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SEISMIC SIGNAL DETECTION AND FURTHER PROCESSING USING ARRAY SEISMOGRAMS : AN OVERVIEW

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ABSTRACT

Digital signal detection and processing involving automated procedures is recognised as an important thrust area activity in modern seismology. Facilitated by the high quality data obtained from mainly Gauribidanur seismic array since its installation in southern India over twenty-five years ago, this activity is purported to progressively evolve efficient methods and techniques to detect signals of seismic events, especially week ones, from any region of the world and identify their sources through feature extraction. This paper gives an overview of major data processing techniques established by us and mentions some future projections including development of a knowledge based expert system. Among the methods of signal detection from essentially short period array records, optimum beamforming, correlogram, cumenerogram and prediction error filtering have been emphasised. For source discrimination employing single array data, particularly in case of events with very shallow focal depth, scaled complexity combined with third moment of frequency of P signal is shown to be reasonably good. However, temporal and spectral characteristics of the secondary arrivals such as PcP and PP are found to be promising discriminants. It is planned to support these processors by extensively employing long period as well as broadband data that would also afford looking into some of the interesting diagnostic features of S (shear wave) phases.

INTRODUCTION

Unambiguous detection of seismic signals well above the background noise is an important prerequisite for seismic data analysis and interpretation. Quite often, these signals, especially if they are weak, are masked by ambient noise due to oceanic microseisms, cultural activity in the neighbourhood of seismic sensors deployed in the field and that generated by the electronic system used at the recording station. The problem is compounded if the frequency band of the signal of interest largely overlaps with that of the unwanted noise.

A seismic array such as the medium aperture linear cross 20-element short period (aroound 1 sec) array of equispaced (2.5 km) seismometers operated at Gauribidanur in southern India since 1965 by Bhabha Atomic Research Centre (BARC), Bombay, affords enhancement of signal to noise ratio (SNR) by special processing techniques which help to lower signal detection threshold. Layout details of the L shaped Gauribidanur array used by us are briefly discussed here. With the help of suitable examples, it is demonstrated how these techniques of processing array data aid detection of low level signals and identification of their sources through feature enhancement.

PROCESSING OF SEISMOGRAMS TO CONFIRM PRESENCE OF SIGNAL

Beamforming

By summing signals from N sensors of an array (N channels) using appropriate time delays between the channels to align the signals in phase (best beam), one can get an SNR improvement upto $N^{1/2}$ compared to single channel SNR (Birtill and Whiteway, 1965; Robinson, 1967; Kulhanek, 1976). This beamforming method assumes that the signals are coherent throughout the array and that the background noise is completely uncorrelated from channel to channel. However, such an ideal condition is seldom met in actual practice so that the enhancement in SNR is usually lower than $N^{1/2}$ (Denham, 1963).

Correlogram and cumenerogram

Using two independent partial sums of signals from the two orthogonal arms of GBA, where the background noise is already suppressed to some extent, signal detection further improves by correlating the two time series corresponding to the partial sums to generate a correlogram (Weichert, 1975; Arora and Basu, 1984, 1985). To obtain a running correlogram, we prefer a 1-sec time window (slightly wider than the expected dominant period of teleseismic P signal) and slide it towards the tail end of the record gradually through only one discrete sample (50 milliseconds apart) in each step.

Similarly, another processor that aids signal detection and identification and uses the array partial sums as mentioned above relies on the computation of cumulative excess energy (excess of energy at a time instant over that at the immediately preceding discrete instant) as a function of time along the seismogram. Called as cumenerogram (Arora and Basu 1984, 1985), it facilitates detection of signals, particularly transients, reasonably well.

Prediction error filtering

Exploiting the properties pertaining to stationarity of the microseismic noise, we have made use of prediction error filters (PFF) following Robinson (1966); and Peacock and Treitel (1969). Such filters are capable of predicting a stationary time series one or more steps ahead with a high degree of accuracy (Roy and Murty, 1982). Thus, parametric modelling of time series using autoregressive (AR) modelling (Ulrych and Bishop, 1975; Ulrych and Clayton, 1976) on account of its ability to accentuate small nonstationary changes, can be effectively employed to detect weak seismic signals in stationary noise background (see, for instance, Fryer et al., 1975; Murty et al., 1979). By processing and analysis of some artificial (synthetic) and real seismograms, we have demonstrated (Roy et al., 1992a, 1992b) using GBA data that an average SNR improvement upto a factor of ten is possible when an integrated method combining the array best beam with PEF and moving autocorrelation (MAC) technique is employed.

In support of the above techniques, we cite here some illustrations (Figs. 1 to 4) of detection and identification of primary as well as secondary signals using GBA short period data from seismic events in a large distance range. Fig. 1 shows typical raw plots of unprocessed digital waveforms acquired in twenty independent short period channels of GBA corresponding to the leading signal (P) and an important secondary arrival (PcP, i.e. core-reflected P signal) from the recent Chinese underground nuclear explosion on 25 September 1992. Located at Lop Nor in the southern Xinjiang province, this event at an epicentral distance (Δ) of 29.6 degrees from GBA (1 deg. of Δ = 111.2 km along the arc of meridian or great circle arc) and having a bodywave magnitude Mb 5.0 (equivalent to an yield of approximately 15 kilotons of TNT) has generated clear P while PcP is not discernable. By processing this event using the techniques described above, we confirm from Fig. 2 clear detection of P as well as of PcP at an interval of 186.2 seconds. Explanations with regard to practical usage of various processors are duly mentioned in Fig. 2. In Fig. 3, we show optimally beamed P and PcP signals from another Lop Nor explosion event known to be a very large (megaton class) underground nuclear test conducted by China on 21 May 1992, where PcP signal strength at GBA is found to be about one-third of maximum P in the coda and nearly the same as that of the initial P within the first few cycles.

Illustrations of processsing and detection of seismic signals from weak sources at far teleseismic distances from GBA in the core shadow zone are presented in two sets in Fig. 4. The first set at left (Fig. 4) pertains to detection of the first arriving main PKP signal (core refracted P) from a small nuclear test explosion (code name 'Shellbourne', Mb 4.8, less than 10 kt yield) in Southern Nevada, USA (Δ = 128 deg.), on 13 May 1988. The second set at right (Fig. 4) demonstrates clear detection of yet another important secondary signal (PP, i.e., P wave singly reflected from earth's surface) in the coda of the GBA recordings of a small shallow-focus earthquake (Mb4.5, focal depth 10 km) that occured on 4 February 1991 in Central California at about the some distance and azimuth from GBA as the companion event in the first set.

EVENT IDENTIFICATION THROUGH SOURCE DISCRIMINATION

For identifying seismic sources in distinguishing natural earthquakes from man made underground detonations, the methods and techniques developed over the years rely essentially on exploiting the difference in the energy release mechanism of the two processes. It is known that occurrence patterns of tectonic earthquakes cannot be easily altered by human activity whereas explosions being governed entirely by human decision, can be modelled to produce such seismic effects as one desires.

In drawing conclusions regarding the nature of a seismic source, it is preferred to join various identifiers in a cascade manner so as to integrate the output from each discriminator. A single discriminant or, for that matter, a number of internally inconsistent discriminants tend to lower the efficiency of the discrimination process. At the same time, event identification using a variety of dynamic parameters is limited by the component which is difficult to evaluate with reliability and precision. It is quite likely that an event is misclassified if its signal is weak (small event close to detection threshold). On the other hand, difficult cases do sometimes arise when signal characteristics cannot be established distinctly and satisfactorily even though the signal is clearly seen above the background noise.

Today we have a number of identifying parameters that operate on short period, long period and broadband data in both time and frequency domains (see, e.g., Dahlman and Israelson, 1977; Husebye and Mykkeltveit, 1981). Among these, the Mb:Ms method based on difference between the bodywave magnitude Mb and the corresponding surface wave magnitude Ms is most frequently applied. Sometimes, the ratio Ms/Mb is also used in addition to Mb minus Ms. A serious limitation of this method confronts, however, when Ms (usually 1 to 1.8 units lower than Mb for explosions depending on the nature of the detonation medium, e.g., hard rock or dry alluvium) cannot be computed because of undetectable surface (Rayleigh) waves in case of small events.

Utility of single array data and of source depth estimate

It is indeed preferable to collate and analyse multi-station data for event identification. This, of course, involves considerable time taken mainly to gather data from various seismological stations, both within the country and outside. We have in recent years devoted attention in evolving and establishing efficient discriminants that rely on mainly single array seismograms (Roy, 1986; Arora and Basu, 1990). One strong reason for this is due to the rapidity with which the status of an event has to be invariably ascertained, which in turn constrains us to use data mostly from a single station under our operational control, namely GBA.

Before we get to process in detail seismic waveforms for feature extraction we find it extremely useful to examine estimates of focal depth (Arora et al., 1983; Nair, 1983; Roy, 1989). Support is also sought from pattern matching of P coda with those of known seismic events recorded at GBA. If, however, the focal depth is less than about 5 km and also when the signal is weak, further processing of the event becomes necessary in search of conclusive evidence confirming the type of seismic source.

Complexity, TMF and CTMF parameters

Using short-period array data of P waves from a large number of shallow focus Central Asian earthquakes and presumed Russian underground nuclear test explosions recorded at GBA as well as at the two other arrays, namely EKA (Eskdalemuir, Scotland) and YKA (Yellowknife, Canada), we have developed an identifier known as CTMF (scaled signal complexity per unit TMF (third moment of frequency)) and examined its efficacy (see illustration in Fig. 6). The complexity parameter involves a comparison of sums of rectified initial P-wave amplitudes and the corresponding coda (e.g., Kelly, 1968; Anglin, 1971; Marshall and Key, 1973). The TMF computed from the amplitude spectra of P signal and the preceding noise in array seismograms of an event helps to accentuate the relative high frequency content in explosion seismic records in preference to predominantly longer periods in earthquake records (Anglin, 1971; Weichert, 1971).

It is found that complexity as a function of event magnitude Mb exhibits generally a non-linear (cubic fits the data best) trend for both explosions and earthquakes. But this trend in the case of earthquakes (complexity increasing with Mb) is just the opposite (complexity decreasing with Mb) of what we get for explosions (Basu and Arora, 1985, 1987). With regard to TMF, although both explosions and earthquakes show steadily decreasing TMF linearly with increase in Mb, we notice (i) that earthquake TMF at any given Mb is comparatively smaller than explosion TMF and (ii) that the slope deduced from the linear least-squares regression analysis is larger for explosions compared to that for earthquakes (Basu and Arora, 1985, 1987). This show that, compared to earthquakes, the relative high frequency signalsfor explosions attenuate more rapidly as the event magnitude increases. This important result can be seen in Fig. 5. The explosion seismic data analysed include GBA records of eighty nine presumed Russian explosions (July 1979-December 1984) in ten different regions including the well known sites at Eastern Kazakh and Novaya Zemlya. The earthquake data obtained at GBA are due to 165 shallow-focus earthquakes (focal depth less than 40 km) that occurred in thirty-five Central Asian regions during the period from February 1980 to October 1985.

Interestingly, the CTMF parameter that combines the complexity and the TMF behaviour of the seismic events studied by us provides at any given magnitude better separation between earthquake and explosion population than does either the complexity or the TMF independently. This is demonstrated in Fig. 6 where the two distinct curves represent typical quadratics fitted by least-squares regression through the exprimental data (Basu and Arora, 1987; Arora and Basu, 1990) in a wide range of magnitude, $3.7<Mb<6.6$.

Relative abundance of PcP energy : the PcP discriminant

Taking a closer look at a large number of shallow focus earthquake and explosion seismic records obtained at GBA, EKA and YKA arrays, we noted that an underground explosion tends to produce PcP more prominantly than does an earthquake from the same region and of comparable magnitude as the explosion. The amplitude of explosion generated PcP, generally limited to only one of two cycles, is usually smaller than the parent P. At times, PcP can be even stronger than P. For example, abnormally large PcP signals have been noticed in the beamed GBA records of small presumed nuclear test explosions near Caspian Sea in southwestern Russia (Arora and Basu, 1985, 1987). This phenomenon is ascribed to a possible typical Q-structure (specific attenuation) in the Caspian Sea region, which seems to influence absorption of P much more than PcP over the travel paths to GBA. On the other hand, earthquakes are found to generate PcP rather weakly, regardless of their region of occurrence. Generally defuse and spread out over a few cycles, earthquake PcP at teleseismic distances ($\Delta > 25$ deg.) is difficult to detect below Mb 4.8.

The observed characteristics pertaining to relative efficiency of generation of PcP in the far field range ($\Delta > 30$ deg.) led us to develop a new identifier that essentially quantifies the ratio of PcP to P energy in time as well as in frequency domain and of PcP in certain preferred frequency passbands. The parameters of this identifier are NTENR(P,PcP) that gives normalised ratio of PcP to P energy in a specific time window, NSENR(P,PcP) giving normalized spectral energy ratio of P and PcP in a certain frequency passband, and SENR(PcP) based on spectral energy ratio of PcP alone in two different passbands (Arora and Basu, 1990; Basu and Arora, 1986, 1987, 1991).

We reproduce in Figs. 7 and 8 typical results obtained on application of our PcP discriminant. Fig. 7 shows estimates of temporal and spectral constituents of the PcP identifier (NTENR, NSENR and SENR) operated on the data of ten Eastern Kazakh explosions during July 1981 - December 1981, obtained at the three arrays, viz. GBA, EKA and YKA. In Fig. 8, we present exclusively GBA data pertaining to NTENR, NSENR and SENR scores from Central Asian earthquakes and presumed Russian explosions in a wide range of magnitude, $4.2<Mb<6.6$. One would notice here that the least-squares regression curve through the earthquake data separates out reasonably well the explosion events consistently in all the three cases. One would also notice exceptionally large scores for explosion events near Caspian Sea in southwestern Russia (12 events including the Orenberg and the Astrakhan explosions in the lower magnitude range of Mb<5.0) and moderately large scores for earthquakes in the same region.

FUTURE PROJECTIONS

Detection and identification of seismic events occurring in far teleseismic distance range, particularly when GBA happens to be situated in the core shadow region (Δ > 110 deg.), often pose difficulty. The PKIKP (core-refracted P signal) from such events is generally difficult to be recognised and characterised for source identification unless the event is moderately large; for example, where Mb is 5.5 and above.

Using our signal detection and processing techniques described in this paper, we have carried out some preliminary work on the important secondary arrival, PP, well suited for processing large distance events in the core shadow zone and beyond where PcP is not observed. We are engaged in studying in detail PP at GBA from NTS (Nevada Test Site) explosions, from earthquakes in California-Nevada border region, Southern California and other adjacent provinces and from sources in and around the test site at Mururoa Atolls (French Polynesia) in South Pacific. It is aimed at developing a PP discriminant, particularly for weak events that occur in the far teleseismic range of distance from our monitoring station.

We are planning to consolidate all established techniques including those developed by us to systematically evolve a knowledge based expert system for on-line discrimination of all seismic single array (GBA) detections. The essential elements and components of such a system are currently under test on a wide variety of known seismic events from different regions including those that usually give rise to simple (relatively less complex) signals originating from deep focus earthquakes. Development of software for achieving this objective is also in progress.

To further improve efficacy of the various processors described in this paper, it is also planned to extensively employ long period and broadband digital data. This would, among other studies, afford investigations of important diagnostic features of S waves related to source mechanism.

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REFERENCES

Anglin, F.M. (1971). Discrimination of earthquakes and explosions using short period seismic array data. Nature, **233**, 51-52.

Arora, S.K and Basu, T.K. (1984). A source discrimination study of a Chinese seismic event of May 4, 1983. Tectonophysics, **109**, 241-251.

Arora, S.K. and Basu, T.K. (1985). A seismic event on August 20, 1983 : double explosion or a single earthquake. Phys. Earth Planet Inter.,, **40**, 309-315.

Arora, S.K. and Basu, T.K. (1987). Reply to Comments from R.C. Stewart on "A seismic event on August 20, 1983 : double explosion or a single earthquake" by S.K. Arora and T.K. Basu. Phys. Earth Planet. Inter., **46**, 384-387.

Arora, S.K. and Basu, T.K. (1990). An overview of seismic discrimination using mainly Gauribidanur short period array data. National Symp. on Recent Advances in Seismology and their Applications, Gauribidanur, Bangalore, Kolar Gold Fields, July 16-19.

Arora, S.K., Basu, T.K. and Krishnan, C.A. (1983). Source depth as a useful parameter in the discrimination of earthquakes and underground explosions. Tectonophysics, **91**, 29-52.

Basu, T.K. and Arora, S.K. (1985). Complexity-TMF patterns of presumed nuclear explosions in USSR as an aid to source discrimination. BARC Publ. No. I-846.

Basu, T.K. and Arora, S.K. (1986) Charactristics of core reflected P waves from known and presumed explosions in Soviet Russia. BARC Publi. No. I-860.

Basu, T.K. and Arora, S.K. (1987). Characteristics of seismic sources of some Asian earthquakes and Soviet underground explosions from Gauribidanur array records. BARC Publ. No. 1348.

Basu, T.K. and Arora, S.K. (1991). Relative abundance of PcP energy in explosion seismic signals from Eastern Kazakh and Southwestern Russia recorded at Eskdalemuir, Yellowknife and Gauribidanur arrays. BARC Publ. No. 1548.

Birtill, J.W. and Whiteway, F.E. (1965). The application of phased array to the analysis of seismic body waves. Phil. Trans. Roy. Soc. Lond., Ser. A, **258**, 421-493.

Dahlman, O. and Israelson, H. (1977). Monitoring Underground Nuclear Explosions. Elsevier, Amsterdam.

Denham, D. (1963). The use of geophone groups to improve the signal to noise ratio of the first arrival in refraction shooting. Geophys. Prospect., **11**, 389-408.

Fryer, G.J., Odegard, M.E. and Sutton, G.H. (1975). Deconvolution and spectral estimation using final prediction error. Geophysics, **40**, 411-425.

Husebye, E.S. and Mykkeltvelt, S. (1981). Identification of Seismic Sources - Earthquake or Underground Explosion. Reidel, Dordrecht, Kelly, E.J. (1968). A study of two short period discriminant. Mass. Inst. Technol., Lincoln Laboratory, Tech. Note 1968-8.

Kulhanek, O. (1976). Introduction to Digital Filtering in Geophysics. Elsevier, Amsterdam.

Marshall, P.D. and Key, P. (1973). An analysis of seismic waves from earthquakes and explosions in the Sino Soviet area during 1966. United Kingdom Atomic Energy Authority, AWRE, Aldermaston, Rep. No. O 5/73.

Mowat, W.M.H. and Burch R.F. (1974). Handbook for the stations which provides Seismograms to the Blacknest Seismological Centre, United Kingdom. Ref. No. AWRE/44/47/29, AWRE, Aldermaston, Berks.

Murty, G.S., Nair, G.J. and Roy, F. (1979). Autoregressive method of detection of weak signals in noise for monitoring precursors. Mausam, **30**, 337-341.

Nair, G.J. (1983). Deconvolution of seismograms by the autoregressive method. Geophysics, **48**, 229-233.

Peacock, K.L. and Treital, S. (1969). Predictive deconvolution : Theory and practice. Geophysics, **34**, 155-169.

Robinson, E.A. (1966). Multichannel z-transforms and minimum delay. Geophysics, **31**, 482-500.

Robinson, E.A. (1967). Statistical Communication and Detection with Special Reference to Digital Data Processing of Radar and Seismic Signals. Griffin Book Co. London.

Roy,F, (1986). Depth of source from long period P-waves. BARC. Publ. No. 1338.

Roy, F. (1989). Depth-phase identification by prediction-error filtering - II, analysis of some presumed explosion signals. Phys. Earth. Planet. Inter., **54**, 231-240.

Roy, F., and Murty, G.S. (1982). Application of FPE based AR model for signal detection and digital data compression. Ann. Inst. Statist. Math., **34**, 181-188.

Roy, F., Arora, S.K. and Basu, T.K. (1992a). Detection of weak seismic signals using parametric modeling of seismic array data. Symp. on Signal Processing and Modeling of Geosignatures for Exploration of Oil and Natural Gas, Varanasi, February 27-29.

Roy, F., Arora, S.K. and Basu, T.K. (1992b). Detection of weak seismic signals using stationarity of noise and coherency of signals at a seismic array. Phys. Earth Planet. Inter., **73**, 264-273.

Ulrych, T.J. and Bishop, T.N. (1975). Maximum entropy spectral analysis and autoregressive decomposition. Rev. Geophys. Space Phys., **13**, 183-200.

Ulrych, T.J. and Clayton, R.W. (1976). Time series modelling and maximum entropy. Phys. Earth Planet. Inter., 12, 188-200.

Weichert, D.R. (1971). Short period spectral discriminant for earthquake and explosion differentiation. Z. Geophys., 37, 147-152.

Weichert, D.H. (1975). Role of medium aperture arrays : the Yellowknife system. In : K. G. Beauchamp (Editor), Exploitation of Seismograph Networks, Noordhoff, Leiden, 167-196.

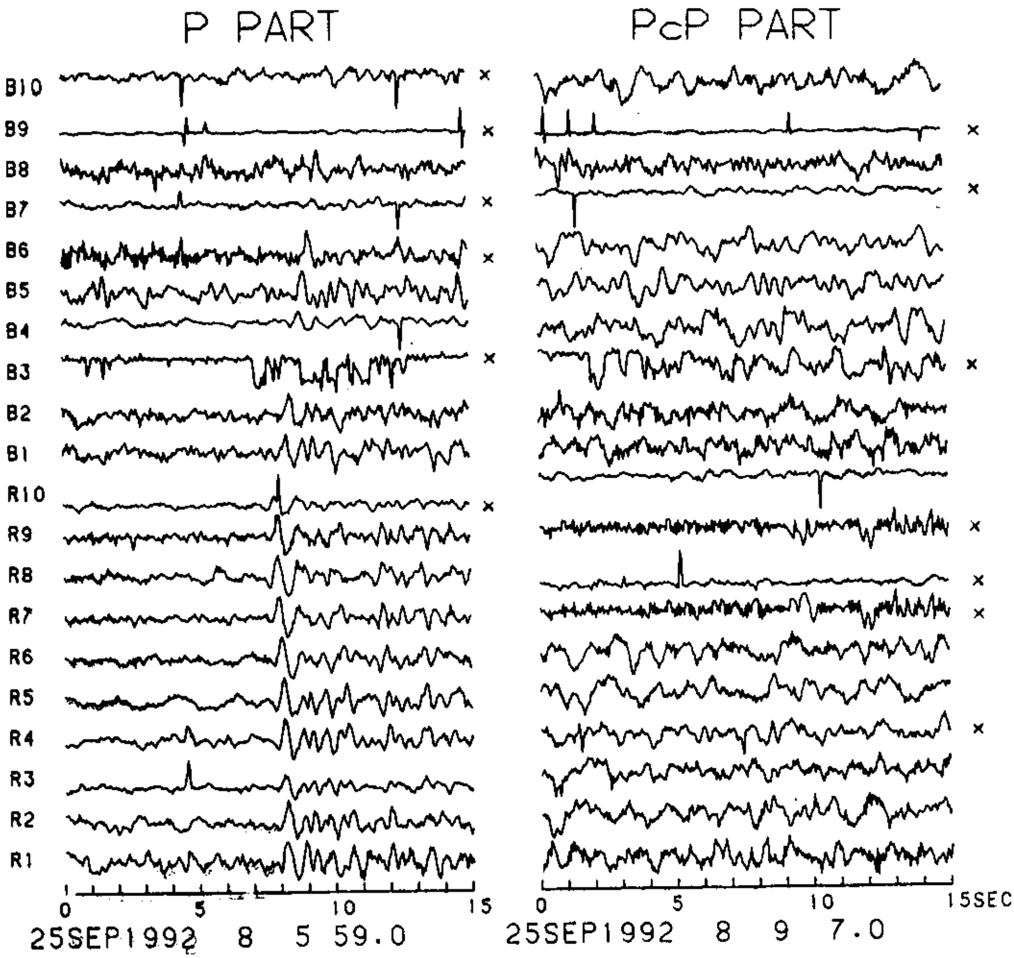

Fig. 1: Raw (unprocessed) waveforms plotted from digital data obtained at GBA corresponding to P and PcP parts (PcP signal is not discernable) of the recent Chinese underground nuclear explosion (magnitude Mb 5.0; yield approximately 15kt) at Lop Nor, Southern Xinjiang Province, on 25 September 1992. Labeled from R1 to R10 and B1 to B10 corresponding to twenty channels of the seismic array, each of the waveforms is reproduced for 15 seconds starting from 08:05:59.0 and 08:09:07.0 GMT respectively as shown by 1 sec time marks at bottom. Unsatisfactory recordings in some channels marked by crosses (x) are not used in further processing.

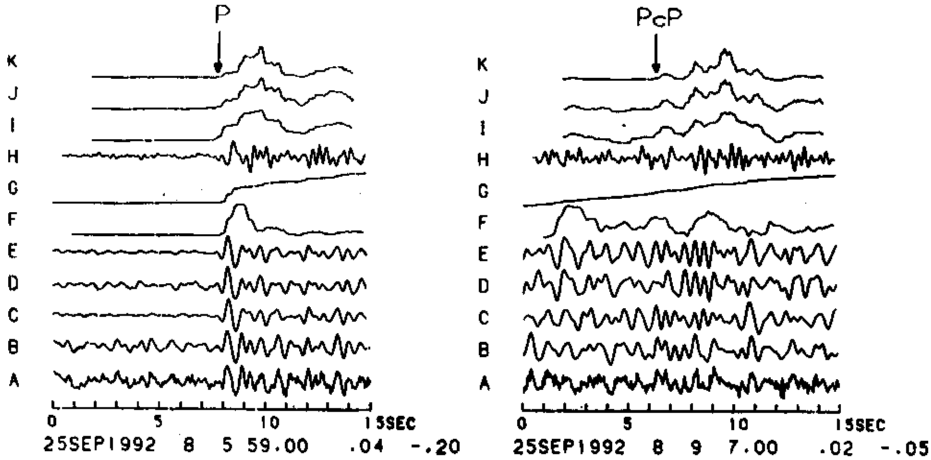

Fig. 2: Processed P and PcP signals, each from 15 sec GBA data of the Lop Nor, China, explosion event of 25 September 1992 (see fig. 1), with their onsets clearly detected at 08:06:07.0 and 186.2 sec later at 08:09:13.2 GMT respectively, marked by vertical arrows over the topmost traces. The eleven traces shown are : (A) typical raw seismogram from one channel (R1) of GBA, (B) bandpass (0.5-5 Hz) filtered version of trace A, (C,D) phased sums of signals from 'R' and 'B' arms of the array respectively, (E) finally beamed signal (overall sum of signals in C and D),. (F) correlogram using 1 sec sliding (by one discrete sample) time window, (G) cumenerogram, (H) prediction error filtered (PEF) version of the beamformed trace E, (I) zero lag moving autocorrelation (MAC) of the PEF trace H using 2 sec sliding window, (J) modulus sum of the MAC trace I from 4th to 40th sample for each step movement of the window, and (K) dot product of the traces I and J.

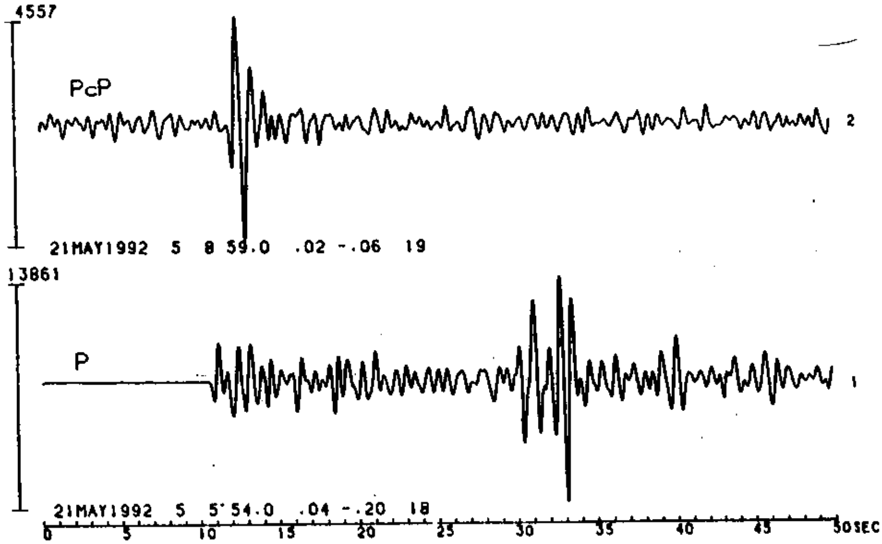

Fig. 3: Beamed P (1 : lower trace) and PcP (2 : upper trace) GBA seismograms of a large (megaton class) Chinese underground nuclear test at Lop Nor on 21 May 1992. Processing starts from 05:05:54.0 and 05:08:59.0 GMT for P and PcP respectively. Time marks at 1 sec interval are shown at bottom. Numbers on top of the vertical bars at left represent relative maximum signal amplitude in digital counts.

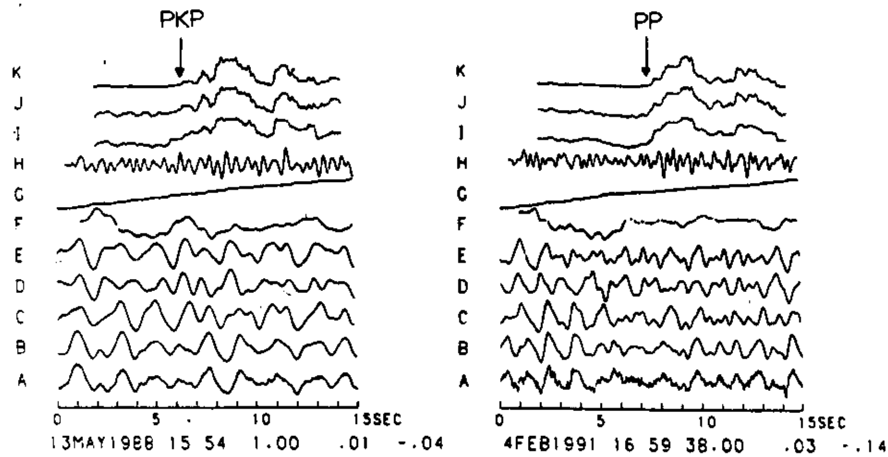

Fig. 4: Left set : processed PKP from 15 sec GBA data of a small (Mb 4.8; less than 10 kt yield) explosion (code named 'Shellbourne') at the Nevada Test Site on 13 May 1988, where the signal onset at 15:54:07.2 GMT is indicated by a vertical arrow over the topmost trace. Details of traces from A to K are as explained in fig. 2. Right set : similarly processed PP from a small (Mb4.5) shallow-focus (depth 10 km) earthquake that occurred in Central California on 4 February 1991.

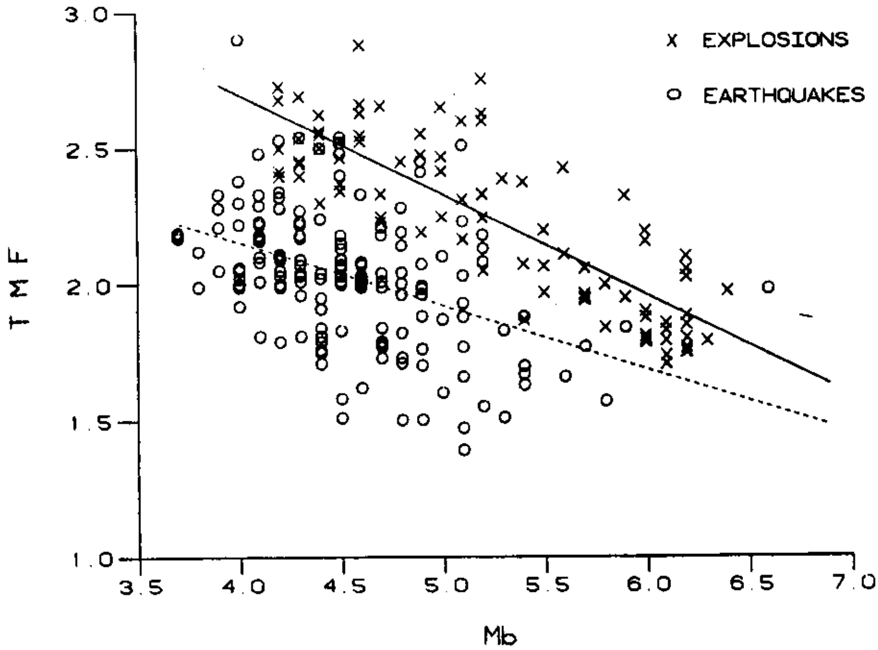

Fig. 5: TMF as a function of Mb for explosions (crosses) and earthquakes (circles) recorded at GBA and the corresponding linear best-fit shown by a continuous line through the data of presumed Russian explosions and by a dashed line through the data of shallow-focus Central Asian earthquakes.

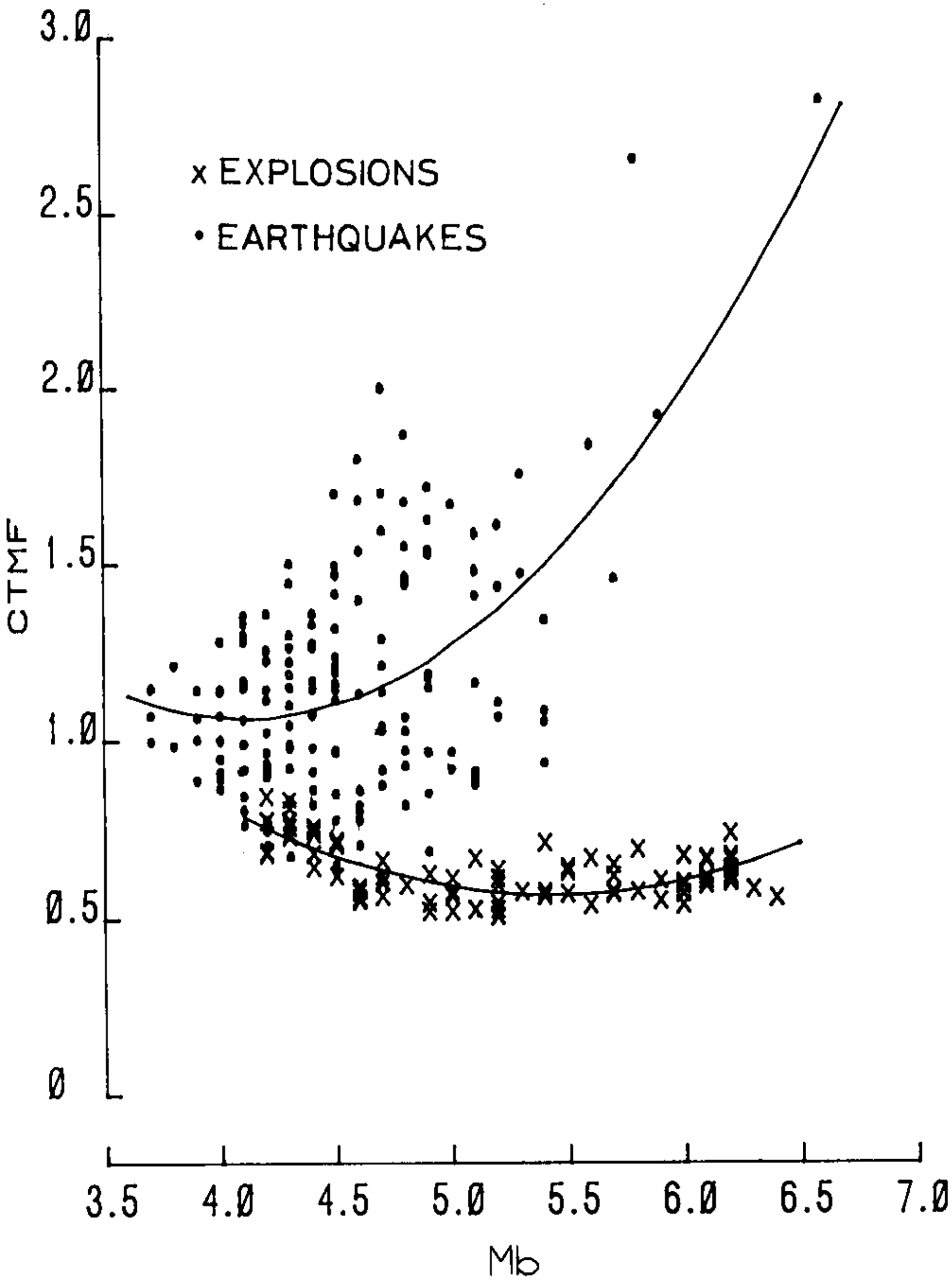

Fig. 6: Scaled TMF (CTMF) as a function of Mb for explosions (crosses) and earthquakes (small circles) mentioned in fig. 5. Notice two distinct branches of the quadratics in Mb.

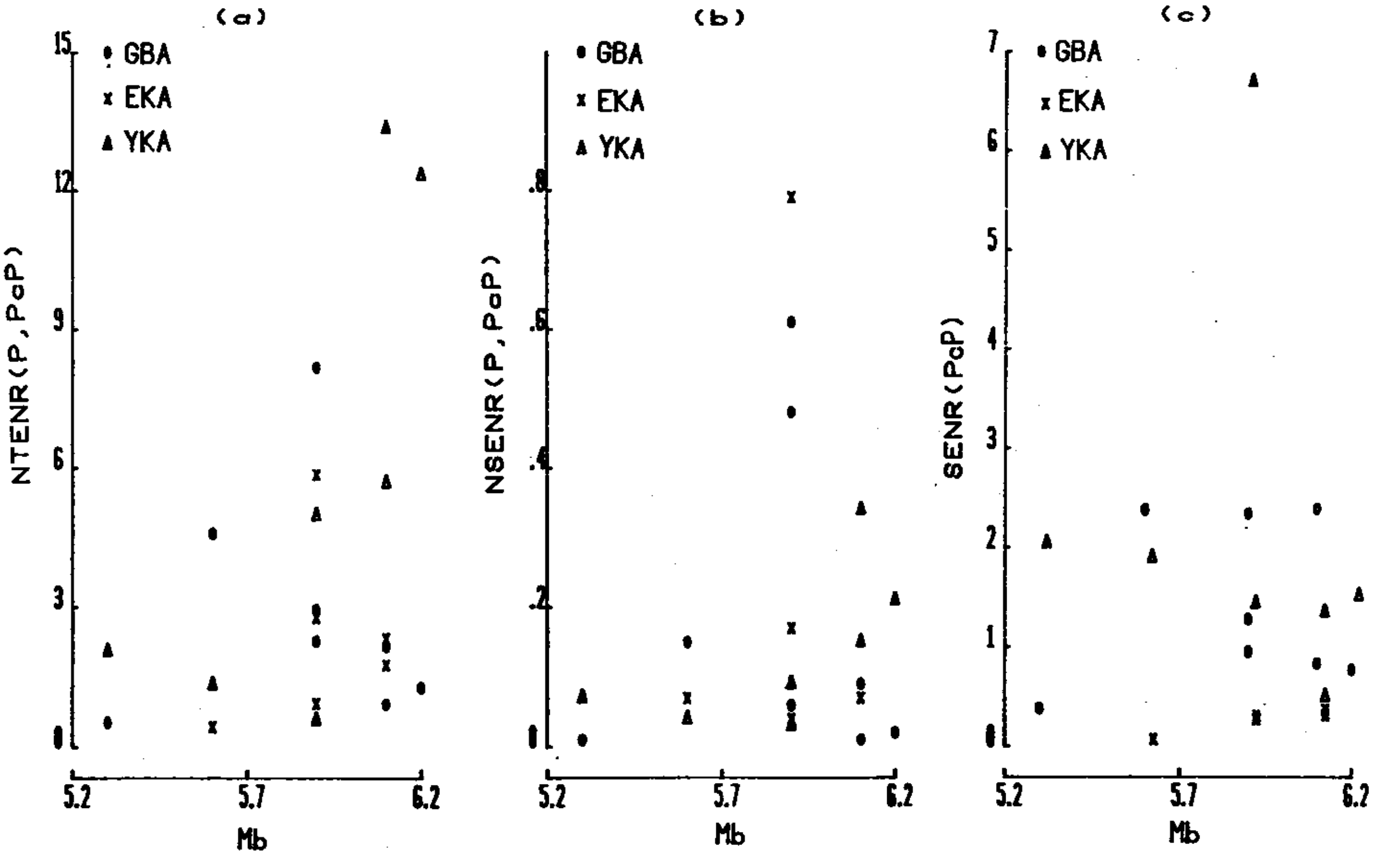

Fig. 7: Typical scores of the three constituents of the PcP discriminant, NTENR (Set a), NSENR (Set b) and SENR (Set c), obtained for three different arrays, namely GBA (circles), EKA (crosses) and YKA (triangles) from Eastern Kazakh explosion seismic data in the magnitude range Mb 5.2 to 6.2.

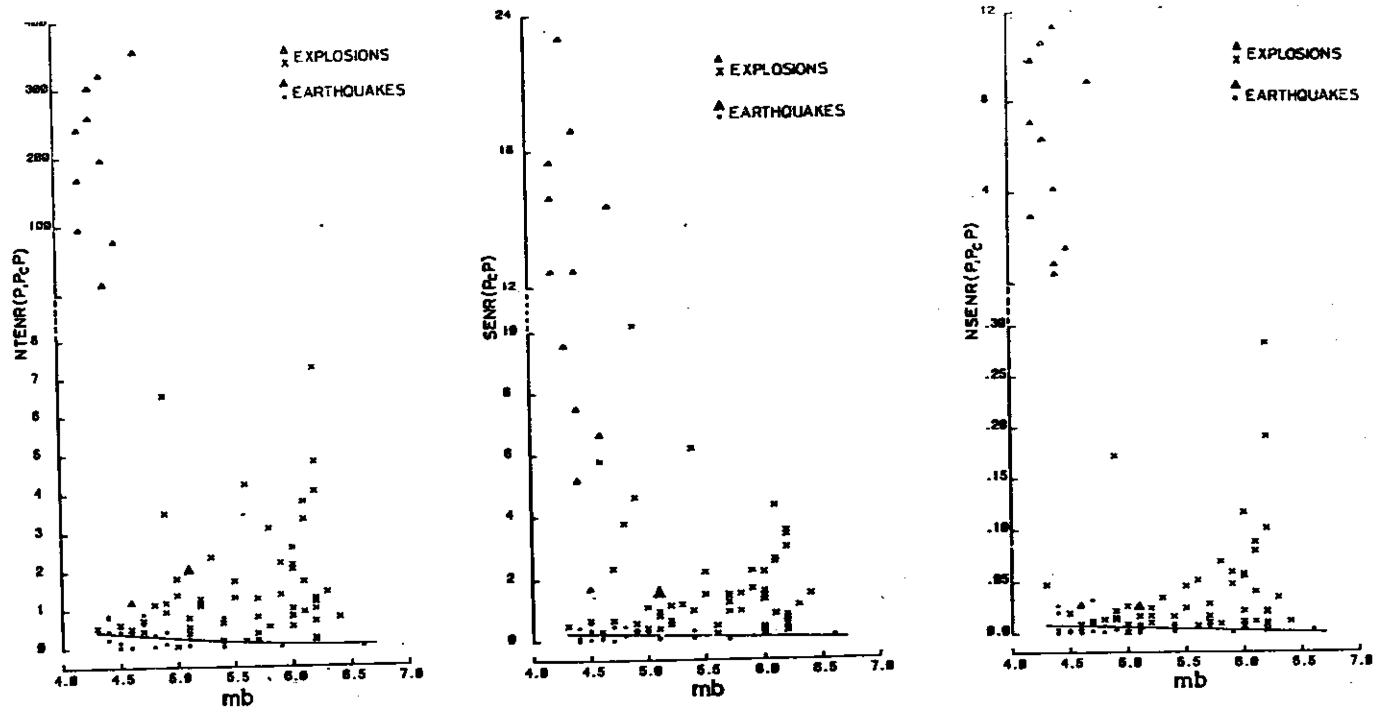

Fig. 8: Estimates of the PcP discriminant parameters, NTENR (at left) SENR (middle) and NSENR (at right) for some of the presumed Russian explosions (plain triangles and crosses) and Central Asian shallow-focus earthquakes (shaded triangles and circular dots) in a wide range of magnitude Mb 4.2-6.6 recorded at GBA. Notice that the best-fit quadratic drawn through the NTENR scores for the earthquakes and the linear best-fit through the SENR and NSENR scores for the same earthquakes clearly separate them out from the explosions. Notice also the exceptionally large estimates of the three identifiers for seismic events from Caspian Sea region (triangles), especially presumed explosions.