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A Survey of Atmospheric Wave Recording at Blacknest

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CONTENTS

SUMMARY

Techniques are described for recording atmospheric waves at the AWRE Blacknest Research Centre.

Examples, with interpretative comments, of various types of atmospheric waves observed over a period of several years are illustrated in a series of figures taken from a representative selection of Blacknest records.

1. INTRODUCTION

For many years microbarographic recordings of very small, relatively rapid fluctuations in atmospheric pressure have been made by AWRE as part of research into the problem of detecting geophysical effects of nuclear weapons tests and discriminating between these effects and those due to other causes. During the past decade, this work has been based at the Blacknest Research Centre where observation of atmospheric waves has been complementary to the main activities in detection seismology.

Of particular interest among the many observed perturbations of atmospheric pressure are disturbances which originate from man-made sources, such as large explosions in the atmosphere, flights of supersonic aircraft and the passage of space vehicles, as well as from natural events, such as large earthquakes. Very low frequency components of the acoustic energy from such sources can be propagated to great distances from the point of origin with relatively low attenuation and are sensed at distant receiving stations as spatially coherent pressure waves with periods in the range 1 to 1000 s and horizontal velocities over the ground surface close to the speed of sound in air.

The purpose of this report is to give a brief description of microbarometric data recording facilities based at Blacknest for the routine monitoring of atmospheric wave phenomena and to give examples of effects observed over several years from various types of events. Some discussion and interpretation of the records is given in the text adjacent to the illustrations.

2. TERMINOLOGY

A universally consistent terminology has not yet been established in the atmospheric wave literature, although a useful summary of nomenclature and types of waves has been given by Georges and Young [1]. The terminology used in this report follows that adopted in previous Blacknest publications in this field and in the following notes some brief outline definitions are given:-

Infrasonic Waves:	Atmospheric waves which travel at sonic speed but are inaudible. This is a convenient description for denoting any of the modes of acoustic-gravity waves which fall within the stated band of interest since only a common property of the waves and not the mechanism of propagation is implied.
Units of Pressure:	The International System (SI) unit for the measurement of pressure is the Newton per square metre, but a number of other units may be encountered in references to the observed amplitudes of atmospheric wave pressure fluctuations. The relationship between the various units in use is:- 1 Newton per square metre (N/m^2) = 1 Pascal (Pa) = 10^{-2} millibar (mb) = 10 microbar (μb) = 10 dynes per square centimetre (dyn/cm^2) ~~= 9.869 standard atmospheres (atm)~~ = 9.869×10^{-6} standard atmospheres (atm)
Dynamic Range:	The dynamic range over which an infrasonic-wave recording system operating within a pass-band of 1 to 10000 s must function extends from amplitudes of the order of 50 N/m^2 for some relatively infrequent large-scale events down to levels well below 0.1 N/m^2 where an ultimate limit of resolution for weak infrasonic waves is imposed by the noise characteristics of the recording system.
Background Noise:	In practice it is the ambient "background noise" of the atmosphere rather than the electrical noise of the recording system which is the principal factor governing the detection of wanted infrasonic signals. Atmospheric noise varies widely with meteorological conditions, originates from a variety of sources and includes in this context some components due to unwanted infrasonic waves. The principal and most obvious components of background noise, however, are usually those due to the local wind.
Arrays:	At a single recording point it may be difficult to identify a particular infrasonic signal among the many other pressure fluctuations of similar frequency content to the signal. This difficulty can be lessened by sensing the pressure at a number of points in an array of suitable spacing and dimensions in order to exploit the differences in velocity, wavelength and waveform coherence which exist between organised coherent infrasonic waves and the various other wave-like components of atmospheric background noise.

Passive Array: The description "array" has sometimes been used in references to purely mechanical-acoustic devices which have distributed pressure sensing inlet geometry but offer no provision for display or time-shifting of individual acoustic signal waveforms sensed at the separate sensing inlet points. A more specific name "passive array" was therefore introduced in an earlier note [2] to designate an inert assembly, such as the original Daniels' type of line microphone [3] or the noise reducing pipe filter described in section 3.6 of this report, in order to differentiate between arrays of that type and more complex systems which make provision for separate handling and processing of signals from individual array positions.

Active Array: An active array can be defined as a system which provides facilities for individually recording infrasonic acoustic signals which appear at well-separated sampling points. Thereby, improved detection and directional estimates are obtained for wanted signals either by direct observation of time relationships of the individually registered wave traces or by further processing of the recorded data. In comparison to the limited dimensions feasible for passive arrays, the size of an active array can be increased (within the constraint of spatial coherence of wanted signals) to dimensions which are optimum for noise rejection and azimuthal determination of detected waves.

Post-recording processes involving bandpass filtering, summation of individual array signals after time-shifting according to their position in the array and cross-correlation of partial sums, can be applied to the output of an active array with consequent improvements in signal-to-noise ratio, detection capability and azimuth determination.

3. DESCRIPTION OF THE BLACKNEST MICROBAROGRAPH ARRAY

3.1 Array configuration and location

The Blacknest microbarograph array uses a combination of both passive and active array principles and consists of a network of sites which function as nodes of an active array linked to a recording centre at Blacknest. In addition, at each site of the network the sensing instrument is associated with a local passive array.

The positions of the 22 instrument sites comprising the complete network are shown in figure 1. Eighteen of these sites are in an "inner zone" group lying within a radius of 10 km from the array recording station at Blacknest centre. The remaining four sites form a sub-group lying to the south-west of the main group at between 30 to

45 km from the array centre point. Normally a maximum of twenty of the available sites in the network are maintained in operation for microbarographic recording.

The co-ordinates of the centre point are:-

Geographic:	51 21 50.8N 01 11 12.8W
Grid:	E456637 N163132

3.2 Array site installations

Each site has a 250 VAC mains supply and a leased telephone line connection for fm telemetry of data to the central recording station. The on-site recording instruments are housed in cylindrical emplacements fabricated from glass fibre-reinforced polymer buried to a depth of 6 ft to provide both temperature stability and security for the equipment. Figure 2 illustrates the arrangement.

The lower chamber of the emplacement houses the pressure sensing instrument assembly which is relatively small but is installed within a larger outer container of fabricated polyurethane which provides further insulation from temperature changes. A smaller cylindrical compartment houses a telemetry unit and forms a simple air lock under a manhole access cover at ground surface level.

3.3 Pressure sensor

The basic instrument which senses the small variations in atmospheric pressure associated with infrasonic waves is a sensitive microbarometer. This instrument produces an electrical output signal proportional to the difference between the ambient pressure at its atmospheric input and the pressure existing in an internal reference volume. A small air leak between the reference volume and atmosphere governs the overall low frequency response of the system and isolates it from the effect of large long-term barometric changes.

The electrical signal is produced by a solid state linear variable differential transformer in which the output varies according to the position of a mu-metal slug in the core of the transducer; the slug is attached to the free end of a flexible metal bellows which undergoes length changes in proportion to pressure differences between the atmosphere and the reference volume which also acts as a backing volume for the bellows.

3.4 Container and calibrator

The microbarometer is housed in a die-cast containing vessel which acts as a protective housing, heat sink and calibrating tank. This vessel can be sealed from the atmosphere by a solenoid-operated valve and small sinusoidal changes can then be made to the sealed volume by means of a motor drive bellows situated in the lid of the tank, thereby generating corresponding pressure variations. This pressure waveform is used to calibrate the instrument and associated recording system.

The operations of sealing the tank and driving the bellows motor are usually carried out at intervals pre-selected by an automatic sequence controller. A sequence which provides weekly calibrations with waveforms of 5 N/m^2 peak-to-peak amplitude and periods of 15 and 120 s is normally preset from a number of possible options of amplitude, period and sequence interval. A sectional view of the microbarometer and calibrator assembly is given in figure 3.

3.5 Signal telemetry

The electrical output signal from the microbarometer is fed to an fm sender unit which is housed in the upper compartment of the array site emplacement. This unit controls the signal telemetry and calibration functions for the microbarometer and provides all necessary power supplies.

In the fm sender the incoming signal is amplified and separated into two frequency bands by bandpass filters. The two resulting channels, designated wide band and narrow band, cover signal components of 1 to 1000 s period and 1 to 60 s period respectively. The outputs of these two filtered channels are used to modulate two carrier frequencies which are combined and transmitted to the recording centre at Blacknest via a Post Office line pair.

A full description of the fm sender system is given in reference [4].

3.6 Noise reducing pipe filter

The various elements from atmospheric input to station recorder output for one of the twenty channels of the microbarograph array are represented diagrammatically in figure 2. It can be seen that the microbarometer is not connected directly to the atmosphere but that its input is instead connected to a circular pipe lying on the ground. The pipe, which is constructed of 50 mm bore polythene tubing, has 120 capillary inlets spaced at 3 m intervals around its circumference and acts as a spatially distributed filter providing a reduction of short period background noise.

Unwanted atmospheric noise arises principally from random fluctuations of pressure associated with local wind turbulence. A wanted signal may be masked by the noise at a single recording point and frequency filtering is often ineffective as the noise spectrum contains frequency components similar to those seen in many acoustic signals. By sampling the atmospheric pressure at a number of distributed points, the pipe filter tends to cancel non-coherent noise components passing to the microbarograph input feeder pipe. On the other hand, pressure changes appearing at the pipe inlets as a result of the passage of infrasonic acoustic waves remain coherent because the wavelengths are large in comparison with dimensions of the array of inlets.

The signal-to-noise improvement obtained from the pipe filter depends on several factors, including the variability of wind speed. Full details of design considerations are given in references [2] and [5].

3.7 Recording centre and available records

Post Office telephone lines from the microbarograph array sites are terminated at the Blacknest recording centre where the dual modulated carrier frequency outputs from each line are fed via line balancing transformers to carrier separation filters. After separation, the two carriers, modulated respectively by wide and narrow band signal information, are passed to frequency dividers. These divide the centre frequencies of the carriers down to the value required by the tape head drive stages of two 24 channel fm analogue tape recorders running at 0.075 in./s. At this speed the recording time per tape reel is 14 days. The recorded wide and narrow band 1 in. wide data tapes are retained for two years before being erased, though certain events are transcribed to an edited library tape for retention.

In addition to the magnetic tape records, the wide and narrow band data are recorded by two drum recorders each of which produces a record, written helically by a heat stylus on sensitive paper every 24 hours. These helicorder charts provide a single channel monitor for routine daily analyses of data from one site of the array; they are stored for reference. An eight channel heat-stylus recorder is available when required for on-line monitoring of selected array channels.

Accurate timing for both tape and chart records is obtained from a time encoder which produces a version of the VELA time code used in seismological data recording. A "slow" code is used for the chart records.

Calibration waveforms, automatically generated at the array recording sites as described in section 3.4, are preset to occur on one day each week in sequence across the array. These waveforms, which can be replayed at any time, with the related signal data from the magnetic tape records, are monitored each week. This provides a useful on-line check of the amplitude response of each system channel from microbarograph to recording medium at two spot periods of the overall bandwidth. Amplitude response curves of the system for both wide and narrow bands are given in figure 4.

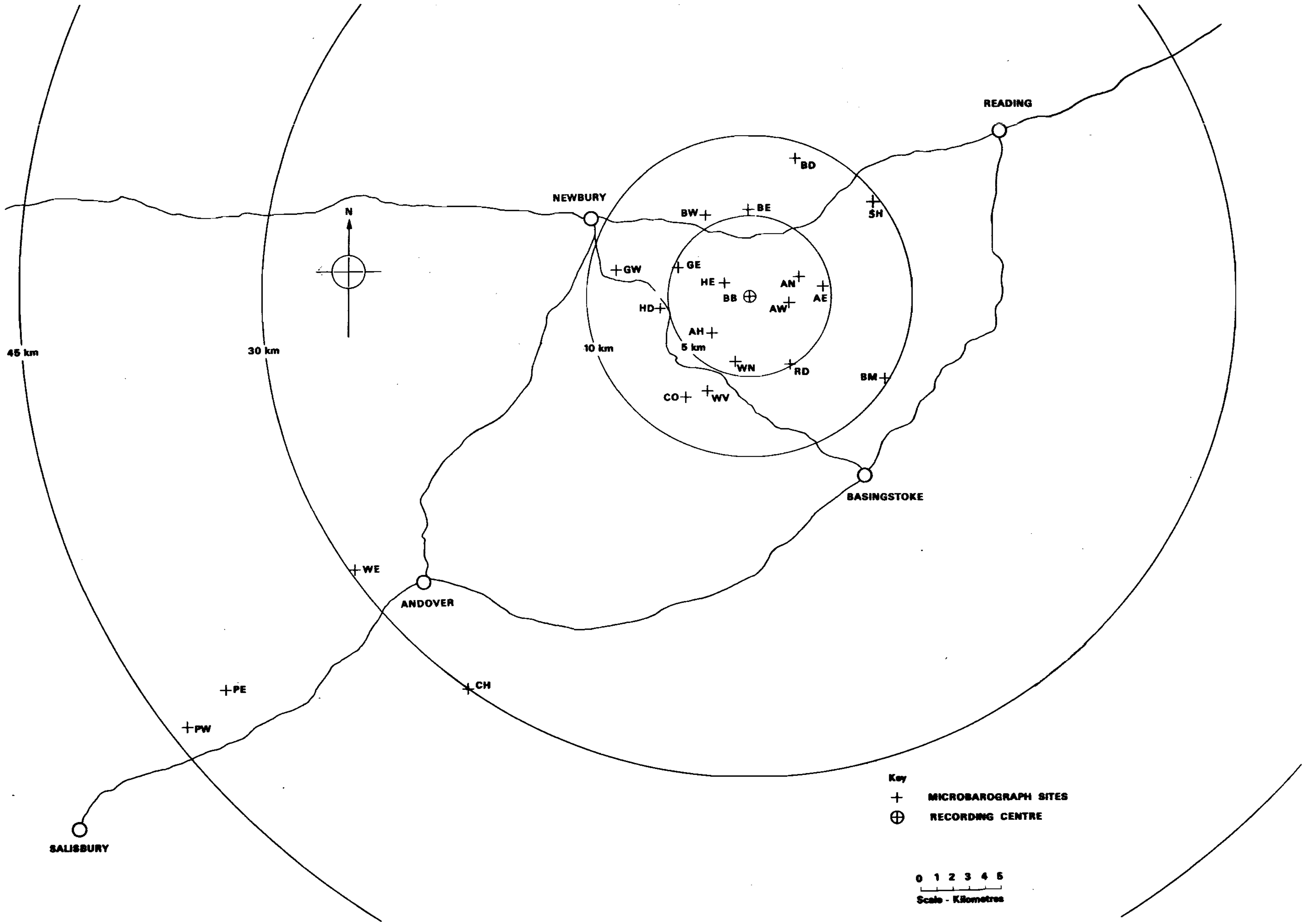


FIGURE 1. BLACKNEST MICROBAROGRAPH ARRAY

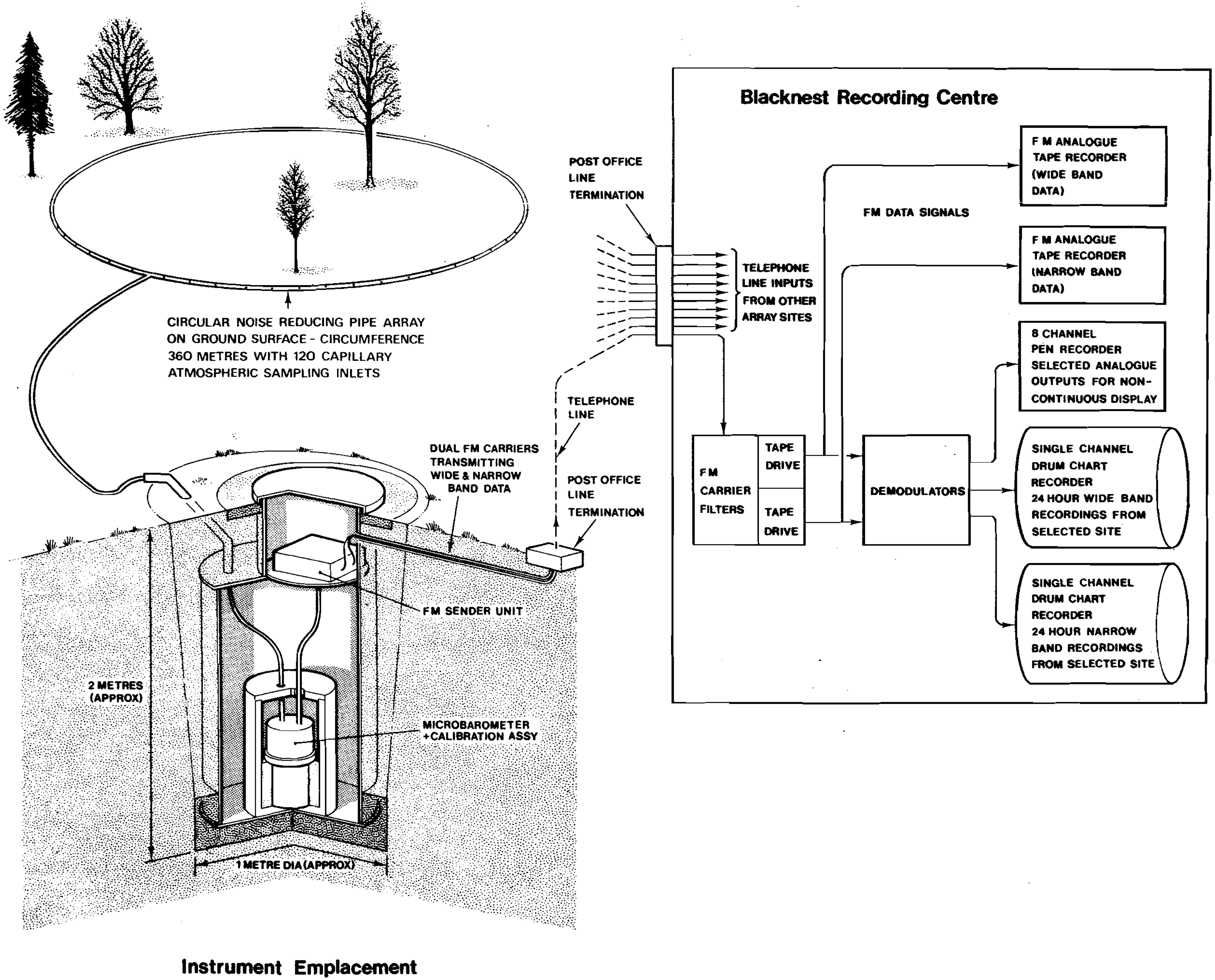


FIGURE 2. SCHEMATIC DIAGRAM SHOWING PRINCIPAL ELEMENTS IN ONE CHANNEL OF THE BLACKNEST MICROBAROGRAPH ARRAY

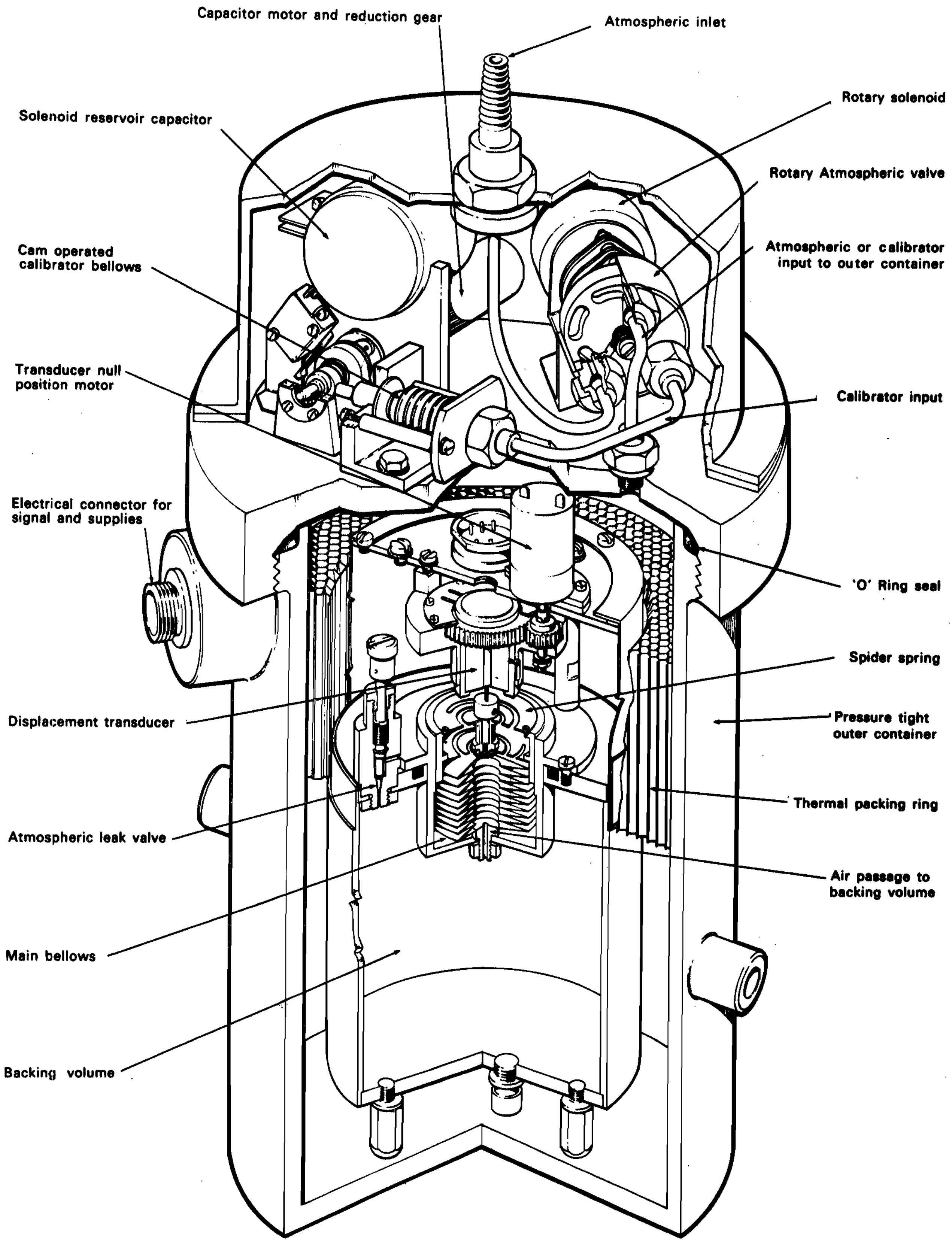


FIGURE 3. MICROBAROMETER AND CALIBRATOR ASSEMBLY

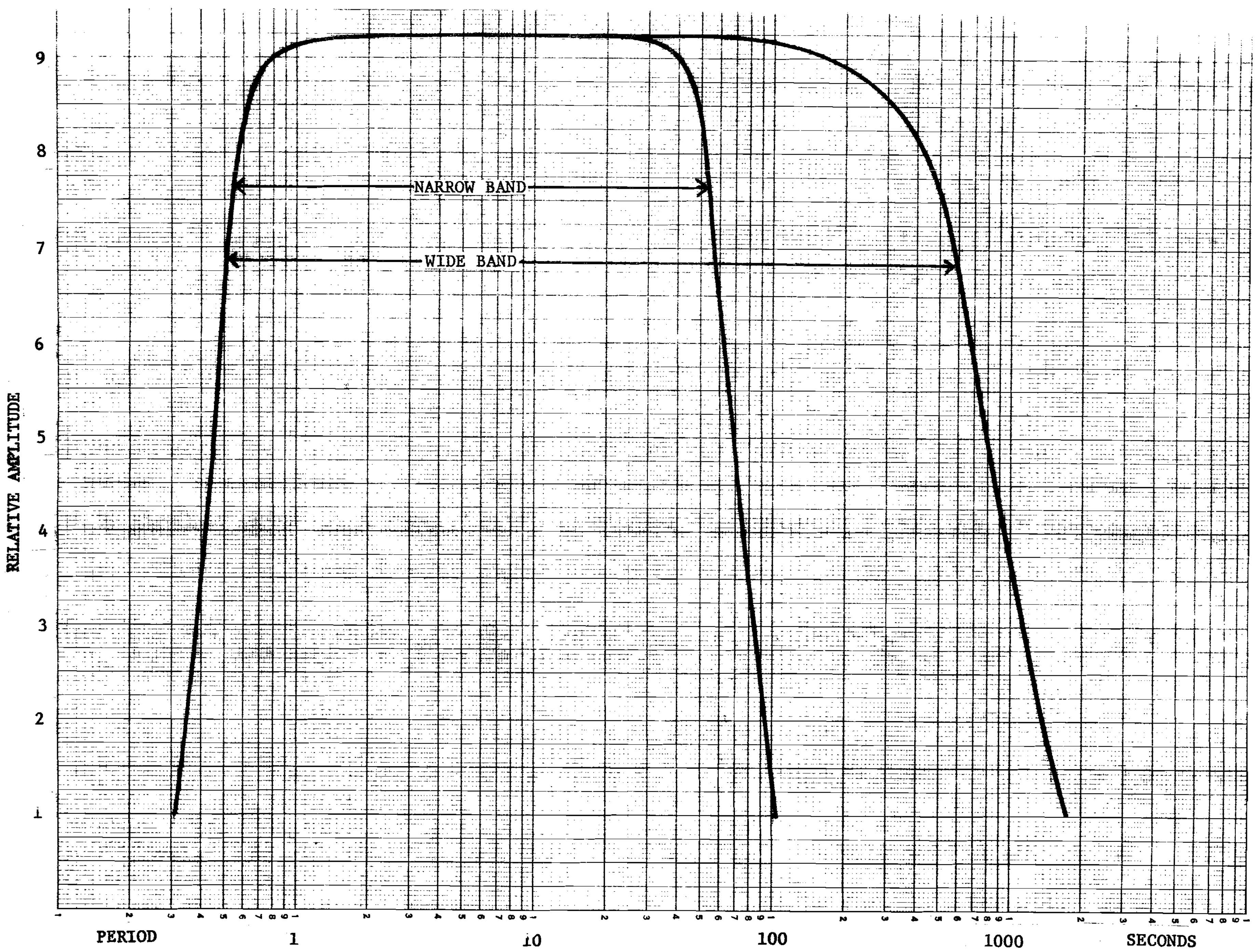


FIGURE 4. AMPLITUDE-PERIOD RESPONSE OF MICROBAROGRAPH RECORDING SYSTEM

4. MICROBAROGRAPH ARRAY RECORDS

4.1 Nuclear explosions

Models for the structure of the atmosphere have been proposed by a number of authors [6-8] to demonstrate the effect of stratification on the propagation of various possible modes of acoustic-gravity waves. All the models are simplifications of the real atmospheric structure as it exists at any particular time. In general, acoustic-gravity wave energy from large explosions is received at a distant recording station as a dispersed train of infrasonic waves in which the long period "gravity" modes arrive first, shading off through shorter period waves to modes which are principally "acoustic". The models show that increase in sound speed at altitudes of around 50 and 100 km, due to the temperature stratification of the atmosphere, are important in providing two principal "sound channels" through which infrasonic waves are ducted over great distances.

4.1.1 Seasonal variations in propagation

The efficacy of the wave guide formed by the 50 km boundary has been shown [9] to be greatly affected by the direction of winds with speeds of the order of 180 km/h which exist at this level. In the northern hemisphere the wind at the 50 km level has a directional behaviour pattern such that four fairly distinct periods can be discerned during a year [10,11], thus:-

A long "winter" period (October to March)	Wind direction and speed westerly, 180 km/h	Propagation from west to east is favourable
A "transitional" period (mid-March to May)	Wind direction and speed changes from westerly to easterly. Winds become weak and variable during this period	Propagation variable
A short "summer" period (June to August)	Wind direction and speed easterly, 180 km/h	Propagation from east to west is favourable
A second "transitional" period (August to end of September)	Wind direction and speed changes from easterly to westerly. Winds weak and variable	Propagation variable

The high dependence of propagation on these seasonal variations in the atmospheric structure can be demonstrated by comparing observations made at different times of the year from atmospheric explosions of similar size which have occurred at the same source point and have been recorded at the same receiver. Figure 5, for example, illustrates a series of records of infrasonic waves from large atmospheric nuclear explosions at the Chinese test site at Lop Nor, Sinkiang. All the explosions were over a megaton and of roughly the same yield. Published estimates of the yields place five of the shots close to 3 Mton and the sixth over 4 Mton. Other details about the explosions, such as height of burst, are not known but for the purposes of this comparison the source parameters are assumed to be similar.

All the recordings were made under the wide-band conditions described previously and are reproduced in figure 5 so that the relative amplitudes (vertical) and time durations (horizontal) of the six traces are to the same scale. The higher background noise in traces 2 and 6 is because the records were obtained at an early stage in the commissioning of the microbarograph array before passive array noise reducers were installed.

It can be seen that, apart from the differences in background noise conditions, the signal waveforms fall into patterns which relate to the time of year of the recordings. Thus, the waveforms of two signals from events which occurred in summer exhibit strongly developed acoustic mode waves of around 45 N/m^2 amplitude and 55 s period. In the recordings of signals occurring in the transitional autumn period, this mode is greatly reduced in amplitude and ultimately becomes indistinguishable in the background noise of the winter record. The total time duration of the received signal also becomes much extended with the progression of the seasons from summer to winter.

It may be inferred from these observations that the boundaries of atmospheric waveguides become modified as a result of changes in the upper stratospheric winds. Thus, the principal acoustic mode is no longer supported after the transition, while the greatly increased dispersion of the acoustic-gravity wave train suggests greater complexity in the propagation paths, followed by the longer wave modes. The long persistence of very short period (20 to 30 s) waves in the tails of the wave trains has been attributed [12] to the existence of other wind ducts in the layered structure of the atmosphere in which short period components of the original pulse are propagated and repeatedly "split" during transit, thus greatly extending the duration of the received signals.

4.1.2 Coherence of noise and signal waveforms

Observations at Blacknest and elsewhere [13] have shown that noise due to the local wind has little coherence at distances greater than 1 km and hence the separation of the sites in an array by that order of distance would be advantageous in improving the detection of signals against wind noise unaffected by local passive array filtering. However, longer wavelength components in atmospheric background noise due to sources other than the wind (such as waves with subsonic velocities generated near the tropopause from sources similar to the jet-stream [14] or in the troposphere under certain meteorological conditions) require even greater spacing of array elements for improvements in signal-to-noise ratio to be achieved.

In practice, the final array aperture is a compromise between logistical considerations and the largest dimensions which are consistent with waveform congruence of wanted signals across all the sites of an array. In the case of signals observed from distant nuclear explosions, wave periods are typically in the range 30 to 300 s, equivalent to wavelengths in the range 10 to 100 km.

The disposition of sites in the Blacknest microbarograph array tests the correlation of nuclear explosion signals in an array of up to 50 km aperture, equivalent to several wavelengths of the shorter period signal components. In figure 6, the upper three traces are signals recorded from the Chinese nuclear explosion of 27 June 1973 at three sites of the Blacknest array. Traces 1 and 2 are from sites separated by 5 km and trace 3 is from a site 30 km distant from the second site. The signal in trace 4 was recorded from the same explosion by an AWRE microbarograph operated by the Institute of Geological Sciences Observatory at Eskdalemuir, 465 km from the array centre (trace 2). It can be seen that the whole wavetrain, including short period acoustic waves, has good coherence across the Blacknest array sites. Summation and cross-correlation processes can therefore be applied with advantage to the individual site outputs of an array of this size to improve detection of weaker signals of the kind illustrated. The Eskdalemuir signal, while having general similarity of form, lacks waveform congruence (except for the longer initial waves) essential for array processing.

4.1.3 Multiple arrivals

Because of the large energy release from major explosions and the low attenuation of infrasonic waves in the atmosphere, multiple arrivals due to successive reflections of waves at the antipodes of the sources have been reported on a number of occasions [15]. An example of this is given in figure 7 which shows successive wave groups, A1, A2, A3 and A4, recorded on three instruments of the Blacknest microbarograph array from the Chinese nuclear test of 14 October 1970.

The arrivals subsequent to the first arrival A1 may be treated as round-the-world waves propagating with a group velocity of approximately 1100 km/h (or 10° arc per hour). Directional and other details of the wave arrivals are therefore as follows:-

A1	Direct waves from the source, Lop Nor	Distance travelled 60°
A2	The first wave group returning from the antipodes of Lop Nor, traversing the array in the opposite direction to A1, ie, travelling towards the source	Effective path length 300°. Travel time approximately 30 h
A3	The second group of waves to arrive from the direction of the source	Effective path length 420°. Travel time very approximately 42 h
A4	The second group of waves to arrive travelling towards the source	Effective path length 660°. Travel time very approximately 66 h

The first arriving, "gravity" mode, waves are in each case annotated "G" and the later, "acoustic" mode, waves are annotated "S". Due to the great distances travelled and the differing group velocities of the wave modes, the dispersion of the wave trains becomes increasingly greater so that the two principal wave modes G and S become separated by ever increasing time intervals in the successive arrivals. In the A2 traces, where the waves are clearly defined, the time separation of the two principal modes is of the order of 2 h. The background noise conditions were worse at the times of the A3 and A4 arrivals and the A3(S) and A4(G) waves are ill defined - their positions on the records are indicated by dotted lines. The S mode waves of the A4 trace, however, are distinct and the time separation from the presumed G wave onset is about 5 h.

4.1.4 Beam-forming techniques

The application of beam-forming processes to the phased outputs of arrays has been valuable for detecting weak signals in background noise and computing their direction of arrival. A complete account of the theory and application to seismic wave analysis in AWRE has been given by Birtill and Whiteway [16] and the techniques evolved for processing seismological data at AWRE were applied to atmospheric wave recordings from the microbarograph array, using the special purpose hybrid processing system described by Hutchins [17]. Details of some early applications of the system to the processing of infrasonic wave data have been reported previously [18].

In this technique the outputs of individual array channels are first bandpass filtered to remove noise components outside the frequency spectrum of the signal and then digitised. The digitised outputs of the array channels are swept through a range of time delays corresponding to the arrival time differences at array instrument positions for various combinations of signal velocity and azimuth. Summation and cross-correlation processes are then applied to the array channel outputs for each time delay condition in the swept range.

The effect of this processing is that a number of "beams" are formed, corresponding to each velocity/azimuthal combination in the range of time delays. A visual presentation of the processed data enables the range of beam outputs to be examined for the "best beam", ie, that in which the cross-correlation between two separately summed groups of the array instruments is optimum. The total sum of all the array instruments under this optimum condition provides the best signal-to-noise display of the wave arrivals.

An example is illustrated in figure 8 in which nine channels of the microbarograph array recording of the first arrival, A1, are summed and cross-correlated. The signal-to-noise ratio of the wavetrains recorded by the individual channels is sufficiently good in the case of this signal for it to be easily detectable before summation, but in the case of the second arrival from the same atmospheric nuclear explosion (figure 9) detection of the presence of the much weaker signal is achieved by array processing. The correlogram is a smoothed, integrated output derived from the cross-correlation products and is useful as an event detector when long sequences of raw data are to be scanned.

4.2 Chemical explosions

Infrasonic waves from chemical explosions have been recorded on a number of occasions by instruments of the Blacknest microbarograph array. Typically, sources have been associated with industrial and shipping activities in the British Isles area, usually involving a major accident situation. Energies equivalent to TNT detonations in the range of a few tons to a few hundred tons have produced signals of the order of 1 to 10 N/m^2 at distances up to several hundred kilometres.

Events recorded include explosions at oil refineries in Wales and in Holland [18], at a chemical works in the English Midlands [19] and in an oil tanker in the English Channel. Two other ship explosions which occurred in the English Channel area were the results of deliberate detonations of cargoes of explosives. These were unrelated episodes in which action was taken by British and French services respectively to destroy an unsafe cargo of explosives in the one case (St Bridget) and to remove a shipping hazard in the other (Amersee). Records of infrasonic waves from the two events are illustrated in figures 10 and 11. Some comparative details of the two events are listed below:-

Vessel	St Bridget	Amersee
Cause of explosion	Detonation of cargo by gunfire (Royal Navy)	Detonation of cargo by bombing (French Air Force and Navy)
Reported cargo	110 tons nitro-glycerine	175 tons dynamite and other unspecified explosives, 320 tons in all
Date-time of explosion	14 February 1972 1817Z	6 October 1974 0830Z
Reported location	49°27'N 04°59'W	49°18'30"N 03°29'30"W
Distance to centre of microbarograph array	344 km	280 km
Bearing of explosion source at array centre point	233°	217°
Amplitude and period of principal waves in first group	7 N/m^2 2.5 s	14 N/m^2 2.7 s
Horizontal trace velocity of waves in first group	333 m/s	355 m/s

Amplitude and period of waves in second group	$1\ N/m^2$ 18 s	)	Coherent waves not seen
Horizontal trace velocity of waves in second group	400 m/s	)	

In the case of St Bridget, the arrival of two main wave groups with horizontal trace velocities across the microbarograph array of 333 and 400 m/s and corresponding apparent surface path velocities from source to receiver of 312 and 255 m/s accord with sound ray paths with reflections at 50 and 110 km altitude levels respectively [19]. The second wave group consists only of a relatively weak low frequency pulse, due to the severe attenuation of higher frequencies in the high altitude path through the upper atmosphere. Weak high frequency arrivals in advance of the principal waves in group 1 would be expected if minor ducts at lower levels than the main refractor at 50 km were present at the time. Meteorological data for 14 February 1972 reported westerly winds of 113 knots at 10.8 km altitude.

Only one coherent wave group can be identified in the case of the Amersee explosion; the reception of a second group via high altitude refractors is critically dependent on the distance from the source to the receiver and on leakage through the seasonally varying 50 km refractor. The horizontal trace velocity, 355 m/s, of the waves recorded from Amersee is comparatively greater than that of wave group 1 from the St Bridget explosion, because of the shorter source to receiver path and consequent higher angle of elevation to the 50 km refractor. The relative amplitudes of the waves are now in accordance with a relationship

$$\frac{A_2}{A_1} = \left(\frac{W_2}{W_1}\right)^{\frac{1}{3}} \times \left(\frac{R_1}{R_2}\right)^2,$$

where A_1 and A_2 are the maximum amplitudes or signals recorded from events 1 and 2,

W_1 and W_2 are the corresponding explosive charge weights,

and R_1 and R_2 are the corresponding source to receiver distances.

4.3 Supersonic flight

Infrasonic waves generated by the flights of supersonic aircraft have been observed on numerous occasions at Blacknest. In particular, systematic observations of the effects of Concorde flights have been made since the first formal test flights began in 1970 [20].

Typically, the signals detected by the microbarographs have amplitudes of a few microbars and periods in the range 1 to 8 s. These signals are long-wave infrasonic components of sound originating at the characteristic "N-wave" shock fronts associated with the supersonic source. Audible sound is not usually detected at the distances of several hundreds of kilometres to which infrasonic waves are propagated, due to the severe attenuation suffered by waves of sonic frequencies from the effects of absorption, scattering and destructive interference. However, in common with the observed behaviour of atmospheric acoustic waves from other sources, the long distance propagation of acoustic waves from supersonic aircraft is subject to seasonal and diurnal variations [20]. Under certain conditions of the upper atmosphere, propagation of all sound wave components may be enhanced sufficiently for audible sound to be perceived at distances of some hundreds of kilometres, together with corresponding large increases in the amplitudes of infrasonic waves recorded on these occasions.

In 1976, the commencement of regular commercial flights, with strictly controlled flight-path parameters, provided an acoustic wave source of constant dimensions (distance, azimuth, energy emission), from which the effect of seasonal variations on the propagation of the emitted acoustic waves could be inferred by observations of waves recorded at Blacknest. Observations to date indicate that large seasonal fluctuations in the amplitudes of the waves can occur; for example, mean fourteen day amplitude levels were 18 times greater in November 1976 than in June 1977.

Because acoustic energy generated by Concorde's supersonic flights is radiated from a moving source at 15 km altitude, the possibilities for propagation to a distant receiver are relatively complex. This is reflected in the variability of arrival patterns of the recorded infrasonic waves. The waves arrive in groups containing a few cycles of a predominant frequency; usually there is more than one group and a pattern of two groups of similar frequency (1 to 2 s period) separated by a minute or two is fairly common. This indicates the likelihood of both initially upward-going and initially downward-going rays from the source arriving at the receiver after undergoing a reflection at the 50 km layer in the one case and two reflections, at the earth's surface and the 50 km layer, in the other.

Under some atmospheric conditions, several groups may be recorded from one flight manoeuvre (approach or departure) and in the example of multiple-path arrivals given in figure 12, five successive arrivals from one flight were recorded across the array. The third arrival of this set is a low frequency pulse of about 10 s period and is probably a wave returning after reflection at the upper refracting layer of the atmosphere (at about 110 km) with corresponding loss of high frequency content. The reception of this low frequency pulse is variable; when the 50 km reflector (normal temperature stratification effect) is strengthened in winter by winds at the same altitude, the propagation of infrasonic waves to the higher levels is inhibited.

By inference, the first arriving signal has travelled the shortest path, ie, one reflection at the 50 km layer, and the second a rather longer path after reflection at the ground surface and then at 50 km; the latter signal is the most consistently arriving wave group throughout the year. The later arrivals, 4 and 5, are wave groups which have probably undergone multiple reflections between the point of emission and final arrival at the receiver.

4.4 Earthquake coupled waves

Acoustic waves in the atmosphere caused by the transfer of energy from the seismic vibrations of earthquakes may be recorded at considerable distances from the epicentre of the disturbance. An early account of waves of this kind was given in 1939 by Benioff and Gutenberg [21].

Close to earthquake sources, some seismic frequencies are high enough to produce audible micropressure variations in the atmosphere. Lower frequency (infrasonic) pressure disturbances have also been recorded at great distances from the epicentres of very large earthquakes [22-24]. A number of possible mechanisms may be involved:-

(a) An acoustic-gravity wave may be set up by violent ground displacement at the epicentre. This wave travels through the atmosphere at approximately 330 m/s.

(b) Air pressure fluctuations coupled to a vertical component of ground motion may be set up and travel with the seismic surface wave at velocities of the order of a few kilometres per second.

(c) Air waves which radiate away from the ground surface at normal sound velocity may be generated when coupling occurs in a region (which could be at some distance from the earthquake epicentre) where the seismic surface wave velocity is very low [21].

Ground to air coupled waves of the type described in (b) above have been detected at Blacknest on a number of occasions. The atmospheric pressure wave fluctuations are coupled to the vertical (Rayleigh wave) components of seismic surface waves travelling from the epicentre and a close analogy therefore exists between microbarographic records of the pressure variations and seismographic records of the ground motion. Figures 13 and 14 give examples of ground-coupled pressure waves recorded by microbarographs of the Blacknest array from two recent major earthquakes, the Friuli earthquake in Northern Italy, May 1976 and the Tangshan earthquake in Northern China, July 1976.

In each figure the atmospheric pressure waves from the main shock are shown, together with a seismographic record of surface waves from an aftershock from the epicentral region where the main earthquake shock occurred. Records from aftershocks have been used because the seismic waves from the large main shocks in both cases caused the sensitive long-period seismograph to overload the recording system. However, because the waves travel over identical paths from the same source, use of the aftershock waveforms can provide a valid basis for comparison between ground motion from the large earthquakes and the related microbarographic phenomena. The difference in the distances of the two earthquake epicentres from Blacknest (1200 km to Friuli and

8400 km to Tangshan) is reflected in the different frequency content of the recorded waves. For this reason a "broad-band" seismographic output (covering an intermediate frequency band) is used for the Friuli recordings and a "long-period" output (covering lower frequencies) is used for the Tangshan event.

4.5 Microbaroms

Infrasonic waves of a particular class, given the name microbaroms because of the analogy with microseisms, are frequently observed as acoustic-velocity components of background noise in microbarographic records. The waves, which generally have amplitudes of a few microbars, though occasionally reaching as high as 10 microbars (1 N/m^2), are characterised by their confinement to a narrow band centred around periods of 5 to 6 s. Figure 15 illustrates the strong peak in the noise spectrum of one of the microbarographs of the Blacknest array on a day when microbaroms were being detected.

The spectral similarities between microbaroms and microseisms and the statistical relationship in their occurrence suggest a common source. Empirical evidence supports the original suggestion [25] of an oceanic source for both wave types and a number of subsequent treatments have dealt with possible mechanisms of generation from standing waves in marine storm centres [26-29]. Thereafter, however, microbaroms and microseisms propagate independently, without coupling, at acoustic and seismic velocities respectively.

McDonald and Herrin [30] used Blacknest microbarographic data in conjunction with data recorded at arrays in Texas and Alaska to show that very similar spectral peaks of around 4 to 7 s period existed in data samples taken on separate occasions when microbaroms were being detected at the three locations. It was also shown that no significant coherence existed between pairs of sensors with 5 km spacing at each of the three arrays; significant coherence was, however, established for sensor spacings of a few hundred metres at the Texas array. This accords with observations at Blacknest where little coherence is apparent for microbaroms detected at array sites separated by distances of 1.5 to 5 km and lends support to a concept of microbarom generation at widespread multiple emitters of acoustic wave energy.

Microbaroms are usually recorded as nearly continuous trains of monotonic waves with rhythmic variations in amplitude which, in the absence of other background noise, produce a "pearl-string" appearance in the waveform envelope. Observations over a long period at Blacknest demonstrate the probability of a link between the occurrence of microbaroms and the existence of zones of high winds at sea, usually associated with depressions in the North Atlantic area. A frequent feature in microbarographic records is for microbaroms to become prominent in the lulls between periods of high wind noise related to the movements of weather systems across the recording area - an example is given in figure 16. In addition there are pronounced seasonal fluctuations, onsets of the waves being frequent in the period October to April and infrequent in the period May to September. The highest amplitudes tend to occur between December and February.

The seasonal fluctuations can be explained in the following general way:-

(a) Microbaroms are generated by large sea waves which occur in strong wind zones of marine storms. These storm centres exist most frequently in the oceanic area to the west of the British Isles.

(b) Because of seasonal changes in the direction of the upper stratospheric winds, propagation of acoustic waves is good from west to east in the "winter" period between the wind transitions in September and April, ie, microbaroms originating in storm centres to the west of the British Isles will be propagated to recording sites in Britain more efficiently in winter than in summer.

(c) This effect is reinforced to some extent by the greater prevalence of storms in the North Atlantic in winter than in summer; consequently, the occurrence of sea conditions favourable for the generation of microbaroms is more likely in winter. For similar synoptic conditions in the North Atlantic area, giving rise to high winds to the west of the British Isle and a calm zone over Southern England (ie, good recording conditions) microbarom levels have a high winter to summer ratio, amplitudes up to 20 times larger in February than in August having been observed.

During periods when microbaroms are being received continuously and the records are free from local background noise, diurnal variations in amplitudes may be apparent. In the USA, Donn and his associates [31-33] have shown that observations of the way in which the average amplitudes of microbarom signals vary can provide information on circulation parameters in the upper atmosphere; also that measurements of the horizontal trace velocities of microbarom waves traversing an array can be used to obtain estimates of wind velocities at the levels where infrasonic waves are reflected downwards in the upper atmosphere. They identify several categories of microbarom conditions:-

(a) Continuous signal reception throughout a day but with semi-diurnal amplitude variations.

(b) Continuous signal reception with three periods of amplitude maxima.

(c) Continuous strong signal reception throughout a day.

(d) Continuous weak signal reception throughout a day.

These characteristic patterns are associated by the authors with the atmospheric circulation at particular altitudes.

In the British Isles, quiet meteorological conditions are comparatively rare, so long periods of continuous microbarom reception are relatively infrequent and opportunities to study diurnal variations are correspondingly limited. However, from observations made over a long period, a characteristic pattern of a diurnal nature can be identified in Blacknest microbarographic recordings of continuous microbarom episodes. The principal feature is that amplitude maxima of received signals tend to occur each day between 1600 and 2100 hours GMT. In winter months the general level of microbarom signals is often large enough to mask any diurnal variations, while in summer months few signals are received; the effect is most apparent in transitional months such as March, as may be seen from the records of microbaroms for the months January, February and March illustrated in figure 17.

These observations are similar in kind but differ in detail from those of Donn *et al.*, the different relationships of land and sea areas and climatology of the two zones, North-West Europe and Eastern USA, from which the data are acquired, probably accounting for the difference.

4.6 Meteorological effects

In order to enhance its sensitivity to small rapidly changing pressure fluctuations, the system with which we are concerned discriminates against large, slow, weather-related changes of barometric pressure. Nonetheless, it records many meteorological phenomena in which the pressure-time function falls within the passbands of the sensing instrument and associated recording system. The array has the further advantage of being able to determine the velocity of pressure waves which traverse it, thereby distinguishing between acoustic, sub-acoustic, or slow-moving (wind velocity) signals having similar waveforms.

For example, the rapid change of pressure which frequently accompanies the passage of a weather front produces a pulse waveform at the output of each microbarograph channel output as the front crosses the array. The exact time of arrival of the front at particular places can thus be readily ascertained and also its velocity and direction of travel. The shape of the pulse waveform is largely determined by the response of the instrument recording system to a step function of pressure, but where, as is often the case, the main pressure step is preceded or followed by pressure oscillations, these may be faithfully recorded if the period of the oscillations falls within the passband of the instrumental system.

The series of figures 18 to 30 include array records of six events of meteorological origin, together with copies of the related synoptic chart data. Brief details of the events and records are as follows:-

Figure 18 The passage of a cold front travelling east-north-east at about 60 km/h across BMBA between 0630 and 0745Z on 22 December 1973 is shown in this figure. Records from 8 instruments of the array are reproduced in order of arrival, with south-westerly sites of the array in the upper traces and north-easterly sites in the lower traces of the illustration. Short-period ($\sim$ 60 s) oscillations occur ahead of the main pressure pulse on most of the channels and fluctuations with periods of several minutes occur thereafter. The amplitudes of the principal pressure pulses (as recorded by the BMBA instruments) are around 20 N/m^2 peak to peak.

Figure 19 — The published synoptic charts indicate little change in wind speed and direction caused by the passage of the pressure disturbances. However, unpublished meteorological observations at the most southerly site of the array, PW, recorded that the wind at 0630 hours was from 210°, gusting to 19 knots between 0630 and 0635 hours, thereafter dropping gradually to 10 knots at 155° by 0700 hours.

Figure 20 — This figure shows pressure pulses, approximately 30 min apart, crossing the array in a generally south-easterly direction at about 30 km/h. The different "move-out" angles made by the two sequences of pulses crossing the array indicate different azimuthal planes for the two fronts which are presumed to be the cause of the recorded pulses. The larger time intervals between the pairs of pulses on the upper traces of the illustration (southerly sites of the array) as compared with the smaller intervals on the lower traces (northerly sites) indicate that the two fronts are closer together in the northern sector of the array. Also the arrival time pattern of the pulses indicates that both fronts were travelling in a generally south-easterly direction at about 20 km/h. A sharp increase in high frequency background noise, due to wind, occurred about 10 min after the passage of the first front and remained at this new higher level thereafter.

Figure 21 — The synoptic charts show a wedge-shaped zone bounded by warm and cold fronts, at the leading and trailing edges respectively, swinging over Southern England in anti-clockwise rotation around a low pressure area to the north of the British Isles. The two fronts are separate over Southern England but become occluded further northwards. The near-occluded frontal zone is shown lying to the east of the BMBA area in the 1800 hour chart.

Figure 22 — This figure illustrates the passage of a minor disturbance which crossed the array from south to north between 1730 and 1745Z on 31 July 1975.

Figure 23 — The synoptic charts illustrated show that a front lying along the line of the English Channel at 1200 hours had shifted northwards to a parallel position across the South Midlands by 1800 hours on 31 July.

Figure 24 — Pressure steps recorded by six channels of the array are shown in the figure. The shapes of the pulses were notably more consistent across the entire array than is usual with recordings of weather fronts. Peak to peak amplitudes were about 30 N/m^2. Ahead of the front conditions were windy (high frequency oscillations on traces); after the transit of the principal pressure step wind subsided, but large amplitude oscillations of pressure of around 300 s period occurred. Pressure oscillations of this period are often seen in the wide-band records under comparable conditions.

Figure 25 — The synoptic charts for 1800 hours of 31 December 1975 and 0000 hours of 1 January 1976 show that a well-defined cold front traversed the array during the late hours of 31 December, travelling in a southerly direction. Moderately strong winds were reported ahead of the frontal trough.

Figure 26 — An unusual sequence of pressure oscillations observed at BMBA sites between 2025 and 2055 hours is shown in the illustration. The dominant feature of the episode is a well-developed train of waves of about 55 s period, preceded and followed by higher frequency waves of 25 s period. Longer period waves in the more commonly observed period range of 5 to 10 min are also present. Pothecary [34] reported the occurrence of short-period pressure fluctuations arising from atmospheric conditions associated with thunderstorms. Pierce and Coroniti [35] suggested that Brunt period oscillations [36] may be induced by convective storms, while observations at Blacknest and elsewhere [37] suggest that the adjacency of a weather front can contribute to the production of atmospheric waves.

Figure 27 — The synoptic charts for 1800 hours of 29 August 1976 and 0000 hours of 30 August showed that a thundery low pressure system was moving slowly northwards from the Northern French coast to the area of Southern England at the time of the oscillations. The other principal feature in the charts was a cold front situated in the Atlantic area north of Scotland which moved slowly south-eastwards towards the British Isles.

Figure 28 — A disturbance which traversed the 14 elements of the array which were operating between 0840 and 0900 hours on 25 January 1977 is illustrated. The disturbance had an apparent velocity of 148 km/h and was moving in a direction of 104°. Excursions in excess of 25 N/m^2 from baseline pressure caused the recording system to limit on several channels, but a more realistic estimate of the true size of the pressure jump is gained from the following unfiltered millibarographic records.

Figure 29 The millibarograph chart for the week of 24 to 31 January 1977, reproduced in this figure, shows that an unusually sharp fall in pressure of 4 mb or more took place around 0800 to 0900 hours. A partial recovery occurred within an hour, after which pressure continued to fall throughout the day at the steady rate established during the 36 h preceding the sudden decrease.

Figure 30 The synoptic charts for 0600 and 1200 hours of 25 January 1977 show the rapid movement eastwards across Southern England of fronts associated with a depression which moved towards the British Isles ahead of a complex area of low pressure over the North Atlantic. It appears that a tongue at the north-east corner of a fast moving warm air mass, bounded by sharply defined fronts, may have caused the pressure step and later partial recovery in pressure as it passed over the array.

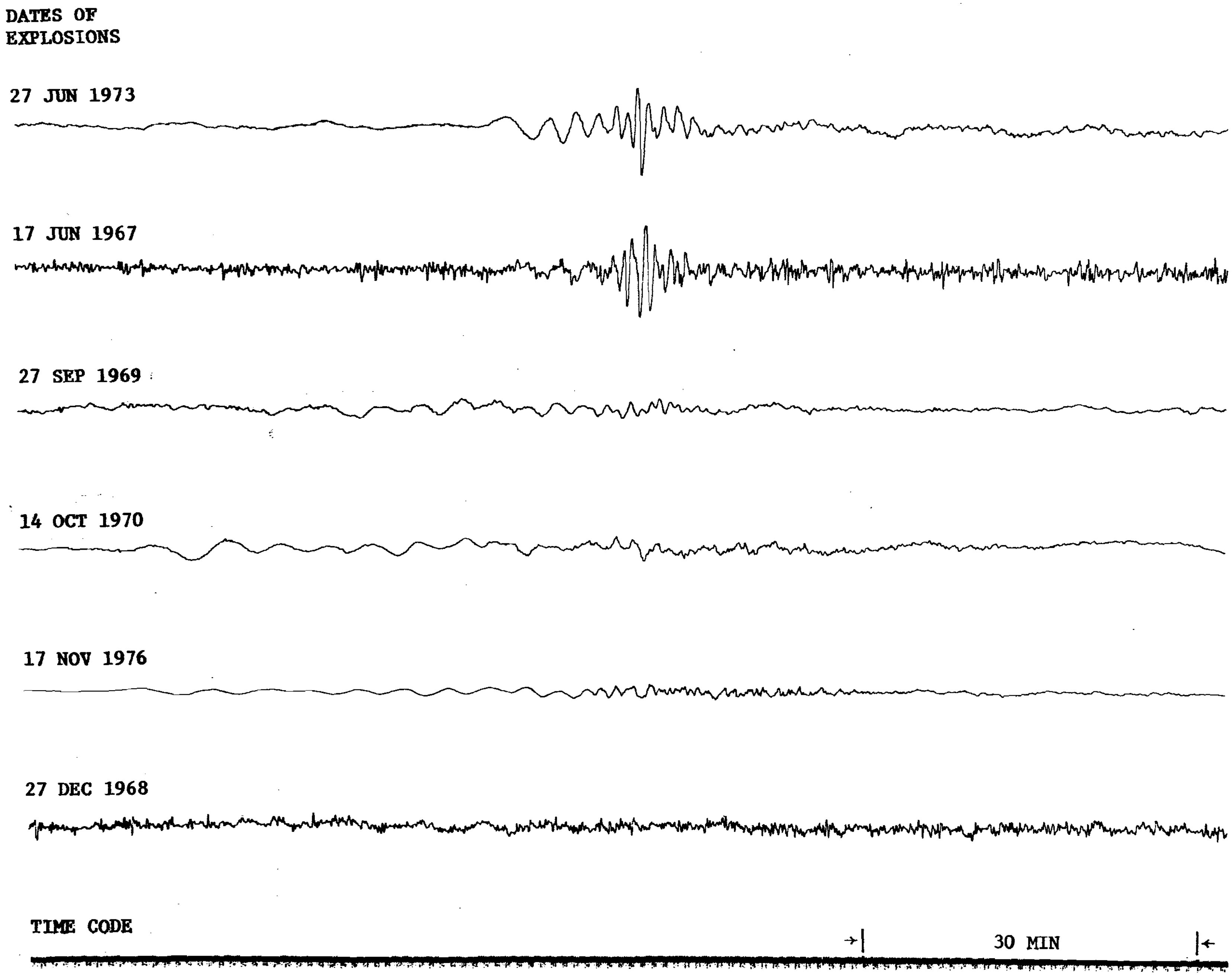


FIGURE 5. BLACKNEST MICROBAROGRAPHIC (SINGLE CHANNEL) RECORDINGS OF LARGE EXPLOSIONS IN THE ATMOSPHERE AT LOP NOR TEST SITE, SINKIANG, CHINA

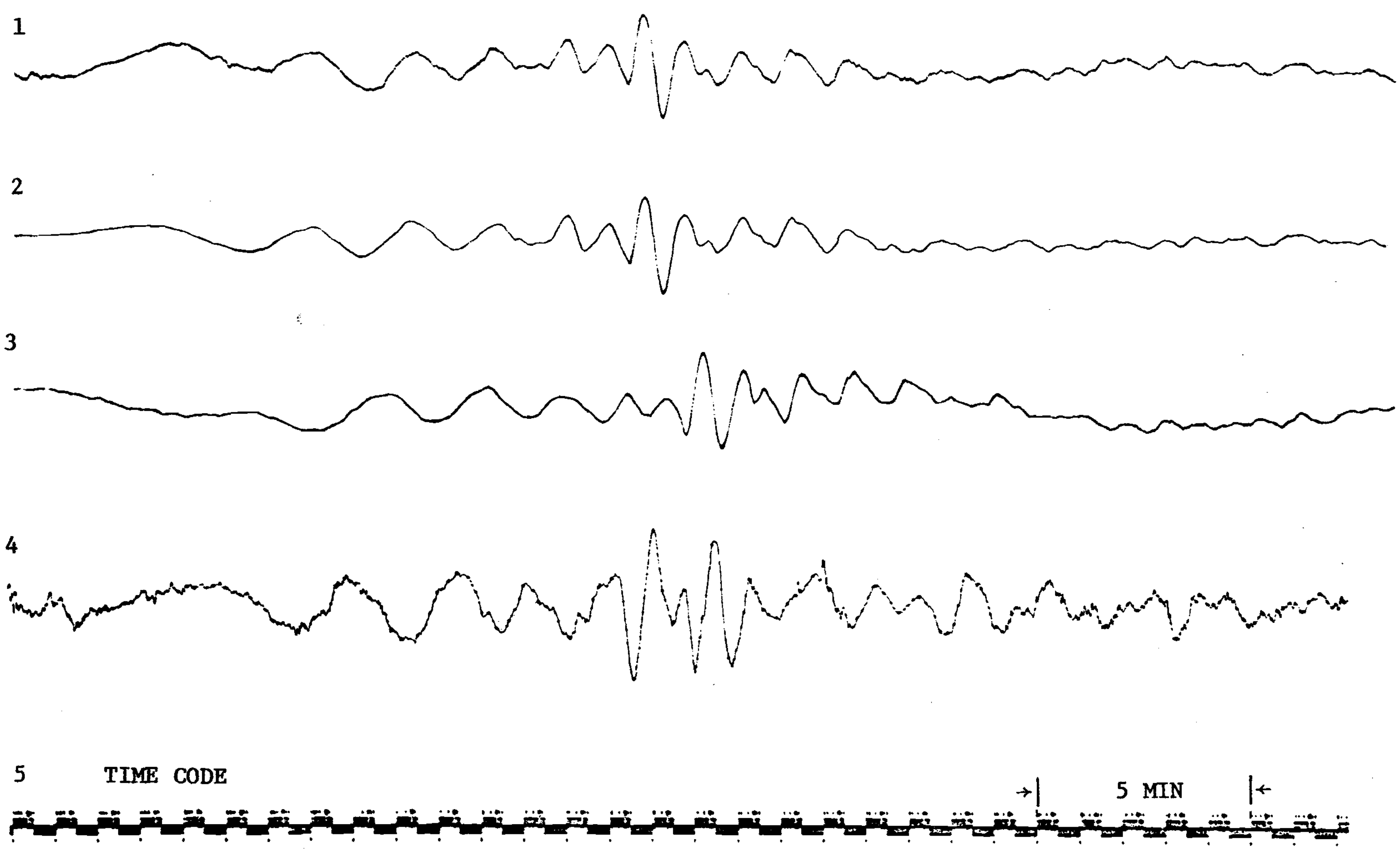


FIGURE 6. WAVEFORMS OF SIGNALS RECORDED AT FOUR UK SITES FROM THE CHINESE NUCLEAR EXPLOSION OF 27 JUNE 1973. RECORDING SITE SEPARATIONS: 1 to 2, 5 km; 2 to 3, 30 km; 2 to 4, 465 km

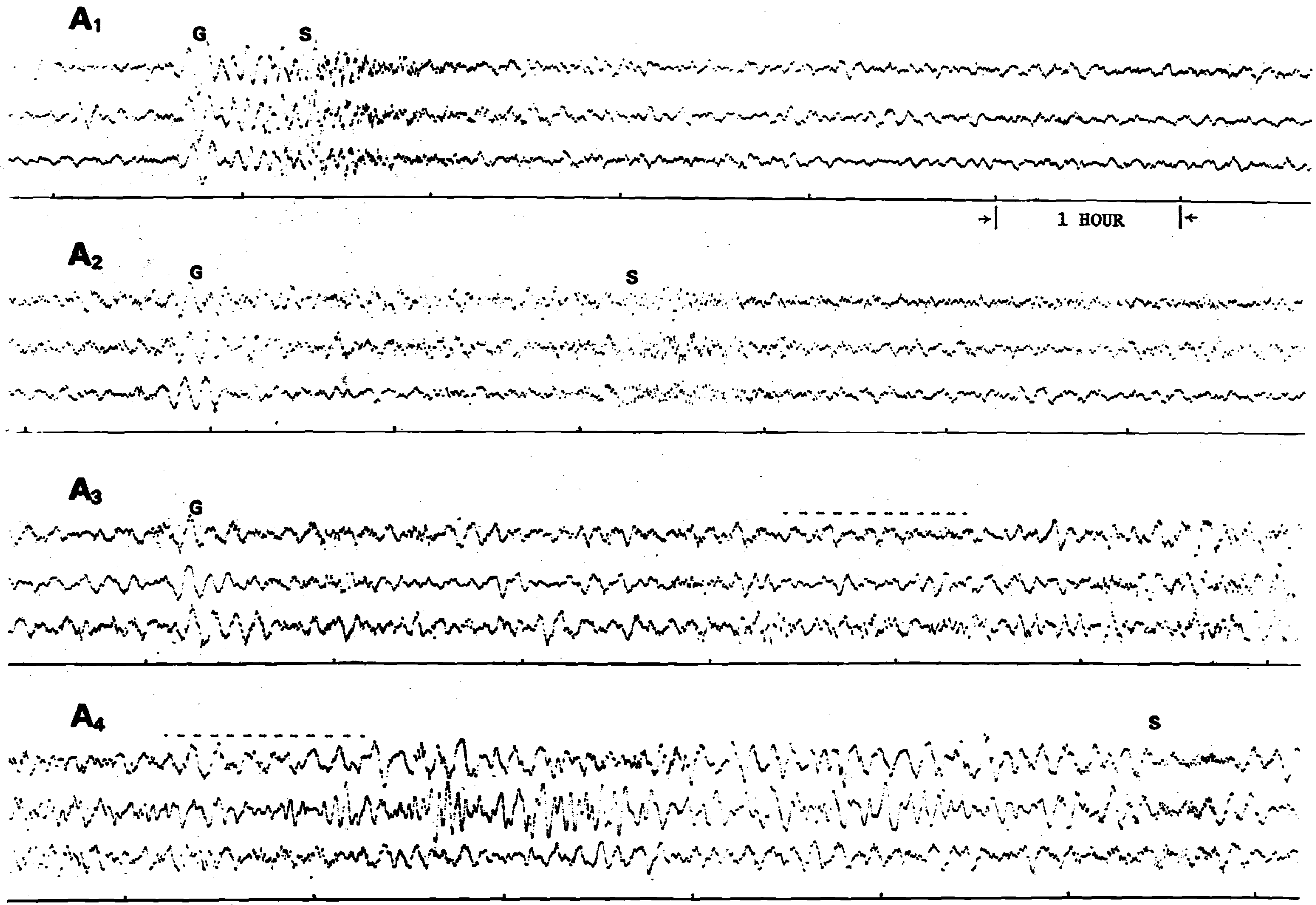


FIGURE 7. SUCCESSIVE ARRIVALS A1, A2, A3 AND A4 FROM THE CHINESE NUCLEAR EXPLOSION OF 14 OCTOBER 1970

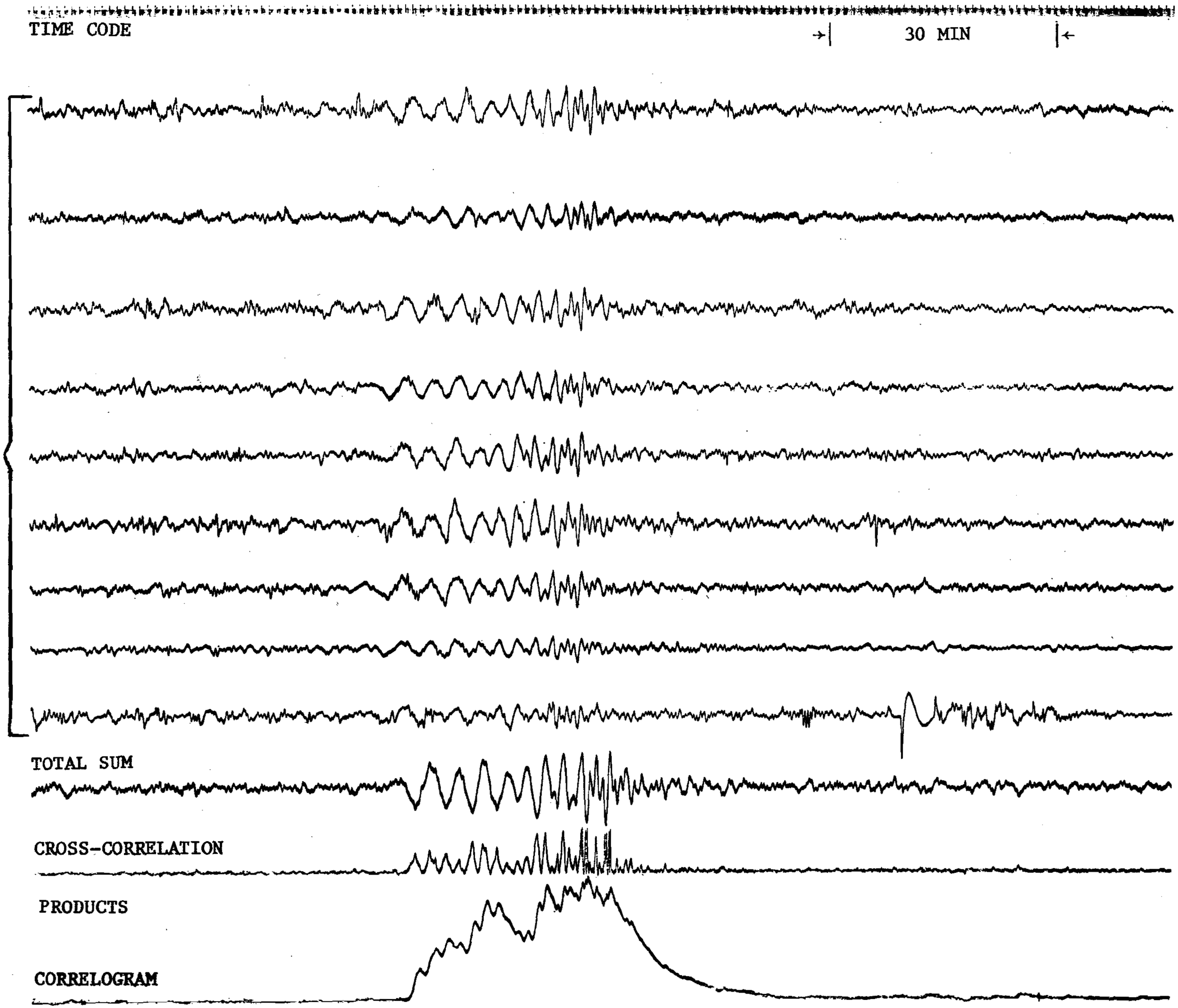


FIGURE 8. ARRAY PROCESSING OF STRONG SIGNAL (FIRST ARRIVAL A1 FROM THE CHINESE NUCLEAR EXPLOSION OF 27 SEPTEMBER 1969)

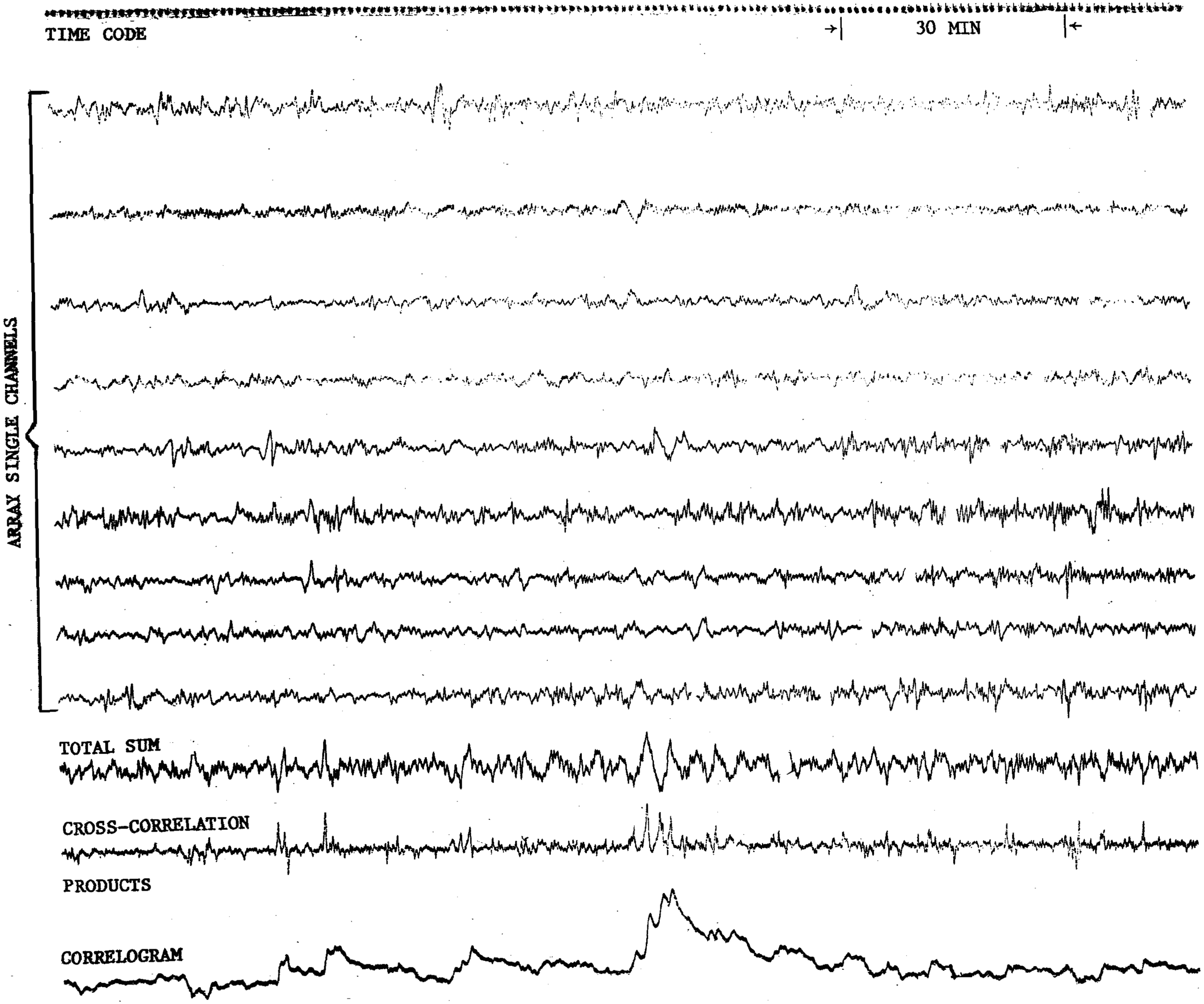


FIGURE 9. ARRAY PROCESSING OF WEAK SIGNAL (SECOND ARRIVAL A2 FROM THE CHINESE NUCLEAR EXPLOSION OF 27 SEPTEMBER 1969)

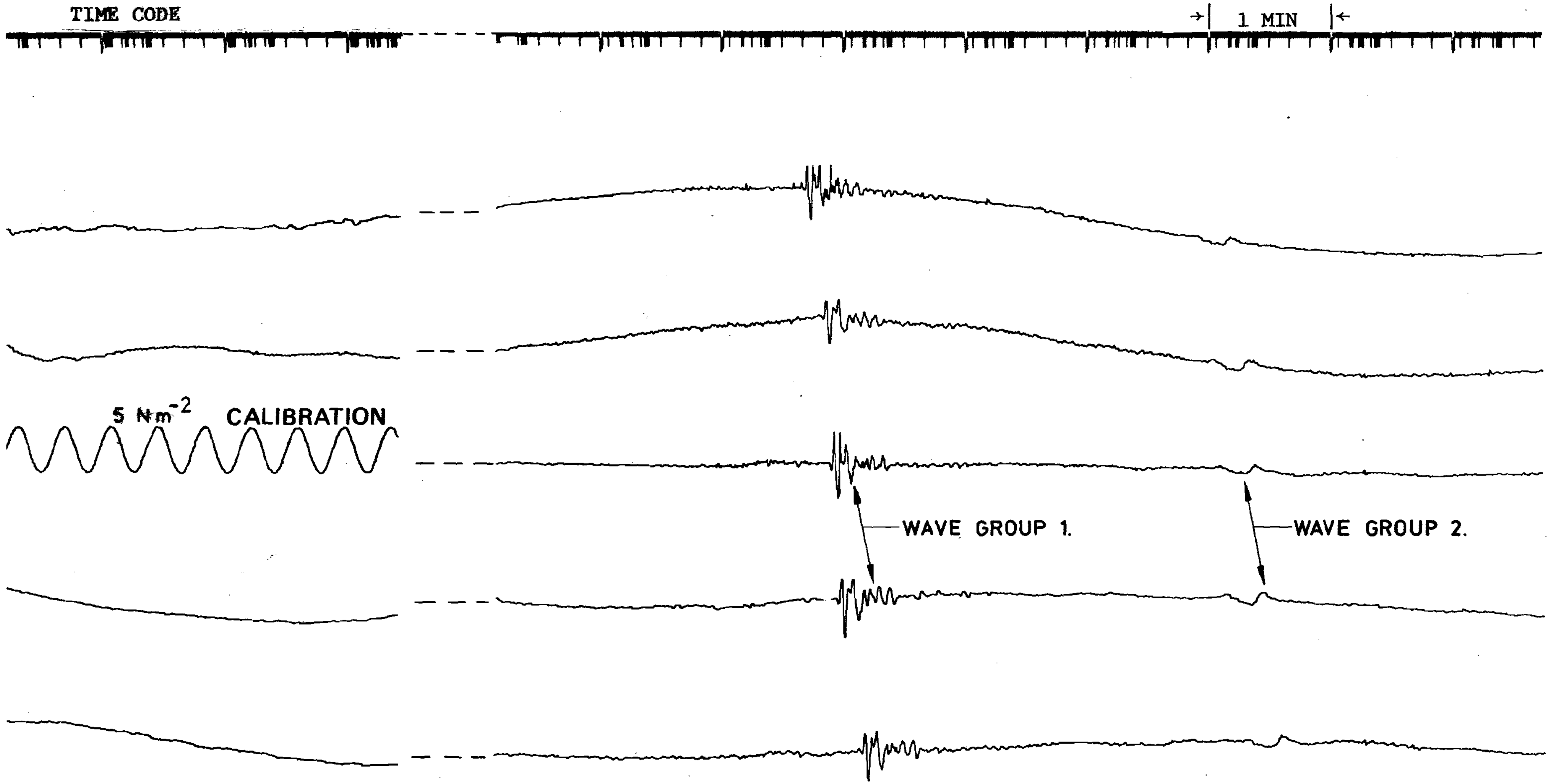


FIGURE 10. ST BRIDGET EXPLOSION, EFFECTS AT BMBA SITES, RANGE 338 TO 348 km

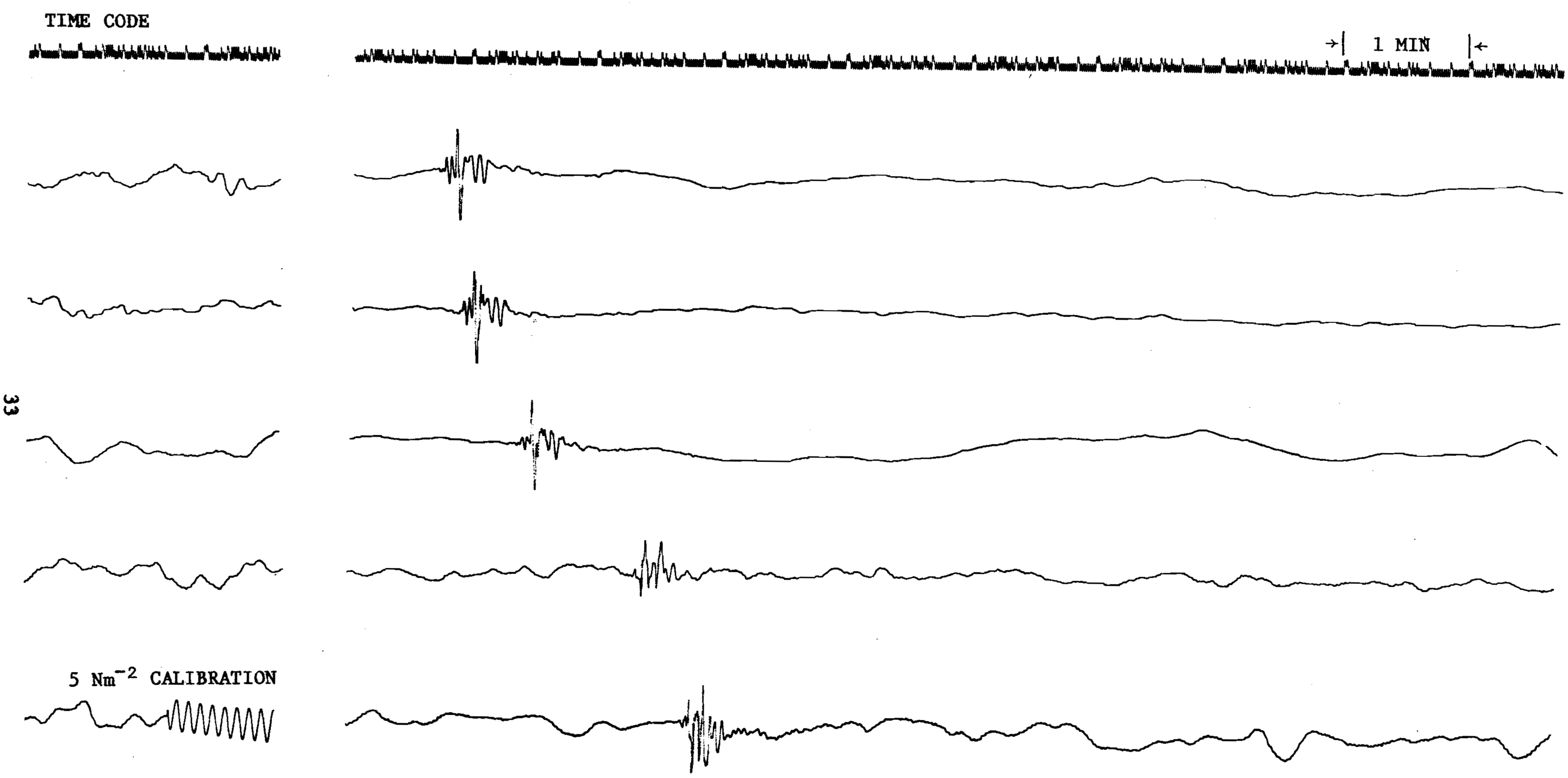


FIGURE 11. AMERSEE EXPLOSION, EFFECTS AT BMBA SITES, RANGE 238 TO 282 km

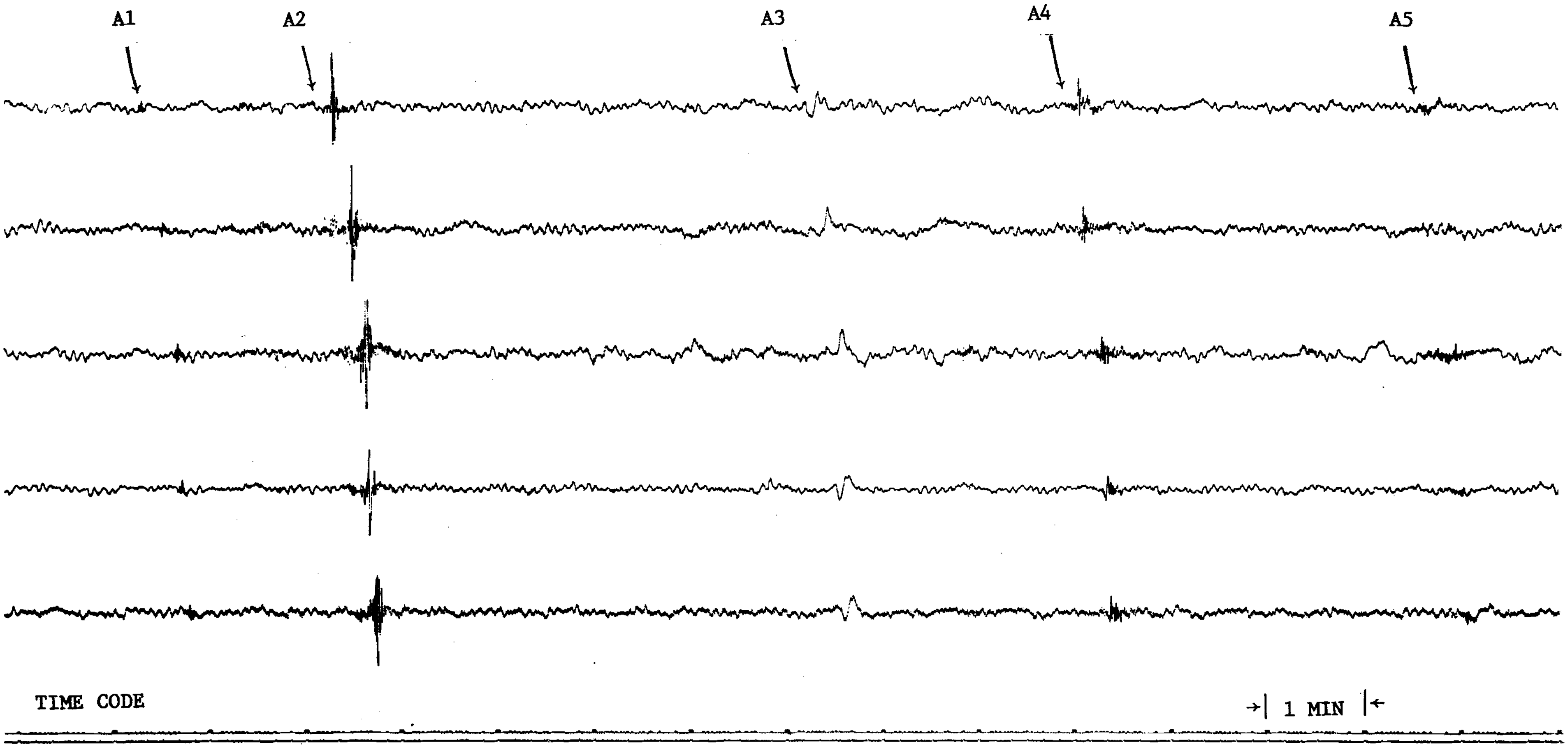


FIGURE 12. SUCCESSIVE ARRIVALS (A1 TO A5) OF INFRASONIC WAVES GENERATED BY A CONCORDE SUPERSONIC FLIGHT

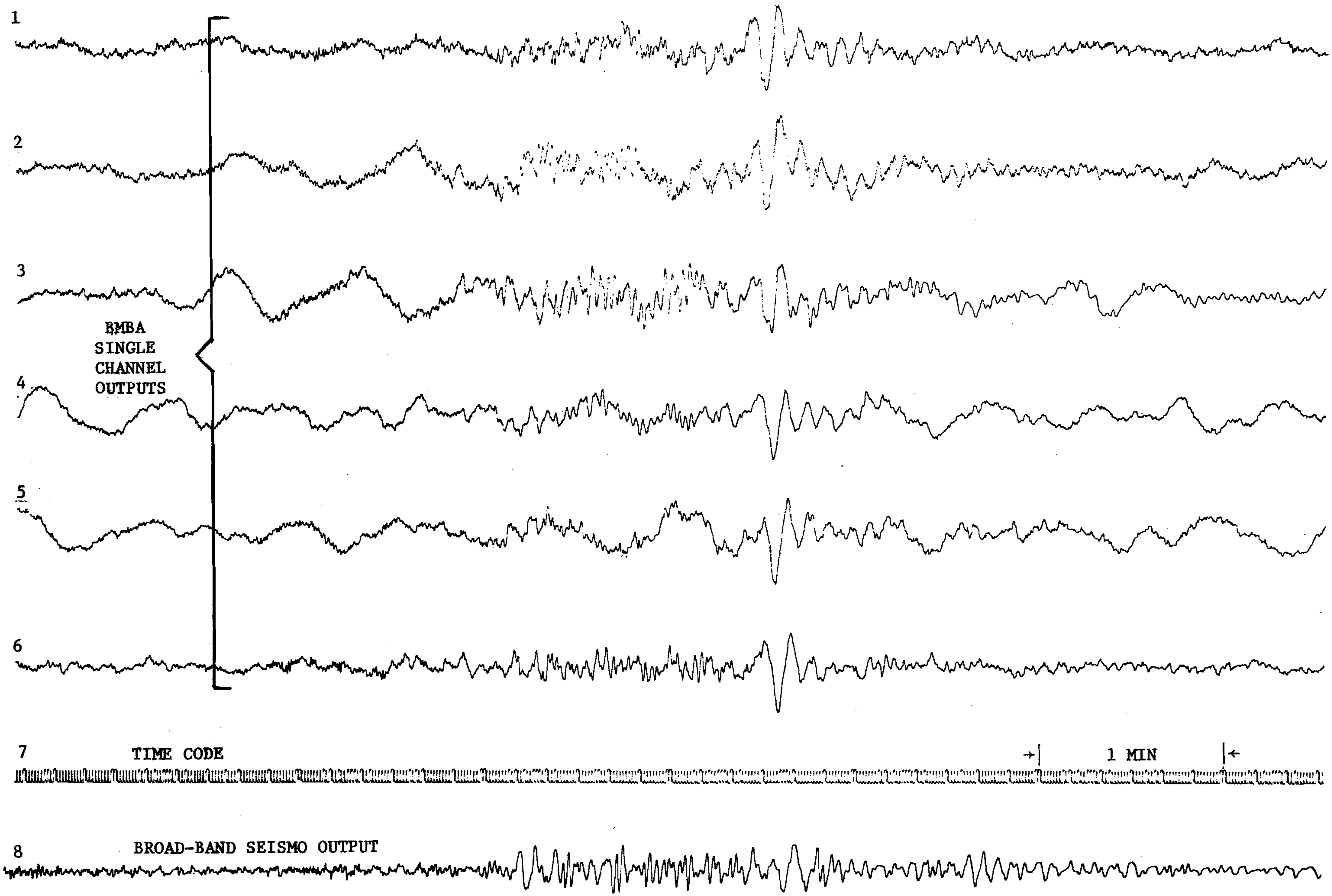


FIGURE 13. GROUND-AIR COUPLED WAVES FROM FRIULI EARTHQUAKE, ITALY.
TRACES 1 TO 6: MICROBAROGRAPH ARRAY RECORDINGS OF AIR WAVES COUPLED TO SEISMIC SURFACE WAVES FROM MAIN SHOCK 6 MAY 1976
TRACE 8: BROAD-BAND SEISMOMETER RECORDING OF SEISMIC SURFACE WAVES FROM A FRIULI AFTERSHOCK 9 MAY 1976

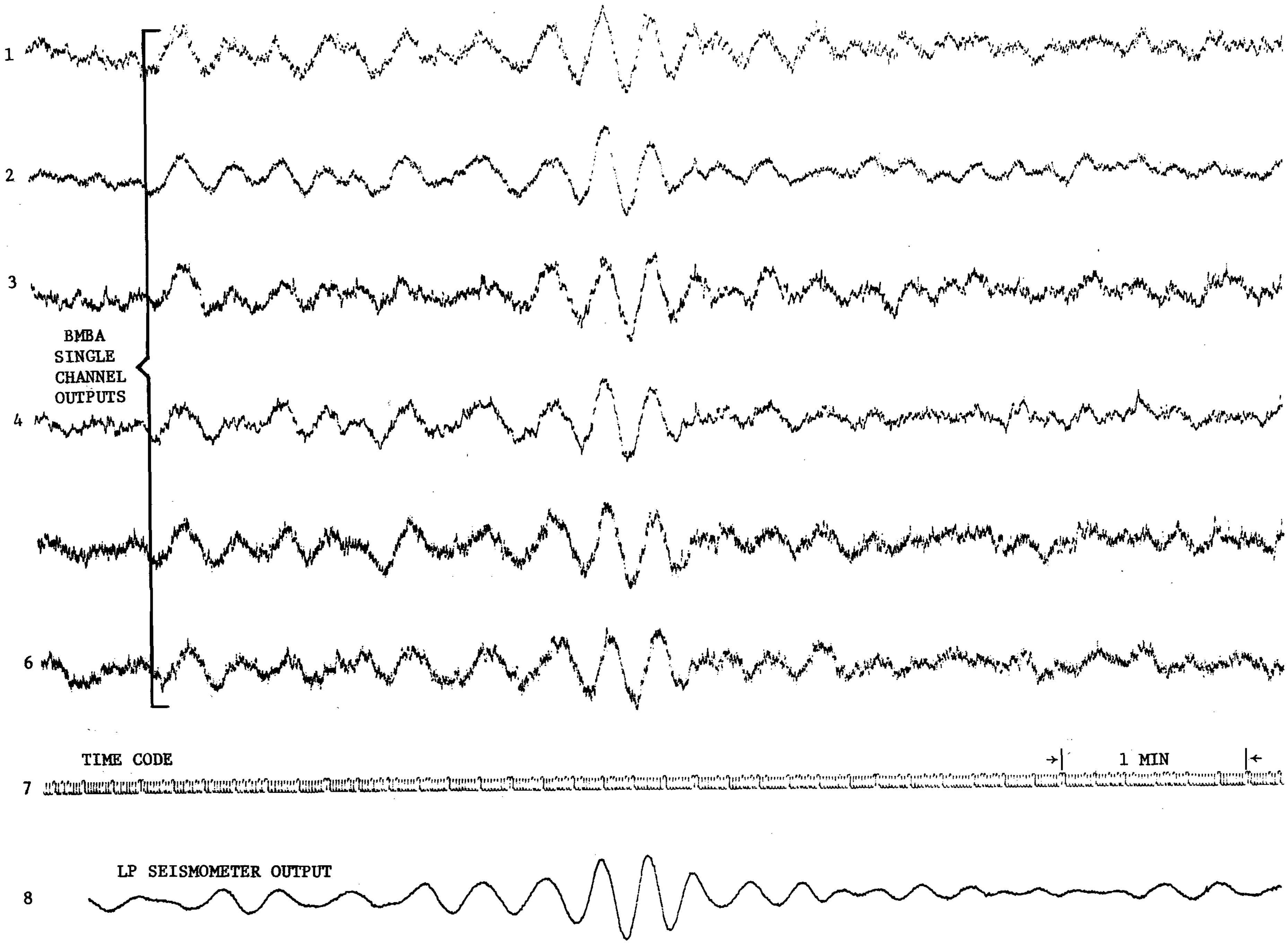


FIGURE 14. GROUND-AIR COUPLED WAVES FROM TANGSHAN EARTHQUAKE, CHINA.
TRACES 1 TO 6: MICROBAROGRAPH ARRAY RECORDINGS OF AIR WAVES COUPLED TO SEISMIC SURFACE WAVES FROM MAIN SHOCK 27 JULY 1976
TRACE 8: LONG-PERIOD SEISMOMETER RECORDING OF SEISMIC SURFACE WAVES FROM A TANGSHAN AFTERSHOCK 30 JULY 1976

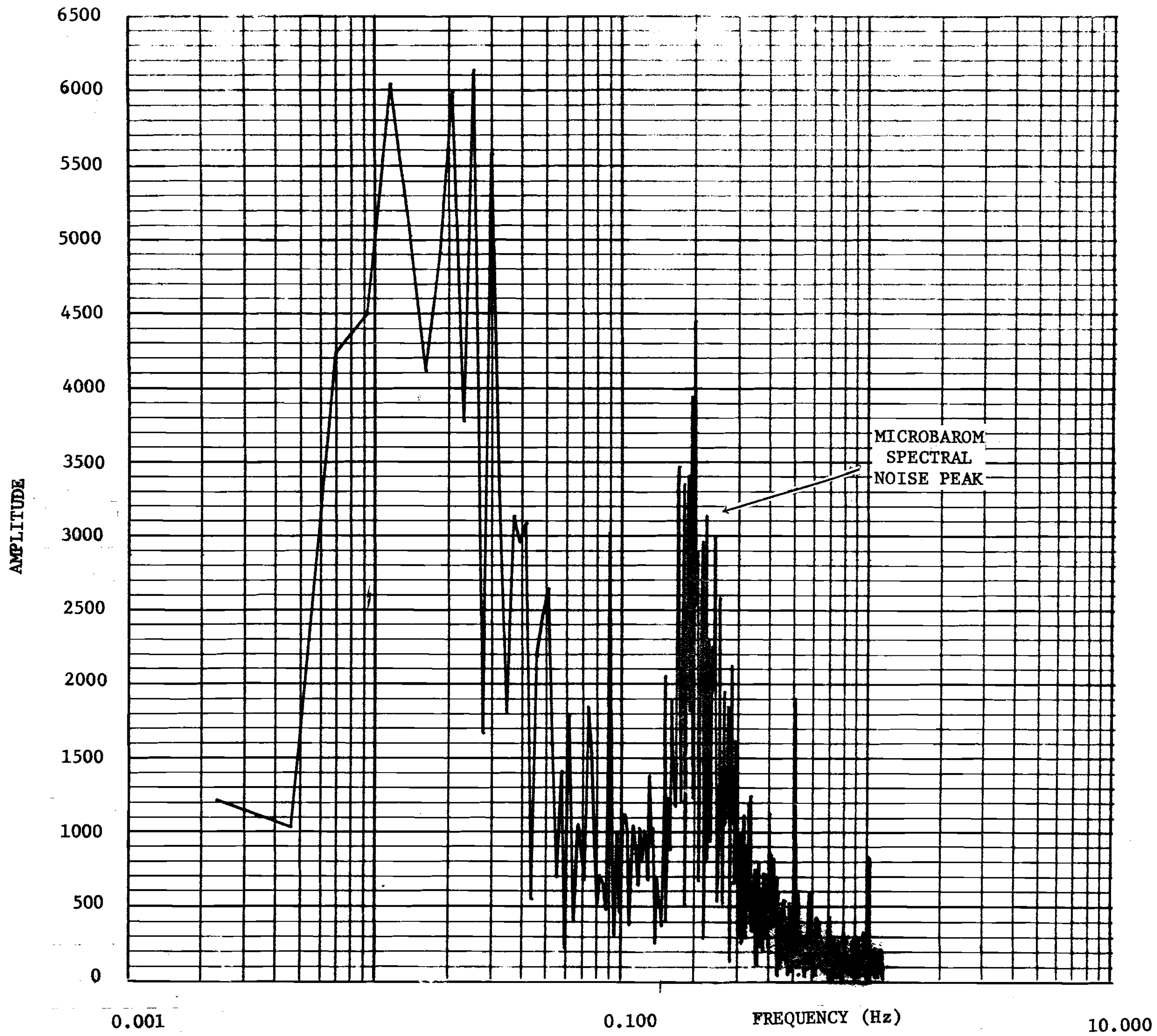


FIGURE 15. SPECTRAL NOISE PEAK DUE TO MICROBAROMS

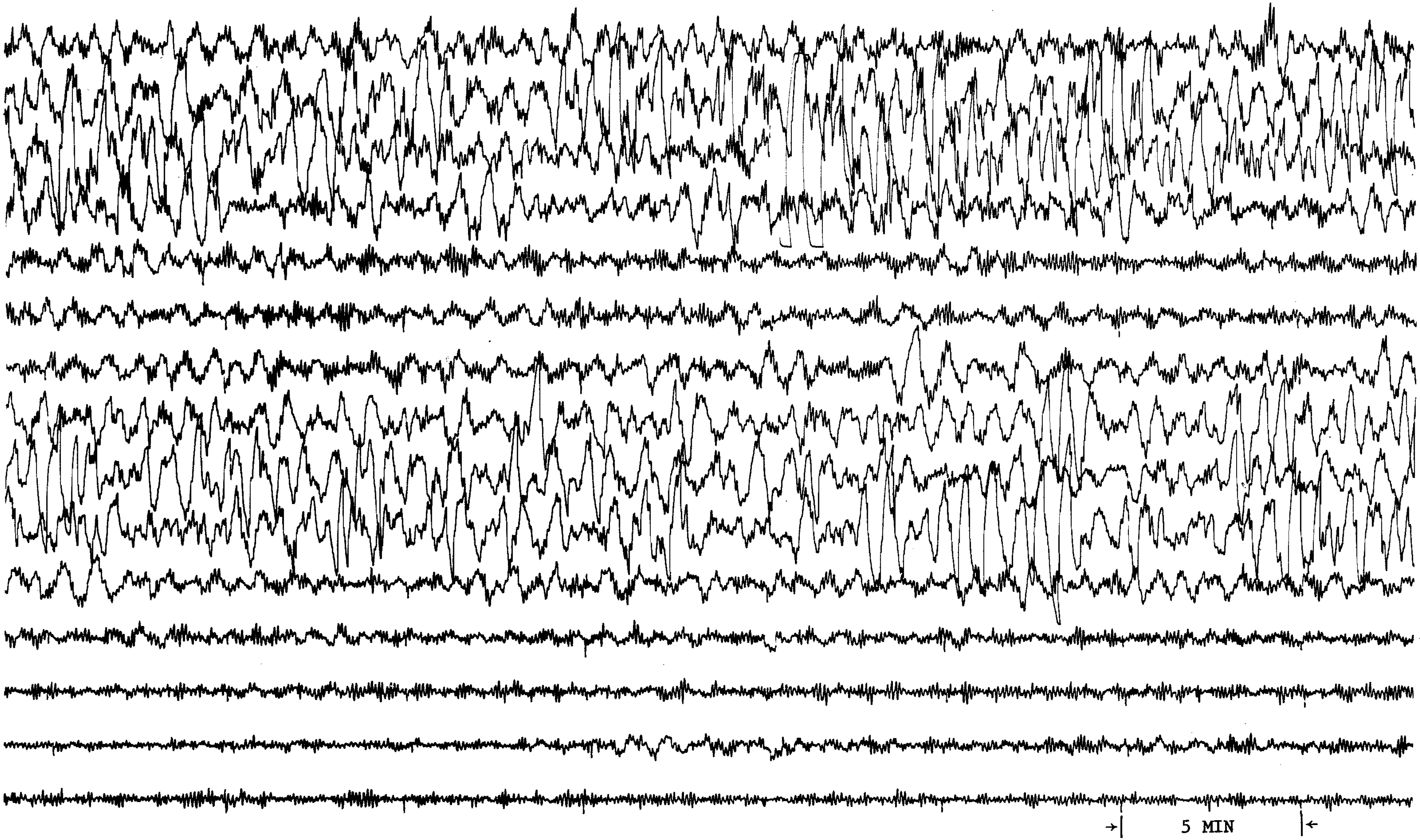


FIGURE 16. ONSETS OF MICROBAROMS BETWEEN PERIODS OF WIND NOISE. THE FIGURE SHOWS A VERTICAL SECTION OF A 24 HOUR DRUM CHART RECORDING WITH A TIME INTERVAL OF 90 MIN BETWEEN SUCCESSIVE LINES

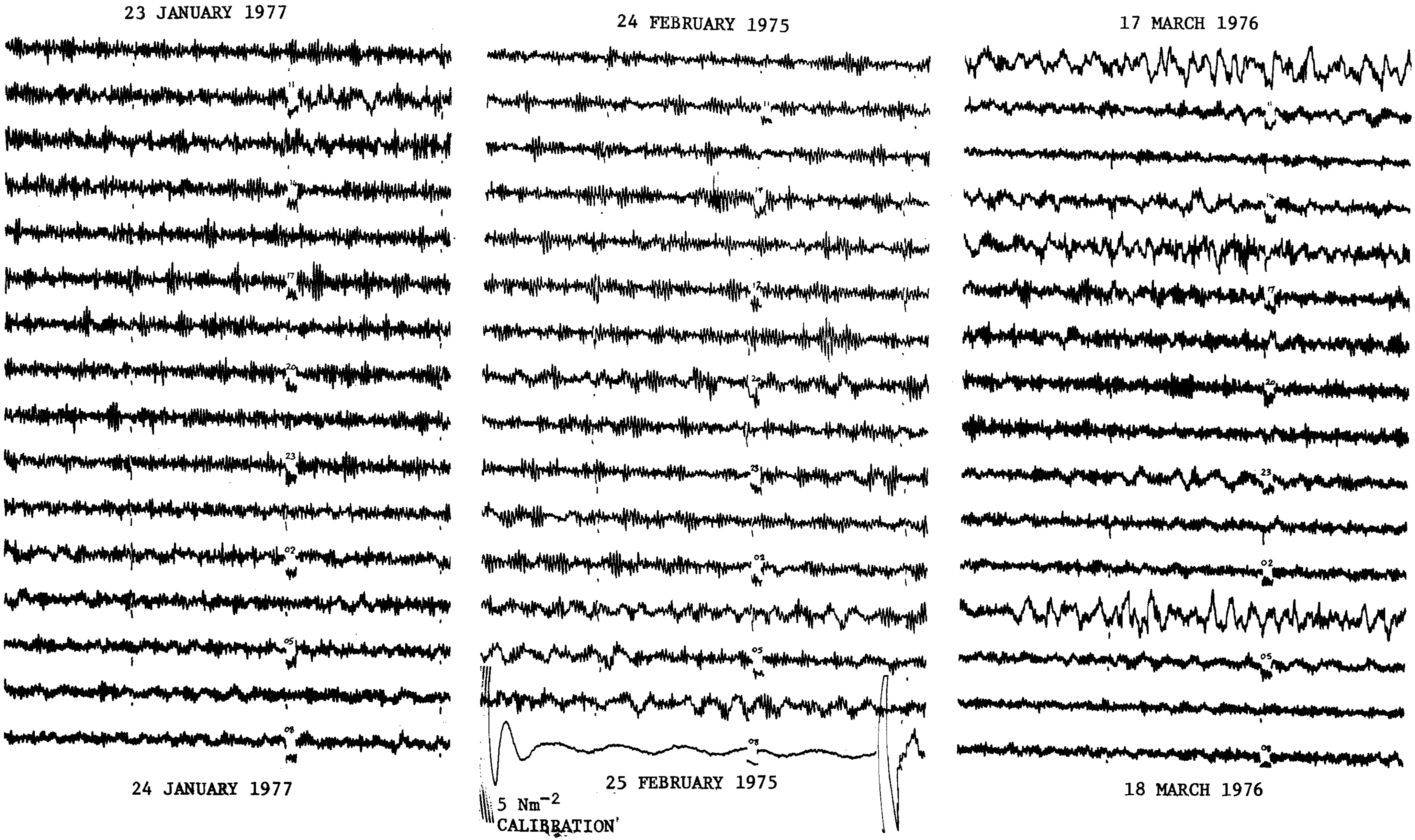


FIGURE 17. COMPARISON OF DIURNAL PATTERNS IN PERIODS OF CONTINUOUS MICROBAROM RECEPTION. THE FIGURE SHOWS VERTICAL SECTIONS FROM 3 DRUM CHART RECORDINGS FOR DAYS IN JANUARY, FEBRUARY AND MARCH

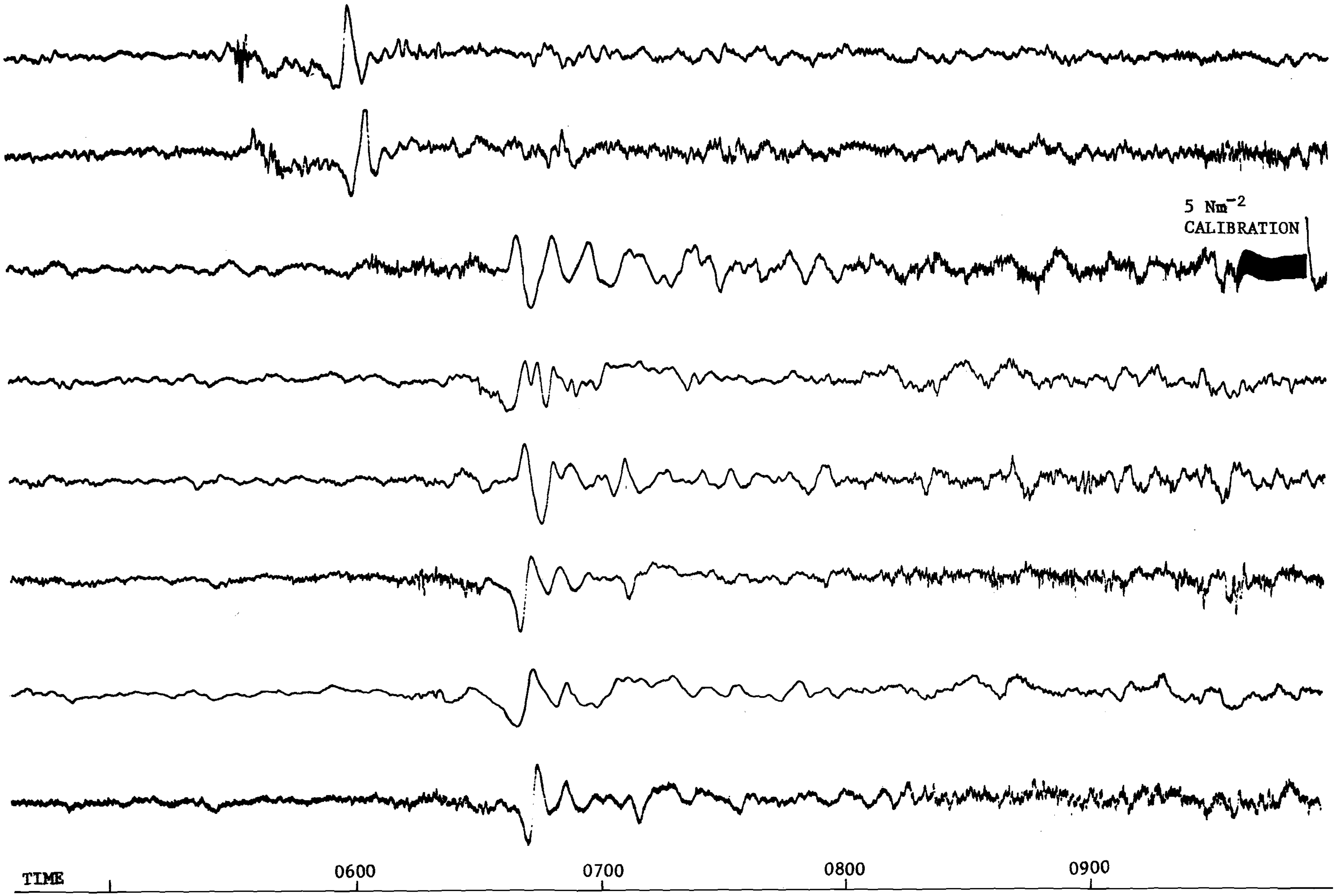
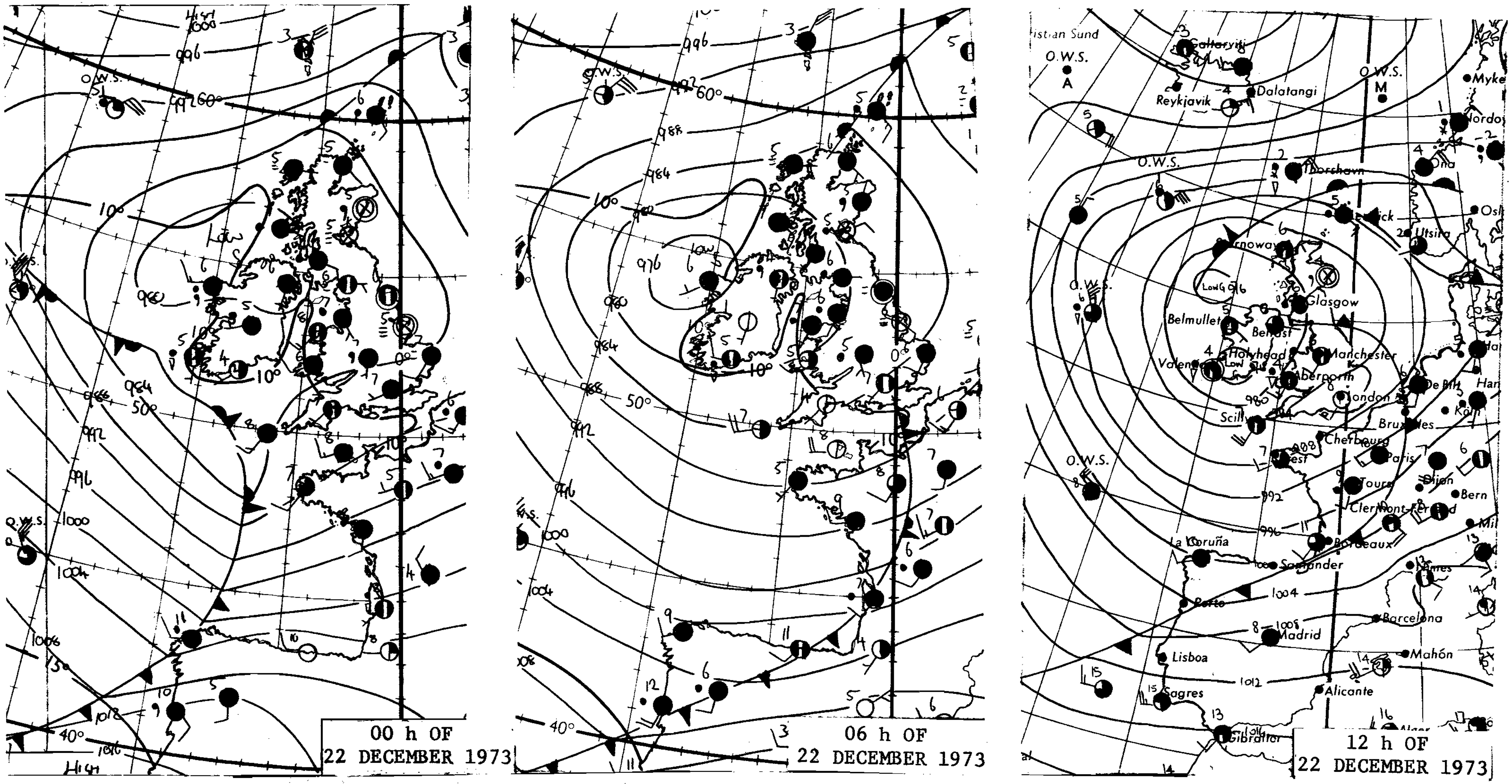


FIGURE 18. PASSAGE OF COLD FRONT TRAVELLING EASTWARDS ACROSS MICROBAROGRAPH ARRAY ON 22 DECEMBER 1973



GENERAL SYNOPTIC DEVELOPMENT

THE SLOW MOVING DEPRESSION OVER SOUTH-WEST WALES IS NOW NEARLY STATIONARY OVER NORTHERN IRELAND AND A SMALL DEPRESSION WHICH MOVED RAPIDLY SOUTH-EASTWARDS FROM SOUTH GREENLAND TOWARDS IRELAND HAS BEEN ABSORBED IN THE GENERAL CIRCULATION OF THE PARENT LOW.

FIGURE 19. EXTRACTS FROM DAILY WEATHER CHART FOR 22 DECEMBER 1973

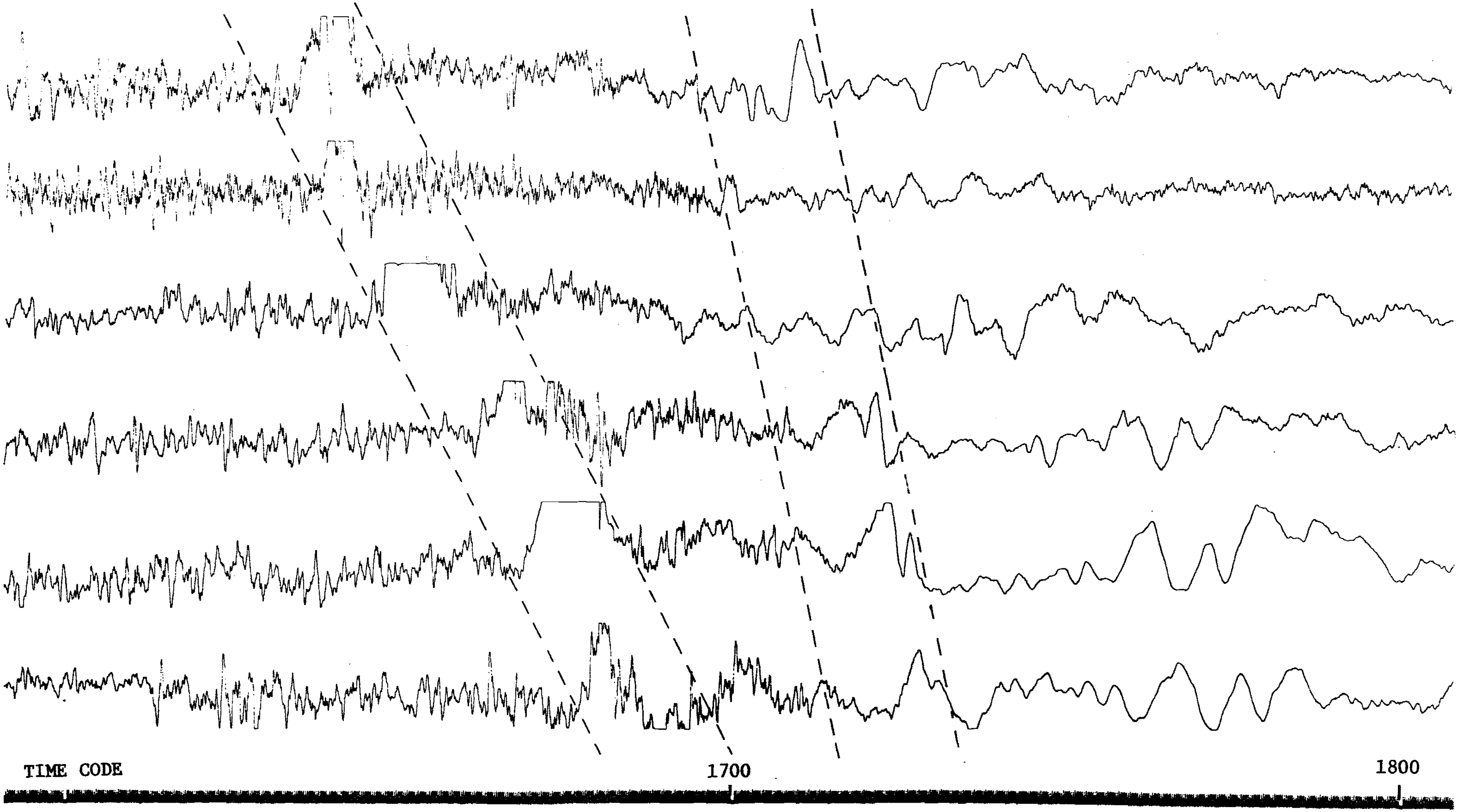
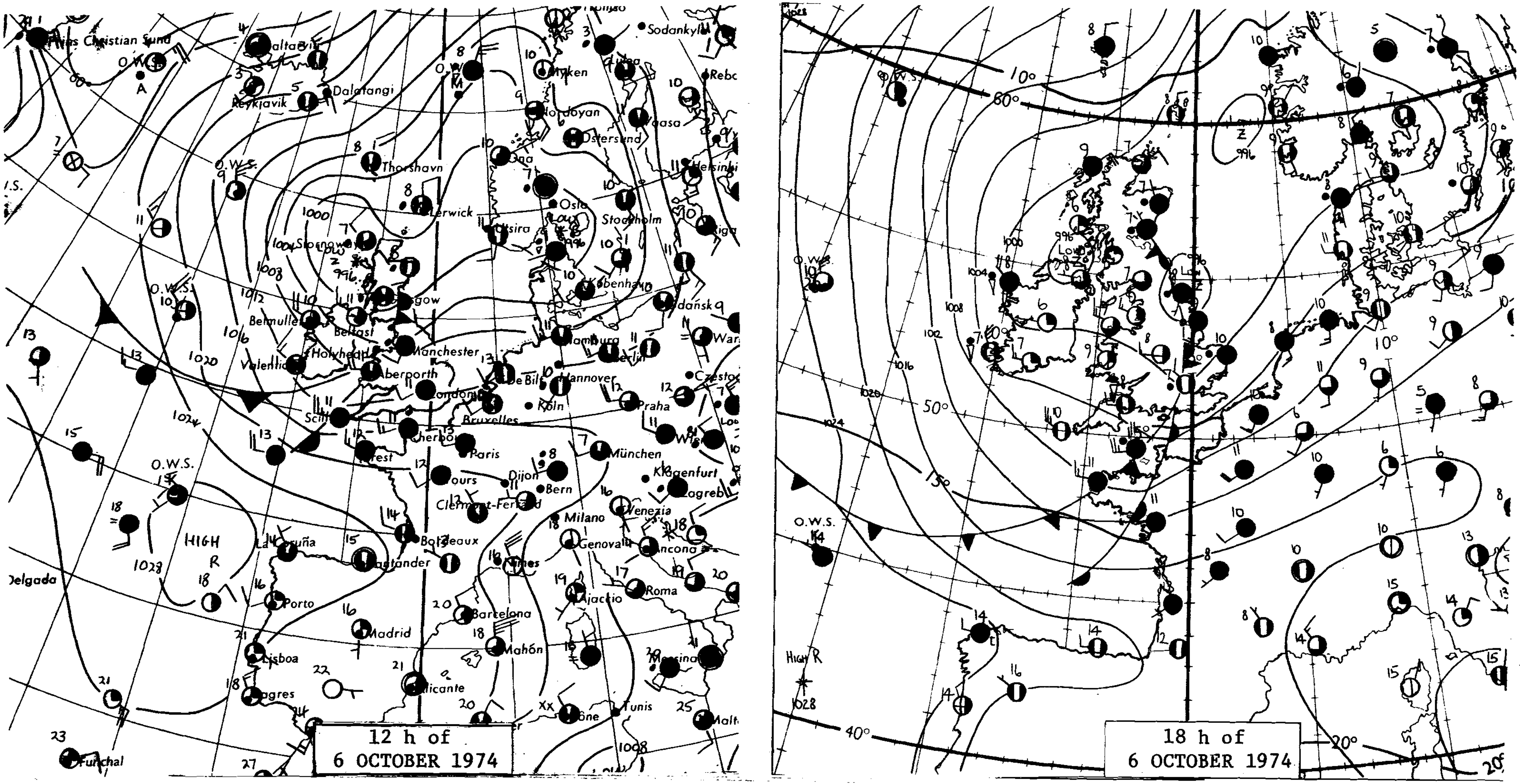


FIGURE 20. PASSAGE OF FRONTS ACROSS MICROBAROGRAPH ARRAY ON 6 OCTOBER 1974



GENERAL SYNOPTIC DEVELOPMENT

DURING THE PAST 24 HOURS A DEPRESSION NORTH-WEST OF THE HEBRIDES MOVED SOUTH-EAST INTO THE NORTH SEA WITH ITS ASSOCIATED TROUGHS CROSSING THE WHOLE OF THE BRITISH ISLES.

FIGURE 21. EXTRACT FROM DAILY WEATHER CHART FOR 6 OCTOBER 1974

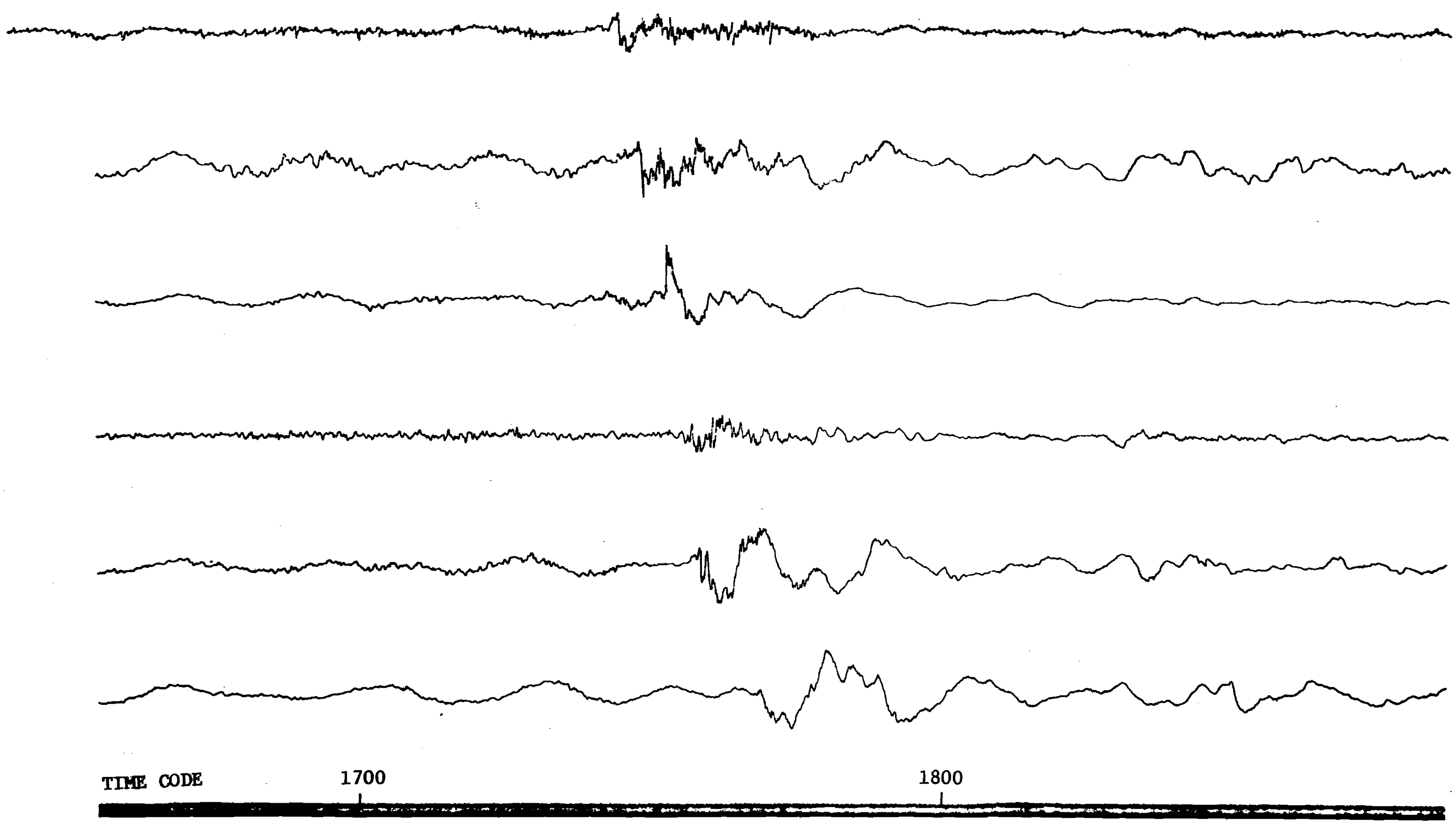
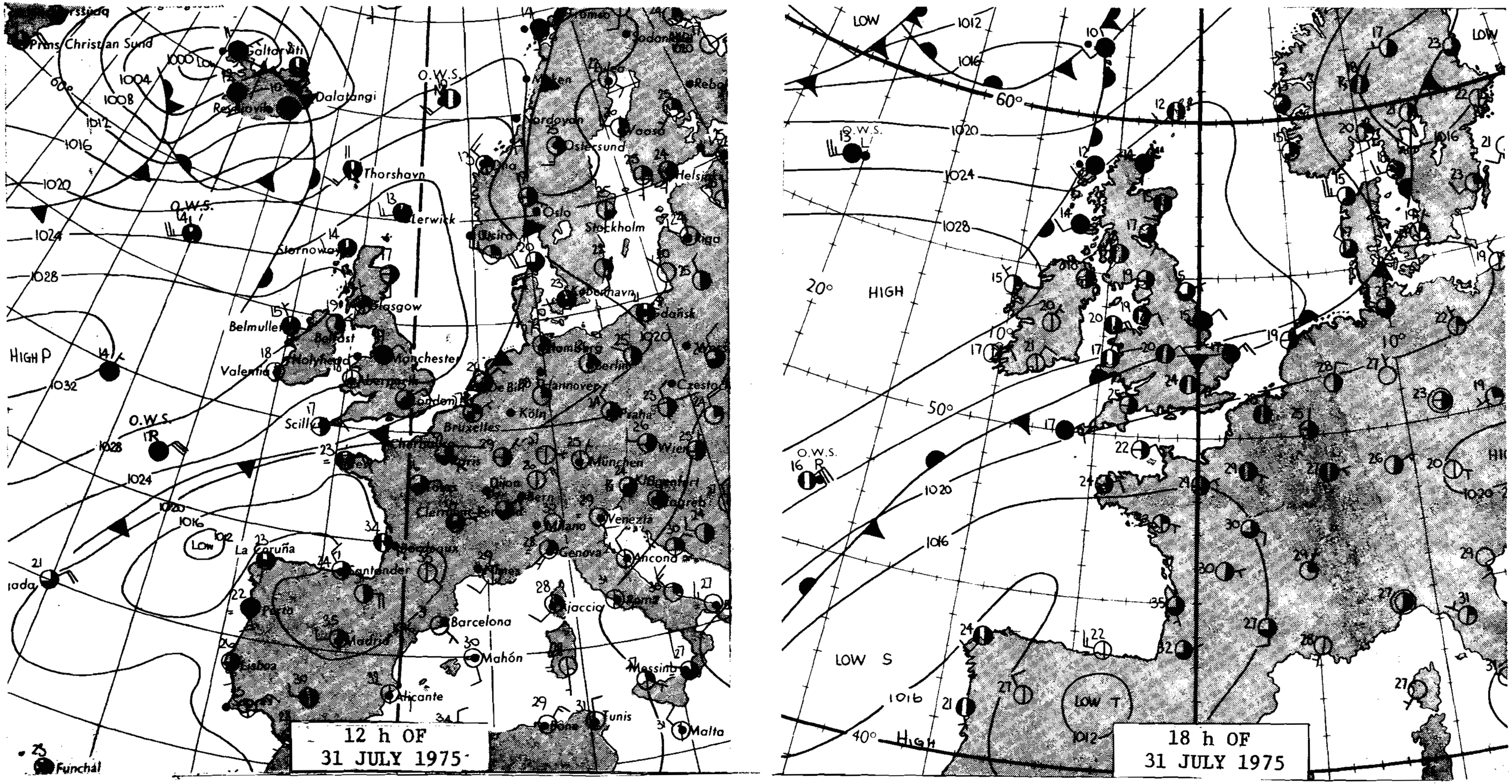


FIGURE 22. WEATHER DISTURBANCE 31 JULY 1975



GENERAL SYNOPTIC DEVELOPMENT

DURING THE PAST 24 HOURS ONLY MINOR CHANGES TOOK PLACE IN THE PRESSURE DISTRIBUTION OVER AND NEAR THE BRITISH ISLES. A RIDGE OF HIGH PRESSURE PERSISTED OVER CENTRAL AND NORTHERN ENGLAND, WHILE PRESSURE REMAINED LOW NEAR ICELAND AND, TO A LESSER EXTENT, OVER FRANCE.

FIGURE 23. EXTRACT FROM DAILY WEATHER CHART FOR 31 JULY 1975

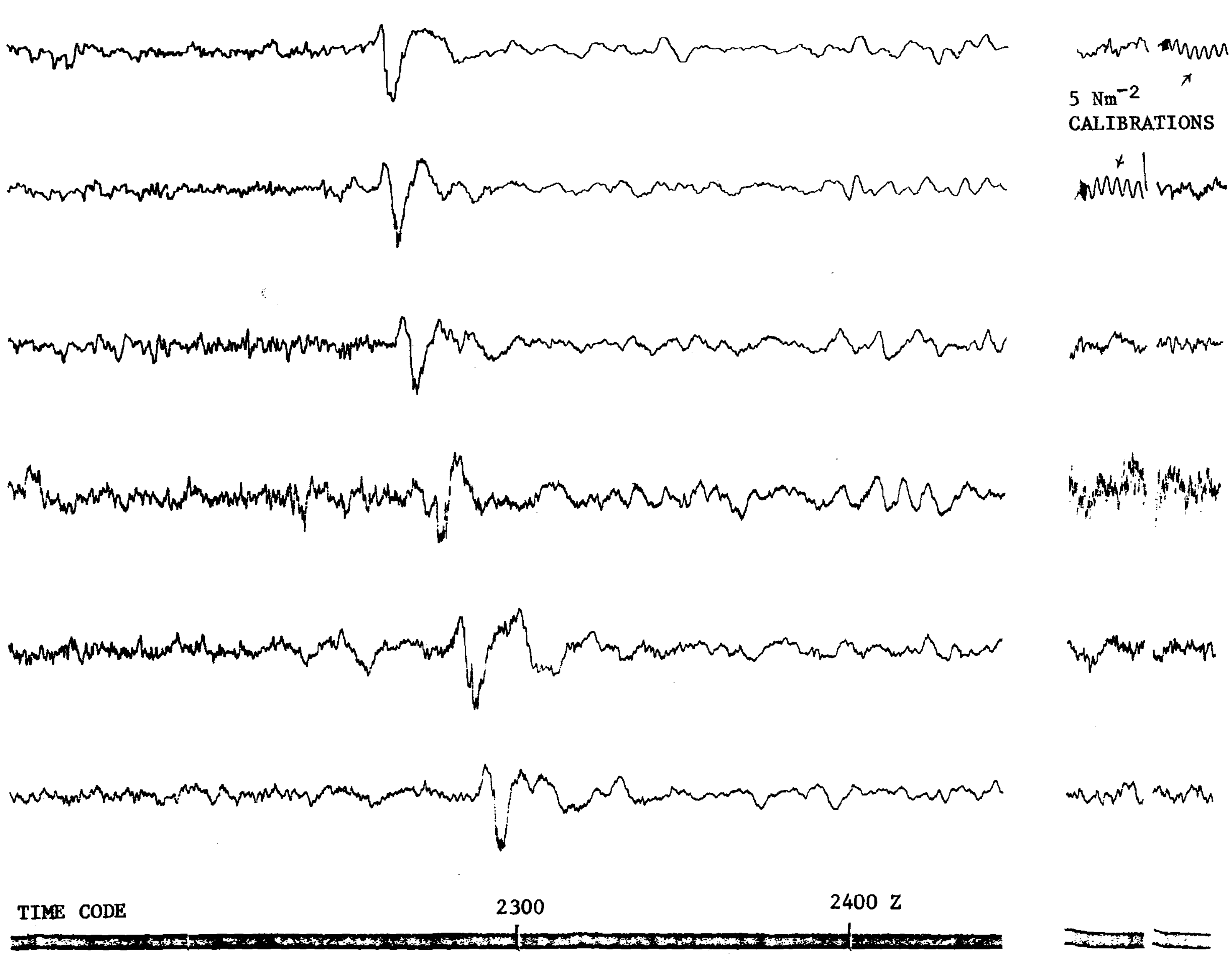
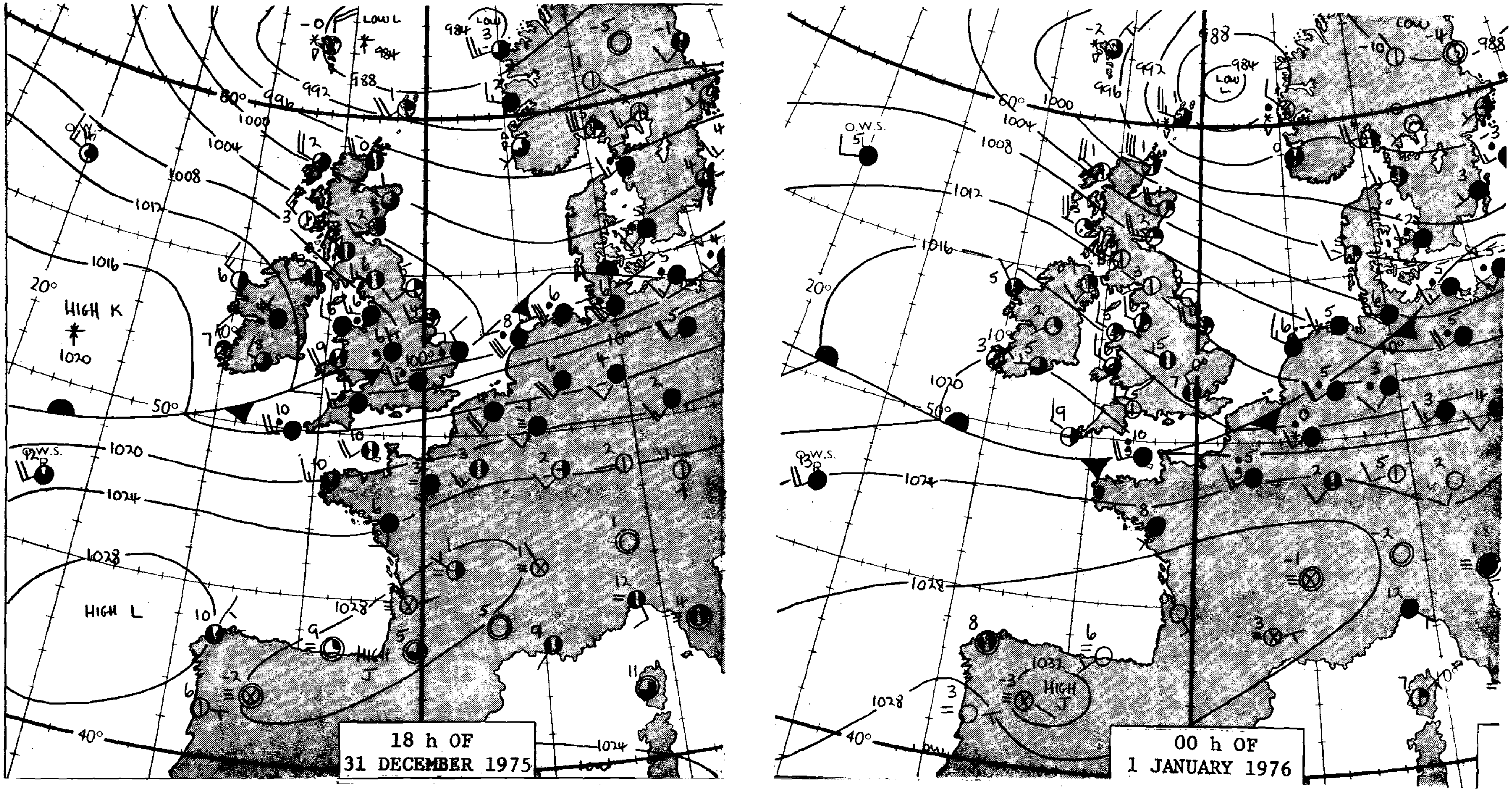


FIGURE 24. PASSAGE OF COLD FRONT ACROSS MICROBAROGRAPH ARRAY ON 31 DECEMBER 1975



GENERAL SYNOPTIC DEVELOPMENT

PRESSURE CONTINUED LOW FROM GREENLAND TO SCANDINAVIA AND HIGH OVER IBERIA AND CENTRAL EUROPE. A FRONTAL TROUGH MOVED SLOWLY SOUTH OVER ENGLAND AND WALES TO GIVE STRONG SOUTH-WEST GRADIENTS AHEAD OF IT.

FIGURE 25. EXTRACT FROM DAILY WEATHER CHARTS FOR 31 DECEMBER 1975 AND 1 JANUARY 1976

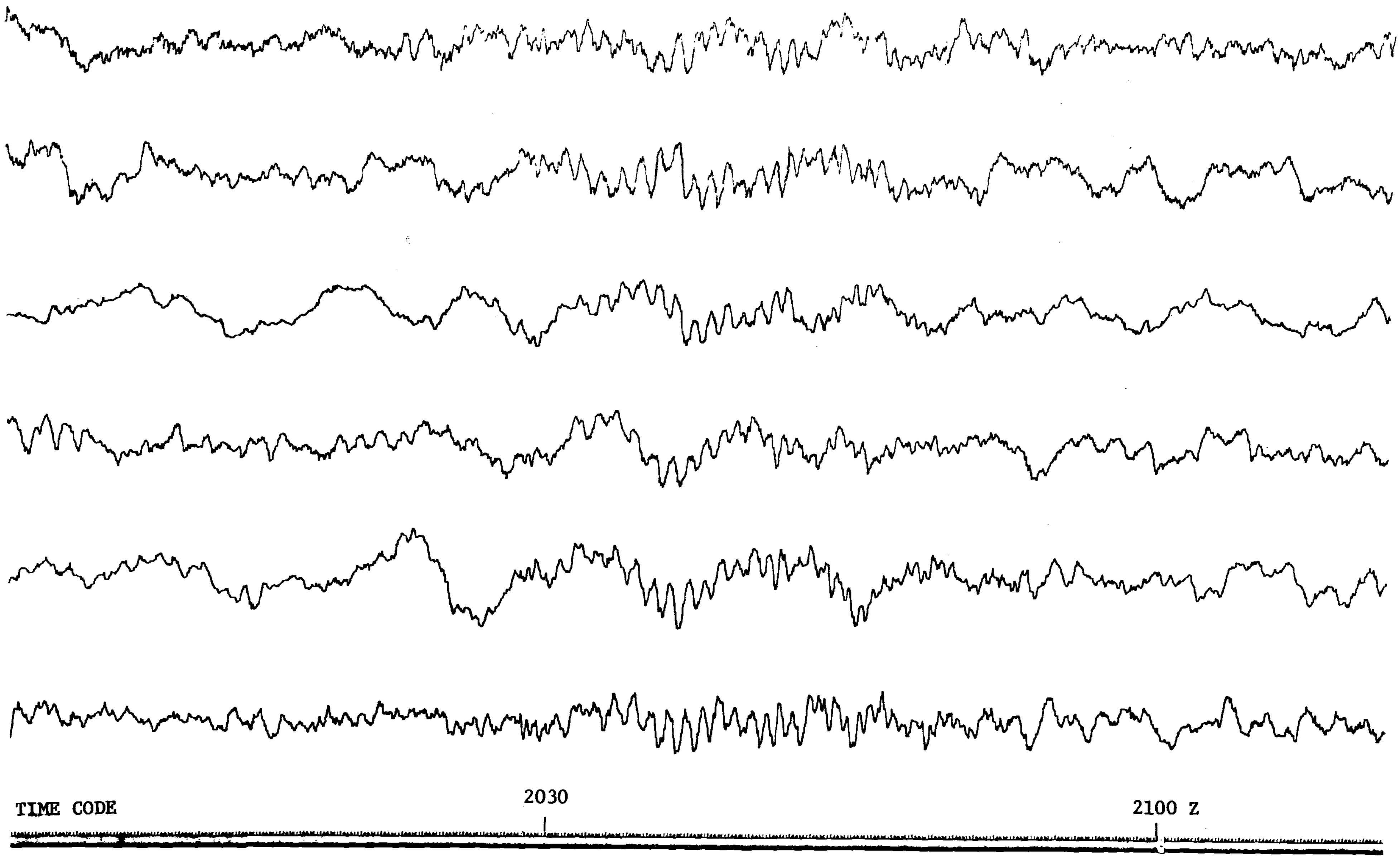
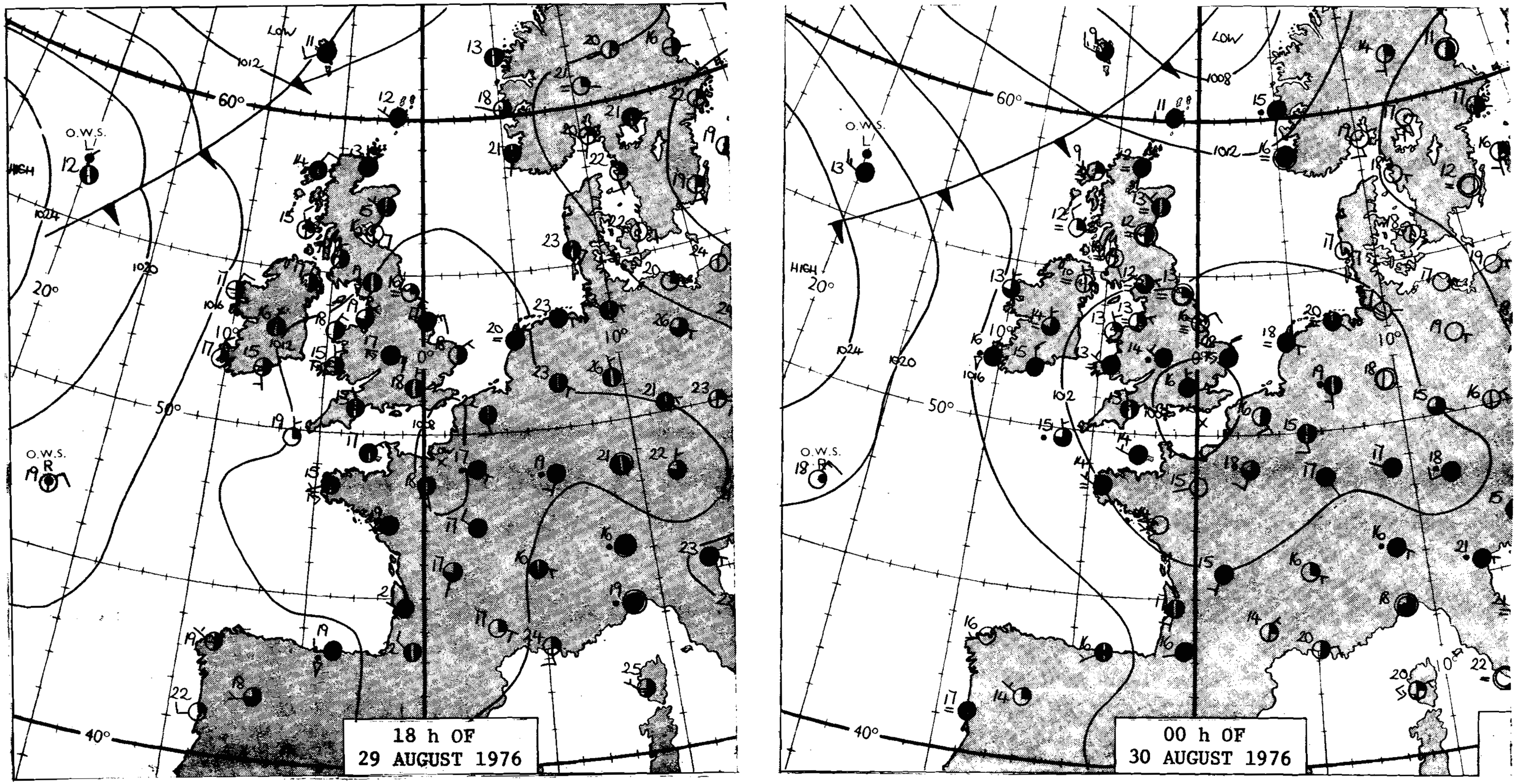


FIGURE 26. ATMOSPHERIC PRESSURE WAVE OSCILLATIONS RECORDED AT BMBA SITES ON 29 AUGUST 1976



GENERAL SYNOPTIC DEVELOPMENT

DURING THE PAST 24 HOURS PRESSURE CONTINUED TO FALL OVER THE BRITISH ISLES AS A SHALLOW AND COMPLEX THUNDERY LOW OVER THE BAY OF BISCAY MOVED SLOWLY NORTH-EASTWARDS TO BE OVER SOUTHERN ENGLAND BY THIS MORNING. THE ANTICYCLONES OVER THE CENTRAL NORTH ATLANTIC AND NORTH-EAST EUROPE REMAINED ALMOST STATIONARY, ALTHOUGH THE LATTER WEAKENED A LITTLE.

FIGURE 27. EXTRACT FROM DAILY WEATHER CHARTS FOR 29 AND 30 AUGUST 1976

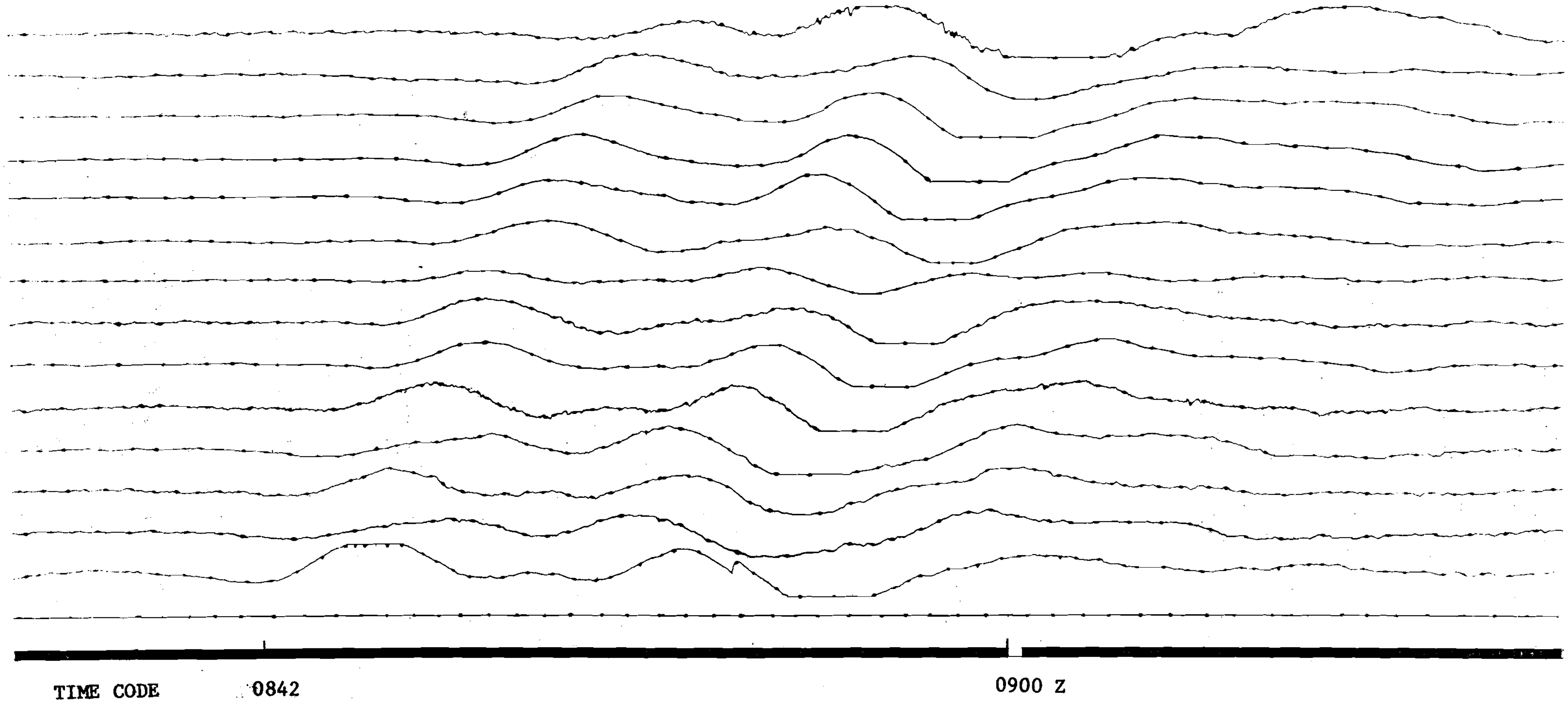


FIGURE 28. PASSAGE OF FRONT ASSOCIATED WITH RAPIDLY MOVING DEPRESSION TRAVERSING MICROBAROGRAPH ARRAY ON 25 JANUARY 1977

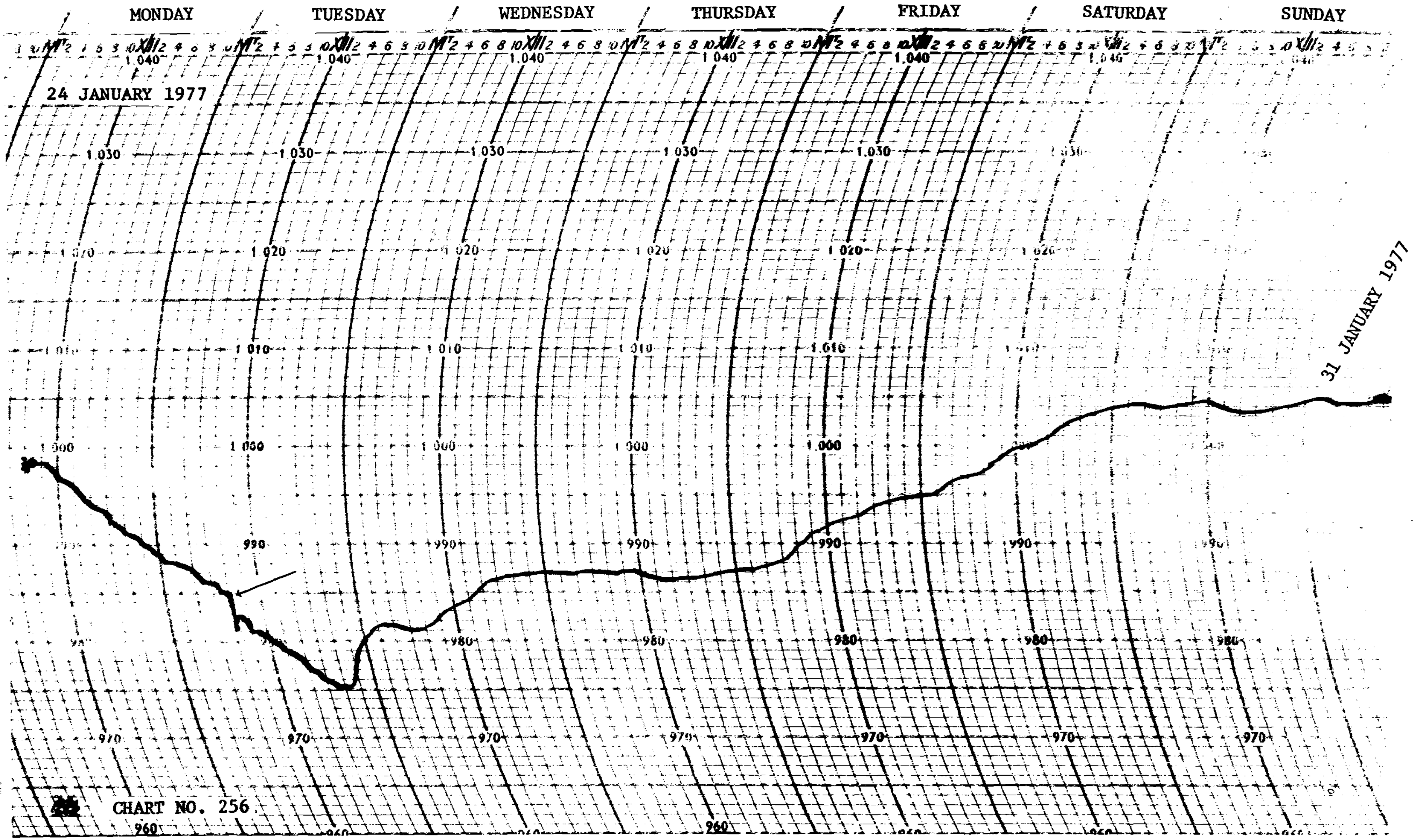
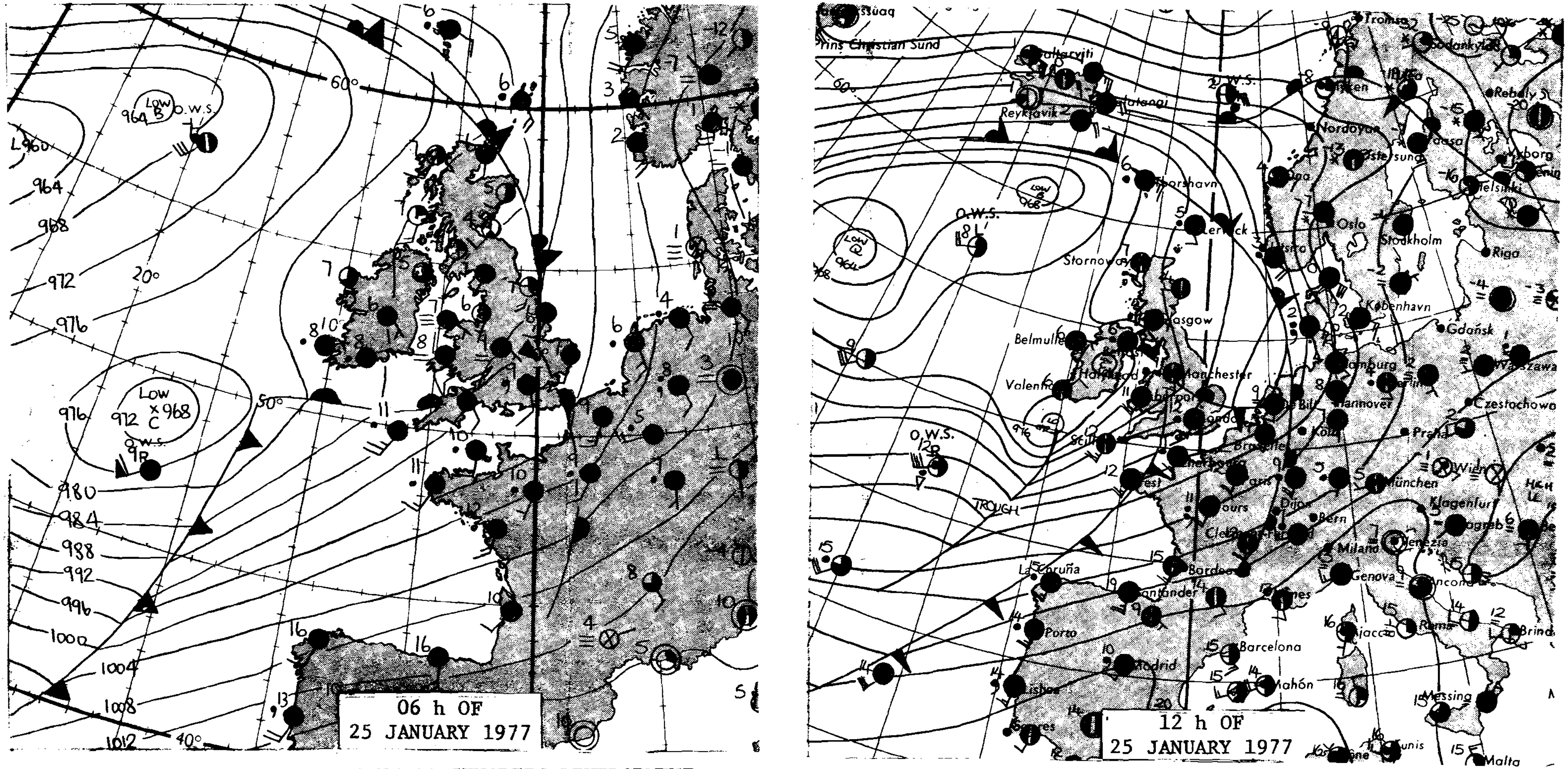


FIGURE 29. MILLIBAROGRAPH CHART FOR WEEK OF 24 TO 31 JANUARY 1977



GENERAL SYNOPTIC DEVELOPMENT

DURING THE LAST 24 HOURS A COMPLEX AREA OF LOW PRESSURE REMAINED OVER CENTRAL AND EASTERN NORTH ATLANTIC, AND EXTENDED EASTWARDS AS A DEPRESSION MOVED RAPIDLY FROM SOUTH-WEST OF IRELAND AND INTO THE NORTH SEA BRINGING STRONG WINDS TO MOST AREAS OF THE UNITED KINGDOM.

FIGURE 30. EXTRACT FROM DAILY WEATHER CHART FOR 25 JANUARY 1977

5. ACKNOWLEDGMENTS

Grateful acknowledgments are made to several colleagues who have contributed in many ways to the success of atmospheric wave recording at Blacknest. Valuable contributions have been made by Mr B Hopkins in developing the beam-forming techniques used for processing many of the early array records, Mr R Allison in producing the engineered version of the microbarometer, Mr S V New and Mr P G Robinson in the design engineering of units for the data-acquisition system currently in operation, Mr P G Gibbs in making regular analyses of visual records produced in the recording centre and Mr C Wood in maintaining the operational status of the field systems.

A major contribution throughout has been made by Mr E W James who has been closely involved with the project at all stages from design and development of the early instrumentation, pipe filters and prototype array system, through to the development and commissioning of the present engineered system.

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Abstract

Techniques are described for recording atmospheric waves at the AWRE Blacknest Research Centre.

Examples, with interpretative comments, of various types of atmospheric waves observed over a period of several years are illustrated in a series of figures taken from a representative selection of Blacknest records.