



Lecture #19- Forensic Seismology

Forensic Seismology

- ◆ It is common for seismometers to record signals from sources other than earthquakes:
 - ◆ seismometers are always “on”
 - ◆ modern seismometers are extraordinarily sensitive
- ◆ Analysis of these non-earthquake sources can often give information that is important to investigative agencies, insurance companies, lawyers, and the general public:

forensic seismology

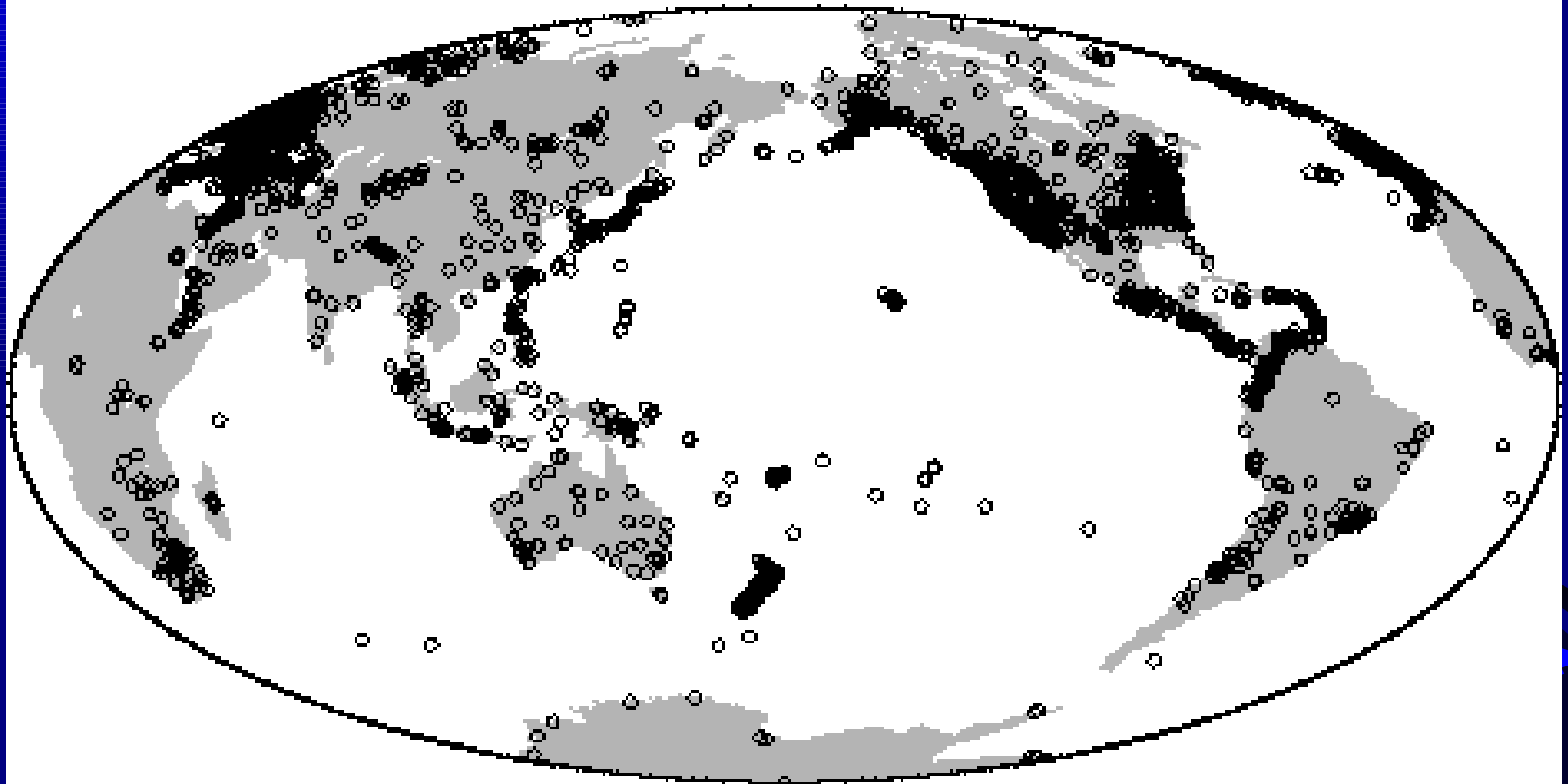


Seismic Data

- ◆ Over 16,000 seismometers are permanently deployed around the world
- ◆ Seismometers are “on” 24 hrs, 7 days a week
- ◆ Most seismic data is free and available over the internet in near real time

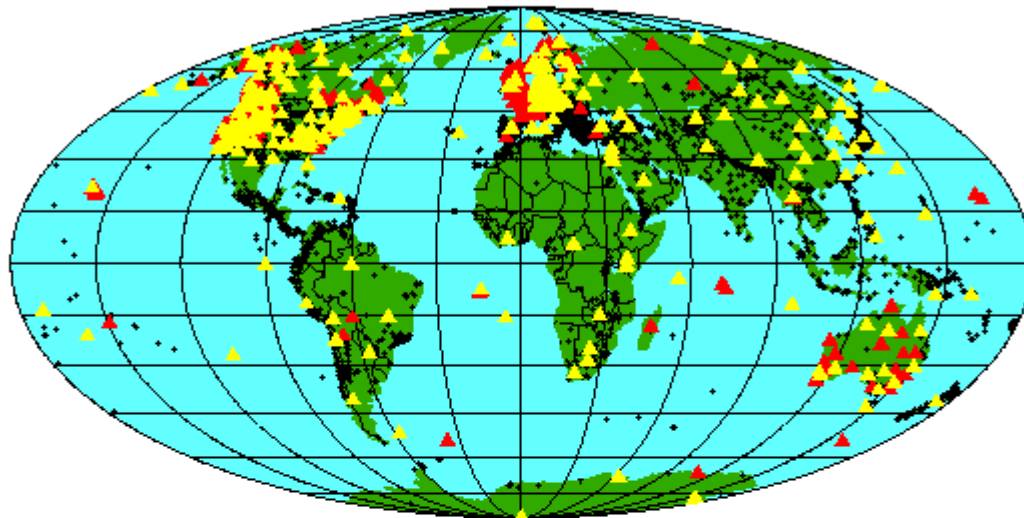


Stations Reporting to NEIC in 2000 (3757)

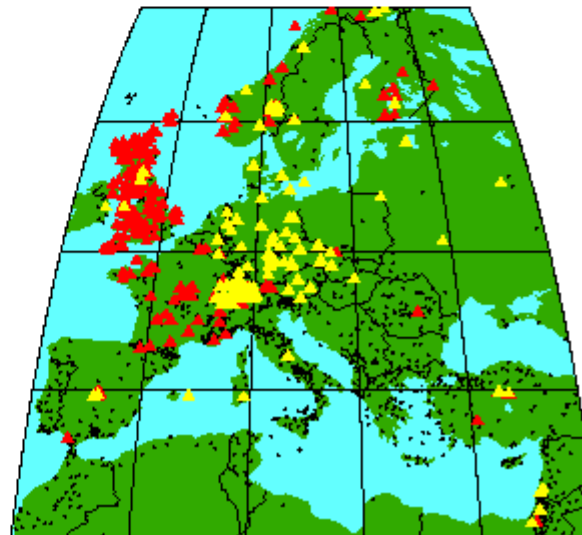
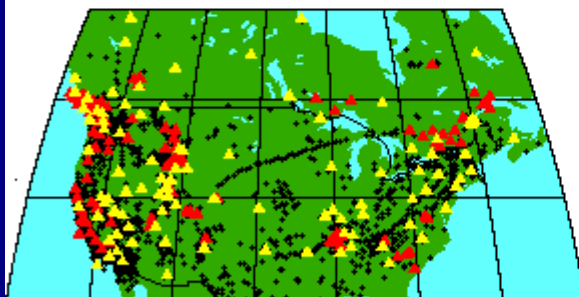


Stations Available via AutoDRM

Last Automatic Update: Oct 22 2001



*Real Time
Seismic Data*



- ▲ Active Broad-Band Station
- ▲ Active Other Station
- Operating Station Registered at ISC/NEIC



Examples of Non-earthquake Seismic Sources

Natural

- bolide/impact
- volcanic eruption
- mine collapse
- rock fall/land slide
- tornado

Man-Made

- nuclear weapons test
- chemical explosions
 - ◆ terrorist attack
 - ◆ industrial accident
 - ◆ routine mining
- airplane crash
- train derailment



Case Studies in Forensic Seismology

- ◆ The terrorist truck-bombing of the U.S. Embassy in Nairobi, Kenya on 8/7/1998
- ◆ The sinking of the Russian submarine *Kursk* in the Barents Sea on 8/12/2000
- ◆ The pipeline explosion near Carlsbad, New Mexico on 8/19/2000

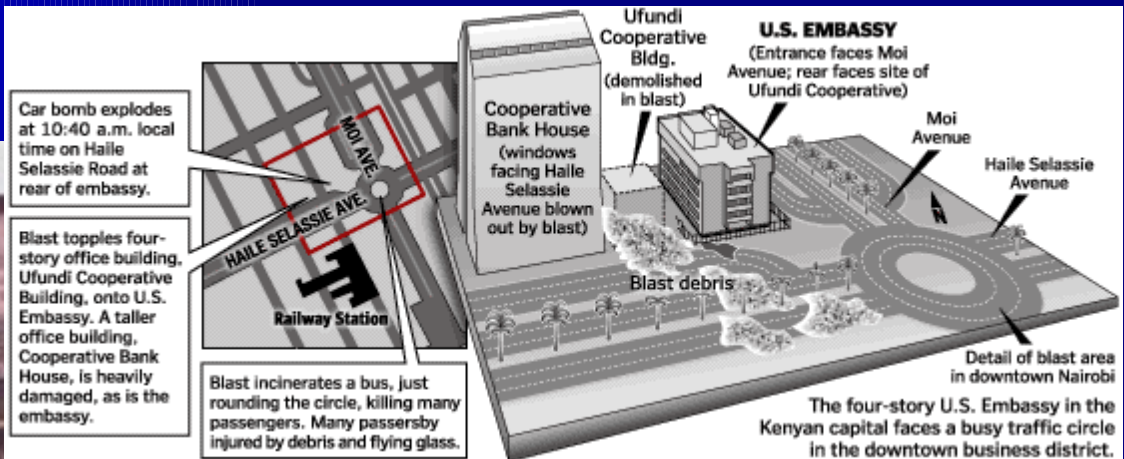


Basic Facts of Nairobi Attack

- ◆ On 10 August 1998 terrorists detonated truck-bombs nearly simultaneously at U.S. Embassies in two African countries:
 - ◆ Dar es Salaam, Tanzania
 - ◆ Nairobi, Kenya
- ◆ Over 4,000 persons were wounded and 220 were killed
- ◆ The Nairobi bombing was seismically recorded



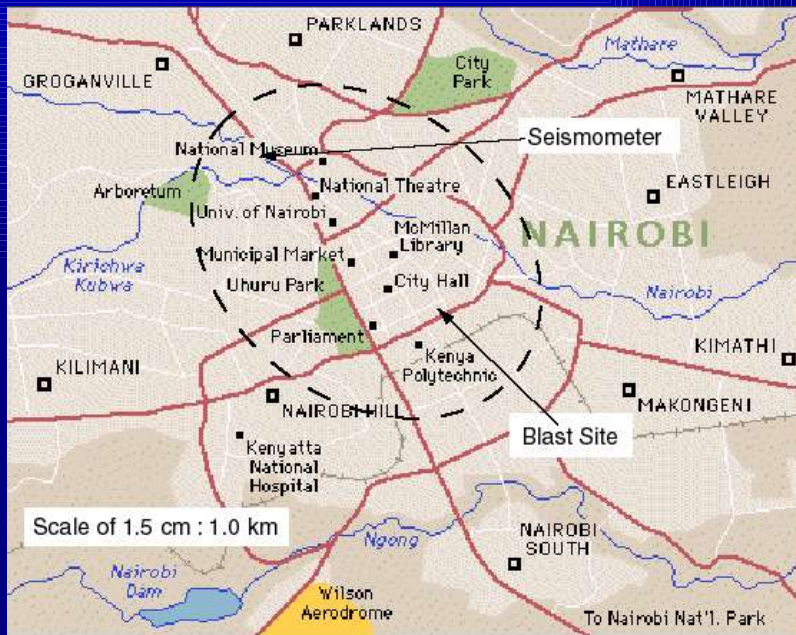
U.S Embassy in Nairobi, Kenya



U.S Embassy in Nairobi, Kenya



Seismic Station NAI



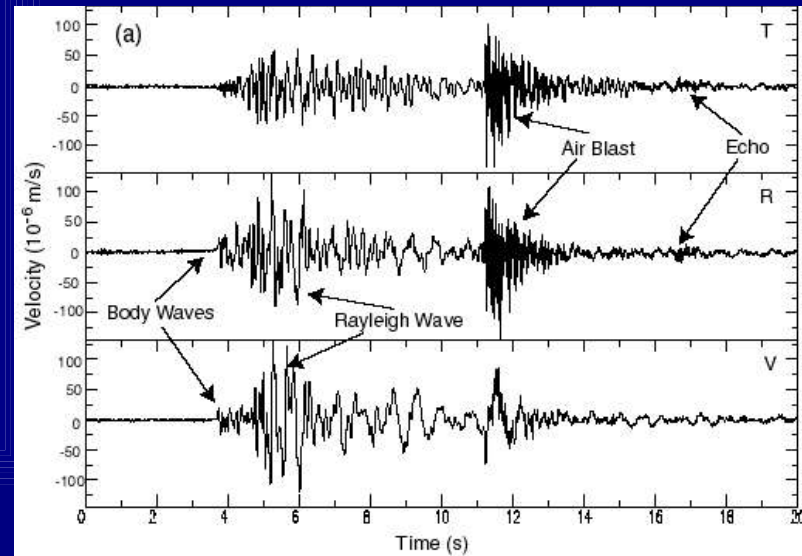
- ◆ A three component, broadband seismometer, operated by the University of Nairobi, was located about 3 km to the northwest of the blast site. The station code for this instrument is NAI.



Seismic Data from NAI

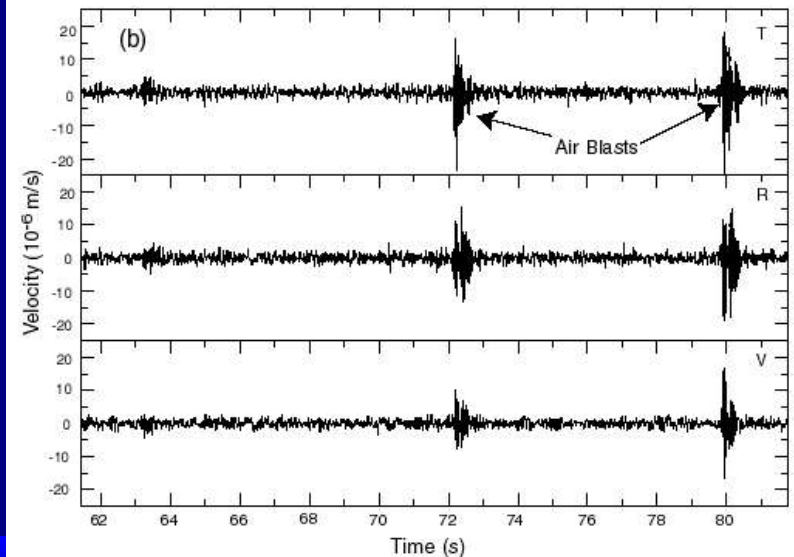
First time span, main explosion and echo.

→

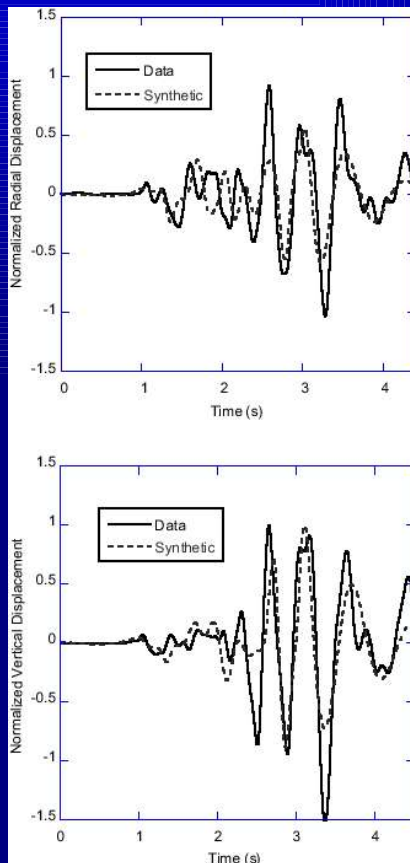


Second time span, unexplained airblasts.

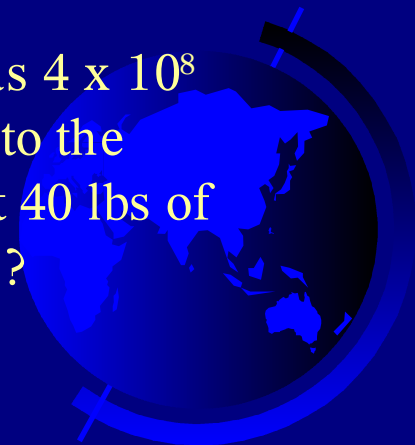
→



Results from Waveform Modeling

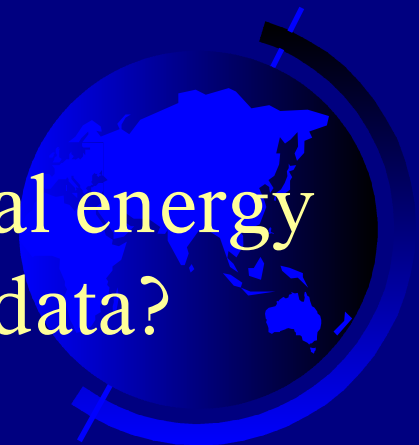


- ◆ The main blast occurred at 10:39:19.8 +/- 0.2 s
- ◆ An “echo” of the airblast from a nearby hill was recorded
- ◆ At least two additional airblasts were recorded within 1 minute of the blast; they are of unknown origin
- ◆ The seismic moment was 4×10^8 Nm, which corresponds to the energy released by about 40 lbs of TNT. Seems very small ?



Energy Partitioning

- ◆ Not all of the energy of a bomb goes into seismic waves. Some other reservoirs are:
 - ◆ crater formation
 - ◆ deformation of truck and buildings
 - ◆ projection of debris (missiles)
 - ◆ atmospheric sound waves
 - ◆ heat generation
- ◆ How then can we determine the total energy released (yield) from only seismic data?



Yield Estimation for Truckbombs

- ◆ Make seismic observations of truck bomb explosions in controlled environments
- ◆ Determine empirical scaling laws that related seismic observables to source properties
- ◆ Use these laws with the Nairobi seismic observations in a “backwards” direction to estimate the Nairobi yield



Truck Bomb Explosions Carried Out at White Sands Missile Range

- ◆ Four truck bomb explosions have been carried out and monitored with seismometers
- ◆ The experiments were sponsored by the Bureau of alcohol, Tobacco, and Firearms (BATF)
- ◆ The tests were originally designed to:
 - train BATF and FBI agents
 - quantify the effects of truckbombs on various structures
 - study the dynamics of truckbomb explosions



Ammonium Nitrate -
Fuel Oil (ANFO), often
used by terrorists



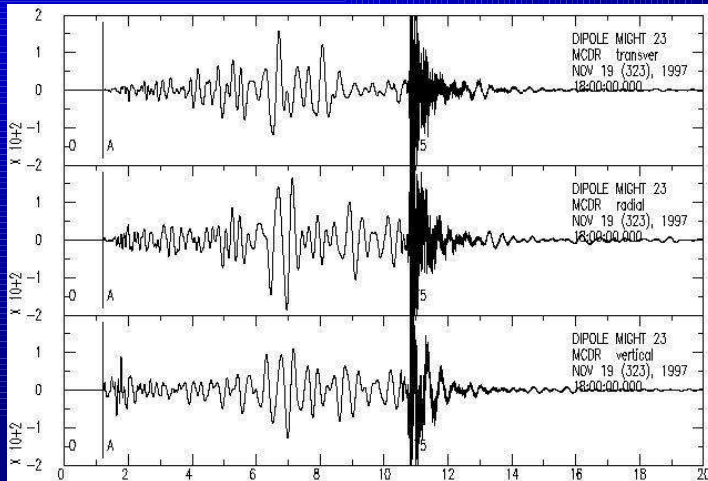
Before



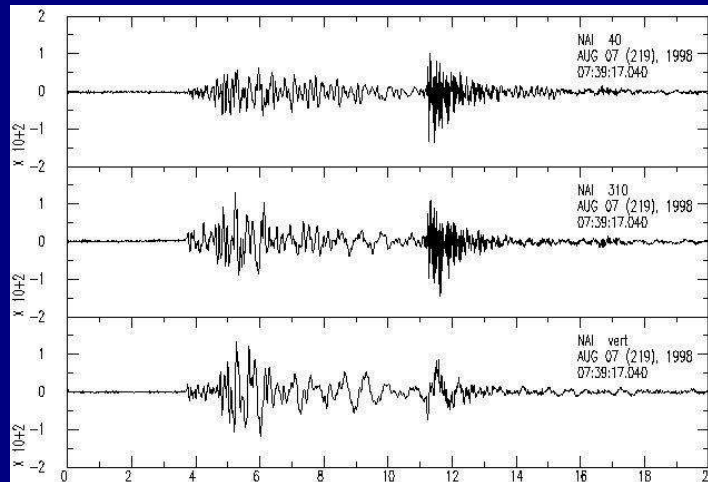
After



Waveform Comparison



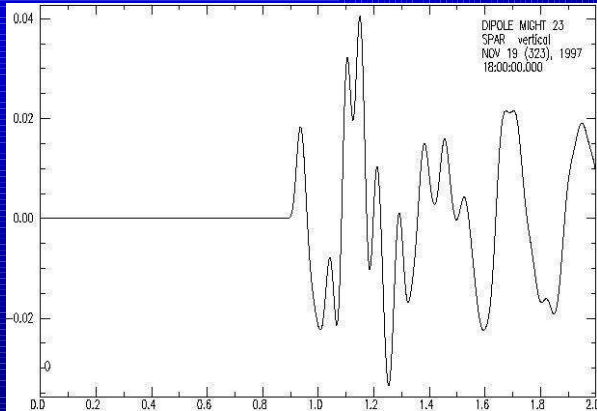
*Example Seismogram
from Controlled Test*



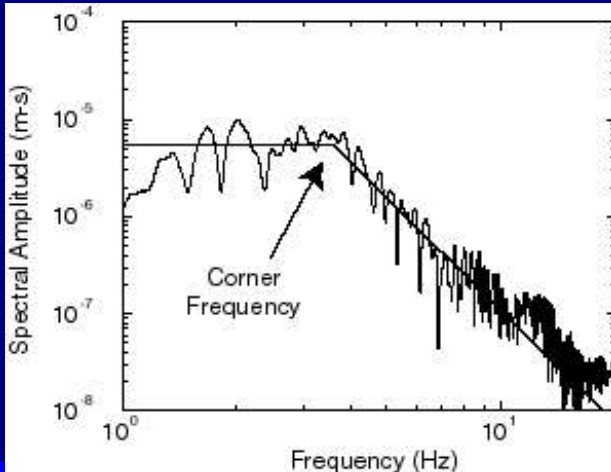
*Actual Nairobi
Seismogram*



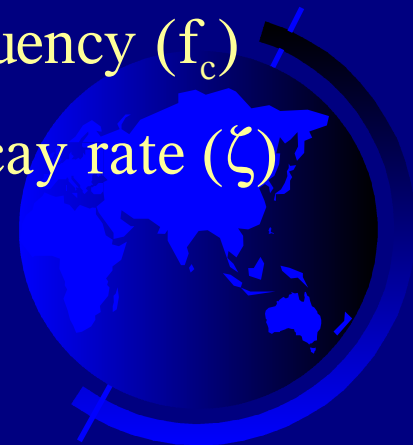
Useful Waveform Properties



Fourier Transform



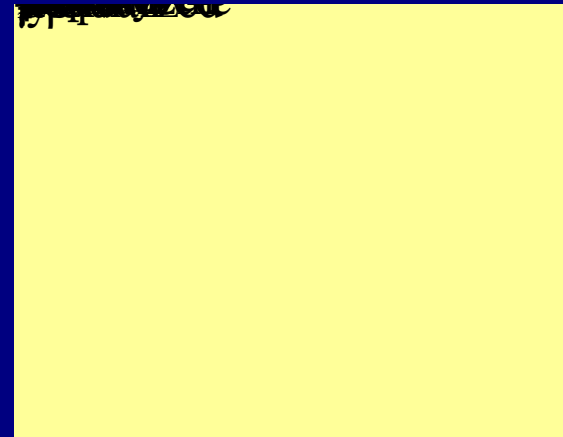
- ◆ Time domain:
 - P-wave amplitude (μ)
- ◆ Frequency Domain
 - Scalar moment (Ω)
 - Corner frequency (f_c)
 - Spectral decay rate (ζ)



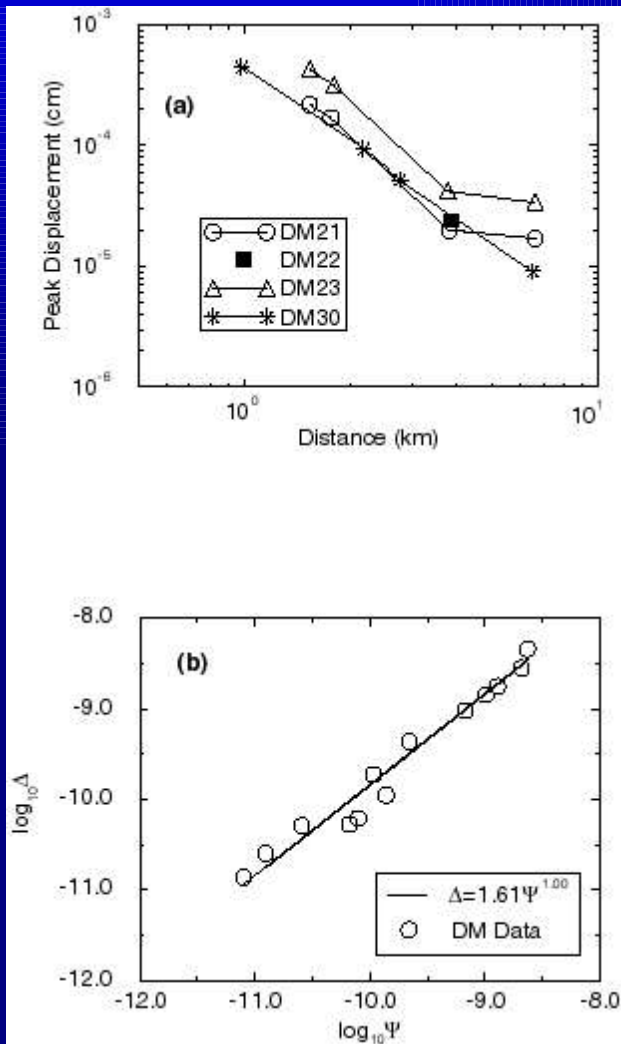
Scaling Law Development

(1) Collect raw data from experiments: peak displacement versus distance.

(2) Convert raw data to dimensionless variables:



(3) Determine relation between dimensionless variables: how are Δ and Ψ related ?



Nairobi Summary

- ◆ Seismic records indicated a single, surface explosion occurred.
- ◆ Combination of Nairobi records with scaling laws from White Sands tests gave a direct yield estimate (explosive size)
- ◆ In this case, the seismic constraints merely corroborated results from the direct investigation.



Case Studies in Forensic Seismology

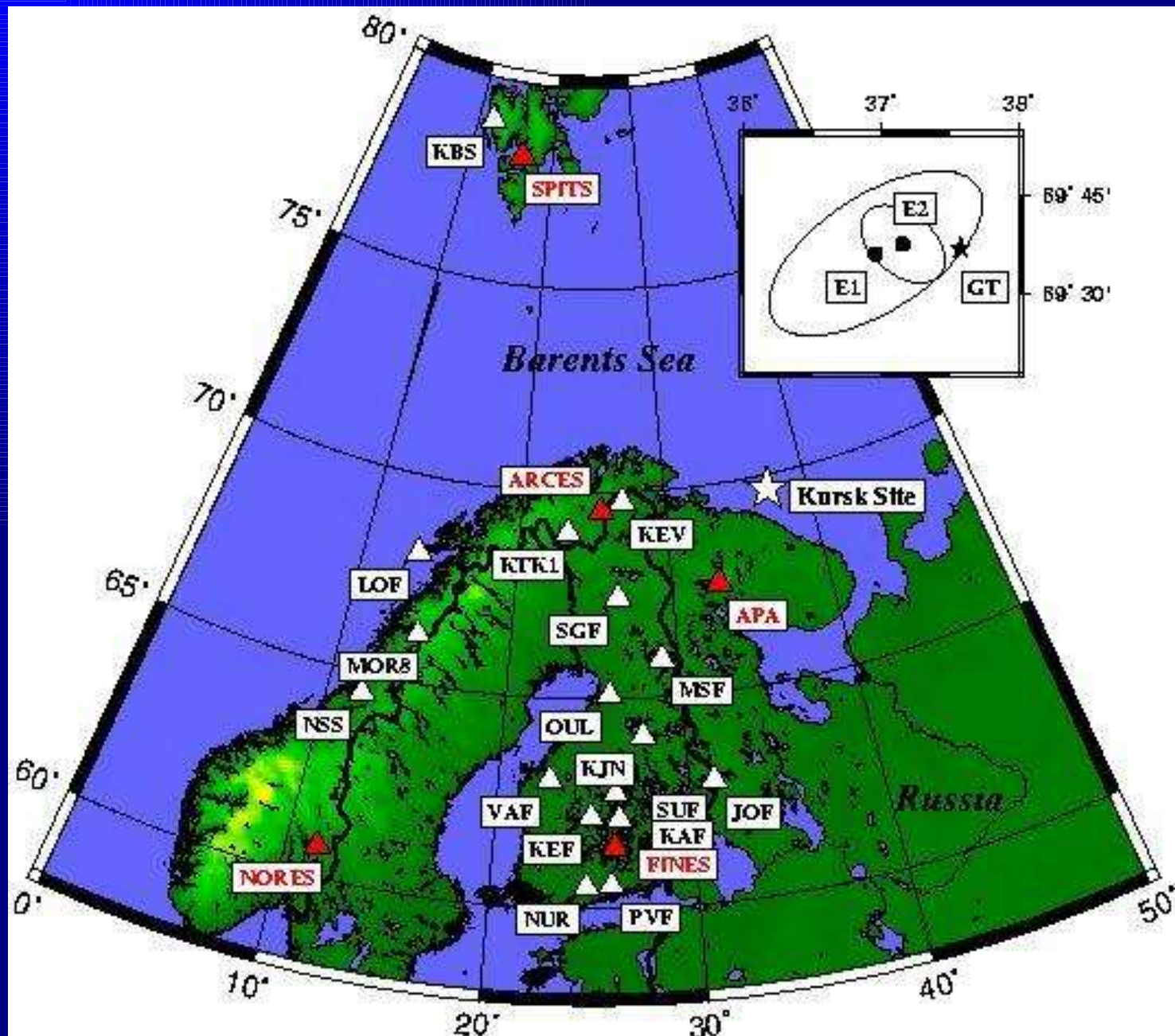
- ◆ The terrorist truck-bombing of the U.S. Embassy in Nairobi, Kenya on 8/7/1998
- ◆ The sinking of the Russian submarine *Kursk* in the Barents Sea on 8/12/2000
- ◆ The pipeline explosion near Carlsbad, New Mexico on 8/19/2000

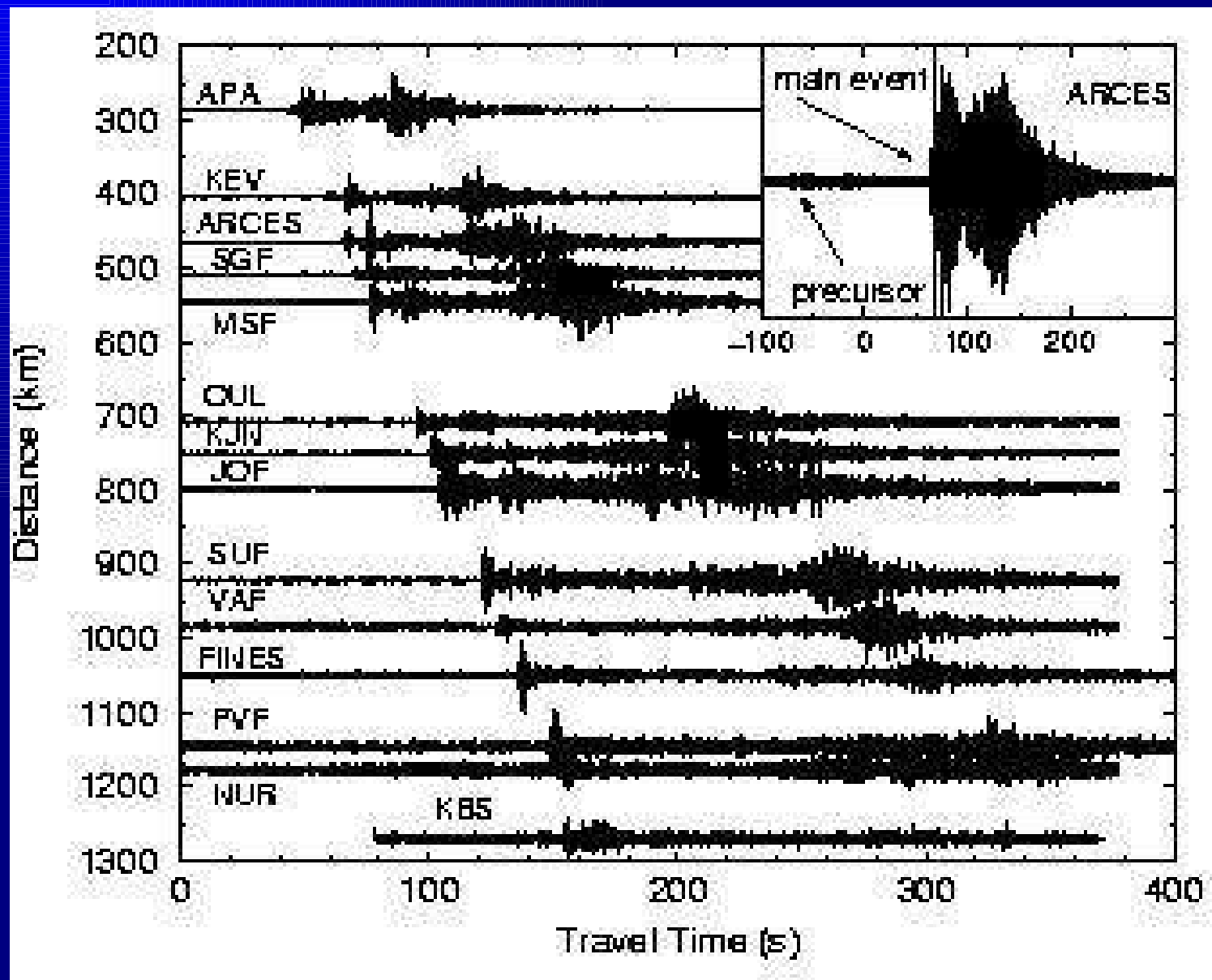


The *Kursk* Disaster

- ◆ The Russian submarine *Kursk* was sunk in August of 2000 while participating in war games in the Barents Sea.
- ◆ Underwater sources are superefficient; the resulting seismic signals were recorded throughout northern Europe



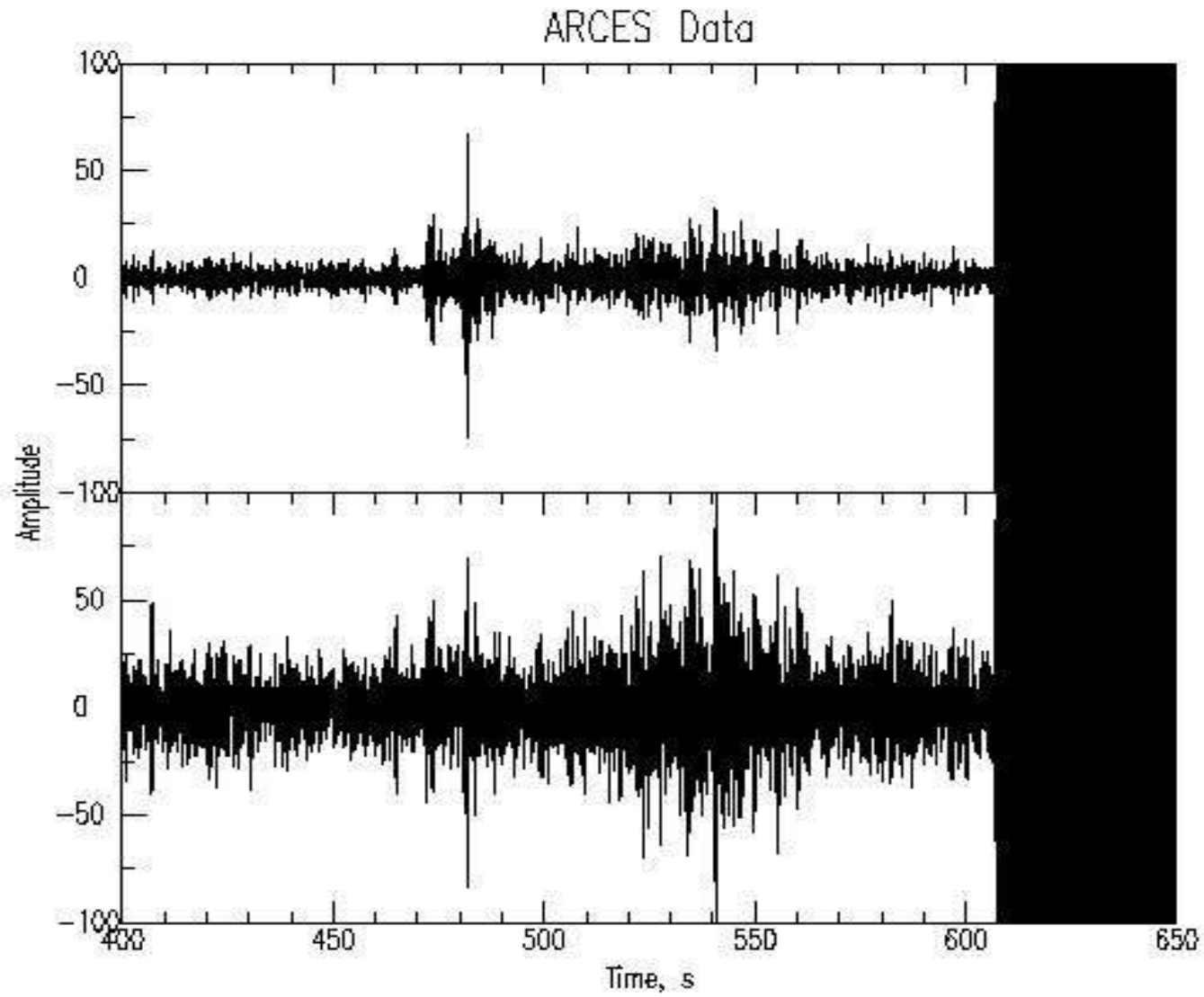




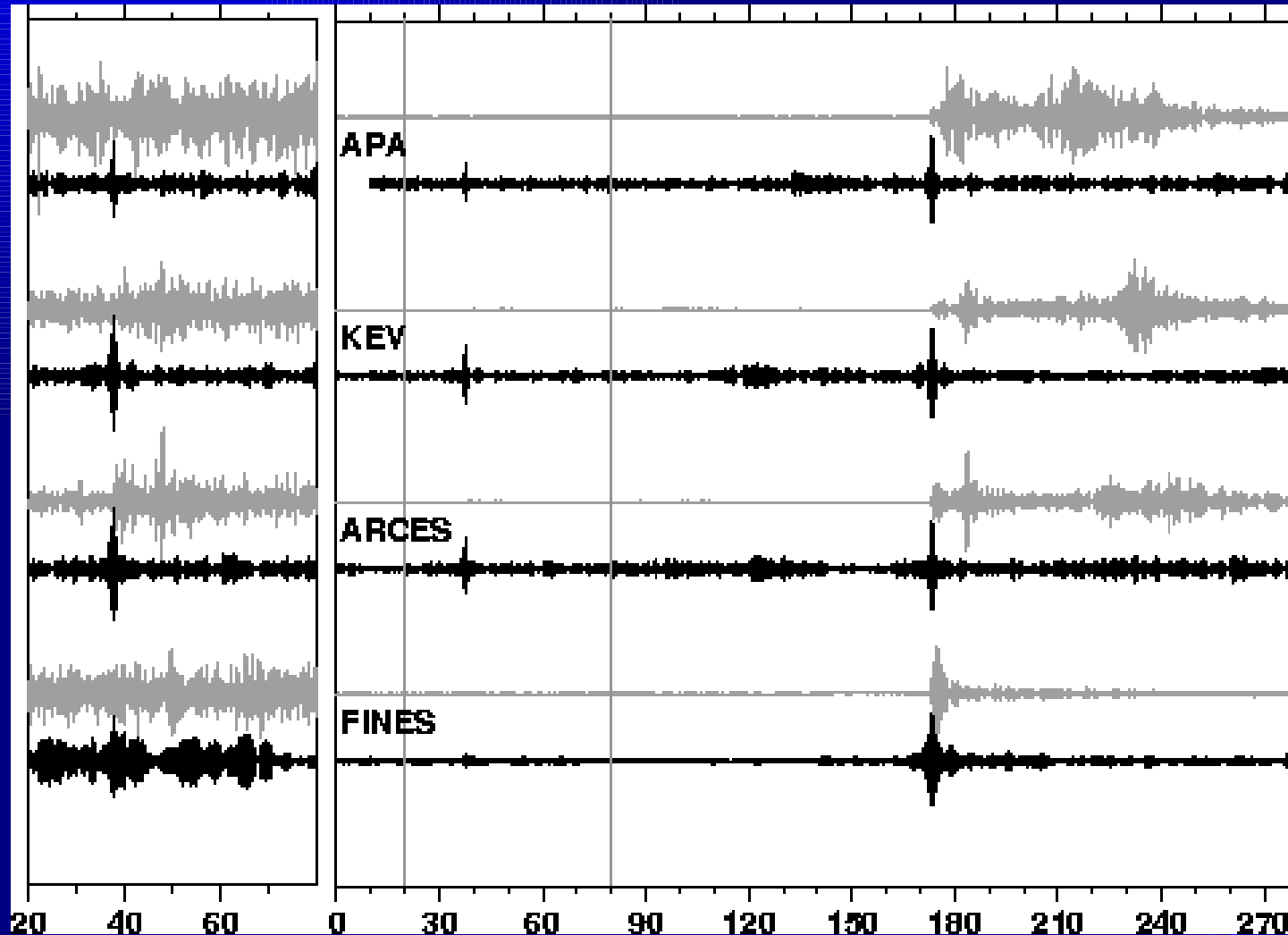
First Seismic Result:

- ◆ *There were two discrete sources*
 - Time separation of 2 minutes 15 sec
 - Virtually same location
 - Waveform similarity argues for same source mechanism (explosions)
- ◆ Seismology was the only non-classified source for this piece of info





Waveform Correlation Detector

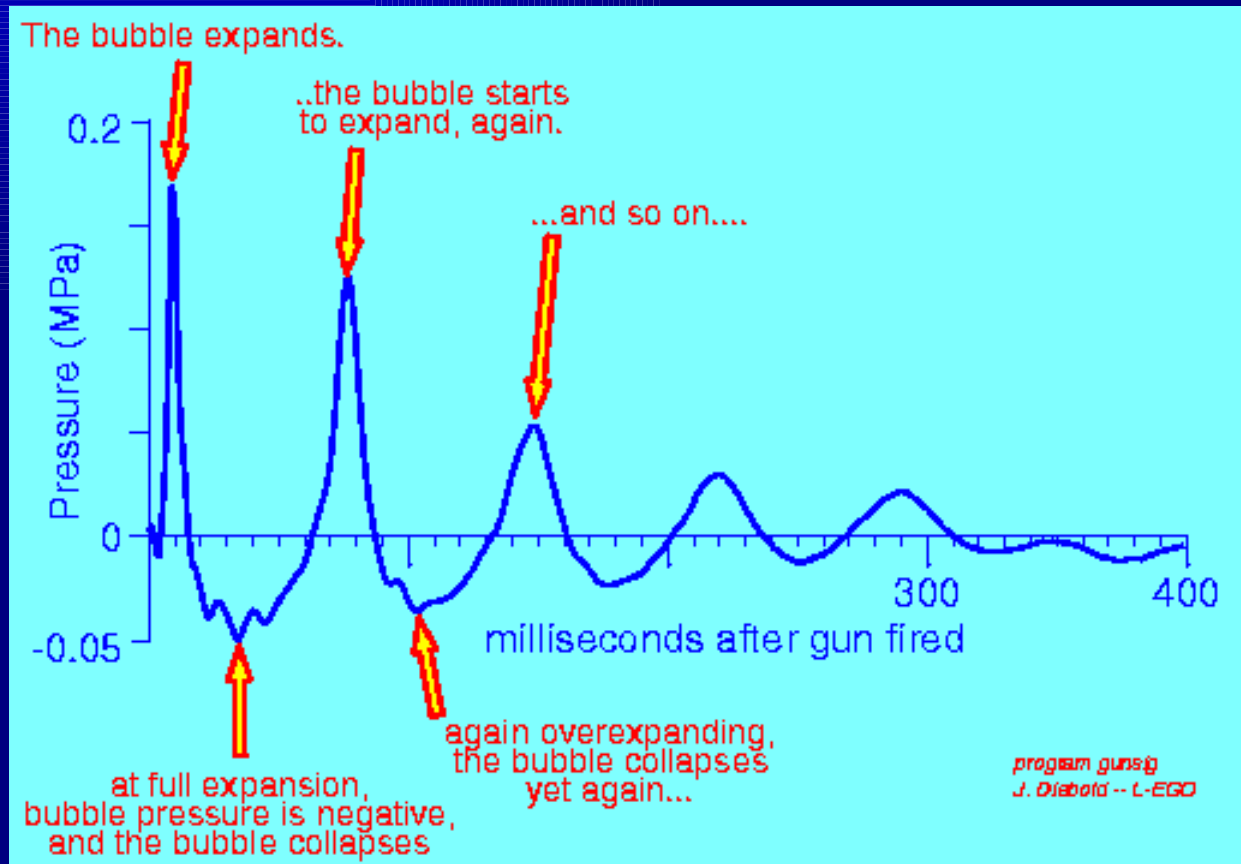


Second Seismic Result

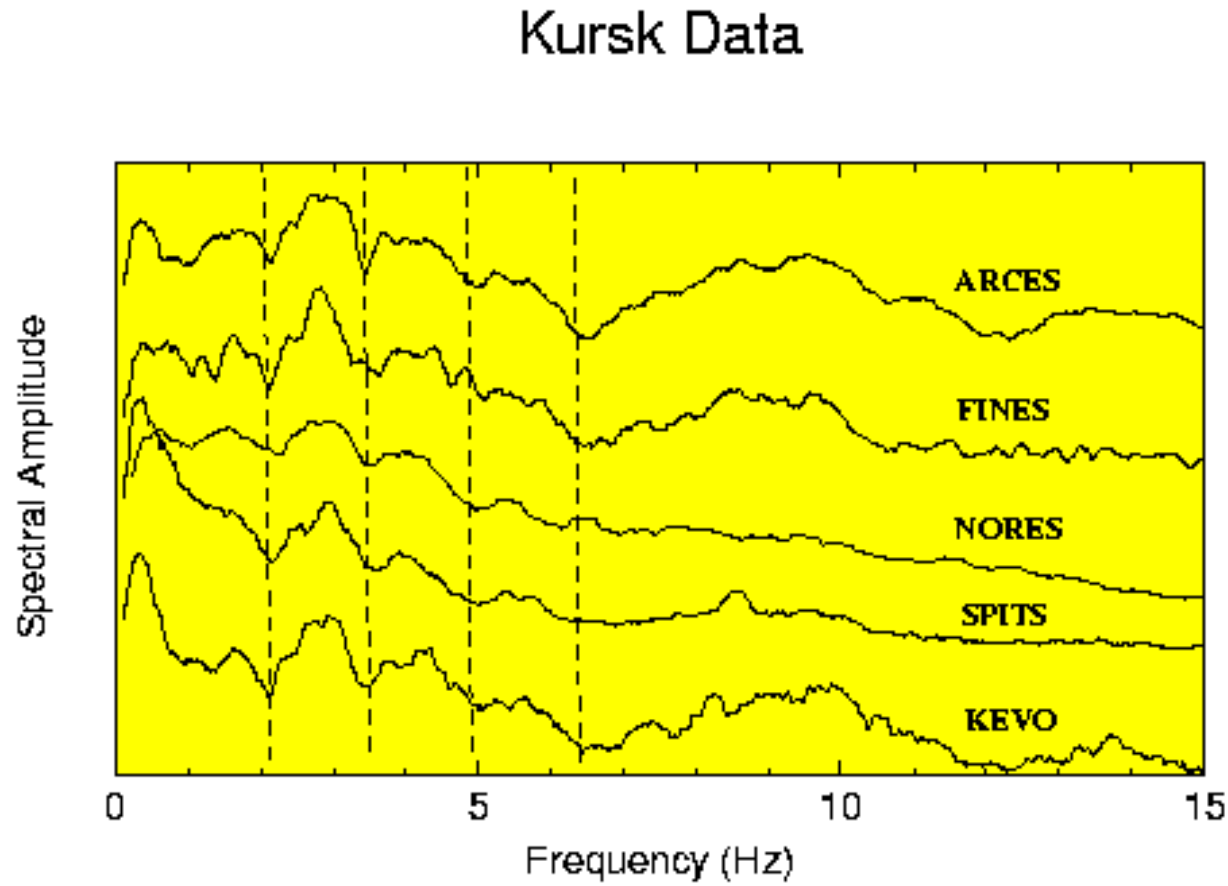
- ◆ The larger (second) event was definitely an explosion, not an earthquake or impact (also, it turns out, not an implosion either)
 - First, smaller, event was *probably* an explosion
- ◆ Again, seismology was the only non-classified source for this piece of info. Also it was known very quickly.



Bubble Pulse: The Fingerprint of an Underwater Explosion



The *Kursk* Bubble Pulse



Third Seismic Result: Relative Size of Explosions

- ◆ Magnitude-yield relations are of the form
$$\text{magnitude} = a * \log(\text{yield}) + b$$

where a and b are the model parameters
- ◆ It turns out that a is virtually constant for all sorts of explosions in all different places (a is 0.75-0.80)



Third Seismic Result: Relative Size of Explosions

- ◆ Given magnitudes for the two *Kursk* events (from the seismic data) and using a standard a value we can determine the ratio of the two yield (explosive strength). Note b cancels out.
- ◆ It turns out that the main (second) event was about 250 times bigger than the precursory event.



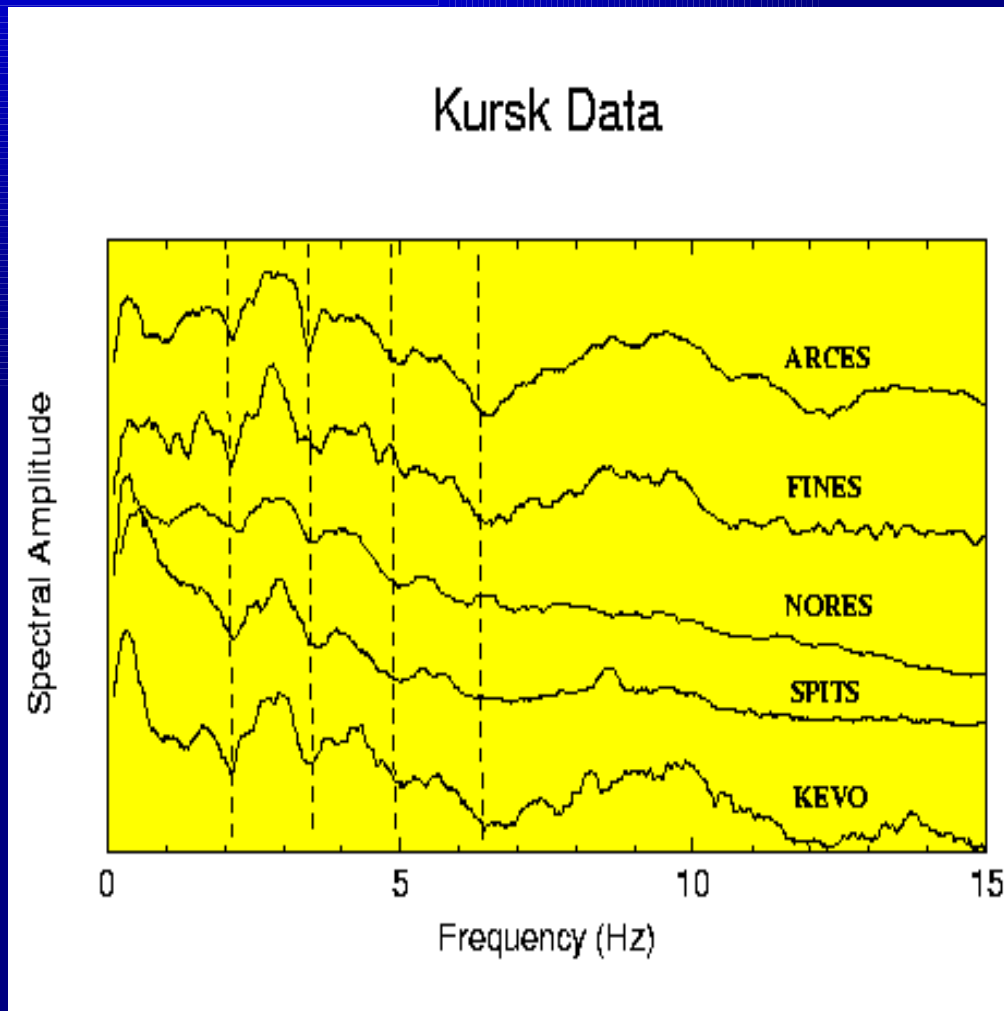
Fourth Seismic Result: Absolute Size of Explosions

Two methods for determining this:

- ◆ Use magnitude-yield relationship previously developed for underwater explosions (Dead Sea IMS shots)
- ◆ Go back to bubble pulse ...



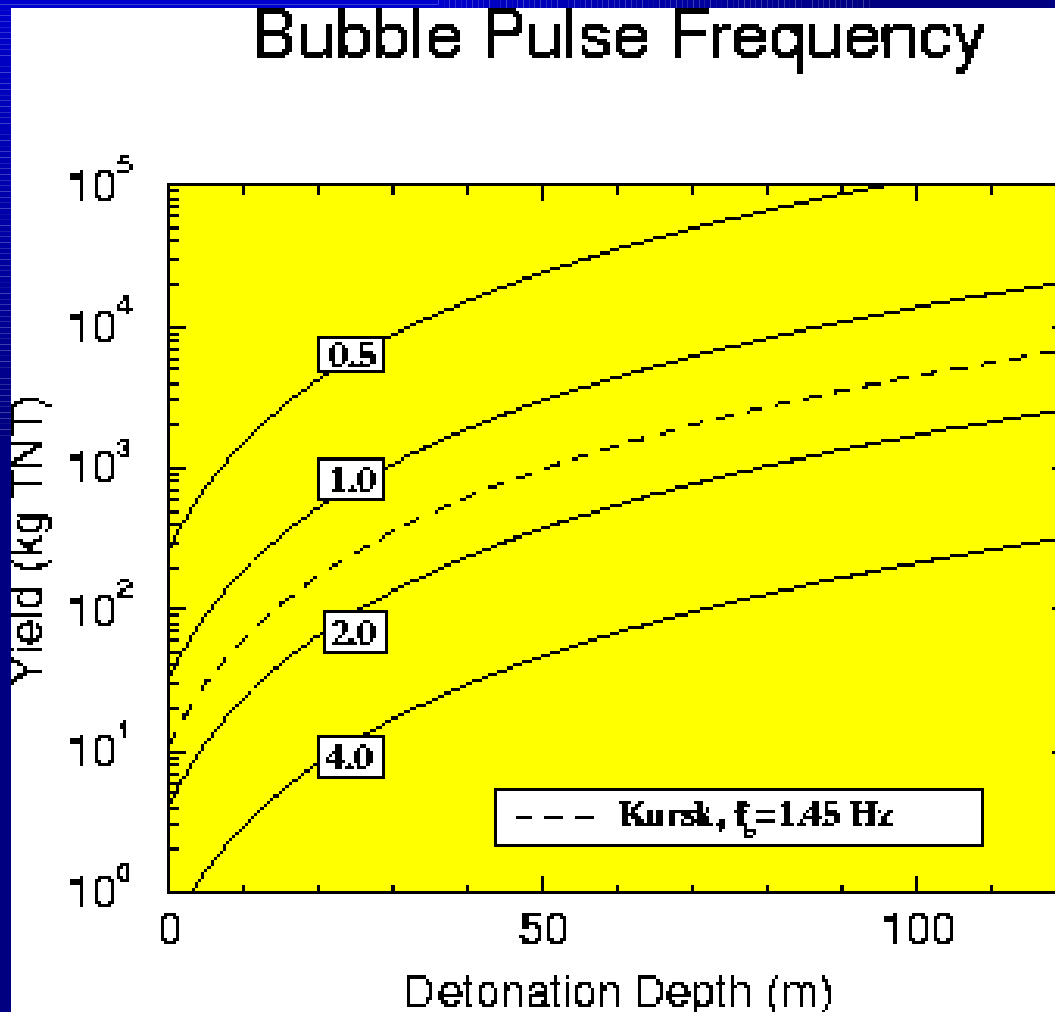
The *Kursk* Bubble Pulse



The spacing between peaks in the frequency domain is a function of yield and depth of detonation.



Bubble Pulse Frequency



Quasi-analytic relationship between yield, depth, and bubble pulse frequency spacing. From WWII experiments.



Bubble Pulse Frequency

- ◆ In theory, analysis of the data can give you depth of detonation, depth of water column and size of explosion (cepstral analysis).
- ◆ In practice, things are more fuzzy and we are left with a trade-off between size and depth of detonation.
- ◆ However we can assume a range of reasonable depths and get bounds on the yield.



Fourth Seismic Result: Absolute Size of Explosions

- ◆ It turns out that the bubble pulse analysis and the magnitude-yield relation give the same answer (within generous error bounds):

About 5 tons TNT equivalent

- ◆ On the same order as Oklahoma City bombing.



Kursk Summary

Four solid seismic results:

- ◆ There were two discrete sources
- ◆ Larger one was definitely an explosion
- ◆ Larger event was about 250 times more energetic than precursory event
- ◆ Larger event was about 5 tons TNT equivalent



Kursk Summary

- ◆ The information derived from seismic analysis of the *Kursk* data provided constraints that were unique among unclassified sources.
- ◆ The *Kursk* seismic results also provided substantial, important, and timely corroboration for the classified analysis.
- ◆ A higher *grade* of forensic information than in the Nairobi case.



Case Studies in Forensic Seismology

- ◆ The terrorist truck-bombing of the U.S. Embassy in Nairobi, Kenya on 8/7/1998
- ◆ The sinking of the Russian submarine *Kursk* in the Barents Sea on 8/12/2000
- ◆ The pipeline explosion near Carlsbad, New Mexico on 8/19/2000



Carlsbad Pipeline Explosion

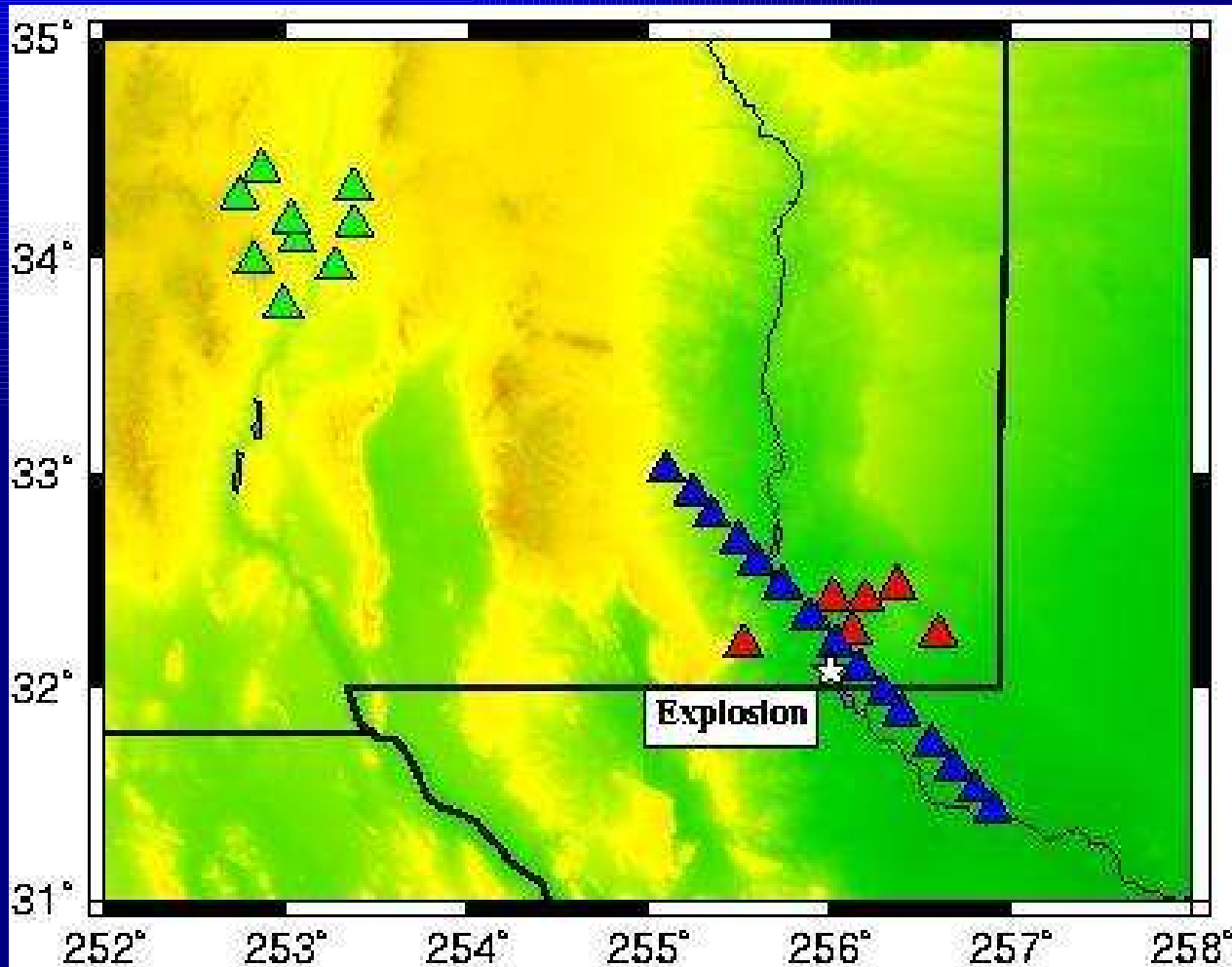
- ◆ In August of last year a buried, natural gas pipeline burst and exploded in southeastern New Mexico
- ◆ The resulting fireball burned for over one hour
- ◆ About 10 nearby campers were burned to death.







Nearby Seismometers

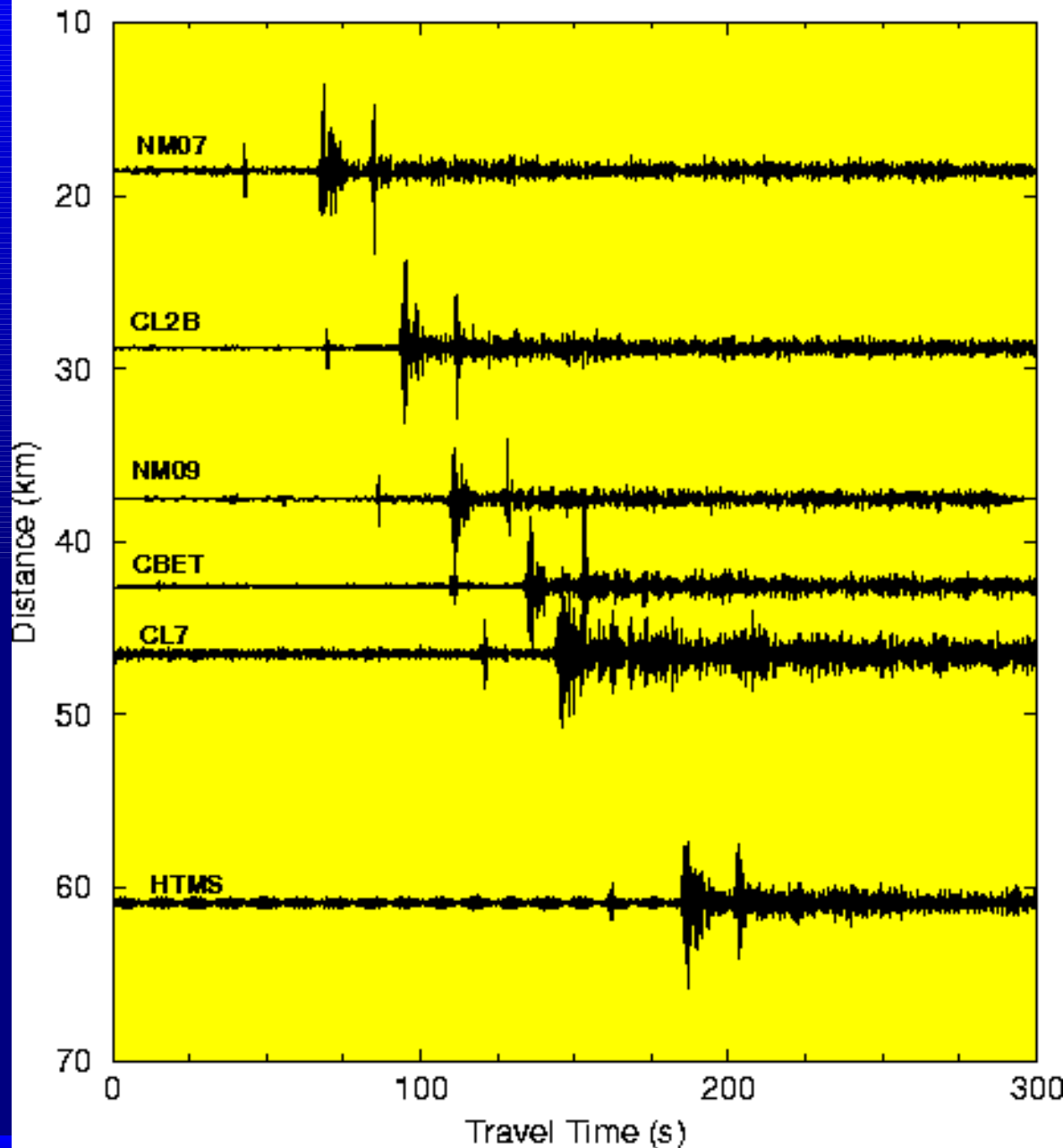


Red: permanent, single component, short period

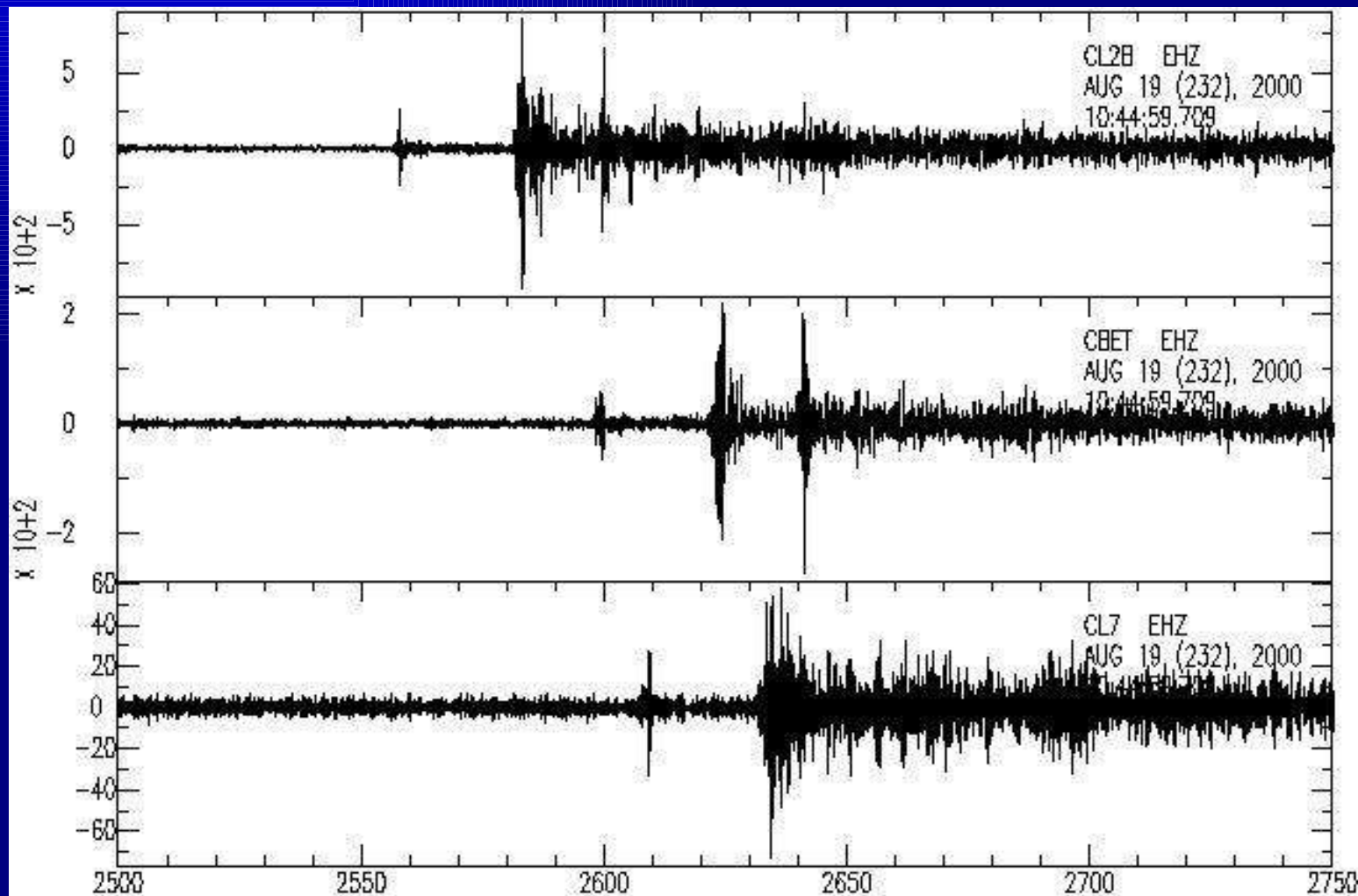
Blue: temporary, broadband, three component



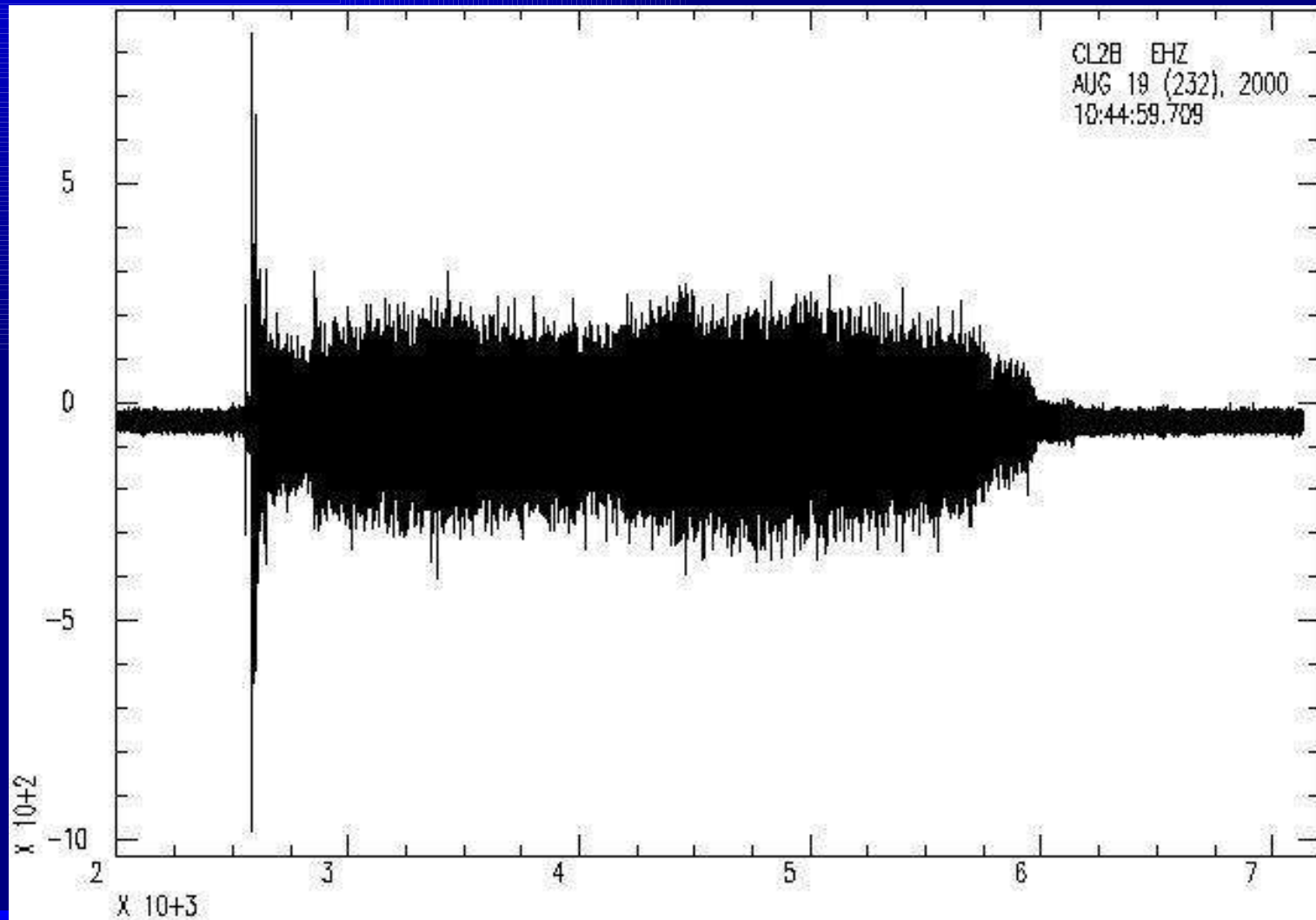
Carlsbad, NM Pipeline Explosion

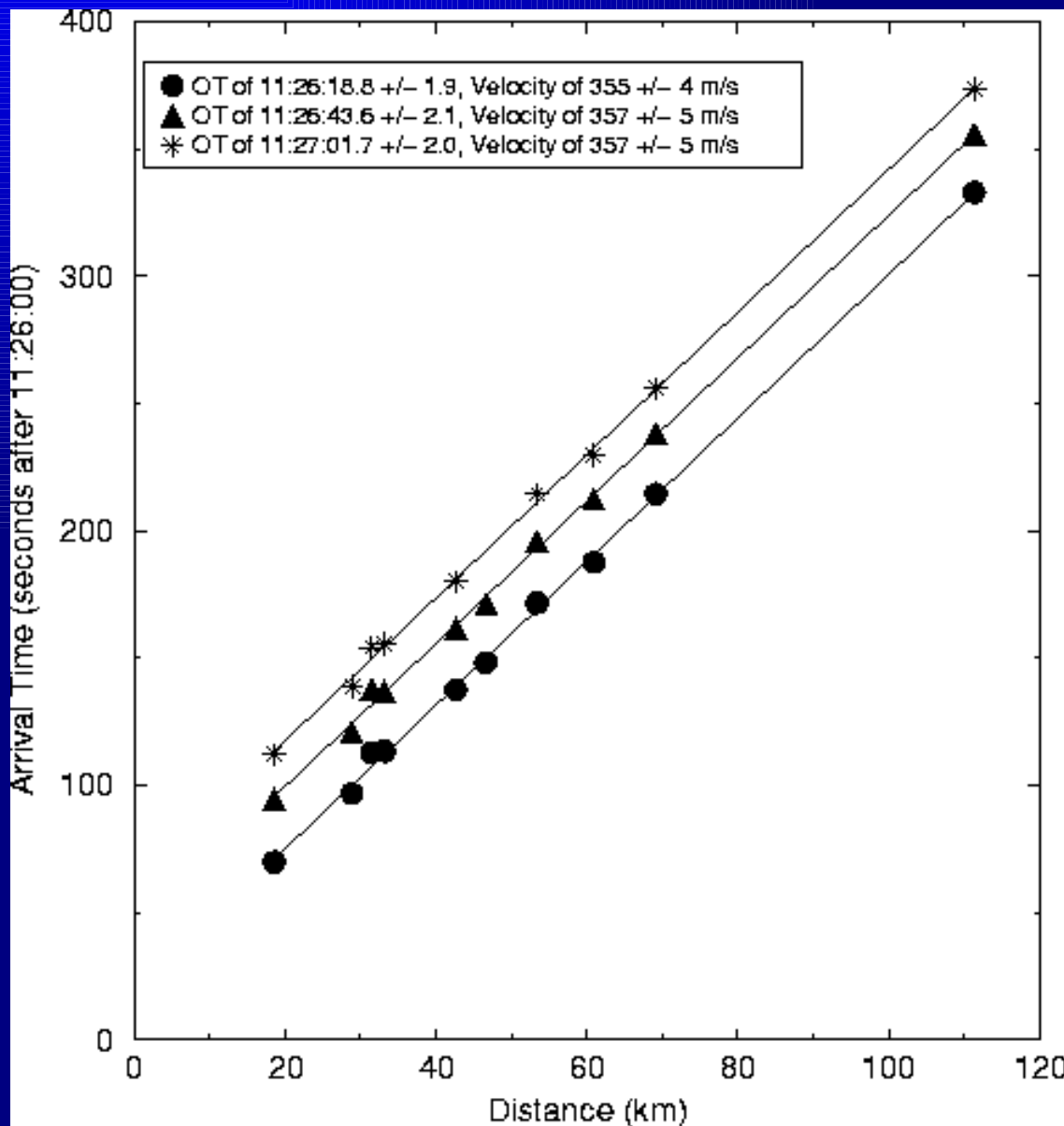


Three Pulses – 1 Blowout, 2 Ignitions



Extended Coda from Fireball





Relative timing of sources from simple linear regression



Carlsbad Summary

(1) Seismic data show three distinct source pulses and one long extended coda (1 hr long)

(3) We interpret these as blowout, primary ignition, secondary ignition, and “fireball roaring”



Carlsbad Summary

- ◆ We have relative timing of events down to fraction of a second
- ◆ This includes precisely when the gas company shutoff the gas and snuffed out the fireball. Rescue workers were prevented from approaching the camp site by the enormous heat of the fireball.



Carlsbad Summary

- ◆ If gas company had an automatic shutoff when a decrease in pressure was detected (the blowout) it's possible ignition could have been prevented.
- ◆ Or at least rescue workers could have attended to the victims much sooner and saved their lives. (Some victims lived for several days)

Seismic data -> ongoing litigation



Carlsbad Summary

- ◆ In this case the seismic data had a direct and influential role in piecing together the disaster.
- ◆ The seismic data provide unique, non-trivial constraints.
- ◆ The seismic analysis has an ongoing role in litigation/prosecution and so is truly forensic seismology.



Forensic Seismology Summary

- ◆ It is common for seismometers to record non-earthquake sources.
- ◆ It will become even more common in the near future.
- ◆ Analysis of these seismic data can contribute to the understanding of important man-made disasters



Forensic Seismology Summary

- ◆ The impact of forensic seismology analyses spans the range from *confirmation and identification of the obvious to unique determination of critical source information.*
- ◆ It is great outreach science.

