Reports

Long-Period Seismic Waves from Nuclear Explosions in Various Environments

Abstract. Large nuclear explosions in the solid earth, the hydrosphere, and the lower and upper atmosphere have generated seismic waves of periods greater than about 5 seconds which have been detected at great distances from the source.

Large nuclear explosions have been detonated in a wide variety of environments including (i) the atmosphere at heights ranging from near zero to about 40 miles, (ii) the hydrosphere at both shallow and great depths, and (iii) the solid earth. In each case, seismic waves of long periods (greater than about 5 seconds) were detected at great distances from the source. This report is a brief summary of the principal evidence now available on this subject, parts of which have already been published in widely scattered places. Some emphasis is placed on unusual features which might not have been anticipated from prior knowledge of seismic wave generation based only on data obtained from small explosions and earthquakes. No attempt is made to give a comprehensive survey of the evidence on seismic waves of short periods,—periods of the order of a few seconds or less—generated by nuclear explosions, or of the dependence of wave amplitudes on yield of the explosion in the case of long-period waves.

Explosions in the atmosphere—near surface. Surface waves recorded at Palisades, New York, from explosions in the air over Nevada and over the Marshall Islands have been reported previously (*1*). Waves corresponding to the fundamental Rayleigh mode in the period range between 14 and 7 seconds were recorded from these Nevada explosions. Waves corresponding to the fundamental Rayleigh mode for each segment of the mixed oceanic-continental path from the Marshall Islands were recorded in the period range between 45 and 15 seconds. Since the original paper was published, new and more sensitive instruments operating at Palisades in the same general period range have detected long-period body waves from Marshall Island explosions. These body waves are of the multiple, surface-reflected types, since Palisades is in the shadow zone for direct *P* and *S* waves.

In the case of the Marshall Island shots, Rayleigh waves similar to those recorded at Palisades were also recorded at many stations (for example, Kogan, *2*) throughout the world, apparently wherever long-period seismographs of adequate sensitivity were in operation. No evidence for generation of Love waves by the Marshall Island shots is known to us.

Long-period waves have also been detected at many stations throughout the world from nuclear explosions at the arctic testing site in Novaya Zemlya of the U.S.S.R. (for example, Brune, *3*). In general, these waves are similar to those from shots in the Marshall Islands, that is, the largest waves correspond to the fundamental Rayleigh mode, regardless of whether the path is simple or complex (mixed oceanic and continental). The periods of these waves range from 50 to 5 seconds, the limiting values in a given case depending partly upon the nature of the path. When ultrasensitive instruments such as those at Palisades were used, long-period waves, including *P*, *S*, and the multiple surface reflections of each, were recorded occasionally.

Seismographs at Uppsala, Sweden, and Agra, India, clearly recorded waves corresponding to the first shear, or M_2, mode from explosions at the arctic site. The Hong Kong station clearly recorded Love waves from arctic explosions. Love-wave generation is extremely unusual in the case of an explosion in the air, and the amplitudes of the Love waves at Hong Kong are an order of magnitude less than those of Rayleigh waves of the same period at that station. There is, however, no question about the identification. Although no official data has been released on the U.S.S.R. explosions, origin times and epicenters deduced from seismic data may be found in the bulletin of the Uppsala seismograph station (*4*). The large air waves, frequently recorded by vertical-component seismographs, as well as microbarographs, suggest that the events took place within the lower atmosphere. For a more detailed study of some waves generated by U.S.S.R. explosions see Brune *et al.* (*3*).

Explosions in the atmosphere—high altitude. The two large nuclear explosions Teak and Orange, fired in the Johnston Island area of the Pacific by the United States in August 1958 unexpectedly generated long-period seismic waves with amplitudes comparable to those generated by the large explosions in the Marshall Islands. According to press reports, Teak and Orange were detonated at altitudes of "about 40" and "about 20" miles, respectively. In contrast, the excitation of short-period seismic waves by high-altitude explosions was apparently very much less than by the near-surface Marshall Island shots. At Palisades, the ultrasensitive instruments detected waves of the fundamental Rayleigh mode as well as body waves, including *P*, *S*, and surface-reflected combinations of *P* and *S*, all with amplitudes comparable to those of the same waves from the Marshall Islands.

Long-period instruments in Honolulu recorded waves corresponding to both the normally dispersed and the inversely dispersed branches of the fundamental Rayleigh mode for oceanic paths. For such paths, the inversely dispersed branch has never been reported when the source was an earthquake. A detailed study of the waves from these high altitude explosions is in preparation (*5*).

Explosions in the ocean. A study has already been published on the seismic waves generated by Wigwam (*6*). This explosion also generated waves corresponding to both the normally and inversely dispersed branches of the fundamental Rayleigh mode. These waves were recorded on the west coast of North America and, after crossing the continent as Rayleigh waves, on the east coast of North America. Waves corresponding to the first shear mode for an oceanic crustal structure were also identified at California stations. The explosion generated unusual *P* and *S* waves as a result of reverberation within the water layer and also made a short-period *T* phase of such intensity that it was felt and misidentified as a local earthquake on the island of Oahu ($\Delta \sim 30°$).

Instructions for preparing reports. Begin the report with an abstract of from 45 to 55 words. The abstract should *not* repeat phrases employed in the title. It should work with the title to give the reader a summary of the results presented in the report proper.

Type manuscripts double-spaced and submit one ribbon copy and one carbon copy.

Limit the report proper to the equivalent of 1200 words. This space includes that occupied by illustrative material as well as by the references and notes.

Limit illustrative material to *one* 2-column figure (that is, a figure whose width equals two columns of text) or to *one* 2-column table or to *two* 1-column illustrations, which may consist of two figures or two tables or one of each.

For further details see "Suggestions to Contributors" [*Science* **125**, 16 (1957)].

Explosions in the solid earth. Surface waves from the two largest nuclear explosions fired deep underground in Nevada were recorded at Palisades. Rayleigh-wave trains very similar to those recorded when the source was in the air over Nevada were detected. Periods of these waves range from about 13 to 6 seconds. In addition, Love waves in the period range between 19 and 7 seconds with amplitudes generally comparable to those of the Rayleigh-wave train were recorded. Identification of these waves is quite certain, being based on measurement of group velocity, phase velocity between Waynesburg, Pennsylvania, and Palisades, surface particle motion, and correlation between the two shots. Furthermore, Love waves in the same period-range were also recorded from one of these underground explosions by similar instruments at Resolute Bay, Northwest Territories, Canada. In this case, the amplitudes of the Love waves are, in general, larger than those of the Rayleigh waves. This surprising result indicates that the heterogeneities of the earth which are effective in producing transverse horizontally-polarized shear waves of short period, as indicated by data from nuclear explosions, are also effective in the case of wavelengths as great as at least 70 kilometers.

A discussion of methods for use of dispersed trains of long-period surface-waves to obtain information on the source, including an illustration based on Rayleigh waves from an underground explosion in Nevada recorded in Wyoming, has been published (*3*).

Most chemical explosions are considerably smaller in yield than the nuclear explosions discussed here. One study of surface waves from very large chemical explosions is that of Kogan *et al.* (*7*). Their results, based on two such explosions, suggest that long-period waves are excited more efficiently by natural earthquakes than by explosions of the same magnitude, but data are limited.

Although there is great contrast between the explosive sources discussed in this paper and natural earthquakes, and although several unexpected waves were generated by nuclear explosions, virtually all the waves so generated can be identified and explained in terms of our knowledge of seismic-wave propagation based on earthquake data. This clearly illustrates the great value of coordination between studies of these two closely related phenomena.

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References and Notes

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8. The research reported here was partially supported by the Air Force Cambridge Research Center, the Office of Naval Research, and the National Science Foundation. This report is Lamont Geological Observatory contribution No 419.

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Early Man Site Found in Highland Ecuador

Abstract. Field investigations in Ecuador have produced archeological evidence for the occupation of the northern Andes by early nomadic hunters. Surface collections and test excavations have demonstrated a complex of stone tools with typological relationships to level I at Fell's Cave in southern Chile, and technological relationships to the late Pleistocene "fluted point" complexes of North America. The date of these materials is estimated at 7000 to 8000 B.C.

From 23 January to 7 February 1960 we carried out preliminary investigations at an early archeological site in the Ecuadorian Andes near Quito. We located the site which had been reported to us earlier by Allen Graffham, an Ardmore, Okla., geologist, and collected a large number of obsidian and basalt artifacts from the surface of El Inga, a badly eroded hillslope flanking Ilalo Mountain, near the town of Tumbaco.

Obsidian artifact types found include several styles of projectile points, side and end scrapers, ovate blades, gravers, drills, prismatic blades, microblades, and small hemispheric polyhedral cores. Two projectile point styles appear from field observation to be most significant: the dominant style is a large stemmed point (Fig. 1*A*), identical in form to the points which characterize level I at Fell's Cave in Chile (*1*); one of the several minority styles, found only in fragments, is a lanceolate form (Fig. 1*B*) like the North American Clovis point. Both of these styles are characterized by basal and edge grinding and have irregular channel flakes removed from either one or both faces. They are, in fact, "fluted" points of two distinct forms.

Basalt artifacts are generally irregular, but well-made scrapers, choppers, "pulping planes," and manos, as well as used flakes and cores, have been recovered.

Two test excavations made in one of the uneroded portions of the site demonstrated that the artifacts are contained in the layer of dark soil 12 to 15 inches thick that comprises the soil mantle at the site. These tests clearly demonstrate the feasibility of extensive excavation at El Inga.

Typologically, there seem to be many elements at El Inga previously unknown in South America. The stemmed point of the Fell's Cave type seems the best chronological marker; in Chile it is associated with extinct sloth and horse, and has been dated by carbon-14 at 6900 B.C. The presence of the fluting technique and channel flake removal, as well as the lanceolate form, suggest early North American types. The presence of blades and microblades is rare for South America, but probably also

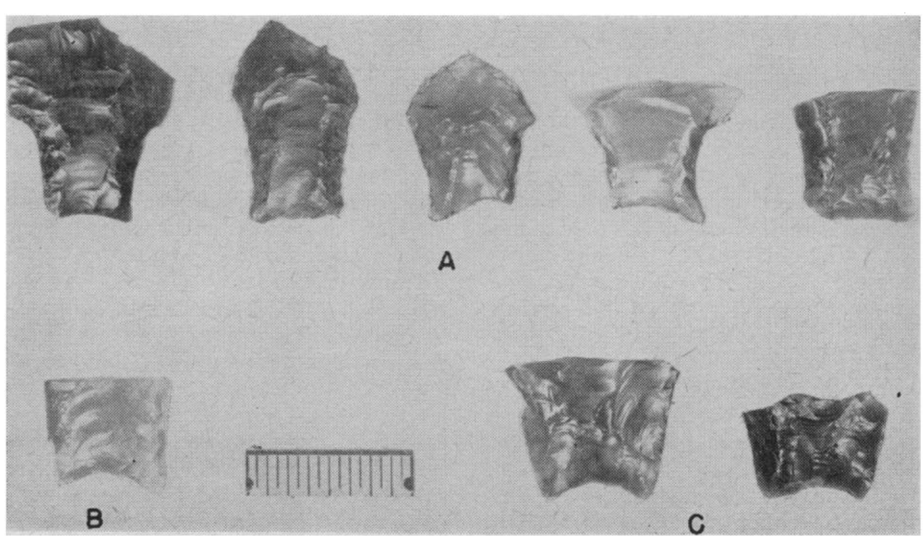

Fig. 1. Projectile points from El Inga, Ecuador. Marker represents 1 inch. (*A*). Fell's Cave (level I) stemmed type (fluted): (*B*). Base of "Clovis fluted" type. (*C*). Thinned bases of lanceolate type.