to measure aquifer parameters from such installations as a very long pumping test would be required.

(ii) Bored Wells

Bored wells are essentially the same as hand-dug wells, except that they are smaller in diameter (about 1 to 1.5 m as a rule) and were constructed by using a large diameter rotary bucket auger. In general the method is restricted to dominantly clay formations where sand beds and cobble size or larger stones are rare. They are usually less than 20 m deep.

These wells are commonly lined with wood and have a concrete surface casing that may extend down to 10 m. The wells are normally completed in the first aquifer encountered during boring. It is very difficult to obtain sufficient drawdown for an aquifer test in bored wells because of the high pumping rates required.

(iii) Drilled Wells

By far the most common water wells in Alberta were drilled and are cased with steel pipe. These wells are constructed by drilling a four to ten inch (25 to 90 mm) hole using cable tool or rotary methods. A suitable steel casing, usually API grade A or B black steel pipe, is then friction fit to the hole.

If surface conditions warrant or if formations containing contaminated water are encountered, a seal between the casing and the surrounding formation is required.

A seal is produced by forcing a slurry of cement grout or swelling clay between the casing and the formation in the zones where the contaminated waters occur. The slurry used depends upon the nature of the problem.

In general a cement grout consisting of 25 to 30 litres of water to 40 Kg of portland cement is used to seal off the weathered overburden portion of the well and may extend up to 5 m into the water bearing formation. Small amounts of bentonite are sometimes added to the grout to improve shrinkage characteristics or to hold the cement particles in suspension during curing. Bridging between the casing and the formation can be improved by the addition of sand to the mixture. This is commonly done when large openings must be filled. Pure bentonite or bentonite based drilling mud is used as a sealing agent when drying or shrinkage are unlikely to occur.

A wide variety of completion methods are available to ensure stable production. By far the most common method used in domestic well practice in Alberta is a simple open hole. Open hole completions are of two types: cased to the bottom and cased to the first water bearing formation. Holes cased to the bottom represent completions in artesian aquifers that are poorly consolidated.

A considerable length of open hole is left when production is taken from several zones in a well-consolidated series of formations or from single aquifer that possesses poor transmissivity and is well consolidated. These are the conditions most commonly encountered in Alberta domestic well practice.

Other methods that are sometimes used when intake conditions demand a more sophisticated approach are slotted casing, well screen and gravel pack techniques.

When the aquifer consists of poorly consolidated coarse materials, the effective well intake area can be increased in size by making longitudinal slots in the casing with a cutting torch.

If the water bearing formation is a fine grained, poorly consolidated sand, a well screen may be required to prevent sand being produced with the water. Well screens can be obtained in a variety of forms. A common type is constructed from cold-drawn wire wound spirally around an array of longitudinal rods such that the distance between winds is constant. The distance between winds is chosen to exclude between 40% and 50% of the sand sizes found in the producing formation. Other types use louvres, horizontal sawcuts or perforations from large caliber bullets or a cutting torch.

If silt continues to be produced with water, a gravel pack can be used to filter out the fine fraction of the formation. A gravel pack is a mixture of sand and gravel that is placed between the well intake and the formation. The material sizes chosen are in the range that will not pass through the well intake and yet will filter out the suspended silt from the formation.

b. Pump Types

After water has been discovered and the well drilled, completed and cased, some means must be found to raise the water from the intake to the surface. In a small proportion of cases this occurs naturally when the aquifers possess a static water level higher than the ground surface. However, most wells require a pump of some sort.

The most familiar type is the hand operated or wind operated piston (or "cylinder") pump. When higher volumes and continueus, rather than pulsating flow is required, a rotary pump is called for. Several types are in common domestic use. At shallow depths, a flexible vane semi-submersible sump pump can be used.

By far the most common pump in use in Alberta is the jet pump. Although these are the most expensive pumps, they operate dependably at depths in excess of 150 m and do not require surface facilities beyond an electrical switch box. They do not require long drive shafts and are tolerant of crooked holes. However, they are prone to clogging from sand and it is important to protect them with a sandscreen or slotted casing.

c. Well Hydraulics

The two most important quantitative characteristics of water wells are drawdown and yield. Drawdown is the distance between the undisturbed ("static") water level in the well and the well water level during pumping.

Well yield is the volume of water discharged per unit of time. The "20 year safe yield" is the maximum rate at which a well can be pumped for a 20 year period without producing undesirable effects. Well efficiency and well losses should also be considered. Well efficiency is the ratio of actual drawdown to the drawdown calculated from one of the standard equilibrium formulae. Well losses are the cumulative effects of turbulence in flow at the intake, degraded transmissivity, and insufficient intake area. Initial well losses are caused by poor design (insufficient intake area,) but losses can increase over time due to calcium compound precipitate encrustation of the intake, clay deposition in pore throats and packing of fine angular materials in the intake area.

Drawdown and yield are determined by pumping tests. Several kinds of pumping tests are used by engineers and hydrogeologists, but the simplest (and the one used in the present study) is the constant discharge test.

The procedure for conducting this test is simple and straight forward. The static water level is measured, then water is withdrawn from the well at a known, constant rate. The water level is measured periodically in the pumping well or a nearby observation well normally according to a logrithmic schedule. Following cessation of pumping, recovery of the water surface toward the static level is recorded according to the same observation schedule used during drawdown. Because the static water level varies with atmospheric pressure, a recording barograph is used at the site to allow computation of corrections if a significant change in pressure occurs during the test.

Field drawdown versus time data derived in this fashion are then plotted on semi-log paper and a straight line fitted to the data points. The slope of the line is proportional to the aquifer transmissivity. These calculations are made for both the drawdown and the recovery data. Details of the method are contained in Walton (1970, pg. 133).

3. Seismic Exploration Procedures

Petroleum exploration by seismic survey is a highly developed technology that is deceptively straight forward in its basic form, but infinitely varied when studied in detail. The objective of a survey is to map the geometry of subsurface rock formations in order to infer their thickness, lateral extent and structural geology. This is done by recording the echos of an explosion from the various layers of rock.

There are two varieties of seismic survey: refraction and reflection. Because the reflection method is the most common in Alberta, all the following comments refer to this method.

a. Field Program

The basic element of a seismic survey is a single record. Single records are organized into lines and the lines are interconnected into a prospect. A record consists of the simultaneous magnetic recording of the output from a large number of geophone groups (usually 48 or 96). A typical output is shown in figure 2. The geophone groups are arrayed at regular intervals, which are multiples of 33 m in Alberta practice, in a straight line on either side of a shot point. The group spacing for a particular prospect is governed by the depth to the target. In Alberta this normally requires a spacing of 33 m in the region east of Highway 2, 66 m west of Highway 2 and 50 m in the Peace River to High Level area.

Other group spacings are used when a particular target is being studied in detail. The rule-of-thumb in this case is that the cable

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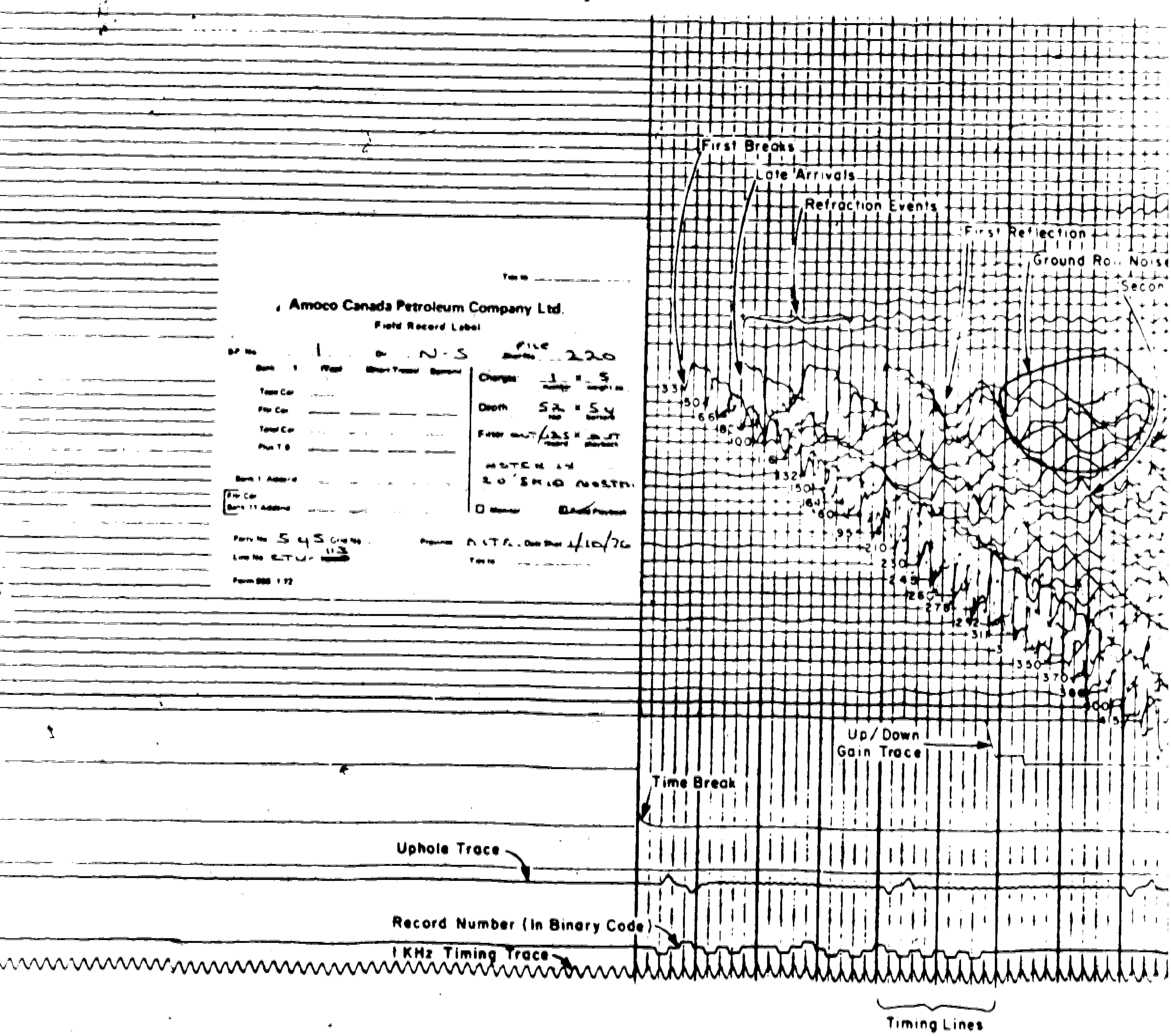
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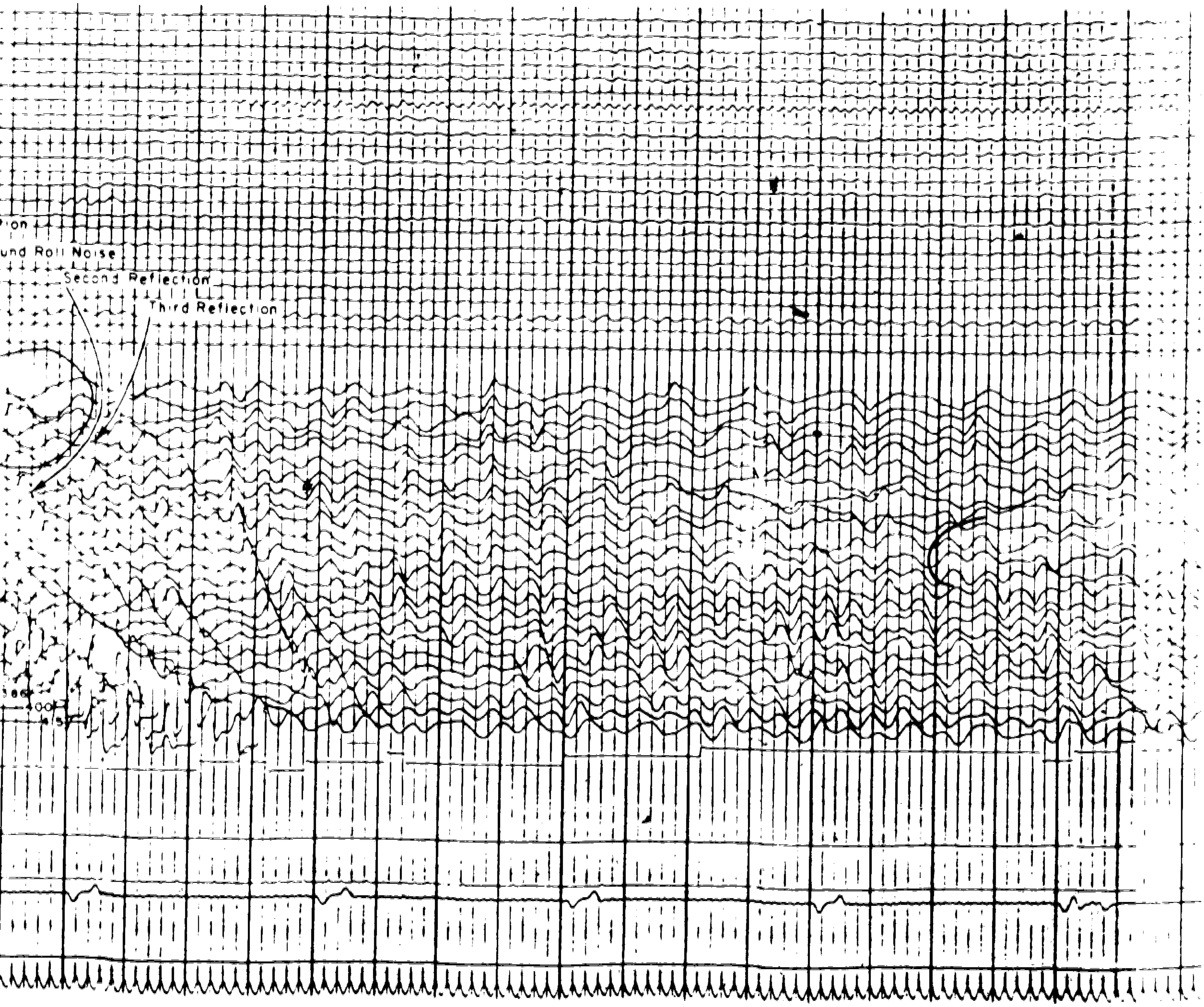

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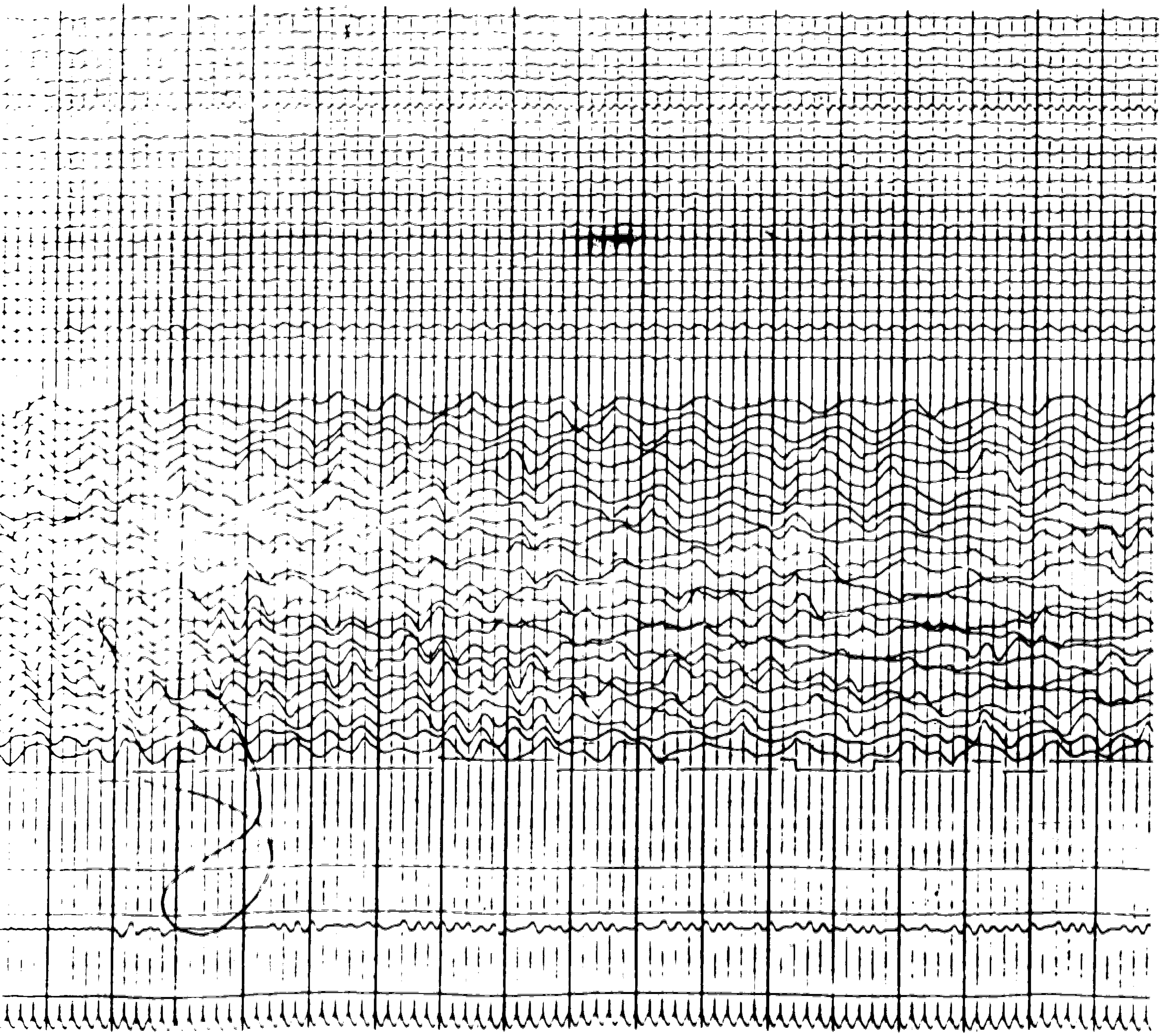

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		FIGURE No. 2

length (one half of the number of geophone groups) should be equal to one half of the depth to the horizon of interest.

The group interval determines the shot point interval. For reasons which will be discussed below, it is usually considered desirable to obtain more than one reflection arrival from a single point on each subsurface plane that can produce such an event. This technique, which is known as "multifold" or "Common Depth Point" (CDP) coverage specifies a shot point at or between each group (1200%), every second group (900%) or every third group (600%). 1200% coverage means each reflection from a single point is recorded 12 times during the survey, 900% means 9 times and 600% means 6 times. The significance of the technique is that a 1200% CDP program requires shot points every 33 to 66 m; a 900% program requires 66 to 132 m spacing and a 600% program (the most common) requires shot points every 132 to 264 m, depending upon the geographic location of the program.

A shot point consists of a shot hole bored to the base of the weathered layer, which in Alberta is usually about 20 m. A primed dynamite charge is then placed at the bottom of the shot hole. In Alberta practice, the charge is usually between 1 and 10 Kg of 60% nitroglycerine equivalent high explosive. The most commonly used charge weight is 2.25 Kg. Good practice requires stemming the charged shothole with water or drill cuttings, however this is rarely observed in routine work due to the labour cost of obtaining stemming material and loading it into the hole. As a general result, only groundwater seepage and leftover drilling fluid stem the shot. Figure 3 illustrates the shot point in cross-section.

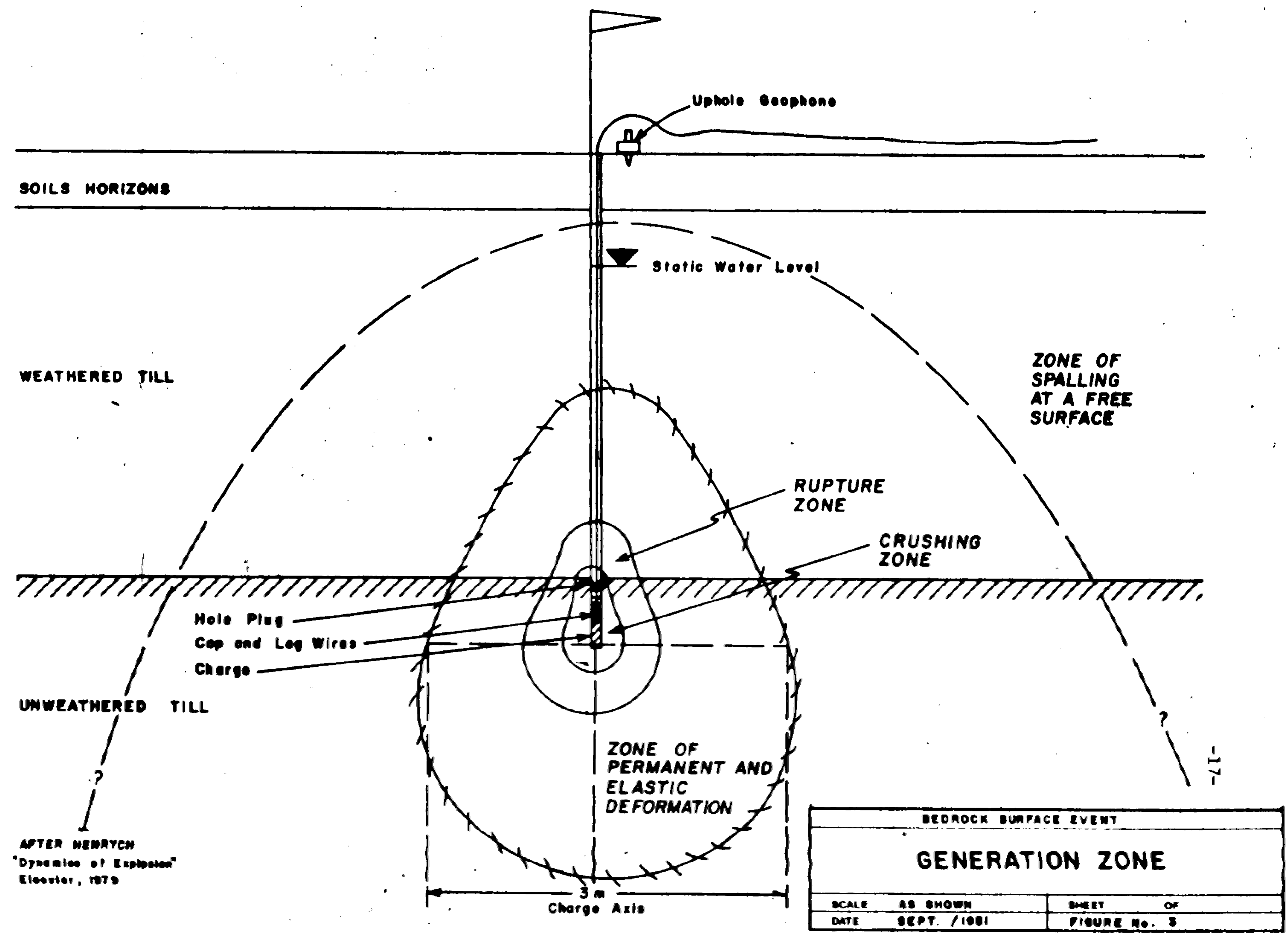
When the shot is detonated, a very large amount of energy is released in a period of time measured in microseconds. This burst of energy is transformed into a elastic pulse that propagates outward and downward. When the pulse encounters a significant change in geological materials, an echo is generated that propagates back toward the earth surface to be received by geophones on the ground which transform the ground vibrations into electrical energy, for recording.

The output voltage is read by truck-mounted recording instruments and converted to a digital format which is then stored on a computer readable magnetic tape. A paper "wiggle trace" monitor record is produced at the same time as an indication of what is on the magnetic tape.

When the recording operation is complete, the cap wires are pulled from the shothole and the hole is plugged. Bond (1975) demonstrated that shotholes tend to seal themselves in a short time, usually within a week of detonation.

Occasionally a shothole encounters an aquifer that possesses a hydraulic head that is higher than the ground surface and produces a "flowing hole". These holes must be sealed, usually by cementing, to preserve aquifer pressure and quality.

The second phase of seismic exploration begins when the field tape, monitor records and notes from the field crew arrive at the geophysicist's office. The geophysicist applies a number of static and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SOILS HORIZONS
Static Water Level
WEATHERED TILL
ZONE OF SPALLING AT A FREE SURFACE
RUPTURE ZONE
CRUSHING ZONE
Hole Plug
Cap and Log Wires
Charge
UNWEATHERED TILL
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DATE SEPT. /1981
FIGURE No. 3

dynamic corrections to the data which allow for the differences in travel time between the shot and echo arrival at each successively more distant geophone group. The depth to a geological horizon can be derived from a series of seismic echo events through knowledge of the shot to detector geometry and the propagation interval velocity between geological strata. Geometry is known from topographical surveys and interval velocities are derived from acoustic log surveys in nearby oil wells.

Quite often, echo events are not very well defined on a record. To enhance these events (i.e. to reduce noise), the geophysicist sums the output from all geophone groups that have received echos from the same point at depth, a procedure known as "stacking". The theory is that the signal from a true event will be repeated on each separate record, while noise is a random phenomenon that will be different on each record. The noise pulses will therefore tend to cancel each other out when the outputs are summed. True events will be multiplied by the number of traces in the stack. The net result is much reduced background noise.

A second category of data enhancement technique available to the geophysicist is filtering. Filtering reduces the strength of "coherent noise" (or interfering echos) and extraneous vibrations below the strength of the echo from the horizon of interest. This can be done by removing certain frequency bands from the recorded signals and by adjusting the amount of amplification (automatic gain control) over time. The two techniques are usually applied simultaneously in a fairly complicated, scheduled, manner to optimize the signal-to-noise ratio at a number of places on the record section.

When the geophysicist is satisfied that all events of interest are as well defined as possible he can begin the third phase of the survey, mapping the results. This involves measuring event arrival times from some datum, usually an assumed initiation time, or a near surface event that is known to possess very little geological relief, and plotting them on a base map next to the shot point location. The values are then contoured to produce an "isochron" map which can be converted to depth, if desired. The inferred relief is then interpreted in the context of known geology to identify the most prospective land.

Many other displays, techniques and interpretive methods are used in modern exploration practice. However the foregoing represents the general approach and basic information derived in all petroleum exploration seismic surveys.

D. <u>POTENTIAL FOR CONFLICT</u>

The interrelation between groundwater flow, water well hydraulics and seismic exploration is at once obvious and subtle.

A dynamite blast can be heard and the subsequent ground motion felt for a considerable distance. Furthermore, everyone knows dynamite is a powerful substance and the blast is often accompanied by a geyser of water and dirt.

Water wells are perceived as cantankerous and fragile entities that have a tendancy to "go dry" for no apparent reason at the best of times. They are costly for an individual to construct and water is frequently not found where it is needed with a sufficiently high quality for its intended use.

Both the seismic blast and the flow of groundwater into the well bore are subtle phenomena as the processes involved cannot be directly observed. They are hidden and therefore can only be speculated upon by the layman.

"Layman" in this context extends to all three groups of people involved with the problem. The farmer, in general, is unfamiliar with both groundwater phenomena and blasting mechanics. He is very much familiar with the behaviour and technology of wells. Geophysical personnel have some familiarity with blasting mechanics, but are less familiar with water wells.

Hydrogeologists are well versed in groundwater phenomena and well hydraulics, but not at all familiar with blasting mechanics and seismic phenomena.

Since no one group of expertise extends across all three sets of phenomena, and all three sets of phenomena are complicated and subtle, the relationship between a seismic blast and changes in performance in nearby water wells has never been satisfactorily worked out. The approach used in the present study is to synthesize existing geophysical, hydrogeological and complaint data into a working hypothesis, test the hypothesis in the field through controlled experimentation and present conclusions concerning the possible failure mechanisms suggested by the results.

The present work grew out of a multiphase program initiated in 1976 by the Exploration Review Branch, Alberta Energy and Natural Resources, in cooperation with the Groundwater Branch, Alberta Environment, and the Groundwater Division of Alberta Research Council.

II. REVIEW OF EXISTING INFORMATION

A. PREVIOUS WORK

The effects of blasting vibrations associated with mining, quarrying and excavation operations on people and surface structures have been studied extensively in North America and Europe. Mining and military engineers have also studied the effects of blasting vibrations on subsurface structures, in particular tunnels, shafts, galleries and missile silos. Very little has been published on the effects of blasting vibrations on domestic water wells and their associated aquifers.

Before the initiation of the present program, only one other research report is known to have been published, that being the results of a Montana project carried out in 1970 by Bond (1975). He found no significant changes to aquifer characteristics occurred following experimental blasts at close range to five tests in south eastern Montana. He also found that shotholes tend to seal themselves in a fairly short time and that little or no interflow occurs that could change aquifer quality.

Phase I of the joint Energy and Natural Resources/Environment/Research Council program essentially duplicated Bond's work under Alberta conditions. Goble (1980a) reported more or less the same results as Bond, although some variation in transmissivity values were observed at some sites. The observed changes were not consistent and Goble concludes they could have been the result of experimental error.

Vogwill (1979) reported on the Alberta Research Council portion of Phase I. The experimental design for his work was significantly different from Bond and the Energy and Natural Resources/Environment effort, in that a strenuous effort was maintained to control experimental error.

Four new wells were installed at a single site. They were completed in two different aquifers that are not in hydraulic communication. One well in each formation was completed with slotted casing and one with an open hole. Vogwill concluded there were no significant changes in well characteristics following treatment by blasting at ranges from 180 m to 4.6 m. A small but consistent change can be discerned in the transmissivity values he presents for the drift well with slotted casing, however.

The experimental method was essentially the same in all three programs. A pumping test was carried out on the test well before blasting and repeated following each blasting episode. An average of 3 treatments were carried out at each site at distances from 3 m to 365 m. The most common shot-point-to-well separation was 180 m. Charge weights were from 2.25 kg to 22.5 kg of 60% nitroglycerine equivalent explosive. Most tests in Bond's program used 11.25 kg charges, while the Alberta tests were conduced dominantly with 4.5 kg charges. Most shot holes had a total depth of about 30 m.

B. ANALYSIS OF COMPLAINTS

To complement the field program described below, a survey of complaints filed with the Exploration Review Branch, Alberta Energy and Natural Resources, was made. The objective of the survey was to: a) obtain a profile of the types of water well failures might be associated with seismic survey activities; b) determine if certain geographic areas were prone to complaints; c) determine whether any correlation exists between and amongst water well failure characteristics and the character of blasting operations associated with seismic surveys.

1. Sampling Technique

The technique used for selecting cases was to draw every fifth file kept in the storage vault until a total of one hundred and fifty were on hand. The files are kept in a numerical sequence governed by the order in which the complaint was received. The indexing method is independent of any other factual element maintained in the file.

Each file contains an initiation memo (usually a handwritten summary of a telephone conversation); an investigation report filled out by the Exploration Inspector assigned to the case; correspondence related to the case including shot point data from the seismic contractor or that firm's client; and a memo describing disposition of the case. An example of an inspection report form appears in figure 4.

2. Data Preparation

A data input form was prepared and a set of codes established for non-numeric variables. The states for each code were established

Form [illegible]

Alberta
ENERGY AND NATURAL RESOURCES

EXPLORATION INSPECTOR'S REPORT

File Number: ____________

Name of Claimant: ____________ Phone: ____________

Name of Owner: ____________

Address: ____________

Land Description: ______ Sec. ______ Twp. ______ Rge. ______ W. ______ Mer.

WATER SUPPLY

Type: ____________ Age: ____________ Total Depth: ____________

Type of Pump: ____________ Casing: ____________ Diam. & Depth: ____________

Cylinder: ____________ Size & Depth: ____________ Log of Well: ____________

Previous Yield: ____________ Present Yield: ____________

Distance to S.P.: ____________ S.P. No.: ____________ Permit No.: ____________

Source of Water Sample and Condition: ____________ Present Static Level: ____________ Previous Static Level: ____________

Seismic Co.: ____________

Oil Co.: ____________

CLAIMANT INFORMATION

______ Sec. ______ Twp. ______ Rge. ______ W. ______ Mer.

Scale: 2" = ½ mile

Date of Investigation: ____________

____
Exploration Inspector

____
Claimant

COPY – File
– Claimant
– Field Copy

Alberta
ENVIRONMENT

EXPLORATION INSPECTOR'S REPORT

SUBMITTED	DESIGNED	SCALE N/A	SHEET OF
DATE	CHECKED	DATE SEPT /1981	FIGURE No 4
APPROVED	DRAWN		
DATE	CHECKED		

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DRAWING No

FILE No

following discussions with Branch officials, persons familiar with water well problems and the writer's personal experience.

A data format was established to allow easy encoding and processing using the Statistical Package for the Social Sciences, SPSS (Nie et al, 1975).

Complaint files were then coded. Those files which did not relate to water well complaints (many refer to unauthorized surface disturbance) or related to spurius claims (the crew had not yet set up or were under suspension at the time of the alleged failure; the shot had not yet been detonated; no geophysical activity had occurred in the area or the nearest activity was in the order of 8 Km from the site or similar circumstances) were not coded. 82 of the 150 cases drawn were considered bona fide complaints and the circumstances were coded.

3. Data Analysis

Following encoding, the data set was subjected to scrutiny for coding errors, out-of-range values and missing data. The validated continuous data were then processed to obtain continuous descriptive statistics which were then used to establish data classes. After classes for continuous variables were established, the data was re-coded and histograms generated for all variables. The test for validity of classes chosen was a reasonable congruence of the means and standard deviations of the classed data versus the same parameters for the continuous data.

Output for the continuous data sub sets appears in Table 1.

PASS #1: FREQUENCY DISTRIBUTIONS FOR COMPLAINT FILES 08/17/80 PAGE 1 of 3
CONTINUOUS DESCRIPTIVE STATISTICS
FILE COMPL (CREATION DATE = 05/17/80)

Table 1.

VARIABLE AGE

MEAN	17.422	STD ERROR	1.623	STD DEV	14.241
VARIANCE	202.810	KURTOSIS	0.649	SKEWNESS	0.973
RANGE	66.500	MINIMUM	0.500	MAXIMUM	67.000
SUM	1341.500				

VALID OBSERVATIONS - 77 MISSING OBSERVATIONS - 4

- -

VARIABLE YIELDI INITIAL YIELD

MEAN	9.281	STD ERROR	1.618	STD DEV	12.323
VARIANCE	151.853	KURTOSIS	3.689	SKEWNESS	2.175
RANGE	49.700	MINIMUM	0.300	MAXIMUM	50.000
SUM	538.300				

VALID OBSERVATIONS - 58 MISSING OBSERVATIONS - 23

- -

VARIABLE DROWNI INITIAL DRAWDOWN

MEAN	13.750	STD ERROR	3.981	STD DEV	11.260
VARIANCE	126.786	KURTOSIS	-1.098	SKEWNESS	0.661
RANGE	28.000	MINIMUM	2.000	MAXIMUM	30.000
SUM	110.000				

VALID OBSERVATIONS - 8 MISSING OBSERVATIONS - 73

- -

VARIABLE WELLEL WELL ELEVATION.

STATISTICS CAN NOT BE COMPUTED FOR THIS VARIABLE.
VARIABLE IS EITHER MISSING FOR EVERY CASE, ALPHANUMERIC, OR HAS NUMERIC VALUES EXCEEDING 10,000,000,000,000.

- -

VARIABLE WELDEP WELL DEPTH

MEAN	93.692	STD ERROR	13.157	STD DEV	116.204
VARIANCE	13603.255	KURTOSIS	17.515	SKEWNESS	3.505
RANGE	795.000	MINIMUM	5.000	MAXIMUM	800.000
SUM	7308.000				

VALID OBSERVATIONS - 78 MISSING OBSERVATIONS - 3

PASS #1: FREQUENCY DISTRIBUTIONS FOR COMPLAINT FILES   Table 1.   06/17/80
CONTINUOUS DESCRIPTIVE STATISTICS
FILE COMPL (CREATION DATE = 06/17/80)

VARIABLE STATIC STATIC WATER LEVEL

MEAN	168.179	STD ERROR	127.471	STD DEV	796.063
VARIANCE	633701.089	KURTOSIS	38.720	SKEWNESS	6.212
RANGE	5003.000	MINIMUM	1.000	MAXIMUM	5004.000
SUM	6559.000				

VALID OBSERVATIONS - 39   MISSING OBSERVATIONS - 42

- -

VARIABLE CASED LENGTH OF CASING

MEAN	77.325	STD ERROR	13.730	STD DEV	108.978
VARIANCE	11876.267	KURTOSIS	31.448	SKEWNESS	4.941
RANGE	799.000	MINIMUM	1.000	MAXIMUM	800.000
SUM	4871.500				

VALID OBSERVATIONS - 63   MISSING OBSERVATIONS - 18

- -

VARIABLE DIAM WELL DIAMETER

MEAN	20.250	STD ERROR	12.495	STD DEV	106.024
VARIANCE	11241.183	KURTOSIS	70.855	SKEWNESS	8.387
RANGE	903.000	MINIMUM	1.000	MAXIMUM	904.000
SUM	1458.000				

VALID OBSERVATIONS - 72   MISSING OBSERVATIONS - 9

- -

VARIABLE SPDIS DISTANCE TO SHOT POINT

MEAN	1267.308	STD ERROR	358.222	STD DEV	2888.076
VARIANCE	**********	KURTOSIS	32.889	SKEWNESS	5.624
RANGE	19880.000	MINIMUM	140.000	MAXIMUM	20020.000
SUM	82375.000				

VALID OBSERVATIONS - 65   MISSING OBSERVATIONS - 16

- -

PASS #1: FREQUENCY DISTRIBUTIONS FOR COMPLAINT FILES
CONTINUOUS DESCRIPTIVE STATISTICS
FILE COMPL (CREATION DATE = 05/17/80)

Table 1.

VARIABLE SPDEP DEPTH TO SHOT

MEAN	25.200	STD ERROR	7.108	STD DEV	44.955
VARIANCE	2020.923	KURTOSIS	38.520	SKEWNESS	6.161
RANGE	297.000	MINIMUM	3.000	MAXIMUM	300.000
SUM	1008.000				

VALID OBSERVATIONS - 40 MISSING OBSERVATIONS - 41

- -

VARIABLE SPEL SHOT POINT ELEVATION

STATISTICS CAN NOT BE COMPUTED FOR THIS VARIABLE.
VARIABLE IS EITHER MISSING FOR EVERY CASE, ALPHANUMERIC, OR HAS NUMERIC VALUES EXCEEDING 10,000,000,000,000.

- -

VARIABLE CSIZE

MEAN	4.218	STD ERROR	0.713	STD DEV	4.454
VARIANCE	19.853	KURTOSIS	6.802	SKEWNESS	2.522
RANGE	19.500	MINIMUM	0.500	MAXIMUM	20.000
SUM	164.500				

VALID OBSERVATIONS - 39 MISSING OBSERVATIONS - 42

- -

VARIABLE TDEL

MEAN	75.349	STD ERROR	21.781	STD DEV	142.827
VARIANCE	20399.661	KURTOSIS	11.368	SKEWNESS	3.173
RANGE	729.000	MINIMUM	1.000	MAXIMUM	730.000
SUM	3240.000				

VALID OBSERVATIONS - 43 MISSING OBSERVATIONS - 38

- -

VARIABLE LFAIL TIME FAILURE PERSISTED

MEAN	758.486	STD ERROR	66.469	STD DEV	393.233
VARIANCE	154632.492	KURTOSIS	-0.636	SKEWNESS	-1.114
RANGE	997.000	MINIMUM	2.000	MAXIMUM	999.000
SUM	26547.000				

VALID OBSERVATIONS - 35 MISSING OBSERVATIONS - 46

Cross tabulations of all variables were then carried out in pair-wise fashion for counts of non-numeric data as a form of contingency table analysis to determine event dependancies. The same analysis was carried out between classed, continuous variables and also between non-numeric events and classed, continuous variables. Contingency table analysis was carried out in two stages. First, 2 X 2 tables were devised where the histograms indicate a bimodal distribution or a presence/absence couplet was obvious.

Contingency tables were also generated to determine if multivariate relationships exist, based on dependancies noted during the bivariate analysis.

4. Results

While it is tempting to interpret the data as information on well failure, what it really implies is a profile of conditions that generate complaints. The conditions surrounding actual well failures will be a subset of these. Without objective, corroborating field evidence, it is very difficult to separate the two, however.

Both the continuous and the discrete data are widely variable, with the standard deviation for each continuous variable commonly being equal to several multiples of the mean. A number of characteristics do appear to be common. The bulk of the complaints are located in three zones: (1) Centred on Edmonton from Vegreville to Evansburg and Leduc to Westlock; (2) Lethbridge to Taber, Skiff to Nobleford; and another cluster appears around (3) Calgary. These areas do represent concentrations of population. Area (1) contains some 33% of Alberta's rural/small town population (1976 census) but attracted 49% of the complaints in the survey.

The age of the wells in the sample varied from six months to sixty-seven years. There appear to be four separate age categories, although only two are considered: "new wells" (0 to 15 years) and "old wells" (over 15 years). The dividing line was chosen to be the second modal group, which also corresponds to the distribution median. The two commonest failure categories were loss of yield (59.3% of all cases) and change in quality (29.6%). The most common yield failure category was 76 to 100% loss of production (28 of 45 cases or 62%) and the most common quality failure was siltation (20 of 36 or 56%).

The wells in the survey were generally drilled and cased (66.7%) or bored and cased (13.6%). They were generally claimed to be good producers, with 51% being classed in the greater than 4.5 gallons per minute (0.69 m^3/day), were steel cased (77.8%) and less than four inches (102 mm) in diameter (54%). Most wells have not undergone pumping tests (76.5%) and are open hole completions (60%). The second most popular completion type is slotted casing (20%). Depth varies considerably. For contingency table purposes, two categories were established: "shallow" (0 to 30 m) and "deep" (greater than 30 metres), based on relative frequency clustering. The "shallow" category represents up to the first mode.

Static Water level was also divided into two categories ("high" and "low") on the basis of the first mode.

Most use either submersible pumps (33.8%) or jet pumps (36.6%).

Sands (consolidated and unconsolidated) were the most common aquifers (22.7% and 45.5%, respectively). No driller's log is available for most (69.3%) wells.

Three variables related to the shot point are significant: (1) Shot point to well distance; (2) Shot depth below ground and (3) Charge size.

, The shot-point-to-well distance parameter is widely variable. It was grouped by multiples of the minimum permitted distance and the result was a multi-modal distribution, with the principal mode being the 180 m to 360 m category. This is reasonable in that the informal minimum of 330 m is in this range as well. The other modes correspond roughly to the most common shot point to shot point distances currently in use (200 m).

Not surprisingly, most of the shotholes were between 15 and 20 m deep. The industry standard is 20 m, which corresponds to the depth of weathered sediments in most of Alberta. 77.5% of the cases were in this range.

The most common charge weight is 2 Kg (40.5% of cases) and 81% were less than 5 Kg. (Dynamite is usually sold in 1 Kg and 2.25 Kg cartridges, thus the majority of shots will be multiples of these values).

65.1% of the cases were reported within one month of the event. 79.1% were reported within 3 months. The longest delay in the sample was two years. In 80.0% of the cases the reported failure lasted more than 9 months.

Most of the reported cases (77.9%) were rejected, while 18.2% were settled privately.

The composite profile of a case that emerges is: a new well, with surface steel casing and an open hole completion producing in excess of 0.7 m^3/day, is either reduced to less than 25% of its pre-blasting production or is silted following a 2 Kg shot at 20 m depth, 250 m or more away. The claim, in the typical case, is rejected by the Branch or settled privately.

The 2 X 2 Contingency tables were constructed to see if any parameter is more important than the others in terms of (a) case disposition and (b) the type of alleged failure.

Insofar as disposition is concerned, at the 5% acceptance limit using the Chi square statistic (χ^2 > 3.8 required to accept the proposition that the observed distribution could be explained equally well by random association) to determine the goodness-of-fit between the variables and the gamma statistic as a measure of association, the following observations can be made:

(1) Disposition is independent of age, well depth, shot point to well distance, shot depth, time delay in reporting and persistence of the failure.

(2) A fairly tight dependancy exists between well diameter and disposition.

Using the same criteria for failure type:

(1) Failure is independent from age, disposition, well depth, shot point to well distance and time delay in reporting.

(2) Dependancies are indicated between failure and static water level, well diameter and persistence of failure.

The extended (n X n) contingency tables, again using a 5% significance level for the Chi square goodness-of-fit criterion and the Gamma correlation measure, suggest:

(1) Age and disposition are independent, as are age and type of failure;

(2) Failure and well type, age, completion type, static water level, casing type, pump type, aquifer type and shot-point-to-well distance are all independent.

(3) Weak correlations exist between failure type and casing length and between failure type and well diameter.

5. Discussion

The widely variable nature of the data and the lack of firm correlations between variables makes it difficult to discern any general characteristics that can be applied to describe the conditions which surround the generation of a complaint. The preponderance of rejected claims also make it difficult to discern the differences between well failures that have been directly attributed to geophysical activity and those produced by other causes.

Correlations were observed between failure type and well diameter, static water level, casing length and persistence of failure. None of these factors relate to any of the geophysical activity variables, apart from the presence of such activity itself.

If geophysical activity is a "dummy variable", i.e. it exists in only two states, presence and absence, it would be worthwhile to compare this data set with a comparable data set of well failures where geophysical activity is absent to determine if the same profile of variables deduced for this set has a comparable set of values and the variables exhibit a similar set of dependancies.

The preponderance of rejected cases is also troublesome. Most cases referred to the Branch for arbitration could not be settled amicably between the well owner and the geophysical contractor, which suggests the data set is heavily biased toward marginal cases. It would be useful to have a survey of industry files to establish the difference in profiles and patterns of dependancies between complaints settled amicably and those referred to the Branch.

C. <u>BLAST MECHANICS</u>

The transfer of energy from a contained (deeply buried) charge of high explosive to the surrounding ground is governed by a number of factors. The most important of these are peak borehole pressure, mechanical impedance and coupling of the charge to the borehole, according to Coates (1970, Chapter 8) and Hagan (1979).

Peak borehole pressure is in turn governed by the density of the explosive, the velocity of detonation (VOD) of the explosive and a constant of proportionality related to charge-to-borehole coupling.

Mechanical impedance is the fórce per unit displacement required to set the system in motion. It is a complex sum of formation stiffness, angular velocity of the exciting force acting on the formation unit mass and the amount of damping present (i.e. internal friction) in the formation.

Charge coupling is simply how loosely or tightly the cartridge fits in the hole. A related variable is the amount and kind of stemming: the presence or absence of water or drill cuttings in the shothole.

1. Zonation of Blast Effects

The sequence of events which occur during and immediately following a detonation have been described by Henrych (1979), Hagan (1979), Jaeger and Cook (1977) and Bollinger (1971). The first is of particular interest in that Henrych devotes an entire chapter to confined explosions in soils. The following is a synthesis of these descriptions.

Bollinger (1971) has proposed a four fold classification for blasting vibration phenomena. This classification is adopted in this project. The categories are zones related to the shot (Generation Zone), the location of the sensing equipment (Recording Site), the media between the shot and the recording site (Seismic Transmission Zone) and the acoustic Transmission Zone. Figure 3 illustrates the relationship amongst the various zones of influence surrounding the shot. Bollinger's work is essentially an annotated bibliography. The reader is referred to it for a thorough review of the pre-1970 literature on blasting vibrations.

The above references suggested the following sequence of events during and immediately following detonation of a contained high explosive charge:

(1) A crushed zone is created immediately adjacent to the charge. The diameter of the crushed zone is a function of the peak compressive stress generated by the detonation and rock strength.

(2) An intensely fractured zone with predominantly radial cracking extends from the outer limit of the crushed zone to an abrupt termination. This point represents the limit to which the rapidly attenuating tangential stress wave, which produces tensile strain in the formation, is capable of generating new cracks.

(3) An outer zone of wide-spaced, radial fractures representing extension of pre-existing fractures is produced. The stress wave has attenuated below to the critical value for initiating new cracks, but is still vigorous enough to extend existing ones.

(4) In granular materials, a zone of plastic strain extends outward a short distance until the vertical elastic front has decayed sufficiently (a function of the soil);

(5) A zone of elastic strain then extends outward an indeterminate distance.

Two categories of energy are involved in a detonation. The first is chemical energy released by the process of detonation. This release lasts a very short time (in the order of a few thousandths of a second) and is transformed to mechanical energy and heat. Mechanical energy is also manifested in two forms: elastic induced vibration and large volumes of rapidly expanding gas. The gases are further energized by the release of heat during the explosion.

The primary results of the explosion are: (1) the generation of a compressional elastic wave type of vibration which propagates outward at a velocity determined by the type of geological material it encounters and (2) production of a system of cracks that are created by failure of the bonds between particles of rock (or soil) caused by the elastic wave and both opened further and extended by expanding gases.

Should the compressive stress wave encounter a free surface it is immediately reflected, becoming a tensile wave in the process. The transmission medium is thrown from compression into tension in a few milliseconds and fails. The extent of the reflection breakage or spalling is a function of the material and intensity of the stress pulse at the free surface. This phenomenon is normally observed close to the shot, and is a function of both charge weight and the strength of the material (Jaeger and Cook, 1977).

The above describes a process common to both consolidated and unconsolidated materials but soils develop two important secondary, post-detonation characteristics (Henrych, 1979). The first of these is an enlarged cavity created by the explosion and the second is a cupola-shaped swell of the soil. If the charge was buried near enough to the surface, the explosion cavity creates a secondary vibration of short duration and the cupola swell produces a high amplitude surface vibration called ground roll. The cupola swell may have sufficient energy to breach the surface and cause a crater. The relationship between depth of burial and crater characteristics is described empirically by Henrych (1979) and Bauer and Crosby (1980), among others.

Given the above phenomena, two questions arise. First, how far from the shothole does the fissuring extend? Second, how much energy is absorbed by the crushing and fissuring process, and under what circumstances can fragmentation be minimized (i.e. under what circumstances will energy transferred to the formation as a stress pulse be maximized)?

The answer to the first question is not simple: it is a function of peak borehole pressure, charge coupling and mechanical impedance in combination.

As for the second question, Hagan (1979) suggests the crushed zone in rock is not greater than 2 cm for a charge 4 cm in diameter for loose coupling. He does not quantify the coupling ratio, and therefore the energy loss cannot be readily computed.

Attempts at quantification of the energy lost in this zone have been made by Terada (1966a, 1966b) and Terada and Tanimoto (1967) using both empirical and fundamental physical arguements. These studies concluded that energy is lost according to a natural logrithmic law that will be discussed in detail in a later section.

2. Influence of Charge Weight

Calder (1979), citing data from published sources, asserts that the radius of rupture for shale using a 60% nitroglycerin dynamite (the most commonly used type in seismograph exploration) in a 4 inch (10.2 cm) diameter borehole is about 10 feet (3 metres). Henrych suggests the following empirical relation for clay soils:

$$R_c = (6\text{-}8)\ \sqrt[3]{W}$$

wherein R_c is the radius of rupture (or plastic zone), and W is the weight of explosive in TNT equivalents. Thus for 2 Kg of TNT equivalent, R_c = 7.6 - 10.1 metres, a distance somewhat greater than the Calder et al estimate. Nevertheless the zone of rupture is clearly less than the 180 metre safe distance prescribed in the Exploration Regulation (Alberta Regulation 423/78).

To maximize the transfer of energy from the explosion to the formation and minimize crushing, Hagan, Calder et al and Henrych agree that the peak borehole pressure exerted by the explosion gases must be kept at or slightly below the compressive strength of the surrounding material and coupling minimized: i.e. the charge should be decoupled. Calder further notes that if a decoupled charge is surrounded by water its effective strength upon detonation increases, and the level of ground vibrations increases by several times.

In discussion with the writer, a number of working geophysicists confirmed these observations for highly elastic materials like clay shales. More rigid formations like consolidated sandstones apparently do not respond in the same way. Unconsolidated dry sand formations usually collapse the borehole anyway and tight coupling cannot be avoided.

Vasil'yev and Molotova (1976) took a more deterministic approach, while recognizing the existence of random variables in the system. They recognized an interaction between the pressure versus time function of the explosion, p(t), and the creation of the cavity, which acts as an emitter function, [where a is the cavity radius and Q is the charge size] and the resulting stress amplitude function a(Q).

The pressure/time function was assumed independent of a(Q) or only weakly correlated with it. Both functions were also assumed frequency dependant. Results were therefore obtained for a single frequency, for both compressional (P) and shear (S) waves.

They determined: (1) over a wide range of charge sizes the source emitter model that produces the closest results to experimental observation is the finite-length cylinder driven by a unit step function; (2) the ratio of shear wave velocity to compressional wave velocity (ie. the Poisson Ratio) is a function of the degree of water saturation in the propagating layers and (3) the dimensions of the emitter are close to those of the explosion cavity.

The significant features of their work for the present study may be seen in their figure 2, reproduced here as figure 5. First, the intensity of the observed pulse is greater in water saturated soils (figures 5a through 5c), by an order of magnitude over dry soils. Second, over the range of charge sizes used in geophysical exploration (1 Kg to 10 Kg) there is no appreciable increase in the observed intensity of the elastic wave. Finally, given accurate information on charge size and ground saturation, a reasonable amplitude can be computed for a given site (the authors claim cross correlation r-values between .90 and .95 between predicted and measured wavelets).

The functional relationship between the amplitude term a(q); and the emitter shape term p(t) is of the form:

$A_i^{\tau}(Q) = \text{mod}[Sp_i(Q) \cdot M_i(Q)]$

$A_i^{\tau}(Q)$ = the amplitude at a single fixed frequency i at time τ for a given charge weight, Q.

$S_{pi}(Q)$ = the component of amplitude spectrum produced by a given emitter shape (i.e. cylindrical or spherical) at a given frequency for a given charge weight, Q.

$M_i(Q)$ = the value of the frequency characteristic of the emitter for the same fixed frequency, produced by a function describing explosion cavity size and shape on the basis of explosive weight. This term assumes these parameters to be proportional to Q.

Each of these three terms can then be specified in terms of the geometry of the explosion cavity chosen. For physically small charges, a point source can be assumed and a spherical mode invoked, while very large charges in boreholes will produce cylindrical cavities.

The main conclusion drawn by Vasil'yev and Molotova is that the amplitude spectrum produced by an explosion is a function of the size and shape of its explosion cavity. This implies that the maximum transfer of energy from a detonation to the surrounding formation occurs

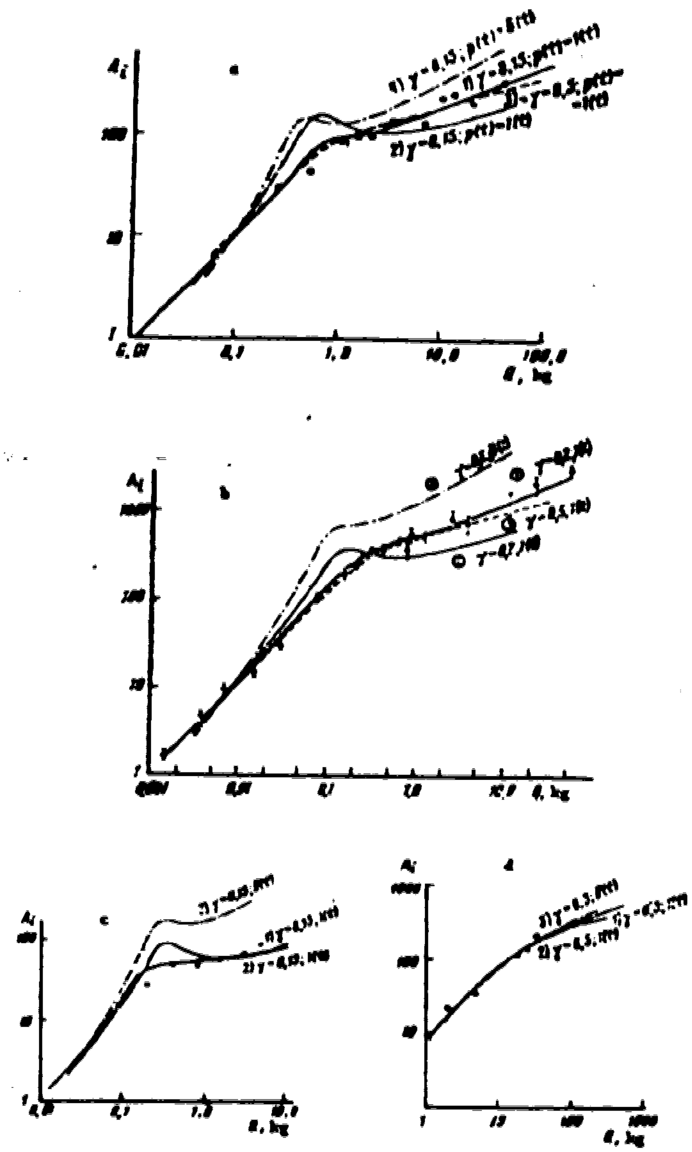

Fig. 2. Comparison of the observed amplitude characteristics of an explosion, taken from the experimental results of the authors and literature data, with the theoretical amplitude characteristics of a spherical emitter and a cylindrical emitter of finite length. In the case of a cylindrical emitter it is assumed that p (t) = 1 (t); for a spherical emitter it was assumed that p (t) = 1 (t) and δ (t). The experimental data are everywhere plotted by points; the frequency of the spectrum to which the experimental results correspond, is indicated. The depth of the explosions was 20–50 m:

a) explosions in water-saturated soil, V_p = 1600 m/sec, V_s = 220 m/sec, γ = 0. 14 (Saratov trans-Volga); the frequency is 60 Hz. 1) Theoretical curve for a cylindrical emitter of finite length, φ = 90°; 2–4) theoretical curves for a spherical emitter; b) explosions in water-saturated soil, V_p = 1700 m/sec, V_s = 300 m/sec, γ = 01. 8 (northern Krasnodar district), frequency 100 Hz; the values of the confidence intervals for a reliability α = 0.9 are noted. 1) Theoretical curve for a cylindrical emitter of finite length, φ = 45°; 2–4) theoretical curves for a spherical emitter; c) explosions in watery argillaceous rocks, γ = 0. 16 (western Siberia, data [20]), frequency 40 Hz, 1) theoretical curve for a cylindrical emitter of finite length, φ = 5°; 2 and 3 are theoretical curves for a spherical emitter. d) Explosions in sandy argillaceous rocks above the level of the subsurface water, V_p = 650 m/sec, V_s = 420 m/sec, γ = 0. 5 (Rostov region), frequency 15 Hz.
1) Theoretical curve for a cylindrical emitter of finite length, 2 and 3) theoretical curves for a spherical emitter.

SOURCE VASIL'YEV AND MOLOTOVA (1976)

Alberta ENVIRONMENT

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APPROVED	DRAWN
DATE	CHECKED

BEDROCK SURFACE EVENT

CHARGE WEIGHT VERSUS INTENSITY OF BLASTING VIBRATION

SCALE AS SHOWN	SHEET OF
DATE SEPT / 1981	FIGURE No 6

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at the natural frequency of the explosion cavity, which functions as a resonator or wave trap. Small cavities could be expected to emit high frequencies and large cavities would produce a spectrum dominated by low frequencies.

If the cavity was a static entity, this concept would be self evident. The cavity is a dynamic entity however, and its dimensions and shape are determined by the amount of explosive used. Because, small explosions produce small cavities and large explosions produce large cavities it follows that small explosions in elastic media produce high frequency rich amplitude spectra and large explosions produce elastic waves that are dominated by low frequencies.

Quantitatively, the function $M_i(Q)$ can be described deterministically if the density and Poisson's ratio for a given site are known. The form of the function is determined by the cavity shape. Vasil'yev et al recommend the cylindrical model as it best corresponds to actual field data (the heavy solid line in figure 5). This is a departure from the usual assumption of a spherical concentrated charge.

They present two cylindrical emitter equations, one for the general case and one for the isotropic medium case. The isotropic (i.e. simplest) case demonstrates the complicated interaction amongst formation propagation velocity, vibration frequency, formation density and charge size in which $M_{pi}(Q)$ is the characteristic of a cylindrical emitter of finite length for longitudinal waves.

$$\mathrm{mod}\ M_{pi}(Q) = 1/\pi\rho\omega_1{}^2 \cdot A$$

$$A = \frac{(1/a)q^2}{\{[(vq/2\gamma)J_o(v\gamma q)-J_1(v\gamma q)]^2+[(vq/2\gamma)Y_o(v\gamma q)-Y_1(v\gamma q)]\}^{1/2}}$$

Here ρ is the density, $v = \omega/\omega_1$, where ω is the angular frequency of the vibration, $\omega_1 = V_s/a_1$ and a_1 is some fixed radius of the emitter; $q = (Q/Q_1)^{1/2}$, where $Q_1 = (V_S/k\omega_1)^2$; k is the proportionality coefficient in relationships of the form $a = kQ^{1/3}$ following from the assumption that the volume of the emitter is proportional to the amount of charge. J_o and J_1 are Bessel functions of the first kind. Y_o and Y_1 are Bessel functions of the second kind.

The authors derived a k value between 0.6 and 0.7 for saturated "terrigenous" sediments (presumably till). They also found that 1/a is very near 1.0 under field conditions.

The dominant variable in the equation is γ, the ratio between the propagation velocities of the shear and compressional waves. Closely associated with γ is ω_1, the ratio between the shear wave velocity and the radius of the emitter (the maximum size of the explosion cavity).

The other function in the amplitude determination modal function, $S_{pi}(Q)$ is the duration of overpressure associated with the explosion. The authors experimented with both the Dirac δ function and a unit step function and found the latter gave the best fit with experimental data.

The implication for the present study of Vasil'yev and Molotova's work is that most shot energy enters a formation that exhibits a shear wave velocity that approaches the compressional wave velocity and the explosion cavity resonant frequency approaches the natural frequency of the formation. It also suggests that the elastic wave amplitude spectra will show minor peaks at integral multiples of the cavity resonant frequency (courtesy of the indices for Bessel function of the first kind). Furthermore, for charge weights between 1 Kg and 10 Kg, there is only a slight increase (less than a factor of two) in ground deflection amplitude.

In summation, it would appear from the literature reviewed that:

(1) The zone of crushing is restricted to the area immediately adjacent to the charge and extending out not more than .2 to .3 m;

(2) The zone of permanent deformation (Radius of Rupture) extends out from 3 to 10 m, for shots of the weight normally used in seismic exploration;

(3) If sufficient energy can be transferred from an explosion to the formation, and the resulting stress wave encounters a free surface before its intensity has been attenuated sufficiently, "spalling" or "reflection breakage" of the formation may occur;

(4) For constant charge weight, charge type, stemming and mode of initiation, the factors determining optimum energy transfer from the explosion to the formation are the peak borehole pressure and the formation mechanical impedance.

(5) Formation mechanical impedance is a function of the ratio between the shear and compressional wave propagation velocity; the ratio of the natural frequency of the formation and the natural frequency of the explosion cavity; and the spectral content of the shot.

(6) The initial amplitude of the vibration is the modal dot product of the excitation function and the frequency characteristic (mechanical impedance) of the formation the charge is buried in.

(7) Mechanical impedance of a formation is dominated by its Poisson ratio, as derived by the ratio:

$$\gamma = V_s / V_p$$

where Vs is the shearwave velocity and Vp is the compressional wave velocity.

D. ELASTIC WAVE PROPAGATION

The propagation of elastic waves is the main concern of the geophysicist who is conducting a seismic survey. In particular, the geophysicist wishes to study the elastic wave that has returned to the surface as an echo from the stratified layers below. The economic importance of. this activity has resulted in a large body of knowledge concerning the behaviour of earth materials subjected to low intensity stress. Those elements of theory that are useful in predicting or evaluating ground behaviour within a 330 m radius of a detonation are reviewed below.

1. Classification of Elastic Waves and Vibrations

Elastic waves, stress waves and vibrations are three words that are often used interchangeably, but which represent two separate concepts. An elastic wave or stress wave is sharp change in force per unit area within the body of a propagating medium. It moves radially from an impulsive point source at a velocity which is a fundamental characteristic of the propagating medium. A vibration is particle motion or oscillation in a fluid or an elastic solid set up by the passage of an elastic wave through the body that is in motion.

Elastic waves (or simply "waves") are described in terms of their propagation (or phase) velocity; frequency; phase relationships and amplitude. They propagate away from their source in a sphereoidal or cylindrical field until they encounter a free surface, after which they propagate as hemispheres. (Telford et al, 1976).

Vibrations are described in terms of particle velocity, displacement, and acceleration as well as frequency of oscillation.

Elastic waves are associated with a transfer of energy, while vibrations represent motions set up in a body or system as a result of elastic wave energy imparted to it.

2. Propagation of Seismic Waves

Seismic waves generated by any kind of source may be studied from two different perspectives: as causal agents (stress waves superimposed upon an existing system of static stresses) or as effects in the form of particle translation within the propagating medium (strains).

A good summary of first principles as they apply to exploration seismology is given by Telford et al (1976) pp 222-295. For a more complete mathematical treatment, the reader is referred to Brinkley and Kirkwood (1947), Kolsky (1952), White (1965), Dobrin (1976), and Ricker (1977). The latter work includes a critique of classical wave mechanics as applied to seismic wavelet theory.

Of immediate concern are those mechanisms that are responsible for transmitting and changing the form of an energy pulse from a detonation through the earth to a water well such that the pulse is strong enough to affect well hydraulics or degrade water quality.

a. Attenuation of Seismic Waves

The value of the peak amplitude of a seismic event (which is equivalent to the peak value of impulsive stress) would reasonably appear to be a function of the (1) initial charge size and coupling,

(2) the radial distance between a detonation and the recording site and (3) the energy absorbing capacity of the propagating medium.

In a layered earth, seismic energy propagates outward via (1) a direct path through the medium the shot occurred in; (2) a refracted path through two or more layers of differing acoustic impedance (characteristic velocity); (3) a reflected ray path through one or more layers of differing characteristic velocity; or (4) some combination of (1) through (3). In general, a seismograph record indicates the direct wave arrival on the geophones nearest the shot first as far as the critical distance, after which the first refracted ray becomes the first arrival and the direct ray shows up as a later arrival (figure 2). Precisely at the critical distance, the direct and the first refracted ray arrive simultaneously, by definition. The resultant wave has a peak amplitude that is the algebraic sum of the incident waves (Layat, 1967).

Layat showed that the increased ground motion that begins at the critical distance due to the in-phase arrival of the direct and refracted waves extends outward for a considerable distance because the time/distance curves for the two wave fronts are tangential.

The relationship between peak amplitude at a recording site and charge size in soils has been explored by a number of writers (Henrych, 1979; Awojobi and Sobayo, 1974), Kirilov (1963). Henrych presents a series of empirical relations (pp 224-227) for contained explosions in soils with varying degrees of water saturation, derived from the Soviet literature, which relate maximum overpressure to charge weight and scaled distance in the form:

$$i_m = A_2\ w(1/R)^{1/3}$$

wherein: i_m = intensity at a point remote from the explosion (presumably maximum overpressure).

A_2 = An efficiency parameter derived experimentally,

W = Charge weight in TNT equivalents

R = Scaled distance

He notes the formula is valid near the shot, but overpredicts elastic wave intensity when R is large.

Awojobi and Sobayo also used an empirical approach to produce a relation that sought to predict impulsive stress values at a large radial distance. They were concerned with the integrity of foundations and walls and therefore chose particle velocity as their intensity parameter. Their formula for Nigerian conditions is (Imperial units):

$$V = KR^{-1}W^{0.55}\exp(4.62(H/R)^{0.1})$$

in which: V = particle velocity

K = An empirical scaling factor

R = radial distance

W = Charge weight (60% NG)

H = depth of charge burial

The relation was derived from data published by Nichols, Johnson and Duval (1971), augmented by the authors' own field observations using mining and quarry blasting vibration monitoring techniques. The blasts observed were from exploration seismic surveys.

They conclude that water saturation affects the received frequency of the vibration wave train, with higher frequency spectra observed in dry ground. Their results indicate amplitudes are not significantly affected by soil water content, contradicting the conclusions drawn by Vasil'yev et al (1976).

Awojobi and Sobayo also found what they call a "stationary point" with respect to depth of shot burial. As the depth to radial distance ratio approaches 1.0 the exponential function, which is the attenuation term, approaches 1.0 (no attenuation). As the depth to distance ratio approaches 1.0, the exponential converges on 1.0 again. Using these extrema, the absorption coefficient which they derived is 4.62 for Nigeria (presumably the coastal plain). The implication of this finding is obvious. Near surface blasts create more surface vibration than blasts at depth, when observed at close range. What is less obvious is that shots at depth also tend to propagate with little attenuation.

These two formulae represent the two main categories of attempts to predict vibration amplitudes at a distance from its source. The first group, represented by Henrych, are purely empirical and depend upon a "scaled distance" parameter that assumes a nonlinear relationship between blast size and distance. These formulae take the general form:

$$I = KQ^{1/3}r$$

in which K is the slope of the regression line on log-log paper.

The second group, represented by Awojobi and Sobayo, may be termed "semi-empirical" formulae. The general form used is:

$$I = I_o e^{-\alpha r}$$

in which: I = Observed intensity,

I_o = a constant related to the intensity of the burst and can be considered the effective initial intensity,

e = naperian constant

α = absorption coefficient of the ground

r = the radial distance.

Born (1941) appears to have been the first exploration geophysicist to derive this relationship. His work was based on empirical field observation. Kolsky (1952, pg. 143) derived the same equation for stress waves along a filament (i.e. the one dimensional case) and generalized it to three dimensions for a variety of elastic media. It is accepted orthodoxy in most standard texts, including Dobrin (1976) and Telford et al (1976). Terada and Tanimoto (1967), and Terada (1966a, 1966b), applied the equation to laboratory specimens of various rocks subjected to tightly coupled charges and obtained values for α and I_o by least squares curve fitting.

Ricker (1977), in his critique of classical wave mechanics as applied to seismic blasting, demonstrates that this equation, modified for phase shifts due to frequency dispersion, is the second derivative of the Stokes' differential wave equation, which is also implied by Kolsky, and Henrych.

Various other workers, such as the Soviet group discussed by Kirillov (1963) have built upon this basic equation by adding variables of various kinds to improve the fit between predicted amplitudes and observed data.

The common element amongst all the semi-empircal formulae is the exponential function raised to an empirical constant. The constant, which is usually denoted by α, is the attenuation coefficient.

Essentially, the attenuation coefficient is an indirect measure of the internal friction of the propagating medium and is sometimes called "specific damping capacity" or "specific loss." The phenomenon is complicated and beyond the scope of this study to pursue. A thorough thermodynamic analysis which includes a pore fluid viscosity argument is given by Henrych.

Another attenuation mechanism is wave dispersion or "spreading". The velocity of propagation in a given medium is different for different frequencies in that high frequencies travel faster than low frequencies. While the differences are not great, they do become significant over long distances. Over the band of frequencies generated by seismic blasting and the distances of interest (up to 1 Km) to this study, however, dispersion is not significant and can be safely ignored.

In summary:

(1) High intensity seismic elastic waves which arrive at a detector do not necessarily arrive at the receiving site in a direct line: they may have followed a complicated path with a net length considerably longer than the radial distance;

(2) There is an intensity attenuation factor introduced during transmission that cannot be explained by radial distance and charge size alone;

(3) The degree of water saturation of a soil governs its acoustic conductivity and the ratio between shear wave and compressional wave velocity;

(4) The intensity of the observed wave is a function of initial intensity, damping due to friction losses (attenuation coefficient) and losses due to phase shifts arising from frequency related wave dispersion. Only initial intensity and friction losses are significant in the situation of concern herein.

E. ELASTIC WAVE AMPLITUDE AT A POINT

Drawing on the theoretical and experimental base outlined in the preceding two sections, it would appear possible to predict the amplitude of an elastic wave at any point remote from a blast, given information about the geology between the blast and the observation site and the seismic properties of the geology.

Two approaches are possible to this problem. If absolute pressure or ground deflection data are available from at least one point, the amplitude of ground motion can be predicted by simple logrithmic regression. It must be shown that geological structure is simple and the phase type of the elastic wave does not change during propagation. In such a case, the amplitude intercept represents the initial amplitude and the slope of the line is the attenuation coefficient.

If only relative amplitude data is available, the Vasil'yev and Molotova (1976) technique could be used to determine the initial amplitude, assuming shear wave and compressional wave velocities and Fourier spectra are also available. The attenuation coefficient could still be readily obtained by regression using the relative amplitude data.

The empirical formulae are largely intended for determining an elastic intensity at a point relatively close to a large burst (within a radius of 100m) and do not take elastic wave propagation into account. They are of limited value to the present problem for explosions at a fairly large distance from the reception zone in layered media.

The semi-empirical exponential curve fit approach is of greatest practical interest. Lumped parameters can be estimated statistically, given adequate data and the main deterministic variables can be measured reasonably accurately in the field. As the variance in each of the lumped variables is known or can be ,approximated using a known probability density function model, confidence intervals around an estimate can be established using the methods of Medearis (1978, 1979); or Awojobi and Sobayo (1974). The error of measurement for the deterministic variables can be found in a similar manner. Like most statistical methods, however, it requires many replications of the experiment to provide reliable data.

The functions proposed that meet these criteria are from Born (1941), Dobrin (1976) and Telford, et al (1976); in the general form

$$I = I_o e^{-\alpha r}$$

For purposes of field experimentation, I and r are measureable and I_o is known from manufacturers standards or can be estimated using the Vasil'yev-Molotova method. This leaves α to be determined. Telford et al (1976, pg. 241) warn of the difficulties in accurately measuring α but suggest it is a characteristic quantity for each earth layer.

Knopoff (1964) has shown α to be a function of Q, the transmission quality factor:

$$\alpha = {}^{f}/2QC$$

where f = frequency of vibration,

c = celerity or velocity of propagation

Q = f/Δf, ie frequency of a wavelet divided by its bandwidth.

Seismic field records can be used to derive the propagation velocity for a particular event. When the event wavelet is passed through a Fourier transform, an amplitude versus frequency spectrum is produced. The highest peak in the spectrum represents f and the width of the peak at the half power point is Δf.

Both an exponential curve fit and the Q method were tried during the present study. The Q method was found to be both accurate and easy to use. The results reported in a later section employ this method.

The attenuation formula, as it stands, does not account for wave-front divergence, nor does it allow for dispersion phenomena. Some authors include such frequency-related corrections in the physical basis for α (Ricker, 1977; Telford et al, 1976). Further, when the shot is deep or the detector is close to the shot, r should be the true path distance from the centre of the burst to the detector via each propagation medium rather than the measured surface distance. Awojobi and Sobayo (1974) clearly demonstrated non-linearity of intensity with depth.

Divergence might be accounted for by a correction in the amplitude term. Anstey (1977) has proposed the reciprocal of the product of the propagation velocity squared and the radial distance; producing:

$$I = I_o(I/rV^2)e^{-\alpha r}$$

Vasil'yev and Molotova (1976) suggest a cylindrical term might be more appropriate:

$$I = I_o(2\ \ell/r^{1/3}e^{\alpha r})^{-1}$$

wherein ℓ is the thickness of the propagating medium. Over the range of distances of interest, the difference between the two is relatively small. In practice, a correction proposed by Dobrin (1976), (1/r), proved to be satisfactory for the purposes of this study.

A further mechanism which could increase peak elastic wave amplitude at a well might be superposition of waves arriving via different ray paths. Each raypath has a different value for α and a different critical distance. Thus, refracted wave energy arriving at the well would be of a different intensity and in a different phase than direct wave energy. Therefore, total ground motion or field strength would be a summation of all such simultaneous arrivals. To keep the estimate simple, only the direct and first refracted rays are considered.

Therefore, to predict the amplitude of ground motion at a point with reasonable assurance, the following data is necessary:

1. The geology of the generation and transmission zones;
2. The velocities of propagation for shear and compressional waves;
3. The absorption coefficient for each layer in the propagation zone;
4. Amplitude data and Fourier spectra for at least one recording site within region under study.
5. Explosive charge weight for the detonation (in 60% nitroglycerine equivalent form) and peak borehole pressure.
6. Reasonable accurate topographic survey data of the site.

F. BLASTING DAMAGE MECHANISMS

The intensity of elastic waves at a site remote from a blasting operation and the possibility of unintentional damage to private property is of concern to everyone who uses explosives commercially or for military purposes. Damage from explosions is also of concern to open pit mine and quarry operators who wish to protect the stability of workings as well as prevent damage complaints, civil engineers who must excavate close to existing structures or wish to design pipelines carrying potentially explosive substances (such as natural gas) or determine the minimum safe distance between such works; and military engineers who are responsible for design of hardened installations.

A second, closely related, body of literature relates to earthquake damage and structural design criteria that have been established to minimize such damage.

Given the large number of studies and case histories published on structural damage from blasting, the literature selected for review was limited to those studies which contain data from field experiments.

An extensive search of the literature for a discussion of stress/strain relationships in fluid-filled tubes subjected to impulsive loading produced very few references and no guidance.

1. Effects on Structures and Structural Damage Criteria

Since 1950, a large number of studies relating to blasting vibrations have been carried out, although only one appears to have been carried out specifically on seismic blasting (Awojobi and Sobayo, 1974). The classic papers in the field are Morris (1950); Langefors, Westerberg, and Kihlstrom (1958); Langefors and Kihlstrom (1963, 1978); Edwards and Northwood (1960); Teichman and Westwater (1957); Duvall and Fogelson (1962); Nichols et al (1971); Northwood, Crawford and Edwards (1963); and Kirillov (1963). Syntheses of these and other studies which concentrate on damage criteria include Obert (1965); Hendron and Dowding (1975?); and Medearis (1978, 1979). As noted elsewhere, none of these papers discuss the effects of blasting on water well behaviour. They do, however, suggest a standard approach for determining the risk of seismic damage to structures in general. In particular, Edwards and

Northwood (1960), Northwood et al (1963), Kirillov (1963) and Medearis (1978, 1979) provide guidance with regard to blasting vibration behavior in soils and provide an approach to defining damage criteria.

Two papers from an extensive project carried out cooperatively between the National Research Council of Canada, Division of Building Research, and the Hydro-Electric Power Commission of Ontario (HEPCO, now Ontario Hydro) to determine the relationship between building damage and blasting operations (Edwards and Northwood, 1960; Northwood et al, 1963) are considered classics in this field. The opportunity to systematically test a variety of sound structures to failure from blasts of various charge weights at various distances arose when HEPCO constructed the Moses-Saunders and Carillon headponds as part of the St. Lawrence Seaway Project in the late 1950's and early 1960's. During the early part of the Project, the Commission aquired a number of suitable masonry and frame buildings which were to be demolished.

The experimental procedure used was to carefully document existing flaws in each building before blasting, instrument each with three component seismic detectors, strain gauges and falling pin gauges. Roofs were accurately plumbed and foundations were precisely leveled. Instrumentation for measuring air-blast was also installed. Charges of increasing weight were then detonated. The structure was inspected and its condition described following each round. The procedure was repeated until failure was observed. The first round consisted of 47 lbs (21 Kg) of 60% NG dynamite at 15 ft (4.6 m) depth, from 100 to 200 feet (30.5 to 61 m) away from the structure. Later rounds ranged up to

750 lbs (333 Kg) at 70 feet (21 m) range. Shots as close as 29 feet (8.8 m) were used at some sites. No attempt to determine propagation paths followed by the elastic waves was reported.

The program established a damage threshold criterion (hairline cracks, in plaster) of 2 in/sec (0.05 m/s) maximum particle velocity which is embedded in the National Building Code. This criterion has been widely quoted and used elsewhere. A blast design criterion based on a charge size weighted for distance parameter was also proposed in the form:

$$\frac{E^{2/3}}{d} = 0.1$$

where E is the charge weight and d is the distance. A more general form:

$$A = CE^{2/3}/d$$

where A is the amplitude of ground motion (particle velocity), was proposed for site specific use where monitoring equipment is available. This magnitude of particle velocity represents the lower 95% confidence interval bound for minor damage. The lower 2 in/sec (0.05 m/s) criterion in the code represents the lower 95% C.I. bound plus a safety factor.

Medearis (1978, 1979) has criticized this approach on two main grounds:

(1) The criterion does not take structural response into account;

(2) A number of significant parameters, notably ground motion frequency, are ignored.

He has proposed a method of peak ground motion analysis which predicts the median peak value of particle velocity and acceleration. In his 1979 paper, Medearis demonstrates, on the basis of three component records from 74 sites, that peak amplitudes are lognormally distributed for any given charge weight and distance. Using the lognormal relation as a probability density function, he develops a probabilistic argument for prediction of a peak amplitude from a given blast and is thus able to establish defensible confidence intervals and standard error of estimate calculations for particle velocity. His peak amplitude formula is:

$$\dot{X}, \ddot{X} = aL^{b}W^{c}$$

such that $\dot{X}, \ddot{X}$ are particle velocity and acceleration, respectively; L is the Shot/Detector distance; W is charge weight and a, b and c are arbitrary constants derived by regression anlysis in the log domain.

Frequency effects are evaluated by development of response spectra for motion of the structure which is assumed to possess a single degree of freedom when subjected to a ground motion forcing function, as determined for various values of the structure's natural frequency. The averages of the relative displacement, "pseudo-relative velocity" and "pseudo-relative acceleration" response spectra are then normalized by dividing through by peak ground velocities to become a measure of response amplification. This quantity is then plotted against frequency to produce a "Pseudo Spectral Relative Velocity" diagram, for various degrees of damping (he concludes 5% damped spectra are most relevant for residential structures). The blast records are then subjected to

Fourier spectral analysis and an amplitude spectrum prepared for any point of interest in the vicinity of the shot.

From data on dwellings in several widely separated areas of the United States, Medearis reports the above analysis indicated:

(1) There is considerable variation in response with distance from the burst for frequencies in the range commonly associated with the natural frequency of houses (less than 20 Hz).

(2) Fourier coefficients for the data set decrease with distance for frequencies greater than 10 Hz and increase with distance for frequencies less than 10 Hz.

(3) Soils typically have natural frequencies in the same range as houses. Damage is commonly (though not always) associated with the structure's natural fundamental frequency and associated amplification.

Medearis' 1978 paper deals specifically with damage criteria and is based on the same data set analysis outlined above. His conclusions are (1) Criteria should be oriented toward damage thresholds rather than structural failure; (2) The response of residential structures seems to be independant of geographic location, design and construction; and (3) component fatigue resulting from cyclic loading (i.e. more than a single blast) has little probability of occurrence.

None of the above refer to the Soviet literature. Fortunately, Kirillov (1963) has been translated into English and a review of the Soviet literature to 1960 is thus available.

It appears Soviet researchers have taken a more deterministic view than their North American counterparts as a result of dissatisfaction with the value of empirical formulae. Using geophysical arguments Kirillov examines the magnitude of seismic effects in the generation zone, the transmission zone and at the structure. The theoretical bases for Soviet damage criteria evolved from the same line of enquiry discussed above in the section on propagation of seismic waves.

The Soviets were also cognizant of the importance of frequency as well as amplitudes and particle velocities to both ground and structural response: in particular, the characteristic natural frequency and damping properties of the structure. Kirillov presents the following functional relationships:

$$P = \beta k_s Q \; ; \; k_s = \eta/g$$

$$\text{and } \beta = [(1 - T_o^2/T^2)^2 + \alpha^2 T_o^2/T^2]^{-1/2}$$

In which P = load; Q = weight of the structure; k_s = a coefficient related to inertia; g = gravitational acceleration; β = dynamic component of stress which shows how much greater acceleration is in the structure than ground acceleration (presumably the amplification factor); T = oscillation period of the structures foundation; T_o = natural period of the structure; α = coefficient of damping, upon which intensity of vibration in the structure depends and which is rarely less than 0.2; η = maximum measured acceleration. The damping factor is the same value as that suggested by Medearis (1978).

Kirillov recommends a combination of model studies and prototype field measurements to obtain a measure of seismic stability, in the course of which the model is tested to failure.

This data is then assembled into an "action spectrum" κ, which is equal to the maximum displacement of a pendulum modelling the subject structure with respect to the natural period, T, and a damping decrement, Λ in the form:

$$\kappa = \chi_o \vartheta(\Lambda) \Psi(T)$$

wherein χ_o is the magnitude of maximum displacement, $\vartheta(\Lambda)$ and $\Psi(T)$ are the damping and frequency characteristics of the structure.

Like Medearis, the Soviet researchers have established that building motions are greater than the surrounding ground motion, while observing that the period of oscillation is shorter. They also found the frequency of oscillation to be unaffected by changes in charge weight. Further, they conclude the key variable in determining the degree of damage potential from a blast is peak ground particle velocity and its magnitude relative to a critical value which is characteristic to a particular category of structure. The critical value for "destruction" is quoted as 10 cm/sec (which corresponds to about 4 in/sec, the Northwood et al damage threshold).

A final relation is offered to compute the radius of the "seismically dangerous zone":

$$r = (k_{ex}^2 \, q \, g)^{1/3} (V_o^2 \gamma C T)^{-1/3}$$

wherein k_{ex} is the coefficient of the seismic characteristic of the explosion (a typical value is given as $7.5 * 10^4$ cm) and V_o is ground velocity and γ = shear velocity/compressional velocity ratio. All other symbols are as previously defined.

It would appear that while Soviet and North American researchers have worked without regard to each other's methods or findings, their results appear to be convergent and certain key characteristics of structural response to ground motions appear to be universal.

Awojobi and Sobayo (1974), in their study of seismic blasting discussed above have obtained results generally convergent with other workers. Their contribution, however, relates to their attention to depth of burial of the charge. They have observed a dramatic increase in peak ground velocity which reaches a maximum when the charge placed at a depth between 20 and 35 m below ground level. Taking this factor into account, they produced an empirical formula:

$$V = KR^{-1}W^{0.55}\exp(4.62(H/R)^{0.1})$$

in which V = particle velocity; R = radial distance; W = charge weight; K = empirical scaling factor, and H = charge depth.

They also found the frequency of vibration detected at the ground surface is affected by charge depth. In saturated ground, shallow bursts produced low frequencies (8-12 Hz) and bursts below 25 m were recorded in the 25 Hz range. Given the Medearis and Soviet findings that natural frequency of most low rise buildings is in the order of 20 Hz, this must rate as an important finding.

For dry soils, shallow bursts produce high frequencies in the order of 40 Hz to 80 Hz, well outside the danger zone.

The Mohr-Coulomb failure criterion as commonly applied to stress testing of granular materials in order to assess their strength, is based on the concept of effective stress.

In soil mechanics, shear strength (S), is a function of pore pressure, (u), applied stress, (σ), apparent cohesion, (C'), and the angle of shearing resistance (ϕ'). The functional relationship (Coulomb's equation) is:

$$S = C' + (\sigma - u)\tan \phi'$$
$$= C' + \sigma' \tan\phi'$$

The importance of these parameters is best explored by the use of Mohr's circle (figure 6). Line AB is the failure line which represent the conditions of shear failure according to Coulomb's equation. The point at which Mohr's circle intersects the line (point R) is a condition of incipient failure. Any circle falling below this line represents a condition of safe stress. Line OX represents the line acted upon by the principal stress (σ_1) and line P_3R, the direction of the plane of rupture, is the line acted upon by shear stress (S). The inclination of the plane of rupture line OX is $45^\circ + \phi/2$ and the shear stress on this line is $1/2(\sigma_1-\sigma_3)/\cos\phi$. Thus, the shear stress depends upon the difference between the greatest and least stresses ($\sigma_1-\sigma_3$), which is called the deviator stress.

In the near-surface borehole wall situation, σ_1 is assumed vertical and σ_3 is at right angles to the borehole free surface. "C" is a property dependent upon any cementation between grains in the formation ("cohesion"). If the formation is not cohesive, which is the usual case, C=0.0 and the failure line passes through the origin (figure 7c). In this case, formation shear strength is entirely dependant upon grain-to-grain pressure and roughness which is represented by ϕ, the angle of shearing resistance.

The case for a uniform sand is shown in figure 7c. If fluid pore pressure (u) is suddenly increased, the effective stress is decreased. The effect of this is to shift Mohr's circle to the left (since σ_1 and σ_3 are both constant, the radius of the circle remains constant). If the pore pressure is increased enough, the circle will intersect the failure line and the formation will collapse into the borehole.

Two additional conditions apply to the borehole case. First the ambient stress distribution have been significantly altered around the borehole producing stress concentrations. If the ambient stress field is not isotropic, a zone of potential or actual shear failure may appear orthogonal to the direction of greatest principal stress. This phenomenon has been observed in oil well bores by Bell and Gough (1979), who present evidence that the direction of principal stress in Alberta is normal to the mountain front. This is manifested in a northeast to southwest orientation of fracture patterns in Cretaceous bedrock. Fractures usually appear in sets with the less well developed shear set approximately at right angles to the mountain front.

Zoback and Byerlee (1975) have shown that relatively small changes in the ambient state of stress can produce quite large changes in permeability to water of an aquifer, under continuous loading.

In their conclusion, Awojobi and Sobayo reproduce a chart of displacement versus frequency from Duvall and Fogalson (1962), with data from the classic papers plotted together with the various damage criteria proposed by each. They note that when frequency effects are taken into account, a much lower particle velocity of 1 in/sec (.025 m/s) becomes the damage threshold, less an unspecified safety factor, for Nigeria.

Workers searching for methods of predicting slope stability/rock wall integrity following blasting have suggested particle velocity criteria similar to those proposed by Langefors and Kihlstrom (1978) in their classic text on blasting practice.

An excellent example of such a set of criteria is the one proposed for Canadian Shield practice by Keil et al (1975) who have developed damage criteria for both intact and fractured rock. Unfortunately, they did not carry their analysis beyond peak particle velocity estimates to stress estimates for comparison with measured rock strengths, a weakness they acknowledged while asserting that their approach does provide insight into the mechanism of crack formation. They then present five case histories from northern Manitoba and assess damage versus measured particle velocities, charge weight per delay and geology in a semi-quantitative fashion.

Keil et al conclude that a maximum particle velocity criterion of 24 in/sec (0.610 m/s) be used for supported and 12 in/sec (.305 m/s) for unsupported rock faces.

2. Effects on Soils and Rock

All the papers reviewed to this point relate a subjective measure of permanent strain in a structure subject to blasting vibration to peak particle velocity. This relationship is indirect and thus unsatisfactory for use in the search for a water well failure mechanism in that a measurable quantity is universally being applied as an independant variable to a qualitative (and somewhat subjective) classification of non-quantified effects ("minor damage", "moderate damage" and "major damage" are most common) as a dependant variable. These classifications are adequate when the preblasting condition of the structure is known, but are not too helpful in assessing damage after the fact when preexisting conditions are unknown. It would be much more useful to be able to relate earth pressure to strain in units which directly and quantitatively measure some change in shape or performance. This would allow a more precise statement as to how close to failure either the water bearing formation or the well itself has been stressed by a particular blast.

Hansen (1976) came to the same conclusion while looking for a rock wall stability criterion for use in quarry and open pit mine practice. His conversion formula for particle velocity to stress is:

$$\sigma = \rho v C$$

with σ = stress, ρ = density, v = particle velocity, and C = wave propagation velocity. Stress/strain curves were derived for the rock in his excavation through triaxial testing in order to obtain values for peak and residual strength.

. He demonstrates the practicality of this relation by assessing published safety criteria for rocks and through a field test in granite gneiss wherein the relation produces an estimate of tensile strength that is within 7% of the tested value.

Hansen argues that the value for v should be the vector sum of peak particle velocities for the longitudinal, (radial), transverse and vertical component seismometers (i.e. the net particle motion). He shows this value has narrower 95% confidence limits than for each individual component.

A further argument for converting particle velocity data to stress data is that it provides a much better measure of the available energy in the pulse. For example, a v = 2fps (0.25 m/s) pulse in granite produces an effective stress of:

$\sigma = (5.12)\ \ (2.00)(16{,}500) = 168{,}960\ \text{lbs/ft}^2$ or 1170 psi (8.07 MPa)

while the same particle motion in shale produces:

$\sigma = (2.33)\ \ (2.00)(6{,}000) = 27{,}960\ \text{lbs/ft}^2$ or 124 psi (0.85 MPa)

or an order of magnitude less.

Being able to directly relate measured stress to measured strain may prove to be a crucial requirement in assessing changes to aquifer characteristics. Brace (1978), in a review of stress-related permeability changes reported in the rock and soil mechanics literature, notes that relatively small stress field changes (less than 15 MPa) can produce large permanent changes in permeability in soils. Literature cited by Brace indicate these responses can be strongly anisotropic as well, particularly where fracture permeability is involved.

Most of the work described by Brace reports laboratory data and little is said about conditions in situ. Further, these are long duration stress application results and apparently little has been done with impulsive or cyclic loading.

In summary the literature reviewed above suggests that:

(1) Damage to structures due to blasting is a function of charge weight and distance. The damage function is non-linear and is not well understood, although a number of approximations are available.

(2) Damage has traditionally been expressed qualitatively in terms of categories of effects.

(3) The most commonly accepted measure of blasting elastic wave amplitude is particle (ground) velocity.

(4) Damage criteria commonly consist of a schedule of minimum peak particle velocities that have been correlated with various categories of damage.

(5) Damage criteria have been established on the basis of experiments conducted on low rise structures founded in soils, without regard to their natural frequency or response spectrum.

(6) Damage criteria have been established without regard to the effects of repeated elastic loading, although there is evidence this may not be a significant factor.

(7) Blasting-induced elastic waves can be treated as stress pulses or forcing functions and structures can be considered mechanical resonators.

(8) Peak particle velocity can be converted to an equivalent stress.

(9) The mechanical characteristics of structural members, soil and rock materials can be tested to determine their strain response to a spectrum of dynamic stresses.

(10) The hydraulic characteristics of soils and ~~rock~~ can be sensitive to stress.

3. Water Well Dynamics

Water wells combine the characteristics of the two situations described above: they are man-made structures, usually of steel and concrete, with some portion of their length consisting of open hole, i.e. walled with natural, albeit somewhat disturbed, geologic materials. In order to remain functional and useful, the open portion must remain stable; the casing must seal off the aquifer to prevent contaminants from ruining water quality; and the permeability of the aquifer must be preserved intact to ensure conveyance of adequate quantities of water to the user from the surrounding formation.

Each well exists in a disturbed stress field, the disturbance having occurred when the well was drilled. The host formations are continuously subjected to lithostatic load; a countervailing hydrostatic pressure; and possibly both tectonic stresses and perhaps residual glacial thrusting stresses. Superimposed on these are dynamic earth tide stresses. These stresses are resisted only by the strength of the formation and the strength of the casing (where it is present). Should any additional stress (i.e. blasting) be applied to the system that exceeds the remaining strength of the formation, the system or, since the earth does not possess the same strength everywhere (it is heterogeneous and anisotropic by nature), some portion of the well will fail.

The failure could occur in many ways but the most likely to be observed would be a collapse or partial collapse of the hole, ~~cracking~~ or breaking of the casing or movement of the casing with respect to the formation (allowing communication between potable and contaminated water). Less obvious mechanisms would include changes to aquifer transmissivity, producing a reduction in yield and/or available drawdown; stirring of silt from the bottom of the hole or dislodgement of material (including iron bacteria slime) from the borehole walls.

The additional stress needed to produce system failure could originate in many ways, but the present review will be restricted to transient stress pulses originating from seismic survey blasting operations.

a. Spalling

One possible mechanism for water well failure is by the "reflection breakage" or "spalling" discussed earlier. This mode of ground breakage occurs when a compressional wave that possesses adequate intensity encounters a free surface. The extent of failure is a function of the material and intensity of the stress pulse at the free surface. Reed, Zelman and Coates (1964) and Coates(1966) describe the results of field experiments during which air filled adits 15 cm in diameter and 3m long driven in lacustrine silt were subjected to a 500 ton contact air burst at distances ranging from 360 feet (110m) to 2000 feet (610m). Air elastic waveoverpressures measured at these sites ranged from 14.8 Kg/cm^2 at the 360 ft station to 0.5 Kg/cm^2 at the 2000 ft station. An erratic pattern of tension cracks, and sloughing was observed which led the researchers to conclude the failure process is essentially stochastic.

In the second paper Coates (1966) describes similar phenomena below the water table in a sewer tunnel buri[illegible]depth of 18 m in clay and in a competent quartz pebble conglomerate in a uranium mine.

Coates observes that: "If failure occurs around an opening as a result of a stress concentration then, other things being equal, failure should propagate into the wall until the opening collapses. This sequence should occur as the initial failure would theoretically create a shape that would produce a more severe stress concentration and hence additional failure".

If Coates' observation is correct, it could apply to unconsolidated granular materials in two ways. Compressional wave energy is transferred to the surface layer of particles from those behind and causes them to fly off. In the case where the grain size is fairly constant, this would result in sheets of material sloughing into the hole. The thickness of the sheets would depend upon the stress concentration pattern. Where ambient stress is not equal in all directions, the shape of the borehole would tend to become irregularly distorted.

The second possible mechanism relates to unconsolidated material that contains poorly sorted particles. Again, compression wave energy is transferred to the surface layer of particles, however if fine material spalls from the borehole wall, coarse material becomes undercut and collapses into the hole.

Both mechanisms depend upon transient effective normal stress being less than borehole wall strength.

The strength of a granular material is usually determined according to some criterion related to its characteristic stress/strain curve as determined by triaxial testing. In the case of sands, two categories of strength are generally recognized: peak strength and residual strength. Peak strength refers to the magnitude of deviator stress applied to a specimen before failure of the specimen occurred in shear. Residual strength applies to the magnitude of deviator stress applied following failure in shear such that large displacements occur.

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The case for a uniform sand is shown in figure 7c. If fluid pore pressure (u) is suddenly increased, the effective stress is decreased. The effect of this is to shift Mohr's circle to the left (since σ_1 and σ_3 are both constant, the radius of the circle remains constant). If the pore pressure is increased enough, the circle will intersect the failure line and the formation will collapse into the borehole.

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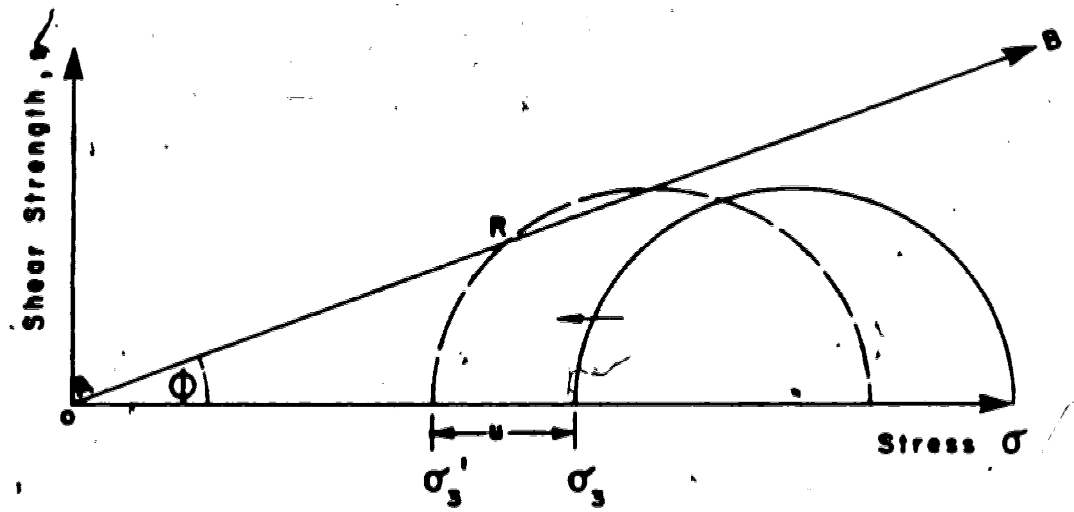
Zoback and Byerlee (1975) have shown that relatively small changes in the ambient state of stress can produce quite large changes in permeability to water of an aquifer, under continuous loading.



AB COLOUMB'S LINE

s SHEAR STRESS

σ_3' EFFECTIVE STRESS

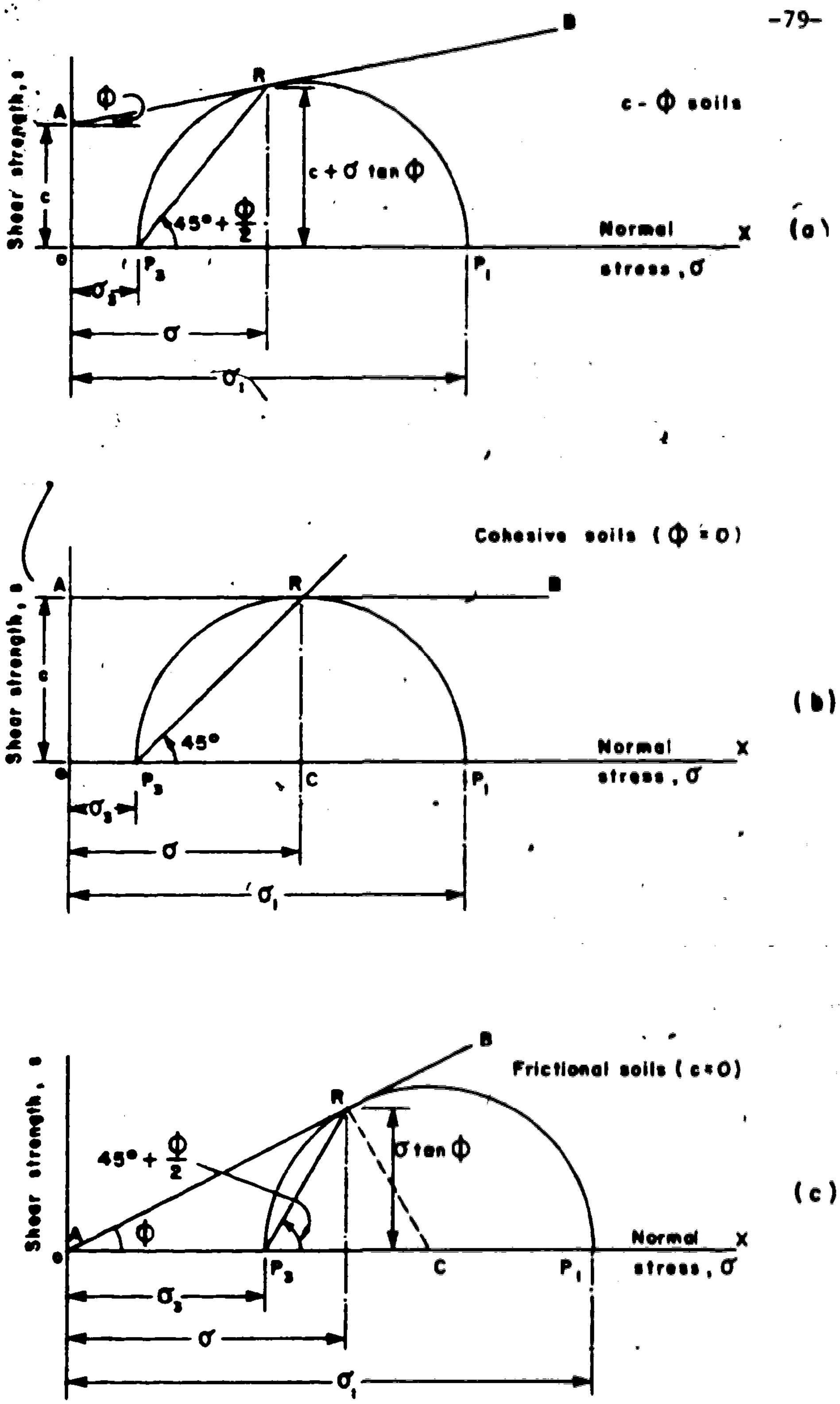
u PORE PRESSURE

R FAILURE ENVELOPE

Φ ANGLE OF INTERNAL FRICTION

Alberta ENVIRONMENT		BEDROCK SURFACE EVENT	
SUBMITTED DATE	DESIGNED D.T.S. CHECKED	EFFECTS OF INCREASED PORE PRESSURES	
APPROVED DATE	DRAWN L.J. CHECKED	SCALE AS SHOWN	SHEET OF
		DATE SEPT. / 1981	DRAWING No 6

FILE No



Source: Copper et al (1975)

Alberta ENVIRONMENT

SUBMITTED		DESIGNED	D. T. B.
DATE		CHECKED	
APPROVED		DRAWN	L. J.
DATE		CHECKED	

BEDROCK SURFACE EVENT

CONDITIONS OF FAILURE

SCALE	AS SHOWN	SHEET	OF
DATE	SEPT. / 1981	FIGURE No	7

FILE No

The effective stress parameters can be obtained from seismic data. It can be shown that

$$Cs = (G/P)^{1/2};\ Cp = (E/P)^{1/2} \quad \text{(Lamb and Whitman, 1969)}$$

t=0

where:

Cs, Cp = Shear wave velocity, compressional wave velocity;

G = Shear modulus

E = Young's modulus

P = bulk density of the propagation medium.

$$G = E/2(1+\mu) \rightarrow \mu = 2({}^{Cs}/_{Cp})^{1/2}$$

μ = Poisson's ratio (Soil mechanics nomenclature)

Thus an instantaneous resolution of stresses for the formation opposite the well intake can be obtained by estimating vertical stress, σ_y', from the bulk properties of the overburden and measuring pore pressures; and by measuring the peak stress exerted by the passing seismic wave train.

Given information about σ', ϕ, G, E and μ, an estimate of the elastic strains, Σ and γ, can be obtained (Lambe and Whitman (1969):

$$\sigma_z' = \gamma \cdot z - \gamma_w h$$

$$\varepsilon_z = \sigma_z'/E$$

$$\varepsilon_x = \tau_y = -\mu\tau_z$$

$$\gamma_{z\chi} = \tau zx/g$$

where: $\mu = (1-\mu)\sigma'_z$

$\sigma\chi$, σy, σz = stresses in the x, y and z directions.

ε_x, ε_y, ε_z = Strains in the x, y and z directions

γ_{zx} = Shear distortion

G_s = Specific weight of solids; G_w = Specific wt of water.

h = hydraulic head.

Lambe and Whitman (1969), demonstrate that soils, and in particular sands, behave in shear as if undrained when subject to high rates of loading. They observe that pore water çavitation can occur in normal saturated sands with initial pore pressures less than 1.5-3.0 atmospheres, a condition which is met by water depths 30 m or less'. In the experiments they cite, it was observed that the effects of such cavitation would by an initial increase in pore pressures to a peak value at about 1/4 % axial strain. Following this peak, pore pressures begin a montonic decline. The rate of decline is a function of initial void ratio, with the denser sands exhibiting the most rapid rate of decline.

Peak strength of loose sands also occurs at very small strains and relatively small deviator stresses. Pore pressures tend to continue increasing after peak strength, producing a quasi-stable or "metastable" soil skeleton. If pore pressure continues to build or total stress increases slightly, the shear stress will approach the failure envelope and the material will fail in shear.

A related condition in which fine particles are spalled off the free surface, but insufficient energy is present to spall coarse grains, can be visualized. What may happen is progressive undercutting of the coarse fraction until it is displaced (the material is assumed cohesionless). A chain reaction occurs when material supported by the coarse material becomes unsupported. Collapse will continue until a stable arch is formed.

b. Casing Seal Breakage

Casing seal breakage would require differential motion between the casing and the formation. This could occur in several ways, some of which are reversable and some of which are permanent changes. The casing could be distorted in cross section, producing a temporary channel up one side. It could be bent at a coupling, particularly if the coupling was near the interface between two formations with significantly different mechanical properties. When grout is present, the casing could move vertically, producing tensile stresses in the grouting material that could result in cracks. Given the low tensile strength of concrete, only a small amount of up and down casing motion could cause a seal to fail and allow contaminated water to enter a potable aquifer. One possible mechanism for this would be passage of a elastic wave containing a sufficient amount of energy at the natural (or resonant) frequency of the casing.

Mechanical engineers have developed a technology physical systems subjected to impulsive loading of the kind associated with blasting operations.

This procedure is used to analyse the mechanical motion of a vibratory system by resolving it into an abstract model consisting of springs, dampers (dash pots) and masses. Models are classified by the number of spatial co-ordinates required to describe its motion, referred to as the system's number of "degrees of freedom".

Assuming the casing to have approximately equal "fit" in the hole throughout its length, it can be considered a two degree of freedom continuous mechanical system. Its two modes of vibration (longitudinal and transverse) may be analysed using conventional mechanical vibration techniques, such as those described by Tse et al (1978) and in more general terms by Coates (1970).

Coates (1970) describes a Magnification Factor as:

$$MF = (1 - (f/f_n)^2)^{-1}$$

wherein f = excitation frequency and f_n = natural frequency of the structure. In turn:

$$f_n = \frac{1}{2\pi} (Kg/W)^{1/2}$$

such that K = spring constant in units of weight per unit length which can be derived experimentally or from published tables (i.e. Birch, 1965); g = gravitational acceleration constant and W = weight of the structure.

The frequency so derived is the fundamental frequency which can be determined from spectral analysis of vibration recordings or by a theoretical analysis. Harmonics, or integer multiples of the fundamental, produce the same response spectrum as the fundamental (Tse et al (1978).

Most systems are damped to some degree. The coefficient of damping (C_c) for a system can be computed as well:

$$C_c = 2W/g\ (Kg/W)^{1/2}$$

The symbols are the same as for the natural frequency formula.

Examination of the magnification factor formula will reveal its relevance to this possible mode of failure. As the frequency (f) of the forcing function approaches f_n, the value of the ratio approaches 1, the value of the denominator approaches zero and the value of the function becomes unbounded [(the mathematical definition of resonance: for a theoretical discussion of such systems, see D'Angelo (1970) and Tse et al (1978)].

A number of characteristics of the magnification factor should be noted:

(1) The actual deflection of the casing is a function of how well damped the system is, which is in turn a function of the surrounding formation and the degree of coupling between the casing and the formation;

(2) The magnification factor is the ratio of the system deflection at its natural frequency to its deflection when f = 0. Hz (i.e. static loading).

(3) A measure of system damping is phase lag.

Phase angle varies from 0 - 180° depending upon frequency and damping. At resonance, phase angle is always 90° (Tse et al, 1978).

To be useful, the damping coefficient for the system must be known before this form of analysis can be performed. In the case of water wells, no standard method for determining this coefficient appears in the literature. Since evidence this mechanism is an important source of failure did not appear during the present field program the problem is left for others to pursue.

c. **Permeability Changes**

Scott and Render (1964) describe the changes in static water level in a well located near Winnipeg, Manitoba and Ottawa, Ontario, in response to the Anchorage earthquake of 27 March, 1964. In their discussion, they cite other cases of water level fluctuations in wells that correlate with teleseismic events. The temporary changes in static water level were assigned to rearrangement of rock materials as a result of the elastic. The authors note that the effects were most noticeable in confined, fractured aquifers. The wells behaved much like those described in many water well complaints related to exploration seismic activity (effluent became silty, head declined), although increases rather than decreases in yield were reported.

A recent review article Brace (1978), has suggested externally induced stress produces fluid permeability changes in geologic materials. Some general trends have been observed by various workers studying (a) unjointed rocks with porosity less than 2%; (b) unjointed rocks or granular aggregates with high porosity; and (c) jointed rocks like granite or coal.

Of particular significance to the present discussion are categories (b) and (c), as these make up the bulk of Alberta aquifers. Insofar as granular aggregates of high porosity are concerned, Brace quotes Zoback and Byerlee (1975) as observing a drop in permeability in the direction parallel to applied stress by a factor of 50 at peak strength in what they refer to as a "granite sand" subjected to confining pressure of 20 and 50 MPa in a triaxial test. In the "average" 33 m deep well, effective pressures would be in the order of 0.6 MPa depending upon the type of aquifer and its state of recharge. Similar results were observed for samples of spherical quartz Ottawa Sand, also at very high confining pressures. Large decreases in permeability were also observed in the direction perpendicular to the major principal stress and while subjecting the specimen to triaxial stress.

Reductions in permeability caused by stress were also observed in jointed media. Witherspoon and Gale (1977) have carried out an extensive literature review related to this phenomenon. Most of the research reported relates to laboratory measurements on continuously stressed specimens and field results describe the effects of fluid injection rather than the effects of elastic waves.

Of perhaps greater significance, Brace quotes Somerton et al (1975) and Pratt et al (1977) as having shown the permeability of fractured materials decreases by 1 to 2 orders of magnitude under vertical stresses of 3 to 12 MPa subjected to confining pressures of 10 MPa.

In his analysis, however, Brace makes the point that the variables (porosity and hydraulic radius) are both affected by mechanical stress in a way that varies according to the type of materials. He also notes these variables appear to change continuously with varying magnitudes of stress.

There appears to be considerable room for laboratory research into this topic.

G. Water Well Stability

A major part of the problem in determining the effects of blasting on water wells is establishing a frame of reference within which the current state of performance can be assessed. The structural condition of a well is also very difficult to assess. A well could reliably produce water for a long time with intake walls that are just barely strong enough to withstand the maximum shear stress exerted by aquifer pressures and ambient loading. A slight increase in formation pressures beyond the normal range of fluctuation could cause wall collapse or enough material to be spalled off to cause siltation in produced water.

A casing seal that is bridging a collapsed zone can also be in a quasi-stable state. The tensile strength of the grout might sustain normal variations in strength for a long time, but could fail with only a slight increase in stress beyond the "normal" peak experienced in the past. As a result, polluted water would escape past the seal and suddenly change the quality of produced water.

It is clear from the literature that obvious structural damage to a water well from a dynamite blast will occur when the well bore is located within the zone of rupture. The radial extent of this zone is governed by the charge weight and the nature of the soil or rock. For typical Alberta conditions this would appear to be in the order of 3 m for the range of charge sizes (1Kg - 10Kg) currently in use by the petroleum industry.

Beyond the rupture zone, damage would appear to depend upon the orientation, frequency and amplitude of the elastically propagating elastic wave. Clearly, to affect the stability of a well dynamic stresses produced by a blast must exceed the strength of some component of the well. Before considering under what circumstances a water well could be considered unstable, however, it would be useful to define the stable condition.

1. Stable Conditions

No satisfactory definition for water well stability was found in published form. Therefore, for the purposes of this study a water well may be considered stable if:

(a) Well depth remains constant over time;

(b) The well bore does not change significantly in diameter from constructed size with depth or over time;

(c) Casing seals effectively prevent mixing between waters of differing chemical quality;

(d) Water quality does not vary significantly over time;

(e) Aquifer transmissivity and storativity remain constant over time or vary over a small range;

(f) Well casing and couplings remain watertight and in the same position as installed.

2. Unstable Conditions

For the purposes of this study, any significant deviation from the above represents instability. "Significant deviation", because of the highly variable nature of wells suggested by the complaint file analysis, means a gross change in the 20% to 25% minimum range or a demonstrably consistent change less than 25%.

3. Metastable Conditions

It was shown earlier that an uncased borehole wall could exist under conditions where the strength of the formation exceeds ambient stresses by only a small amount. This condition could last for a long time and the well could produce normally without any indication of instability. When a small overpressure, such as vibration from a nearby blast, is applied to the borehole wall, the formation could fail. In such a circumstance the pre-blast condition will be referred to as a "quasi-stable" state.

It can be seen that for each criterion of stability noted above a quasi-stable state could exist.

H. DISCUSSION

Research and professional study reports provided little direct information on the effects of blasting on water wells, apart from a few brief descriptions of the beneficial use of explosives to improve production. The only non-Alberta study identified in the literature search essentially confirmed the results from a continuing Alberta study that the wells tested were insensitive to blasting vibrations. Yet hundreds of complaints alleging changes to well performance from blasting have been received by government agencies and hundreds more by seismic contractors.

Analysis of complaint files showed a wide variety of changes are alleged, although a clear pattern was observed. Most complaints allege complete loss of production or a drastic reduction in production immediately following the blasting operation. The next largest group of complaints allege persistent siltation.

Published work from a variety of scientific and engineering disciplines suggested three plausible classes of failure mechanism for wells that are in a condition that would make them susceptible to vibration damage at the distances and charge weights associated with seismic work:

1. Water quality deterioration through casing seal failure.
2. Failure of an uncased borehole wall through spalling. This could be a catastrophic (collapse) failure, or a partial failure resulting in suspended silt in the water.
3. Reduction in formation permeability resulting from consolidation phenomena or by closing fractures.

Since none of these phenomena had been explicitly observed in the field and reported publicly, a field experiment was proposed to the Earth Sciences Division of Alberta Environment and to the Exploration Review Branch of Alberta Energy and Natural Resources. The experiment and field program are described in Chapter III and Appendix 1.

III. EXPERIMENTAL PROGRAM

A. OBJECTIVES AND CONCEPT

Previous work suggests that blasting does not significantly affect the performance of nearby water wells, although some minor changes in aquifer characteristics were observed by Vogwill (1979). In particular, he observed some indication of leakiness in a confined sand and gravel aquifer following treatment by blasting that was not evident from pretreatment pumping tests.

Despite the contrary experimental evidence, a large body of complaint data suggests there must be a set of geological conditions under which the energy released by a dynamite explosion would be propagated at least 180 m through an aquifer and still be sufficient to damage a domestic water well in some way. The literature provides little guidance as to what level of energy would represent the damage threshold. The present program was therefore designed to establish what minimum seismic energy level at a well intake is required to demonstrably change the performance of a domestic waterwell.

As a working hypothesis to be tested in the field, it was asserted that:

1. Shock waves at the completion depth of most Alberta wells (about 30 m) propagate as instantaneous changes in pore pressure within the propagating medium:
2. Pore pressure changes induced by explosions of dynamite charges in the range of weights from 1 Kg to 10 Kg pass by too quickly

and are too low in amplitude to significantly affect the transmissivity of domestic waterwells. This hypothesis assumes that damage to a water well is characterised by a statistically significant change in transmissivity.

A two part field experiment was proposed to test these two hypotheses. A seismic program was designed to emulate an industrial seismic program in the vicinity of a domestic water well in order to obtain elastic wave amplitude data at various points in the test site, particularly opposite the well intake. This was coupled to a series of pumping tests which were designed to measure aquifer parameters, in particular transmissivity, following each repetition of seismic blasting. As charge weight was doubled for each round of blasting, not only elastic wave amplitude versus distance could be measured, but elastic wave amplitude versus charge weight as well. By coupling aquifer testing with amplitude measurement, the possibility of obtaining a functional relationship between elastic wave amplitude and transmissivity change could be tested as well.

B. EXPERIMENTAL DESIGN

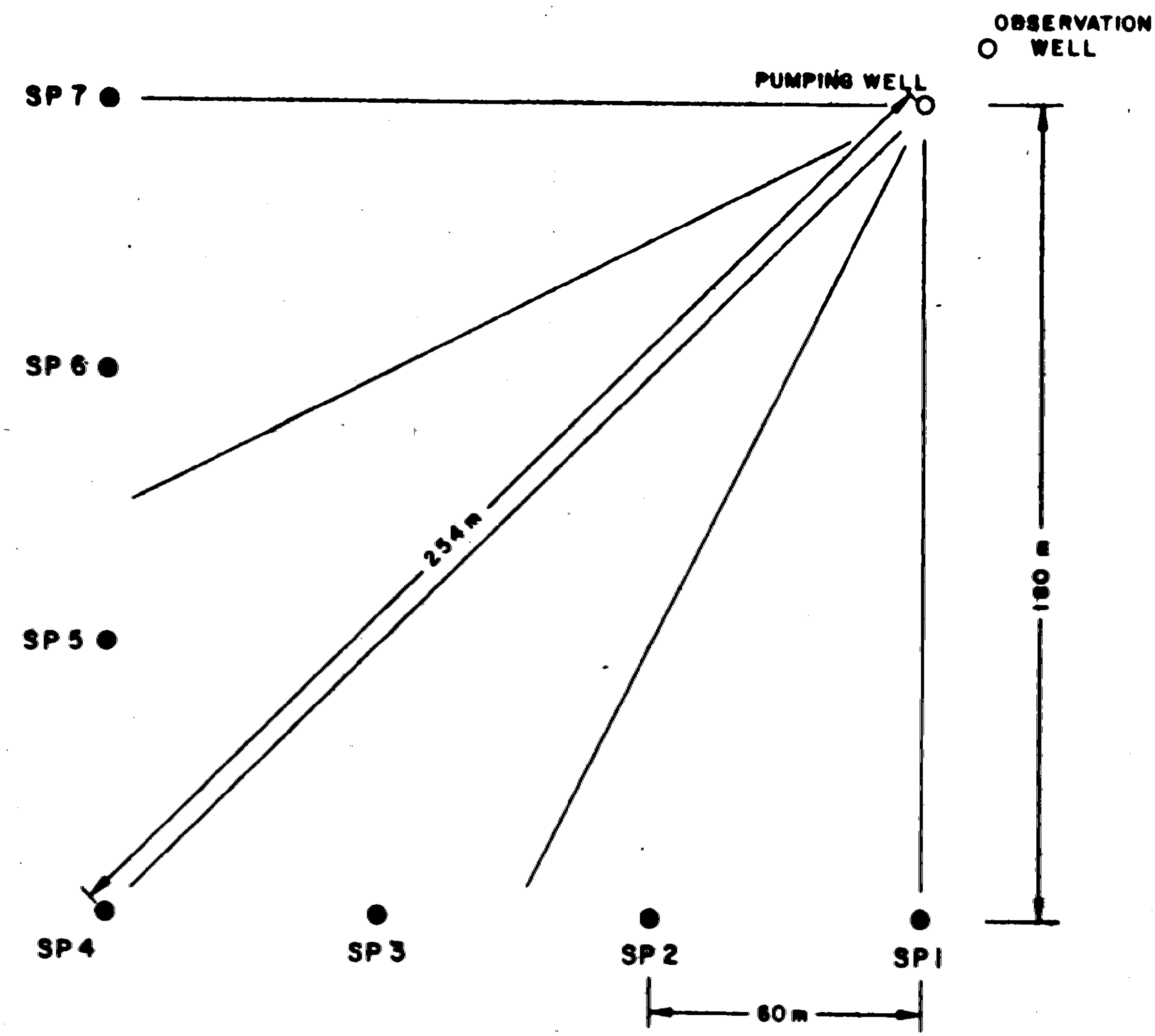
1. Site Layout and Selection Criteria

Field experiments of the kind proposed are complicated by a large number of variables which can be categorized as controllable (site geometry, instrumentation procedures, etc.), uncontrollable but measureable (geology, climate, geophysical parameters, etc.) and neither controllable nor measureable variables (hydrogeological anomalies undetected by drilling or surficial mapping).

The boundaries amongst these categories are indistinct. For instance, the amount of error in topographical survey positioning of the site elements is in part controllable (instrument precision) and partly uncontrollable (crew competence). Random recording errors in the seismic data aquistion system also fall between categories.

Clearly, as many variables as possible should be controlled and some attempt made to minimize the sources for uncontrollable error. In an attempt to do this, a standard site design which could be installed in whole or in part at every site tested was devised. A standard testing activity sequence procedure was also imposed. Certain elements in the procedure were randomized to minimize or highlight consistent errors that might be related to the sequence in which the steps were executed.

The site plan chosen is shown in figure 8. It represents what was inferred to be a "worst case" scenario wherein a well is located at a crossroads along which seismic blasting was carried out in both the north/south and the east/west directions. The perpendicular distance between the well and both "roads" is 180 m, the minimum distance permitted under the Exploration Regulations. The shot hole configuration was intended to emulate a 1200% common depth point program exploring a shallow horizon, with an initial charge weight of 1 Kg of 60% nitroglycerine equivalent explosive contained at a depth of 20 m. All holes were to be naturally stemmed (existing groundwater) and



Alberta ENVIRONMENT		BEDROCK SURFACE EVENT	
SUBMITTED DATE	DESIGNED D. T. B. CHECKED	TYPICAL SITE PLAN	
APPROVED DATE	DRAWN L. J. CHECKED	SCALE AS SHOWN DATE SEPT /1981	SHEET OF FIGURE 8

charges were electrically detonated. The data aquisition system and geophysical field procedure are described below.

Water wells were constructed according to good engineering practice as dictated by aquifer conditions; or were tested in the condition they were found, in the case of existing wells. The pre-treatment state of existing wells was documented as carefully as site conditions permitted.

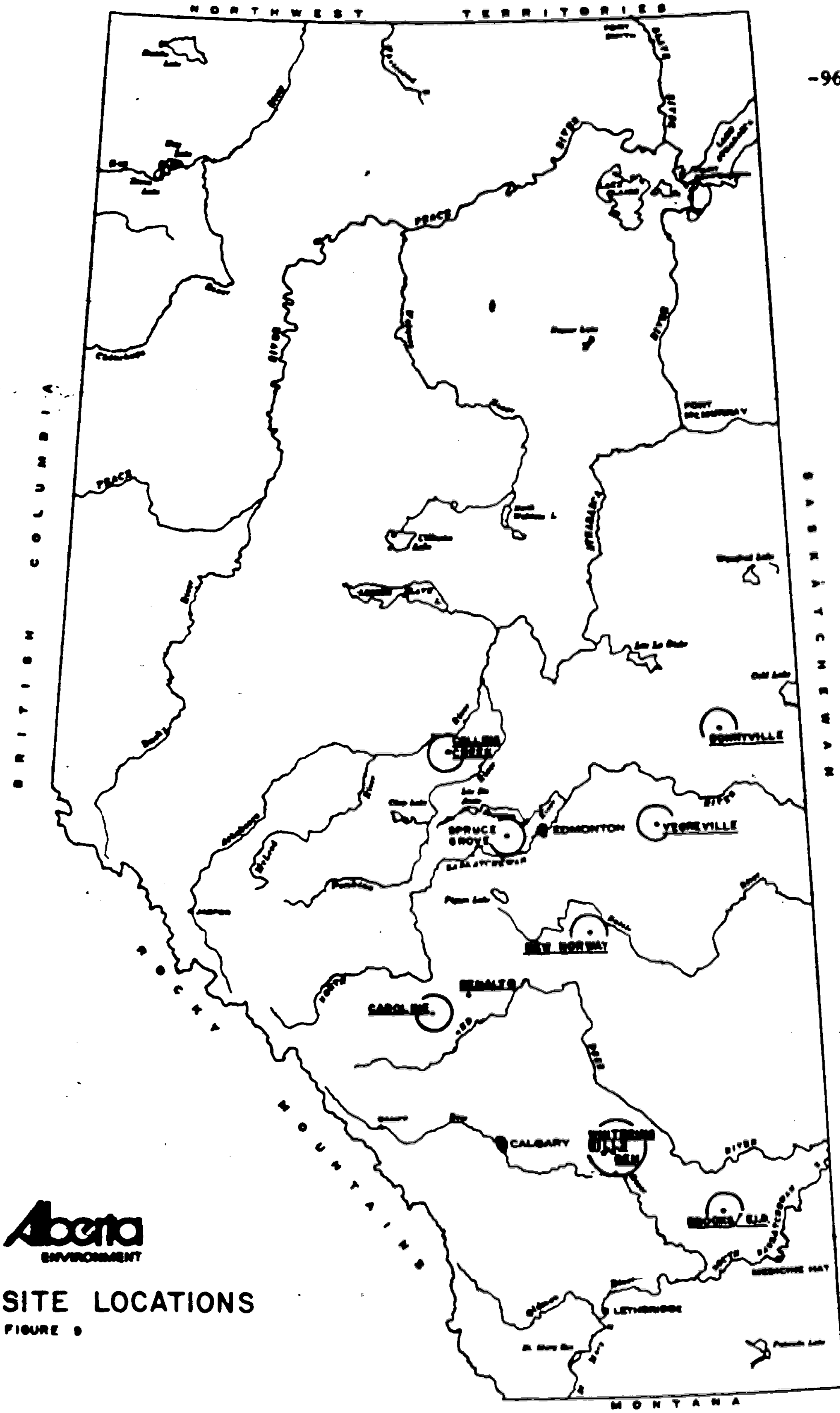
Sites were selected on the basis of physical and legal access, simplicity of geology and operational safety considerations. Ideally, the sites chosen would not have been previously affected by blasting. However, rural Alberta has been subjected to 50 years of seismic exploration, consequently most of the sites had a history of blasting nearby.

Ten sites were selected according to these criteria and their locations are shown in figure 9. An additional site near Spruce Grove, Alberta was used as a control where a series of pumping tests were carried out without treatment by blasting.

2. Data Acquisition System and Procedure

a. Hydrogeological Data

Pumping test data was obtained using standard methods by crews from the Exploration Review Branch of Alberta Energy and Natural Resources and reported by Gobel (1980b) for all sites except new Norway, Gem and Wintering Hills. At these latter sites, a crew from the Groundwater Branch of Alberta Environment drilled and tested the waterwells. The data is reported by Prosser (1980). Further data on the Gem site was



Alberta
ENVIRONMENT

SITE LOCATIONS

FIGURE 9

obtained from Carlson et al (1969). Pumping test data reported by Vogwill (1979) were used at New Norway.

The design pumping test method followed by both Alberta Energy and Natural Resources (AENR) and Alberta Environment (AE) was a six hour drawdown at a constant pumping rate followed by a six hour recovery period, monitored by water level measurement using an electric sounding tape. Whenever an observation well was available, both drawdown and recovery were measured at the observation well at logrithmic time increments to allow comparison of results.

b. Geophysical Data

Geophysical data was recorded using a Texas Instruments DFS-III, 48 track digital field system leased from Northern Geophysical Ltd. of Calgary. The DFS-III is described in Telford et al (1976).
Seismometer arrays consisted of:

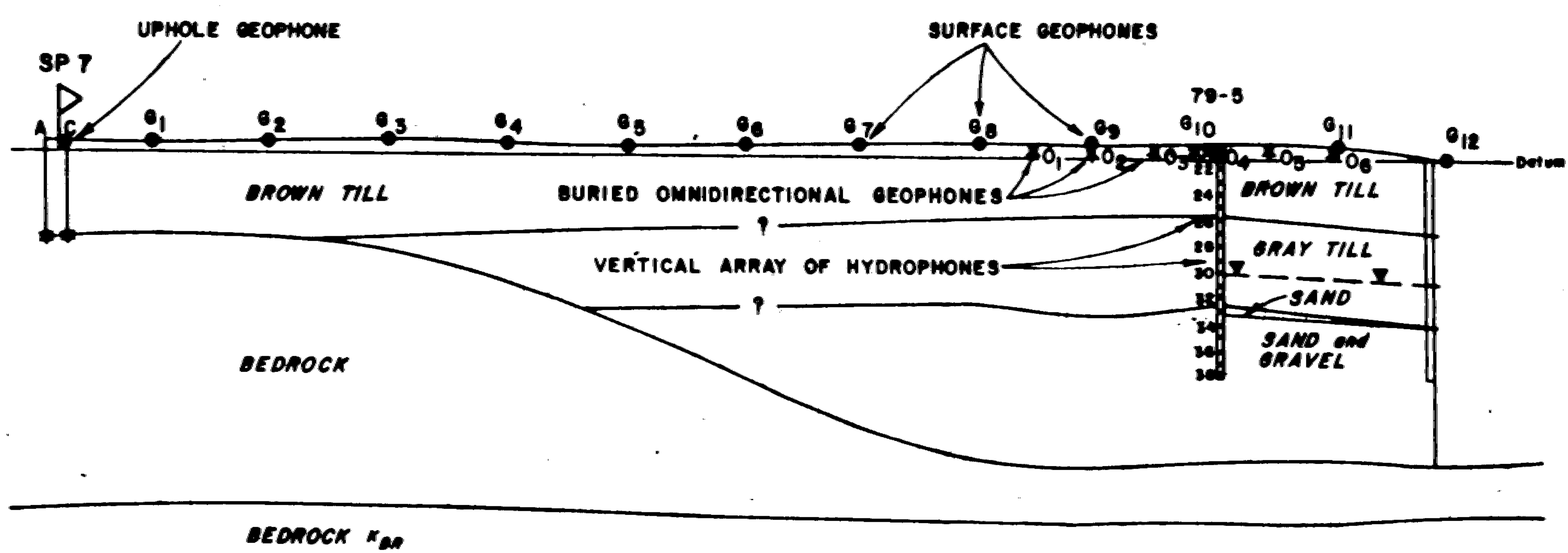
(a) A surface spread of 12 single Geo-Space 20-D 10 Hz geophones;

(b) a buried array of 6 Geo-Space HS-1 14 Hz omnidirectional geophones; and

(c) a vertical array of from 12 to 14 Geo-Space MP24 10 Hz hydrophones.

At the Gem site, long single-end profiles were also recorded from an array of 48 groups of 14 Hz Mark Products geophones, using 6 geophones per group.

A standard surface array geometry was imposed as shown in figure 10, which was constant throughout the program, with the exception of the



Alberta ENVIRONMENT		ARRAY GEOMETRY (Wintering Hills Site Data)	
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Wintering Hills site where a minor change to the orientation of the shotpoint 4/5 spread was made.

Initially, the omnidirectional array was laid out in the chevron pattern shown in figure 11a. Preliminary results from experimental processing was disappointing however, and the in-line pattern shown in figure 11b was adopted for the balance of the program. The in-line pattern proved to be satifactory for interpretative purposes.

Each of the 14 hydrophones was on a separate cable. To be manageable in the field, they were taped together with a single hydrophone breaking out of the composite cable at 2 metre intervals. At each site, the array was lowered into the well until the lowermost hydrophone touched the bottom. The composite cable was then secured at the surface in a manner that ensured the hydrophones remained a constant elevation. Each individual hydrophone lead was then plugged directly into the DFS-III, through a patch panel. Those hydrophones that were located below ground but still above the static water level in the well were patched in. While data from hydrophones suspended in the air showed very low amplitudes, the system sensitivity was high enough to obtain useable data from the detectors.

Each array was intended to obtain a different category of information about ground motion between the shot point and the well. The surface spread measured vertical ground motion at the surface. From the behaviour of the wave train it was possible to infer information about the propagation characteristics of the near surface strata. Omni-directional geophones are constructed from three

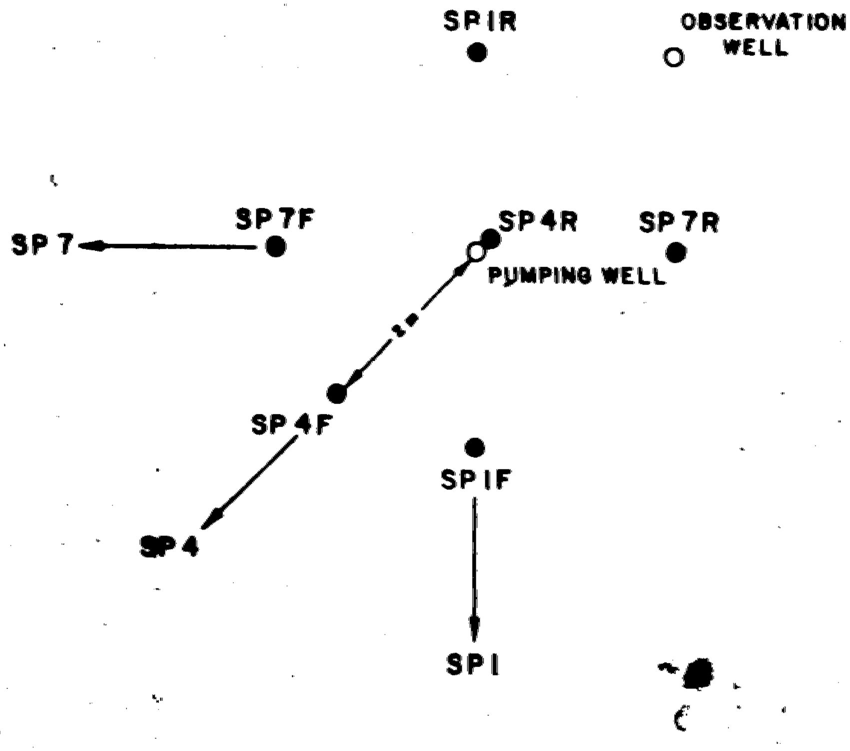

Figure 11a.

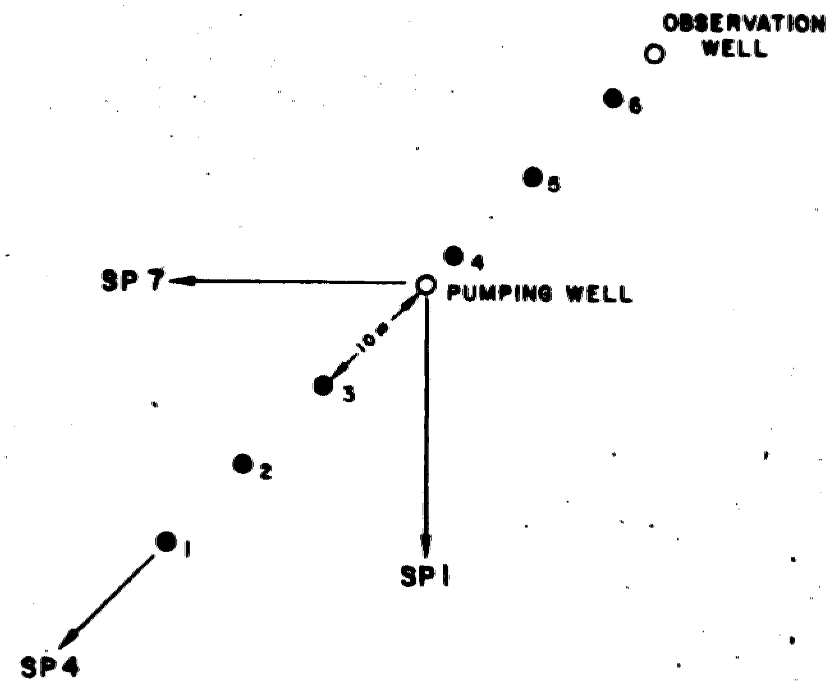

Figure 11b.

Alberta ENVIRONMENT		BEDROCK SURFACE EVENT OMNIDIRECTIONAL GEOPHONE ARRAY
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orthogonally-mounted geophones in a single case. They respond to ground motion in the vertical, longitudinal and shear directions (Cartesian z, x and y coordinates respectively). These devices were used to obtain shear (S) wave velocities and to both identify and relate the S-and compressional (P) waves associated with a given event.

Hydrophone data served several purposes:

(a) To obtain a numerical value for instantaneous peak water pressures;

(b) To obtain stratigraphic data from a quasi-continuous vertical profile using the method of Wuenschel (1976).

When integrated, the data from the various detector arrays could be used to produce a three dimensional model of the site and measure some of the fundamental properties of the geologic materials in the aquifer and adjacent strata. This information could then be used to assess the ability of the aquifer to transmit seismic energy. The absolute magnitude of the energy arriving at the well, in terms of particle motion and wave pressure, might then be compared to any changes in well behaviour or aquifer characteristics observed in a pumping test conducted after treatment by blasting.

C. TESTING SEQUENCE

1. Field Procedure

A standard testing procedure was devised and applied to each site, although some variation in the procedures occured to meet local conditions. Two pumping tests were to be performed at each site before treatment by blasting. Each treatment consisted of detonating a standard sized charge at each shot point in the site plan. The pumping test was then repeated. The blasting/pumping test couplet was repeated from two to four times depending upon the site.

Charge weights of 1 Kg, 2.25 Kg, 4.5 Kg and 9 Kg were used, as dictated by the standard package sizes supplied by CIL. Two varieties of dynamite were used, both rated as 60% nitroglycerine equivalent. An assessment of their performance is described below. The two kinds were quasi randomly distributed amongst the tests.

Some concern was raised that pumping test results may be confounded by changes to the aquifer induced by frequency and duration of pumping tests themselves. Nothing in the literature or the files of any of the agencies involved (AENR, AE or the Alberta Research Council) reported on the degree of variability that might be expected in aquifer parameters computed for a single well from multiple pumping tests. As a control, a series of pumping tests were performed on a well that was not treated by blasting between tests. The results from the control suggested that while some variability in results occur, they are random and the variation is not consistent (Goble, personal communication). These test results suggest that if consistent changes to measured aquifer parameters are observed, they are unlikely to be caused by repeated constant rate pumping. The information must be used with caution however since they were obtained from a well that exhibited a very high value of transmissivity and were taken from only a single location.

2. Data Reduction and Analysis

Data reduction and analysis proceeded in three stages:

(a) Extraction of hydrogeological and hydrogeochemical parameters from pumping test data;

(b) Processing of seismic data to produce

(i) Seismic profiles for each record; from refraction data;

(ii) Amplitude listings for selected traces for selected records;

(iii) Amplitude and phase spectra for the above;

(iv) Record Sections for each site;

(c) Synthesis of geological, hydrogeological and geophysical data to produce:

(i) Geological profiles for each site;

(ii) Tables of stress data;

(iii) Estimation of strains in aquifer materials;

(iv) Estimation of aquifer strength.

The Hydrogeological data and computed aquifer parameters for the project have been reported elsewhere by Goble (1980b) and Prosser (1980). No change from the usual variability found in hydrogeochemical data was observed at any of the sites. Consequently this data was not considered further, with the exception of using suspended solids as a quantitative indicator of siltation.

Seismic data was processed by Geotech Ltd. of Calgary according to the following schedule:

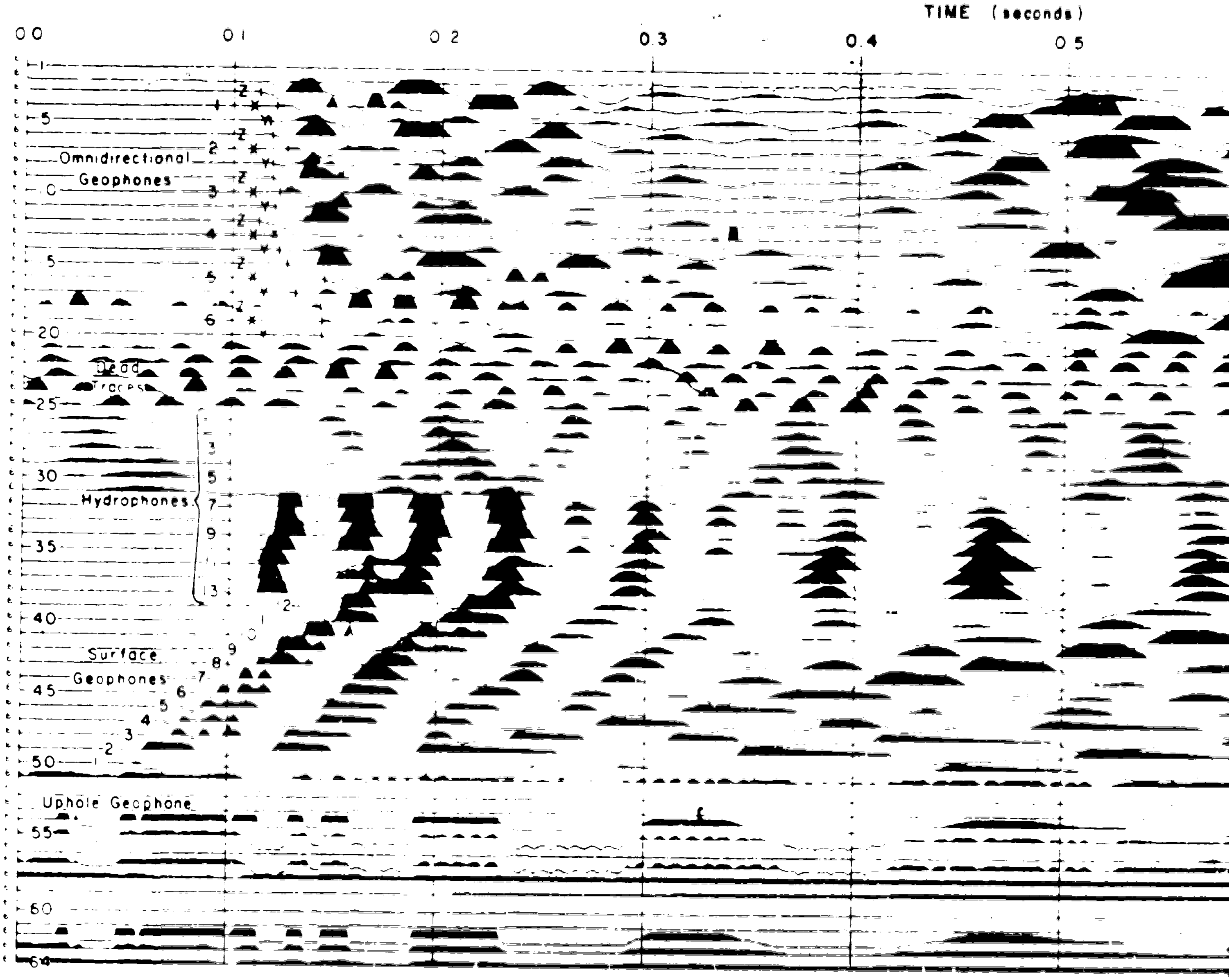
(a) Field tapes were demultiplexed from SEG-B format to a sequential trace-by-trace format and true amplitudes computed in binary coded digit format after the binary gain numbers were removed. Fixed gain multipliers were left in the data and removed manually during the peak pressure computation task as part of the analysis procedure.

(b) The demultiplexed data was displayed in variable area wiggle trace format (figure 12) without any corrections or gain adjustment applied. This provided a visual clue as to which events were the strongest and best defined. The best (least noisey) record for each shotpoint was then selected for further processing to allow construction of record sections. The uncorrected plots were also used to compute first arrival times and for selection of traces to be listed. First arrival times were later used to compute characteristic velocities of propogation and interface depths for near surface geological materials.

Trace listings consisted of a printout of machine-recorded data from the trace header label and the magnitude of each sample in digital units (DU). The data was recorded at 2 millisecond (ms) intervals for 2 seconds. Each trace therefore contains 1000 samples.

Amplitude and phase spectra were computed for each record selected for record section display, using representative traces from each

1 of 1


TIME (seconds)
0.0
0.1
0.2
0.3
0.4
0.5
Omnidirectional Geophones
Dead Traces
Hydrophones
Surface Geophones
Uphole Geophone
5
10
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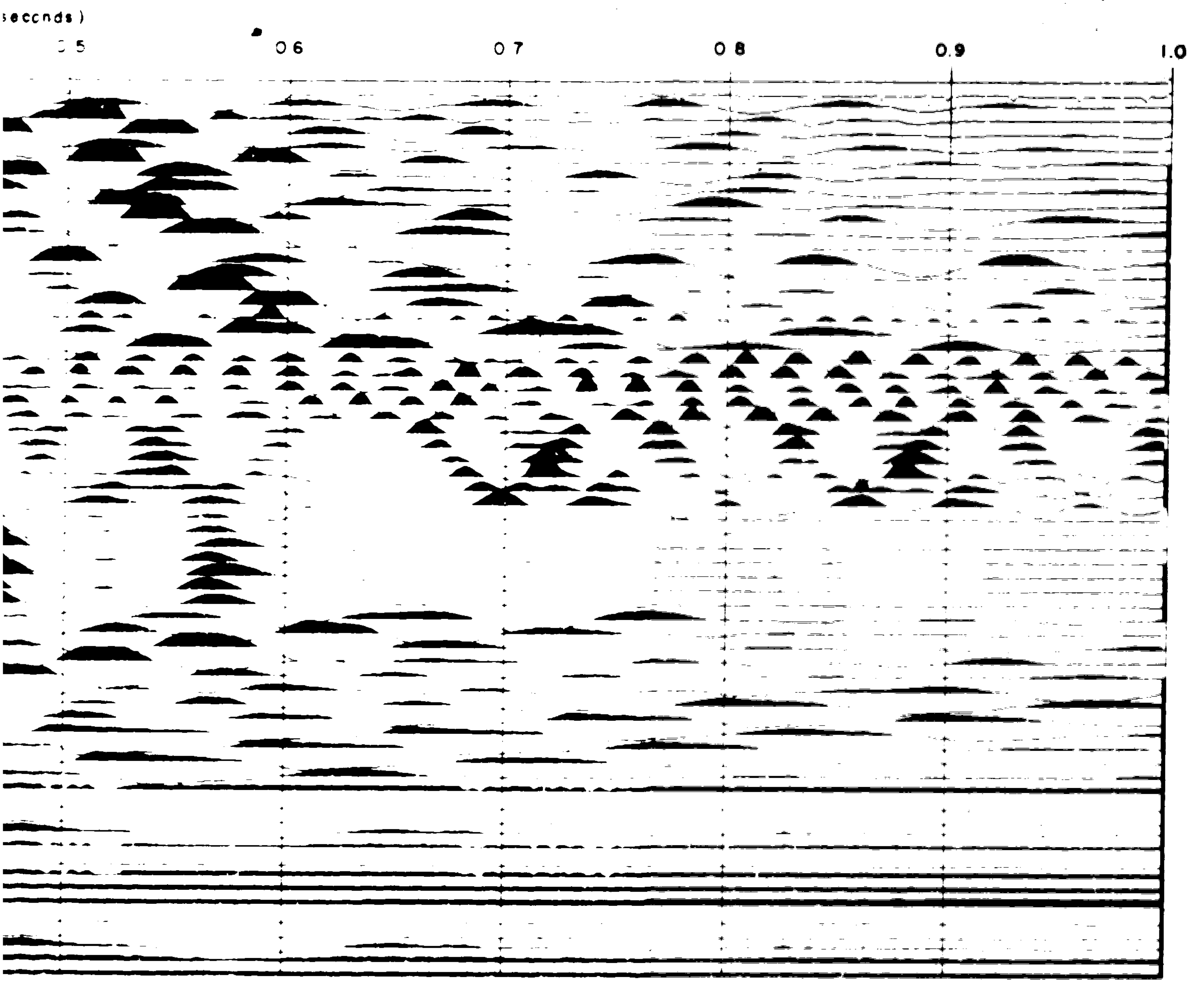

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SAMPLE UNCORRECTED PLAYBACK

FIGURE No. 12

seismometer array. As a control, amplitude spectra for some sites were also prepared for a misfire record (pure noise) and oscillator test records, to assist with identifying signal frequencies and verifying the reliability of the recording equipment. At least one oscillator test was recorded each day the DFS-III was in operation. Amplitude listings were also made of both oscillator and misfire records to ensure the DU to millivolts of signal ratio remained constant over time (the DFS-III acts like a digital voltmeter) and to assess the relative amplitude of background noise at each site.

Record sections were prepared by playing selected records such that the traces for each type of detector are displayed together and in sequence, i.e. the surface array traces for shotpoint 7 are displayed adjacent to the surface array traces from shotpoint 6, which are next to shotpoint 5 and so on. The prime reason for this task is to facilitate identification and correlation of seismic events from one record to the next. This in turn permits easier timing of late arrivals.

Because the main reason for preparing a record section is the easy identification and correlation of events for mapping purposes, it is important to place the record "in trim", i.e. to equalize the amplitudes of events: by enhancing the amplitudes of weak events and alternating strong ones. Further, since timing the peak arrival time of an event is an important task, an effort must be made to reduce interference to events by noise or other events that are close in time. Amplitude equalization was carried out by applying a rather narrow gain window that was tailored to the site. Interference was minimized by application of deconvolution techniques to the gain adjusted data in a manner similar to that suggested by Kanasewich (1975). In each case, a number of gain and deconvolution window lengths were tried and the most successful applied to the full data set for each site.

After the digital field data had been reduced to sets of seismic profiles, amplitude listings for key traces, amplitude and phase spectra and record sections for each site; and hydrogeological data had been reduced to tables of transmissivity, storage coefficient data and borehole data, a synthesis was possible.

"Synthesis" in this case means preparation of geological profiles; resolution of ambient and transient stresses and estimation of elastic strains in the aquifer opposite the well intake. This definition represents a first approximation to a solution of the problem in that not all the data is used and that stresses and strains are computed at a point rather than a plane or a zone.

Geological cross sections were drawn from driller's log data and depths derived from time versus distance plots using the method described by Dobrin (1976) and Telford et al (1976). Additional depth information was drawn from the vertical array data, particularly where blind zones were a problem and refracted energy was not returned to the surface. The profiles were then used to identify characteristic P-wave velocities of propogation for each layer.

Using all three sets of seismometer data in combination, S-wave arrivals were associated with as many layers as possible, but particularly with the aquifer. When a P-wave and an S-wave velocity had been associated with the aquifer, its peak amplitude was identified on the amplitude listing for the lower most hydrophone trace for both the P- and S-wave events. The amplitude in DU was converted to pressure change in megapascals (MPa) using the formula:

$$P = \frac{DU \times 2^n \times .001}{15} \times \frac{1}{512} \times 0.1$$

wherein:

P = pressure (MPa)

DU = digital units

$\frac{1}{512}$ = removal of fixed gain of 24dB

2^n = bit shift applied by the amplitude listing program n is usually zero.

.001 = conversion of millivolts to volts

15 = ratio of volts to bars detected by HP-24

0.1 = conversion of bars to megapascals

Effective overburden stress (σ_v') for a point in the aquifer immediately opposite the lower most hydrophone was then computed using the equation.

$$\sigma_v' = \left(\sum_{i=1}^{n} \gamma_i Z_i \right) - u$$

where: σ_v' = Effective stress in the vertical direction

γ_i = Specific weight of geological material in layer i

n = number of layers in the sequence above the aquifer

Z_i = Thickness of layer i

u - Pore pressure = $Z\gamma_w$ (γ_w is the specific weight of water).

Values for γ_i were estimated from tables produced by Locker (1973). These values are reasonably dependable for the central Alberta sites, but are suspect for southern Alberta. Where a zone contained a material not described by Locker, the closest table value for standard materials from Ter izaghi and Peck (1967) was used. For the purposes of this study these values were deemed good enough for a rough estimate of σ_v'.

To complete the table of stresses, it was necessary to compute in-situ shear stress (τ) and effective horizontal stress (σ_h') at the same point in the aquifer opposite the lowermost hydrophone. No direct measurement of these parameters was possible, but their magnitude can be inferred from geophysical data.

Poisson's Ratio (m) is a fundamental property of a material and is the ratio of the transverse normal strain to the longitudinal material strain of a substance subjected to small uniaxial stresses. If seismic stresses are assumed small, i.e. are in the linear portion of the stress versus strain curve for the propogating material, μ can be computed from S-wave velocities (C_s) and P-wave velocities (C_p) derived from seismograms:

$$\mu = 2\ (Cs/Cp)^{1/2} - 1$$ [(Lamb and Whitman (1973)]

When σ_v' and μ are known, σ_h' can be computed.

$$\sigma_h' = \mu(1-\mu)^{-1}\sigma_v' \qquad \text{(ibid)}$$

The equation for determining shear stress, the Mohr-Coulomb equation:

$$\tau = C' + \sigma' \tan \phi' \qquad \text{(ibid)}$$

requires data on cohesive strength (C') and the effective angle of internal friction (ϕ'). For most of the sites tested, C' can be assumed zero as the aquifers were normally consolidated granular material. With both σ_v' and σ_h' known, the coefficient of earth pressure at rest (K_o) can be computed:

$$K_o = \sigma_h'/\sigma_v' = \mu/(1-\mu) \qquad \text{(ibid)}$$

and ϕ' can also be computed:

$$\phi' = \text{Sin}^{-1}(1-K_o) \qquad \text{(ibid)}$$

Having completely described the state of stress at the borehole wall under geostatic and blasting disturbed conditions, strains may now be estimated using principles from solid mechanics.

Assuming small stresses and isotropic material properties:

$$\varepsilon_v = \sigma_v'/E \text{ and } \varepsilon_h = -\mu\varepsilon_v \text{ (ibid)}$$

wherein:

ε_v = vertical strain

ε_h = horizontal strain

E = Young's modulus

Young's modulus (or compressive modulus) is a fundamental material property that can be determined geophysically:

$$E = C_p^2 \rho$$

where ρ is the mass density of the propagating material (ie the aquifer).

Likewise the mean shear strain, can also be computed from previously derived quantities and field data:

$$\gamma = \tau / G$$

where G is the shear or secant modulus (modulus of deformation) which can be derived from geophysical data:

$$G = C'_s{}^2 \rho$$

Having specified all stresses and strains at a point in the borehole wall opposite the lower-most hydrophone, which at most sites corresponded to the well intake, an estimate of borehole strength was made using the method proposed by Richart (1977).

Richart's method assumes (a) some soils show strain softening at very low stress levels; (b) all soils exhibit some strain softening when subjected to repeated seismic events; (c) elastic stress/strain relations developed in pure shear involve no change in volume and (d) a strain softening curve can be approximated by a hyperbolic curve.

Richart proposes the following equation for the peak shear strength of a given soil using the parameters derived above:

and a "reference shearing strain": $\gamma_r = \tau_{max}/G_o$

in which G_o is the slope of a hyperbolic stress-strain curve at $\gamma = 0$. The stress-strain curve is asymptotic to the τ_{max} line.

The extended hyperbolic stress-strain curve is defined by the equation.

$$\tau = \frac{\gamma G_o}{1+\gamma/\gamma_r}$$

Since the strains observed in the present study were all near $\gamma = 0$, the G computed from seismic data and G_o were considered equal.

3. Summary

An experiment was proposed to test the hypothesis that seismic energy released by a blast of dynamite in the range of weights commonly used by the seismic exploration industry, has insufficient seismic energy to damage a domestic waterwell 180 m away from the blast. The experiment consisted of measuring various aquifer properties and water well performance before and after a series of blasts, measuring the intensity of seismic energy arriving at the well intake and then comparing the before and after data to see if any changes in properties occurred. If changes occured in any of the aquifer or well parameters, such changes could then be directly related to differences in charge weights and the distance between the blast and the well.

The aquifer parameters considered most important were transmissivity and physical stability.

D. CASE HISTORY: GEM SITE

1. Site Description

The Gem Site is located at NW-36-23-17W4, approximately 13 km northwest of Gem, Alberta on a community pasture. The site itself is flat, although it is part of a hummocky disintegration moraine associated with an icewalled channel (Crawling Valley) which is located to the south and east. The near surface stratigraphy is a sequence of Cretaceous Bearpaw shale overlain by preglacial alluvium, which is in turn overlain by a thick till. The till is weathered to a depth of about 15 m and contains discontinuous aggregate lenses. The alluvium is believed to be the preglacial Bow River by Carlson et al (1969) who mapped the area for the Alberta Research Council. Carlson's well number 66-7 was used as an observation well during this study.

2. Site Layout

This site was laid out exactly according to plan. Four shotholes were drilled at each shot point and named "A" through "D" as shown in the site plan (figure 13). Hole "A" was initially loaded with 1 Kg of dynamite. Holes "B", "C" and "D" were each loaded with 2.25 Kg charges. A boulder lens was encountered at about 10 m during shothole drilling and could not be penetrated by the hollowstem augur equipment. Consequently, 17 of 28 shotholes were less than the 20 m design depth, although 6 of the 17 were between 19 and 20 m deep. The boulders also produced crooked holes which resulted in some problems with sympathetic detonations and dead-pressed charges that later misfired.

The wells at the Gem site were designated AE (for "Alberta Environment") 79-4 and ARC ("Alberta Research Council") 66-7. Details of well construction and completion can be found in Carlson et al (1969) and Prosser (1980).

Both wells encountered the bottom of weathered till at 9.5 m and the alluvium at 24 m. Well ARC 66-7 penetrated bedrock ("Brown Shale") at 33.8 m. Well AE79-4 was cased to total depth (29.57 m) and an intake constructed by cutting torch slots over the interval from 24.99 m to 29.57 m below ground level.

Well AE79-4 was used for geophysical observations because it was also used as the pumping well. Counting from the bottom, hydrophones 1, 2 and 3 were opposite the intake, although only data from hydrophone #1 was used for amplitude processing. Hydrophone #9 was the highest live detector. It was submerged at a depth of about 1 m.

Surface spreads were placed according to plan and pivoted at geophone #10 as the spread was moved from shot point to shot point. Surface geophone stations were marked by the field party with blue glow-stake flags which were located by standard positional survey techniques with a precision of +/-0.25 m. Elevations at each geophone location are accurate to about +/-0.1 m. All other site elements were positioned by staff from the Survey Branch of Alberta Environment and are considered to be accurate to +/-0.1 m or better.

The omnidirectional array was in-line, oriented toward shot point #4. The geophones were spaced at 10 m intervals at a depth of 0.5 m. Geophone #4 was placed in direct contact with the well casing and immediately adjacent to surface array geophone #10. Therefore, surface geophone #10; hydrophone #9 and omnidirectional geophone #4 were in close proximity to each other and would therefore respond to the same event simultaneously.

3. Field Procedure

Four trials of the experiment were carried out between August 25 and 29, 1979. The first trial began with two pumping tests carried out by Earth Sciences Division Staff, followed by detonation of 1 Kg charges in the "A" shotholes at each shotpoint. Geophysical operations proved to be difficult at night, therefore the standard operating policy was to carry out the blasing phase in daylight and the twelve hour pumping test at night.

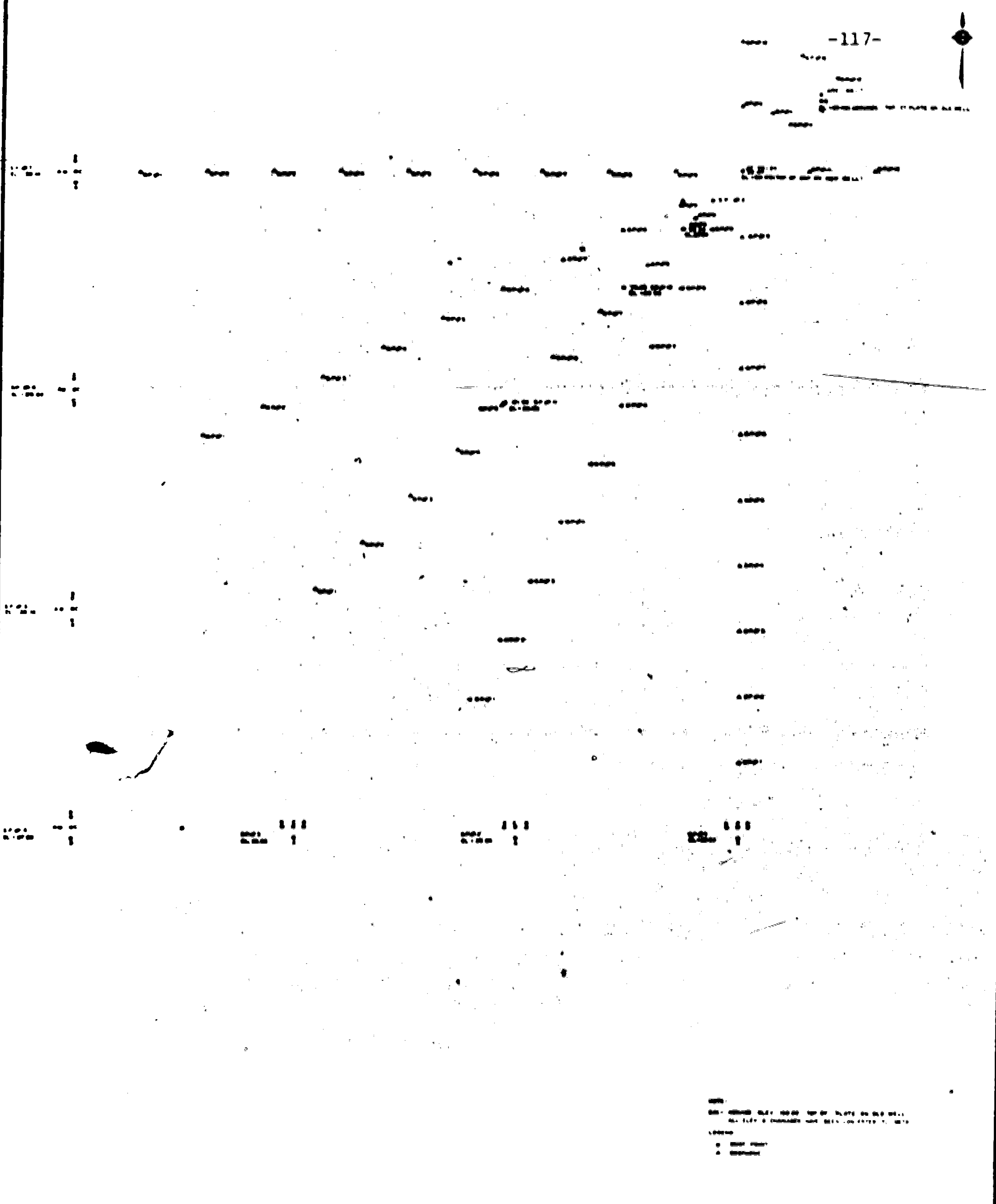
The second trial consisted of a pumping test and detonation of 2.5 Kg charges in the "B" and "D" holes sequentially. The reason for this procedure was to ensure reproducibility of amplitudes recorded at the well. A third trial consisted of 2.5 Kg charges in the "A" and "C" holes detonated simultaneously, to assess the effect of patterned shooting. Two and three hole patterns have been used in Alberta for production seismic explorations, when surface wave interference was a problem.

Trial four was designed to assess the effect of near detonations on well performance. Shotpoints 8 through 12 were arrayed in a line between the wells and shotpoint 4 and spaced at half distances (125 m, 62.5 m, 31.3 m and 16 m). Shotholes 8, 9 and 11 remained open and were reloaded with 4.5 Kg (two locked 2.25 Kg) charges at depths of 9, 8 and 8.5 m respectively, to assess the effect of increased charge weight. The decreased hole depths were considered a confounding factor, however, and only stratigraphic data was taken from these holes.

In view of the proximity of shotpoints 8 through 12 to the wells during the fourth trial, the design seismometer arrays were not used. Instead, a conventional 48 trace single ended surface array was laid out using 6 Mark Products 14 Hz geophones per group at 18.2 m centres. First break data from these records was used to confirm and extend velocity data derived from the 12 trace single geophone records taken during the previous three trials.

4. Data Reduction and Analysis

Data reduction was carried out as described in part III. B3. Goble (1980b) and Prosser (1980) have reported the pumping test results in detail. A summary of their results are reported here in table 2. Figure 14 is a sample of the field records obtained during trials 1 through 3, with the type of seismometer associated with each group of traces indicted. Amplitude listings have not been reproduced, however samples representing the largest amplitudes observed from hydrophone data observed from shot points 1, 4 and 7 are presented together with



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SEISMIC/WATER WELLS

GEM SITE # 1

N.E. 36-23-17-4

SCALE	N/A	SHEET	OF
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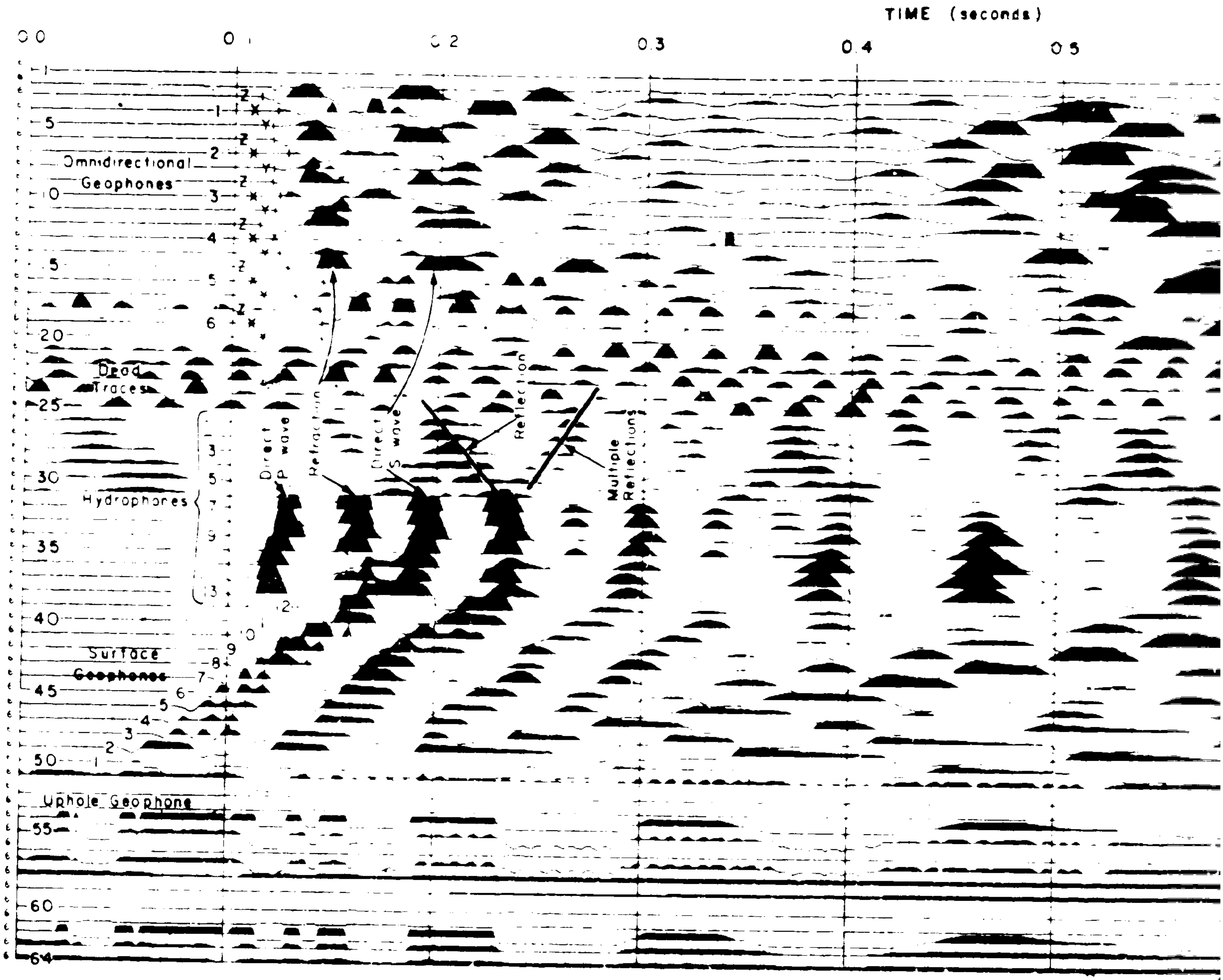

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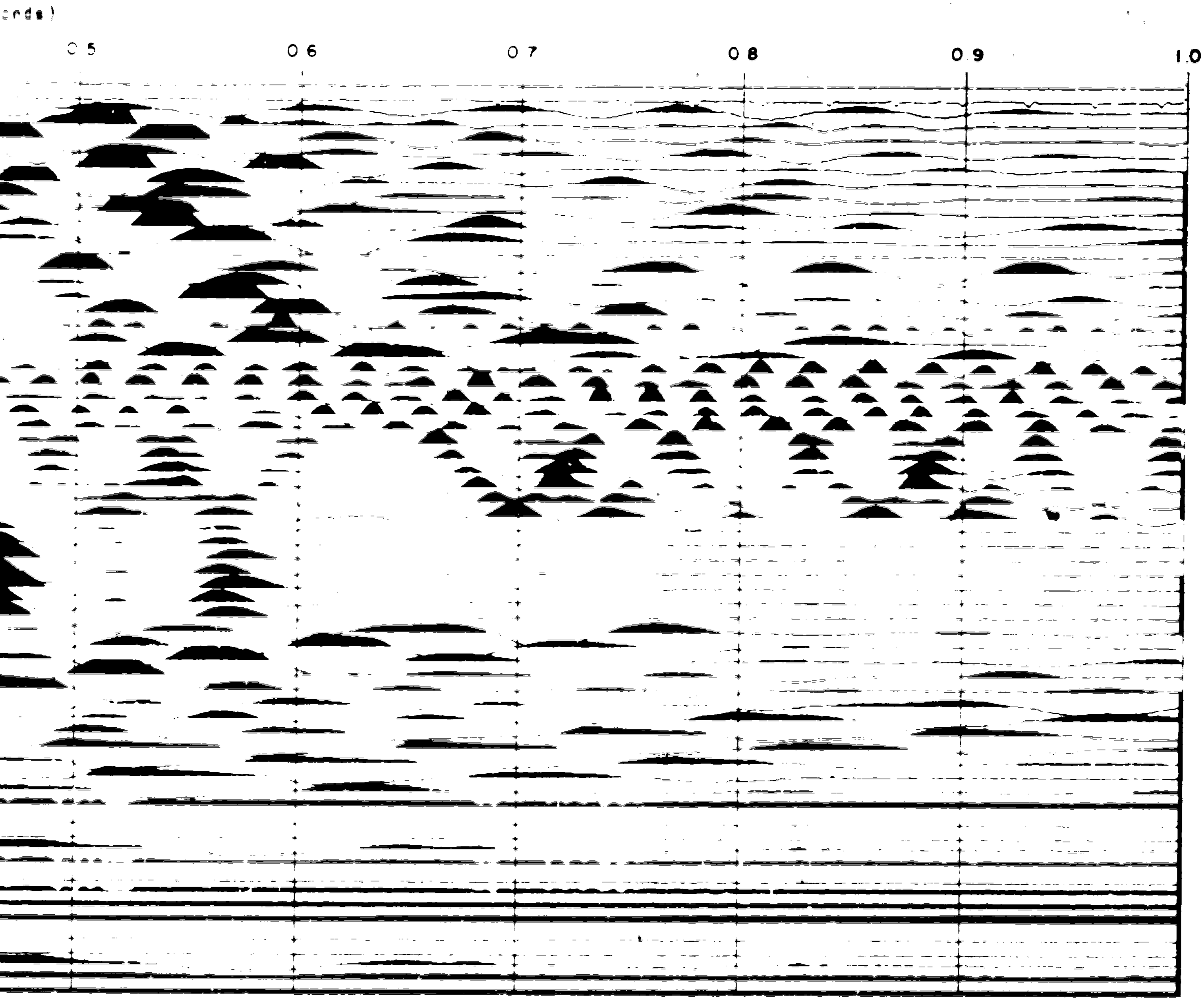
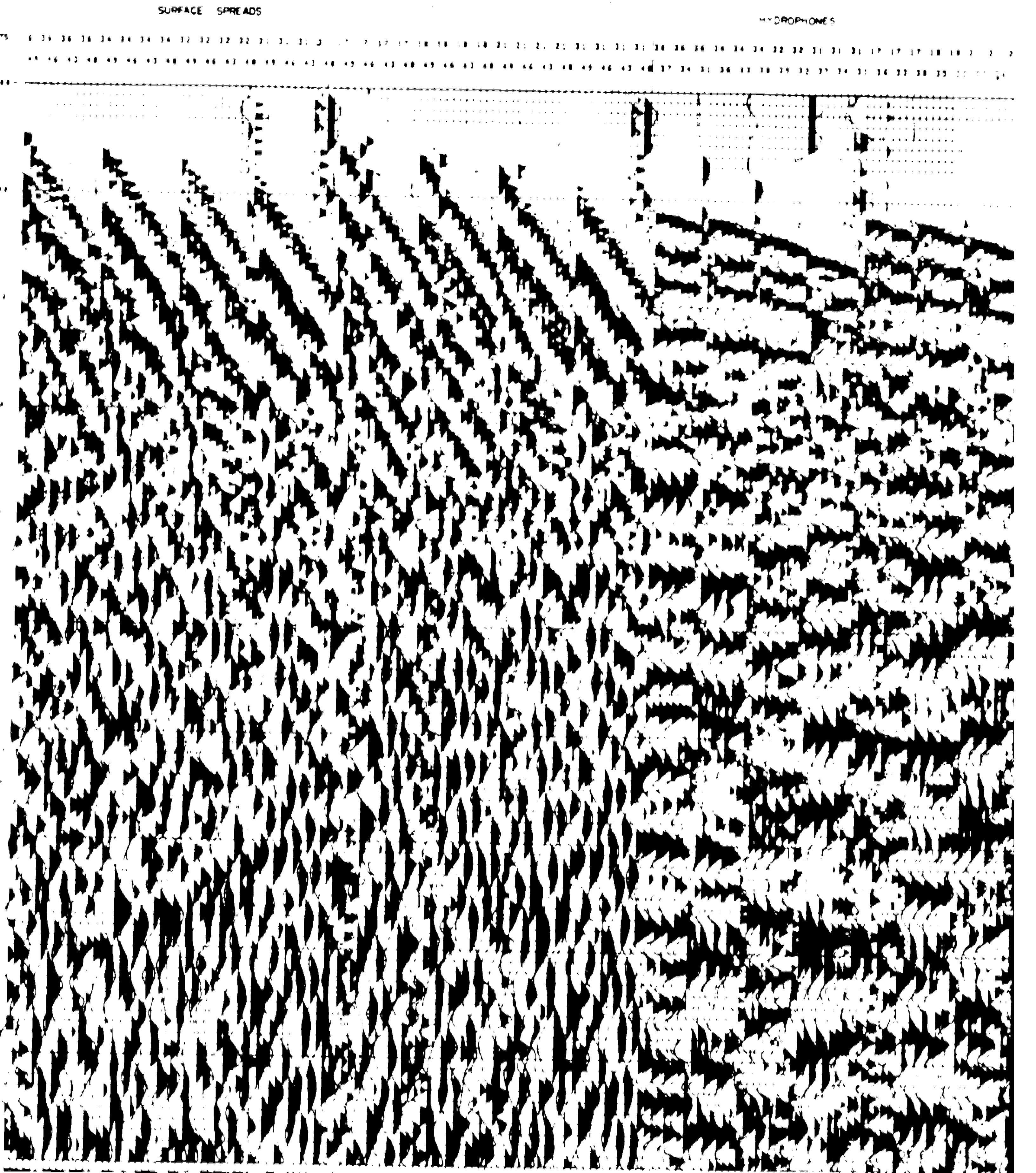


Alberta ENVIRONMENT

D T S	AS SHOWN	GEM FIELD RECORDS	
	SEPT / 1981		FIGURE No. 14



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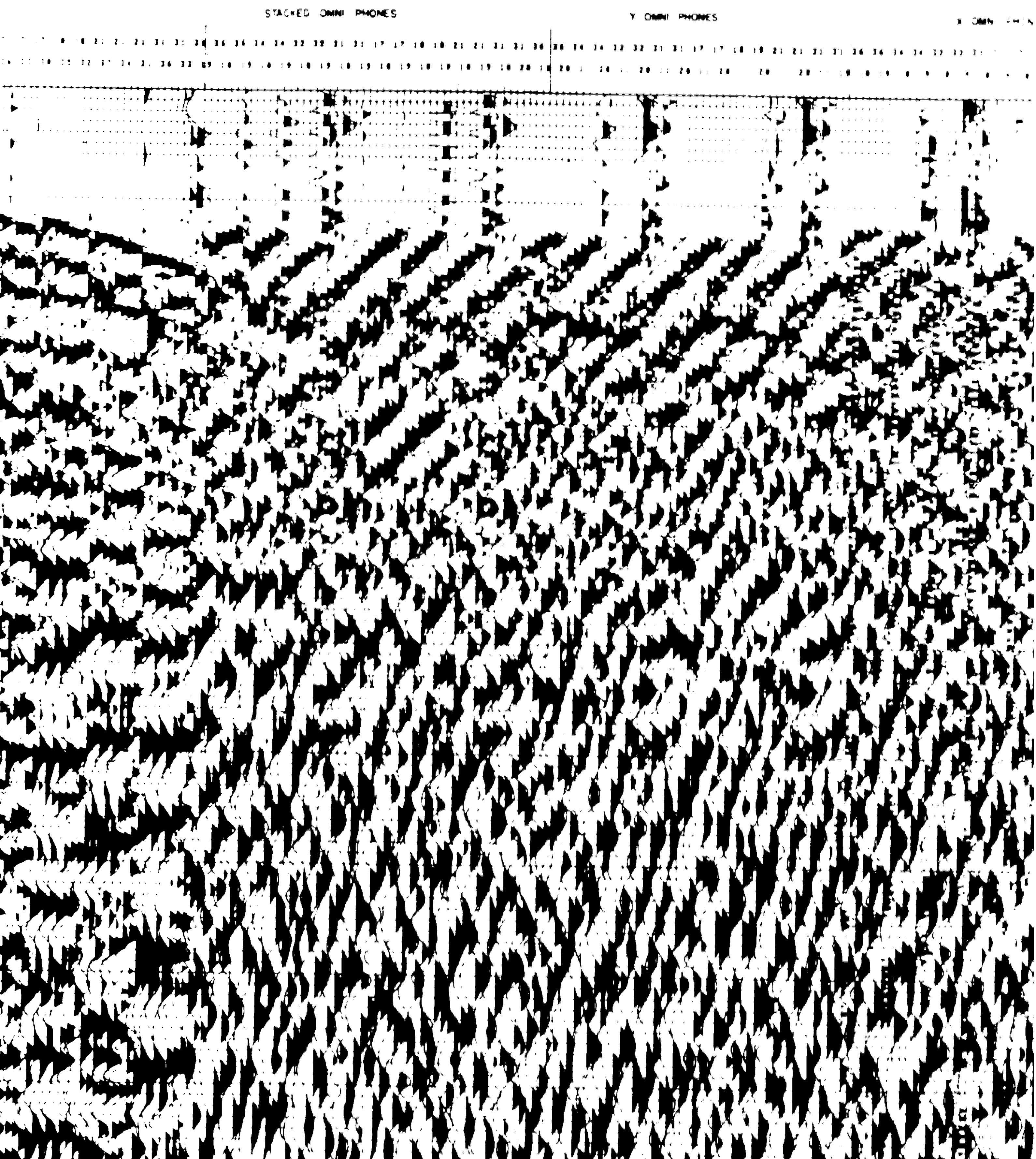
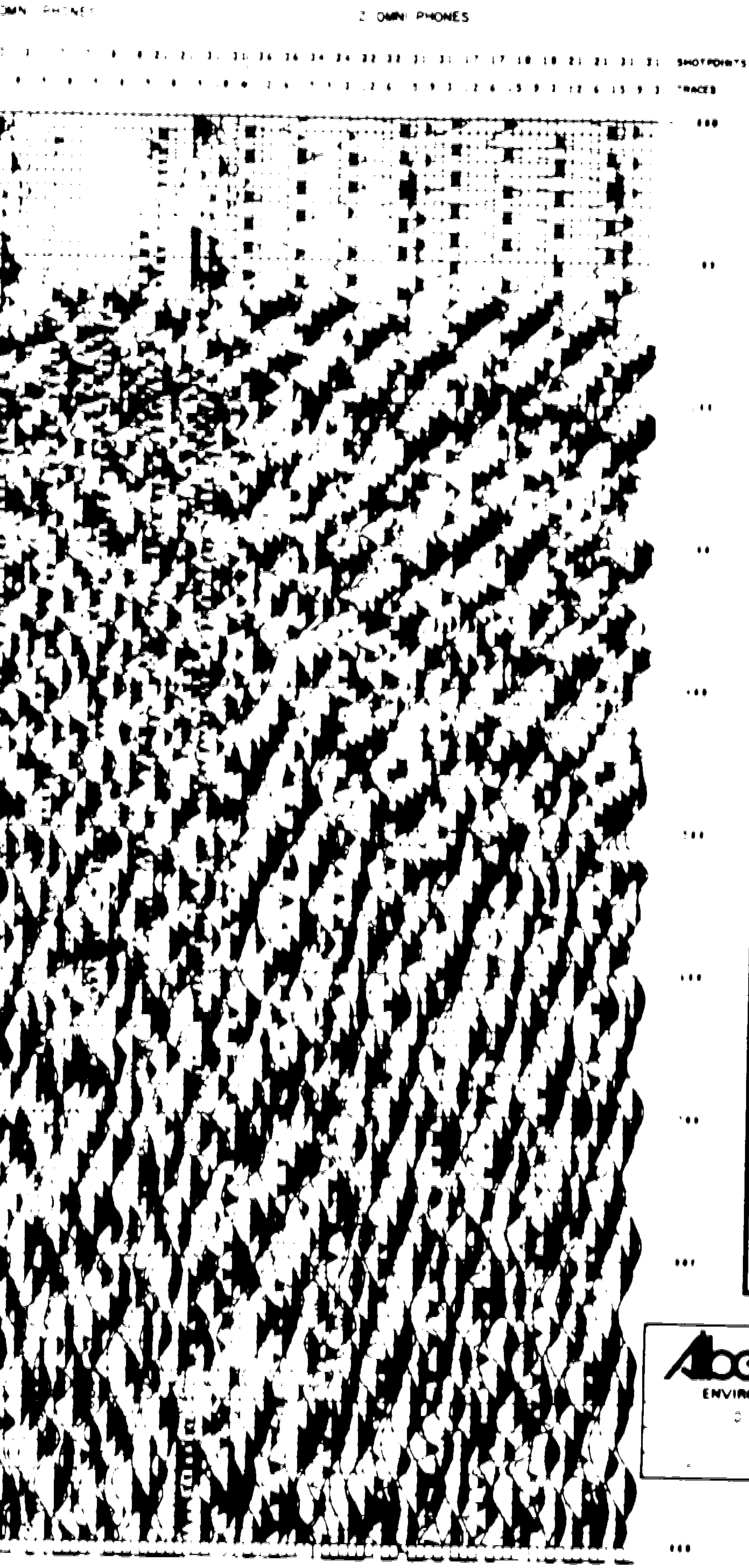


2 of



GEODIGIT

ALBERTA ENVIRONMENT

WATER WELL SURVEY

GEM

AREA

REFERENCE NUMBER 602020.

ALBERTA

FIELD RECORDING

	NORTHERN GEOPHYSICAL [illegible] LTD
	[illegible] TRACES INCLUDING
	A 3 COMPONENT OMNI PHONES AROUND THE WELL
	B HYDROPHONES INSIDE THE WELL
	C SURFACE SPREADS AROUND THE WELL
RECORD LENGTH	1 SECOND
SAMPLE RATE	2 MILLISECONDS
ENERGY SOURCE	[illegible]

PROCESSING

[illegible] AND GAIN RECOVERY

[illegible] THE WINDOW LEVEL TO 5000
FROM ORIGINAL FILE ID 5 33 34 36 38
SHOT PT NUMBERS 31 32 34 36
FROM ORIGINAL FILE ID 5 33 22 19 18

TRACE SELECTION SHOT PT NUMBERS 31 21 18 17

TRACE NUMBERS	REFER TO
4 7 10 13 16 19	X OMNI PHONES
5 8 11 14 17 20	Y OMNI PHONES
3 6 9 12 15 18	Z OMNI PHONES
(31-38)	HYDROPHONES
(39-50)	SURFACE SPREADS

STACK OF THE X Y Z COMPONENTS OF THE OMNI PHONES

PREDICTIVE DECONVOLUTION TO REMOVE MULTIPLES OF 130MS PERIOD
GAP 80MS OPERATOR 100MS DESIGN WINDOW 100-700MS

DYNAMIC EQUALISATION 40MS SLIDING WINDOW

FILM DISPLAY

DISPLAY

PLOTTER	DIGITAL [illegible]
SCALE	8 TRACES PER INCH
	20 INCHES PER SECOND

REMARKS

A OMNI PHONES
B STACKED OMNI PHONES
C HYDROPHONES
D SURFACE SPREADS

Alberta ENVIRONMENT

GEM RECORD SECTION

FIGURE No. 15

ONLY COPY AVAILABLE
SEULE COPIE DISPONIBLE

3 of 3

explanatory data and reduced data in table 3. The record section summarizing all seismic data and enhanced by deconvolution is included as figure 15.

A 1:100 scale geological cross section which integrated borehole and geophysical data is presented in figure 16.

When a P-wave/S-wave couplet was identified for the aquifer event, an estimate for the attenuation coefficient was calculated, as were the stress and strain parameters required for a resolution of stresses at a point in the aquifer opposite the intake. The results are shown in tables 4 and 5. Analysis was complicated by the lack of a refractor in the near-surface. The first breakover on the long spreads relates to the 2100 m/s "Deep Reflector" event shown on the geological cross section. The aquifer events are interpreted to be the first arrivals at the hydrophones and the surface spread (P-wave) and the headwave event at 0.346 seconds (S-wave). The S-wave event has been interfered with by multiple reflection and refraction events, but is still reasonably strong on the hydrophone record. The x and y channel omnidirectional geophone records are ambiguous. A signal is present on geophone #4 traces that corresponds to the presumed S-event on the hydrophone records, but is strongly interfered with by ground roll. On the basis of the hydrophone record, a 519 m/s S-wave velocity and a 1368 m/s P-wave velocity is assigned to the aquifer. The corresponding peak pressure wave amplitudes are 0.415 MPa and 4.110 MPa.

From amplitude spectra, the aquifer P-wave event frequently is interpreted to be 18 Hz with a Q of 6.0, producing an α of 0.0069. When

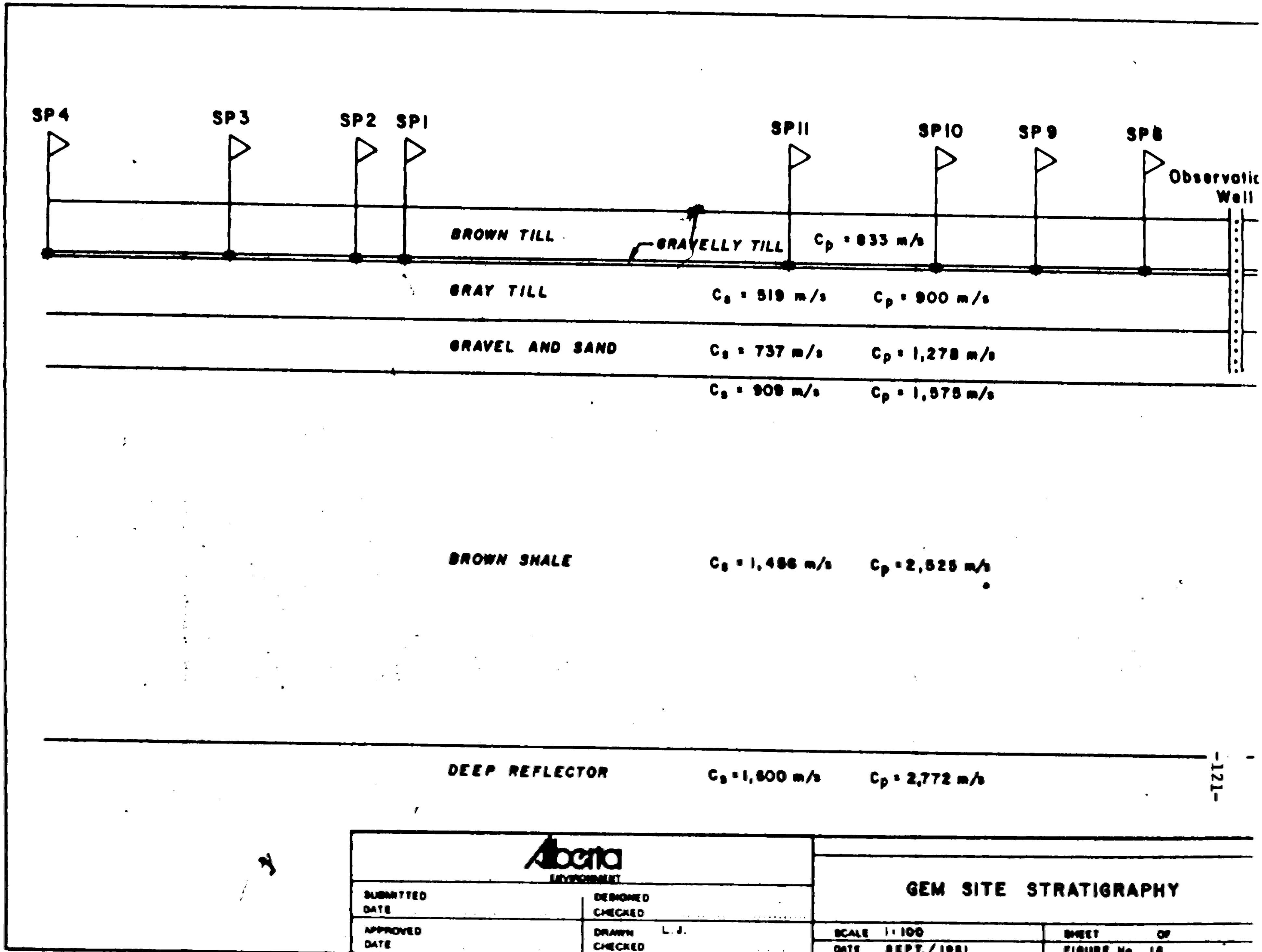

SP4
SP3
SP2
SP1
SP11
SP10
SP9
SP8
Observatio
Well
BROWN TILL
GRAVELLY TILL
Cp = 833 m/s
GRAY TILL
Cs = 519 m/s
Cp = 900 m/s
GRAVEL AND SAND
Cs = 737 m/s
Cp = 1,278 m/s
Cs = 909 m/s
Cp = 1,578 m/s
BROWN SHALE
Cs = 1,486 m/s
Cp = 2,525 m/s
DEEP REFLECTOR
Cs = 1,600 m/s
Cp = 2,772 m/s
Alberta
SUBMITTED
DATE
APPROVED
DATE
DESIGNED
CHECKED
DRAWN L.J.
CHECKED
GEM SITE STRATIGRAPHY
SCALE 1:100
DATE SEPT./1981
SHEET OF
FIGURE No.

Table 2a: Gem Pumping Test

Pumping Test Results Obtained From Semilogarithmic Data Plots

Test Number	Duration (min)	Pumping Rate (1/min)	Transmissivity drawdown (m^2/day)	Transmissivity recovery (m^2/day)	Storage Coffecient	Friction Losses at t = 20 min. (m)
Gem 1 (pumping well)	670	305	89.4	75.1		1.35 m
(observation well)	670	305	61.3	62.8	2.4×10^{-4}	0.13 m
Gem 2 (pumping well)	360	223	72.5	71.7		0.74 m
(observation well)	360	223	67.0	67.2	1.8×10^{-4}	-0.03 m
Gem 3 (pumping well)	360	223	71.0	72.5		0.72 m
(observation well)	360	223	65.2	67.2	2.2×10^{-4}	-0.05 m
Gem 4 (pumping well)	360	223	75.3	71.7		0.71 m
(observation well)	360	223	71.4	71.4	1.7×10^{-4}	0
Gem 5 (pumping well)	360	223	74.4	74.7		0.74 m
(observation well)	360	223	72.8	67.7	1.6×10^{-4}	0
Gem 6 (pumping well)	360	223	74.4	74.4		0.75 m
(observation well)	360	223	73.1	72.8	1.7×10^{-4}	0
Gem 7 (pumping well)	360	223	76.2	73.7		0.74 m
(observation well)	360	223	75.0	71.4	1.6×10^{-4}	0.04 m

(After Prosser, 1980)

Table 2b: Gem Pumping Test

Pumping Test Results Obtained By Curve Matching Techniques

Test Number	Type Curve (r/B)	Pumping Rate (l/min)	Transmissivity (m^2/day)	Storage Coefficient
Gem 1	0.4	305	26.5	2.1×10^{-4}
Gem 2	0.3	223	42.5	2.8×10^{-4}
Gem 3	0.2	223	46.5	3.1×10^{-4}
Gem 4	0.3	223	40.9	2.6×10^{-4}
Gem 5	0.3	223	41.8	2.9×10^{-4}
Gem 6	0.7	223	44.1	2.9×10^{-4}
Gem 7	0.05	223	55.8	2.2×10^{-4}

(After Prosser, 1980)

Table 3.

SEISMIC/WATER WELL STUDY
FIELD DATA

SITE: GEM

SP#	EXP (*)	WEIGHT (KG)	DEPTH (M)	DIST (M)	AMPLITUDE (DIG UNITS)	PRESSURE (MPA)	ARRIVAL TIME (SECONDS)	PHASE VELOCITY (M/S)
4	1	4.	18.	254.	299106304.	3.894	0.154	1648.
2	2	4.	10.	180.	295698432.	3.850	0.124	1452.
7	2	1.	20.	180.	305004544.	3.971	0.118	1529.
4	2	1.	20.	254.	292192256.	3.804	0.152	1671.
3	2	1.	18.	216.	284672000.	3.706	0.122	1770.
1	2	1.	20.	180.	301563904.	3.926	0.114	1579.
4	1	2.	17.	254.	301170688.	3.921	0.152	1671.
7	2	1.	20.	180.	305004544.	3.971	0.120	1500.
7	1	1.	14.	180.	209027072.	2.722	0.122	1475.
7	1	2.	20.	180.	302514176.	3.939	0.122	1475.
7	2	2.	19.	180.	313458688.	4.081	0.184	978.
1	1	4.	16.	180.	315457536.	4.107	0.118	1525.

*1= Geo-Gel
2= Geo-Mex

Table 4

Attenuation Calculation

Site	Event	f (Hz)	Δf (Hz)	Q	C (m/s)	α	Pest (MPa)	Pobs (MPa)	γ_{Mohr} (Est.)	γ_{Mohr} (Obs.)	γ_o	γ_{Dyn} (Prange)
		1	2	3	4	5	6	7	8	9	10	11
Brooks/EID	Bedrock P											
	Aquifer P	12			1,578							
	Aquifer S	24	4.0	6	545	0.02305	0.272	0.913	3.46×10^{-7}	2.22×10^{-7}	3.80×10^{-3}	6×10^{-5}
	Ch Wave	36			450							
Collins Creek	Bedrock P	12										
	Aquifer P	15	2.7	5.6	1,565	0.00542	6.492	3.398				
	Aquifer S	17.5	2.0	8.75	584	0.001075	2.483	3.111	3.84×10^{-6}	6.23×10^{-6}	4.51×10^{-3}	6.52×10^{-4}
	Ch Wave	40.0	4.0	10.0	292	0.04304	0.007					
Bonnyville	Bedrock P	4	2.5									
	Aquifer P	15.5	1.7	9.11	1,400	0.00381	1.4×10^{-6}	-				
	Aquifer S	26.0	3.0					-				
	Ch Wave				260			$\bar{P}$=0.309				
Vegreville	Bedrock P											
	Aquifer P											
	Aquifer S	27.5	1.5	18.3	525	0.00897	3.423	3.422	-	-	-	-
	Ch Wave	31.0	1.5	20.6	203	0.02321	0.264	4.618				
New Norway	Bedrock P	15	2.0	7.5								
	Aquifer P	18	2.0	9.0	1,326	0.00473	7.339	3.800				
	Aquifer S	29	2.0	14.5	535	0.01744	2.080	1.569	3.47×10^{-6}	1.21×10^{-7}	5.23×10^{-3}	2.26×10^{-4}
	Ch Wave											

Table 4

Attentuation Calculation

Site	Event	f (Hz)	Δf (Hz)	Q	C (m/s)	α	Pest (MPa)	Pobs (MPa)	γ_{Mohr} (Est.)	γ_{Mohr} (Obs.)	γ_o	γ_{Dyn} (Prange)
		12	13	14	15	16	17	18	19	20	21	22
Gem	Bedrock P											
	Aquifer P	18	3.0	6.0	1,365	0.0069	4.970	4.110				
	Aquifers	29	5.0	5.8	519	0.0302	0.655	0.415	1.22×10^{-6}	7.75×10^{-7}	6.39×10^{-3}	2.78×10^{-5}
	Ch Wave											
Wintering Hills	Bedrock P				1,920							
	Aquifer P	16	3.0	5.3	1,385	0.00680	5.060	4.365				
	Aquifer S	33	3.0	11.0	562	0.01677	0.842	4.853	1.40×10^{-6}	8.90×10^{-6}	5.07×10^{-3}	2.48×10^{-4}
	Ch Wave											
Caroline	Bedrock P	14	1.5	9.3	2,308	0.00204	11.92	4.502				
	Aquifer P	26	2.0	13.0	1,690	0.00372	8.820	5.116				
	Aquifer S	39	4.0	9.75	585	0.02148	0.364	5.324	4.17×10^{-7}	6.09×10^{-6}	4.32×10^{-3}	9.04×10^{-5}
	Ch Wave	70										
Benalto	Bedorck P				2,565			3.197				
	Aquifer P	25	5.0	5.0	1,676	0.00937	3.187	6.990				
	Aquifer S	32	4.0	8.0	588	0.02137	0.368		5.60×10^{-7}		4.96×10^{-3}	1.06×10^{-4}
	Ch Wave	45	9.0	5.0								

substituted into the attenuation function, this value of α overestimates the pressure wave amplitude by some 26%. The average estimate across four records is 18% low compared to the observed values, although there is considerable variability in the data. The poorly defined S-wave event recorded from the x and y channels of the omni-directional geophones eliminated the opportunity of calculating S-wave attenuation parameters.

5. Experiment Results

Values obtained for in situ stresses (Table 5 columns 1 and 5) are reasonable for an uncemented, normally consolidated gravel and sand deposit buried under 33 m of overburden. The drilling crew reported that the gravels cave into an uncased drillhole, therefore a $\tau_{max} < \tau$ would be expected. The value for shear strain may be unrealistically low, however at ~1 x 10^{-8}.

The estimated strain for each impulsive event under the worst case conditions used for calculation purposes is extremely small at 1 x 10^{-6} per event or 2.6 x 10^{-5} if all strains were permanent (irrecoverable) and cummulative. The 9% cumulative increase in transmissivity following treatment was considered by Prosser (1980) to be insignificant.

Peak amplitudes of the pressure wave do not appear to be significantly affected by depth of charge burial, weight of charge or distance between the detonation and the well intake over the range of distances used in this experiment. The mean peak amplitude was 3.824 MPa, with a coefficient of variation of .095 or about 10% across the 12

Table 5

Peak Strain Calculation

Page 1 of 3

Site	σ_v' (MPa)	C_s (m/s)	C_p (m/s)	μ	σ_h' (MPa)	K_o	ϕ' (deg)	τ_{Mohr} (MPa)	P	E	ε_v	ε_n
	1.	2	3	4	5	6	7	8	9	10	11	12
Brooks	0.603	545	1578	.176	.128	.213	51.9	0.768	2.65	6.60×10^{6}	9.14×10^{-8}	-1.16×10^{-8}
Collins Creek	0.671	542	1565	.177	.144	.214	53.1	0.894	2.20	5.38×10^{6}	1.25×10^{-7}	-2.25×10^{-8}
Vegreville	0.363	-	-	-	-	-	-	-	2.05	-	-	-
New Norway	0.204	535	1300	.283	.081	.397	37.1	0.154	2.10	3.55×10^{6}	5.75×10^{-8}	-1.63×10^{-8}
Gem	0.543	519	1368	.231	.163	.300	44.4	0.531	1.99	3.72×10^{6}	1.46×10^{-7}	-3.37×10^{-8}
Wintering Hills	0.673	562	1385	.275	.254	.378	38.4	0.533	1.90	3.64×10^{6}	1.84×10^{-7}	-5.07×10^{-8}
Caroline	1.540	584	1690	.175	.354	.230	50.4	1.860	2.56	7.31×10^{6}	2.10×10^{-7}	-3.69×10^{-8}
Benalto	0.507	588	1676	.176	.108	.213	51.9	0.647	1.90	5.49×10^{6}	9.23×10^{-8}	-1.62×10^{-8}

Table 5

Peak Strain Calculation

Site	G	γ	τ_{max}	γ_r	τ_{est} Richart	τ_{obs} (MPa)
	13	14	15	16	17	18
Brooks	7.87×10^5	9.76×10^{-7}	.162	3.07×10^{-7}	.134	0.175
Collins Creek	6.46×10^5	1.38×10^{-6}	.402	6.22×10^{-7}	.318	4.024
Vegreville	-	-	-	-	-	4.618
New Norway	6.01×10^5	2.56×10^{-7}	.085	1.41×10^{-7}	.167	0.073
Gem	5.36×10^5	9.91×10^{-9}	.247	4.61×10^{-7}	.169	0.415
Wintering Hills	6.00×10^5	3.16×10^{-6}	.197	3.28×10^{-7}	.178	0.418
Caroline	8.73×10^5	2.13×10^{-6}	.729	1.68×10^{-7}	.599	5.324
Benalto	6.57×10^5	9.84×10^{-7}	.241	3.68×10^{-7}	.339	0.849

Table 5

Peak Strain Calculation

Site	P_{obs} (MPa)	γ_{imp}	ε_n	γ_{Total}	ε_{Total}	$\frac{\Delta T}{T}_{Total}$
	19	20	21	22	23	24
Brooks	0.952	2.22×10^{-7}	1.44×10^{-7}	2.10×10^{-6}	1.15×10^{-6}	- 8 %
Collins Creek	3.923	6.23×10^{-6}	7.29×10^{-7}	7.49×10^{-5}	8.75×10^{-6}	+ 8 %
Vegreville	-	-	-	-	-	- 3 %
New Norway	1.627	1.21×10^{-7}	4.58×10^{-7}	1.21×10^{-6}	4.58×10^{-6}	-10.0%
Gem	2.170	7.75×10^{-7}	5.83×10^{-7}	1.94×10^{-5}	2.58×10^{-5}	+ 9.0%
Wintering Hills	2.520	8.90×10^{-6}	6.92×10^{-7}	2.49×10^{-4}	1.73×10^{-5}	+22 %
Caroline	4.502	6.09×10^{-6}	6.15×10^{-7}	2.44×10^{-6}	3.70×10^{-6}	-16 %
Benalto	6.990	1.29×10^{-6}	1.27×10^{-6}	1.27×10^{-6}	1.27×10^{-5}	-28 %

measurements shown in table 3. The coefficient of correlation between distance and amplitude was .05. A similar situation existed between charge weight and amplitude. The mean charge weight was 2 Kg, with a range of weights from 1 to 10 Kg. The coefficient of correlation between charge weight and peak amplitude was 0.31.

IV. RESULTS AND DISCUSSION

A. OBSERVED DAMAGE

"Damage" for the purposes of this study, is defined as any permanent degradation of water well yield or quality. Both "yield" and "quality" are further defined in part I and in the study terms of reference, these definitions being based on those accepted by Vogwill (1979). As defined, "damage" was observed at five sites and, somewhat surprisingly, enhancement was observed at three sites (Collins Creek, Gem and Wintering Hills).

*The degree of damage or enhancement was minor in all cases according to Goble (1980a, 1980b) Prosser (1980) and Vogwill (1979). To produce a major change in yield the relative changes in transmissivity would have to be in the hundreds of per cent. The observed changes were from -28% to +22%, performance changes which would be unnoticeable in a domestic well.

With regard to quality, short term siltation was observed at Collins Creek, Caroline and Benalto. In the case of Benalto a fair amount of siltation was reported by the user following the first treatment.

B. MAXIMUM PEAK PRESSURES

A basic hypothesis for the experiment was that the degree of damage to a well depends on the intensity of vibration at the well intake induced by a dynamite blast. If this hypothesis is correct, then it follows that peak pore pressures at the well intake produced by blasting must be small because the observed damage was insignificant. In this case "small" is taken to mean any pressure that would induce elastic strains less than 6×10^{-5} m, which corresponds to the median grain diameter of the coarsest saturated sand subject to liquifaction during earth quakes, according to Studor and Kok (1981). Such strains are also small enough to justify an assumption of pure elasticity, even if the granular material under test is shown to have a curvilinear failure envelope. Since the point at which the stresses were resolved was opposite the well intake, it was also assumed that the aquifer behaved in a drained mode for the purposes of calculating the magnitude of strains.

1. Recorded Peak Pressures and Event Identification

The large volume of data available precluded analysis of amplitudes from every event from every record. Instead only the highest peak amplitude and the P and S events interpreted to be associated with the aquifer formation from the least ambiguous records were analysed. Wherever possible, records from shot points 1, 4 and 7 were used, to allow easy comparison of data from site to site in that geometric variables were kept nearly constant. In all cases, the data were recorded from the lowest (deepest) active hydrophone.

The greatest peak pressure wave amplitudes and associated data for all test sites are presented in Appendix 1. These data were analysed using descriptive statistics, which are summarized in tables 6. The histogram of maximum peak pressures (figure 17) suggests a type 1

STATISTICAL ANALYSIS OF MAXIMUM AMPLITUDE DATA 03/25/80 PAGE 1 of 2
CONTINUOUS DESCRIPTIVE STATISTICS
FILE SEIS (CREATION DATE = 03/25/80)

Table 6.

VARIABLE VEL VELOCITY

MEAN	828.068	STD ERROR	95.811	STD DEV	735.939
VARIANCE	541606.306	KURTOSIS	-0.825	SKEWNESS	0.443
RANGE	2511.000	MINIMUM	0.0	MAXIMUM	2511.000
SUM	48856.000				

VALID OBSERVATIONS - 59 MISSING OBSERVATIONS - 0

VARIABLE FREQ FREQUENCY

MEAN	21.610	STD ERROR	1.592	STD DEV	12.229
VARIANCE	149.552	KURTOSIS	-0.536	SKEWNESS	-0.096
RANGE	44.000	MINIMUM	0.0	MAXIMUM	44.000
SUM	1275.000				

VALID OBSERVATIONS - 59 MISSING OBSERVATIONS - 0

VARIABLE CSIZE CHARGE SIZE

MEAN	3.051	STD ERROR	0.334	STD DEV	2.569
VARIANCE	6.601	KURTOSIS	8.131	SKEWNESS	2.486
RANGE	14.000	MINIMUM	1.000	MAXIMUM	15.000
SUM	180.000				

VALID OBSERVATIONS - 59 MISSING OBSERVATIONS - 0

VARIABLE SHD SHOT HOLE DEPTH

MEAN	21.907	STD ERROR	3.451	STD DEV	26.511
VARIANCE	702.858	KURTOSIS	37.246	SKEWNESS	5.826
RANGE	200.000	MINIMUM	0.0	MAXIMUM	200.000
SUM	1292.500				

VALID OBSERVATIONS - 59 MISSING OBSERVATIONS - 0

STATISTICAL ANALYSIS OF MAXIMUM AMPLITUDE DATA
CONTINUOUS DESCRIPTIVE STATISTICS
FILE SEIS (CREATION DATE = 03/25/80)

Table 6.

VARIABLE SDDIST DISTANCE TO SHOT

MEAN	500.585	STD ERROR	117.932	STD DEV	905.852
VARIANCE	820567.725	KURTOSIS	5.363	SKEWNESS	2.683
RANGE	3162.000	MINIMUM	6.000	MAXIMUM	3168.000
SUM	29534.500				

VALID OBSERVATIONS - 59 MISSING OBSERVATIONS - 0

- -

VARIABLE MAXA MAXIMUM AMPLITUDE

MEAN	36.218	STD ERROR	2.132	STD DEV	16.373
VARIANCE	268.091	KURTOSIS	0.459	SKEWNESS	-0.789
RANGE	69.917	MINIMUM	0.028	MAXIMUM	69.945
SUM	2136.887				

VALID OBSERVATIONS - 59 MISSING OBSERVATIONS - 0

STATISTICAL ANALYSIS OF MAXIMUM AMPLITUDE DATA
HISTOGRAM GENERATION FOR ALL VARIABLES
FILE SEIS (CREATION DATE = 03/25/80)

MAXA MAXIMUM AMPLITUDE

```
  CODE
         I
    1.   ********** (      9)
         I  00 - 10 KG PER CM**2
         I
         I
    2.   ** (      1)
         I  10 - 20 KG PER CM**2
         I
         I
    3.   ****** (      5)
         I  20 - 30 KG PER CM**2
         I
         I
    4.   **************** (     15)
         I  30 - 40 KG PER CM**2
         I
         I
    5.   ************************* (     24)
         I  40 - 50 KG PER CM**2
         I
         I
    6.   *** (      2)
         I  50 - 60 KG PER CM**2
         I
         I
    7.   **** (      3)
         I  60 - 70 KG PER CM**2
         I
         I.........I.........I.........I.........I.........I
         0        10        20        30        40        50
         FREQUENCY
```

MEAN	4.051	STD ERR	0.209	MEDIAN	4.467
MODE	5.000	STD DEV	1.602	VARIANCE	2.566
KURTOSIS	-0.030	SKEWNESS	-0.685	RANGE	6.000
MINIMUM	1.000	MAXIMUM	7.000		

VALID CASES 59 MISSING CASES 0

Alberta ENVIRONMENT

SUBMITTED		DESIGNED	
DATE		CHECKED	
APPROVED		DRAWN	
DATE		CHECKED	

BEDROCK SURFACE EVENT

HISTROGRAM OF MAXIMUM PEAK PRESSURES

SCALE	AS SHOWN	SHEET	OF
DATE	SEPT. /1981	FIGURE No.	17

MICROFILM DATE
DRAWING No
FILE No

(maximum) extreme value distribution with a mode of about 4 MPa and an outlier peaking at about 2 MPa.

The criteria for a type 1 extreme value (Gumbel) distribution require that events be statistically independant and possess a common distribution function (Benjamin and Cornell (1970)). Dynamite bursts in fresh holes meet these criteria as each burst is unaffected by either previous or future bursts in other holes.

The peak bore hole pressure produced by a detonation is a continuous random variable whose value is determined by variability in the manufacturing processes and such borehole parameters as acoustic coupling and acoustic impedance. It would appear from the data these influences produce a fairly well defined cumulative distribution function.

The mean for the maximum peak pressures can be approximated using the relations suggested by Benjamin and Cornell (1970):

$$M_y = U + \frac{0.577}{\alpha}$$

where U is the mode of the distribution and α, the dispersion parameter, is computed from another approximation derived from the standard deviation, σ_y:

$$\alpha = 1.282/\sigma_y$$

For the whole data set,

$$\alpha = 1.282/1.67 = 0.767$$

$$M_y = 4.59 + 0.577/0.767 = 5.339 \text{ MPa}$$

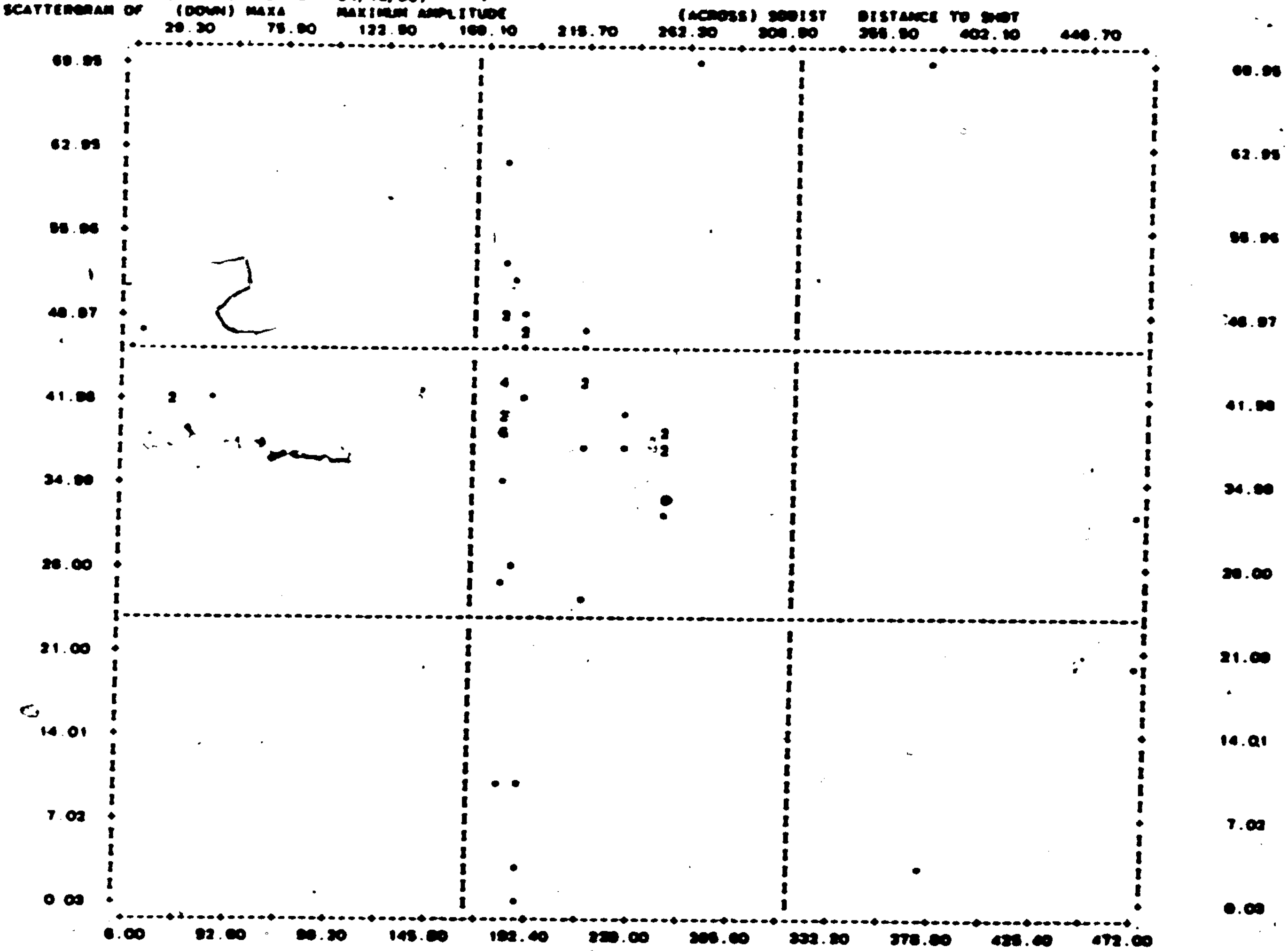
The largest amplitudes of record were observed at Benalto where peaks in excess of 6.5 MPa were observed. These values were clipped and represent the maximum value that can be measured on the DFS-V instruments rented from Quest Explorations Ltd. for that site only. The instrument tests run immediately before the experiments indicated nominal operation and the unclipped readings are considered to be accurate. It is perhaps significant that several hydrophones failed during the test sequence and that the largest change to aquifer transmissivity (-28%) occurred at the Benalto site.

For the whole data set, the only correlations that indicated any sort of significance were between amplitude and distance (figure 18) and between amplitude and charge size (figure 19).

No clearly defined relationship exists between the highest peak amplitude pressure on a record and the propagation history of the event associated with it. On some records, the highest peak is the sum of interfering waves which are usually refractions. In some cases, notably at Wintering Hills, the direct, refracting and reflecting P-waves arrived at the lowermost hydrophone simultaneously and in phase to produce the largest peak.

The wavetrain associated with a confined aquifer was generally the second largest peak, and occasionaly the largest, amplitude event on the record.

STATIS...CAL ANALYSIS OF MAXIMUM AMPLITUDE DATA — 04/13/80 — PAGE 2
SCATTERGRAM OF MAXA VS DISTANCE, UNCLASSED DATA.
FILE SEIS (CREATION DATE = 04/13/80)
SCATTERGRAM OF (DOWN) MAXA MAXIMUM AMPLITUDE (ACROSS) SDDIST DISTANCE TO SHOT



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Alberta ENVIRONMENT

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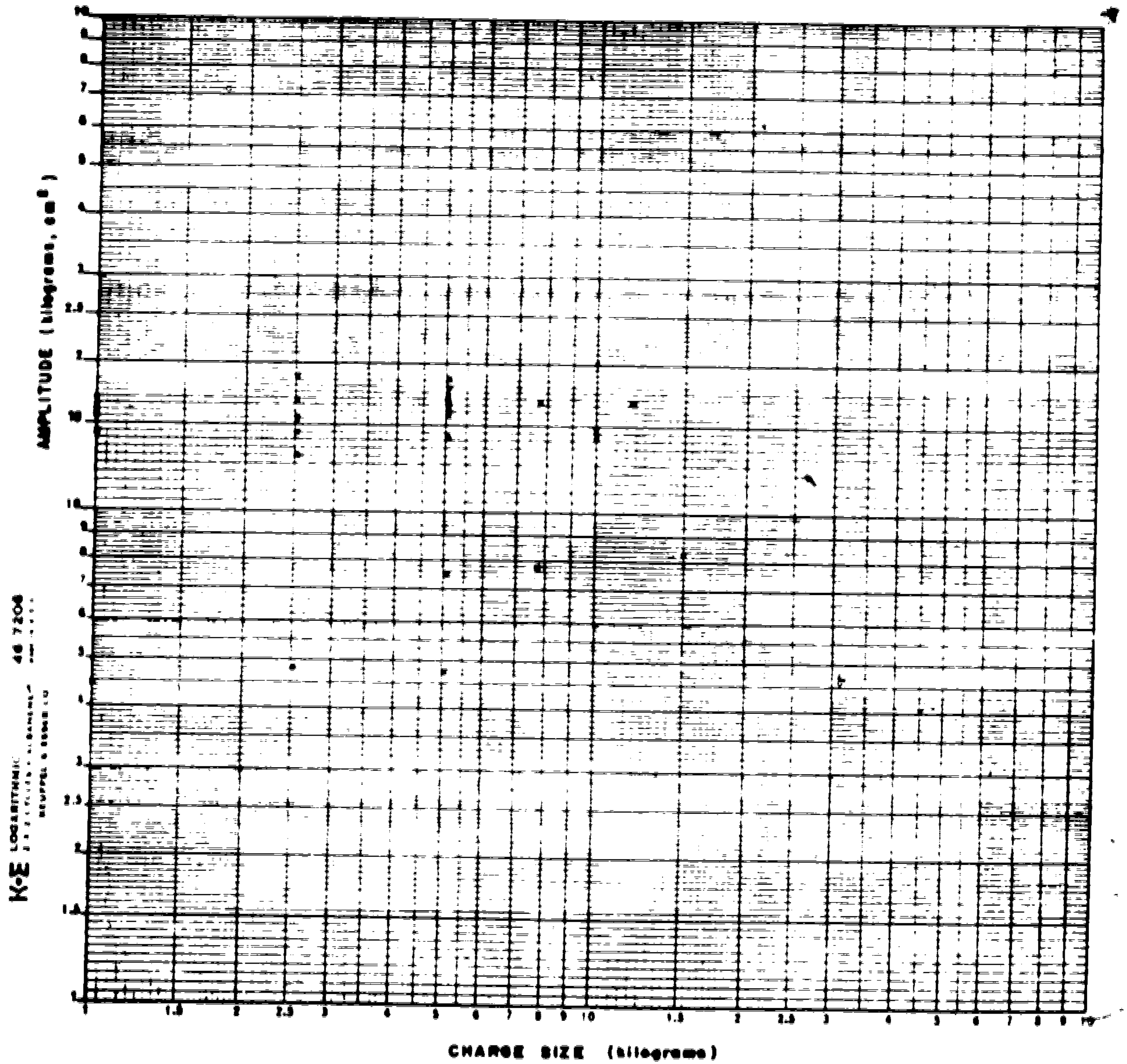
BEDROCK SURFACE EVENT

AMPLITUDE VERSUS DISTANCE SCATTERGRAM

SCALE	AS SHOWN	SHEET	OF
DATE	SEPT. /1981	FIGURE	18



Alberta

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AMPLITUDE VERSUS CHARGE SIZE SCATERGRAM

SCALE AS SHOWN	SHEET OF
DATE SEPT/1981	FIGURE No. 19

FILE No.

2. Event Amplitude Prediction

A major objective of the present study was to develop a method for predicting the strength of blasting vibrations at a waterwell intake and relating that value to some quantifiable change in well hydraulic characteristics.

Logically, there should be a functional relationship between the strength of a vibration, ie. its amplitude, and the distance between its source and the place where it is measured. The attenuation function proposed by Born (1941) and modified by Dobrin (1976) was tried using a damping coefficient derived from a semilog regression. The peak amplitude data used was selected by its propagation velocity. The method worked, in that estimates of measured values were similar. However it was not satisfactory because only two or three data points were available for regression purposes and these were usually closely grouped.

A more satisfactory estimate was made by estimation of the attenuation coefficient (α) using a method presented by Knopoff (1964) based on spectral analysis techniques described earlier in part II. Attenuation estimates for the readily recognizable events at each site are presented in table 4. These estimates are accurate if the correct event frequency can be determined by measuring wavelet period and no other unrelated events have that period.

It may be concluded, on the basis of these experiments that if seismic velocity and amplitude spectra are available for the geological materials at the weakest point of a particular water well, which is usually the intake, the amplitude of an elastic wave from a source of known intensity at a known distance can be predicted with reasonable accuracy.

3. Prediction of Aquifer Formation Strains

The parameter chosen to indicate water well performance before and after treatment by blasting was transmissivity.

Transmissivity is the product of the coefficient of permeability and the thickness of the aquifer. If the thickness is constant, only the values for permeability can vary. The coefficient of permeability, P, is derived from:

$$P = \gamma_w/\mu \; P_s \qquad \text{(Walton, 1970)}$$

where γ_w is the specific weight of water, a constant, μ is the viscosity of water, also a constant, and P_s is the intrinsic permeability.

In turn,

$$P_s = \gamma_w/[\mu(\theta/A_s)]$$

where P_s, γ_w and μ are as defined above;

θ is the porosity of the aquifer formation, and A_s is an empirical factor related to the shape of the pores and is a constant as well.

Of all the parameters described above, only θ is affected by stress.

Under drained yet fully saturated conditions, a change in porosity results in a volume of water, V_w, flowing out of an element of aquifer. If the element of aquifer is associated with the point where the stresses have been resolved:

$$\Delta V_w = \Delta V$$

where ΔV is a global volume change in response to the application of a stress.

Using the principles of effective stress described in part II, peak strains related to in situ overburden stresses and peak pressures related to blasting vibrations were calculated. These are presented in table 5.

These same data have been expressed in per cent volume change in table 7 and compared with the corresponding relative change in transmissivity data. The correlation between the computed change in volumetric strain and relative change in transmissivity is surprisingly good. The disparity between the Benalto data and computed strain might be related to the unreliable peak pressure data discussed previously. The discrepancies between the calculated and observed values for the Gem and Wintering Hills sites cannot be readily explained.

4. Effect of Charge Weight on Peak Pressures

The statistical relationship between charge weight and observed peak pressure is shown in figure 19. Over the range of charge weights commonly used in Western Canada, there is no consistent difference in observed peak pressures with increases in charge weight. The chief difference would appear to be in spectral content: large (2.5 to 10 Kg of 60% Nitroglycerine equivalent explosive) charges produce signals rich in low frequencies and small (1 to 2.5 Kg) charges produce a larger proportion of higher frequencies.

Table 7

Computed Volume Strain

Site	E	P_{obs}	ϵ_{Total}	$\Delta\epsilon$	$\frac{\Delta T}{T}$
Brooks	6.6×10^{6}	0.952	1.15×10^{-6}	8.3%	- 8%
Collins Creek	5.38×10^{6}	4.024	8.75×10^{-6}	8.54%	+ 8%
Vegreville	-	-	-	-	-
New Norway	3.55×10^{6}	1.627	4.58×10^{-6}	10.0%	-10%
Gem	3.72×10^{6}	4.110	2.58×10^{-5}	4.3%	+ 9%
Wintering Hills	3.64×10^{6}	4.365	1.73×10^{-5}	6.9%	+22%
Caroline	7.31×10^{6}	4.502	3.70×10^{-6}	16.6%	-16%
Benaíto	5.49×10^{6}	6.990	1.27×10^{-5}	10.0%	-28%

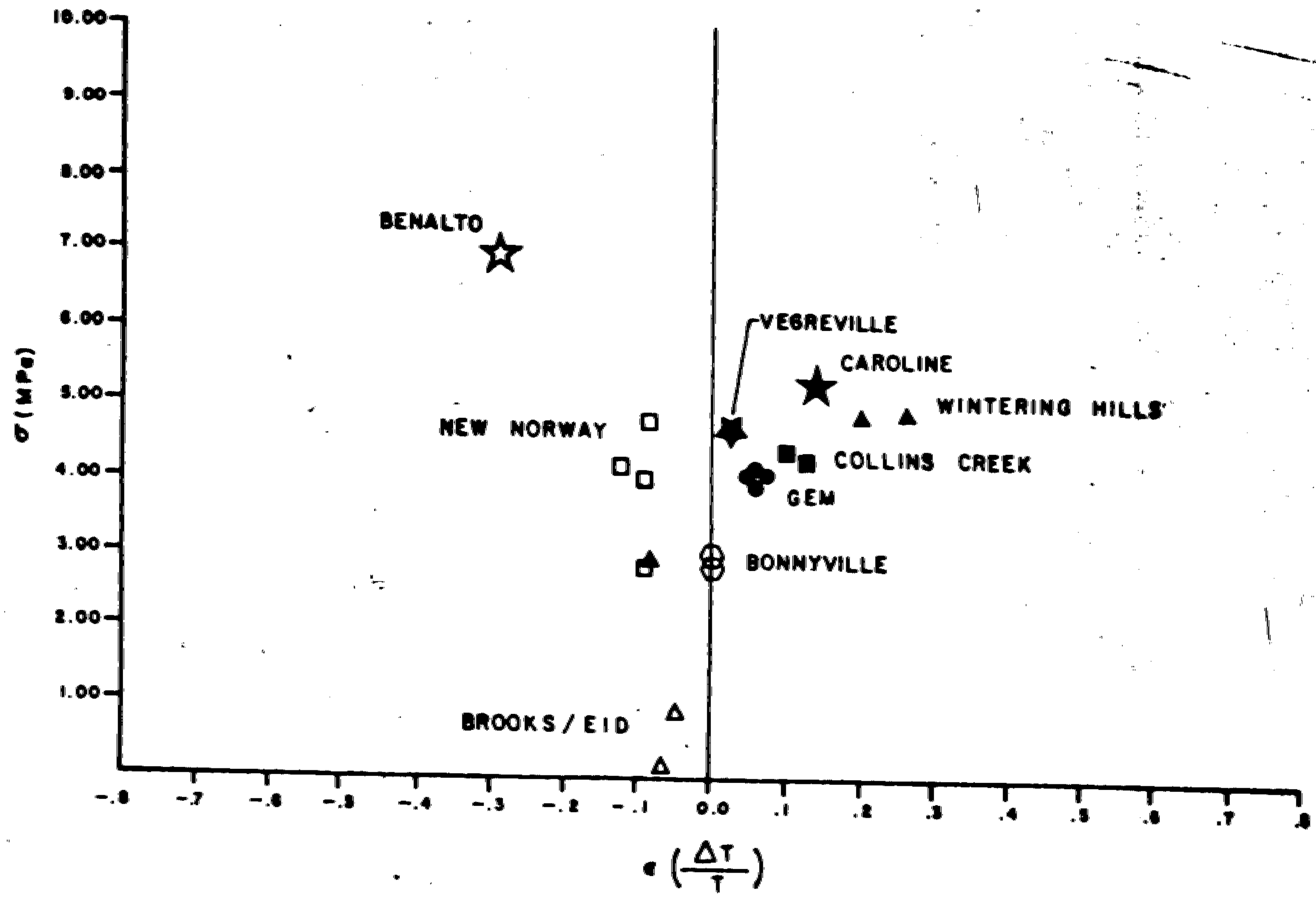
There was one major exception to the rule: channel waves do not appear to behave according to the same attenuation law as those waves propogated by other mechanisms. The Bonnyville data suggest that a low velocity (~250 m/s), high frequency (26 Hz) signal can be transmitted over great distances (35 Km) with high amplitudes. The same data show that by doubling the charge, the wave amplitude is doubled. Elsewhere, the charge weight had to be increased ten fold to double the peak amplitude over the same shotpoint to receiver distance. While signals with such a low velocity of propagation were not commonly observed at other sites, where they were observed (Vegreville) they possessed anomolously high amplitudes compared to predicted values for a given charge size.

C. POTENTIAL DAMAGE PRODUCING MECHANISMS.

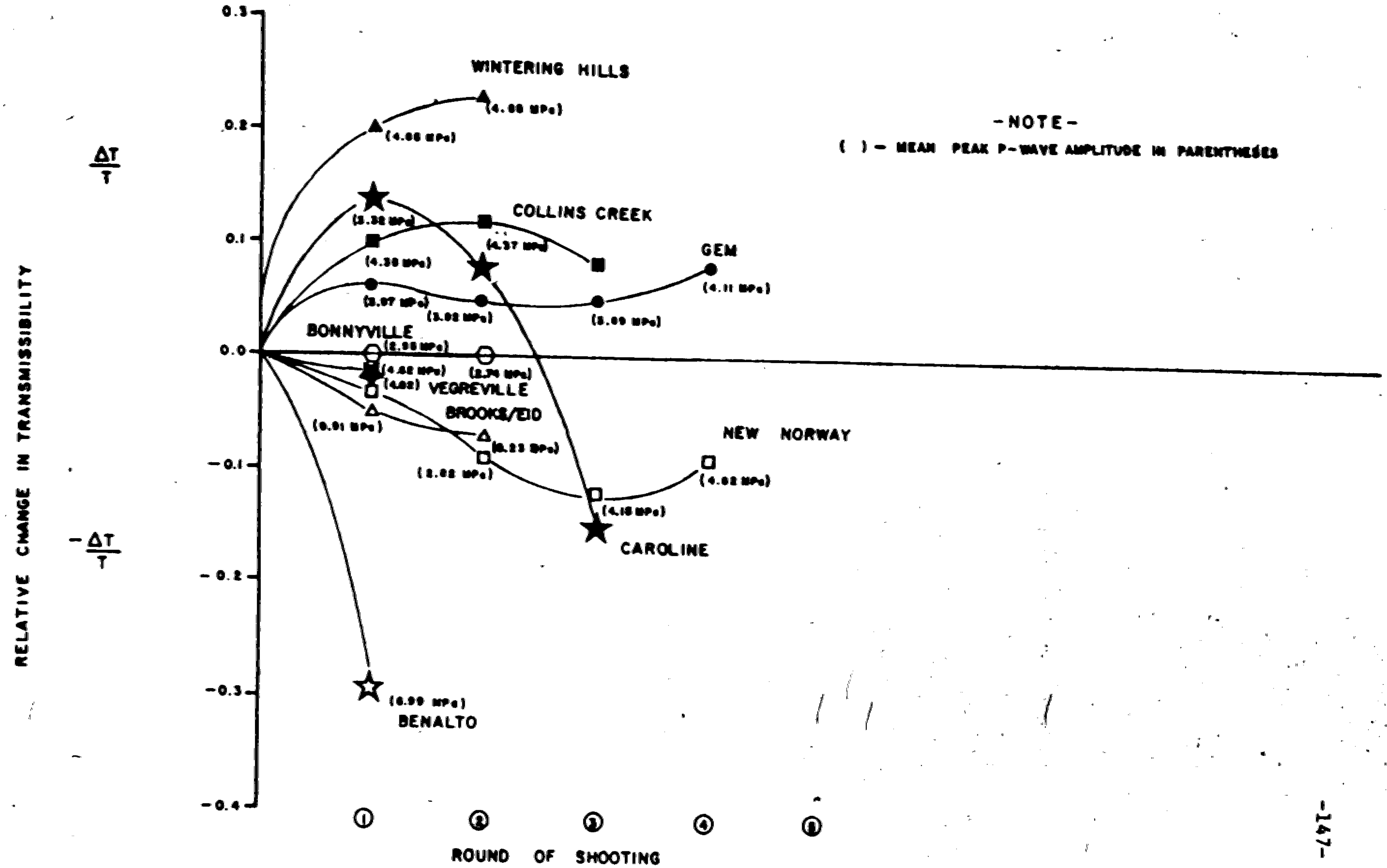
1. Aquifer Consolidation

The data presented in part III. B3 above suggest that aquifer consolidation accompanies every blast, although the amount of permeability change was very small in the cases observed.

These changes, although small, are apparently consistant and would appear to be related to the number of episodes of significant levels of impulsive stress. Figure 21 illustrates these general trends for each of the sites tested. The amount of strain does not appear to be related to the magnitude of impulsive stress, as no clear pattern emerges from the peak stress versus transmissivity change scattergram shown in figure 20.



Alberta ENVIRONMENT		BEDROCK SURFACE EVENT	
SUBMITTED	DESIGNED D. T. S.	RELATIVE CHANGE IN TRANSMISSIVITY VERSUS MAGNITUDE OF PEAK IMPULSIVE STRESS	
DATE	CHECKED		
APPROVED	DRAWN L. J. -	SCALE AS SHOWN	SHEET OF
DATE	CHECKED	DATE SEPT. / 1981	FIGURE 20



Alberta ENVIRONMENT	BEDROCK SURFACE EVENT
	CHANGES IN TRANSMISSIVITY BY ROUND OF SHOOTING
SUBMITTED ..... DATE	DESIGNED D.T.S. CHECKED .....
APPROVED ..... DATE	DRAWN L.J. CHECKED .....
SCALE AS SHOWN	SHEET OF
DATE SEPT. / 1981	FIGURE No. 21

2. Liquifaction Phenomena

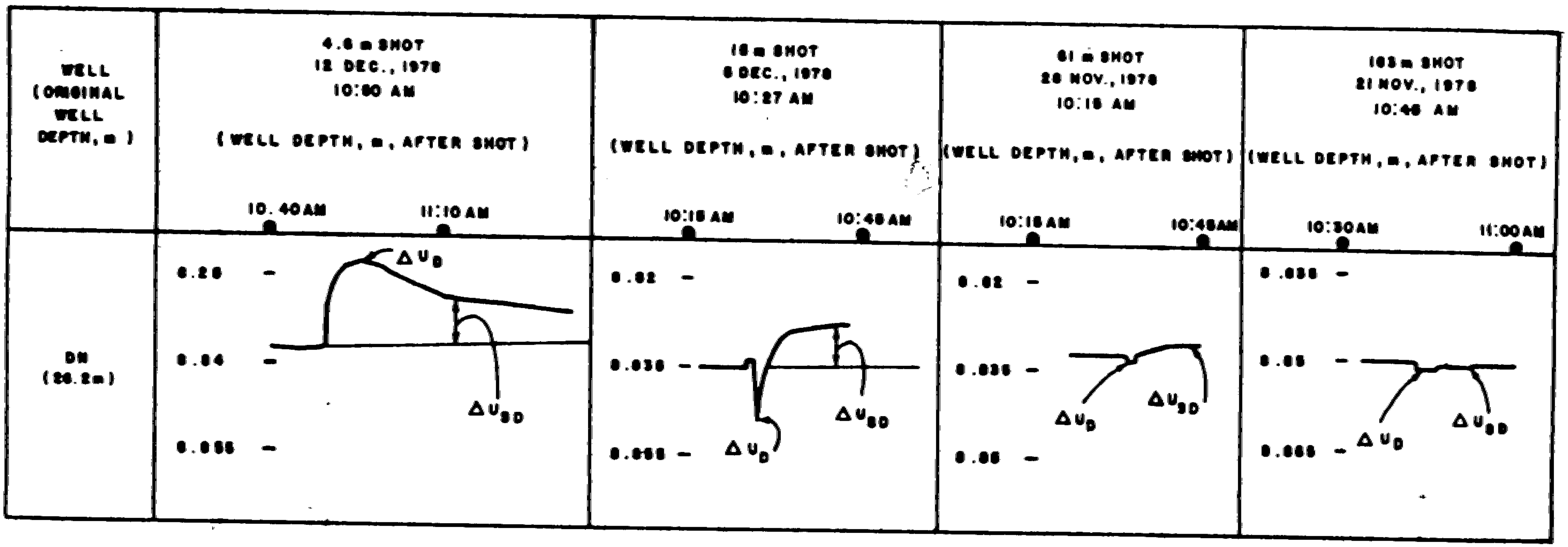
Liquifaction of sands result from the progressive decrease in effective stress produced by rapid volume changes brought on by impulsive or vibratory loading [Studer and Kok (1981)]. The phenomenon is usually associated with very large strains brought on by earthquakes, large blasts and in the immediate vicinity of pile driving operations. Studer and Kok (1981) have proposed a parameter for assessing the danger of liquifaction occuring, the "liquifaction coefficient".:

$$Liq = \frac{\Delta U_{SD}}{\sigma'}$$

where ΔU_{SD} is the "semidynamic excess pore pressure" resulting from trapped porewater bleeding slowly from a zone of reduced permeability, and σ', is the value of effective stress. When Liq > 1.0, sand grain contacts breakdown and the soil mass acts as a liquid.

ΔU_{SD} was measured by Vogwill (1979) at the New Norway site. Using his data, the danger of liquifaction can be assessed using the Studer-Kok method.

In well DN, Vogwill reported static water elevation changes observed with a fast chart speed stage recorder as shown in his figure 9 and reproduced here as figure 22. Table 8 reduces this data to the parameters used by Studer and Kok to derive a liquifaction coefficient. The coefficients compare favourably to those published by Studer and Kok and are very much smaller than 1.0. Clearly, liquifaction is a remote



SOURCE : VOGWILL (1979)

Alberta ENVIRONMENT

SUBMITTED. DATE	DESIGNED D.T.S. CHECKED	BEDROCK SURFACE EVENT	
		SEMIDYNAMIC PORE PRESSURE CALCULATION FROM WATER LEVEL DATA	
APPROVED DATE	DRAWN C.F. CHECKED	SCALE AS SHOWN	SHEET OF
		DATE SEPT / 1981	FIGURE No. 22

Table 8

Liquifaction Coefficient Calculation

Shot/Well Distance (m)	Δh_{peak} (m)	ΔU_D (MPa)	Δh_{SD} (m)	ΔU_{SD} (MPa)	$\sigma 1$ (MPa)	Liq.
4.6	0.015	1.47×10^{-4}	0.005	4.9×10^{-5}	.204	2.4×10^{-4}
15.0	-0.006	-5.88×10^{-5}	0.005	4.9×10^{-5}	.204	2.4×10^{-4}
61.0	-0.0015	-1.47×10^{-5}	0.0015	1.5×10^{-5}	.204	7.2×10^{-5}
183.0	-0.001	-9.86×10^{-6}	0.0009	8.8×10^{-6}	.204	4.3×10^{-5}

possibility in domestic water wells subject to blasting vibrations from exploration seismic operations.

3. Borehole Cracking

One possible pathway for mixing contaminated and potable water through cracks in the borehole wall and/or the surrounding formation. This could defeat casing seals as well.

Goble (1980a) and Vogwill (1979) both employed borehole television to inspect the casing and intake following blasting treatment. No new cracks were observed at any of the sites tested, including those where blasts as close as 4.6 m were detonated. This is perhaps due to the disturbed stress field in the vicinity of a borehole locally deflecting the orientation of the least principal stress. Since fractures tend to propagate in the direction of greatest principal stress, they may curve around the local disturbance where the least principal stress is oriented radially into the borehole. There is some evidence from oil field practice that this phenomenon occurs in competent rocks (personal communication from Dr. M. Dusseault, Department of Mineral Engineering, University of Alberta).

4. Changes in Fracture Width

Fracture permeability is difficult to quantify and even more difficult to detect in aquifers. Witherspoon and Gale (1977), whose results were reviewed in Part I, note that relatively small stresses, in the same range as the pressures observed during the present study, were capable of producing large changes in permeability. The permeability changes in fractured material show two major characteristics: (1) they are stress dependant in magnitude and (2) the sign of the change (ie dilation or closure) is dependant upon the orientation of the stress.

Movement in fracture systems could affect water wells in two ways. First, if the well is completed in the fractured formation, well production would be directly affected by the change in apparant transmissivity resulting from the changes in the available void space. An indirect effect might be leakage between a perched aquifer and an underlying fractured formation.

Identification of fracture system orientation in the field is difficult, although Bell and Gough (1979) have developed a four armed dipmeter method that appears useful, and note in a recent article [Gough and Bell (1981) asserts] that in general, the long axis of a fracture system is perpendicular to the mountain front in Alberta, that is northeast to southwest.

Refraction P-wave data derived from the bedrock surface at all sites shows a strong northeast/southwest anisotropy in propagation velocity (table 9). The anisotropy is not consistant however, in that at three sites the velocity is lower along that axis, at two sites it is higher and at one it is intermediate (velocity increasing eastward). It might be argued that a water-filled fracture system would tend to lower P-wave velocities, hence the orientation of the fracture system could be mapped by using shotpoints located at the main compass points and plotting the resulting bedrock P-wave velocities on a rosette. The Gem and Wintering

Table 9

First Layer P-Wave Velocities

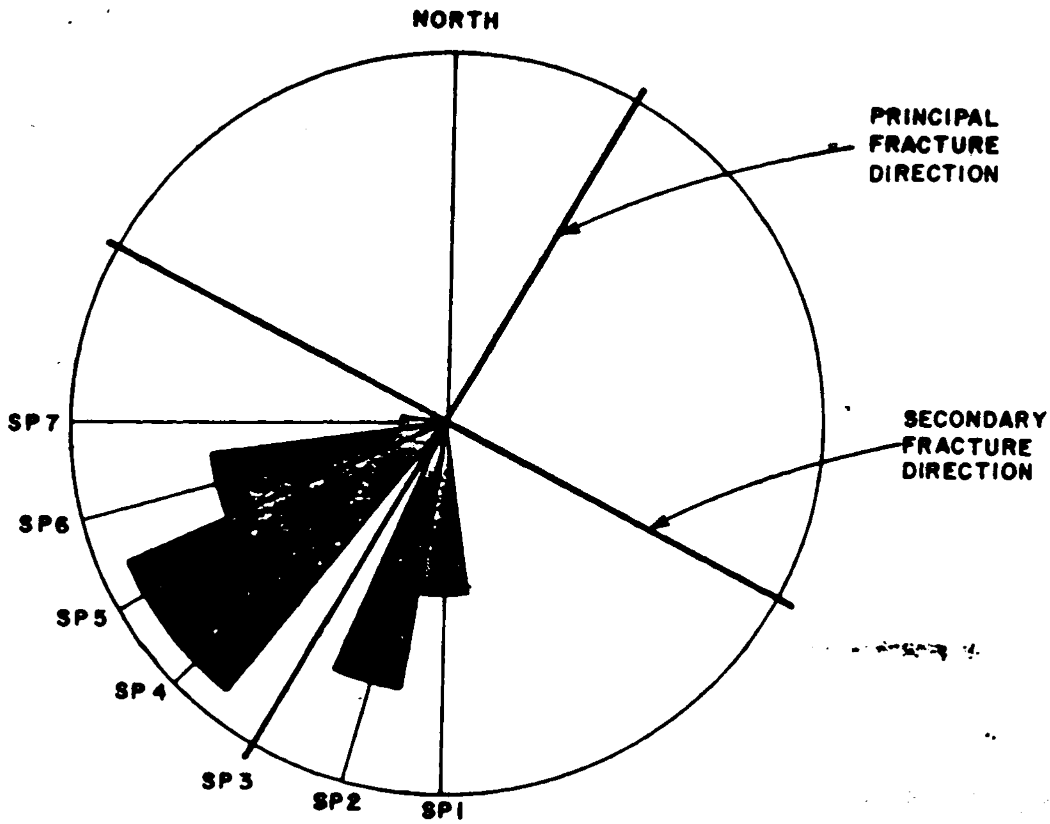
Site	SP#1	SP#4	SP#7	Well/SP Bearing
Brooks/EID	-	1,035	1,160	NE
Collins Creek	1,965	1,865	1,985	NE
Bonnyville	-	280	-	W
Vegreville	1,880	-	-	-
Norway	-	1,935	1,890	NE
Gem	2,090	2,180	2,020	SW
Wintering Hills	1,920	1,970	2,245	N
Caroline	2,365	-	-	-
Benalto	-	2,500	2,572	WNW

Hills sites represent single quadrants and are oriented differently, however when velocity data is plotted on rosette, strong Northwest/Southeast and Southwest/Northeast trends are evident, particularly when the data from both sites are plotted together (figures 21 through 24). These are in close accord with data presented in Gough and Bell (1981) in their figures 1 and 2 (reproduced here as figures 27 and 28). There was insufficient data from the other sites to establish trends, but the results are not inconsistent with the published data.

The small transmissivity changes at Gem and Wintering Hills could not be fully explained by changes in the material. If the velocity data accurately describes fracture orientation, an increase in fracture permeability could be expected at Wintering hills (all shotholes in the same quadrant as the primary joint set producing dilation and enhanced permeability) and also at Gem where the shot holes were in the same quadrant of the secondary joint set which would also enhance permeability, but to a lesser extent.

If the computed volume strains from the one dimensional stress analysis in table are correct for these sites, the additional transmissivity changes from fractured dilation, would be 4.7% at Gem and 15.1% at Wintering Hills.

The same analysis was attempted for the Benalto data. No data was available to the north or south of the well, however the 2500 m/s event was completely absent from the records from shot points 3 and 4. A 3,050 m/s event was observed from SP#3 alone and may be the bedrock refracted P-wave (Figure 24.) If there is a northeast to southwest



NOTE: ORIGIN AT 2000 m/s

SCALE

Alberta ENVIRONMENT

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DATE	CHECKED
APPROVED	DRAWN L.J.
DATE	CHECKED

BEDROCK SURFACE EVENT

GEM SITE

P-WAVE VELOCITY ANISOTROPY

SCALE AS SHOWN	SHEET OF
DATE SEPT. / 1981	FIGURE No. 23

MICROFILM DATE

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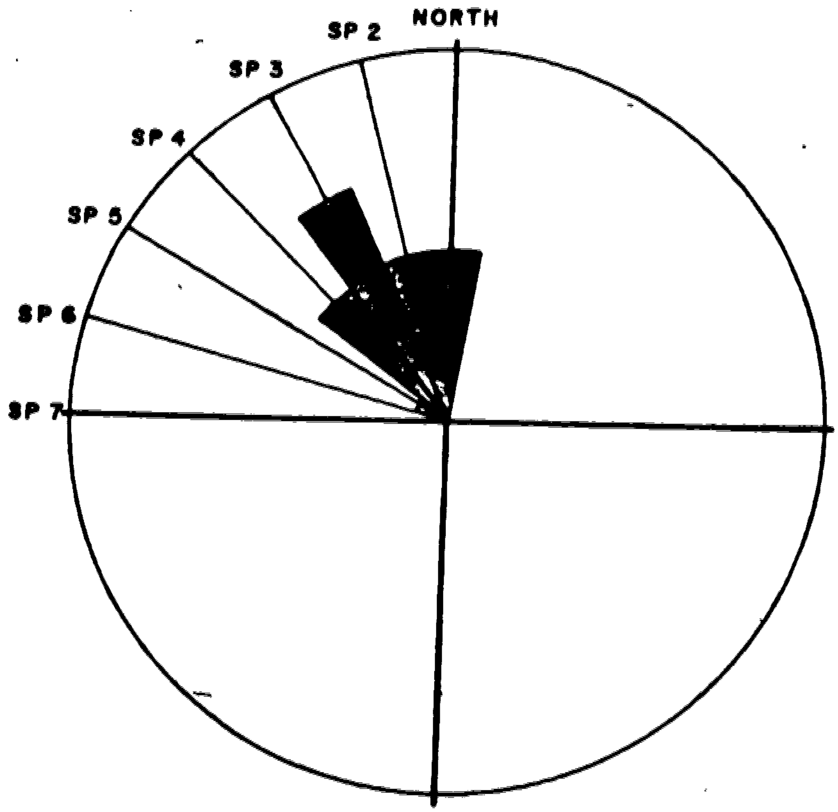

NOTE: ORIGIN AT 1800 m/s

1800 m/s — 2000 m/s — 2200 m/s

SCALE

Alberta

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APPROVED	DRAWN L.J.
DATE	CHECKED

BEDROCK SURFACE EVENT

WINTERING HILLS SITE
P-WAVE VELOCITY ANISOTROPY

SCALE AS SHOWN	SHEET OF
DATE SEPT / 1981	FIGURE No. 24

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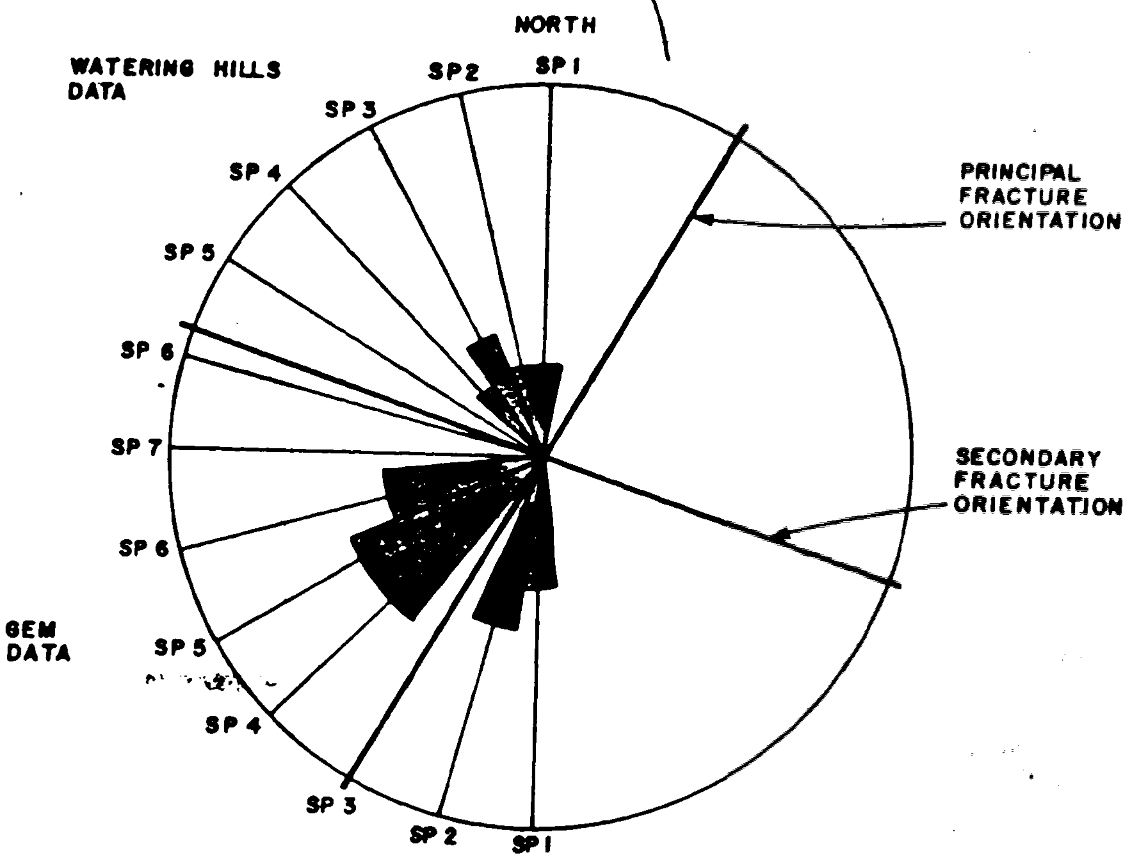

NOTE: ORIGIN AT 1800 m/s

1800 m/s 2000 m/s 2200 m/s

SCALE

MICROFILM DATE

DRAWING No

FILE No

Alberta ENVIRONMENT

SUBMITTED
DATE

APPROVED
DATE

DESIGNED D.T.S.
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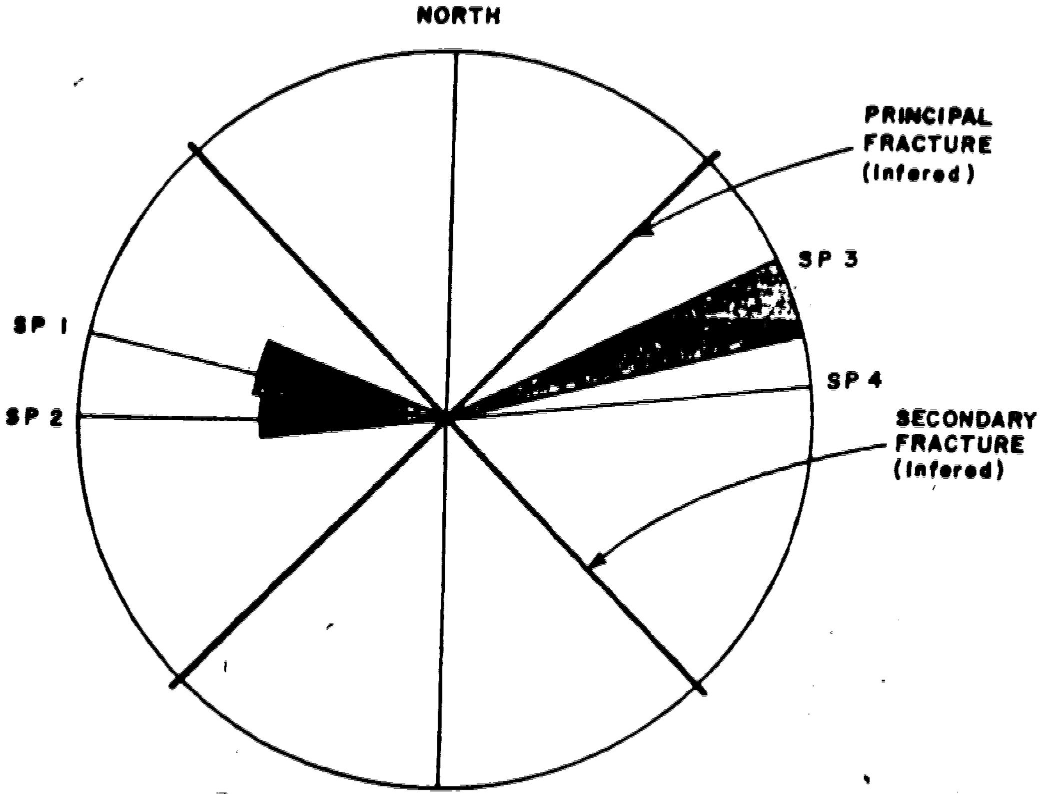
DRAWN L. J.
CHECKED

BEDROCK SURFACE EVENT

COMBINED GEM & WINTERING HILLS SITE
P WAVE VELOCITY ANISOTROPY

SCALE AS SHOWN
DATE SEPT./1981

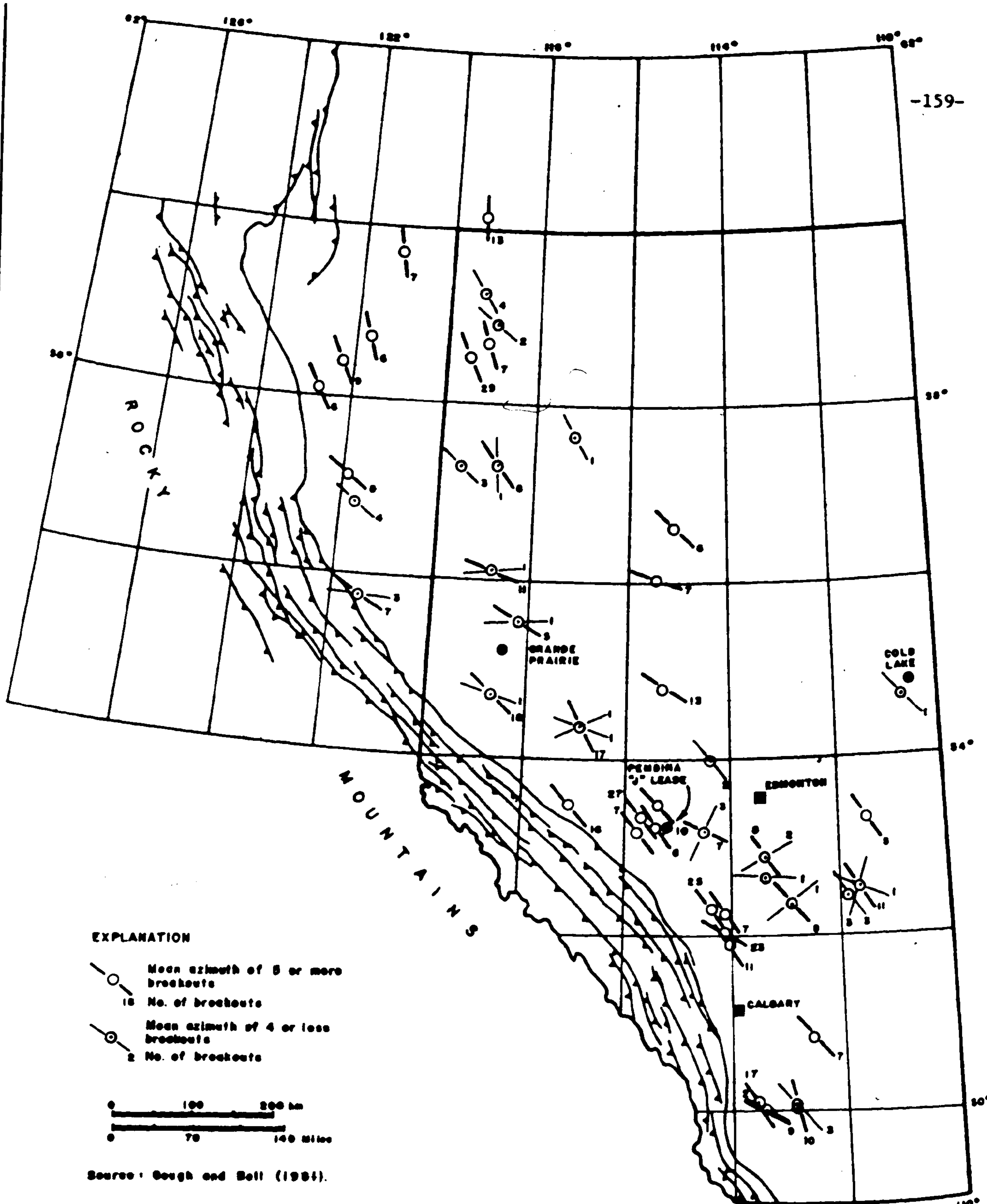
SHEET OF
FIGURE No. 26



NOTE: ORIGIN AT 2000 m/s

2000 m/s 2500 m/s 3000 m/s
SCALE

Alberta ENVIRONMENT	BEDROCK SURFACE. EVENT
	BENALTO SITE
SUBMITTED / DATE / DESIGNED B.T.G. / CHECKED	REFRACTED P-WAVE VELOCITY ANISOTROPY
APPROVED / DATE / DRAWN L.J. / CHECKED	SCALE AS SHOWN / SHEET
	DATE SEPT. / 1981 / FIGURE No. 26



Alberta		AZIMUTHS OF LONG AXES OF OIL WELLS CAUSED BY BREAKOUTS
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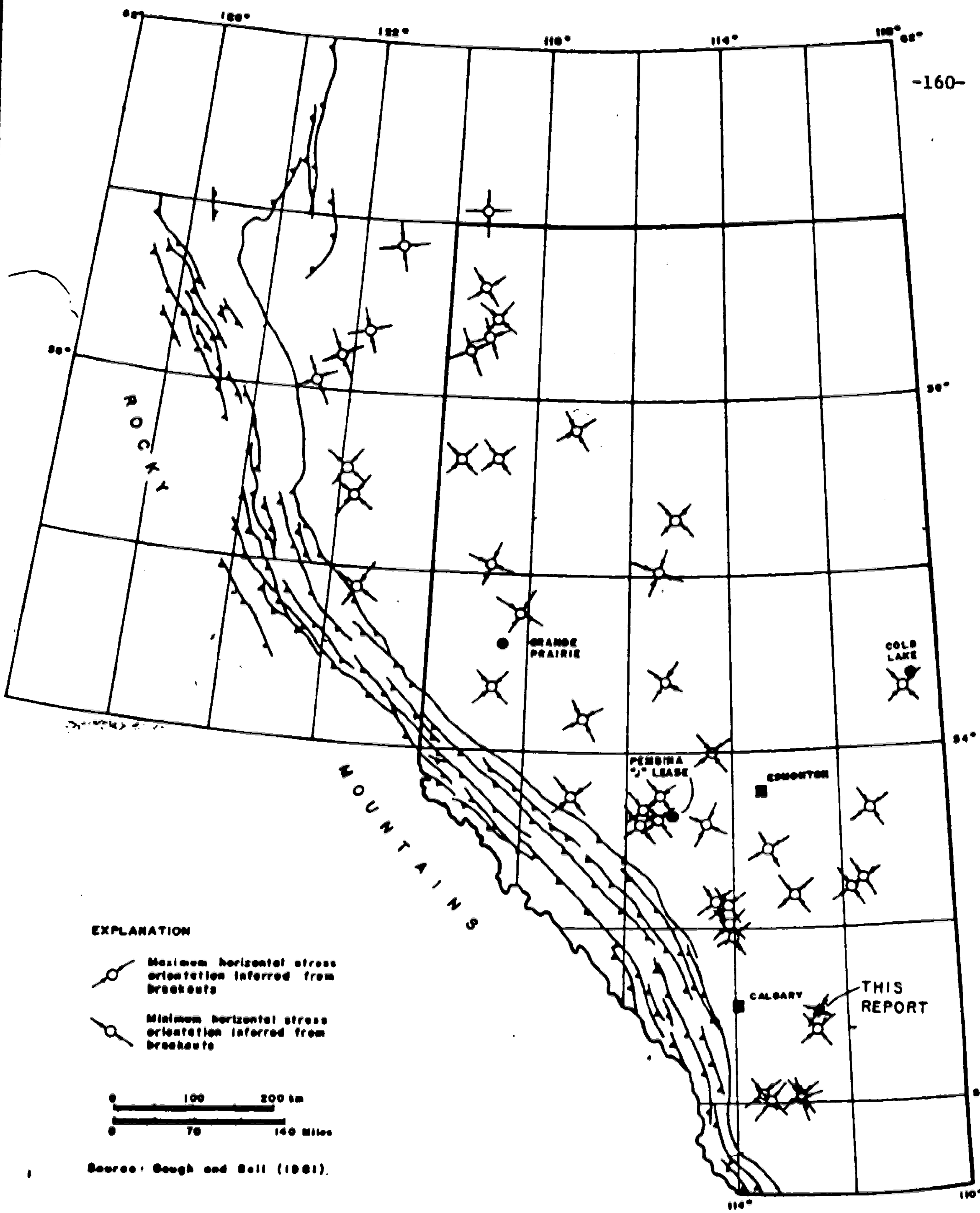
APPROVED / DATE	DRAWN L.J. / CHECKED	SCALE AS SHOWN / DATE SEPT. / 1981 — SHEET OF / FIGURE No. 27



Alberta

INFERED DIRECTION OF LARGE AND SMALLER HORIZONTAL PRINCIPAL STRESSES

SUBMITTED	DESIGNED	SCALE AS SHOWN
DATE	CHECKED	DATE SEPT. / 1981
APPROVED	DRAWN L.J.	SHEET OF
DATE	CHECKED	FIGURE No. 26

fracture system underlying the aquifer sand at this site, the shot points would have been arrayed exactly along the bisectrix of the intersection of the major and minor fracture system. The effect of this would have been to close the fractures in both directions, resulting in a reduction in apparant permeability. In fact, the largest reduction in transmissivity observed during the study occurred at this site (-28%). If pore volume reduction can account for -10% of the change, as much as a -18% transmissivity change may have been caused by fracture width reduction.

A major problem exists with the fracture mechanics argument proposed above in that four wells were not affected by regional fracturing. In the case of the New Norway site, Vogwill (1979) demonstrated that the drift and bedrock aquifers were not in hydraulic communication. Brooks/EID, Collins Creek and Caroline are all fine grained, Upper Cretaceous continental deposits with interbedded coal seams that are presumably subject to the same regional stresses as the other sites. The resolution of this conundrum is left to other investigations.

Bonnyville is a special case involving channel or gravity perturbed waves. The mechanics surrounding this problem are also left for future investigation.

V. CONCLUSIONS

A. DAMAGE TO WELLS FROM BLASTING

1. No major changes to well performance were observed during the study, although small consistent and cumulative changes to aquifer permeability occur red in response to blasting vibrations.

2. The two most probable mechanisms for permeability changes are volume changes in response to shear stresses and closure or dilation of fractures in response to normal stresses.

B. MINIMUM SAFE DISTANCE BETWEEN SHOTPOINTS AND WATERWELLS

1. No single distance can be considered safe under all circumstances. The energy attenuating properties of the ground between the shotpoint and the waterwell and both the orientation and sensitivity of the regional fracture system to impulsive stress appear to dictate the minimum safe separation.

2. Charge size is less of a determining factor in determining vibration amplitude than the peak borehole pressure generated during detonation. It would appear that for direct and refracted path waves, it requires a ten fold increase in charge weight to double the elastic wave amplitude. Channel or gravity perturbed wave propagation appears to follow a linear attenuation law since a doubled charge weight doubles the observed elastic wave amplitude.

C. ANALYSIS OF COMPLAINTS

1. Complaints referred to the Exploration Review Branch, Alberta Energy and Natural Resources, tend to be marginal cases in which physical changes to well behaviour alleged to have been caused by blasting are not clear cut.

2. It is possible that the conditions which could generate a complaint are different from those that could actually produce a water well failure. The experiments carried out during this study did not induce a failure and therefore the problem of separating these conditions remains unresolved.

VI. RECOMMENDATIONS

A. DAMAGE TO WELLS FROM BLASTING

1. A laboratory study of the effects of repetitive impulsive loading on the permeability of granular media to water under undrained triaxial stress should be carried out to establish whether this mechanism can cause hydraulic failure of an aquifer within the range of stresses observed by the present study (3 to 7 MPa peak overpressure).

2. Further field experimentation should be carried out to determine the influence of changes in fracture width on the apparent transmissivity of nearby water wells.

B. MINIMUM SAFE DISTANCE BETWEEN SHOTPOINTS AND WATER WELLS

1. There is no compelling reason to change the 180 m criterion presently in the Regulations. In those cases where damage is alleged however, the strain estimating procedured described in this study should be applied to determine whether enough energy reached the well intake to significantly affect transmissivity. Further, an attempt should be made to determine the magnitude of fracture permeability and fracture orientation with respect to the well and the line of shot points alleged to have caused damage.

2. The mechanism of long range propagation of seismic energy by formations acting as wave guides should be explored.

3. An analysis of existing data should be carried out to determine the importance of Rayleigh waves from seismic blasting with respect to existing United States Bureau of Mines and the National Research Concil of Canada Division of Building Research particle velocity based damage criteria.

4. Study should continue into the mechanism whereby energy is transferred from a blast to the surrounding formation in unconsolidated materials, in order to obtain a reliable estimate of the initial blast intensity without having to resort to field experimentation.

5. Exploration Inspectors should make every effort to obtain all available information on the characteristics and conditions surrounding both the well and the shot point for each complaint investigaton, including geological information.

C. ANALYSIS OF COMPLAINTS

1. A complaint survey of the type done in Chapter I should be carried out on a sample of industry complaint files to determine if there is any difference between complaints settled amicably amongst the parties concerned and those referred to the Exploration Review Branch for mediation.

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APPENDIX 1: TEST DATA

TABLE 1.1

SEISMIC/WATER WELL STUDY
FIELD DATA

SITE: BROOKS/EASTERN IRRIGATION DISTRICT

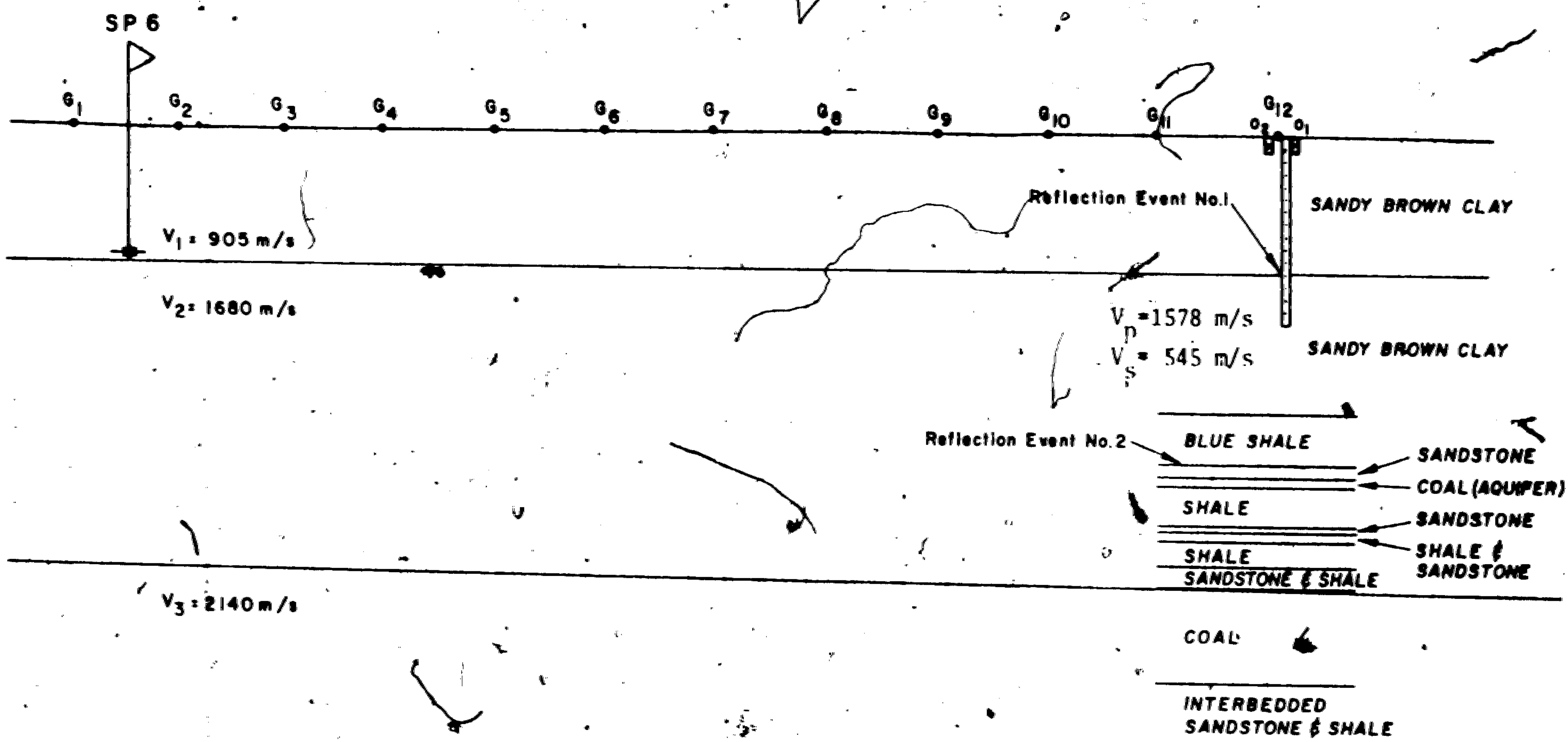
SP#	EXP (*)	WEIGHT (KG)	DEPTH (M)	DIST (M)	AMPLITUDE (DIG UNITS)	PRESSURE (MPA)	ARRIVAL TIME (SECONDS)	PHASE VELOCITY (M/S)
5	1	1.	20.	216.	9877760.	0.129	0.450	480.
7	1	1.	20.	180.	70156288.	0.913	0.148	1216.
6	2	1.	20.	190.	74727424.	0.973	0.148	1284.
6	1	2.	20.	190.	218090.	0.003	0.880	216.
7	2	2.	20.	190.	17623040.	0.229	0.894	213.

* 1= Geo-Gel
2= Geo-Mex

Table 1.2: Brooks/EID Site Pumping Test

Detonations	Remarks	Pumping Tests	
		Yield (m^3/day)	Transmissivity (m^2/day)
Prior to detonations	Water murky Water murky	21.0 18.7	0.95 0.85
Detonations (4 - 1 kg) 180 metres from well	No water level movement Water clear	19.6	0.89
Detonations (4 - 2 kg & 1 - 1 kg) 180 metres from well	No water level movement Water clear	18.2	0.83

Source: Goble (1980b).



Alberta

FIGURE 1.1

Scale: 1:100

BROOKS / E.I.D. SITE STRATIGRAPHY

TABLE 2.1

SEISMIC/WATER WELL STUDY
FIELD DATA

SITE: COLLINS CREEK

SP#	EXP (*)	WEIGHT (KG)	DEPTH (M)	DIST (M)	AMPLITUDE (DIG UNITS)	PRESSURE (MPA)	ARRIVAL TIME (SECONDS)	PHASE VELOCITY (M/S)
1	2	4.	20.	180	336035840.	4.375	0.224	804.
4	2	2.	18.	254	249692176.	3.251	0.150	1693.
7	1	2.	20.	180	301268992.	3.923	0.118	1525.
8	2	2.	20.	90	309035008.	4.024	0.166	542.
9	2	2.	20.	45	319979520.	4.166	0.154	292.
10	2	2.	20.	23	321126400.	4.181	0.232	97.
1	1	2.	20.	180	334200832.	4.351	0.246	732.

*1= Geo-Gel
2= Geo-Mex

Table 2.2: Collins Creek Pumping Test

Detonations	Remarks	Pumping Tests			
		Production Well		Observation Well	
		Yield (m^3/d)	Trans. (m^2/d)	Yield (m^3/d)	Trans. (m^2/d)
Prior to detonations	Rusty for 30 mins., then clear	25.1	25.2	25.0	22.2
	Rusty for 30 mins., then clear	25.7	23.8	29.4	23.5
First round of detonations (7-2 Kg)	Rusty for 60 mins., then clear	21.9	20.7	31.8	26.3
Second round of detonations (3-4 Kg)	Rusty for 25 mins., then clear	21.5	20.7	32.2	27.6
Third round of detonations (1-34 Kg)	Rusty & cloudy for 105 mins., then clear	17.2	16.9	31.2	26.3

Source: Goble (1980b)

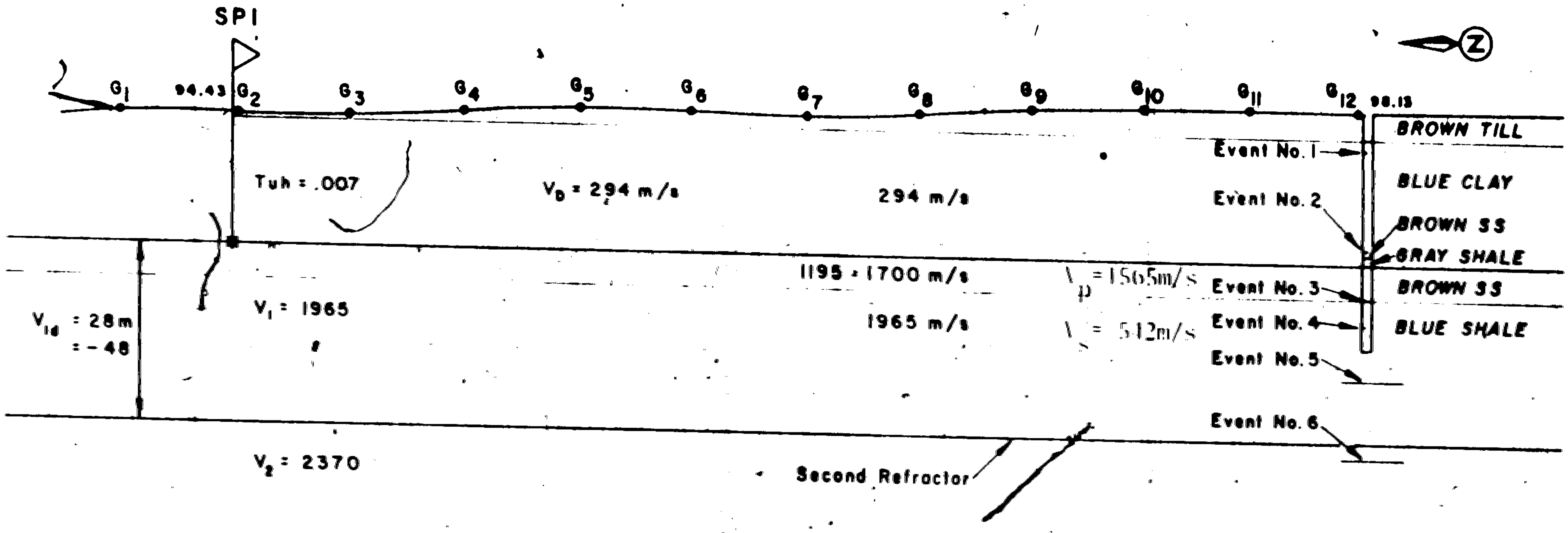


FIGURE 2.1

Scale 1:100

COLLINS CREEK
SITE STRATIGRAPHY

C. Bonnyville Site (NE-10-60-7W4)

1. Site Description

Situated on the William Wycenko property near the hamlet of Hoselaw, Alberta, the well used for geophysical observations was formerly used for domestic purposes and draws water from a sand and gravel aquifer at 19.8 m below ground level. The surrounding country is hilly and is believed to be an ice-thrust terrain by Dr. M. Fenton of the Alberta Research Council, who was mapping the Sand River Map Sheet at the time of writing. Dr. Fenton kindly provided test hole logs and laboratory data for his closest test hole (LSD1-9-60-7W4) to this site.

The shot points were located on an east-west line 3.2 Km south of the well, along a road allowance which follows the township line.

Stratigraphically, both the Alberta Research Council and the Wycenko Well driller's logs agree that there are two tills separated by an arenaceous interval that coarsens upward. The upper till is reported to be 65 feet (19.8 m) thick and the sand/gravel/silt layer is 23 feet (7.0 m) thick. The extent of the lower till is unknown. The water table outcrops approximately 100 m southeast of SP 6.

Shotholes drilled for the present project were all 20 m deep and were completed in sand.

2. Site Layout

The objective at this site was slightly different from the rest of the project, in that it was designed to determine (a) whether or not sufficient energy to be detected could be propagated over such a long distance; (b) if so, what its peak amplitude would be (i.e. how much attenuation would occur) and (c) what path would the peak arrival follow.

The recording site was located in the Wycenko farmyard and thus seismometer array geometry was governed to a large extent by the location of buildings, livestock pens and thorough fares. Further, highway 28A fronts the property and the possibility of highway noise had to be considered. It was decided to lay out the surface array parallel to the highway and surround the well with the omnidirectional phones at 0.75 m depth in the Brooks EID fashion. The #4R omniphone was placed inside the well against the concrete surface casing at the water surface. Hydrophones were arrayed in the normal fashion with the lowermost at the bottom of the well opposite the aquifer.

No radio controlled shooting system was available, so shots were timed to occur at fifteen minute intervals and the DFSIII internal time break was used to time arrivals. It was hoped that the wave travel time would be great enough to reduce human response differences to insignificance.

Clearly, the velocities computed from this field procedure are suspect. To obtain corroborating evidence, the first breaks from a line of 600% CDP conventional dynamite seismic data, shot along the road immediately east of the Wycenko property and tying the line of shotholes drilled for the project was obtained from Amoco Canada Ltd. This data was analysed to obtain drift velocities and interface depths. Figure 8.2 illustrates the relationship amongst site elements.

The results from a seismic monitoring program carried out east of Bonnyville by Dr. E. Kanasewich, Department of Earth and Planetary Physics, University of Alberta for Imperial Oil Ltd. were also obtained for the same purpose.

The observation well is the bored type, 1 m in diameter with concrete surface casing in the upper 10 m and wooden cribbing to total depth. It is an open hole completion. No log is available for the observation well, however one is available for a second, recently drilled well located approximately 100 m west.

Computation of the natural frequency of this structure was not attempted in that a rather more complex model would have to be designed. The size of the concrete portion suggests that it might act much as a house foundation might, in which case a resonant frequency in the order of 20 Hz would be expected.

2. Geophysical Results

Records were unexpectedly good and appeared about 12 seconds down the record, suggesting a P wave velocity of about 260 m/s if the first arrival is a direct ray, which the vertical array profile suggests it is. Activity on the longitudinal and transverse components of the omni phones suggests the second arrival is the shear wave associated with the primary. The wave train sequence, or coda, is repeated three times on each record, with the third set appearing to be the strongest. This same coda pattern was repeated for each shot.

Only a few of the Amoco records exhibit break-overs and thus a depth profile was not attempted. The lowest velocity observed from first breaks was 1,475 m/s and the highest 3,134 m/s. Shooting downhill to the slough, the average first break velocity was 1,923 m/s (Standard deviation 61 m/s over 23 records). In the vicinity of the slough, velocities increased to an average of 2,115 m/s (Standard deviation 280.3 m/s).

Shooting uphill from the slough, the average velocity was 1,983 m/s (Standard deviation: 96 m/s, n=25 records). West of the slough, the average velocity was 1,929 m/s (S.D.=34 m/s).

Velocities calculated from uphole times vary from 1,000 m/s to 2,000 m/s. From the top of the hill to the slough, the 1,000 m/s value is most common, while a mid range value persists in the vicinity of the slough. The 2,000 m/s velocity persists west of the slough. This data suggests a major change in drift characteristics occurs in the vicinity of the slough.

There is no evidence of a low velocity, high amplitude event on the Amoco line that corresponds to that observed on the records shot for the project, which implies that a blind zone exists somewhere in the section.

The maximum peak amplitude observed was 2.95 MPa from a 11.25 Kg burst. The other 11.25 Kg burst measured 2.74 MPa. The 4.5 Kg shots averaged 0.31 MPa, although the peaks were quite variable (see table 2.4.9.1).

Amplitude spectra were prepared for ambient noise and for one of the 4.5 Kg shots for comparison purposes. Most of the ambient noise at the bottom hydrophone appears in a band from 20 Hz to 70 Hz (maximum extent

0-100 Hz), while the signal spectrum is very narrowly defined around 15 Hz (maximum extent, 0-30 Hz). This appears to be consistent for all seismometers and for both vertical and horizontal polarization. The noise spectra for the longitudinal and transverse phones are distinctly different.

3. <u>Discussion</u>

The ray path is conjectural, however the character of the vertical array record (apparently infinite section velocity) suggests refraction, very possibly a channel wave. The 250 m/s average phase velocity is rather low for a channel wave (something approaching 1,400 m/s would be expected), suggesting a longer path than is measurable at the surface.

The aquifer stratigraphy tends to support this hypothesis as it is thin compared to a 12 Hz wavelength (λ=233 m, assuming a 1,400 m/s phase velocity; aquifer thickness = 9 m) and is bedded between tills, which are likely to have phase velocities that are around 1000 m/s.

A similar phenomenon was observed by Dr. E. Kanasewich (personal communication) at Ethel Lake, east of Bonnyville, while monitoring the level of natural and cultural microseismic activity of the area. He noted a series of regional events propagating to his surface array at velocities between 250 and 350 m/s with fairly high amplitudes which were similar to surface bomb bursts observed from the Cold Lake Canadian Forces Base, but which occurred in a different quadrant at times when no practice bombing was in progress.

Charge size is clearly an important factor at this range in that a tripling of charge weight increased signal intensity nine times.

TABLE 3.1

SEISMIC/WATER WELL STUDY
FIELD DATA

SITE: BONNYVILLE/HOSELAW

SP#	EXP (*)	WEIGHT (KG)	DEPTH (M)	DIST (M)	AMPLITUDE (DIG UNITS)	PRESSURE (MPA)	ARRIVAL TIME (SECONDS)	PHASE VELOCITY (M/S)
10	2	10.	10.	3168.	226754560.	2.952	12.700	249.
9	2	10.	20.	3165.	210173952.	2.736	12.100	262.
8	1	4.	20.	3150.	15337062.	0.200	11.400	276.
7	1	4.	20.	3136.	21358224.	0.278	11.000	285.
9	1	4.	100.	3168.	11655168.	0.152	12.700	249.
10	1	4.	200.	3165.	46645248.	0.607	12.100	262.

* EXPLOSIVE TYPE: 1= GEO-GEL, 2= GEO-MEX

Table 3.2: Bonnyville Site Pumping Test

Detonations	Remarks	Pumping Tests: Drilled Well — Yield (m^3/d)	Trans. (m^2/d)
Prior to detonations	Water clear	309.3	13.5
	Water clear	418.0	18.2
Detonations (.5 - 4.5 kg) 3 km from wells	Water clear	417.2	18.2

The Alberta Research Council determined that the pumping test data for the well was too erratic for an accurate calculation of results.

Source: Goble (1980b)

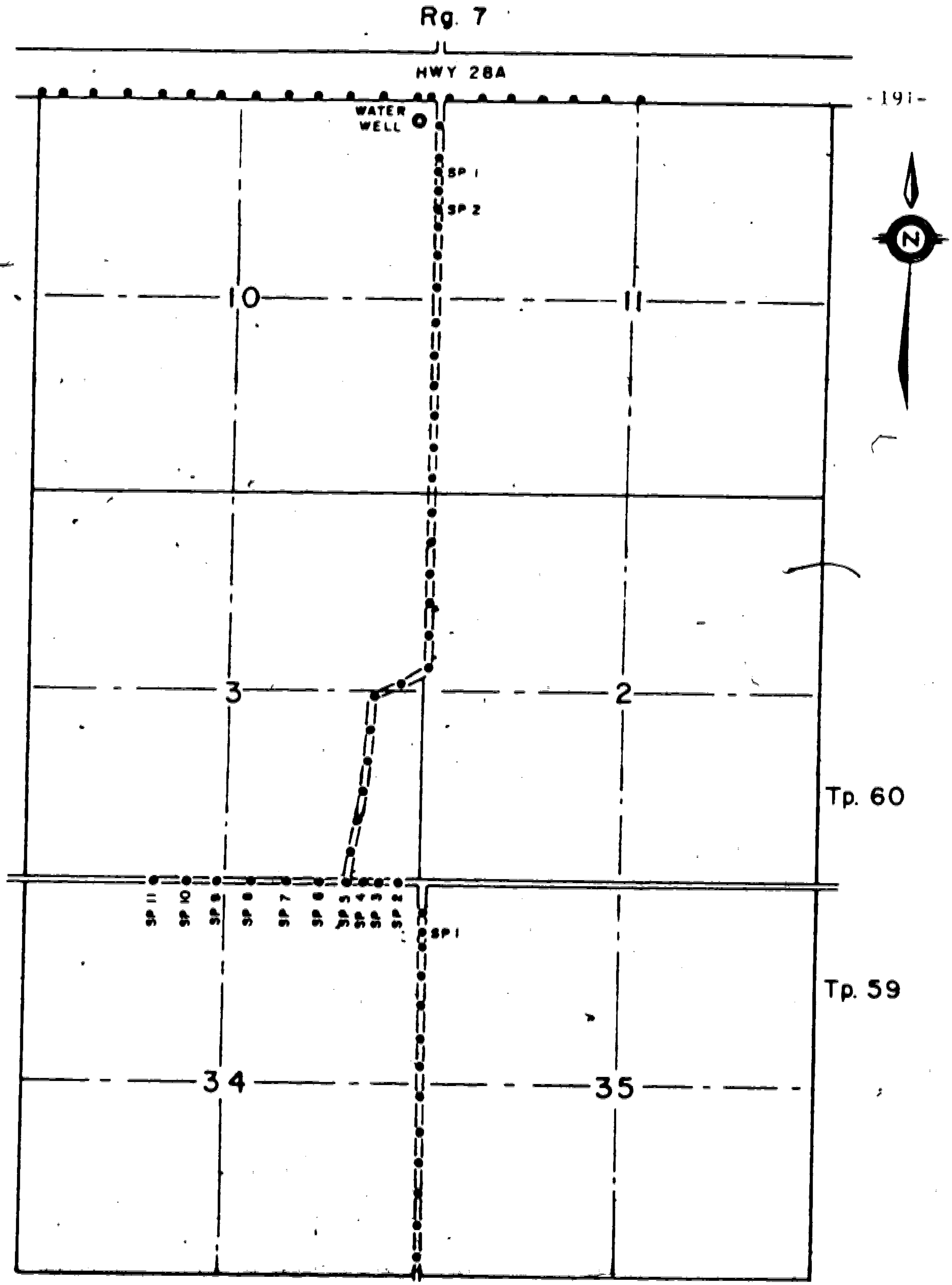


Figure 3.1

DATE OF SURVEY JULY 26 - 27, 1979

Alberta ENVIRONMENT

SEISMIC / WATERWELLS

BONNYVILLE SITES
SEISMIC TEST PATTERN LAYOUT

SUBMITTED	DESIGNED	SCALE 1" = 2 000'	SHEET 1 OF 1
DATE	CHECKED	DATE JUNE, 1980	DRAWING No
APPROVED	DRAWN SP		
DATE	CHECKED		

SEISMIC/WATER WELL STUDY
FIELD DATA

TABLE 4.1

SITE: VEGREVILLE

SP#	EXP (*)	WEIGHT (KG)	DEPTH (M)	DIST (M)	AMPLITUDE (DIG UNITS)	PRESSURE (MPA)	ARRIVAL TIME (SECONDS)	PHASE VELOCITY (M/S)
1	2	15.	34.	6.	354648064.	4.618	0.306	20.

*1= Geo-Gel
2= Geo-Max

Table 4.2: Vegreville Site Pumping Test

Detonations	Remarks	Pumping Tests	
		Yield (m^3/d)	Transmissivity (m^2/d)
Prior to detonations	Water murky for 120 mins.	10.2	0.58
	Water murky for 30 mins.	9.8	0.57
Detonation (1-15 kg) 15 metres from well			
Detonations (4 -2 kg) 180 to 360 metres from well	Water murky for 150 mins.	9.3	0.56

Source: Goble (1980b)

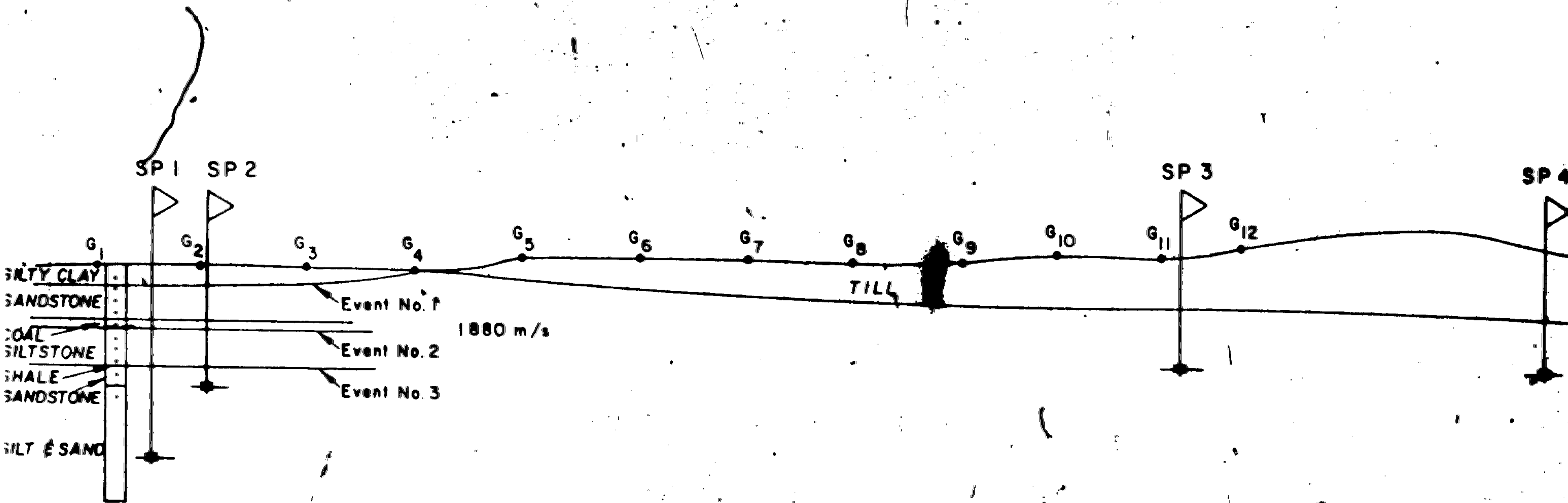


FIGURE 4.1

Scale: 1:100

VEGREVILLE
SW-13-53-14-W/4

TABLE 5.1

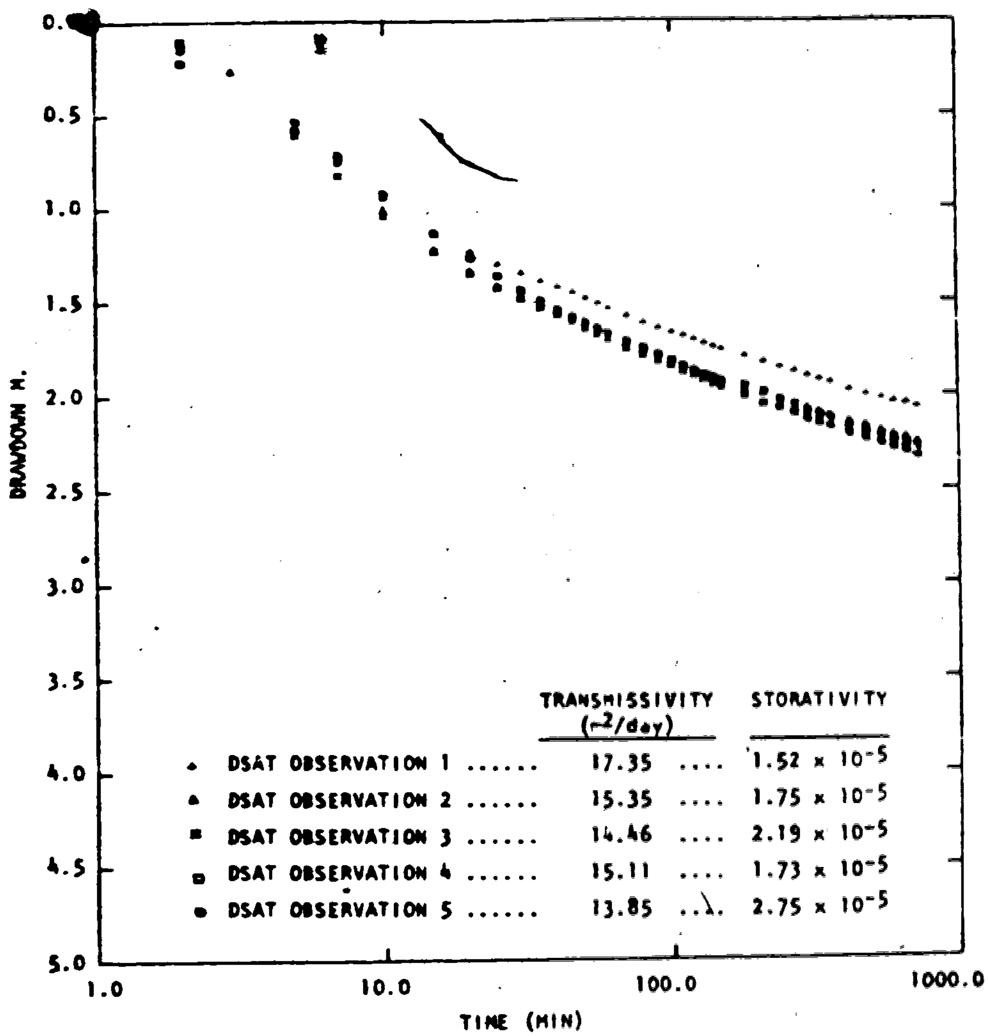
SEISMIC/WATER WELL STUDY
FIELD DATA

SITE: NEW NORWAY

SP#	EXP (*)	WEIGHT (KG)	DEPTH (M)	DIST (M)	AMPLITUDE (DIG UNITS)	PRESSURE (MPA)	ARRIVAL TIME (SECONDS)	PHASE VELOCITY (M/S)
3	1	2.	20.	183.	216563712.	2.820	0.808	226.
6	1	2.	16.	235.	309067776.	4.024	0.808	291.
2	1	6.	24.	23.	320929792.	4.179	0.514	45.
1	1	6.	24.	10.	370442240.	4.823	0.446	22.
6	1	2.	16.	235.	291622912.	3.797	0.222	1059.

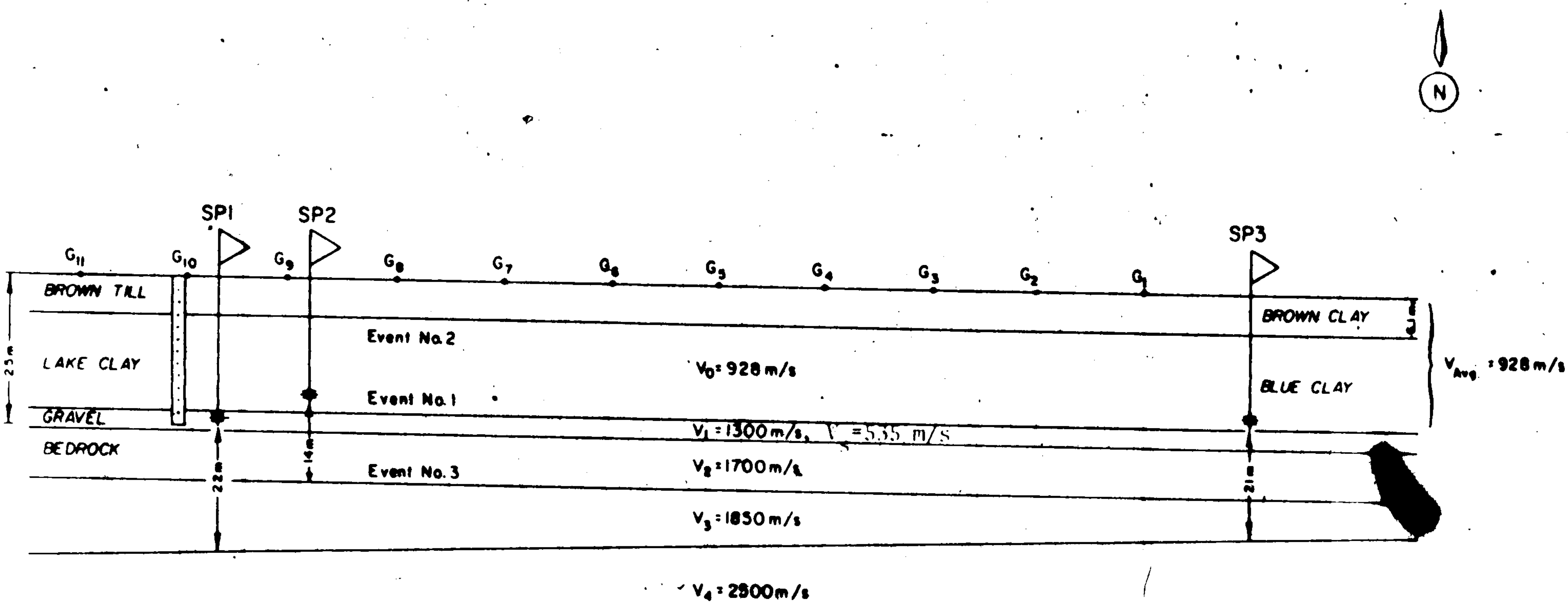
*1= Geo-Gel
2= Geo-Mex

Table 5.2: New Norway Site Pumping Test



Composite drawdown plots for DSAT observation well

Source: Vogwill (1979)

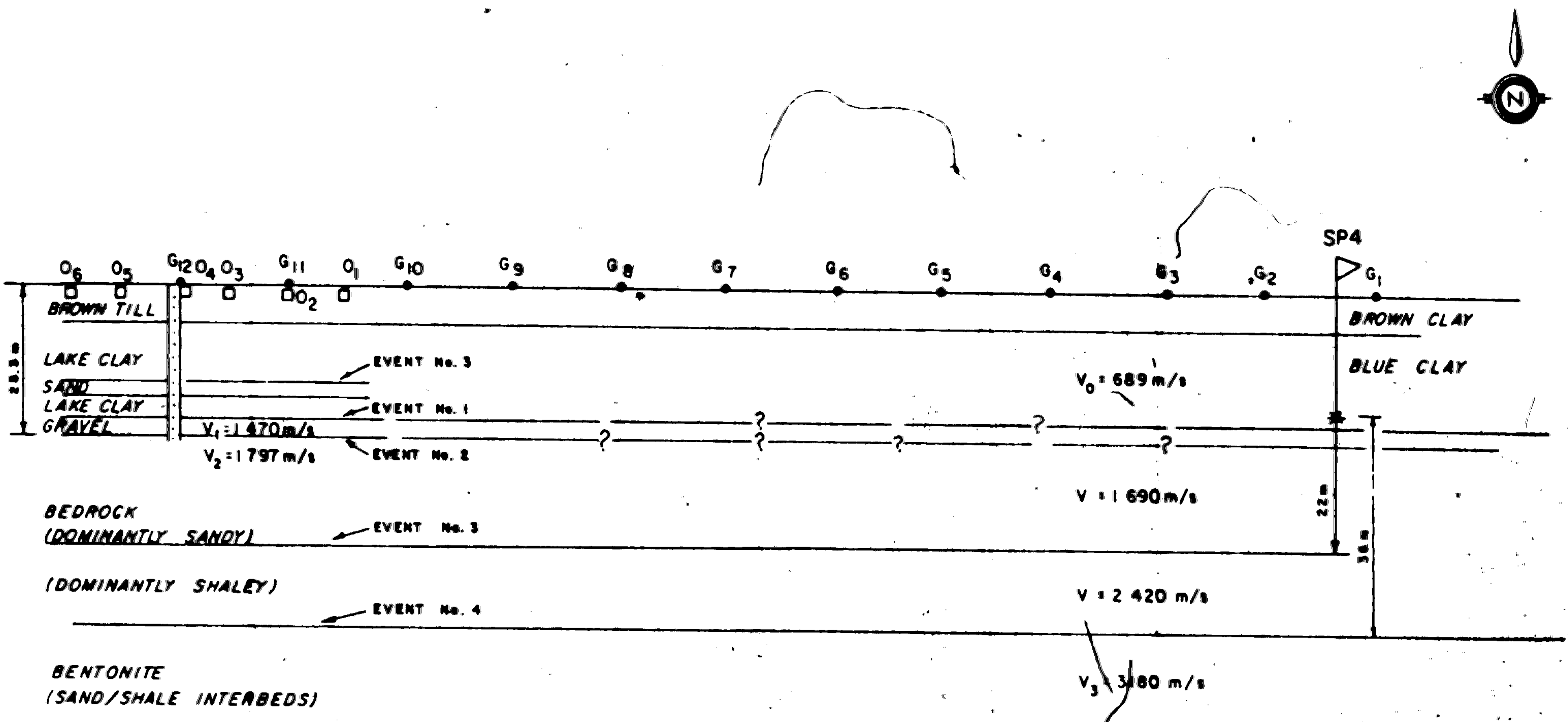


Alberta

FIGURE 5.1

Scale 1:100

NEW NORWAY SITE STRATIGRAPHY

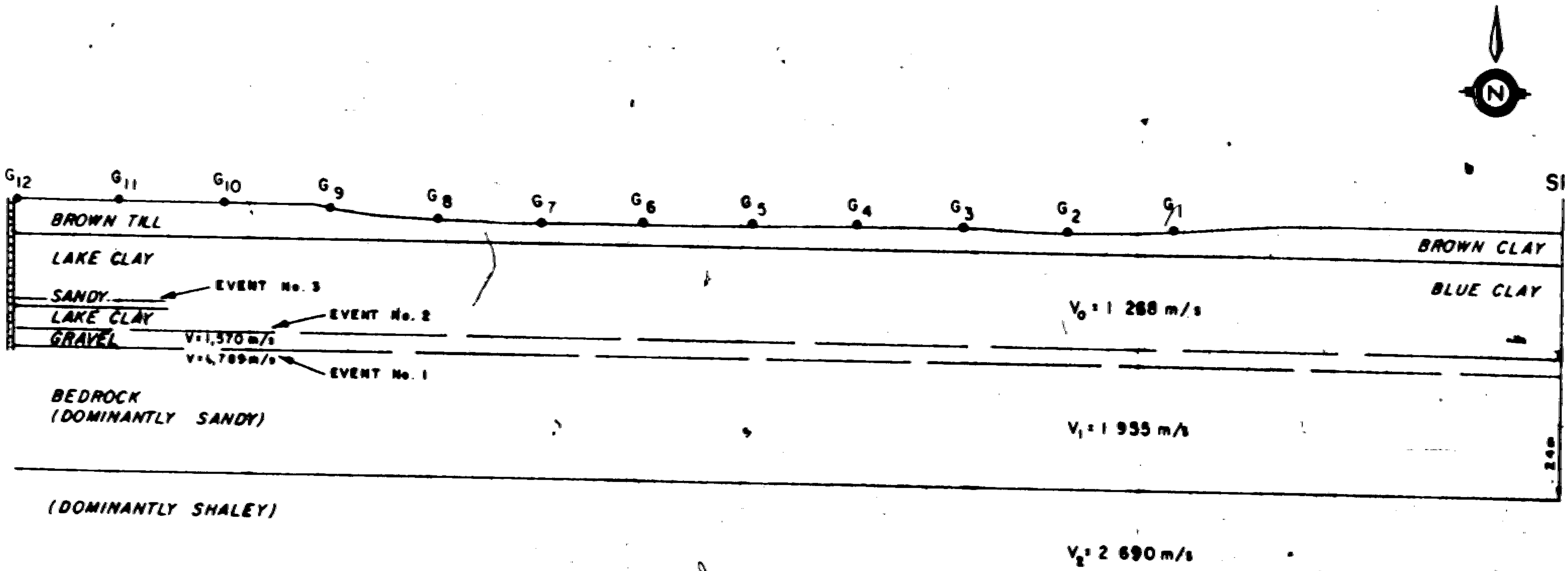


Alberta ENVIRONMENT

FIGURE 5.2

Scale 1:100

NEW NORWAY SITE STRATIGRAPHY



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Alberta ENVIRONMENT

FIGURE 5.3

Scale 1:100

NEW NORWAY SITE STRATIGRAPHY

TABLE. 6.1

SEISMIC/WATER WELL STUDY
FIELD DATA

SITE: WINTERING HILLS

SP#	EXP (*)	WEIGHT (KG)	DEPTH (M)	DIST (M)	AMPLITUDE (DIG UNITS)	PRESSURE (MPA)	ARRIVAL TIME (SECONDS)	PHASE VELOCITY (M/S)
1	2	1.	4.	180.	304087040.	3.959	0.062	2903.
2	1	1.	20.	190.	366215168.	4.768	0.076	2500.
1	2	6.	3.	180.	372768768.	4.853	0.134	1343.
1	1	1.	[illegible].	180.	335282176.	4.365	0.134	1343.
3	2	1.	20.	216.	335544320.	4.369	0.152	1421.
4	2	2.	15.	254.	287047680.	3.737	0.176	1443.
5	2	1.	19.	216.	332136448.	4.324	0.278	777.
6	1	1.	20.	190.	322699264.	4.202	0.210	906.
7	2	1.	20.	180.	336855040.	4.386	0.154	1169.
7	2	2.	15.	180.	351535104.	4.577	0.074	2432.
6	2	6.	15.	190.	375390208.	4.888	0.376	505.
6	2	2.	20.	190.	367001600.	4.778	0.378	503.
5	2	2.	20.	216.	366215168.	4.768	0.430	502.
5	2	2.	20.	216.	352583680.	4.591	0.164	1317.
5	2	4.	16.	216.	192937984.	2.512	0.086	2512.
2	2	4.	3.	190.	351272960.	4.574	0.396	480.
1	2	6.	3.	180.	372768768.	4.853	0.336	536.

*1= Geo-Gel
2= Geo-Mex

Table 6.2: Wintering Hills Site Pumping Test

Results Obtained From Semilogarithmic Data Plots

Test Number	Duration (min)	Pumping Rate (1/min)	Transmissivity drawdown (m^2/day)	Transmissivity recovery (m^2/day)	Storage Coefficient	Friction Losses at t = 20 min. (m)
WH 1 (pumping well)	360	87	207	207		0.35m
(observation well)	360	87	207	207	2.3×10^{-5}	0.12m
WH 2 (pumping well)	360	87	234	197		0.37m
(observation well)	360	87	207	207	2.1×10^{-5}	0.14m
WH 3 (pumping well)	360	87	207	207		0.36m
(observation well)	360	87	203	207	3.0×10^{-5}	0.12m
WH 4 (pumping well)	360	87	197	197		0.35m
(observation well)	360	87	203	203	1.8×10^{-5}	0.13m

Results Obtained By Curve Matching Techniques

Test Number	Type Curve (r/B)	Pumping Rate (1 min)	Transmissivity (m^2/day)	Storage Coefficient
WH 1	0	87	203	2.1×10^{-5}
WH 2	0	87	175	3.7×10^{-5}
WH 3	0	87	210	1.9×10^{-5}
WH 4	0	87	216	1.3×10^{-5}

Source: Prosser (1980)

Figure 6.1

REFRACTION PROFILES (DEPTH SECTIONS)
SEISMIC/WATER WELL PROGRAM
WINTERING HILLS SITE

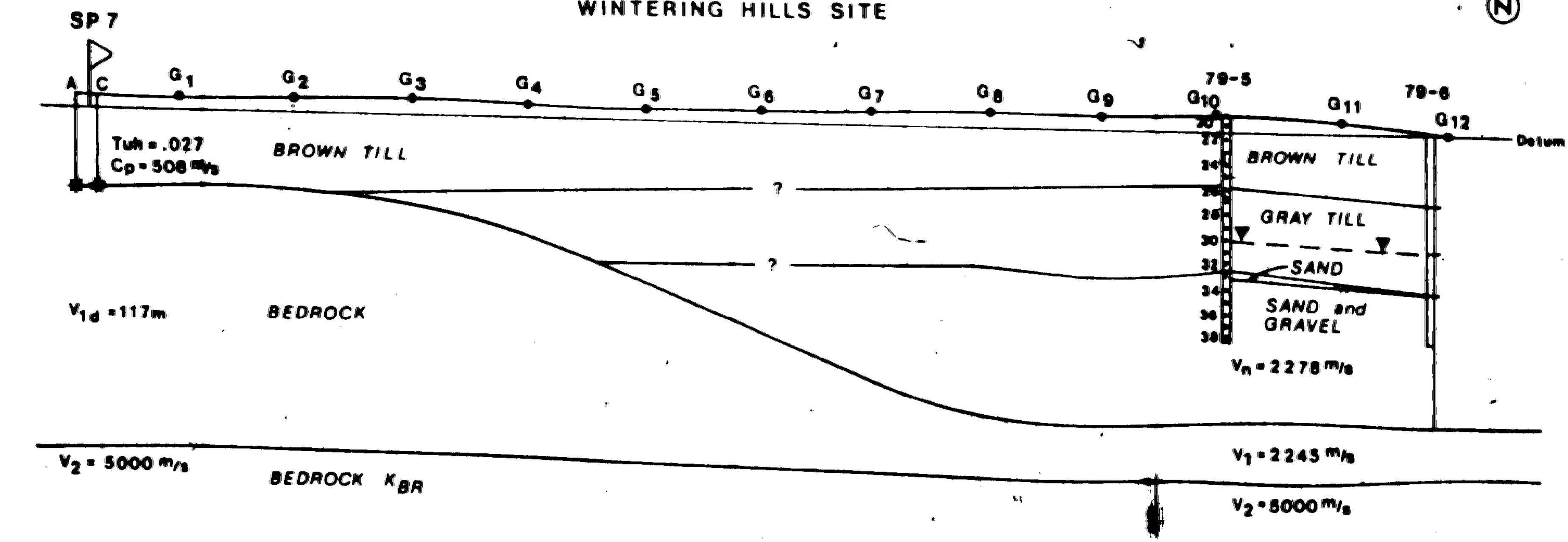


Figure 6.2

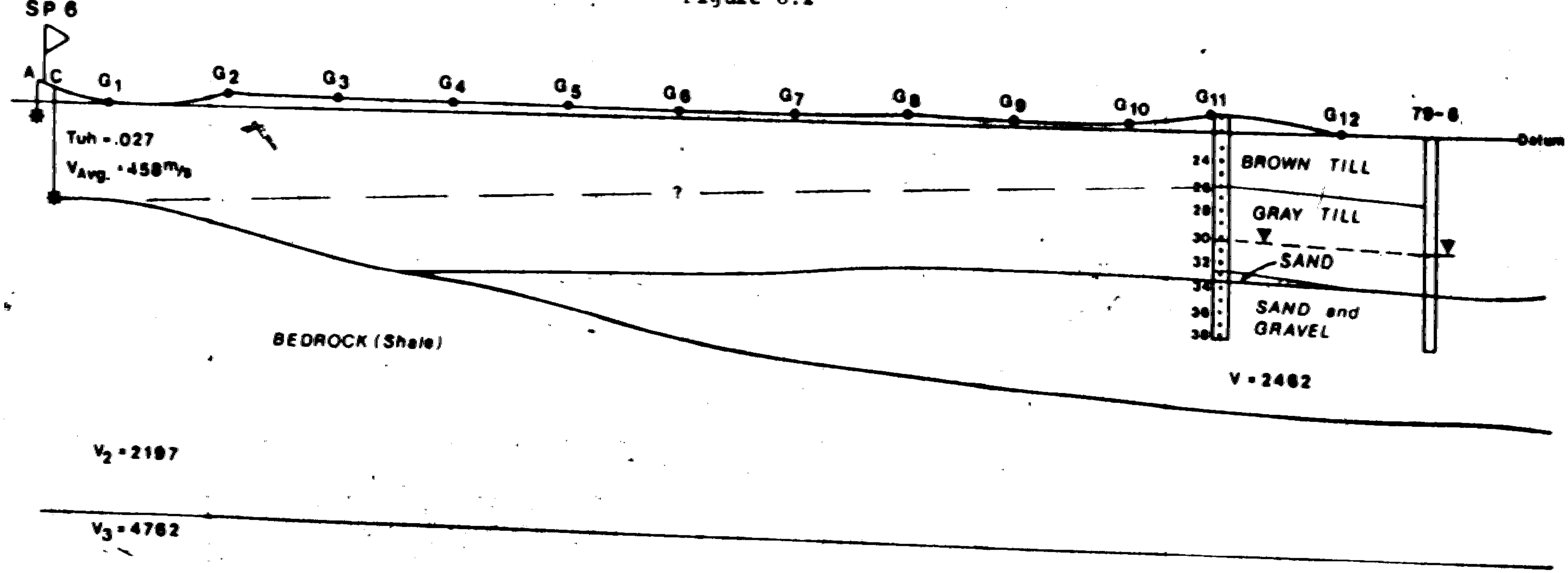


Figure 6.3: Wintering Hills Stratigraphy

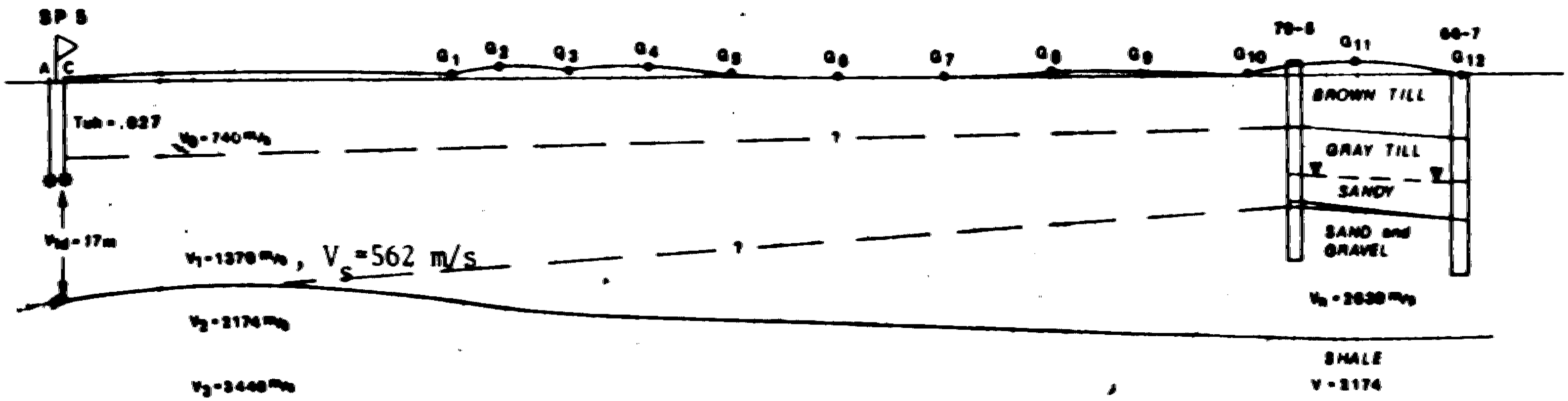
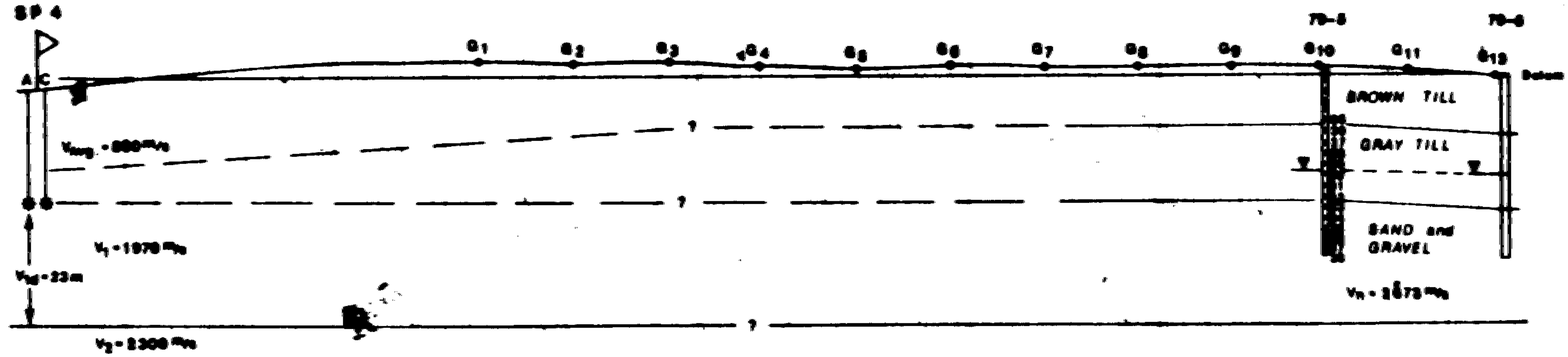


Figure 6.4: Wintering Hills Stratigraphy



SEISMIC/WATER WELL STUDY
FIELD DATA

TABLE. 7.1

SITE: CAROLINE

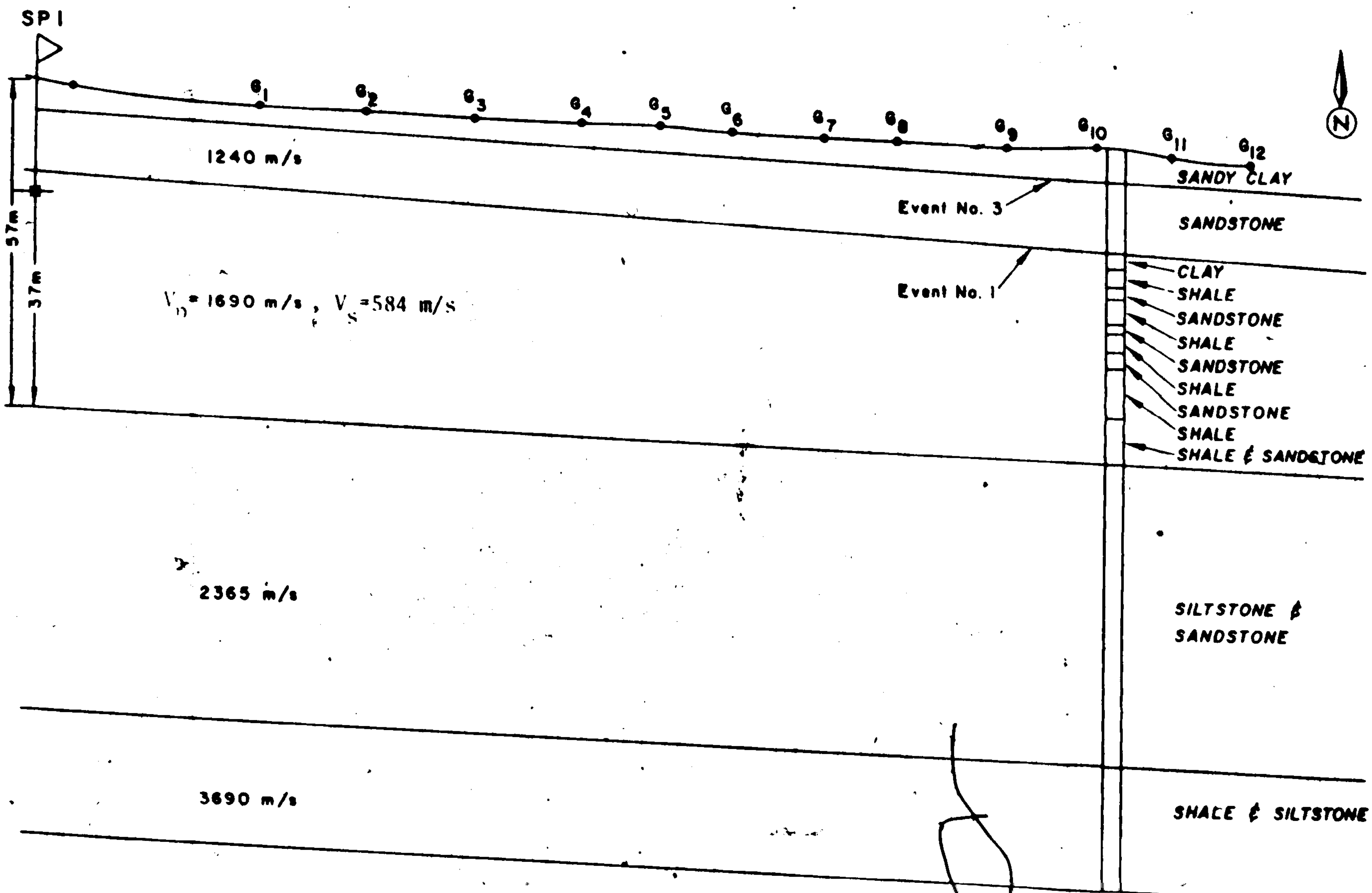
SP#	EXP (*)	WEIGHT (KG)	DEPTH (M)	DIST (M)	AMPLITUDE (DIG UNITS)	PRESSURE (MPA)	ARRIVAL TIME (SECONDS)	PHASE VELOCITY (M/S)
1	1	4.	20.	180.	408944640.	5.324	0.308	584.
2	1	4.	20.	182.	400975616.	5.221	0.308	591.

*Geo-Gel

Table 7.2: Caroline Site Pumping Test

Detonations	Remarks	Pumping Tests	
		Yield (m^3/d)	Transmissivity (m^2/d)
Prior to detonations	Silty for 90 mins.	10.1	0.87
	Silty for 70 mins.	9.4	0.78
Detonations (2-5 kg) 180 metres from well	Silty for 70 mins.	10.8	0.89
Detonations (1-5 kg) 60 metres from well	Silty for 40 mins.	9.7	0.84
Detonations (1-14 kg and 1-22 kg) 6 metres from well	Silty for 210 mins.	8.1	0.66

Source: Coble (1980b)



Alberta

FIGURE 7.1

Scale : 1:100

CAROLINE SITE
STRATIGRAPHY

TABLE 8.1

SEISMIC/WATER WELL STUDY
FIELD DATA

SITE: BENALTO (SYLVAN LAKE, GULL LAKE)

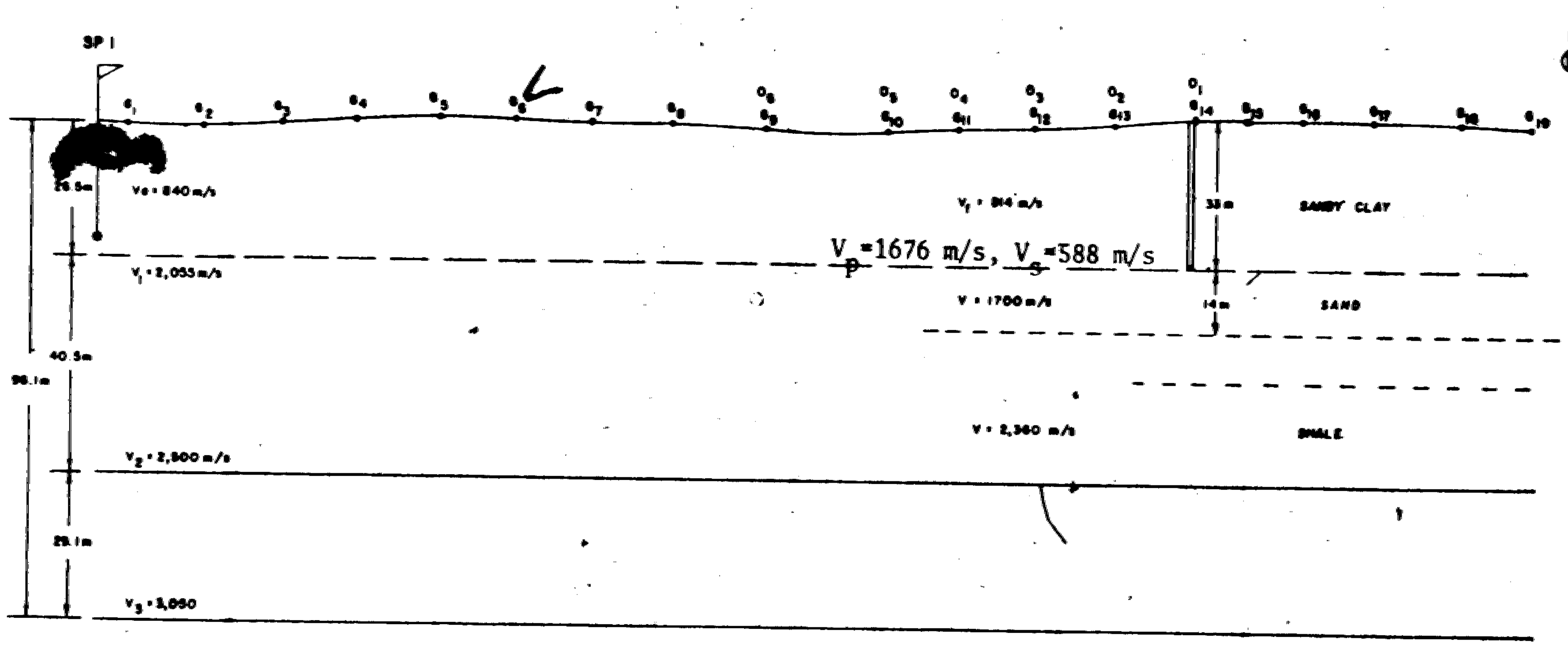
SP#	EXP (*)	WEIGHT (KG)	DEPTH (M)	DIST (M)	AMPLITUDE (DIG UNITS)	PRESSURE (MPA)	ARRIVAL TIME (SECONDS)	PHASE VELOCITY (M/S)
95 2	2	2.	18.	472.	146964480.	1.913	0.252	1873.
94 1	2	2.	18.	269.	536838144.	6.990	0.152	1770.
95 2	2	2.	18.	472.	245930624.	3.197	0.184	2568.
92 3	2	2.	18.	179.	263749632.	3.434	0.220	814.
914B	2	1.	18.	372.	25849856.	0.337	0.242	1537.
914C	2	4.	18.	372.	536870912.	6.990	0.222	1676.
923B	2	4.	18.	179.	472776704.	6.956	0.186	962.

*Geo-Mex

Table 8.2: Benalto Site Pumping Test

Detonations	Remarks	Pumping Tests	
		Yield (m^3/d)	Transmissivity (m^2/d)
Prior to detonations	Water clear	24.3	1.88
Industry Seismic Program Detonations decreased in distance to 180 m (using 1 kg detonations)	Farm owner reported sand in water	31.7	2.54
Detonation (4 - 4 kg, 3 - 4 kg, and 1 - 5 kg			
58 to 375 metres from well			
Final pumping test	Water clear	23.5	1.80

Source: Gohle (1980b)



Alberta
FIGURE 8.1
Scale : 1:100

BENALTO SITE STRATIGRAPHY

APPENDIX 2: GLOSSARY

A. HYDROGEOLOGICAL GLOSSARY

- SOURCE: BOND (1975) -

Anisotropic: Having physical properties that vary in different directions. In hydrology, permeabilities vary with direction within an aquifer.

Aquifer: (1) A geologic material that will yield water to a well in measurable quantities. (2) An aquifer is a water-saturated geologic unit that will yield water to wells or springs at a sufficient rate so that the wells or springs can serve as practical sources of water supply.

Artesian aquifer: An aquifer overlain by an aquiclude and containing water under artesian conditions.

Artesian water: Ground water under sufficient hydrostatic head to raise the water level above the upper surface of the aquifer.

Aquiclude: A formation which, although porous and capable of absorbing water slowly, will not transmit it fast enough to furnish an appreciable supply for a well of spring.

Capillarity: The action by which the surface of a liquid, where it is in contact with a solid (as in a capillary tube), is elevated or depressed. Synonym: Capillary attraction.

Capillary: A tube of extremely small bore.

Capillary attraction: The apparent attraction or repulsion caused by capillarity.

Cone of depression: A conical depression, on a water table or piezometric surface, produced by pumping.

Confined aquifer: (artesian aquifer) An aquifer in which the water is under greater than atmospheric pressure. The water in a well penetrating a confined aquifer will rise above the top surface of the aquifer, but does not necessarily flow at ground surface.

Depletion: The progressive withdrawal of water from surface- or ground-water reservoirs at a rate greater than the rate of replenishment.

Direct runoff: The water that moves over the land surface directly to streams promptly after rainfall or snowmelt.

Discharge, ground water: The process by which water is removed from the zone of saturation; also, the quantity of water removed.

Equipotential surface: A surface on which the potential is everywhere constant for the attractive forces concerned.

Evaporation: The process by which water is changed from the liquid or the solid state into the vapor state. In hydrology, evaporation is vaporization that takes place at a temperature below the boiling point.

Evapotranspiration: Water withdrawn from a land area by direct evaporation from water surfaces and moist soil and by plant transpiration.

Ground water: Water in the groundthat is in the zone of saturation, from which wells, springs, and ground-water runoff are supplied.

Ground-water reservior: An aquifer or a group of related aquifers.

Ground-water runoff: That part of the streamflow that consists of water discharge into a stream channel by seepage from the ground-water reservoir; same as base flow.

Ground-water system: The total dynamic occurrence of ground water from recharge to discharge. The subsurface segment of the hydrologic cycle.

Head: (hydrostatic head) The height of a vertical column of water, the weight of which, in a unit cross section, is equal to the hydrostatic pressure at a point.

Homogeneous: (1) Consisting throughout of identical or closely similar material, which may be a single substance or a mixture whose proportions and properties do not vary. (2) Of the same kind or nature; consisting of similar parts or of elements of like nature, opposed to heterogeneous.

Hydraulic gradient: Same as pressure gradient. As applied to an aquifer it is the rate of change of pressure head per unit of distance of flow at a given point and in a given direction.

Hydraulic pressure: Pressure exerted by a fluid against its container.

Hydrogeology: The study of the earth's water in relation to the geology of the earth.

Hydrograph: A graph showing changes in stage, flow, velocity, or other aspects of water with respect to time.

Hydrologic budget: An accounting of the inflow to, outflow from, and storage in a hydrologic unit, such as a drainage basin, aquifer, soil zone, lake, reservoir, or irrigation project.

Hydrologic environment: The size and configuration of ponds and streams, and the extent, boundaries, and water-bearing properties of aquifers.

Hydrology: The science that concerns study of all the waters of the earth.

Impermeable: Having a texture that does not permit water to move through it perceptibly under the head differences ordinarily found in subsurface water.

Infiltration: The flow of a fluid into a substance through pores and small openings. It connotes flow into a substance in contradistinction to the word percolation, which connotes flow through a permeable substance.

Isotropic: Having the same properties in all directions. In hydrology, the term refers to an aquifer in which permeability is the same in all directions.

Joints: Fractures or cracks in rock along which no appreciable movement has occurred.

Laminar flow: That type of low in which the stream lines or stream surfaces remain distinct from one another (except for molecular mixing) over their entire length.

Part per million: One milligram of solute in 1 kilogram of solution.

Percolation: Movement under hydrostatic pressure of water through interstices of the rock or soil, except movement through large openings such as caverns.

Permeability, coefficient of: The rate of water in gallons per day, through a cross section of one square foot under a hydraulic gradient of one foot per foot at a temperature of 60°F; also referred to as the field coefficient of permeability when the units are given in terms of the prevailing temperature of the water.

Piezometric surface: The surface to which the water in an artesian aquifer will rise under its full head; the potentiometric surface.

Porosity: The ratio of the aggregate volume of interstices in a rock or deposit to its total volume, expressed as a percentage.

Precipitation: As used in hydrology, precipitation is the discharge of water in liquid or solid state, out of the atmosphere, generally upon the land or water surface. It is the common process by which atmospheric water becomes surface or subsurface water. Precipitation includes rain, snow, hail, and sleet, and is therefore a more general term than rainfall.

Pressure gradient: Same as hydraulic gradient. As applied to an aquifer it is the rate of change of head per unit of distance of flow at a given point and in a given direction.

Recharge, ground-water: The process by which water is added to the zone of saturation; also the quantity of water added.

Reflection, seismic: (1) The returned energy (in wave form) from a shot that has been reflected back to a detector. (2) The indication on a record or reflected energy.

Refraction, seismic: The deflection of the direction of wave propagation when waves pass obliquely from one region of velocity to another.

Rock: Any naturally formed aggregate or mass of mineral matter, whether or not coherent, which constitutes an essential and appreciable part of the earth's crust.

Runoff: The water draining from an area. When expressed in inches, it is the depth to which an area would be covered if all the water draining from it in a given period were uniformly distributed on its surface.

Sedimentary rocks: Descriptive term for rock formed of sediment, especially (1) clastic roacks, such as conglomerate, sandstone, and shale, formed of fragments of other rock transported from their sources and deposited in water, and (2) rocks formed by precipitation from solution such as rock salt and gypsum, or from secretions of organisms, such as most limestone.

Seismic: Pertaining to, characteristic of, or produced by earthquake or earth vibration.

Seismograph: Instrument that records seismic waves, i.e., records movements or shock waves in the earth.

Seismology: A geophysical science that is concerned with the study of earthquakes and measurement of the elastic properties of the earth.

Soil moistues: Water diffused in the soil or in the upper part of the zone of aeration from which water is discharged by the transpiration of plants or by soil evaporation.

Specific conductance: The conductance of a cube of a substance one centimeter on a side, measured as reciprocal ohms or mhos. Commonly reported as millionths of mhos or in micromhos, at 25°C.

Specific retention: The ratio of (a) the volume of water retained in a saturated deposit against the pull of gravity to (b) the volume of the deposit.

Specific yield: The ratio of the volume of water drained from a saturated deposit by gravity to the volume of the deposit.

Steady state: Hydrologic term indicating that the water level in a well being pumped at a fixed rate stabilizes at some time (t) after pumping began, i.e., the water level does not change with time after an initial period.

Storage, coefficient of: The volume of water, expressed as a decimal fraction of a cubic foot, released from storage in a column of the aquifer having a cross-sectional area of one square foot and a height equal to the full thickness of the aquifer when the head is lowered one foot.

Transmissibility, coefficient of: The rate of flow of water in gallons per day, at the prevailing water temperature, through each vertical strip of aquifer one foot wide having a height equal to the thickness of the aquifer and under a hydraulic gradient of one foot per foot; also transmissivity.

Unconfined aquifer: (water-table aquifer) The upper limit of the aquifer is defined by the water table. At the water table (the top of the saturated portion of the aquifer) the water in the pore space of the aquifer is at atmospheric pressure.

Water table: The upper surface of the zone of saturation, except where the surface is formed by an impermeable body.

Water-table aquifer: An aquifer containing water under water-table conditions.

Water-table condition: The condition under which water occurs in an aquifer that is not overlain by an aquiclude and that has a water table.

Zone of aeration: The zone above the water table. Water in the zone of aeration does not flow into a well.

Zone of fracture: A zone below the ground surface where the rock has been extensively broken. In hydrology, zones of interconnected fractures may be sources of domestic and stock water.

Zone of saturation: The zone in which interconnected interstices are saturated with water under pressure equal to or greater than atmospheric.

B. GEOPHYSICAL GLOSSARY

- SOURCE: SHERRIFF (1968)

absorption; A process whereby the energy of a seismic wave is converted into heating of the medium through which the wave passes.

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.

acoustical impedance; Seismic velocity multiplied by density. Reflection coefficient depends on changes in acoustical impedance.

A/D = analog to digital.

AGC = Automatic gain control.

air wave: Energy from the shot which travels in the air at the velocity of sound: 1051 (1 + 0.00271T) ft/sec, where T = Fahrenheit temperature, or 331.3 (1 + 0.00366C) m/sec, where C = Centigrade temperature.

algorithm: A step-by-step procedure, usually for carrying out a numerical or algebraic operation, often followed in solving an inplicit equation.

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, $f_N + \gamma$, appears to have the smaller frequency $f_N - \gamma$. 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 every 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 bankds 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.

ammonium nitrate: A commercial fertilizer which becomes an explosive when mixed with oxidizer, usually diesel fuel. It is cheaper and safer than most explosives. After being mixed with the oxidizer and confined by tamping, it is detonated by the explosion of a primer. It is water-soluble and will not detonate if wet.

amplitude spectrum: Amplitude versus frequency relationship such as is computed in a Fourier analysis. See Fourier transform.

analog-digital converter: Device for converting analog signals into digital form.

AN/FO: Ammonium nitrate - fuel-oil mixture, used as an explosive.

anisotropy: Variation of a physical property depending on the orientation along which it is measured.

(a) In seismic usage, usually refers to any difference between velocity along the bedding plane and the velocity perpendicular to the bedding. Velocity along the bedding (as measured by refraction, for example) is typicall 10-15% higher than velocity measured perpendicularly in a well. This difference may be caused by selective orientation of the particles composing the rock.

(b) Anisotropy is sometimes (but not strictly properly) used to denote a difference between the velocity parallel and perpendicular to the bedding for an entire layered sequence. In such sequences the velocity parallel to the bedding appears greater because the higher-velocity members carry the first energy, whereas in measurements perpendicular to the bedding all members contribute in proportion to their thickness.

anti-alias filter: Filtering before sampling to remove undesired alias frequencies which a sampling system would otherwise pass. An anti-alias filter should provide linear phase response and nearly flat amplitude response over the signal pass band and roll off rapidly above the pass band to provide high attenuation above the Nyquist frequency.

apparent velocity: (1) The velocity with which a wavefront registeres on a line of geophones. (2) The inverse slope of a time-distance curve.

array: (1) A group of geophones connected to a single recording channgel of shot-points to be fired simultaneously, sometimes called a pattern or patch. (2) The arrangement or pattern of such a group of geophones or shotpoints.

arrival: A lineup of coherent energy signifying the passage of a wavefront; an event.

attenuation: (1) A decrease of signal magnitude during transmission. (2) A reduction in amplitude or energy without change of waveform. (3) The decrease in seismic signal strength with distance which does not depend on geometrical spreading but may be related to physical characteristics of the transmitting media causing reflection absorption and scattering.

auger: A drilling tool designed so that the cuttings are carried to the top of the hole continuously during the drilling operation by helical grooves on a rotating drill pipe. In the wet auger, fluid is injected at the bit to assist in the removal of cuttings.

average velocity: The distance traversed by a seismic pulse divided by the time required, both often corrected to a reference datum plane.

bandpass: Describing a range of frequencies between which transmission is nearly complete while signals at frequencies outside these limits are attenuated substantially. See also filter.

base of weathering: The boundary between the low-velocity surface layer and an underlying comparatively high-velocity layer. May or may not correspond to the geolocial base of weathering or to the water table. The boundary is involved in deriving time corrections for seismic records. See also weathering.

binary: Composed of two elements. Applies to the binary number system in which two digits, 0 and 1, are used to represent numbers, the position of the digits representing powers of two; thus, e.g., 11011 represents $2^4 + 2^3 + 2^1 + 2^0 = 16 + 8 + 2 + 1$ or the decimal number 27. Negative numbers may be represented by a minus sign or by codes such as the one's complement or two's complement codes.

binary digit = bit: The marks 0 or 1 used in the binary system.

bit: (1) A binary digit, the smallest unit of information. (2) A magnetized spot on a digital magnetic tape conveying a binary digit. (3) The element on the end of a drill pipe which actually does the cutting.

bit density = packing density: The number of bits per unit length of magnetic tape, normally measured in bits per inch (BPI).

black box: A unit or device whose basic function is specified but for which the method of operation is not specified.

blind zone: Hidden layer.

BPI = bits per inch: Refers to the spacing of bits along a single track on magnetic tape in the direction of motion.

break: Onset of an event, especially the first break. A burst of energy indicating the arrival of new energy. See time break and uphole time.

bridge: (1) An obstruction in a drill hole above the bottom of the hole, usually formed by caving, such as obstructs passage of drilling tools or the explosive charge. A bridge plug may also be set deliberately. (2) One of several types electrical networks containing one branch (the bridge) which connects two points of equal potential when a circuit is properly balanced. Used for measuring electrical impedance. (3) A jumper of wire used to short-circuit around an electrical circuit.

broad-side: (1) A reflection shooting arrangement in which the shotpoint is appreciably (more than say two hundred feet) outside the line of the spread. Also called L spread or T spread, depending on whether the shotpoint is opposite one end or the center of the spread. (2) A refraction shooting technique in which the spread is perpendicular to the line connecting it with the shotpoint. The shot-to-spread distance is usually kept nearly constant.

buffer: An intermediate storage device which accommodates differences between the rate at which information is fed into a computer and the rate at which the computer can receive it, or which performs the same function for information at the computer output.

byte: A portion of a digital tape word consisting of several bits (as those across the width of a tape) manipulated as a unit. See also character.

C

cable: The assembly of electrical conductors used to connect the geophone or hydrophone groups to the recording truck. See also streamer.

camera: A recording oscillograph used to produce a visible pattern representing electrical signals, or to make the visible seismic record, usually on photosensitive paper or film.

cap: A small explosive designed to be detonated by an electrical current and which in tern detonates another explosive.

casing: Tubes or pipes used to line shotholes to keep them from caving in. Usually made in tenfoot lengths which screw together.

CDP = common depth point.

CDPS = commong depth point stack.

channel: (1) A single series of interconnected devices through which geophysical data can flow from source 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 problem. (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. See also byte, with which it is sometimes used interchangeably.

charge: The explosive combination used for a seismic shot, specified by the weight and type of explosive and sometimes by its length.

check shots: Shots in a well seismometer (see well shooting) to check the results of integrating a continuous velocity or sonic log.

clipped: Having seismic-wave amplitudes in excess of a certain amount removed, usually by saturation in some element of the recording system, resulting in distortion of the waveform.

coherence: (1) The property of two wave trains being in phase. (2) A measure of the similarity of two time functions or portions of functions. If the functions have power spectra, P_{ii} and P_{jj}, and cross-power spectra, P_{ij}, their coherence is:

$$P_{ij}/\sqrt{P_{ii}P_{jj}}$$

Coherence is the concept in the frequency domain analogous to correlation in the time domain.

coherent: The aspect of all members mvoing together or with similar phasing; specifically, all traces of a seismic record moving in a systematic fasion. Coherence is the principal evidence of an event. See Figure 2.

common depth point = CDP: The situation where the same portion of subsurface produces reflections at different offset distances on several profiles. See common-depth-point shooting.

common-depth-point-shooting: The shooting technique designed for multiple subsurface coverage so as to record seismic data from which a common-depth-point stack is made. Different shotpoint-geophone combinations are used so that reflections are recorded on several profiles for essentially the same depth points. Also called "roll-along."

common-depth-point-stack: A composite of traces which correspond to the same subsurface reflection point but which are from different profiles and have different offset distances. The records are corrected for statics and normal moveout before stacking. The objective is to attenuate random effects and events whose dependence on offset is different from normal moveout. Hence multiple reflections which have a different apparent average velocity from primaries, surface waves, refractions, diffractions, etc. will be attenuated relatively to primary reflection events. Also called roll-along and horizontal stacking. Petty Geophysical Engineering Company patent.

compositing = mixing: Combining the energy of different channels without first applying static and NMO corrections.

compressional wave = P wave = dilational wave = longitudinal wave: An elastic body wave in which particle motion is in the direction of propagation. The type of seismic wave assumed in conventional seismic exploration.

conductivity: A measure of the ease with which current can be driven through a material; the reciprocal of electrical resistivity.

continuous profiling: A seismic method in which geophone groups are placed uniformly along the length of the line and shot from holes so spaced that continuous (or 100%) subsurface coverage is obtained. See Dobrin, p. 111.

continuous velocity log = CVL: A log of formation velocity against depth (like a sonic log) measured in a well.

contour: Line connecting points of equal value, or representing the locus of a constant value of a quantity, on a map or diagram.

contour interval = C.I.: The difference in value between two adjacent contour lines.

convolution: The change of wave shape as a result of passing a signal through a linear filter. If the input function is S(t), then the output, O(t), will be given by the convolution operation:

$$O(t) = S(t) * F(t) = \int_{\infty}^{\infty} S(\tau)\ F(t - \tau)\ d$$

where F(t) is the impulse response of the filter, or its response to an impulsive input. The input can be thought of as a series of impulses of varying size, each of which will generate an F(t) of proportional magnitude, and the output as the superposition of these. The output at the time 5 can also be found by (a) reversing one function in time, (b) time shifting by τ, (c) multiplying and (d) summing for all τ. For equally sampled (digital) data:

$$O = S * F = \sum_{k=0}^{L} S_{t-k}\ F_k$$

L is the convolution operator length in time divided by the sample interval, or L + 1 is the operator length in number of points. The equivalent operation in the frequency domain involves multiplying the frequency-amplitude curves and adding the frequency-phase response curves.

correlation: (1) Identifying a phase of a seismic record as representing the same phase on another record. Indicating that events on two seismic records are reflections from the same stratigraphic sequence, or refractions from the same marker. (2) The degree of linear relationship between a pair of traces; a measure of how much two traces look alike or the extent to which one can be considered a linear function of the other. The time-domain concept analogous to coherence (in the frequency domain). See autocorrelation and crosscorrelation.

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 (see Figure 6): (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.

crossover distance: The distance at which refracted waves following a high speed deep marker overtake refracted waves following a shallower lower speed marker. In early seismic prospecting, emphasis was placed upon observations of and deductions from crossover distances. See also critical distance.

cross-section: A plot of seismic events. See plotted section.

curved path: A seismic raypath that is curved because refraction results in corresponding changes in the direction ot the ray, as velocity (or, strictly, acoustic impedance) changes continuously with depth. Increase in velocity with depth makes the ray path concave upward. In curved path conputations and plotting, account must be taken of the change in velocity with depth.

<u>cutoff</u>: The frequency at which a <u>filter</u> response is down by a predetermined amount, such as 3 db or 6 db. The cutoff points designate the filter; e.g. an 18-57 filter has a low frequency cutoff at 18 cps and a high frequency cutoff at 57 cps.

<u>CVL</u> = continuous velocity log.

D

<u>D/A</u> = digital to analog.

<u>damping</u>: Resistance which slows down or opposes oscillations. <u>Critical damping</u>, μ_c, is the minimum damping which will prevent oscillation from taking place. For a mass, m, subject to a restoring force with a force constant, k:

$$\mu_c = 2\sqrt{km}$$

The damping factor, μ, is the ratio of the system friction to that necessary for critical damping, or the quotient of the logarithm of the ratio of two successive oscillations if the system is underdamped. The damping factor is one for critical damping, less than one for an underdamped system (which will tend to oscillate), and greater than one for an overdamped system. Increased damping shifts the peak response toward higher frequencies. Most geophones are slightly underdamped, often having "optimum damping" which is 0.66 μ_c.

<u>datum</u>: (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.

<u>db</u> = decibel.

<u>db/octave</u>: Unit for expressing the slopes of curves in which parameters such as filter curves are plotted vs. frequency.

<u>decibel</u> = db: A unit used in expressing power or intensity ratios: 20 $\log_{10}$ of the amplitude ratio, or 10 $\log_{10}$ of the power ratio. An amplitude ratio of 2 (which represents a power ratio of 4) is equivalent to 6 db.

<u>deconvolution</u>: (1) The process of undoing the effect of another filter. An <u>inverse filter</u> is designed and convolved with the signal, the objective being to <u>nullify</u> an objectionable effect of some earlier filter action. (2) More specifically, deconvolution may mean:

(a) Dereverberation or desinging, removing the filtering action of a water layer. See also <u>gapped deconvolution</u>.

(b) Removing the filtering action of a more complex near-surface.

(c) Deghosting.

(d) Whitening or equalizing all frequency components within a bandpass in order to shorten the reflection pulse length.

(e) Removing multiples.

(f) Shaping the amplitude-frequency and/or phase response to match that of adjacent channels.

(g) Shaping the response to certain specifications, such as the matched filter of a particular wavelet.

(h) Predictive deconvolution.

Deconvolution results may vary markedly with different phase assumptions or a different gate or operator length in the filter design.

delta function = an impulse:

delta t = Δt = moveout: (1) The time difference between the arrival times at different geophone groups. (2) The time difference between groups at maximum offset on opposite sides of a summetrical spread or opposite ends of a single-ended spread corrected for normal moveout. The moveout is interpreted in terms of the component of geological dip in the plane of the section barring lateral changes of velocity. See dip calculation. (3) Sometimes used for the sum of dip delta t as in (2) and normal moveout. (4) Also used in connection with refraction and other traveling events.

density = mass per unit volume: Commonly measured in gm/cc, often without the units being expressed explicitly.

density contrast: The difference in density between two formations.

depth point: The position at which the depth of a horizon has been calculated, generally midway between shotpoint and geophone for seismic reflections.

depth probe: A group of a few test refraction profiles designed to obtain information on the layering pattern in an area. Approximate depths and velocities of refraction markers thus obtained are used to ascertain the nature of the stratigraphic section. Also called "refraction test."

detector = geophone.

detonator = cap.

digital: Representation of quantitities in discrete units. A digital system is one in which the information is contained and manipulated as a series of discrete numbers, as opposed to an analog system, in which the information is represented as a continuous flow of the quantity constituting the signal.

digital to analog = D/A: Conversion of a digital (usually binary) number into a corresponding voltage.

digitize: To sample a continuous voltage at discrete regular time intervals, quantize the measurements, and record the values as a sequence of numbers in bit combinations on magnetic tape.

dip: The angle which a reflector or a refractor makes with the horizontal.

Dirac function = delta function = impulse.

directional charge: An explosive charge or charge array in which the explosion front travels at approximately the seismic velocity, so that energy traveling in the desired direction (usually vertically) adds up constructively as opposed to that traveling in other directions. In refraction shooting a directional charge detonating at a horizontal velocity equal to the refractor velocity is sometimes used to concentrate the energy traveling along the refraction path.

dispersion: Distortion of the shape of a wave train because of the variation of velocity with frequency, f. The peaks and troughs may advance towards (or recede from) the beginning of the wave as it travels. Leads to the separation of group velocity, u, from phase velocity, v. Where λ = wave length.

$$v = f/(1/\lambda)$$

$$u = df/d(1/\lambda).$$

The dispersion of seismic body waves (compressional and shear) is very small under most circumstances but surface waves may show appreciable dispersion in the presence of near-surface velocity layering.

displacement: (1) Plotting refraction data with respect to where the refracted energy presumably leaves the refractor rather than under the geophone positions where the arrivals are actually observed. Sometimes called "offset" or "transplacement." (2) Relative movement of the two sides of a fault. (3) The distance a particle is removed from its equilibrium position, as in the ground motion associated with a seismic wave.

distortion: An undesired change in waveform, as opposed to desired changes in wave shape like those from modulation.

(1) Amplitude-frequency distortion is due to undesired amplitude-frequency response characteristics.

(2) Delay distortion occurs if the rate of change of phase shift with frequency is not constant over the bandpass; a special case of phase distortion.

(3) Harmonic distortion is nonlinear distortion characterized by the appearance in the output of harmonics of a sine wave frequency in the input. See also distortion, percent harmonic.

(4) Intermodular distortion is nonlinear distortion characterized by the appearance in the output of frequencies equal to the sum and difference of integral multiples of the component frequencies present in the input.

(5) Nonlinear distortion is caused by a deviation from a linear relationship between input and output.

(6) Phase distortion is due to a lack of direct proportionality of phase shift to frequency over the bandpass. Delay distortion is a special case, as is the case where the zero-frequency intercept is not a multiple of π.

doghouse: The hut (or cab) which contains seismic recording instruments.

double-layer weathering: Situation where corrections must be made for two distinctive near-surface low-velocity layers.

drift: (1) A gradual and unintentional change in the reference value with respect to which measurements are made. If drift is slow and fairly steady in time, the difference produced by drift can be determined by rereading the value of the quantity being measured at the same position where it was previously observed and prorating the difference between the successive values over other readings made in between. Gravity meter drift may be caused by gradual heating up of the meter as the day progresses or by "creep" in the spring. Drift is different from "tear," which is a sharp, sudden change in reference value. (2) The layer of glacial deposits which may vary with position and hence require a variable correction on seismic records. The effect can be the same as that of a weathering layer. Often requires a double-layer weathering correction, for the entire drift layer and also for the lower-velocity layer of the top part of the drift.

drill: A device for boring shotholes. Usually means a rotary drill, often truck mounted, mechanically driven with a means for rotating the drill pipe and with a pump for circulation of a fluid (air or water or mud) down through the pipe to wash the cuttings away from the bit and carry them up to the surface in the annular space between the wall of the hole and the drill pipe. Portable drills, water jets, spudder or cable tools, and air-blast equipment are also used under certain conditions.

driller's log: A record of the formations drilled through.

dynamic range: The ratio of maximum recoverable signal (for a given distortion level) to the noise level of the system. For direct recording magnetic tape, the noise level is for unrecorded tape; bandwidth should be specified because selected narrow bandwidths may give improved dynamic range. The maximum range of standard magnetic tape is about 50 db, of high output tape about 60 db. In digital recording the dynamic range is limited by word length; a 13-bit word represents about 84 db.

E

elastic impedance: Seismic velocity multiplied by density. Also called acoustic impedance. Reflection coefficient depends on changes in elastic impedance.

elevation correction: (1) The correction applied to reflection time values to reduce observations to a common reference datum. (2) In gravity, the sum of the free air and Bouguer corrections. See e.c.f.

event = arrival: A lineup on a number of traces which indicates the arrival of new seismic energy, denoted by a systematic phase change of amplitude difference on a seismic record. May be a reflection, refraction, diffraction, or any other type of wavefront.

F

filter: (1) That part of a system which discriminates against some of the information entering it. The discrimination is usually on the basis of frequency, although other bases such as wavelength or moveout (see velocity filter)may be used. The act of filtering is called convolution. (2) Filters may be characterized by their impulse response or more usually by their amplitude and phase response as a function of frequency. Filter characteristics are often designated by specifying the frequencies at which their amplitude is down by a given amount, often 3 db (70% or half power), and by the slope of their cotoff. Simple RC or RL filters have slopes of 6 db/octave but they may be cascaded to achieve higher slopes. Thus a double-section simple filter may have a slope of 12 db/octave. A K-type filter has a slope of 18 db/octave. These may also be cascaded; hence, a KK filter has a 36 db/octave slope. See also high-cut filter and low-cut filter. (3) Bandpass filters are often specified by listing successively their low-cut and high-cut component filters. Hence, 2-21,1-55 might mean a double-section simple low-cut filter down 70% at 21 cps and a single-section simple high-cut filter down 70% at 55 cps; or a 21KK-55K might mean two cascaded low-cut K filters and a single high-cut K. filter. The order of the specification may also be reversed. (4) Notch filters reject sharply at a particular frequency. The m-derived filter is such a type; it is usually used in conjunction with another filter, e.g., MK; otherwise it would partially pass all frequencies above the notch as well as those below the notch. (5) Digital filters provide a means of filtering data numerically in the time domain by summing weighted samples at a series of successive time increments. Digital filtering can be the exact equivalent of electrical filtering. Digital filtering is very versatile and permits one to filter easily in accordance with arbitrarily chosen characteristics which might prove very difficult or impossible to introduce with electrical components. See also inverse filter and Robinson and Treitel, Geophysics, vol. 29, pp. 395-404.

first arrival = first break.

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; see Figure 2. Refraction work is based principally on the first breaks, although secondary (later) refraction arrivals are also used.

frequency: Symbol: f. The number of times a waveform repeats itself per second as it moves either forward or backward along the time axis (f can be positive or negative); the reciprocal of period.

frequency response: See amplitude response and phase response.

G

gain control: Control of the amplification or attenuation of a seismic amplifier which varies with time. Types in present use include:

(a) Automatic gain control, in which the gain of each channel is controlled automatically and independently of other channels.

(b) Ganged automatic gain control, in which the gain of all channels is the same although automatically determined, usually based on an average of the energy levels of a number of the channels.

(c) Preset or programmed gain control, in which the gain as a function of record time is determined arbitrarily prior to the shot.

(d) Binary gain control, in which gain is allowed to vary only by factors of two but the time at which the gain changes is determined automatically; may be ganged or individual for each channel.

gap: (1) Shotpoint gap. (2) An interval of space on a digital magnetic tape in which no information is recorded, which serves as a sentinel to indicate the beginning of a new record or a new block of data. Gaps facilitate the input of data into a computer in quantized blocks of information.

gelatin: Usually a dynamite-type explosive.

geophone = seismometer - jug - pickup: The instrument used to transform seismic energy into an electrical voltage. Most geophones are velocity detectors, their outputs being proportional to the velocity of the inertial mass with respect to the geophone case (which is proportional to the velocity of the earth motion). But below the natural frequency the response of most geophones decreases linearly with frequency so that they operate as accelerometers. See also hydrophone and streamer.

ghost: Energy which travels upward from the shot and then is reflected downward at the base of the weathering or at the surface. Ghost energy usually joins with the downward traveling wave train, changing its phasing and adding a tail, but a ghost energy is sometimes separated sufficiently from the main wave train to form a separate wave and separate although spurious reflection events on a record. Correcting for the change in wave shape which ghosting produces is the objective of vertical stacking. Also called secondary reflection. See Figure 1 and Dobrin, pp. 143-144.

ground roll: Surface wave energy which travels along or near the surface of the ground. Usually characterized by relatively low velocity and low frequency but high amplitude. Shot and geophone patterns, filtering and stacking are used to discriminate against ground roll. Rayleigh waves are usually the main source.

group: An array of geophones which collectively feed a single channel. The number of geophones may vary from one to several hundred.

group interval: The distance between the centers of adjacent geophone groups.

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. See also dispersion.

H

head wave: The wave which gives a refraction first break. See refraction wave.

hidden layer: A layer which cannot be detected by refraction methods, typically a low velocity layer lying beneath a high velocity layer.

high-cut filter = low pass filter: A filter that transmits frequencies below a given cutoff frequency and substantially attenuates all others.

high-pass filtering = low-cut filtering.

high-speed layer: A layer in which the speed of wave propagation is greater than in the layer above it and which tends to carry refraction energy.

hole blow: (1) Ejection of water, mud, and sometimes rocks from the shothole as a result of the shot explosion. (2) Noise on a seismic record caused by such ejection.

hole fatigue: The effect involved when there is a delay between the detonation of a shot and the initiation of the seismic impulse from it because of changes in the shot environment, usually cavity formation, produced by an earlier shot in the same hole.

hole noise: Noise from the shot, caused by hole blow or discharge of the gases resulting from the explosion, which may last for several seconds. Often excessively strong on geophone groups near the shothole; attenuates rapidly with distance.

hole plug: A device used to plug a shothole after shooting. Usually the plug is pushed far enough into the hole to prevent its being dislodged and earth is shoveled over it to level it with the surrounding ground.

horizon: (1) The surface separating two different rock layers. Where such a surface (even though not itself identified) is associated with a reflection which can be carried over a large area, a map based on the reflection event may be called a "horizon map," as opposed to a phantom map. (2) A line which indicates the horizontal direction.

Huygens' principle: The concept that every point on an advancing wavefront can be regarded at the source of an elementary wave and that a later wavefront is the envelope tangent to all the elementary waves.

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 as a well seismometer. The frequency response of the hydrophone plant depends on its depth beneath the surface because of a standing wave pattern subject to the boundary condition that pressure be zero at the surface and a maximum at a quarter wave length.

I

impulse = Dirac function = delta function = δ (t): The limiting single rectangular pulse of unit area as its width approaches zero and its height approaches infinity. It has a value at only one instant and unity energy content:

$$\delta(a) = \int_0^{\infty} \quad \begin{matrix} \text{if } t = a \\ \text{if } t \neq a \end{matrix}$$

$$\int_{\infty}^{\infty} \delta(t)\, dt = 1$$

An impulse contains all frequencies in equal proportions.

impulse response: The response of a system to an impulse input. Characterizes the system if the system is linear, containing the same information as the transfer function, which is its Fourier transform.

incident angle: The angle which a raypath makes with a perpendicular to an interface.

in-line offset: A spread shot from a shotpoint which is separated (offset) from the spread an appreciable distance (more than a few hundred feet) but along the line of the spread.

intercept time: The time obtained by extrapolating the refraction alignment on a refraction time-distance (T-X) plot back to zero offset. See Figure 6 and Dobrin, p. 72.

interface: (1) The common surface separating two different media in contact. (2) The contact or connecting element between two computing machines by means of which information is passed between the two machines.

interference: The superposition of two or more waveforms. Interference is constructive where peaks add to peaks, destructive where peaks add to troughs.

interpreter: (1) One who determines the geological significance of geophysical data. (2) A machine which reads coded information (such as punched cards) and prints out the translation. (3) A computing machine routine which translates from one machine language into another, such as from Fortran into the machine's own language.

interval velocity: Seismic wave velocity measured over a depth interval. In sonic log determinations the interval may be 1 to 3 feet, in well shooting it may be as great as 1000 feet or more. Usually refers to compressional velocity and usually implies measurements across the bedding.

iso-: A prefix meaning "equal," used in conjunction with other words to denote contour lines through points at which the measured value is the same. Examples include the following.

(a) isobars: Lines joining places of equal barometric pressure.

(b) isobaths: Lines of equal water depth.

(c) isochrons: Lines of equal reflection time, or equal time difference, or equal time delay time.

(d) isogals: Lines of equal gravity anomaly.

(e) isogams: Lines of equal magnetic intensity.

(f) isohyets: Lines of equal amounts of rainfall.

(g) isotherms: Lines of equal temperature.

J

jug - geophone:

juggie - jug hustler.

jug hustler: One who lays and picks up seismic spread and geophones.

jug line: (1) Cable connecting geophones to instruments. (2) The spread.

K

k: Symbol for wave number, the number of waves per unit distance, the reciprocal of wavelength.

$$k = 1/\lambda = f/v$$

where λ = wavelength, f - frequency, and v - apparent velocity. Because apparent velocity is used, k for a particular energy train varies with the angle between the raypath and the line of measure (the line of the spread, usually).

L

least time path = minimum time path - brachistochrone: The path which a seismic ray takes according to Fermat's principle. The raypath will generally be curved or bent because of velocity variations.

leg: A cycle of more or less periodic motion. When following a seismic event from trace to trace or from record to record, one usually concentrates on a particular trough or peak of the energy. If an erroneous jump is made into an adjacent trough or peak, one has jumped a leg.

leggy: Tailing; the character of a wave train which includes a number of cycles as opposed to a few; a result of too narrow a filter bandpass.

linear system: A system whose output is linearly related to its input. If a linear system is excited by an input sine wave of frequency f_1, the output will contain only the frequency f_1; the amplitude and phase may be changed, however. The rules of scaling (if A input results in B output, then k^A input results in k^B output) and superposition (if A results in B and C results in D, then A + B results in C + D) apply.

longitudinal wave = compressional wave = P wave.

long-path multiple: A seismic reflection whose travel path is much longer than required for direct reflection from the deepest interface reached. The energy is reflected by a deep reflecting interface, then at or near the surface, and again by the same or another deep interface. Also called surface multiple or simple multiple. See Figure 1.

Love wave - Q wave: A surface seismic wave associated with layering in which the vibration is transverse to the direction of propagation with no vertical motion.

low-cut filter = high-pass filter: A filter that transmits frequencies above a given cutoff frequency and substantially attenuates lower frequencies.

low-pass filter = high-cut filter.

low-velocity layer = weathering.

LVL = low velocity layer = weathering.

M

magnetic tape: A sheet or strip of plastic (such as Mylar) coated with a sensitive material on which information can be stored in the form of magnetization patterns.

marker bed - marker horizon: (1) A bed or sequence of beds which yields characteristic reflections over a more or less extensive area. (2) A bed which accounts for a characteristic segment of a seismic refraction time-distance curve and which can be followed over a reasonably extensive area.

marker velocity: The velocity with which refracted waves are transmitted along a marker bed.

millisecond - 10^{-3} second.

modulus: A measure of the elastic properties of a material. Moduli include.

(1) Bulk modulus, k: The stress-strain ration under simple hydrostatic pressure:

$$k = \frac{\Delta P}{\Delta V/V}$$

where P = pressure change, V = volume, and V = change in volume.

(2) Shear modulus = rigidity modulus - Lame's constant, μ: The stress-strain ratio for simple shear:

$$\mu = \frac{\Delta F/A}{\Delta L/L}$$

where ΔF - the tangential force, A = cross-sectional area, L = distance between shear planes, and ΔL = shear displacement. The shear modulus can also be expressed in terms of other moduli as:

$$\mu = \tfrac{1}{2}E/(1 + \sigma)$$

(3) Young's modulus = stretch modulus, E: The stress-strain ratio when a rod is pulled or compressed:

$$E = \frac{\Delta F/A}{\Delta L/L}$$

where ΔF/A = stress force per unit area, L = original length, and ΔL = change in length.

(4) Lame's λ constant: If a cube is stretched in the up-direction by a tensile stress, S, giving an upward strain, s, and S' is the lateral tensile stress needed to prevent lateral contraction, then:

$$\lambda = S'/s$$

This constant can also be expressed in terms of Young's modulus, E, and Poisson's ratio, σ:

$$\lambda = \frac{\sigma E}{(1 + \sigma)(1 - 2\sigma)}$$

See also Dobrin, pp. 16-18, or Dix, pp. 282-305.

moveout = stepout: (1) The difference in arrival time at different geophone positions. Includes (a) normal moveout, differences because of variable shotpoint to geophone distance along the reflection paths, (b) dip moveout, differences because of reflector dip, and (c) statics, differences because of elevation and weathering variations. See also delta t. (2) Dip moveout alone, especially across a single record.

multiple: Seismic energy which has been reflected more than once. See Figure 1 and long-path multiple, short-path multiple, peg-leg multiple, ghost.

multiple geophones: A number of geophones feeding a single channel; see group. Used to attenuate ground roll and other undesirable energy which approaches the spread more or less horizontally and to improve the signal-to-noise ratio by increasing the sampling and thereby randomizing planting factors, non-coherent energy, etc.

multiple shotholes: Two or more shotholes which are shot simultaneously. The holes are usually spaced to minimize near-surface wave interference.

multiplex: (1) A process of carrying several channels of information over a single channel without crossfeed. Usually different input channels are sampled in sequence at regular intervals and the samples are fed into a single output channel. Digital tapes are sometimes multiplexed in this way. Multiplexing can also be done by using different carrier frequencies for different information channels. (2) A stereoscopiec plotting instrument used in preparing topographic maps by stereophotogrammetry.

N

NMO = normal moveout.

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 (included wind noise, instrument noise, and all other energy which is non-coherent). To the extent that noise, is is random, it can be attenuated by a factor of $\sqrt{n}$ 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-surface material.

normal = orthogonal: A line perpendicular to a surface or to another line. A condition of being perpendicular to a surface or line.

normal moveout: The variation of reflection arrival time because of variation in the shotpoint to geophone distance (offset) which causes an increase of the length of the reflection travel path. Normal moveout depends on velocity and dip (to a lesser extent) as well as offset and decreases with reflection time. To the extent that long-path multiples travel at a lower average velocity than primary reflections at the same travel time (because velocity usually increases with depth) they will show greater normal move-out; the attenuation of such multiples by common-depth-point stacking is made possible by this fact.

notch filter: A filter which is designed to remove a single frequency.

Nyquist frequency = folding frequency associated with sampling, equal to half sampling frequency. See alias.

O

observer: The man in charge of the recording on a seismic crew. Sometimes the observer is also the field manager; sometimes he is principally an electronic technician.

offset: (1) The distance from the shotpoint to the nearest geophone group-center. Often resolved into components: perpendicular offset, the distance at right angles to the spread line, and in-line offset, the distance from the projection of the shot point onto the line of the spread. (2) The perpendicular offset only. (3) The distance between the shotpoint and the center of any geophone group. (4) The distance between shotpoint and any geophone. (5) Sometimes, in refraction work, the displacement. (6) In marine shooting, the distance from the recording boat where the radio-location equipment is usually located to the mid-point of the subsurface coverage; stepback. (7) Displacement of the plot of a reflection to its proper position on a cross-section; migration. (8) Displacement of a formerly continguous body.

one-way time: Half the corrected travel time for a reflection arrival. One-way time multiplied by average velocity gives reflector depth.

onset: The beginning of a wave train. See break.

operator: (1) A symbol for a mathematical (or sometimes physical) process to be performed on data. For example, a plus sign is an operator meaning, "add the number ahead of it to the number behind it." The symbols for differentiation, integration, convolution, Fourier transformation, cross-correlation, etc., are likewise "operators." (2) Observer. See also operator length.

oscillograph: Camera.

P

parameter = variable: (1) A factor which can be changed independently and (usually) arbitrarily between calculations but which remains constant during any calculation. (2) A factor (which may represent a combination of quantities) sufficient to determine the response characteristics of a system.

parity bit: One of the bits in a byte which is dependent upon the others in such a way as to detect dropout anywhere in the byte. See Figure 3.

party: The group of men working together to carry out a geophysical field project.

party chief: The man in charge of a geophysical party, usually including the interpretation of the results.

party manager: The man working under the party chief usually responsible for the field work. Sometimes in charge of the operations of a party, the interpretation being in charge of a seismologist.

peak: The maximum upward (positive) excursion of a seismic wavelet. Opposed to trough.

peg-leg multiple: (1) A multiple reflection involving different interfaces so that its travel path is non-symmetric. See Anstey, Geophysical Prospecting, vol. 8, pp. 242-259. (2) A short-path multiple which is multiply reflected within thin formations, i.e., less than a wave length apart. See Trorey, Geophysics, vol. 27, p. 778.

period: The time, T, for one cycle. The time for a wave crest to traverse a distance equal to one wavelength or the time for two successive wave crests to pass a fixed point.

$$T = 1/f = \lambda/v$$

where f - frequency, λ = wave length, and V = phase velocity.

permeability: The ratio of the magnetic induction, B, to the magnetic intensity, H. See paramagnetic, diamagnetic, ferromagnetic.

permit man: A member of a geophysical field party whose duty is to obtain permission from landowners and officials for the party to work on their land.

phase: The angle of lag or lead (or the displacement) of a sine wave with respect to a reference; the stage in the period in which rotation, oscillation, or variation has advance, considered in relation to a reference or assumed instant of starting. Commonly expressed in angular measure. Phase information, being the measure with respect to the instant of starting, carries the timing information of a seismogram, and hence proper phase preservation is of utmost importance. See also phase response and compare phasing.

phase distortion: Change in pulse shape which occurs because phase shift is not proportional to frequency. See also phase response.

phase inversion: A change of 180° in phase angle. Mirror-imaging a trace about the zero-deflection position.

phase response: A graph of phase shift vs. frequency, which illustrates the phase characteristics of a system. The amplitude-frequency response of a filter to the shape of pulses put through it will be different for different phase characteristics, leading to different phase distortion. (1) A minimum-phase filter is that one of the set of possible filters with identical amplitude response, which delays the energy the least; it also is called the "minimum-delay" filter. If the input to a minimum-phase filter is itself minimum phase, then the output will also be minimum phase. A large number of the filtering actions to which seismic signals may be subjected are minimum-phase and much of the filtering done in digital

Phase response (continued)

processing is minimum-phase. A minimum-phase wavelet is sometimes called "front loaded," because its energy is concentrated in the front end of the pulse. Maximum-phase is the other extreme, and mixed-phase is intermediate. See Figure 5. (b) A zero-phase filter is a mixed-phase filter in which the component frequencies are not shifted with respect to each other, although all will be delayed equally (but this can be compensated by moving the time reference or time break). The phase shift vs. frequency graph of a zero-phase filter is linear over the bandpass (that is the phase shift is proportional to frequency) and the intercept is a multiple of 2 π, so that the relative timing of all the component frequencies will be unchanged except that everything will be delayed in time. Such a filter produces no phase distortion. If the intercept is an odd multiple of π, it will produce phase inversion. Zero phase filters are anticipatory, i.e., some of the energy is pushed forward with respect to the new time reference. If the input to a zero-phase filter is symmetric, then the output will also be symmetric.

Phase spectrum: Phase response.

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. "Trough velocity" might be a better term.

phasing: A change in pulse shape as a result of filtering or interference.

pick: (1) To select an event on a seismic record as "to pick" reflection events. (2) An event of time on an event which has been selected.

pickup: (1) Geophone. (2) High Line.

playback: (1) Producing a new form of seismic record from magnetic tapes (or other reproducible forms of recording). Filtering, gain adjustment, time shifting, mixing, stacking, etc., may be included in the playback process. (2) The result of such processing, as opposed to the original recording.

plot: To draw lines representing seismic events in their proper position on a cross-section or plotted section.

plotted section: Section on which seismic events are indicated by lines or sequences of points. The horizontal scale is usually the distance along the seismic line and the vertical scale is usually either depth or travel time. Data may or may not be migrated.

plotter: (1) A device for making a seismic record or record section display, frequently (but not necessarily) photographic. (2) A device for graphing data, as an x-y plotter. (3) A person or device for drawing graphs, maps or sections.

Poisson's ratio, σ: The ratio of the transverse contraction to the longitudinal extension when a rod is stretched:

$$\sigma = \frac{\Delta d/d}{\Delta L/L}$$

where Δd = change in diameter, d, and L = the change in the length, L. See also modulus.

polarization: Equivalent to magnetization, but concerns only the vector direction and not the magnitude.

powder = explosive.

power spectrum: A graph of power density vs. frequency. The power spectrum is the square of the amplitude-frequency response of the Fourier cosine transform of the autocorrelation function.

predictive deconvolution: Use of information from the earlier part of a seismic trace to predict and deconvolve the latter part of that trace; as opposed to deconvolution based on the characteristics (such as frequency spectrum) of the same portion of the trace.

profile: (1) The series of measurements made from a shotpoint location into a recording spread. Additional shots from the same general shotpoint location into the same spread are part of the same profile even though different shotholes may be used. However, if the same spread is shot into from a different shotpoint location it is a different profile. (2) A refraction profile also denotes the collection of individual profiles (as defined in (1) above) shot from the same shotpoint. Use of the term for both the component profiles and for the aggregate sometimes produces confusion. "Refraction set" is also used for the aggregate. (3) A drawing showing a vertical section of the ground along a line. (4) A graph of a measured quantity against horizontal distance, as in a gravity profile.

pulse: A waveform whose duration is short compared to the time scale of interest and whose initial and final values are the same (usually zero). A seismic disturbance which travels like a wave but does not have the cyclic characteristics of a wave train.

P wave = compressional wave = longitudinal wave.

R

random noise: Energy which exhibits only a small degree of phase coherence or continuity between successive receiving channels. By adding together n elements, random noise can be attenuated by the factor $\sqrt{n}$. A large attenuation of such noise can be obtained by the use of many geophones per group or the careful stacking of several records.

Rayleigh wave = R wave: A type of seismic wave propagated along the surface; one type of ground roll. Particle motion is elliptical and retrograde in the vertical plane containing the direction of propagation and its amplitude decreases exponentially with depth.

raypath: A line everywhere perpendicular to wavefronts (in isotropic media). The path which a seismic wave takes.

real time: Having the same time scale as actual time. Processing of seismic data at same rate at which it was recorded.

record: (1) A recording of the energy from one shot or similar type of energy release picked up by a spread of geophones. May be on photographic or other paper or on magnetic tape. See Figure 2. (2) A collection of data, such as data to be input to a computer. This definition may differ from (1) above; thus a record to a computer might be a single magnetic tape containing several seismic records. (3) To make a record. (4) A group of data handled by a computer as a single block of data.

record section: Display of seismic records side-by-side to show the continuity of events.

record time: (1) Time after the shot instant. (2) Time after a certain reference.

reduced travel time - intercept time.

redundancy: A repetition of information, such as the same measurement made several times. Redundancy permits the attenuation of some nonsystematic effects involved in the measurement. For example, sixfold CDP shooting involves measuring the reflected energy from a given portion of the subsurface six times and hence has a redundancy of 6.

reflected refraction: An event which results from refracted energy being reflected or diffracted back from a discontinuity in the refractor, such as by a fault. Characterized by the apparent velocity of the refractor and no normal moveout. See Figure 1.

reflection: The energy or wave from a shot or other seismic source which has been reflected (returned) from an elastic impedance contrast or series of contrasts within the earth.

reflection coefficient: The ratio of the amplitude of a reflected wave to that of the incident wave. For normal incidence on an interface which separates media of densities ρ_1 and ρ_2 and velocities V_1 and V_2, the reflection coefficient for plane wave is:

$$\frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

In the more general case, the plane wave reflection coefficient may be found by solving Knott's equations. A negative reflection coefficient indicates phase inversion. The ratio of the reflected energy to the incident energy is the reflection coefficient squared.

refraction: See refraction wave.

refraction test = depth probe.

refraction wave = head wave = Mintrop wave = conical wave: Wave travel from a point source obliquely downward to and along a relatively high velocity formation or marker and thence obliquely upward. Snell's law is obeyed throughout the trajectory. Angles of incidence and of emergence at the marker are critical angles. Typically, refracted waves following successively deeper markers appear as first arrivals with increasing range (shot to detector distance). Refracted waves following different markers may occur at different arrival times for any given range. Such waves cannot arise for angles of incidence less than the critical angle for any given marker. At the critical angle, the refracted wave path (and its travel time) coincides with that of a wide angle reflection.

refractor = refraction marker: A relatively high velocity extensive layer, underlying lower velocity layers, which transmits a refraction wave nearly horizontally.

regional: Describing the general attitude or configuration of an area disregarding features smaller than a given size. Regional dip is the general dip attitude of a given portion of a basin ignoring local structure. The regional gravity is the attitude of the gravity field produced by large-scale variations ignoring anomalies of smaller size. See also residualize.

reverberation: Multiple reflection in a layer, usually the water layer in marine work; singing. Sometimes distinction is made between the case where water is so deep that the successive multiples are discrete and the case where they blend together into a more or less steady oscillation. Reverberations sometimes occur on land records also but are most commonly encountered in marine shooting. Removing reverberation effects is the objective of most deconvolution in digital processing.

Ricker wavelet: A particular seismic pulse with a waveform mathematically defined by Ricker to represent the transmission of a seismic impulse through an ideal material with elastic characteristics similar to those of rocks. See Ricker, Geophysics, vol. 18, pp. 10-40.

rig = drill.

RMS - root mean square.

roll along: The field method for recording for a common-depth-point stack.

root mean square - RMS: A type of average, the square root of the average of the squares of the measurements. Autocorrelation value (without normalizing) for zero lag. For a sine wave $\frac{1}{2}\sqrt{2}$ times the peak amplitude.

R wave = Rayleigh wave.

S

scattering: The irregular and diffuse dispersion of seismic energy caused by inhomogeneities in the medium through which the energy is traveling.

seis - seismometer - geophone: Device for detecting seismic energy and transforming it into an electrical voltage.

seismogram: A seismic record.

seismometer = geophone.

sensitivity: The least signal input capable of causing an output signal having desired characteristics.

setup: A particular arrangement of cables, geophones, shotholes, etc., for making a recording in the field. Repeated records may be taken at one setup.

shear wave = S wave - transverse wave: A body wave in which the particle motion is perpendicular to the direction of propagation.

shoot: (1) To fire an explosive. (2) To carry out a seismic survey, as "to shoot a prospect."

shooter: The man on a seismic party in charge of detonating the explosive.

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.

shothole noise = hole noise.

shotpoint: (1) The location where an explosive charge is detonated in one hole or in a hole pattern to generate seismic energy. (2) The location of other sources of seismic energy such as thumper drops, Dinoseis pops, etc. (3) The area surrounding the shotholes.

shotpoint gap: A gap in an otherwise uniform spread, so that the geophone groups nearest the shotpoint will be far enough from it that hole noise will have less adverse effect.

signal-to-noise ratio = S/N: The energy of a desired event divided by all remaining energy (noise) at that time. Sometimes the energy of the desired event is measured with respect to the total energy at that time, S/(S + N). Difficult to determine in practice because of the difficulty in separating out the signal constituting the desired events. One must presuppose some characteristic of the signal to effect the separation. This distinction is sometimes made on the basis of moveout, it being assumed that all coherent energy within a certain band of moveouts is signal and all else is noise. Signal-to-noise is sometimes represented in f,k plots on which the signal is indicated as a specified area. Amplitude ratios are sometimes used instead of energy ratios.

signature waveform = character.

simple multiple: A long path multiple which has undergone only three reflections (that is, twice reflected from deep interfaces and once from the shallow interface at the base of the weathering or at the surface.)

single-ended spread = end-on spread: A reflection profile which is shot from one end.

slurry explosive: A bulk-type explosive which can be poured into boreholes. Not cap sensitive, requiring a primer charge to detonate.

S/N = signal-to-noise ratio.

Snell's Law: When a wave crosses a boundary, the wave changes direction such that the sine of the angle of incidence (angle between normal to the wave and normal to the boundary) divided by the velocity in the first medium equals the sine of the angle of refraction divided by the velocity in the second medium.

sonic log: A record of the seismic velocity (or of interval time) as a function of depth. Measured over short intervals (often as little as one to three feet) in a well.

spherical divergence: The decrease in wave strength (energy per unit area of wavefront) with distance as a result of geometric spreading. For a spherical wave traveling through the body of a medium away from a point source, varies inversely as the square of the distance the wave has traveled. For energy which travels along a surface the analagous term is cylindrical divergence, which varies inversely as the distance.

spike: (1) hot shot. (2) An impulse.

split spread: A method of reflection shooting in which the shotpoint is at (or perpendicularly offset from) the center of the geophone spread. Commonly used in continuous profiling and in dip shooting.

spread correction = normal moveout.

SPS = shotpoint seismometer - uphole geophone.

stack: A composite record made by mixing traces from different records. See common-depth-point stack and vertical stack.

stadia: An instrument for measuring distances, consisting of a telescope with special horizontal parallel lines, used in connection with a vertical graduated rod; also, the rod alone.

statics: Corrections applied to seismic data to eliminate effect of variations in elevation, and of weathering thickness or velocity. See Dobrin, pp. 123-129.

station: A ground position at which a geophysical instrument (gravity meter, geophone, etc.) is set up for an observation.

step function: An abrupt increase or decrease from one constant value to another (often zero to one or vice versa). The first derivative of a step function is an impulse .

step function response: Output of a system when the input consists of a step function.

stepout = moveout.

streamer: A marine cable incorporating pressure hydrophones internally as an integral part, designed for continuous towing through the water.

structure: (1) A subsurface area characterized by folding, faulting, etc. (2) Seismic anomaly, usually a closed high.

subsurface coverage: The length, along a profile, of reflecting interface from which reflections may be obtained on a particular record. Equal to half the spread length for a plane reflector.

subweathering velocity: Velocity immediately below the base of the weathering. Sometimes taken as the velocity of a refraction at the base of the weathering.

supervisor: The man overseeing the work of two or more seismic parties. Immediate supervisor of the party chief.

surface waves: Energy which travels along or near the surface; ground roll. Includes Rayleigh, Love, hydrodynamic, Stoneley waves, etc.

S wave = shear wave = transverse wave.

T

takeout: Pair of leads from a multiconductor cable to which geophones or geophone flyers can be connected.

tamp: To pack material about an explosive in a shothole to effect better coupling of the explosive energy with the earth and thereby improve the conversion of explosive energy to seismic energy. Water or mud is usually used, sometimes sand and earth.

TAR = true amplitude recovery: A process for removing the effects of variable gain in the field recording, the effects of spherical divergence, and other time-dependent energy decay.

T-D curve: (1) Time-distance curve = T-X_2 plot. (2) Time-depth plot.

T^2-D^2 = T^2-X^2 = X^2-T^2: A method of velocity analysis from seismic surface data.

T - ΔT analysis: Normal moveout (ΔT) as a function of offset (X) and total time (T) can be used to yield average velocity ($\bar{V}$) and as a by-product information about multiples (because they show abnormal average velocities for their arrival times). The formula for average velocity is:

$$\bar{V} = X / \sqrt{2T\,\Delta T}$$

terrain correction: (1) A correction of gravity data because the surroundings are not all at the same elevation as the meter. Relief in the immediate vicinity of the station may require special surveying, called terrain surveying, whereas relief more remote from the station is often made from a topographic map using a terrain correction template or zone chart. See Dobrin, pp. 230-234. (2) A correction to seismic data because of topographic loading.

time: See record time.

time break: The mark on a seismic record which indicates the shot instant or the time at which the seismic wave was generated. See Figure 2.

time constant: (1) The time taken for the current in a curcuit having a steady emf to reach a definite fraction of its final value after the circuit is closed. The fraction is 1 - 1/3 = 0.633. (2) The time taken for the current to decay to 1/3 - 0/367 of its value after the emf is removed. (3) AGC time constant.

time delay: See delay time, filter correction and Elcord.

time-depth chart = T-D chart: A graph or table of reflection time against reflector depth, specific for a particular velocity function. Used in converting times to corresponding depths. Compare time-distance curve.

time-distance curve = T-X curve: A plot of the arrival time of refracted events against the shotpoint to geophone distance. The slopes of segments of the curve give the reciprocals of the apparent velocities for the various refractor beds. See also normal traveltime curve.

time-domain processing: Processing in which time is used as the variable. For example, filtering or the relative attenuation of certain frequencies can be done by passing a signal through frequency-selective circuitry, but the equivalent operation can be carried out in the time domain by picking up the energy at successive time intervals, multiplying by appropriate constants, and recombining (convolving).

total reflection: Reflection where the angle of incidence equals or exceeds the critical angle.

trace: (1) A record of one seismic channel. See Figure 2. (2) A line on one plane representing the intersection of another plane with the first one, such as a "fault trace."

trace analysis: Determining and plotting the corrected arrival time of events for every trace.

trace equalization: Adjusting a seismic channel so that the amplitudes of adjacent traces are comparable in the sense of having the same RMS value over some specified interval.

trace gather = spit out - point sort: See gather.

trace sequential: A format on magnetic tape in which one channel (trace) for an entire record is recorded without interruption followed sequentially by other channels. As opposed to multiplexed format in which the sequence is that of record time.

track: (1) A trace. (2) The data positions which can be read by a single magnetic head.

train: A series of successive repetitive events, as a "train of waves."

transcribe: To transform information from one form to another, as to make a magnetic tape from a paper seismic record. See also reformat.

transducer: A device which converts one form of energy into another; for example, a geophone which converts mechanical motion to electrical voltage.

transfer function: Filter characteristics in the frequency domain as represented by the amplitude vs. frequency and phase angle vs. frequency curves. Contains the same information as the impulse response in the time domain and convertible into the impulse response through the Fourier transform.

transient: A voltage or current or seismic pulse of short duration.

transverse wave = shear wave.

trap: (1) A waveguide phenomena; see channel wave. (2) A portion of the section which is able to confine fluids (such as oil) which float on other fluids (water). A closed structure in porous formations may be a trap if it has an impermeable cap; an unclosed structure may also be a trap if permeability variations block off the escape route of fluids. Compare closure.

traveltime: The time between time break and the recording of a seismic event.

TV = time variant.

T-X curve = time-distance curve.

U

uphole geophone: A geophone placed a few feet from a shothole to detect uphole time.

uphole seis = uphole geophone.

uphole shooting: The successive detonation of a series of charges at varying depths in a shothole in order to determine the velocities of the near surface formation and (sometimes) the variations of record quality with shot depth. Used to establish weathering thickness.

uphole stack = vertical stack.

uphole time: Time for the first wave from an explosion to reach the surface at or near the shotpoint. See Figure 2.

V

velocity: A vector quantity which indicates time rate of motion. Often refers to the propagation rate of a seismic wave without implying any direction; when used in this sense the term is not a vector quantity.

velocity inversion: A decrease in velocity with depth.

velocity profile = X^2-T^2: A seismic shooting setup designed to record reflections over a large range of shot-geophone distances to permit determination of velocity from the time-distance relationship for reflection events. See expanding spread.

velocity survey: A series of measurements to determine average velocity as a function of depth, as in well shooting. May also refer to sonic logging and sometimes to surface velocity shooting (X^2-T^2 or T- ΔT).

vertical stack: (1) a stack of records from shots at different depths to attenuate ghosts. (2) Mixing together of the records of several shots made in nearly the same location. Used especially with surface sources in which the records from several successive weight drops, vibrations, pops, etc., are added together without making different static or dynamic corrections to the components before adding. In marine work where the system is in continual motion this produces a slight smearing.

vertical time: (1) Uphole time. (2) Travel time it would have taken to reach a reflecting point if the energy had traveled vertically from a point directly overhead, as opposed to the time it actually took in case the reflector is dipping so that reflecting point is not directly under observation point, or in case where travel path is longer because geophone and shotpoint are not coincident.

W

waveform: A plot of voltage, current, seismic displacement, etc., as a function of time.

wave guide: A situation which permits channel waves.

wavelength = λ: The distance between successive similar points on two wave cycles measured perpendicularly to the crest.

$$\lambda = v/f - 1/k$$

where v - wave velocity, f - frequency and k = wave number.

wavelet: A seismic pulse usually consisting of $1\frac{1}{2}$ to 2 cycles. A Ricker wavelet is a particular type.

wavenumber = k: The number of wave cycles per unit distance; reciprocal of wavelength.

weathering = low velocity layer - LVL: A zone of low velocity material near the surface at the base of which the velocity abruptly increases. The seismic weathering is usually different from the geological weathering so that the term LVL is preferable. Frequently the base of the weathering is the water table. Sometimes the weathering velocity is gradational; sometimes it is fairly sharply layered. Weathering velocities are typically 1500 to 2500 ft/sec (after 500 to 1500 ft/sec for the first few feet) compared to subweathering velocities of 5000 ft/sec or greater.

weathering corrections: A correction of seismic reflection or refraction to remove the delay in the LVL. The simplest correction is based on uphole times from shots in the subweathering layer. Correction methods based on first break times include the ABC method, the Blondeau method, the summation method, and the first-break intercept-time method. See also double-layer weathering.

well shooting: A method of determining the average velocity as a function of depth by lowering a geophone into a hole and recording energy from shots fired from surface shotholes. Often run in addition to a sonic log to supply a reference time at the base of the casing and to check the integrated time, in which case they are called check shots.

wind noise = Random noise attributed principally to ground unrest caused by wind moving plants, trees, etc., and shaking their roots. Seismic background noise (in absence of shot) regardless of source.

window: (1) A portion of a seismic record free from certain disturbances, that is, where certain important noise trains are absent. (2) The portion of a record chosen for designing operators such as those used for auto-correlation or frequency analysis. (3) A tapering function to suppress sideband energy such as a Hamming window.

word: A group of characters occupying one storage location in a computer. This unit is treated by the computer as an entity. It is treated by the control unit as an instruction and by the arithmetic unit as a quantity.

X

x: The distance from the shotpoint to a particular geophone group; offset.

$X^2 - T^2$ analysis: A method of determining average velocity, $\bar{V}$, and the depth of a reflector, Z, from the arrival time vs. offset relationships:

$$X^2 + \bar{V}^2T^2 = 4Z^2.$$

The square of the horizontal distance or offset (X^2) is plotted against the square of the reflection time (T^2); the slope gives the inverse of the average velocity squared and the intercept gives four times the depth squared. Also used for identifying multiples because multiples tend to show abnormally low velocities for their arrival times.

Y

Z

zero phase: See phase response.