EARTH STRUCTURE & DYNAMICS

EARTHQUAKE SEISMOLOGY PRACTICALS

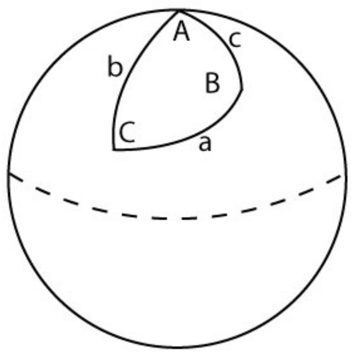
G.R. Foulger

1. A large earthquake is recorded well at a three-component seismic station in Hawaii (co-ordinates 205˚E, 20˚N). The epicentral distance was measured, by examining the arrival times of the P, PP, S, Rayleigh and Love phases, and found to be 33.28˚. The direction of arrival of the waves was measured, using the amplitudes of S waves on the horizontal components and the phases of the Rayleigh waves, and the azimuth of the earthquake from the station was found to be 50.64˚.

   Using spherical trigonometry, calculate the longitude and latitude of the earthquake and plot it on Figure 1. The formulae you require are:

$$a = \cos^{-1}(\cos b \cos c + \sin b \sin c \cos A)$$

$$C = \cos^{-1}\left(\frac{\cos c - \cos a \cos b}{\sin a \sin b}\right)$$



Spherical geometry for great-circle paths

2. Sketch a cross section of the Earth showing the major seismic boundaries and sketch the following waves: PKIKP, PKiKP, PKJKP, sS, Sg, Pn, PS.

3. Your are provided with three-component teleseismic seismograms, with clock marks at minute intervals, for two earthquakes, Earthquake 1 and Earthquake 2. Determine their epicentral distances.

To do this, take a long strip of paper and lay it on the seismograms one-by-one, marking the positions of the phases you can see. The following phases are clear:

	Phase	EQ 1	EQ 2
°	P	√	√ (very faint!)
°	PP	√	√
°	SKS	√	√
°	S	√	√
°	PS		√
°	SS		√
°	G (Love)	√	√
°	R (Rayleigh)	√	√

Note that P arrivals and R are expected to be clearest on the vertical component. For the vertical record of Earthquake 1, R is the strongest arrival, P is second strongest, PP third strongest and S fourth strongest. S arrivals and G are expected to be clearest on the horizontal components.

You are provided with a Gutenberg-Richter travel time chart for earthquakes at 25 km depth. This is a chart of time in minutes (vertical axis) : epicentral distance in degrees (horizontal axis). The vertical axis is at the same scale as your seismograms.

Lay your marked paper strip on the chart and estimate the epicentral distance of each earthquake.

4. Measure the magnitudes of Earthquakes 1 and 2 using the surface waves. The equation is:

$$M_S = \log A - \log A_0(\Delta^\circ)$$

M_S = surface-wave magnitude
A = amplitude in mm of surface waves with period ~ 20 s
Δ° = epicentral distance of the earthquake,
$\log A_0(\Delta^\circ)$ = logarithm of the amplitude of a magnitude zero earthquake at distance Δ°

Use the zero-earthquake amplitude table given below to compute $\log A_0(\Delta^\circ)$.

Table 22-3 Logarithms of the Maximum Combined Horizontal Ground Amplitude *A* (in microns) for Surface Waves with Periods of 20 Seconds Produced at the Given Distance by a Standard Shock Taken as Magnitude Zero.

Δ (degrees)	−log A	Δ (degrees)	−log A
20	4.0	90	5.05
25	4.1	100	5.1
30	4.3	110	5.2
40	4.5	120	5.3
45	4.6	140	5.3
50	4.6	160	5.35
60	4.8	170	5.3
70	4.9	180	5.0
80	5.0		

Zero-earthquake amplitude table, from Richter (1958).

5. You are provided with three-component seismograms for surface waves from a large, distant earthquake recorded at station CMB (Earthquake 3). This station is located in the Sierra Nevada of California (Figure 1). Label the Love and Rayleigh waves. Remember that Love waves travel faster than Rayleigh waves. On rotated seismograms, Love waves are only recorded on the transverse component and Rayleigh waves are only recorded on the vertical and radial components.

   Determine the approximate direction of approach by looking at the particle motion of the earliest part of the Rayleigh wave train. Remember that particle motion in Rayleigh waves traces a retrograde ellipse in a direction parallel to the direction of travel of the ray. The NS component seismogram shows clear Love waves but very poor Rayleigh waves. Is this observation consistent with your conclusion from the particle motion?

   Construct a surface-wave dispersion curve for Earthquake 3. For the first 5 cycles of the Rayleigh wave, and every 5th cycle thereafter, measure the arrival time from the first arrival and the period of one cycle. The time marks on the seismograms are spaced at intervals of 1 minute.

   Calculate the group velocity of each cycle, assuming the epicentral distance to be 10,000 km and the travel time of the earliest Rayleigh wave arrival to be 50 min. Plot a graph of group velocity (km/s) : period (s). You are provided with surface-wave dispersion curves for typical oceanic and continental structures. Which does your curve most resemble? Is your conclusion in agreement with the direction of approach you calculated for this earthquake?

6. The table below gives the numbers of earthquakes Ms ≥ 7.1 for the world. In the right most two columns write down the cumulative numbers of earthquakes ≥ each magnitude range. Plot a graph of cumulative number : magnitude on semi-log graph paper. (Assign the average magnitude to the earthquakes in each magnitude band, and plot magnitude on the linear scale).

≤ Ms <	**# eqs (M_S)**	**#eqs (Mw used for 10 largest eqs)**	**Cum. # eqs (M_S)**	**Cum. # eqs (M_w used for 10 largest eqs)**
9.4 - 9.6		1		
9.2 - 9.4		1		
9.0 - 9.2		2		
8.8 - 9.0		1		
8.6 - 8.8	3	3		
8.4 - 8.6	8	10		
8.2 - 8.4	17	13		
8.0 - 8.2	25	22		
7.8 - 8.0	52	52		
7.6 - 7.8	97	97		
7.4 - 7.6	104	104		
7.2 - 7.4	162	162		
7.0 - 7.2	252	252		

If the events are distributed fractally they will follow the formula:

$$\log_{10} \Sigma N = a - bM$$

where ΣN is the cumulative number ≥ magnitude M and a and b are constants. The value of b for the world is almost exactly = 1. Draw a best-fit line with slope -1 passing through the points for the smallest magnitudes. These points are dependent on larger numbers of earthquakes than the points for the largest magnitudes, and thus they are more reliable.

Your write-up should include the following:

1. A table showing your data;
2. Your “*b*-value” plot;
3. A 300-word write-up describing your results. This should include:
    a. a description of how the data are distributed, whether they fit both the low- and high-magnitude ends of the plot well, a) for M_S and b) for M_W;
    b. suggested reasons for your observations.

Marks will be given for evidence of clear understanding of the goodness-of-fit of the data in the low- and high-magnitude ranges, and for critical comment that illustrates understanding of the relevant interpretive issues.

7. A system where a series is generated by inputting the output from a previous step has the potential to behave chaotically. Thus, natural systems have this potential, as their evolution following any point in time is dependent upon their state at that point.

   Chaotic systems are very sensitive to starting conditions and, although their state may vary within certain bounds and have structure, can only be predicted exactly a short time into the future. The weather is a well-known example of a chaotic system. However, the weather is a very complicated system. What is less well known is that even extremely simple systems can behave chaotically. This is an exercise designed to increase your understanding of chaos and provoke thoughts about what implications it has for earthquake occurrence and prediction.

   Work in pairs for this exercise.
   You are provided with four graphs of the parabolic function $y = 4\lambda x(1-x)$, for $\lambda = 0.7$, 0.785, 0.87 and 0.9. Also drawn on the graphs is the line $x = y$.

   1. Starting with the graph for $\lambda = 0.7$, draw a line vertically upwards from the x-axis at $x = 0.04$ until it reaches the parabola.
   2. Note the value of y. Your partner will simultaneously plot a graph of step # : y-value. (Adjust the axes on the paper to give room to go up to 30 steps.)
   3. Your value of y at this point (the "output") will become your next value of x (the "input"). In order to make it easy to continue, draw a line horizontally from the point of intersection with the parabola until it intersects the line $y = x$. Then draw a second vertical line to the parabola from that intersection point.
   4. Go to 2

   Continue repeating steps 2 - 4 until the resultant pattern is clear.

   Repeat this exercise for the other three graphs. How do the four graphs of step # : y-value differ? When the whole class has finished all four graphs, compare all the graphs of step # : y-value. How similar are they for each of the four values of λ?

   This exercise illustrates the different types of behaviour that can occur when what happens next is dependent on what the situation is now. What implications does it have for earthquake occurrence? Stress in the Earth is governed by many factors (*e.g.,* rain, nearby earthquakes, Earth tides, plate motions, heat flow) and thus how it varies is complicated. Is this the reason why earthquakes are difficult to predict?

   For more information on this fascinating subject, look at:

   Hofstadter, D. R., Mathematical Chaos and Strange Attractors, Chapter 16, pp 364 - 395, in Metamagical Themas, Basic Books Inc., New York, pp 852, 1985.

8. You are provided with an equal-area transparent plot of seismogram polarities for the M ~ 6 earthquake of 1633:44 UTC 25 May 1980 at Mammoth Lakes, California. Use the stereo net provided to plot nodal lines of the best-fitting double couple solution. These

nodal lines are great circles and should intersect at 90˚. What is the minimum number of violations you can achieve?

You are also provided with a plot of the nodal lines of a CLVD source with its plane of symmetry with a hade of 8˚. Also shown are the nodal lines for a CLVD+20% explosion and a CLVD+20% implosion. Plot on the polarity plot the best fitting nodal lines for an interpretation involving a CLVD+implosion. These lines will form members of the "family" of CLVD+implosion lines shown. What is the minimum number of violations you can achieve? What can you say about the area of the focal sphere violated by each interpretation? Do you think that these data are convincing evidence for non-double couple earthquakes?

9. For the case of an expanding cavity, the equivalent seismic moment is given by the equation:

$$M_o = \frac{4\pi}{3} a^3 (\lambda + \frac{2}{3}\mu) \Delta\theta$$

where a = the radius of a spherical volume, $\Delta\theta$ = the fractional change in volume, and $\lambda \cong \mu \cong 3$ N m^{-2}.

In the period 1975 to 1984 the magma chamber beneath the Krafla volcano, Iceland, which is thought to be roughly spherical and about 50 km^3 in volume, was inflated by the continuous inflow of 5 m^3 s^{-1} of magma. Calculate the equivalent seismic moment of this inflation. If all this energy was released seismically, what would be the moment magnitude of the resulting earthquake? The moment magnitude relationship is:

$$M_w = \frac{2}{3} \log Mo - 6.0$$

10. You are provided with seismograms for events A, B, C and D (Figure 2). The events occurred in southern Xinjiang, China, and the seismograms were recorded at station ARU (Figure 3). The objective of this exercise is to discriminate which is/are earthquake(s) and which is/are nuclear explosion(s).

Comment on the quasi-sinusoidal signal on the seismogram for event D.

Below is a table of co-ordinates. Calculate the epicentral distances in degrees between ARU and the events.

Event/station	**Longitude**	**Latitude**
ARU	58.562500	56.430199
A	75.699997	39.400002
B	89.099998	41.500000
C	84.800003	44.000000
D	88.699997	41.599998

Assuming all the events to have occurred at or close to the surface, use the Gutenberg-Richter travel time chart to predict the time of arrival of the S waves and the first Rayleigh waves. Figure 4 shows the seismograms high-pass filtered at 12.5 s. Mark the first P-wave arrivals and the predicted first S- and Rayleigh-wave arrivals. How clear are the S waves compared to the P waves for each event? How strong is the surface wave train compared with the P-wave train for each event?

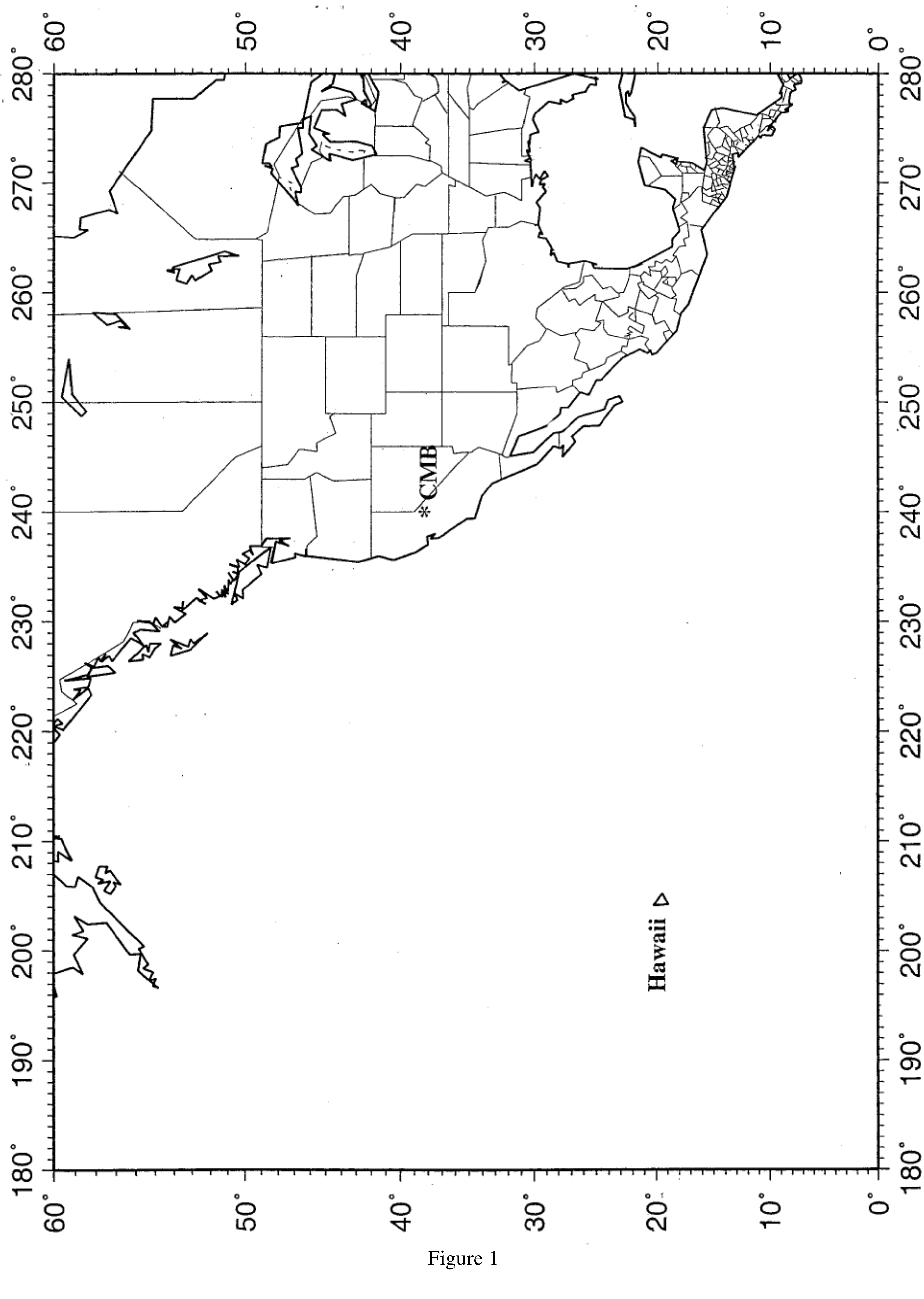
Using the blow-ups of the seismograms (Figures 5 - 8), measure the amplitudes of the highest-amplitude body and surface wave for each event and tabulate the results. Tabulate also the ratio of the logarithm of the surface-wave amplitude to the logarithm of the body-wave amplitude. This is analogous to (but not the same as) the ratio of M_S:m_b. Comment on your results.

You are provided with spectra for the P and S waves for each event (Figures 9 - 12). For frequencies of 0.5, 1, 2, 3, 4 and 5 Hz, measure the amplitudes of the P and S waves. Smooth the spectra by eye as you make the measurements. Plot graphs of

$$\frac{amp_P}{amp_S} : frequency$$

for each of the four events, on the same piece of paper.

Use all your results to decide which events are nuclear explosions and which are earthquakes. State clearly the evidence you have for your conclusions.



CMB
Hawaii
60°
50°
40°
30°
20°
10°
0°
180°
190°
200°
210°
220°
230°
240°
250°
260°
270°
280°

Figure 1

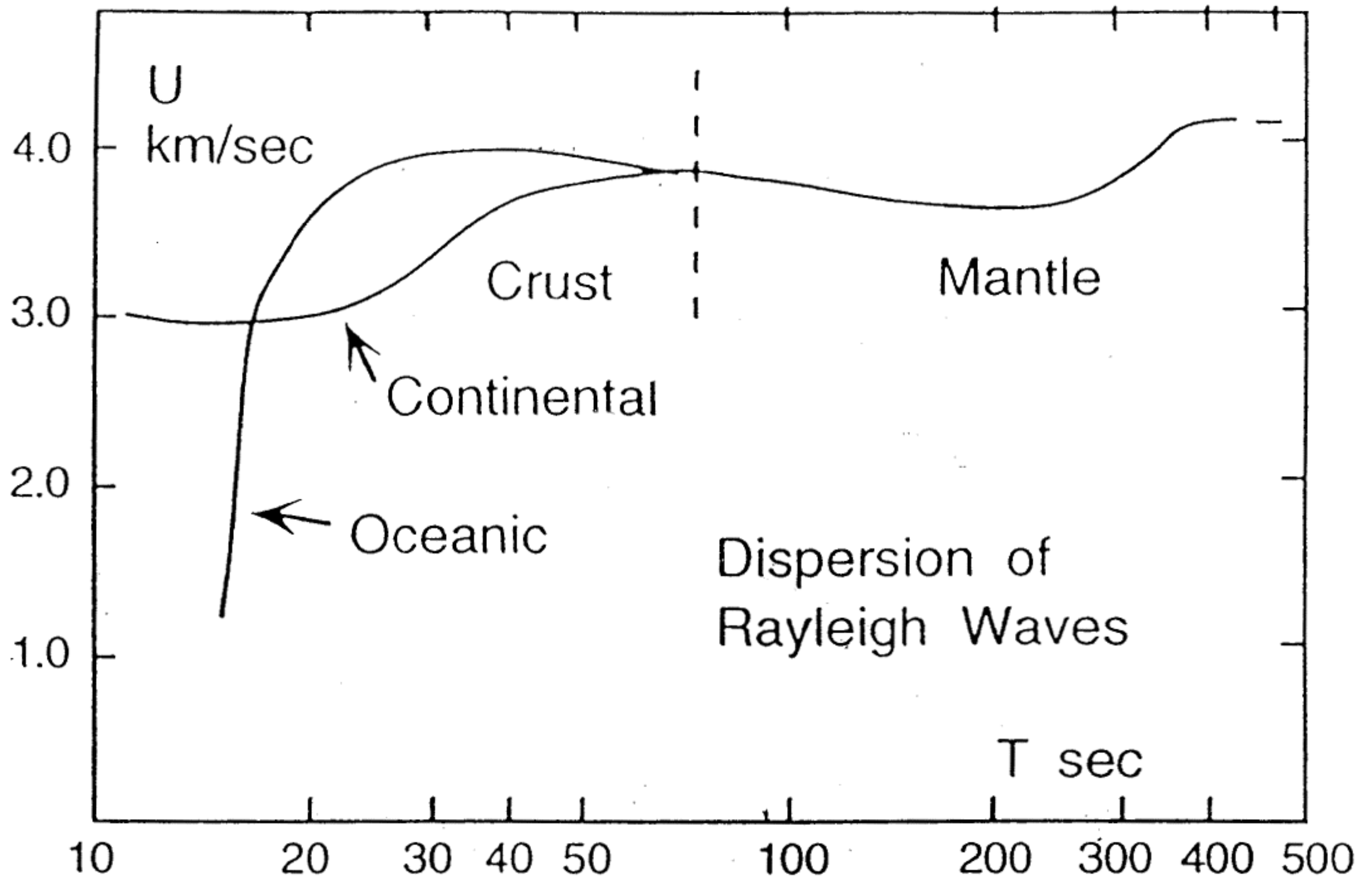
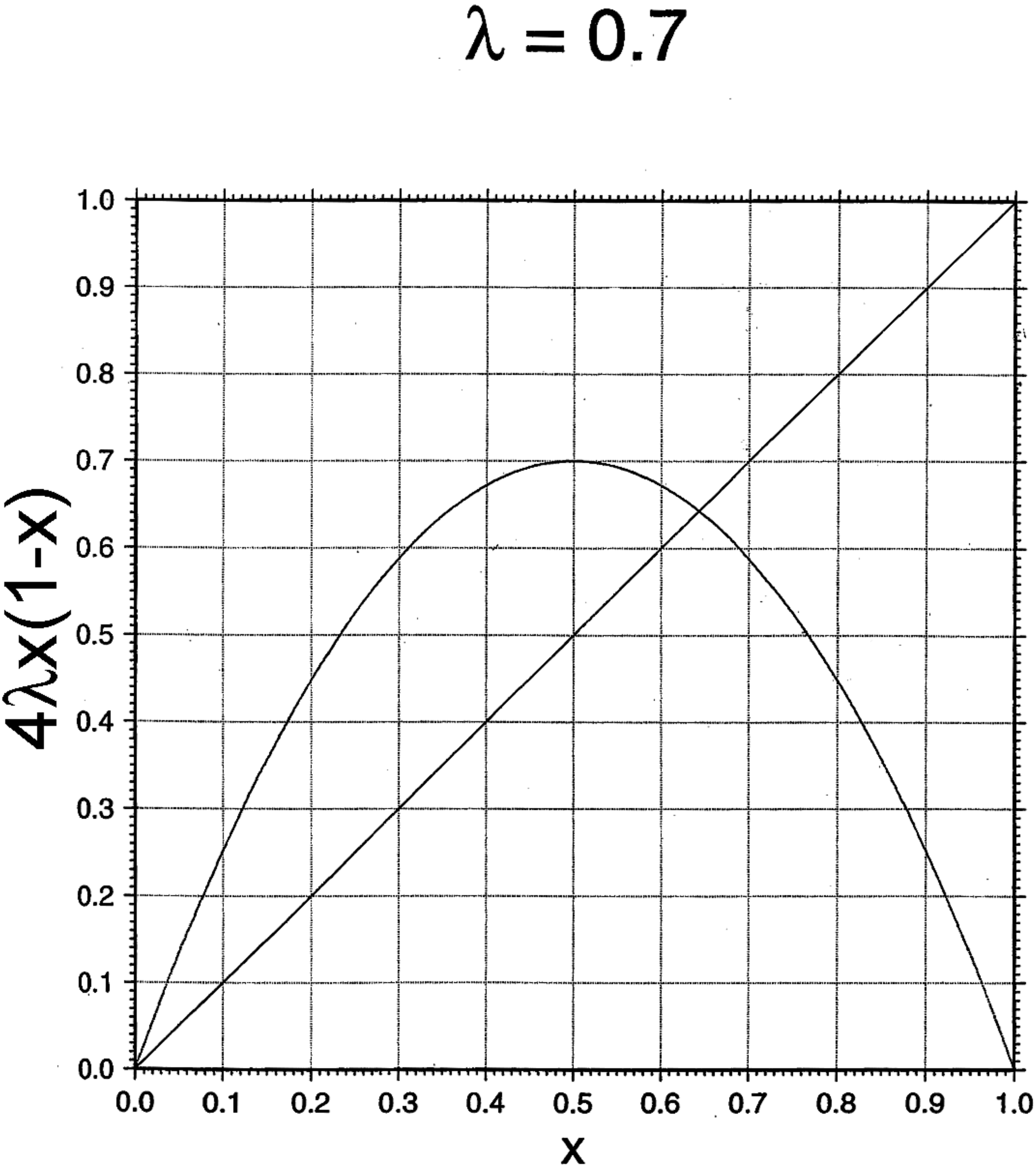
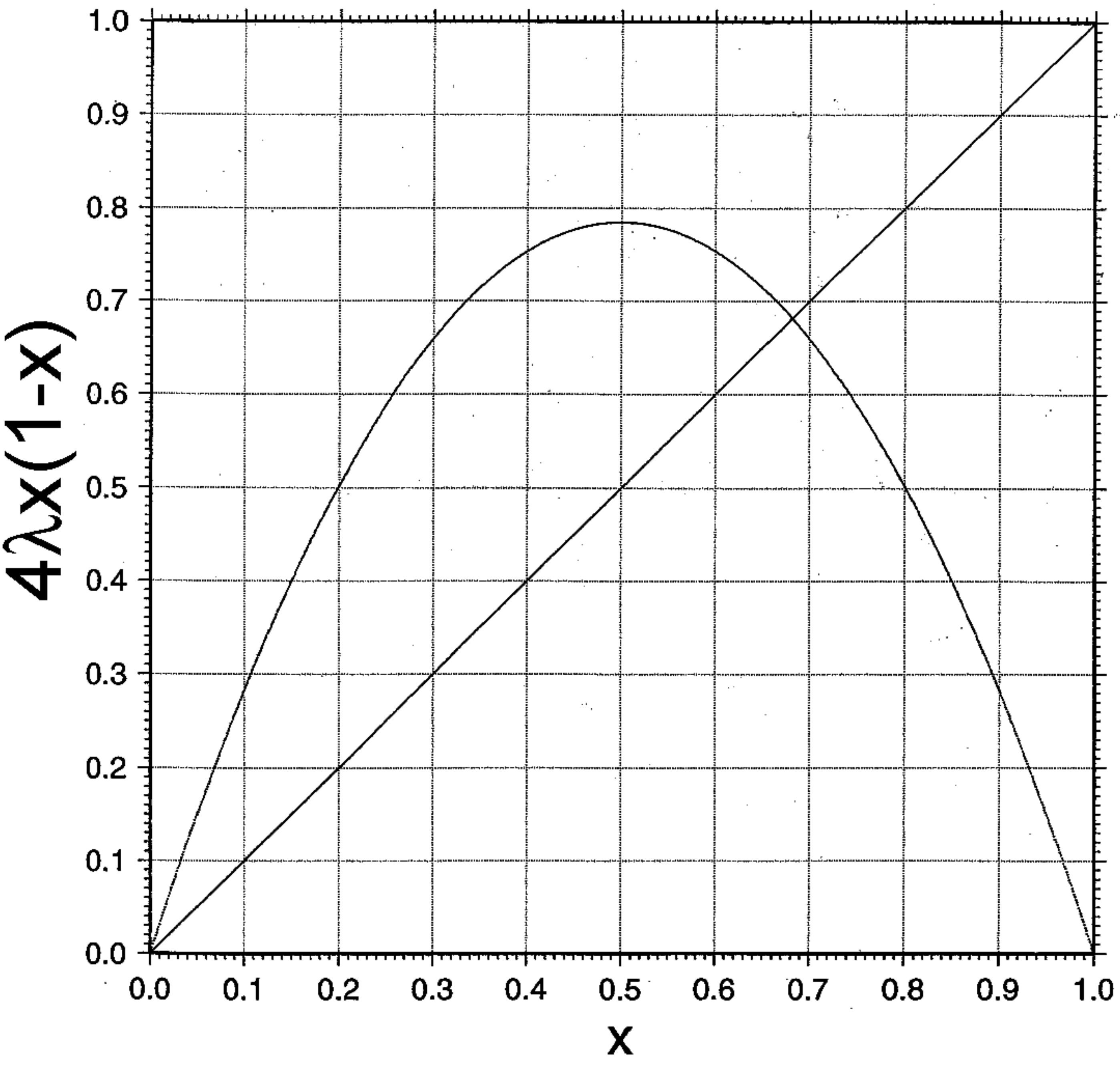


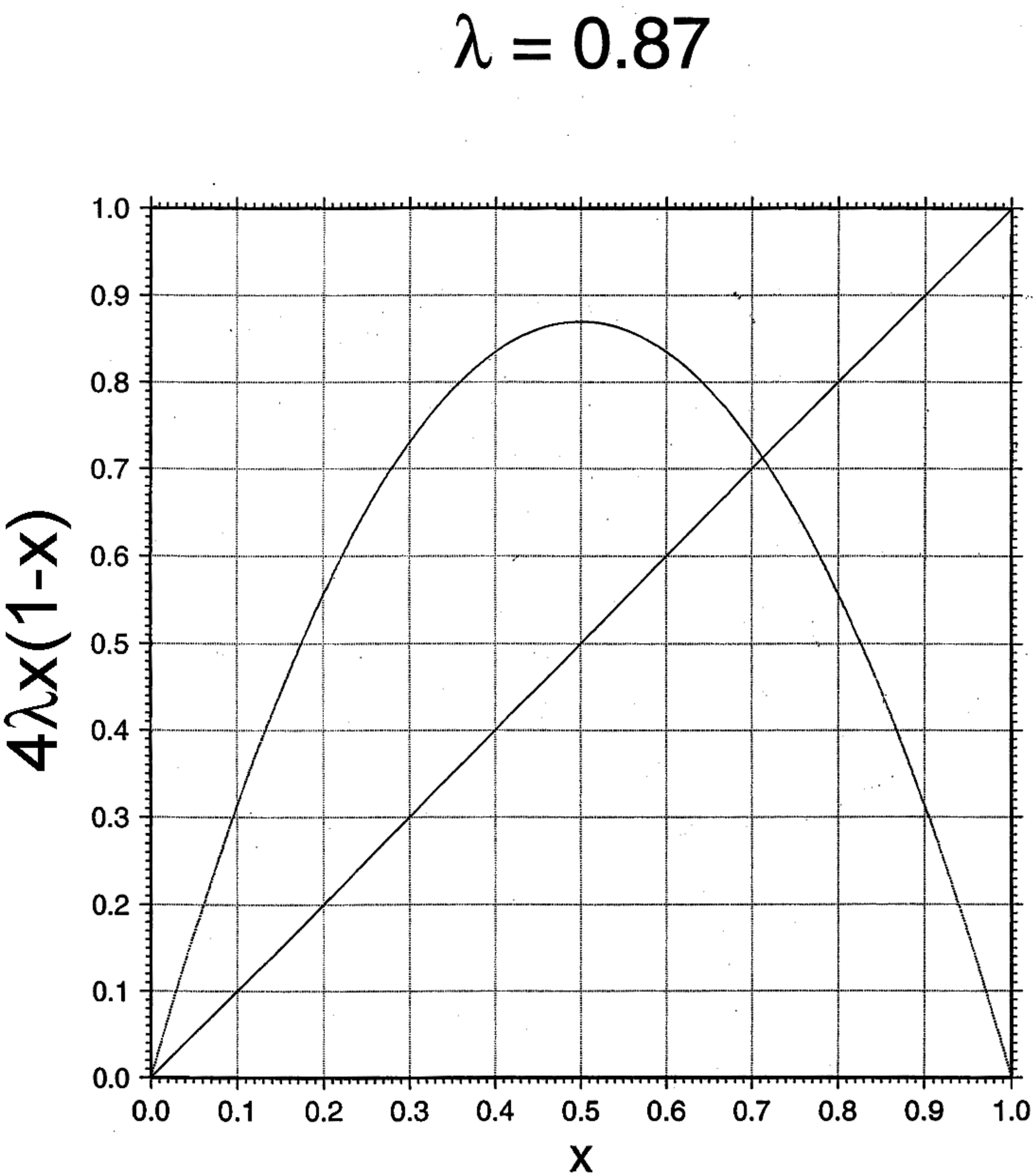
FIGURE 4.16 Observed group-velocity curves for Rayleigh waves. Averaged values for oceanic and continental paths are shown for periods less than 80 s. (Modified from Båth, 1979.)


λ = 0.7
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
4λx(1-x)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
x

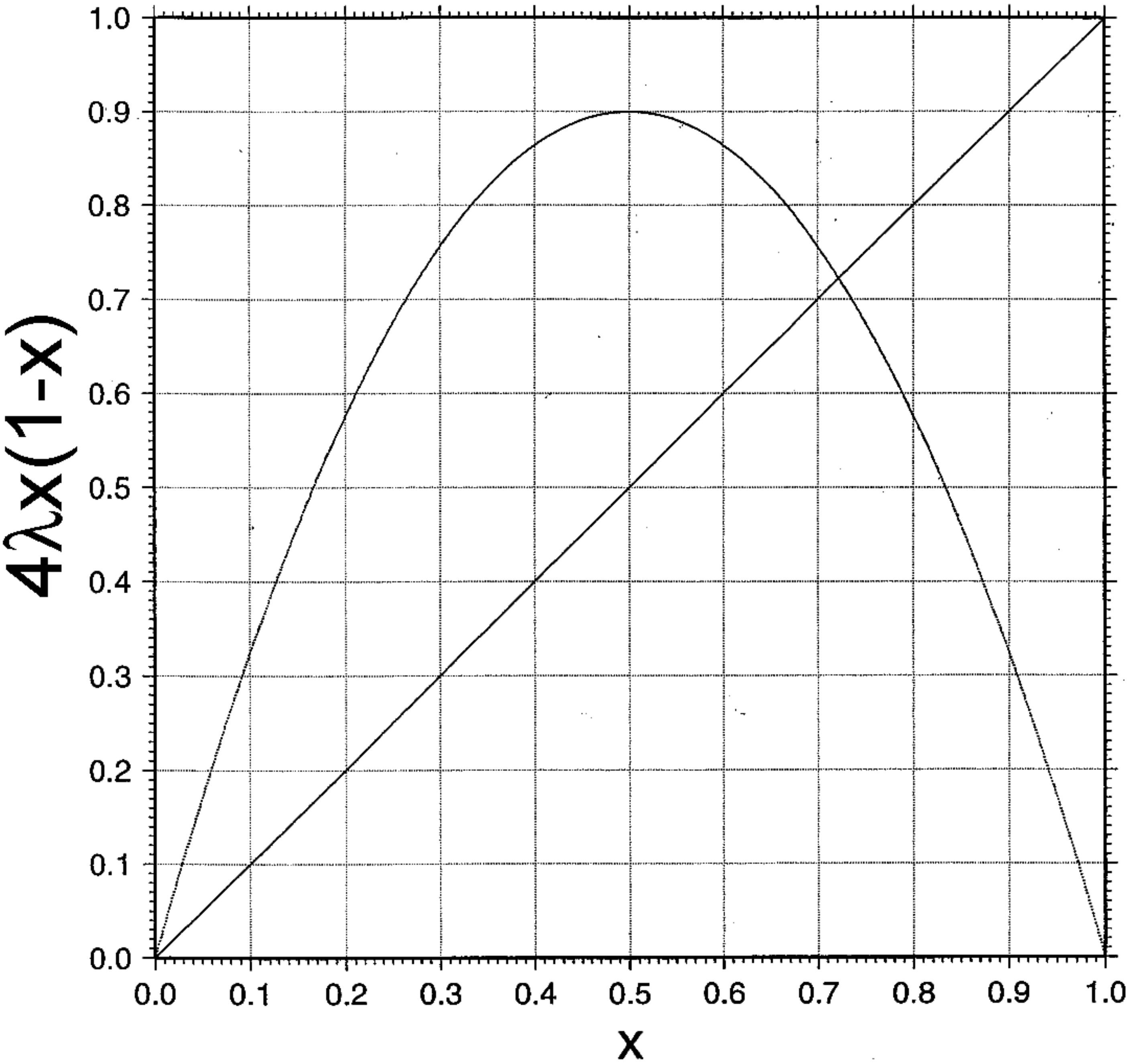
$\lambda = 0.785$



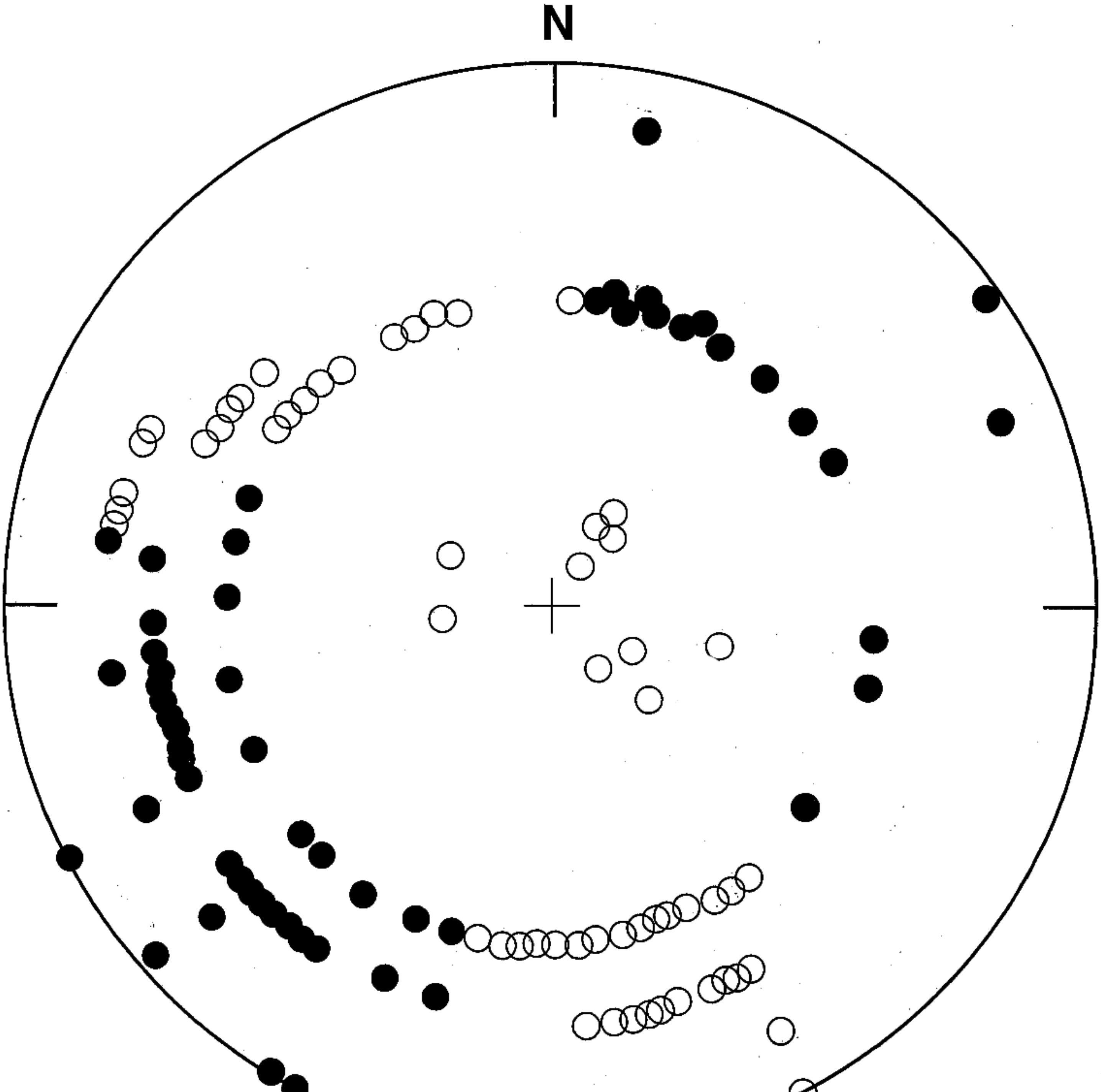
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
4λx(1-x)
x

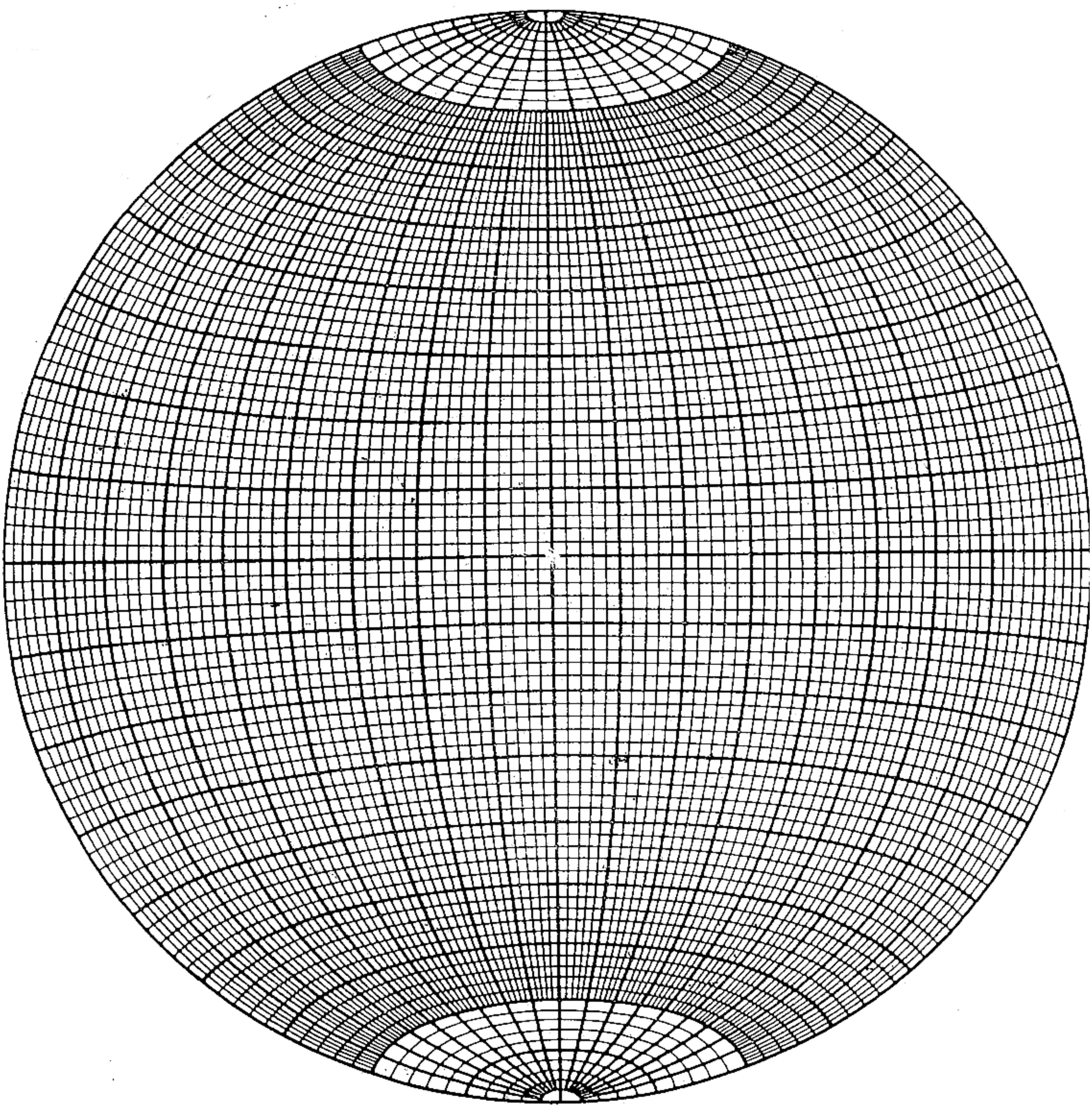

λ = 0.87
4λx(1-x)
x
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

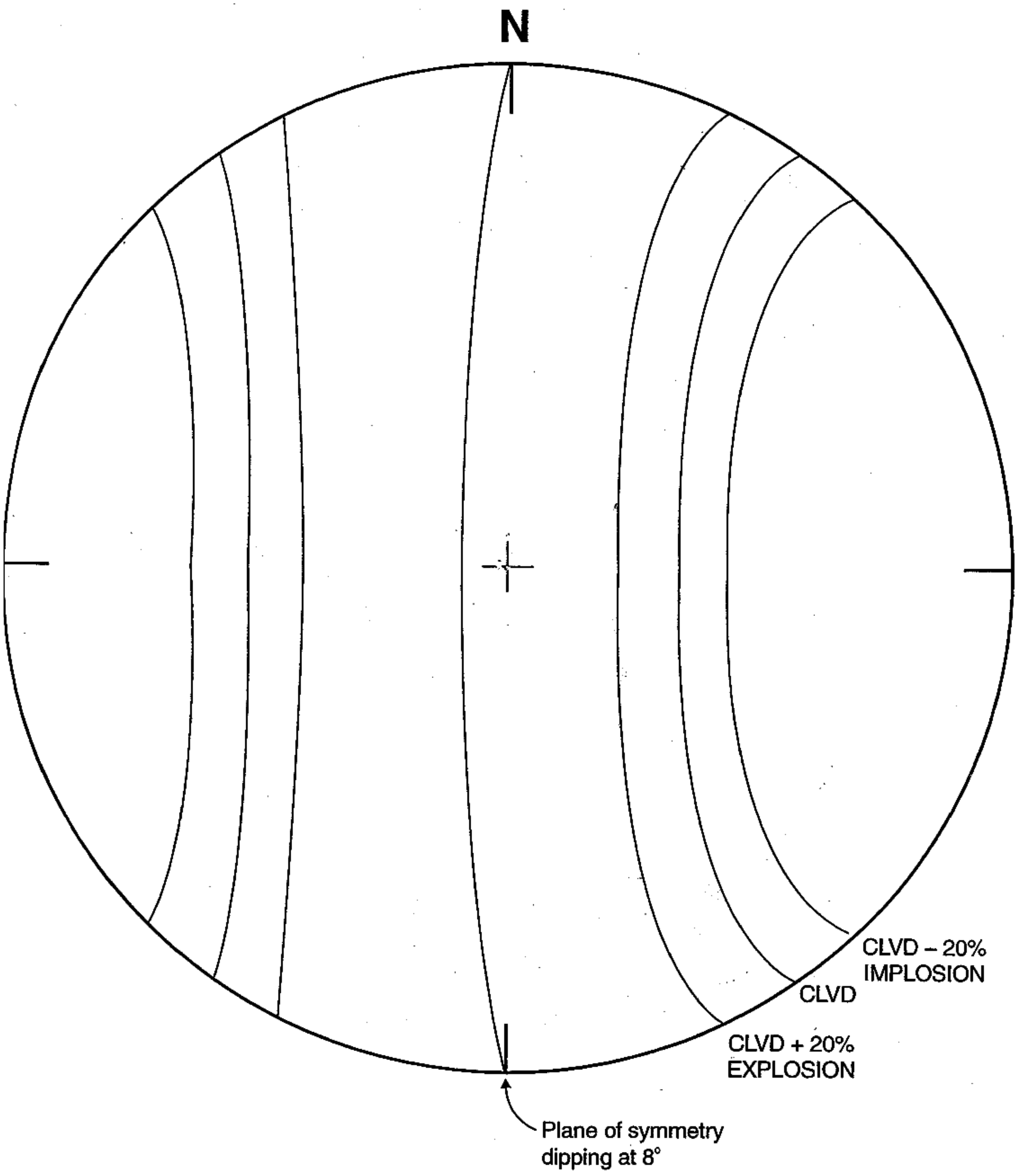
$\lambda = 0.9$



1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
4λx(1-x)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
x


N




N
CLVD – 20%
IMPLOSION
CLVD
CLVD + 20%
EXPLOSION
Plane of symmetry
dipping at 8°

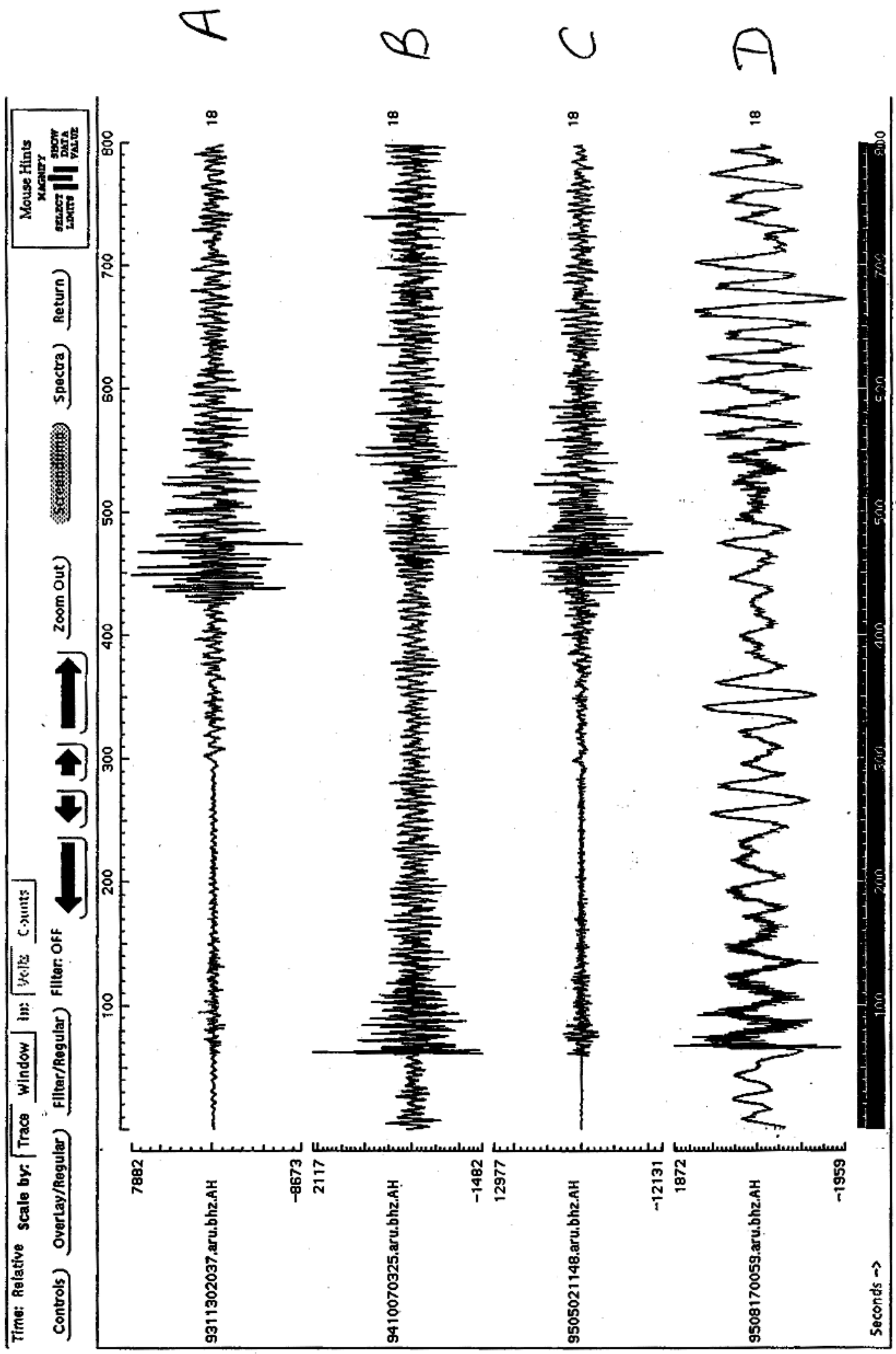

A
B
C
D
Time: Relative Scale by: Trace Window
Controls
Overlay/Regular
Filter/Regular
Filter: OFF
Zoom Out
Spectra
Return
Mouse Hints
7882
9311302037.aru.bhz.AH
-8673
2117
9410070325.aru.bhz.AH
-1482
12977
9505021148.aru.bhz.AH
-12131
1872
9508170059.aru.bhz.AH
-1959
Seconds ->
100
200
300
400
500
600
700
800
18

Figure 2

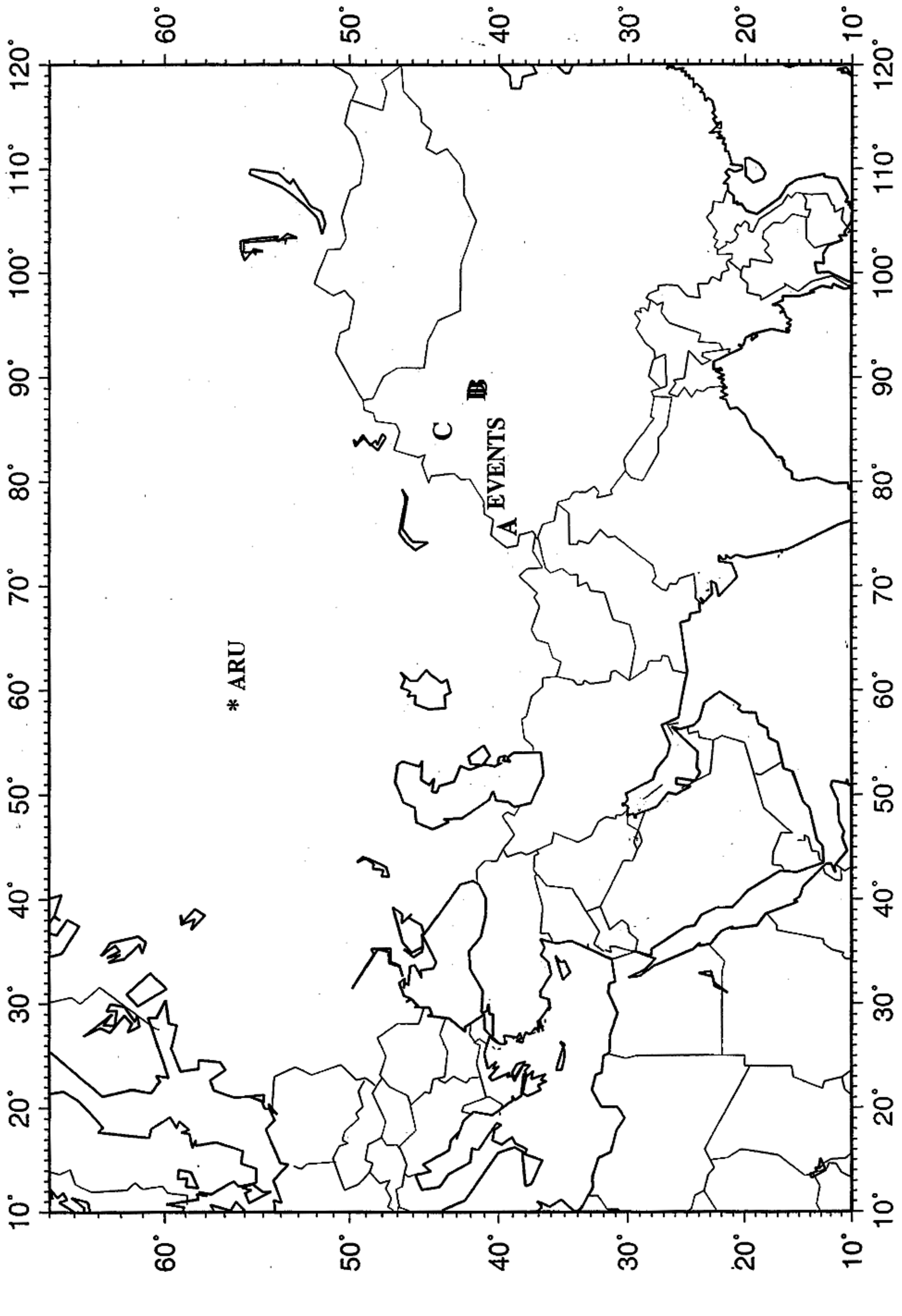


Figure 3

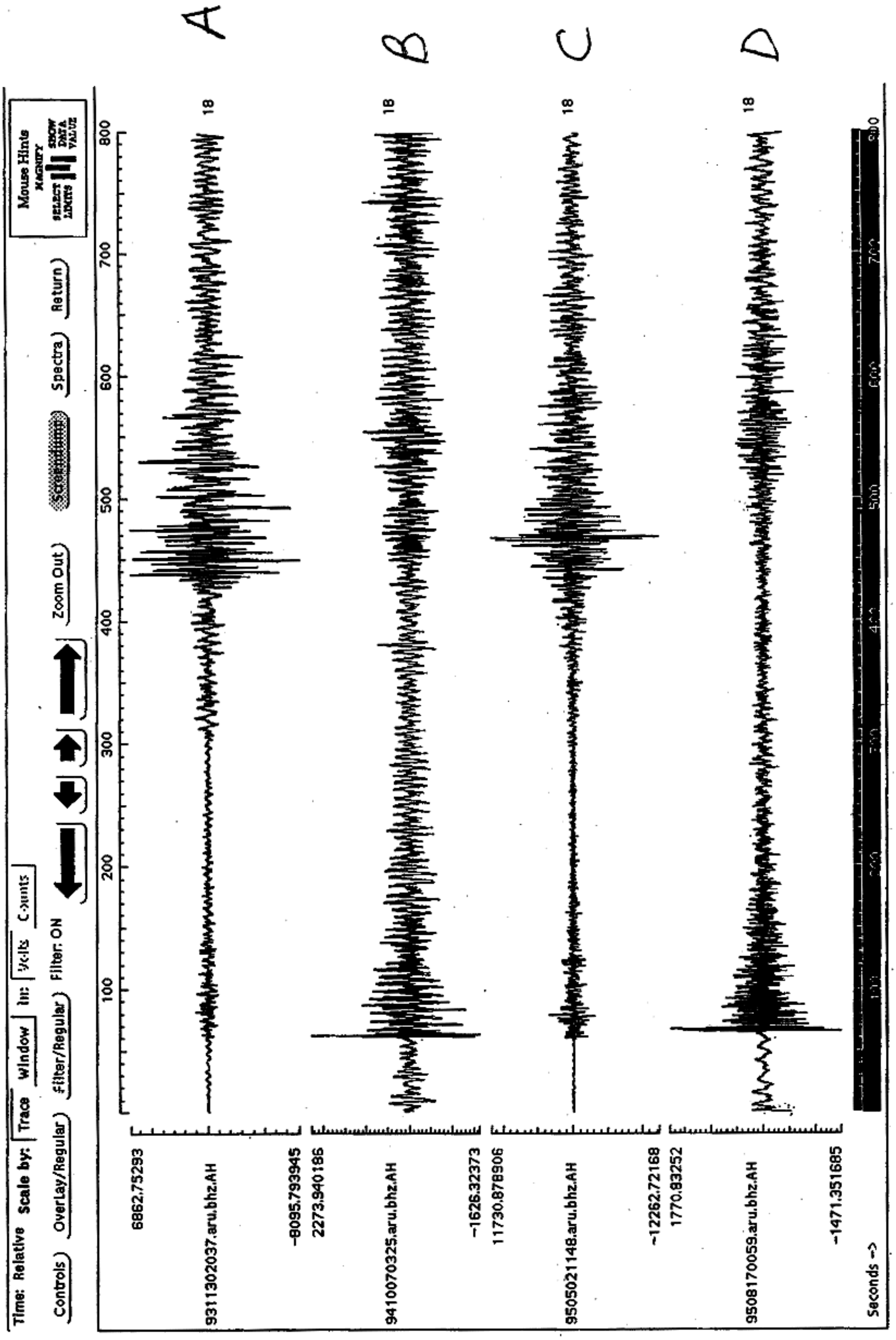
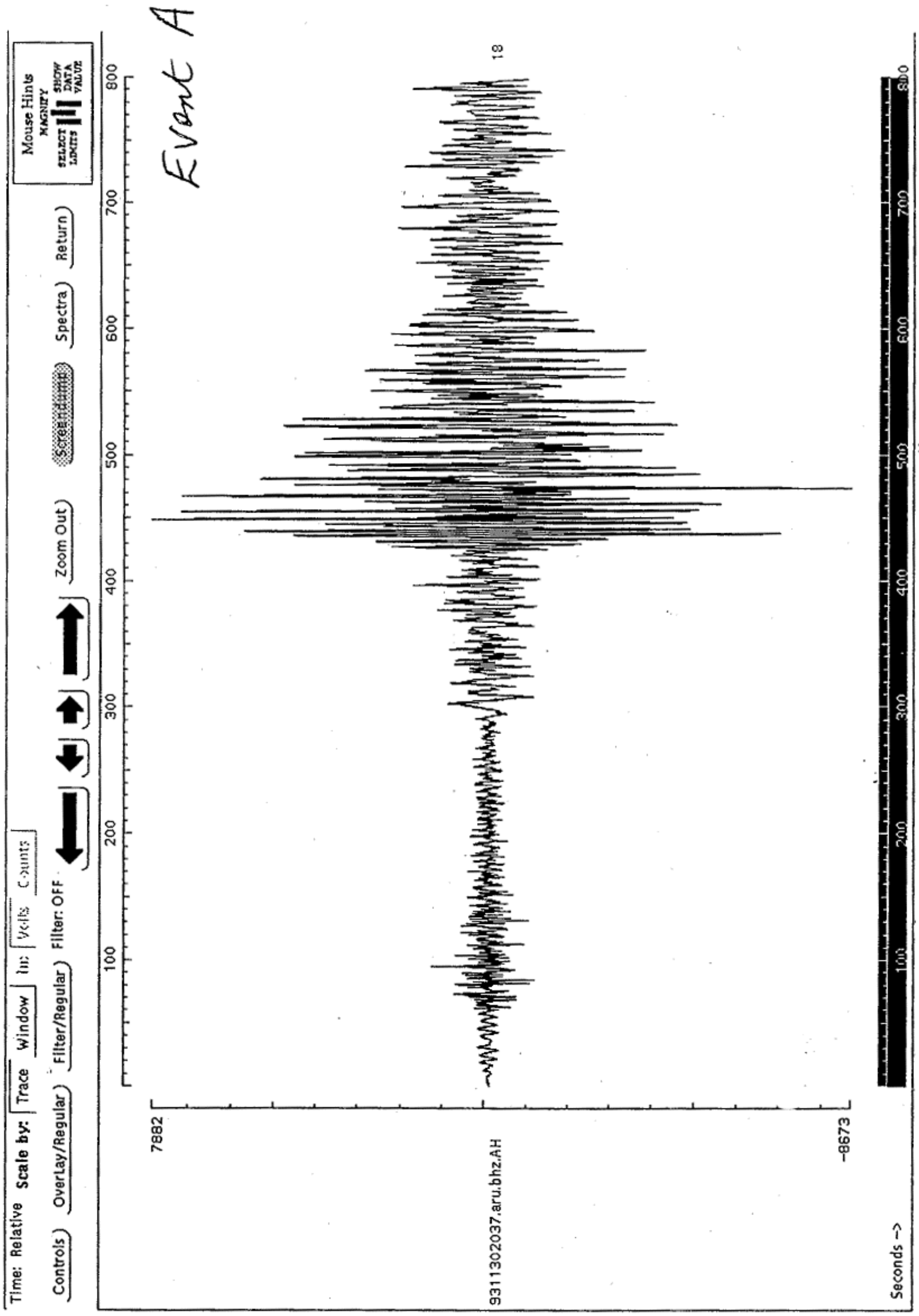

Time: Relative
Scale by:
Trace
Window
In:
Volts
Counts
Controls
Overlay/Regular
Filter/Regular
Filter: ON
Zoom Out
Screendump
Spectra
Return
Mouse Hints
MAGNIFY
SELECT LIMITS
SHOW DATA VALUE
A
B
C
D
6862.75293
9311302037.aru.bhz.AH
-8095.793945
2273.940186
9410070325.aru.bhz.AH
-1626.32373
11730.878906
9505021148.aru.bhz.AH
-12262.72168
1770.83252
9508170059.aru.bhz.AH
-1471.351685
Seconds ->
18
100
200
300
400
500
600
700
800

Figure 4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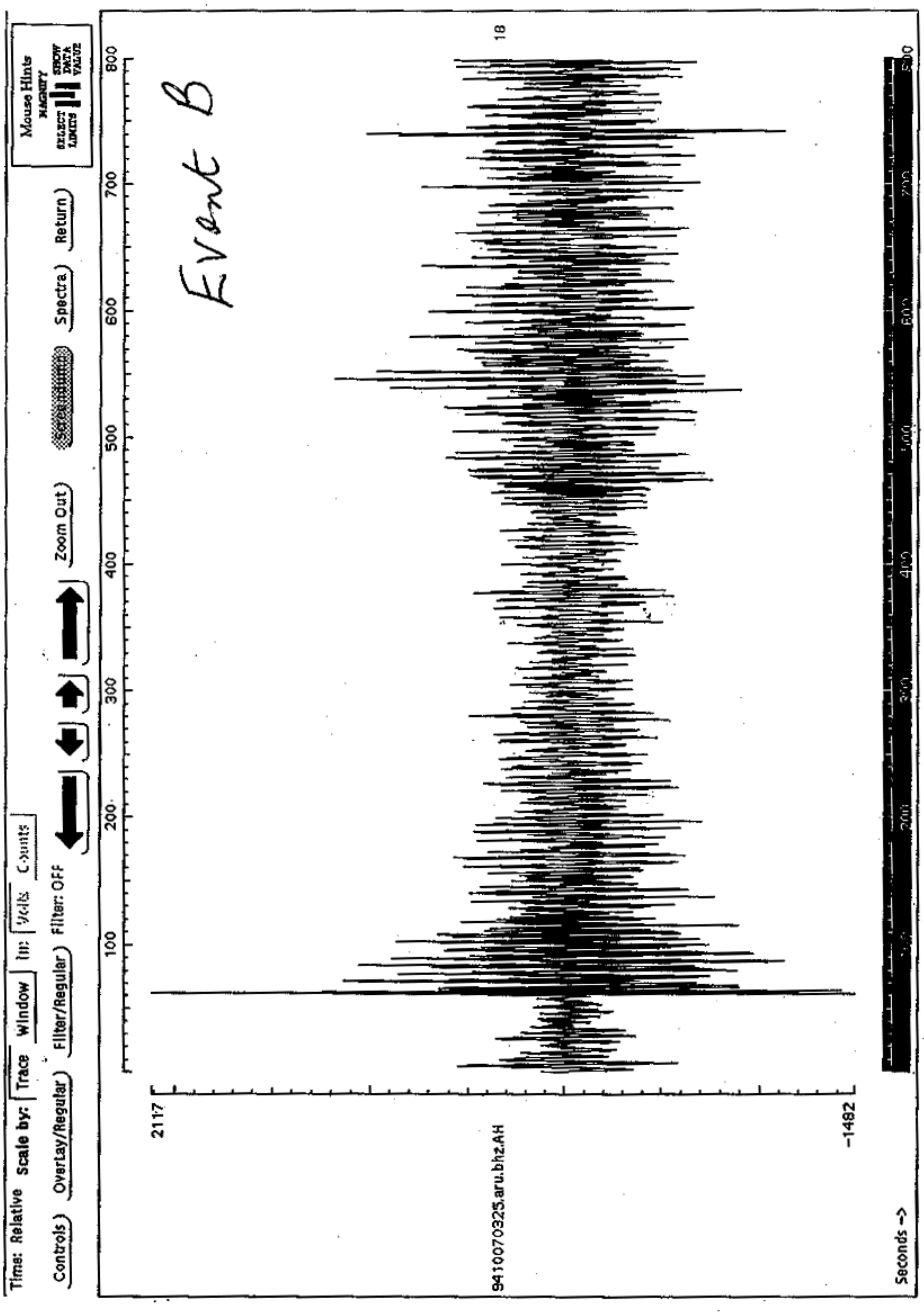
Scale by:
Trace
Window
In:
Volts
Counts
Controls
OverLay/Regular
Filter/Regular
Filter: OFF
Zoom Out
Spectra
Return
Mouse Hints
Event A
18
9311302037.aru.bhz.AH
7882
-8673
100
200
300
400
500
600
700
800
Seconds ->

Figure 5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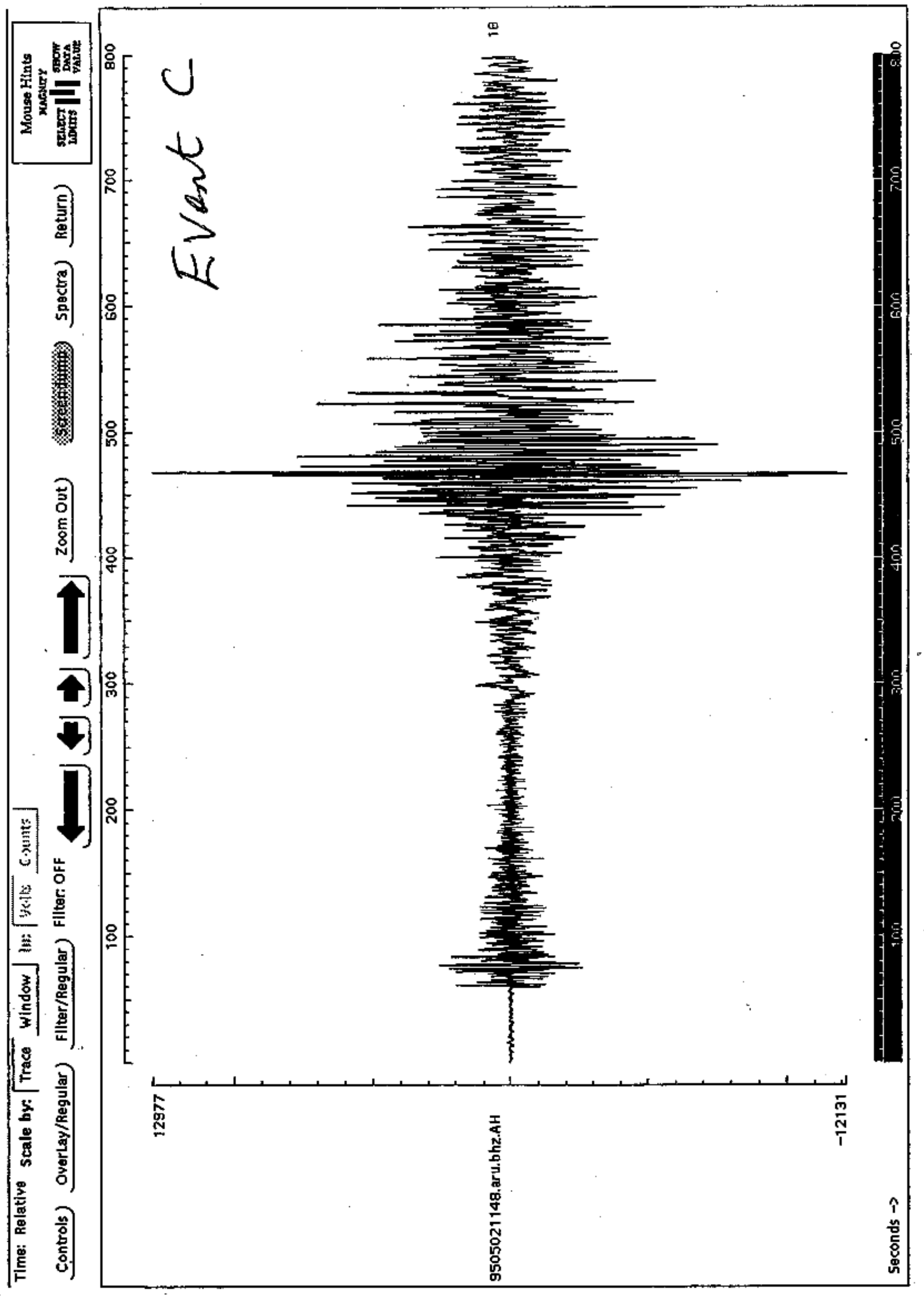
Scale by:
Trace
Window
Counts
Controls
Overlay/Regular
Filter/Regular
Filter: OFF
Zoom Out
Spectra
Return
Mouse Hints
Event B
18
9410070325.aru.bhz.AH
2117
-1492
Seconds ->

Figure 6



Time: Relative
Scale by:
Trace
Window
Counts
Filter: OFF
Controls
Overlay/Regular
Filter/Regular
Zoom Out
Spectra
Return
Mouse Hints
Event C
12977
9505021148.aru.bhz.AH
-12131
Seconds ->

Figure 7

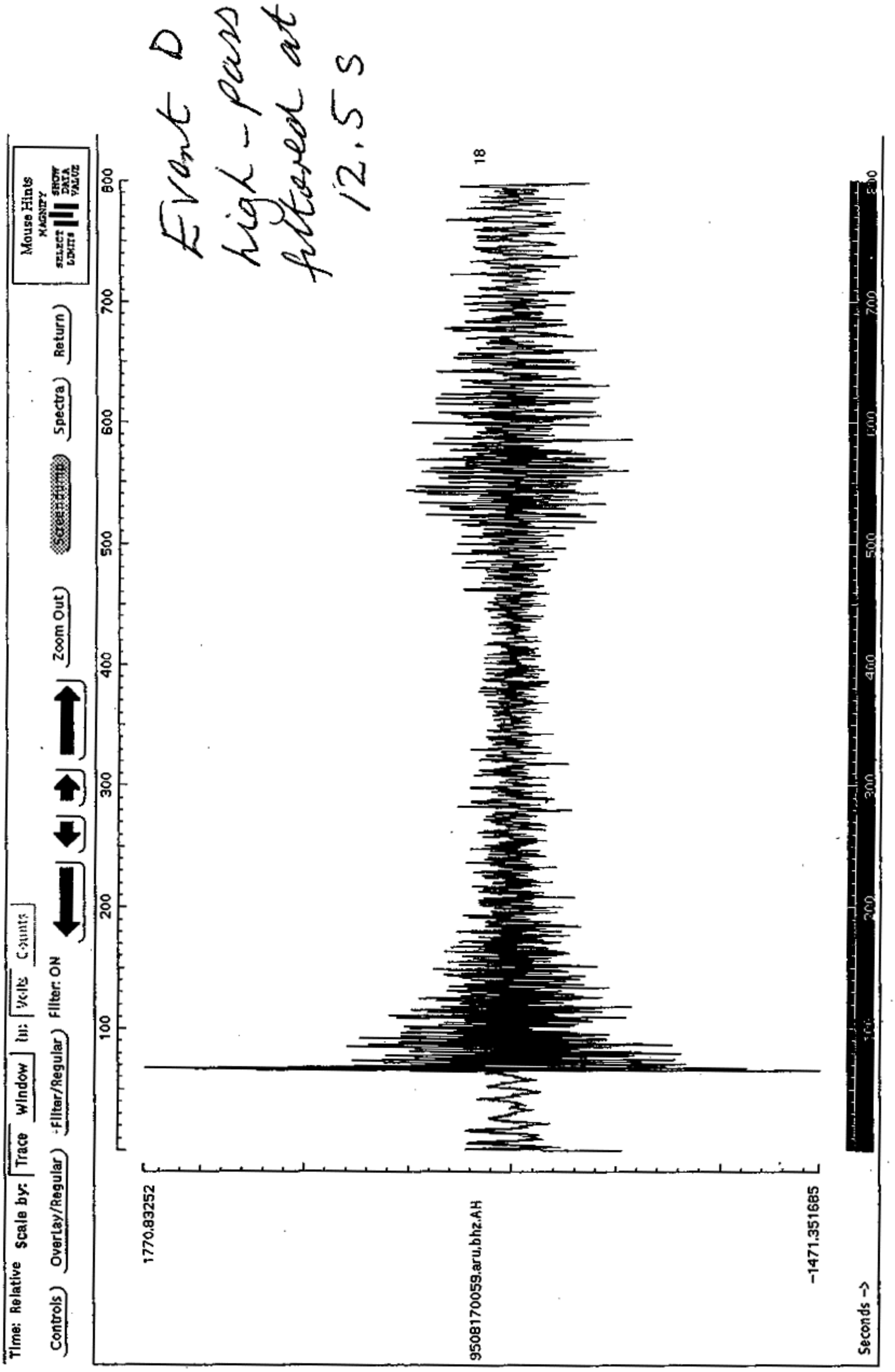
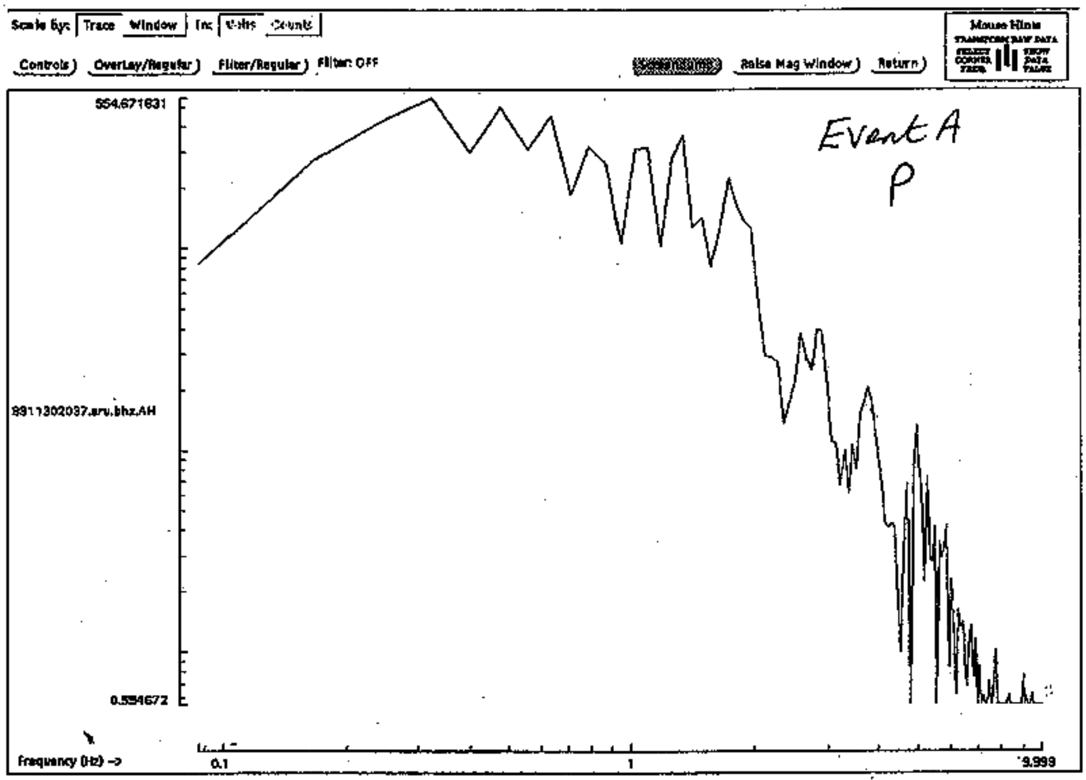
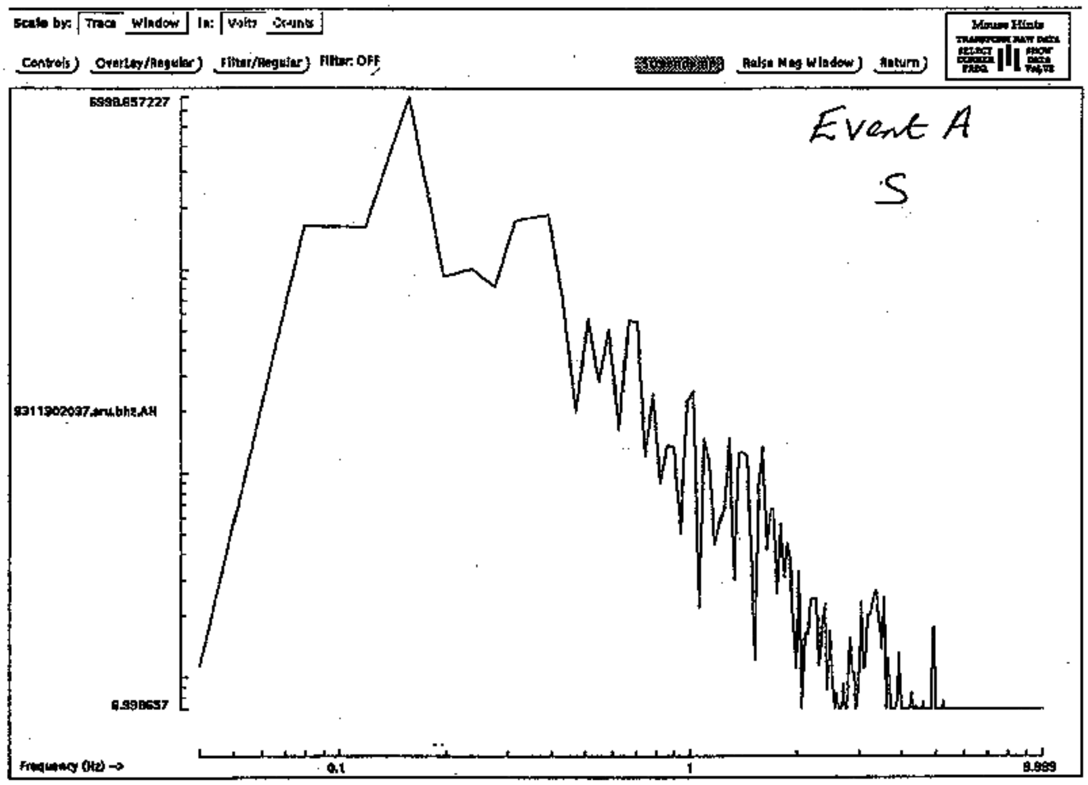

Time: Relative Scale by: Trace Window In: Volts Counts
Controls Overlay/Regular +Filter/Regular Filter: ON
Zoom Out
Screendump
Spectra
Return
Mouse Hints
1770.83252
9508170059.aru.bhz.AH
-1471.351685
Seconds ->
Event D
high-pass
filtered at
12.5 s

Figure 8


Scale by: Trace Window In: Volts Counts
Controls Overlay/Regular Filter/Regular Filter: OFF
Raise Mag Window Return
Mouse Hints
554.671631
0.554672
Frequency (Hz) ->
0.1
1
9.999
Event A
P


Scale by: Trace Window In: Volts Counts
Controls Overlay/Regular Filter/Regular Filter: OFF
Raise Mag Window Return
Mouse Hints
9311302037.aru.bhz.AH
Frequency (Hz) ->
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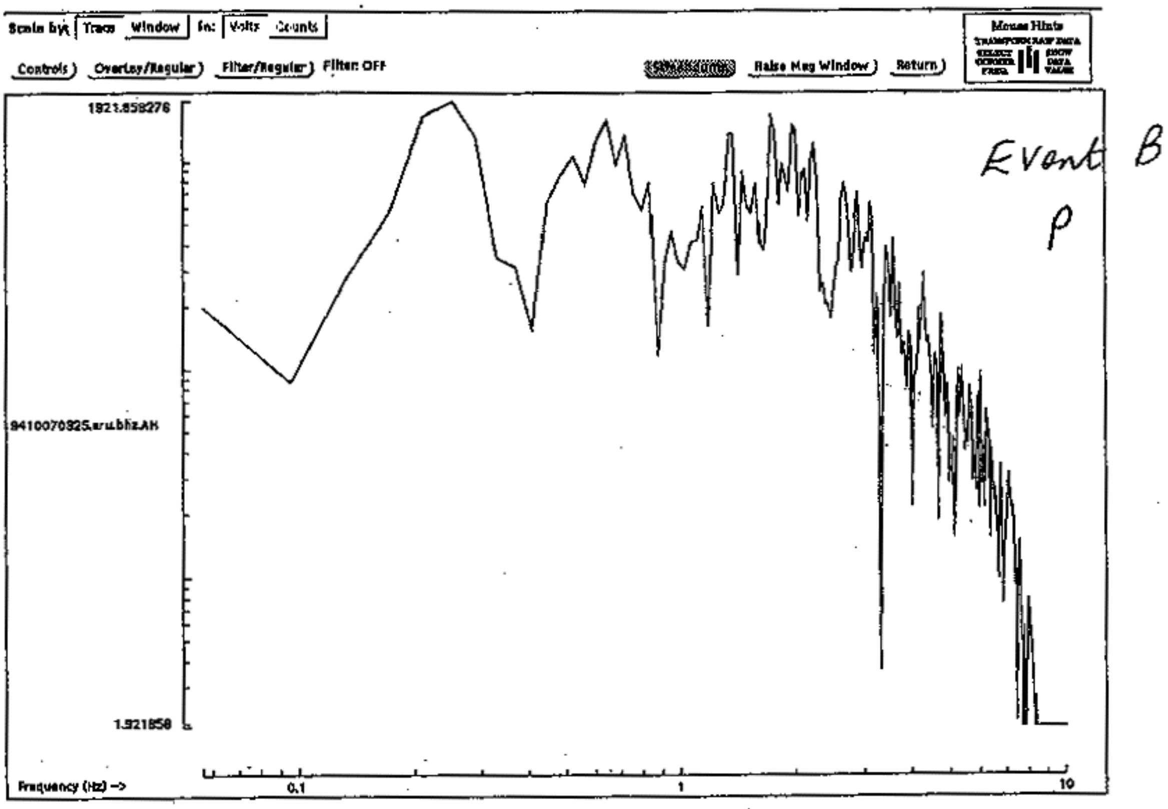
1
9.999
Event A
S

Figure 9


Scale by: Trace Window In: Volts Counts
Controls Overlay/Regular Filter/Regular Filter: OFF
Raise Mag Window Return
Mouse Hints
1921.858276
9410070325.aru.bhz.AH
1.921858
Frequency (Hz) ->
0.1
1
10
Event B
P

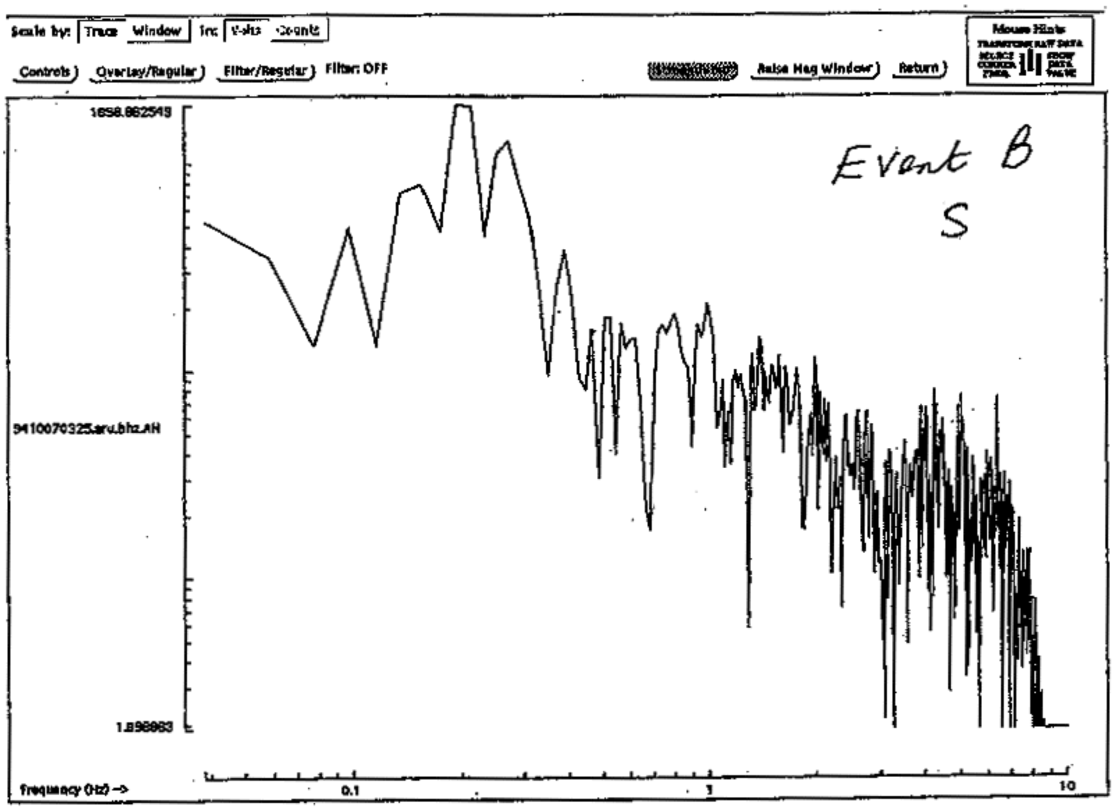
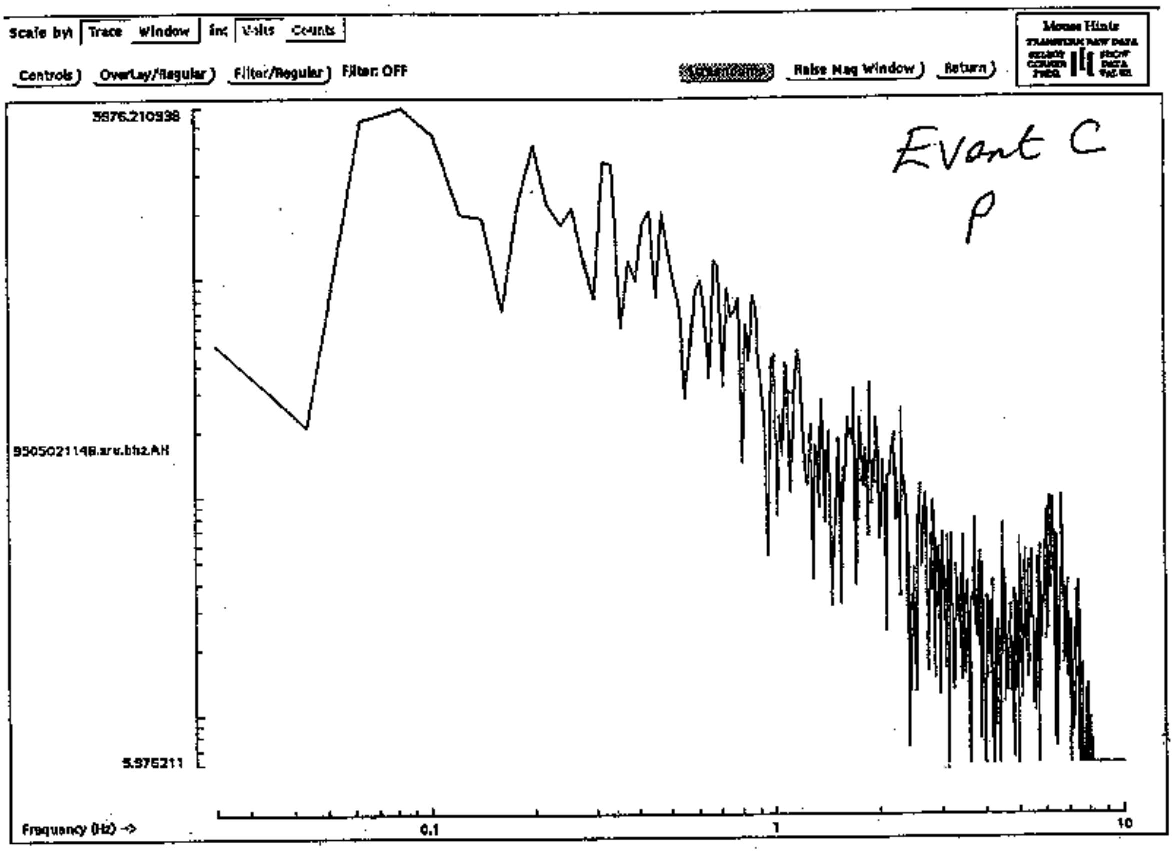

Scale by: Trace Window In: Volts Counts
Controls Overlay/Regular Filter/Regular Filter: OFF
Raise Mag Window Return
Mouse Hints
1898.882549
9410070325.aru.bhz.AH
1.898883
Frequency (Hz) ->
0.1
1
10
Event B
S

Figure 10


Scale by: Trace Window in: Volts Counts
Controls Overlay/Regular Filter/Regular Filter: OFF
Raise Mag Window Return
Mouse Hints
5976.210938
9505021148.aru.bhz.AH
5.976211
Frequency (Hz) ->
0.1
1
10
Event C
P

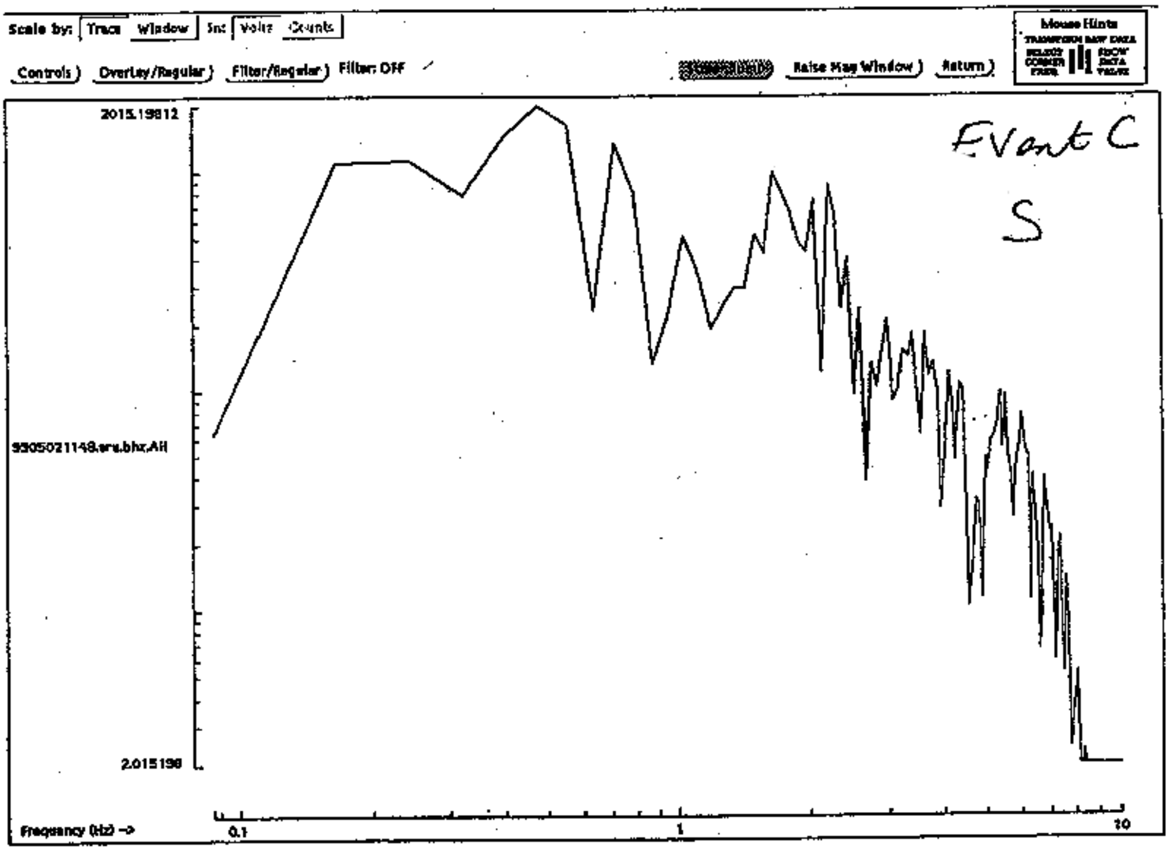
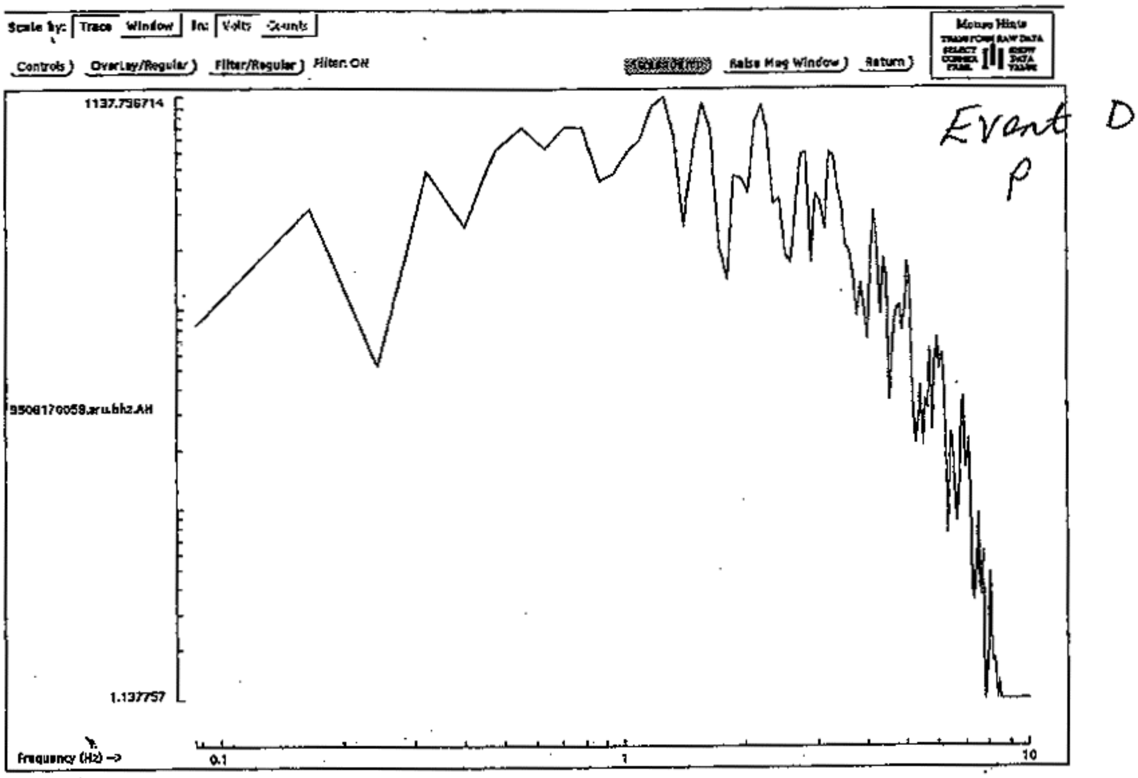

Scale by: Trace Window in: Volts Counts
Controls Overlay/Regular Filter/Regular Filter: OFF
Raise Mag Window Return
Mouse Hints
2015.19812
9505021148.aru.bhz.AH
2.015198
Frequency (Hz) ->
0.1
1
10
Event C
S

Figure 11


Scale by: Trace Window In: Volts Counts
Controls Overlay/Regular Filter/Regular Filter: ON
Raise Mag Window Return
Mouse Hints
1137.736714
9508170059.aru.bhz.AH
1.137757
Frequency (Hz) ->
0.1
1
10
Event D
P

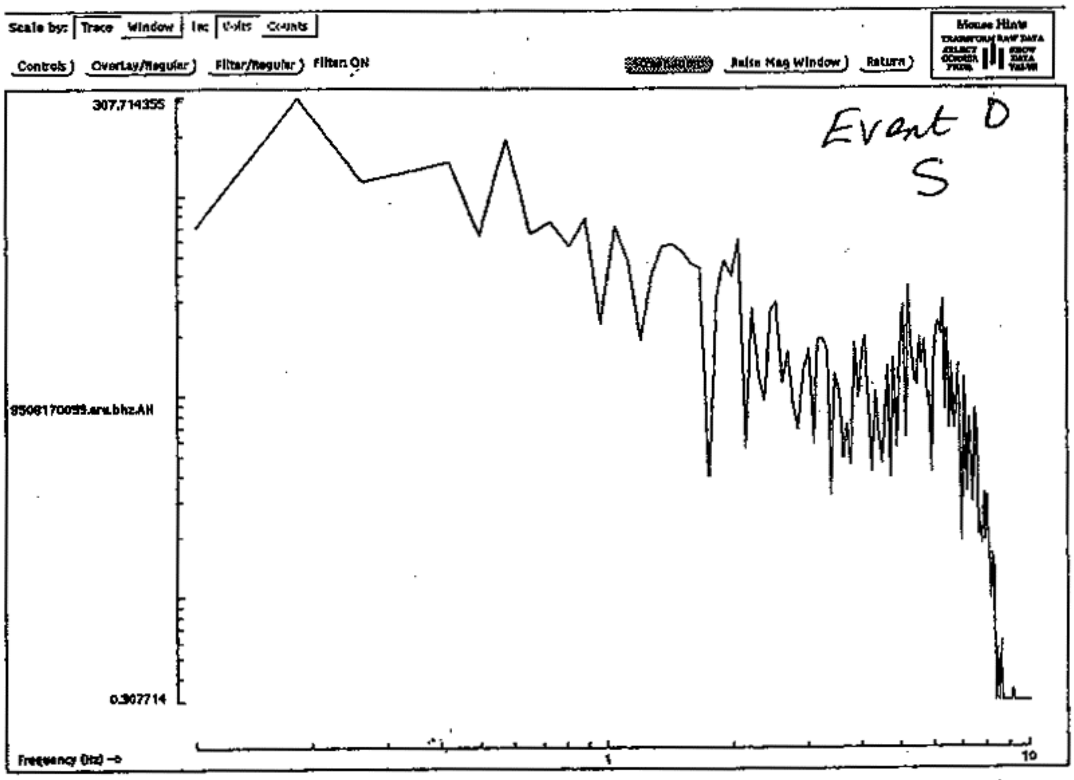

Scale by: Trace Window In: Volts Counts
Controls Overlay/Regular Filter/Regular Filter: ON
Raise Mag Window Return
Mouse Hints
307.714355
9508170059.aru.bhz.AH
0.307714
Frequency (Hz) ->
1
10
Event D
S

Figure 12