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24. We thank C. Finnie, H. F. Hinteregger, G. Purcell, T. Sato, L. Skjerve, D. Spitzmesser, and the staffs of the Goldstone and Haystack facilities for assistance in the engineering and technical aspects of the experiment, and the Mathematics and Computing Branch, Space and Earth Sciences Directorate, Goddard Space Flight Center, for support. We also thank D. L. Jauncey of the Arecibo Observatory and W. E. Howard III of the National Radio Astronomy Observatory for the use of the Mark I recording systems, and C. C. Counselman III and J. M. Moran, Jr., for critically reading the manuscript. The M.I.T. Haystack Observatory and the M.I.T. experimenters are supported in part by grants from the National Science Foundation. The Jet Propulsion Laboratory is sustained by NASA contract NAS 7-100.

14 May 1971

Underground Nuclear Explosions: Tectonic Utility and Dangers

Abstract. *The tectonic strain energy released by several underground nuclear explosions has been calculated through an analysis of seismic surface waves. The proportionally great amount of energy released in certain events suggests the possible uses for, as well as the hazards of, underground testing.*

Seismic waves generated by underground nuclear explosions quite often indicate complications arising from the interaction of the explosive source with the surrounding inhomogeneous medium. The clearest evidence of such an interaction is the generation of horizontally polarized *SH* and Love waves by many explosions. The radiation patterns of these waves and the mechanisms of their generation have been the subject of a number of studies (*1–4*). It is generally agreed that an explosion detonated in a prestressed medium radiates some ambient strain energy because of relaxation around the cavity and extended cracks. The extent of this relaxation and the amount of energy released have not, however, been accurately determined.

The radius of the zone of relaxation and the amount of tectonic strain energy release are two characteristics of nuclear explosions that are of extreme importance. The first consideration that depends upon a knowledge of these characteristics is the feasibility of utilizing underground explosions for earthquake control. Explosions might be effective in periodically releasing accumulating tectonic strain energy in active areas and, thus, could possibly prevent major earthquakes. The second consideration concerns the safety of large underground explosions. An explosion that releases very large amounts of strain energy would have the same effect as that of a large earthquake. If larger devices are tested in new locations where ambient stress patterns are not known, the strain release problem becomes more critical. As a third point, the release of large amounts of preexisting strain energy may affect some (but not all) of the seismic discrimination methods between earthquakes and explosions.

The cases that have been studied to date indicate that some strain energy was released by most nuclear explosions detonated in relatively hard media (*5*). However, the strain energy released was less than the equivalent seismic energy of the explosions themselves in all but one case. The exception was Hardhat, detonated in granite. The excessive strain energy release in this case was attributed to the possible triggering of an earthquake (*2*, *6*).

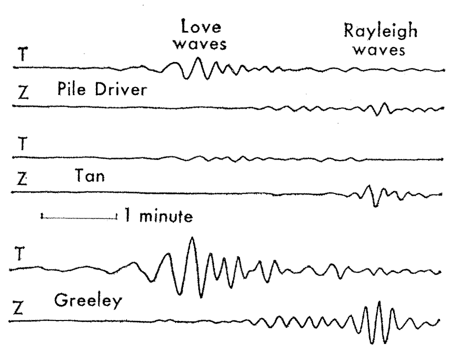


Fig. 1. Long-period filtered seismograms illustrating relative generation of Love waves by three explosions at the Nevada Test Site recorded at Weston, Massachusetts. Love waves appear on the tangential components (T) about 2 minutes earlier than the Rayleigh waves on the vertical components (Z). Note the large amplitude of Love waves relative to Rayleigh waves for Pile Driver and Greeley explosions.

We will report here on two other Nevada Test Site explosions (Pile Driver and Greeley), which generated large Love waves and released significant amounts of tectonic strain energy. Data from these events were obtained from LRSM (Long Range Seismic Measurements), WWSS (World Wide Standard Seismograph), and CSS (Canadian Standard Seismograph) system stations located throughout North America. The long-period records were digitized and filtered. The two horizontal components at each station were rotated to radial and tangential directions with respect to the explosions in order to separate the Love waves. The resulting tangential component (Love waves) and the vertical component (Rayleigh waves) were then Fourier-analyzed to obtain the amplitude spectra.

In Fig. 1, long-period seismograms of three explosions are illustrated. Tan, detonated near the other events, has been included as an example of a typical explosion that did not generate extensive Love waves. In this study both the radiation patterns of Rayleigh waves and the amplitude ratios of Love to Rayleigh waves were used to determine the strain energy release.

An explosion with associated tectonic strain release can be represented by a composite source consisting of an isotropic explosion component and a double-couple strain release component (*3*, *7*). On the assumption that the time delay between the explosion and the strain release and the differences between time functions of Love and Rayleigh waves are negligible, expressions for Rayleigh and Love wave far-field displacements from such a composite source are given by

$$U_R(\omega) = C_R(\omega)(1 + F \sin 2\theta) \exp [i(\omega t - k_R r)]$$
$$U_L(\omega) = C_L(\omega) \cos 2\theta \exp [i(\omega t - k_L r)] \quad (1)$$

where C_R and C_L are functions of frequency, distance, and the medium, ω is frequency, t is time, k_R and k_L are the Rayleigh and Love wave numbers, r is the radial distance from the source, θ is the azimuthal orientation of the double couple, and F, the parameter of greatest interest, is the strength of the double couple relative to the explosion.

If the differences between Love and Rayleigh wave attenuation and source time functions are considered negligible, the following expression is obtained for the amplitude ratio of Love over Rayleigh waves:

$$\frac{|U_L|}{|U_R|}=\frac{C_{LR}(\omega)\,F\cos 2\theta}{1+F\sin 2\theta} \qquad (2)$$

where C_{LR} is a function of frequency and the medium. An automatic error scheme was applied to fit the observed data in the 15- to 22-second range to this formulation (*4*). A grid was formed between the two parameters F and θ, which were then varied in small increments from 0 to 6.00 and from 0 to 180 degrees, respectively. For each combination of F and θ, the corresponding theoretical ratio was compared with the observed data and an error term was calculated. The resulting error terms were then contoured over the entire grid, and the minimum was taken to correspond to the true source parameters.

Figure 2 shows the best fitting Love over Rayleigh wave radiation patterns for Pile Driver and Greeley, with the observed data. The parameter F (strength of the tectonic double-couple component relative to the explosive source) determined for these two events was 3.2 and 1.6, respectively, in the 15- to 22-second range. In Fig. 3A, the best fitting Rayleigh wave pattern for Pile Driver is shown with the observed data and some filtered seismograms. In addition to amplitude, phase (polarity) has been included. The polarity reversals predicted by our best fitting theoretical model (since $F > 1$) are indeed observed when the Pile Driver data are compared with those of Tan.

The Rayleigh wave radiation pattern for Greeley is shown in Fig. 3B. In this case, the strength of the strain release component was close to that of the explosion, and the amplitudes of the inverted lobes were therefore small. Nevertheless, a very clear phase reversal can be observed relative to the Boxcar event as seen at LASA (Large Aperture Seismic Array, in Montana) from the data of Filson (*8*). The source model for the Hardhat event was studied by a similar technique and described in a previous publication (*9*). The results were almost identical to Pile Driver, and clear polarity reversals could be observed.

Table 1. Characteristics of tectonic strain release from a sampling of underground nuclear explosions. All events were at the Nevada Test Site except for Shoal (western Nevada) and Gnome (New Mexico). The F value is relative strength of tectonic strain release component. Energy ratios apply only to surface waves.

Explosion	Yield (kT)	Medium	F value	Energy ratio (E_{tect}/E_{exp})
Pile Driver	58	Granite	3.20	13.65
Hardhat	6	Granite	3.00	12.00
Greeley	825	Zeolitized tuff	1.60	3.41
Shoal	12.5	Granite	0.90	1.05
Boxcar	1200	Rhyolite	0.59	0.46
Bilby	200	Tuff	0.47	0.29
Tan	Low to intermediate	Tuff	0.39	0.20
Haymaker	56	Alluvium	0.33	0.14
Gnome	3.1	Salt	0	0

Since the radiation patterns of P waves are similar to those of Rayleigh waves, we investigated these body waves to determine any polarity reversals. The short-period records, however, appeared to be dominated by the explosive component and near-source irregularities. Only on the long-period components of three stations did P waves from Greeley appear reversed relative to Boxcar. These stations were located to the northeast in the azimuthal range, where Rayleigh wave reversals were predicted. In the case of Pile Driver, the long-period P waves were far too small to be useful.

The source data for the three explosions of concern, Hardhat, Pile Driver, and Greeley, as well as for some other events, are summarized in Table 1. Most of these events are in Nevada. For two events in the Aleutians (Longshot and Milrow) we could not find sufficient surface wave data because of poor station coverage. The available data seem to indicate, however, that, for Milrow, $F \leq 0.6$. For two presumed explosions in the U.S.S.R., we found F values to be 0.80 and 0.67, comparable to Shoal and Boxcar values. In addition to double-couple strengths, we have computed the ratio of surface wave energy of the double-couple component E_{tect} to the surface wave energy of the explosion in the 15- to 22-second range. This ratio (*3*) is closely approximated by

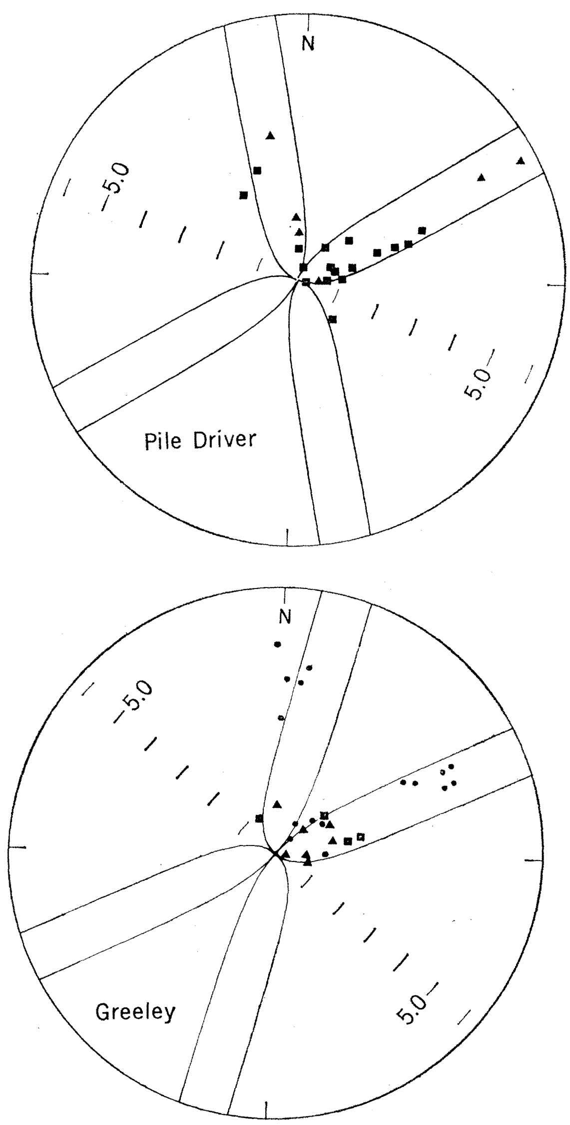
$$E_{tect}/E_{exp} = 4/3\,F^2$$

Energy ratios are also listed in Table 1.

Several conclusions can be derived from these data. Generally (in the Nevada Test Site), explosions in harder media such as granite release more tectonic strain energy than do explosions in softer formations such as tuff or alluvium. These softer media have low rigidities and cannot accumulate shear strain energy because of plastic deformation under stress. Salt is a very good example of such a plastic medium. None of the explosions in salt generated measurable Love waves. Not all explosions in a given medium, however, have proportionally the same strain release associated with them, as indicated by Shoal versus Pile Driver and Hardhat. Thus, in addition to a rigid medium, high ambient tectonic stresses are important in determining the strain energy release by an explosion. The similarity of the Pile Driver and Hardhat results indicate (i) that the regional tectonic framework controls the radiation pattern, (ii) that, in a given medium and area, each explosion releases strain energy proportional to its own explosive energy, and (iii) that the spontaneous energy release comes from the vicinity of the shot rather than from an earthquake triggered at a distance of 10 km or more. Strain adjustments at such distances appear to take place gradually, as is indicated by the spread of aftershock activity that follows some large explosions (*10*).

The implications of these results in terms of the utility of nuclear explosions for the release of tectonic stresses and earthquake control are encouraging. Since an explosion can release accumulated strain energy considerably greater than its own (more than ten times greater in the cases of Pile Driver and Hardhat) in the vicinity of the shot point, such events could be used to relax small regions. One possible application would be to deactivate a site in a seismically active region prior to the construction of a project such as a nuclear power plant. However, at present we do not know how long it takes for the tectonic stress field to build up to its initial level after an explosion. Furthermore, an explosion releases strain energy from a relatively small volume. Regional strain fields of major tectonic zones are not likely to be affected by a single explosion. The locations of Hardhat and Pile Driver shots were only about ½ km apart. Yet Pile Driver, detonated 4 years after the Hardhat explosion, radiated proportionally the same amount of strain energy. This does not necessarily mean that strain energy reaccumulated at the Hardhat site in only 4 years. Since the yield of Pile Driver was ten times greater than that of Hardhat, the stress relaxation (primarily due to cracking) probably extended beyond the relaxation zone of the Hardhat explosion. Thus, tectonic strain energy was released from a larger volume in the case of Pile Driver. More work must be done before all aspects of this problem are understood. The use of explosions to release tectonic strain energy in areas that are already developed is, however, clearly not feasible.

For the same reasons that explosions could prove useful, nuclear testing in regions of high ambient



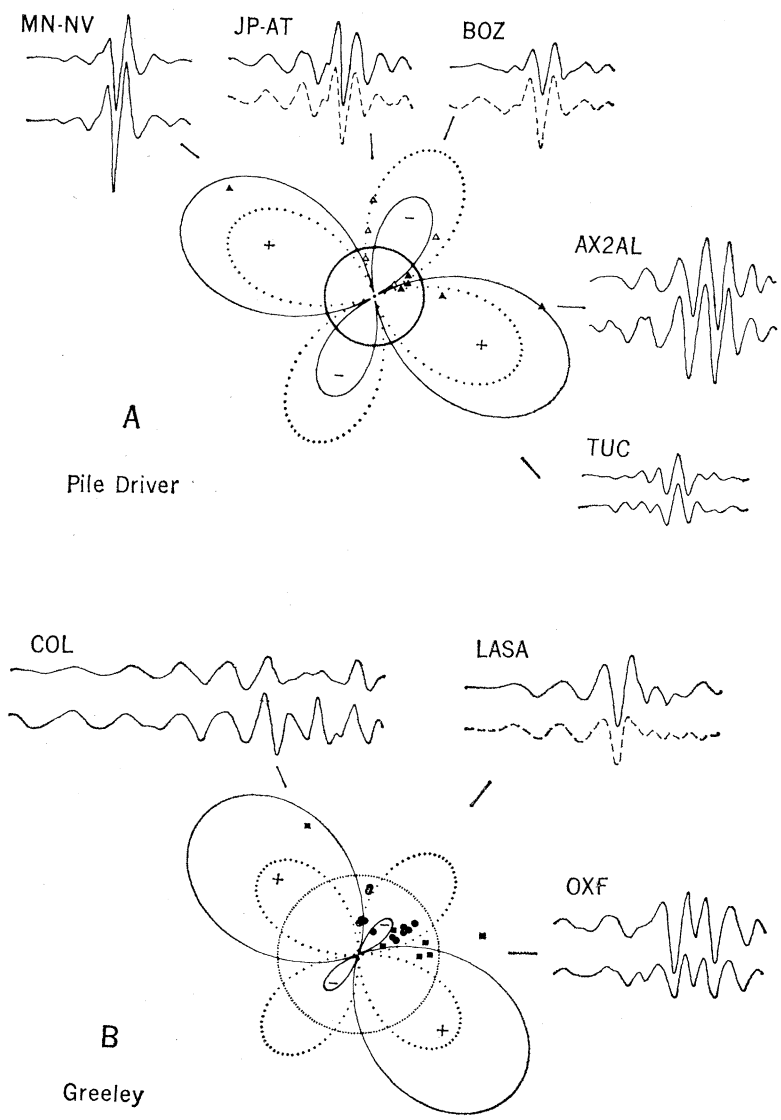


Fig. 2 (left). Amplitude ratios of Love over Rayleigh waves as a function of azimuth for Pile Driver and Greeley. For theoretical curves (solid lines), the following parameters were used: orientation (θ) and strength of double-couple (F), 340° from north and 3.2, respectively, for Pile Driver, and 355° and 1.6 for Greeley. Data symbols: ■, WWSS stations; ▲, LRSM stations; ●, CSS stations. Fig. 3 (right). Rayleigh wave radiation patterns for explosive component (circles), strain release component (broken curves), and composite source representing the theoretical models (solid curves, with parameters those of Fig. 2). The polarity (phase) of Rayleigh waves in different quadrants of the radiation pattern is indicated by (+) and (−). (A) Pile Driver with seismograms compared to those of Tan. Amplitude factors are arbitrary. Pile Driver traces are below those of Tan. Dashed line traces have their polarities reversed. Note the perfect match of wave shapes, with polarities reversed at JP-AT and BOZ as predicted by the model. MN-NV, Mina, Nev.; JP-AT, Jasper, Alta.; BOZ, Bozman, Mont.; AX2AL, Alexander City, Ala.; TUC, Tucson, Ariz. (B) Greeley with seismograms compared with those of Halfbeak (COL and OXF) and Boxcar (LASA). The lower traces are from Greeley. Polarity reversal is very clear at LASA. COL, College, Alaska; LASA, Large Aperature Seismic Array, Mont.; OXF, Oxford, Miss. Data symbols: ▲, LRSM stations; △, LRSM stations where reversed polarity was observed; ■, WWSS stations; ●, CSS stations.

stresses might have serious consequences. Since the medium properties, and not the shot yield, control the proportion of energy release, a large explosion could release large amounts of tectonic strain energy. For example, with the energy factor of Pile Driver or Hardhat, a 1-megaton explosion could release energy equivalent to that of a magnitude $M_S = 6.3$ earthquake. For a 10-megaton explosion, this could be equivalent to a magnitude $M_S = 7.2$ earthquake, indeed a potentially destructive earthquake. Thus, in any testing program, these factors must be taken into account, and hard media should be avoided unless the ambient stress levels are known to be low.

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8 March 1971

Fossil Fuel Combustion and the Major Sedimentary Cycle

Abstract. *The combustion of the fossil fuels coal, oil, and lignite potentially can mobilize many elements into the atmosphere at rates, in general, less than but comparable to their rates of flow through natural waters during the weathering cycle. Since the principal sites of fossil fuel combustion are in the mid-latitudes of the Northern Hemisphere, changes in the composition of natural waters and air, as a consequence of this activity, will be most evident at these latitudes.*

The combustion of fossil fuels (fuel oils, lignite, coal, and natural gas) may introduce some elements into the atmosphere and subsequently into the oceans at rates comparable to those of natural processes. Previous work has indicated that the rate at which sulfur is introduced into the atmosphere by fuel burning appears to be the same as that for the combined emissions from anaerobic areas and from volcanism, two processes that do not involve man (*1*). The amount of carbon dioxide introduced into the atmosphere in 1967 by energy production, 13×10^{15} g, is close to the amount of carbon dioxide produced by photosynthesis on land and on sea, 50×10^{15} g (*2, 3*). More lead has been transferred from the land to the oceans by the use of tetraethyl lead as an antiknock additive in gasolines than has been added to the marine environment through rivers (*4*).

Such figures prompted us to investigate what other elements might be mobilized about the surface of the earth as a result of fossil fuel combustion and to compare the potential rates of movement of these elements with those observed for elements entering the oceans each year by way of the rivers as a result of weathering processes upon the continents.

The total amounts of fossil fuels produced in 1967 and presumably the amounts consumed in 1967 were as follows (*3*): coal, 1.75×10^{15} g; lignite, 1.04×10^{15} g; fuel oils, 1.63×10^{15} g; and natural gas, 0.66×10^{15} g. The estimated world production of crude oil (1969) amounted to 2.13×10^{15} g, of lignite (1970) to 0.77×10^{15} g, and of bituminous plus anthracitic coal (1970) to 2.18×10^{15} g (*5*). Although the yearly production figures for solid fuels, that is, coal plus lignite, appear to be static at the present time, there is a substantial yearly increase in the production and consumption of petroleum.

The amount of an element entering the world's oceans yearly as a result of the weathering cycle can be obtained from river discharge and composition data or from rates of sedimentation in marine areas (*6*). The river data reflect the transfer of dissolved phases, whereas the sedimentation data take into account the movement of both the dissolved and the particulate loads of rivers. Both techniques depend upon global averages of geologic parameters, and these numbers are characterized by a certain degree of uncertainty.

Since the river load of particulate matter is, on the average, four times higher than that of the dissolved phases, the mobilization calculated from the dissolved contents of rivers would be expected to be less than that from sedimentation values. Such is the case for two-thirds of the elements considered in Table 1. However, the significance of the exceptions is difficult to evaluate. More important for this study is the order of magnitude and the relative rank for the dispersion of a given element during the weathering cycle.

It is possible to determine only approximately the percentage of the ash from the fuel burning that actually enters the atmosphere as compared with the percentage that is incorporated in the furnace residues, the so-called bottom ash. Estimates made over the past several decades at the U.S. Bureau of Mines (*5*) suggest that the fly ash released to the atmosphere appears to be about 10 percent of the total ash in coals and perhaps a similar value is applicable to the combustion of liquid petroleum fuels. Thus, for the elements listed in Table 1 we have reduced by a factor of 10 the potential amount of material that might enter the atmosphere from the burning of coal and oil.

An additional correction on the computations for coal involves the amounts that are combusted in power production and in the manufacture of coke. Estimates at the U.S. Bureau of Mines (*5*) suggest that there is about an equal division of the bituminous and anthracitic coals between these two uses. Hence, for the elements listed in Table 1 we have applied a reduction factor of 2 to the potential amount of material that might enter the atmosphere from the combustion of coal and lignite.

Thus far, we have assumed that the elements are accommodated in either the fly ash or the bottom ash during the combustion process and are not introduced as volatile species to the atmosphere. Clearly, selective volatilization can introduce the readily distillable materials into the atmosphere at concentrations far above those indicated in Table 1. An indication of what