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High-frequency Seismic Signals Recorded at Eskdalemuir, Scotland

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SUMMARY

The report describes some analyses of chart (Helicorder) recordings from a seismological recording system at Eskdalemuir, Scotland with a pass band of 2-15 Hz. These are referred to as high-frequency recordings. It has been claimed by some seismologists that nuclear explosions of low yield and particularly decoupled explosions would be most easily detected and identified at frequencies well above the 1-2 Hz pass band of conventional short-period (SP) recording systems. One problem with using high-frequency recordings to which the UK drew attention, is the difficulty of distinguishing by seismological methods between nuclear explosions (either low yield or decoupled explosions) and the numerous chemical explosions that take place each year in industrialised countries. As well as industrial explosions there are other seismic disturbances - many man-made - that would also have to be identified. All man-made disturbances are likely to have their largest signal-to-noise ratio at frequencies above the SP pass band. This suggests that the use of high-frequency recordings is unlikely to be of much value for the identification of nuclear explosions.

The main purpose of this report is to obtain an estimate of the number and variety of seismic disturbances that would be detected by a high-frequency recording system in an industrialised country (the UK). The study shows that there are on average 30-40 signals per day showing the P & S phases characteristic of local seismic disturbances. The source of most of these signals appears to be quarry blasts although some are known to be from small earthquakes. In addition to these there are numerous other signals such as those from air guns operating at regular (~1 min) intervals in the North Sea and road making machinery being used close to the array. These signals although they may be identifiable have the effect of raising the noise level for many minutes or even hours and make the observation and analysis of other local signals either very difficult or impossible. Even if it were demonstrated that signals from low yield and decoupled explosions are most easily detected at frequencies above the conventional SP band the analysis effort that would be needed to disentangle overlapping signals and identify all the signals seen would seem to make use of such a system for verification impractical, at least in highly industrialised countries such as the UK.

1. INTRODUCTION

Most of the research in the UK over the past 30 years on seismological methods of verifying compliance with test ban treaties has used recordings with frequencies of a few hertz and less, recorded at long range. Currently it should be possible with such recordings to detect and identify explosions of 3-5 kton fired close-coupled in hard rock with the possibility of reducing this level to around 1 kton. In 1986 Evernden, Archambeau & Cranswick [1] published a paper suggesting that explosions of low yield and particularly decoupled explosions (a 1 kton explosion decoupled is roughly equivalent to 10 tons close-coupled) would most easily be detected and identified, using recordings at what, for seismology, are high frequencies. The conventional recording bands used in seismology are 0.5-2 Hz (the short-period, SP, band) and 0.01-0.1 Hz (the long-period, LP, band) although some SP systems such as those used in the UK designed arrays are wider band covering the range 0.5-8 Hz. The high-frequency band suggested by Evernden et al [1] would extend up to 100 Hz. The UK regarded the conclusion of Evernden et al [1] as premature and pointed to some assumptions that would need to be verified if high-frequency recordings are to make a significant contribution to test ban verification [2].

One problem to which the UK drew attention was the difficulty of distinguishing by seismological methods between nuclear explosions (either low yield or decoupled explosions of a kiloton or more) and the numerous chemical explosions that take place each year in industrialised countries. The only reason (in the absence of direct evidence) that underground explosions of large yield (say 5 kton and larger) are assumed to be nuclear is that chemical explosions of such yields are difficult to carry out because of the large volume of explosive that has to be emplaced below ground. As well as industrial explosions there are other seismic disturbances - many man-made - that would have to be shown to be non-nuclear. To obtain some estimate of the number and variety of seismic disturbances that would be detected at high frequencies in an industrialised country (the UK) a single vertical-component seismometer with a pass band of 2-15 Hz was installed on 9 August 1985 at the MOD seismometer array station at Eskdalemuir, Scotland (EKA). The array is designed to optimise detection of 1-5 Hz P-waves at a distance of 10°. This report describes the results of some analyses of the chart (Helicorder) recordings from the 2-15 Hz system. These are referred to in what follows as HF recordings. Ideally of course a system recording up to say 100 Hz would have been used but to install such a system would require significant changes to be made to the array instrumentation whereas it was easy to adapt part of the system to record up to 15 Hz.

EKA is the national seismological station (NSS) from which the UK has guaranteed to supply data during international data exchange experiments organised by the Ad Hoc Group of Scientific Experts (AHGSE). The AHGSE is a working group set up by the UN Committee on Disarmament. So far the AHGSE has carried out two experiments: the first GSETT/1 in October 1984 and the second GSETT/2 in April/May 1991. One of the requirements of those participating in the data exchange experiments is that times and amplitudes must be reported of local seismic disturbances; such disturbances being those with epicentres within 5° of the array. The study described here, as well as providing information on HF detections also enabled staff at AWE and EKA to gain experience in interpreting recordings from 'locals' to improve UK performance in data exchange experiments.

2. THE SEISMIC SPECTRUM AND RECORDING BANDS

Figure 1 shows diagrammatically, spectra of the P signals from explosions at epicentral distances of 60° from the array superimposed on the EKA noise spectrum for the range 0.5 and 8 Hz. The spectrum of the seismic waves radiated by earthquakes and explosions tends to be flat from zero frequency to some frequency f_c, the corner frequency, above which the amplitude falls-off as ω^n, where n is usually assumed to be 2 or 3. On propagation the high frequencies in the signal are preferentially attenuated due to anelastic attenuation. At frequency ω the effect of anelasticity is usually assumed to have the form, $\exp(-\omega t^*/2)$ where t^* is the ratio of travel time to the specific quality factor, Q. In deriving the signal spectra of the P waves shown in figure 1 it has been assumed that $f_c = 2$ Hz, $n = 2$ and $t^* = 0.2$s. The spectrum of the source with body-wave magnitude (m_b) of 6.5 has roughly the form for an explosion of 100-200 kton; that of the m_b4.5 source of an explosion of a few kilotons. Theoretical studies show that f_c should be proportional to $Y^{-1/3}$, where Y is yield. However, this assumes that other factors such as depth of burial do not vary with yield. In practice, depth of burial is usually proportional to $Y^{-1/3}$ and because of this and the variation in other factors, f_c should vary only slowly with yield (Denny and Johnson [3]) and observation shows that this is so (see for example Stewart [4]). For this reason the corner frequency for the two explosion spectra shown in figure 1 are assumed to be the same.

From figure 1 it is clear that a m_b6.5 explosion will be easily seen above noise on the SP system. For a m_b4.5 explosion the signal at EKA will be swamped by noise around 1 Hz although the signal might be detected by filtering in a narrow band around 2 Hz. This agrees with experience that weak explosion signals that are barely visible above noise on the SP system can sometimes be extracted with additional high pass filtering.

Now, decoupled explosions of around 1 kton are expected to have magnitudes of about m_b2.0 so there is no possibility that signals from such an explosion will be visible above noise on conventional recording systems except at ranges of less than about 200 km. Evernden et al [1] however, argue that such explosions will have high corner frequencies (~20 Hz) and that anelastic attenuation over distances of several degrees is much less than is usually assumed. Thus as noise amplitudes at most stations fall-off rapidly with frequency, decoupled explosions should be detectable at much greater distances at high frequencies than on the conventional SP system. Whatever the validity of the argument put forward by Evernden et al [1] it is clear that such high frequency recordings will pick up signals from many other low magnitude seismic disturbances that occur close to the recording station as these will also usually have high corner frequencies. In fact one of the reasons most SP systems cut-off at around 2 Hz is to attenuate the signals from very local man-made disturbances (usually referred to as cultural noise) which can swamp the signals from larger magnitude disturbances that occur at long range. Examples of differences in the signals recorded by the SP and HF channels are shown in figures 2 & 3. The SP and HF signals are obtained from the same seismometer.

The Eskdalemuir array is a 20 element array with an aperture of about 10 km, near the town of Langholm in southern Scotland (figure 4). Initially the array data was recorded in analogue form and the response with frequency of the SP system (figure 1) had no well defined upper frequency limit although in practice the system noise exceeded seismic noise from around 10 Hz upwards. In 1983 digital recording was installed at the station. The sampling interval of the digital system is 0.05 s giving a Nyquist frequency of 10 Hz. Such a system cannot be used for signal frequencies much above 8 Hz. To provide a back-up to the digital system and also to collect data for HF studies the analogue system continued in operation until 1992. To study coherence of signals and noise across the array digitised analogue data were used. This showed that for most disturbances recorded at the station the upper limit of signal frequencies is about 6 Hz (Lilwall [5]). In addition to the tape recorded signals a SP Helicorder is also operated at the station (from seismometer B3). The HF Helicorder covering the band 2-15 Hz was also run from seismometer B3. It is data from the HF Helicorder that is used for most of the study.

An automatic detection system is operated at EKA; detection being carried out on the SP channel filtered in the band 1-2 Hz. In this band the signal-to-noise ratio for local disturbances is so low that they are rarely detected.

Examination of the HF records shows there is a wide variation in the number of signals observed each day but the number is rarely less than 10 and is often over 100. Some are signals from earthquakes and explosions with epicentres at long range which are of sufficiently large magnitude to be seen on the HF channel (figure 5). A few of the signals are from earthquakes within the UK. Examples of signals from four local earthquakes are shown in figure 6. Many of the local earthquakes are detected by the network operated by the British Geological Survey (BGS) and reported in their monthly bulletins of UK seismic disturbances. Details of locations and other data from this network for the signals illustrated in figure 6 are given in the bulletins for the relevant dates. Study shows that apart from local earthquakes the sources of the signals recorded on the HF channel can be roughly divided into 4 types: quarry blasts; marine sources; atmospheric disturbances; and those that produce signals of long duration. Each type is considered in turn in what follows.

3. QUARRY BLAST SIGNALS

The number of local seismic signals recorded at EKA in any given period is largest during normal working hours (figure 7). It seems reasonable therefore, to assume that the signals are generated by industrial blasting for quarrying or mining within a few hundred kilometers of the station. Although such circumstantial evidence provides an explanation for the likely origin of many local signals, it does not meet the requirements of the AHGSE for participants in international data exchange experiments. In these experiments Level 1 data (ie, amplitudes, periods, onset times, etc) for all seismic signals detected by NSSs must be reported to agreed Experimental International Data Centres (EIDCs). Abbreviation of the reporting procedure is permissible only when the analyst can identify the signal as falling into certain defined categories of local disturbances. For example, the comment 'QB' would signify confirmation that the source of a reported signal was a quarry blast.

In the interval between GSETT/1 and the scheduled commencement of GSETT/2, further attention was given to this problem by the AHGSE. Experience gained during the first test showed that, in practice, it is difficult to positively identify the sources of presumed 'locals' in the time between a signal being detected and the deadline for reporting to EIDCs. It was therefore decided to try and obtain details such as firing time and epicentre of the explosions at each mine and quarry. The co-operation of companies with quarries within a few hundred kilometers of EKA (the locations of some of the quarries is shown in figure 4) was therefore sought in order to obtain regular information on blasting, particularly the times and locations of the explosions. With this information the analysts could learn to recognise signals from particular quarries and mines, thus enabling the source of many signals to be identified and reported to EIDCs within the specified time. An example is given in figure 8, which shows records of explosions fired at Eastgate Quarry in consecutive weeks. The data provided by quarry managers has been particularly useful for establishing relationships between seismic magnitudes and charge size (see section 8). For quarry blasts that were large enough to be recorded by the SP array the reliability of epicentres estimated using the array of SP seismometers could be assessed by comparing estimated and true epicentres.

4. SIGNALS FROM MARINE SOURCES

Deep seismic profiling on the continental shelf around the British Isles produces distinctive signals at EKA. The sources are usually large airguns towed by ships operating under contract to commercial organisations and academic institutions. The airguns generate seismic waves which, upon arrival at a distant recording station, produce signal bursts in patterns that experience shows are characteristic of the source. Seismic reflection profiling takes place at all times of day, so resulting signals may appear as clear distinctive groups or be intermingled with those from other activities such as quarry blasting. Under favourable conditions for signal reception, seismic surveys at sea can be a near continuous source of interference at EKA for many days at a time.

These signals are almost invisible on the standard SP records from EKA but are prominent on the HF channel. The pattern of signal arrivals varies with the distance of the ship from the recording station. A common feature, however, is the symmetry (enhanced by the geometry of Helicorder displays) in the recorded arrival patterns, produced by the regular firing as the ship moves along the survey line. figures 9, 10 and 11 show examples of such records. The signals shown in figure 9 are from the 'Mobil 87' experiment carried out under the auspices of the British Institutions Reflection Profiling Syndicate (BIRPS) centred at the Bullard Labs, Cambridge. The operation took place in the North Sea in June 1987 using the Mobil ship which has a particularly energetic airgun capable of obtaining reflections from discontinuities down to the base of the crust (the Mohorovičić discontinuity or Moho). The time interval between airgun firings was 40-50 s. Professor Blundell (University of London) provided a list of airgun firing times along one line (line 2) off the Northumberland/Berwickshire coast (figure 4) and the start and finishing times for firings along the other survey lines, covering a 10 day period in all. With these times it was confirmed that the signals are indeed from the airgun firings. Signals were recorded by EKA from lines 1-3, at distances in the range 150-200 km, but were not detectable at the greater ranges of the other lines.

5. SEISMIC SIGNALS GENERATED BY THE COUPLING OF ATMOSPHERIC DISTURBANCES INTO THE GROUND

Seismic disturbances arising from the effects of atmospheric coupling to the ground are all-pervading though, in general, spatially incoherent. Those which originate from the passage of objects through the atmosphere however, form a distinctive category, and usually produce coherent signals. The only source of signals in this category that are likely to be frequently observed are those produced by flying aircraft. This kind of signal is not usually identifiable as such unless supported by actual sightings - the 'spurious' tripping of EKA on-line detectors, is often associated with the sighting of low-flying aircraft in the vicinity of the array (Grover [7]). Direct overflights generate signals by pressure loading and acoustic interaction with the seismometer as the aircraft passes close to the instrument. With aircraft travelling at supersonic speed, such overflights can produce dramatic results (Grover [7]), but this is a rare occurrence. The signals from distant aircraft may be:

(a) seismic waves propagated to the recording station from the area (ie, possibly a few tens of kilometers distant) where the shock-wave energy of the acoustic waves is coupled into the ground;

(b) ground waves resulting from local coupling with atmospheric acoustic waves arriving at the station from the flight path area (possibly over 100 km distant).

The waveforms resulting from air-ground coupling at a station are not necessarily identifiable as of non-seismic origin from the output of a single seismometer but, with an array, this is apparent from the low speed of the waves. Figure 12 shows the seismic effects of a test flight of the Concorde prototype aircraft recorded by the array at EKA at a range of 120 km from the flight path. The frequency of the waves is around 5 Hz.

6. SIGNALS OF LONG DURATION

Signals from local seismic disturbances such as quarry blasts, airgun firings and earthquakes usually have maximum durations of around a minute or so. In addition to these signals the HF recordings also show signals that last many minutes. Many of these signals appear to be generated within a few kilometers of EKA.

Possible very local sources for long duration signals of continuous high amplitude, are ditching and road-making machines. Hand-held machinery and road traffic may account for shorter episodes of activity. Some of these sources of interference can be readily identified as man-made if, for instance, certain types of disturbances with distinctive seismic signatures, are noticed only during daylight hours on normal working days. For example, the long and intrusive disturbances of the kind shown in figure 13 are caused by a particular type of road-rolling machine used in maintenance of forestry roads.

In contrast to the often overlapping records typical of weekday activity it might be expected that isolated signals occurring at weekends are unlikely to be of very local origin. In general this holds true, although it is noted that at least one type of long duration signal of unknown and possibly very local origin, occurs most frequently during silent hours. Figure 14 gives an example in which several disturbances of the latter type arise during the same (silent hours) period as a teleseismic signal with sufficiently high f_c to be clearly recorded on the HF record. Other long duration signals seem to be overlapping sequences of signals from local disturbances. Examples are shown in figure 15. Similarities can be seen to other types of HF records in which several short-duration signals arrive sequentially at differing time intervals. Examples of these types are shown in figure 16. It is possible that most of the records of this kind originate from coastal firing ranges in the region, but this has not been confirmed.

There are long duration signals however, that cannot be explained as described above. Some of these may be low magnitude earthquakes occurring at distances much more than 5° from the array and which are only detected because fortuitously the path from source to station is one of low attenuation. One mechanism which can give rise to such long durations of signals is suggested by for example Shurbet [8] and Cansi & Bethoux [9]. Shurbet [8] describes wave trains recorded in the USA and Bermuda from earthquakes in the W Indies/Central America region. The durations of the wave trains are of some minutes, frequencies are as high as 5-6 Hz, and amplitudes tend to increase and decrease only slowly from the background to a maximum and back. Both P and S phase groups are distinguishable. These waves are P and S phases which travel as guided waves in a thin channel formed by a minimum in the variation of wave speed with depth below the Moho in a manner analogous to that of T phases in the sound channel in the ocean.

Cansi & Bethoux [9] describe analyses of recorded seismic signals which are of long duration (3-4 minutes) compared to the duration of the source (one an oceanic underwater explosion). These land-recorded signals arise from conversion of T-phase energy in the water to crustal waves at the continental slope at the SOFAR channel depth. They conclude that the long durations of the signals are a result of acoustic to seismic conversion taking place at several different locations along the continental slope. Cansi & Bethoux [9] show typical waveforms for signals of T-phase origin with long inland paths. They lie in the 2-7 Hz band, have durations of the order of minutes, and amplitudes which in general increase slowly to a maximum and decrease gradually thereafter. Such seismograms are usually the result of multipathing, ie, the superpositioning of signals that have travelled by many different ray paths. Analysis suggests the existence of a double conversion into Pg and Sg (or Lg) waves propagating along different azimuths corresponding to the different points at which the conversions occur along the slope. Signals of generally similar appearance to these types are seen from time-to-time on the EKA records. Despite these superficial resemblances the majority of them seem likely to be produced by various other mechanisms although a few are probably genuine. Figure 17, for example, shows arrivals that are consistent with travel times for P and S phases from a near- regional disturbance located by the International Seismological Centre (ISC) in the North Sea. A later arrival, shown in figure 17(b), displays features similar to those described by Shurbet [8] for inland-propagating seismic waves which have undergone conversion from seawater-channelled waves at multiple points along the coastline. Note however for explosions in the North Sea the water-borne wave is channelled in the water and not in the SOFAR channel which is too deep to be found in the North Sea. However, acoustic waves in the water are converted to seismic waves at the coast/land border.

The HF signal arising from the onset of these presumed phase conversions emerges slowly from the background noise and has a duration of about 100 s. Using the arrival time of the principal waves in the package an overall travel time of 6 min 24 s from epicentre to the recording station at EKA is obtained.

The configuration of the coast line in the region is complex, but taking distances along the direct line of travel from the epicentre to EKA gives sea and inland propagation path lengths of 528 km and 112 km respectively. This corresponds to travel times for the water channel of 354 s (using a value 1490 m/s for the wave speed in water) and about 19 s for the inland path (from tables), ie, 6 min 13 s total, in comparison with the noted time of 6 min 24 s.

Figure 18 shows another example of a long duration signal that does not appear to be due to activity very close to the array. The signal was recorded by all elements of the array, and cannot be associated with any reported disturbance. It is one of a series recorded during a half-hour period of a (week day) morning. The duration of these signals ranges from 2 to 5 min. An attempt was made to determine the source of these waves using the array recordings. The array can be used to determine the direction of approach of the waves and the apparent surface speed across the array. Four of the discrete arrivals were analysed and the conclusion reached is that the arrivals are P_n-wave types with an apparent surface speed close to 7.8 $km.sec^{-1}$ from a back-bearing of about 110°. In the absence of any other clearly identifiable waves, such as S waves, it is not possible to estimate a distance other than to say that the source lies beyond about 120 km possibly in the North Sea off the coast close to Sunderland. No bulletin reports any significant disturbance for the relevant time period, except the ISC which lists a small earthquake in the Leeward Islands region but this cannot be the source of the signal as it lies on a very different azimuth to that of the signal.

7. DETERMINATION OF DURATION MAGNITUDES AT EKA

The difficulty of determining the magnitude M_L, for small local disturbances such as those recorded on the HF system is well known. One way round these difficulties is to use the duration of the signal coda to determine a 'duration magnitude'. The duration magnitude is of the form:

$$M_D = a \log D + b\Delta + c,$$

where M_D is the duration magnitude, D is the duration of the signal, Δ the epicentral distance and a, b and c are constants which depend on the local geological structure and the seismograph used to record the disturbance. If M_L and M_D are available for a series of disturbances then the relation between M_D and M_L can be determined. Writing the relation in the form:

$$M_D = dM_L + e$$

then it is possible to define a duration magnitude M_L^D which is tied to the M_L scale. Thus

$$M_L^D = \frac{a}{d} \log D + \frac{b}{d} + \frac{(c-e)}{d}$$

The amplitude cut-off is arbitrary and any variation in the selection of the cut-off amplitude affects only the constant c.

For EKA HF seismograms the signal duration is defined as the time between the first arrival and that time when the coda falls, for the last time, below a peak-to-peak amplitude of 1 mm on the seismogram. The magnitude scale was calibrated against the M_L estimates of the BGS for seismic disturbances which were also detected at EKA. 26 seismic disturbances were used to estimate by least squares the relation between M_L and M_D. Combining this result with the expression for M_D gives:

$$M_L^D = (2.67 \pm 0.34) \log_{10}D + (0.17 \pm 0.04)\ \Delta - (3.22 \pm 0.68).$$

This definition of M_L^D is used to estimate the magnitude of small local disturbances at EKA.

8. MAGNITUDES OF LOCAL DISTURBANCES

In an attempt to estimate the frequency of occurrence of small local disturbances the recordings for a two week period were closely scrutinised. A total of 405 signals showing P & S phases characteristic of locals were used to determine M_L^D as defined above. The S-P times were used to estimate the distance Δ. The total sum of the measured durations represents approximately 15 minutes per day or about 1% of the days recording. The frequency of occurrence of the 405 disturbances is given in figure 19 which shows the number per day and the frequency distribution as a function of the time of day. It would appear that the large majority of these signals are man-made since both the mean rate of occurrence of about 28 per day falls to 13.5 per day at weekends (23 per day on Saturdays and 4 per day on Sundays) and the majority of signals occur during the working day with a slight bias towards the afternoon. This suggests that the sources are probably associated with quarrying activities such as blasting.

The duration magnitude was determined for the 405 seismic disturbances and frequency of occurrence and cumulative number plotted against magnitude (figure 20). The cumulative curve shows the number of seismic disturbances above a particular magnitude. On the assumption that the frequency of occurrence has the form:

$$\log_{10} N = a - bM_L^D$$

a and b can be estimated using the method of Kelly & Lacoss [10]. The resulting relationship (for the annual occurrence) is

$$\log_{10} N = 4.42 - 0.70M_L^D$$

The 50% detection threshold is $M_L^D 0.41$ with a standard deviation of 0.42. This relationship gives a description of the local seismicity at EKA but should be used with some caution since the application of the method to a data set made up principally of man made sources is obviously open to question.

Using the data supplied by quarry managers on charge weight it is possible to determine magnitude-yield relationships for quarry blasts. As an example M_L^D for explosions at the Eastgate quarry have been plotted against total charge weight. The results are given in figure 21. The equation of the least squares line through the data is:

$$M_L^D = (1.06 \pm 0.35) \log_{10}Y + (1.77 \pm 1.00)$$

where Y is the charge weight in kg. Also shown in figure 21 is the relationship between magnitude and yield for well-coupled explosions in hard rock (eg, granite). Note that the large majority of data points fall below this line indicating that coupling efficiency at Eastgate quarry is lower than for hard rock. This may be because the rock at Eastgate is Carboniferous limestone and not granite. The scatter in the observations is large but this is expected because of the differences in charge distribution and variation in the porosity and water content of the rock which gives rise to large variations in coupling efficiency.

9. DISCUSSION AND CONCLUSIONS

The study described here on HF signals demonstrates clearly some of the difficulties of using such recordings for test ban verification. Even if it were demonstrated that signals from low yield and decoupled explosions can be detected at frequencies well above those covered by the conventional SP band the possibility that the seismic signals from the explosions would be mixed with signals from other sources and the data analysis effort that would be needed to account for all the other signals seen on the HF channel would seem to make use of such systems for verification impractical, at least in highly industrialised countries such as the UK. Obviously some analysis of the data could be automated and small aperture arrays used to try and separate overlapping signals but in the end the large volume of data seems likely to overwhelm any HF system.

The problem for any station required to report local disturbances using a HF channel is demonstrated by UK experience in reporting EKA data to EIDCs during GSETT/1 and GSETT/2. In GSETT/1 where it was only necessary to report times and amplitudes of noise and signals the UK reported up to 40 locals a day from the analysis of HF recordings. For GSETT/2 where seismograms as well as times and amplitudes had to be transmitted to EIDCs the data load would have been too large to include seismograms of unidentified signals recorded on the HF channel so only those locals seen on the SP channels were reported to the EIDCs. The EIDCs had difficulty in coping with the data they did receive. Had all 60 stations reported signals from a HF channel then it seems the EIDCs would have been swamped.

10. ACKNOWLEDGEMENTS

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CAPTIONS TO FIGURES

Figure 1 Spectra of P signals from explosions at epicentral distances of 60° and that of a small magnitude (m_b1.5) source recorded at 1° superimposed on the noise spectrum for Eskdalemuir. Also shown are the responses of the short-period array and the high frequency (2-15 Hz) systems normalised to a gain of unity at 1 Hz. The scale on the left of the figure applies to the signal and noise spectra; that on the right to the system responses. Diagrammatic only.

Figure 2 A section of the standard SP chart for 6-7 April 1988.

Figure 3 A section of the high frequency (2-15 Hz) chart for the same period as shown for the SP in figure 2. Note how this figure shows many more signals than the SP.

Figure 4 (a) Map showing the location of the Eskdalemuir array and some of the main quarries from which seismic signals are detected at the arrays. Also shown is the survey line (line 2) from the British Institutions Reflection Syndicate: Mobil 87 exercise.

(b) Seismometer lay-out at the Eskdalemuir array.

Figure 5 Example of seismograms from seismic disturbances at long range recorded on the high-frequency channel at Eskdalemuir.

(a) P waves from underground explosions in East Kazakhstan and Novaya Zemlya.

(b) P waves from an earthquake on the Afghanistan-USSR border.

Figure 6 Seismograms recorded at Eskdalemuir on the high-frequency channel from local earthquakes.

Figure 7 Section from the chart recording of the high-frequency channel showing that the number of local disturbances is much larger during the day than at night.

Figure 8 Seismograms recorded at Eskdalemuir on the high-frequency channel from two quarry blasts at Eastgate quarry.

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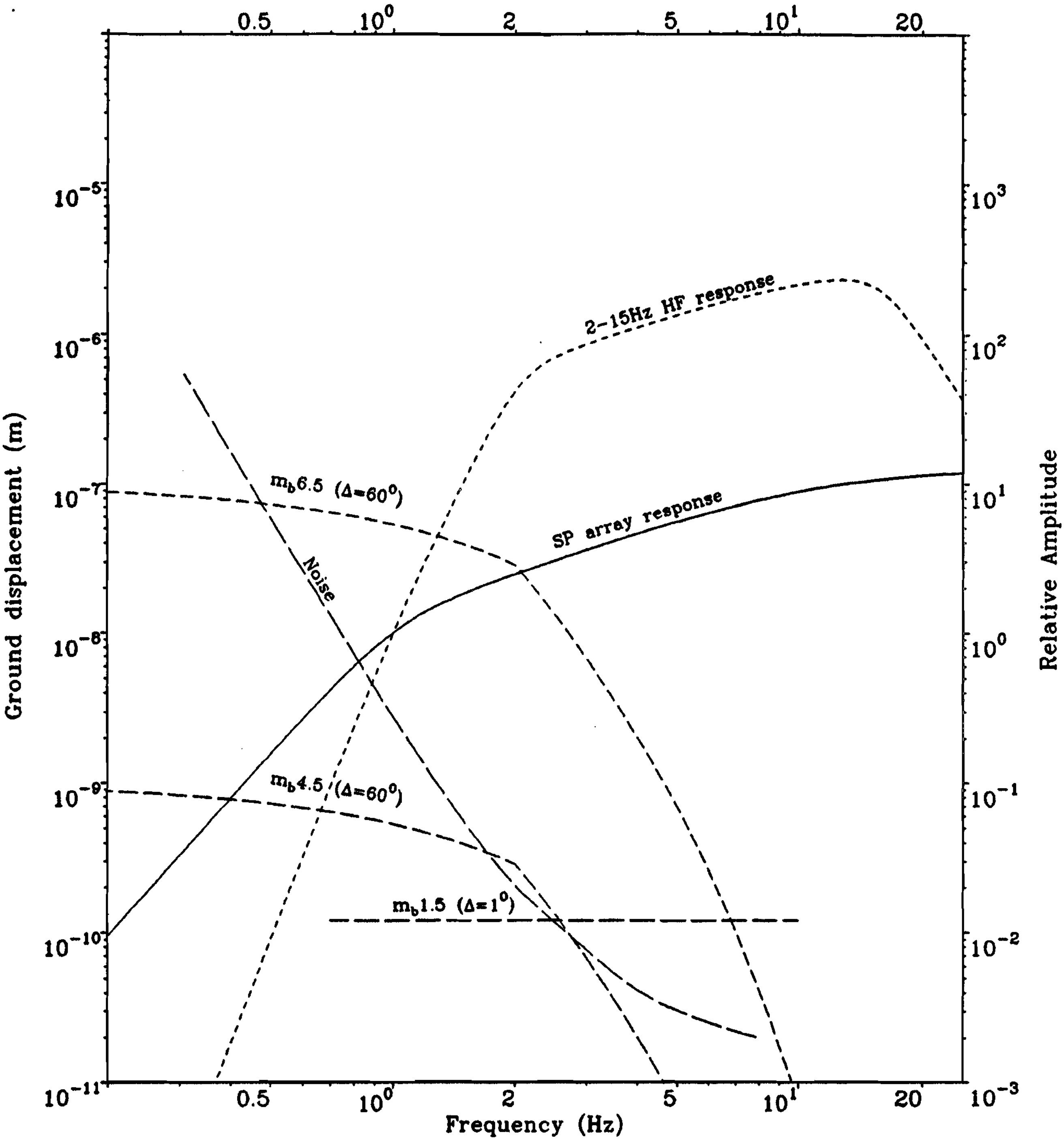


Figure 1 Spectra of P signals from explosions at epicentral distances of 60° and that of a small magnitude (m_b1.5) source recorded at 1° superimposed on the noise spectrum for Eskdalemuir. Also shown are the responses of the short-period array and the high frequency (2-15 Hz) systems normalised to a gain of unity at 1 Hz. The scale on the left of the figure applies to the signal and noise spectra; that on the right to the system responses. Diagrammatic only.

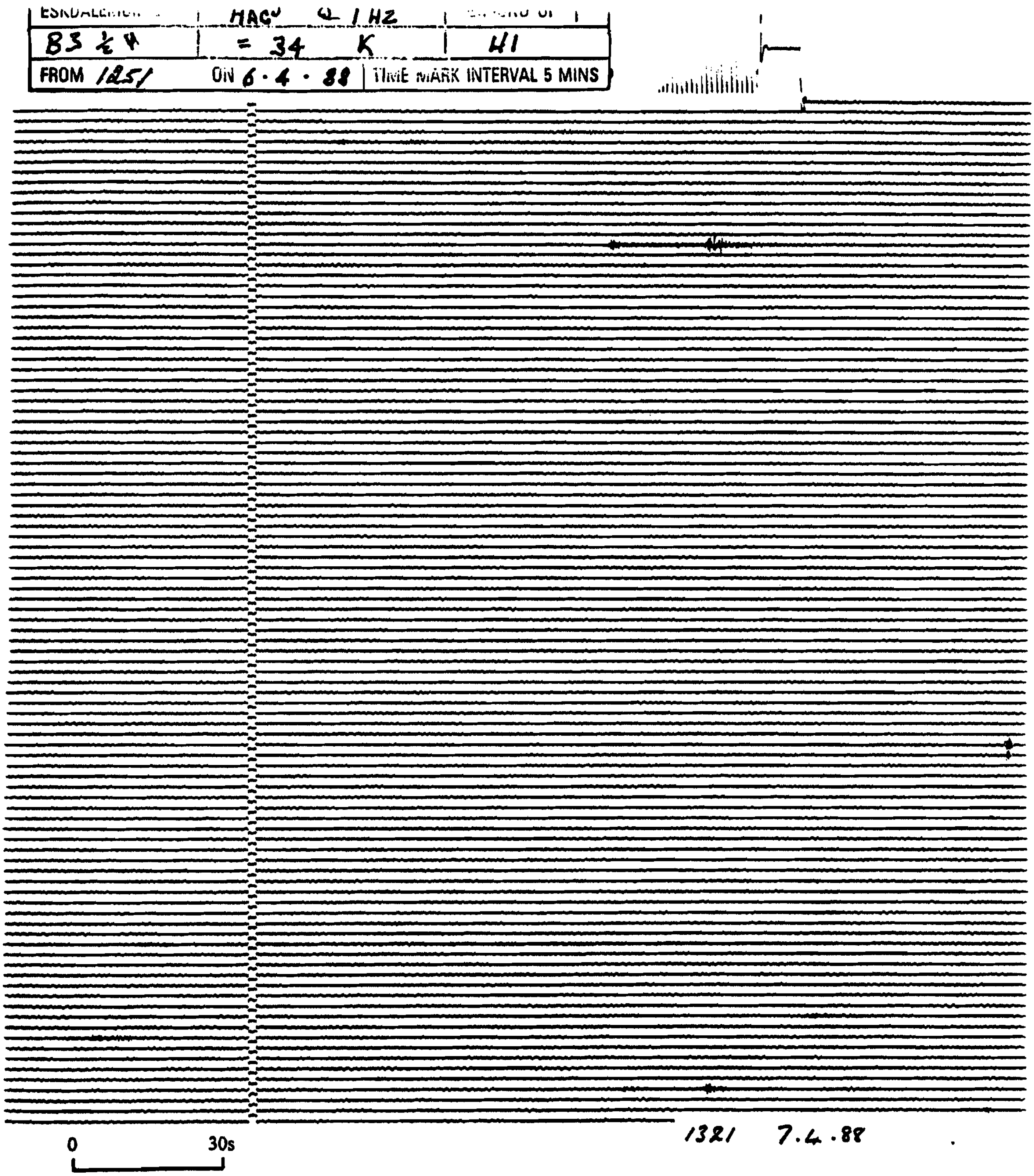


Figure 2 A section of the standard SP chart for 6-7 April 1988.

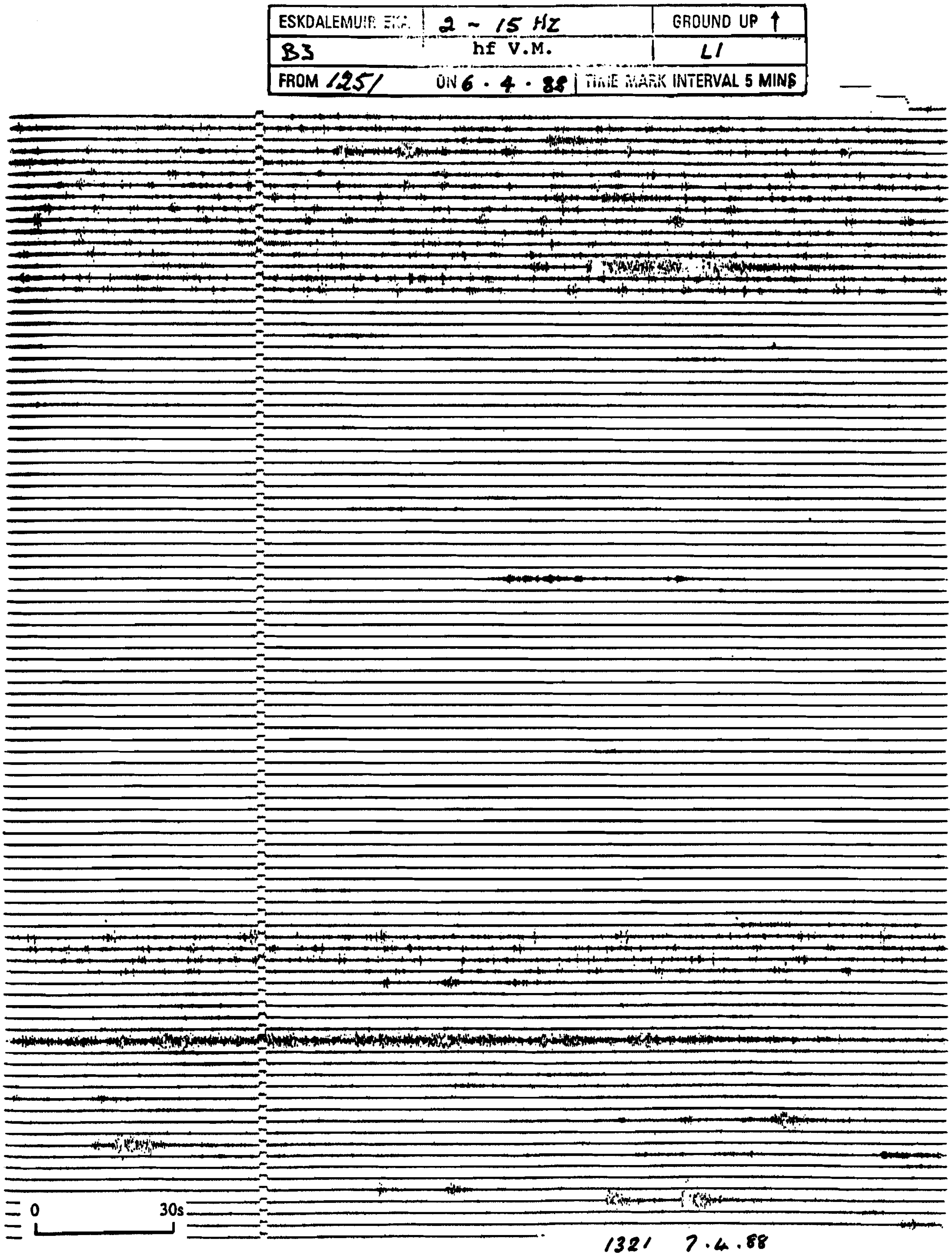


Figure 3 **A section of the high frequency (2-15 Hz) chart for the same period as shown for the SP in Figure 2. Note how this figure shows many more signals than the SP.**

Figure 4 (a)

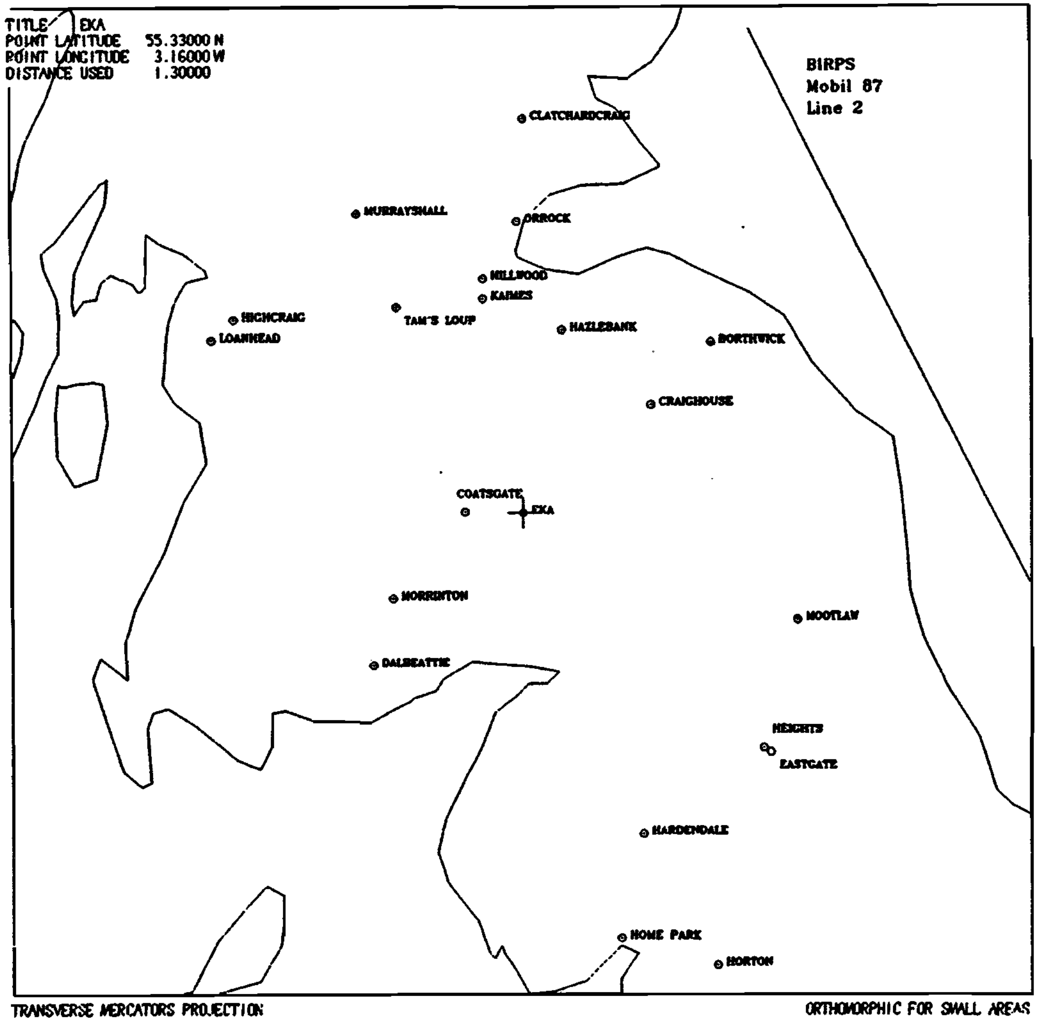


Figure 4 (b)

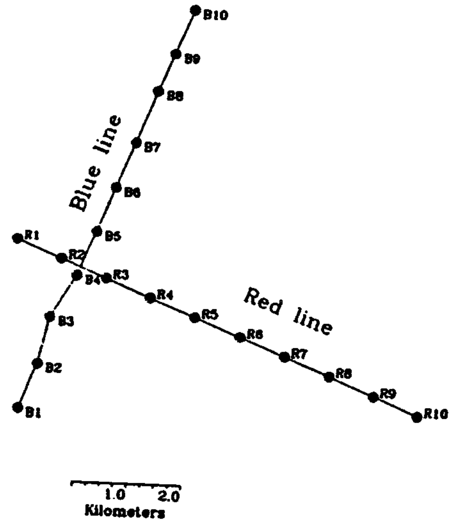


Figure 4 (a) Map showing the location of the Eskdalemuir array and some of the main quarries from which seismic signals are detected at the arrays. Also shown is the survey line (line 2) from the British Institutions Reflection Syndicate: Mobil 87 exercise.

(b) Seismometer lay-out at the Eskdalemuir array.

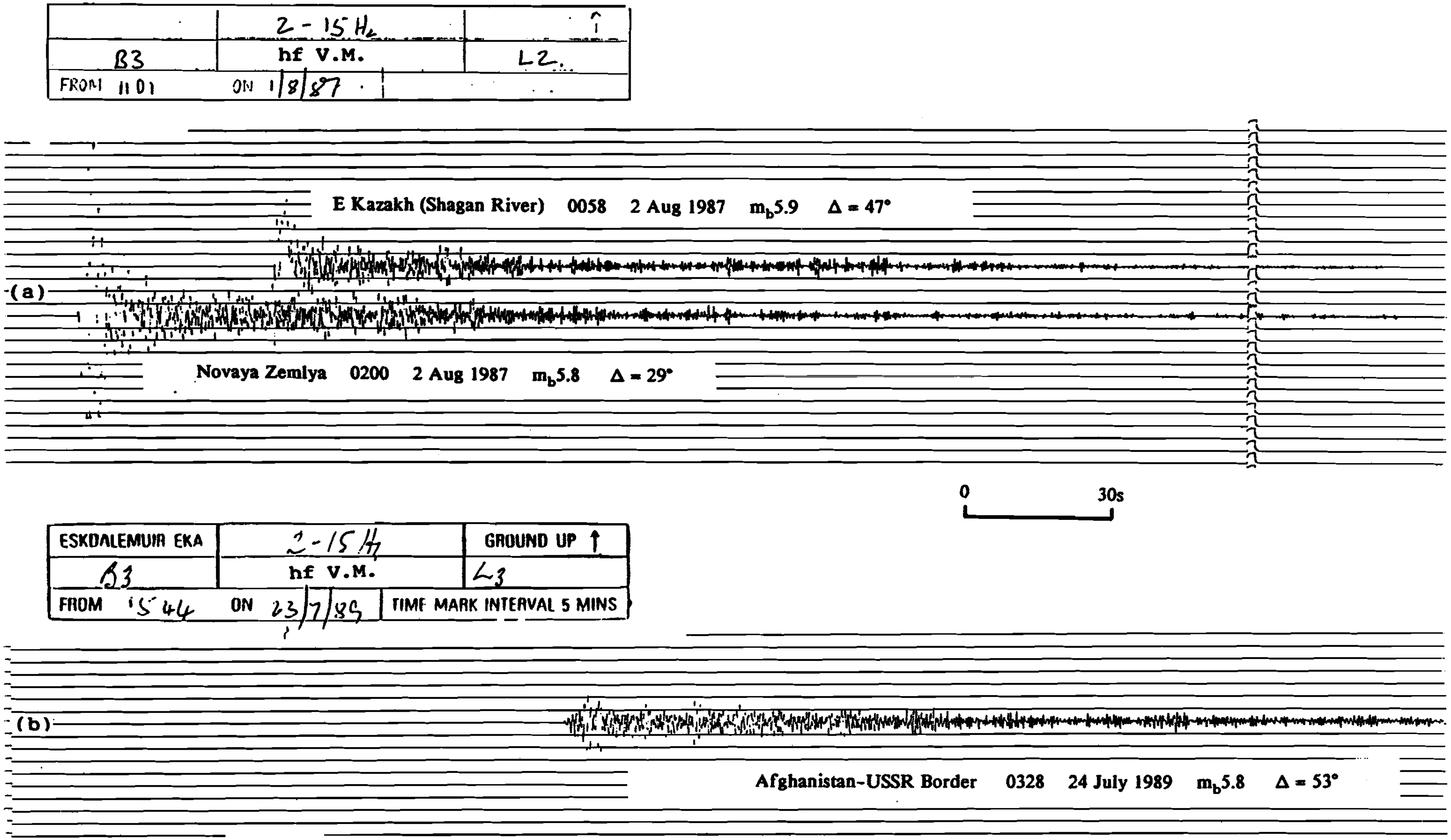


Figure 5 Example of seismograms from seismic disturbances at long range recorded on the high-frequency channel at Eskdalemuir.

(a) P waves from underground explosions in East Kazakhstan and Novaya Zemlya.

(b) P waves from an earthquake on the Afghanistan-USSR border.

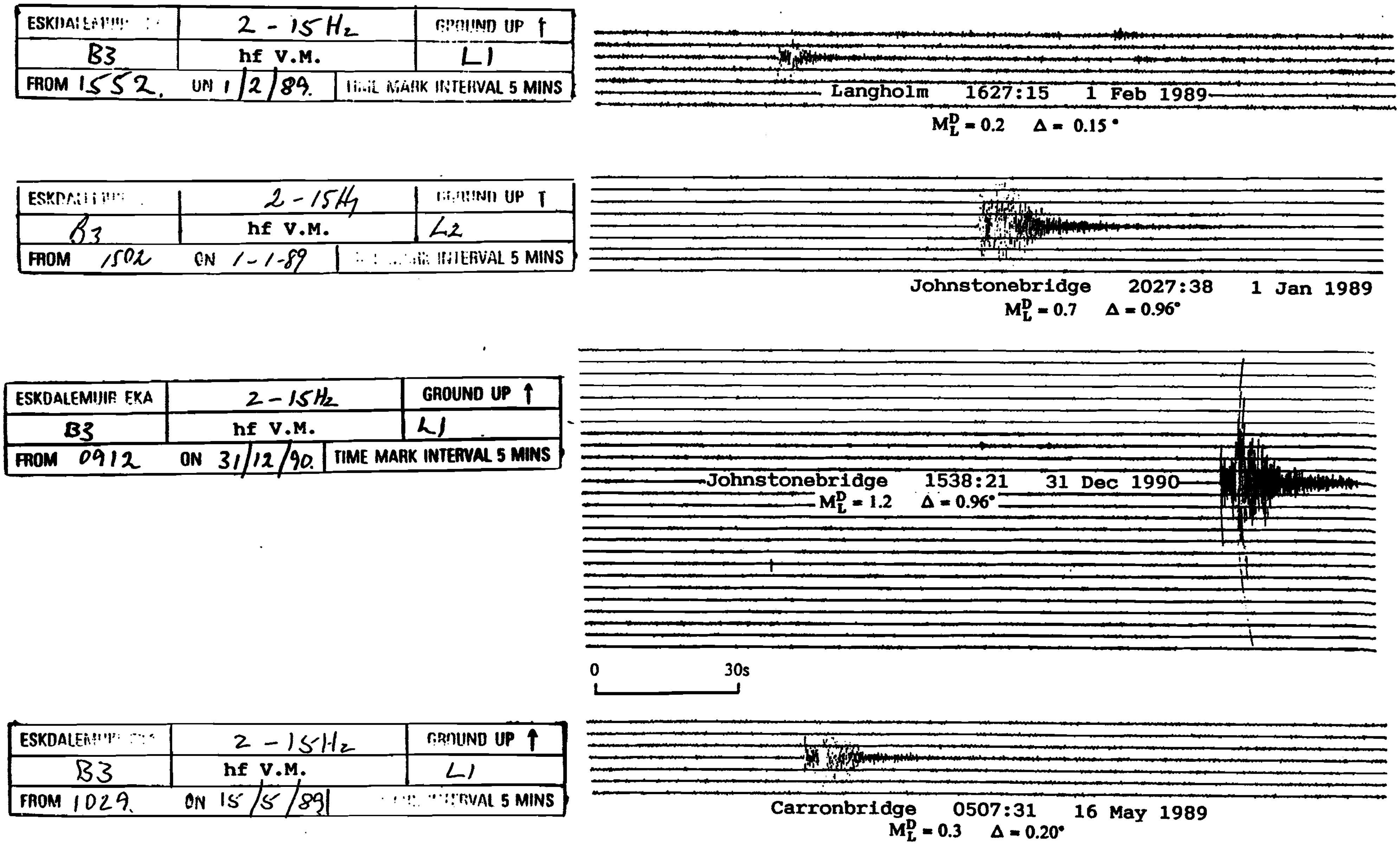
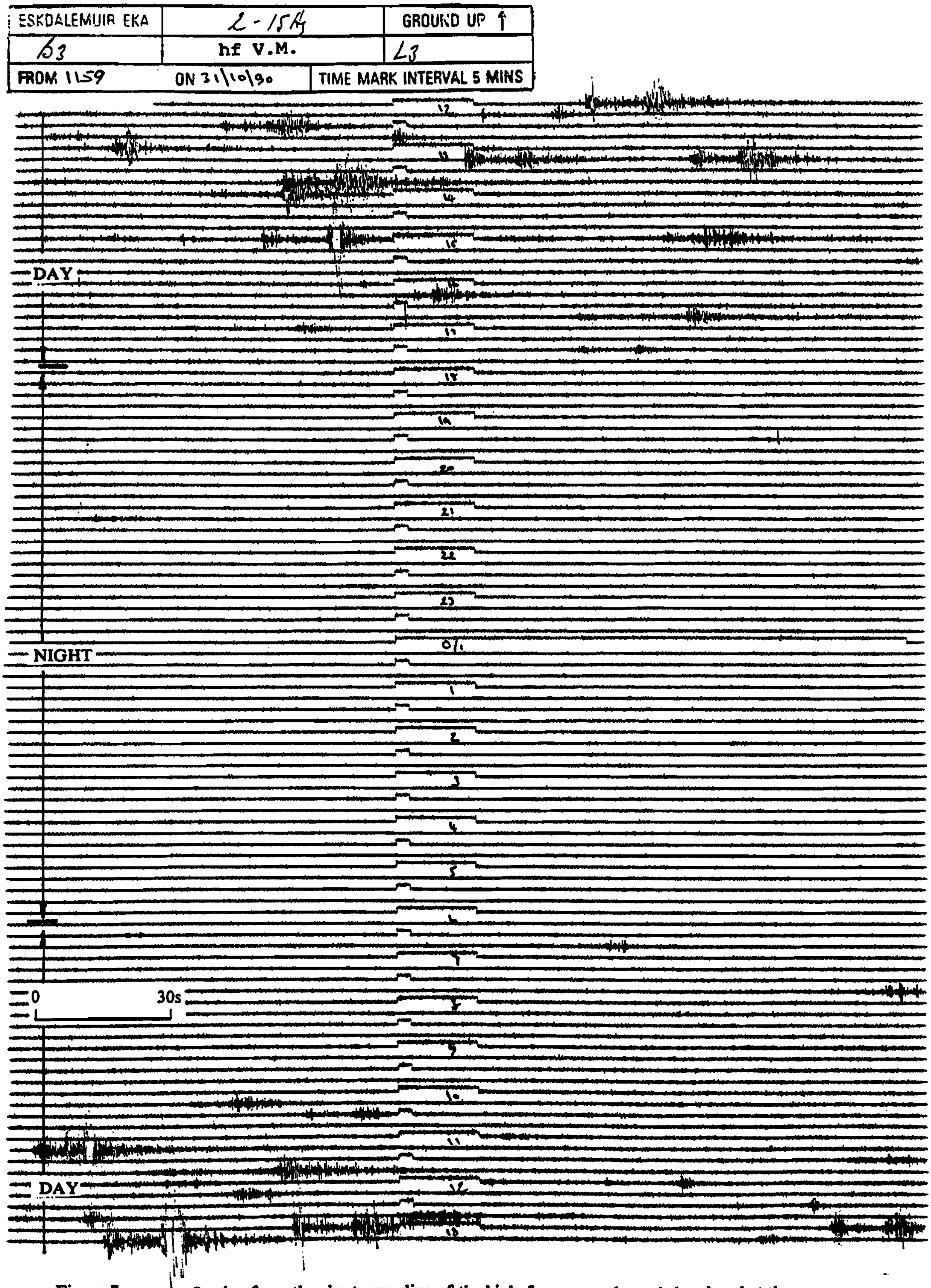


Figure 6 Seismograms recorded at Eskdalemuir on the high-frequency channel from local earthquakes



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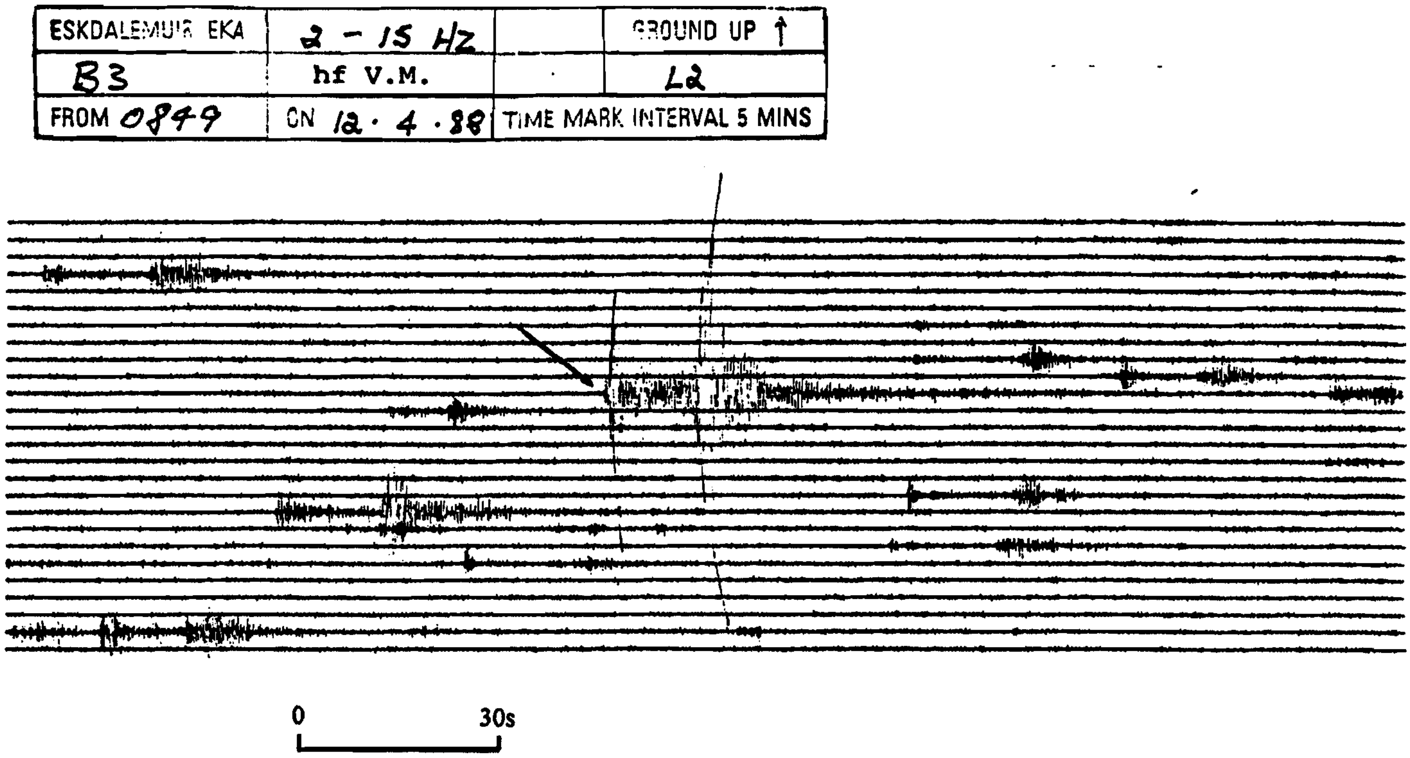

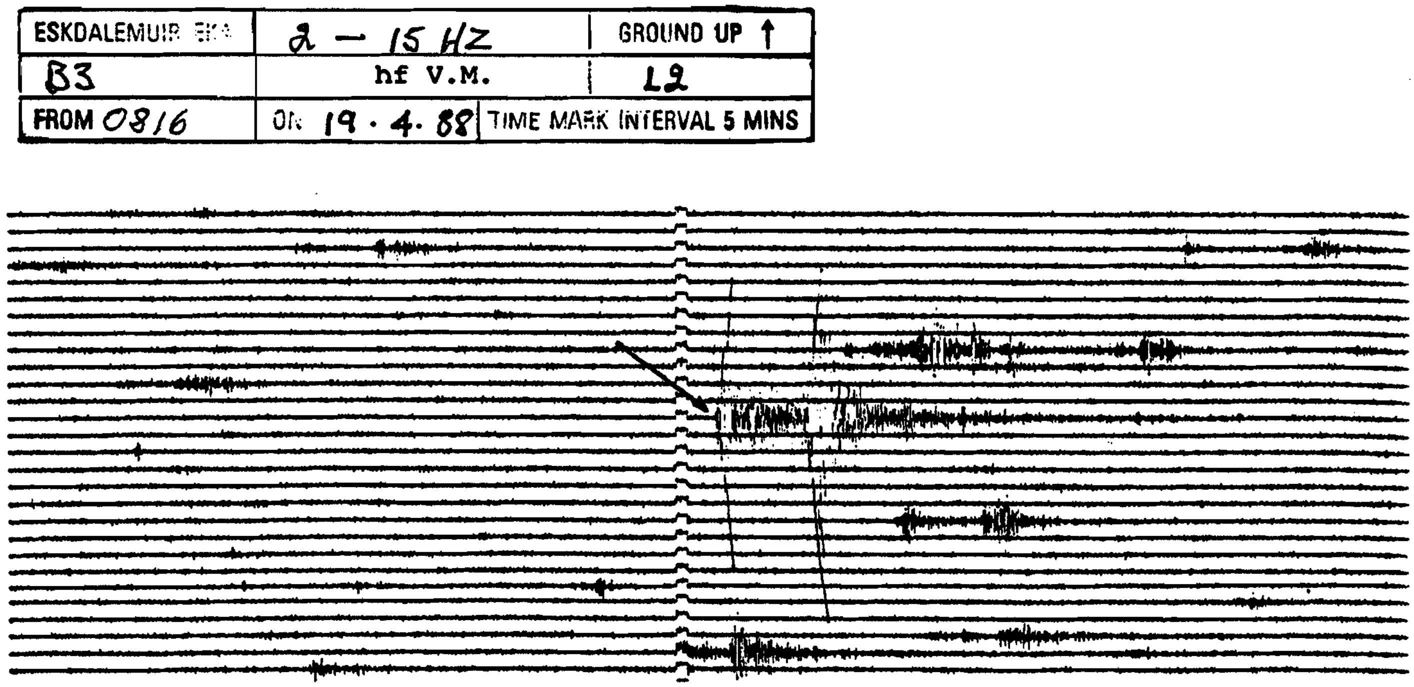

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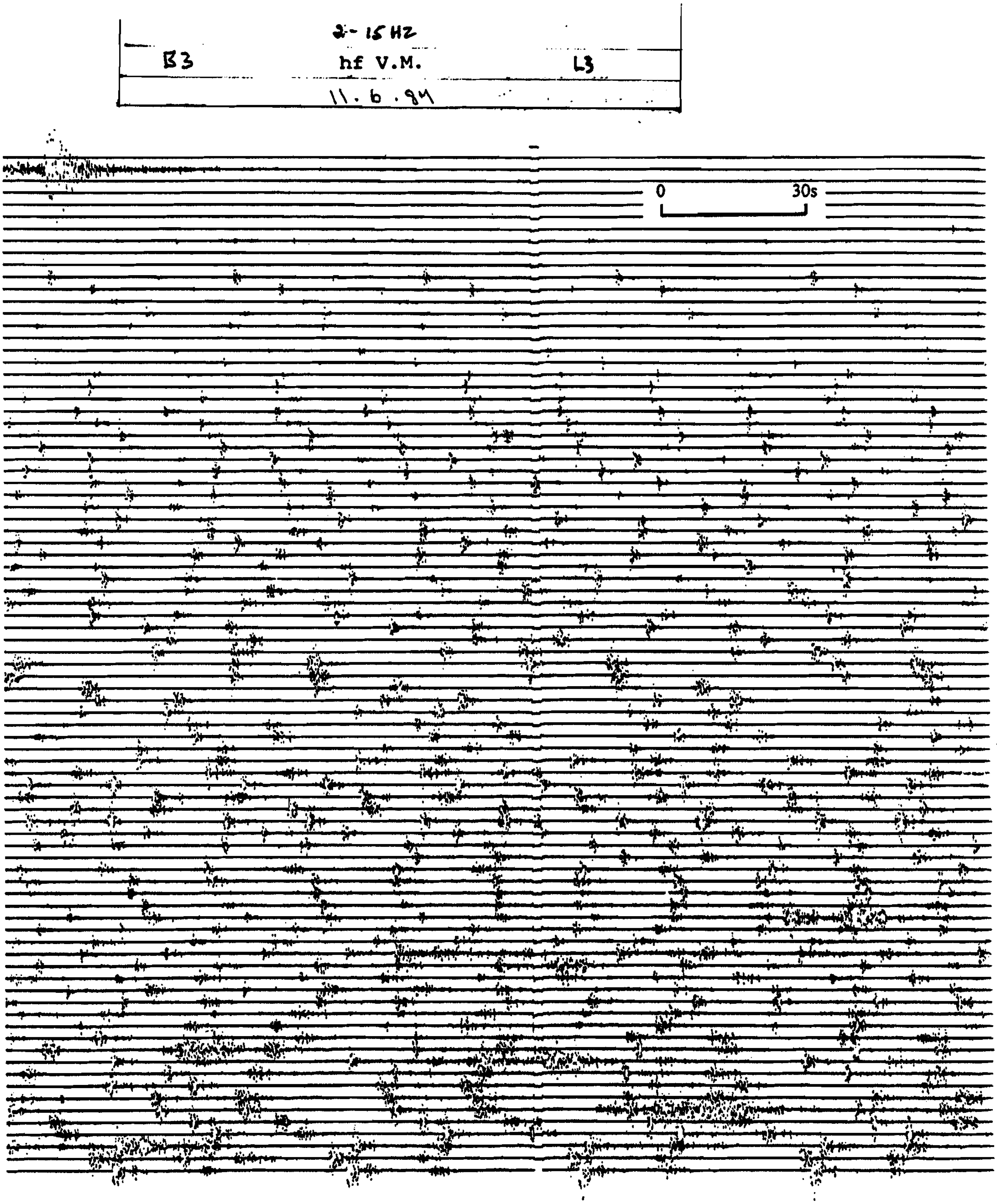

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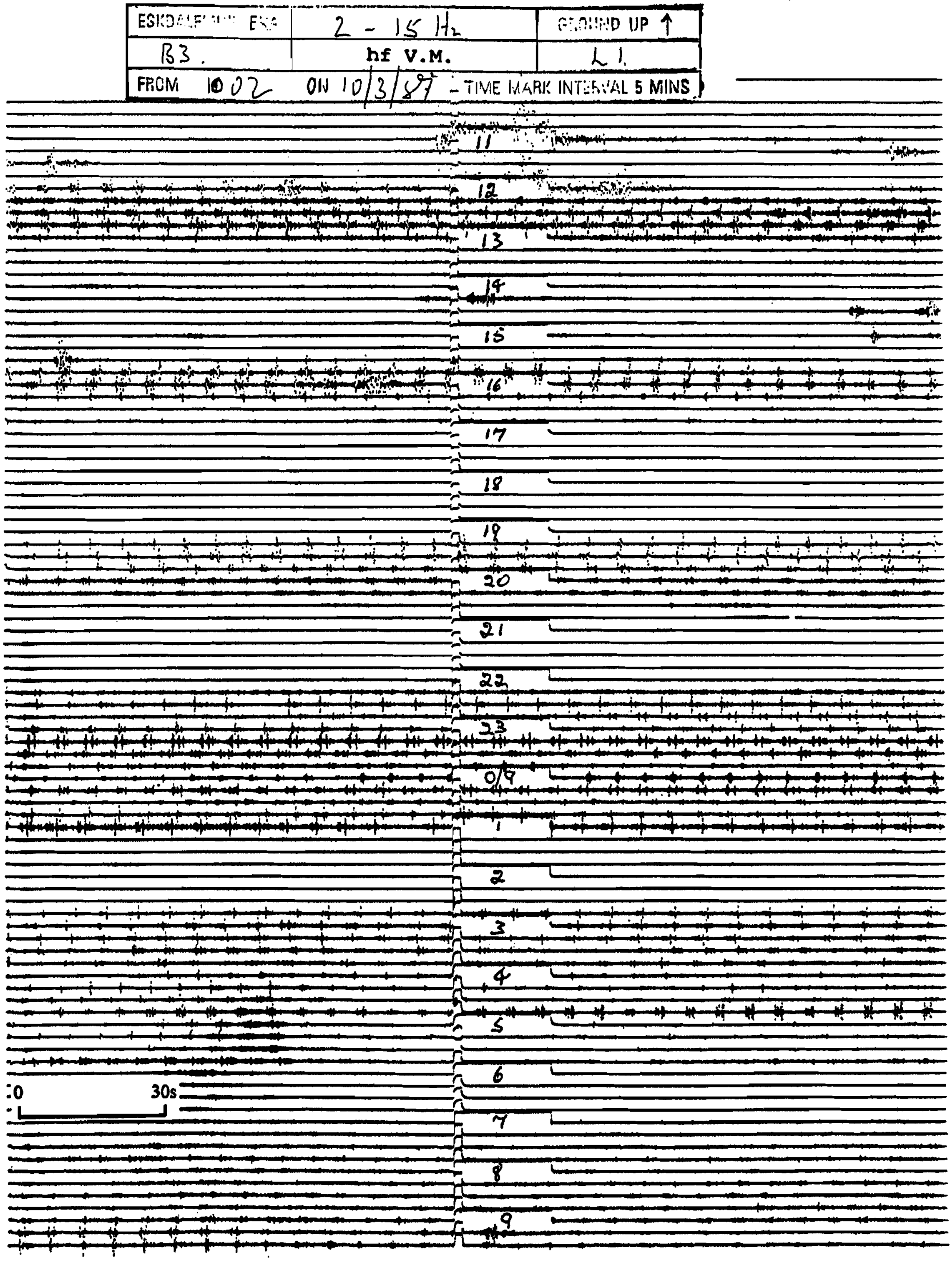

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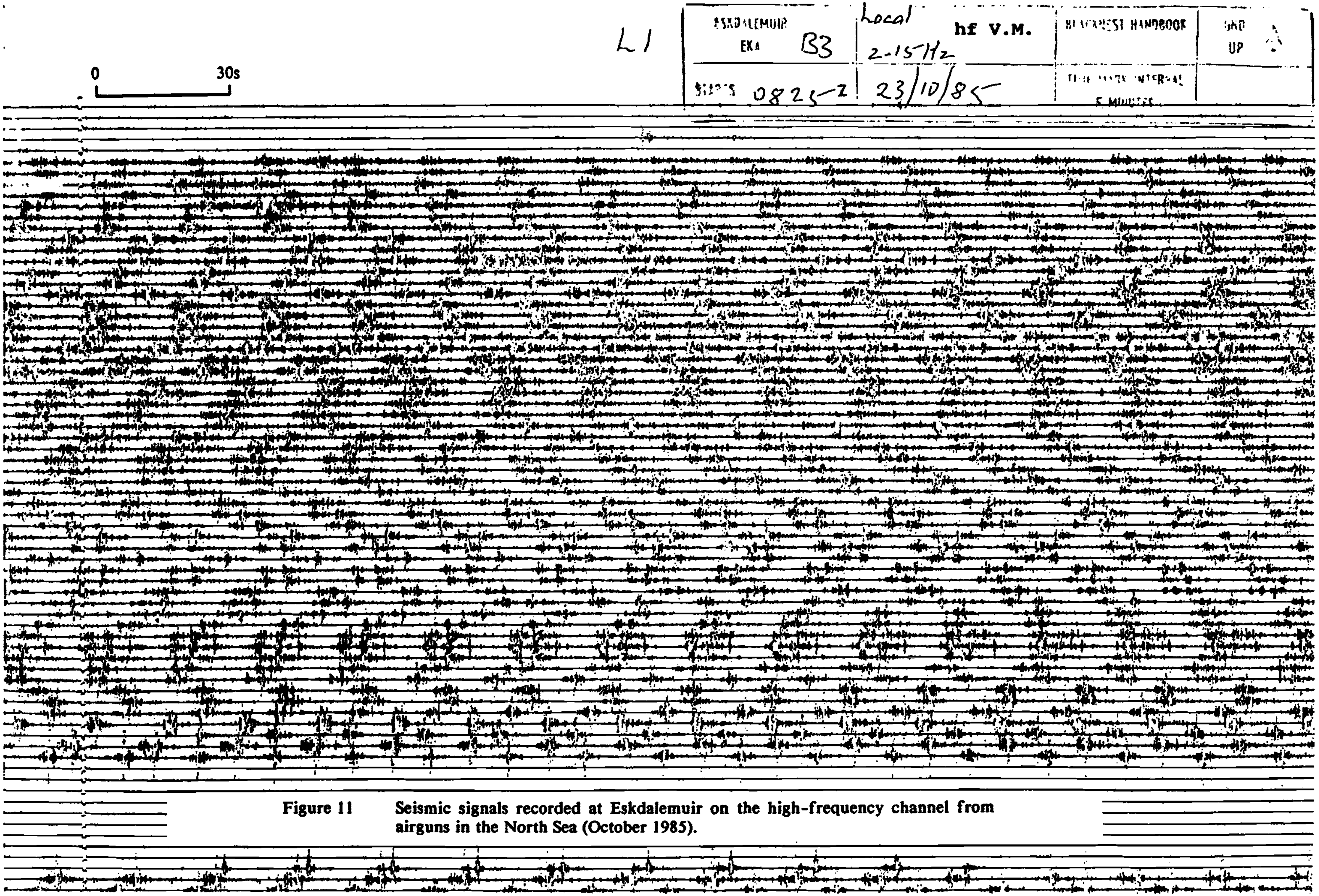

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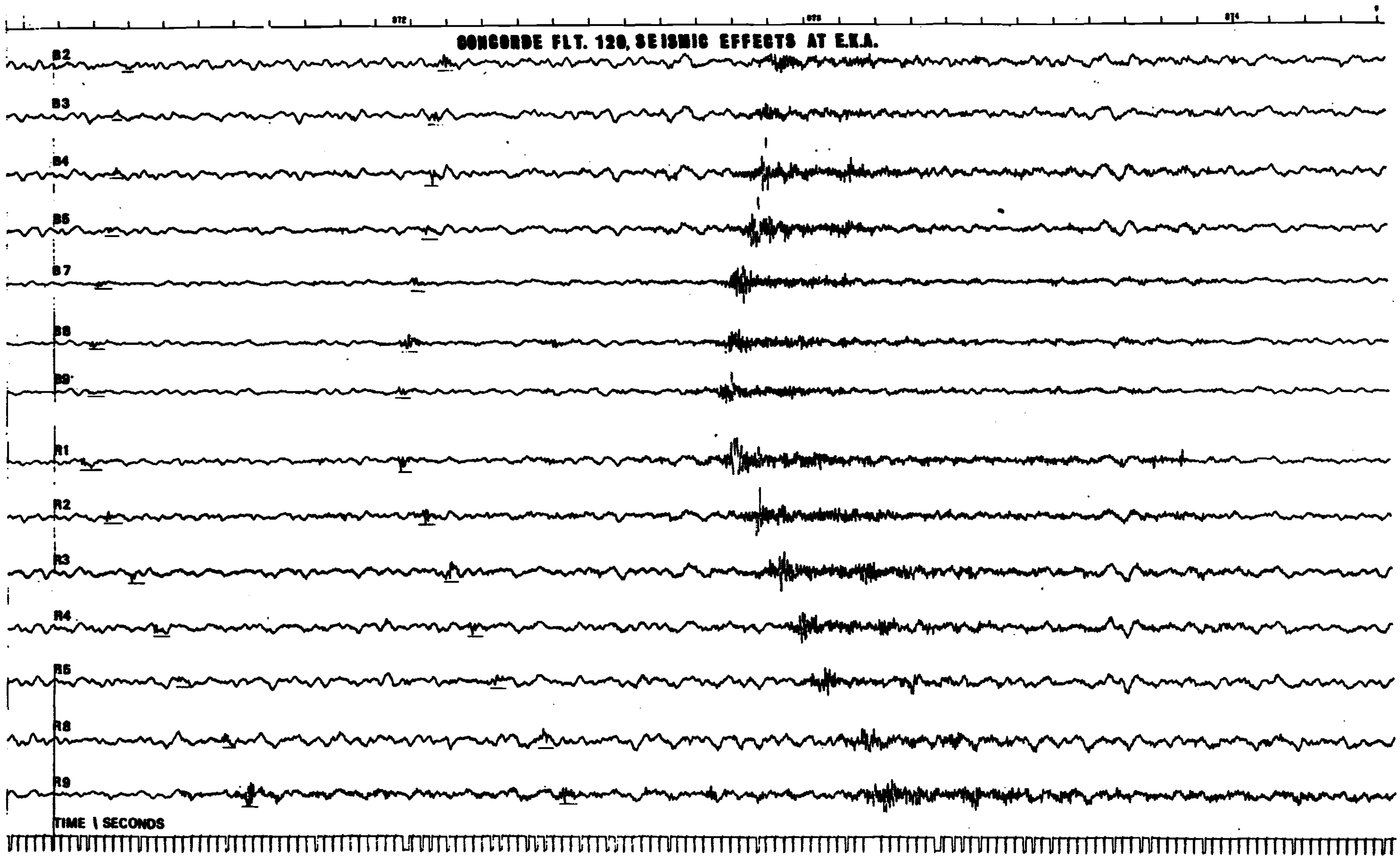

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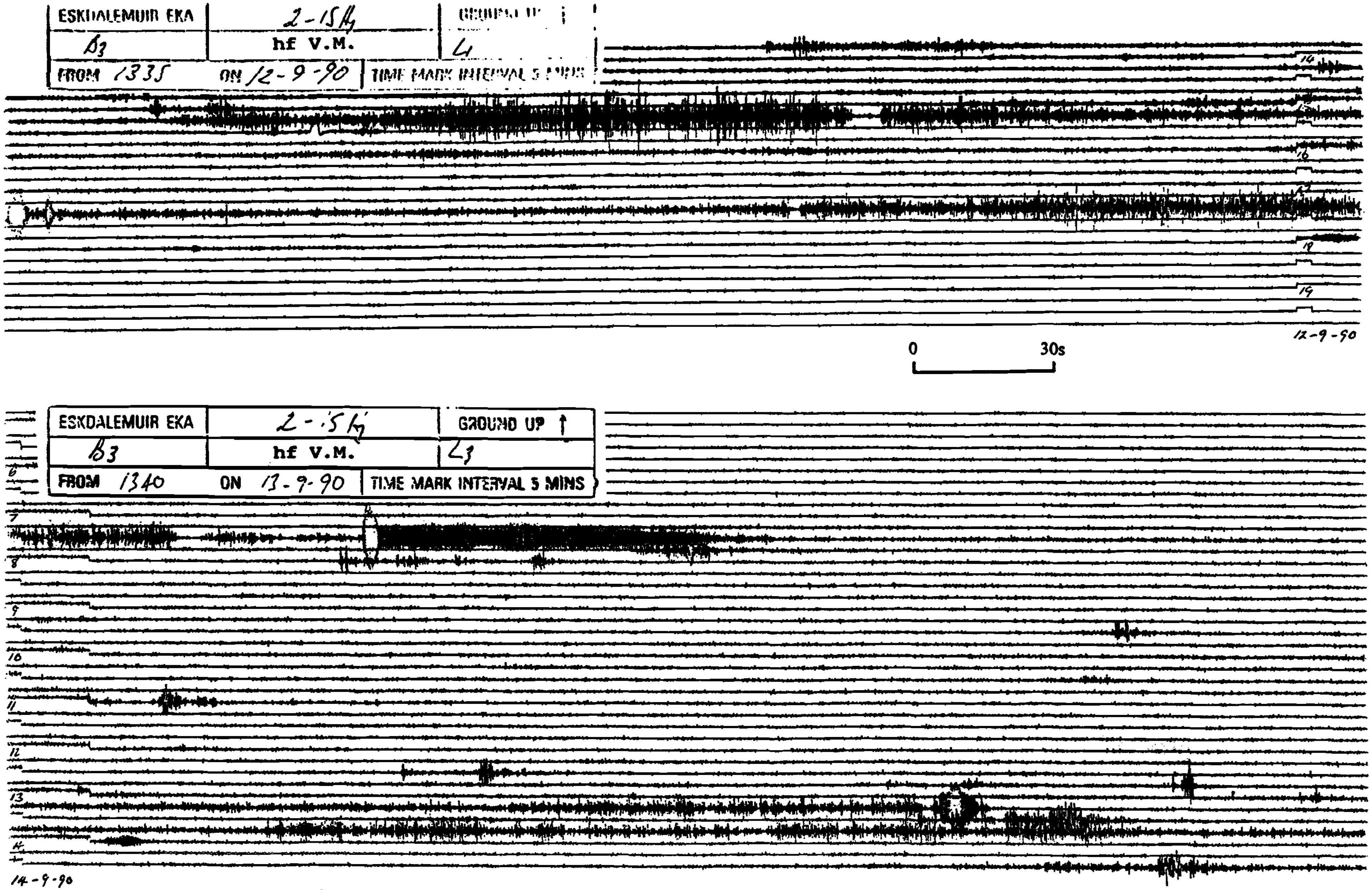

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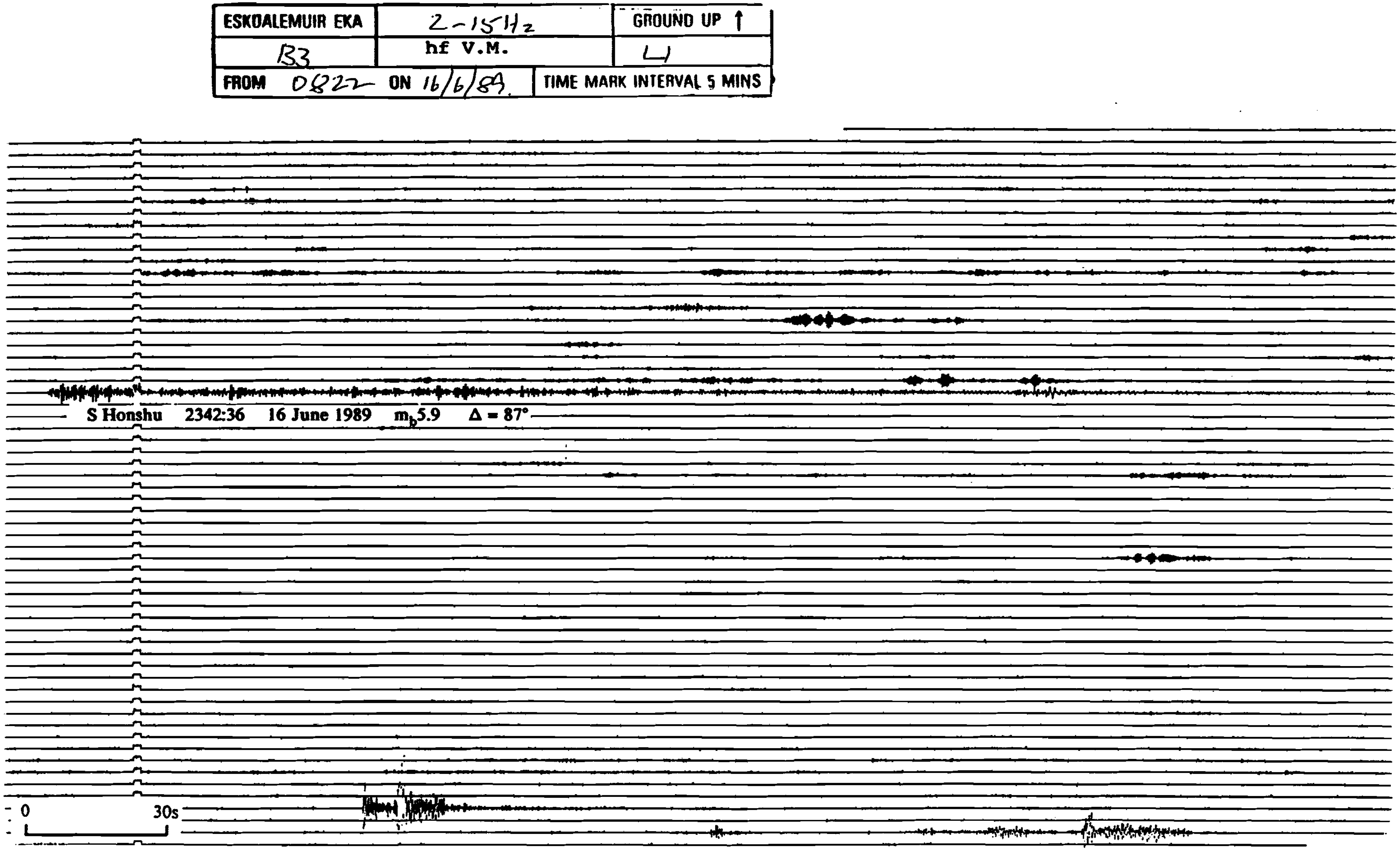

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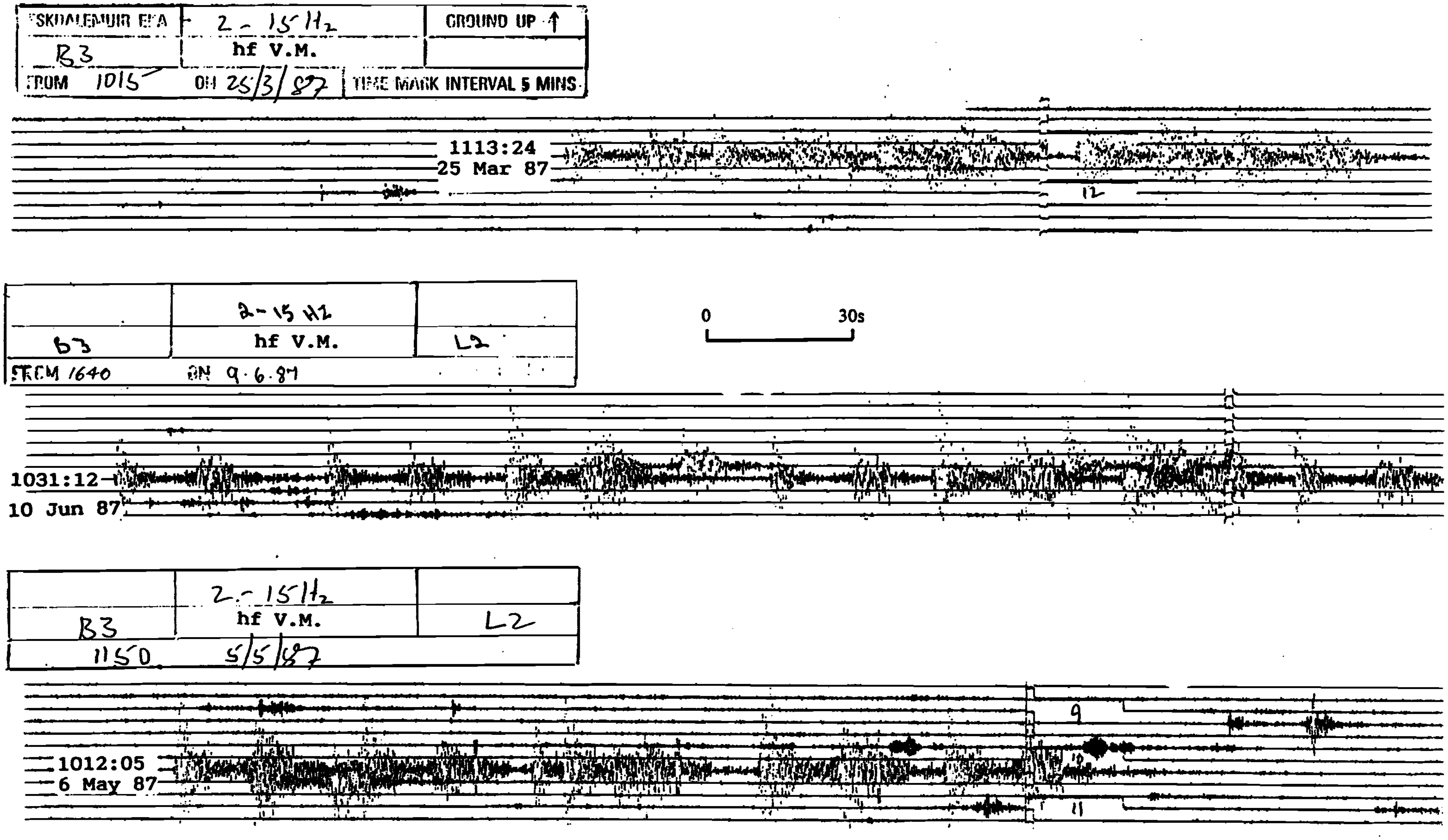

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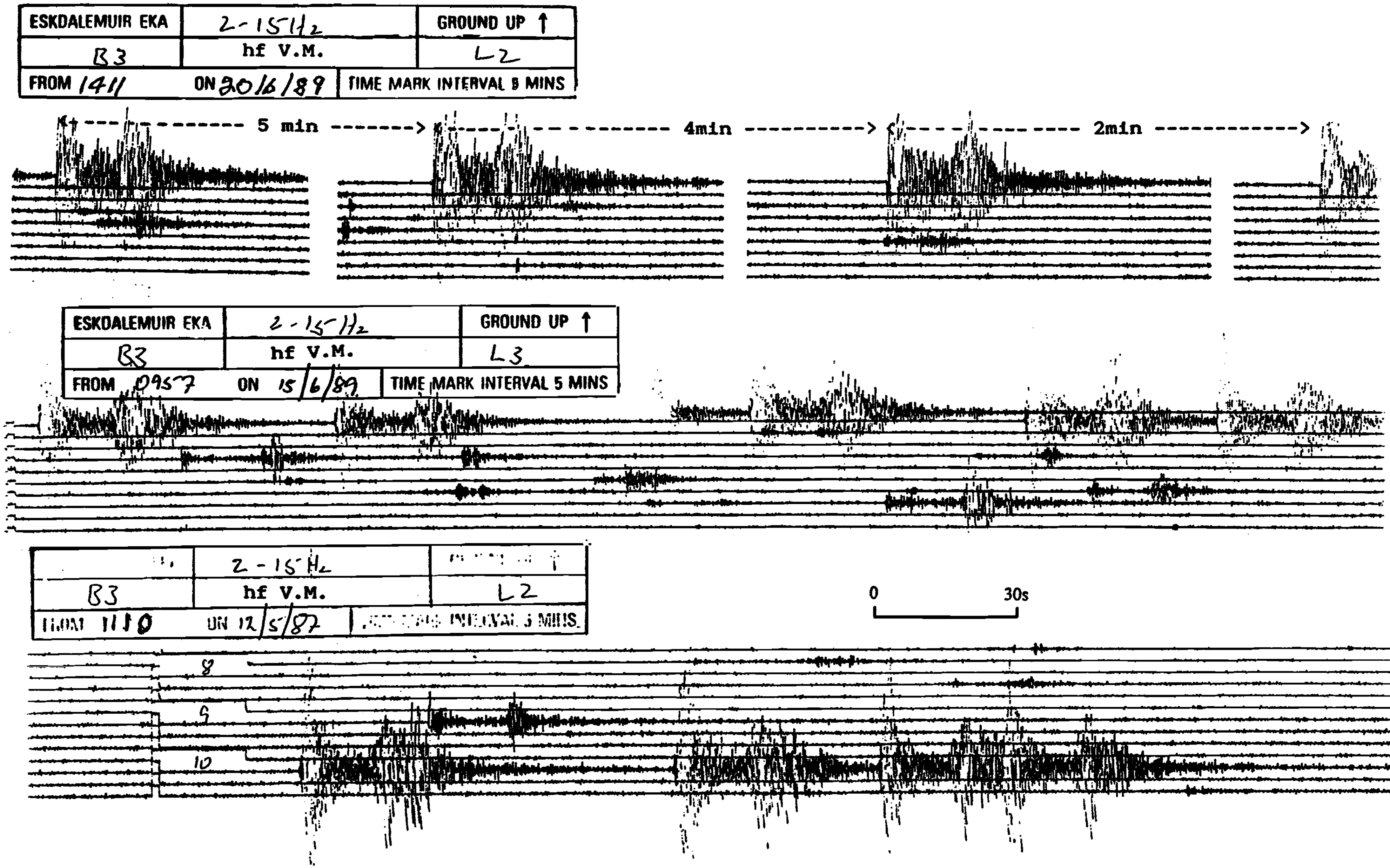

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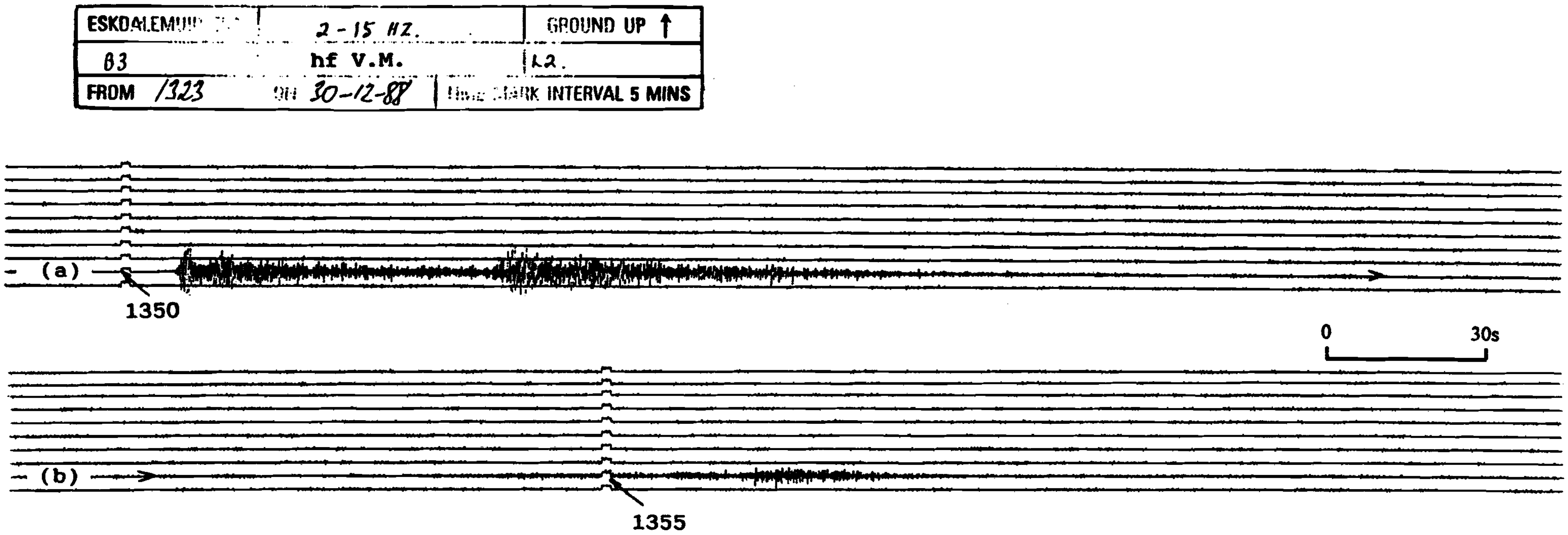

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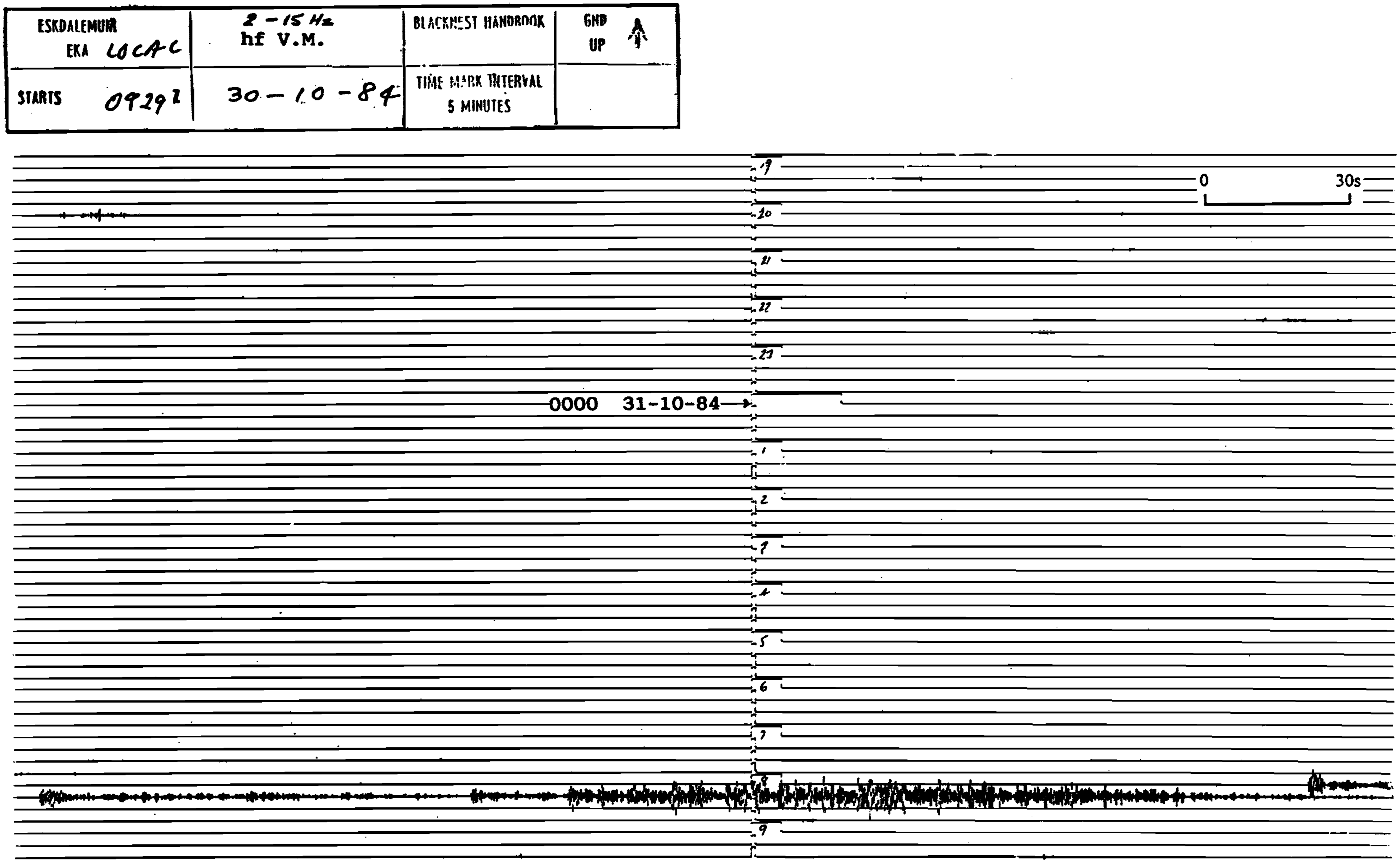

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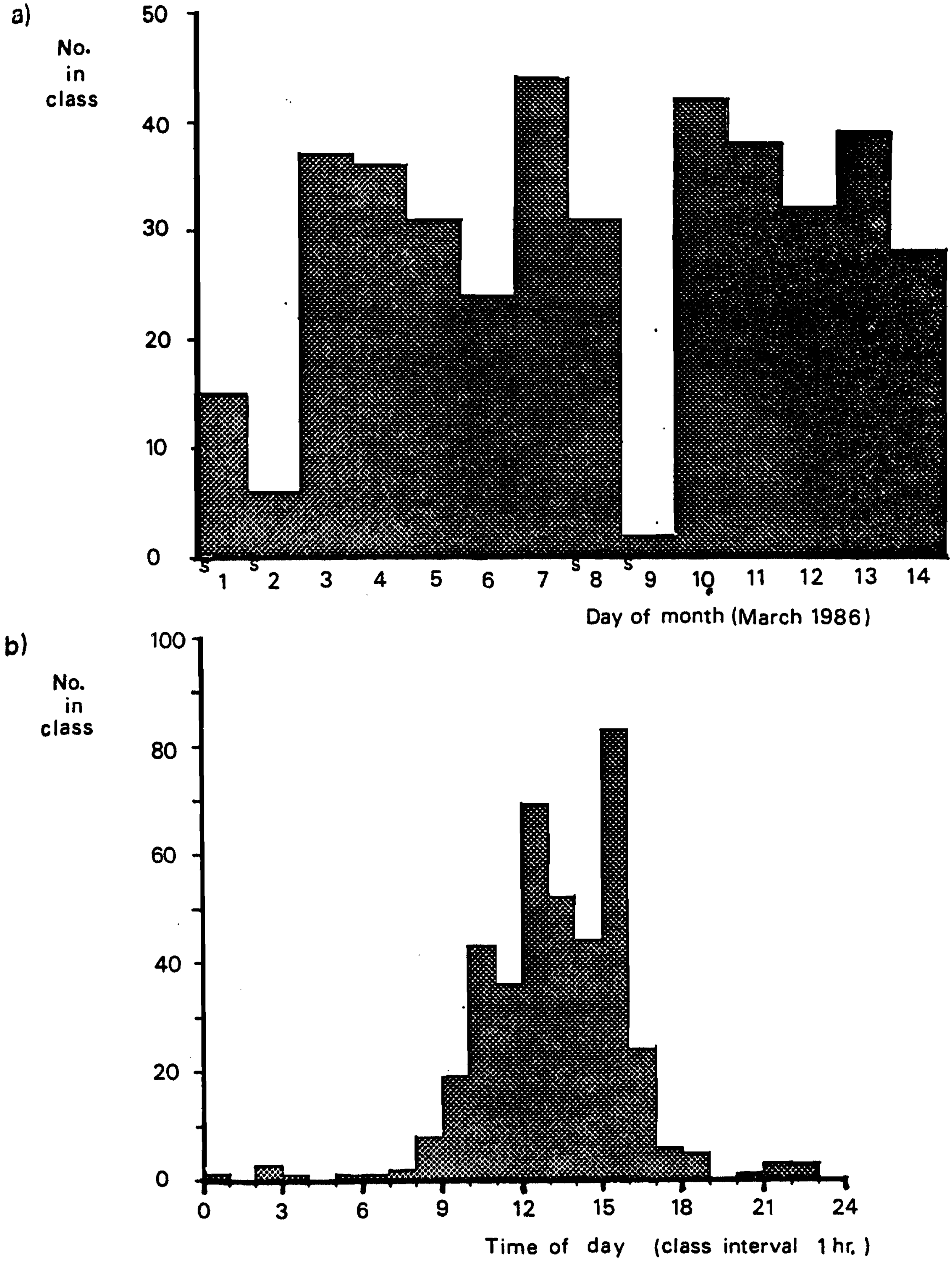

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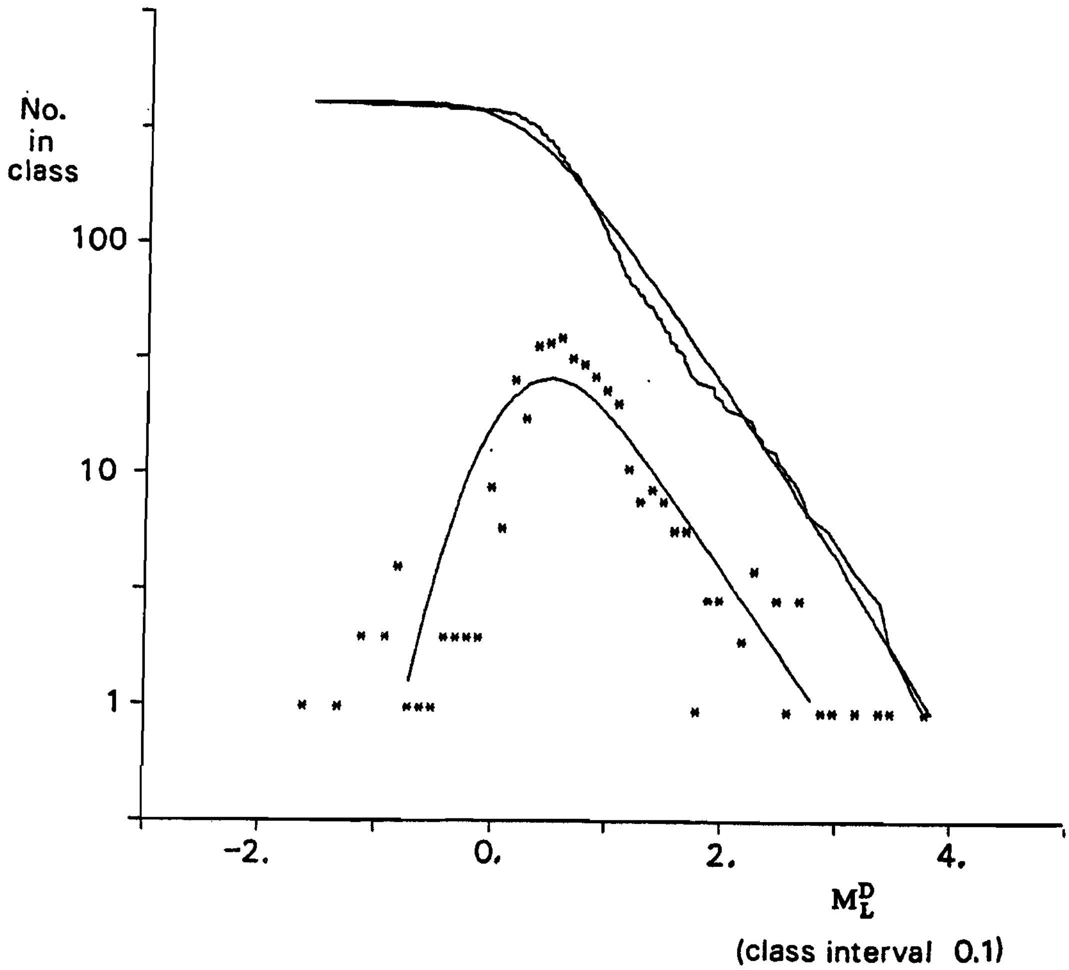

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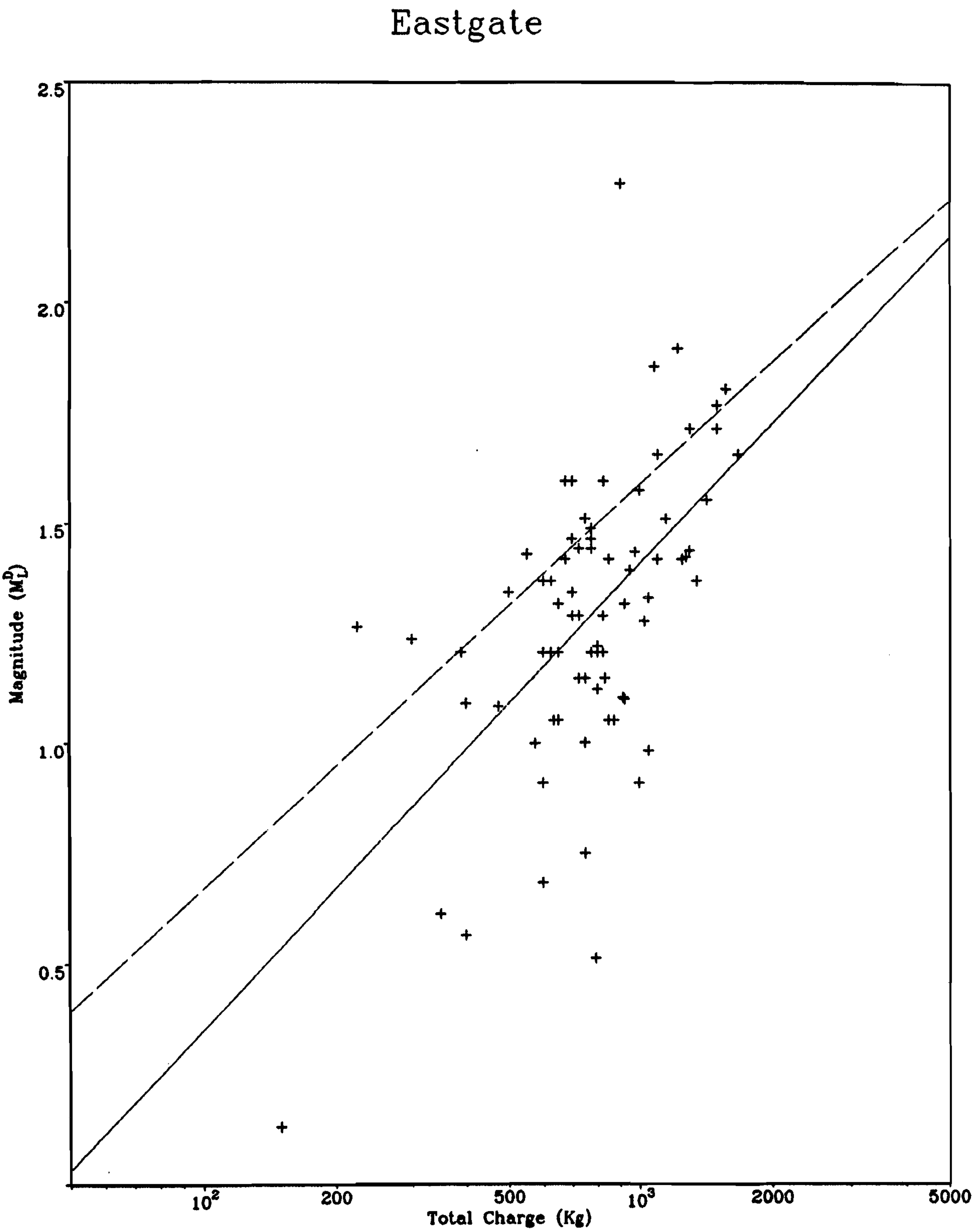

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