Some Practical Applications of

FORENSIC SEISMOLOGY

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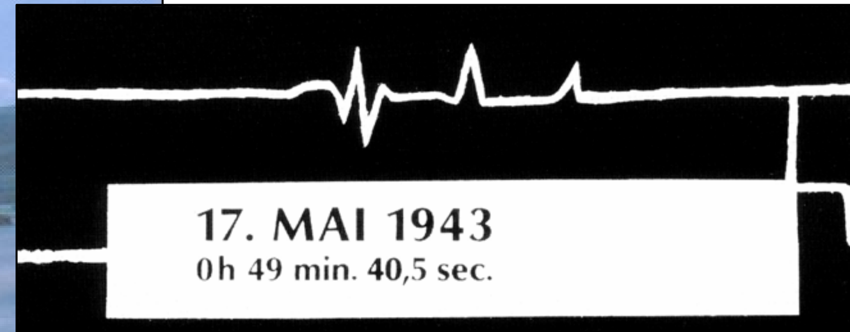
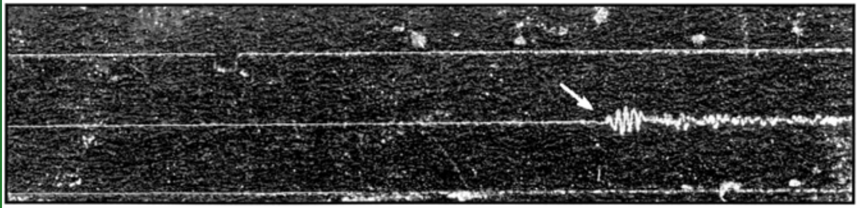
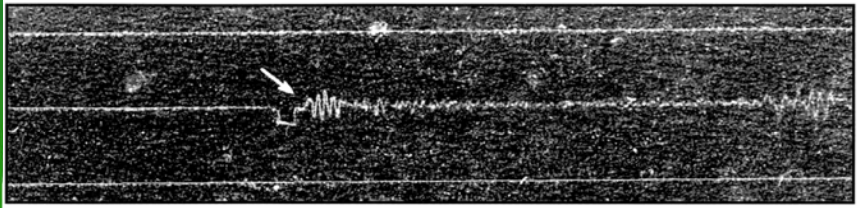


Explosions release energy similar to earthquakes

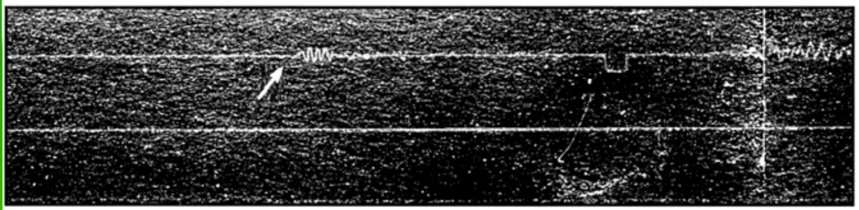
- **On the night of May 16-14, 1943 British bombers struck the Mohne, Eder and Sorpe Dams in the German Ruhr Valley, destroying two of them. The inset image shows the blips on the trace of the seismograph at the Institut für Geophysik at Göttingen, 130 km distant.**



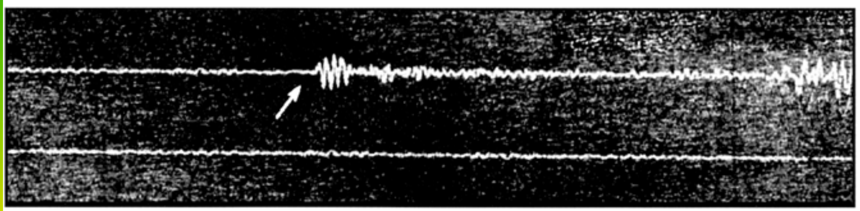
[1] 00:27:29.8 Uhr DSZ



[2] 00:38:04.1 Uhr DSZ

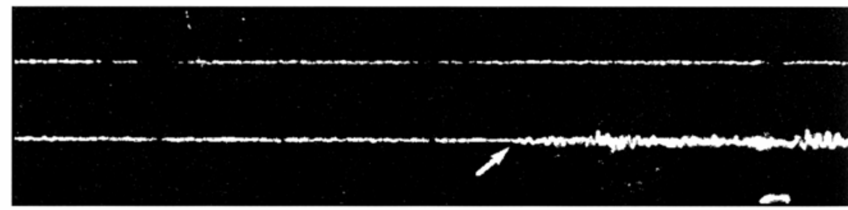


[3] 00:43:51.4 Uhr DSZ

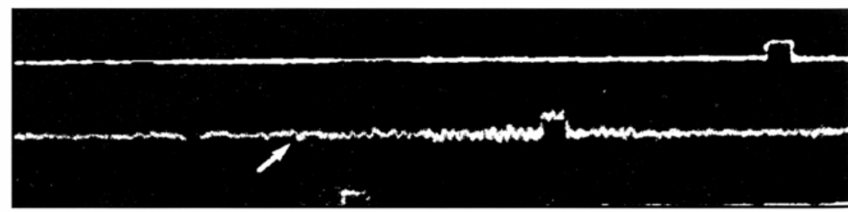


GEOPHYSIKALISCHEN INSTITUT GÖTTINGEN

	Time (DSZ)	*Pilot*	*Period*	*Maximum Deflection*
		Möhne dam		
[1]	00.27:29.8	Gibson	40,8 sec	0,6 mm
[2]	00.38:04.1	Martin	14,9 sec	0,8 mm
[3]	00.43:51.4	Young	2,6 sec	0,2 mm
[4]	00.49:29.5	Maltby	40,5 sec	0,8 mm (Destruction)
		Eder dam		
[5]	01.37:28.1	Shannon	34,0 sec	0,4 mm
[6]	01.50:53.9	Knight	57,0 sec	0,2 mm (Destruction)
		Ennepe dam		
[7]	03.38:	Townsend	Faint mark only	



[5] 01:37:28.1 Uhr DSZ



- **The Göttingen seismograph recorded 7 of 11 explosions at the Mohne (130 km), Eder (75 km) Sorpe (139 km) dams. The explosions that were not recorded occurred either in the air above ground or within the earthen embankment of the Sorpe Dam.**

The origins of forensic seismology can be traced to the establishment of nuclear test ban treaties

NUCLEAR TEST BAN TREATY VERIFICATION

Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO)

- **Organized in 1996**
- **Most recent international effort to reduce nuclear weapons proliferation**
- **By the end of 2004, 41 of 44 countries had signed it; 33 of 44 nations have ratified it**
- **CTBTO created the International Monitoring System (IMS)**
- **"*Convinced that the most effective way to achieve an end to nuclear testing is through the conclusion of a universal and internationally and effectively verifiable comprehensive nuclear test-ban treaty, which has long been one of the highest priority objectives of the international community in the field of disarmament and non-proliferation*"**

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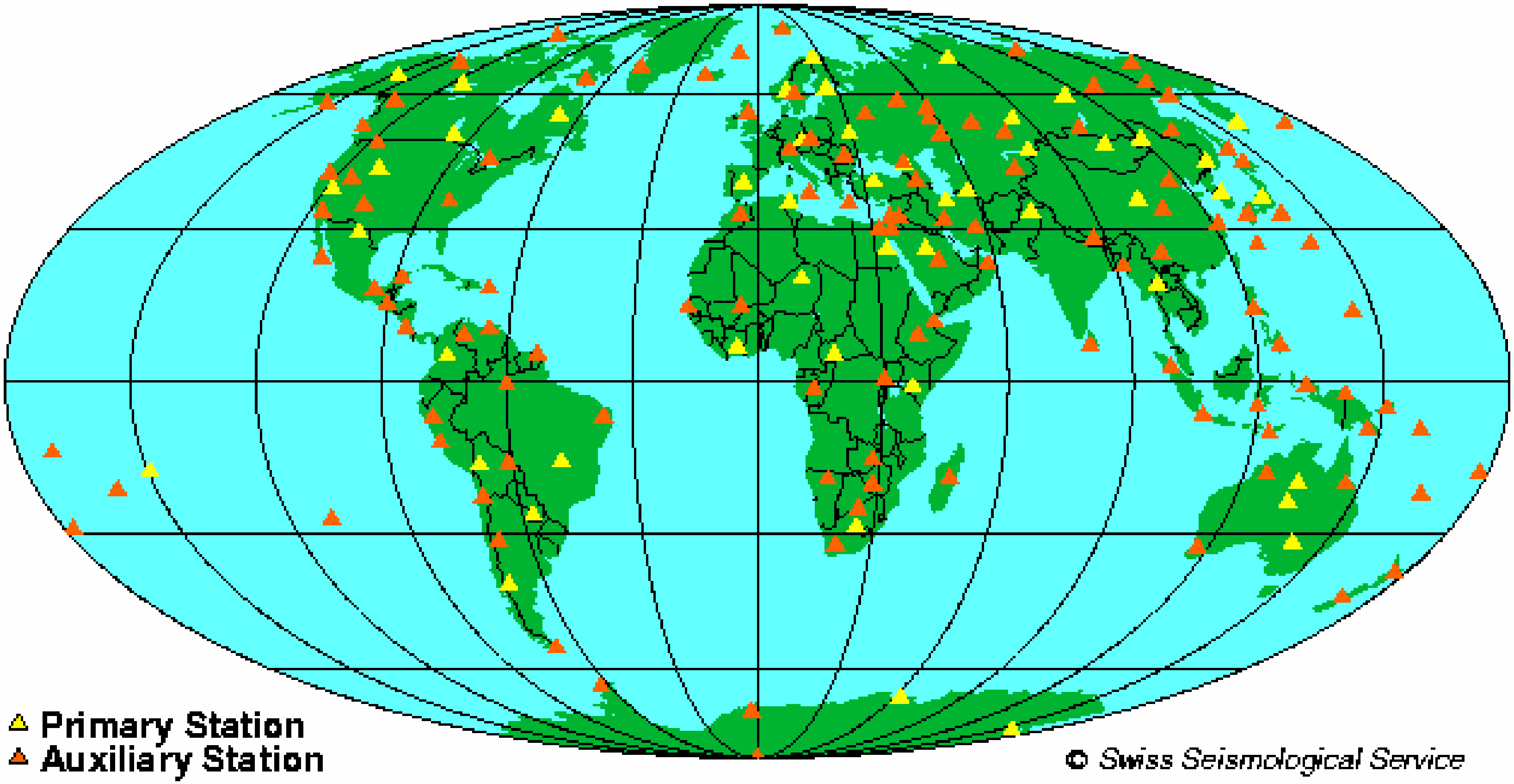
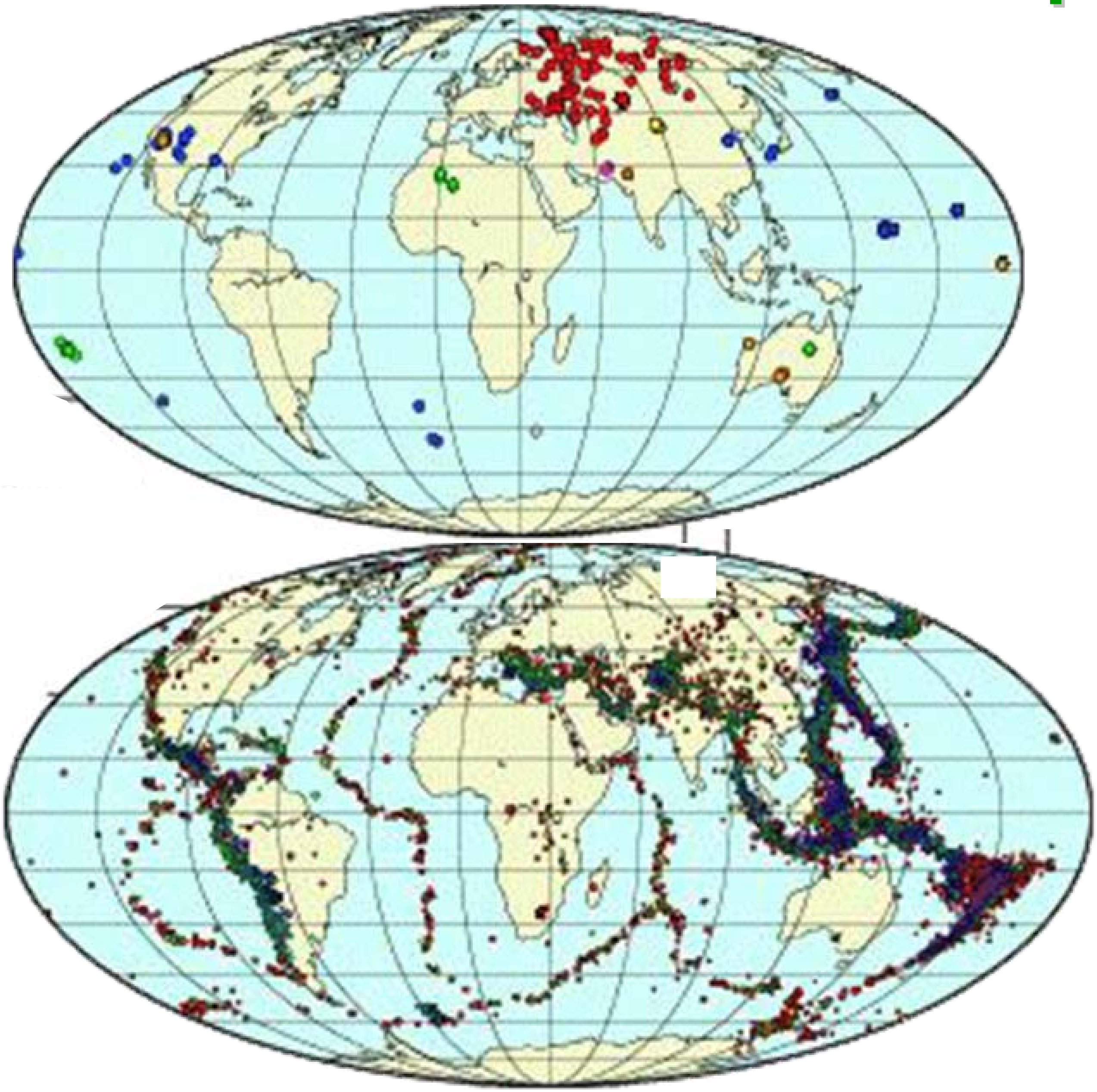
International Monitoring System



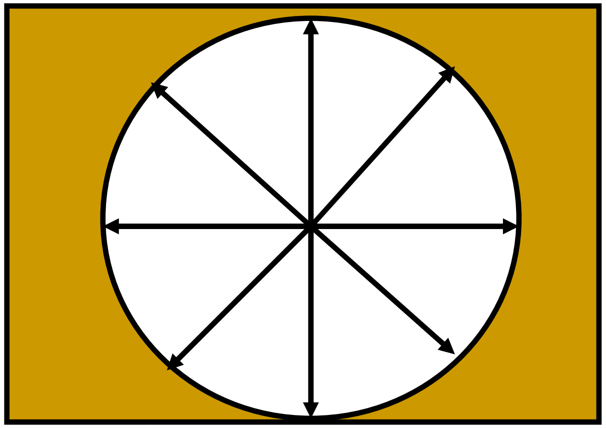
The seismic network will consist of 50 primary stations and 120 auxiliary stations.

Nuclear Detonations vs. Earthquakes



SEISMIC WAVE PROPERTIES

UNDERGROUND NUCLEAR BLASTS

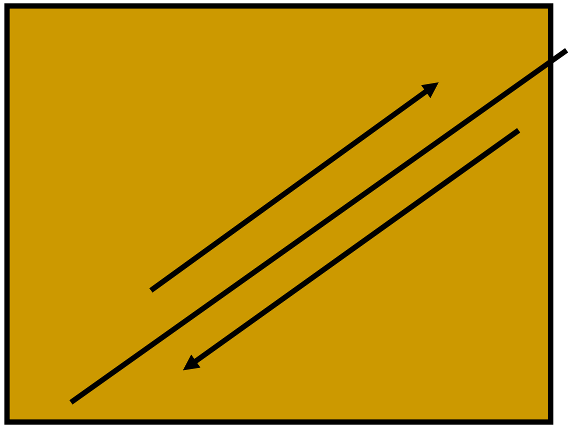


P waves dominate

Compressional waves

Similar to sound waves

NATURAL EARTHQUAKES



S waves dominate

Transverse waves

Similar to shaking one end of rope

INDIA - PAKISTAN NUCLEAR TESTS IN 1998

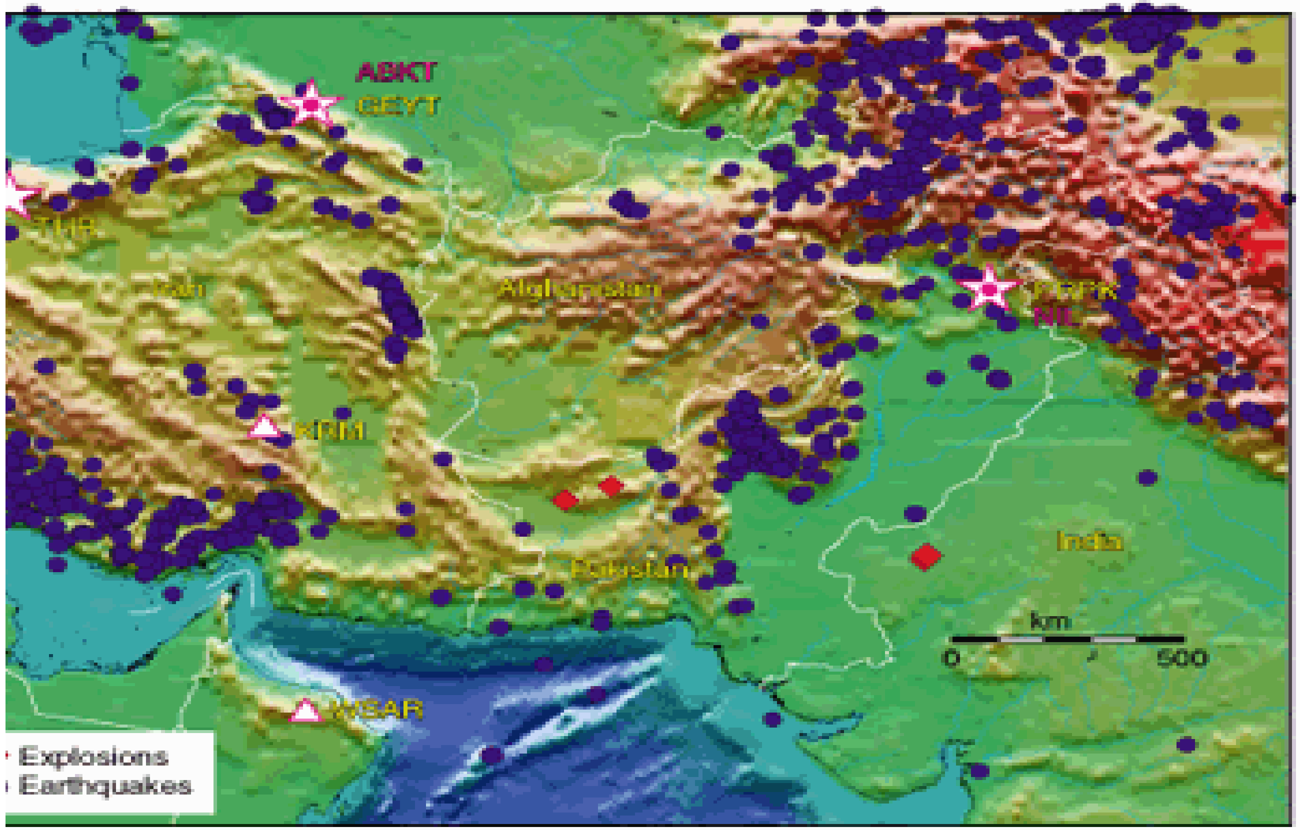


Figure 1. Topographic map showing the locations of the Indian nuclear tests in 1974 and on May 11 and 13, 1998, the Pakistani nuclear tests on May 28 and 30, 1998, and earthquakes recorded in the region between 1995 and 1997. Also shown are the planned locations of the International Monitoring System's primary (stars) and auxiliary (triangles) seismic stations and the Incorporated Research Institutions for Seismology's stations closely collocated at Alibek, Turkmenistan (ABKT), and Nilore, Pakistan (NIL).

SEISMIC SIGNATURES

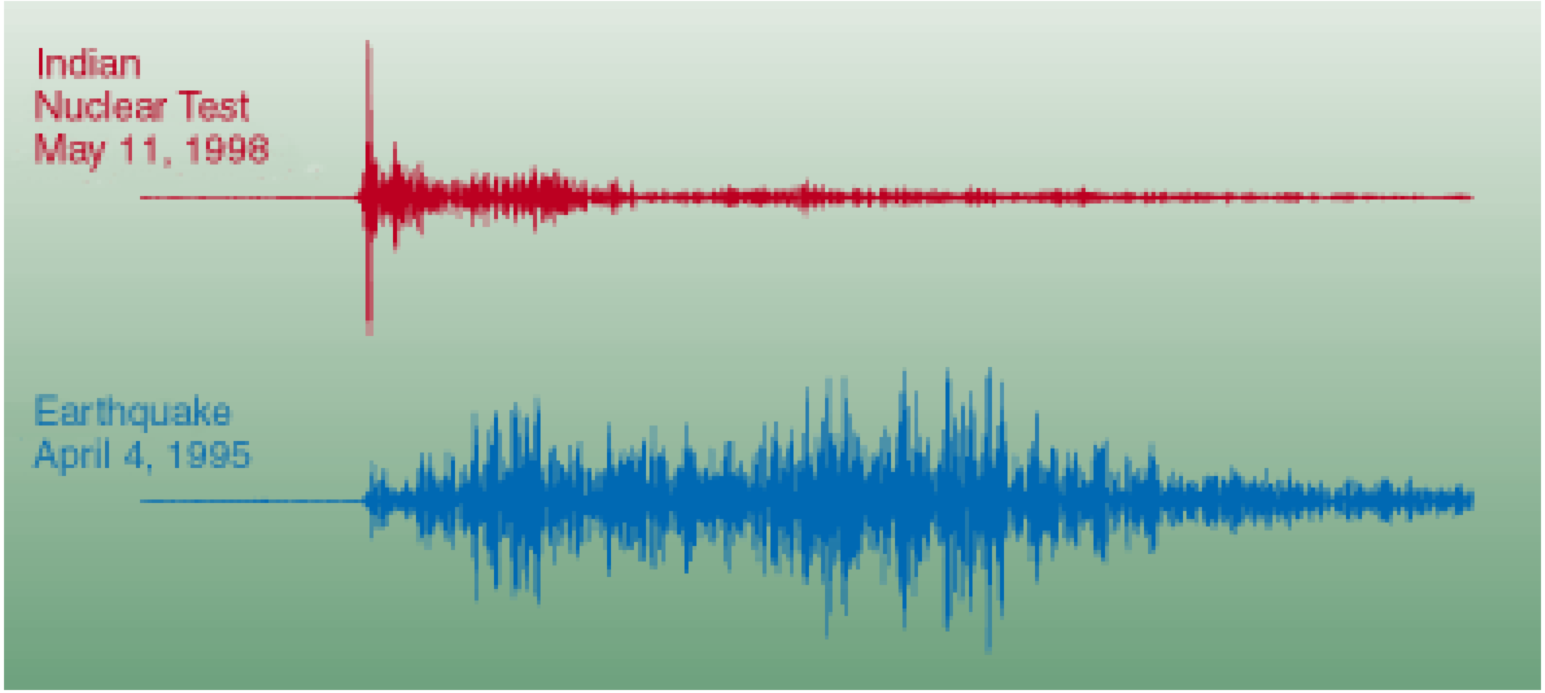


Figure 2. Seismograms of the Indian nuclear test (top) and a representative nearby earthquake (bottom) recorded at the seismic station at Nilore, Pakistan. These seismic signatures for an explosion and earthquake are typical and clearly distinguish one from the other.

P/S RATIOS

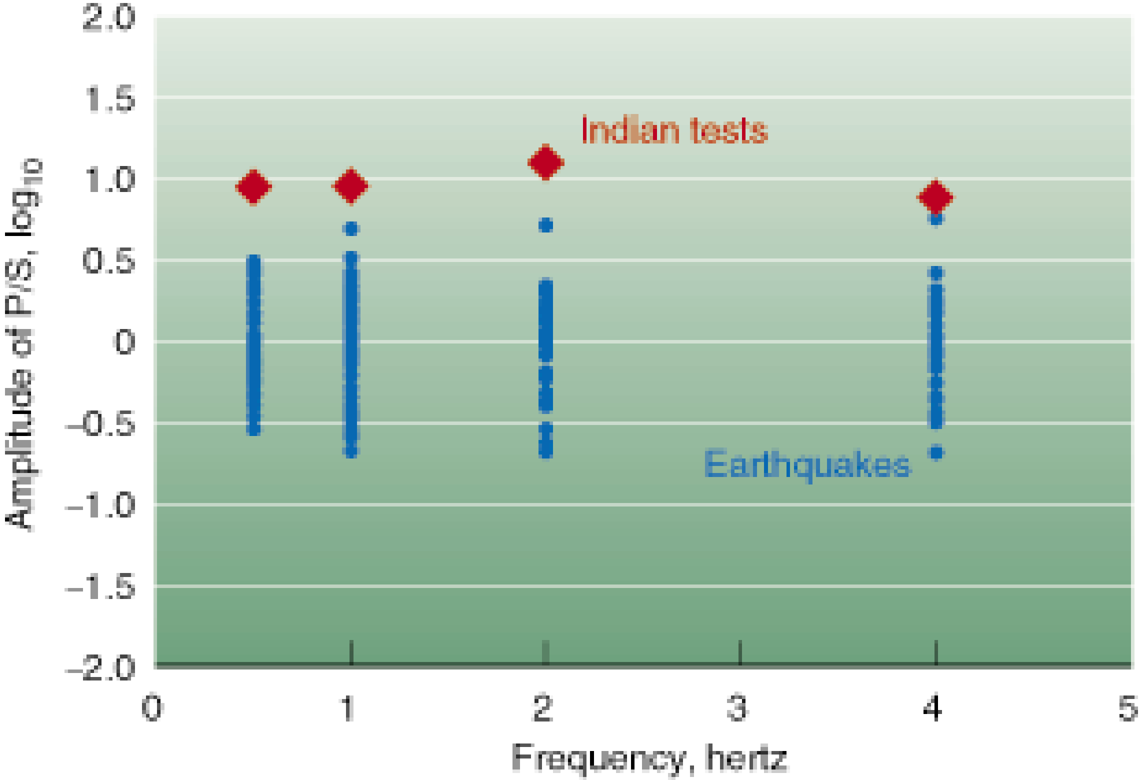


Figure 3. P-to-S amplitude ratios versus frequency for the Indian nuclear test (diamonds) and nearby earthquakes (circles). Note that the P- to S-wave ratios are higher for the Indian test than for the earthquakes.

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SEISMIC DISCRIMINATE BETWEEN EARTHQUAKES AND EXPLOSIONS

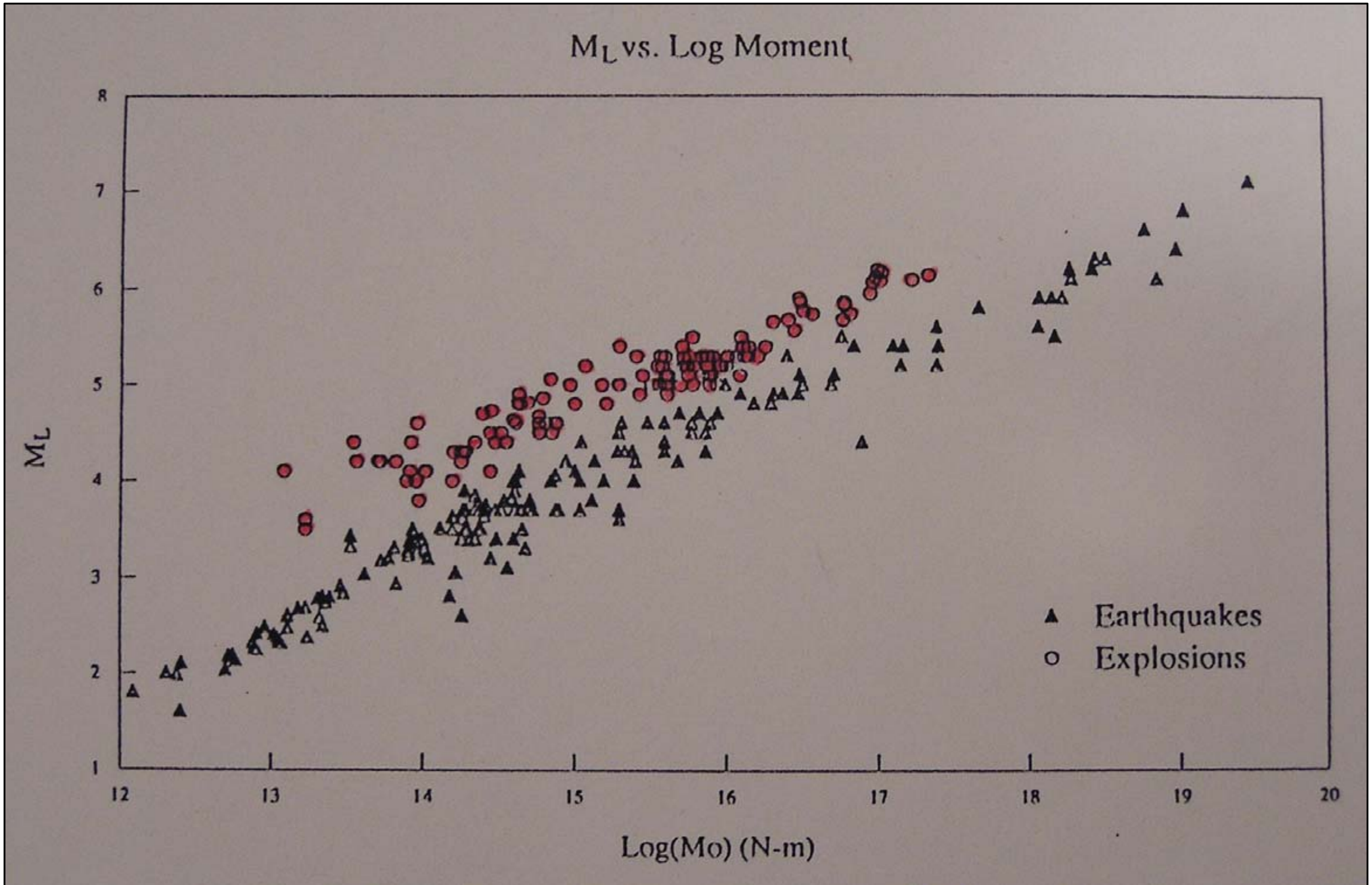

Fig. 1. M_L vs. log M_0 for 173 earthquakes and 128 explosions.

M_L local Richter Magnitude Scale short period energy

M_O Scalar Moment long period energy

SEISMIC DISCRIMINATE BETWEEN EARTHQUAKES AND EXPLOSIONS

- **Explosions have a significantly smaller surface wave magnitude (M_s) than an earthquake with the same body wave magnitude (m_b).**
- **This is because the source spectrum of an earthquake is richer in long-period energy than that of an explosion. Larger, deeper-seated energy releases emit longer wavelength energy than smaller sources near the Earth's surface. Much of an explosion's energy is lost into the atmosphere.**

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FUTURE MONITORING

(a)

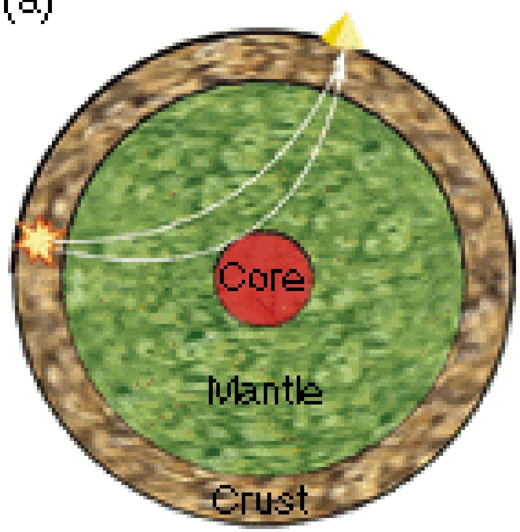
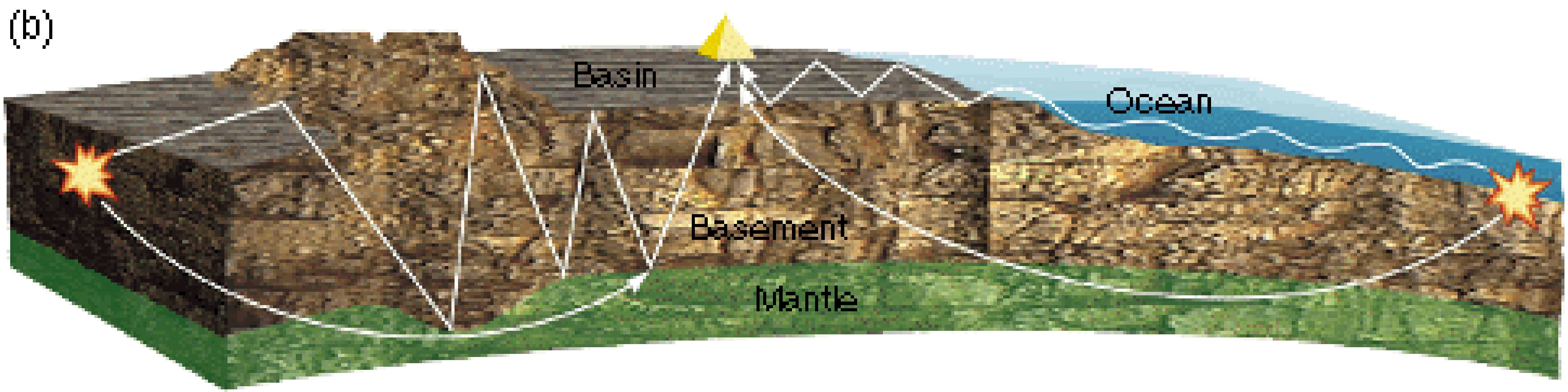


Figure 2. (a) Seismic signals from most nuclear tests under the current Threshold Test Ban Treaty (banning nuclear explosions above 150 kilotons) travel thousands of miles through Earth's relatively homogeneous lower mantle and core and are detected by far-away seismic stations. (b) Under the CTBT, a nation attempting to conceal a test would presumably detonate a much less powerful warhead. Signals from such an event would be confined to Earth's upper mantle and crust, a region that readily distorts the signals.

(b)



THE EMERGING FIELD OF FORENSIC SEISMOLOGY

- What is it?
- How can we use it?
- Can it be used to provide valuable clues and information on secret detonations by rouge nations or terrorist acts?

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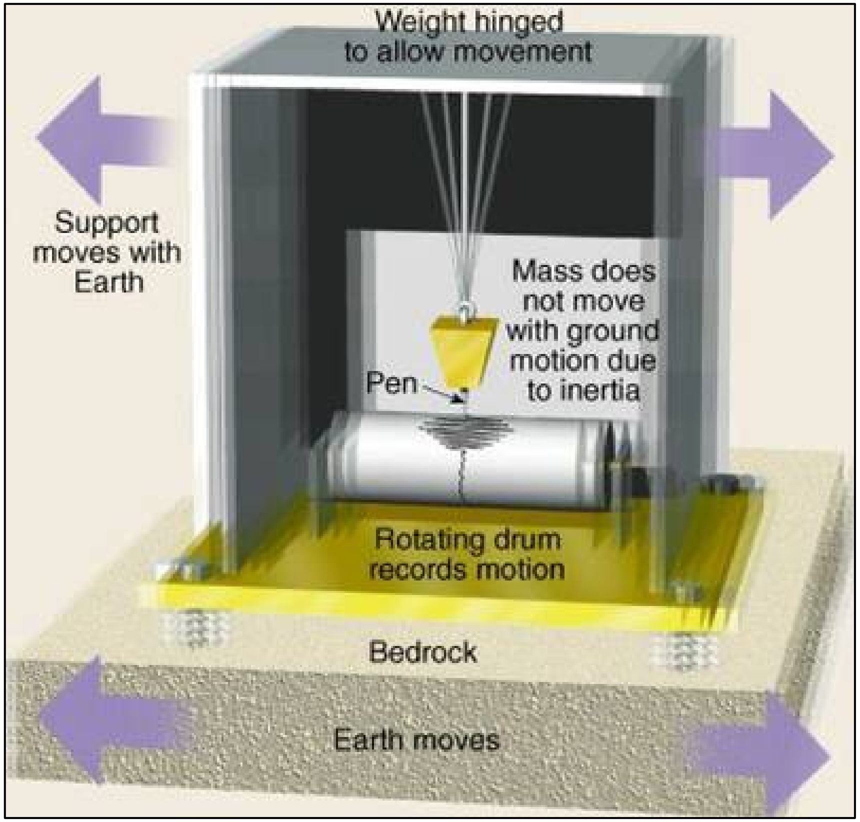
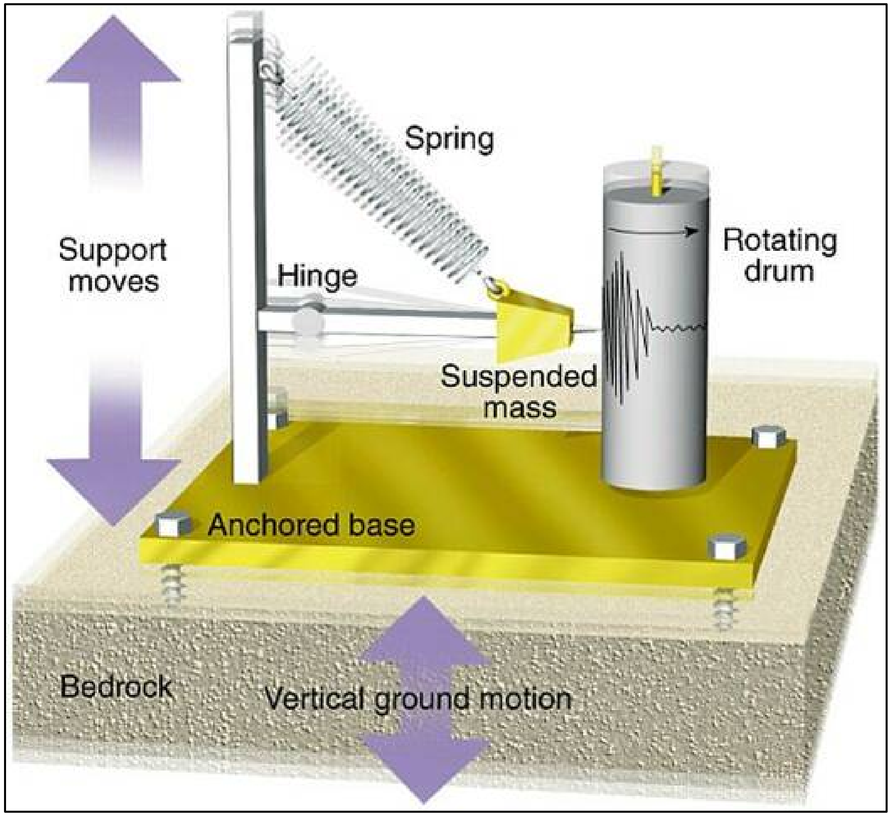
What is a Seismograph?





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What is a Geophone?

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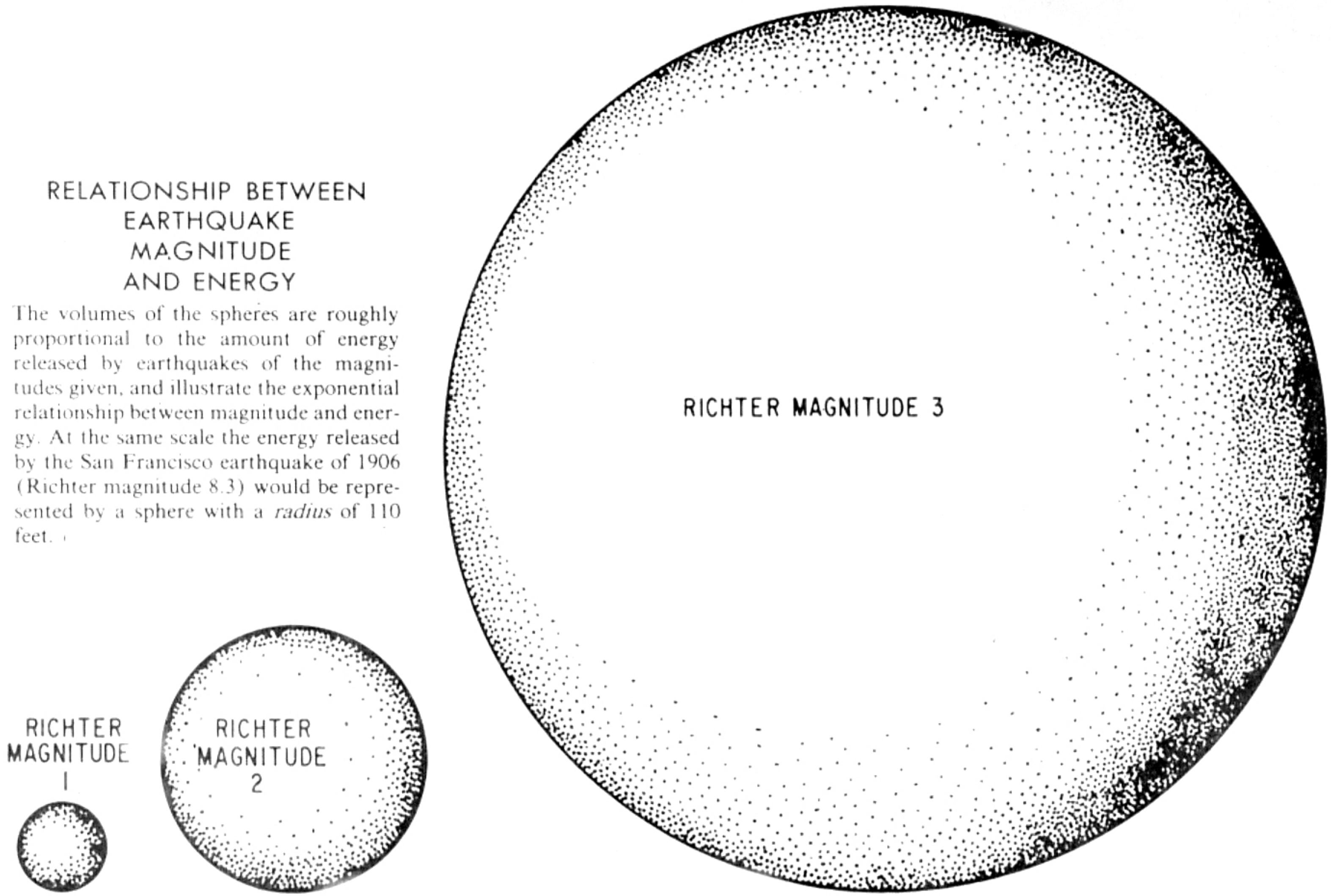
QUAKE'S RELEASE ENERGY DESCRIBED USING A LOGARYTHMIC SCALE

RELATIONSHIP BETWEEN EARTHQUAKE MAGNITUDE AND ENERGY

The volumes of the spheres are roughly proportional to the amount of energy released by earthquakes of the magnitudes given, and illustrate the exponential relationship between magnitude and energy. At the same scale the energy released by the San Francisco earthquake of 1906 (Richter magnitude 8.3) would be represented by a sphere with a *radius* of 110 feet.



Old Richter Scale Magnitude	Equivalent Energy (Weight of TNT)	
1.0	6	Ounces
1.5	2	pounds
2.0	13	pounds
2.5	63	pounds
3.0	397	pounds
3.5	1,990	pounds
4.0	6	tons
4.5	32	tons
5.0	199	tons
5.5	1,000	tons
6.0	6,270	tons
6.5	31,550	tons
7.0	199,000	tons
7.5	1,000,000	tons
8.0	6,270,000	tons
8.5	31,550,000	tons
9.0	199,000,000	tons

SEISMIC DATA

- Over 10,000 seismometers are 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
- The International Monitoring System (IMS) utilizes 321 seismograph stations and 16 radionuclide labs
- Effectiveness of CTBTO monitoring network apparent in aftermath of Pakistani and Indian nuclear blasts in 1998

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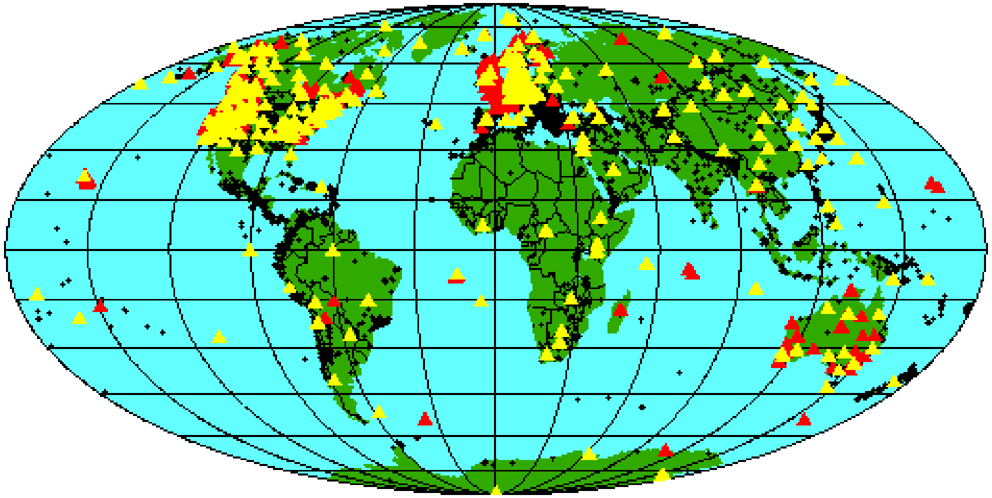
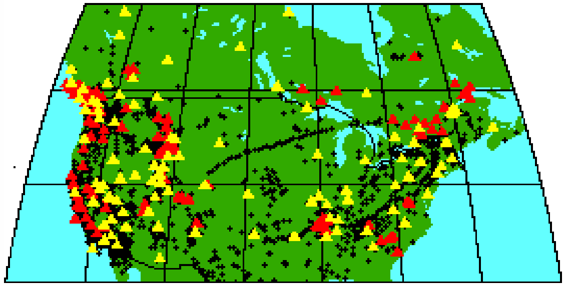
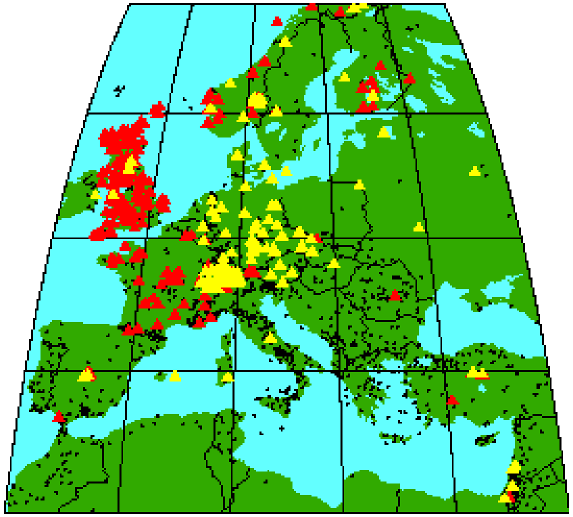
Stations Available via AutoDRM



The Auto Data Request Manager System provides Real Time Seismic Data worldwide





Active Broad-Band Station

Active Other Station

Operating Station Registered at ISC/NEIC

http://seismo.ethz.ch/waves4u or autodrm@gldfs.cr.usgs.go

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SEISMIC DATA CAN BE USED TO CHARACTERIZE ALL KINDS OF ENERGY RELEASE EVENTS

- **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 as: *forensic seismology***

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EXAMPLES OF NON-EARTHQUAKE SEISMIC SOURCES

Natural Events

- bolide/impacts
- volcanic eruptions
- mine collapse
- rock fall/land slides
- tornados

Man-Caused Events

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

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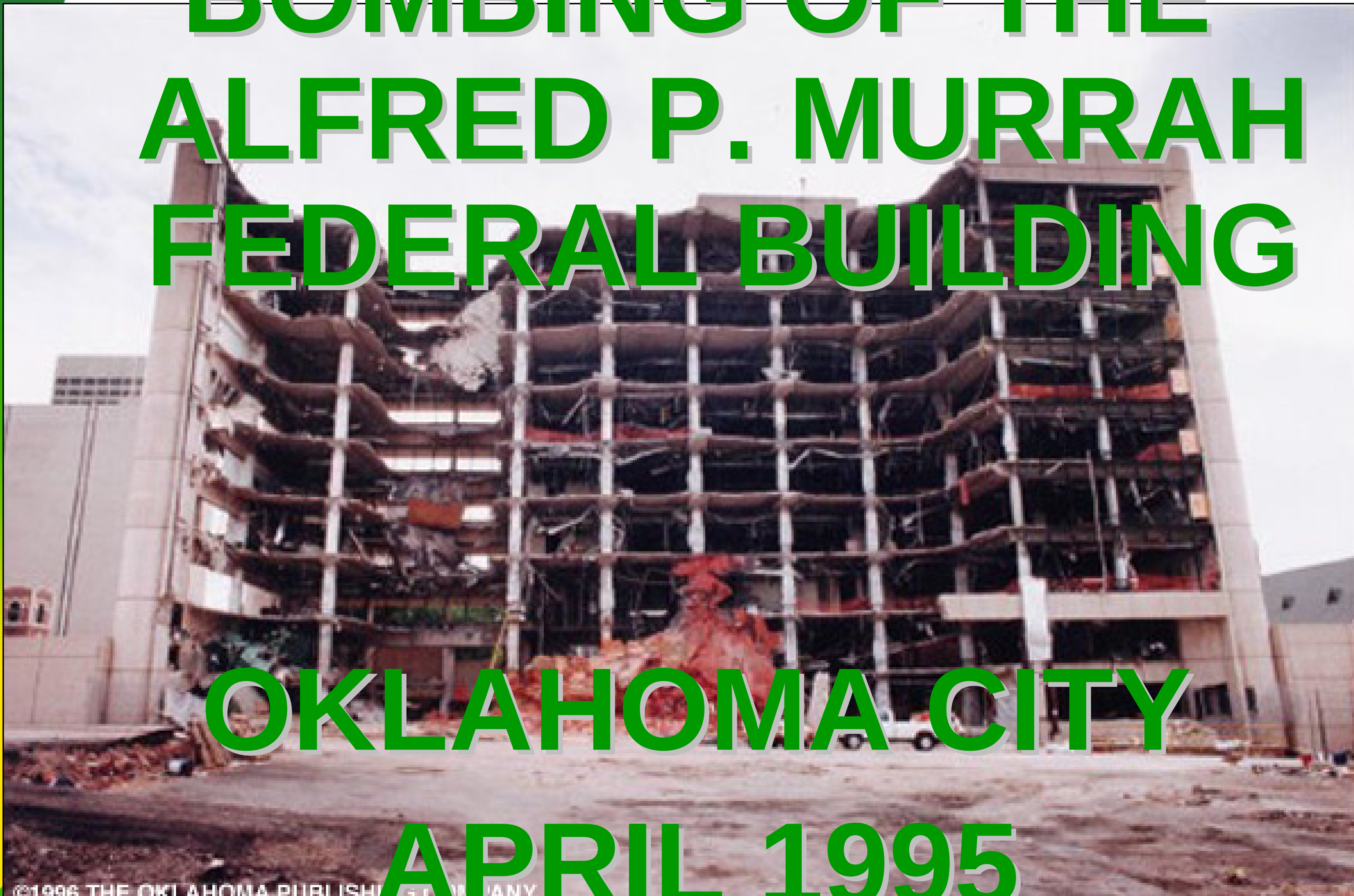
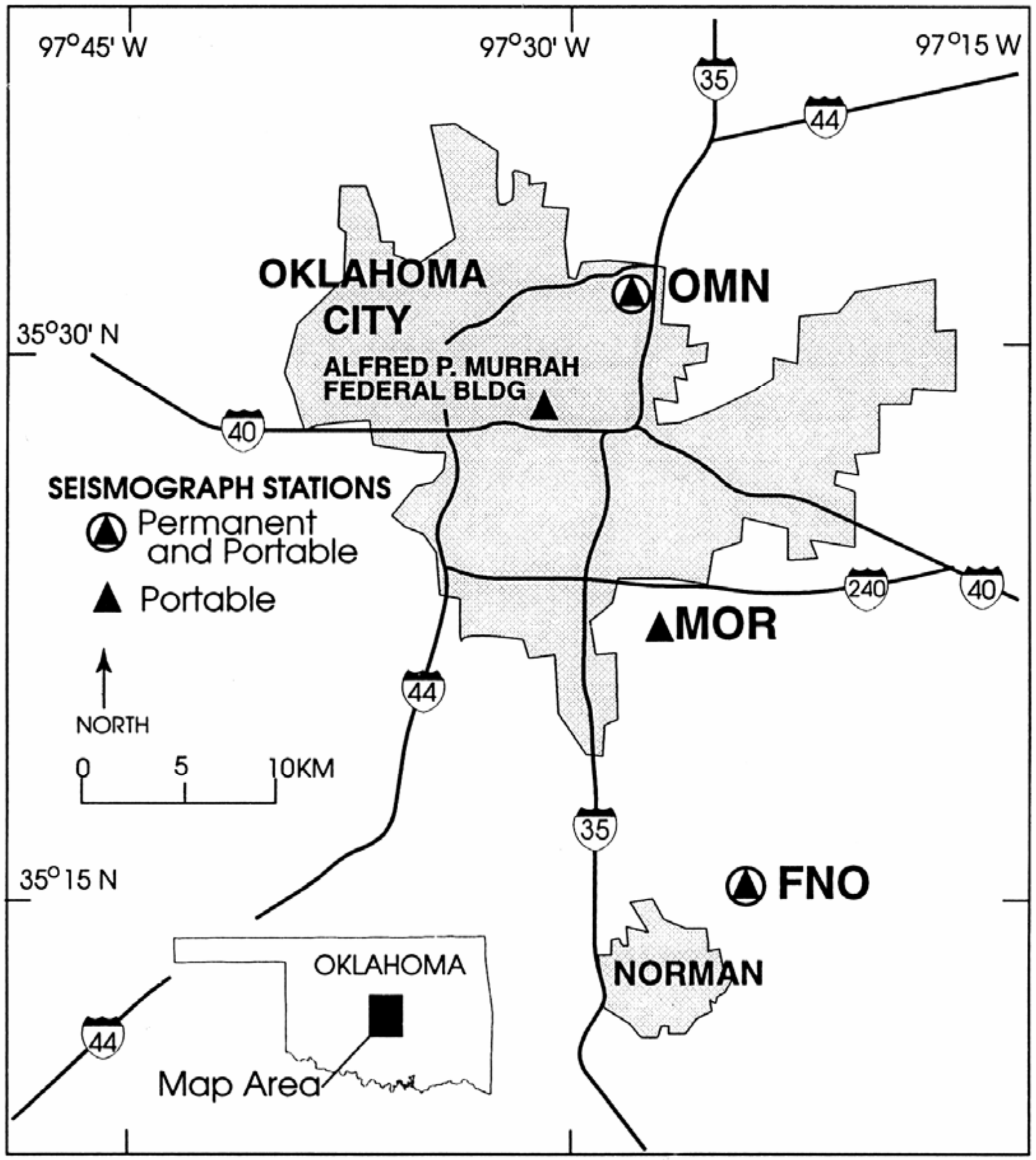
BOMBING OF THE ALFRED P. MURRAH FEDERAL BUILDING



OKLAHOMA CITY

APRIL 1995



LOCATIONS OF SEISMOGRAPHS IN OKLAHOMA CITY

- **Locations of permanent and portable seismographs that recorded April 1995 bombing and subsequent demolition of the Murrah Federal Building in Oklahoma City**

April 19, 1995 Truck Bomb Explosion

- Two seismographs recorded the explosion and ensuing structural collapse; one at 6.86 km northeast and another at 26.02 km south
- Two distinct wave trains were recorded, about 10 seconds apart
- Were these recording two separate explosions?
- Bloggers on Internet created enormous confusion and doubt

- **Four portable seismographs were brought in to record the controlled demolition of the building on May 23, 1995**
- **Two wave trains were recorded, with distinct seismic phases that traveled in a near-surface zone, over which the seismic velocity increased sharply with depth**

RESULTS OF MONITORING BUILDING DEMOLITION

- The first phase wave train appeared to be a packet of scattered seismic shear waves
- The second is the fundamental-mode Rayleigh surface wave
- The two wave trains recorded on April 19^{th} are consistent with a single explosion, not evidence of two explosions

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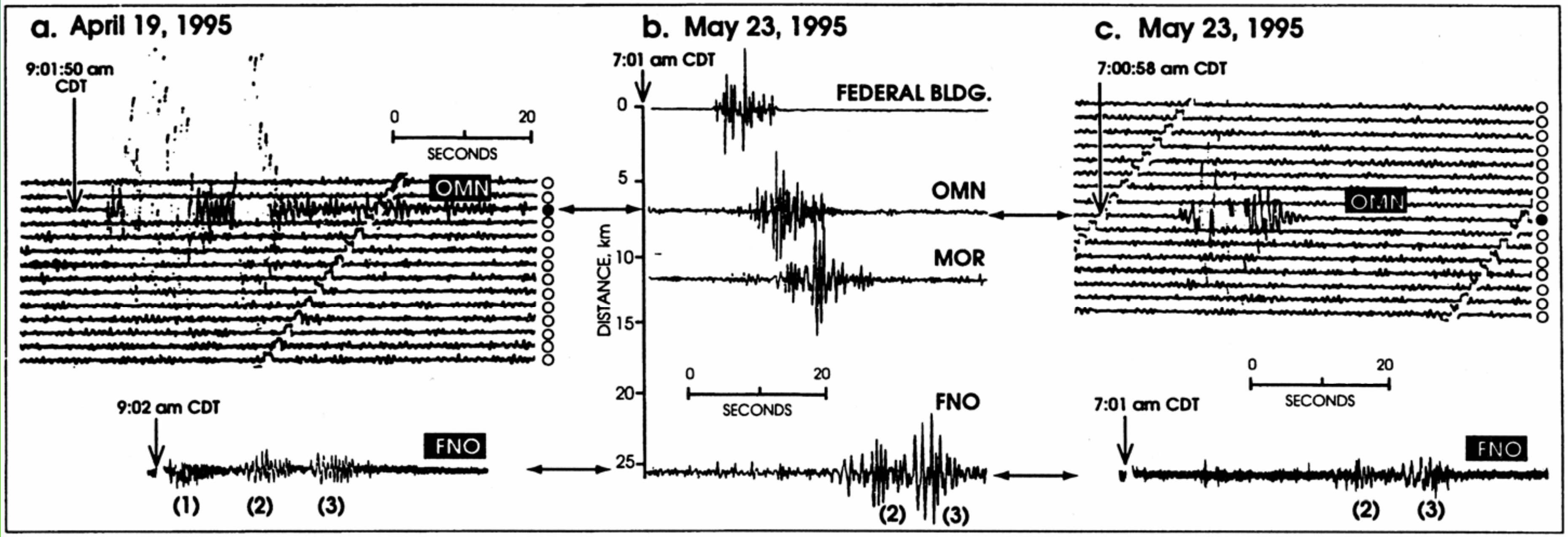
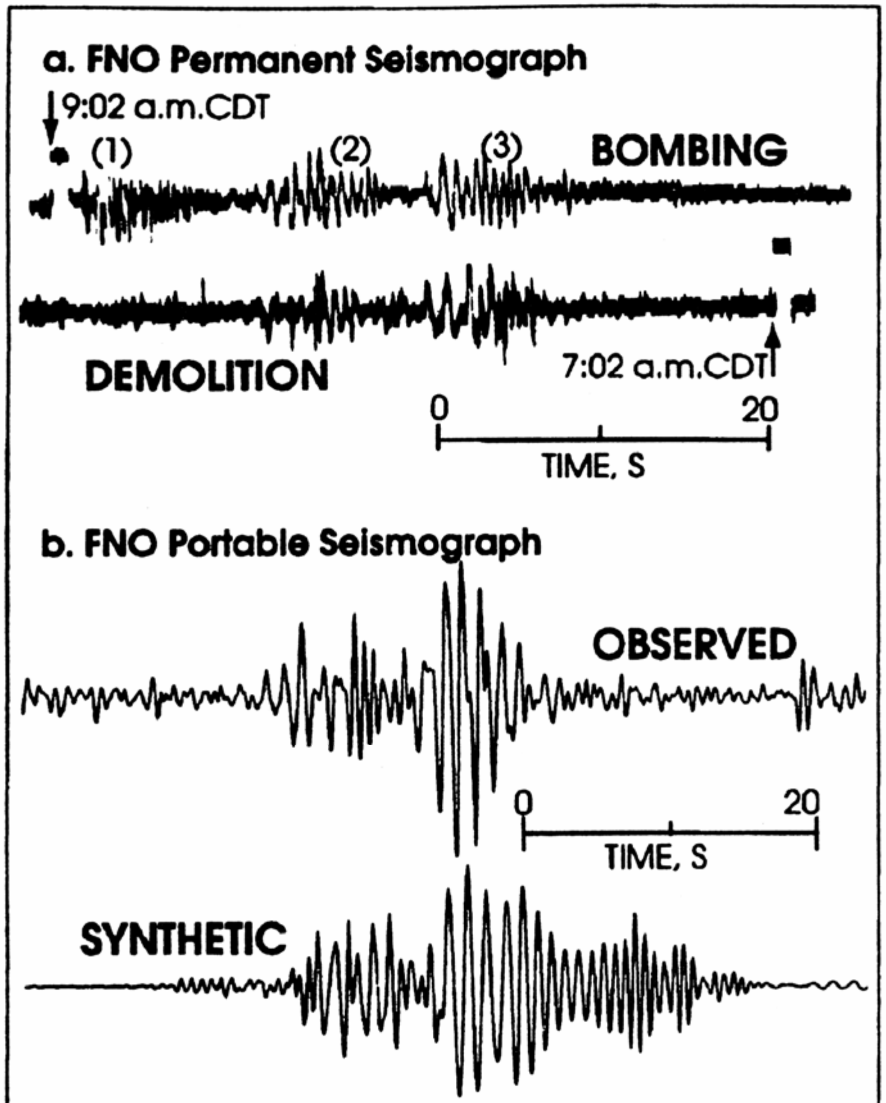


- **Comparisons of seismograms recorded during the April 19th bombing and May 23rd demolition. Base of left plot shows numbers assigned to various wave trains (5X amplification). Middle plot shows seismograms of vertical velocity recorded by portable digital units at the site, plotting as function of distance from the building. Trace at right shows permanent seismograph recording of May 23rd demolition at 6.86 km distance.**

VALIDATION OF SEISMIC MODEL



- **Comparison of April 19th bombing and May 23rd demolition recorded at Univ of Oklahoma, 26 km away.**
- **Numbers in parentheses refer to wave train packets.**
- **Lower plots compare recorded trace with synthetic seismogram for a 1-D velocity model assuming a near-surface 350 m thick zone where S-wave velocity increases significantly with depth**

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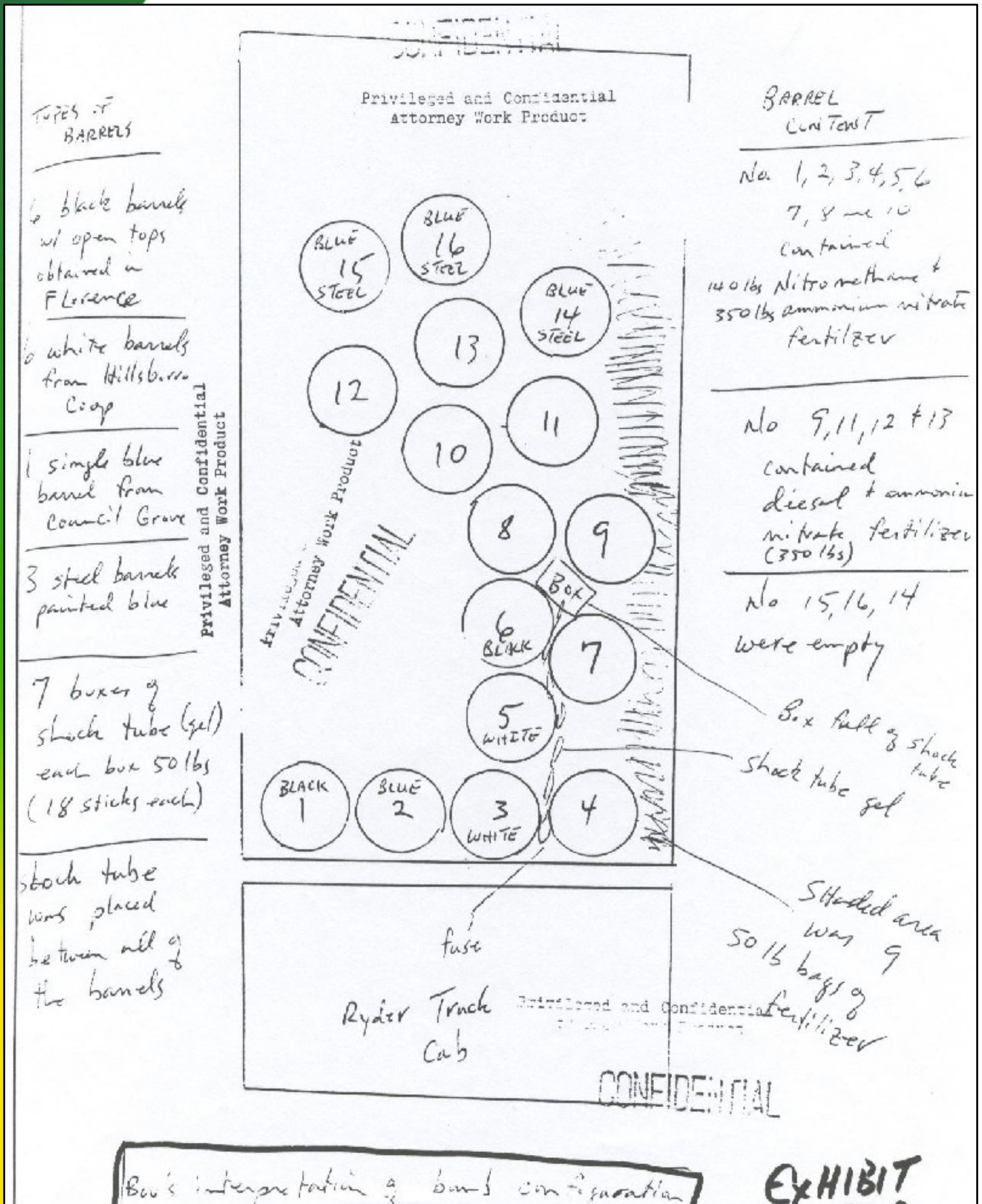

ANFO Barrels arraigned to form a Shaped Charge

- The sketch at left was made by Timothy McVeigh explaining how he arraigned the plastic barrels containing the ANFO mixture, to focus the blast laterally, towards the Murrah Federal building
- The ANFO truck bomb had in excess of 6,200 pounds of 'energetic materials' – equivalent to about 5,000 pounds of TNT.

CONCLUSIONS from USGS STUDY - 1

- The May 23rd detonation lasted 8 seconds, but also generated two distinct wave trains, 10 seconds apart at the University of Oklahoma seismograph station, 26 km distant.
- Most of the seismic energy generated by the demolition occurred in first 5 seconds; with explosives release limited to first 2.5 seconds (remainder is collapse-related)
- Wave Train 3 appears to be fundamental mode Rayleigh surface wave, moving across land surface at 1.7 km/sec

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CONCLUSIONS from USGS STUDY - 2

- Synthetic seismograms were generated based on what was known about the underlying structure and computed for the May 23rd detonation (known energy source)
- Average velocities were 2.7 and 5.5 km/sec for wave train 1.
- 5.5 km/sec wave train velocity appears to be a deeply refracted P wave, off the top of the underlying Arbuckle Limestone

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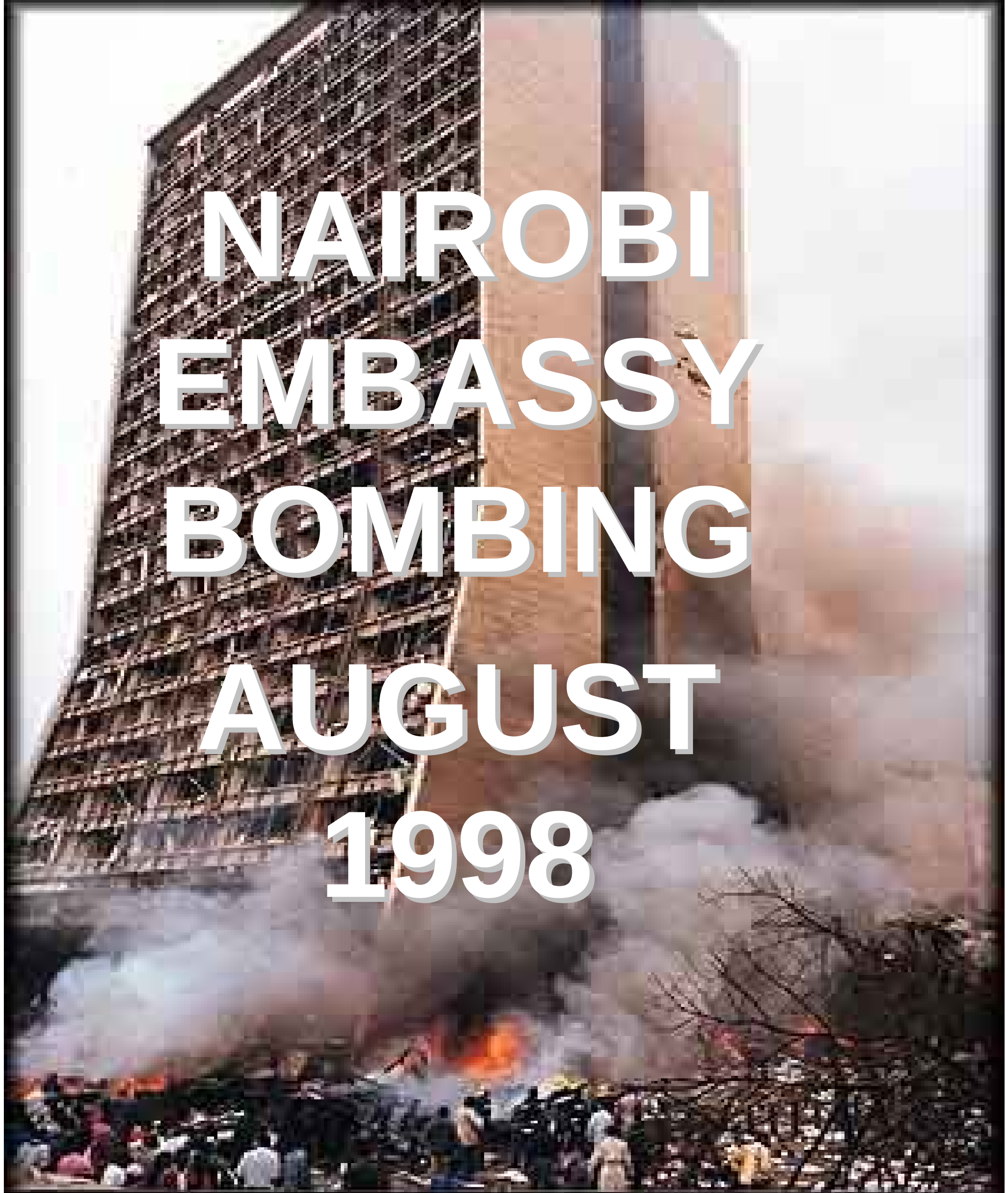
CONCLUSIONS from USGS STUDY - 3

- Applying velocities recorded during May 23rd demolition to the April 19th bombing suggest the time of detonation as between 9:01:52 and 9:01:57 AM local time
- The building demolition on May 23rd only used 68 kg of dynamite.
- Energy source for the April 19th truck bomb estimated to be approximately 1820 kg (4022 lbs), about 28X that used in the May 23rd building demolition
- This weight and volume of ANFO could have easily been contained within the Ryder rental truck parked next to the building, seen in the electronic teller surveillance camera from across the street

NAIROBI EMBASSY BOMBING

AUGUST 1998



ATTACK ON U.S EMBASSY IN NAIROBI, KENYA – AUGUST 1998

Basic Facts of Nairobi Attack

- On 10 August 1998 al-Qaeda 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

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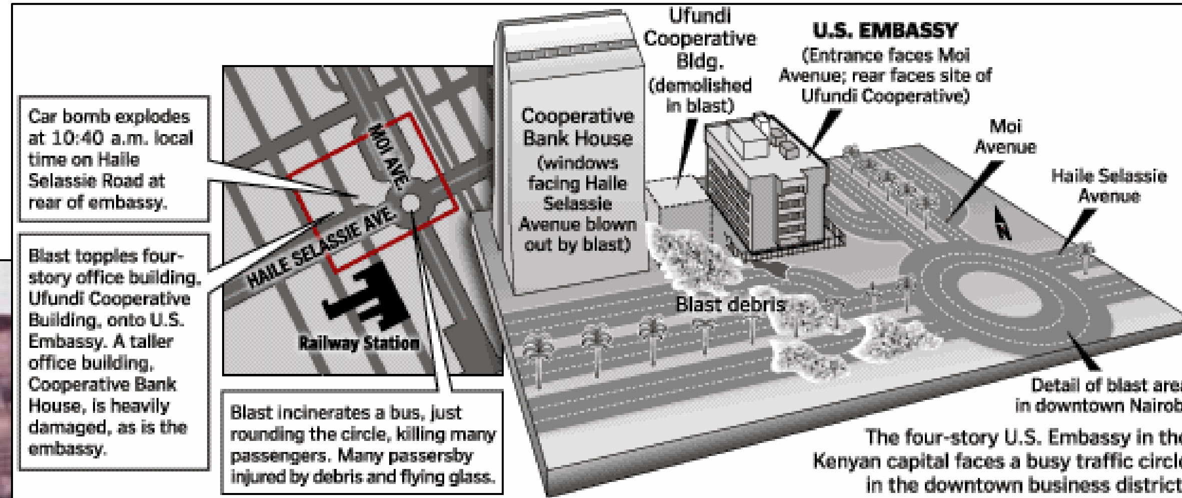
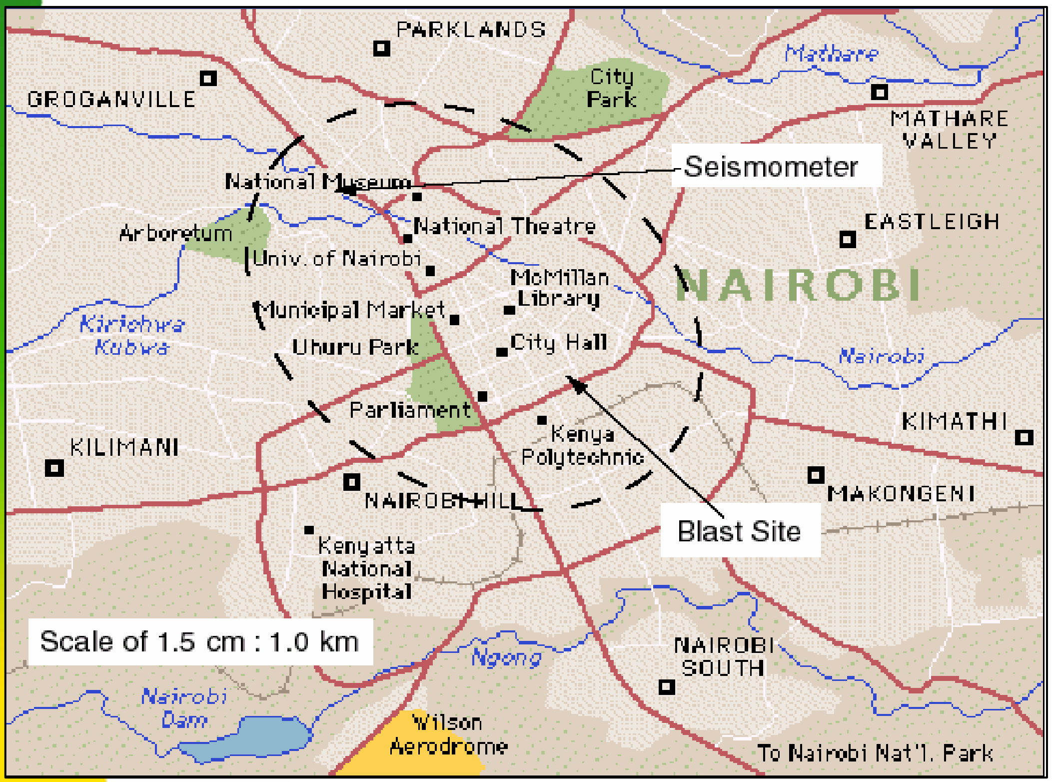
U.S EMBASSY IN NAIROBI, KENYA



SEISMIC STATION NAI



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

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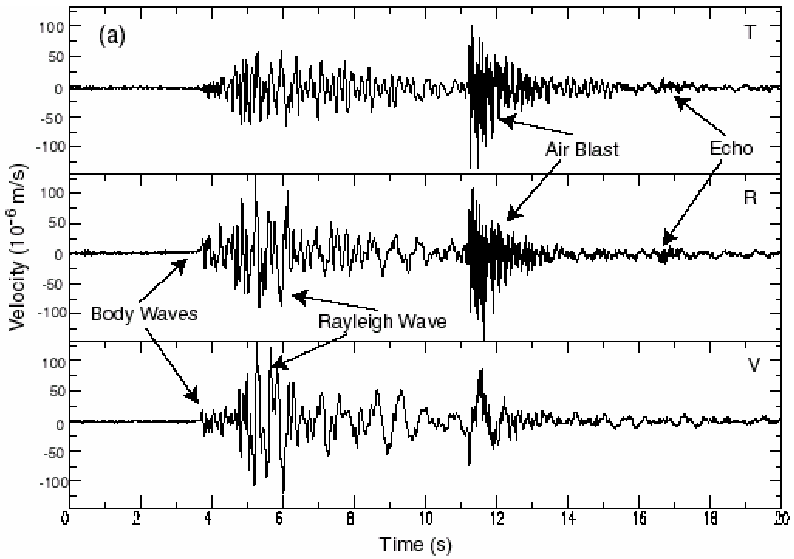
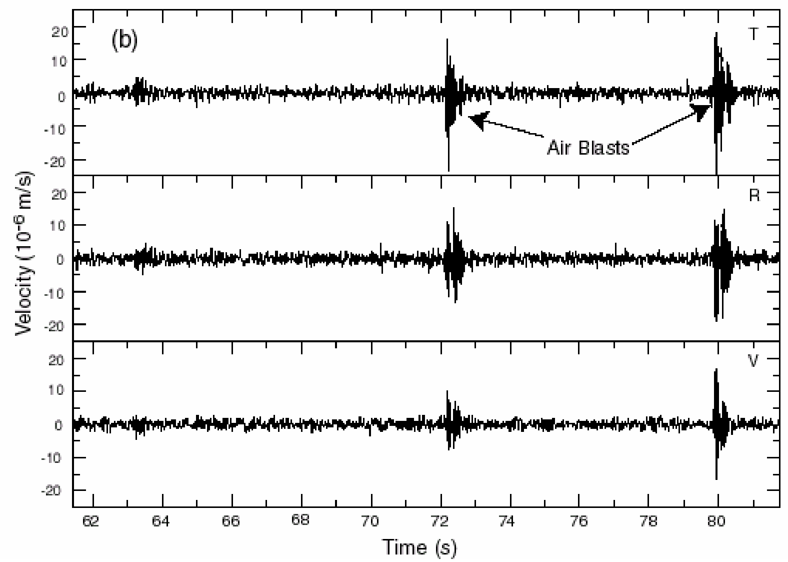
SEISMIC DATA FROM NAI

First time span, main explosion and echo.



Second time span, unexplained airblasts.



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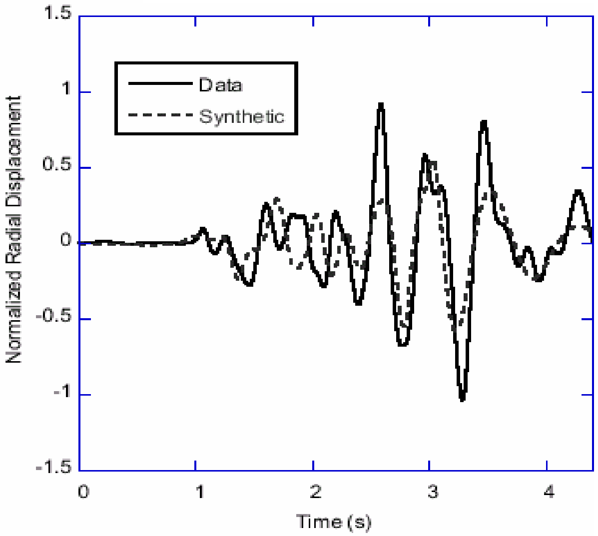
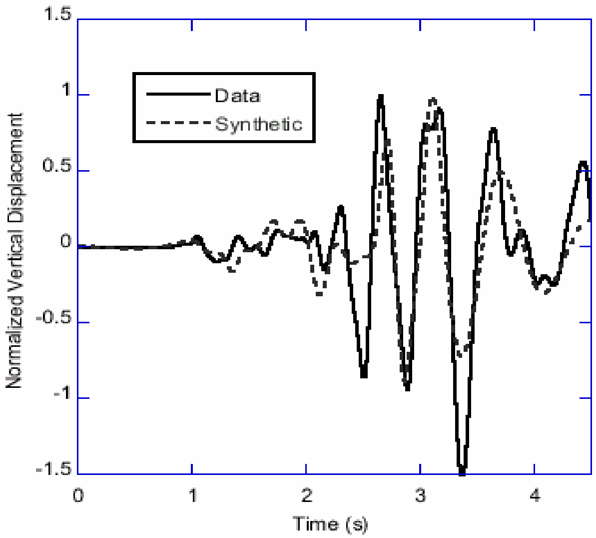
Results from Waveform Modeling





- 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 x 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 energy reservoirs are:
  - crater formation
  - deformation of truck and buildings
  - projection of debris (missiles)
  - atmospheric sound waves
  - heat generation
- How can we determine the total energy released (yield) from only seismic data?

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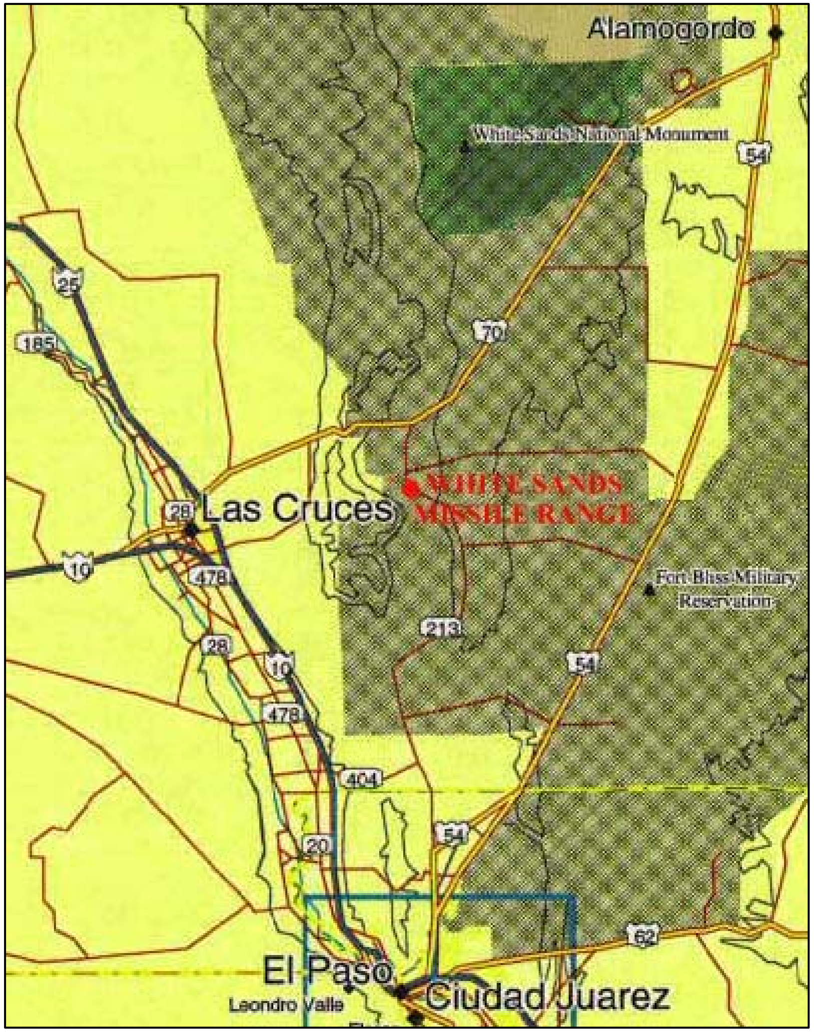
YIELD ESTIMATION for TRUCKBOMBS

- Record 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 explosive 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 (ATF)
- The tests were originally designed to:
  - train ATF and FBI agents
  - quantify the effects of truckbombs on various structures
  - study the dynamics of truckbomb explosions



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

Before

After

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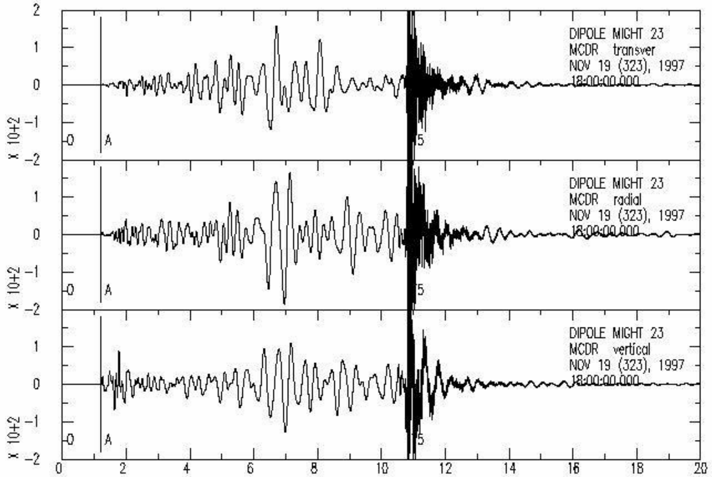
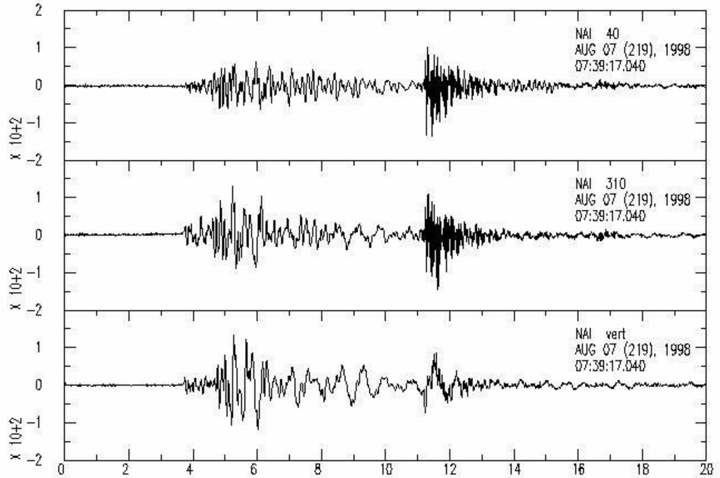
Waveform Comparison

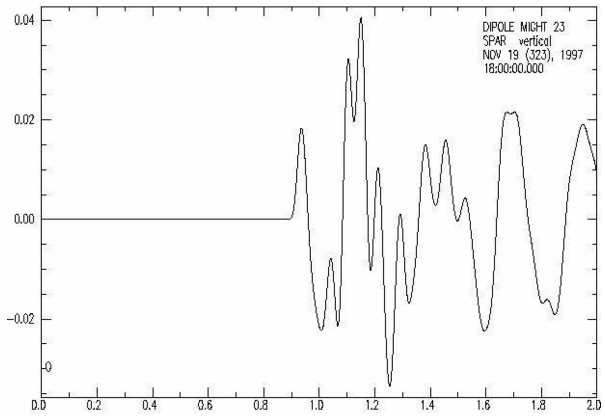


Example Seismogram from Controlled Test

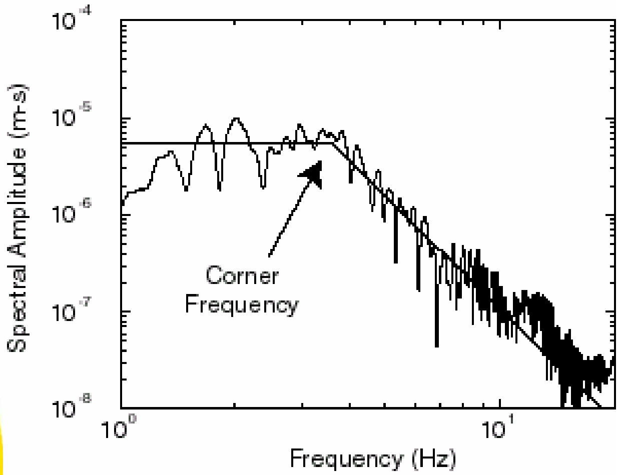


Actual Nairobi Seismogram

Useful Waveform Properties

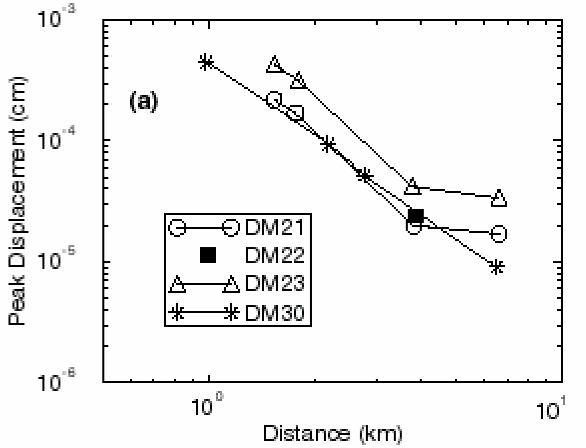


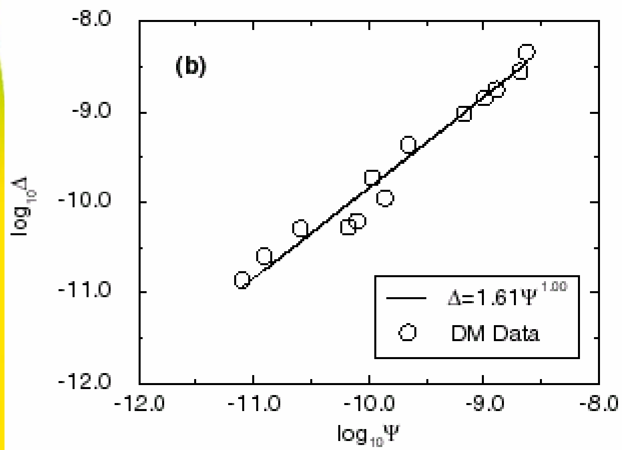
Fourier Transform



- 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:

$$\mu \equiv \text{displacement}$$

$$r \equiv \text{distance}$$

$$m \equiv \text{mass of explosive}$$

$$\rho \equiv \text{density}$$

$$\Delta = \frac{\mu}{r} \equiv \text{normalized displacement}$$

$$\Psi = \frac{m}{pr^3} \equiv \text{normalized yield}$$

(3) Determine relation between dimensionless variables: how are D and Y related ?

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NAIROBI BOMBING SUMMARY

- Seismic records indicate a single, surface explosion occurred, with an upper limit explosive yield of 17 tons. The lower bound value was not determinable. Estimate was based on standard tables for chemical explosions.
- Adjustment for seismic efficiency of the truck bomb (upper bound of 3%) gives a estimate of about 3 tons of explosives, probably much closer to the actual size.
- Combination of Nairobi seismic records with scaling laws from White Sands Missile Range tests provide an estimate of direct yield (explosive size)
- In this case, the seismic constraints merely corroborated results from the direct investigation.

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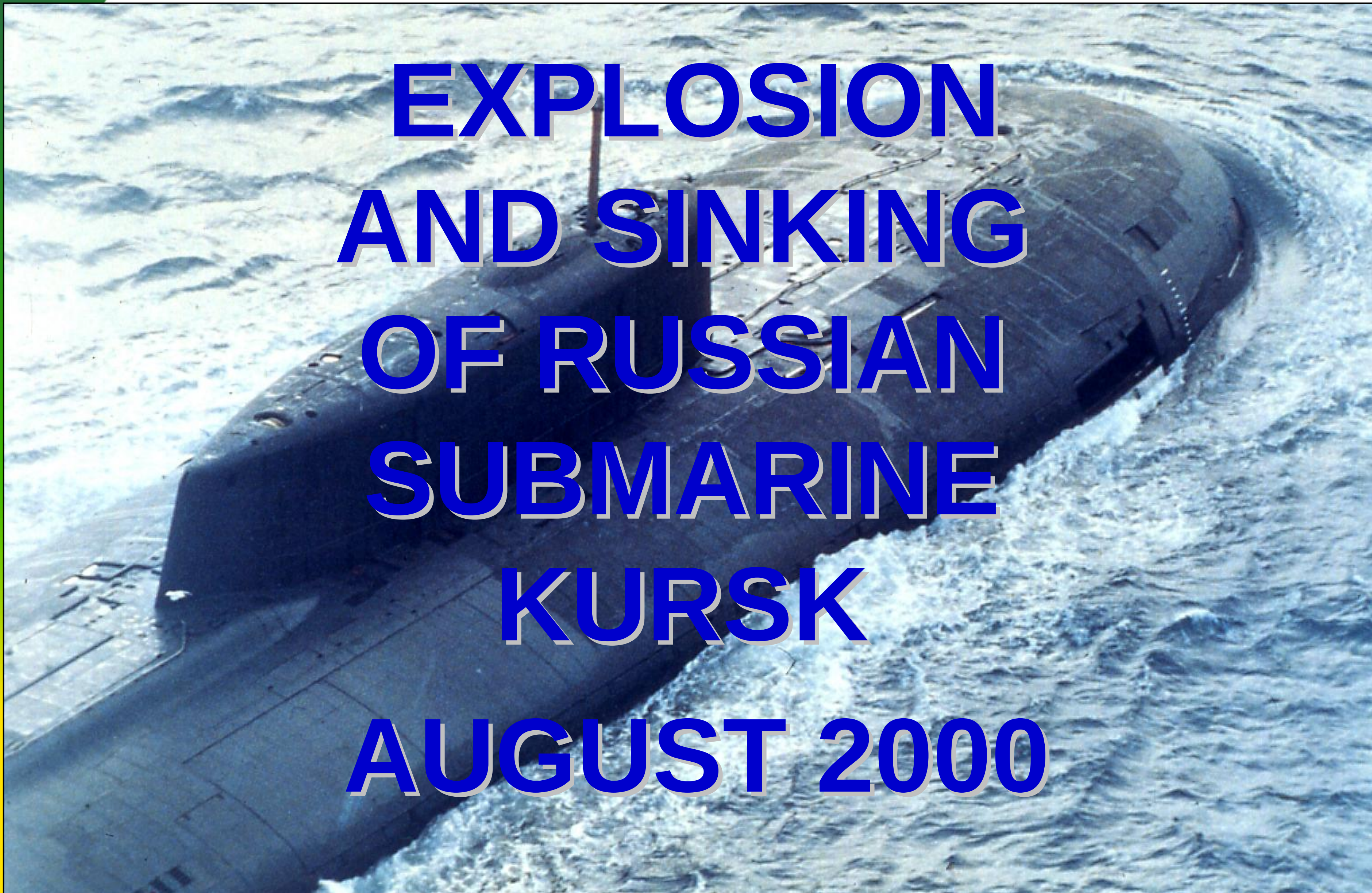
EXPLOSION
AND SINKING
OF RUSSIAN
SUBMARINE
KURSK
AUGUST 2000

KURSK DISASTER

- **On 12 August 2000, the Oscar II nuclear-powered cruise missile submarine, *Kursk* (K 141), sank in the Barents Sea, with the loss of all 118 crew. Commissioned in Jan 1995, the *Kursk* was part of the Russian Northern Fleet.**
- **From Norwegian seismological records, it appeared that the submarine was destroyed by two explosions. A subsequent inquiry confirmed that these were caused by the explosion of a Type 65 high test peroxide (HTP) 650mm torpedo, which triggered a much larger explosion in the weapons compartment that caused the submarine to sink. The blast appears to have been caused by highly volatile torpedo propellant that leaked and came in contact with kerosene and metal.**
- **In vain efforts to rescue any surviving crew were aided by the UK's LR5 submarine rescue vehicle and a Norwegian diving team.**

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KURSK DISASTER

- **The Russian submarine *Kursk (K-141)* was sunk in August of 2000 while participating in war games in the Barents Sea.**
- **BIG KILLER SUB: 18,300 tons submerged displacement; length 505 feet; diameter 60 feet. Compliment 107-118 men. Max speed 28 kts submerged; 15 kts surfaced.**

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Armament Carried by the *Russian Submarine Kursk*

- *Kursk* was a recently commissioned (January 1995) *Antey* (Oscar II) *Class* nuclear powered cruise missile carrying attack submarine (SSGN). Roughly same size as USN *Ohio Class* SSBN
- Designed to be an potent ship killer. Armament consists of:
- Surface to surface missiles (SSM's): Up to 24 SS-N-19 Shipwreck (Granit); inertial with command update guidance; active radar homing to 20-550 km *(10.8-300 nm)* at 1.6 Mach; warhead 750 kg HE or 500 kT nuclear.
- Other antiship weapons: Novator SS-N-15 Starfish (Tsakra) fired from 53 cm tubes; inertial flight to 45 km *(24.3 nm)*; warhead nuclear 200 kT or Type 40 torpedo. Also Novator SS-N-16 Stallion fired from 65 cm tubes; inertial flight to 100 km *(54 nm)*; payload nuclear 200 kT (Vodopad) or Type 40 torpedoes (Veder).
- Wire-guided torpedoes: 4-21 in *(533 mm)* and 2-26 in *(650 mm)* tubes. Combination of 65 and 53 cm torpedoes. Total of 28 weapons including tube-launched A/S missiles. 32 mines could also be carried.

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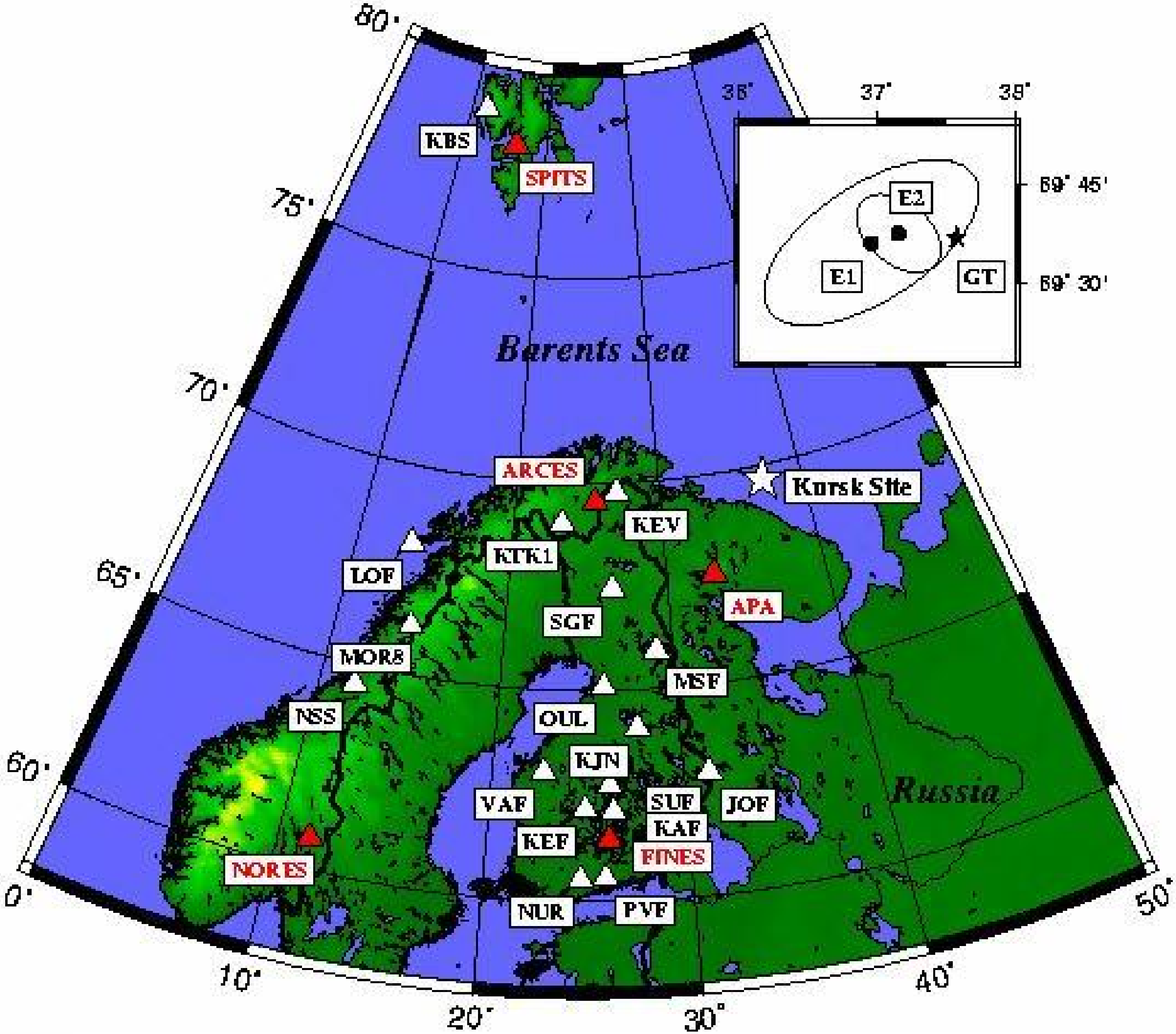
80°
75°
70°
65°
60°
0°
10°
20°
30°
40°
50°
36°
37°
38°
69° 45'
69° 30'
E2
E1
GT
KBS
SPITS
Barents Sea
ARCES
Kursk Site
KEV
KTK1
LOF
APA
SGF
MOR8
MSF
NSS
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KAF
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NORES
NUR
PVF
Russia

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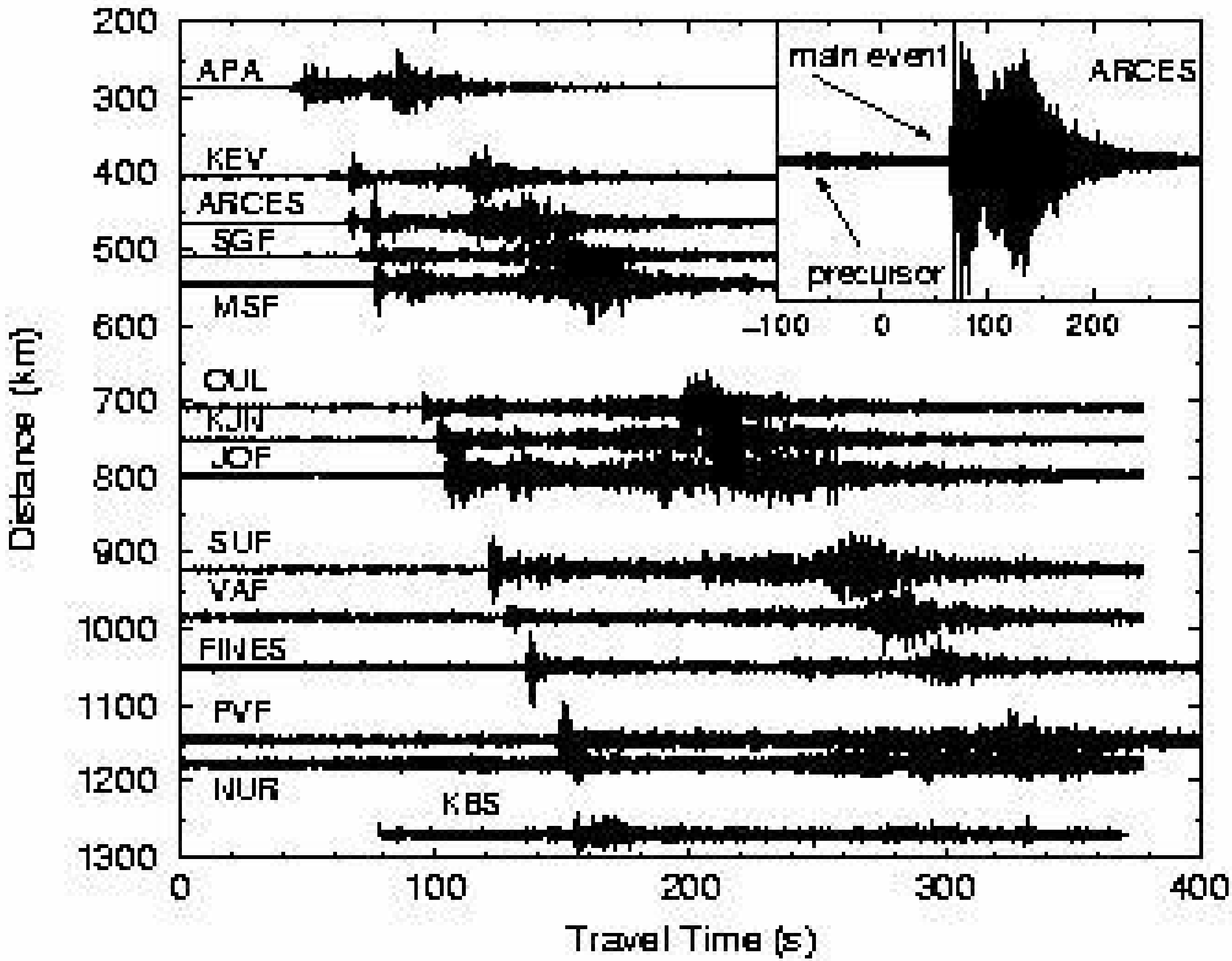
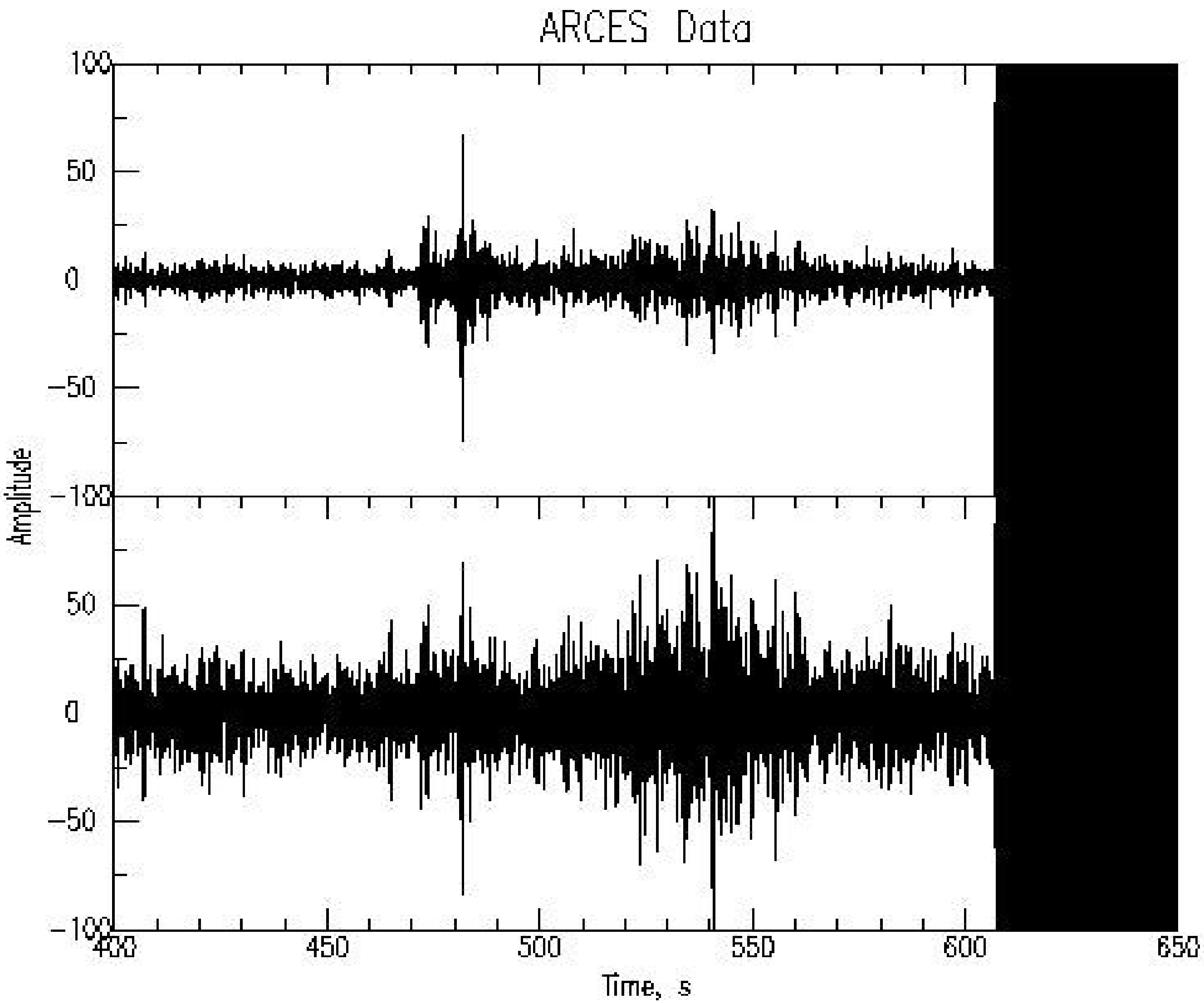


- Underwater energy sources are super-efficient; the resulting seismic signals were recorded throughout northern Europe on the Auto DRM system

FIRST SEISMIC RESULT:

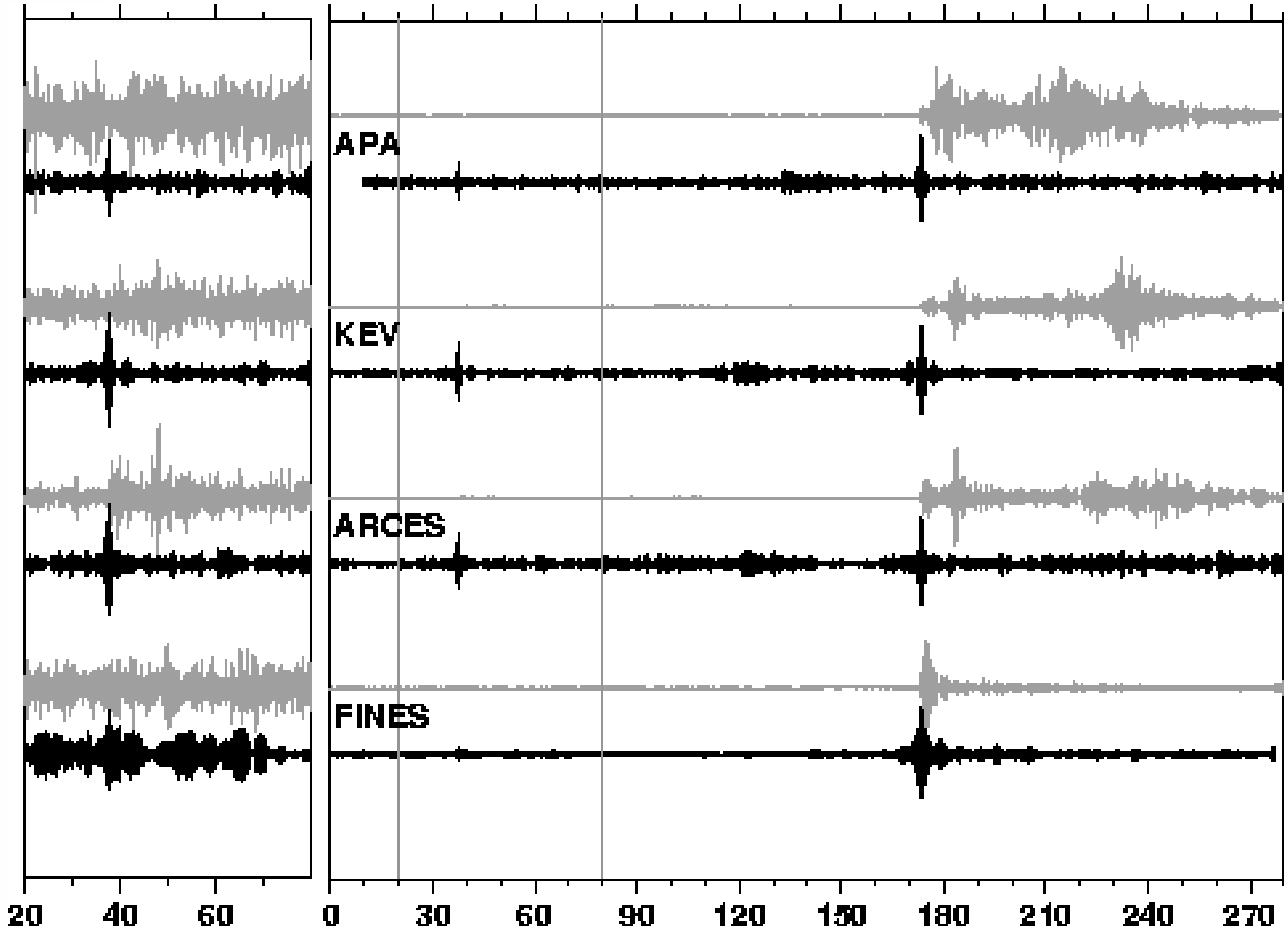
- ***There were two discrete sources***
  - **Time separation of 2 minutes 15 sec**
  - **Emanated from virtually the same location**
  - **Waveform similarity argues for same source mechanism (explosions)**

- **Seismology was the only non-classified source for this tidbit of information**



ARCES Data
Amplitude
Time, s
100
50
0
−50
−100
400
450
500
550
600
650

Waveform Correlation Detector

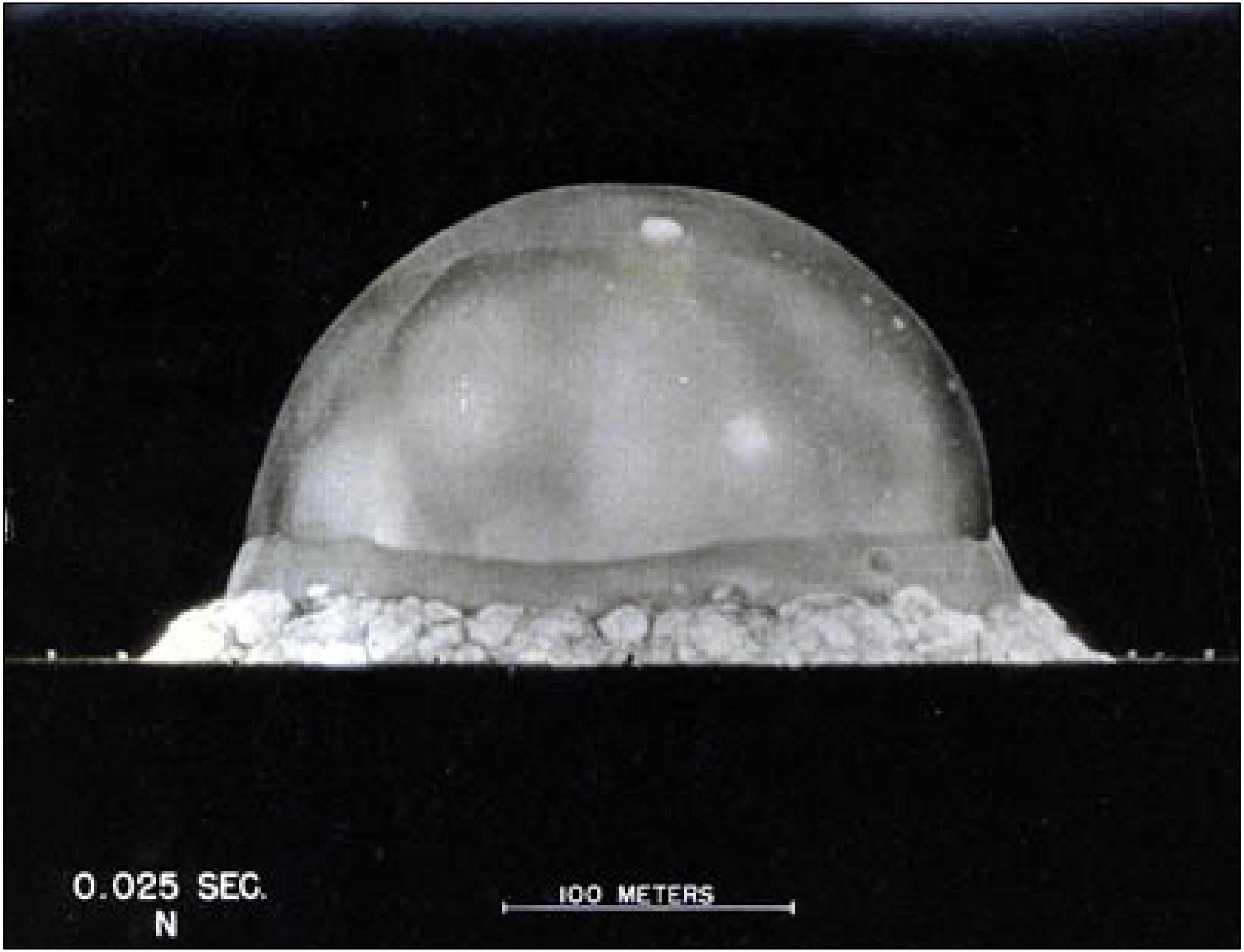


SECOND SEISMIC RESULT

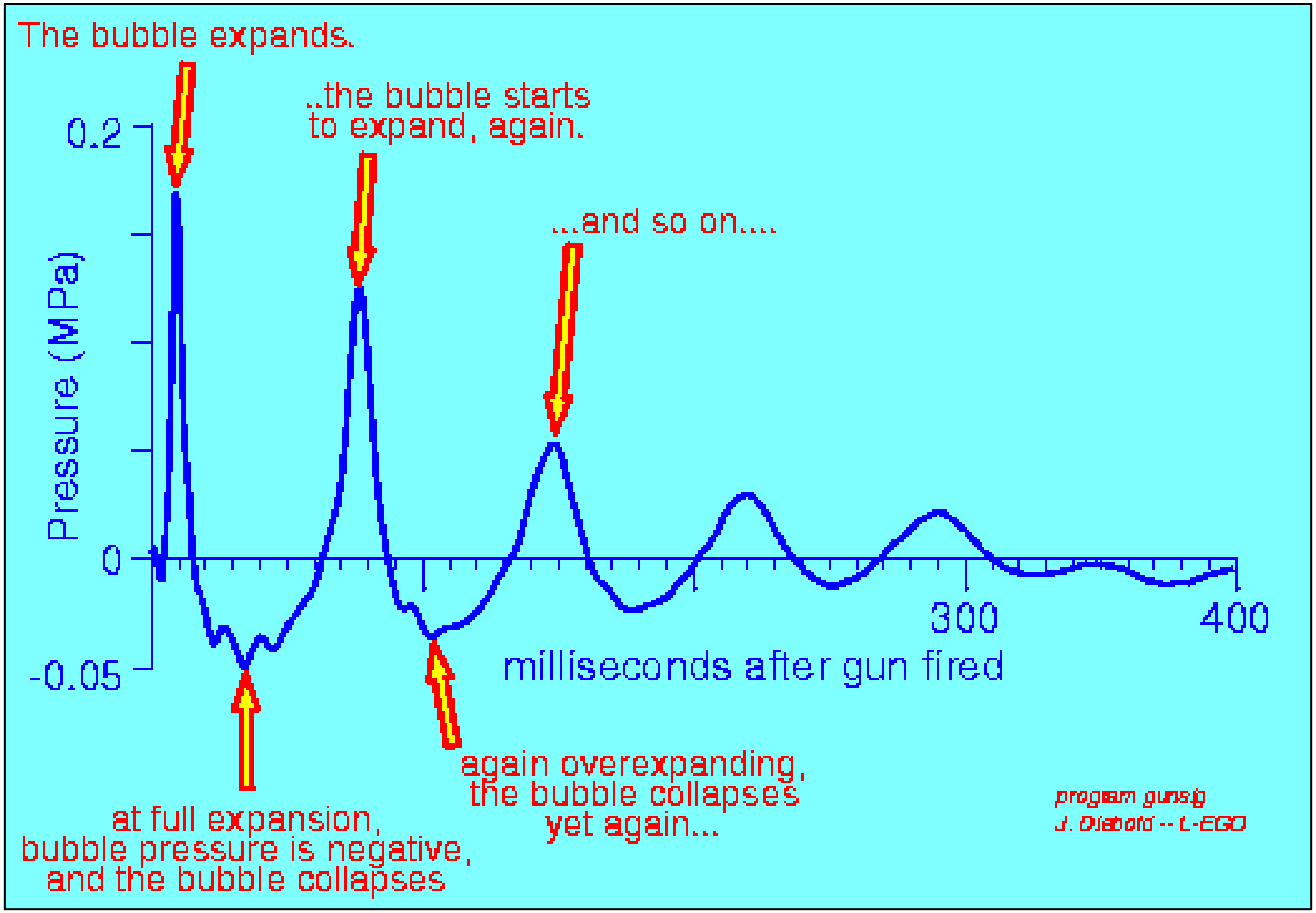
- **The larger (second) event was definitely an explosion, not an earthquake or impact (also, it turns out, not an implosion either)**
  - **First, smaller, event was *probably* an explosion**

- **Again, seismology was the only non-classified source of this information. It was also known very quickly.**

BUBBLE PULSES



BUBBLE PULSES: The Fingerprint of an Underwater Explosion



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Typical Shock Test

- Aerial view of a shock test being carried out against the *USS Arkansas* (CGN-41). The *Arkansas* is a nuclear powered *Virginia Class* cruiser, commissioned in 1980.

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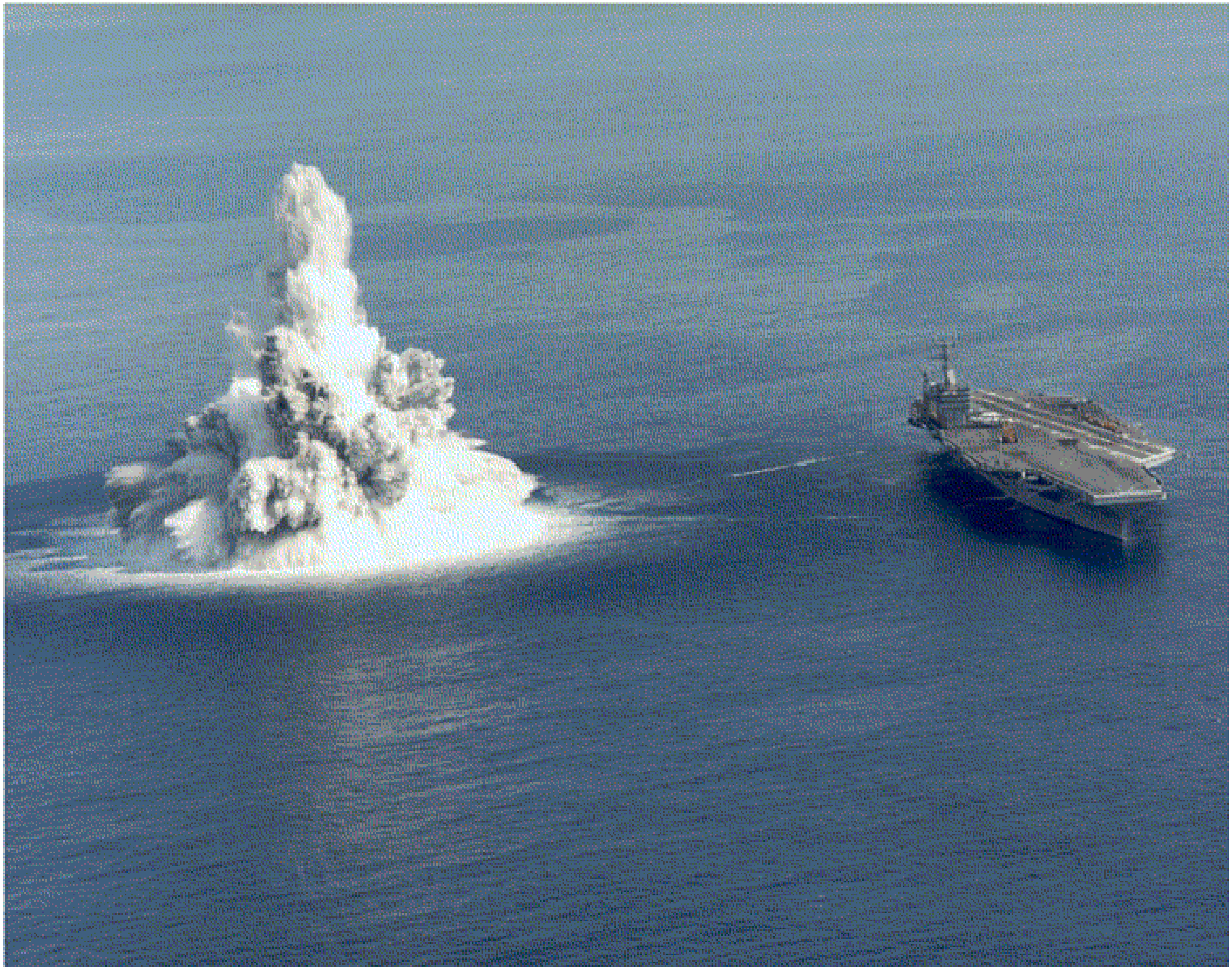
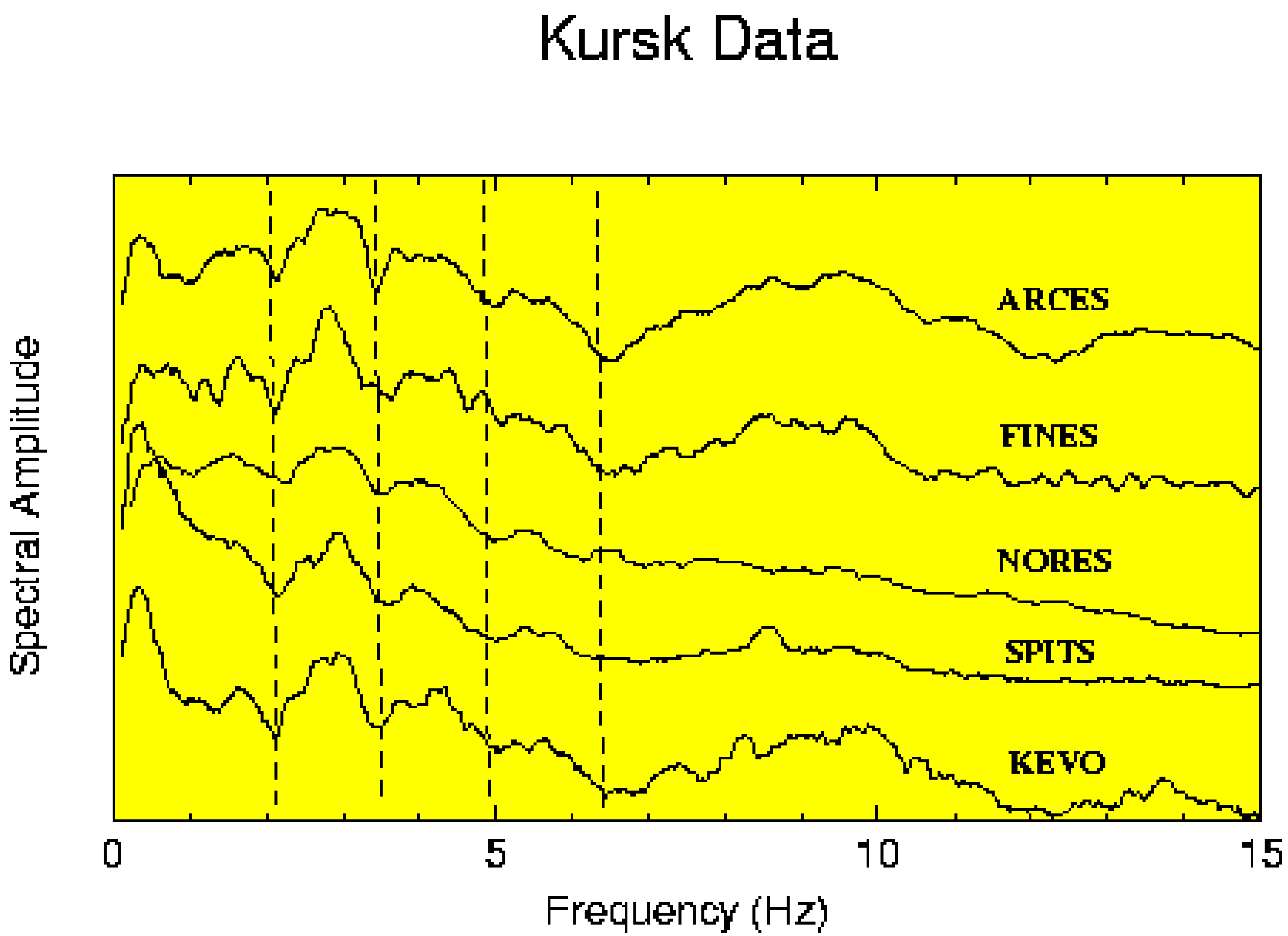
Shock Test Adjacent to Aircraft Carrier



THE *KURSK* BUBBLE PULSE



THIRD SEISMIC RESULT: Relative Size of Explosions

- **Magnitude-yield relations are of the form:**

magnitude = *alog(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)**

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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.

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FOURTH SEISMIC RESULT: Absolute Size of Explosions

Two methods for determining this:

1. Use magnitude-yield relationship previously developed for underwater explosions. 5000 kg test shots detonated in the Dead Sea and recorded by International Monitoring System [IMS] stations in November 2002

2. Go back to bubble pulse …

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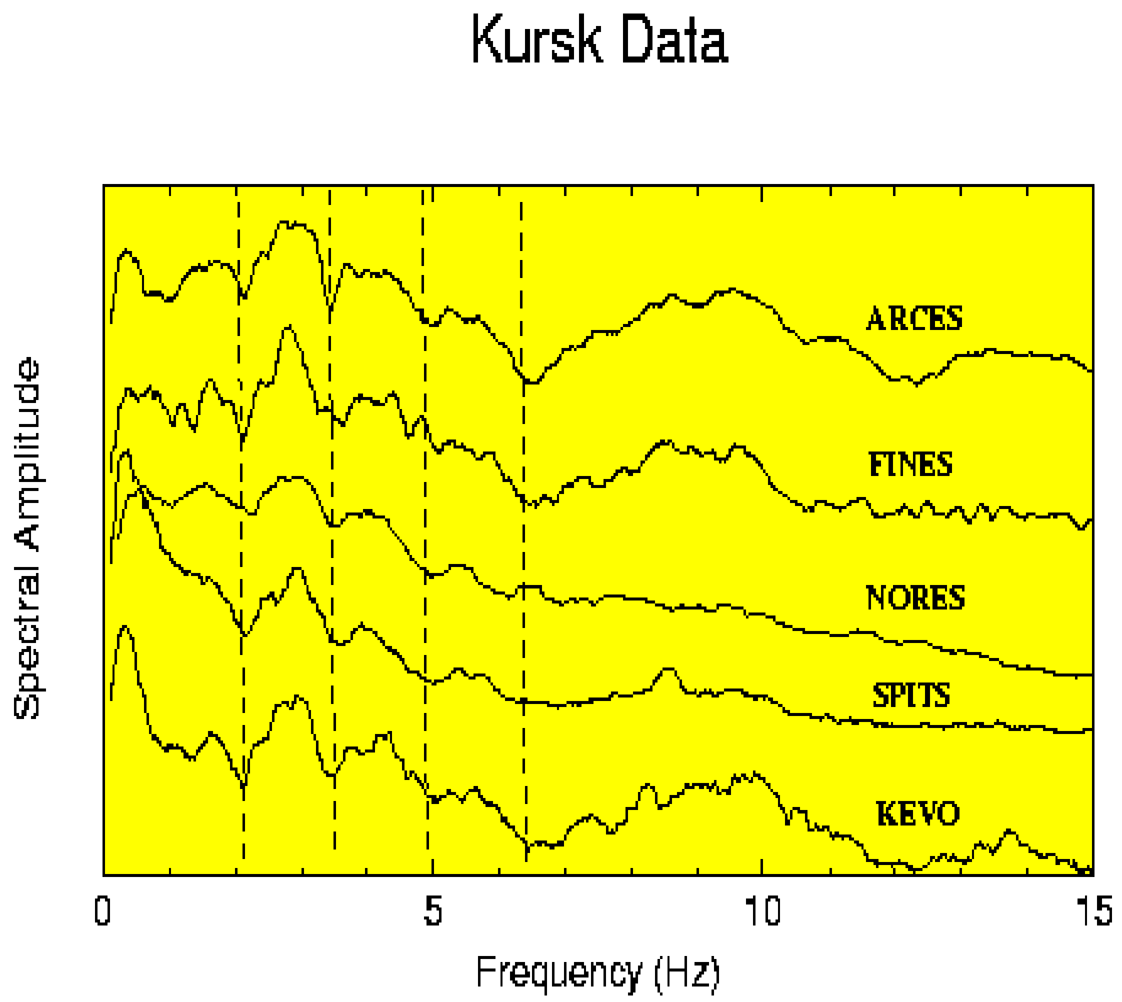
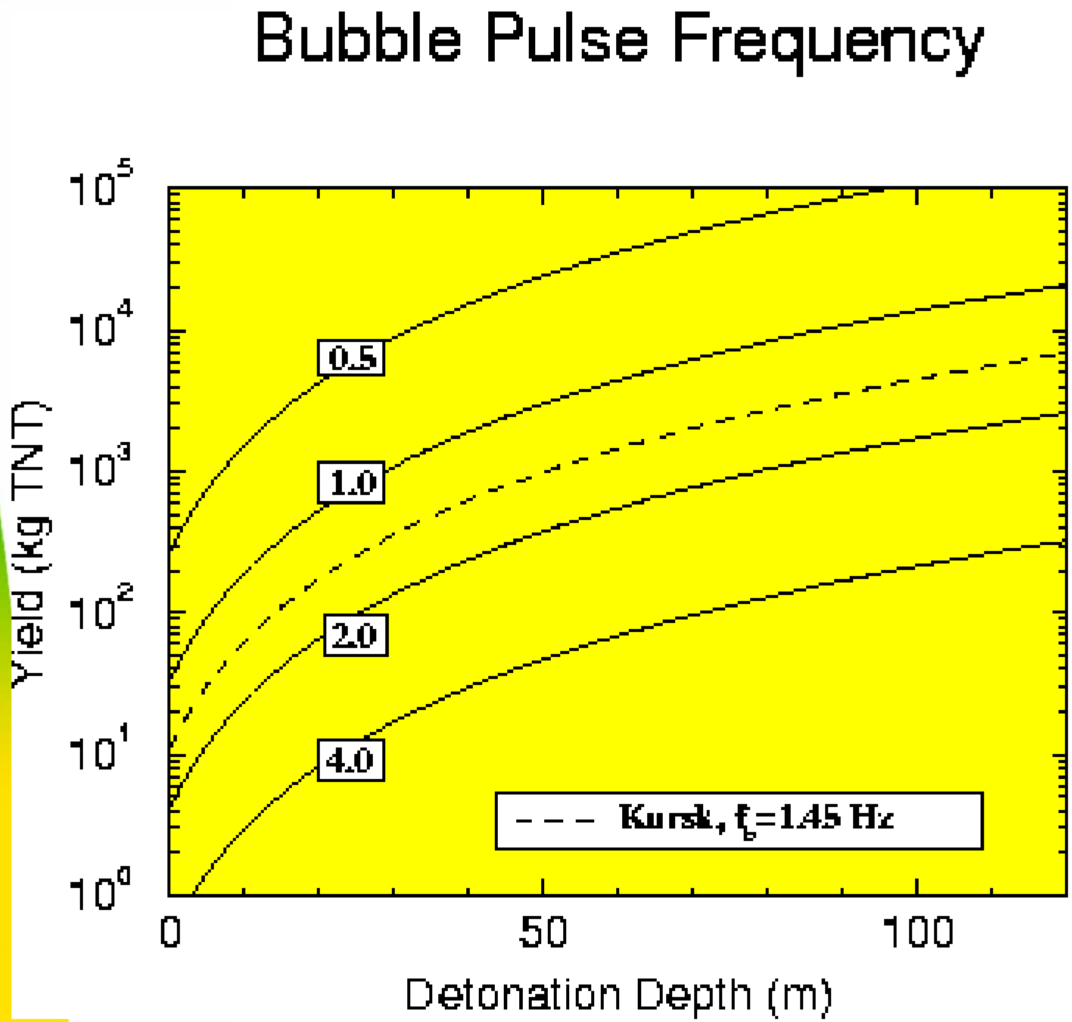
THE *KURSK* BUBBLE PULSE



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 World War II experiments at NUWL-Morris Reservoir.

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.

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FOURTH SEISMIC RESULT: Absolute Size of Explosions

- In 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 the 1995 Oklahoma City bombing.

RESULTS of *KURSK* INVESTIGATION - 1

Four solid seismic results:

1. There were two discrete sources
2. Larger one was definitely an explosion
3. Larger event was about 250 times more energetic than precursory event
4. Larger event was about 5 tons TNT equivalent

RESULTS of *KURSK* INVESTIGATION - 2

- 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.

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KURSK POSTSCRIPT -1

- The *Kursk* was raised in October 2001 and towed to the Russian naval shipyard in Murmansk.
- The forward weapons compartment was cut out prior to lifting and sections were later lifted in May 2002. The wreckage remaining on the seabed was demolished to prevent recovery by others.
- The nuclear reactors and SS-N-19 Granit cruise missiles were all recovered. The salvage operation was carried out by two Dutch companies, Mammoet Worldwide and Smit International.

Nuclear powered submarines are designed to withstand considerable battle damage. These views show massive damage to forward section of *USS San Francisco* (*SSN 711*) on Feb 12, 2005 when she collided with seamount off Guam. Only 1 crewman killed and 98 injured, 23 seriously, out of 137 aboard.


CARLSBAD PIPELINE
EXPLOSION
AUGUST 2000

CARLSBAD PIPELINE EXPLOSION

- On Saturday August 19, 2000 a buried natural gas pipeline burst and exploded about 30 miles south of Carlsbad, in southeastern New Mexico
- Line 1103, a 30” diameter natural gas pipeline was one of four crossing the Pecos River at this location, operated by the El Paso Natural Gas Company
- The resulting fireball burned for over one hour
- 12 people camping approximately 300 feet away were killed. Cause of death was extensive thermal burns, carbon monoxide poisoning, and smoke inhalation.

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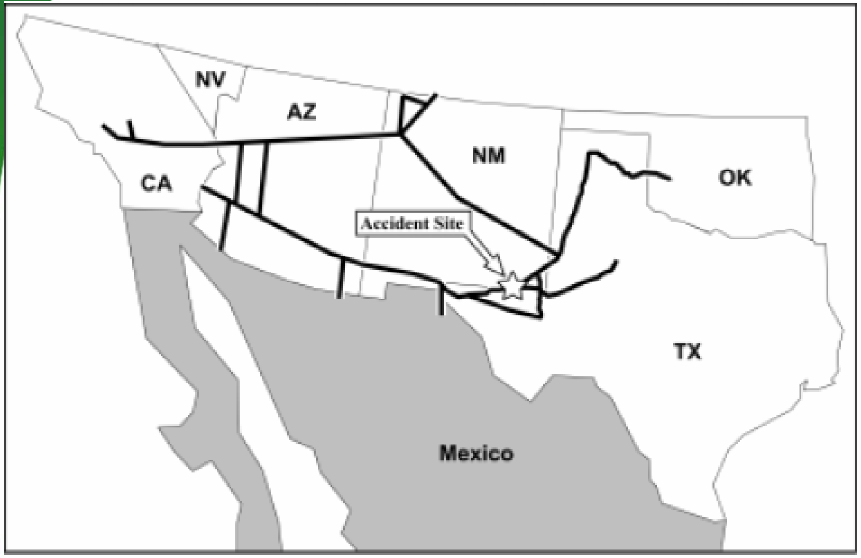
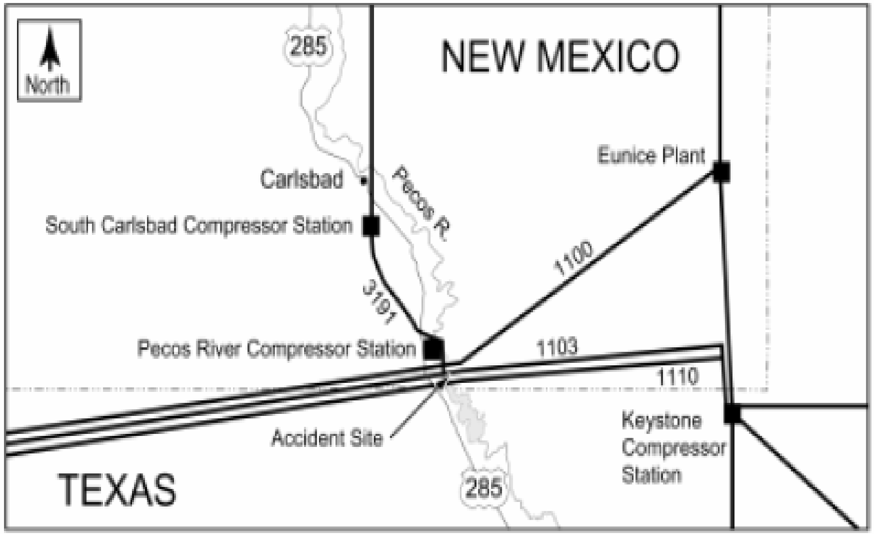
LOCATION



Map showing buried trunk lines operated by the El Paso Natural Gas System



Vicinity map of the accident scene, along eastern bank of the Pecos River just north of the New Mexico-Texas panhandle border. Note Line 1103.

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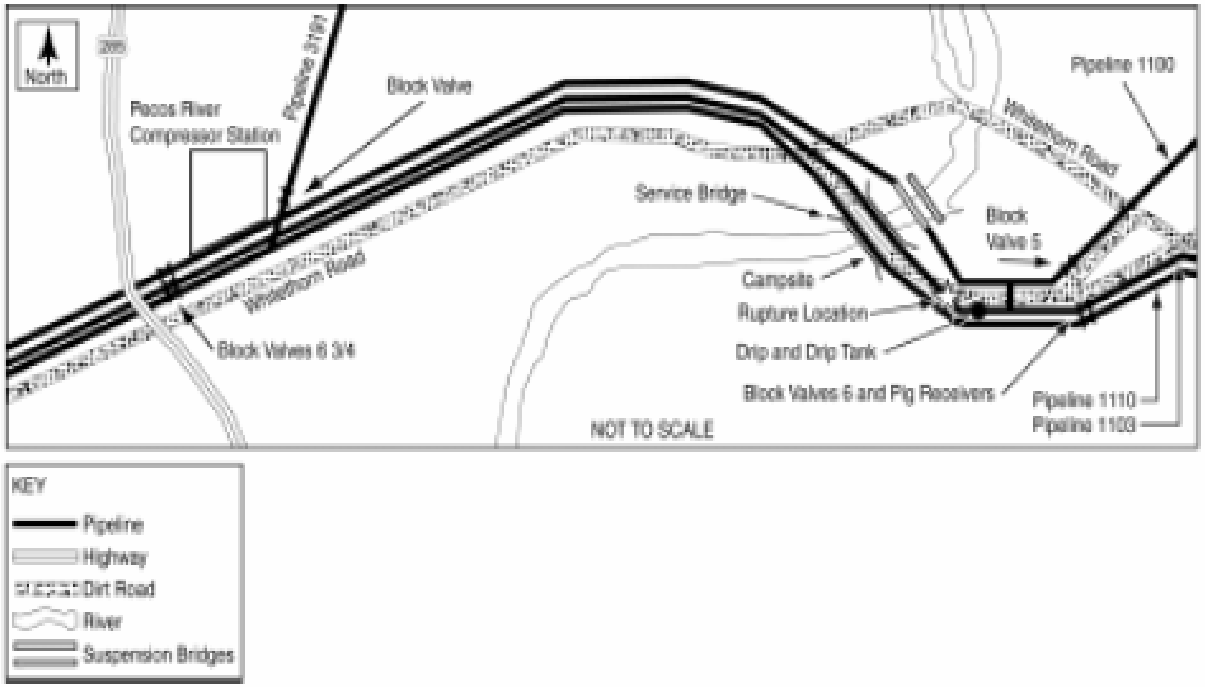
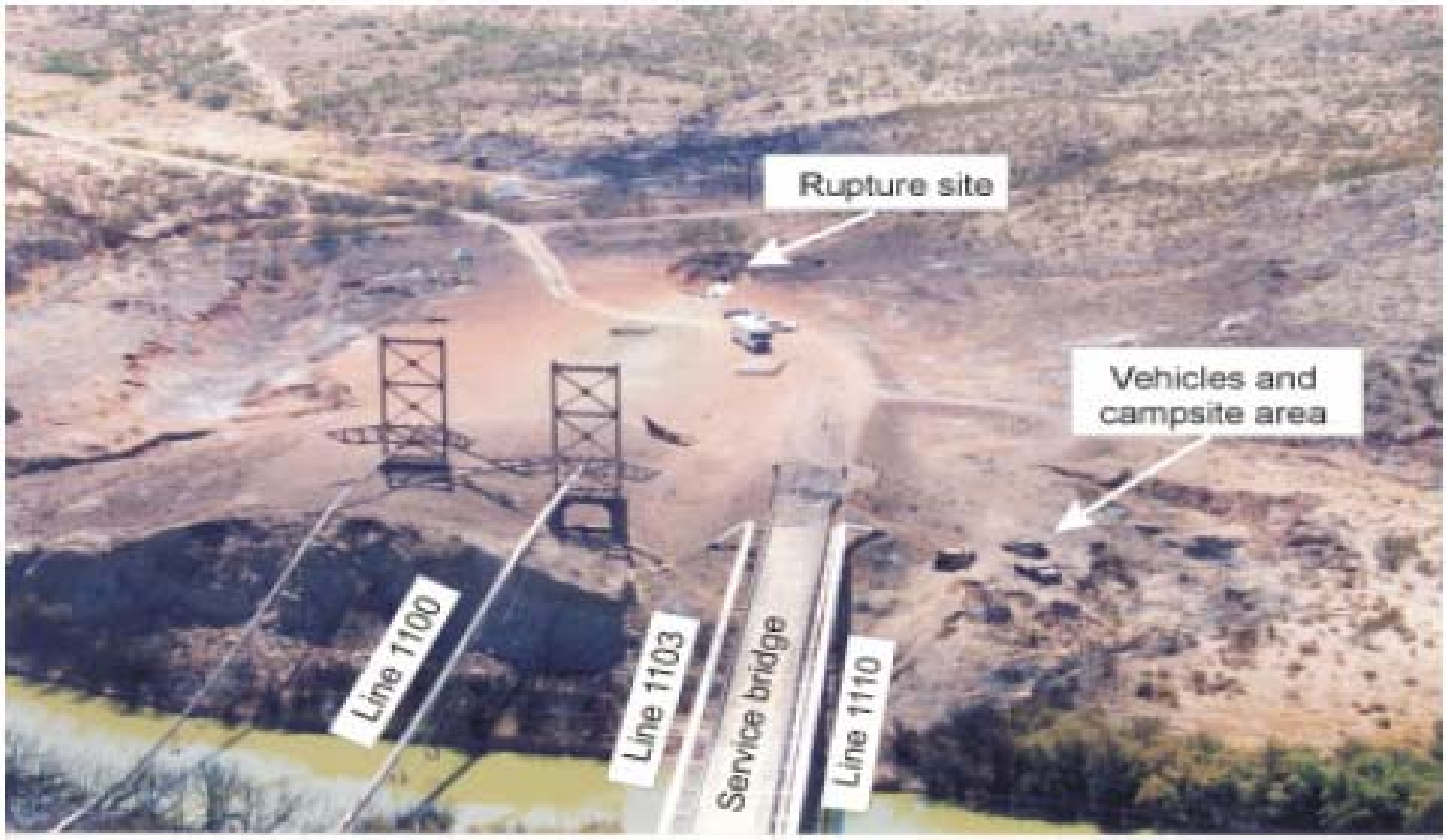


The explosion occurred adjacent to five bridges that convey four natural gas pipelines across the Pecos River about 4.5 miles north of the New Mexico-Texas border. The fifth bridge is for a service road along the buried pipelines. Note nearby compressor station.



Overview of accident scene looking east. Note four natural gas pipeline crossing Pecos River in foreground, rupture site, and campsite area. Line 1103 was the one that exploded. From NTSB Report PAR-03/01

Fire burning from crater area for over an hour after the initial explosion. Note bridge towers.

The explosion created a 51 ft wide crater along 113 lineal feet of Pipeline 1103. 49 lineal feet of pipeline was ejected from the crater in four segments.

Looking west at a portion of the blast crater. Four sections of pipe (comprising 49 lineal feet) between the arrows were ejected from the crater. A 22 ft long segment was recovered 270 feet from the crater.

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12 people were camping adjacent to the service road bridge supporting the gas pipelines over the Pecos River. Pipeline 1103 was constructed in 1950. The explosion occurred at 5:26 AM and all 12 campers were incinerated, most beyond recognition.

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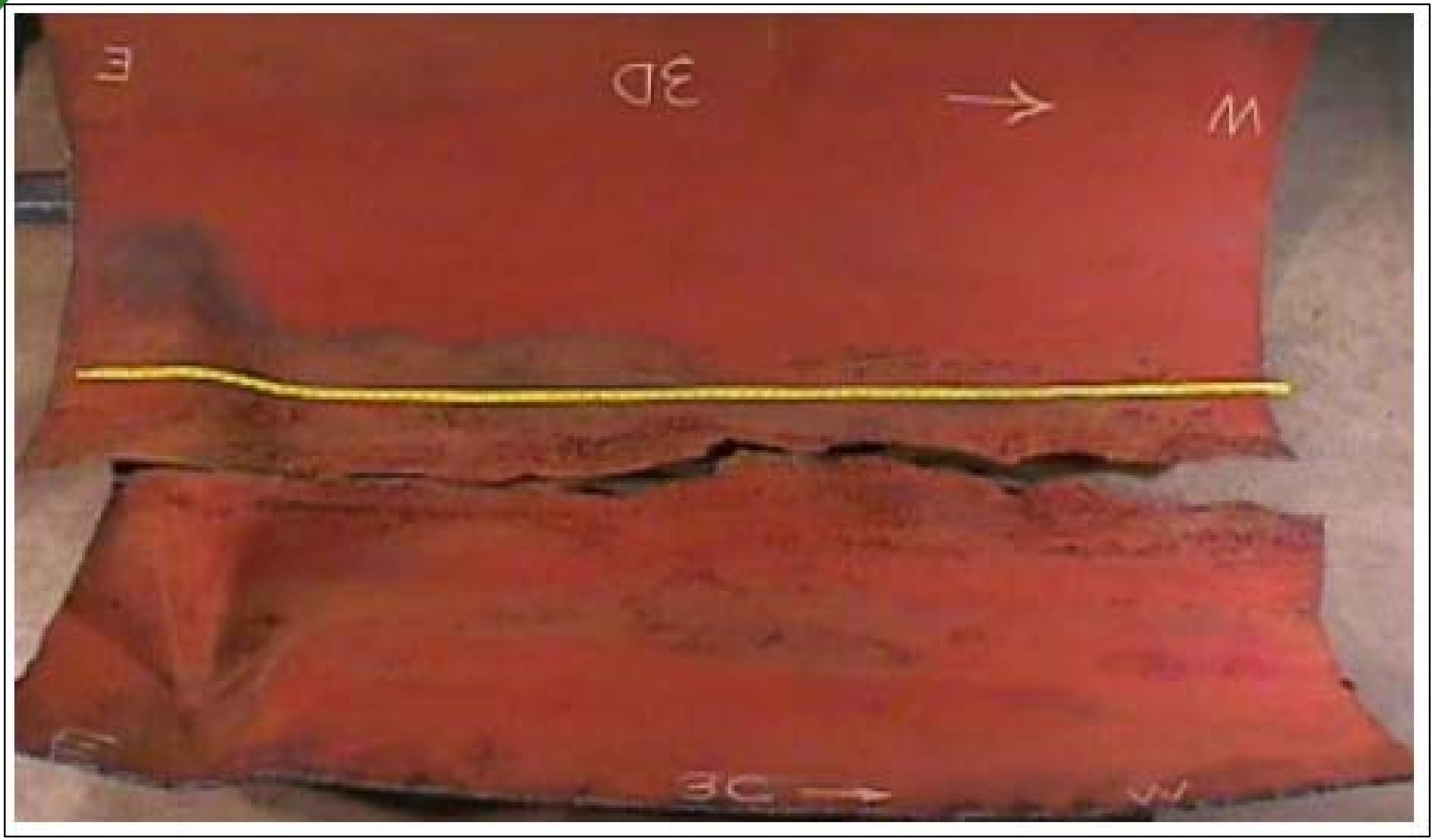
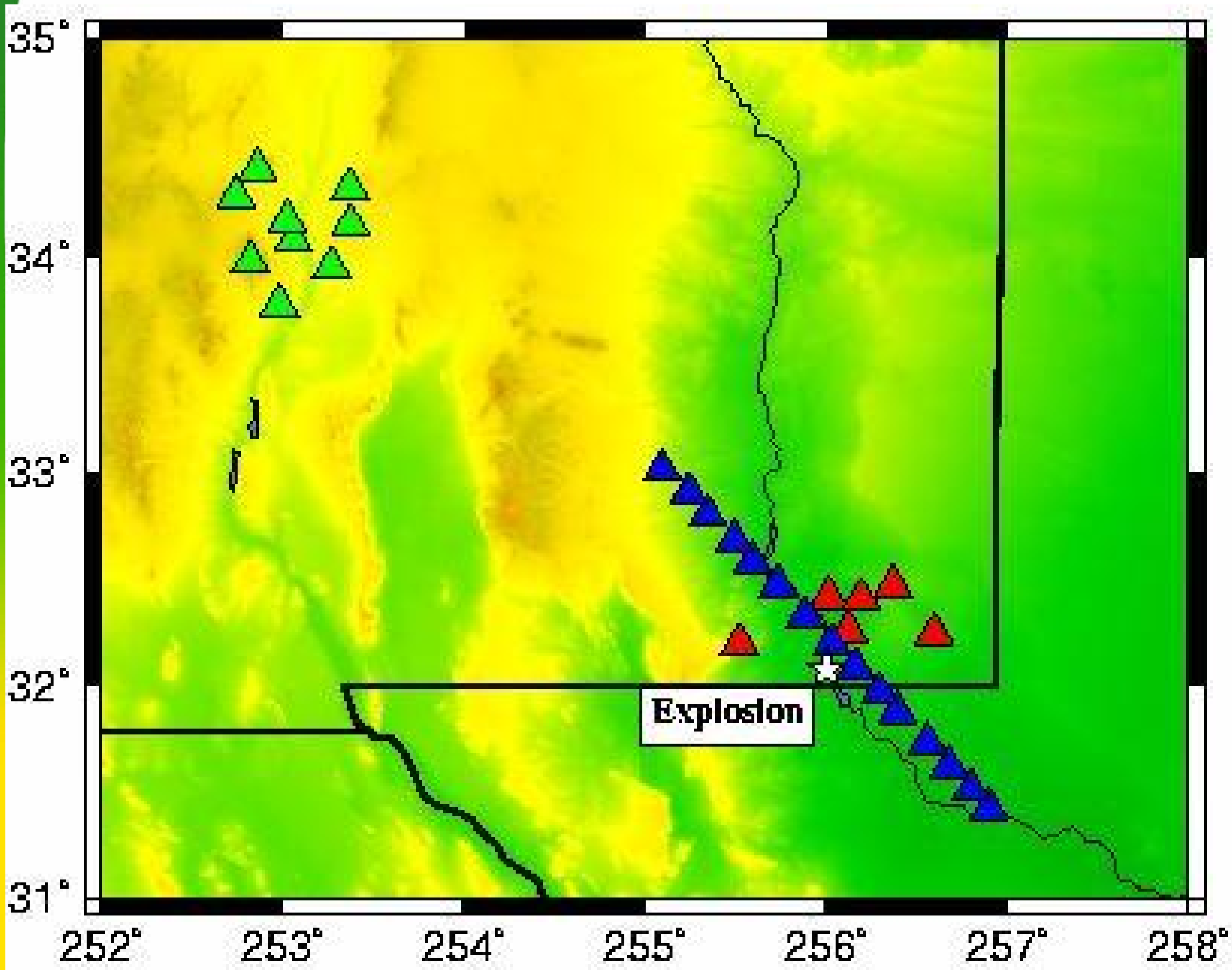


Fractured section of Pipeline 1103. Examination of the four sections of pipe ejected from the blast crater revealed extensive corrosion along the inside of the bottom of the pipe, reducing cross sectional thickness by 72%. Affected length was about 22 ft. This pitting was caused by acid-producing bacteria.

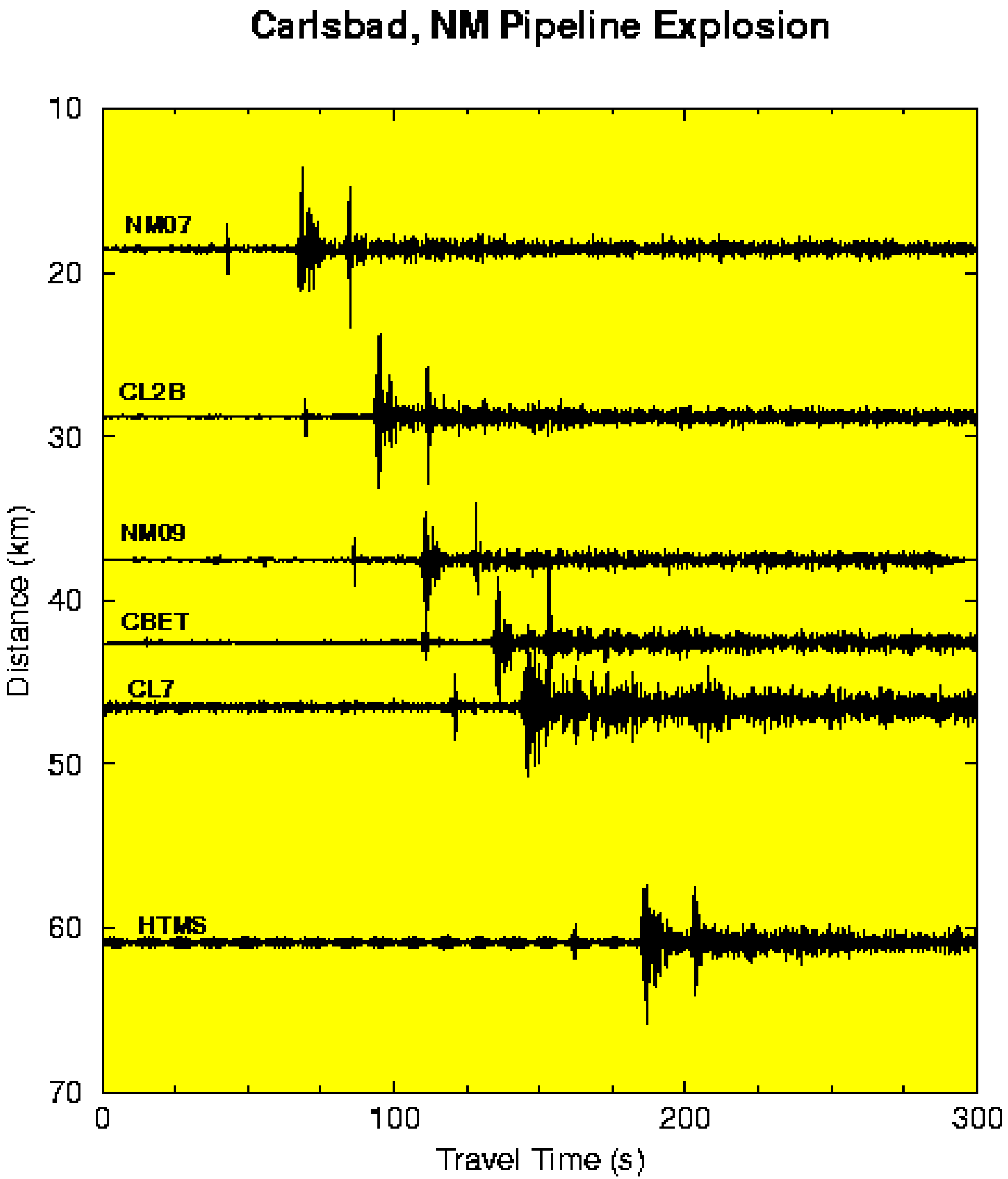
ESTIMATING THE SIZE OF THE EXPLOSION



Nearby seismometers

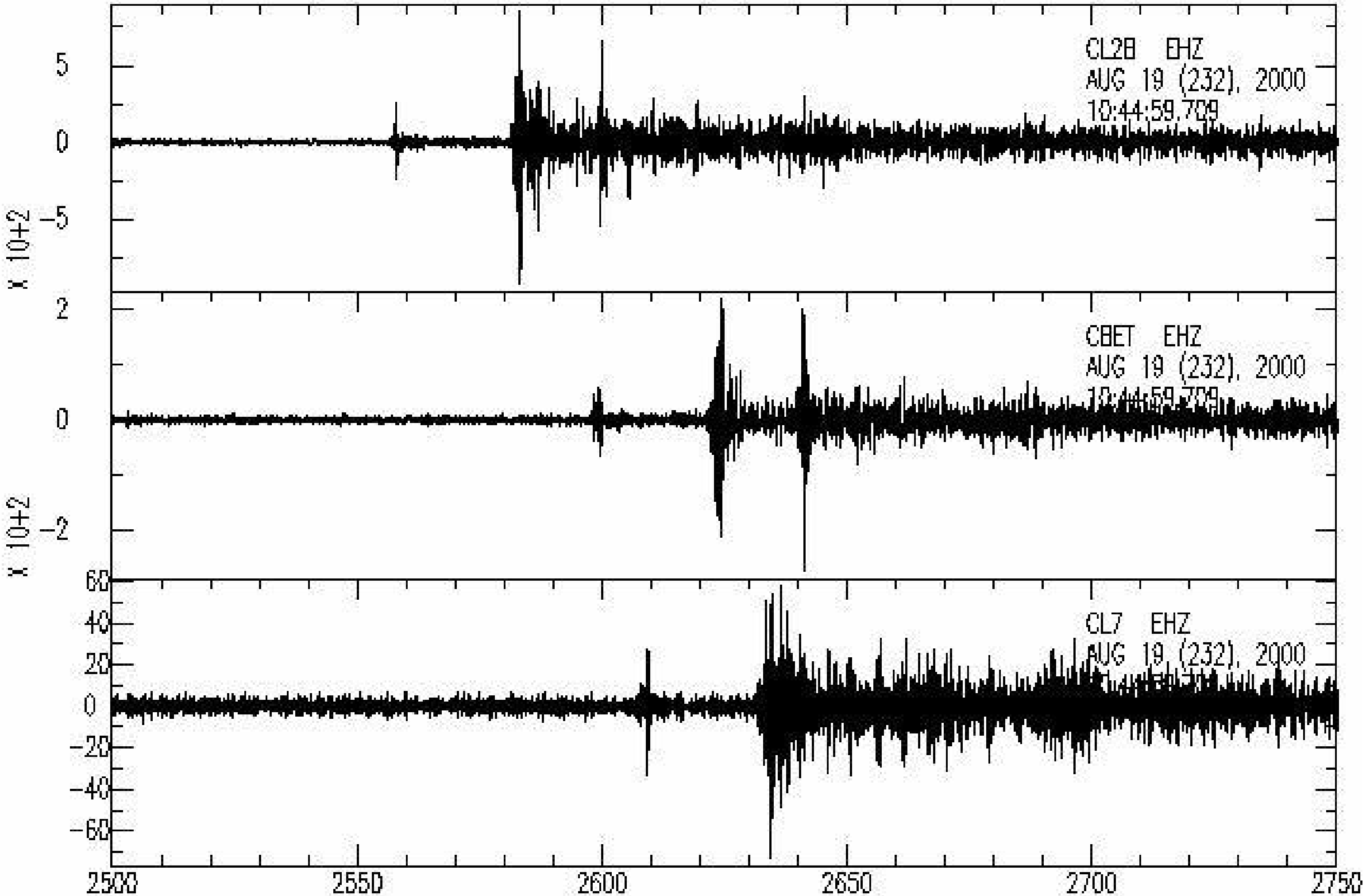
Red: permanent, single component, short period

Blue: temporary, broadband, three component



Carlsbad, NM Pipeline Explosion
NM07
CL2B
NM09
CBET
CL7
HTMS
Distance (km)
10
20
30
40
50
60
70
0
100
200
300
Travel Time (s)

Three Pulses –
1 Blowout, 2 Ignitions



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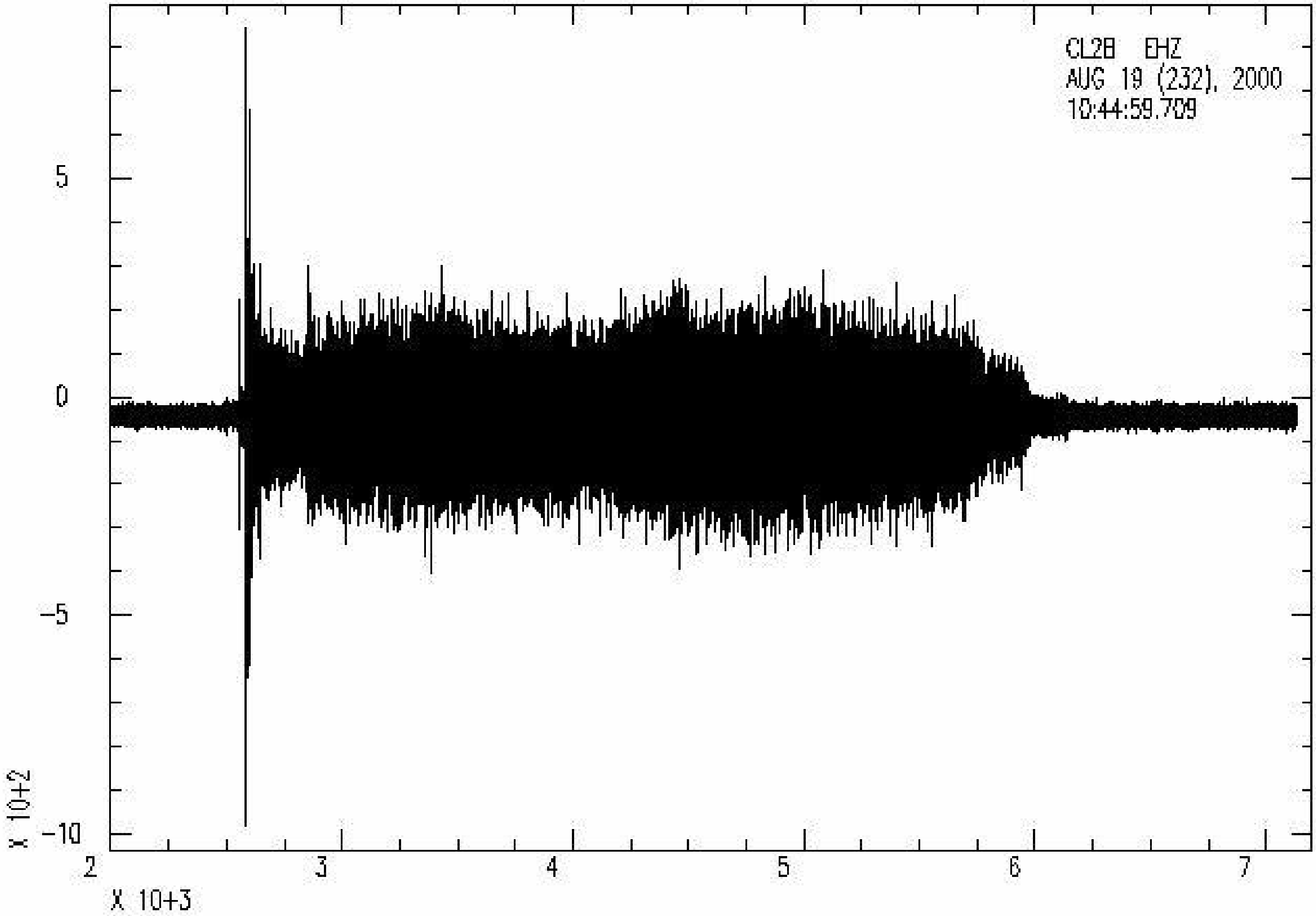
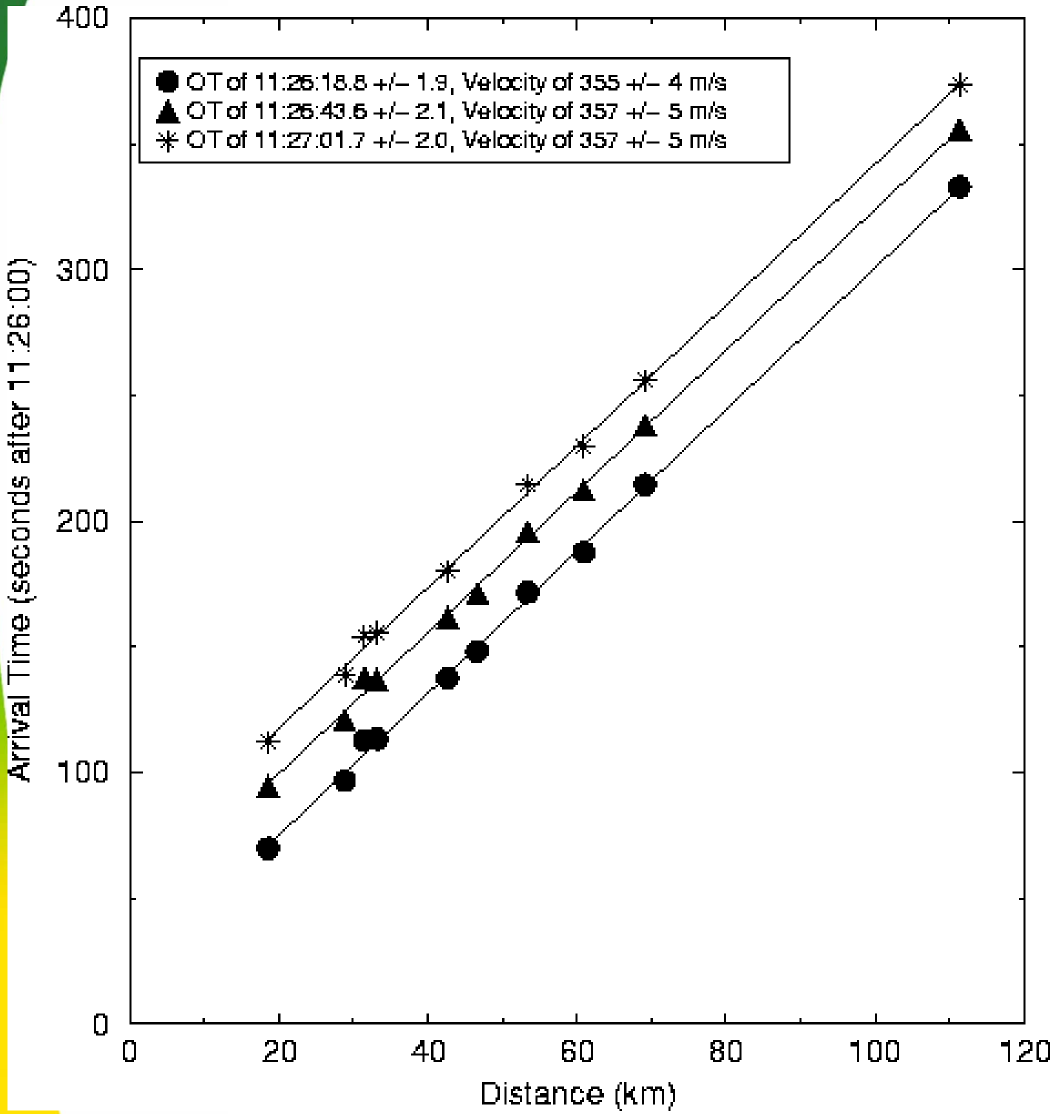
Extended Coda wave train from Fireball Combustion



The coda is the concluding portion of a seismogram following the early, identifiable waves. During earthquakes, long trains of coda waves may last for hours, especially if long oceanic travel paths are involved.



- Relative timing of sources, deduced from simple linear regression

Freshman math courses occasionally useful in real world applications

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CARLSBAD EXPLOSION SUMMARY Slide # 1

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

- We interpret these as:

1) Blowout of pressurized pipeline
2) Primary ignition of escaping gas
3) Secondary ignition; and
4) Sustained “fireball roaring” (combustion)

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CARLSBAD EXPLOSION SUMMARY
Slide # 2

- Professor Koper calculated the relative timing of events down to fraction of a second
- These estimates include precisely when the gas company shut off the gas and snuffed out the fireball. Rescue workers were prevented from approaching the camp site by the enormous heat generated by the fireball.

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CARLSBAD EXPLOSION SUMMARY
Slide # 3

- **If gas company had employed an automatic shutoff when a decrease in pressure was detected (the blowout), it's possible the ignition could have been prevented; or**
- **At least rescue workers could have attended to the victims much sooner and possibly saved their lives (some victims lived for several days).**

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CARLSBAD EXPLOSION SUMMARY
Slide # 4

- In this case the seismic data had a direct and influential role in piecing together the disaster. This was important because there were no surviving witnesses.
- The seismic data provided unique, non-trivial constraints, with a "*reasonable degree of scientific certainty*."
- The seismic analysis has an ongoing role in litigation/prosecution, and so, is truly *forensic seismology*.

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SUMMARY COMMENTS ON FORENSIC SEISMOLOGY

Crater field at Nevada Test Site

SUMMARY COMMENTS - 1

- **It is <u>common</u> for seismometers to record non-earthquake energy sources.**
- **It will become even more common in the foreseeable future.**
- **Analysis of these seismic data can contribute to the understanding of important man-caused disasters, anywhere, anytime.**

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SUMMARY COMMENTS - 2

- **The impact of forensic seismology analyses spans the range from *confirmation and identification of the obvious* to *unique determination of critical source information.***
- **It will increase public awareness of seismology and it's importance to society at large, as well as national and global security**

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