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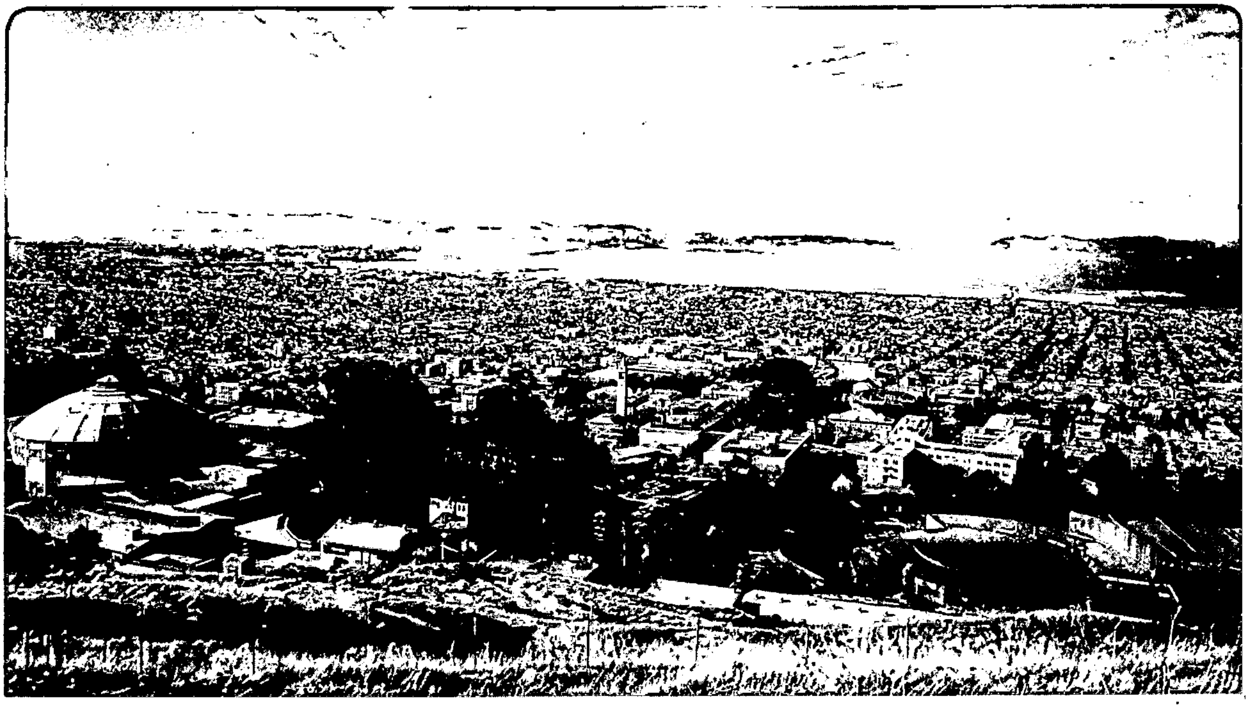

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Seismic Source Parameters

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Abstract

The use of information contained on seismograms to infer the properties of an explosion source presents an interesting challenge because the seismic waves recorded on the seismograms represent only small, indirect, effects of the explosion. The essential physics of the problem includes the process by which these elastic waves are generated by the explosion and also the process involved in propagating the seismic waves from the source region to the sites where the seismic data are collected. Interpretation of the seismic data in terms of source properties requires that the effects of these generation and propagation processes be taken into account. The propagation process involves linear mechanics and a variety of standard seismological methods have been developed for handling this part of the problem. The generation process presents a more difficult problem, as it involves non-linear mechanics, but semi-empirical methods have been developed for handling this part of the problem which appear to yield reasonable results. These basic properties of the seismic method are illustrated with some of the results from the NPE.

Introduction

The study of seismic sources is based on the fact that any rapid change of conditions within the earth will generate elastic waves that then propagate outward from the source region to other parts of the earth. The motions caused as these elastic waves pass various locations are recorded as a function of time to form graphs called seismograms, and the analysis of these seismograms is a fundamental task of seismology. An extensive set of analysis techniques have been developed for determining the location of the source, properties of the source such as its magnitude and focal mechanism, and the velocity structure of the earth. These analysis techniques, which were originally developed for the study of earthquakes, are easily adapted to the study of underground explosions. In the case of an explosion the source properties which are of interest are it size (yield), physical dimensions, type of explosive, method of detonation, and the coupling efficiency.

The purpose of this presentation is to give a general outline of methods by which the study of seismograms can lead to estimates of various properties of an explosive source. While this is just one aspect of the more general problem of seismic verification, it is one of the more critical aspects because it attempts to make definitive inferences about the physical properties and processes of the explosion itself. Some of the basic steps of this process will be illustrated with data and results from the NPE.

Seismic Verification - Basic Problems

In considering the general problem of seismic verification, it is important to keep in mind two features of the problem which strongly influence the methods which must be employed. The first is the fact that seismic waves are not produced directly by the explosion, but are only an indirect consequence of the disturbance within the earth caused by the explosion. This means that a geophysical inverse problem must be solved in order to convert the information contained in seismic waves into estimates of the explosion properties. The second is the fact that the fraction of the explosive energy that is converted to seismic waves is actually quite small, generally only a few percent. This second feature increases the difficulty of the inverse problem which must be solved and tends to magnify the uncertainty of the results.

Seismic Verification - Basic Methods

The various methods that have been developed for estimating the properties of explosions on the basis of seismic data can be roughly grouped into three different approaches:

- direct comparisons
- magnitude-based methods
- solution of an inverse problem

The method of direct comparison depends upon having a calibration explosion of known properties located at the same point and recorded with the same instrumentation as the explosion under study. Then, a direct comparison between the seismograms from the calibration explosion and seismograms from the explosion of interest is possible, which can lead to estimates of the relative strength and dimensions of the two explosions. Such a calibration event was included in the NPE and presentations which discuss direct comparisons include Goldstein and Jarpe (1994), Hutchings (1994), Reinke et al. (1994), and Stump et al. (1994). An advantage of this approach is that it involves the fewest number of assumptions and thus has the potential to obtain the most accurate results. A disadvantage is that a very specific calibration event is required, and this may not be included in all verification scenarios.

The second approach is a group of related methods which are essentially extensions of the magnitude scales which were developed for measuring the size of earthquakes. Such methods were developed first and are still the most commonly used for the estimation of explosion properties. The basic idea is to assemble a comprehensive set of seismic observations that have been obtained from a group of seismic sources having known properties, and from this data set develop empirical relationships that relate measurements made on the seismic data to properties of the explosion source. The previous presentation by Garbin (1994a) provides a general overview of this approach and examples of its application can be found in many of the papers of this symposium, including Garbin (1994b), Mayeda (1994), Patton (1994), Rohrer (1994), Smith (1994), and Walter et al (1994). Advantages of this approach are that estimates of uncertainty are conveniently included and it lends itself to both discrimination and source parameter estimation problems. A disadvantage is that it requires an extensive calibration data set and misleading results can be obtained when it is applied to events that differ significantly from the calibration set.

The third approach includes the more formal methods which attempt to characterize the estimation procedure as the solution of a geophysical inverse problem. Actually, as described below, it is necessary to consider two separate inverse problems. The first is the conversion of the observed seismograms to an estimate of the seismic source, while the second involves the conversion of the seismic source to an estimate of the explosion properties. The remainder of this presentation will concentrate on a description of this third approach, not because it is the best or most popular, but because it requires an explicit examination of most of the fundamental problems that are common to all methods of estimating explosion source properties.

Basic Physics of Elastic Wave Generation by Explosions

In the case of tamped underground explosions there are a number of different processes that are involved in the generation of elastic waves. These are illustrated schematically in Figure 1. The explosion is initially contained within a cavity of radius R_c which has been excavated from the surrounding rock. At the time of detonation a hot pressurized gas is created within the cavity which causes it to expand. Some of the surrounding rock may be vaporized and added to the cavity at this time also. The sudden expansion of the cavity generates a shock wave which propagates outward and causes major damage to the surrounding rock, first in a crushed zone and then in a fractured zone. The energy density of this shock wave decreases with distance from the explosion, partly due the fact that it is spreading in three dimensions and partly due to the fact that energy is being used to crush and fracture the rock. Thus the shock wave gradually decays into an inelastic wave, which is still strong enough to involve nonlinear motions and permanent deformation of the material. This nonlinear wave also decays with distance from the explosion and eventually a radius is reached where the motions are sufficiently reduced so that they can be satisfactorily described by the ordinary elastodynamic equations of linear elasticity. Beyond this distance, labeled R_s and called the elastic radius, the disturbance caused by the explosion propagates as elastic waves, and hence in this region all of the standard linear methods of seismology can be applied to explain how these waves propagate throughout the earth, including the reflection and refraction that takes place when variations in earth structure are encountered, the conversion between different types of elastic waves, and the generation of surface waves. It is the motions caused by these elastic waves that are generally recorded on seismograms.

This simple description of the explosion process is sufficient to illustrate the fundamental problems of using seismic waves to estimate properties of the source. The basic task is to take seismograms observed some distance from the explosion and extract from these records information about the properties of the source. However, the seismogram is a product of all of the processes that have taken place, including the explosion process that takes place within the radius R_c, the nonlinear processes that take place between the radius R_c and R_s, and the linear wave propagation processes that take place outside the radius R_s. Thus, if one wants to extract information about the source process, it is first necessary to remove the effects of the other processes that have taken place between the source and the location where the seismogram was recorded. In effect, removing the effects of these other generation and propagation processes is equivalent to moving the observation point back to the surface of the explosion cavity. This concept of transporting the information on the seismogram from the observation point back to the explosion source is conveniently divided into two steps. The first involves movement from the observation point to the elastic radius R_s, and this consists of removing the linear effects of ordinary elastic wave propagation. The result of this first step is an estimate of the motion that occurred at the radius R_s, and this will be referred to as the *seismic source.* The second step involves movement from the elastic radius R_s to the cavity radius R_c, and this requires that the strongly nonlinear effects of shock waves and inelastic waves be described and removed. The final result is an estimate of the motion that occurred at the cavity radius R_c, and this will be referred to as the *explosion source.*

The basic problem of using seismic waves to estimate the properties of an explosive source can now be stated. The observational data, the seismograms, contain the combined effects of the explosion process, the nonlinear processes that lead to the generation of the elastic waves, and the propagation processes that carry the elastic waves out to the locations where the data are recorded. In order to isolate the explosion process and thus determine the explosion properties, it is necessary to remove the effects of both the propagation process and the generation process.

Estimation of the Seismic Source

Consider the processes which take place as elastic waves propagate outward from the elastic radius R_s to the location where the seismogram is recorded. If the displacement at this elastic radius is known and if the properties of the surrounding material are sufficiently well known, then the propagation process can be modeled and it is possible to predict the time history that appears on the seismogram. This is known as a forward problem and is written schematically as

$$\textit{seismogram} = \textit{seismic source} \ \ x \ \ \textit{propagation process}$$

In practice, the solution of this problem consists of solving the differential equations that describe linear elastic wave propagation, and methods for obtaining such solutions are relatively well established. However, this is not actually the problem of interest in the present situation because it is the seismogram, being the observational data, which is known and it is the seismic source which is not known. Thus what must actually be solved is the inverse problem

$$\textit{seismic source} = \frac{\textit{seismogram}}{\textit{propagation process}}$$

The right-hand side of this expression represents the process of deconvolving the propagation process from the observed seismogram. Although the solution of this inverse problem is more complicated than the forward problem, fortunately it too has a well behaved solution with properties which have been extensively studied. Obtaining such a solution requires that the earth structure in the region outside the elastic radius be known and depends upon the fact that the propagation process involves ordinary linear mechanics. What results is a linear inverse problem. This means that, given sufficient observational data (generally a minimum of six different seismograms), it is possible to obtain a unique estimate for the seismic source. Of course, as in all inverse problems, this estimate will carry with it a certain amount of uncertainty, but there are methods of estimating this uncertainty also.

One of the consequences of considering the estimation of the seismic source as the solution of an inverse problem is that it forces one to examine the question of how the seismic source is to be represented. It turns out that a method used in many branches of physics, the method of multipole expansions, provides a convenient method of representation. The forces acting in the source region are expanded in terms of moments of various orders, as shown by Stump and Johnson (1977). The monopole term in this expansion is zero because the source exerts no net force on the earth. The first nonzero terms involve dipoles and these dominate higher order terms for localized sources such as an explosion. Thus it is usually sufficient to retain only the dipole terms in the force-moment expansion, and the complete set of these force couples is depicted in Figure 2. In seismology these dipole terms are known collectively as the *seismic moment tensor.* This is a symmetric second-order tensor and consists of six independent terms, with three terms being extensional force couples and three being shear force couples. It serves as a convenient mathematical representation of the seismic source.

This process of estimating the seismic source can be illustrated with some of the data collected for the NPE (Johnson, 1994). Figure 3 shows the accelerations measured in the vertical direction at six different sites located on the surface of Rainier Mesa, with slant distances ranging between about 700 and 850 meters. Records such as these contain the combined effects of both the seismic source and the propagation process and comprise the basic data for the inverse problem. The propagation process is represented by calculating Green functions for elastic wave propagation in a model of the Rainier Mesa structure, in this case obtained from a reflection survey performed prior to the NPE (Majer, et al., 1994). Then the result of solving this first inverse problem, the seismic moment tensor estimate for the NPE, is shown in Figure 4. Note that the extensional force couples (11, 22, and 33 terms) dominate the shear force couples (21, 31, and 32 terms), which is exactly what is predicted for an explosion. In contrast, an earthquake would be dominated by the shear force couples, so this analysis has already established that the NPE was definitely an explosion. Also note that the 33 term is somewhat larger than the 11 and 22 terms, which indicates there was some asymmetry in the explosion, with the expansion in the vertical direction greater than in the horizontal directions. The seismic moment tensor of Figure 4 represents the solution to the first inverse problem, the elastic propagation effects having been removed so that an estimate of the motion at the elastic radius R_s is now available.

Estimation of the Explosion Source

The next step is to understand the relationship between the seismic source, which is a description of the elastic displacements at the radius R_s, and the explosion source, which is a description of what happens at the radius R_c. First consider the forward problem in which it is assumed that the explosion source is known and that the physical processes that take place between R_c and R_s, here collectively called the generation process, are well enough understood so that it is possible to predict the seismic source.

$$\textit{seismic source} = \textit{explosion source} \;\; x \;\; \textit{generation process}$$

Solutions to this forward problem are possible, but the task is much more difficult than the forward problem involved in the estimation of the seismograms. This is because the generation processes for the most part are non-linear, involving the propagation of shock waves and non-linear elastic waves and permanent changes in the material properties, such as crushing, fracturing, and collapse of pore space. Considerable effort has gone into modeling these phenomena, resulting in the development of a series of fairly elaborate hydrodynamic computer codes. An important part of these calculations is the equation of state for the material in the vicinity of the explosion, and this type of information must often be obtained by extensive laboratory and field testing. The NPE provided an opportunity to check these types of calculations and the results are described in the papers by Bos (1994), Glenn and Goldstein (1994), Hill (1994), McKown (1994), Patch et al. (1994), and Souers and Larson (1994).

As before, the problem to be solved is actually an inverse problem, as it is assumed that an estimate of the seismic source has been obtained from the analysis of the seismograms and the objective is to convert this to an estimate of the explosion source. This inverse problem can be represented as

$$\textit{explosion source} = \frac{\textit{seismic source}}{\textit{generation process}}$$

In order to solve this inverse problem it is necessary to estimate the effects of the generation process and remove these from the representation of the seismic source. Unfortunately, as discussed above, this generation process involves some strongly non-linear mechanics and this makes it very difficult to construct a formal solution to the inverse problem. In fact, at the present time no direct methods of solving this particular inverse problem have been developed, and this represents one of the major obstacles in the study of explosion sources using seismic methods. Even if direct methods can be developed for solving this problem, because of the basic nonlinearity of the processes involved, the solution is likely to be highly non-unique and contain considerable uncertainty. Thus, the complexity and strong non-linear character of the forward problem in the immediate vicinity of an explosion source creates a situation where it is very difficult to obtain a satisfactory solution to the inverse problem that must be solved in order to obtain an estimate of the explosion source. Faced with this fundamental conundrum, some indirect methods of obtaining certain properties of the solution have been devised, and these will be described below. Fortunately, some of these indirect methods appear to be quite successful in circumventing the basic difficulties of the generation process.

One indirect method of solving this inverse problem is to solve the forward problem for a variety of different assumed explosion sources, and then select as the solution the one that produces a simulated seismic source which is the most similar to the observed seismic source. In principle, this could be formalized into a Monte Carlo procedure, although this is rarely done for this particular problem. It is important to keep in mind that the solutions obtained with this approach contain a fundamental non-uniqueness and uncertainty, and both of these properties are difficult to characterize in a quantitative manner. Contributing to this non-uniqueness and uncertainty is the fact that material properties in the source region play an important and complex role in determining how the the explosion source at radius R_c is transformed into the seismic source at the radius R_s. Included in the relevant material properties for this region are:

- density, natural and compressed
- bulk elastic properties, modulus and strength
- shear elastic properties, modulus and strength
- porosity
- type of material in pores
- overburden pressure
- tectonic stress field

There is still not complete agreement about how these material properties should be incorporated into the forward calculations, and in many practical applications they may be poorly known. However, these types of parametric studies of the forward problem play an important role in providing guidelines and limits for more empirical studies.

There is another indirect approach to the inverse problem for the explosion source which does not produce an actual solution but does attempt to estimate certain properties of that solution. The basic idea is to parameterize both the explosion source and the seismic source and then try to find simple relationships that connect the parameters of these two sources. In general, these relationships are guided by the relevant theory but also have an empirical component, and, in view of the discussion above, one would expect them to be dependent upon the material properties of the source region. The following section describes one approach to the parameterization of the seismic and explosion sources, and this is followed by a discussion of some possible relationships between the parameters.

Spectral Models for Explosions

Given that a satisfactory solution to the inverse problem that converts the seismic source into the explosion source has not yet been developed, it is worth considering whether it might be possible to relate certain properties of the seismic source to the explosion source. A common approach of this type makes use of the fact that some of the pertinent properties of these sources are more easily identified in the frequency domain than in the time domain. For instance, if the explosion is assumed to be symmetric, then the seismic moment tensor can be reduced to a single time function, the *isotropic moment tensor.* This is simply the average of the three extensional force couples (the 11, 22, and 33 terms in Figure 4). Then taking the Fourier transform of the time derivative of the isotropic moment tensor and extracting the modulus of this quantity as a function of frequency, one arrives at amplitude spectrum of the moment rate tensor. Such a spectrum for the NPE (calculated from the results of Figure 4) is shown in Figure 5.

The spectrum shown in Figure 5 illustrates the basic features which are common to the spectra of most seismic sources. At low frequencies the spectrum approaches a constant level which is called the *low frequency level.* At high frequencies the spectrum decreases with increasing frequency at a more or less constant rate known as the *high-frequency decay rate.* The intersection between the low frequency level and the high frequency decay is the *corner frequency.* In the vicinity of the corner frequency there may be some peaking in the spectrum, which is known as the *spectral overshoot.* Simple theoretical models can be used to relate these spectral features of the seismic source to properties of the explosive source. The rough correspondence is as follows:

spectral feature	*explosion property*
low frequency level	yield
corner frequency	physical dimension
spectral overshoot	amount of oscillation
high-frequency decay rate	sharpness of initial pulse

Note that the low frequency level of the spectrum is also known as the *scalar seismic moment,* and is proportional to the constant part of the *reduced displacement potential.*

To proceed further with this approach of relating spectral features of the seismic source to explosion properties it is necessary to obtain quantitative estimates of the spectral features. This is commonly done by fitting parameterized models to the spectrum. A variety of such models have been proposed, some based on theoretical models of a simple explosion and some being purely mathematical, and the properties of these models are listed in Table 1 of Denny and Johnson (1991). Figure 6 shows what happens when one of these models is fit to the spectrum of the isotropic moment tensor estimated for the NPE. The estimates of the spectral features which were obtained with this fit are as follows:

spectral feature	*estimate*
low frequency level	$20\ 10^{20}\ dyne\ cm$
corner frequency	$3.3\ Hz$
spectral overshoot (damping)	0.09
high-frequency decay rate	2.6

The next step is to relate these estimates of the spectral features to explosion properties such as yield or source dimension. Unfortunately, the simple theoretical models of an explosive source which were used to model the spectrum are not adequate for this purpose, primarily because these models do not take into account the strong non-linear processes which take place in the interval between R_c and R_s. Although these models suggest a qualitative relationship between spectral features of the seismic source and properties of the explosion source, they do not allow a quantitative estimates of these explosion properties. It is thus necessary to appeal to more empirical approachs in order to make these quantitative conversions between seismic source and explosion source.

Scaling Relationships

A common method used to quantitatively relate spectral models of the seismic source to explosion properties consists of deriving a set of scaling relationships. The mathematical forms of these scaling relationships are guided by simple models of an explosive source and by results of the hydrodynamic code simulations, but the constants of the relationships are obtained by fitting these equations to empirical data. In setting up these scaling relationships it is important to identify and attempt to isolate the several independent factors that can affect the manner in which the seismic source is produced when an explosion is detonated. Some of the factors which must be considered are as follows:

- effects of explosion yield and dimension
- effects of depth of burial
- effects of material properties in the source region
- effects of type of explosive
- effects of tectonic strain release

Some of these effects enter directly into the scaling relationships, but others enter in an indirect manner. A good example of an indirect effect is that of depth. While the models of an explosion do not contain an explicit dependence upon depth, many of the parameters in the models such as confining pressure, elastic properties, density, and porosity are directly dependent upon depth, and thus, acting through these parameters, depth may have a significant indirect effect.

As an example of a scaling relationship, consider how the yield of an explosion is related to the low frequency level of the seismic source. Figure 7 is taken from Denny and Johnson (1991) and shows empirical data of this type for a variety of different types of explosions, ranging from small chemical explosions in the laboratory to large buried nuclear explosions. These explosions were also detonated in a variety of different media, ranging from alluvium to granite. Taking all of these factors into account, it is possible to estimate the following empirical relationship between explosion yield and low frequency level of the seismic source (Denny and Johnson, 1991).

$$W = 294\ 10^{-12}\ \beta^{1.1544}\ P_o^{0.4385}\ 10^{0.0344GP}\ \frac{M_o}{4\pi\rho\alpha^2} \qquad (1)$$

where

W is explosion yield in kilotons

M_o is low frequency spectral level in Newton meters

and the material properties involved are

α is P velocity
β is S velocity
ρ is density
P_o is overburden pressure
GP is gas porosity

A similar type of scaling relationship can be developed between the corner frequency of the seismic source and the cavity radius R_c. Using material properties appropriate for the NPE and the spectral fit shown in Figure 6, the following explosion properties of the NPE are obtained:

yield $W = 1.4\ kt$
cavity radius $R_c = 15.5\ meters$

The scaling relationship given above as Equation 1 illustrates why this type of approach has been more successful than one might initially suspect. Note that, while the material properties enter this equation in a fairly complicated manner, the basic relationship between the low frequency level of the spectrum of the seismic source and the yield of the explosion is linear. This implies that, while a variety of non-linear processes are involved in the generation of elastic waves by an explosion, it appears that these processes act in such a way that the the fraction of energy which goes into low frequency seismic waves is independent of the size of the explosion. In essence, the explosion is acting as a self-similar event with respect to the generation of elastic waves. While this is basically an assumption of the method, it seems to be verified by the validity of the straight-line fit in Figure 7, which spans almost nine orders of magnitude in the explosion size. The existence of relationships such as this which express a fairly simple scaling between properties of an explosion source and the properties of the seismic source is a key element of all seismic methods and a crucial factor in their success. Of course, given the complexity of the generation processes that are involved and the empirical nature of the method, it is important that relationships such as this be continually checked against observational data in order to uncover any deficiencies.

Discussion and Summary

All methods which use seismic data to infer properties of a seismic source must deal with the same set of fundamental difficulties. The seismic waves are only an indirect effect of the explosion and represent only a small fraction of the energy which is released. Given this indirect nature of the problem, some interpretation procedure must be used to convert properties of the seismic waves to properties of the explosion source. This interpretation procedure must take account of the fact that several different processes are involved in converting the motion of the explosion cavity to the motion of the ground recorded by the seismograms. These processes are conveniently grouped into two classes, the nonlinear processes which lead to the generation of the elastic waves at the elastic radius R_s and the linear processes which are associated with the propagation of the seismic waves out through the rest of the earth. The seismograms are the combined effect of the explosion source plus these generation and propagation processes, and thus any attempt to infer properties of the explosion is successful only to the extent that the effects of these intervening processes can be removed. The treatment of the propagation processes is amenable to many of the standard methods of seismology, as it involves the linear mechanics of elastic wave propagation. The generation process is more difficult to handle, as it involves a number of strongly non-linear processes that depend upon a variety of material properties in the source region, and at the present time this part of the problem is treated with various empirical scaling relationships. Fortunately, the explosion source appears to have some self-similar properties which allow such scaling relationships to be used as a substitute for a complete treatment of the rather complicated generation process.

It is interesting to compare the different approaches to the seismic verification problem in terms of how the difficulties with the generation and propagation processes are addressed. The method of direct comparison takes advantage of the fact that the propagation processes are independent of the type of source and uses a calibration event to cancel out the propagation processes. This method also generally assumes the existence of simple scaling relationships between the explosion source and the seismic source. Because the material properties in the source region also cancel out in the comparison process, one is left with the particularly simple situation where the ratio of amplitudes on seismograms is equal to the ratio of explosion sizes. As mentioned earlier, this approach has the potential for the most accurate results, but does require the existence of a calibration event. The method of empirical Green functions belongs to this general class of methods.

The magnitude-based methods take the additional step of treating both the generation and propagation processes as empirical corrections. That is, the propagation process is characterized as a simple distance correction that can be used to relate the seismograms to properties of the seismic source. As in the case of direct comparison, this method also assumes simple scaling relationships between the explosion source and the seismic source. In some cases the scaling relationship of the generation process is combined with the distance correction to provide a single relationship between measurements on the seismogram and properties of the explosion source. For example, relationships have been developed that relate the amplitude of a particular phase on seismograms to the yield of the explosion source. A limitation of this approach is that the distance corrections used to approximate the propagation process are known to be dependent upon the type of seismic phase which is being considered and the earth structure in the entire region between source and receiver. Thus the method must be calibrated for each different region of the earth. However, some imaginative techniques have been developed whereby a combination of different types of magnitudes may be less sensitive to the details of the calibration process than either of the magnitudes separately.

The approach of formulating the explosion estimation procedure as a formal inverse problem is useful in that it brings out the basic problems and assumptions that are common to all approaches. For instance, it is clear that two inverse problems must be solved, one involving removal of the propagation processes and the other involving removal of the generation processes. The first inverse problem is linear and well posed, and a variety of methods have been developed for the purpose of removing the propagation effects from the seismogram. All depend upon having available a model of the earth structure which was sampled by the propagating waves, but calibration explosions and calibration data sets are not explicitly required. Most of the waveform modeling methods of studying explosion sources belong to this general approach, although in many such cases the inverse problem is effectively solved by a series of trial and error solutions of the forward problem. The second inverse problem, that of removing the generation processes, can be clearly stated with this approach, but the complexity and non-linear nature of these processes prevent a direct solution of this problem at the present time. Thus, just as with the other two approaches described above, this part of the estimation process must be treated by relying on empirical scaling relationships.

It is clear from the above discussion that all seismic methods currently being employed to estimate the properties of explosion sources contain an implicit assumption that the non-linear zone surrounding an explosion can be bridged by empirical scaling relationships. This is a critical assumption, and the success of seismic methods as they are currently practiced is heavily dependent upon it. While there are arguments that provide a theoretical basis for the use of such scaling relationships (see for example Latter et al., 1959), the fact remains that they contain a strong empirical component. Consequently, it is important that the applicability of these relationships be continually checked against observational data. In particular, some of the assumptions implied by the use of these relationships may not be suitable for all applications. For instance, there is the question of whether the same scaling relationships can be used for both nuclear and chemical explosions, for both contained and partially contained explosions, and for both symmetric and unsymmetric explosions.

This discussion of the seismic method of estimating properties of explosion sources has attempted to outline the general foundations of the method and to highlight some of the areas where additional research is required. This last element is particularly appropriate in the case of the NPE, as this experiment was specifically designed to answer some of these remaining questions. All of the seismic methods outlined above were represented in the experiment, so the relative merits of the various approaches can be checked in a quantitative manner. It should also be possible to compare the information contained in various types of data, as the experiment included the collection of seismic data in the free-field, local, and regional distance ranges. The choice of the explosion site allows a close comparison between nuclear and chemical explosions. The comparison of small and large explosions, both chemical and nuclear, in the same source environment permits a very useful check on empirical scaling relationships. Finally, the broad scope of the experiment should allow a useful comparison between seismic methods and other methods of quantifying the properties of explosion sources.

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Figure Captions

Figure 1. Diagram showing some of the different zones and processes that surround a buried explosion.

Figure 2. The orientation of the force couples that comprise the second-order seismic moment tensor. The usual orientation of the axes is 1 north, 2 east, and 3 down. Conservation of angular momentum for the earth requires symmetry relations for the shear couples of the form: 12 = 21, 13 = 31, and 23 = 32.

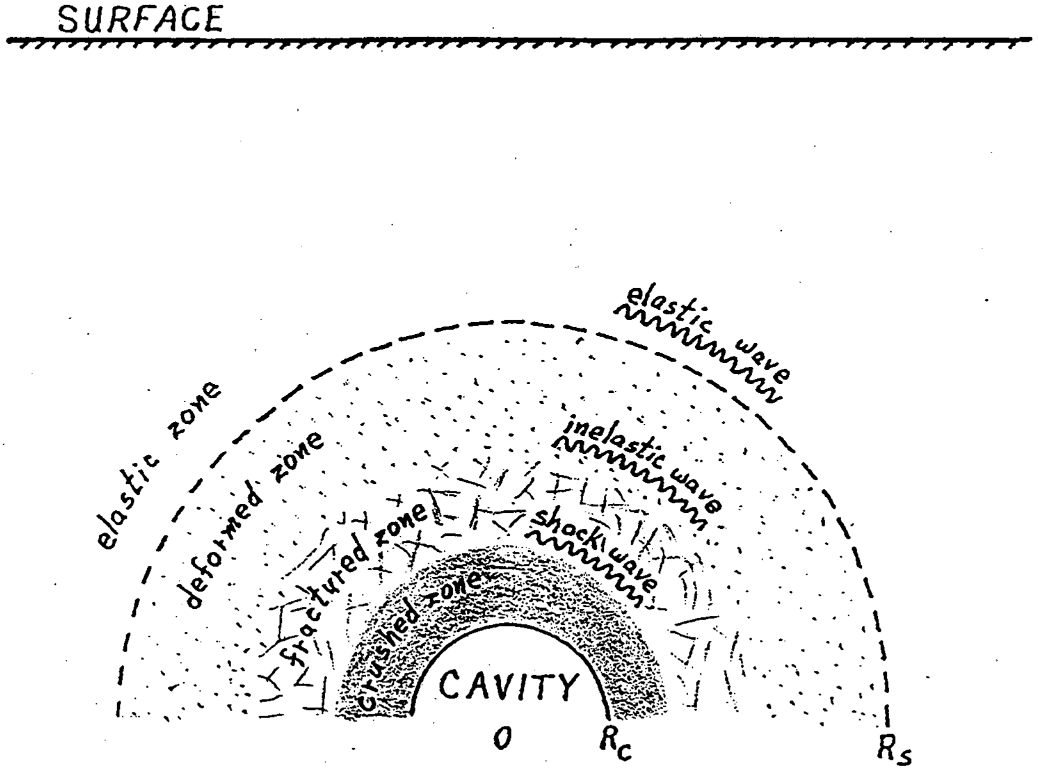
Figure 3. A sample of the seismograms that were recorded from the NPE. These seismograms show the vertical accelerations that were recorded on the surface of Rainier Mesa along a north-south line about 600 meters west of the epicenter.

Figure 4. The six independent elements of the second-order seismic moment tensor that were estimated for the NPE.

Figure 5. The modulus of the amplitude spectrum of the isotropic part of the seismic moment rate tensor which was calculated from the estimates contained in Figure 4. The dashed line is an estimate of the noise.

Figure 6. Similar to Figure 5 with the addition of the dotted line which is a spectral model which has been fit to the estimated modulus.

Figure 7. Figure taken from Denny and Johnson (1991) showing the relationship between seismic scalar moment and yield for explosions, with the data compiled from various published studies which used different types of data and different analysis methods to arrive at the estimated moments. These explosions were also detonated in a variety of source media, which accounts for some of the scatter in the data.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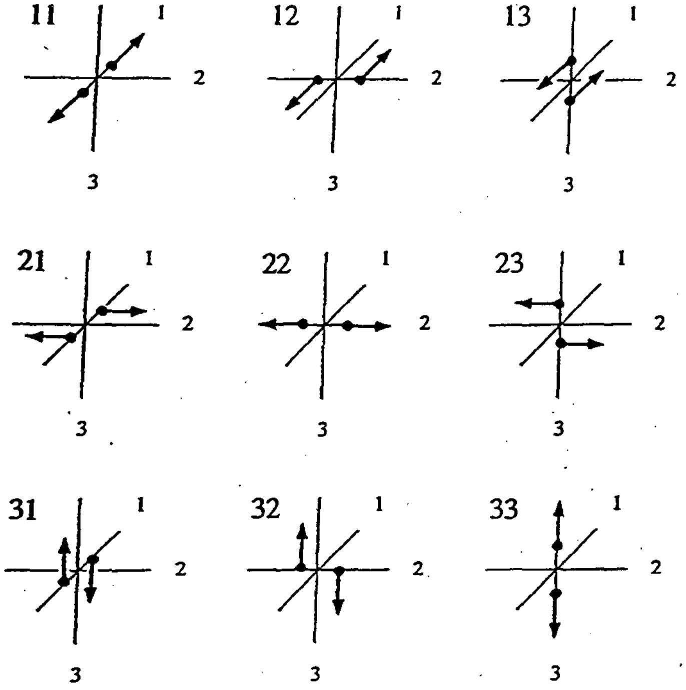
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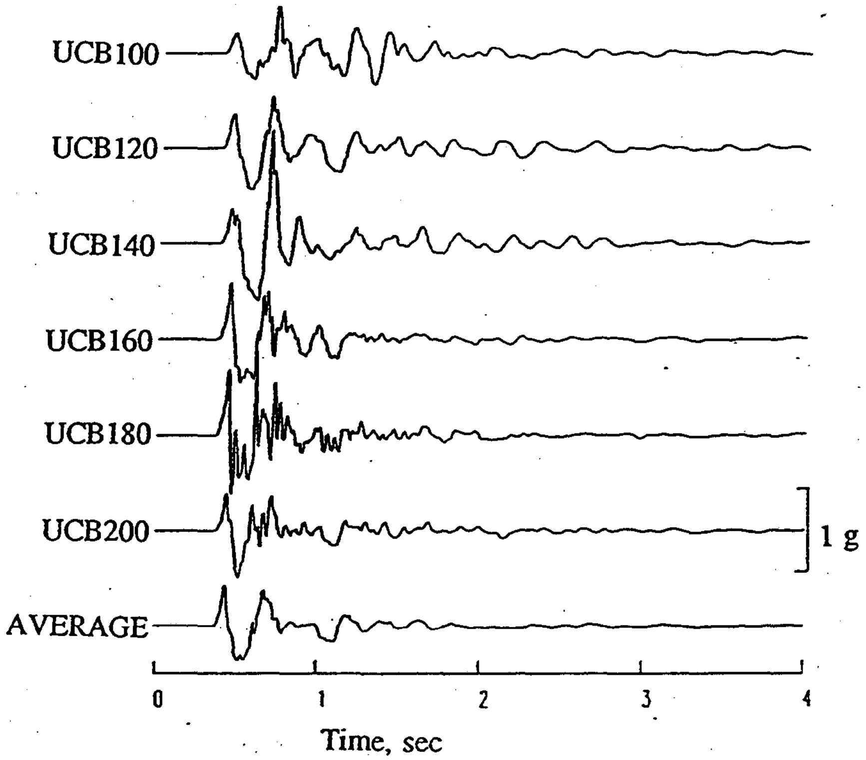
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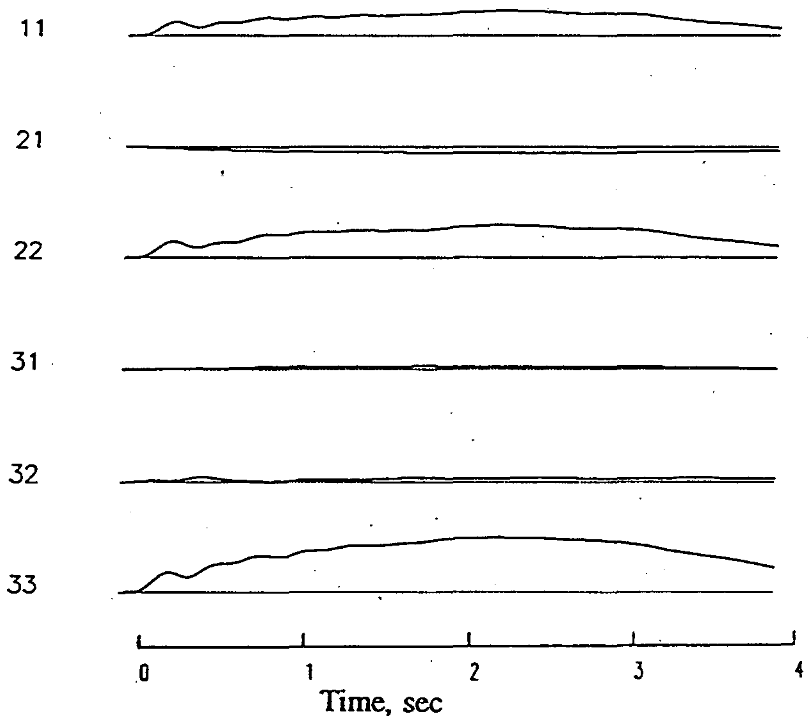
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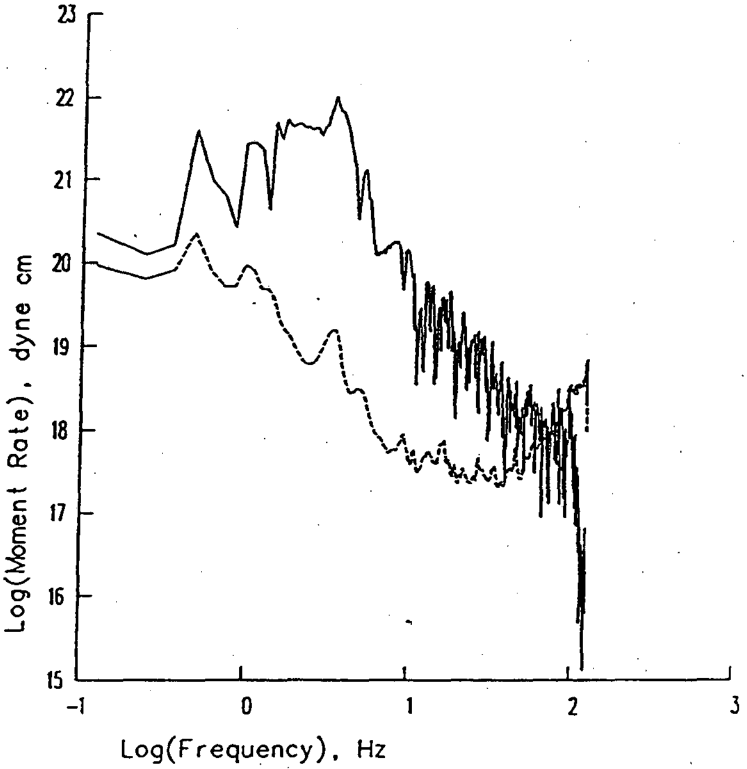
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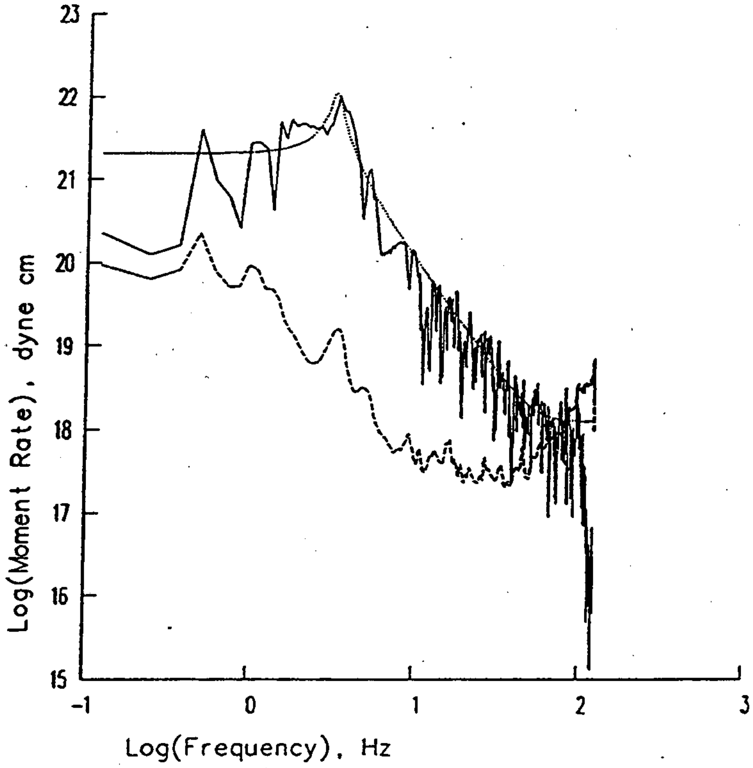
Log(Frequency), Hz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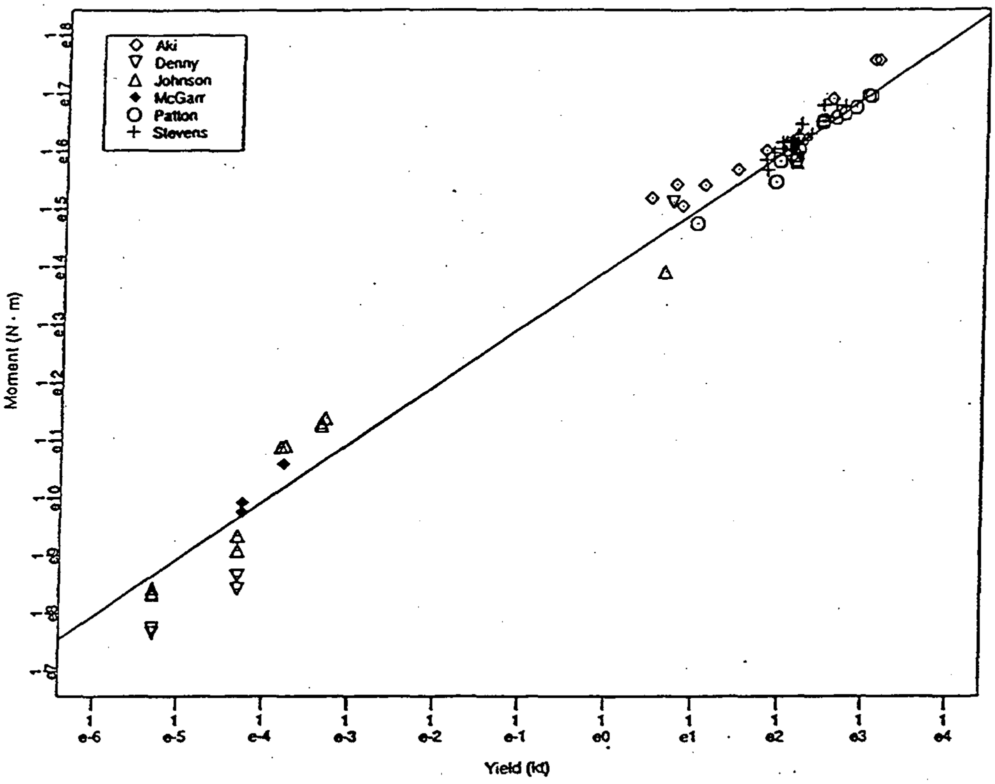
◇ Aki
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△ Johnson
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Moment (N · m)
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Yield (kt)

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