Bulletin of the Seismological Society of America, Vol. 93, No. 4, pp. 1427–1432, August 2003

Seismic Recordings of the Carlsbad, New Mexico, Pipeline Explosion of 19 August 2000

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Abstract On 19 August 2000 two seismometer networks in southeastern New Mexico recorded signals from a natural gas pipeline explosion. Analysis of the particle motion, arrival times, and durations of the seismic signals indicates that three impulsive events occurred with origin times of 11:26:18.8 ± 1.9, 11:26:43.6 ± 2.1, and 11:27:01.7 ± 2.0 (UCT). The first event was caused by the explosive blowout of the buried, high-pressure pipeline, and the second event was caused by the ignition of the vented natural gas. The nature of the third event is unclear; however, it was likely created by a secondary ignition. There were also two extended seismic events that originated at the same time as the first two impulsive events. The first resulted from the preignition venting of the gas and lasted for about 24 sec, while the second resulted from the postignition roaring of the flames and lasted for about 1 hr. Many of the source constraints provided by the seismic data were not available from any other investigative technique and thus were valuable to a diverse range of parties including the New Mexico state police, law firms involved in litigation related to the accident, the National Transportation and Safety Board, and the general public.

Introduction

On 19 August 2000 a buried natural gas pipeline in southeastern New Mexico ruptured and exploded. The resulting fire burned for nearly an hour until maintenance workers were able to shut off the flow of gas. The incident was the deadliest pipeline accident in the United States in the last 25 years and resulted in the deaths of 12 nearby campers. Investigations of this tragedy have been performed by the New Mexico state police, the National Transportation Safety Board, and private experts contracted by lawyers representing the victims' estates in a lawsuit against the pipeline operator. The investigations have been significantly influenced by seismic data that were recorded by two nearby seismometer networks. Analysis of the seismic data has helped answer questions related to the fundamental nature of the accident and has affected the amount of legal damages that were awarded to the families of the victims. The seismic data constrain (1) the number of discrete sources, (2) the relative and absolute timing of the sources, and (3) the underlying cause of two of the sources. Some of the timing constraints are unique to the seismic data and are unavailable from other means of investigation, such as witness interviews, records of pipeline pressure from the gas company, observations of rescue personnel, or postaccident crater analysis. In this note we describe the seismic observations, present a basic source model, and comment on the importance of the seismic results in determining the details of the accident.

Specifics of the Pipeline Disaster

At approximately 5:30 a.m. local time on 19 August 2000, fire and rescue personnel from Carlsbad, New Mexico, and surrounding areas were alerted to an explosion near the Pecos River compressor station along the El Paso natural gas pipeline in southeastern New Mexico. The workers were initially able to venture only within about 1.2 km of the blowout because of the intense heat from the burning gas. Analysis of damage to two nearby concrete pads indicate that the temperature was as high as 1150°C. The flames reached a height of 150 m and were visible for tens of kilometers. Maintenance workers for El Paso Energy Corporation had arrived at nearly the same time as the rescue personnel and began shutting off the gas flow at valves upstream of the blowout. By about 6:30 a.m. the fire had died out and rescue workers were able to approach the accident site. It then became clear that an extended family group had been camping in the vicinity of the pipeline during the accident and needed medical attention. Ultimately all 12 of these individuals died from injuries sustained at the scene.

Summary of Seismic Observations

Two seismic networks were deployed in southern New Mexico at the time of the pipeline accident (Fig. 1). One network consisted of three-component, PASSCAL broadband

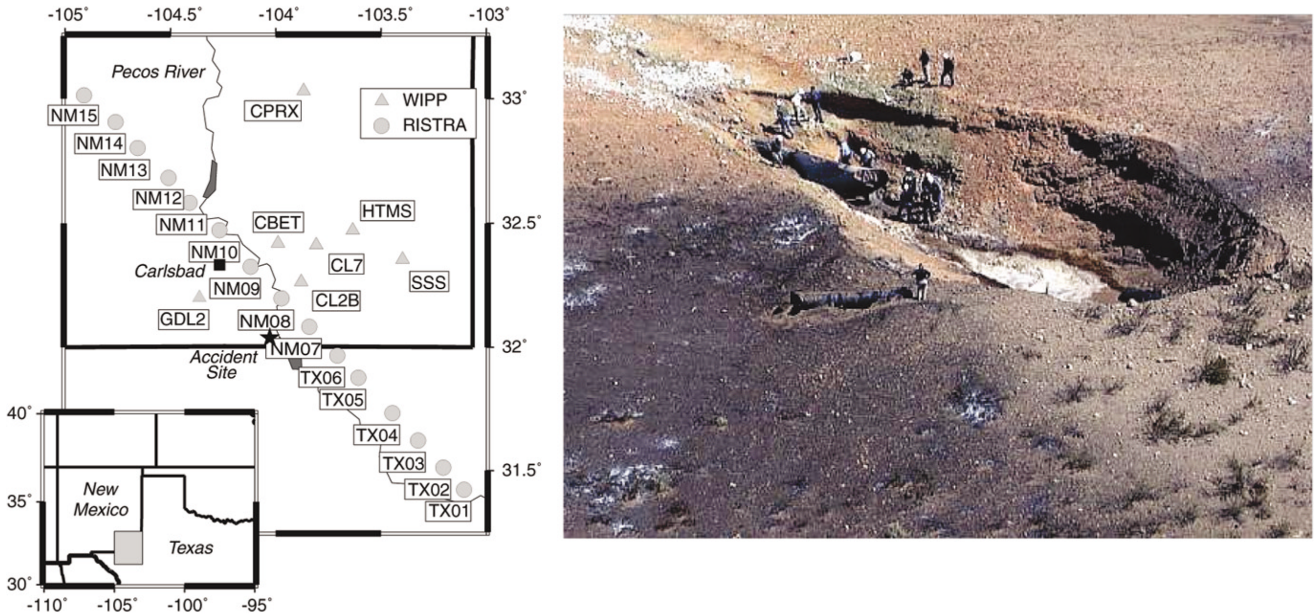

Figure 1. Station geometry for the two seismic networks deployed at the time of the pipeline accident. The WIPP stations, indicated by triangles, are short-period vertical component instruments, while the RISTRA stations, indicated by circles, are broadband, three-component instruments. Two of the stations shown, NM08 and TX04, were not operating properly at the time of the accident. The crater created by the pipeline blowout, shown on the right, was located at 104.0286° W, 32.0378° N.

seismometers that were temporarily deployed as part the Rio Grande Rift Seismic Transect (RISTRA) passive source experiment (Wilson *et al.*, 2002). The other network consists of permanently deployed, short-period, vertical component seismometers that monitor regional seismicity in support of the Waste Isolation Pilot Plant (WIPP) (Sanford *et al.*, 1980). Seismic signals from the pipeline accident were clearly visible at 17 of the sites shown in Figure 1 and were recorded as far away as NM15 (136 km). However, the propagation efficiency was strongly dependent on azimuth, and signals were observed only as far as TX05 (43 km) to the southeast.

The seismograms from broadband station NM09 are presented in Figure 2. Six discrete arrivals are clearly visible, all of which have particle motion that is dominantly retrograde elliptical in the plane of propagation, implying that they are Rayleigh waves. These arrivals naturally break into two groups, consisting of the first and last three arrivals. The first group (A_1, A_2, A_3) has nearly equal amplitude on the radial and vertical components, while the second group (A_4, A_5, A_6) shows much higher amplitude on the vertical. However, the differential arrival times and relative durations among the arrivals in the first group match the corresponding values among the second group exceptionally well. For example, the differential time between the first and second arrivals (A_1 and A_2) is 24.1 sec, while the differential times between the fourth and fifth arrivals (A_4 and A_5) is 24.6 sec. The 0.5-sec difference can easily be accounted for by observational uncertainties in the arrival time picks. Therefore it appears that three discrete seismic sources occurred, each of which generated two Rayleigh waves propagating at different velocities.

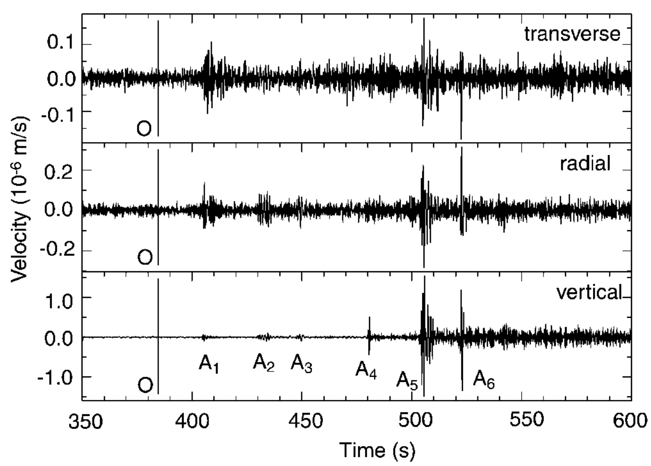

Figure 2. Seismograms of the pipeline accident at station NM09 (Fig. 1). The data have been bandpass filtered from 0.5 to 2.0 Hz using a Butterworth filter. Note that the vertical scales differ among the components. The six primary Rayleigh-wave arrivals are labeled A_1–A_6, and the origin time of the first of the three main sources is labeled with an *O*. This station is 31.4 km away from the accident site.

This interpretation is further supported by a record section of the second group of arrivals (Fig. 3). These phases have much higher amplitude than those in the first group and so are visible at the more distant stations. Precise arrival time picks show that the move-out of each arrival is linear and that the differential times among the arrivals are independent of distance. A linear fit to each set of arrival times gives estimates of the apparent velocity of each phase as well as the absolute origin time of each seismic source (Table 1). The apparent velocity of the phases, about 355 m/sec, is only slightly higher than the expected value for atmospheric wave speed at a temperature of 22°C (345 m/sec). Air-coupled Rayleigh waves are often generated by near-surface explosions and form when the shallow geologic structure has a surface wave phase velocity equivalent to the local atmospheric wave speed (Murphy, 1981; Kitov *et al.*, 1997). The exceptionally large amplitudes of the air-coupled Rayleigh waves are most likely related to a thermal inversion at the time of the accident. This weather condition is especially common in New Mexico valleys during the early morning hours. The relatively cool air near the surface creates a low-velocity zone, which acts as a wave guide for acoustic energy (e.g., Garces *et al.*, 1998). This also explains the azimuthal dependence of the amplitudes, since the Pecos River valley extends to the northwest from the explosion site but not to the southeast.

The first group of Rayleigh waves (A_1, A_2, A_3) is most clearly visible at stations CL2B, NM09, NM10, and CBET. At the closest station, NM07, the waves have not yet emerged as distinct phases and are obscured by diffuse high-frequency energy. At more distant stations, such as NM11 and SSS, the amplitudes have decayed below the ambient noise level. Combining the origin times derived from regressing the air-coupled Rayleigh waves with arrival time picks of the first group of Rayleigh waves gives apparent velocities of 1.7–1.9 km/sec. Solid-earth Rayleigh waves recorded at local distances (R_g) are often generated by explosions and shallow earthquakes with group velocities near 3.0 km/sec (Lay and Wallace, 1995); however, since these phases travel in the uppermost 2–3 km of the crust, they have large regional variations and R_g group velocities below 2.0 km/sec are common (e.g., Kocaoglu and Long, 1993; Goforth and Bonner, 1995; Mackenzie *et al.*, 2001). Hence, our group velocity estimates are consistent with previous R_g observations. Furthermore, the lack of R_g observations at the more distant stations is consistent with the strong attenuation of R_g (e.g., Myers *et al.*, 1999).

A remarkable feature of the seismic data is the extended codalike signal that begins with the second air-coupled Rayleigh wave and continues for approximately 1 hr (Fig. 4). Because of its high frequency content this signal is particularly clear on the unfiltered short-period instruments. On the three-component instruments the signal shows particle motion similar to that of the air-coupled Rayleigh waves but

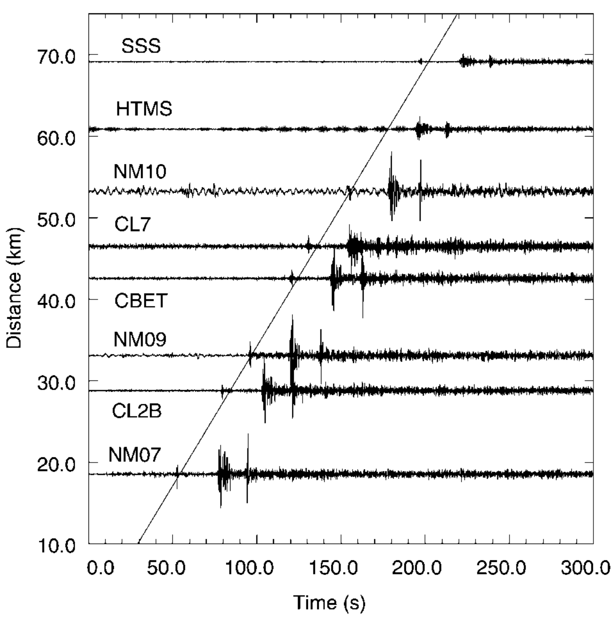

Figure 3. Record section of the seismic data associated with the pipeline accident. All the data have been bandpass filtered at 0.5–3.0 Hz. The zero time is the origin time of the first subevent. The sonic travel-time curve, shown as a solid line, has a velocity of 0.342 km/sec. The move-out and particle motion of the three large impulsive arrivals implies that they are air-coupled Rayleigh waves.

Table 1
Seismic Sources Related to the Pipeline Disaster

Source Number	Origin Time (UCT)	Approximate Duration	Cause
1	11:26:18.8 ± 1.9	1.0 sec	Pipeline blowout
2	11:26:43.6 ± 2.1	3.0 sec	Primary ignition
3	11:27:01.7 ± 2.0	1.0 sec	Secondary ignition (?)
4	Same as 1	24 sec	Venting of gas
5	Same as 2	1 hr	Roaring of flames

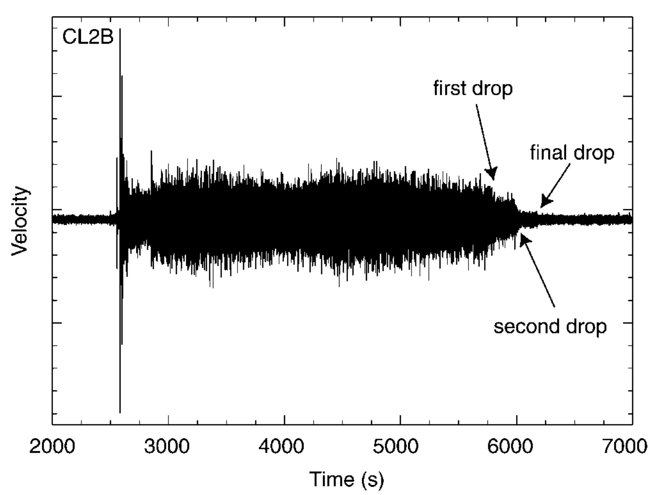

Figure 4. Unfiltered seismogram from the short-period station CL2B. The extended coda was created by the roaring of the flames at the accident site. The amplitude drops occurred as gas valves were successively shut down by maintenance workers.

with less coherence. The signal amplitude shows two distinct reductions after about 53 and 57 min and totally fades into the noise after about 60 min. These times are only accurate to within about 20 sec because of the gradual nature of the amplitude drops. There also appears to be a more subtle, higher-frequency coda between the first two air-coupled Rayleigh-wave arrivals (Fig. 5); however, this feature is visible only at the closer stations.

Nature of the Seismic Sources

The hour-long duration of the extended coda presented in Figure 4 implies that its source was the roaring flames at the accident site. At each station this coda begins at a time indistinguishable from the arrival time of the second air-coupled Rayleigh wave (A_5). Therefore the coda either consists of seismic waves driven by near-receiver loading of the surface by acoustic energy that has traveled through the atmosphere or is itself air-coupled Rayleigh-type energy. At most stations the ground motion after A_2 is similar to the motion between A_1 and A_2, and so the roaring of the flames appears to have generated little near-source seismic energy. The main exception to this comes from the seismogram of the closest broadband station (NM07), which shows diffuse high-frequency energy in the time window of expected R_g arrivals.

It follows that the source responsible for the second set of Rayleigh waves (A_2 and A_5) was the main ignition of the natural gas that had presumably been pooling in the area since the initial blowout of the pipeline. The blowout is likely responsible for the first set of Rayleigh waves (A_1 and A_4). The waveforms of the first set of Rayleigh waves are shorter and simpler than the second set, as is expected for the localized, impulsive blowout source compared to the diffuse, ignition source. The high-frequency coda visible at the closer stations between the first and second air-coupled Rayleigh arrivals would then represent the jetting of gas from the broken pipeline. The source of the third set of Rayleigh waves (A_3 and A_6) is unclear. One possibility is a secondary ignition of gas that remained intact after the primary ignition.

The relative times among the three main impulsive sources can be obtained with higher accuracy than the absolute origin times by averaging the differences in the Rayleigh-wave arrival times from all the stations. This gives 24.04 ± 0.66 sec between the blowout and primary ignition and 17.77 ± 0.68 sec between the primary ignition and the third impulsive source. The delay between blowout and ignition implies that the ignition was unrelated to the blowout process and so, for example, was not caused by the initial rending of the pipeline. The delay may be related to the time it took for the venting gas to reach an ignition source near the campsite.

A likely source for the primary ignition is the campers' vehicles, which were parked about 140 m downstream of the blowout site. If any of the vehicles were idling or if any of

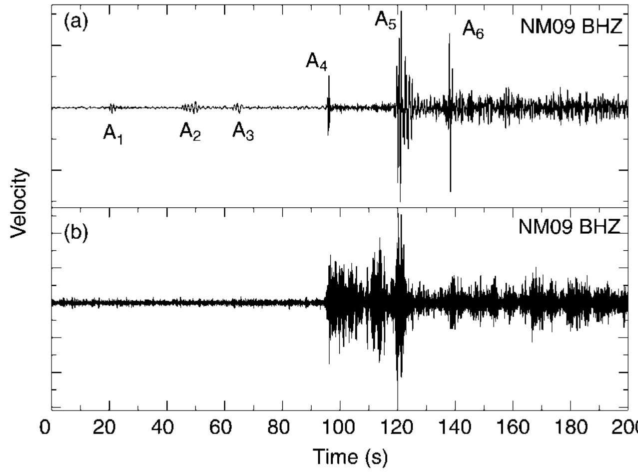

Figure 5. Vertical component seismogram from station NM09 shown (a) bandpass filtered at 0.5–3.0 Hz and (b) highpassed filtered at 3.0 Hz. The zero time is the origin time of the first subevent. The high-frequency coda between A_4 and A_5 is due to the venting of the natural gas.

the electrical systems were in use, then the natural gas cloud could have ignited. This would imply a minimum velocity of 5–6 m/sec for the escaping gas. This is slightly faster than the nominal flow rate within the pipe of 3–4 m/sec; however, the gas velocity may be expected to increase when encountering the low-pressure atmosphere. A second possibility for the source of the primary ignition is the lanterns of the campers, which were located an additional 30–50 m away from the vehicles in the downstream direction. However, this site was on the banks of the Pecos River, with an elevation about 10 m lower than that near the blowout site, and since natural gas is lighter than air it is not clear that the gas could attain the minimum concentration for combustion (4%–5% by volume) near the lanterns.

Energy Release

The blowout of the pipeline was an exceptionally energetic event because of the high pressure (4.6×10^6 Pa) of the natural gas. Three sections of the 0.76-m-diameter pipe were ejected, the largest of which was 8 m long and landed 87 m from the blowout site. The resulting crater was elongated in the direction parallel to the pipeline and measured 34 m (length) by 15 m (width) by 6 m (depth); however, the width decreased with depth in an irregular manner, resulting in an estimated volume of 1180 m^3. Calculations made with a model based on previous chemical explosion data show that it would take approximately 5700 kg of TNT, buried at a depth of 4 m, to create a crater of similar volume in a similar medium (J. K. Ingram, personal comm., 2002). This implies that the energy released during the blowout was approximately 2.4×10^{10} J. However, it is unlikely that the entire crater volume was created during the blowout, and so the value given above is probably a gross overestimate. We prefer to determine an upper bound based on the overpressure of the natural gas. We estimate a scale volume of 6.75 m^3 based on the fact that a total length of 15 m of pipeline was ejected. Combining this with an overpressure of 4.5×10^6 Pa yields a potential energy of 3.0×10^7 J, about 3 orders of magnitude smaller than the estimate based on crater volume.

An upper bound for the energy release of the primary ignition can be obtained by assuming that the entire volume of gas that had been vented up to that point exploded at one time. We further assume that the venting velocity is approximately equal to the transport velocity (4 m/sec) and that both ends of the pipeline were leaking gas after rupture. Using a cross-sectional area of 0.45 m^2, a time lapse of 24 sec between blowout and ignition, and an energy content of 3.9×10^7 J/m^3 for the natural gas gives an energy release of 3.4×10^9 J, or about 100 times larger than the energy release associated with the blowout.

It is difficult to estimate absolute seismic magnitudes for each event because solid-earth energy is only seen for a few close-in stations and the only distinguishable phase is R_g. A duration-based magnitude scale that has been developed for local events (Sanford *et al.*, 1998) is not appropriate for these data, and we are not aware of any calibrated M_l scale for the region. Nevertheless, if we assume that the peak amplitudes of the R_g waves (A_1 and A_2) can be used as proxies for the amount of energy radiated seismically, then it appears that the two sources were approximately equivalent in the release of seismic energy. This can be reconciled with the 2-orders-of-magnitude difference in total energy release between the two events by recognizing that the seismic efficiency of the buried, impulsive blowout source would be expected to be much larger than that the of diffuse, ignition source occurring in the atmosphere. It is also worthwhile to note that although the first and second R_g arrivals have similar amplitudes, the first air-coupled Rayleigh wave is substantially smaller than the second air-coupled Rayleigh wave. This is again consistent with the model of the first source being buried and the second occurring on the surface within the atmospheric wave guide.

Conclusions

The seismic recordings of the natural gas pipeline accident in southeastern New Mexico provide source constraints that are unavailable from traditional investigative techniques. The seismic analysis reveals that three discrete events occurred and constrains the absolute origin times of these events to within ± 2.0 sec. More importantly, the seismic data constrain the first event to be the blowout of the pressurized pipeline and the second event to be the primary ignition of the vented gas and constrain the differential time between these two events be 24.04 ± 0.66 sec. Such a large time between the two events implies that the source of the ignition was not sparking or heat produced by the pipeline rupture but more likely a heat source at the victims' campsite 100–200 m away. This 24-sec time span also bears on the amount of punitive damages the pipeline operator is responsible for, since the victims were in a state of extreme distress during this time period. The seismic data also corroborate gas company records and witness interviews as to precisely when the gas company was able to shut off the flow of gas, thus extinguishing the fire and allowing rescue workers to approach the scene.

In many forensic seismology studies the seismic analysis gives results that are important, but mainly in a corroborative sense (e.g., Byerly, 1946; Holzer *et al.*, 1996; Ichinose *et al.*, 1999; Koper *et al.*, 1999; Kim *et al.*, 2001; Koper *et al.*, 2002). In other instances forensic seismology can provide constraints that are unique with respect to publicly available information and complementary with respect to classified information (e.g., Koper *et al.*, 2001; Gitterman, 2002). In contrast, in the case presented here the seismic constraints are unique with respect to all other sources of data and means of investigation.

Acknowledgments

We thank Alan Sanford, Kuo-Wan Lin, John Schlue, and Larry Jacksha for assistance in obtaining and using data from the WIPP network. The WIPP network is supported by funding from Westinghouse Corporation. The RISTRA experiment was supported by NSF Grants EAR 9707190 and 9706094 and by the Institute of Geophysics and Planetary Physics at Los Alamos National Laboratory. The instruments used in RISTRA were provided by the PASSCAL facility of the Incorporated Research Institutions for Seismology (IRIS) through the PASSCAL Instrument Center at New Mexico Tech. RISTRA data are available through the IRIS Data Management Center. The facilities of the IRIS Consortium are supported by the National Science Foundation under Cooperative Agreement EAR 0004370. We thank G. Bokelmann, G. Ichinose, and J. Schweitzer for helpful reviews.

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Manuscript received 13 September 2002.