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Some Seismic Results from a World Wide Sample of Large Underground Explosions

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SUMMARY

Short period seismic array data, together with long period data from standard stations, have been analysed to provide estimates of the location and yield of explosions in China, North Africa, the Soviet Union and the USA.

1. ACKNOWLEDGMENTS

In the preparation of this report almost every member of the Seismological Research Group at AWRE has been involved in some way. I would like to acknowledge, in particular, the assistance and advice given by Messrs C Blamey, D J Corbishley, A Douglas, P G Gibbs, F A Key and J B Young. Mr G McKenzie and his colleagues were responsible for Eskdalemuir array recordings, while data from the other three arrays were provided through the co-operation of the Earth Physics Branch, Department of Energy Mines and Resources, Ottawa, Canada; the Bhabha Atomic Research Centre, Trombay, India; Department of Geophysics and Geochemistry, Research School of Physical Sciences, Australian National University, Canberra, Australia. I thank all concerned for making possible the data of high quality on which the analyses reported here have been based. I would finally like to thank Mr A Douglas and Dr H I S Thirlaway for their criticism and advice in the preparation of this report.

2. ABBREVIATIONS

PNE	Peaceful Nuclear Explosion.
USCGS	United States Coastal and Geodetic Survey, now known as National Ocean Survey (NOS) operated under the auspices of the US Department of Commerce.
EDR	Earthquake Data Report. A summary of epicentre solutions and P wave arrival times published by an international data collection centre operated by the US Department of Commerce, National Oceanic and Atmospheric Agency in Rockville, Maryland, USA.
N	Station non operational.
X	Event not detected by a station.
Ov	Signal is so large the recording system is overloaded. No amplitude information available.
WWSSN	World Wide Standard Seismograph Network.
ISC	International Seismological Centre, Edinburgh. Publishes a monthly bulletin of earthquake epicentres, P wave arrival times and magnitudes of earthquakes.

m_b Short period body wave magnitude.

M_s Long period surface wave magnitude.

Q The absorption parameter.

3. INTRODUCTION

From time to time AWRE have issued Shot Reports* which give the principal seismic data of well documented underground explosions recorded at four seismological arrays deployed to provide a data base on which to study the technical problems of the proposals for a comprehensive test ban treaty. The initiative for these reports resulted from the invitation by the US representative Ambassador William C Foster to the United Nations on 5 December 1968 to use some underground nuclear explosions for the collateral objective of a world wide seismological investigation. The useful role these reports have played may be judged from the wide circulation given to them by the Conference of the Committee on Disarmament and from the many references to them in the scientific literature.

However, these Shot Reports record only seismic data on underground explosions for which complete geophysical data, including the approximate energy (yield) of the source, are publicly announced by the authorities concerned with the main purpose of the explosion. The purpose of the study reported here was to take a world wide sample of suitably large explosions (in all, 23 including six which have been the subject of Shot Reports) and to extract the maximum information possible by analyses of seismic records only. Most of the explosions took place in the Soviet Union, and other than the seismic signals, little or no information is available about them.

All the events have been identified as explosions by the ratio of the mean (array) body wave magnitude (m_b) to the mean (WWSSN) Rayleigh wave magnitude M_s. The standard stations were used to estimate M_s because long period data from the AWRE arrays were not available for the period the study was made. The best estimates of seismic yield were also made from these M_s values. Emplacement depths were estimated by specially developing the technique of spike filtering for the purpose.

With the exception of the continental USA explosions, shot to receive distances lie between 30° and 90° of all four arrays, if complete data were recorded, the arrays were used to estimate locations.

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*Shot Report No. 1 LONGSHOT, AWRE Report 067/66 (October 1966)
Shot Report No. 2 MEDEO, AWRE Report 033/70 (June 1970)
Shot Report No. 3 GASBUGGY and RULISON, AWRE Report 046/70 (June 1970)
Shot Report No. 4 Explosions at NTS, AWRE Report 032/72 (March 1972)

The parameters of each explosion are summarised in the report as follows:-

Epicentral Data:

The majority are provided by the Earthquake Data Reports (EDRs) of the US Department of Commerce. In these cases the epicentral co-ordinates are derived from onset times at WWSSN stations (CGS locations). Springer et al. seismic source summary [1] is the principal source for explosions in the USA. The epicentral co-ordinates in these cases represent the actual locations of the explosions.

Array Data:

Principal data measured at each array.

Surface Wave Data:

From the World Wide Standard Seismograph Network (WWSSN).

Array Location:

Epicentral co-ordinates derived from the four arrays.

The major part of the report consists of these data, together with illustrations of the spiking filter record from which the emplacement depth is estimated and comments on the geological structure of the area in which each explosion was fired, on the possible effects of the deeper structures on seismic signals, and on the seismic yield.

For easy reference, a summary table (table 1 in section 9) is provided.

Notes on the estimation of epicentres, seismic magnitudes, yield, and emplacement depth precede this main part and are provided to guide the reader as to the seismological techniques which have been employed in the analyses. The principal error in depth estimates is likely to be due to an incomplete knowledge of the up-hole velocity of the reflected signal. Usually this parameter can be estimated only from a rough idea of the rock types at the epicentre. The velocities which have been adopted in this report are given in table 2 in section 9.

4. EXPLOSIONS SELECTED

Kazakh, SSR (figure 1)	Explosion No. 1	15 January 1965
	2	7 May 1966
	3	21 July 1966
	4	22 September 1967
Uzbekistan, USSR (figure 1)	Explosion No. 5	30 September 1966
	6	21 May 1968
Caspian Sea, USSR (figure 1)	Explosion No. 7	1 July 1968
	8	26 September 1969
	9	6 December 1969
Urals and Novaya Zemlya, USSR - Urals: (figure 1)	Explosion No. 10	6 October 1967
	11	2 September 1969
	12	8 September 1969
Novaya Zemlya:	Explosion No. 13	21 October 1967
	14	7 November 1968
Sinkiang Province, China (figure 1)	Explosion No. 15	22 September 1969
Aleutian Isles, USA (figure 2)	Explosion No. 16	29 October 1965 LONGSHOT
	17	2 October 1969 MILROW
Nevada, USA (figure 2)	Explosion No. 18	13 September 1963 BILBY
	19	2 June 1966 PILEDRIVER
	20	20 December 1966 GREELEY
New Mexico and Colorado, USA (figure 2)	Explosion No. 21	10 December 1967 GASBUGGY
	22	10 September 1969 RULISON
Algerian Sahara	Explosion No. 23	16 February 1966 GRENAT

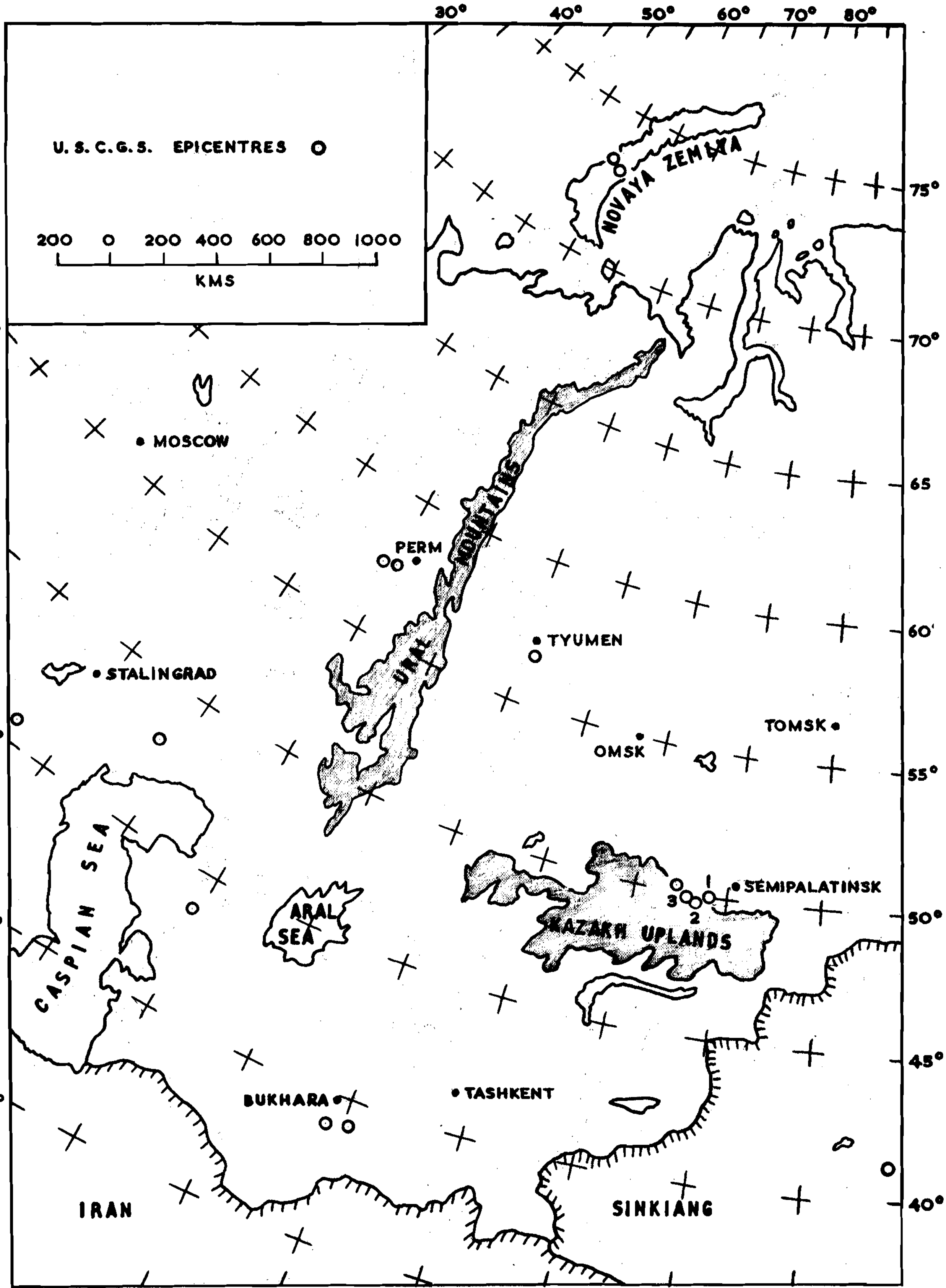


FIGURE 1. LOCATIONS OF RUSSIAN UNDERGROUND EXPLOSIONS USED IN THIS REPORT

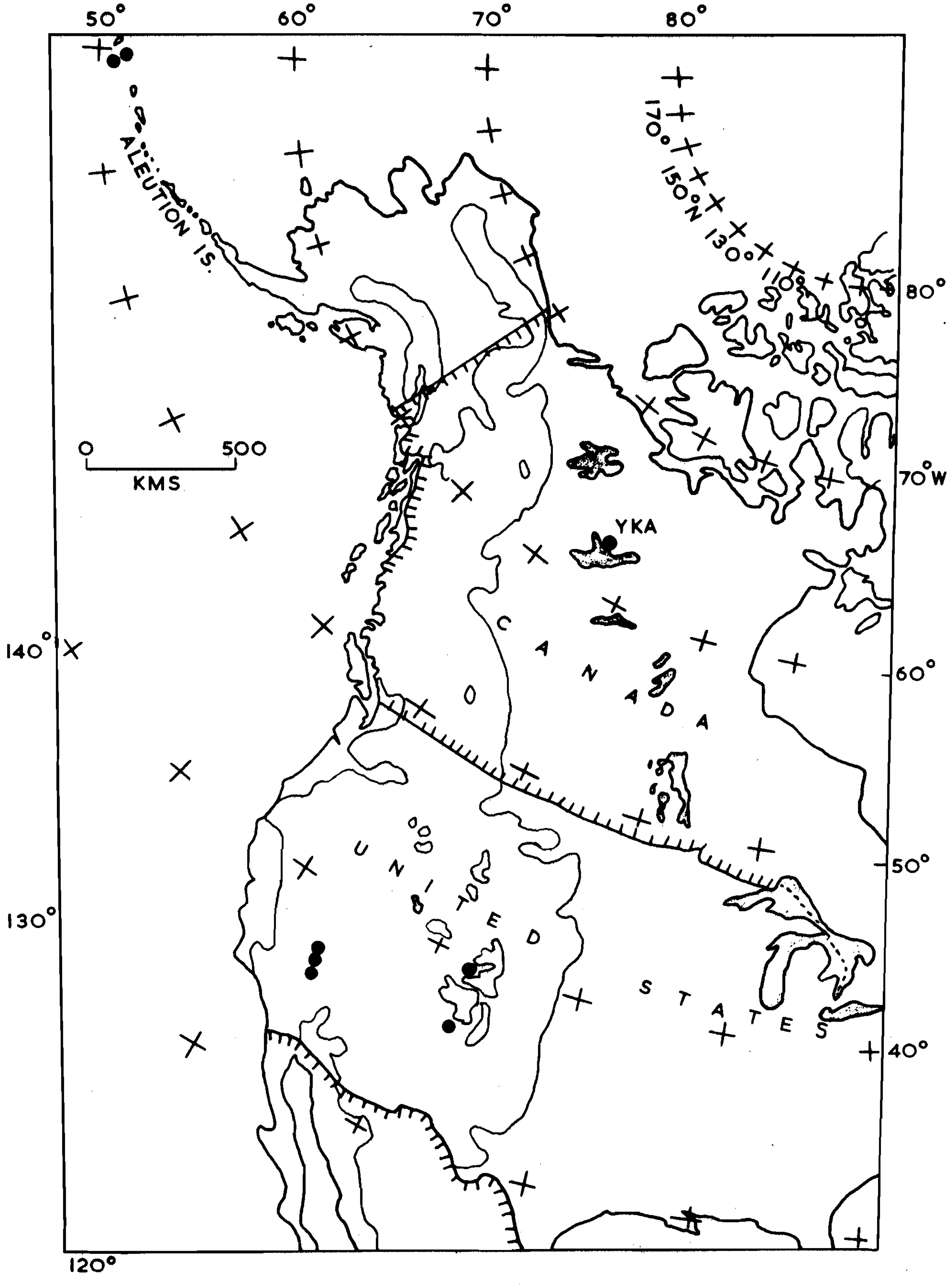


FIGURE 2. LOCATION OF UNDERGROUND EXPLOSIONS IN NORTH AMERICA USED IN THIS REPORT

5. EPICENTRE LOCATION

The location and origin time of a seismic event can be estimated from the arrival time of the P waves at a number of recording stations. An epicentre location service is provided by the United States Department of Commerce Environmental Research Laboratories (ERL) using P wave arrival time data provided on a routine basis by a large number of seismic stations around the world. The epicentres are published in the form of earthquake data reports (EDR); a minimum of five P wave arrival times are required before an epicentre is published by ERL. Epicentre location is, in theory, possible with only three arrival times although the uncertainty in each location is large. Thus, it is possible to locate an event and estimate its origin time using the arrival time data at the four arrays and where possible this has been done for the events contained in this report. The locations obtained are given in section 9; the accuracy of these locations is not discussed here but for comparison the epicentral shift relative to the ERL locations is given. The four array location is included simply to give an indication of the capacity of four arrays to locate an event.

6. SEISMIC MAGNITUDES

The amplitudes of short period P waves can be used to determine the magnitude of an event. The relationship between amplitude and magnitude is defined by Gutenberg and Richter [2] as

$$m_b = \log_{10} \left(\frac{A}{T}\right) + B(\Delta),$$

where A is the half peak to peak amplitude of the first two or three cycles of the P wave in millimicrons ($m\mu$) and T is the period of the wave in seconds. $B(\Delta)$ is a distance normalising term which corrects for the effects of geometric spreading and absorption of the seismic wavefront. The magnitude determined at each array station is included in this report; the values of A and T have been taken from the processed records.

The long period surface waves can also be used to determine magnitude. The long period magnitude M_s is defined as

$$M_s = \log_{10} A_{max} + B'(\Delta) + P(T),$$

where A is the maximum amplitude, defined as half the peak to peak, in the surface wave train measured in $m\mu$, $B'(\Delta)$ a distance normalising term and P(T) is a frequency dependent term which corrects for the effect of the group velocity characteristics of the particular transmission path over which the waves have propagated. A full description of the magnitude formula is given by Marshall and Basham [3].

Since the four array stations were not equipped with long period recording equipment until 1971, measurements of M_s have been made on the seismograms produced by the WWSSN. The M_s values quoted in this report are average values determined from 1 to 10 observations depending on the size and location of the explosion.

7. YIELD ESTIMATES

The estimation of the yield of an explosion is most difficult. For historic reasons the size of a seismic source has been estimated from the magnitude of the seismic waves generated. The magnitude scale was designed for use with earthquake generated waves and was applied directly to explosion generated waves, but the source function and the distribution of energy by the two types of sources is different and gives rise to uncertainties in relating the magnitude of an explosion to the yield.

However, the yield of an underground explosion can be estimated from the magnitude of the seismic signals generated by the explosion. The yield estimated in this way is known as the seismic yield estimate to avoid any confusion with yield estimations based on analysis of radioactive debris.

The amplitude, and hence magnitude, of the seismic waves recorded from an explosion are determined by (a) the yield of the source, (b) the environment in which the explosion took place, eg, granite, alluvium etc, (c) the properties of the transmission path, including the upper mantle of the earth, and (d) the receiver or seismograph used to record the seismic signal, the important feature here is the pass band or frequency response of the seismometer relative to the spectral content of the signal one wishes to record. These factors affect both short period and long period waves though generally the effects are more noticeable for the shorter period P waves. For example the dynamic response of the rock surrounding the explosion exhibits greater variability at the higher frequencies than the lower frequencies. For this reason the m_b:yield relationship is more dependent on the shot medium than M_s:yield.

The transmission path effects are more significant for P waves since lateral variations in the upper mantle perturb the shorter period waves. The lateral variations in the mantle may be the presence of velocity gradients or of highly absorbent rock material. The absorption of a region is measured by the absorption parameter Q, a region of <u>high</u> Q absorbs less of the energy than a region of <u>low</u> Q. The presence of lateral variations in the upper mantle can cause the P waves to be absorbed, scattered or diffracted whereas the surface waves generally propagate above such inhomogeneities. The crust of the earth is very heterogeneous but the wavelengths of the surface waves are long enough to be unaffected by the layering in the crust.

The bandwidth of the recording systems used to detect the seismic waves is also important since a wide band system allows more of the spectrum through, whereas a narrow band system filters out some of the wave energy. In this way a wide band system is particularly useful for investigating the spectral content of the wave and magnitude estimates from such a system are generally larger than estimates made on a narrow band system in which some of the spectrum has been cut out. The response of the WWSSN short period seismographs is particularly narrow band when compared with systems such as the arrays. It should be noted that the signal to noise ratio for small magnitude events decreases as the band width increases, so, to improve detection, the bandwidth is made narrower but the magnitude estimates will be smaller than estimates made with wide band systems. For this reason great caution should be exercised when comparing magnitude measurements from say a wide band Kirnos seismometer, operated by seismologists in the USSR, with measurements made from WWSSN seismograms. The short period P signals are affected more than the long period waves recorded by the WWSSN by this problem of band limitation.

A further effect which causes perturbation in the observed teleseismic P wave signal is the effect of the arrival of the free surface reflection pP (see section 8). As pointed out in section 8 pP may arrive within a fraction of a second of the main P wave. The superpositioning of these two waves can cause either constructive or destructive interference depending on the pP - P time interval. This interference problem is illustrated in figure 3 which shows a simulation of an observed teleseismic P wave with a free surface reflection arriving 0.1 seconds, then 0.2, 0.3 etc seconds after the P wave. Each waveform illustrates the result of adding a P wave to itself with a phase reversal introduced to simulate the free surface effect. Clearly the observed amplitude varies as a function of source depth and any estimate of yield based on a magnitude measured from a seismogram of P + pP must have regard for the effects of this wave interference. The effects of the depth of focus can easily introduce a factor of 2 in the amplitude resulting in a variation of 0.3 in magnitude since the magnitude scale is logarithmic. For example, a 20 kton explosion fired at great depth such that pP and P are well separated will give a smaller magnitude m_b than 20 kton fired at a depth which will cause pP and P to interfere constructively. The interference effects mentioned here refer only to pP and P, but interference can be caused with rays following slightly different paths from the source to the receiver. This has been discussed in a paper by Douglas, Marshall and Corbishley [4].

The limitations of the magnitude scale m_b have been briefly described and are accepted by seismologists; there are also shortcomings in the M_s scale but because this scale is least affected by the parameters described above, the M_s magnitude should be a better indicator of yield than m_b. For this reason more emphasis is given in this report to the M_s - yield relationship.

For more detailed information see reference [5] in which the relationship between yield and magnitude is given as $M_s = \log Y + 2.0$ where Y is the yield in kilotons. This is the relationship used in this report to produce the best estimate of yield. There is less site dependence in the M_s:Y relationship than m_b:Y which requires a knowledge of the geology of the test site which is not always known. The M_s:Y is valid for all consolidated rocks and does not include explosions in unconsolidated rocks. The estimated yield for explosions in alluvium for example would be underestimated by about a factor of 5 by the above M_s:Y relationship.

For explosions in hard rock and in a shield region the relationship between the short period magnitude and yield is estimated to be $m_b = \log Y + 4.0$ and applies to events in which P + pP superimpose to produce enhanced P waves. This relationship gives a yield which is the lowest yield estimate; the yield may be greater if the device is fired in an unconsolidated medium or in the crust above a region of the earth in which there is evidence of low Q material.

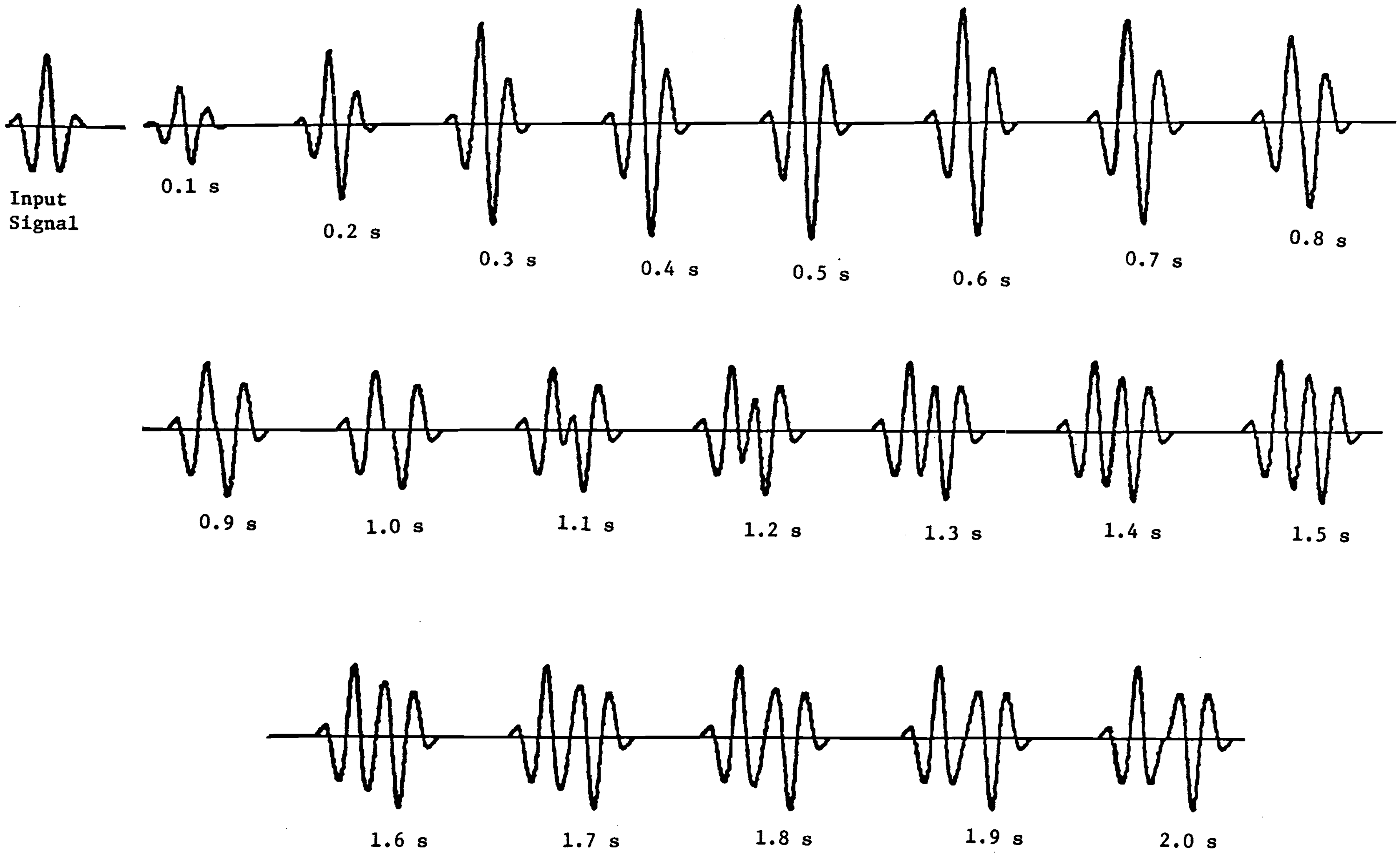


FIGURE 3. A SIMULATION OF THE INTERFERENCE OF A FREE SURFACE REFLECTION AND ITS EFFECT ON THE P WAVE AMPLITUDE

In summary, the yield is estimated from the magnitude of surface waves and the results are given in table 1 (section 9).

8. ESTIMATION OF EMPLACEMENT DEPTHS

The seismograms from each explosion are illustrated in section 10. The upper trace shows the unfiltered array processed seismogram. To produce these seismograms the array is tuned or beamed on to the incoming signal after it has been recorded by applying time delays appropriate to the velocity of the wave front across the array. The delayed signals are then added; in this way only the signal and not the noise is coherent and the summed seismogram shows an improvement in the signal to noise ratio. This method is known as the "delay and sum" array process [6].

Beneath the illustrations of the delay and sum processed records is an example of a "spiked" seismogram. This "spiked" seismogram is produced by processing the digitised record to replace the frequencies removed from the seismic waves by the seismometer recording system and the absorption effects, ie, Q of the mantle of the earth. In theory, these records should show a series of spikes which have been generated near the source by the explosion impulse and reflections from discontinuities close to the source. In practice the arrival of distinct pulses within the P wave coda can often be observed; these arrivals have travelled from the source to the receiver by slightly different paths to the P wave. This means that the absorption parameter used to produce a clear spike corresponding to the P wave is not the optimum parameter to produce the best spike for later arrivals; to investigate all these arrivals would require passing the seismogram through a series of spike filters which is time consuming; however, here we are concerned with the main arrival, ie, the P wave and the illustrations in section 10 are of the processed record to produce the best spiked P wave record.

The spiked seismogram should be useful in estimating the depth of focus of very shallow sources such as underground explosions. This is because the most powerful seismic wave reflector close to the source is the air-ground interface, or free surface, and the spiked record allows the time delay between the initial impulse P and the free surface reflection pP to be estimated. From an underground explosion the direct P wave is compressional and the direction of first motion of ground movement is upwards. The outward going pulse from the explosion which reaches the free surface is also compressional but upon reflection at the free surface the phase is reversed and when recorded at teleseismic distances would cause the ground to move downwards. Thus, pP on a spiked record should appear as a large negative spike. The time interval between pP and P is related to the depth of focus and to the compressional wave velocity in the medium above the shot point. To estimate the depth of focus we use the relationship

$$d = \frac{V \times (P - pP)\ \text{time}}{2},$$

where d is the depth in kilometres, V the compressional wave velocity in km/s and (P - pP) the time separation in seconds. V is estimated from a knowledge of the age of the rocks in the source region (reference [7] and table 9.1 of reference [8]), and on occasions more precisely from publications concerning the area of the explosion. The depths of focus for the explosions analysed in this report have been estimated in this way and are given for each explosion in section 10.

Though this technique is an improvement in the identification of pP it still relies to some extent on the subjectivity of the analyst. The characteristic compressional first motion from an explosion is enhanced in the spiked record and the identification of pP is made easier by the knowledge that pP is reversed in phase to the P wave. The inclusion of the spiked records in this report is primarily intended to give an indication of a technique still being developed which shows considerable promise in the interpretation of seismograms. A more detailed report on the spike filter process is published by Douglas et al. [9].

9. SUMMARY OF RESULTS

The results and conclusions of the analysis of the seismic signals generated by the explosions discussed in this report are summarised in table 1. For specific details concerning individual explosions, reference should be made to the explosion analysis in section 10.

The data given in table 1 include the date, origin time, estimated epicentre, depth of firing and the short period magnitude determined from the four arrays. The yield estimates are made from the surface wave magnitude M_s for the reasons given in section 7. A detailed explanation of the preference for M_s over m_b is also given in the UK Working Paper presented to the CCD Geneva in April 1972.

TABLE 1

Explosion Number	Date of Explosion	Approx. Origin Time* GMT, h min	4 Array Location†		Epicentre Shift Relative to CGS		Estimated Depth, m	Average of Array m_b Magnitude	Average WWSSN Magnitude M_s	Best Estimate of Yield, kton	Yield Range, kton
			Lat. °N	Long. °E	E of N	km					
1	15 January 1965	0600	-	-	-	-	370	6.07	3.90	80	40 - 160
2	7 May 1966	0358	49.62	77.98	137	14	720	4.67	2.80	6	3 - 12
3	21 July 1966	0358	49.68	78.03	135	9	720	5.43	3.55	35	20 - 70
4	22 September 1967	0504	49.85	77.54	225	20	540	5.39	3.32	21	10 - 40
5	30 September 1966	0600	39.03	64.51	3	26	1550	5.16	3.79	62	30 - 120
6	21 May 1968	0359	38.76	64.91	231	28	2240	5.56	3.89	80	40 - 160
7	1 July 1968	0402	47.74	47.87	197	21	560	5.91	3.67	47	25 - 90
8	26 September 1969	0700	45.55	42.33	196	40	1400	5.22	3.37	23	10 - 40
9	6 December 1969	0703	43.82	54.70	256	7	910	5.89	3.98	95	50 - 200
10	6 October 1967	0700	57.53	65.56	135	25	590	4.67	2.95	9	5 - 20
11	2 September 1969	0500	57.00	55.15	160	50	1200	5.17	3.29	20	10 - 40
12	8 September 1969	0500	57.06	55.24	167	35	1080	5.17	3.29	20	10 - 40
13	21 October 1967	0500	73.42	55.27	70	15	600	5.82	4.34	220	100 - 400
14	7 November 1968	1002	73.43	55.30	78	14	615	5.83	4.47	300	150 - 600
15	22 September 1969	1615	41.24	88.19	210	18	620	5.17	3.25	18	10 - 40
16	29 October 1965	2100	51.43	179.00	269	12	730	6.07	4.06	115	60 - 220
17	2 October 1969	2206	51.54	179.00	315	18	2900	6.60	5.15	1400	700 - 2800
18	13 September 1963	1700	-	-	-	-	-	5.45	4.40	250	180 - 450
19	2 June 1966	1530	-	-	-	-	490	5.23	3.76	58	30 - 120
20	20 December 1966	1530	-	-	-	-	1250	6.03	5.06	1150	650 - 2000
21	10 December 1967	1930	-	-	-	-	-	4.83	3.40	25	15 - 40
22	10 September 1969	2100	-	-	-	-	2600	4.71	3.55	36	20 - 70
23	16 February 1966	1100	24.18	05.26	55	28	840	5.01	3.35	22	10 - 40

*Origin time rounded off to nearest minute.
†Less than 3 stations reported arrival times.

TABLE 2

The Geological Time Scale and Associated Rock Velocities

Eras		Periods	Beginning of Period 10^6 years	Approximately P Wave Velocity [8], km s^{-1}	Regions Relative to this Report
Caenozoic	Quaternary	Recent	0.01	2.5	Nevada
		Pleistocene	1.5 - 2.0		) Caspian Sea
					) Uzbekistan
		Pliocene	7	2.75	) Sinkiang
		Miocene	26		) Kazakh
		Oligocene	38	3.3*	Aleutians
		Eocene	54		
		Palaeocene	65		
Mesozoic		Cretaceous	136		) Colorado
		Jurassic	195	3.3	) New Mexico
		Triassic	225		) Nevada
Palaeozoic		Permian	280	3.3	) Caspian Sea
					) Urals, Novaya
					) Zemlya
		Carboniferous	345	3.6	Kazakh
		Devonian	395		
		Silurian	435	3.9	Sahara
		Ordovician	∿ 500		
		Cambrian	∿ 570	4.25	Novaya Zemlya
Pre Cambrian					

*Known velocity. Measured in area of test site.

10. ANALYSIS OF SEISMOGRAMS

In this section, the principal part of this report, the detailed analysis of the seismograms from the four arrays is presented. The location of the four arrays is:-

Eskdalemuir, Scotland	EKA	55° 19' 59.0"N
		3° 09' 33.0"W
Yellowknife, Canada	YKA	62° 29' 34.3"N
		114° 36' 16.5"W
Gauribidanur, India	GBA	13° 36' 15.0"N
		17° 26' 10.0"E
Warramunga, Australia	WRA	19° 56' 52"S
		134° 21' 03"E

The explosions selected for analysis have been grouped together as far as possible into geographical regions and discussed, when known, in terms of local geology, topography, and upper mantle structure. A table of the geological time scale and the compressional wave velocity for rocks of certain ages found at the various test sites is included. Information of the type contained in this table is useful for interpreting the character of P waves and estimating the emplacement depth.

Each explosion is accompanied by a table summarising the array data, WWSSN long period data, epicentral data and yield information where this has been announced. The seismograms from each array are illustrated for each explosion. The letter "i" indicates a delayed and summed unfiltered short period vertical component seismogram, the letter "ii" indicates a spiked version of record "i".

The order in which the explosion analysis is presented is the same as that given in section 4 starting with the Soviet test site at Kazakh.

10.1 Kazakh, SSR

Explosions 1, 2, 3 and 4 were selected from this area which appears to be the main test site in the USSR for low-intermediate underground explosions and is located approximately 50°N and 79°E some way between Semipalatinsk and Karaganda in Kazakhstan, SSR. The main test area appears to cover an area no larger than a circle of about 5 km radius.

The first underground explosion at this test site detected by a UK type array occurred on 2 February 1962, and after a pause during 1963 the test site came into continued use from 1964.

The largest elevation in this area is a small mountain 1085 m above sea level but only about 500 m above the surrounding terrain. This means that it would be possible to use conventional mining techniques as vertical drilling for emplacement of the device to be detonated. The site is located on the late Paleozoic Kazakh fold system, part of the Russian shield region with an upper mantle P_n wave velocity above 8 km/s indicating a region of high Q hence low seismic wave attenuation making it possible to detect explosions of the order of 1 kton in this particular region. It is expected that explosions fired in hard rock in this area would be recorded with very little high frequency loss, hence very short period P waves and would be very simple in character since the sources are located in a shield region.

10.1.1 15 January 1965 (Explosion No. 1)

The location of this explosion is shown in figure 1 and is the most easterly event detected at the Kazakh test site. Only two array stations were operating at the time of this explosion, EKA and YKA. The signal was sufficiently large to overload the recording system at YKA but good signals were recorded at EKA. The record and spiked record are displayed in figure 4.

This explosion is probably a cratering experiment, described by USSR delegates at the IAEA Vienna, in which a nuclear explosive of some 125 kton was used to shift large volumes of earth for the construction of a reservoir. This would mean that the charge is emplaced, by vertical drilling, at a shallow depth. The spiked seismogram does exhibit a negative pulse 0.3 s after the positive P wave pulse. The superficial layering in this area indicates a compressional wave velocity of 2.5 km/s which gives a depth of firing of 370 m. This is more than twice the announced depth; the error may be due to mis-identification of pP or an error in the assumed velocity of 2.5 km/s. However, a yield of 125 kton would require an overburden of 800 m for containment if the USSR depth-yield relationship [10] of $h = 160Y^{1/3}$ is used (h is depth in metres, Y is yield in kilotons). The conclusion is that this explosion must have broken the surface and probably led to a release of radioactive debris into the atmosphere.

The surface wave magnitude indicates a yield of 80 kton within the range 40 - 160 kton.

No epicentre location was possible since only two arrays recorded the event. An indication of the epicentral position can be obtained from the phasing conditions required to beamform an array; the phasing condition for EKA indicates an epicentre in the Kazakh region.

Explosion No. 1

Epicentral Data:

Date:	15 January 1965
Time GMT:	05 59 58.5
Latitude:	49.89°N
Longitude:	78.97°E
Code Name:	
Source of Data:	EDR 6-65
Yield:	

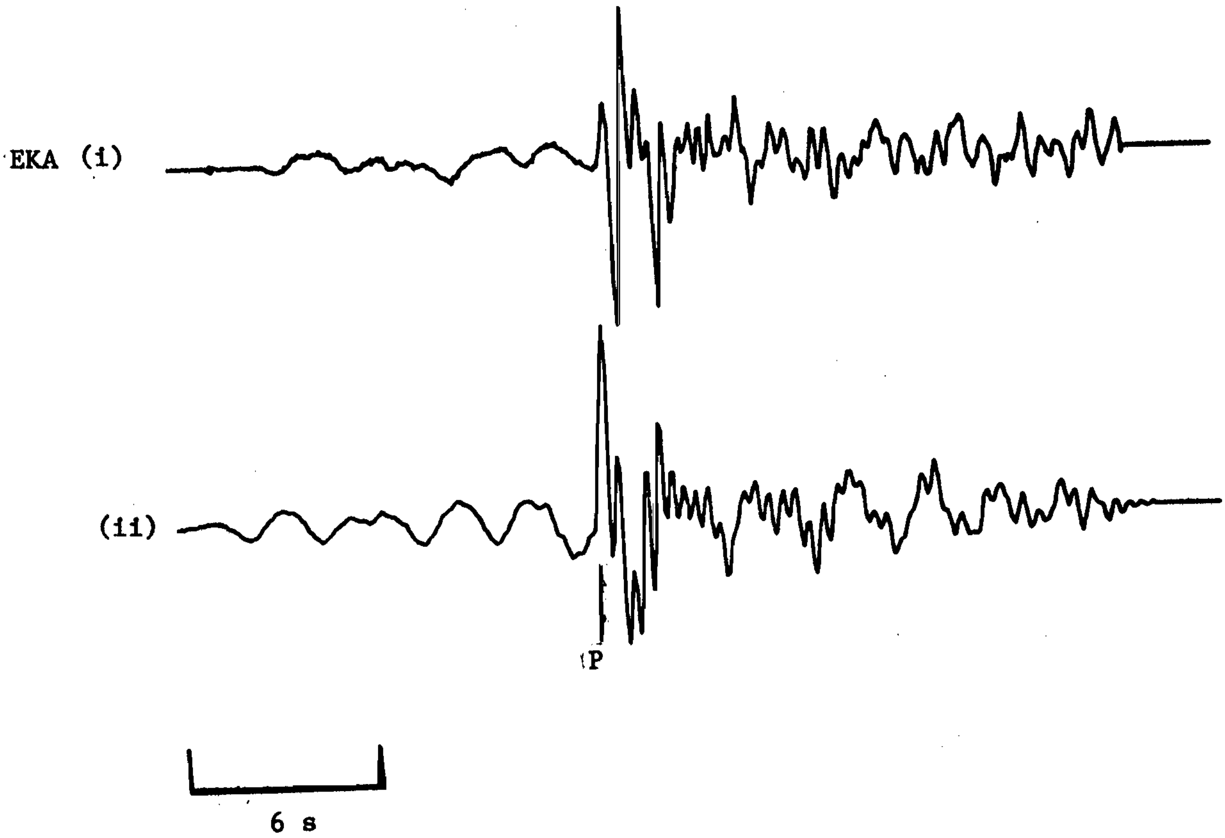
Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
GBA				N			
EKA	47.4	30.9	60	06 08 35.4	82	0.55	6.07
YKA	67.4	6	350	06 10 56.1	Ov	-	-
WRA				N			

Surface Wave Data (WWSSN):

Magnitude M_s: 3.9 ± 0.2

Array Location:



<u>FIGURE 4</u>

10.1.2 7 May 1966 (Explosion No. 2)

This explosion is located in the southern region of the Kazakh test site very close to the epicentre of the 21 July 1966 event. It is a small explosion with the result that the signal to noise ratio at each array is not good. It was detected at all four arrays although the initial onset at GBA and EKA is not very clear (figure 5(a); however, the spiked record enables us to pick a clear compressional feature corresponding to the arrival of the P wave. The depth phase pP is assumed to be the negative spike occurring some 0.4 s after the direct P wave. The P - pP separation time would give a depth of 720 m for P wave velocity of 3.6 km/s close to the source.

The surface wave magnitude determined from one observation gives a yield of 6 kton. This yield would be fully contained at the estimated depth of 720 m.

Explosion No. 2

Epicentral Data:

Date:	7 May 1966
Time GMT:	03 57 58.0
Latitude:	49.74°N
Longitude:	77.90°E
Code Name:	
Source of Data:	EDR 30-66
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
GBA	36.0	180.8	0.5	04 05 02.0	3	0.50	4.37
EKA	47.0	309.5	61.3	04 06 32.7	9	0.60	5.06
YKA	67.7	6.2	351.3	04 08 57.4	6	1.02	4.77
WRA	85.4	128.1	327.1	04 10 37.8	2	0.62	4.57

Surface Wave Data (WWSSN):

Magnitude M_s: 2.80 (1 station)

Array Location:

49.62°N
77.98°E

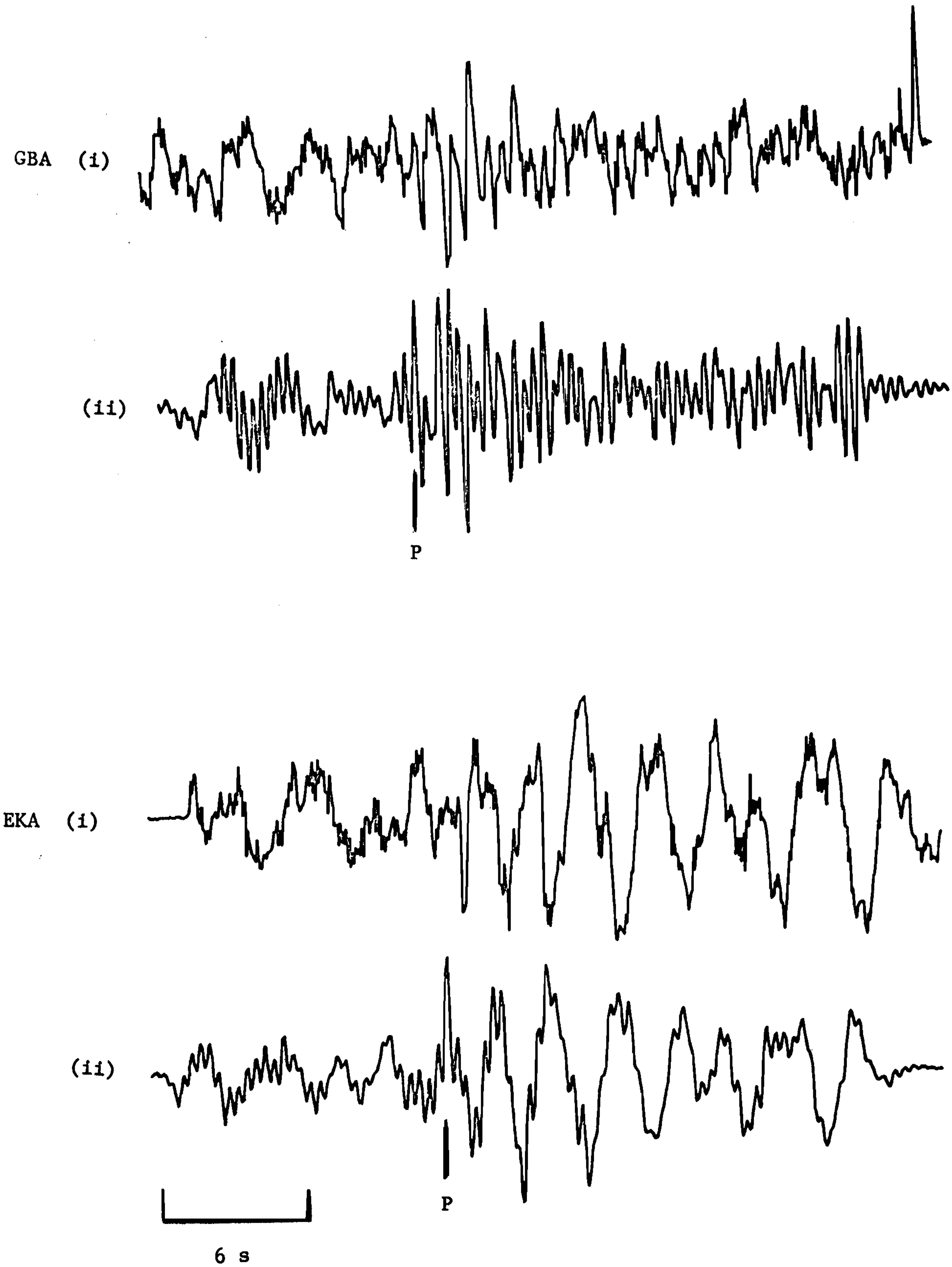


FIGURE 5(a)

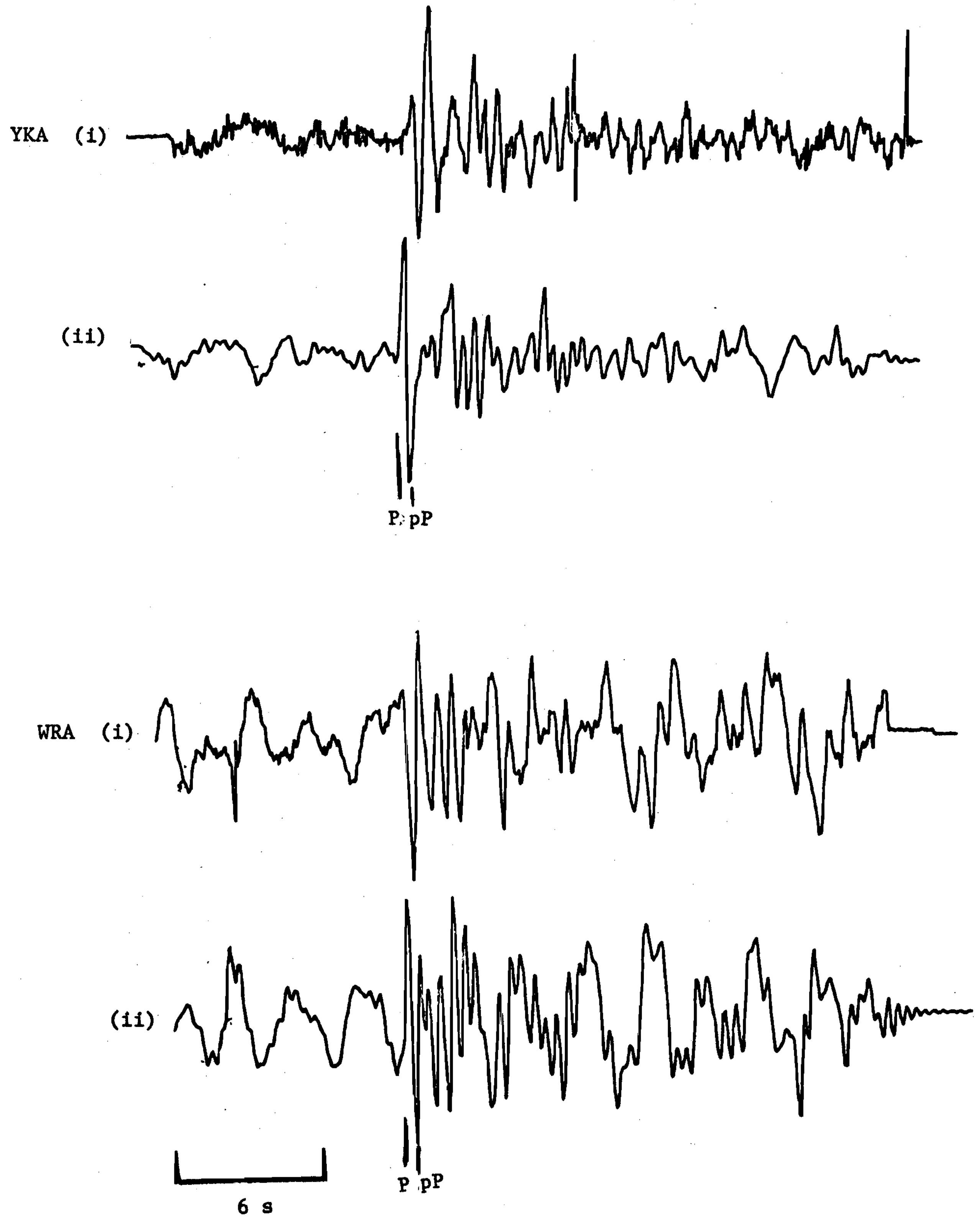


FIGURE 5(b)

10.1.3 21 July 1966 (Explosion No. 3)

This explosion is located very close to the explosion on 7 May 1966 but is somewhat larger giving a better signal to noise ratio at all four array stations. The records are displayed in figures 6(a) and 6(b). As with the previous event GBA gave no clear evidence of a pP arrival but this phase is identified at the other arrays. The average P - pP time is 0.4 s and assuming 3.6 km/s indicates a depth of 720 m. This is the same depth estimated for the previous event which may suggest that the phase identified as pP is not a surface reflection but a feature associated with perhaps the transmission path. This is very unlikely. It is more probable that access to the firing chamber was made through a mined adit so that both devices were emplaced at a similar depth. This would indicate either that there is no strict adherence to the depth-yield relationship or that the explosion of 7 May 1966 was expected to give a yield nearer to this particular explosion.

The surface wave magnitude gives a yield of 35 kton in the range 20 - 70 kton. An overburden of 720 m would be sufficient to contain up to 90 kton.

Explosion No. 3

Epicentral Data:

Date:	21 July 1966
Time GMT:	03 57 57.8
Latitude:	49.71°N
Longitude:	77.92°E
Code Name:	
Source of Data:	EDR 51-66
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
GBA	36.0	180.8	0.5	04 05 02.1	12	0.45	5.04
EKA	47.0	309.5	61.3	04 06 32.2	43	0.6	5.76
YKA	67.7	6.2	351.3	04 08 56.7	24	0.6	5.61
WRA	85.4	128.1	327.1	04 10 37.4	12	0.62	5.30

Surface Wave Data (WWSSN):

Magnitude M_s: 3.55 ± 0.25

Array Location:

49.68°N
78.03°E

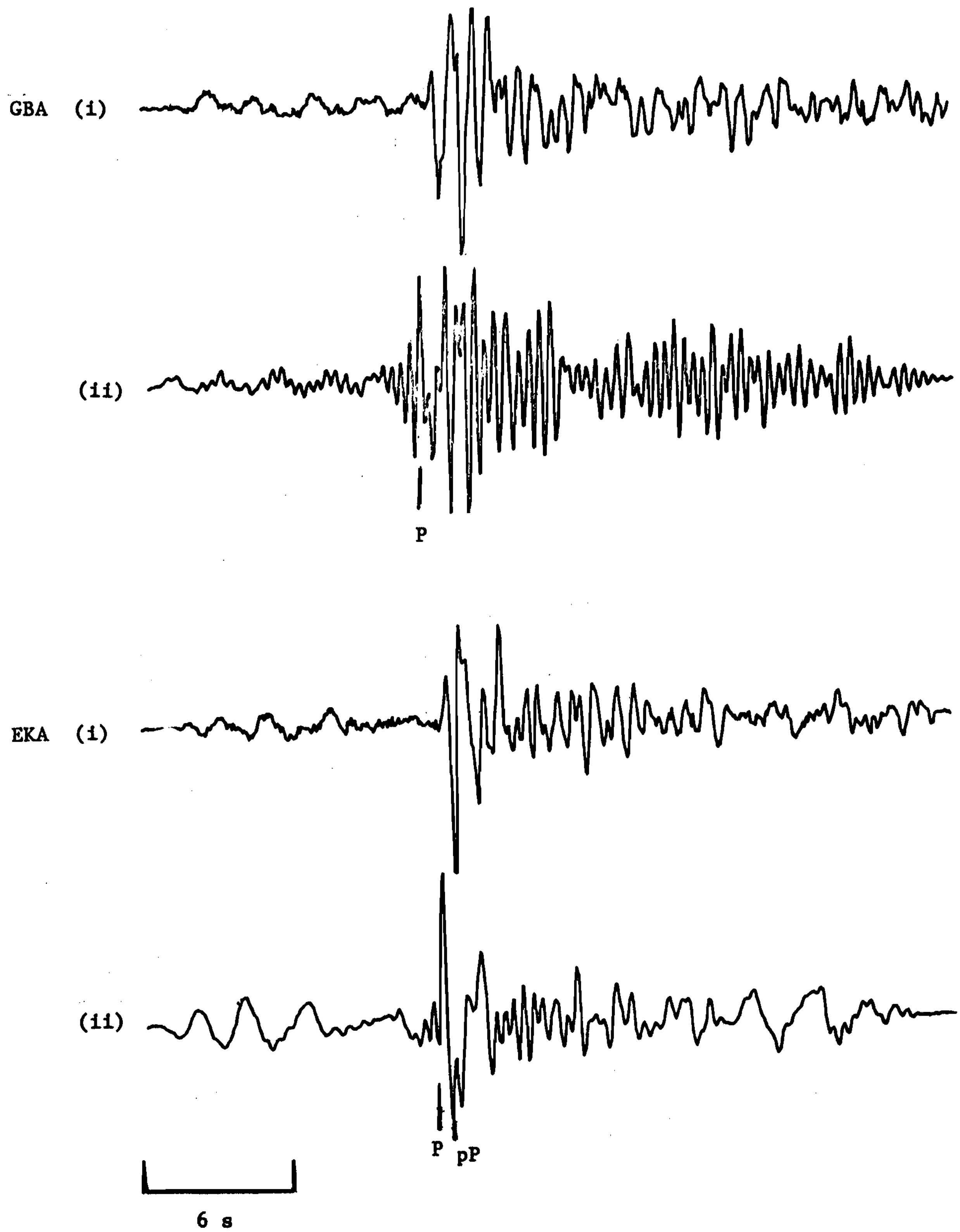


FIGURE 6(a)

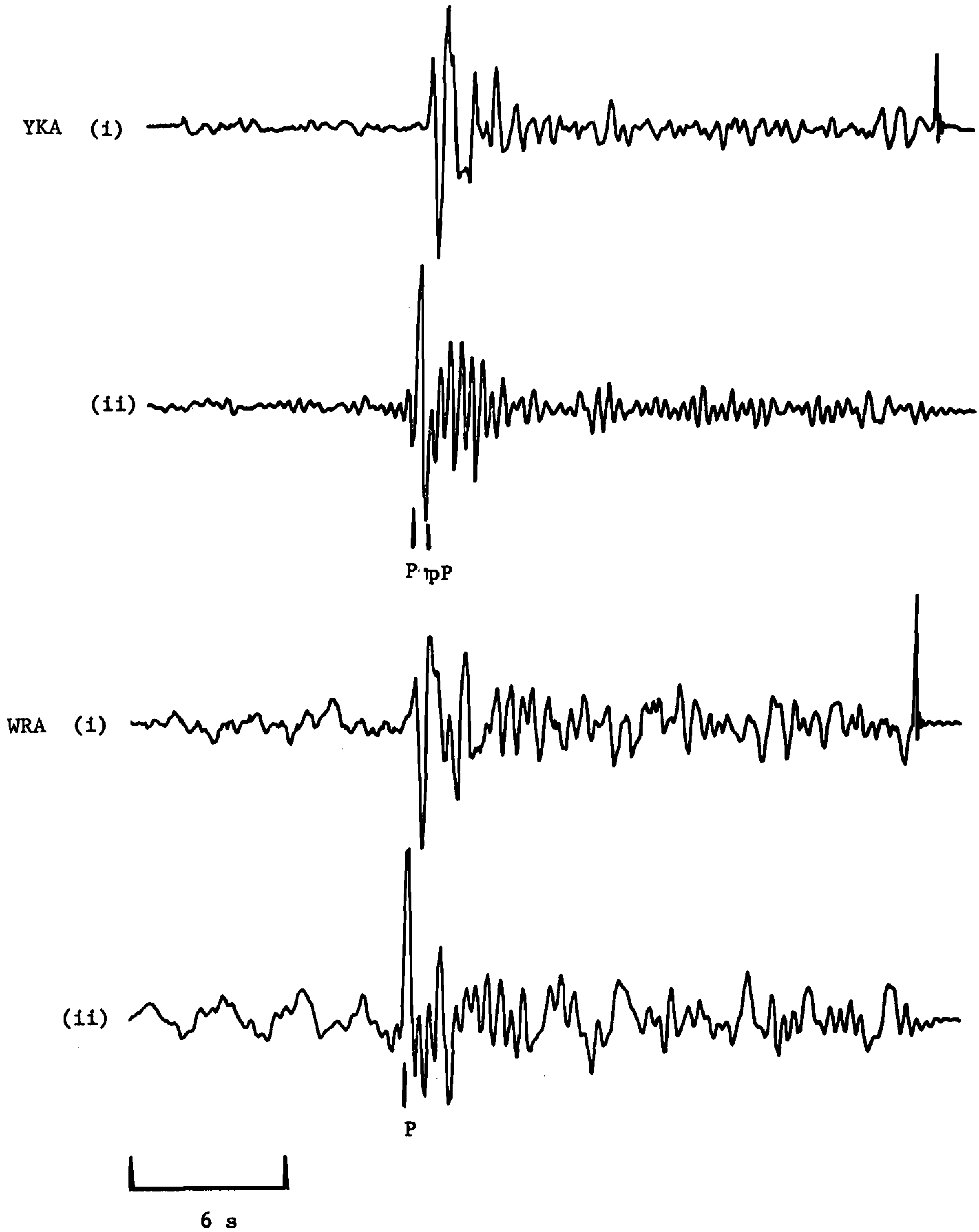


FIGURE 6(b)

10.1.4 22nd September 1967 (Explosion No. 4)

This explosion was selected because it is the most westerly of all the events in the Kazakh test site area. It was recorded by all four arrays and the records are displayed in figures 7(a) and 7(b). The GBA array spiked seismogram shows pP, the separation time between P and pP is 0.3 s. This gives a depth estimate of 540 m assuming a P wave velocity of 3.6 km/s.

The yield estimated from the surface wave magnitude is 21 kton in the range 10 - 40 kton. This yield should be fully contained at the estimated depth. It should be noted that EKA gave a small magnitude for this event. Normally explosions from Kazakh are recorded with high magnitude at Eskdalemuir, and it gives an insight into the variation one may expect in the P wave signals from even small shifts in epicentral position.

Explosion No. 4

Epicentral Data:

Date:	22 September 1967
Time GMT:	05 03 57.9
Latitude:	50.03°N
Longitude:	77.61°E
Code Name:	
Source of Data:	EDR 62-67
Yield:	

Array Data:

Station	$\Delta°$	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
GBA	36.3	180.3	0.2	05 11 03.6	58	0.70	5.49
EKA	46.7	309.2	61.1	05 12 29.2	7	0.5	5.00
YKA	67.4	6.1	351.5	05 14 55.4	33	0.8	5.62
WRA	85.8	127.9	327.2	05 16 39.0	23	0.75	5.40

Surface Wave Data (WWSSN):

Magnitude M_s: 3.32 ± 0.25

Array Location:

49.85°N
77.54°E

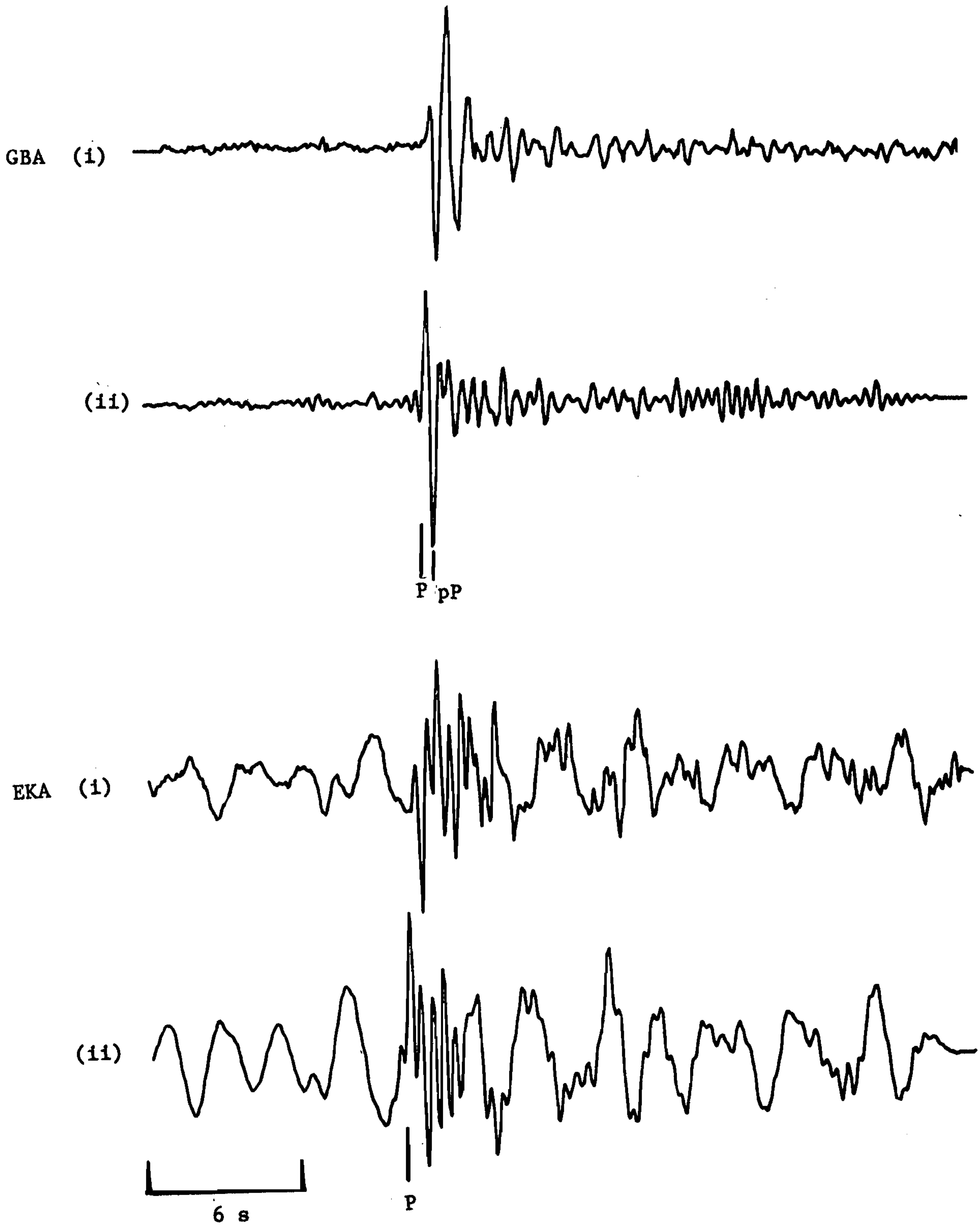


FIGURE 7(a)

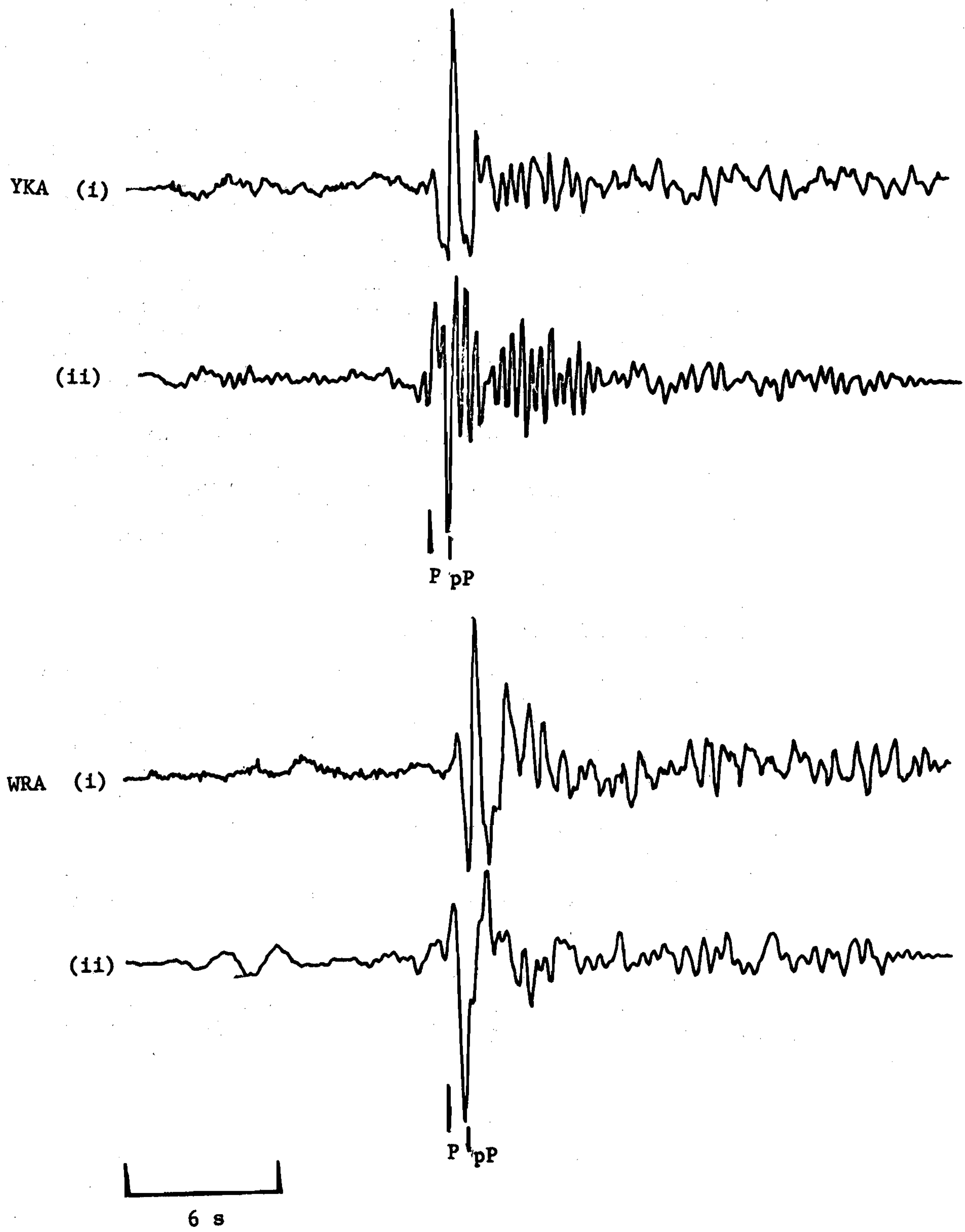


FIGURE 7(b)

10.2 Uzbekistan, USSR

This is a region with gas and oil deposits. It is known that nuclear devices have been detonated to suppress a runaway gas well fire and to plug a runaway oil well. Each of these events has been described in some detail by USSR delegates at IAEA Vienna [11]. The two events analysed in this section are believed to be the events referred to above.

The location of the shots is in the vicinity of Bukhara some 250 km west of Samarkand. This region has been tectonically stable since the end of the Palaeozoic era. The crystalline basement is generally buried at great depth beneath folded geosynclinal rocks with Mesozoic-Cenozoic platform cover. The crustal thickness is of the order of 40 - 45 km and the P_n wave velocity is 8.15 km/s. This would indicate a region of high Q, ie, low seismic wave attenuation, however, seismic waves travelling to the south and east of Bukhara may be perturbed by the complex fold structures of the Northern Pamir fold belt and by Tien Shan fold belt. This would cause considerable absorption and scattering of the seismic waves. Thus, the radiation of energy from the source is expected to be asymmetric.

The surface elevation in this region is of the order of 200 m above sea level and is relatively flat over a large area. This makes it unlikely that device emplacement would be achieved by mining into hill-sides; rather vertical drilling techniques would be used. According to the Russian descriptions [11] this was so for the two explosions analysed here.

10.2.1 30 September 1966 (Explosion No. 5)

An extensive description of this explosion is given in reference [11]. The experiment was conducted to see if a 30 kton explosion fired in clay would force the clay into the well hole and seal the hole such that the supply of gas to the fire at the well head was cut off and the fire extinguished. It would appear that the test was successful.

Seismic signals from this explosion were detected at all four array stations and are displayed in figures 8(a) and 8(b). Assuming a velocity of 2.75 km/s consistent with rocks of the age in this area, and a clearly defined P - pP separation time, the depth of firing is estimated to be 1550 m; the announced depth is 1532 m.

The seismic yield estimate based on surface wave data is 62 kton in the range 30 - 120 kton. The range of yields predicted here would be fully contained by the overburden of 1532 m and it would not be expected to leak radioactivity into the atmosphere.

Explosion No. 5

Epicentral Data:

Date:	30 September 1966
Time GMT:	05 59 52.8
Latitude:	38.8°N
Longitude:	64.5°E
Code Name:	
Source of Data:	ISC Bulletin September 1966
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
GBA	27.4	153.4	339.0	06 05 41.9	21	0.9	4.91
EKA	47.3	313.8	80.5	06 08 21.8	13	0.5	5.31
YKA	79.0	359.9	0.2	06 11 54.6	13	0.9	4.97
WRA	87.2	118.3	313.1	06 12 40.1	22	0.8	5.46

Surface Wave Data (WWSSN):

Magnitude M_s: 3.79 ± 0.25

Array Location:

39.03°N
64.51°E

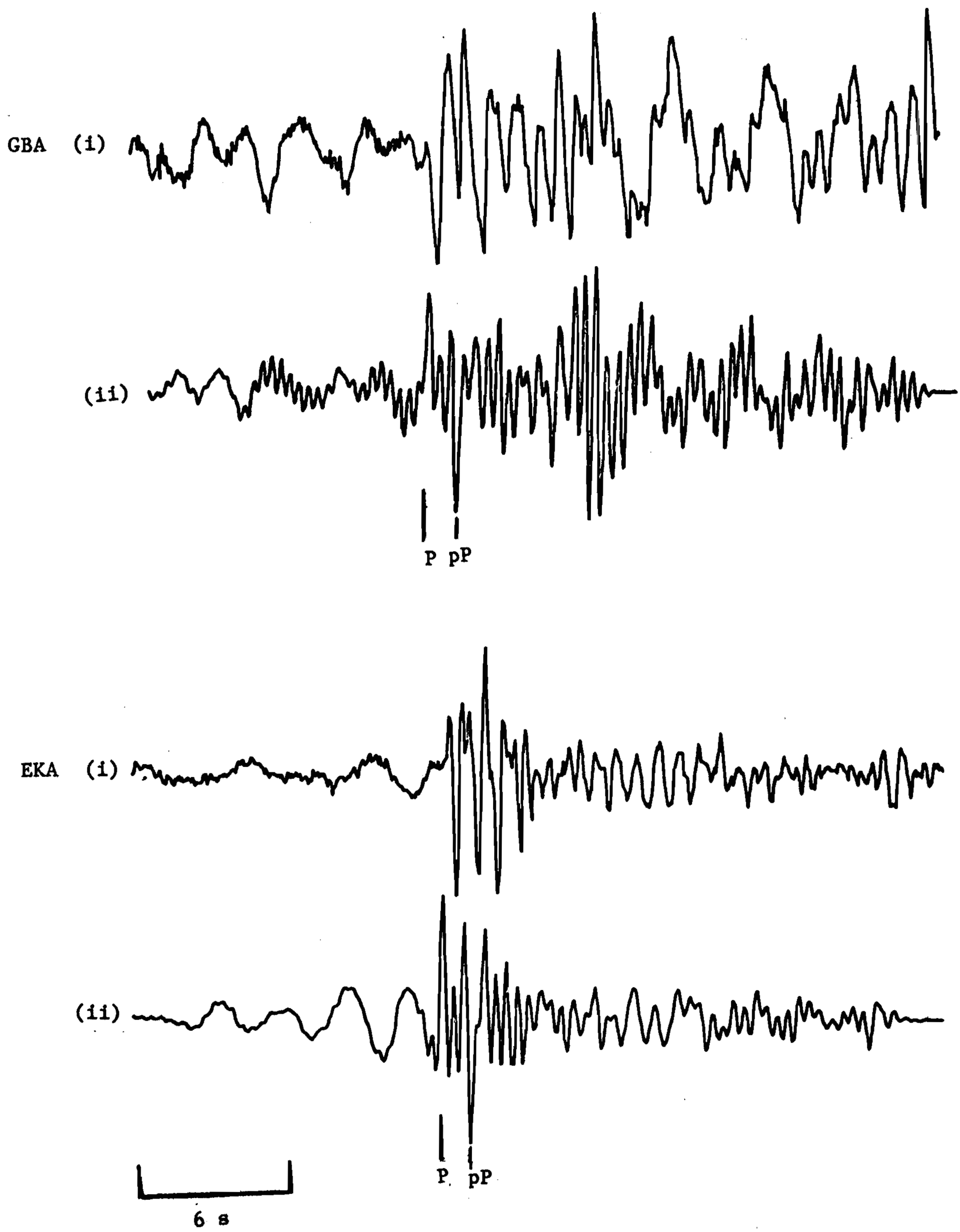


FIGURE 8(a)

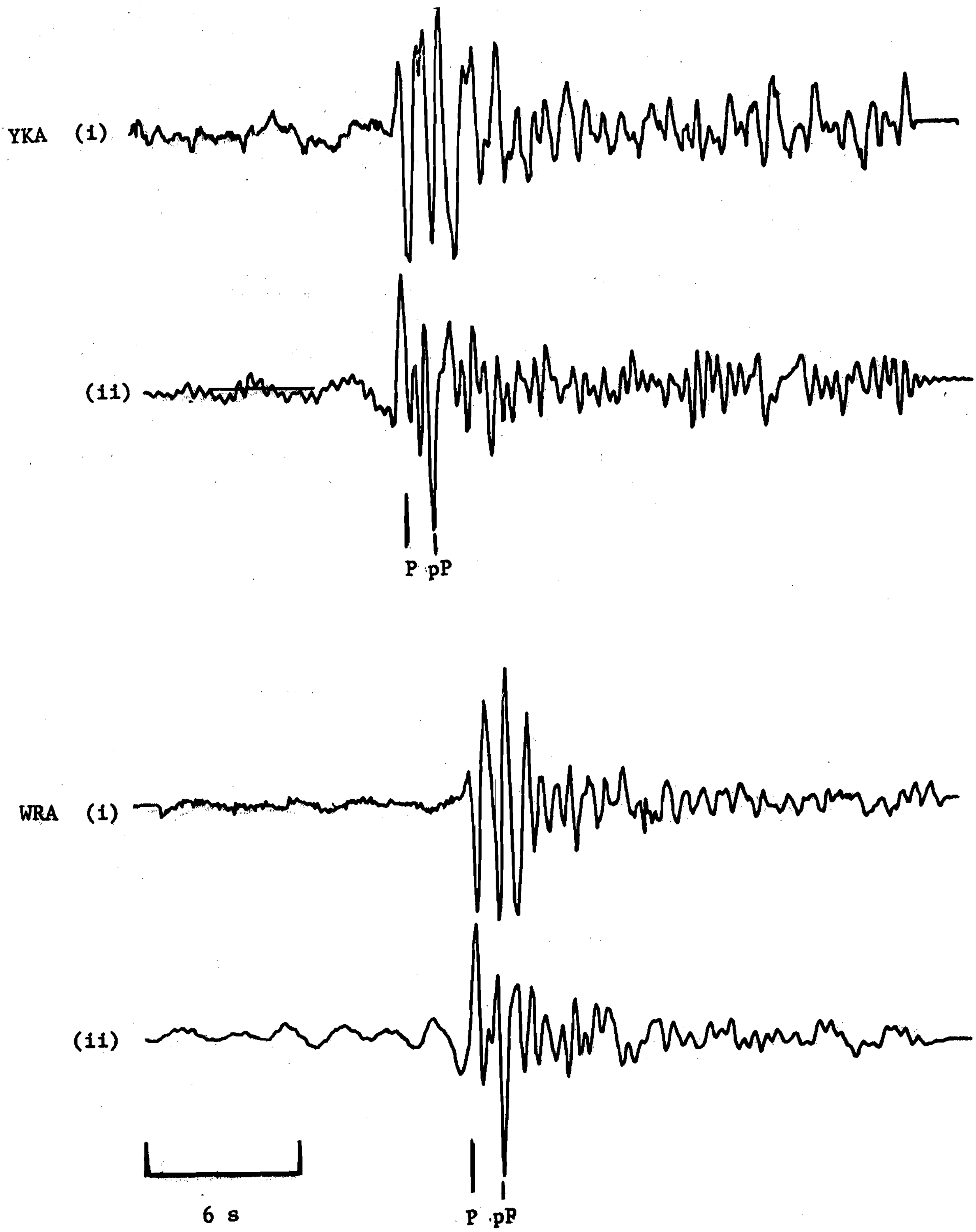


FIGURE 8(b)

10.2.2 21 May 1968 (Explosion No. 6)

This is the second of the PNE shots in this region. This was the experiment to stop or plug a runaway oil well. The yield of this shot was 47 kton and it was detonated in salt in an effort to force the salt to flow into the well hole and cut off the supply of oil. Only three of the arrays were operational on this day and each recorded good signals; these are illustrated in figures 9(a) and 9(b). As with the previous event, pP is clearly seen on the spiked seismograms giving a P - pP separation of 1.63 s and again using a velocity of 2.75 km/s a depth of firing of 2240 m is obtained, which in good agreement with the announced depth of 2450 m.

The record at GBA is very complex, a feature it is believed of the transmission path from the test site. This event is the subject of a recent paper in Nature [4] describing a low Q region which could cause the complexity of the signal and the relatively long period of the P wave.

The surface wave magnitude indicates a yield of 80 kton in the range 40 - 160 kton, somewhat higher than the announced yield. Again, this yield range would be fully contained at a depth of over 2000 m.

Explosion No. 6

Epicentral Data:

Date:	21 May 1966
Time GMT:	03 59 11.5
Latitude:	38.92°N
Longitude:	65.16°E
Code Name:	
Source of Data:	EDR 30-68
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
GBA	27.4	153.4	339.0	04 04 58.4	49	0.9	5.28
EKA	47.3	313.8	80.5	04 07 45.4	68	0.8	5.83
YKA	79.0	359.9	0.2	04 11 16.0	46	0.8	5.56
WRA				N			

Surface Wave Data (WWSSN):

Magnitude M_s : 3.89 ± 0.28

Array Location:

38.76°N
64.91°E

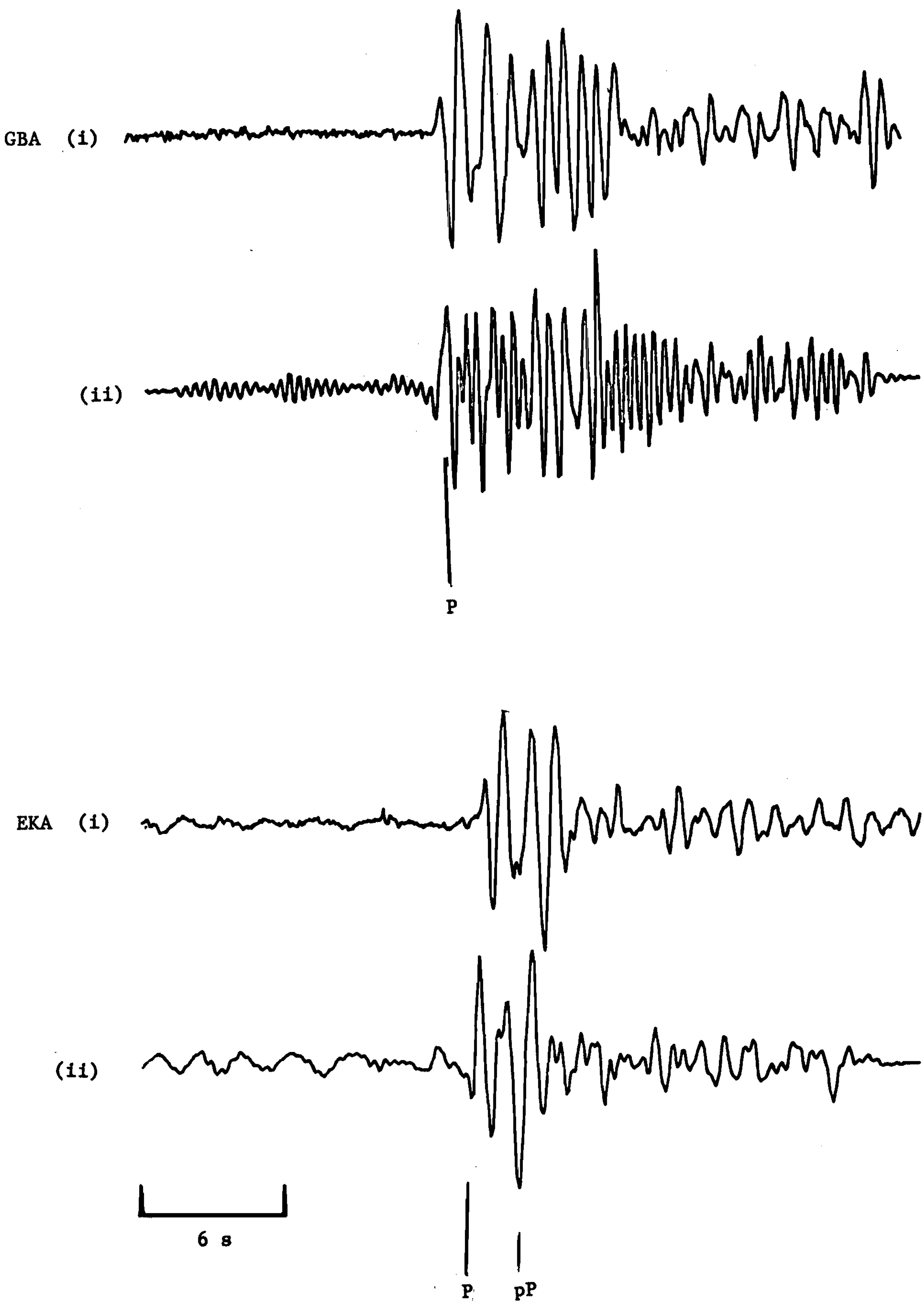


FIGURE 9(a)

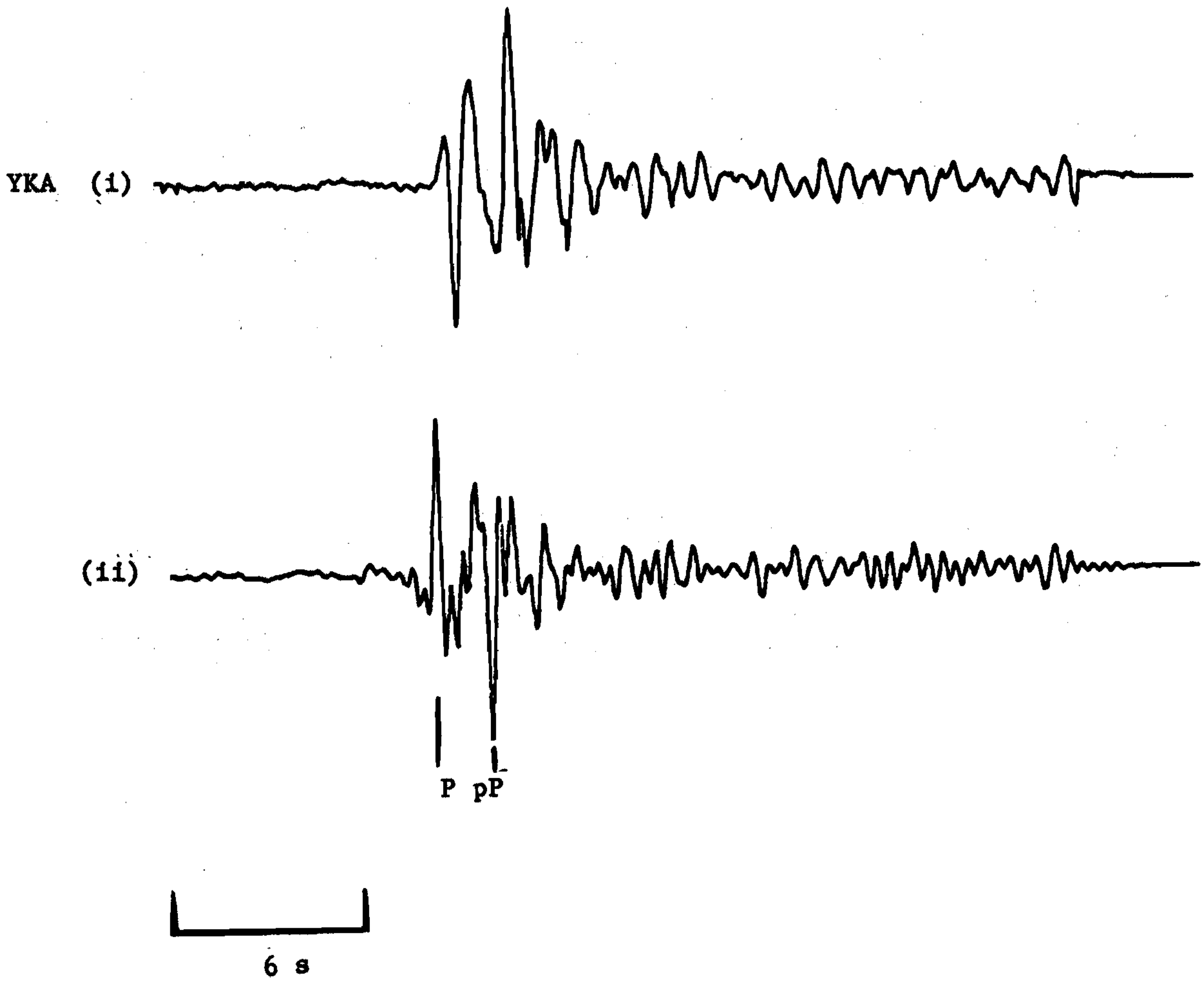


FIGURE 9(b)

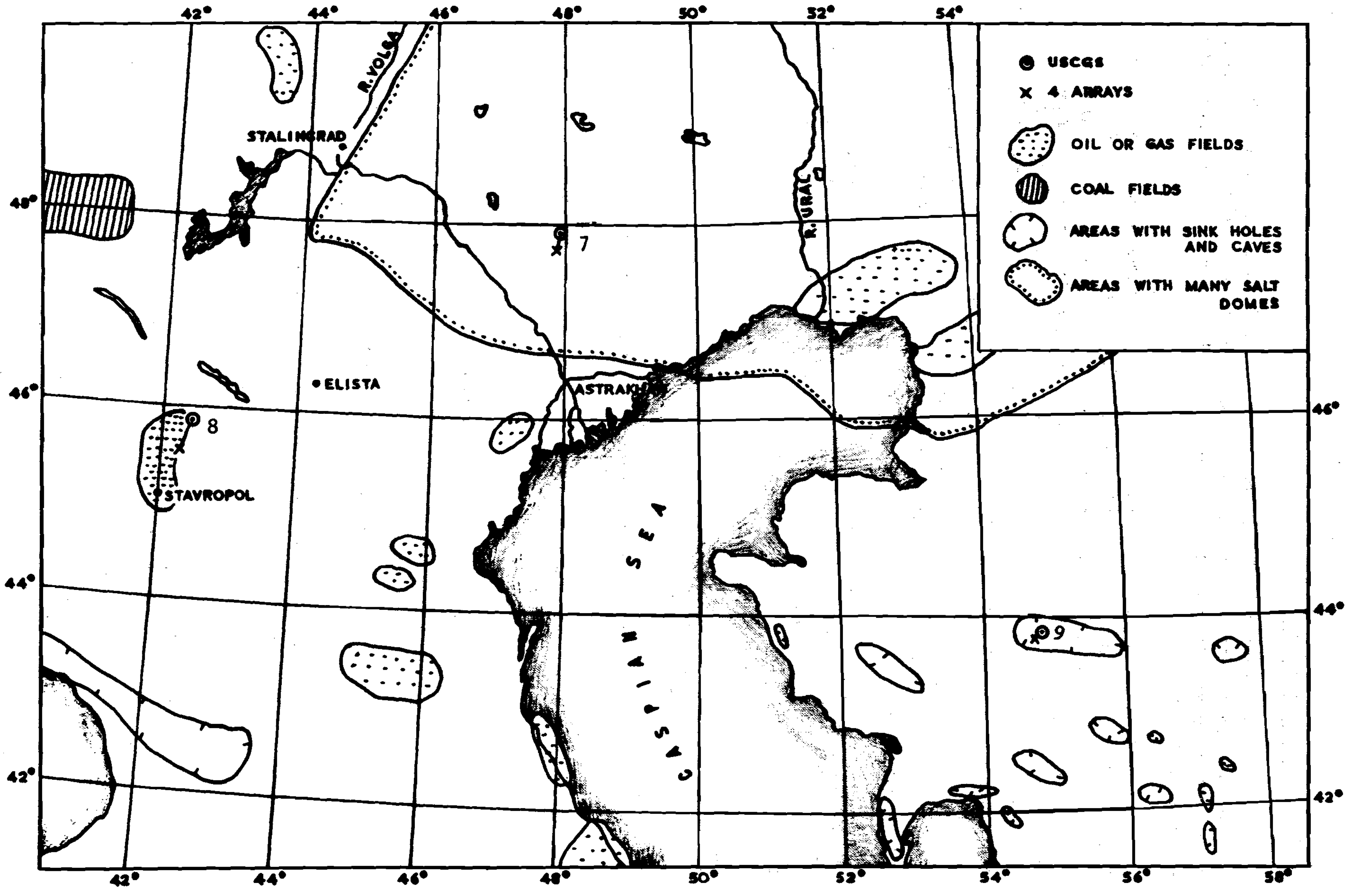
10.3 Caspian Sea

The locations of events fired in this and the Uzbek region are given in figure 10. The Caspian Sea region for the purposes of this report can be divided into two tectonic regions: (a) The north Caspian basin, part of the Russian platform, and (b) the Scytho-Turanian platform. These are described below.

(a) Most of the platform has been relatively stable since the Proterozoic era; the north Caspian basin subsided receiving 4 to 10 km of sediments. Many dome and other gentle uplift structures formed in this region up until the early Jurassic period. The extensive salt domes in this region were derived from Permian beds.

The crustal thickness in this area is of the order of 40 km and the P_n wave velocity is 8.15 km/s. This would indicate a region of high Q in the upper mantle but explosions near the Caucasus Mountains may not exhibit the same characteristics as events near the north Caspian Sea due to presence of the mountains with its associated deep structure. The surface elevation in this area is of the order of only a few metres above sea level and it is fairly certain that device emplacement is achieved by vertical drilling. This would be true if any of the explosions were made in the salt domes. If explosions do occur in the salt domes of this region it is expected that the P wave recorded at teleseismic distances would have high frequencies and large amplitudes and be fairly simple in character. If waves propagate to the south they may of course be perturbed by the structure to the south in the same way that explosions in the Bukhara region are affected.

(b) The Scytho-Turanian platform exhibits similar structure to the Bukhara, Uzbekistan region referred to earlier. However, the crustal thickness in this region is of the order of 30 km and the P_n wave velocity is 8.15 km/s. It is presumed that the seismic waves from explosions in this region would be similar to the waves from events in Uzbekistan.



USCGS
X 4 ARRAYS
OIL OR GAS FIELDS
COAL FIELDS
AREAS WITH SINK HOLES AND CAVES
AREAS WITH MANY SALT DOMES
R. VOLGA
STALINGRAD
R. URAL
ELISTA
ASTRAKHAN
STAVROPOL
CASPIAN SEA
7
8
9
42°
44°
46°
48°
50°
52°
54°
56°
58°

FIGURE 10

10.3.1 1 July 1968 (Explosion No. 7)

This explosion is located in an aseismic area north of the Caspian Sea in a region with extensive salt deposits in the form of salt domes. It is also situated to the west of a region of known oil deposits (figures 11(a) and 11(b)).

All four array stations recorded good P wave signals and at EKA the high frequency content of the signal is very apparent. Depth phases are particularly clear at EKA and YKA giving a P - pP separation of 0.34 s. Using a velocity of 3.3 km/s this gives a depth of firing of 560 m. (This depth is sufficient to penetrate into a salt dome.) The high frequency content of the EKA record would indicate a hard rock coupling, characteristic of explosions in salt.

The surface wave magnitude indicates a yield of 47 kton in the range 25 - 90 kton. The estimated depth is sufficient to contain an explosion of up to 50 kton.

The Soviets have discussed plans to detonate devices of the order of 40 kton in salt domes to create underground storage cavities for gas and oil. It is possible that this explosion is a PNE shot to create such a storage cavity.

Explosion No. 7

Epicentral Data:

Date:	1 July 1968
Time GMT:	04 02 01.7
Latitude:	47.92°N
Longitude:	47.95°E
Code Name:	
Source of Data:	EDR 46-68
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
EKA	31.9	302.8	81.7	04 08 24.9	108	0.48	6.05
GBA	42.1	134.4	330.4	04 09 52.1	10	0.44	4.84
YKA	69.1	351.4	12.5	04 13 05.1	49	0.8	5.78
WRA	102.2	106.1	316.1	04 15 53.2	8	1.0	(5.33)

Surface Wave Data (WWSSN):

Magnitude M_s: 3.67 ± 0.27

Array Location:

47.74°N
47.87°E

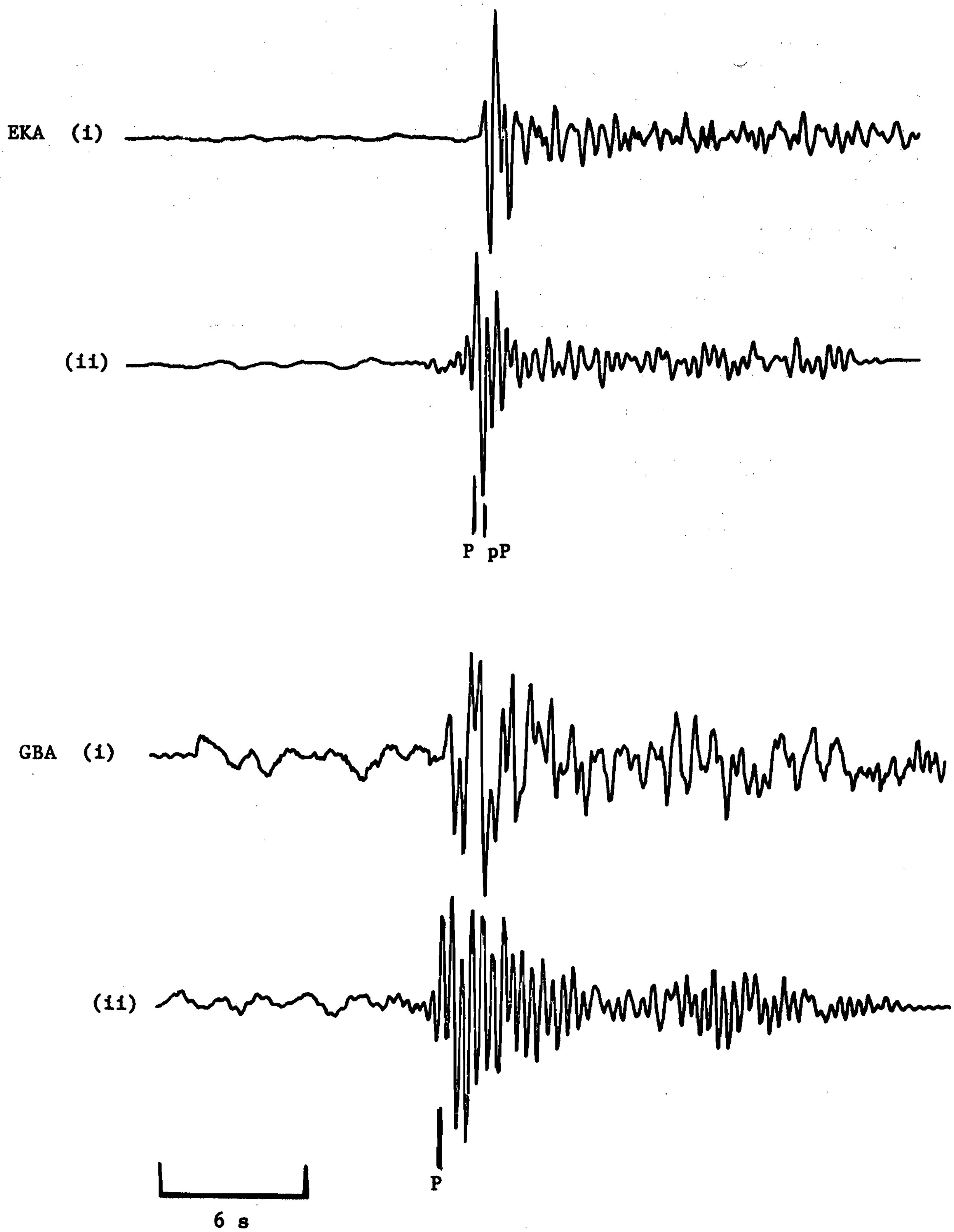


FIGURE 11(a)

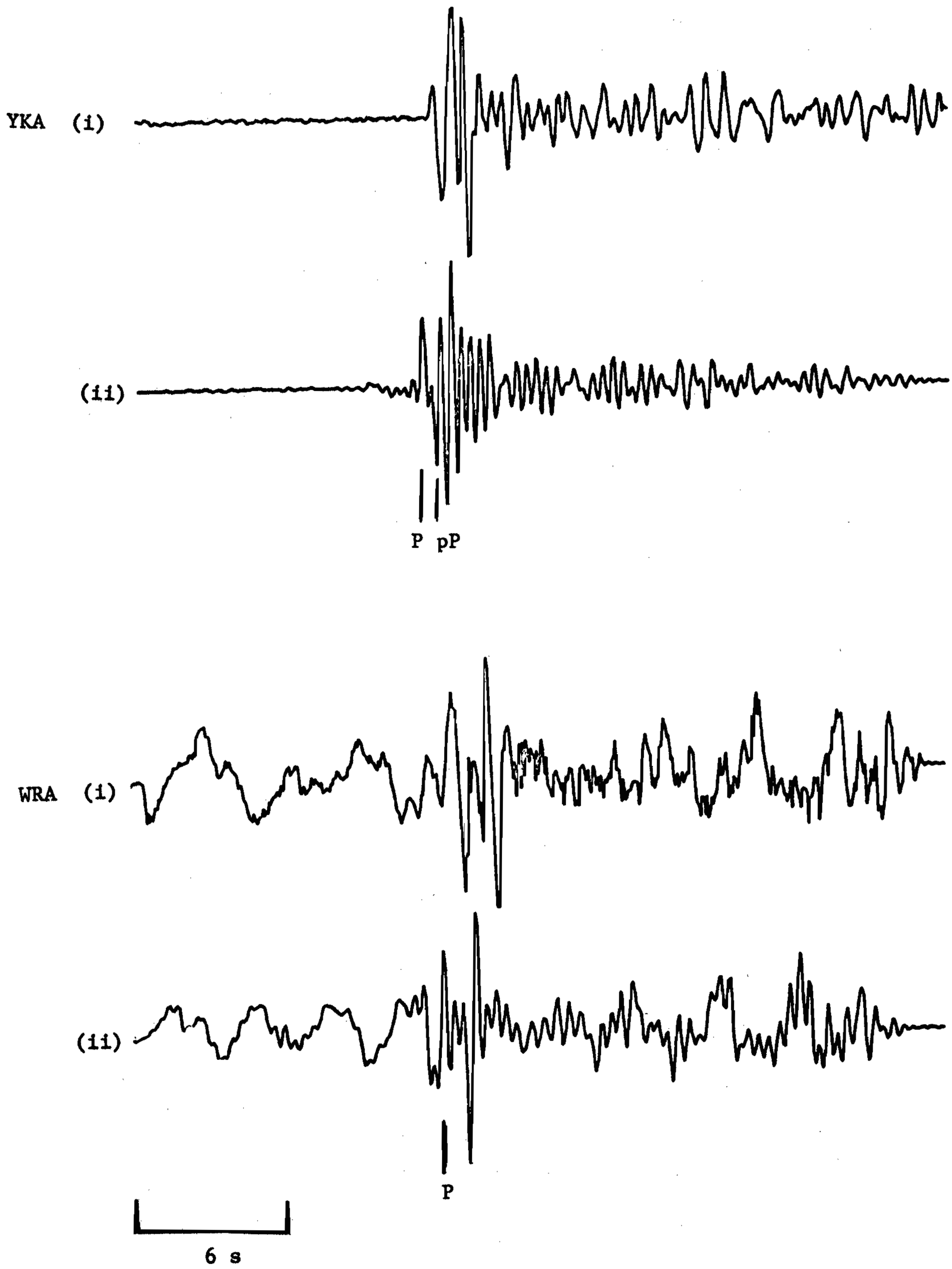


FIGURE 11(b)

10.3.2 26 September 1969 (Explosion No. 8)

This event is located in an oil and gas field near Stavropol. This implies that this event is a PNE shot. Three arrays gave good P wave records (figures 12(a) and 12(b)), WRA being too distant to detect clear P waves. The depth phase pP is very clear at YKA and indicates a P - pP separation time of 0.85 s. If the explosion occurred in rocks of the Pleistocene age a velocity of 2.75 km/s would be of the right order for P waves close to the source, but for direct comparison with events from the region a velocity of 3.3 km/s is taken to estimate depth. This gives a depth of 1400 m which is rather deep.

The surface wave magnitude gives a yield of 23 kton in the range 10 - 40 kton. From the frequency content of the body waves the shot medium does not appear to be very hard rock though the frequency content may be more a function of the transmission path from this particular region.

The emplacement depth would fully contain an explosion of the yield range given here. The excessive depth for such a yield in this region suggests that this explosion is for either a gas or oil stimulation PNE experiment.

Explosion No. 8

Epicentral Data:

Date:	26 September 1969
Time GMT:	06 59 55.8
Latitude:	45.89°N
Longitude:	42.47°E
Code Name:	
Source of Data:	EDR 63-69
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
EKA	30.0	305.1	89.1	07 06 07.2	48	0.96	5.30
GBA	43.6	126.1	324.5	07 08 02.3	9	0.84	4.52
YKA	70.4	348.9	16.8	07 11 12.9	63	0.72	5.84
WRA	105.3	102.9	313.6	07 14 08.2	1	0.65	(4.82)

Surface Wave Data (WWSSN):

Magnitude M_s: 3.37 ± 0.24

Array Location:

45.55°N
42.33°E

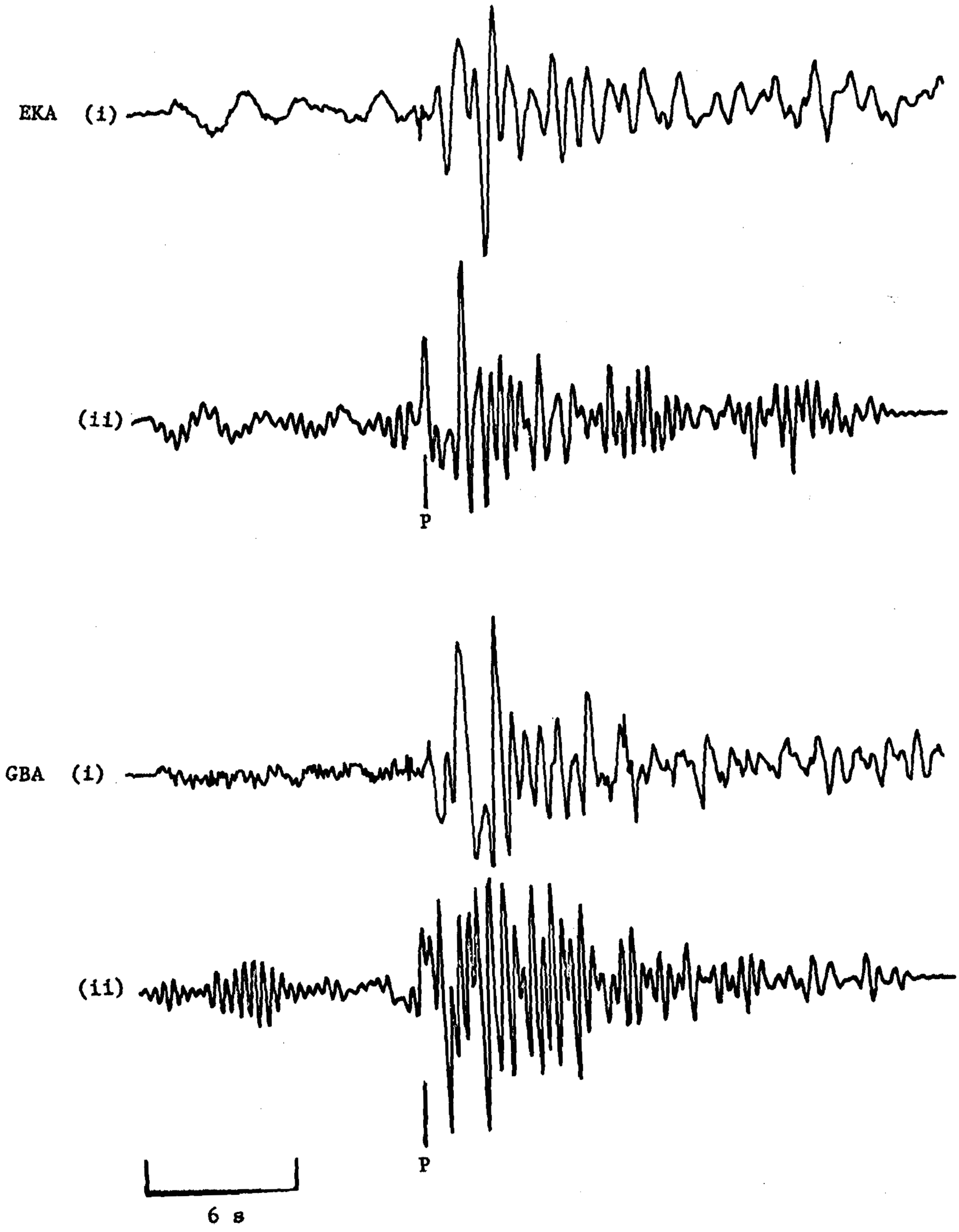


FIGURE 12(a)

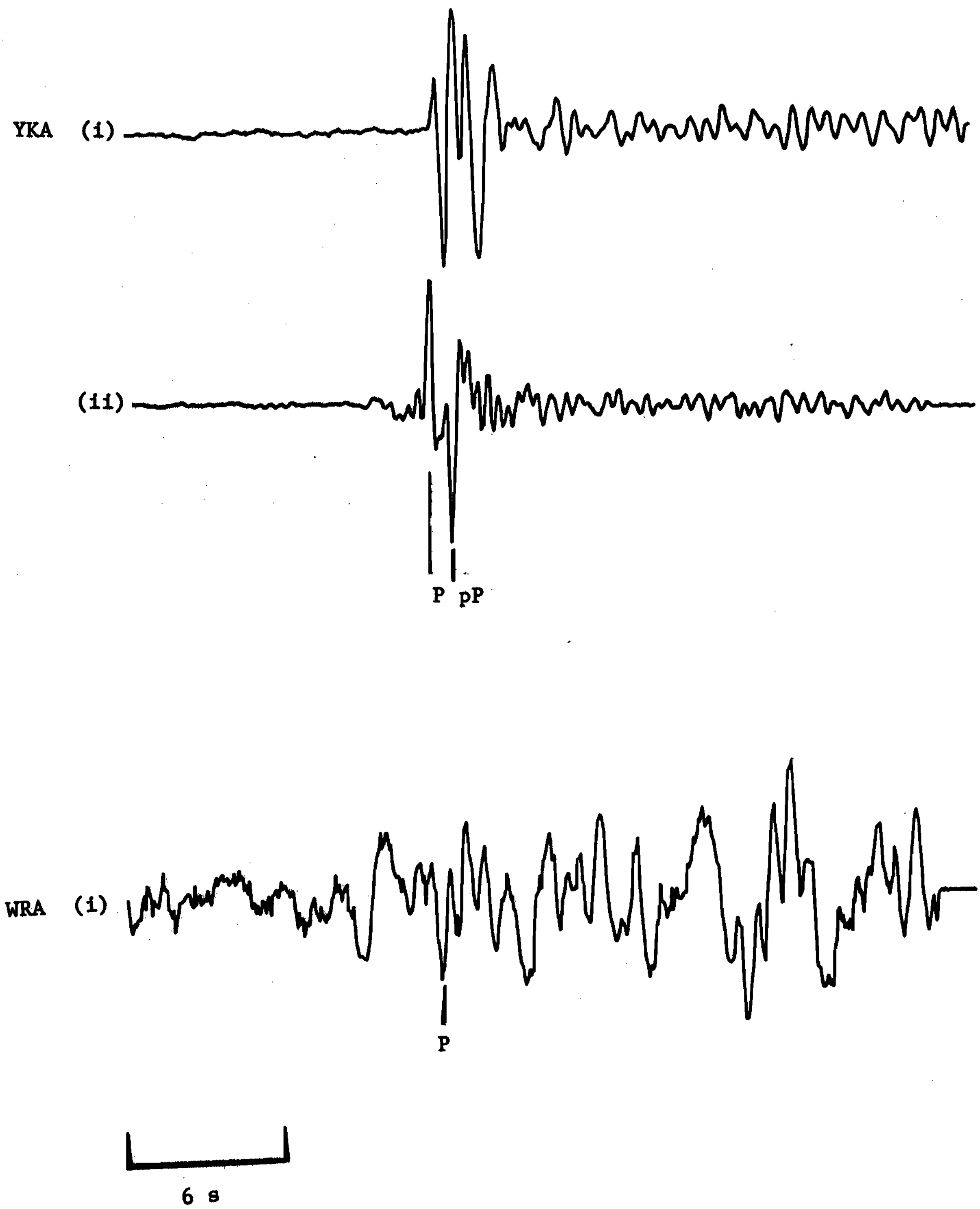


FIGURE 12(b)

10.3.3 6 December 1969 (Explosion No. 9)

This explosion is located between the Caspian and Aral Seas in the Scytho-Turanian platform and was recorded by all four arrays with good signal to noise ratio.

All four arrays gave good P and pP (figures 13(a) and 13(b)) signals and give a separation time of 0.55 s and assuming a velocity of 3.3 km/s gives an estimated depth of 910 m.

The surface wave magnitude gives a yield estimate of 95 kton in the range 50 - 200 kton. The depth of firing would be expected to fully contain a yield of about 150 kton.

Explosion No. 9

Epicentral Data:

Date:	6 December 1969
Time GMT:	07 02 57.4
Latitude:	43.83°N
Longitude:	54.78°E
Code Name:	
Source of Data:	EDR 77-69
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
GBA	35.8	140.2	331.6	07 10 01.4	132	0.96	5.76
EKA	38.2	308.5	82.7	07 10 19.4	427	0.76	6.22
YKA	73.7	354.9	8.0	07 14 33.3	79	1.0	5.73
WRA	96.4	111.4	314.3	07 16 28.7	11	0.80	5.48

Surface Wave Data (WWSSN):

Magnitude M_s: 3.98 ± 0.23

Array Location:

43.82°N
54.70°E

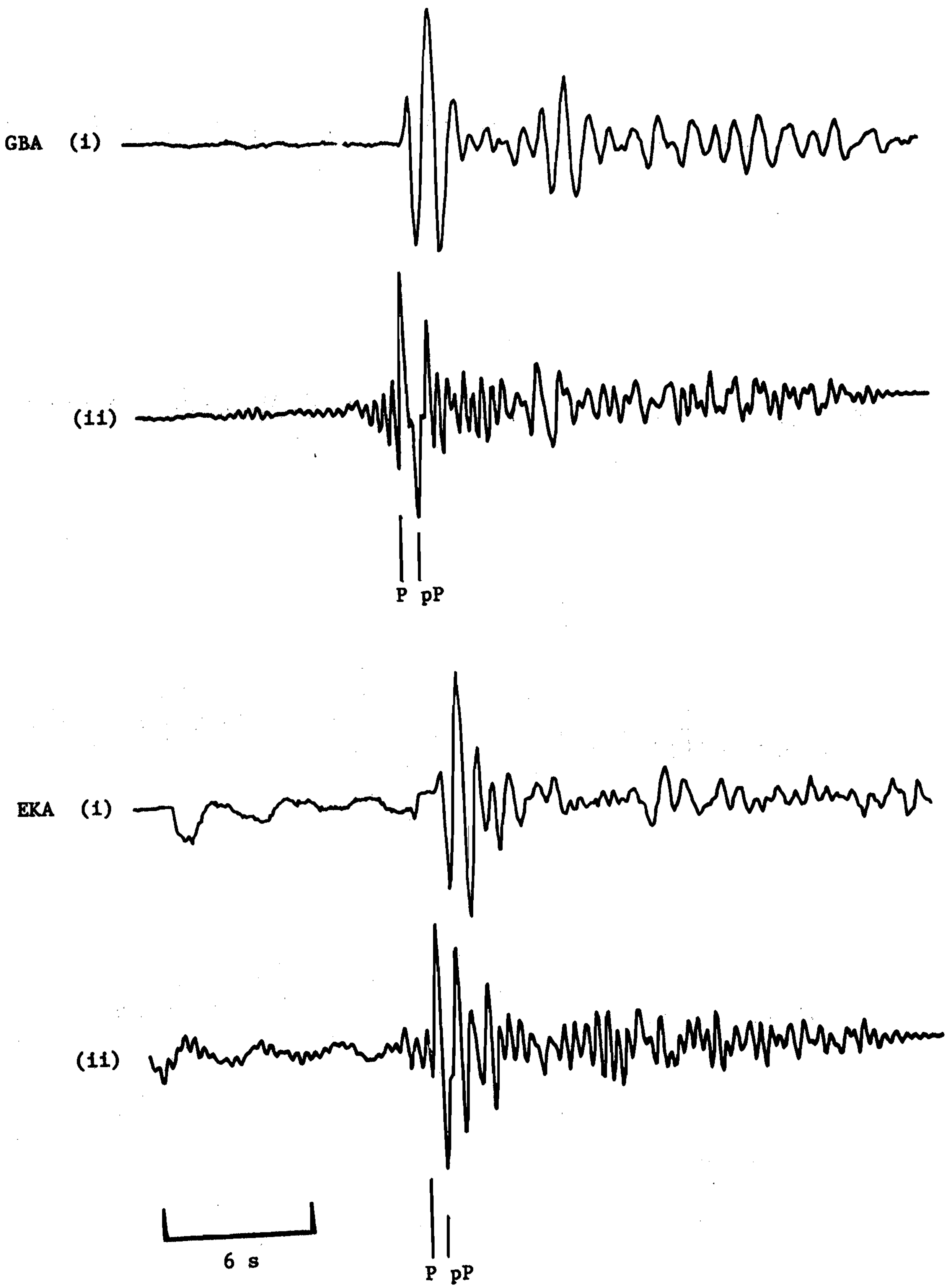


FIGURE 13(a)

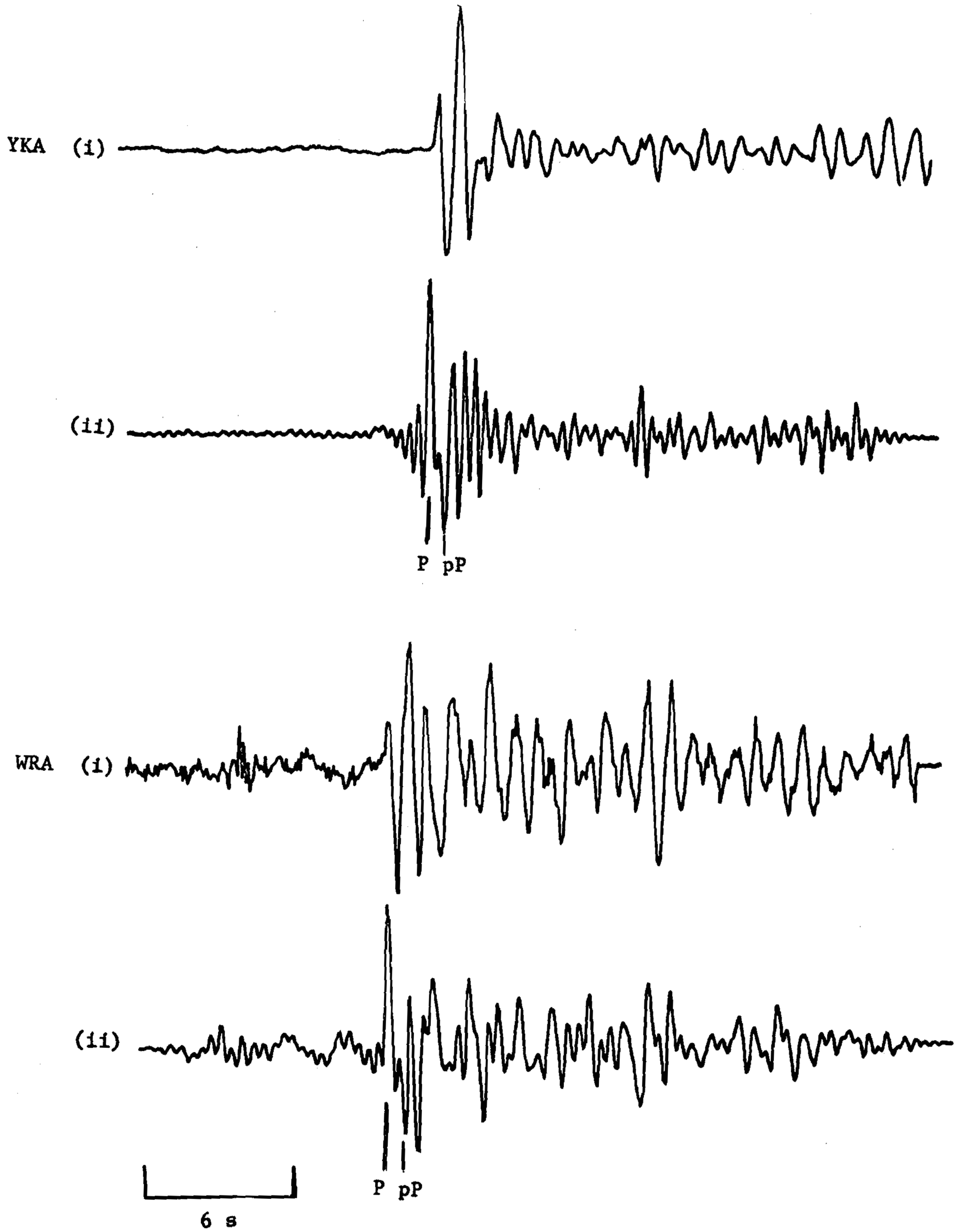


FIGURE 13(b)

10.4 Urals and Novaya Zemlya

A total of 5 explosions were selected from this region for analysis (10 - 14 inclusive). It is believed that explosions fired at Novaya Zemlya are large weapon tests whereas explosions around the Urals are of a PNE nature. The reason for grouping all these events is the similarity of the structure and geology in which the explosions occurred.

Novaya Zemlya is a direct continuation of the Ural Mountain chain, a fold mountain belt which does not achieve particularly great surface elevation. Being a fold mountain system the Ural belt may be expected to have a crustal thickness of about 50 km. In Novaya Zemlya there is a complete absence of rocks older than the Cambrian as found elsewhere in the Ural fold belt. Rocks of both Ordovician and Silurian ages are extensively represented and are mainly limestones, greywacke-type sandstones and shales. The eastern portion of the Urals contains a relatively greater proportion of shales and sandstones than the western portion where the Devonian rocks consist mainly of limestone. The Novaya Zemlya portion of the fold belt differs markedly from the main part to the south in that large intrusive granitic bodies are extensively developed. In addition basic and ultrabasic rocks are common.

This suggests that the seismic coupling between the explosion and the medium is good, generating waves of relatively high frequency. These waves however, may be subject to scattering due to the complex folding in the source region. The P_n velocity in this region is over 8 km/s; though not as high as the Kazakh region, it does suggest that the transmission of elastic waves from this region would be quite efficient with little loss of high frequency energy due to absorption.

The elevation in the region of Novaya Zemlya is just over 1000 m above sea level and in the region of the Matochkin Straits the contours are rather steep which suggests that, again, mining techniques can be used for device emplacement rather than drilling. For the Ural events, fired in regions to the east and west of the Urals where the elevation is very low, it is suggested that drilling techniques would be required to emplace the device to provide the required depth for containment.

10.4.1 6 October 1967 (Explosion No. 10)

This event is located to the east of the Ural Mountains close to the town of Tyumen and east of a region of known oil deposits. The signals from this event were recorded at all four arrays but the signal to noise ratio is poor (see figures 14(a) and 14(b)). After processing the three arrays, clear pP phases can be seen. The time separation between P and pP is 0.33 s and assuming a velocity of 3.6 km/s consistent with the age of the rocks in this area indicates a depth of 590 m.

The surface wave magnitude gives a yield estimate of 9 kton in the range 5 - 20 kton. The short period array signals are not characterised by particularly high frequency which would indicate a coupling less efficient than consolidated rock.

The depth of firing estimated above would be sufficient to fully contain a yield of about 50 kton. It is thus assumed that the explosion was fully contained and was probably a PNE experiment possibly associated with the oil fields to the west of Tyumen.

Explosion No. 10

Epicentral Data:

Date:	6 October 1967
Time GMT:	07 00 02.3
Latitude:	57.69°N
Longitude:	65.27°E
Code Name:	
Source of Data:	EDR 69-67
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
EKA	36.4	296.4	57.3	07 07 04.8	14	0.55	4.98
GBA	45.0	163.2	350.8	07 08 13.5	4	0.60	4.54
YKA	60.1	359.9	0.2	07 10 06.3	3	0.7	4.48
WRA	96.1			X			

Surface Wave Data (WWSSN):

Magnitude M_s: 2.95 ± 0.30

Array Location:

57.53°N
65.56°E

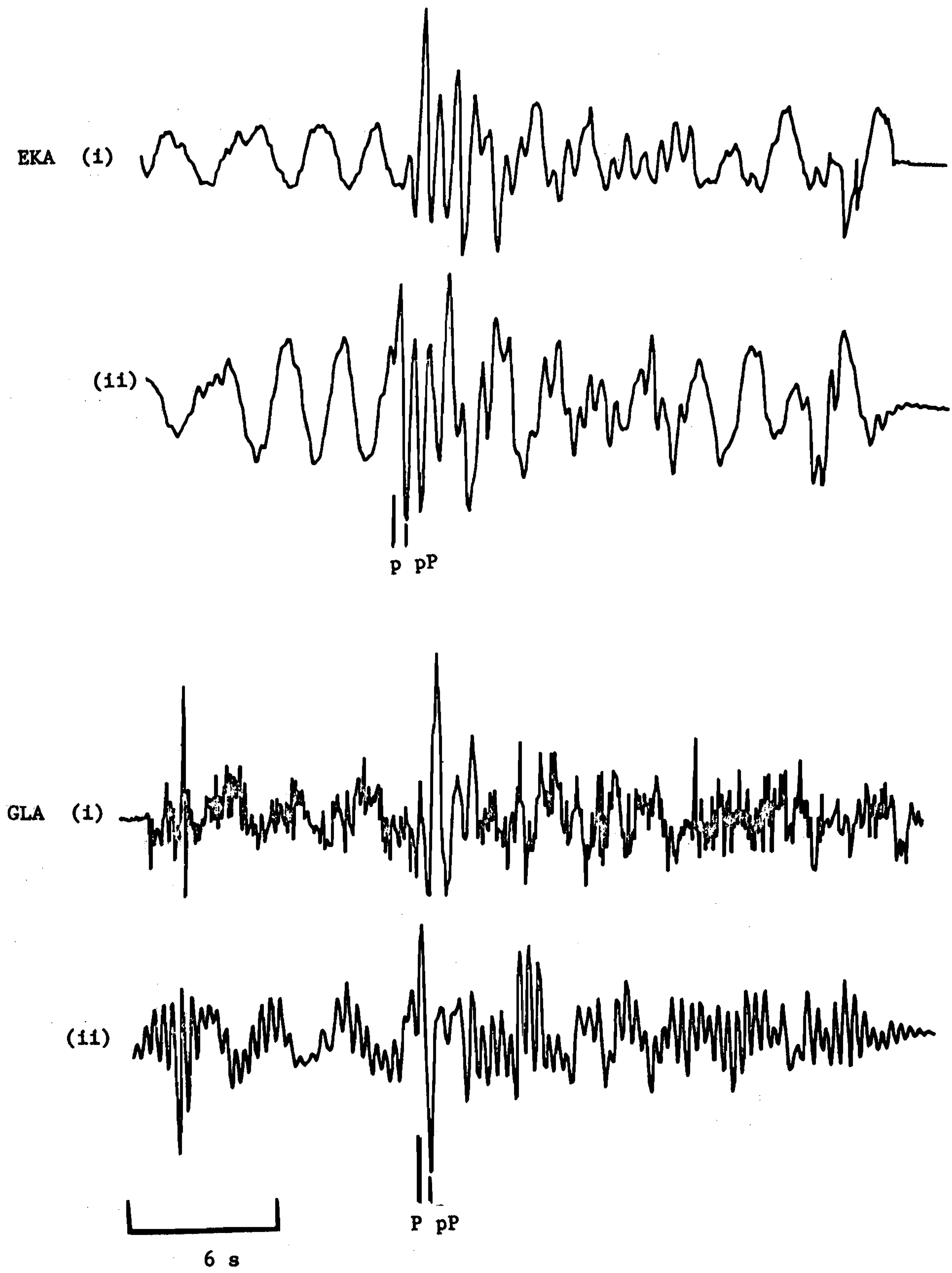


FIGURE 14(a)

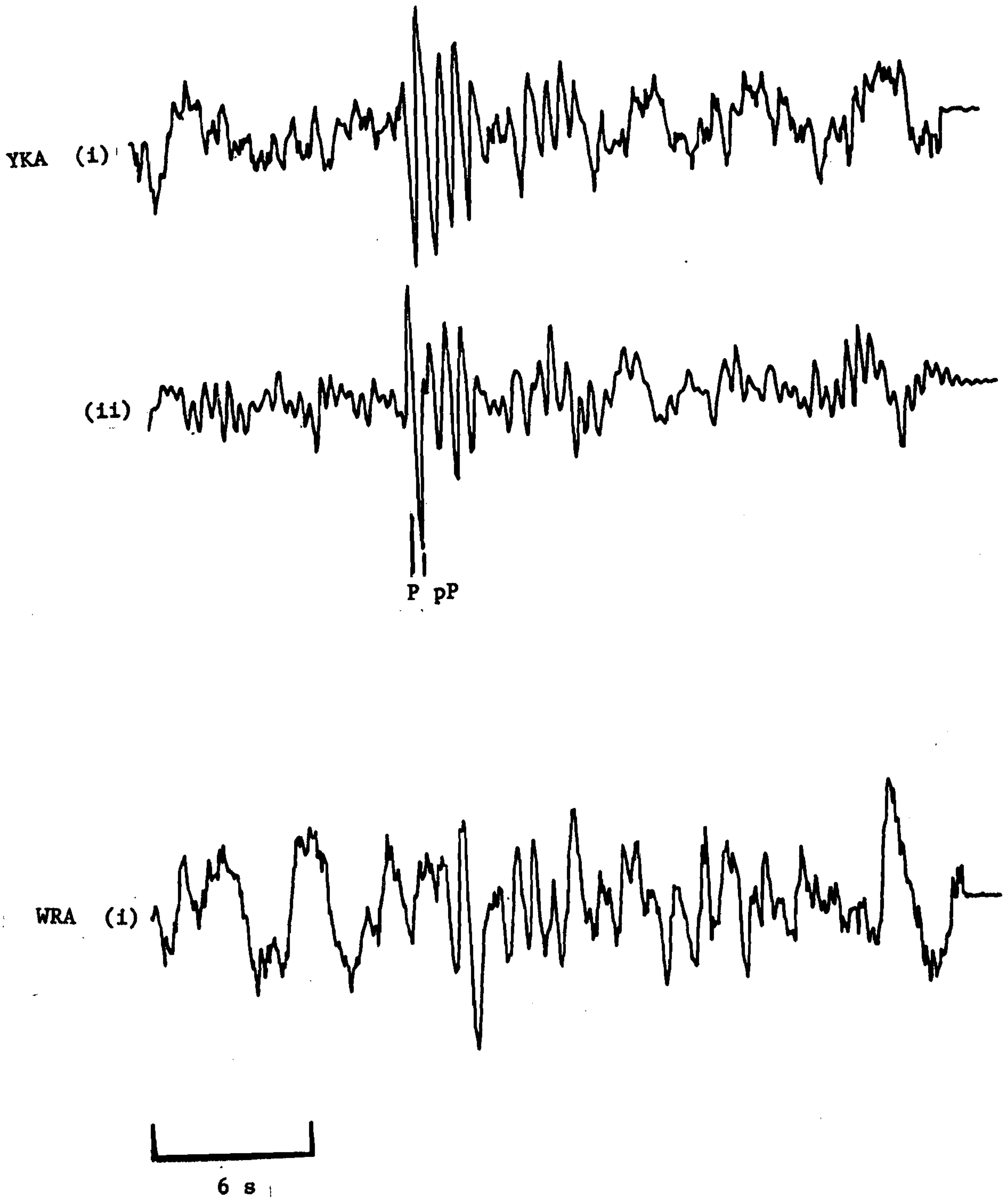


FIGURE 14(b)

10.4.2 **2 September 1969 (Explosion No. 11)**

This explosion and the one following (section 10.4.3) occurred at almost the same location near Perm to the west of the Urals near known oil fields.

Signals were recorded from this explosion at all arrays (figures 15(a) and 15(b)) and depth phases are tentatively identified giving a P - pP separation of 0.67 s. Using a velocity of 3.6 km/s this implies a depth of 1200 m.

The surface wave magnitude gives a yield estimate of 20 kton. The depth calculated for this event clearly would contain an explosion in the yield range 10 - 40 kton. Its proximity to the oil fields and its depth suggest that this explosion may be a PNE experiment.

Explosion No. 11

Epicentral Data:

Date:	2 September 1969
Time GMT:	04 59 57.3
Latitude:	57.42°N
Longitude:	54.86°E
Code Name:	
Source of Data:	EDR 59-69
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
EKA	31.4	291.4	61.9	05 06 21.1	15	0.7	5.03
GBA	47.0	149.3	343.5	05 08 27.6	21	0.55	5.48
YKA	60.1	354.4	6.6	05 10 08.3	10	0.6	5.01
WRA	101.1	109.5	327.2	05 13 45.7	3	1.0	(4.84)

Surface Wave Data (WWSSN):

Magnitude M_s: 3.29 ± 0.18

Array Location:

57.00°N
55.15°E

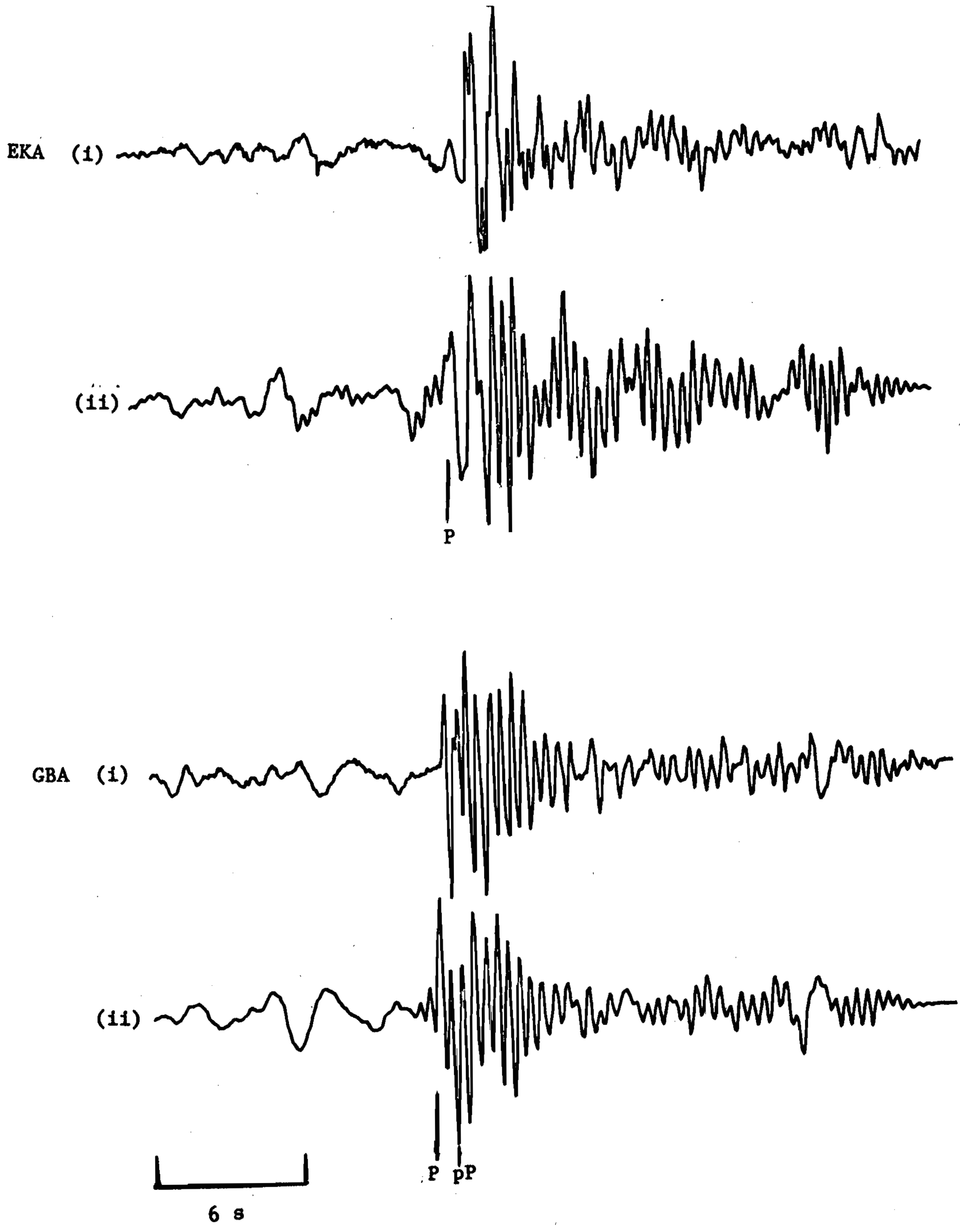


FIGURE 15(a)

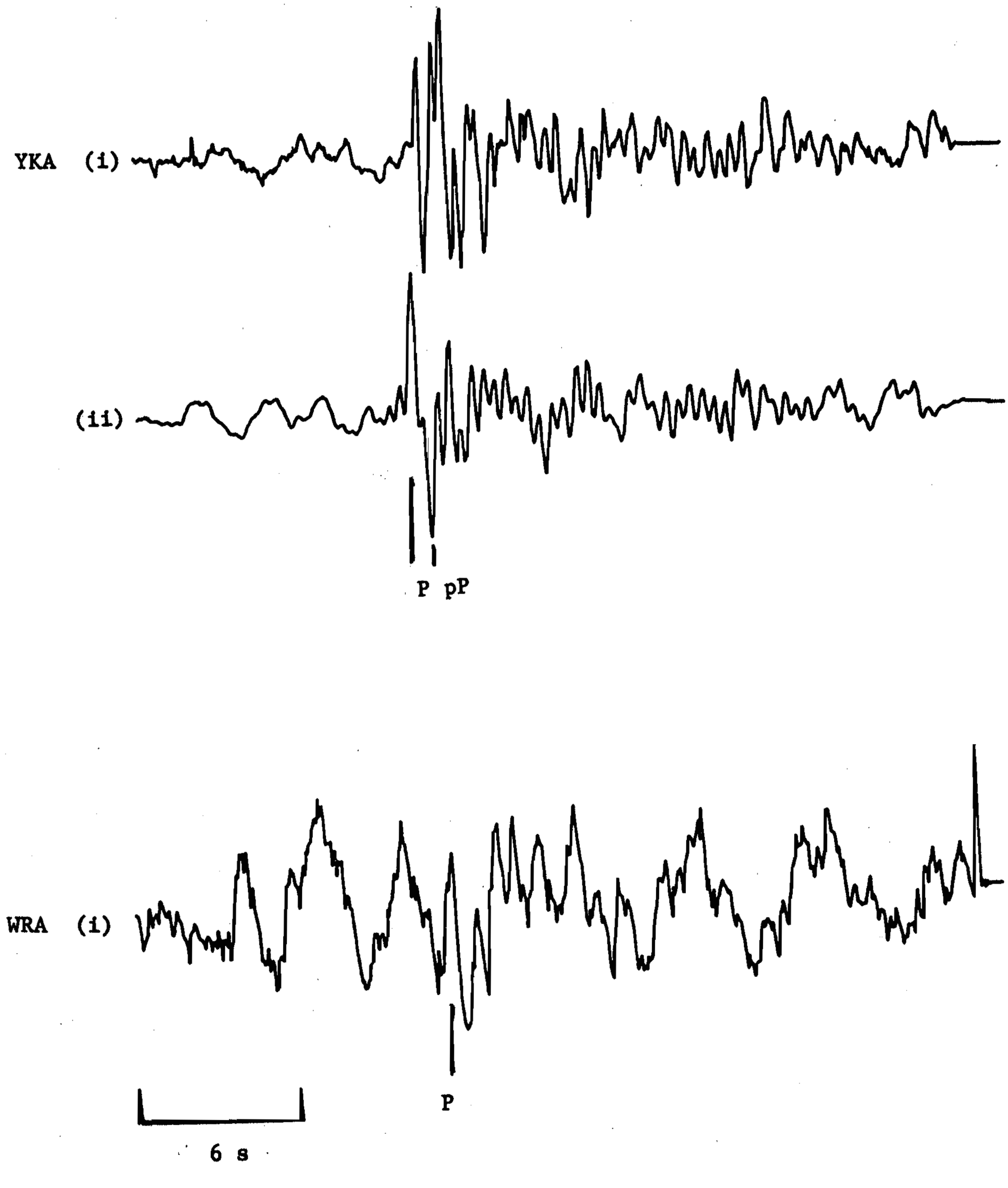


FIGURE 15(b)

10.4.3 8 September 1969 (Explosion No. 12)

This explosion is very similar to the previous shot (section 10.4.2) in almost every respect. The array signals are illustrated in figures 16(a) and 16(b). The P - pP depth estimate for this event is a little shallower at 1080 m than the previous explosion. The yield estimate is exactly the same from the surface wave measurements. This appears to be a repeat of the earlier experiment and the discussion regarding that explosion also applies.

Explosion No. 12

Epicentral Data:

Date:	8 September 1969
Time GMT:	04 59 56.1
Latitude:	57.37°N
Longitude:	55.11°E
Code Name:	
Source of Data:	EDR 59-69
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
EKA	31.5	291.6	61.9	05 06 21.2	20	0.70	5.16
GBA	46.9	149.6	343.6	05 08 27.4	19	0.55	5.42
YKA	60.2	354.5	6.4	05 10 07.5	8	0.6	4.93
WRA	100.9	109.7	327.2	05 13 45.8	2	1.0	(4.59)

Surface Wave Data (WWSSN):

Magnitude M_s: 3.29 ± 0.23

Array Location:

57.06°N
55.24°E

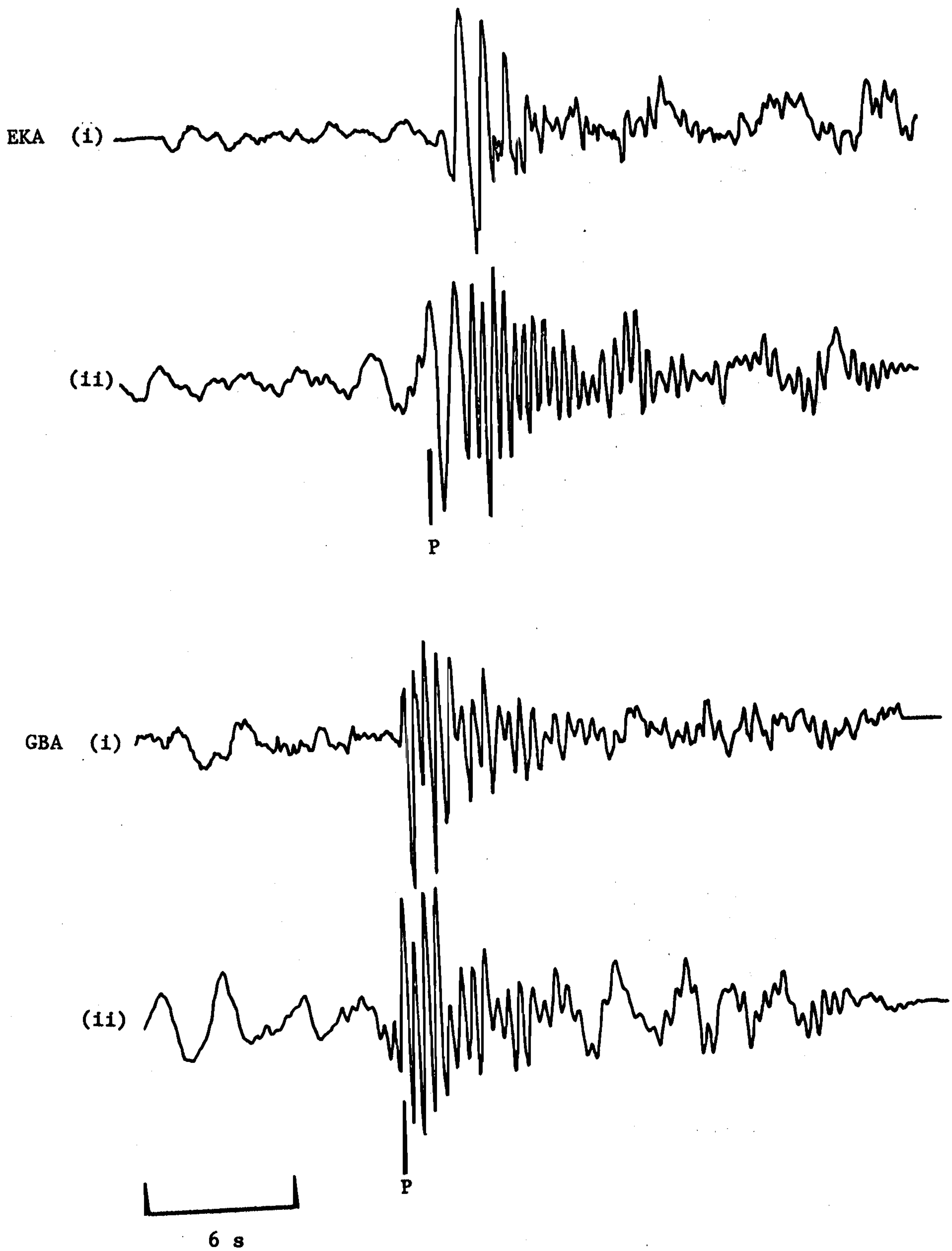


FIGURE 16(a)

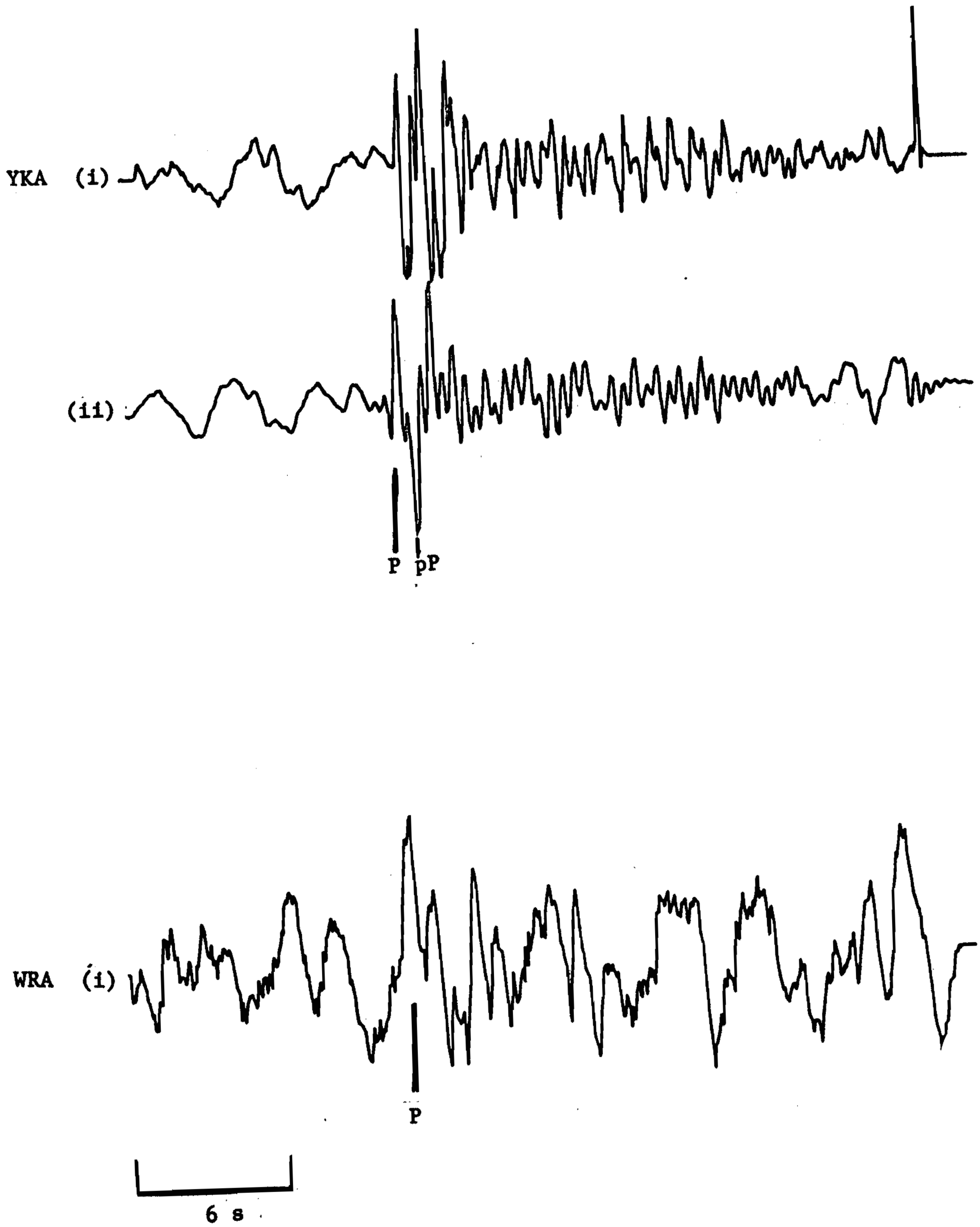


FIGURE 16(b)

10.4.4 21 October 1967 (Explosion No. 13)

Since 1966 this area has been used to test large explosions underground at the rate of one per year. The last really large explosion at the Kazakh test site was fired in February 1966 and vented. It may be that the proximity of the test site to towns such as Semipalatinsk caused safety experts some concern regarding the release of radioactive material and this was the reason for using the remote northerly area of Novaya Zemlya. Novaya Zemlya was the test site used for the extensive series of atmospheric tests in 1961 and 1962.

The location of all the Novaya Zemlya explosions to date has been on the northern tip of the south island just south of the Matochkin Straits. The explosion of the 21 October 1967 was recorded at all stations with a good signal to noise ratio (figures 17(a) and 17(b)). The record at YKA is relatively complex; the P wave has a low frequency onset and the magnitude for YKA is particularly low.

The only clear evidence of a depth phase is at EKA which gives a P - pP time of 0.28 s. The velocity of the P waves in this part of Ural Mountain system is taken as 4.25 km/s consistent with Ordovician limestone, the material in which it is believed these events are detonated. This gives a depth of about 600 m; this overburden could be readily achieved by mining an adit into the side of the mountain which drops sharply from a height of some 1000 m to sea level within the Matochkin Strait.

The surface wave magnitude indicates a yield of 220 kton in the range 100 - 400 kton.

A depth of 600 m would be sufficient to contain a yield of the order 50 kton. This is considerably lower than the yield estimated here; this would suggest that the explosion vented. If this is not so then the explosion was fired deeper which would mean that the velocity assumed for this area is too low.

Explosion No. 13

Epicentral Data:

Date:	21 October 1967
Time GMT:	04 59 58.1
Latitude:	73.37°N
Longitude:	54.81°E
Code Name:	
Source of Data:	EDR 65-67
Yield:	

Array Data:

Station	$\Delta°$	Az°	BB°	P Wave Arrival Time	Amplitude, $m\mu$	Period, s	Magnitude, m_b
EKA	29.2	263.6	30.0	05 06 02.7	199	0.5	6.20
YKA	44.2	353.0	4.3	05 08 09.4	48	0.6	5.44
GBA	61.2	154.7	352.7	05 10 16.4	36	0.6	5.70
WRA	106.0	105.7	342.9	05 14 11.3	23	0.9	(6.20)

Surface Wave Data (WWSSN):

Magnitude M_s: 4.34 ± 0.25

Array Location:

73.42°N
55.27°E

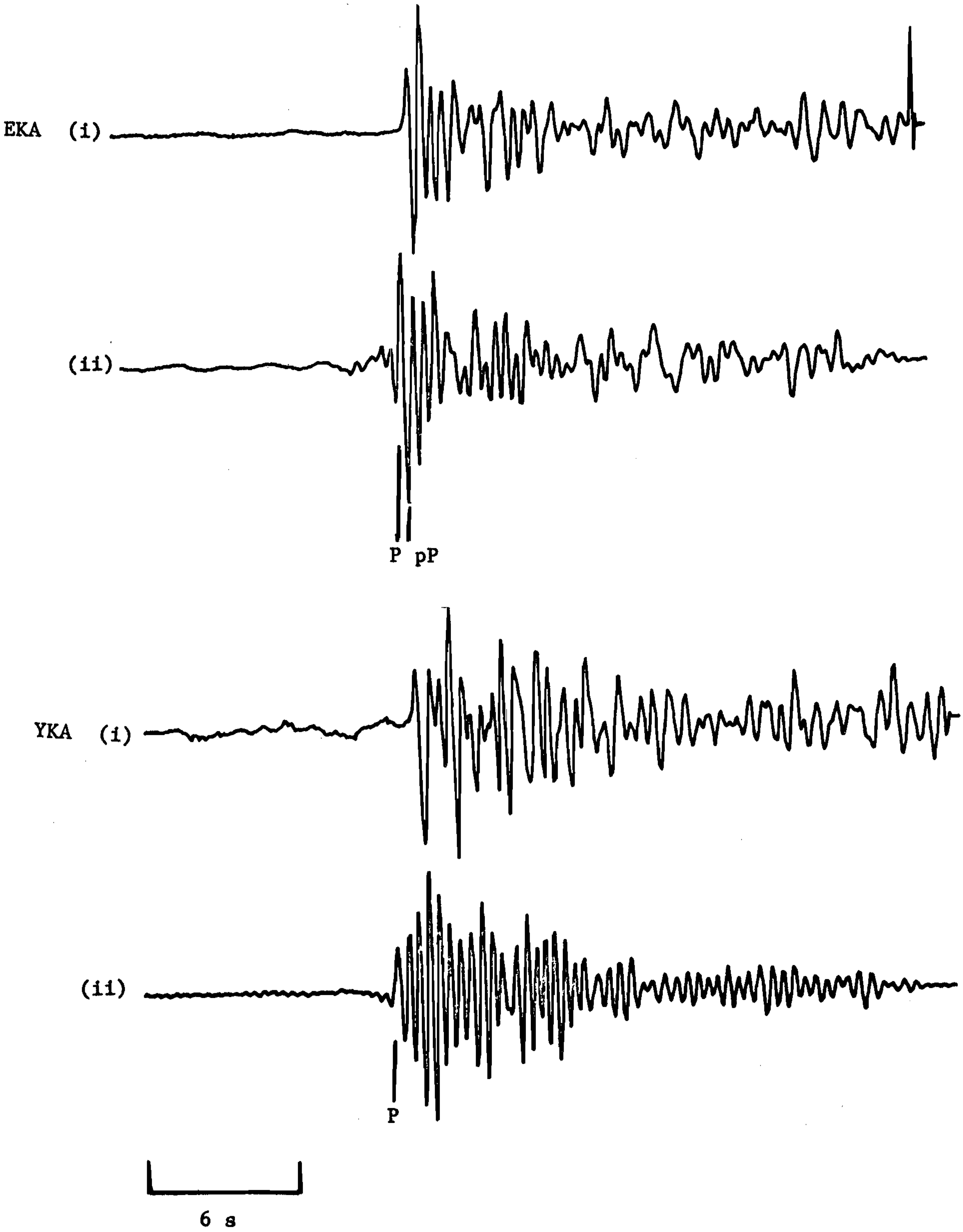


FIGURE 17(a)

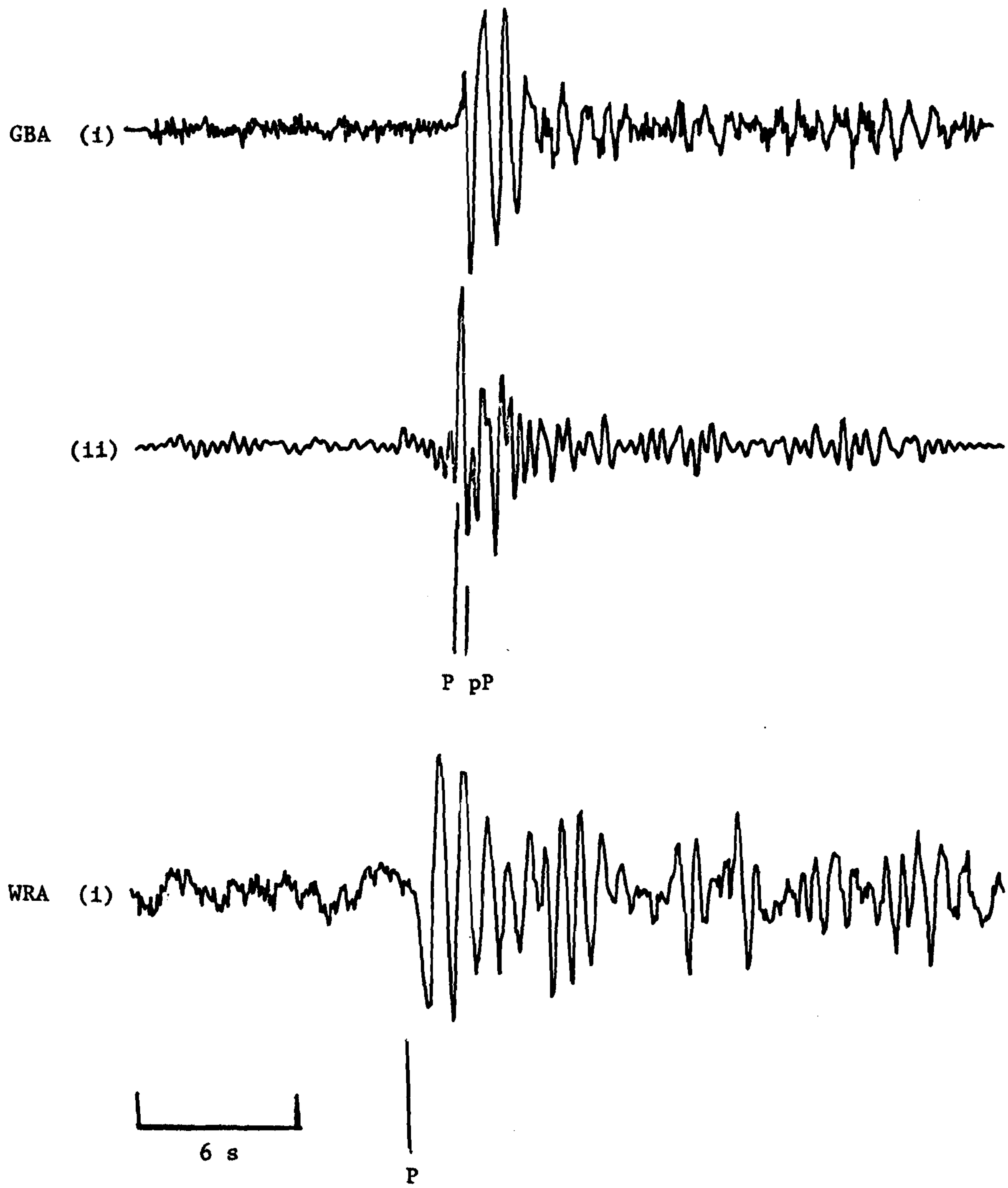


FIGURE 17(b)

10.4.5 7 November 1968 (Explosion No. 14)

This explosion, just south of the Makochkin Straits, gave signals which were well recorded at the four arrays (figures 18(a) and 18(b)). YKA produced a complex record, similar in general details to the previous event. The depth phase pP can be seen at EKA and GBA and gives a P - pP separation time of 0.29 s; assuming a velocity of 4.25 km/s this gives a depth of 615 m.

The surface magnitude gives a yield of 300 kton in the range 150 - 600 ktons.

As with the previous event the indicated depth would not fully contain such an explosion and venting may well have occurred. If we use the depth-yield relationship for containment published by the Russians and assume they have used it for these events we can estimate the velocity of P waves in this region. This gives a velocity near 7.5 km/s which seems excessively high. It must therefore be assumed that this explosion vented.

Explosion No. 14

Epicentral Data:

Date:	7 November 1968
Time GMT:	10 02 05.29
Latitude:	73.41°N
Longitude:	54.86°E
Code Name:	
Source of Data:	EDR 87-68
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
EKA	29.2	263.6	30.0	10 08 09.7	320	0.64	6.30
YKA	44.2	353.0	4.3	10 10 16.1	52	0.8	5.35
GBA	61.2	154.8	352.8	10 12 23.2	26	0.55	5.60
WRA	106	105.8	342.9	10 16 18.3	32	1.00	(6.30)

Surface Wave Data (WWSSN):

Magnitude M_s: 4.47 ± 0.29

Array Location:

73.43°N
55.30°E

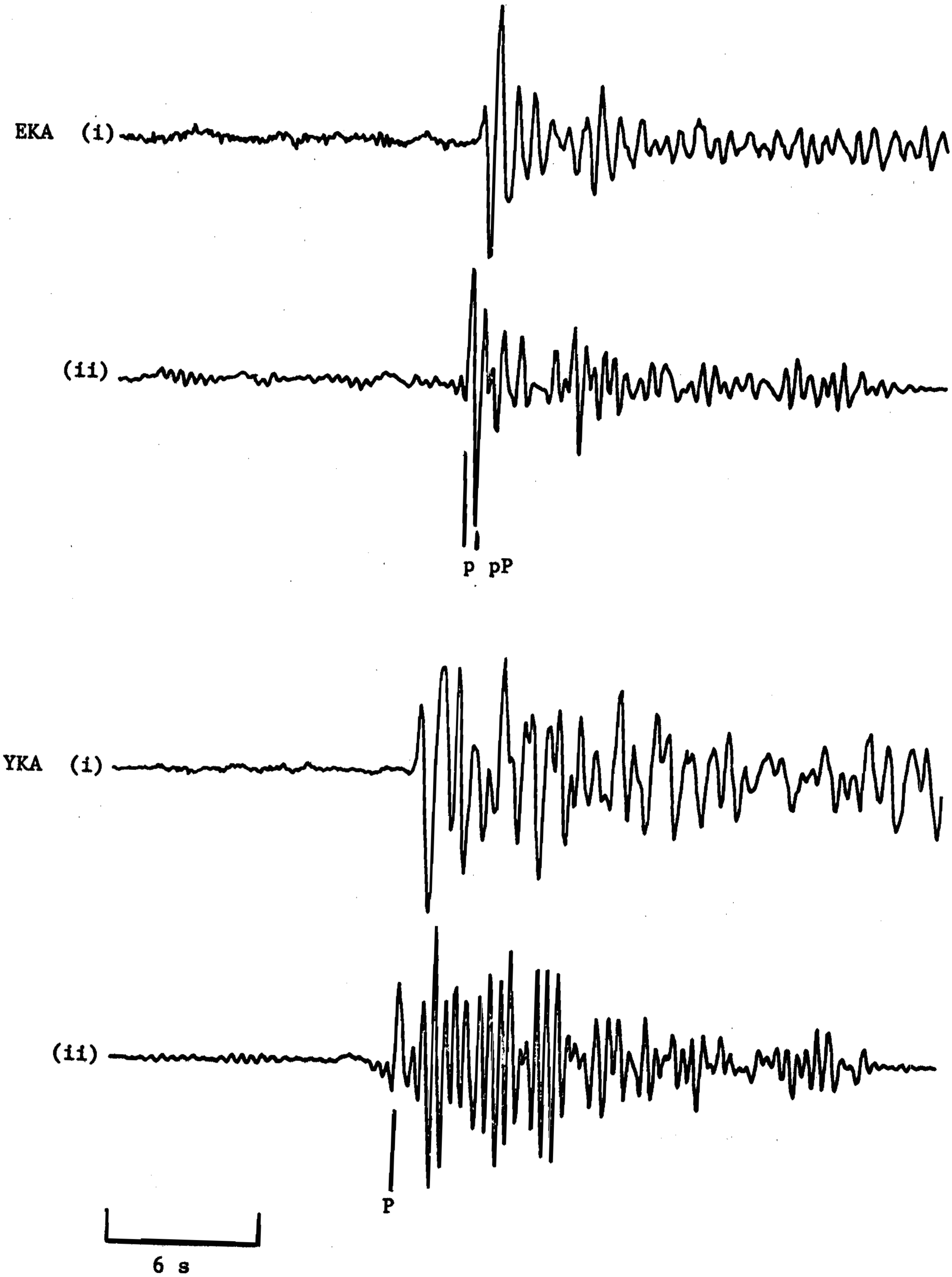


FIGURE 18(a)

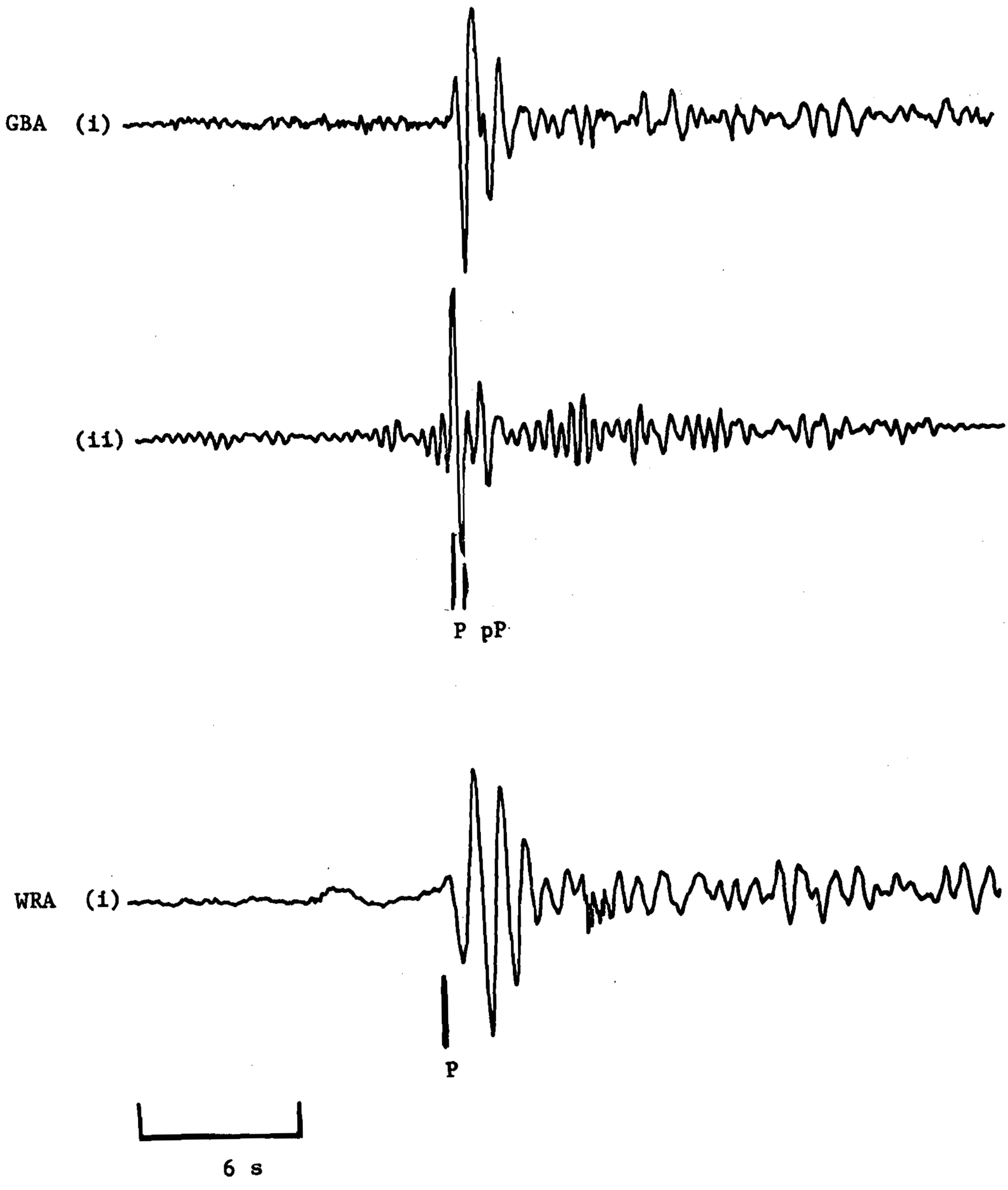


FIGURE 18(b)

10.5 Sinkiang Province, China

The underground explosion discussed in this report was detonated in the Lop Nor region of the Sinkiang province. Lop Nor is an is an area of shallow salt water and marsh covering some 200 km^2 situated at the eastern end of the intermountain structural depression known as the Tarim Basin. This area is part of an ancient tectonically stable block which from the late Proterozoic time has resisted deformation by the series of orogenic movements which have occurred along its borders. The comparatively recent, late Tertiary, development of the Tarim Basin has led to the almost complete masking of the solid geology in the floor of the depression by terrestrial deposits of considerable thickness. The oldest rocks are crystalline quartzites, granites and gneisses and are overlain by, in parts, several thousand metres of sedimentary and volcanic rocks. Silts and fine sands represent the last stage of deposition since the Pliocene era and where this has been measured it amounts to a thickness of about 200 m.

The Tarim Basin is at an altitude of about 500 m above sea level, the elevation increasing very rapidly at the southern edge of the basin rising to 5000 m. In view of the plateau nature it is likely that to provide the required overburden for containment the devices are emplaced by vertical drilling or vertical shaft mining.

The depth to the base of the crust is between 45 and 50 km and it would be expected that the P_n wave velocity immediately beneath the Tarim Basin was close to 8 km/s. However, the extremely complex, and still seismically active fold belts to the north and south of the Basin may produce complex P wave signals exhibiting some absorption. This will depend very much on the angle and direction from which the seismic waves leave the source.

10.5.1 22 September 1969 (Explosion No. 15)

This event is believed to be the first underground nuclear explosion conducted by the Chinese. The word "nuclear" is used simply because of the size of the event.

The signals from this event were detected at all array stations and are illustrated in figures 19(a) and 19(b). The signal to noise ratio and appearance of the seismogram varies from station to station and from a knowledge of the structural geology this is not surprising. The GBA record is fairly complex and as expected for a complex record gives a low magnitude. The processed seismograms show a depth phase at a time 0.45 s after the P wave. If the velocity of 2.75 km/s is assumed a depth estimate of 620 m is obtained. This would put the device below the superficial alluvial deposits. Because of the flat topography it is assumed that the device was emplaced by vertical drilling or shaft mining techniques.

The surface wave magnitude gives a yield of 18 kton in the range 10 - 40 kton. The depth estimated above is sufficient to fully contain a yield of about 60 kton.

It is interesting to note that seven days after this underground explosion a test in the megaton range was conducted in the atmosphere above Lop Nor.

Explosion No. 15

Epicentral Data:

Date:	22 September 1969
Time GMT:	16 14 58.8
Latitude:	41.39°N
Longitude:	88.30°E
Code Name:	
Source of Data:	EDR 63-69
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
GBA	29.3	202.0	16.9	16 21 03.7	14	0.76	4.85
EKA	58.0	317.7	62.5	16 24 55.6	24	1.00	5.18
WRA	74.5	135.3	325.3	16 26 40.4	19	0.72	5.23
YKA	74.8	10.8	342.3	16 26 42.2	28	0.64	5.44

Surface Wave Data (WWSSN):

Magnitude M_s: 3.25 ± 0.25

Array Location:

41.24°N
88.19°E

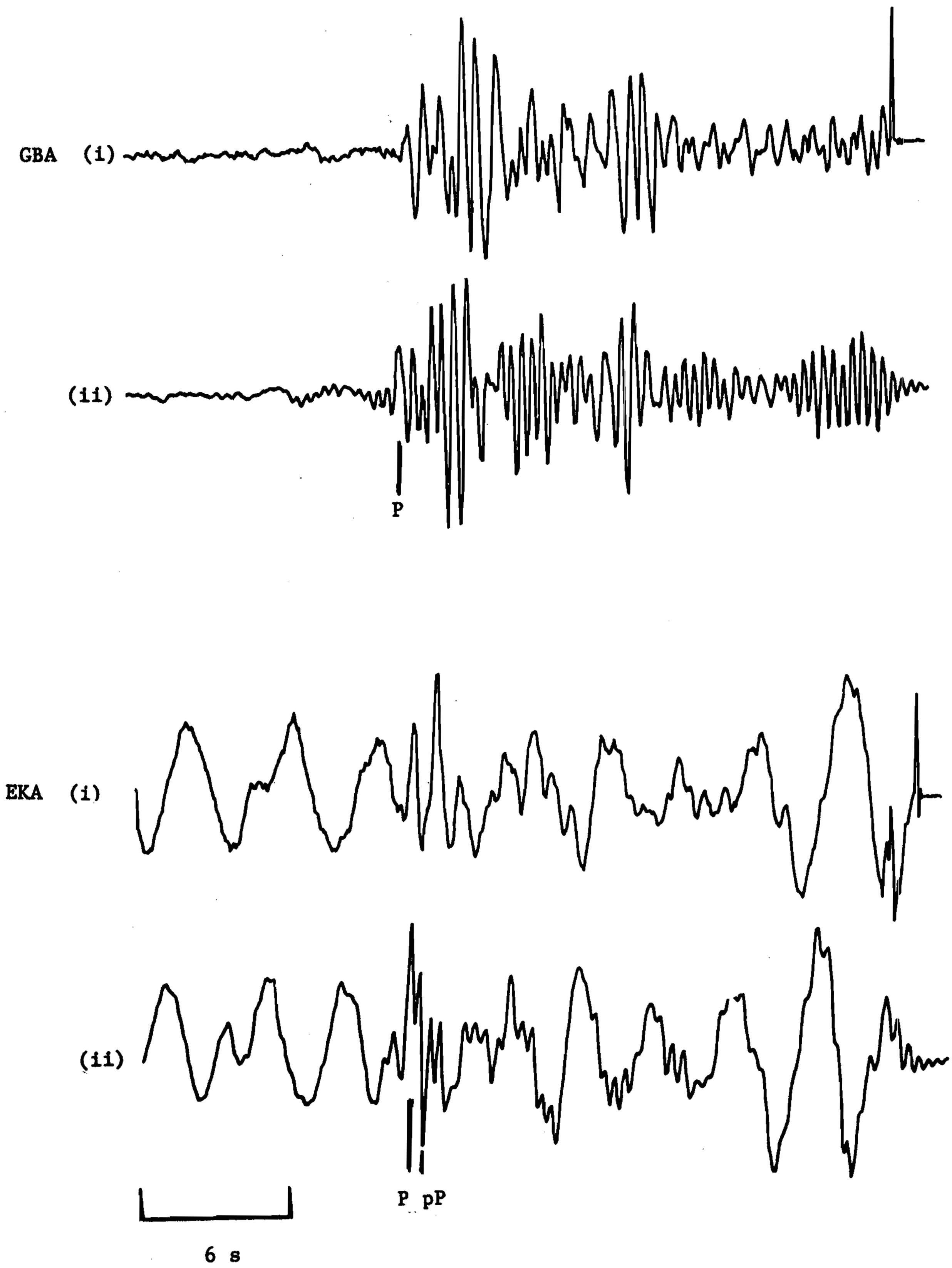


FIGURE 19(a)

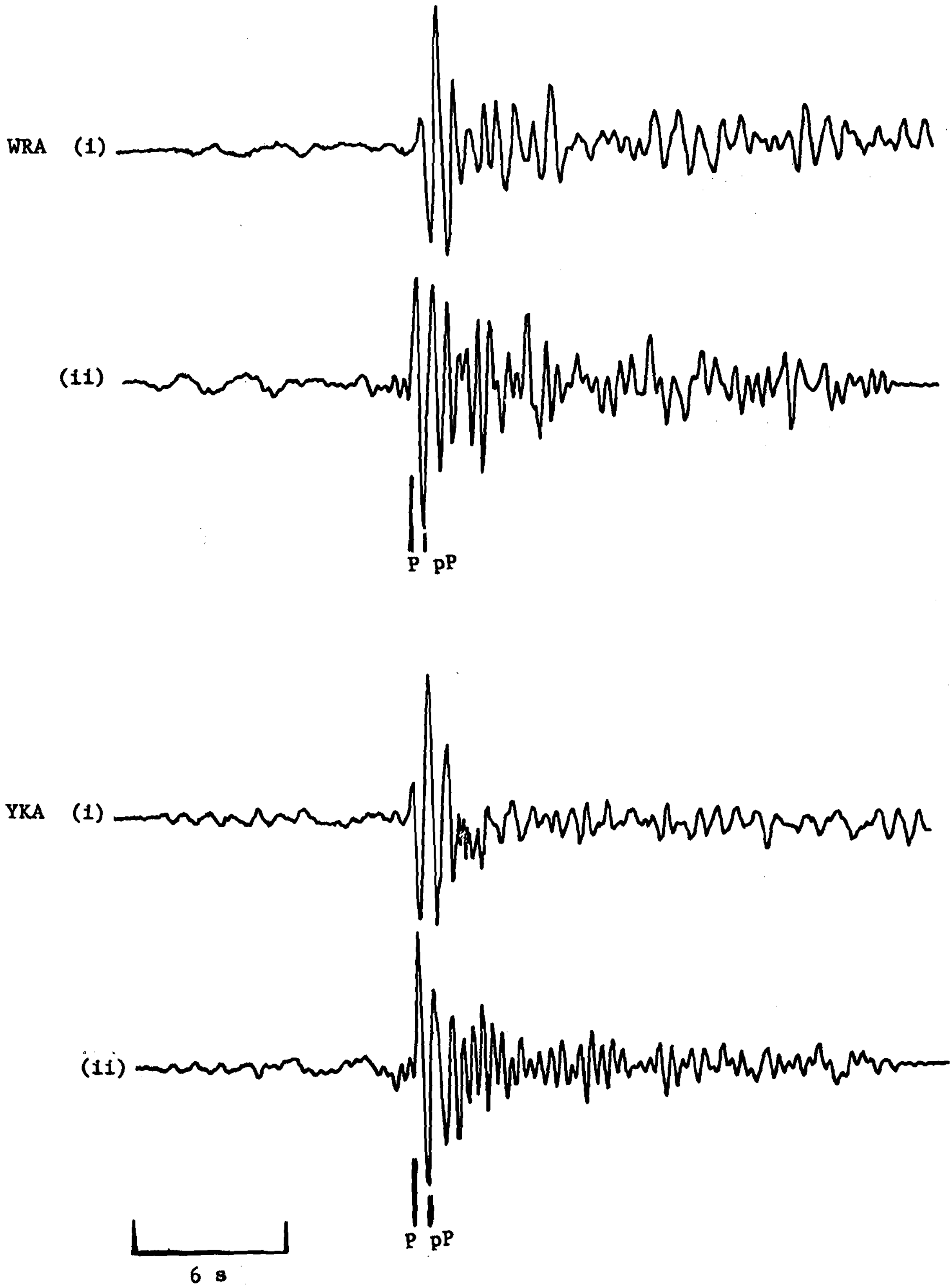


FIGURE 19(b)

10.6 Aleutian Isles, USA

The test site for underground explosions in this area is situated on the island of Amchitka on the western end of the Aleutian Arc. This is a very active region seismically indicating instability. Amchitka is on a portion of the Aleutian Ridge which is a great fault block tilted southwestwards towards the area of the Aleutian Trench. This block consists of Tertiary volcanic tuffs and brecchias bounded by fracture zones. There is a weathered layer close to the surface some 15 m thick overlying brecchias with interbedded tuff, siltstones and greywackes. The island arc system consists of a narrow mountainous belt of Tertiary volcanics. This suggests a narrow band of structure which will cause asymmetry in the radiation of elastic waves from this region.

The thickness of the crust is about 20 km but the P_n wave velocity immediately below Amchitka is as low as 7.6 indicating a region of low Q and hence high seismic wave attentuation. However, the P_n velocity is as high as 8.2 km/s only 250 km south of the island; similarly as one goes further north from the island the P_n velocity increases. This means that rays leaving the source either to the north or south will experience little attenuation but rays leaving the source along the axis of the arc will be severely attenuated and, in view of the structure, may experience considerable scattering. Many scientific papers concerning propagation of seismic waves from this region have been published and a number of hypotheses have been suggested to explain the observations obtained from explosions in this region.

The interpretation of seismograms, travel times and amplitude anomalies from events in this region are of considerable importance relative to "test ban" seismology since the Aleutian Arc is very similar in structure to the arcuate structure around Kurile and Kamchatka. Thus, the knowledge gained from explosions in the Aleutian Isles can be used to interpret seismograms of seismic events in the highly seismic area of the Kurile-Kamchatka region.

10.6.1 29 October 1965 LONGSHOT (Explosion No. 16)

This was an explosion of 80 kton fired in the island arc structure of the Aleutians on the island of Amchitka and has been the subject of an AWRE Report [12]. The test was conducted as part of the US Government Vela Uniform programme. Many stations around the world were alerted prior to the event which gave station operators the opportunity to adjust their instrumentation to produce the optimum records in terms of signal to noise ratio and accurate timing. Seismologists have given this event close attention and a large number of scientific papers have been published on the analysis of the observations enhancing our understanding of the problem of seismic discrimination.

Signals were recorded at all array stations (although most seismographs at GBA were overloaded) and are illustrated in figures 20(a) and 20(b). YKA has a small precursor to the large amplitude signal and as seen on the spike seismogram this large amplitude signal is of opposite ground motion to the small compressional P signal. This means that the large amplitude arrival may be pP and that the low frequency, small amplitude precursor is a heavily absorbed or scattered direct P wave. This may be caused by the structure beneath the island arc system. The remaining arrays produced very simple records. The pP - P time interval was estimated at 0.43 s and using the measured up-hole velocity of 3.38 km/s gives a depth of 730 m. This agrees very well with the announced depth of 755 m.

The surface wave magnitude gives a yield of 115 kton in the range 60 - 220 kton.

This test was conducted as part of the Vela Uniform programme to discriminate between explosions and earthquakes by seismic methods.

Explosion No. 16

Epicentral Data:

Date:	29 October 1965
Time GMT:	21 00 00
Latitude:	51.43°N
Longitude:	179.18°E
Code Name:	LONGSHOT
Source of Data:	[1]
Yield:	80 kton

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
YKA	36.1	46	283	21 07 02.0	253	0.90	6.04
EKA	73.6	1	358	21 11 32.4	175	0.80	6.18
WRA	81.2	222	26	21 12 14.6	121	0.80	6.00
GBA	86.7	287	37	21 12 43.6	Ov	-	-

Surface Wave Data (WWSSN):

Magnitude M_s: 4.06 ± 0.2

Array Location:

51.43°N
179.00°E

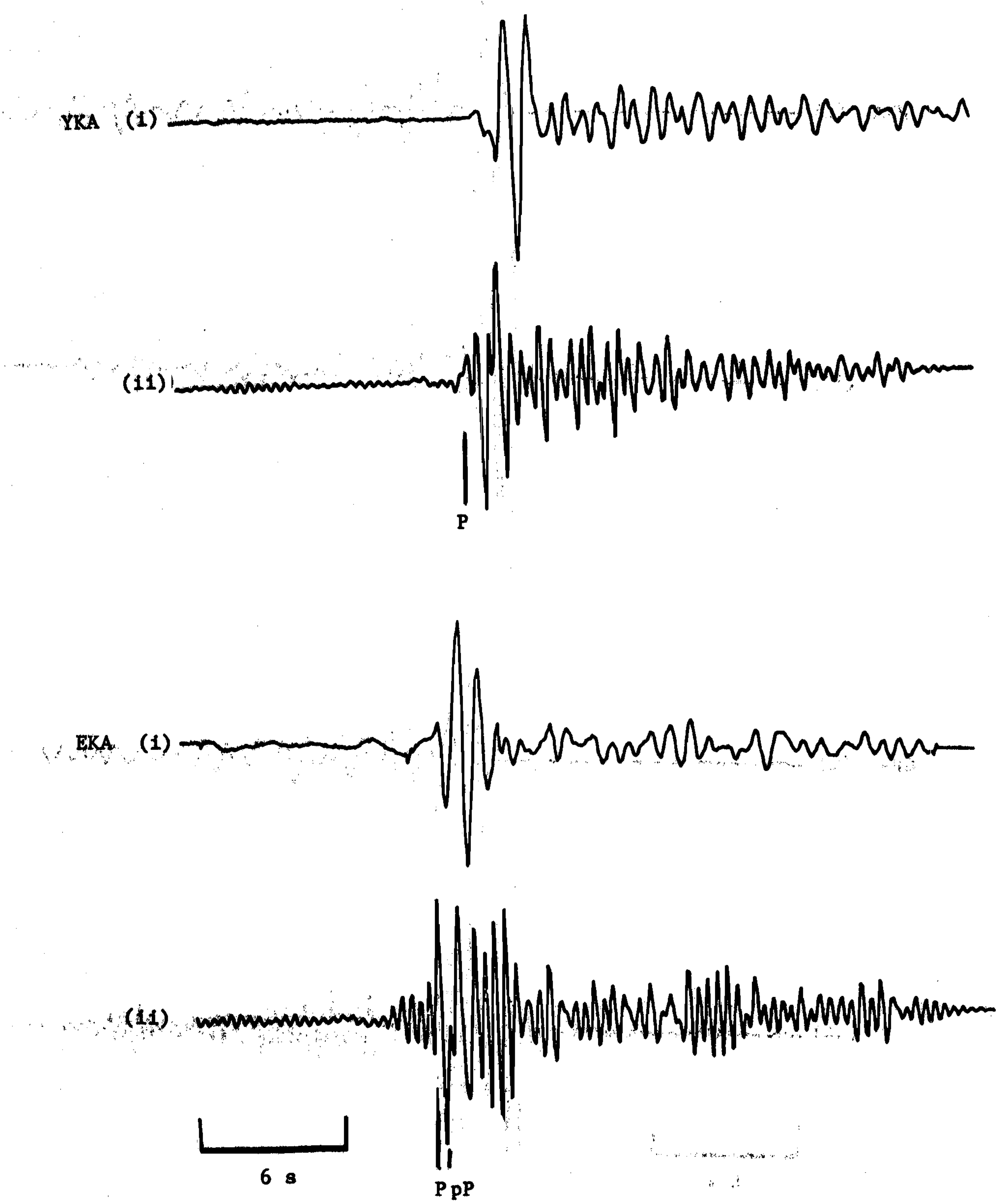


FIGURE 20(a)

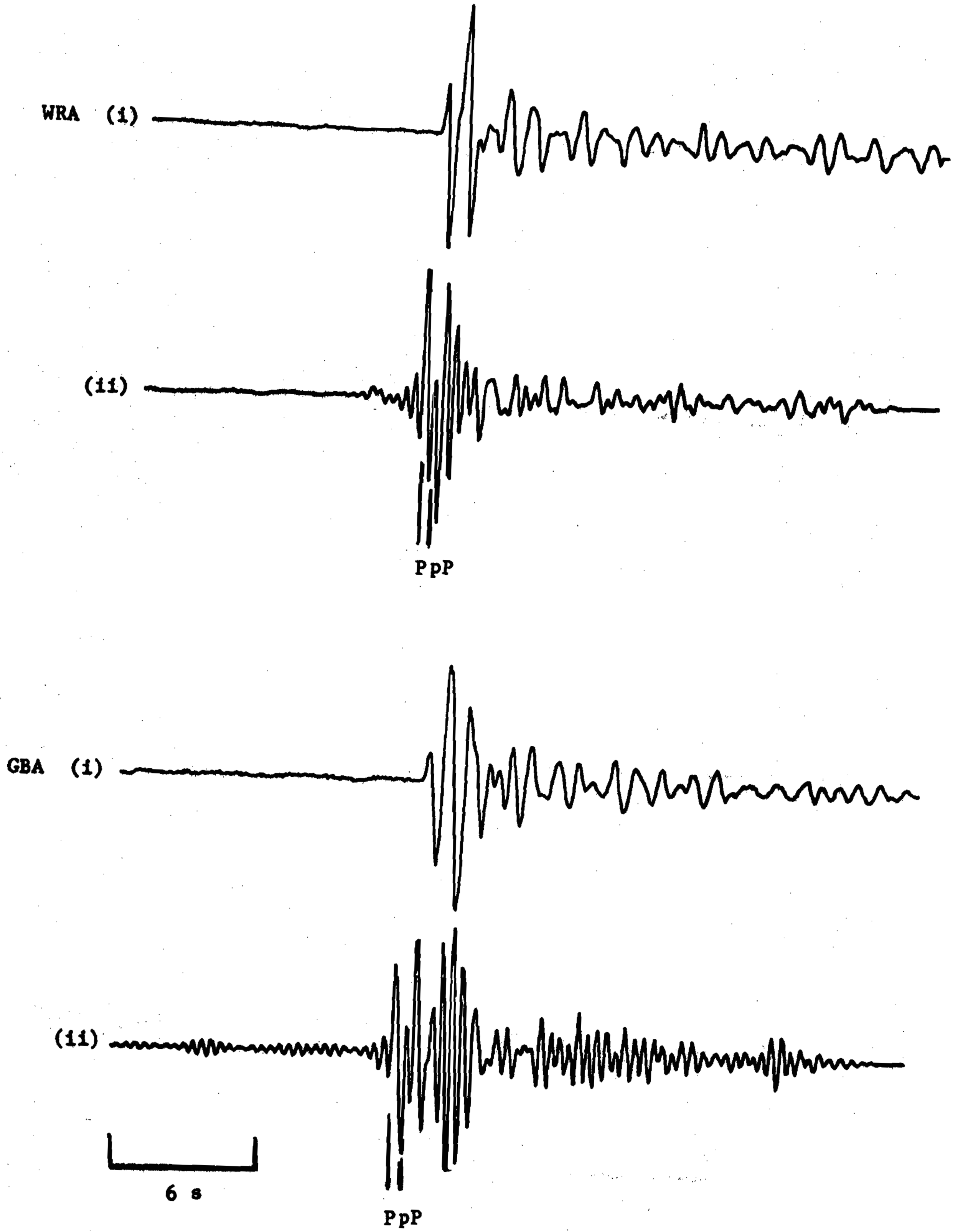


FIGURE 20(b)

10.6.2 2 October 1969 MILROW (Explosion No. 17)

This explosion, in the low megaton range, was detonated at a location 5 km south of the LONGSHOT epicentre and was the subject of an AWRE Report. Since no prior announcement was made of the exact date and time of detonation no attempt was made to adjust the sensitivity of the recording stations; with the exception of EKA all the array stations were overloaded. The record from EKA is illustrated in figure 21.

The EKA spiked record shows a very large negative spike at P + 1.72 s. Assuming the same wave velocity given for LONGSHOT the depth calculated for MILROW is 2900 m, which is considerably deeper than the announced depth. Subsequent processing of this event shows that the small arrival at P + 0.67 s could well be pP and the very large arrival initially identified as pP is in fact an example of multipathing. There are alternative arguments to explain this record but they are beyond the scope of this report.

The surface wave magnitude gives a yield of 1.4 Mton in the range 700 - 2800 kton.

This explosion was the subject of a previous AWRE Report [16]

Explosion No. 17

Epicentral Data:

Date:	2 October 1969
Time GMT:	22 06 00.0
Latitude:	51.42°N
Longitude:	179.18°E
Code Name:	MILROW
Source of Data :	[1]
Yield:	Low megaton

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
YKA	36.1	46.1	283.6	22 13 01.6	Ov	-	-
EKA	73.6	1.4	358.5	22 17 32.6	480	0.75	6.6
WRA	81.2	222.2	26.5	22 18 15.6	Ov	-	-
GBA	86.7	287.5	37.9	22 18 43.4	Ov	-	-

Surface Wave Data (WWSSN):

Magnitude M_s: 5.15 ± 0.25

Array Location:

51.54°N
179.00°E

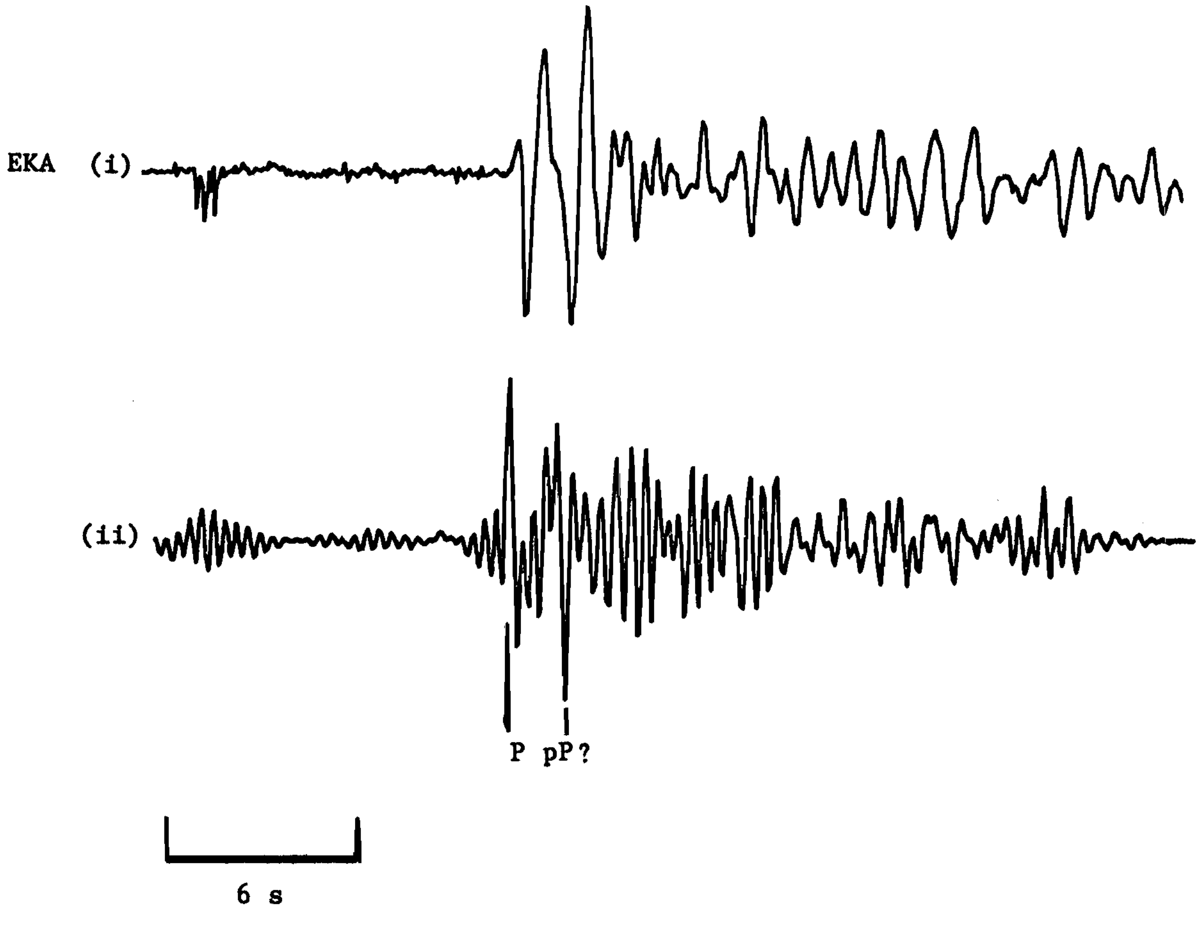


FIGURE 21

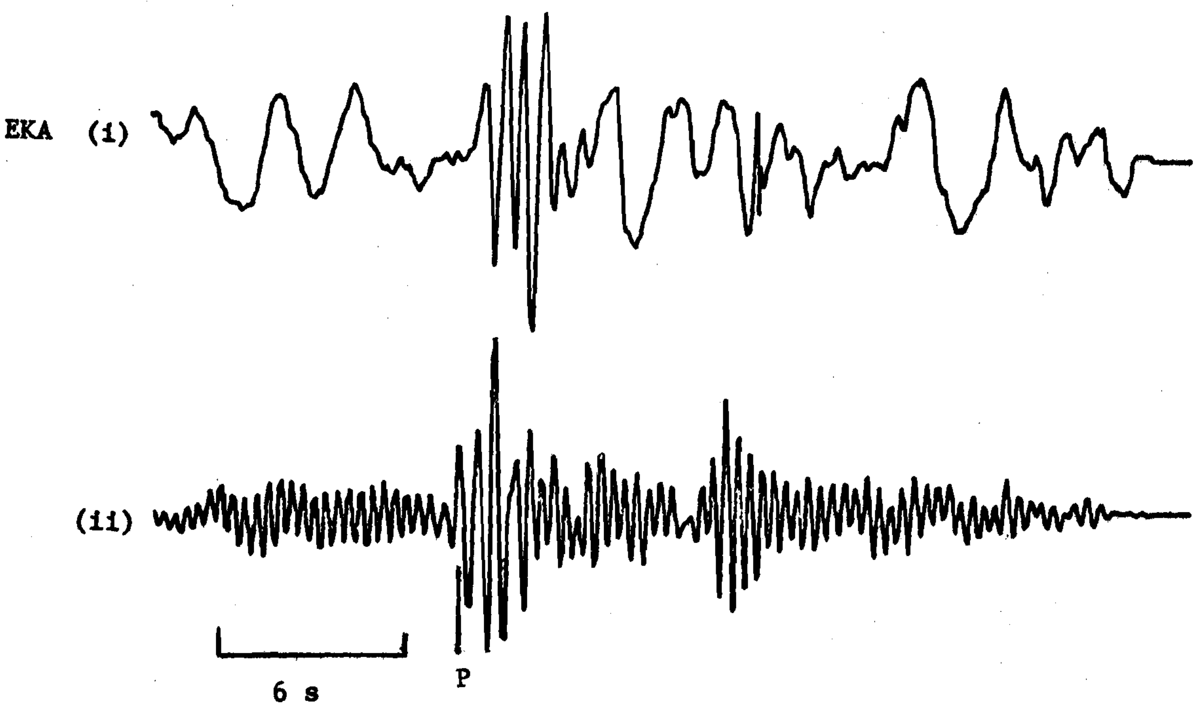


FIGURE 25

10.7.1 13 September 1963 BILBY (Explosion No. 18)

The seismogram from the EKA array is shown in figure 22. The large amplitude positive spike is the onset of the P wave and there is no clear pulse which can be identified as pP. The P wave is certainly complex and the arrival of several pulses after the P wave, indicated on the spiked seismogram, suggests that this is another example of multipathing.

The surface wave magnitude indicates a yield of 250 kton in the range 180 - 450 kton. From the announced depth of 716 m it is assumed that a yield of about 200 kton would be fully contained; it is possible that slight venting may have occurred.

Explosion No. 18

Epicentral Data:

Date:	13 September 1963
Time GMT:	17 00 00
Latitude:	37.2°N
Longitude:	116.0°W
Code Name:	BILBY
Source of Data:	[1]
Yield:	235 kton

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
EKA	71	33.7	309.0	17 11 22.5	27	0.80	5.45

Surface Wave Data (WWSSN):

Magnitude M_s: 4.39 ± 0.25

Array Location:

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
YKA	23.5	352.2	167.0	21 05 10.0	16	0.60	4.72
EKA	66.1	37.2	305.0	21 10 47.8	4	0.82	4.69
WRA	123.6	270.9	55.4	21 19 00.6 PKP	-	-	-
GBA	127			X			

Surface Wave Data (WWSSN):

Magnitude M_s: 3.55 ± 0.25

Array Location:

-

10.7.2 2 June 1966 PILEDRIVER (Explosion No. 19)

This is one of the few explosions in granite at the Nevada Test Site and is located at the north end of the Yucca Flat region. The seismogram from EKA is shown in figure 23; the P wave is recorded with good signal to noise ratio and is relatively simple in appearance.

The spiked seismogram shows a clear direct compressional P wave spike followed by a rarefractional spike 0.68 s later. From the known depth of firing this second arrival is too late for pP and is probably caused by a multipath arrival, an arrival which has taken a slightly different route from the source to the receiver. If the first negative spike is taken as pP then the estimate of depth is 490 m assuming a velocity of 3.3 km/s appropriate for granite of this age.

The surface wave magnitude gives a yield estimate of 58 kton in the range 30 - 120 kton. The depth of focus is just sufficient to fully contain the PILEDRIVER explosion particularly as the overburden was granite.

Explosion No. 19

Epicentral Data:

Date:	2 June 1966
Time GMT:	15 30 00.1
Latitude:	37.23°N
Longitude:	116.05°W
Code Name:	PILEDRIVER
Source of Data:	[1]
Yield:	56 kton

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
EKA	71.7	33.7	309.0	15 41 21.7	14	0.65	5.23

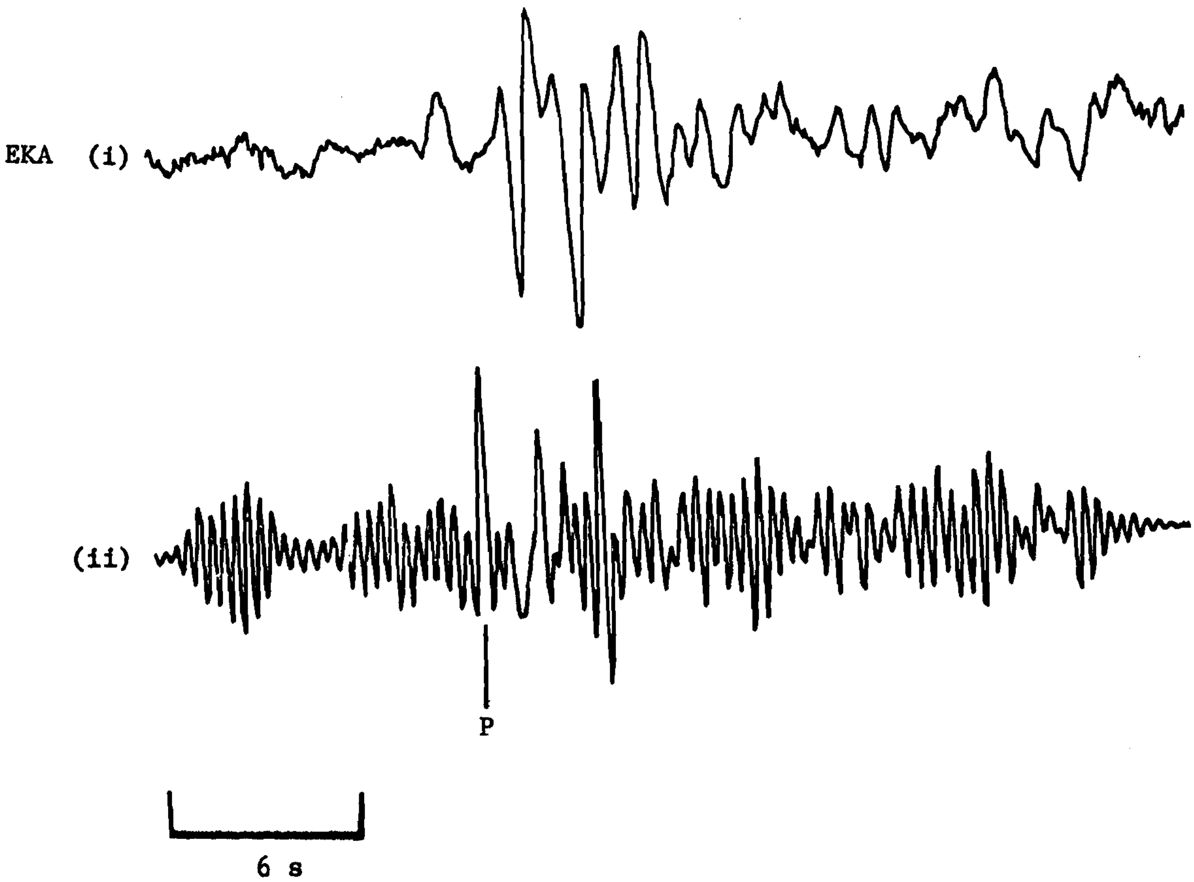


FIGURE 22

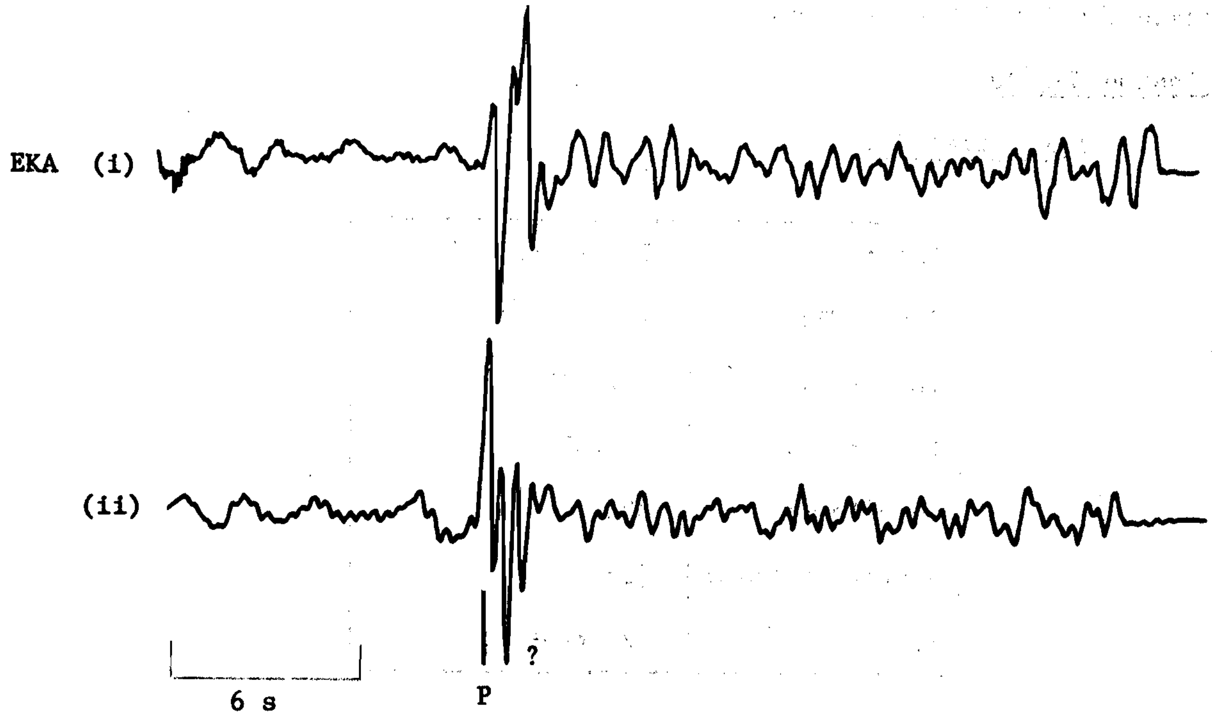


FIGURE 23

Surface Wave Data (WWSSN):

Magnitude M_s: 3.76 ± 0.15

Array Location:

-

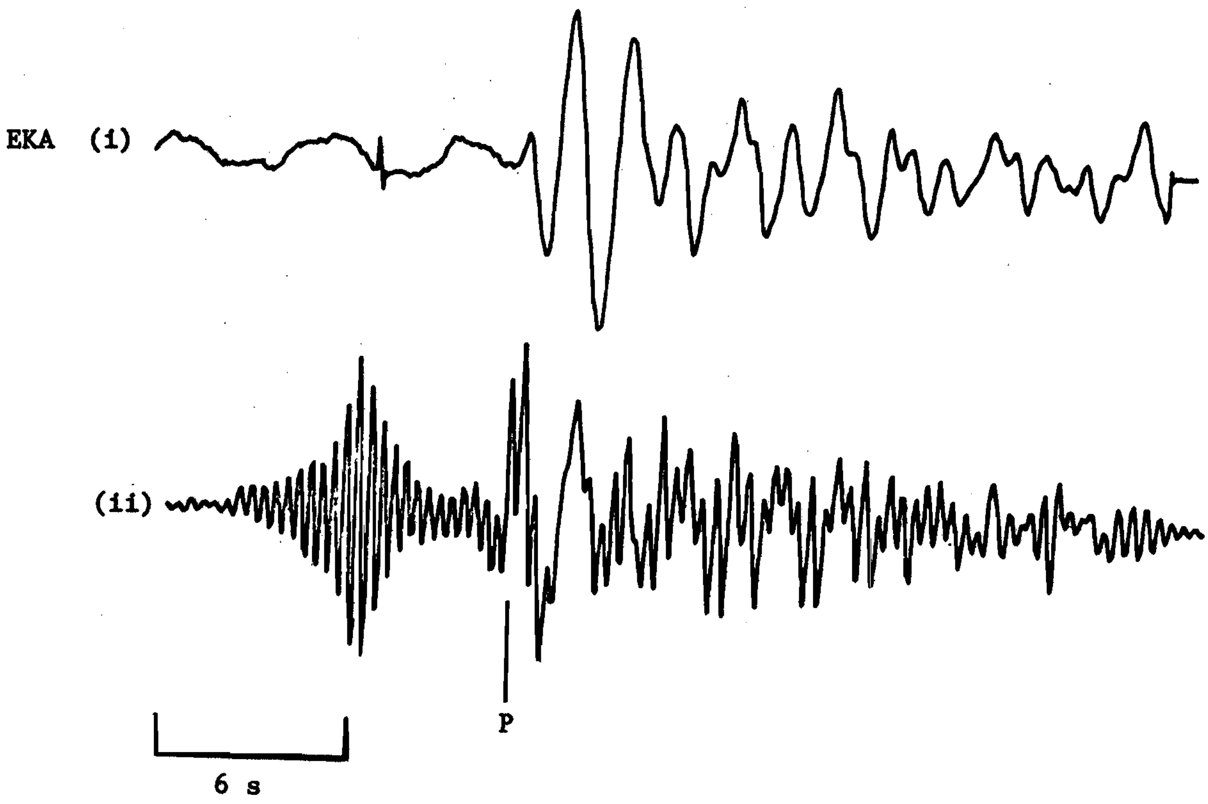


FIGURE 24

10.7 Nevada, USA

This is the principal test site in the US. Tests of all types have taken place in this area including weapon, PNE and physics tests. The first underground explosion occurred in 1957 and the site has been in use ever since. The US Government have announced more details of their underground explosions than any other nation which has proved particularly useful to researchers investigating the problem of seismic discrimination. It has been very useful not only in location of epicentres but also in the understanding of the problem of shot medium coupling, vital in estimating yield ranges from seismic waves from underground explosions.

The geology of the Nevada Test Site is complex. The outcropping rocks of the central part of the test site, the Yucca Flat area, range from the Pre-Cambrian quartzite to Quaternary basalt and have a thickness of about 12000 m. The only Mesozoic rocks exposed in this area are intrusive bodies of quartz and granodiorite. The remaining bedrock outcrops in the area consist of volcanic rocks of Miocene or younger age and are the order of 1200 m thick. This rock is known as tuff. Overlying the tuff are deposits of Quaternary alluvium, consisting of gravel and sand; the thickness of the alluvium varies from 0 - 700 m and is dry alluvium to a depth of about 400 m.

The Yucca Flat region is about 1100 m above sea level rising sharply in the east and west to a height of about 2000 m. This elevated region consists mainly of volcanic tuff. This means that vertical drilling is probably the procedure used for device emplacement but use can also be made of mining into the hillside for explosions in tuff. Tuff is a friable material so drilling is easy and it is supposed that vertical drilling is also used in the Pahute Mesa tuff as the area to the west of the test site is known.

The crust is not very thick beneath the Nevada Test site; measurements give a thickness of 28 km. The upper mantle velocity immediately beneath the crust is low (around 7.81 km/s).

Thus, we have a wide range of media in which the device may be located, ranging from dry alluvium to granite. This will greatly affect the spectral content of the initial seismic waves leaving the source; this, coupled with a sub-crustal region of low Q and hence high seismic wave attenuation, suggests that waves recorded from explosions in Nevada will be low frequency, fairly complex, and of low magnitude.

The depth of firing for full containment of the explosion and yield relationship used for this area is taken as $h = 125\ mY^{1/3}$ where h is the depth in metres. This relationship is a little different to the Russian relationship [10] and is approximately that used by Mueller and Murphy [17]

The only array records from explosions in Nevada analysed in this report are from EKA. This is the only array station within the distance range 30° - 90° from the Nevada Test Site. A selection of explosions has been analysed and an AWRE Report [13] prepared on the results from the four array stations.

10.8.1 10 December 1967 1967 GASBUGGY (Explosion No. 21)

Only one array station is within the 30° - 90° distance range, EKA, and the record of the GASBUGGY explosion is given in figure 25. No clear depth phase is visible on the spiked record, which is a somewhat surprising result in view of the depth of the explosion since a clear well-separated depth phase may be expected. This may be due to a series of arrivals; P waves by two slightly different routes arriving at about the same time producing a complex P wave onset which is at present beyond the resolution of the spike filter.

The magnitude of the surface waves gives a yield estimate of 25 kton in the range 15 - 40 kton. This explosion is a PNE experiment and at this depth would be fully contained.

Explosion No. 21

Epicentral Data:

Date:	10 December 1967
Time GMT:	19 30 00.1
Latitude:	36.68°N
Longitude:	107.21°W
Code Name:	GASBUGGY
Source of Data:	[1]
Yield:	29 kton

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
YKA	26.2	352.2	166.4	19 35 36.7	7	0.90	4.33
EKA	67.9	36.8	302.7	19 40 59.6	11	0.65	5.33
WRA	124.2	269.6	58.7	19 49 00.9 PKP	-	-	-
GBA	129.8	354.1	4.8	19 49 9.2 PKP	-	-	-

Surface Wave Data (WWSSN):

Magnitude M_s: 3.40 ± 0.20

Array Location:

-

10.7.3 20 December 1966 GREELEY (Explosion No. 20)

The record from EKA is shown in figure 24; the interesting feature immediately apparent is the very low frequency content of the main P wave arrival. This low frequency is a function of the high yield, the medium response and the low Q in the upper mantle. The spiked seismogram shows a very complicated record with a possible depth phase pP arriving at 1.0 s after the P wave. Assuming a local P wave velocity of 2.5 km/s consistent with the type and age of the rocks the depth estimated is 1250 m or 30 m shallower than the announced depth.

The surface wave magnitude indicates a yield of 1.15 Mton in the range 650 - 2000 kton. The depth of firing is sufficient to fully contain the GREELEY explosion.

Explosion No. 20

Epicentral Data:

Date:	20 December 1966
Time GMT:	15 30 00.1
Latitude:	37.30°N
Longitude:	116.41°W
Code Name:	GREELEY
Source of Data:	[1]
Yield:	825 kton

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
EKA	71.6	33.7	309.0	15 41 21.8	175	1.30	6.03

Surface Wave Data (WWSSN):

Magnitude M_s: 5.06 ± 0.25

Array Location:

-

10.8.2 10 September 1969 RULISON (Explosion No. 22)

This event has also been the subject of an AWRE Shot Report [14]. As with the previous event only EKA is within the 30° - 90° distance range and the record of RULISON is shown in figure 26. The signal to noise ratio is poor and the spiked record gives no clear depth phase. In view of the signal to noise ratio this is not surprising and is perhaps more a reflection of the complexity of arrivals (multipathing) which make up the initial P wave. In the AWRE Shot Report, using a different spiking filter, a depth phase was tentatively extracted giving a P - pP time of 1.57 s. Assuming a velocity of 3.3 km/s this gives a depth estimate of 2600 m, only 30 m deeper than the announced depth. Note the velocity used here, measured in situ, is the same as assumed for the Caspian Sea region, an area in which it is assumed that some PNE experiments are conducted by the USSR.

The magnitude of RULISON at EKA is anomalously low when compared with the magnitude from GASBUGGY and this anomaly is believed to be caused by structural differences close to the source. The azimuth from both events to EKA is 67° ± 1° E of N (see figure 27). From RULISON the waves recorded at EKA have entered the deeply dipping structure of the Southern Rocky Mountains, an area of known low Q, whereas the GASBUGGY epicentre is far enough away from the Southern Rocky Mountains structure for the waves to enter the high Q upper mantle directly beneath the Colorado Plateau. It is possible that this is the cause of the magnitude difference; the reason is however not yet fully understood.

The surface wave magnitude indicates a yield of 36 kton in the range 20 - 70 kton. This explosion is a PNE experiment and would be fully contained at the announced depth.

Explosion No. 22

Epicentral Data:

Date:	10 September 1969
Time GMT:	21 00 00.1
Latitude:	39.41°N
Longitude:	107.95°W
Code Name:	RULISON
Source of Data:	[1]
Yield:	40 kton

10.8 New Mexico and Colorado, USA

Two PNE experiments have been conducted in conjunction with the American Oil and Gas Industry in the USA. These tests were conducted at two locations: (a) Colorado, and (b) New Mexico.

(a) Colorado. This is the location of the RULISON experiment. The geology beneath the shot point is composed of thin layers of inter-bedded alluvium and basalt flows overlying a thick sedimentary column of Tertiary, Mesozoic and Palaeozoic rocks. Pre-Cambrian basement rocks exist at a depth of about 6000 m. The device was located in a layer of inter-bedded Upper Cretaceous sandstone and shale.

The test site is within the Colorado Plateau Province, the boundaries of which are formed by the Great Basin to the south and west and the Rocky Mountains on the north and east. This extremely complex structure surrounding the RULISON site suggests that seismic waves recorded at teleseismic distances in an azimuth range 270° - 180° east of north may produce complex records with low magnitudes.

The crustal structure of the Colorado Plateau is intermediate between a relatively thin crust found in the Basin and Range Province characterised by a P_n wave velocity of 7.8 km/s, and a thick crust beneath the Southern Rocky Mountains where the P_n velocity is of the order of 8.1 km/s.

(b) New Mexico. The location of GASBUGGY is also on the Colorado Plateau located in the east central portion of the San Juan Basin. The structure is very similar to the RULISON site but the shot point is further from the structures which surround the Plateau. The rocks in the southern part of the Basin exhibit extensive folding and faulting but since the epicentre is well separated from the complex structures surrounding the Colorado Plateau it would be expected that teleseismic records of the GASBUGGY shot would be relatively simpler and give slightly higher magnitudes relative to the RULISON location. The crustal thickness is of the order of 40 km and the P_n velocity around 7.8 km/s. Note the P_n velocity is somewhat lower beneath the US PNE shots than the P_n velocity in the upper mantle beneath the Caspian Sea region. Effectively this means that a 20 kton shot in the Caspian Sea would give a larger magnitude than 20 kton fired in this area of the Colorado Plateau region.

The two events from this region are the subject of AWRE Shot Report No 3 [14].

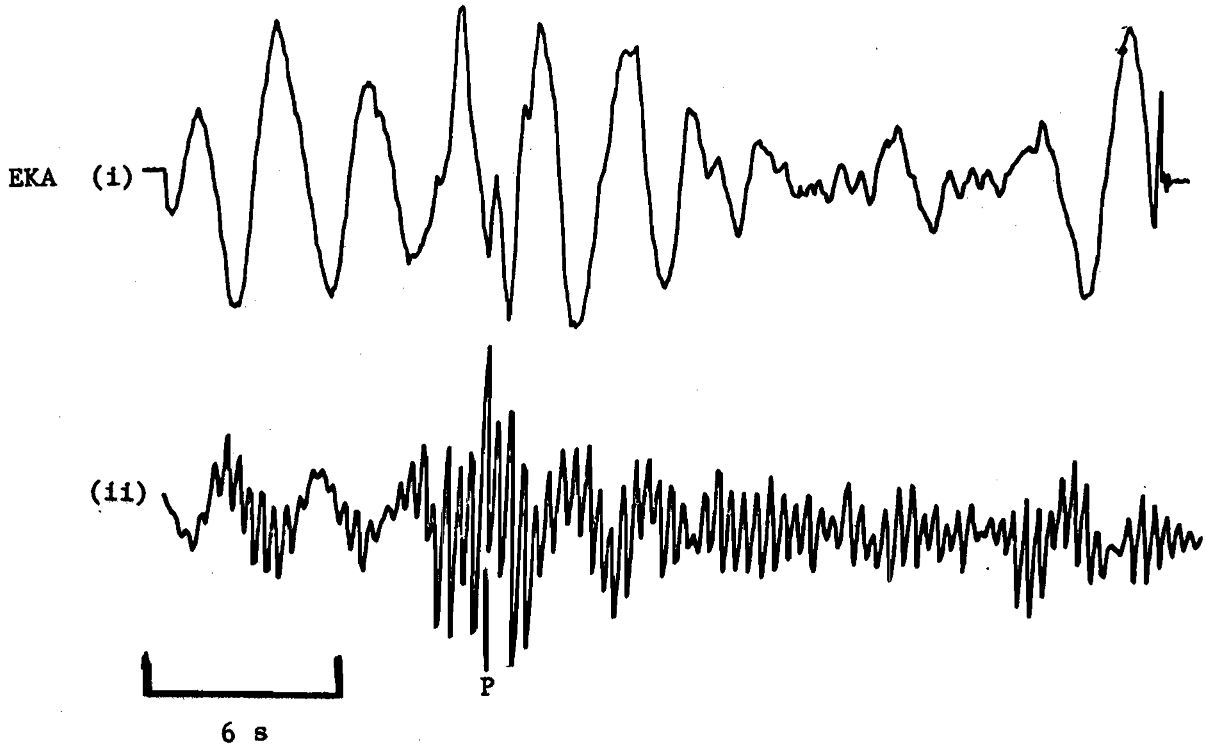


FIGURE 26

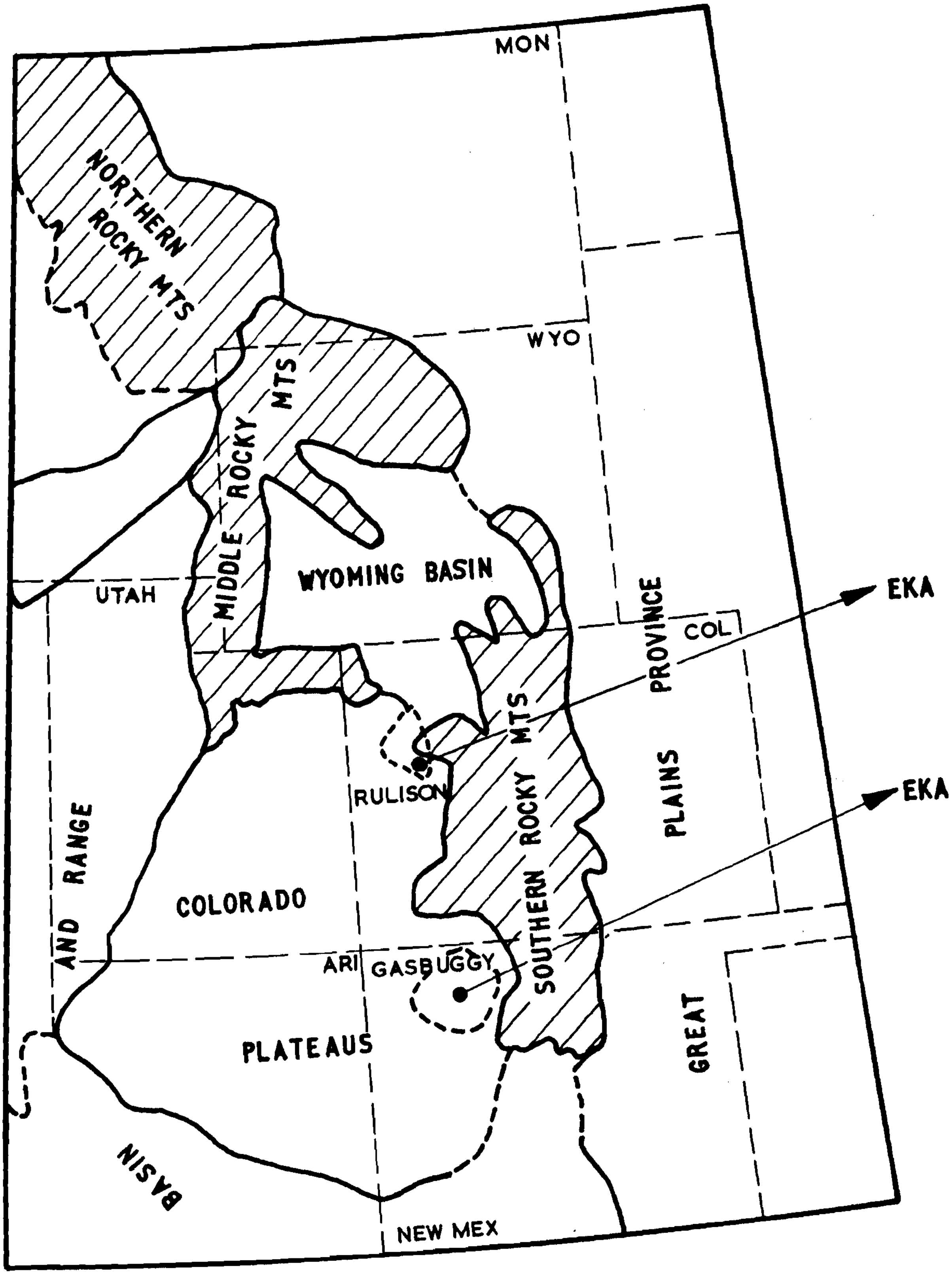


FIGURE 27. LOCATION OF THE RULISON AND GASBUGGY EXPLOSIONS RELATIVE TO THE LOCAL STRUCTURE

10.9 Algerian Sahara

This area was used extensively by the French for testing nuclear weapons both in the atmosphere and underground. The last underground explosion occurred on 16 February 1966 and this is the explosion selected for analysis in this report.

The exact location of these explosions [15] indicates that they are detonated in a granite massif in the Hoggar Mountains. The granitic intrusion is in the form of an ellipsoidal dome 8 km by 5.6 km and rises 1000 m above the surrounding terrain which itself is some 1000 m above sea level. This suggests that conventional mining techniques could be used rather than drilling for charge emplacement.

The velocity of P_n in this region is not known but it is probably close to 8.0 km/s. This assumption is based simply on the age of the rocks around Hoggar. Thus, seismic wave transmission from this region should be good with little attenuation of the higher frequencies. However, it is reported that the cavities which result from the explosions are somewhat smaller than cavities from equivalent yields fired in Nevada, USA. This may be due to the extent of weathering of the granite or more likely the low water content of the rocks in this region. Since the cavities are smaller one may expect lower amplitude seismic signals from an explosion in Hoggar than for the equivalent yield fired in Nevada. Note this does not however include any absorption effects over the transmission path to a particular recording station.

10.9.1 16 February 1966 GRENAT (Explosion No. 23)

Three array stations detected P waves from this explosion; the signal to noise ratio is low at EKA but good at YKA and GBA (figures 28(a) and 28(b)). A phase corresponding to pP arrives 0.50 s after the P wave. The velocity is assumed to be 3.9 km/s giving an estimated depth of firing of 840 m. This depth is consistent with a shaft driven into the mountain using mining techniques from the plateau level; this would produce a maximum overburden of 1000 m.

The short period waves are longer period than the P waves from Kazakh, this suggests that the coupling between the explosion and the medium is less efficient at Sahara than Kazakh or that there is more attenuation in the upper mantle between the two sites.

The surface wave magnitude of this explosion gives a yield estimate of 22 kton in the range 10 - 40 kton.

The estimated depth is sufficient to fully contain an explosion of up to 180 kton so it is unlikely that this explosion vented.

Explosion No. 23

Epicentral Data:

Date:	16 February 1966
Time GMT:	11 00 00.0
Latitude:	24.04°N
Longitude:	5.04°E
Code Name:	GRENAT
Source of Data:	[15]
Yield:	

Array Data:

Station	Δ°	Az°	BB°	P Wave Arrival Time	Amplitude, mμ	Period, s	Magnitude, m_b
EKA	31.7	351	165	11 06 25.8	17	0.60	5.15
GBA	68.6	84	290	11 11 05.1	5	0.60	4.90
YKA	81.3	325	53	11 12 18.0	8	0.70	4.87

Surface Wave Data (WWSSN):

Magnitude M_s: 3.35 ± 0.15

Array Location:

24.18°N
5.26°E

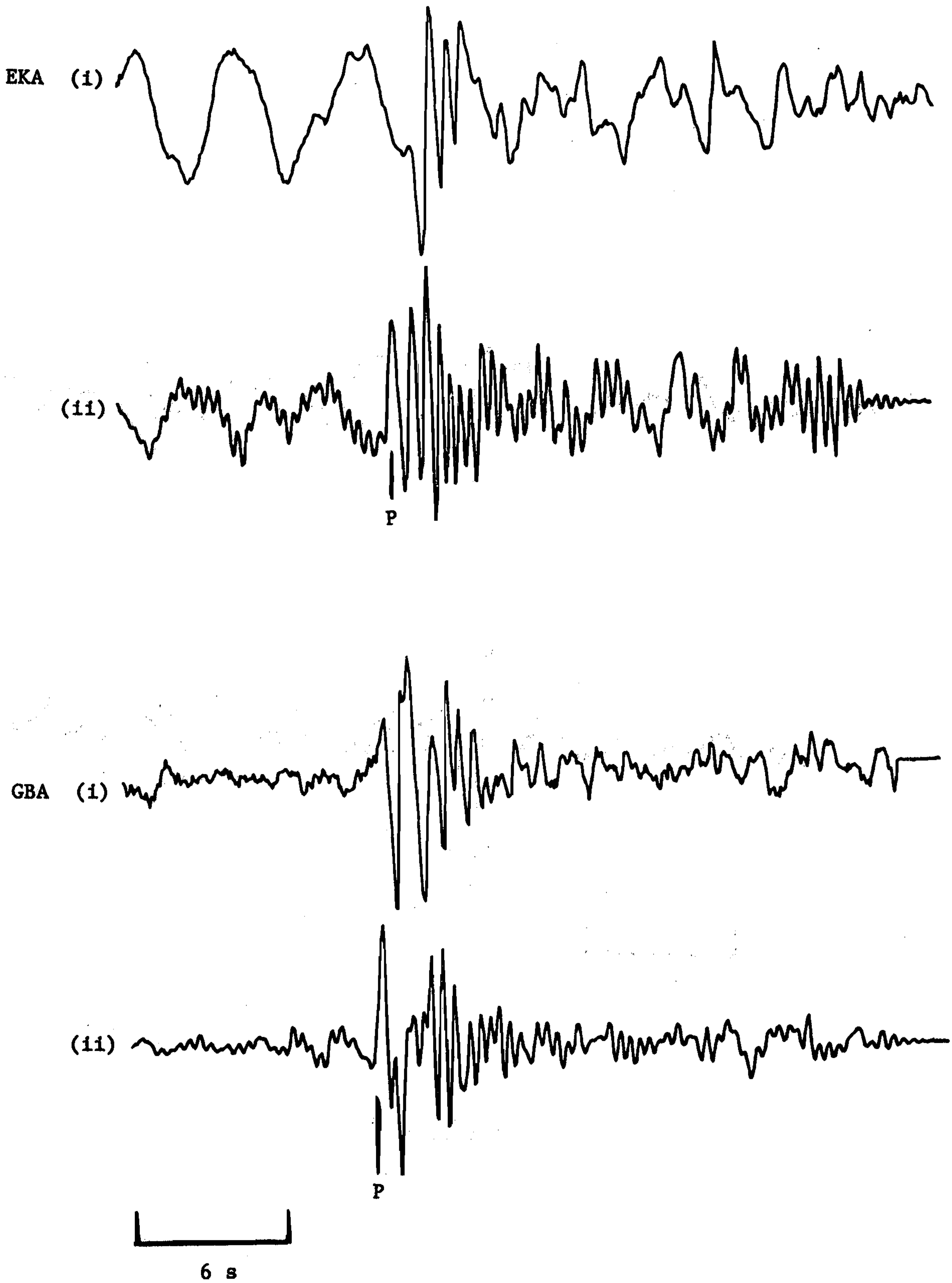


FIGURE 28(a)

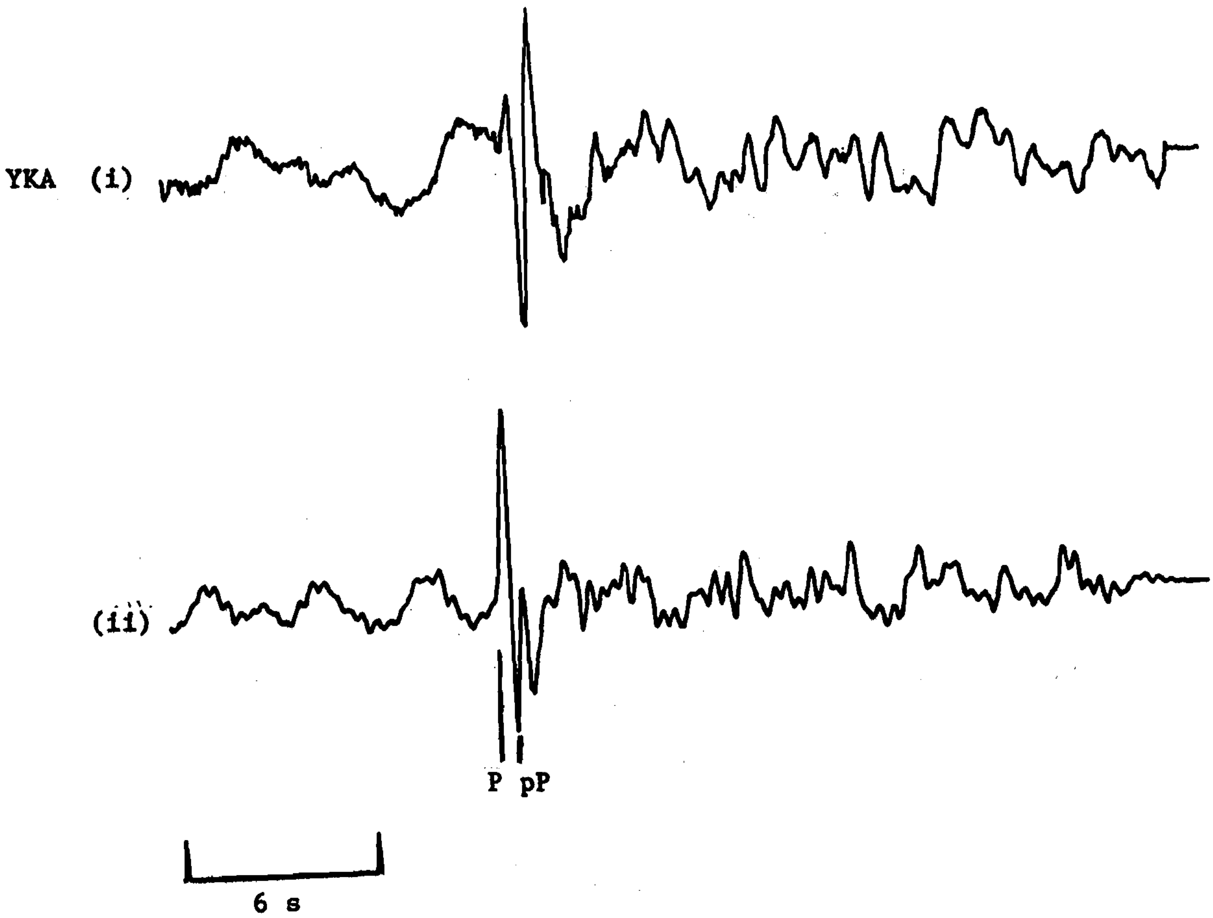


FIGURE 28(b)

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