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세 성분 단일 관측을 이용해서 지진 인자의 정확한 산출을 위한 기술
A Technique of the Accurate Estimation for the Earthquake Parameters Using a Single Station of 3−component

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요약/Abstract

본 연구에서 세 성분 단일 관측을 이용해서 국지와 광역 지진 및 폭발의 진원 깊이, 진원시등을 재결정 했다. 우리는 진원 방위각, 시범 지진 진앙이 산출될 수 있는 편파분석 방법에 의해서 이 연구를 수행하려고 한다. 일정한 층속도 모델에 기초를 두고 이론적 주시표가 각 이벤트 입력 지진 위상들에 맞도록 계산 될 수 있다. 지진 규모는 P파 코다(coda)의 지속시간을 이용해서 결정한다. 최소 오차에 대응하는 결과는 이 연구에서 모두 지진의 평균 깊이는 15km 이라는 것을 보여주는데 이것은 다른연구 조사와 매우 일치함을 알 수 있다(Kang and Choi, 1993).

In this study, hypocenter parameters of some local and regional earthquakes and explosions, including focal depth and origin time, were redetermined by using a single station of three−component. We attempt to do the job by the combination of polarization analyses, by which azimuths and trial epicenters of earthquakes can be figured out, and a layered constant velocity model, on the basis of which theoretical travel times can be computed to match a series of input seismic phases of the event. Magnitudes were determined by using coda duration. Results, which correspond to the least misfit, showed that the average focal depth of all earthquakes in this study is around 15km, which fits well to that by investigation (Kang and Choi, 1993).

Introduction

Of all the hypocenter parameters of an earthquake, focal depth is the most difficult one to reliably determine and deviation can be as large as 15km even for a crustal hypocenter. For the purpose of a reliable determination, usually data from a seismic network, large or small, should be available, on the basis of which regression algorithm can be carried out to match all data from different stations. But for such regions as the Korean peninsula where data from a seismic network are rarely obtained, some other method should be developed to estimate hypocenter parameters by using a single station of three—component.

Determination of hypocenter parameters usually begins with azimuth which can be reliably estimated by polarization analysis applied to three—component digital data of one single station(Roberts *et al.*, 1989;Roberts and Christoffersson, 1990;Kim and Lee, 1995). Here we first get three—component digitized data of an event filtered to enhance the signal—to—noise ratio and then apply the polarization analysis to *P*(e.g. *Pn*) phases. We choose *P* phases because they usually have well—defined polarization characteristic, e.g. higher rectilinearity, thus azimuths can be more reliably estimated than using other phases. After this, the epicenter (latitude and longitude of an earthquake) can be preliminarily estimated by using $S-P$ method, which are useful for our next step.

Now we already have some ideas about the hypocenter of the event after polarization analysis. Suppose that the hypocenter was fixed at a certain place underground, from which all seismic phases should arrive at the receiver in a time sequence as what we have seen in the three—component waveforms. So it is natural for us to compute travel times of different phases to match the time sequence as what we have seen in waveforms.

So for a solution, at least two valid phases should be picked up in the three components, as is generally satisfied, e.g., *P*,*S* phases. Two phases, accompanied by their arrival times, were input to our next procedure. So theoretically, one azimuth and two phases form a minimum condition under which a hypocenter solution can be guaranteed. But to calculate theoretical travel times, a priori knowledge about the velocity distribution in the concerned area is needed. We copied a layered constant velocity model previously set up for the southern Korean peninsula by Kim and Lee(1994), on the basis of which theoretical travel times can be calculated to match the input phase arrivals. To do this, we input a trial epicenter determined by polarization analysis and a trial focal depth which form a trial hypocenter. Given the trial hypocenter for the earthquake, travel time misfit for every phase and mean residual sum(RMS) were computed in each iteration loop. RMSs were compared between loops and the initial parameters were corrected if RMS becomes decreasing, then misfit and RMS were recalculated, leading the solution to converge to a best one, e.g., the solution when the minimum RMS was reached.

All above analyses can be carried out efficiently on a PC computer by using two programes, one for polarization analysis and one for hypocenter determination.

Method and analyses

In our case, preparing the input parameters, including one azimuth, at least two valid seismic phases plus one layered constant velocity model for the area where receiver and epicenter lie, etc., is the critical point to get a reliable hypocenter solution.

Given three components *NS*, *EW*, *UD* of an earthquake from a digitized record, polarization analysis can be applied to them to obtain the azimuth AZ of the event after they are properly filtered to improve the three—component signal—to—noise ratio. Here AZ was obtained by applying polarization analysis to only the *P* phase of en event(e.g., *Pn*) since it usually has well—defined polarization characteristic, i.e., higher rectilinearity than other phases and it can be counted as a input phase.

Two more phases, which usually are the first arrival phases of an earthquake, e.g., *Pn* and *Sn* phase since they are two phases of great importance and easy to indentify, should be picked up from the three—component waveforms. For explosions, we can use such phases as *Pg* and *Sg* if there are no *Pn*and *Sn* phases available. One azimuth and two seismic phases(3 phases) will guarantee a reliable solution if other input parameters can also be reliably prepared. The input phases can be more if available such as *Sg*, *Lg* and *Rg* etc., but all these phases, together with their arrival times, should be well identified, otherwise severe outliers would occur. For the sake of objectiveness, we input more phases only if they can be accurately made out. It is superbly recommended to include such reflected phases as *pP* etc., (so−called depth phases) to preliminarily estimate the focal depth by using an averaging apparent velocity.

To calculate the theoretical travel times of regional phases, a velocity model for *P* and *S* phases about the area conserned, e.g., the Korean peninsula, is necessary. In the present study, we just copied the layered constant velocity model previously developed by Kim and Lee(1994) who constructed a crustal model for the southern part of the Korean peninsula(see Table 1). We extend the app licability of the model a little more north to south Pyongyang area where a small earthquake($M<4.0$) took place recently. The four−layer velocity model gives velocities of *P* and *S* waves in each layer and the average depth of the Moho interface, e.g., 32km. The model can only be applied to calculating travel times of basic phases(*P* and *S* type phases) in local and regional earthquakes and explosions due to its limited applicability. All events in our present study cover epicentral distances $\Delta<3°$, within which the model is reasonably applicable. As for teleseismic events($\Delta>20°$), the IASPEI91 velocity model will be automatically chosen(not our case).

Table 1 Layered constant Velocity model(Kim and Lee, 1994)

Depth(km)	Vp (km/s)	Vs (km/s)
6.0	4.50	2.20
18.0	6.00	3.50
24.0	6.30	3.70
32.0	6.70	3.90
50.0	7.95	4.60

To estimate magnitude of an event, an empirical formula which defines the duration magnitude of an event was used as following :

$$M_d=-0.37+2.0*\log(T)+0.0035*\Delta+C \cdots\cdots(1)$$

for earthqukaes and

$$M_d=-0.87+2.0*\log(T)+0.0035*\Delta+C \cdots\cdots(2)$$

for explosions, where M_d is the duration magnitude; T is the coda duration in seconds; Δ is the epicentral distance and C is the station correction.

Suppose that the hypocenter is in the second layer with depth *h*km, then the travel time of *Pn* wave is :

$$t_n=\frac{H_1+2H_2-h}{\sin e_2u_2}+\frac{2H_3}{\sin e_3u_3}+\frac{2H_4}{\sin e_4u_4}+\frac{H_1}{\sin e_1u_1} +t' \cdots\cdots(3)$$

where t' is the time for the seismic rays travelling with velocity u_5 at the fourth interface(Moho discontinuity), where total reflection takes place, that is

$$t'=\frac{\Delta-(H_1+2H_2-h)ctge_2-2H_3ctge_3-2H_4ctge_4-H_1ctge_1}{u_5} \cdots\cdots(4)$$

where e_1,e_2,e_3 and e_4 are emergence angles, corresponding to incidence angles i_1,i_2,i_3 and i_4 (i.e., $e_1+i_1=90°$, and so on) at the four interfaces where seismic rays refract. They follow the relations below :

$$\cos e_1=\frac{u_1}{u_2}\cos e_2 \cdots\cdots(5)$$

$$\cos e_2=\frac{u_2}{u_3}\cos e_3 \cdots\cdots(6)$$

$$\cos e_3=\frac{u_3}{u_4}\cos e_4 \cdots\cdots(7)$$

$$\sin e_4=\frac{u_4}{u_5} \cdots\cdots(8)$$

H_1,H_2,H_3,H_4 and v_1,v_2,v_3,v_4 are the layer thicknesses and *P* wave velocities in each layer, respectively and Δ is the epicentral distance.

Here the focal depth h and t_n are the unknown parameters and for another phase such as *Sn*, we have similar relations as equations (3)−(8), that is :

$$t_s=f(h) \cdots\cdots(9)$$

and the last one is the $S-P$ time difference :

$$t_s - t_n = \Delta t_{s-n} \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (10)$$

where Δt_{s-n} can be read from seismic records.

As for *Pg* and *Sg* waves which propagate to the receiver directly from a source, their travel times can be easily deduced in a similar procedure as above.

Up to here, we have three equations (3),(9) and (10), and three unknowns h, t_n and t_s, thus a self-defined system forms. So it seems that a solution about the hypocenter would be accurately obtained by finding a solution of the system. However, the system defined by above relations is only a first-order approximation of the real case and never has an exact solution due to the following reasons : (1) The input layered constant velocity model is just an approximation of the real velocity distribution modelling. Deviations could increase especially where severe inhomogeneity was encountered. Accuracy of the final hypocenter solution depends closely on that of the model, as can be proved by our experience that the hypocenter solution is very sensitive to the model parameters. (2) Inaccuracy of other input parameters make them never exactly match each other and the input phases. For these reasons, it is reasonable to apply a trial and error method, following the principle that the best solution is the one with the minimum residual. We applied a least-square iteration loop within which theoretical travel times as well as mean residual sum(RMS) were computed. RMS is the weighted sum of all residuals of those parameters for one hypocenter solution, describing the extent to which the input phases were matched. Between iteration loops, RMSs were compared and a damping algorithm was used to enable the solution converge efficiently to a best one, i.e., the solution when the minimum RMS was reached.

To cook the cake, earthquakes and explosions (five each) were processed with their parameters and hypocenter solutions listed in Table 2. The five

Table 2 Hypocenter parameters of earthquakes determined by using single station of three-component

Events	OT.			Focal Depth(km)	Duration Magnitude	epicenter lat long	rms
	h	m	s				
South Pyongyang EQ (11/10/1995)	14	03	52.94	11.8	3.6	38.7 125.9	0.00
Paekryong-do EQ (8/11/1995)	18	16	24.24	18.5	3.5 †(3.6)	38.0 124.5 ‡(38.0 124.6)	0.00
Puyo EQ (9/16/1995)	15	12	28.90	18.9	2.5 †(2.4)	36.3 126.8 ‡(36.3 126.8)	0.00
Samchok EQ (10/6/1995)	12	06	16.72	17.4	3.8 †(3.7)	37.4 129.9 ‡(37.5 129.8)	0.00
Munchon EQ (7/19/1992)	08	02	18.42	10.7	3.2 †(3.1)	39.3 127.0 ‡(39.1 127.1)	0.00

† Magnitudes from the KMA report.

‡ Epicenter parameters from KMA report.

earthquakes all happened within the Korean peninsula or in seas around it. From Table 2, we can see that they have an average depth at 15.5km, i.e, within the second layer of the velocity model. All focal depths were measured with their depth origin at sea level. It is reported that earthquakes in the Korean peninsula all have their focal depths around 15km. Duration madnitudes for these earthquakes fit well to those from the Korea Meteorological Administration(KMA). Processing procedures as well as input phases for the Munchon earthquake(7/19/1992) were shown in Figure 1. After being bandpass filtered, three components seismic data of the earthquake were input to the first program to make a polarization analysis on. Pure continental path, which results in two clear *Lg* phases with different velocities(see Figure 1), lies between the Munchon earthquake and its receiver, Wonju station(37.48°N, 127.90°E) and clear first−breaks in waveforms make phases easy to indentify (see Figure 1). Polarization analysis applied to its *Pn* phases yields an azimuth of 339°. Latitude and longitude of the epicenter were preliminarily determined by using $S-P$ method and were regarded as trial values for next program. The azimuth, trial epicenter and arrival times of four phases : *Pn*,*Pg*,*Sn* and *Lg* were input to the second program which, after 5 iteration loops, yields an hypocenter solution with its RMS of 0.001(see Table 2). However, it is noteworthy that the solution here means that it is the best one under the present condition of given inputs. So overall a priori knowledge about the hypocenter is advantageous for the reliable determination of its parameters. Among the four phases, normally *Pn* and *Sn* have larger weights for a hypocenter solution than *Pg* and *Lg*. Good fit between our final epicenter position, magnitude and those from KMA report shows the reliability of our final hypocenter solution. The same analyses were also applied to the South Pyongyang Earthquake(11/10/1995) (see Figure 2), the Puyo Earthquake(9/16/1995) (see Figure 3), the Samchok Earthquake(10/6/1995)(see Figure 4) and the Paekryong−do Earthquake(8/11/1995) with their results listed in Table 2. Epicenters and magnitudes of these earthquakes determined in our study are all close in value with those from KMA reports. Based on above analysis, an epicentral distribution map was plotted in Figure 5.

Through Figures 1 to 4, we can hardly see *Rg* waves, except in Figure 4 for the Samchok Earthquake which covers the longest epicentral distance in this study, about 288km(see Figure 5). But *Lg* waves, which can be clearly seen in the transverse components, exist in all these events. It has been recognized that the focal depth of a regional or local event is of great significance for waveform generation of *Rg* waves and complexity of *Lg* waves(Kim, 1994). So from an earthquake like the Puyo earthquake, which covers a shorter epicentral distance and has a larger focal depth, we can not observe *Rg* waves.

We made an attemption to determine the hypocenter parameters of explosions by the method. As we know, the hypocenters of explosions are usually above sea level, e.g., their focal depths are negative. The programs can do the job after a little modification. We give three examples in Figures 5, 6 and 7 where processing procedures to the KSRS09 Explosion(1/24/1988), the KSRS15 Explosion(1/26/1988) and the KSRS21 Explosion(1/29/1988) were shown respectively. For each case, we also have four or five phases and an azimuth from polarization analyses. But among the four or five phases, *P* and *S* phases normally have larger weights for a hypocenter solution than other phases, the same as in case of earthquakes. Of the three explosions, only the KSRS21 Explosion has *Sn* phase while the other two have *Sg* phase. *S* type phases of explosions always have smaller transverse amplitudes, compared with those of earthquakes, as has been pointed out by Kim(1994). It holds true for all the explosions in the present study. The focal depths of the explosions in final solutions are zero or negative(see Table 3), which should be understood that the hypocenter is very shallow while their absolute values are of no physi-

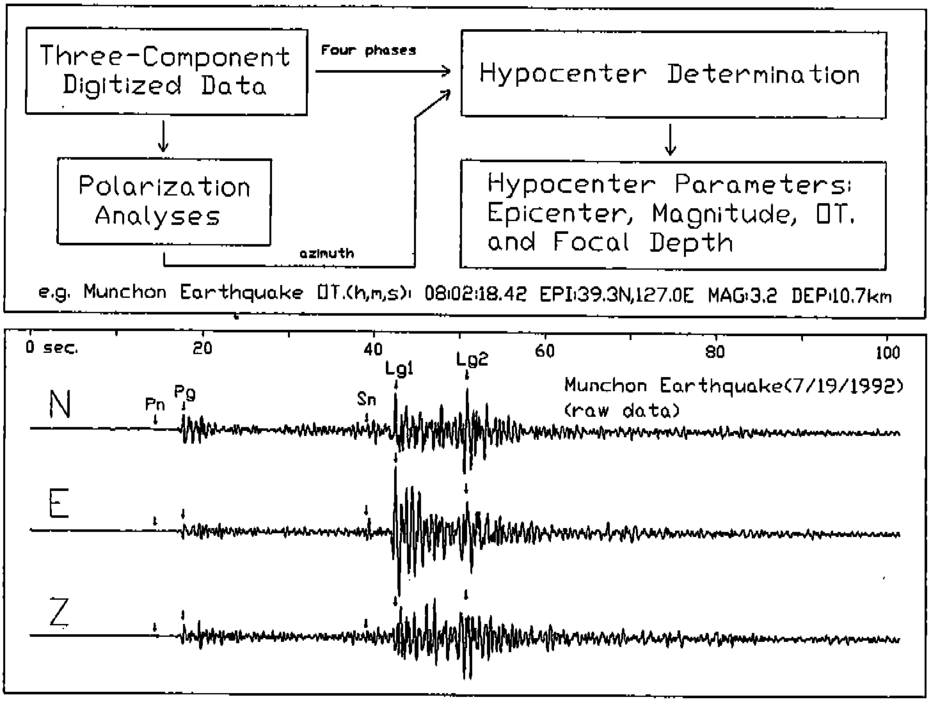

Figure 1 The technique in the present study being applied to the Munchon Earthquake(7/19/1992). The upper part is the flow chart showing the main processing procedures described in the text. The lower part shows the three-component seismograms with arrows denoting all the phases that can be found in the earthquake.

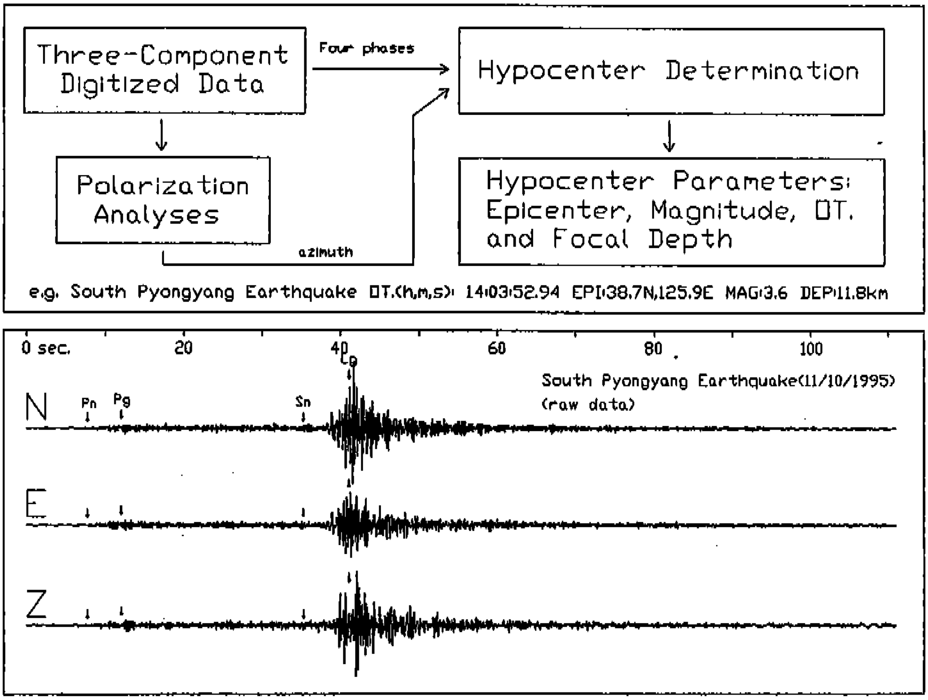

Figure 2 The same as Figure 1, but to the South Pyongyang Earthquake(11/10/1995)

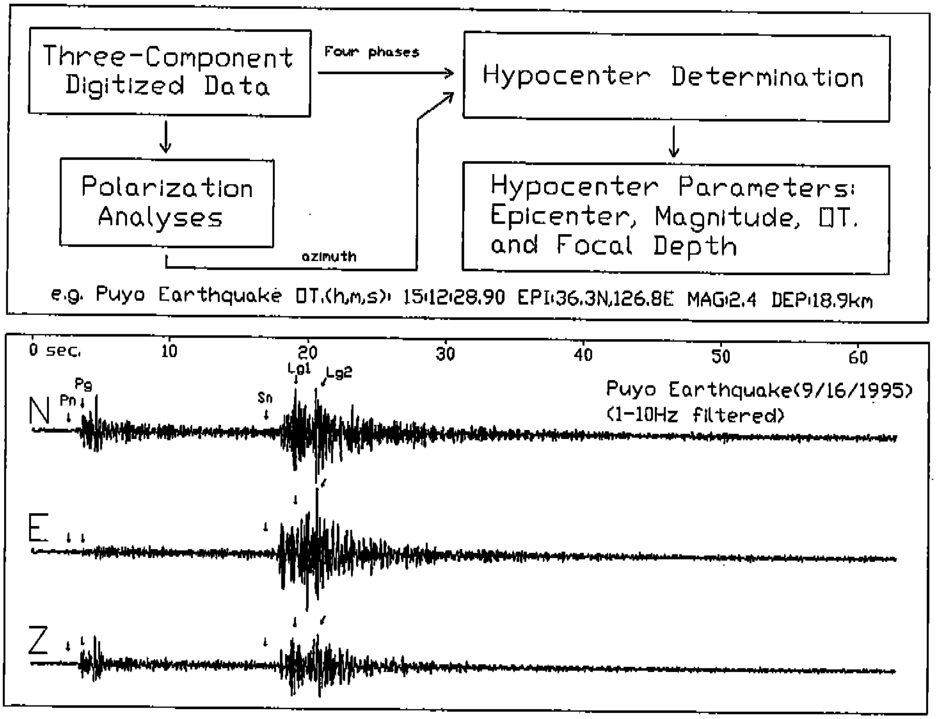

Figure 3 The same as Figure 1, but to the Puyo Earthquake(9/16/1995), which was 1-10Hz bandpass filtered to make phases more distinct in the waveforms.

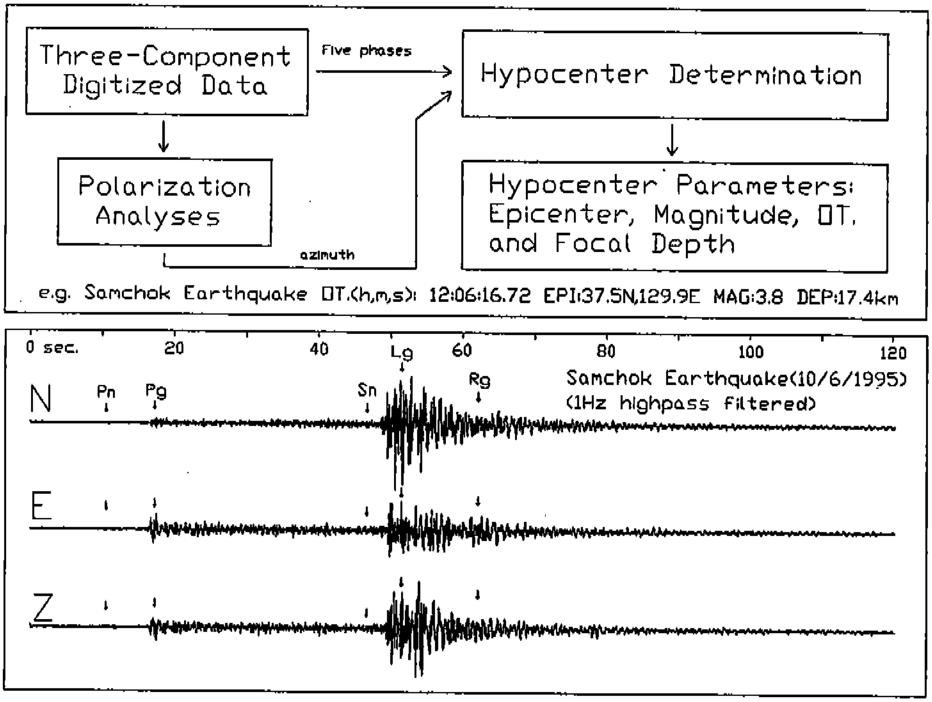

Figure 4 The same as Figure 1, but to the Samchok Earthquake(10/6/1995), which was 1Hz highpass filtered to make phases more clear in the waveforms.

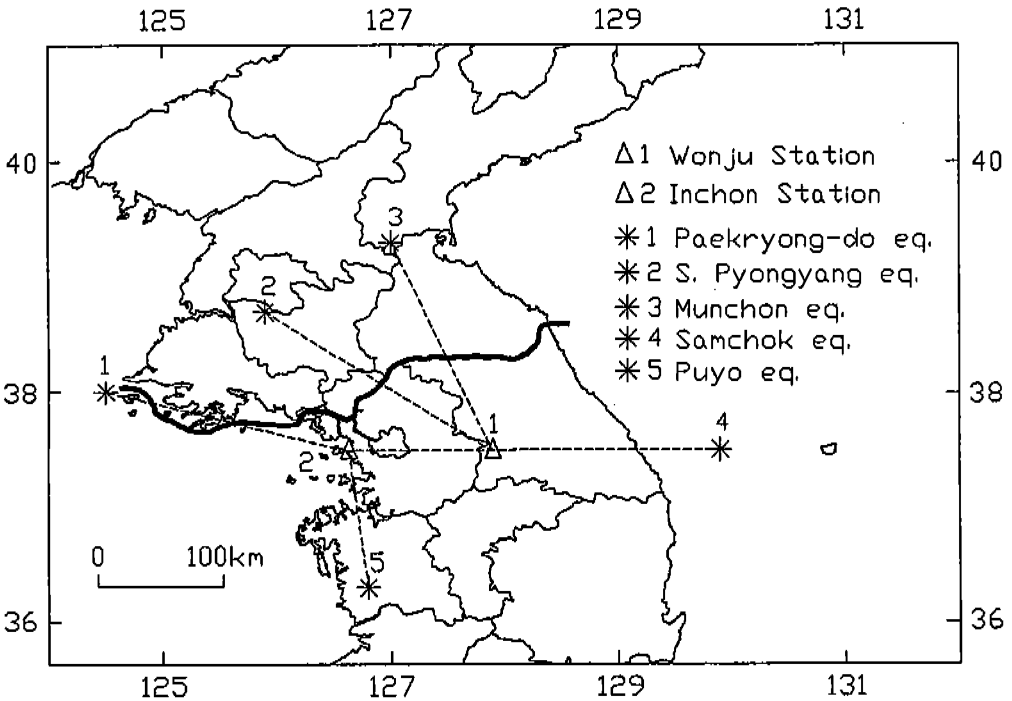

Figure 5 Epicenter distribution map of the earthquakes in this study. The epicenters were plotted by using parameters determined by the present study(for details, see the text and Table 2).

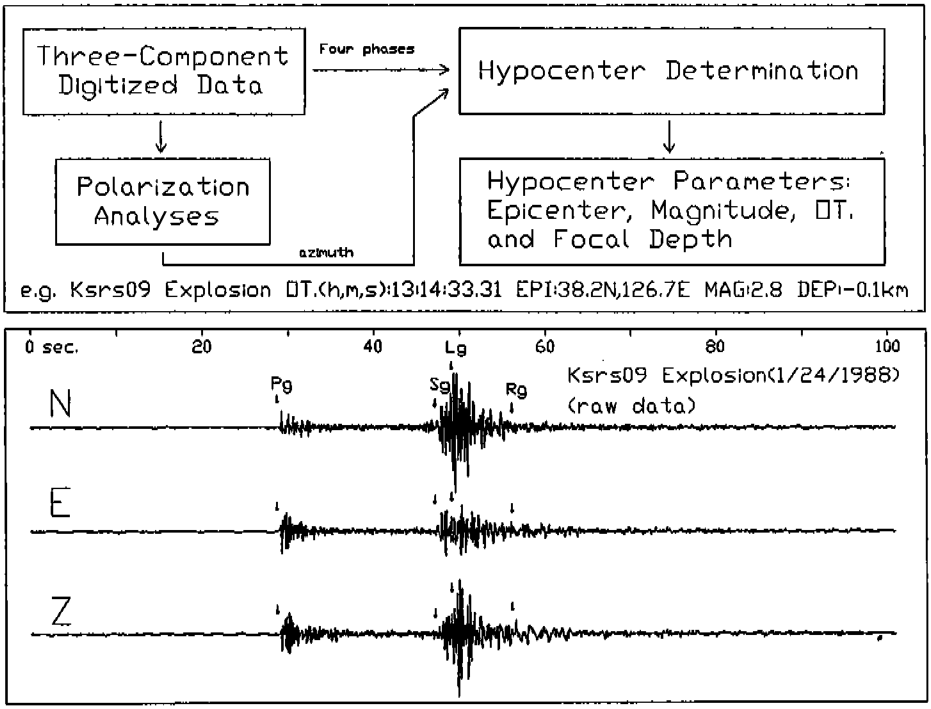

Figure 6 The same as Figure 1, but to the KSRS09 Explosion(1/24/1988).

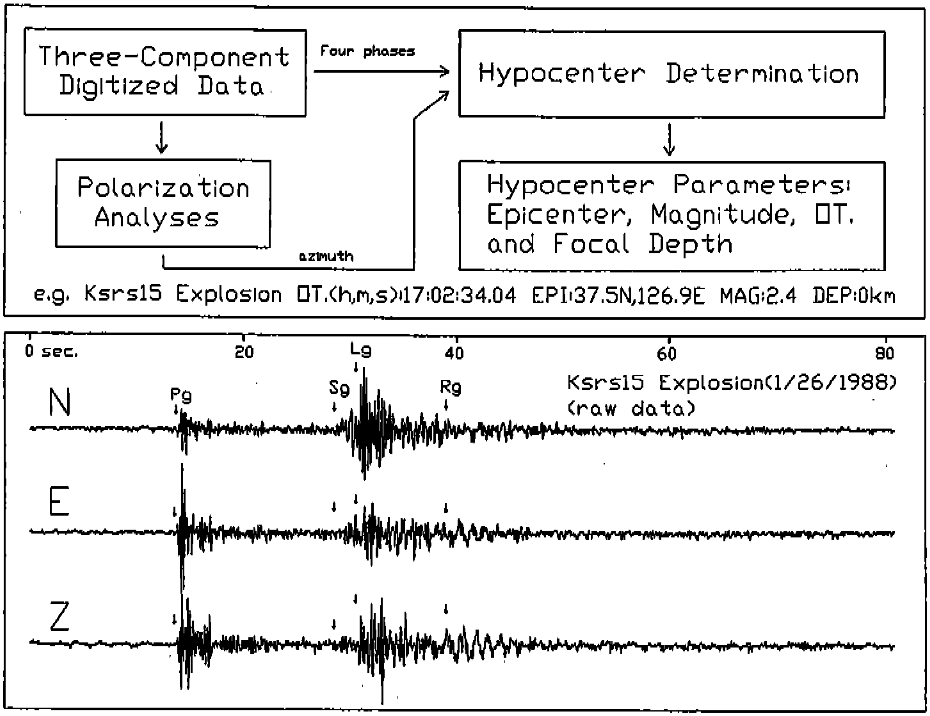

Figure 7 The same as Figure 1, but to the KSRS15 Explosion(1/26/1995).

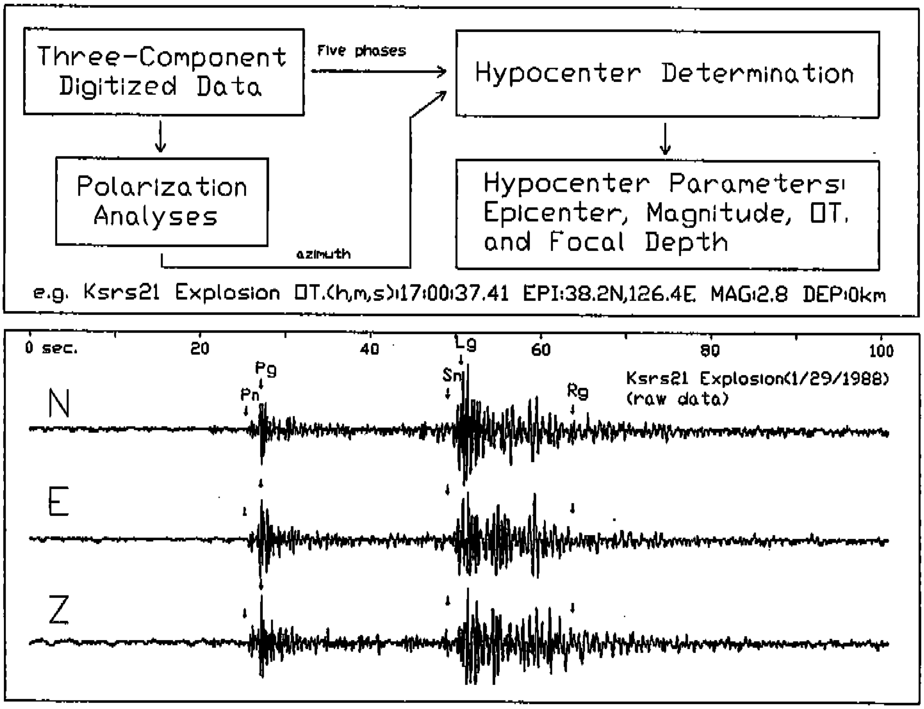

Figure 8 The same as Figure 1, but to the KSRS21 Explosion(1/29/1995).

cal meanings, because in our study, the resolution is not high enough to resolve such focal depths. As the depth origin was set at sea level and positive down, negative depths indicate that the sources were above the sea level, as is the normal case for explosions.

Table 3 Hypocenter parameters of explosions determined by using single station of three-component

Events	OT.			Focal Depth(km)	Duration Magnitude	epicenter Lat long	rms
	h	m	s				
Ksrs09 EX (1/24/1988)	13	14	33.31	−0.1	2.8	38.2 126.7	0.02
Ksrs15 EX (1/26/1988)	17	02	34.04	0	2.4	37.5 126.9	0.01
Ksrs21 EX (1/29/1988)	17	00	37.41	0	2.7	38.2 126.4	0.00
Ksrs11 EX (1/25/1988)	12	13	2.33	−0.1	3.0	38.9 125.9	0.37
Ksrs23 EX (1/30/1988)	11	58	2.58	0	1.8	38.1 127.1	0.00

Negative focal depths mean that the souces are above the sea level.
RMS is the mean residual value.

Discussion and conclusions

In this study, a method to determine hypocenter parameters of local and regional earthquakes and explosions, including focal depth, origin time and magnitude, by using a single station of three−component has been presented. Our practice shows that it is an efficient and economic way to make an estimation of almost all parameters of a hypocenter, compared with other methods, such as to do the same job by using a seismic array, etc..

Polarization analysis, giving an azimuth of an earthquake and a trial epicenter for the next program and an iteration algorithm, computing theoretical travel time to match all input phases involve in the whole procedure. Magnitudes were defined by using coda duration which yield reasonable values. Final focal depth and epicenter results were taken out from the hypocenter solution which corresponding a minimum RMS. As long as our inputs are well prepared, the final results will be reasonable and reliable, as can be seen from our results.

As we mentioned, the minimization of errors arose due to approximations in the whole prcessing procedure, which can be the target for future study.

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