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Seismic excitation by the space shuttle Columbia

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SEISMIC stations in southern California recorded the atmospheric shock waves generated by the space shuttle Columbia on its return to the Edwards Air Force base on 13 August 1989 (Fig. 1). In addition to the shock wave, the broad-band IRIS–TERRAscope station at Pasadena recorded a distinct pulse with a period of ~2–3 seconds, which arrived 12.5 seconds before the shock wave (Fig. 2). This pulse was also recorded at the University of Southern California, near downtown Los Angeles, where it arrived 3 seconds after the shock wave. The origin of this pulse could not be readily identified. We show here that it was a seismic P wave excited by the motion of high-rise buildings in downtown Los Angeles, which were hit by the shock wave. The proximity of the natural period of the high-rise buildings to that of the Los Angeles basin enabled efficient energy transfer from shock wave to seismic wave.

The shock-wave arrival times can be best explained with Mach cones (the conical shock-wave fronts produced by the passage of supersonic aircraft) propagating N40E across the Los Angeles (LA) basin. The velocity varies from 1,300 m s^{-1} (Mach 4.4) on the coast to 700 m s^{-1} in the Mojave desert. The shock wave excited by a supersonic aircraft is called an N wave because of its distinctive N-shaped pulse[1] (Fig. 3). Cook and Goforth[2] describe two kinds of seismic effects of sonic booms: a moving strain in the immediate vicinity of the surface loads, caused by the N-wave overpressure, and coupled seismic waves, which follow the passage of the N wave. The N waves shown in Fig. 3 are of the first kind. The positive pressure causes downward ground motion near the seismograph site, which is consistent with the observed polarity. We estimated the pressure from these records by approximating the shock front with a plane wave incident on a half-space. Following equation (9.187) of ref. 3, we calculated the response of the half-space to an N wave, convolved it with the instrument response, compared it with the observed seismogram, and thus estimated the pressure changes to be from 0.7 to 2.2 mbar, which are similar to those measured directly by pressure gauges for the earlier space shuttles[4].

The most unusual observation was the very distinct long-period (about 2 to 3 s) pulse with an amplitude of about 1 μm observed at Pasadena (PAS) 12.5 s before the arrival of the shock wave. The initial horizontal particle motion is in the northeast direction, and is in phase with the vertical motion, indicating that this pulse is a seismic P wave arriving at the station from the southwest. The time difference of 12.5 s between the shock wave and the P pulse suggests that the origin of the P pulse is located near downtown Los Angeles, 14.5 km southwest of Pasadena (see Fig. 1 inset). A broadband instrument at station SCS (at the University of Southern California) also recorded this pulse as well as the shock wave (Fig. 2). Unlike the Pasadena record, this record shows the P pulse arriving about 3 s after the shock wave. The amplitude is 10 μm, ten times larger than that at Pasadena. These observations support the interpretation that the P pulse originated from downtown Los Angeles.

To excite the P wave in this area, the shock-wave energy must have been transferred to the ground there through some coupling mechanism. The most prominent feature in downtown Los Angeles is a group of high-rise buildings with a natural period of 1-6 s. This led us to believe that the P pulse was excited by the high-rise buildings which were hit simultaneously by the

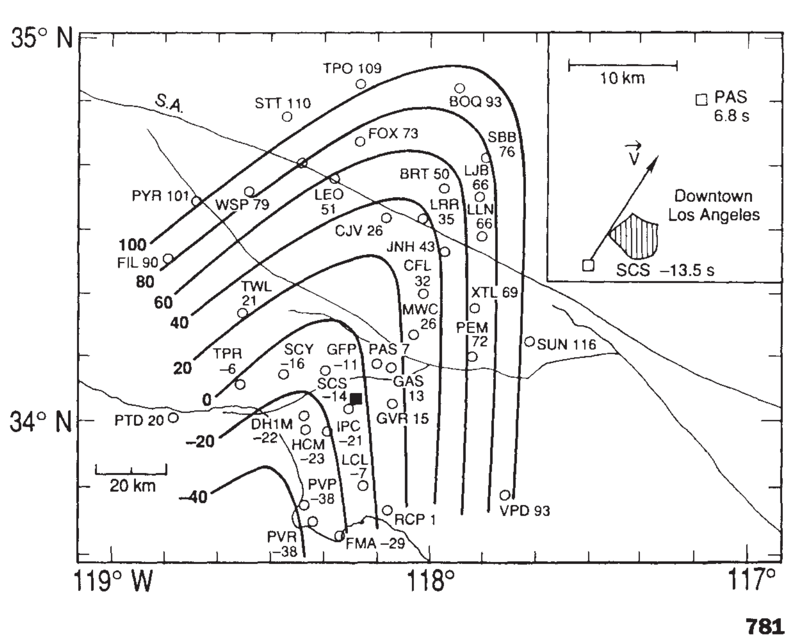

FIG. 1 Arrival times of the shock waves excited by the space shuttle Columbia, recorded by seismic stations of the Southern California Seismic Network and The University of Southern California Los Angeles Basin Seismic Network. The numbers below the station codes are the arrival times (in seconds from an arbitrary reference time). Hyperbolas at 20 s intervals are fitted to the arrival-time data. The inset shows the stations PAS and SCS (at the University of Southern California) with respect to downtown Los Angeles. The vector V indicates the shuttle path. The arrival-time difference between PAS and SCS is 20.3 s.

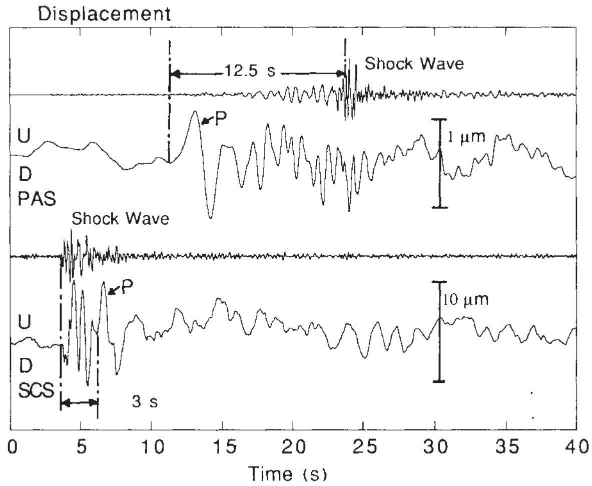

FIG. 2 Comparison of the displacement records at PAS and SCS (for station locations, see Fig. 1) displayed on a common timescale. A high-pass-filtered record is shown above the displacement record for each station to indicate the arrival time of the shock wave. Note that at PAS the long-period P pulse arrives 12.5 s before the shock wave, whereas at SCS it is 3 s after the shock wave.

shock waves. According to the Los Angeles City Fire Department (F. Border, personal communication), there are about 100 buildings taller than 20 stories in downtown Los Angeles and the Wilshire district.

Because of the weak damping of the building, the oscillation of the individual building hit by a shock wave lasts for a long time. The resulting ground motion will be a long, damped oscillation instead of an impulse. If, however, many buildings with different periods are excited simultaneously, the first cycle will contribute constructively to excitation of ground motion, but the later cycles will interfere destructively with no significant net contribution; the resulting ground motion will be impulsive,

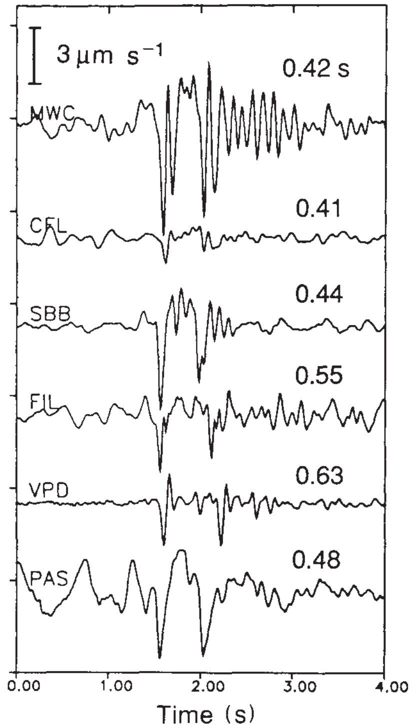

FIG. 3 Examples of N waves. The records represent ground-motion velocity in a frequency range of 1–10 Hz. The numbers to the right are the separations (in s) between the two pulses of an N wave.

as observed. This situation may be viewed as an inverse Fourier transform of a delta function.

The excitation of seismic waves by shaking of a building has been demonstrated by Jennings[5]. Shaking of the Millikan Library building (nine stories) on Caltech Campus excited seismic waves which were observed with a seismograph at Mount Wilson, 11 km away. The observed acceleration on the roof of the Millikan Library was 0.02 g, and the observed amplitude at Mount Wilson was 0.02 μm.

The efficient excitation of the seismic pulse with a period of 2–3 s by the buildings suggests, by reciprocity, that seismic-wave energy coming into the Los Angeles basin will be transferred efficiently to the buildings with this range of natural period. This points to the importance of investigating the long-period site response of the Los Angeles basin[6,7]. The importance of site effects has been demonstrated repeatedly for recent major earthquakes, such as the 1985 Mexico earthquake and the 1989 Loma Prieta earthquake.

As many recent studies have suggested, large earthquakes with a long fault length, such as those expected on the San Andreas fault, excite a highly significant amount of energy at periods longer than 1 s. In view of the high probability of large ($M > 7.5$) earthquakes on the San Andreas fault in the next 30 years[8], and possible large earthquakes on the blind faults beneath the Los Angeles basin[9], it is important to assess the long-period response of the Los Angeles basin quantitatively so that more comprehensive hazard mitigation measures can be taken. □

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Gene flow between African- and European-derived honey bee populations in Argentina

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IN the Neotropics, introduced European honey bees (*Apis mellifera* L.)[1,2] have been largely supplanted by bees descended from an African race, *A. m. scutellata* Lepetier, which were introduced into Brazil in the 1950s. Recent restriction enzyme analyses indicate that mitochondrial DNA in some neotropical populations is almost entirely of African origin[3,4], and these data have been cited as evidence for asymmetrical gene flow between African- and European-derived populations[3,4]. Evaluation of the nature of hybridization in the Neotropics is, however, confounded by possible