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Infrasonic and Seismic Wave Records from the Flixborough and St Bridget Explosions

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CONTENTS

SUMMARY

Microbarometric and seismic perturbations recorded at distances in the range 245 - 350 km from two large explosions are described and compared. The explosions were at the NYPRO (UK) Chemical Works, Flixborough, Lincolnshire on 1 June 1974 and in a small ship, the St Bridget, in the English Channel on 14 February 1972.

1. INTRODUCTION

An explosion occurred on 1 June 1974 at the NYPRO (UK) Chemical Works, Flixborough, North Lincolnshire, causing major damage to the plant and killing 28 people. The cause of the explosion is still under investigation, but it is known from Press reports that a process used at the plant for producing Caprolactam, the raw material from which nylon is made, involved the oxidation in reaction vessels of large quantities of a petroleum-like liquid, cyclohexane.

In addition to the more apparent local manifestations of the explosion, microbarometric and seismic disturbances were observed at distances in the range 245 - 280 km by microbarographs and seismographs deployed at a number of sites in the UK by AWRE for the detection of atmospheric infrasonic waves and low level seismic vibrations.

Effects at comparable ranges, 300 - 350 km from an earlier large explosion, were also recorded at some of the same instrument sites when a cargo of explosives carried in a small coaster, the St Bridget, blew up in the English Channel about 80 km south of Falmouth on 14 February 1972. The cargo consisted of 110 tons of nitroglycerine which had been condemned after being found to be in too dangerous a condition to unload.

2. EVENT DATA

2.1 Flixborough explosion

Source:	NYPRO (UK) Chemical Works, Flixborough, Lincolnshire
Location:	53°36.4'N 0°41.2'W
Date:	1 June 1974
Origin time:	1553Z (reported in the Press) 1552.15Z (estimate from EKA seismic data)
Explosive:	Probably vapourised cyclohexane
Quantity:	Unknown
Meteorological conditions:	Fronts associated with a depression north-west of the British Isles moving eastwards across Ireland. Surface winds in the source area and recording station areas were generally southerly 8 - 12 knots. Wind at altitude 11 km, westerly, 64 - 75 knots

2.2 St Bridget explosion

Source:	St Bridget, coaster, 709 tons displacement, at sea off South Cornish coast
Location:	49°27'N 04°59'W
Date:	14 February 1972
Origin time:	1817Z (reported by the Royal Navy) 1815.35Z (estimate from WOL seismic data)
Explosive:	Nitroglycerine
Quantity:	110 tons (reported)
Meteorological conditions:	Ridge of high pressure extending over the British Isles. Surface winds in source area and recording area very light, west-south-west 1 - 2 knots. Wind at altitude 10.8 km, westerly, 113 knots

3. DETAILS OF RECORDING STATIONS

3.1 Microbarographic data recording stations

BMBA (Blacknest microbarograph array) - Twenty-one microbarographs in an array of maximum aperture 50 km (figure 1) operating in the frequency band 0.001 - 1 Hz. Seventeen of the instruments are deployed in an inner zone group of approximately 20 km aperture (figure 2).

The array is operated by the Blacknest Data Centre for the parent establishment, AWRE, Aldermaston.

ESK - Single microbarograph of standard AWRE/BMBA type.

The station is operated by the Institute of Geological Sciences, The Observatory, Eskdalemuir, Langholm, Dumfriesshire on behalf of Blacknest/AWRE.

BYBH - Single microbarograph of standard AWRE type.

The station is operated by RAF Brawdy, Pembrokeshire on behalf of Blacknest/AWRE.

Figure 3 gives the locations of these three UK infrasonic data recording stations and also of the two explosion points.

All three stations were operational at the time of the Flixborough explosion, but only the BMBA instruments were deployed at the time of the St Bridget explosion.

3.2 Seismographic data recording stations

EKA (Eskdalemuir Seismological Array Station) - A twenty element array of Willmore Mk II short-period seismometers deployed in two 10 element arms of 8 km length (figure 4).

Vault instruments include three AWRE long-period seismometers in a 3-component set and three Willmore Mk II short-period seismometers in a 3-component set.

The station is controlled by Blacknest Data Centre for the parent establishment, AWRE, Aldermaston.

WOL (Wolverton Seismological Station) - All instruments are in one vault and include 1 Willmore Mk II short-period seismometer and 3 Geotech long-period seismometers.

The station is operated via direct telemetry links from the Blacknest Data Centre.

Refer again to figure 3 for the locations of these two stations in relation to the explosion centres. Station WOL is $5\frac{1}{2}$ km south-south-west of Blacknest. EKA array centre point is within a few kilometres of ESK observatory near Eskdalemuir, Dumfriesshire. Seismographic data are available from WOL for both explosions. EKA data are available only for the Flixborough explosion.

4. DETAILS OF THE RECORDS

4.1 Records of acoustic effects

BMBA microbarographs detected infrasonic waves from both the Flixborough and St Bridget events, which took place at comparable ranges from the array. Similar patterns of atmospheric pressure perturbation were observed on both occasions, distinctive features of the records being the arrivals of two wave groups separated by several minutes and characterised by dominant frequencies of widely differing values, see figures 5 and 6.

At the time of the Flixborough explosion, stations ESK and BYBH were also operational; an acoustic signal was recorded at ESK (figure 7) but not at BYBH.

The principal observations from the various acoustic data are tabulated below. In tables 1 and 2 arrival times of wave groups are listed for each event, together with corresponding values of V_p, the apparent velocity of the signals over the path from source to recording point, and of V_H, the apparent velocity of waves crossing the array. The values for V_p have been calculated using the observed arrival times of wave groups at particular recording points and the estimated origin times for each event derived from the supporting seismic data.

Values for V_H have been calculated, using the observed arrival times at particular array recording points, the known array dimensions and estimated azimuthal directions of propagation for the signals.

TABLE 1

Event:						Flixborough Explosion, 1 June 1974		
Reported Origin Time:						1553Z		
Estimated True Origin Time:						1552.15Z		
Recording Site	Distance from Source, km	Arrival Times		V_p, m s^{-1}		V_H, m s^{-1}		
		Wave Group 1	Wave Group 2	Wave Group 1	Wave Group 2	Wave Group 1		Wave Group 2
BE/BMBA	246.7	1606.06	1610.50	297	223	327	(BE - BB)	400
BB/BMBA	252.1	1606.22.5	1611.03.5	297.5	223.5	300	(BB - WV)	355
WV/BMBA	257.6	1606.41	1611.19	297.5	225	315	(WV - CH)	375
CH/BMBA	279.0	1607.49	1612.16	299.5	231.5		Mean Array Velocity	
ESK	251.0	1606.19	1610.33	297.5	228	318	(BE - CH)	376

TABLE 2

Event:						St Bridge Explosion, 14 February 1972		
Reported Origin Time:						1817Z		
Estimated True Origin Time:						1815.35Z		
Recording Site	Distance from Source, km	Arrival Times		V_p, m s^{-1}		V_H, m s^{-1}		
		Wave Group 1	Wave Group 2	Wave Group 1	Wave Group 2	Wave Group 1		Wave Group 2
PW/BMBA	300	1831.46	1836.14	310	242	333	(PW - WE)	433
WE/BMBA	314.3	1832.29	1836.47	311	247	334	(WE - BB)	390
BB/BMBA	344	1833.58	1838.03	312	255	333	(BB - AE)	400
AE/BMBA	348	1834.10	1838.13	313	257	333	Mean Array Velocity (PW - AE)	403

In tables 3 and 4 signal amplitude and period data are listed for a number of instrument sites from which system calibrations were available near to the times the signals were recorded.

TABLE 3

Event:	Flixborough Explosion			
Recording Site	Dominant Waves Group 1		Dominant Waves Group 2	
	Amplitude, N m^{-2}	Period, s	Amplitude, N m^{-2}	Period, s
AN/BMBA	3.2	2.8	2.1	22
AE/BMBA	4.1	2.8	3.1	22
BB/BMBA	3.7	2.6	2.6	22
ESK	4.1	3.0	2.0	28

TABLE 4

Event:	St Bridget Explosion					
Recording Site	Dominant Waves				Dominant Waves Group 2	
	Group 1(a)		Group 1(b)			
	Amplitude, $N\ m^{-2}$	Period, s	Amplitude, $N\ m^{-2}$	Period, s	Amplitude, $N\ m^{-2}$	Period, s
GE/BMBA	0.45	2	3.5	3.5	0.75	18
GW/BMBA	0.75	2	6.7	3.5	1.0	18
CH/BMBA	1.25	2	7.0	3.5	1.25	18
PW/BMBA	0.45	2	4.6	3.5	0.8	18
RD/BMBA	0.5	2	7.0	3.5	1.25	18

The principal waves (b) of group 1 from St Bridget were preceded by a lower amplitude and higher frequency train of waves (a). The whole suite formed a continuous and distinct group travelling with the same horizontal trace velocity, but the sub-groups were sufficiently pronounced to justify listing them separately in table 4 as "Groups 1(a) and 1(b)".

4.2 Records of seismic effects

The Flixborough and St Bridget explosions produced two kinds of seismic disturbances at stations EKA and WOL. The first disturbances occurred at times which were consistent with arrival times for normal P and S seismic waves propagating at typical velocities over the distances involved.

The second onsets of ground motion occurred many minutes later and corresponded precisely in time with the passage of the atmospheric acoustic waves, independently detected by microbarographs in the vicinity.

Figure 8 is a record from the EKA short-period seismometer array which shows the onsets of ground motion across the array caused by normally-propagating seismic waves from the Flixborough explosion. Figure 9 shows the disturbances observed several minutes later when the first group of higher frequency atmospheric infrasonic waves traversed the same array. Air-ground coupled effects from the second acoustic wave pulse (period 28 s at ESK) were recorded only by the wide-band long-period seismometers at the EKA vault. These instruments operate with peak amplitude response of 25 s period.

Figure 10 shows a sequence of records from WOL where direct seismic waves and coupled effects from both first and second atmospheric wave groups were detected following the Flixborough explosion.

The direct seismic waves have rather greater amplitudes than those recorded at EKA although, due to the higher level of natural background noise prevailing at WOL, their signal-to-noise ratio is poorer.

The coupled disturbances caused by the arrival of the first set of acoustic waves (figure 10, group 1) were recorded at WOL by a standard Willmore short-period seismometer and also via a high-pass filtered output derived from a vertical component long-period seismometer (designated LPSP in figure 10).

Ground motion associated with the arrival of the second, low frequency wave group from the Flixborough explosion was registered by the narrow band (figure 10, LPNB) output from the long-period seismometer which provides a high gain channel with a peak amplitude response at 25 s period.

The seismographic records obtained at WOL from the St Bridget explosion are shown in figure 11. The P wave group was well-defined but S waves from this event were rather weak. A coupled disturbance associated with the arrival of acoustic wave group 1 was recorded, but no ground motion could be identified positively at the time of arrival of the much smaller amplitude, low frequency second wave group.

Onset time, amplitude and period data for the seismic effects caused by the explosions are given in tables 6 and 7.

TABLE 6

Event	Recording Station/Site	Distance, $\Delta°$	P Wave Onset Time	Travel Time (from Tables)	Calculated Origin Time (to nearest second)
Flixborough	EKA R9 WOL vault	2.21 2.32	1552.52.5 1552.57	38.5 40.1	1552.14 1552.17
St Bridget	WOL vault	3.05	1816.25.3	50.4	1815.35

TABLE 7

(All amplitudes refer to the vertical component of ground motion)

Event	Recording Station/Site	Direct Seismic Waves				Coupled Disturbances			
		P Group		S Group		Wave Group 1		Wave Group 2	
		Amplitude, $\mu m \times 10^{-3}$	Period, s	Amplitude, $\mu m \times 10^{-3}$	Period, s	Amplitude, $\mu m \times 10^{-3}$	Period, s	Amplitude, $\mu m \times 10^{-3}$	Period, s
Flixborough	EKA R9 EKA vault WOL vault	26 14 46	0.4 0.3 0.4	20 17 33	0.4 0.35 0.25	24 - 100	0.4 - 0.27	- 1760 1050	- 49 28
St Bridget	WOL vault	70	0.43	26	0.33	72	0.33	-	-

5. COMMENTS ON THE RECORDS

5.1 Acoustic effects

An apparent contradiction exists in the acoustic wave velocity data listed in tables 1 and 2 in that the later arriving wave group 2, travelling between source and receiver at an apparent path velocity, V_p, of about 75% of the V_p for wave group 1, traverses the microbarograph array with a horizontal trace velocity, V_H, 20% higher than V_H for wave group 1. A second point also evident from the tabled values of V_p for each wave group is that the apparent path velocity increases with distance of the receiver from the source.

Both points may be explained by supposing that the infrasonic waves arrive at the recording instrument array via paths which are different and are aligned at angles of elevation well above horizontal. The BMBA records may thus be adduced as evidence supporting the existence of two principal zones in the upper atmosphere from which infrasonic sound waves may be reflected back to the earth's surface due to the refractions of "acoustic rays" by variations in the speed of sound resulting from the vertical temperature structure of the atmosphere. Long range propagation of infrasonic waves by successive reflections in "sound channels", which are formed by the earth's surface and these upper zonal layers, has been described by Diamond [1], Wilson and Nichparenko [2] and others.

Sound ray path diagrams published by Balachandran, Donn and Kaschak [3] indicate that in general (with some variations due to the effects of winds at high altitudes) the apexes of the paths of refracted sound rays can be assumed to be situated at altitudes of about 40 and 120 km. At nearer ranges, of the order of the distance of BMBA from the Flixborough and St Bridget explosions, the reflected signals which are received may also be assumed to be returning from the first upper atmospheric reflection. Using these assumptions, simplified representations can be constructed for the possible paths along which each of the wave groups received by the recording instruments has travelled from the explosion source in each case.

In figure 12(a) the distance (279 km) from Flixborough to the recording point CH has been drawn as the base line aa'. The path travelled by the first arriving wave group is represented by aba' and the path travelled by wave group 2 is represented by aca'. By measurement aba' = 290 km and aca' = 370 km, while from data in table 1 the corresponding travel times are found to be 934 and 1201 s. An average value for the group velocity Vg may therefore be obtained from

$$Vg_1 = \frac{290 \times 10^3}{934} = 310 \text{ m s}^{-1}$$

and

$$Vg_2 = \frac{370 \times 10^3}{1201} = 308 \text{ m s}^{-1}.$$

The corresponding values of the mean horizontal trace velocity across the array are 318 m s^{-1} for wave group 1 and 376 m s^{-1} for wave group 2.

The angles of elevation $\hat{e}_1$ and $\hat{e}_2$ for the two groups of refracted waves are given by

$$\hat{e}_1 = \cos^{-1} \frac{310}{318} = 13°$$

and

$$\hat{e}_2 = \cos^{-1} \frac{308}{376} = 35°.$$

The angles of elevation for the two wave paths found by measurement from figure 12(a) are 16° and 40°.

For the St Bridget event, the base line aa' is drawn to represent the distance of 300 km from the explosion point to recording point PW. The values of aba' and aca' are 311 and 385 km and the corresponding travel times from table 2 are 970 and 1238 s.

The group velocities therefore are:-

$$V_{g1} = \frac{311 \times 10^3}{970} = 321 \text{ m s}^{-1},$$

$$V_{g2} = \frac{385 \times 10^3}{1238} = 311 \text{ m s}^{-1}.$$

The mean horizontal trace velocities, V_H, over the array are 333 and 403 m s^{-1}, giving angles of elevation

$$\hat{e}_1 = \cos^{-1} \frac{321}{333} = 15°$$

and

$$\hat{e}_2 = \cos^{-1} \frac{311}{403} = 39°.$$

The angles of elevation for the two wave paths found by measurement from figure 12(b) are 15° and 38.5°.

The second wave group of the acoustic records from each event consists of a single pulse of much lower frequency and smaller amplitude of air pressure than waves of the first groups. Attenuation and loss of high frequency components would be expected in a wave packet which had travelled a longer path through several possible refracting sub-layers to higher atmospheric altitudes where the mean free path of air molecules is long.

Station ESK: The single instrument acoustic record (figure 7) from station ESK is complicated by the effects of a change in barometric pressure and wind speed associated with the passage of a weak weather front which took place 2 min after the arrival of the second acoustic wave group. The microbarograph trace remains disturbed by a higher level of short-period background noise caused by the doubling of the wind speed following the barometric pressure jump recorded on the wide-band microbarograph channel as a double pulse of about 17 N m^{-2} amplitude.

Station BYBH: No identifiable signal from the Flixborough explosion could be found in the single instrument record from BYBH. This station, at 352 km range, was 100 km more distant than either BMBA or ESK. Also the prevailing westerly wind of 65 - 75 knots at 11 km altitude was an adverse factor for propagation to a station situated westwards of the explosion epicentre.

5.2 Seismic effects

5.2.1 Direct waves

Direct seismic waves were recorded by all the short-period seismometers which were operational, either in the array pits or station vaults, at the dates on which the explosions occurred. From table 7 it can be seen that the seismic amplitude recorded at WOL, 257 km from Flixborough, was about double the amplitude recorded at EKA at a similar range. This ratio is an effect of the different geological environments and is normally seen in records from the two stations.

Valid comparisons can, however, be made between the records from the two explosions which were recorded at the same station, WOL. From table 7 we see that the S waves from the St Bridget explosion, effectively a water-coupled event, were relatively weak. An arbitrary comparison of the P wave data shows that the amplitude of the ground motion recorded from Flixborough (range 257 km) was 66% of the amplitude recorded from St Bridget (range 339 km).

5.2.2 Coupled disturbances

Comparison of the signal arrival patterns produced by the particular configuration of array records replayed for figures 8 and 9 illustrates the expected large ratio in phase velocity between direct and acoustically-coupled seismic effects. For example, the "move-out" time interval between array sites R_2 and R_9 is 0.7 s for the first arriving direct seismic waves and 16 s for the coupled disturbances, giving a ratio of 23:1, corresponding to the respective velocities across the array for seismic P waves and infrasonic sound waves. A similar example of seismic disturbances coupled to infrasonic waves at EKA has been described previously [4].

There is an apparent anomaly in the records of air wave-ground coupled seismic effects. Disturbances associated with the transit of the first group of atmospheric acoustic waves from Flixborough were recorded by all short-period seismometers of EKA but not by those in the EKA vault. On the other hand, the long-period instrument in the vault appeared to respond to the transit of the second acoustic wave group and also to the arrival of the meteorological pressure step noted on the ESK microbarograph record. The onset times of these two coupled effects corresponded to a few seconds travel time from the ESK microbarograph to the EKA vault long-period seismometer in the case of the acoustic wave pulse and to a few minutes for the slow-moving weather associated pulse. The apparent velocity of the latter was 20 knots along the direction of the prevailing wind which was in agreement with the ESK meteorological data and corroborated the presumption that the large pulse on the ESK microbarograph record, immediately following acoustic wave group 2, was not associated with the Flixborough explosion signals.

At WOL short-period and long-period seismometers responded to the respective transits of the short-period and long-period acoustic wave groups 1 and 2 from Flixborough, see figure 10. Coupled disturbances were recorded (by the short-period WOL seismograph) for only the first arriving acoustic wave group from the St Bridget explosion, see figure 11. A combination of a relatively weak signal (1 N m^{-2}) and high prevailing background noise effectively prevented identification of a second, long-period coupled disturbance.

The failure of the short-period seismometers in the EKA vault to record any coupled disturbances from the first acoustic wave group of the Flixborough explosion, unlike nearby array instruments, remains an anomaly. If it is accepted that the movements recorded by the array seismometers were true ground motion caused by air wave-ground surface coupling, then site geology and vault construction should be considered as factors which might contribute significantly to the observed effects. In the case of the EKA array, seismometer emplacements are sited on weathered shale at an average depth of 1.5 m, whereas the vault has been constructed on a massive concrete base cast on to unweathered rock at a depth of about 4 m [5]. The WOL vault, where short-period coupled disturbances were recorded, is built into a chalk hillside. The above data, in conjunction with the records obtained from both short-period and long-period instruments, suggest that the coupled disturbances are near-surface wavelength-dependent phenomena.

5.3 Comparison of the explosion energies

If the amplitudes of the largest pressure variations recorded at BMBA sites from the first-arriving groups of infrasonic waves (which have travelled the shorter and simpler path) are compared, it is found that the Flixborough signals on average are 67% of the St Bridget signals. The average distance of recording sites from which calibrated data were available for the Flixborough event was 78% of the similarly averaged distance of sites used in the St Bridget amplitude calculations.

Assume the simple scaling relationship

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

to apply for acoustic waves, then, substituting values from Flixborough data for A_1 and R_1 and values from St Bridget for A_2 and R_2, we have

$$\left(\frac{W_2}{W_1}\right)^{1/3} = \frac{100}{67} \times \frac{100}{78} = 1.9,$$

$$\frac{W_2}{W_1} = 7,$$

then from the reported value of 110 tons of nitroglycerine on board St Bridget,

$$W_1 = \frac{110}{7} = 15.7 \text{ tons HE equivalent of nitroglycerine for the Flixborough explosion.}$$

Similarly a comparison of the seismographic data may be made using the values for P wave amplitudes at WOL listed in table 7. The maximum amplitude of seismic P waves from Flixborough is found to be 66% of the maximum amplitudes from St Bridget. The distance from Flixborough to WOL is 76% of the distance from St Bridget to WOL.

Assuming a scaling relationship for seismic body waves of

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

and substituting values for A_1, R_1 and A_2, R_2 and W_2 as before, we have

$$\left(\frac{W_2}{W_1}\right)^{1/3} = \frac{100}{66} \times \left(\frac{100}{76}\right)^2,$$

$$= 2.63.$$

$$\frac{W_2}{W_1} = 18,$$

W_1 = 6.1 tons HE equivalent of nitroglycerine.

These values of HE equivalent for the Flixborough event can at best only be regarded as a guide as to the probable order of magnitude of the explosion. The source conditions for the two explosions were entirely dissimilar and it seems very unlikely that the Flixborough explosion was well coupled to the seismic medium. Also it has been well established that propagation of infrasonic waves can vary greatly with seasonal fluctuations in upper atmospheric winds and other meteorological factors. Finally it has been assumed that the St Bridget explosion, used as a basis of comparison, was fully efficient.

With these reservations, the explosion energy may be estimated as being within perhaps a factor of 2 either way of the acoustic wave yield of 15.7 tons. Because of the probability of imperfect coupling to the ground, it seems likely that the yield value obtained from the seismic data is low and that the explosion energy may reasonably be assumed to be above that value.

6. CONCLUSIONS

The infrasonic waves recorded from the explosions at Flixborough and St Bridget provide supporting evidence for the existence of two main zones of refraction for acoustic waves in the upper atmosphere.

Air wave-ground coupled effects can be recorded by seismometers in near surface emplacements but they may be critically dependent on the depth of vault emplacement and surface geology.

Comparisons of the seismographic and microbarographic records obtained from the two events indicate that the HE equivalent of the Flixborough explosion was of the order of 16 tons of nitroglycerine.

7. ACKNOWLEDGMENTS

Grateful acknowledgment is made to the Superintendent, Mr P Robinson and to Mr Dawson of Eskdalemuir Observatory and to the Commanding Officer, RAF Station Brawdy for their co-operation in operating the microbarographic recorders. Thanks are also due to my colleagues Messrs J Young, R Burch and E James for instrument site position computations and instrumentation information.

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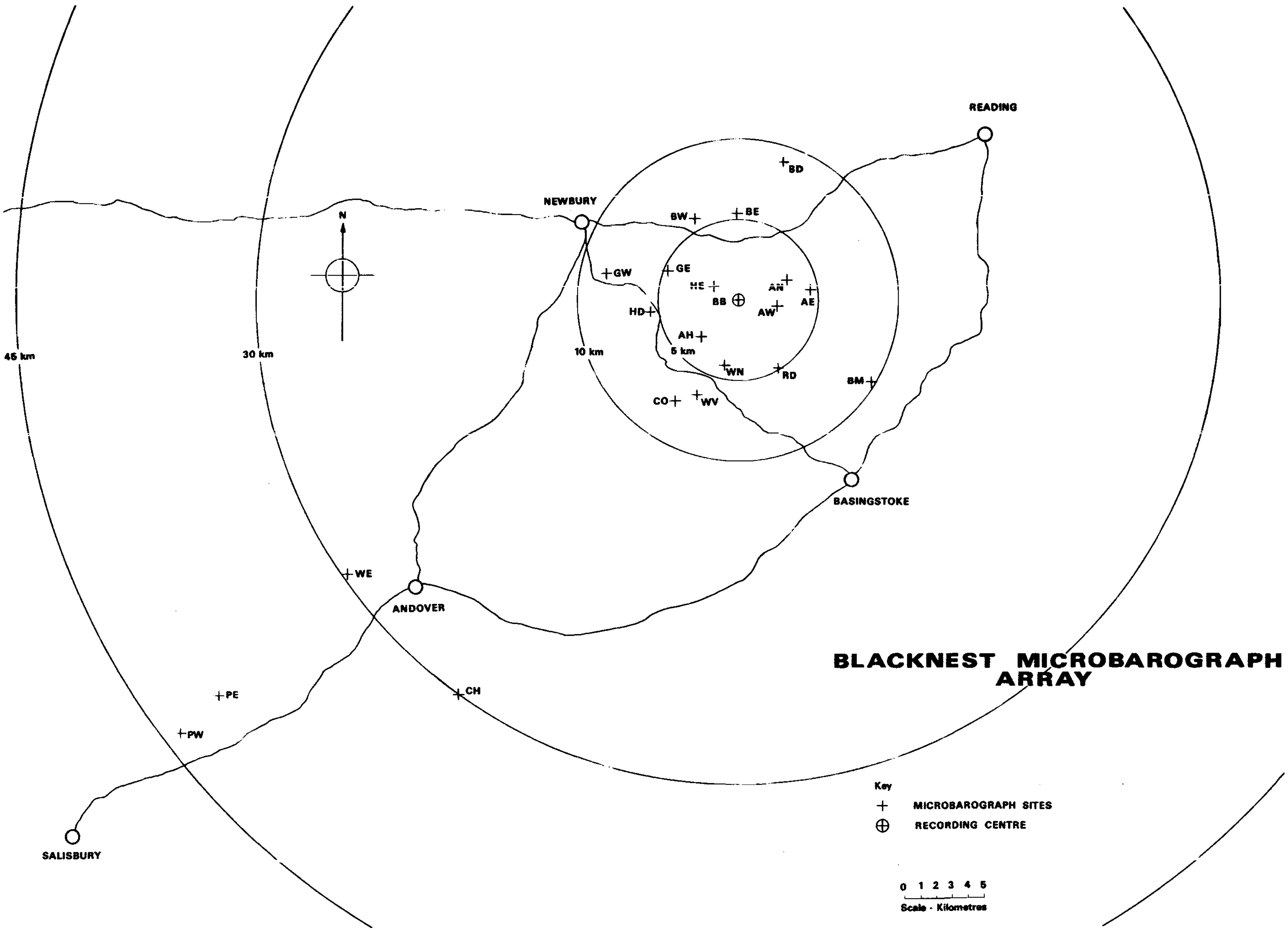
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NEWBURY
BASINGSTOKE
ANDOVER
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45 km
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CO
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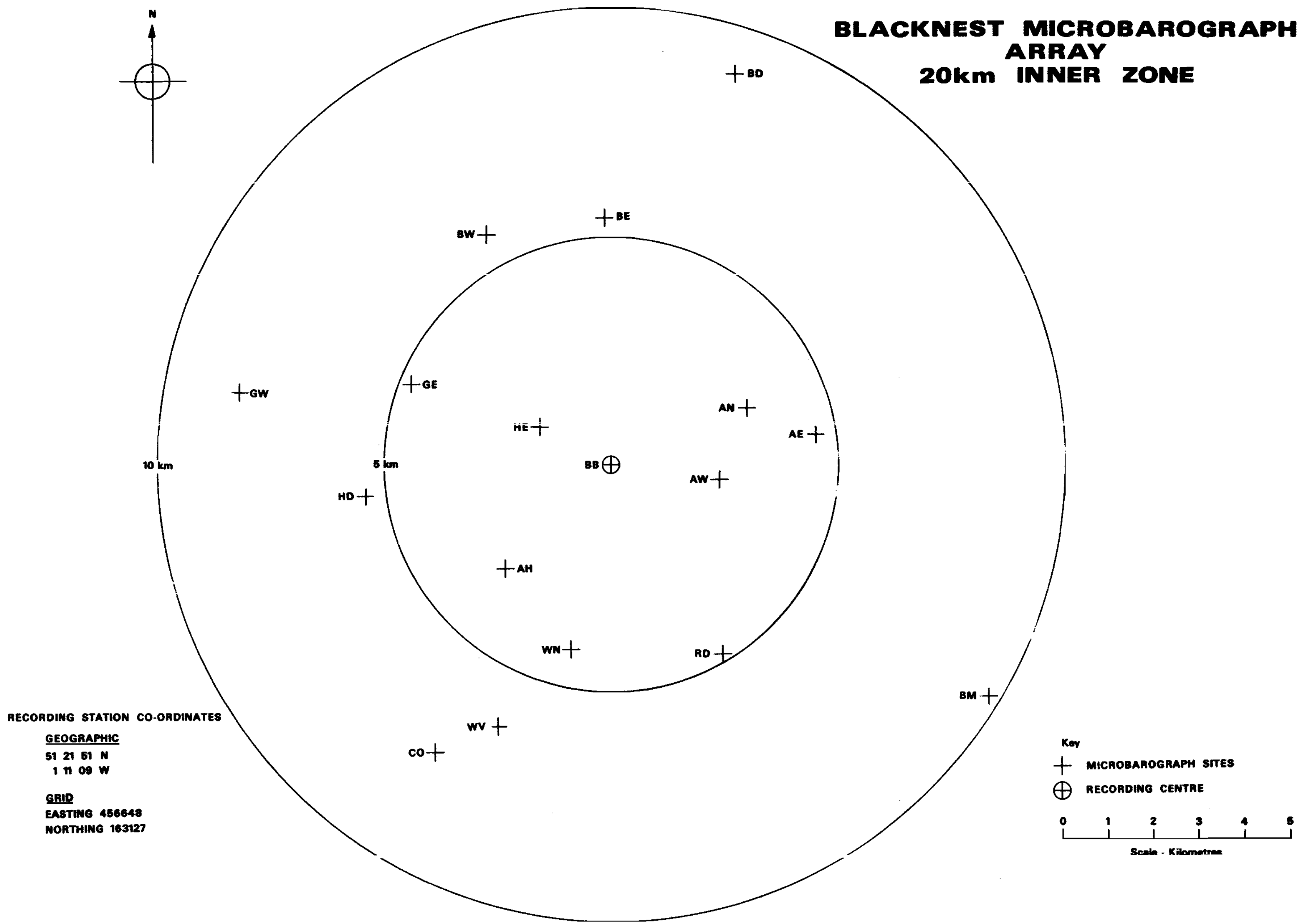
Key
MICROBAROGRAPH SITES
RECORDING CENTRE
0 1 2 3 4 5
Scale - Kilometres

FIGURE 1


BLACKNEST MICROBAROGRAPH
ARRAY
20km INNER ZONE
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GW
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HE
AN
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10 km
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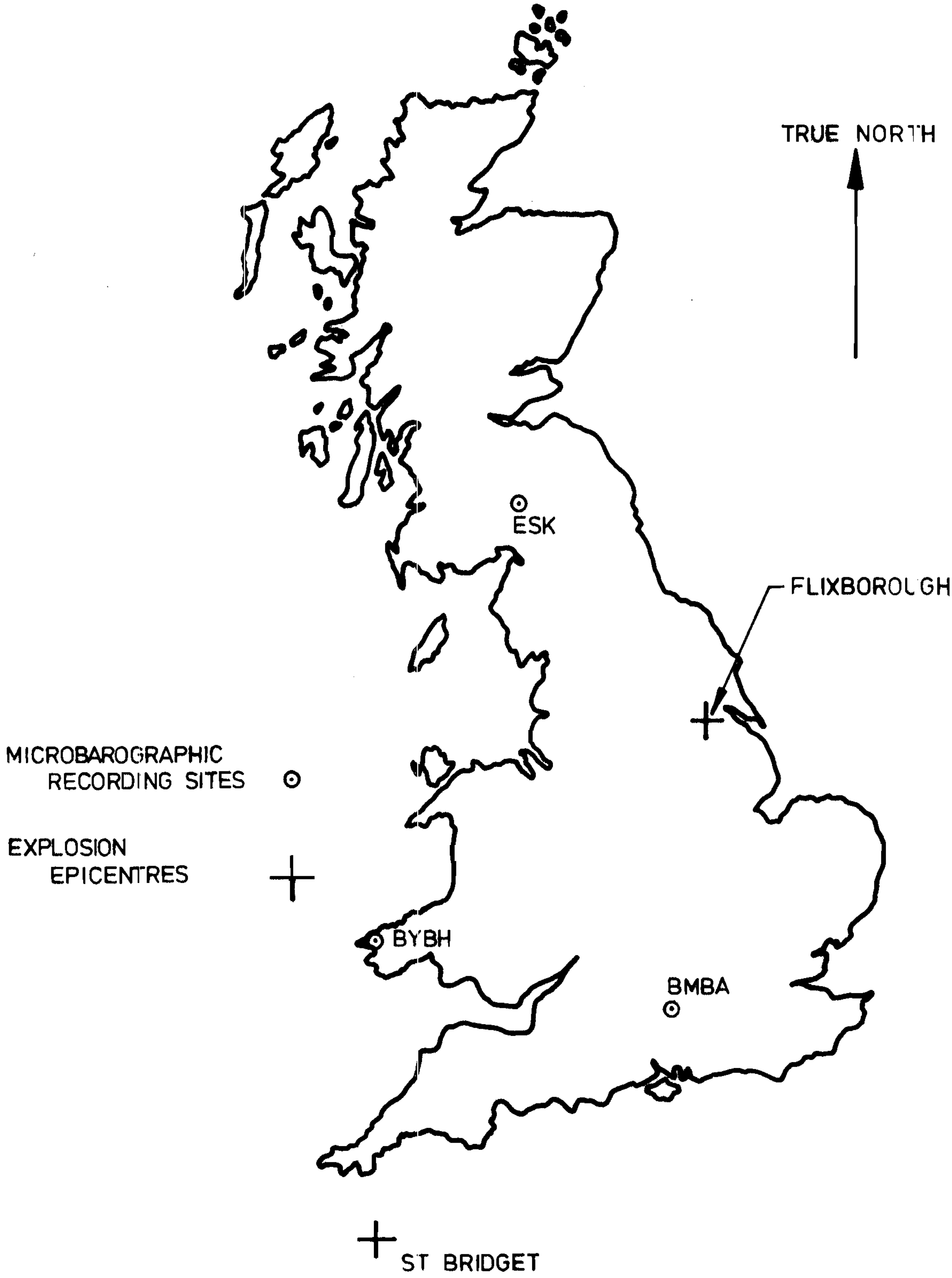
HD
AH
WN
RD
BM
WV
CO
RECORDING STATION CO-ORDINATES
GEOGRAPHIC
51 21 51 N
1 11 09 W
GRID
EASTING 456648
NORTHING 163127
Key
MICROBAROGRAPH SITES
RECORDING CENTRE
0 1 2 3 4 5
Scale - Kilometres

FIGURE 2



TRUE NORTH
ESK
FLIXBOROUGH
MICROBAROGRAPHIC
RECORDING SITES
EXPLOSION
EPICENTRES
BYBH
BMBA
ST BRIDGET

FIGURE 3

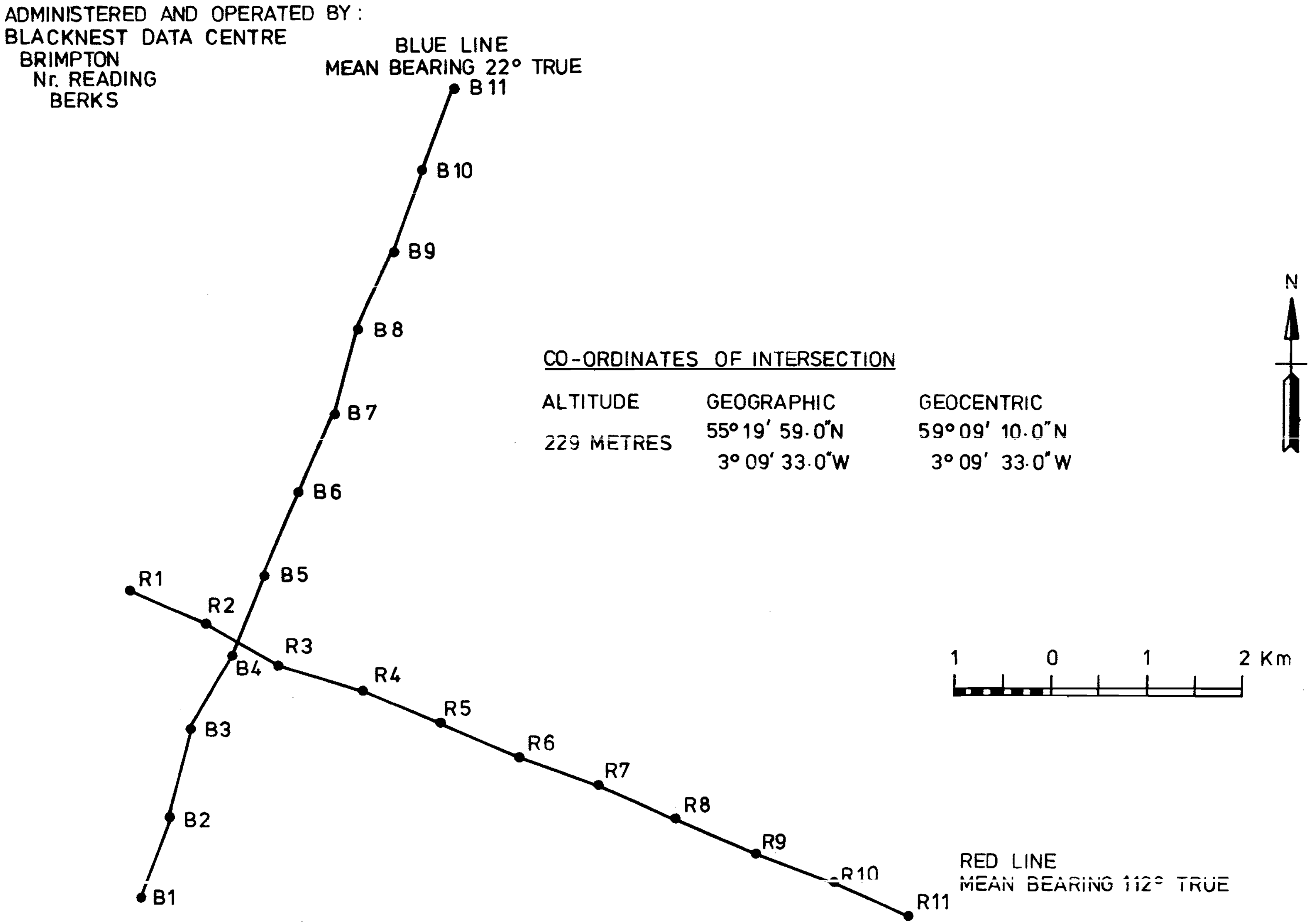


FIGURE 4. ESKDALEMUIR ARRAY

VERTICAL WILLMORE SEISOMETERS
MK II AT ALL PITS

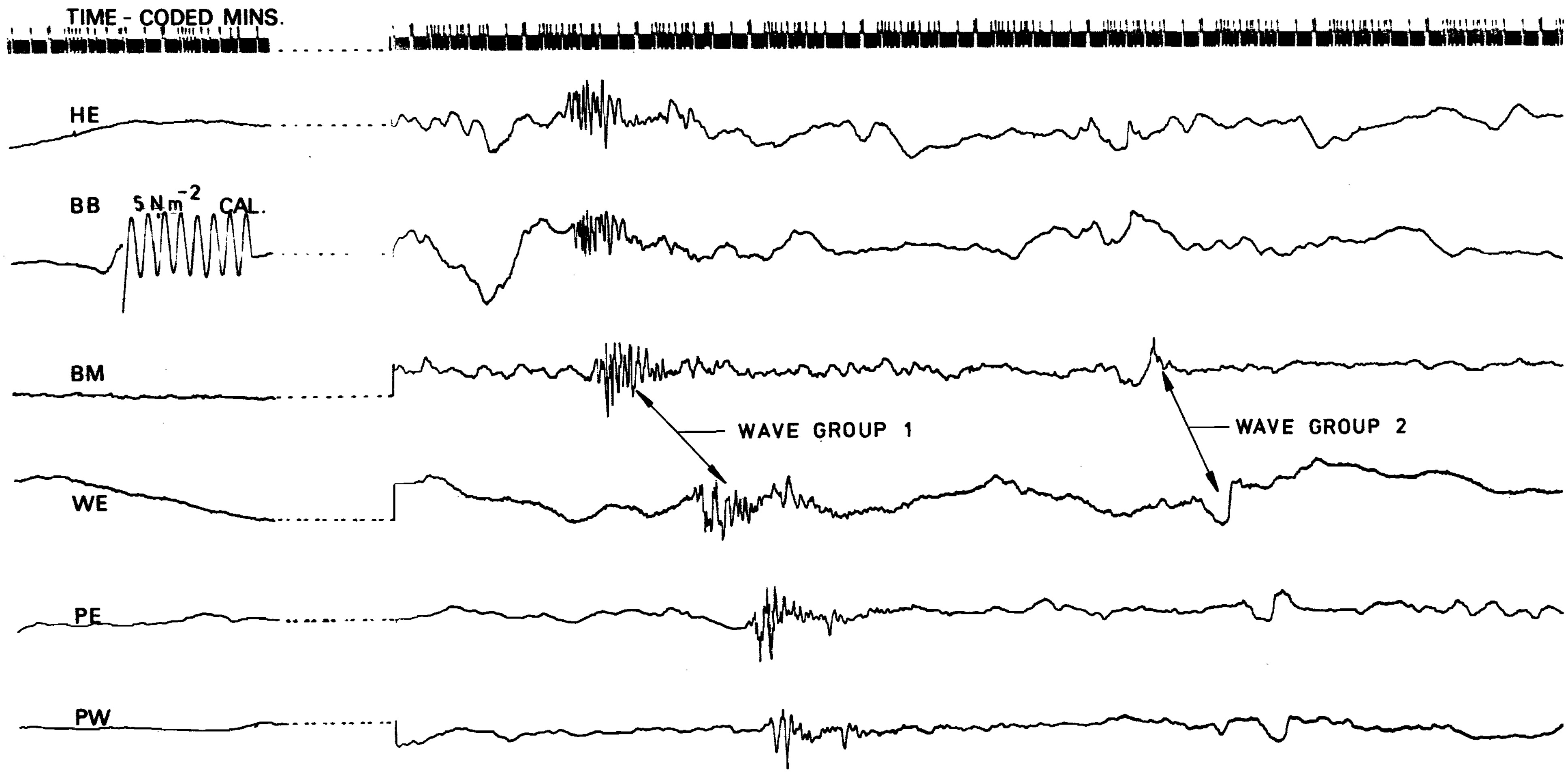


FIGURE 5 FLIXBOROUGH EXPLOSION, EFFECTS AT BMBA SITES, RANGE 250 - 280 km

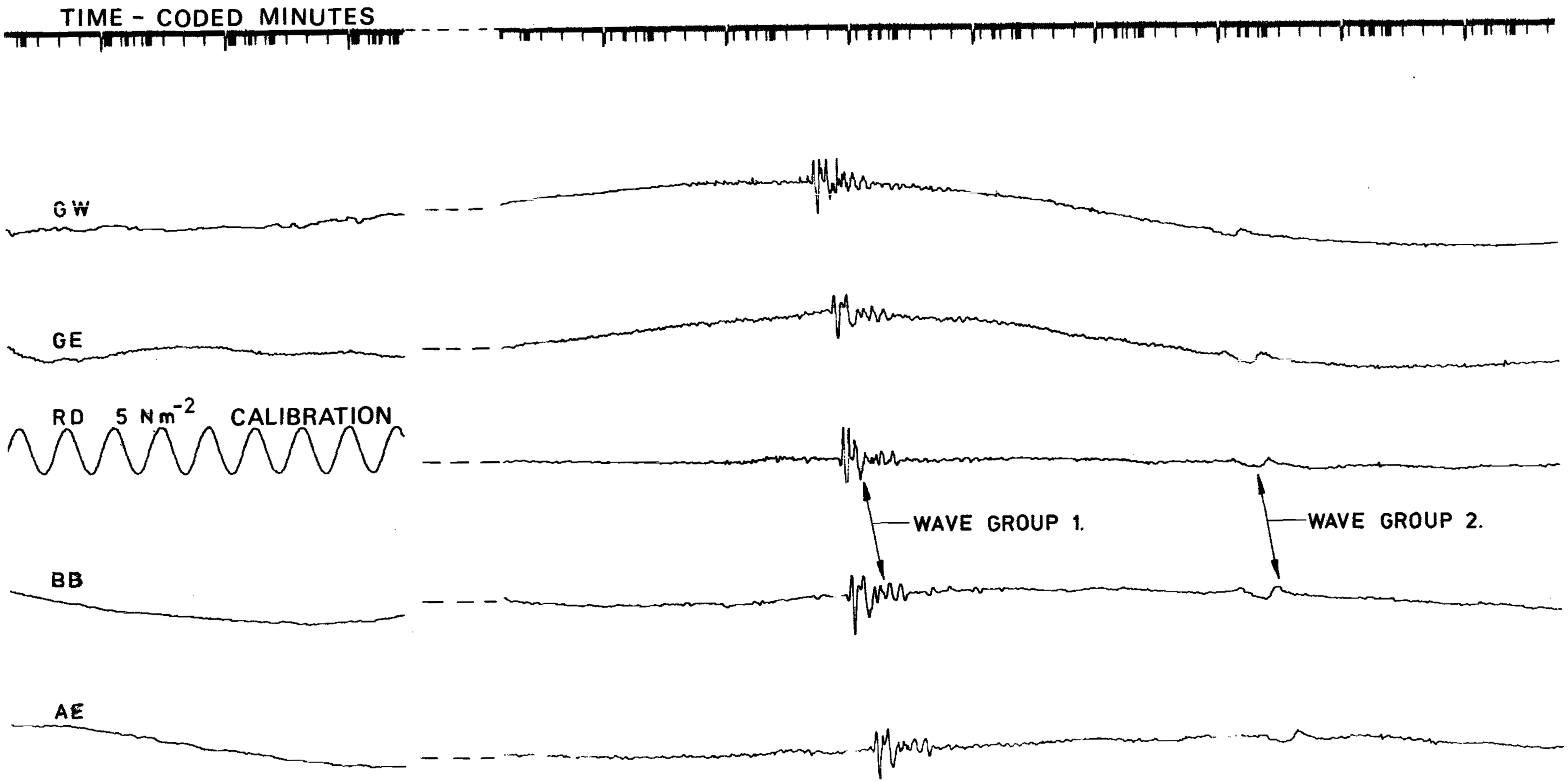


FIGURE 6. ST. BRIDGET EXPLOSION, EFFECTS AT BMBA SITES, RANGE 338-348 km

TRACE 1 : TIME, CODED MINUTES
TRACE 2 : WIDE-BAND MICROBAROGRAPH RECORD (BAND 1-1000S)
TRACE 3 : BAND-PASS FILTERED RECORD (BAND 1-10S)

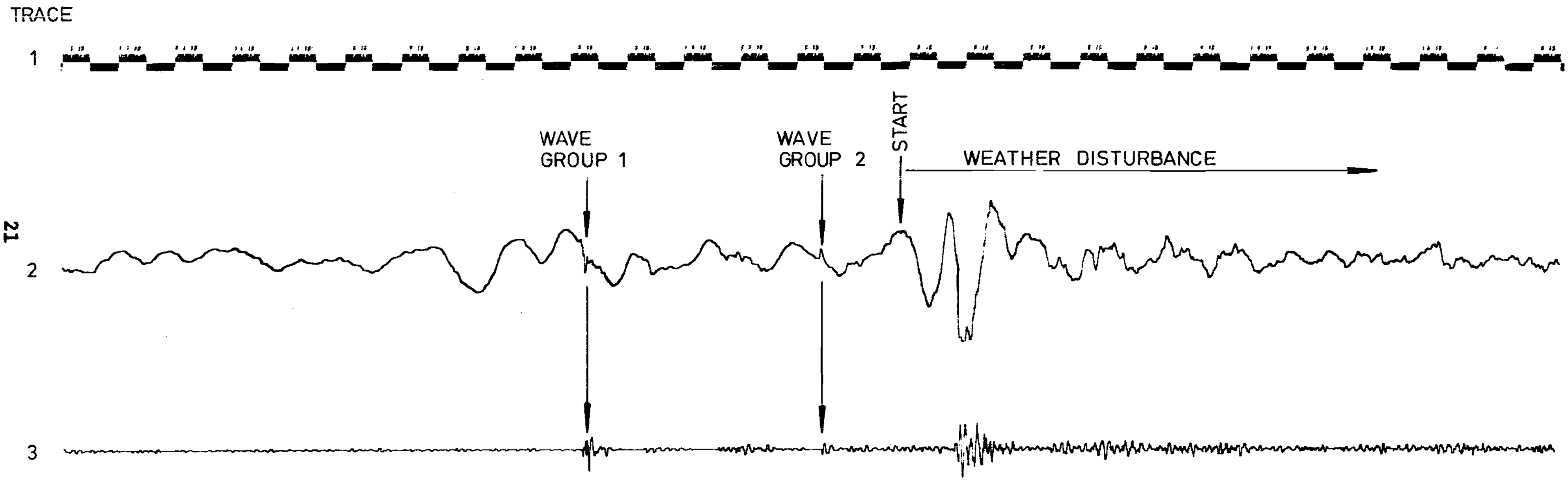


FIGURE 7. FLIXBOROUGH EXPLOSION. MICROBAROGRAPHIC RECORD AT ESK

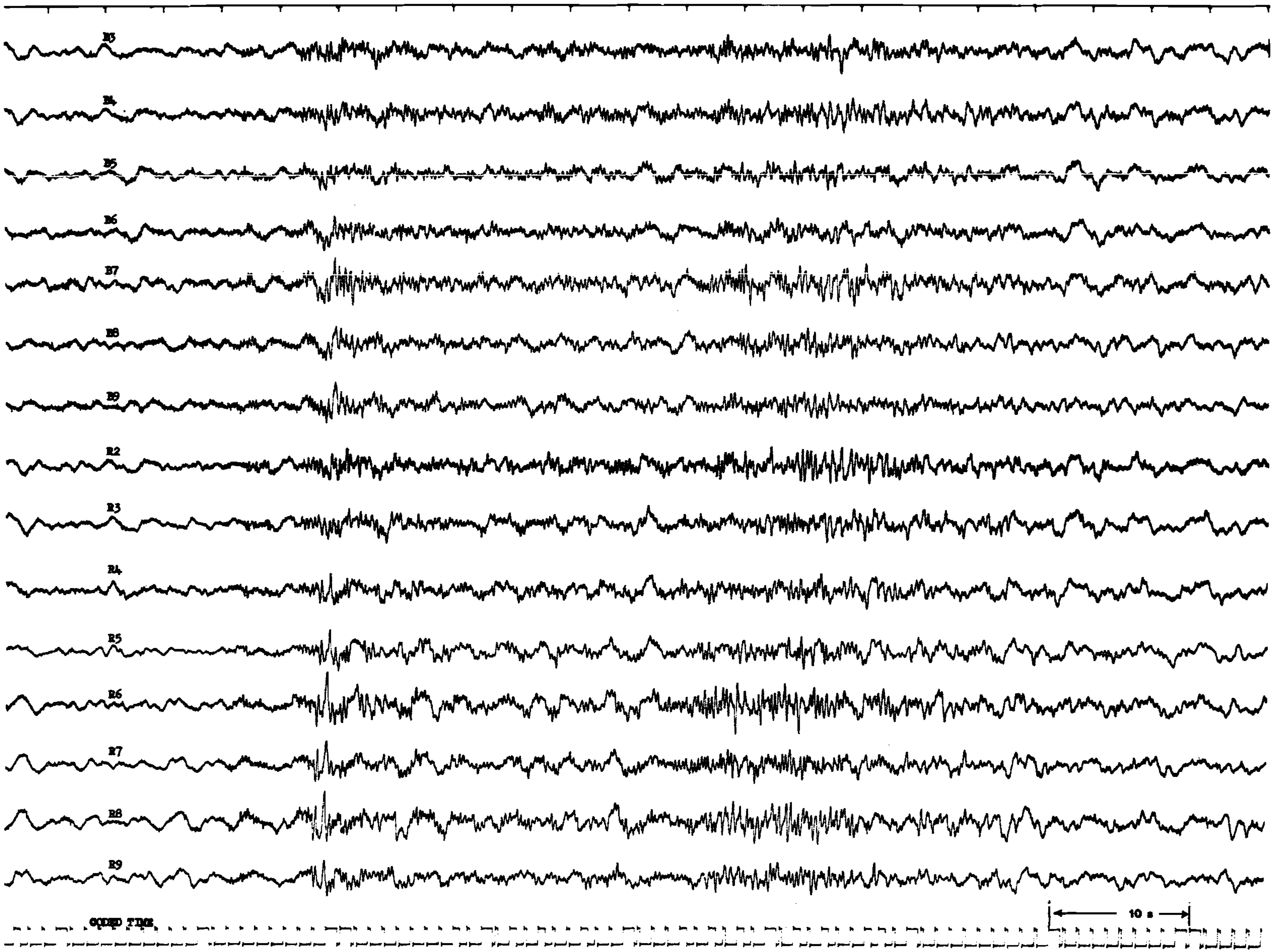


FIGURE 8. FLIXBOROUGH EXPLOSION; EKA SHORT-PERIOD ARRAY RECORD OF DIRECT SEISMIC WAVES

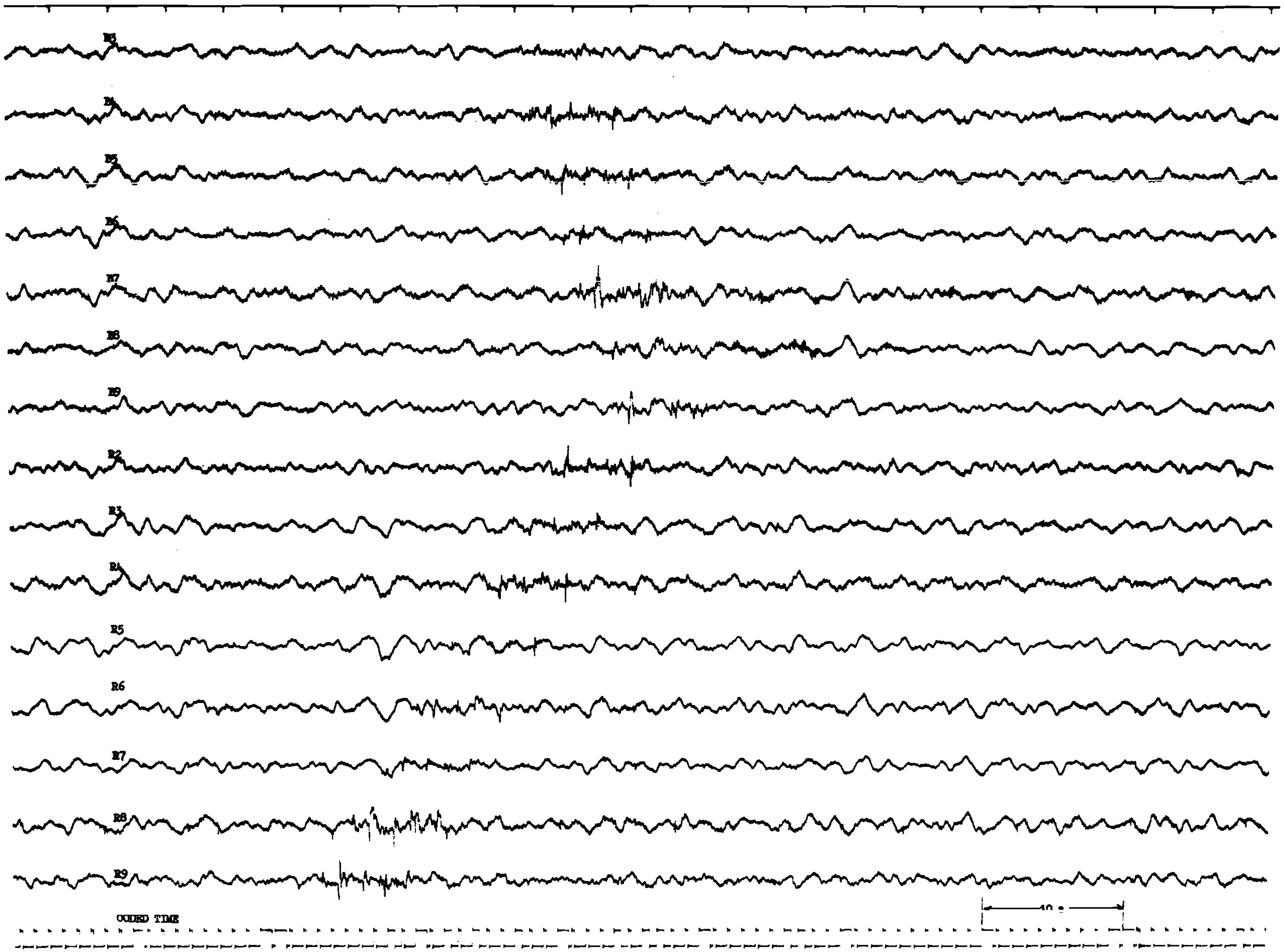


FIGURE 9. FLIXBOROUGH EXPLOSION; EKA SHORT-PERIOD ARRAY RECORD OF AIR-GROUND COUPLED DISTURBANCES

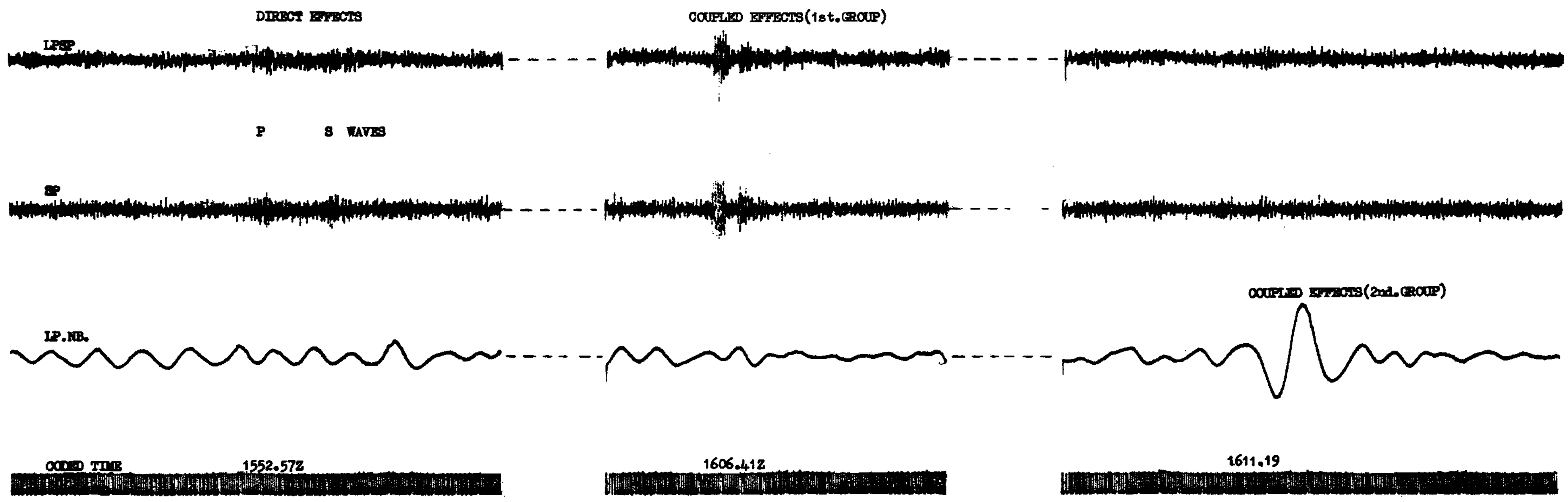


FIGURE 10. FLIXBOROUGH EXPLOSION; WOL RECORDS OF DIRECT SEISMIC WAVES AND ACOUSTICALLY-COUPLED SEISMIC DISTURBANCES

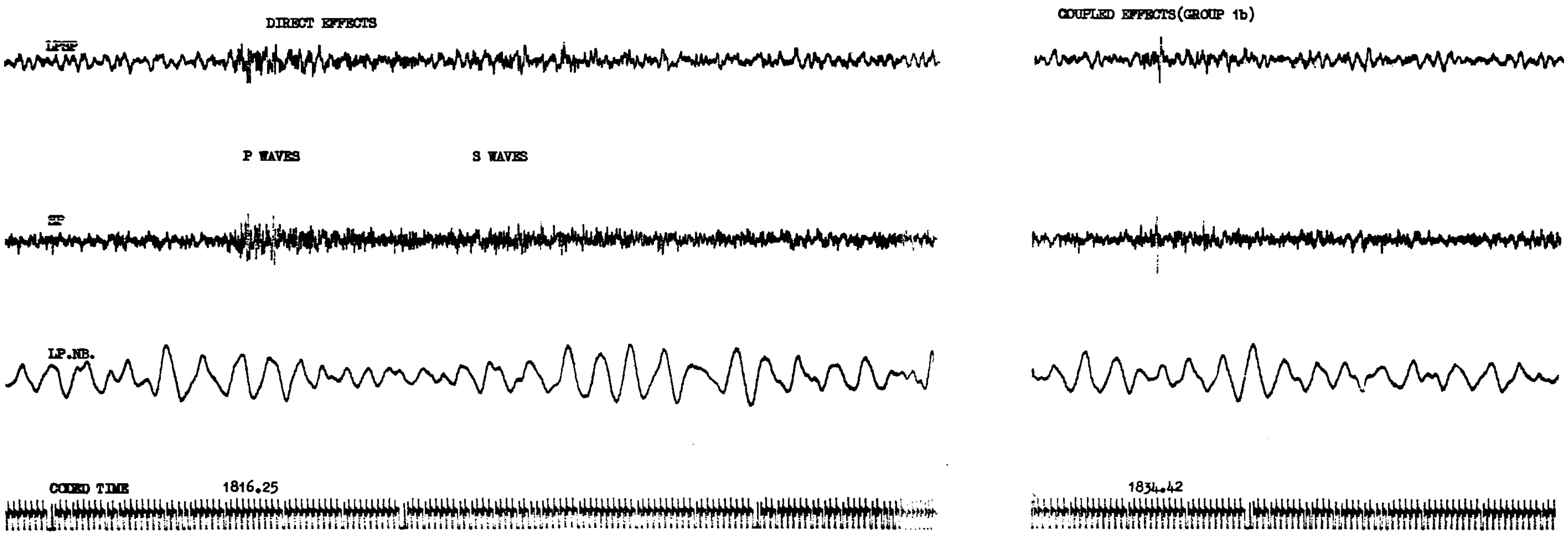
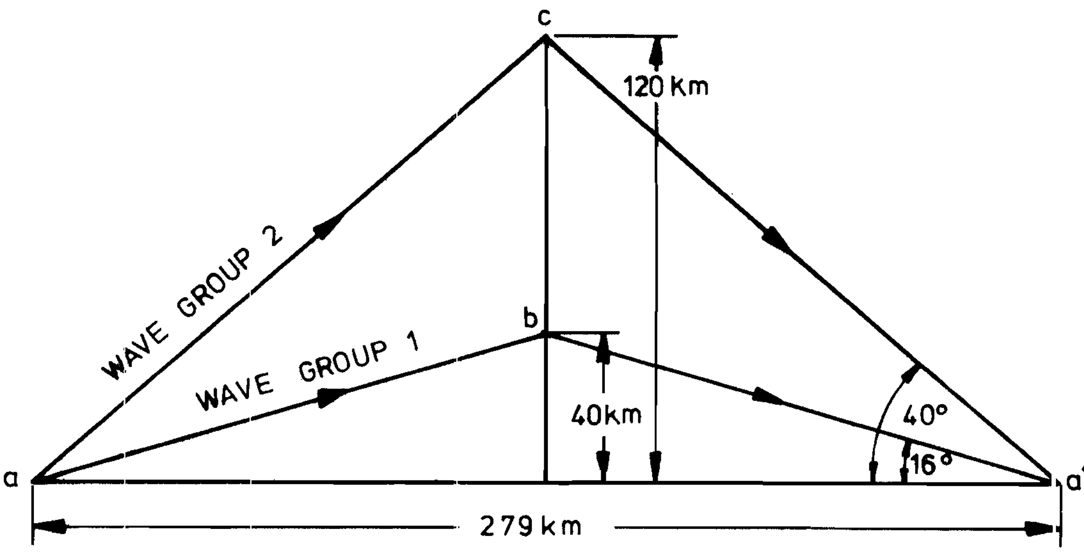
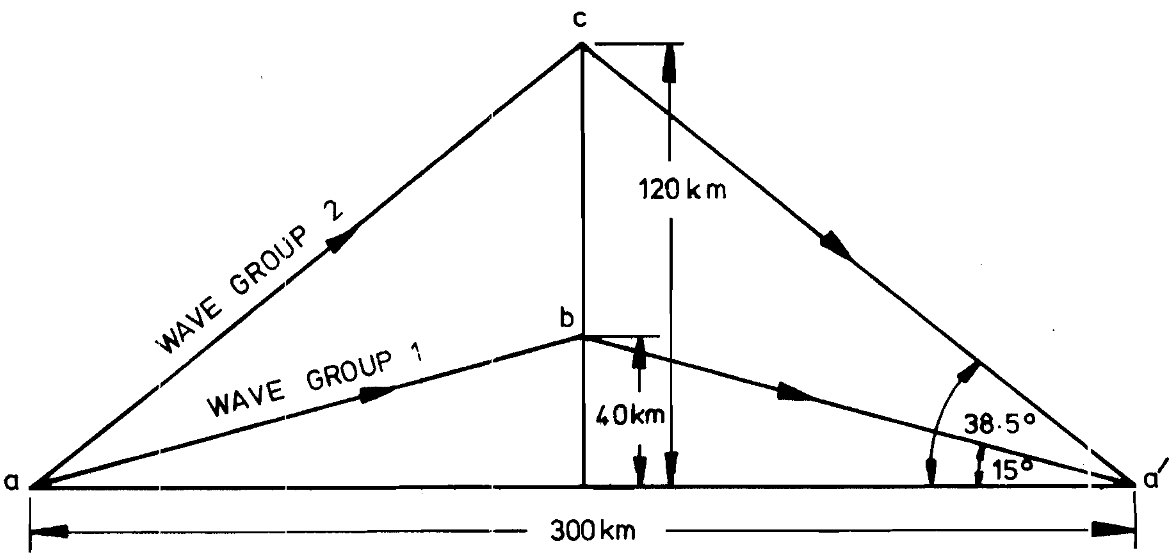


FIGURE 11. ST BRIDGET EXPLOSION; WOL RECORDS OF DIRECT SEISMIC WAVES AND ACOUSTICALLY-COUPLED SEISMIC DISTURBANCES



a. ACOUSTIC WAVE PATH DIAGRAM, FLIXBOROUGH EXPLOSION



b. ACOUSTIC WAVE PATH DIAGRAM, ST BRIDGET EXPLOSION

(SCALE : 2 km = 1 mm)

FIGURE 12

DOCUMENT CONTROL SHEET

Overall security classification of sheet ....Unclassified........

(As far as possible this sheet should contain only unclassified information. If it is necessary to enter classified information, the box concerned must be marked to indicate the classification eg (R), (C) or (S)).

1. DRIC Reference (if known)	2. Originator's Reference	3. Agency Reference	4. Report Security Classification
-	AWRE Report No. /74	-	On Sale

5. Originator's Code (if known)	6. Originator (Corporate Author) Name and Location
-	Atomic Weapons Research Establishment, Aldermaston, Berkshire
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-	-

7. Title

Infrasonic and Seismic Wave Records from the Flixborough and St Bridget Explosions

7a. Title in Foreign Language (in the case of Translation)

-

7b. Presented at (for Conference Papers). Title, Place and Date of Conference

-

8. Author 1.Surname, Initials	9a. Author 2	9b. Authors 3, 4	10. Date	pp	ref
Grover F H	-	-	October 1974	27	5
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15. Distribution Statement

No restriction.

16. Descriptors (or Keywords) (TEST) Explosions, Nitroglycerin, Cyclohexane, Nylon 6, Lactams, Seismic detection, Pressure measurement

Abstract

Microbarometric and seismic perturbations recorded at distances in the range 245 - 350 km from two large explosions are described and compared. The explosions were at the NYPRO (UK) Chemical Works, Flixborough, Lincolnshire on 1 June 1974 and in a small ship, the St Bridget, in the English Channel on 14 February 1972.