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FREQUENCY RESPONSE OF THE USGS SHORT PERIOD TELEMETERED SEISMIC SYSTEM AND ITS SUITABILITY FOR NETWORK STUDIES OF LOCAL EARTHQUAKES

by

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I. DESCRIPTION OF THE SYSTEM

The USGS telemetered seismic system was intended primarily to record small to moderate earthquakes (magnitude 0 to 4) at distances of a few km to several hundred km. Its frequency response is such that the recorded background noise at a moderately quiet Coast Range site has a relatively flat "record" spectrum from about 1/3 hz to about 20 hz. With the system magnification set so that the background noise is clearly recorded (about 1 mm peak-to-peak) one can anticipate that any seismic signal that exceeds background noise appreciably in this spectral region will be large enough to be seen on the seismogram. This response represents the highest sensitivity and broadest bandwith that we were able to attain with a 1 hz seismometer, a simple amplifier VCO employing very low-power integrated circuits, and an 8-channel constant bandwidth fm subcarrier multiplex system for use with commercial voice grade phone lines.

The system configuration is shown in the block diagram, Figure 1. Signals from the field units (seismometer, amplifier, VCO) are transmitted via radio and/or phone lines on fm subcarriers in an 8-channel constant bandwidth multiplex system. At the recording site (Menlo Park) the multiplexed phone line signals are 1) recorded in the direct record mode on magnetic tape and 2) fed to banks of discriminators to recover the analog seismic signals for recording on Develocorders and/or Helicorders and for analysis in the automatic real-time earthquake detection and location system. On playback from tape, the multiplexed signals are recovered and are fed to banks of discriminators to recover the analog seismic signals. If the playback discriminators have the same characteristics as the real-time discriminators, the seismic signals recovered from tape will be the same as those from the real-time discriminators except for noise introduced in the record/playback process.

The frequency response of the system as a whole is determined by the frequency responses of its component parts. If the amplitude vs frequency responses of the components are plotted on log amplitude vs log frequency plots, the combined responses of several (or all) components can be obtained by simple addition of the plots. Such plots for individual system components and for various combinations of components are shown diagramatically in Figure 2. The individual components include:

1) the seismometer,

2) the "electronics" - a) amplifier, b) modulator, and c) discriminator, and

3) the recorder - a) Oscillomink, b) Develocorder, c) Helicorder, and d) A/D convertor.

The frequency responses of these components are approximately as follows:

1) Seismometer - 1 hz-natural-frequency moving coil seismometer: for constant amplitude, varying frequency ground motion, the seismometer output voltage increases 6 db/octave above 1 hz and falls off 18 db/octave below 1 hz.

2a) Amplifier - for a constant voltage-varying frequency input signal, the amplifier output voltage is "flat" between about 0.1 hz and 30 hz. It falls off 12 db/octave below 0.1 hz and above 30 hz.

2b) Modulator - the ratio of frequency change to input voltage change (hz/volt) is essentially constant from less than 0.1 hz to more than 30 hz.

2c) Discriminator - the ratio of output voltage change to input frequency change is essentially constant from DC to about 30 hz. Above 30 hz this ratio drops off at 30 db/octave in the Develco discriminator and 24 db/octave in the J101 (USGS) discriminator.

3a) The Oscillomink (an ink-jet direct-write multichannel oscillograph) used to reproduce records played back from magnetic tape has a frequency response that is essentially flat from DC to more than 100 hz. It is commonly used, however, with a 6 db/octave low cut filter with a corner frequency of about 0.1 hz. The 0.1 hz to 100+ hz pass band of this recorder extends well beyond the upper and lower limits on the overall system response imposed by other elements.

3b) The Develocorder (without an input filter) has a frequency response that is essentially flat from DC to the 10 hz natural frequency of its recording galvanometers. Above 10 hz its response falls off at a rate of 12 db/octave. Because of the very limited amplitude range available to individual traces on the Develocorder (to avoid trace overlapping) and the high level of 1- to 2-second period microseisms in the California Coast Ranges during winter months, it has been found to be desirable to couple the Develocorder to the Discriminators with a 6 db/octave low-cut filter with a corner frequency of 1 hz. This practice improves the legibility of small local earthquakes but further reduces the system's sensitivity to teleseism P-phases.

3c) The combined response of the Helicorder penmotor and its amplifier is flat between 0.1 hz and 5.0 hz. It falls off at a rate of 6 db/octave below 0.1 hz and 12 db/octave above 5 hz. This response is more favorable for recording teleseism P-phases than is that of the Develocorder (with input filter).

3d) The A/D Convertor works directly with the signals reproduced by the discriminators; so it imposes no further analog frequency characteristics on the system response. However, a serious frequency dependent problem of another sort arises: the digitization rate must be sufficient to cope with the highest frequency waves that emerge from the discriminator with appreciable amplitude. If the digitization rate (per trace) is 50 samples/sec and if we require at least 3 samples per data cycle, then data frequencies above about 17 hz pose serious problems. It appears that the standard USGS seismic system, viewed at the discriminator output, requires a digitization rate of about 100 samples per second.

If the digitization rate is limited to 50 samples per second, then the high frequency response of the systems should be reduced. The simplest and most effective way of accomplishing this goal is to modify the discriminator output filter, which has a very steep attenuation slope (30 db/octave in the Develco and 24 db/octave in the J101). The corner frequency of this filter should be reduced from 30 hz to 15 hz or lower. This change will also suppress system noise arising from interchannel modulation and other problems in the telemetry system.

II. SUITABILITY OF THE SYSTEM'S RESPONSE FOR NETWORK STUDIES OF LOCAL EARTHQUAKES

A. Practical Observations

Having briefly examined the USGS telemetered seismic systems and its frequency response, we should next consider the suitability of that response for a multipurpose telemetered short-period seismic array. Unfortunately, little or no systematic work has been done to answer this question on the basis of experience with records from the existing networks employing the USGS system. Some impressions are available, however.

1) For small earthquakes ($M \leq 2$) recorded at short distances ($\Delta < 100$ km), the system response seems quite good.

2) For somewhat larger events (M 2 to M 4) a number of problems arise. At near-in stations the records are seriously overdriven because of limited dynamic range. Recorded amplitudes are large and the seismograms are rather featureless (i.e., difficult to pick later phases) at ranges near and beyond 100 km, where one might hope to read S-wave arrivals. The relative importance of frequency response and magnification level in these problems has not been resolved.

3) For studies of teleseismic P-waves, the signal to noise ratio is significantly lower for the standard USGS system than for systems with lower response at high frequencies, particularly narrow-band systems with a peak response at 2 to 5 hz. Such peaked-response systems can be operated with much higher peak magnifications at frequencies of 1 to 5 hz than is possible with a broad-band system at any but the quietest sites.

B. Theoretical Considerations

Another approach to assessing the suitability of the frequency response of the USGS system is to estimate the record motion spectra of the seismograms that this system is expected to record from earthquakes of various magnitudes and a variety of background noise situations. These estimates can be obtained by combining the system's response curve with ground motion spectral amplitude curves for the events in question. The combination can be carried out conveniently by plotting log displacement spectral amplitude curves and log system response curves and then adding them graphically (Figure 3).

The earthquake ground motion displacement spectral amplitude curves are based on Brune's (1970) model as presented by Hanks and Thatcher (1972). They were drawn for earthquakes of magnitude 0 through 6 in accordance with the assumption that effective shear stress equals shear stress drop (i.e., $\varepsilon = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_f} = 1$).

Under this condition the ground motion displacement spectral amplitude Ω_0 is constant below a "corner frequency" f_0 and drops off as $1/f^2$ above f_0. The relationships between moment (Mo), magnitude (M_L), spectral amplitude (Ω_o), corner frequency (f_o), stress drop ($\Delta\sigma$), recording distance (R), density (ρ), and shear wave velocity (β) were taken from Thatcher and Hanks (1973), as follows:

$Mo = 4\pi\rho\beta^3\Omega_o R/0.85$ T & H (1) Keylis-Borok

$\Delta\sigma = 106\,\rho R\Omega_o f_o^3/0.85$ T & H (3) Brune

$\log Mo = 1.5 M_L + 16.0$ T & H (6) Figure 7

For southern California earthquakes with M = 3 to M = 6, the average stress drop is about 5 bars ($\overline{\Delta\sigma}$ = 5 bars) according to the data of T & H Figure 3. We also follow T & H in setting ρ = 2.7 gm/cc and β = 3.2 km/sec (= 5.7/1.78) and in evaluating Ωo at R = 100 km. From the foregoing we have:

$\log \Omega o_{100} = 1.5\ M_L - 9.1$

$\log fo = 1/3\ (\log \Delta\sigma + 5.6) - M_L/2.0 = 2.10 - M_L/2.0$; (for $\Delta\sigma$ = 5 bars)

M_L	$\log \Omega o_{100}$	log fo	fo
0.0	-9.10	2.10	126.0 hz
1.0	-7.60	1.60	40.0 hz
2.0	-6.10	1.10	13.0 hz
3.0	-4.60	0.60	4.0 hz
4.0	-3.10	0.10	1.3 hz
5.0	-1.60	-0.40	0.40 hz (2.5 sec)
6.0	-0.10	-0.90	0.13 hz (7.9 sec)

These results are the basis for the $\log \Omega o_{100}$ vs log f curves in Figure 3.

The quiet-site ground noise displacement spectral amplitude curve was adapted from Peterson and Orsini (1976). The curve for intermittent ground noise due to weather disturbances and cultural activities is an estimate for a noisy site.

The system response curve is rather stylized: it is the assymtote that the actual curve approaches at frequencies that are not too near the sharp bends in the curve, which are associated with filter corner frequencies and natural frequencies of the seismometer and recording galvanometer. The curve was drawn for an amplifier setting of -12 db and for records played back from magnetic tape and recorded on the Oscillomink.

The system response curve was combined appropriately with each of the ground motion curves to produce the set of record motion curves for earthquakes of magnitudes 0 through 6 (recorded at a distance of 100 km) and for the quiet-site and the noisy-site background noise. The record motion curves were discontinued where they fall below 1% (-40 db) of their respective maxima.

For $M \geq 6.2$ the record motion log spectral amplitude curve is invariant in shape for frequencies above 0.1 hz. Its peak is at 1.0 hz and it falls off at a rate of 6 db/octave toward higher (up to 30 hz) and lower (down to 0.1 hz) frequencies. The vertical separation of the curves (for $M \geq 6.2$) is 0.5 unit of $\log \Omega'_{o_{100}}$ for each unit of magnitude.

For $M \leq 1.2$ the record motion log spectral amplitude curves are invariant in shape for frequencies below 30 hz and have their peaks at 30 hz. The vertical separation of the curves is 1.5 units of $\log \Omega'_{o_{100}}$ for each unit of magnitude. The shape of the curves is that of the log magnification curve.

For magnitudes between 1.2 and 6.2 the shape of the curve depends on magnitude. The peaks of the curves move from 30 hz for M = 1.2 to 1.0 hz for M = 4.2 and then remain at 1.0 hz for larger M. The height of the peaks increases by 1.0 unit of $\log \Omega'_{o_{100}}$ for each unit of magnitude for magnitudes of 1.2 to 4.2; then by 0.5 unit of $\log \Omega'_{o_{100}}$ for each unit of magnitude for magnitudes of 4.2 to 6.2.

The record motion log spectral amplitude curve for quiet-site noise is quite flat between 0.1 hz and 30 hz. It has a gentle maximum near 1 hz and falls off toward both higher and lower frequencies. However, the record motion log spectral amplitude curve for the estimated weather and cultural noise at a moderately noisy-site peaks strongly at high frequencies.

Comparing the record spectrum for noise at a quiet site with the record spectra of earthquakes smaller than magnitude 4, which have pronounced peaks at frequencies above 1 hz, we see that signal-to-noise ratios for these quakes should increase with increasing frequency between the peak of the noise curve, about 1 hz, and the peaks of the earthquake curves. This effect is most pronounced for quakes smaller than magnitude 2.

For earthquakes larger than magnitude 4, signal to noise decreases slightly above 1 hz; but the signals are large enough that the signal-to-noise ratio is not our primary concern. Rather, the question is whether the high-frequency component of the recordings of the larger quakes, which brings considerable complication as well as information to the record, is sufficiently strong to saturate the recording systems and to block recovery (by use of high-cut filters on playback) of significant lower frequency information. Examination of the record motion spectral amplitude curves for quakes larger than magnitude 3 reveals that one of their most striking features is a 6 db/octave falloff with increasing frequency above the frequency of the maximum - about 4 hz for M3 and 1 hz for M 4. This feature appears to insure against the high-frequency swamping of records of the larger quakes. Signals from earthquakes with higher stress drops would be richer in high frequency energy because of a shift in corner frequency; but to double the corner frequency requires an 8-fold increase in stress drop. A magnitude 3 earthquake with a 40-bar stress drop would have a record spectrum peak of 8 hz instead of 4 hz.

If we consider noisy sites, as represented by the estimated weather and cultural noise curve, the situation is quite different. Record motion spectral amplitudes depicted by this curve rise steadily from a few hz to the system cutoff near 30 hz. In the presence of such noise there is little hope of detecting signals from the smaller earthquakes; and the signal-to-noise ratio for the larger quakes (M3 and larger) is greatest at frequencies below 5 hz. Thus, for sites that are subject to serious weather and cultural noise (specifically wind and vehicular traffic near a site on soft rock), the response of the system would be improved by moving the high-frequency cutoff down to a lower frequency. Considering the elements that determine the overall system response, the easiest and most effective means of accomplishing this end is to lower the cutoff frequency of the discriminator output filter, which has a very steep cutoff slope. At a very noisy site it may even be desirable to alter the frequency characteristics of the amplifier in the field to avoid the possibility of saturating the amplifier and data transmission and recording system with noise and losing the possibility of recovering lower frequency earthquake signals by high-cut filtering in the discriminator.

For work with teleseisms, it would be desirable to play them back from tape through standard high-cut filters designed to produce an optimum response for this purpose. If small teleseism signals must be recorded at noisy sites, it may also be necessary to modify the response of the amplifier in the field to flatten its frequency characteristic and to decrease the high cut filter cutoff frequency from 30 hz to a lower value. Such a change will reduce the ability of the system to detect small nearby earthquakes, however.

III. SPECTRAL CHARACTERISTICS OF RECORDS OF SOME ILLUSTRATIVE EARTHQUAKES

To illustrate the characteristics of records of local earthquakes obtained by the USGS system, records of several recent central California earthquakes at selected stations were played out through a set of band-pass filters onto the Oscillomink (Figs. 4-9). A single data channel (from one discriminator output) was fed simultaneously into 8 adjustable band-pass filters whose outputs were recorded on the Oscillomink. Each data trace is labeled to show the Oscillomink sensitivity (g) and the filter pass band (f). The filter attenuation slopes are 24 db/octave. The Oscillomink sensitivity is 100 x g (mv/mm). Most commonly the filter settings were (top trace to bottom trace): (1) filter out, (2) 30 hz - 60 hz, (3) 20 hz - 40 hz, (4) 10 hz - 20 hz, (5) 5 hz - 10 hz, (6) 2.5 hz - 5 hz, (7) 1.0 hz - 2.5 hz, (8) D.C. - 1.0 hz. Departures from this convention are evident from the labels.

Most of the central California stations have only a high-gain vertical component instrument (labeled AAAV) operating with an attenuator setting of -6 db to -24 db. Several stations, however, have a matched 3-component set of instruments (labeled BBBZ, BBBN, and BBBE) operating with attenuator settings of -42 db in addition to the normal high-gain vertical (BBBV). Except for gain, the characteristics of the low-gain instruments are identical to those of the high-gain instrument.

Figure 4(a-f) shows the band-pass playbacks from the low-gain 3-component instruments at stations HQR and BSR for a magnitude 2.8

earthquake near Bear Valley. The P-Picker location of this earthquake (11 km deep, 4 km N 6° E of BVL) is in the San Andreas rift zone 26 km S of station HQR and 32 km E of station BSR. By comparing Figures 4a and 4d, we see that the signals recorded on the Z components of these two stations are quite similar. BSR is relatively stronger in the 20 hz - 40 hz band (about x 3), and HQR is relatively stronger in the 1 hz - 2.5 hz band (about x 2).

Figure 5 (a-f) shows the band-pass playbacks for the same stations (HQR and BSR) for a magnitude 3.0 earthquake near station BLR. The P-Picker location of this earthquake (3 km deep, 5 km W 21° S of BLR) is in the Gabilan block west of Bear Valley about 22 km S of station HQR and 18 km E of station BSR. By comparing Figures 5a and 5d we see that the signals recorded on the Z components of these two stations are strikingly different. (Note that trace 2 on Figure 5 is a DC to 10 hz band-pass rather than a 30 hz-60 hz bandpass as on Figure 4). The BSR record is much stronger at high frequencies and much weaker at low frequencies than the HQR record. The approximate ratio BSR/HQR in the various bandpass windows is: 20 hz-40 hz, 10/1; 10 hz-20 hz, 4/1; 5 hz-10 hz, 3/2; 2.5 hz-5 hz, 1/3; 1 hz-2.5 hz, 1/4; 0-1 hz, 1/4.

The Z-component record spectral peaks for the first quake (Fig. 4) are near 5 hz at both HQR and BSR; for the second quake (Fig. 5), the peak appears to be near 10 hz at BSR and near 3 hz at HQR.

Figure 6 shows the band-pass playout of a magnitude 1.5 quake recorded on station NHM. The focus was 10 km west of NHM at a depth of 17 km. The recording path to NHM traversed a very thick section of Tertiary sediments. The record spectral peak appears to be a little above 10 hz, and the signal level in the 20 hz to 40 hz band is larger than that in the 2.5 hz to 5 hz band.

Figure 7 shows band-pass playouts at 3 stations, with epicentral distances of 85 km to 112 km, of a magnitude 2.6 earthquake from the deep source of quakes 10 km W of station NHM. The record spectral peak appears to be near 5 hz at all 3 stations (JSF, 85 km; NWR, 91 km; AGI, 112 km). There is appreciable energy in the 20 hz to 40 hz band, particularly at AGI, which lies in the Sierra Nevada Mountains across the Sacramento Valley from the epicenter. Station NWR (Fig. 7c) was included to illustrate how high-frequency cultural noise (footsteps?) can be eliminated by filtering during playback.

Figure 8 shows a band-pass playout of a magnitude 3.6 earthquake from the deep source 10 km west of station NHM recorded on JSFZ (the low-gain vertical at station JSF. This record should be compared with Figure 7a (JSFV) for a magnitude 2.6 quake from the same source. These two records are quite similar, the higher gain of JSFV (-24 db atten) compared to JSFZ (-42 db atten) offsetting the 1 unit difference in magnitude of the two quakes. Both records have their peaks near 5 hz, but the M 2.6 quake has a more complex (i.e., persistent) record than the M 3.6 quake. It also has a relatively higher level signal in the 1.0 hz to 2.5 hz band than the larger quake.

The foregoing comparison suggests that both quakes had the same source dimension, and that the larger one had a larger stress drop (by a factor of 10 for a 1-unit increase in magnitude with no shift in center frequency).

Figure 9 explores how the "character" of a seismogram depends on its frequency content. Figure 9a is a band-pass playout of the record from CAOZ of a magnitude 2.3 quake that occurred 6 km NE of that station. The record spectral peak is near 8 hz, and the signal is strong in the 20 hz-40 hz band. (Note the spectral shift between the P and S waves). In Figure 9b the same record is played out through a bank of high-cut filters (Open, 32 hz, 20 hz, ..., 5 hz). The change in character (which is a deterioration of the record, to my eye) is progressive with decreasing cutoff frequency. Cutoff frequencies below 15 hz produce a record of significantly diminished amplitude and sharpness. On the other hand, the record in Figure 9c is subjected to the same set of high-cut filters. This record is of the same earthquake but from station BSC, which lies 87 km from the epicenter. The path also crosses the San Andreas rift zone very obliquely near the station. The higher frequencies that were so plain at CAO have been strongly attenuated along the propagation path; and the character of the record does not depend strongly on the cutoff frequency. The 5 hz high-cut filter does have a clear effect, however.

IV. CONCLUDING REMARKS

Brune's model of the earthquake source, with $\mathcal{E}$ set equal to 1 and $\Delta \sigma$ = 5 bars, combined with the magnitude vs moment relationship of Thatcher and Hanks, predicts that the spectral corner frequencies of earthquakes in the range M 4.2 to M 1.2 will lie in the range 1 hz to 30 hz, which is the frequency range over which the USGS seismic system has a slope of +6 db/octave. By combining the theoretical ground motion spectral amplitude curves with the USGS system response curves, we found that the record motion spectral amplitude curves for earthquakes of M 4.2 to M 1.2 have their peaks in the frequency range 1.0 hz to 30 hz, i.e., in the "full response" pass band of the system. Neglecting effects of attenuation along the propagation paths, we therefore should expect the largest record amplitudes to be associated with frequencies near the corner frequencies for earthquakes in the M 1.2 to M 4.2 range. For earthquakes smaller than M 1.2, the peak record amplitudes will be associated with the system high-frequency cut-off frequency (about 30 hz) and/or the transmission path high-frequency cutoff limit. Ground amplitudes computed from the observed peak record amplitudes, making use of the system response curves, will relate to periods that lie at or below the source corner frequencies for earthquakes smaller than M 4.2; i.e., on the "flat" portion of the ground motion spectral curves.

For earthquakes larger than M 4.2, the peak record amplitudes are associated with the 1 hz "corner" on the system response curve that is related to the 1 hz natural frequency of the seismometer. Ground amplitudes computed from such peak record amplitudes, making use of the system response curves, are associated with portions of the source spectral amplitude curve that drops off as $1/f^2$.

From Figure 3 and the foregoing discussion we should expect that ground motion amplitudes computed from peak record amplitudes will increase 1.5 units of $\log \Omega o_{100}$ for each unit of magnitude below M 4.2 but only 0.5 units of $\log \Omega o_{100}$ for each unit of magnitude above M 4.2. This effect should not be overlooked in the calculation and interpretation of magnitudes.

The primary reasons for considering reducing the high frequency response of the USGS system appear to be:

1) to reduce the masking effect of high-frequency noise of local origin on the records of M 3^+ earthquakes occurring at some distance from the station, and

2) to avoid recording frequencies that are too high for available digital recording and/or analysis systems.

The most direct means of accomplishing such a reduction in high-frequency response is to modify the discriminator output filters. Only for the most noisy sites (Imperial Valley?) should it be necessary (or desirable) to modify the response of the field unit.

Because of the limited dynamic range of the USGS system (46 db$\pm$), it is very desirable to have a skeletal network of "low gain", preferably 3-component, seismic systems that are co-located with normal high-gain systems. Choice of gain settings for the low-gain systems depends on the magnitude of a nearby event (ca. 10 km, say) for which clipping should not occur. The -42 db setting results in unclipped records of M 3 quakes at epicentral distances greater than about 20 km.

Examination of band-pass playout of earthquakes in the M 1.5 to M 3.5 range recorded at distances of 10 to 100+ km shows that very significant energy levels are present in the 20 hz to 40 hz band. The possibility of using such information to study the properties of earthquake sources, propagation paths, etc. is of course eliminated if the high frequency response of the system is substantially reduced to accommodate noisy stations or inadequate recording systems.

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FIGURE CAPTIONS

Fig.1. Block diagram of the USGS telemetered short-period seismic system.

Fig. 2. Relative response of individual components and combinations of components of the USGS telemetered short-period seismic system.

Fig. 3. Ground motion spectral amplitudes and record motion spectral amplitudes plotted versus frequency for earthquakes of M 0 to M 6 and for quiet-site and noisy-site background conditions.

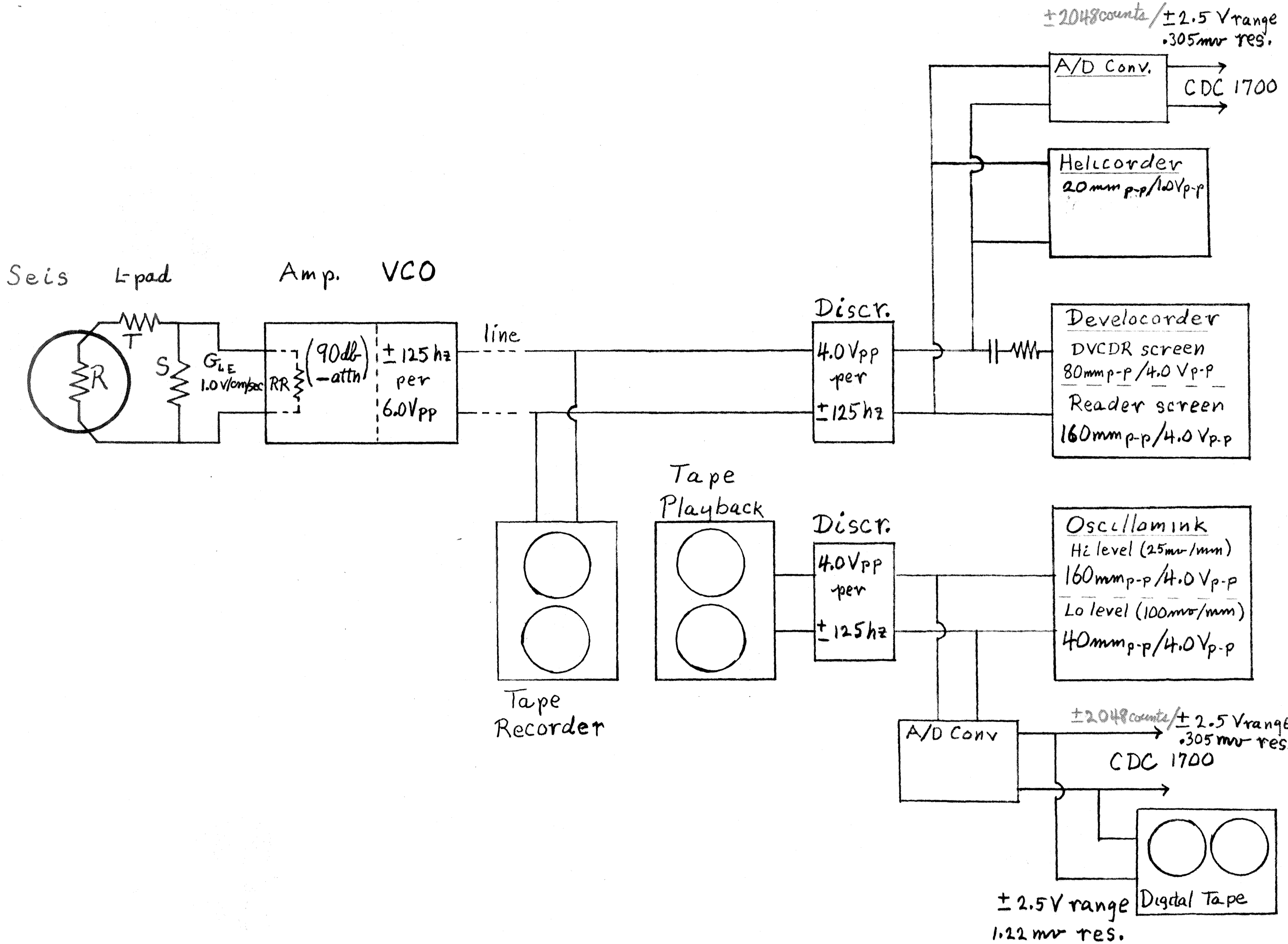
Fig. 4. Multiple bandpass playbacks from the low-gain 3-component seismic instruments at stations HQR and BSR of the M 2.8 earthquake near station BVL at 10:00 Z on May 30, 1977.

Fig. 5. Multiple bandpass playbacks from the low-gain 3-component seismic instruments at stations HQR and BSR of the M 3.0 earthquake near BLR at 0627 Z on May 28, 1977.

Fig. 6. Multiple bandpass playback from the high-gain instrument at stations NHM of the deep M 1.5 earthquake near NHM at 2130 Z on June 4, 1977.

Fig. 7. Multiple bandpass playbacks from the high-gain instruments at stations JSF, AGI, and NWR of the deep M 2.6 earthquake near NHM at 2107 Z on June 4, 1977.

Fig. 8. Multiple bandpass playback from the high-gain instrument at station CAO and multiple high-cut playbacks from the low-gain CAO vertical and the high-gain BSC vertical of the M 2.3 earthquake near CAO at 1521 Z on June 13, 1977.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A/D Conv.
CDC 1700
Helicorder
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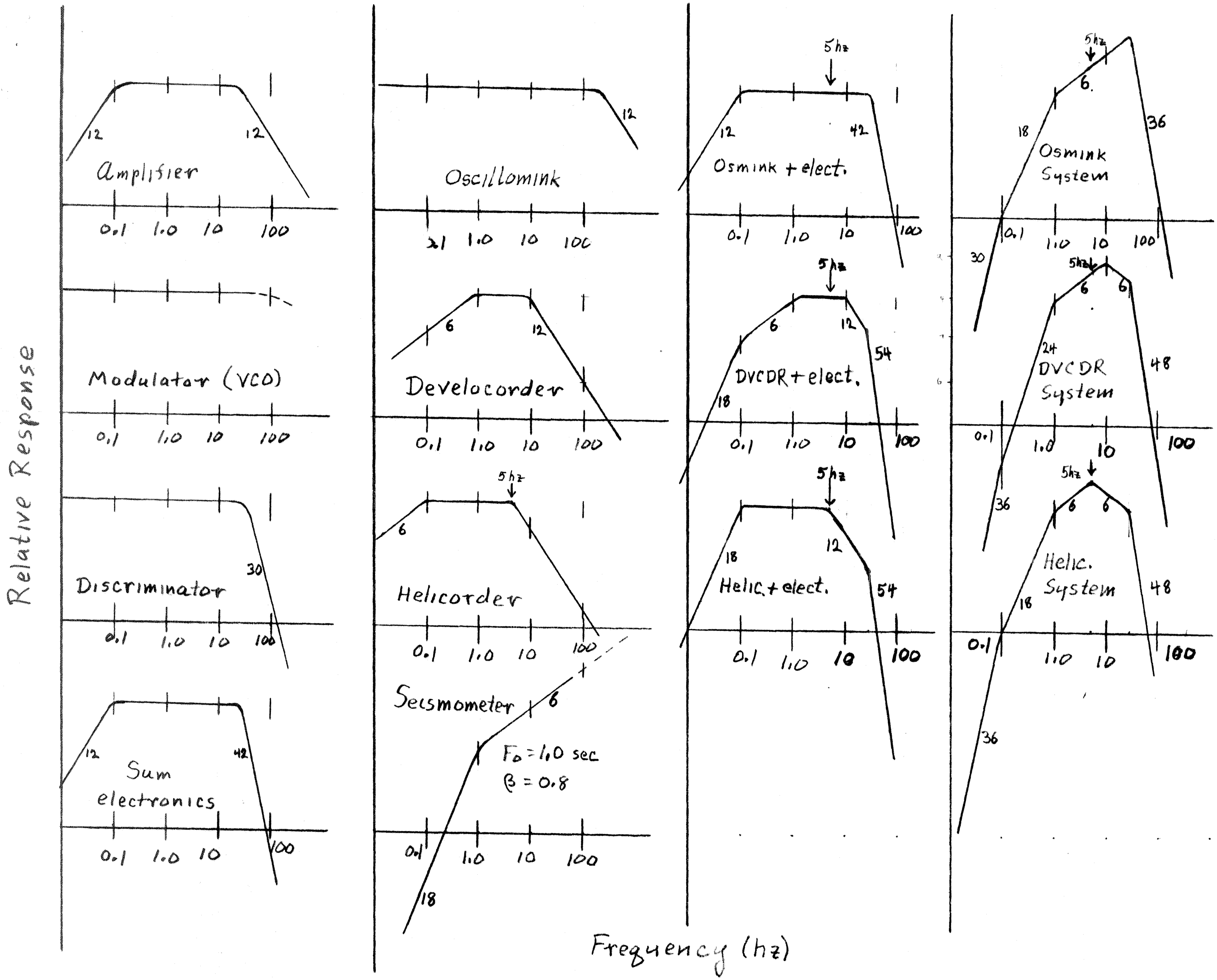
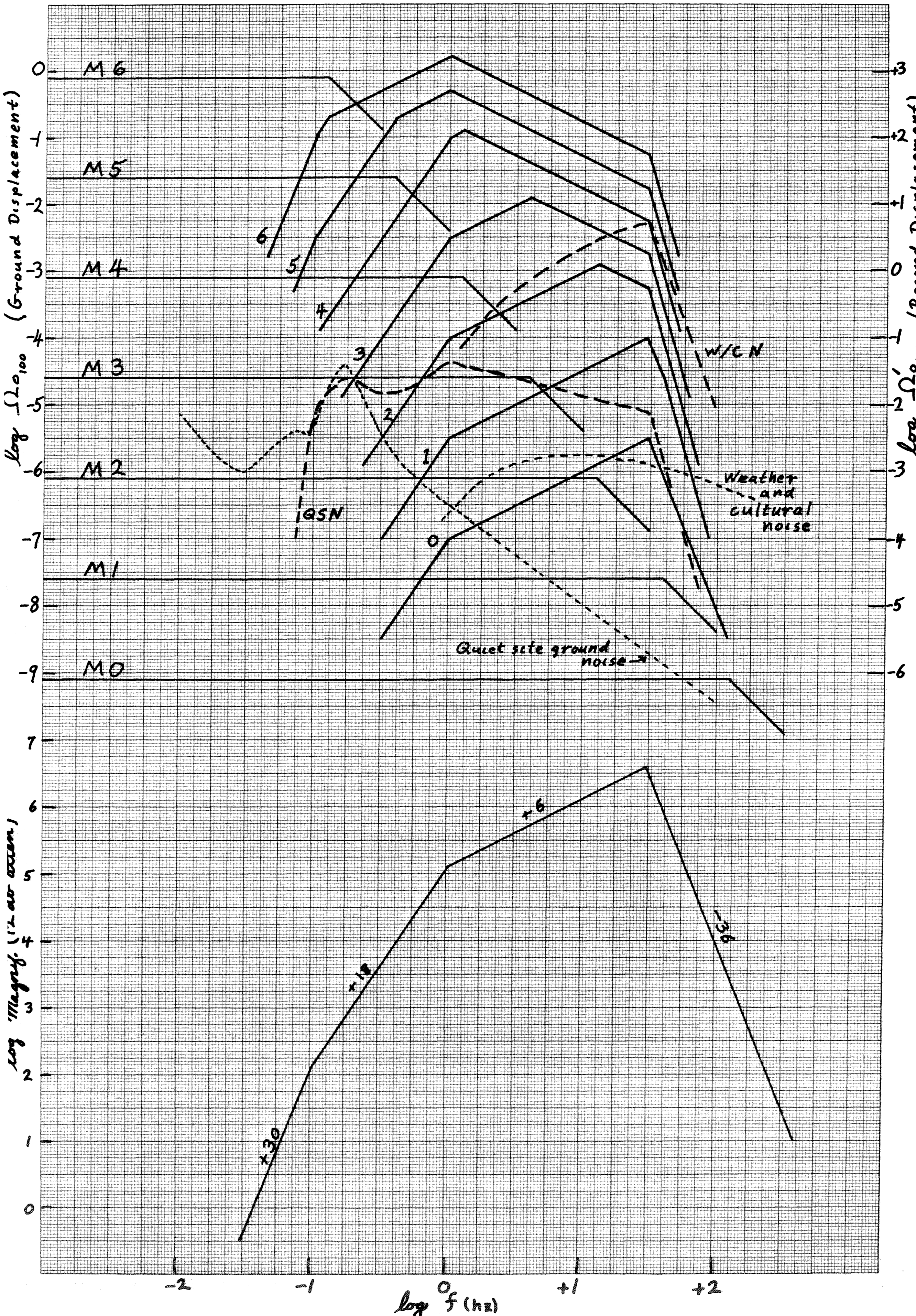
Seis
L-pad
T
R
S
G_{LE}
1.0 V/cm/sec
RR
Amp.
(90 db -attn)
VCO
±125 hz per 6.0 Vpp
line
Discr.
4.0 Vpp per ±125 hz
Develocorder
DVCDR screen
80 mm p-p/4.0 V p-p
Reader screen
160 mm p-p/4.0 V p-p
Tape Playback
Tape Recorder
Discr.
4.0 Vpp per ±125 hz
Oscillomink
Hi level (25 mv/mm)
160 mm p-p/4.0 V p-p
Lo level (100 mv/mm)
40 mm p-p/4.0 V p-p
A/D Conv
±2048 counts/±2.5 V range .305 mv res.
CDC 1700
Digital Tape
±2.5 V range
1.22 mv res.

Fig 1



Relative Response
Frequency (hz)
Amplifier
Modulator (VCO)
Discriminator
Sum electronics
Oscillomink
Develocorder
Helicorder
Seismometer
Fo = 1.0 sec
β = 0.8
Osmink + elect.
DVCDR + elect.
Helic. + elect.
Osmink System
DVCDR System
Helic. System
5hz
0.1
1.0
10
100
12
42
30
6
18
24
36
48
54

Fig 2


M6
M5
M4
M3
M2
M1
M0
6
5
4
3
2
1
0
QSN
W/CN
Weather and cultural noise
Quiet site ground noise
log Ω₀₁₀₀ (Ground Displacement)
log Ω'₀₁₀₀ (Record Displacement)
log Magnif. (1 No atten)
log f (hz)
×30
×18
×6
-36
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
+3
+2
+1
0
-1
-2
-3
-4
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7
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-2
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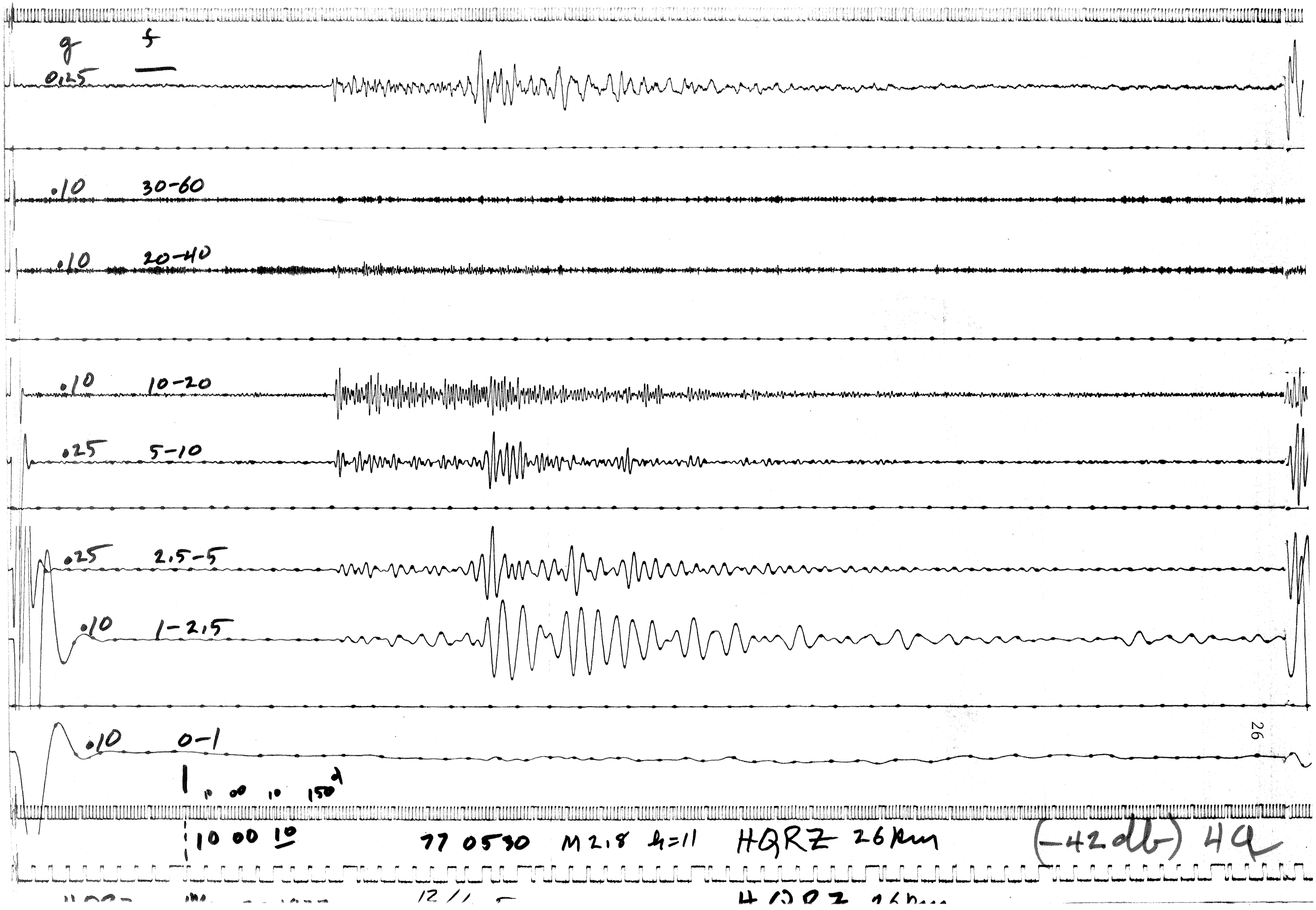
0
+1
+2

Fig 3


g
f
0.125
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30-60
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20-40
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10-20
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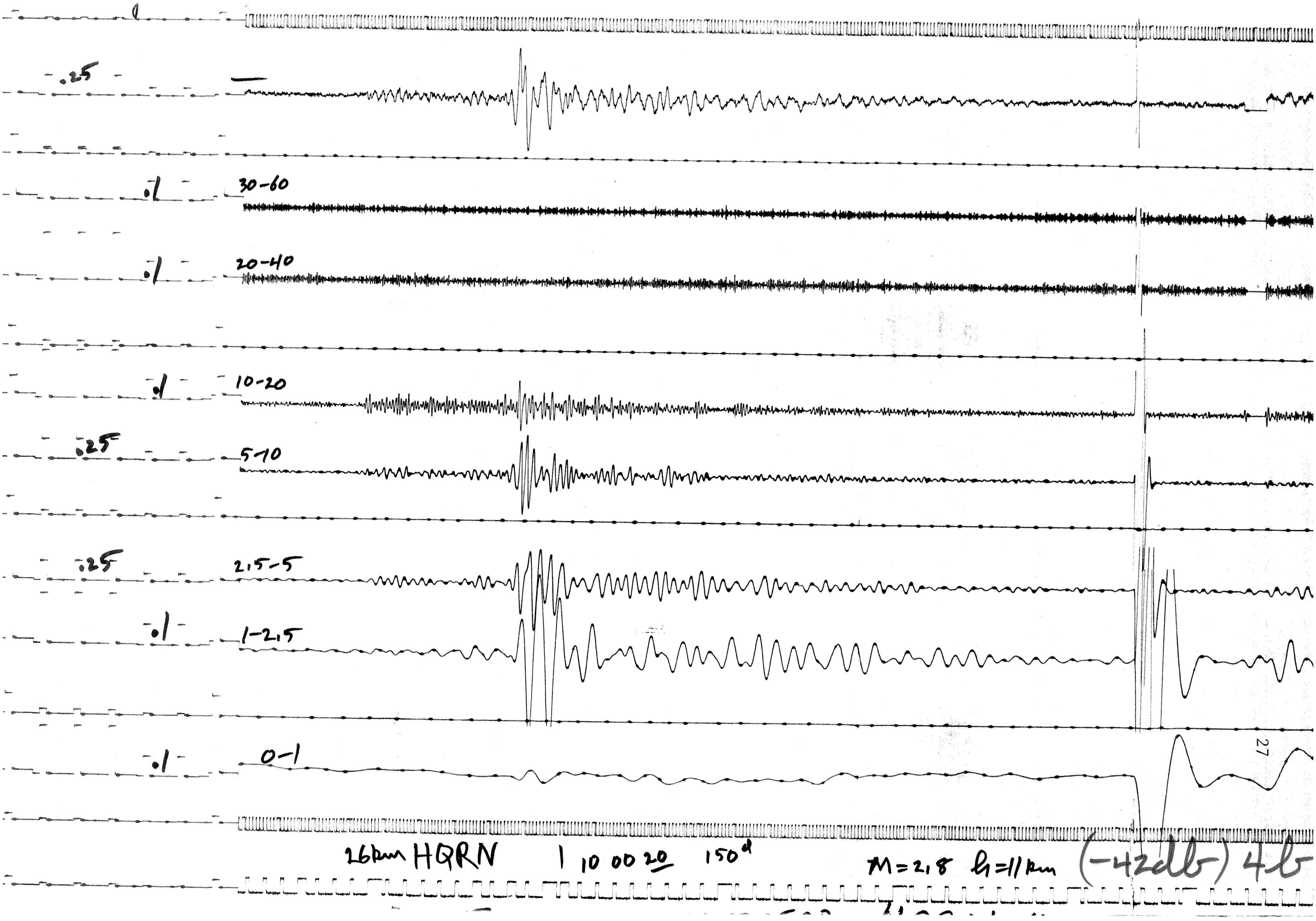
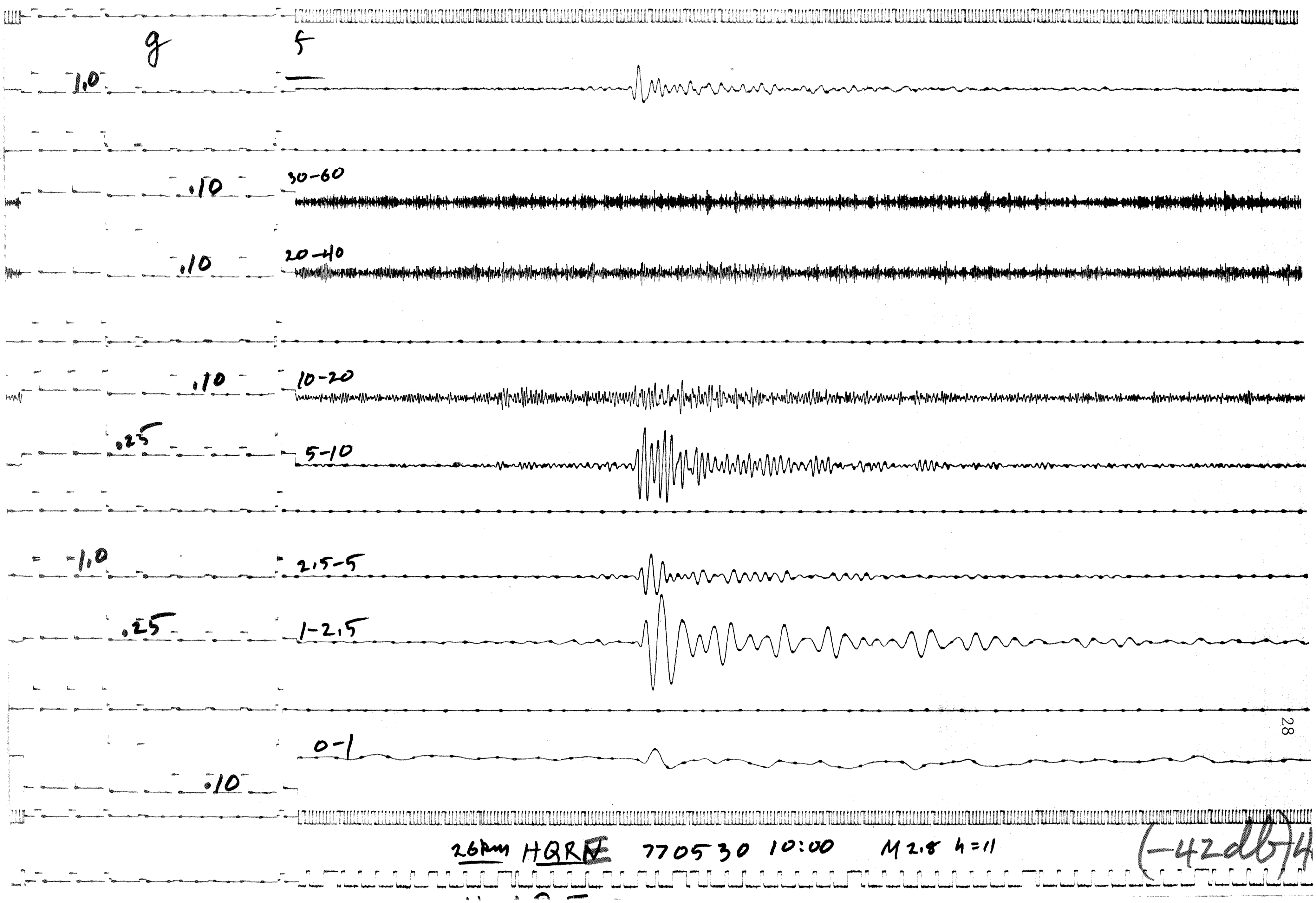
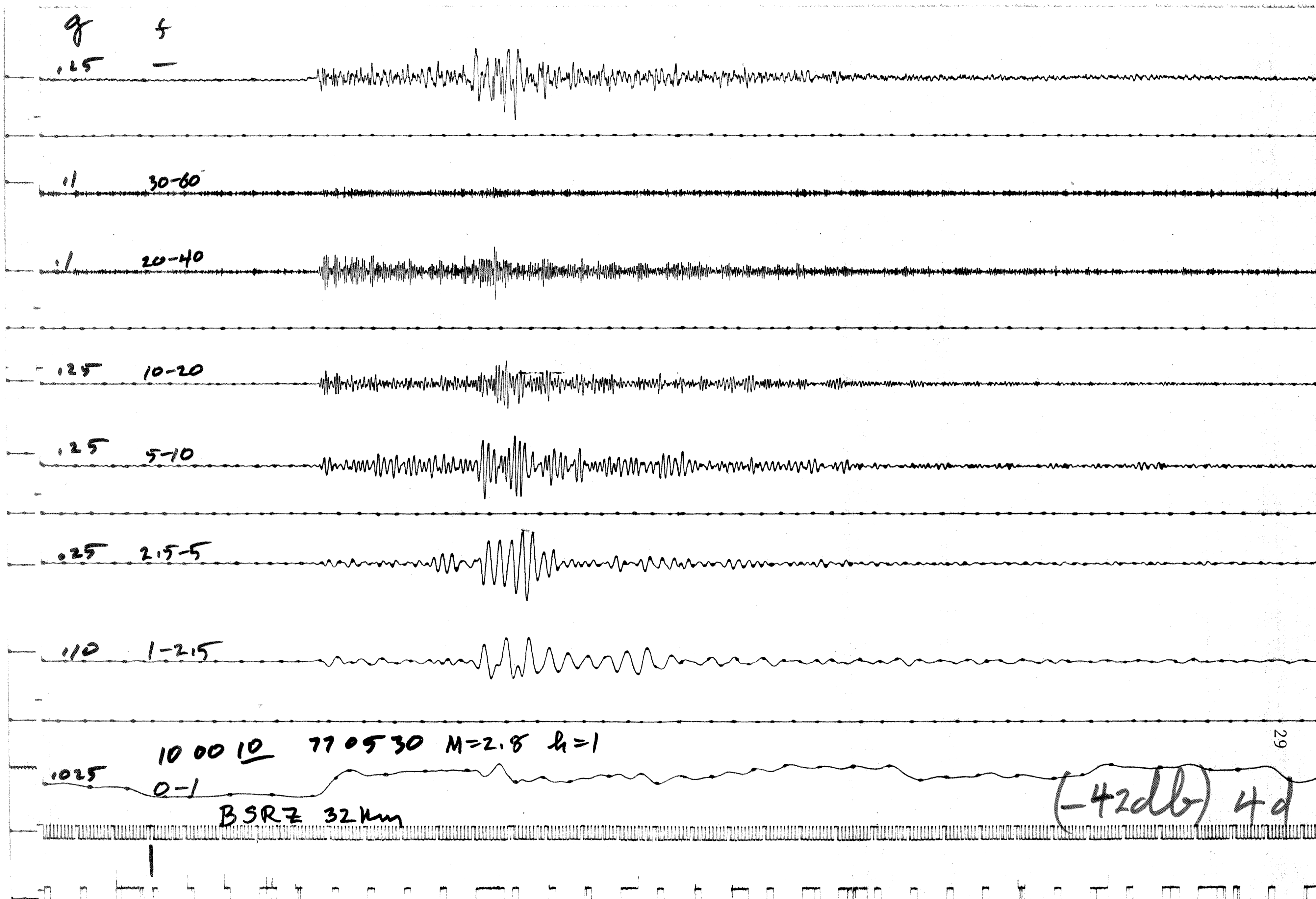
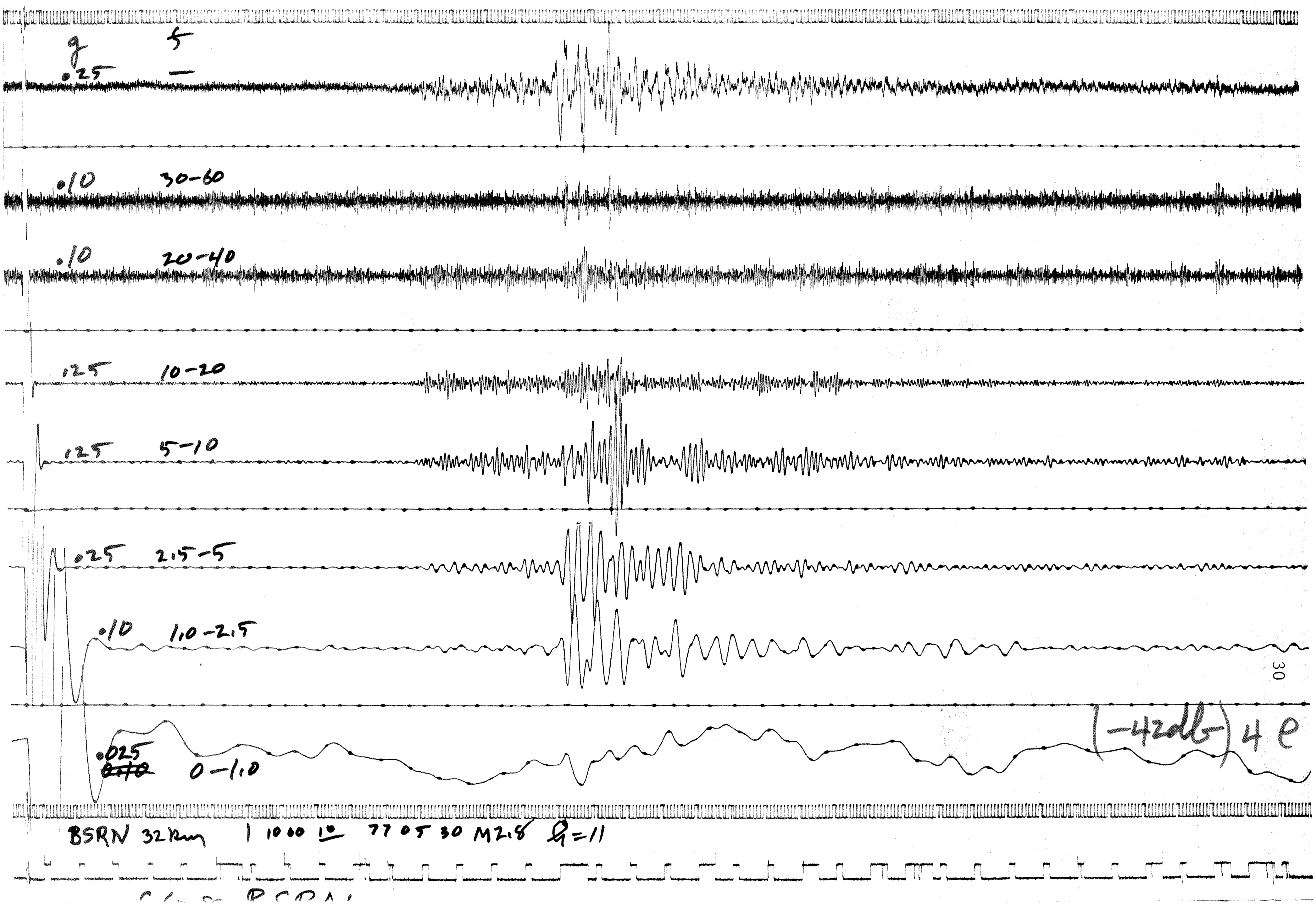
5-10
.025
2.5-5
.10
1-2.5
.10
0-1
10 00 10
77 0530 M2.8 h=11 HQRZ 26km
(-42db) 4a

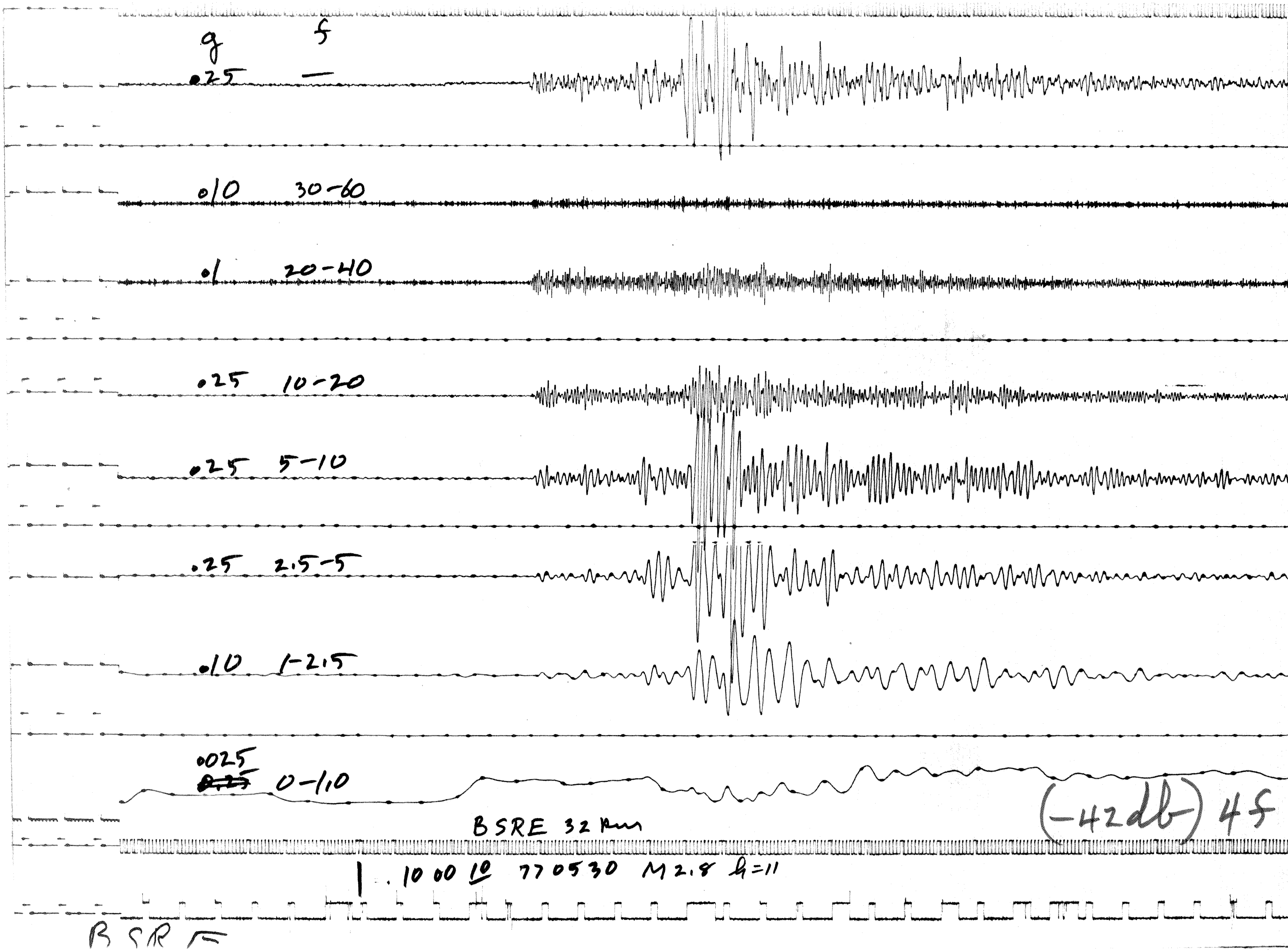

.25
.1
30-60
.1
20-40
.1
10-20
.25
5-10
.25
2.5-5
.1
1-2.5
.1
0-1
27
26km HQRN 1 10 00 20 150d
M=2.8 h=11km (-42db) 4b

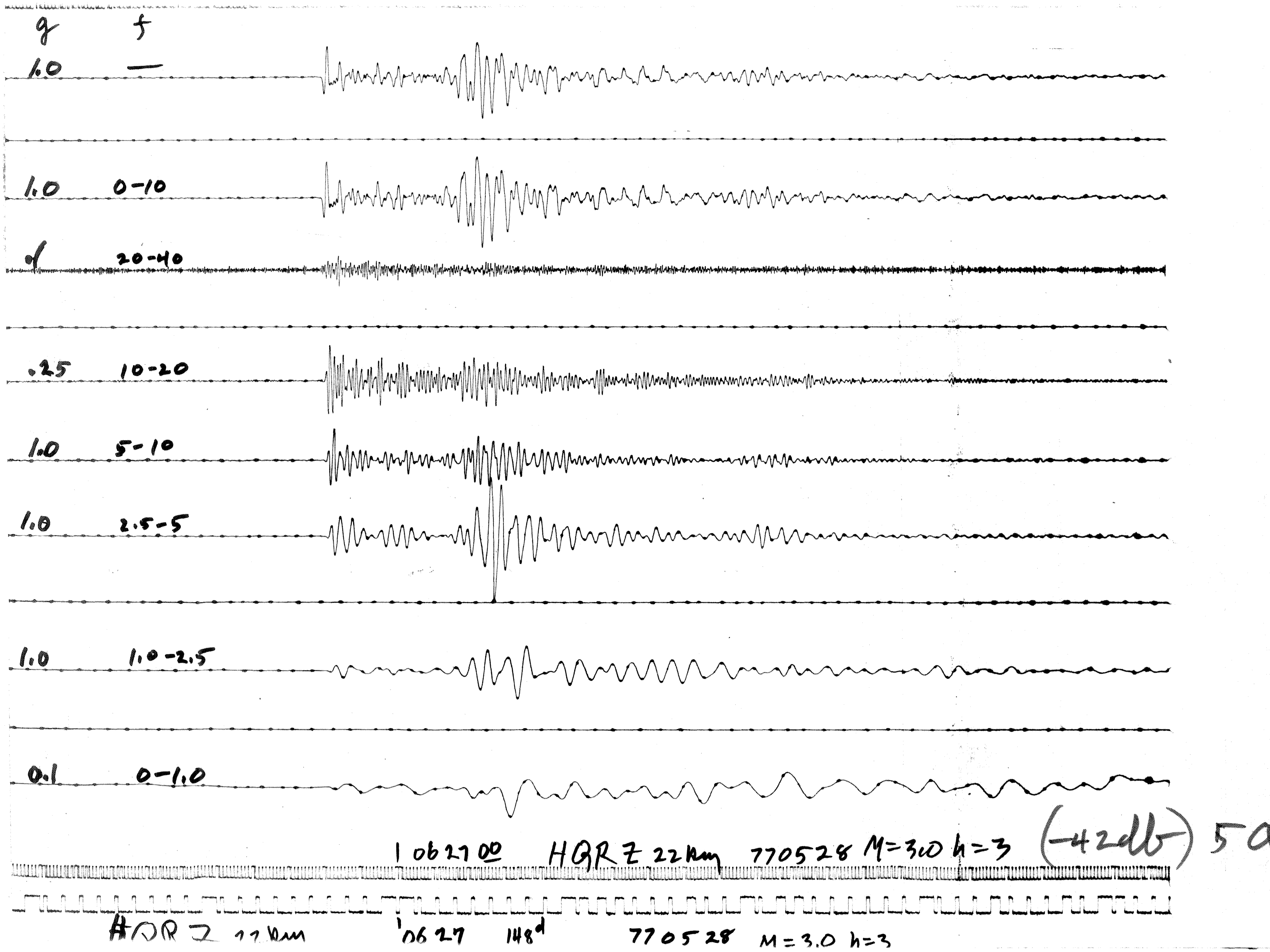

g
5
1.0
.10
30-60
.10
20-40
.10
10-20
.25
5-10
1.0
2.5-5
.25
1-2.5
0-1
.10
26Am HQRN 770530 10:00 M2.8 h=11
(-42db)4

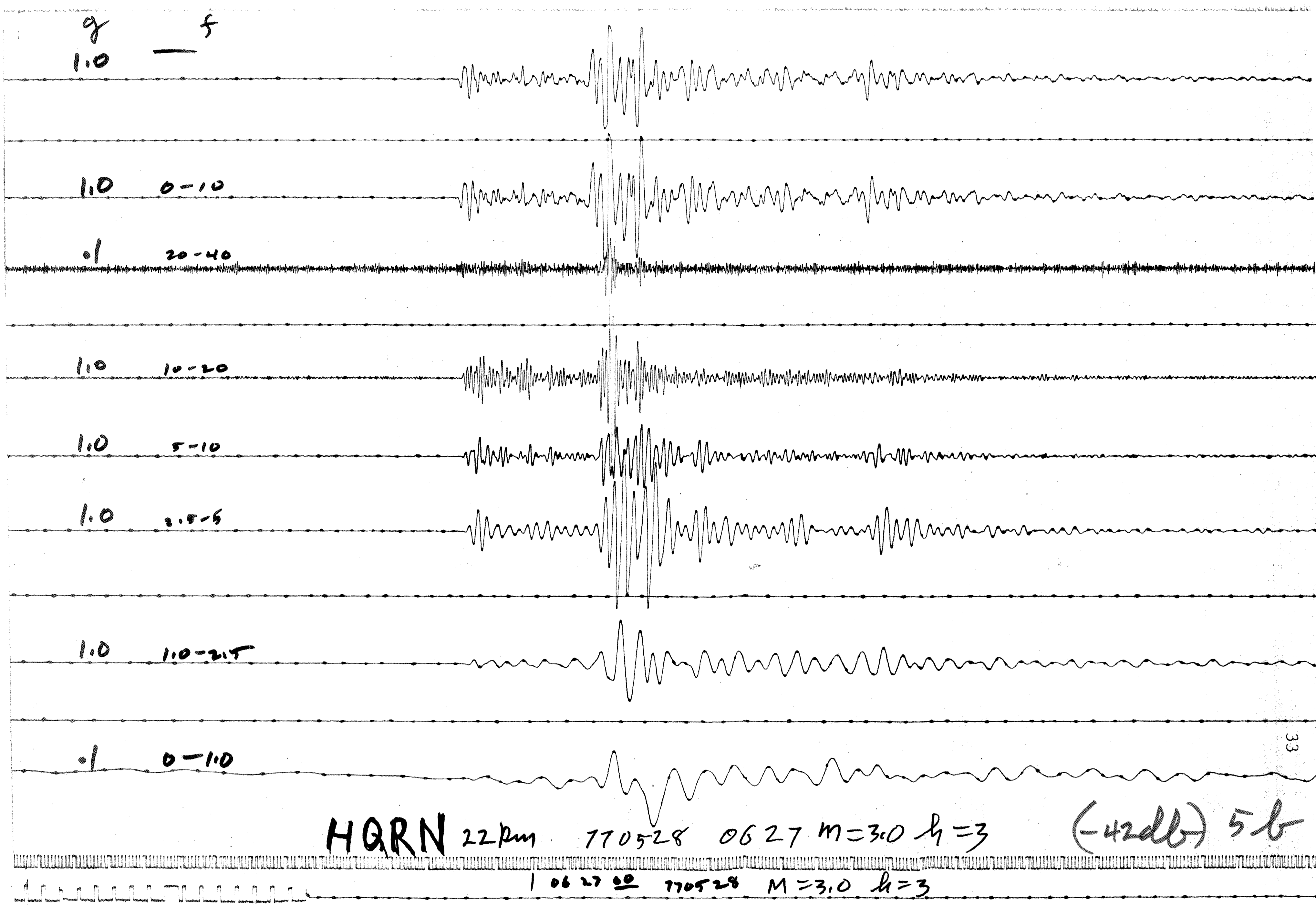

g f
.25 —
.1 30-60
.1 20-40
.125 10-20
.125 5-10
.25 2.5-5
.10 1-2.5
10 00 10 77 05 30 M=2.8 h=1
.025 0-1
BSRZ 32 km
(-42db) 4d

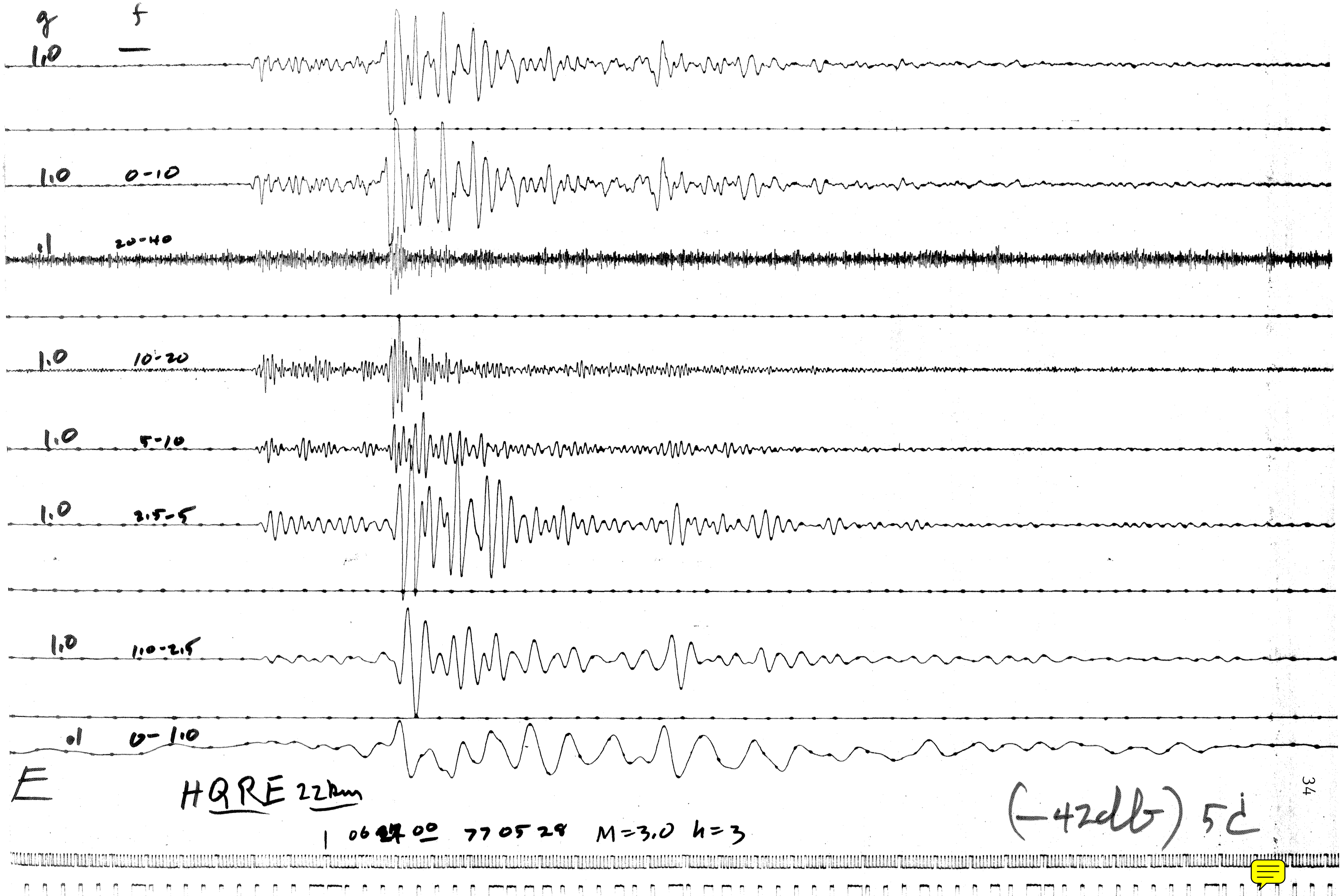
BSRZ 01-3


g 5
.025
.10 30-60
.10 20-40
.125 10-20
.125 5-10
.025 2.5-5
.10 1.0-2.5
.025 0-1.0
(-42db) 4 e
BSRN 32km 1 1000 1° 77 05 30 M2.8 Q=11
BSRN

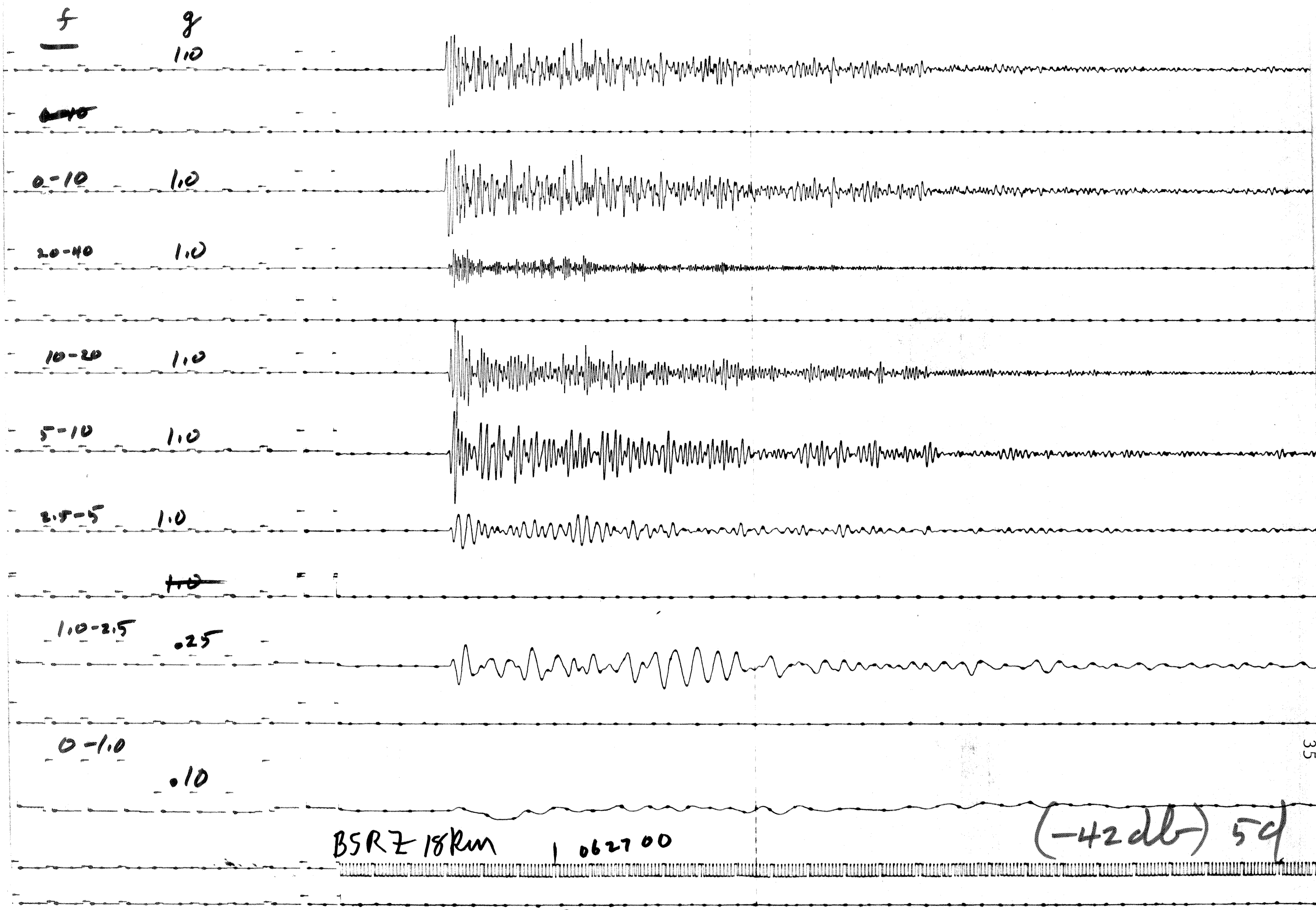

g
f
.25
.010 30-60
.1 20-40
.25 10-20
.25 5-10
.25 2.5-5
.010 1-2.5
.0025
0-1.0
BSRE 32 km
(-42db) 4f
1 . 10 00 10 770530 M2.8 h=11
BSRE


g f
1.0 —
1.0 0-10
20-40
.25 10-20
1.0 5-10
1.0 2.5-5
1.0 1.0-2.5
0.1 0-1.0
1 062700 HQRZ 22km 770528 M=3.0 h=3 (-42db) 5a
0627 148d 770528 M=3.0 h=3

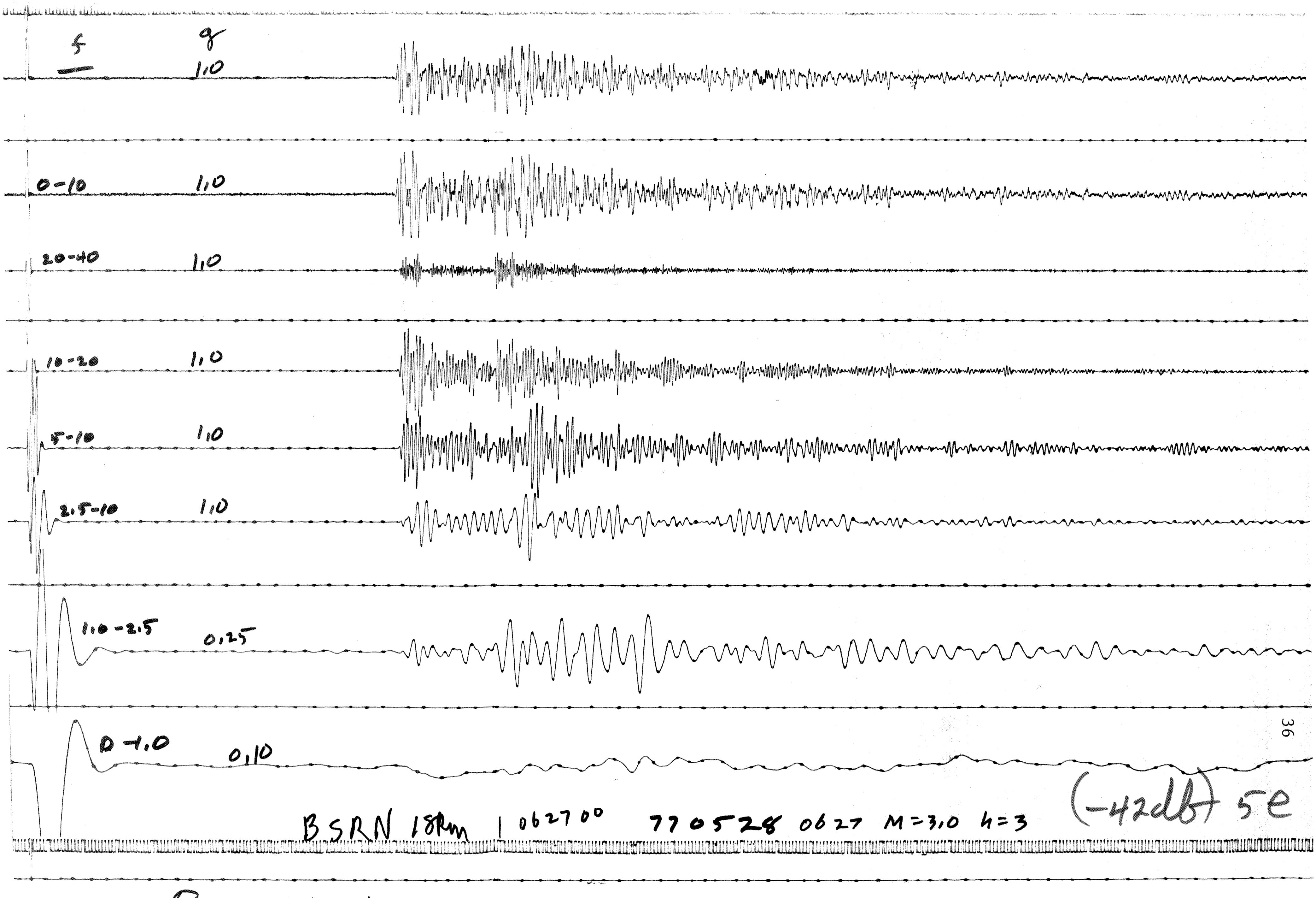

g f
1.0
1.0 0-10
.1 20-40
1.0 10-20
1.0 5-10
1.0 2.5-5
1.0 1.0-2.5
.1 0-1.0
HQRN 22km 770528 0627 M=3.0 h=3 (-42db) 5b
1 06 27 00 770528 M=3.0 h=3

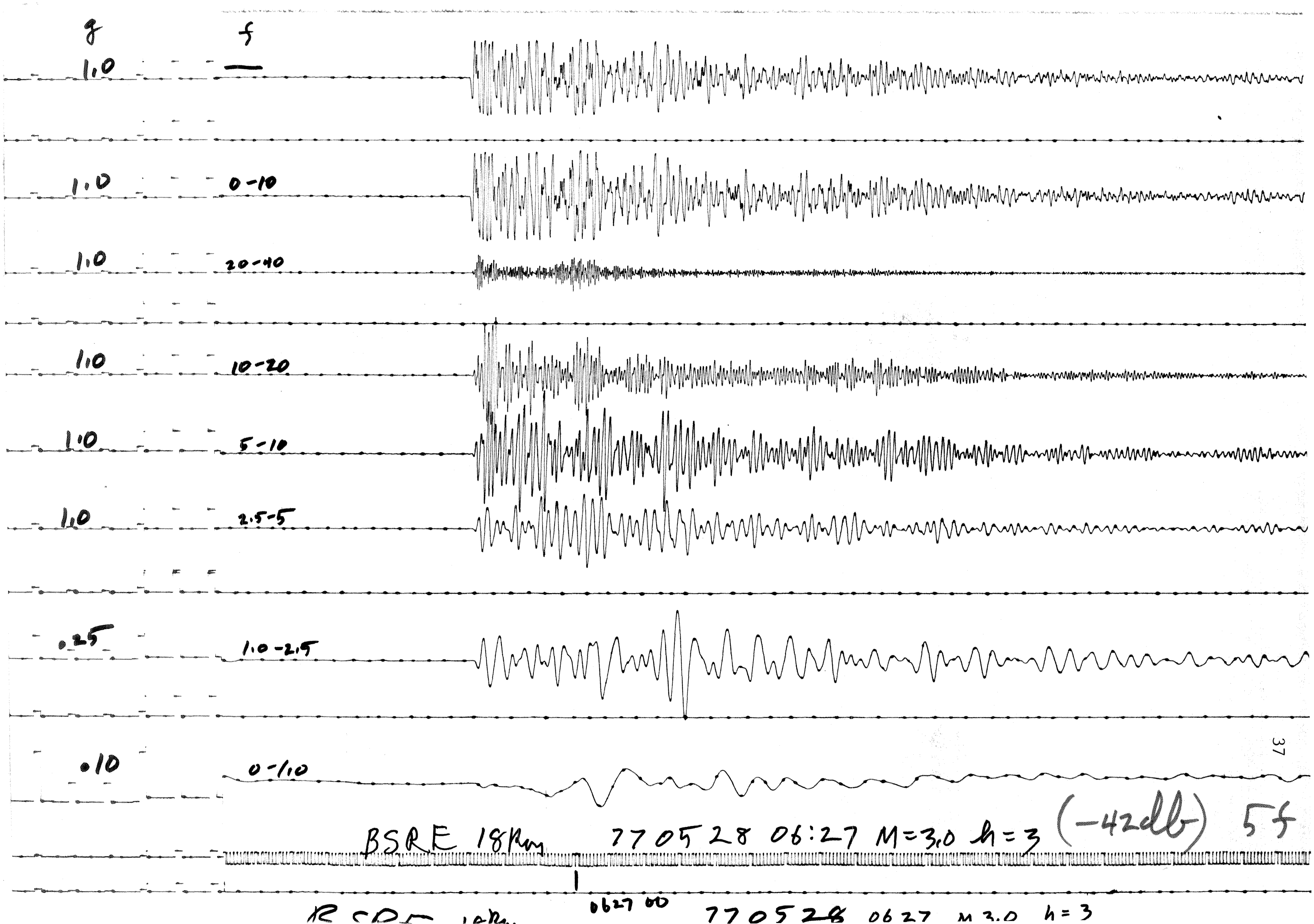


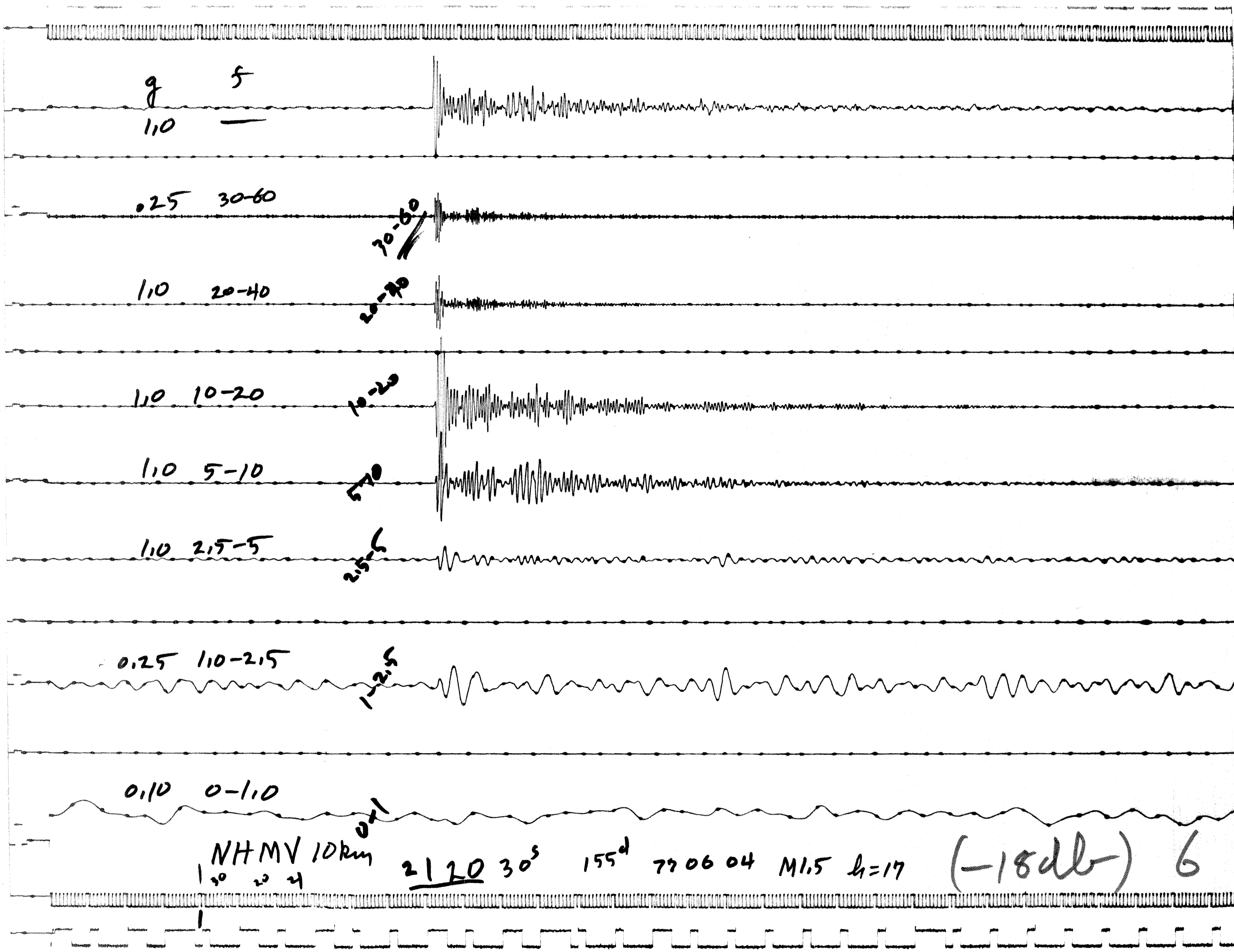
g
f
1.0
1.0
0-10
.1
20-40
1.0
10-20
1.0
5-10
1.0
2.5-5
1.0
1.0-2.5
.1
0-1.0
E
HQRE 22km
770528 M=3.0 h=3
(-42db) 5c

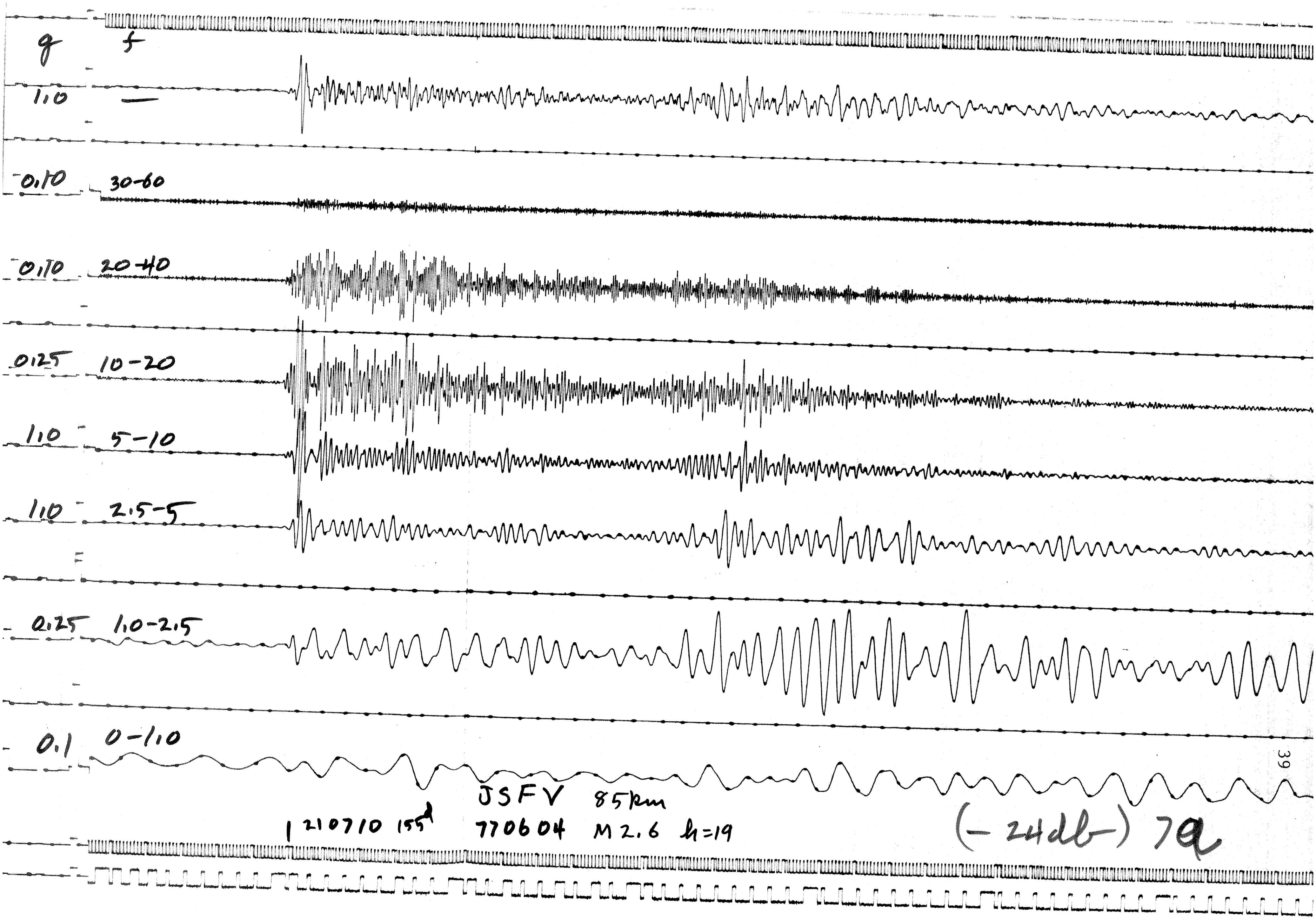


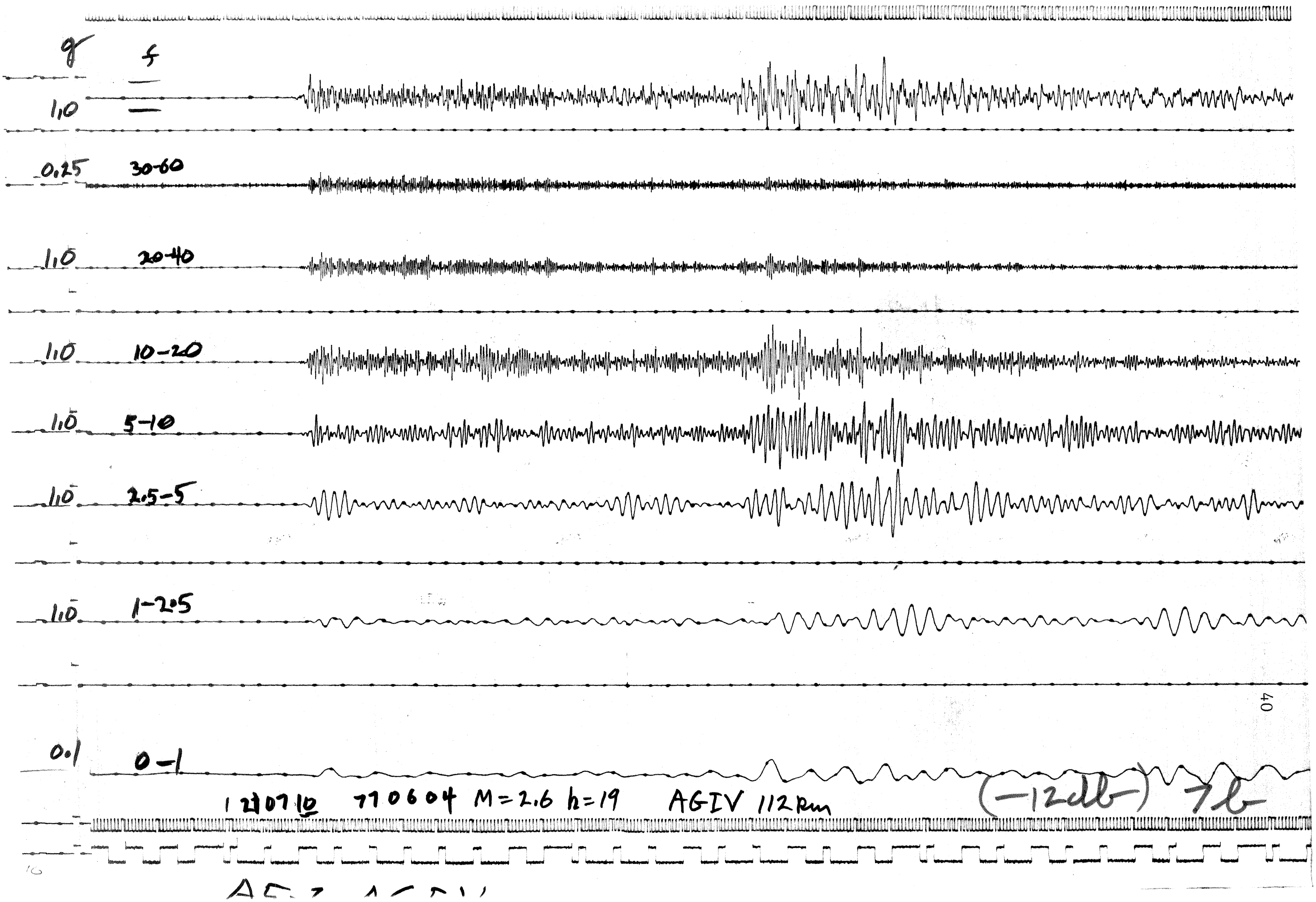
18km BSRZ 770528 06:27 M 3.0 h=3

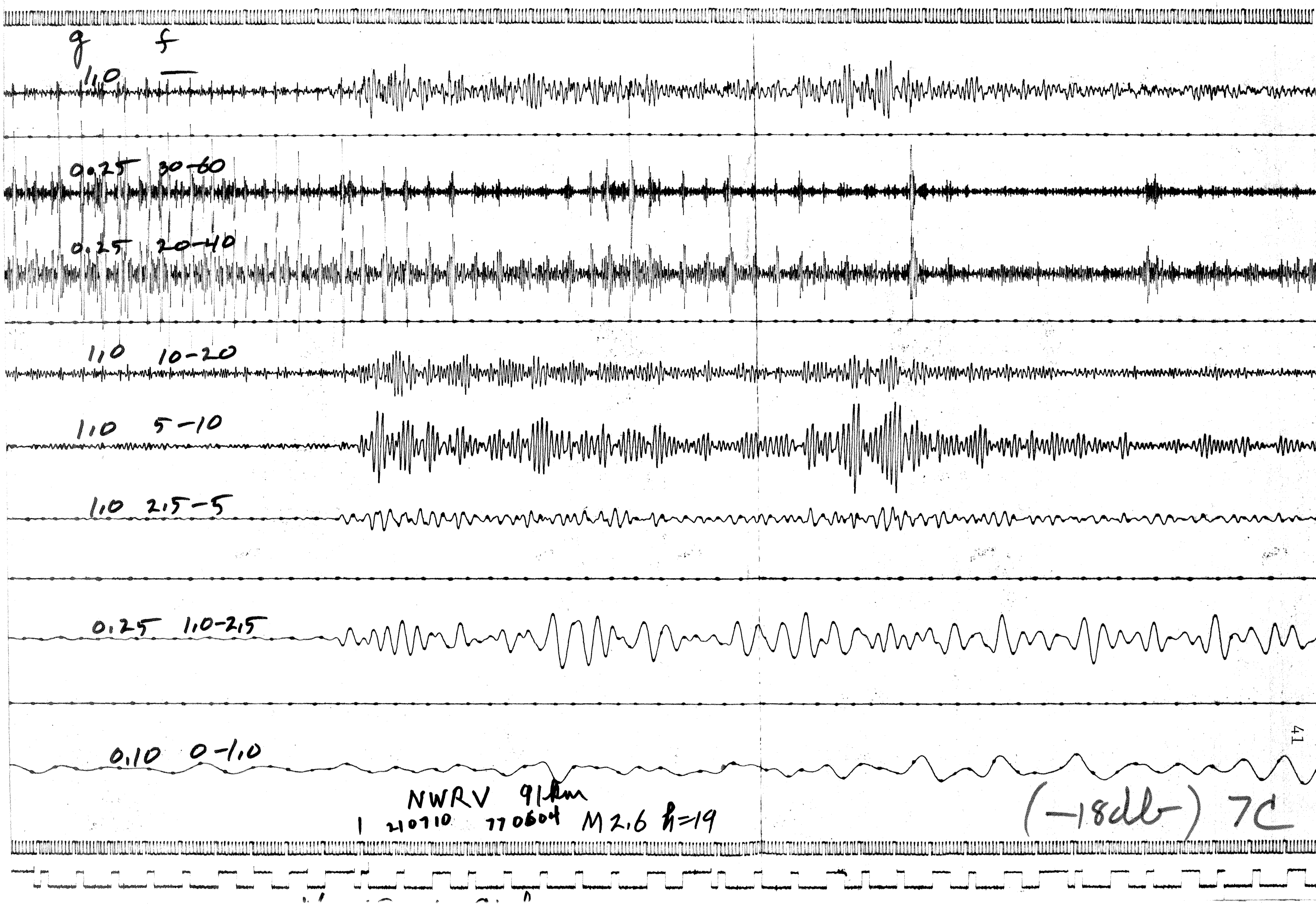

f
g
1,0
0-10
1,0
20-40
1,0
10-20
1,0
5-10
1,0
2.5-10
1,0
1.0-2.5
0,25
0-1.0
0,10
BSRN 18km | 062700
770528 0627 M=3,0 h=3
(-42db) 5e

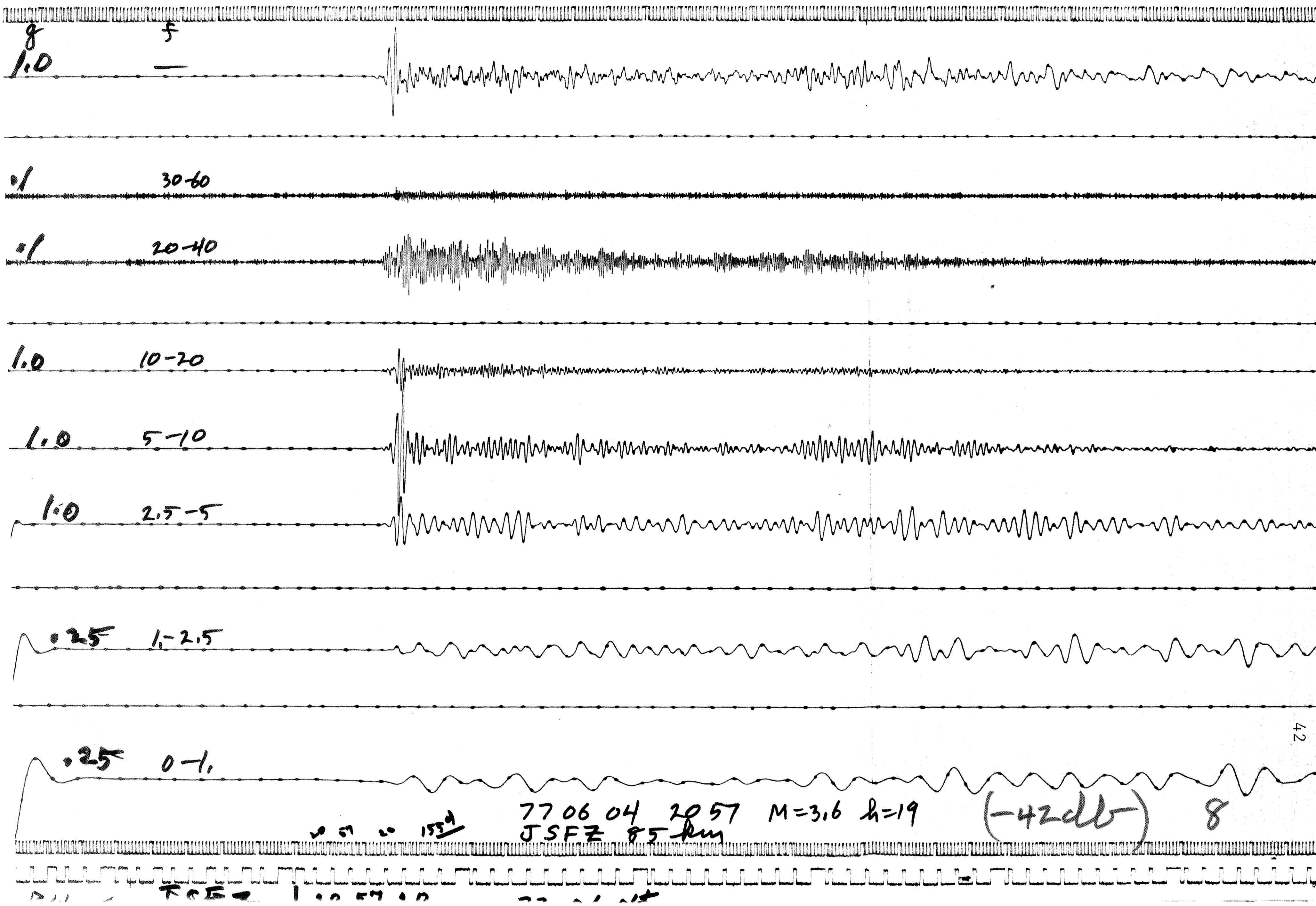

g
f
1.0
0-10
1.0
20-40
1.0
10-20
1.0
5-10
1.0
2.5-5
.25
1.0-2.5
.10
0-1.0
BSRE 18Km 770528 06:27 M=3.0 h=3 (-42db) 5f
0627 00

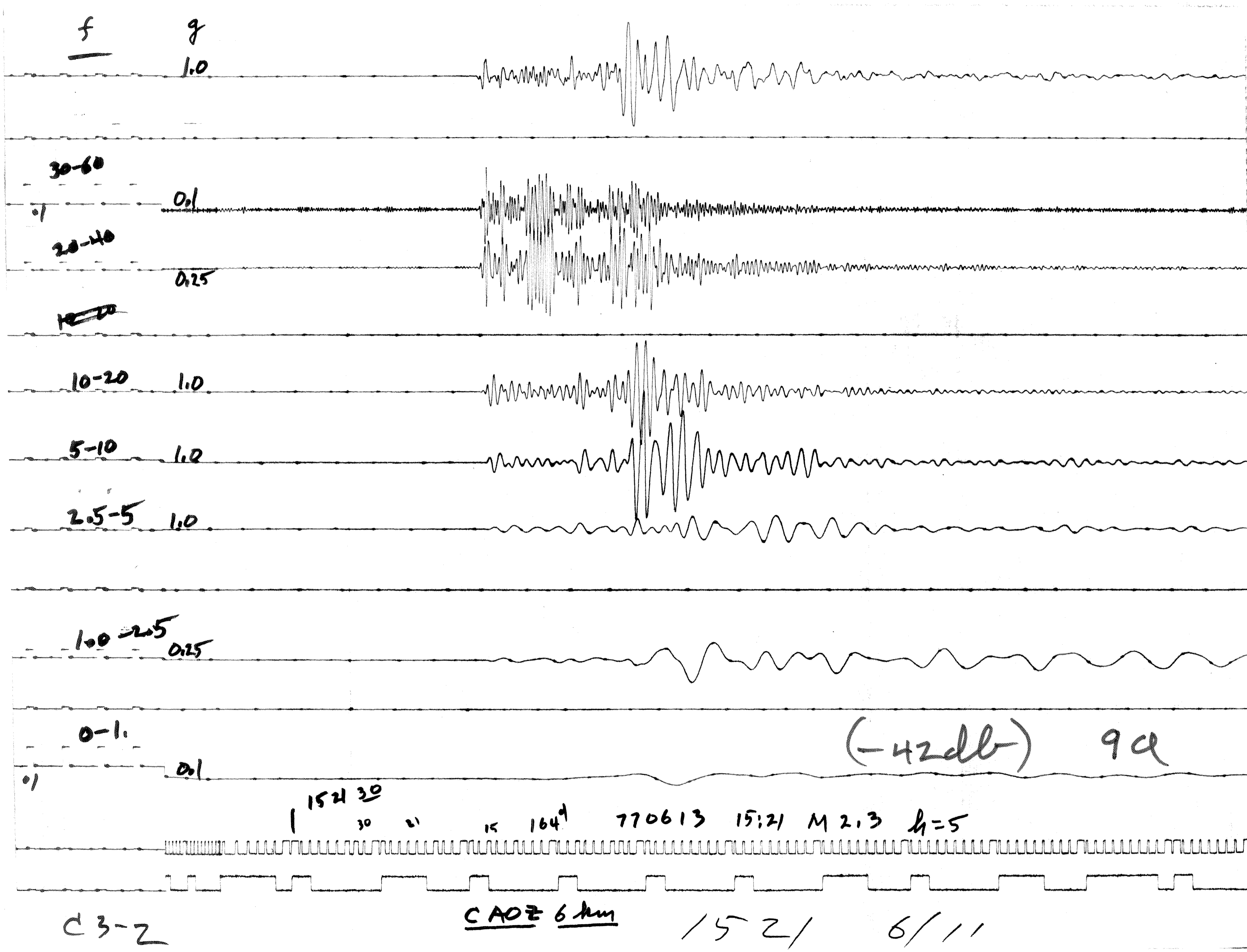

g 5
1,0
.25 30-60
1,0 20-40
1,0 10-20
1,0 5-10
1,0 2,5-5
0,25 1,0-2,5
0,10 0-1,0
NHMV 10km
2120 30s 155d 770604 M1.5 h=17
(-18db) 6

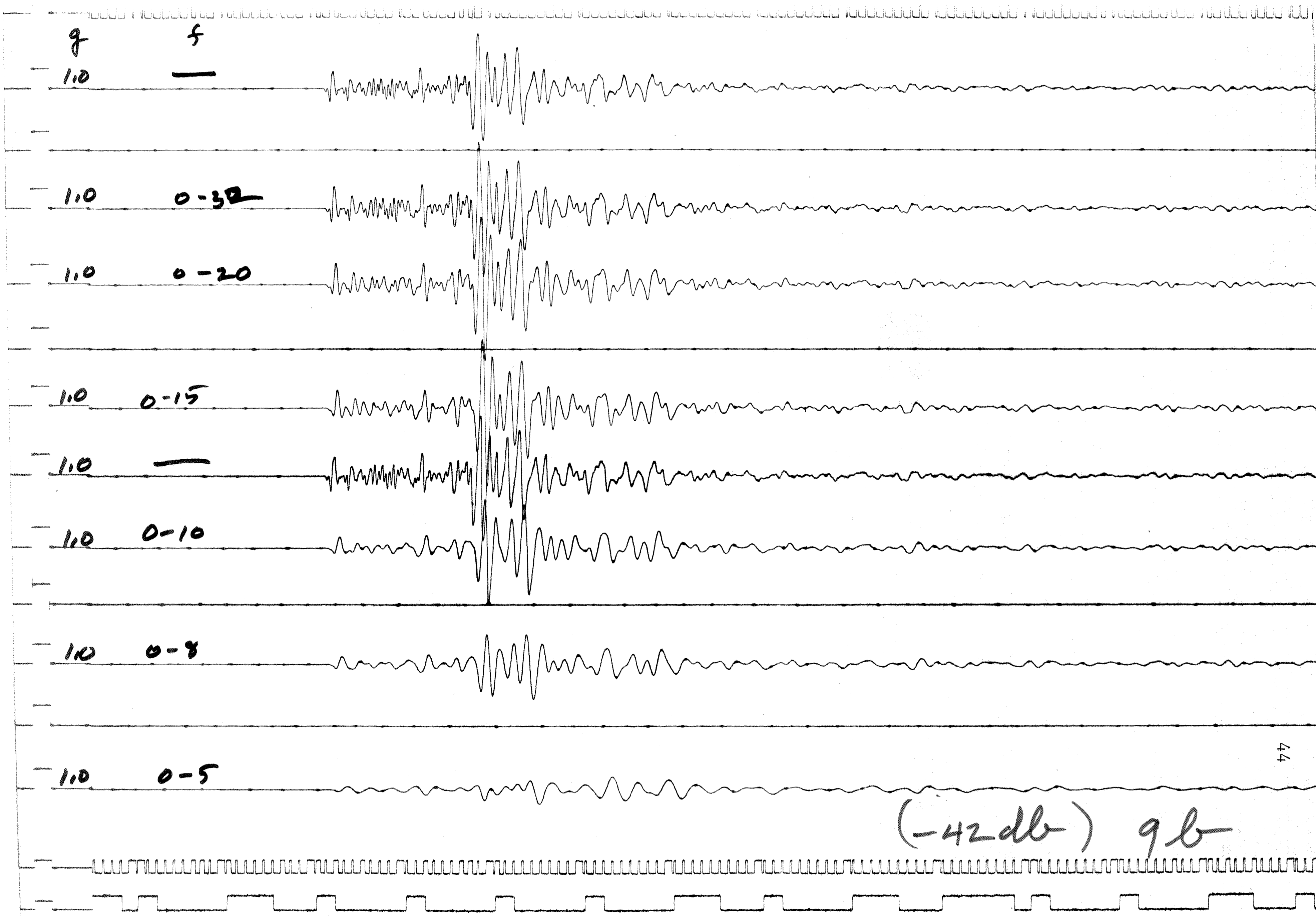

g
f
1.0
—
0.10
30-60
0.10
20-40
0.25
10-20
1.0
5-10
1.0
2.5-5
0.25
1.0-2.5
0.1
0-1.0
JSFV 85km
1 210710 155d
770604 M2.6 h=19
(-24db) 7a


g f
1,0
0,25 30-60
1,0 20-40
1,0 10-20
1,0 5-10
1,0 2.5-5
1,0 1-2.5
0.1 0-1
1 21 07 10 770604 M=2.6 h=19 AGIV 112km
(-12db) 7b

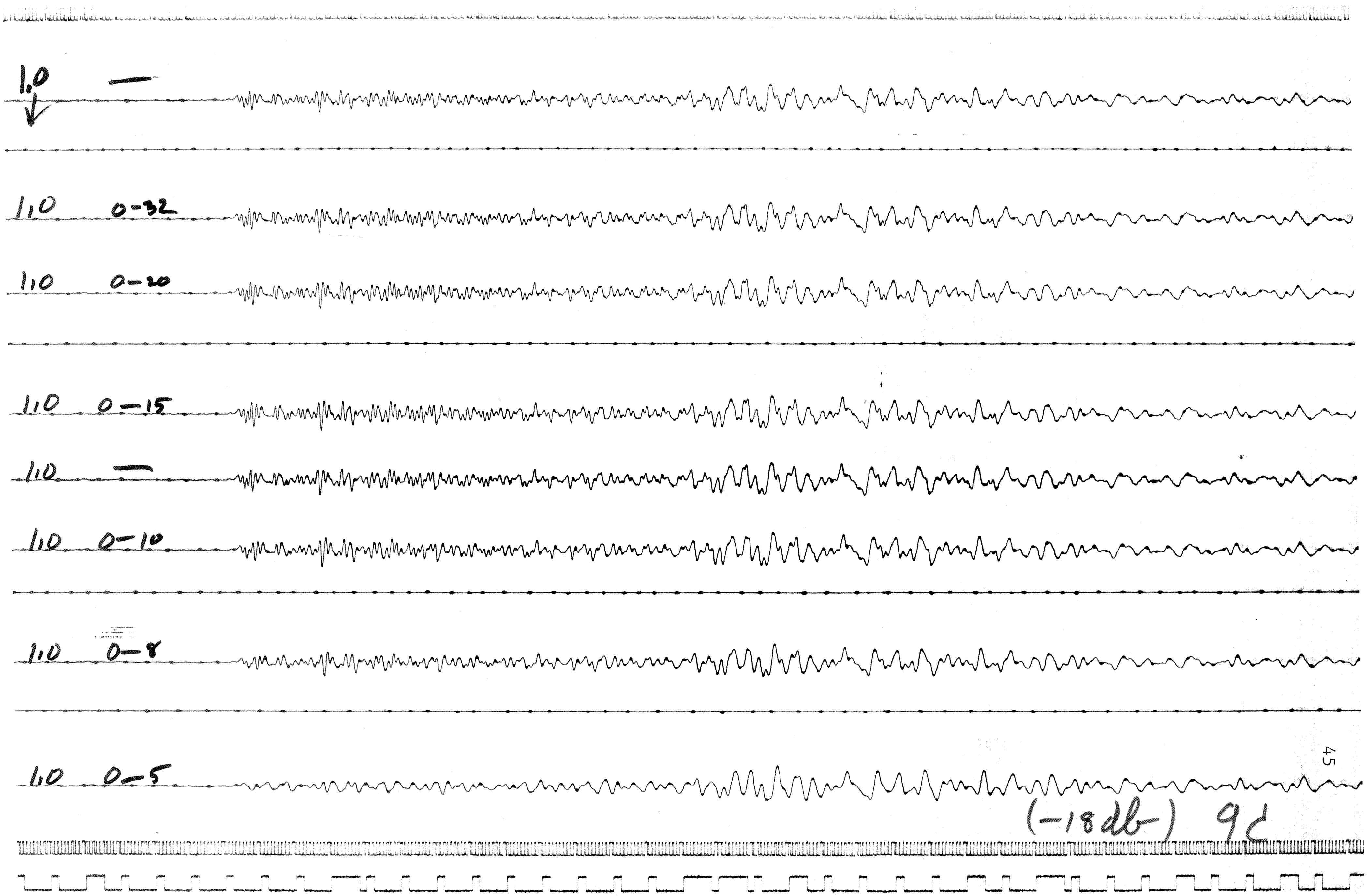

g f
1.0
0.25 30-60
0.25 20-40
1.0 10-20
1.0 5-10
1.0 2.5-5
0.25 1.0-2.5
0.10 0-1.0
NWRV 91km
1 210710 770604 M2.6 h=19
(-18db) 7C


g f
1.0
.1 30-60
.1 20-40
1.0 10-20
1.0 5-10
1.0 2.5-5
.25 1.-2.5
.25 0-1.
77 06 04 2057 M=3.6 h=19
JSFZ 85 km
(-42db) 8


f
g
1.0
30-60
0.1
20-40
0.25
10-20
1.0
5-10
1.0
2.5-5
1.0
1.0-2.5
0.25
0-1.
0.1
(-42db)
9a
1521 30
30
21
15
1649
770613
15:21
M 2.3
h=5
C3-2
CAOZ 6 km
1521
6/11



C3-7 CAOZ 6km 770613 1521 M2.3 h=5



BSCV 87km 770613 15:21 M2.3 h=5 C/3-3