AMPLITUDES OF SEISMIC WAVES ON ICE SHEET IN EAST ANTARCTICA

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***Abstract*:** In 1979–81, ten shots were fired in drill holes at the Prince Olav Coast and the Mizuho Plateau, Antarctica, for explosion seismic experiments by JARE-20, -21 and -22. The yield ranged from 10 to 1400 kg. An empirical relationship between yield and maximum amplitude of seismic wave was derived for shots in drill holes in ice sheet. This will help to design an adequate charge size for explosion seismic experiments in Antarctica. The maximum amplitudes obtained are compared with those generated from explosion in sea water in Antarctica and in solid rock in Japan. For yields smaller than 500 kg, the logarithm plots of the amplitudes are in a linear relation with the logarithm of yields, and the amplitudes are about 1/5 to 1/8 of those generated in solid rock. For the yields larger than 500 kg, the wave amplitudes in the ice sheet become larger than those estimated from the above relationship. The amplitude of the biggest shot of 1.4 t detonated in the ice sheet is nearly the same as that in solid rock in Japan. This is because small shots were fired in shallow drill holes where the ice is very porous, its density is only about 500 kg/m^3. The biggest shot was fired at a depth of 140 m in the ice with a density of 800 kg/m^3 or greater. The maximum amplitudes of seismic waves generated from a 1-t explosion in sea water are about 8 to 10 times larger than those from equivalent explosions in the ice sheet. The relation is similar to the results obtained for shots in sea water and solid rock in and around Japan.

1. Introduction

In 1979, members of the 20th Japanese Antarctic Research Expedition (JARE-20) fired a charge of 560 kg of dynamite in a drill hole in the ice sheet at the Prince Olav Coast to study the crustal structure of Antarctica (IKAMI *et al.*, 1981). The amplitudes of the seismic waves, however, were unexpectedly smaller than those produced by explosions of the same size in drill holes on land in Japan. In order to succeed in the following large-scale seismic experiments planned by JARE-21, an adequate design of yields has been required. We carried out a preliminary experiment at the Prince Olav Coast in the early part of the 1980 wintering season. Seven shots with yields ranging from 10 to 100 kg were fired in drill holes in the ice sheet to find an empirical relationship between the maximum amplitude of seismic wave and the yield. On the basis of this relationship, the large-scale experiments by JARE-21 were conducted. The seismic waves observed in the JARE-21 experiments, however, were large against expectation.

We, in the present paper, describe the relationship obtained using all the data from JARE-20, -21 and -22 experiments. We also compare the results with those obtained in and around Japan for explosions in drill holes on land and in sea water.

2. Data

Shot points and yields of explosions carried out by JARE are listed in Table A-1 of the Appendix. Detailed descriptions of the experiments were published by IKAMI *et al.* (1980) and ITO *et al.* (1983). Ten shots ranging from 10 to 1400 kg were fired in drill holes at depths of 5 to 140 m in the ice sheet at the Prince Olav Coast and at the Mizuho Plateau, East Antarctica. The seismic waves on the ice sheet recorded with a seismograph which consists of a vertical, velocity-transducer (natural frequency of 2 Hz and damping constant of 0.7), three amplifiers with different magnifications, a

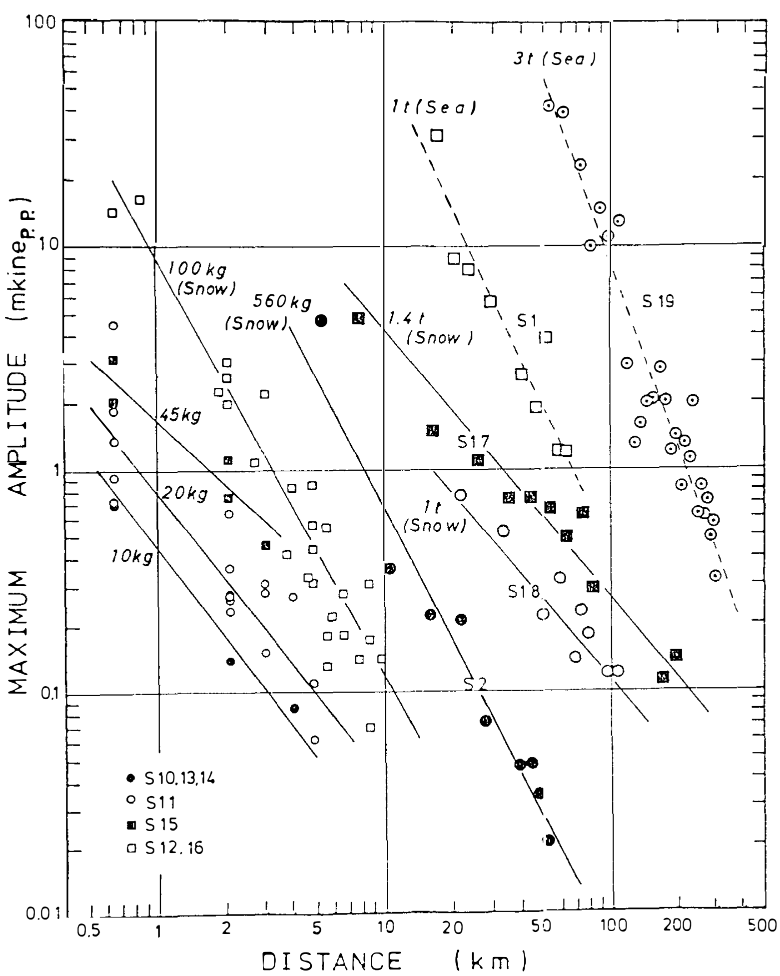

Fig. 1. Maximum amplitude of P-wave vs. shot-detector distance for shot fired in an ice sheet and in sea water in Antarctica. Symbols indicate differences in yields. For shot numbers refer to Table A-1 of the Appendix.

direct-analogue data-recorder, a crystal clock and batteries. The overall frequency response is flat from 2 to 20 Hz. It is sufficient to observe explosion seismic waves, since their frequency contents range mostly from 5 to 15 Hz (IKAMI *et al.*, 1981). The peak-to-peak maximum amplitudes of the *P*-waves were measured on the seismograms and plotted against shot-detector distances (Fig. 1). Explosions in sea water in Antarctica are also included in Fig. 1. The maximum velocity amplitude of the *P*-waves is given in mkine (1 kine = 1 cm/s) and the distance in km. Symbols indicate the difference in yield. The variation of amplitude with distance is so large that we tried to fit a line on the log-log plot of data for each shot.

3. Relationship between Amplitude and Yield

In order to derive an empirical but simple relationship between amplitude and yield, amplitude normalization at a fixed reference distance is necessary. Assuming that, as shown in Fig. 1, the logarithm of amplitude is in a linear relation with the logarithm of distance, the gradients of the lines were averaged to be -2. Then the amplitude is normalized at a shot distance of 50 km as shown in Fig. 2 for Shots 12 and 19. The normalized amplitudes for shots in Antarctica are given in Fig. 3, where asterisks show all the shots fired by JARE-20 to -22 in the ice sheet; diamonds indicate shots in the sea water. The following equation can be fitted to the data in Fig. 3 for yields less than 560 kg.

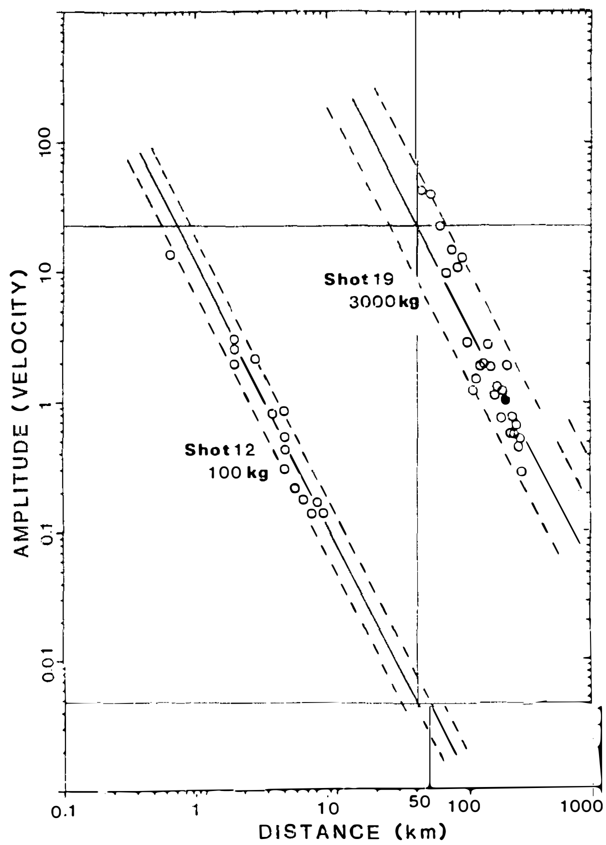

Fig. 2. Examples indicating the method of amplitude normalization.

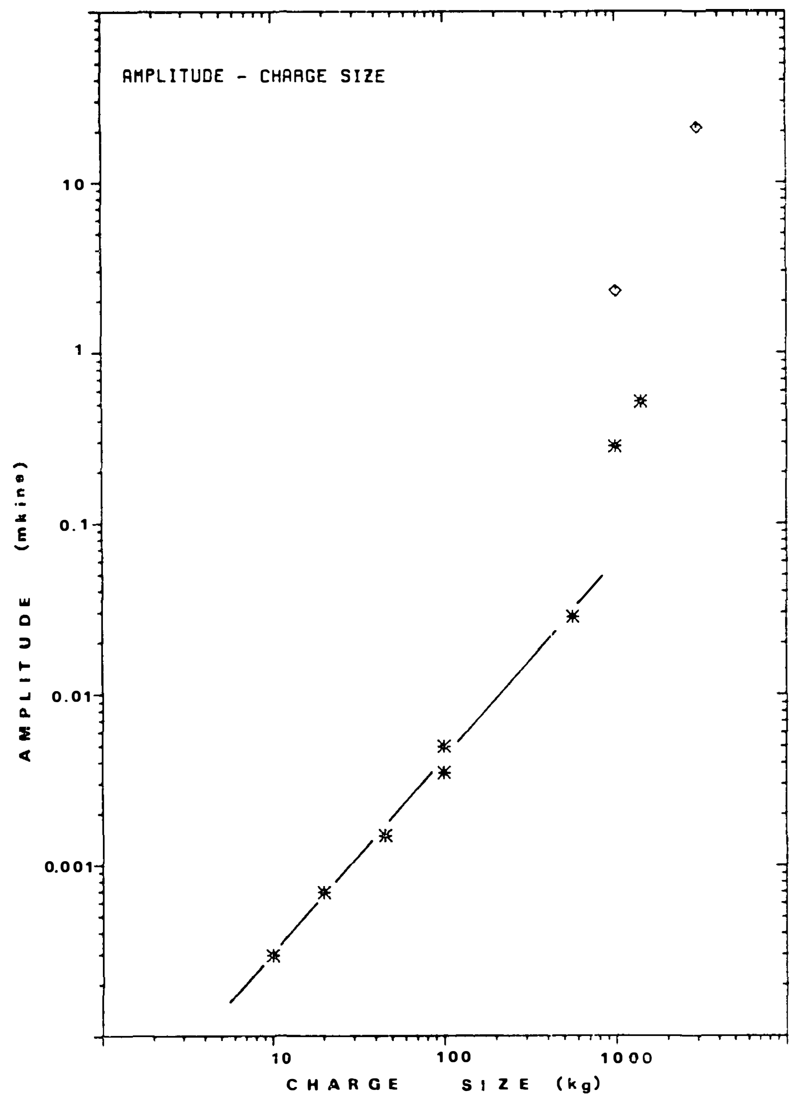

Fig. 3. Maximum amplitude of P-wave (mkine) vs. yield (kg), normalized at a shot distance of 50 km for explosions in the ice sheet (asterisks) and in sea water (diamonds) in Antarctica. A line can be fitted to the data for charge sizes less than 560 kg in this log-log graph.

$$\text{Log } V_{\max} = 1.14 \log W - 2 \log D - 1.27, \qquad (1)$$

where $V_{\max}$ is the maximum peak-to-peak velocity amplitude measured in mkine, W yield in kg and D the shot distance in km.

For yields larger than 560 kg, the relation does not hold; the observed amplitudes become larger than those given by the above formula. It is five times as large as that estimated from the equation for a 1-t yield. This is because the small shots were fired in shallow drill holes in the ice sheet where the ice is very porous with a density less than 700 kg/m^3, whereas the large shots in the deep drill holes with a density 800 kg/m^3 or greater. In Fig. 4, the bulk density and concentration of air bubbles *vs.* depth are given with a sketch of core texture for the ice core at Mizuho Station after NARITA *et al.* (1978), adding the depths of explosives of our experiments.

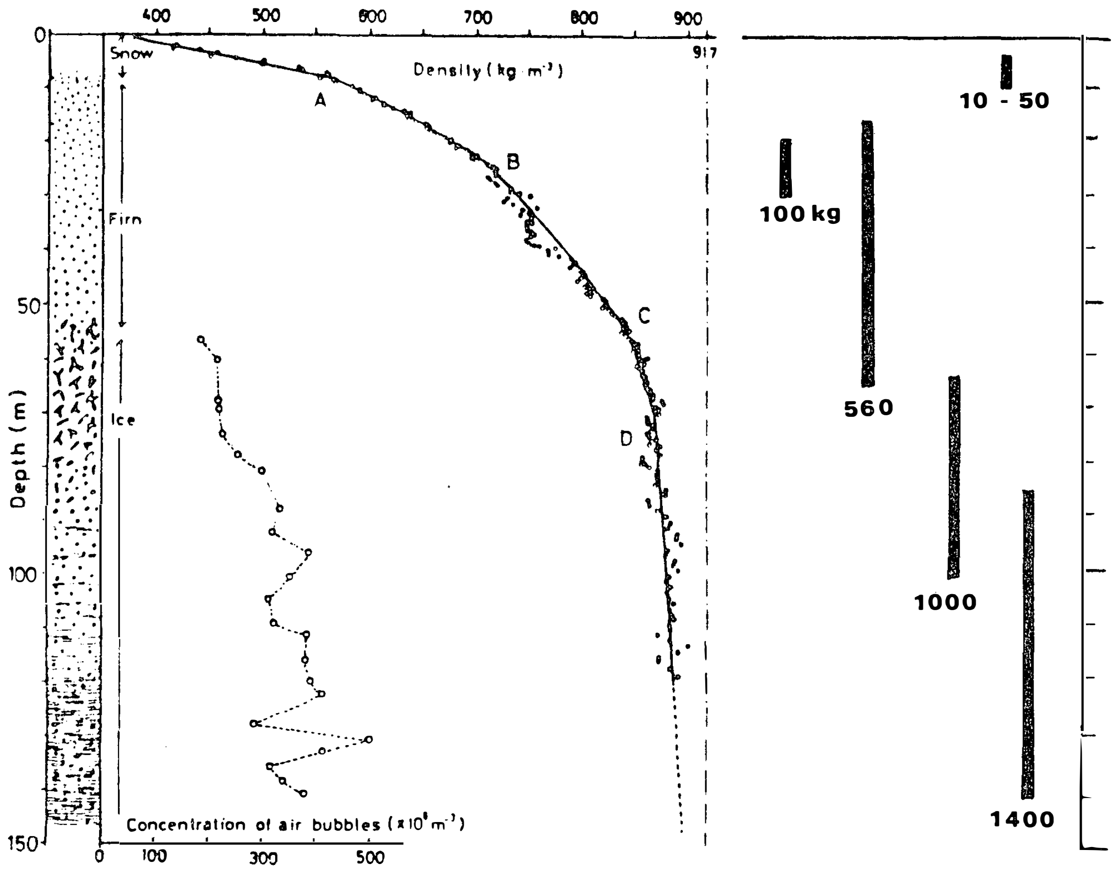

Fig. 4. Bulk density and concentration of air bubbles vs. depth together with a sketch of core textures for the drilled core at Mizuho Station after NARITA et al. (1978). The depths of explosives of our experiments are added in the right part of the figure, where numerals indicate charge sizes.

The depths of the shots with yields less than 560 kg were fired are shallower than 64 m in the ice sheet, in which the ice density steeply increases with depth from 300 to 800 kg/m^3. As shown in Fig. 4 the ice density changes at a depth of about 55 m, as firn changes to ice. The large shots were fired in the drill holes deeper than 64 m where the density is 800 kg/m^3 or greater increasing gradually with depth.

4. Discussion

A similar analysis was made for explosions in Japan. The maximum amplitudes of P-waves normalized at a distance of 50 km are plotted in Fig. 5 together with the results in Fig. 3. Symbols indicate combinations of shot and observation sites. Sea-ice (diamonds) and ice-ice (asterisks) data are the same as those shown in Fig. 3. Other data were provided by the Research Group for Explosion Seismology in western and central Honshu, Japan (RESEARCH GROUP FOR EXPLOSION SEISMOLOGY, 1966, 1981, 1982). The rock-rock data (octagons) mean that the explosions were fired in drill holes 40 to 100 m deep in solid rock and the observations were made on outcrops on land. The sea-rock data (pluses) mean that the shots were fired in sea water and the

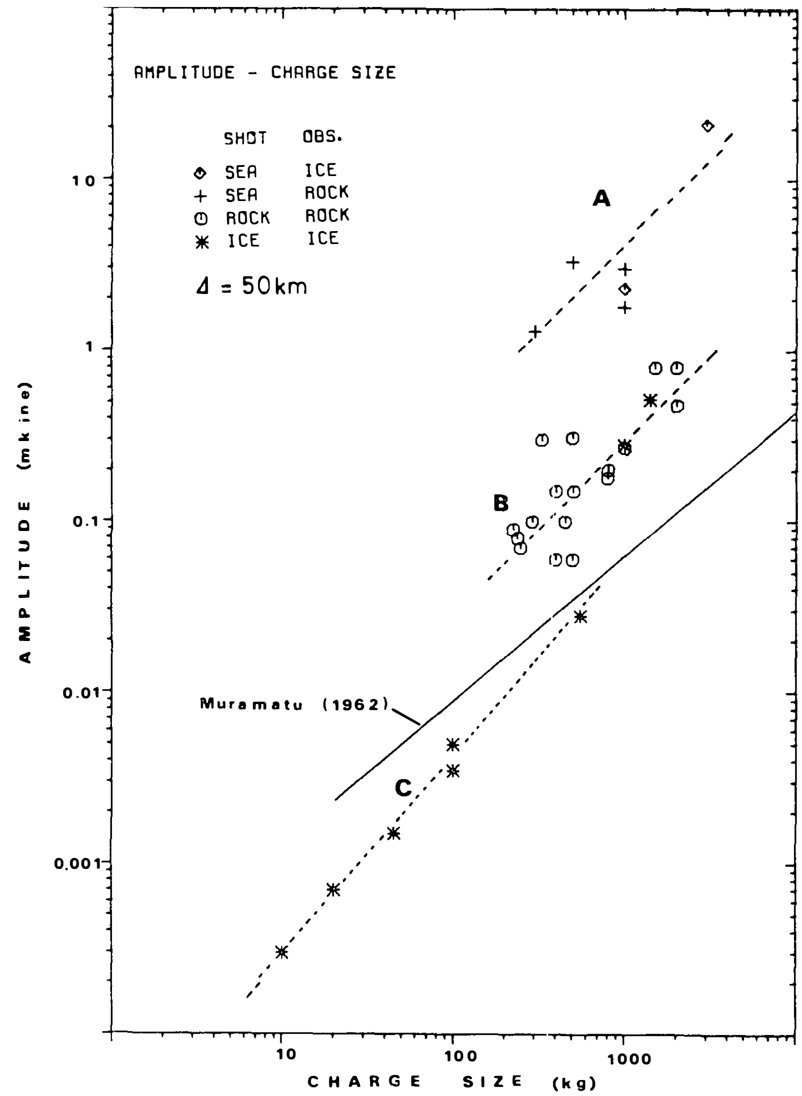

Fig. 5. Maximum amplitude of P-wave vs. charge size normalized at a shot distance of 50 km. Symbols indicate the combinations of shot and observation sites. The data can be divided into three sets, A, B and C.

seismic observations were made on outcrops on land. The profile lines are 150 to 300 km long in both cases.

We can divide the data shown in Fig. 5 into three sets. The amplitudes of each set are roughly proportional to yield. Set A consists of sea-rock data (pluses) and sea-ice data (diamonds). Shots in sea water give nearly the same amplitudes regardless of the location of the observation sites. Set B consists of rock-rock data (octagons) and ice-ice data for large yields (asterisks) and set C is for the ice-ice data discussed in the previous section. If we assume that the amplitude is proportional to yield, the amplitudes of set A are 8 to 10 times larger than those of set B, and the amplitudes of set B are 5 to 8 times larger than those of set C. The amplitudes of shots less than 560 kg yield in the ice sheet are 1/5 to 1/8 of shots detonated in solid rock. The amplitude of the 1-t yield shot in the ice sheet belongs to set B, not set C, since it was fired at a depth of 100 m where the ice density is about 870 kg/m^3. More data for small shots in deep drill holes are needed to define the sudden increase of amplitude with yield at the density around 800 kg/m^3.

MURAMATU (1962) derived a relation between yield, shot-detector distance and velocity amplitude for explosion seismic data in Japan. His result is represented in Fig. 5 by a solid line. The coefficient of log D in Muramatu's formula, which represents the attenuation of amplitude with distance, is eventually the same with ours. He included quarry blast data for large yields of 7 to 10 t but amplitudes from quarry blasts are usually much smaller than those of shots of the same size in deep drill holes on land. Therefore, predicted amplitudes derived by Muramatu's empirical relationship come out lower than those predicted by our formula.

Acknowledgments

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