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SEISMIC TRAVEL TIME ANOMALIES FROM EVENTS IN THE WESTERN SOVIET--ETC(U)
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Seismic Travel Time Anomalies from Events in the Western Soviet Union

Michael J. Shore

November 24, 1980

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SEISMIC TRAVEL TIME ANOMALIES FROM EVENTS IN THE WESTERN SOVIET UNION

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TABLE OF CONTENTS

SEISMIC TRAVEL TIME ANOMALIES FROM EVENTS IN THE WESTERN SOVIET UNION

FIGURES

TABLES

Abstract

An iterative technique and the joint epicenter determination technique are utilized to compute improved locations for 33 presumed underground explosions in the western Soviet Union and station corrections to the Herrin et al (1968) travel time curves for 98 stations. Comparison of the results of the two techniques indicates that the iterative procedure produces improved location accuracy relative to the joint epicenter determination technique. Analysis of the station corrections determined by this study indicate that epicenters located on a worldwide basis with these corrections are as reliable, or slightly better than those determined using corrections from previous studies. For events in the western Soviet Union, the station corrections are superior to previous estimates. Comparison of the travel time corrections with magnitude residuals previously determined by North (1977) fails to indicate a strong worldwide correlation of early arrivals with increased amplitudes and late arrivals with decreased amplitudes.

I. INTRODUCTION

A considerable effort has been expended in the past twenty years to refine and explain the variations observed in the travel time of P-waves at teleseismic distances. The early travel-time curves were based primarily on observations from a large number of earthquakes at a limited number of seismic stations. Later work involved the use of underground explosions for which the locations and origin times were precisely known and recordings were made at well distributed networks of stations.

Utilizing a number of underground explosions and a large suite of well located earthquakes, Herrin et al (1968) developed a revised travel time curve which was to represent an average earth. Many authors (Cleary and Hales (1966); Engdahl, Sindorf and Eppley (1977); Hales et al (1968); Hales and Doyle (1967); Herrin and Taggart (1968); Lilwall and Douglas (1970); Hales and Herrin (1972) and others) have examined the computation of corrections to the travel time curves. These corrections have been interpreted in various ways; relating them to upper mantle inhomogeneity, near station effects including azimuthally varying corrections, and also as refinements to the actual average earth relationships. The overriding conclusion is that in order to conduct extremely accurate epicenter location calculations, specific, but variable, travel time corrections must be developed for each station. When a "worldwide" average correction is developed for a station, an improvement in location capability is achieved. However, significantly improved location capabilities only come through the development of station corrections for paths to each geographical area.

It is the purpose of this paper to present the results of an analysis of travel time corrections to the Herrin et al (1968) curves for a worldwide network of stations for events in the western Soviet Union. Through the use of these corrections, improved location determination of events in this area will be possible. Two techniques, an iterative epicenter determination procedure and the Joint Epicenter Determination (Douglas, Lilwall and Young (1974)) are utilized to develop travel time corrections based upon 33 presumed underground explosions. The two techniques are compared for this application and the resulting travel time corrections are related to previous tabulations for other geographical regions.

II. TRAVEL TIME CORRECTION PROCEDURE

The procedure utilized to locate the presumed explosions and determine the travel time corrections is quite similar to that used by Herrin et al (1968) whereby residuals are developed from best estimates of hypocenters. Corrections are then developed from the residuals and applied to the data prior to relocating the epicenters. In this case, measurements for epicentral distances less than 20 degrees and PKP distances are rejected. The hypocenter program (Cannon (1967)) which was used in this study, estimates the event location through a least squares procedure and was set to automatically reject a station when the travel time residual for the P-phase was greater than three standard deviations from the predicted travel time for the particular event. The residuals for all events were sorted by station and any phase more than three standard deviations from the mean residual of the station was also rejected. The mean station residuals for the selected geographical region were then determined as the average for each station. Corrections for these residuals were then applied to the initial data base, including those phases which were previously rejected for having large residuals. The procedure was repeated using the corrected arrival times.

A data base of 33 presumed underground explosions in the western Soviet Union was selected from tabulations by Dahlman and Israelson (1977). Presumed explosions were chosen so that depth could be constrained to sea level and thereby minimize depth uncertainty. The events were chosen to maximize coverage of a specific geographical region, namely the western USSR, thus minimizing any specific aspect of a local region, and to include events whose sizes would ensure that they were relatively well recorded at a large number of stations. The distribution of these events is indicated in Figure 1. Available seismological bulletins from the US Geological Survey, International Seismological Centre, VELA Uniform Program, and several other international sources were searched for all available P-phase arrival times for the event set. This resulted in a tabulation of 4,893 reported phases at 635 different stations. Only tabulated arrival times as reported by the various bulletins were used in this study. In order to eliminate those stations which detected a small number of events, only those which detected at least half of the events were selected. This reduced the number of detections to 2,361 and the number of stations to 102. Four additional stations were deleted when preliminary estimations of the

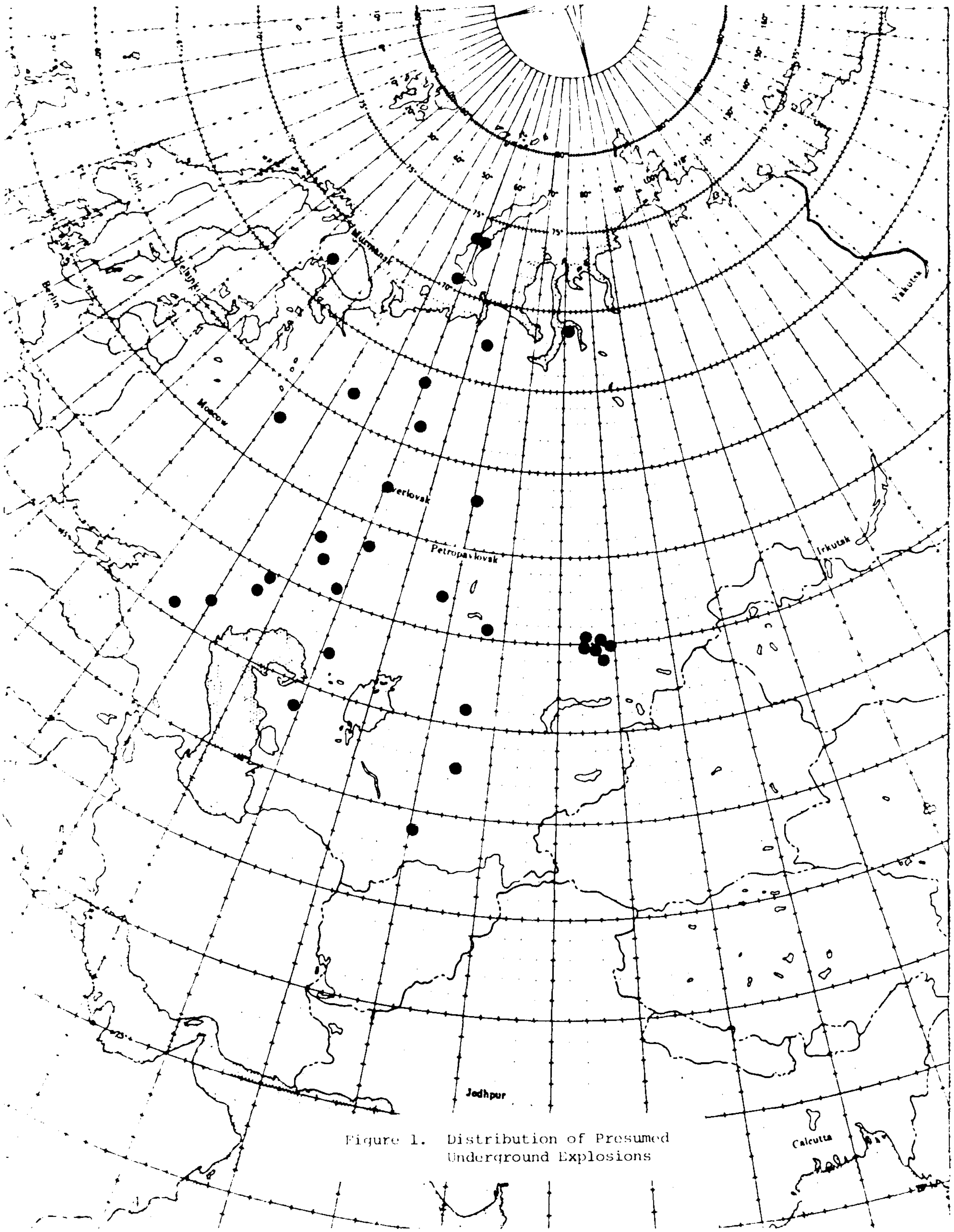

Figure 1. Distribution of Presumed Underground Explosions

standard deviation of their travel time residuals were found to be significantly larger than the majority of the data set. These stations (KJN, NUR, SOD, and TEH) were found to also have the smallest average source-to-receiver distance. Their standard deviations were, therefore, large because of increased travel time scatter observed at regional distances. As a result of these contraints, the final data set included 2,262 detections at 98 stations. Less than 9 percent of this data set was later rejected for exceeding the three standard deviation limits in the data reduction phase of the task. The 98 station network averaged 63 stations per event, ranging from a minimum of 25 to a maximum of 87.

The iterative procedure described above was followed while several estimates of the convergence of the method were being monitored. The shift in the epicenters from one iteration to the next was noted to be fairly random for the first three iterations and then to degenerate rapidly to shifting all epicenters approximately 0.8 kilometers in the same direction during successive iterations. The mean of the absolute values of the travel time residual for each iteration decreased rapidly for three iterations and then held fairly constant. Other criteria for monitoring the convergence indicated a similar relationship and it was determined that the third iteration results were as accurate as the procedure was capable of producing for the given data set.

In order to assess the effect of a disproportionate number of stations in North America and Europe, a reduced network of 33, averaging 22 stations per event, was selected to provide the best azimuthal coverage possible within the constraints of the initial data base. Figure 2 indicates the locations of both the 33 and 98 station networks. The same pattern of convergence to the third iteration was observed for the 33 station network as with the larger network. In most cases, the resulting epicenters were within the 95 percent confidence ellipses of the larger network. However, the areas of the 95 percent confidence ellipses were approximately 40 percent larger in the reduced 33 station network. This variation in confidence ellipses is nearly as expected since the square root of the number of stations is used in computing the ellipses. Taking this effect into account, there is no observable difference in confidence region for the two networks. This indicates that the precision of the procedure utilized to determine epicenters and estimate travel time residuals is fairly insensitive to concentrations of stations provided that the widest possible azimuthal variation is utilized. The results of these two sets of calculations are tabulated in Tables I and II.

It is difficult to evaluate the absolute accuracy of the epicenters which are determined through this procedure. The confidence ellipses which are used to estimate the location accuracy are, in actuality, measuring the fit of the travel time data and are not related to the actual locations of the events. In order to assess the true accuracy of the procedure, the exact location of an event must be known. Because the Soviets do not release specific details of their underground nuclear testing program, we must resort to circumstantial evidence. Of the 33 events utilized in this study, the location of only one is known with some degree of confidence. This event was described by Marshall (1972);

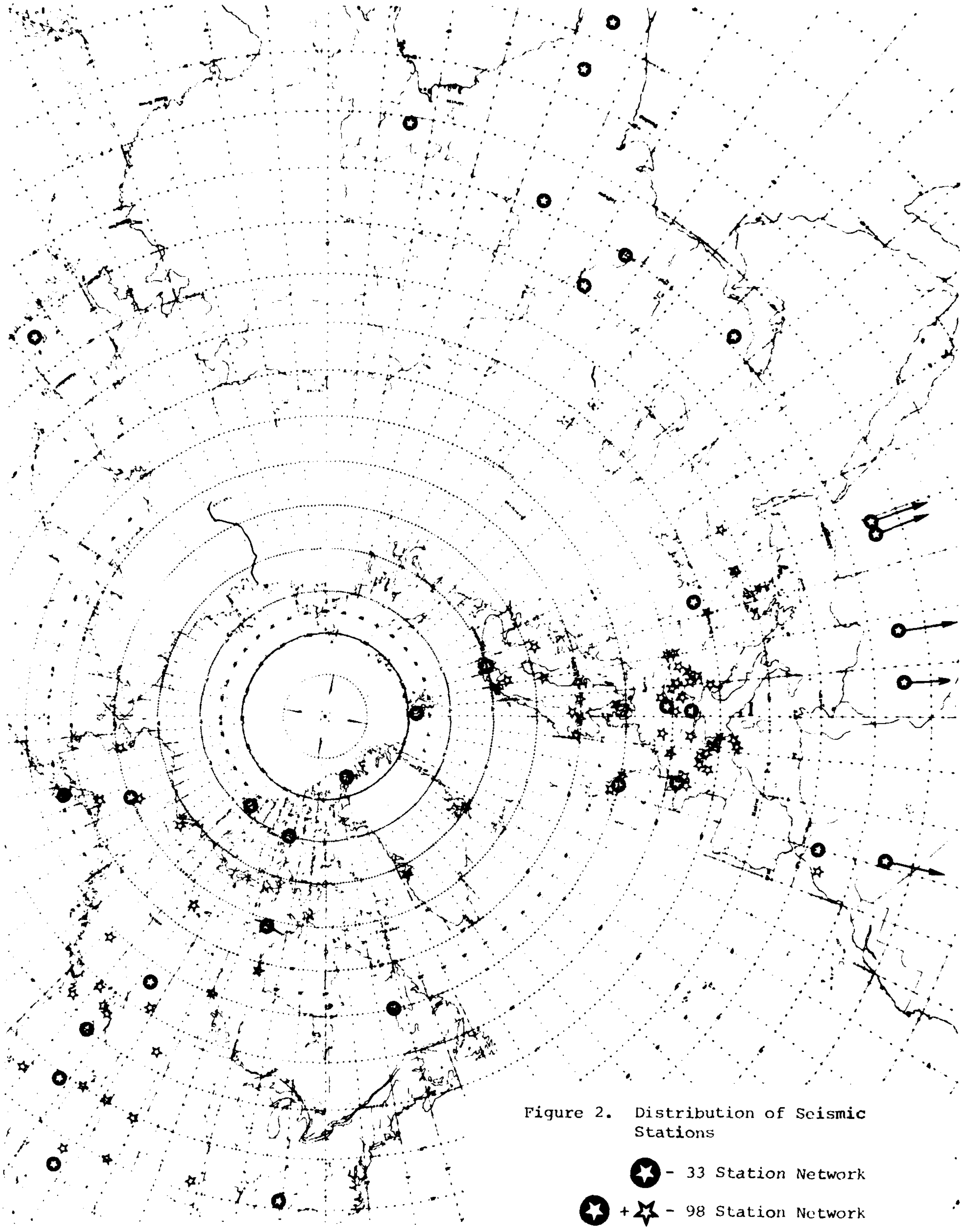

Figure 2. Distribution of Seismic Stations

✪ - 33 Station Network

✪ + ☆ - 98 Station Network

Table I

Hypocenter Locations Resulting From Iterative Procedure

	98 Station Network							33 Station Network						98 Sta Net/ 33 Sta Net
				95% Coverage Ellipse							95% Coverage Ellipse			
Date	Origin Time	Lat (°N)	Long (°E)	Semi Maj Axis (km)	Semi Min Axis (km)	No Stations	mb	Origin Time	Lat (°N)	Long (°E)	Semi Maj Axis (km)	Semi Min Axis (km)	No Stations	Epicenter Separation (km)
15 Jan 65	0600:00.8	49.912	79.022	11.2	10.6	50	5.34	0600:00.5	49.895	79.016	18.6	12.2	19	1.9
26 Feb 67	0357:59.8	49.740	78.178	11.4	9.4	62	5.54	0357:59.5	49.708	78.222	17.5	11.9	22	4.8
06 Oct 67	0659:58.7	57.649	65.759	22.0	14.7	26	4.24	0659:58.7	57.632	65.740	33.6	21.4	9	3.2
21 May 68	0359:12.1	38.945	65.089	11.6	10.1	60	4.99	0359:11.9	38.935	65.107	17.5	12.1	24	1.9
07 Nov 68	1002:07.9	73.408	54.622	10.1	6.1	77	5.53	1002:07.7	73.360	54.455	13.7	9.9	29	7.5
08 Sep 69	0459:58.4	57.194	55.227	11.2	9.5	50	4.51	0459:58.2	57.195	55.273	15.7	12.3	20	2.8
26 Sep 69	0659:58.3	45.873	42.491	12.1	8.3	72	5.30	0659:58.2	45.844	42.506	16.1	10.5	28	3.4
25 Jun 70	0459:56.0	52.299	55.613	11.8	11.0	43	4.35	0459:55.8	52.288	55.644	17.9	11.8	20	2.4
23 Dec 70	0701:00.1	43.910	54.791	9.8	8.0	85	5.91	0701:00.0	43.868	54.805	14.0	10.7	29	4.8
23 Mar 71	0659:58.7	61.326	56.276	9.5	7.4	82	5.17	0659:58.3	61.282	56.316	13.8	10.1	27	5.4
10 Jul 71	1700:02.3	64.189	54.883	10.3	8.7	70	4.95	1700:01.8	64.126	54.919	17.1	10.7	25	7.2
19 Sep 71	1100:01.9	57.528	42.055	28.4	18.7	25	4.10	1100:02.0	57.581	41.968	55.2	28.7	7	7.9
04 Oct 71	1000:00.8	61.358	47.619	19.0	13.6	29	4.33	1000:00.5	61.305	47.839	29.1	19.8	10	13.4
22 Oct 71	0500:02.2	51.595	54.502	9.1	7.9	73	5.00	0500:02.1	51.565	54.499	15.3	9.8	26	3.3
22 Dec 71	0659:59.1	47.890	48.095	9.8	7.6	83	5.63	0659:59.0	47.880	48.092	14.9	9.6	28	1.1
30 Dec 71	0621:00.3	49.783	78.124	9.5	8.1	83	5.34	0621:00.0	49.746	78.169	17.1	10.2	27	5.2
20 Aug 72	0300:00.6	49.466	48.110	10.2	7.7	78	5.49	0300:00.4	49.439	48.117	14.1	10.1	27	3.0
26 Aug 72	0346:59.8	50.014	77.758	9.3	8.9	71	4.97	0346:59.7	49.995	77.771	18.0	11.6	20	2.3
28 Aug 72	0559:59.4	73.415	54.508	11.5	6.2	80	5.99	0559:59.2	73.378	54.390	15.1	10.6	26	5.6
04 Sep 72	0700:05.5	67.754	33.490	27.5	12.1	29	3.98	0700:05.1	67.756	33.716	36.2	15.1	12	9.5
21 Sep 72	0859:59.9	52.122	51.944	11.2	9.8	55	4.56	0859:59.7	52.077	51.914	17.3	11.1	21	5.4
03 Oct 72	0900:00.5	46.841	44.817	10.1	7.2	85	5.47	0900:00.3	46.813	44.782	13.7	9.6	32	4.1
02 Nov 72	0127:00.1	49.905	78.826	8.6	7.7	87	5.83	0126:59.9	49.883	78.863	15.6	9.6	29	3.6
24 Nov 72	0900:00.1	51.956	51.782	19.0	16.5	26	4.15	0859:59.7	51.900	51.818	42.9	21.8	6	6.7
24 Nov 72	1000:00.6	51.837	64.113	8.5	8.2	72	4.82	1000:00.5	51.801	64.077	15.2	9.8	27	4.7
19 Apr 73	0433:00.1	50.006	77.671	8.7	8.1	76	4.98	0432:59.9	49.982	77.643	15.9	10.0	25	3.3
15 Aug 73	0200:00.7	42.745	67.346	10.4	9.7	76	5.07	0200:00.5	42.738	67.305	20.1	12.3	23	3.5
28 Aug 73	0300:00.7	50.584	68.377	10.3	10.1	52	4.77	0300:00.4	50.540	68.288	20.3	11.5	19	8.0
19 Sep 73	0300:00.3	45.700	67.755	12.1	8.6	57	4.77	0300:00.1	45.695	67.734	19.5	11.0	24	1.7
27 Sep 73	0700:01.2	70.790	53.320	10.4	6.7	85	5.65	0700:00.8	70.738	53.458	14.1	10.4	28	7.7
26 Oct 73	0600:00.1	53.571	55.314	17.2	11.3	46	4.32	0600:00.0	53.564	55.231	24.9	16.7	13	5.6
14 Aug 74	1500:01.3	68.945	75.738	10.3	7.2	75	5.19	1500:00.9	68.920	75.752	14.0	10.7	25	2.8
29 Aug 74	1500:01.1	67.129	62.547	12.9	9.2	46	4.75	1500:01.0	67.105	62.679	16.4	12.5	17	6.3

Table II

Travel Time Corrections Resulting from Iterative Procedure

	98 Station Network			33 Station Network		
Station	Travel Time Correction (sec)	Standard Deviation (sec)	No Events	Travel Time Correction (sec)	Standard Deviation (sec)	No Events
ALE	-0.1	0.55	22	-0.1	0.50	22
ALQ	-0.5	0.47	18			
AVE	0.0	0.71	16			
BER	-0.2	0.66	20			
BLC	0.4	0.23	23	0.4	0.22	23
BMO	0.6	0.53	32	0.5	0.53	32
BNG	1.0	0.55	21	0.7	0.53	21
BNS	-0.7	0.53	16			
BRA	0.2	0.82	12			
BSF	-0.2	0.61	18			
BUH	-0.6	0.61	18			
BUL	0.7	0.50	26	0.4	0.52	26
CLL	0.0	0.32	30			
CMP	-2.0	0.66	15			
COL	-0.7	0.46	30	-0.8	0.44	30
COP	-0.3	0.50	17			
CPO	0.9	0.42	23	0.8	0.45	23
DOU	-0.5	0.61	16			
DUG	-1.0	0.47	21			
DUR	-0.5	0.74	13			
EDM	-0.1	0.26	26	-0.1	0.26	26
EKA	0.1	0.44	23	0.0	0.49	23
ESK	0.2	0.54	16			
EUR	-0.9	0.41	30	-0.9	0.40	30
FCC	0.2	0.51	18			
FFC	0.5	0.51	25			
FLN	0.1	0.49	26	0.0	0.44	26
FSJ	-0.7	0.36	16			
FUR	-1.0	0.63	21	-1.1	0.56	20
GBA	0.5	0.51	21	0.1	0.41	21
GDH	0.1	0.50	16			
GIL	-0.7	0.39	24			
GMA	-0.1	0.42	16			
GOL	-0.1	0.39	15			
GRF	-1.1	0.38	26			
GRR	0.3	0.47	25			
HFS	0.9	0.77	25			
HYB	0.9	0.67	18	0.5	0.54	18
IFR	0.5	0.68	20	0.3	0.57	20
INK	0.2	0.43	21			

Table II (Continued)

Travel Time Corrections Resulting from Iterative Procedure

Station	98 Station Network Travel Time Correction (sec)	Standard Deviation (sec)	No Events	33 Station Network Travel Time Correction (sec)	Standard Deviation (sec)	No Events
ISK	-0.2	0.48	13			
JAS	-0.6	0.43	22			
KAS	-0.6	0.82	15			
KBL	-0.3	0.64	18	-0.5	0.62	20
KBS	-0.1	0.47	17	-0.2	0.54	18
KDC	0.6	0.50	23	0.5	0.50	23
KEV	0.6	0.64	27	0.7	0.56	27
KHC	-0.6	0.39	31			
KIC	1.0	0.46	20	0.7	0.44	20
KIR	0.9	0.67	26			
KJF	1.1	0.80	13			
KON	0.2	0.37	25			
KRA	0.0	0.62	21			
KRR	0.6	0.52	19	0.3	0.53	19
KTG	-1.3	0.26	15			
LAO	-0.8	0.22	29			
LBF	0.4	0.30	19			
LJU	-1.2	0.41	19			
LMR	-0.2	0.50	19			
LNS	0.2	0.72	16			
LON	-0.2	0.41	15			
LOR	0.4	0.27	28			
MAT	1.1	0.51	21	0.9	0.40	21
MBC	-0.4	0.39	28	-0.4	0.34	28
MNY	0.3	0.55	16			
MOX	-0.4	0.41	32	-0.6	0.35	32
NAO	1.2	0.52	15			
NDI	0.1	0.50	24	-0.3	0.46	24
NEW	-0.2	0.40	25			
NIE	-0.2	0.80	16			
NTI	-0.5	0.50	21			
PMR	0.6	0.39	26			
PNT	0.2	0.36	21			
PRA	-0.9	0.61	19			
PRU	-0.7	0.41	30			
QUE	-0.2	0.63	16	-0.7	0.57	16
RES	0.1	0.52	14	0.1	0.50	14
RSL	-0.1	0.43	18			
SCH	0.6	0.42	18	0.5	0.40	18
SDB	0.4	0.38	18	0.1	0.32	18

Table II (Continued)

Travel Time Corrections Resulting from Iterative Procedure

	98 Station Network			33 Station Network		
Station	Travel Time Correction (sec)	Standard Deviation (sec)	No Events	Travel Time Correction (sec)	Standard Deviation (sec)	No Events
SES	0.4	0.41	27			
SHI	-0.3	0.57	19	-0.8	0.54	19
SHL	0.8	0.63	15	0.7	0.68	15
SPF	-0.3	0.35	19			
SSC	0.1	0.37	25			
SSF	0.3	0.38	17			
TCF	-0.2	0.33	18			
TFO	-1.2	0.36	30			
TRO	0.6	0.59	25			
TUC	-0.7	0.63	15	-0.8	0.64	15
TUL	0.1	0.46	25			
UBO	-0.2	0.40	24			
UME	0.9	0.57	22			
UPP	1.2	0.66	26			
VIE	-1.3	0.62	18			
VKA	-1.2	0.57	20			
VRI	-0.2	0.72	11	-0.5	0.79	13
YKC	0.5	0.42	23			
Mean		0.504				
Standard Deviation		0.137				
Rejected Stations						
KJN		1.33	13			
NUR		1.61	23			
SOD		0.99	31			
TEH		1.06	11			

Dahlman and Israelson (1977); and Nordyke (1973) as being a cratering experiment in a river bed near 49.9N, 79.0E on 15 Jan 1965. As a result of the experiment, Dahlman and Israelson (1977) report that a crater 408 meters in diameter was formed and the placement of the crater in the river bed caused the formation of a reservoir in the river. A later excavation of the lip of the crater caused the crater itself to also fill with water (Nordyke, 1973). A dammed river and accompanying circular water-filled feature approximately 400-450 meters in diameter can be observed in a LANDSAT photograph taken on 15 Aug 1975. The geodetic coordinates of the crater are 49.950 degrees N by 79.010 degrees E. This is approximately 3.1 kilometers north of the hypocenter located using 98 stations. If we assume that this crater is truly associated with the 15 Jan 65 event, then the apparent error is well within the 95 percent coverage ellipse which was estimated to be 22.4 by 21.2 kilometers. Although this accuracy cannot be extrapolated to the other events or even to this event absolutely (the event conceivably could be associated with the wrong feature on the photograph), it does serve to lend some confidence to the locations and the procedure which was utilized.

III. JOINT EPICENTER DETERMINATION COMPARISON

In order to evaluate the relative usefulness of the iterative hypocenter location technique which was described above and the joint epicenter determination procedure, Douglas, Lilwall and Young (1974), a reduced data base was constructed from that used in the iterative procedure. Since the joint epicenter determination procedure computer program, which was obtained from the Seismic Data Analysis Center, did not have provisions for eliminating erroneous data points, only those P-wave phases which were utilized in the final iteration of the iterative technique were included. Both the 98 and 33 station networks were evaluated. The results of this analysis are tabulated in Tables III and IV.

A comparison of the results of the two techniques indicates a slight reduction in the estimated 95 percent coverage limits of the joint epicenter determination procedure. This is to be expected as pointed out previously by Ahner, Blandford and Shumway (1971), since the joint epicenter procedure is based upon minimizing the error of the travel times of the entire data set through least squares procedures whereas the iterative reduces the error for each event individually. It should also be noted that the 98 station joint epicenter determination epicenters are shifted an average of 11.6 kilometers to the northwest of the iterative procedure epicenters. The variation in this shift is remarkably low as if most epicenters were shifted as a group. A similar relationship exists with the 33 station network epicenters as determined through the joint epicenter determination procedure. The 95 percent confidence limits are slightly larger for the 33 station network but the shifts from the iteratively determined epicenters averages only 7.7 kilometers to the northwest with a slightly larger scatter. The 98 station joint epicenter determination site for the 15 Jan 65 event is approximately 12.6 kilometers northwest of the LANDSAT crater. The 33 station joint epicenter determination site is approximately 12.2 kilometers west of the LANDSAT crater. Figure 3 presents a map of the locations determined

[illegible]

	[illegible] Station Network						[illegible] Station Network					
				95% Confidence Limit		Shift From				95% Confidence Limit		Shift From
Date	Origin Time	Lat (°N)	Long (°E)	Lat (km)	Long (km)	[illegible] Station Iterative (km)	Origin Time	Lat (°N)	Long (°E)	Lat (km)	Long (km)	[illegible] Station Iterative (km)
[illegible] Jan [illegible]	[illegible]	[illegible]	[illegible]	±[illegible]	±[illegible]	13.7	0600:00.8	49.92[illegible]	78.[illegible]	±[illegible]	±5.[illegible]	[illegible]
[illegible] Feb [illegible]	[illegible]	[illegible]	[illegible]	±[illegible]	±[illegible]	[illegible]	0357:59.6	49.73[illegible]	78.[illegible]	±6.[illegible]	±4.9	[illegible]
[illegible]	0659:[illegible]	[illegible]	65.[illegible]	±7.[illegible]	±1.8	11.6	0659:58.9	57.63[illegible]	65.64[illegible]	±9.7	±6.8	[illegible]
[illegible] May 68	[illegible]	[illegible]	[illegible]	±4.[illegible]	±[illegible]	[illegible]	0359:12.1	38.945	64.990	±5.7	±5.9	6.5
[illegible] Nov 68	1002:[illegible]	[illegible].401	54.[illegible]	±3.1	±1.[illegible]	12.8	1002:[illegible]	73.359	54.284	±[illegible].7	±2.[illegible]	12.2
[illegible] Sep 69	[illegible]	[illegible]	55.[illegible]	±4.3	±2.[illegible]	12.8	0459:58.5	57.192	55.170	±6.1	±3.9	3.4
[illegible] Sep 69	0659:[illegible]	[illegible]	42.[illegible]	±[illegible]	±[illegible]	13.1	0659:58.3	45.839	42.436	±6.5	±3.6	[illegible]
[illegible] Jun 70	0459:[illegible]	[illegible].308	55.[illegible]	±4.5	±2.9	11.8	0459:56.0	52.290	55.549	±5.9	±4.7	[illegible]
[illegible] Dec 70	0701:[illegible]	[illegible].925	54.[illegible]	±4.2	±2.7	11.8	0701:00.3	43.870	54.725	±5.4	±4.2	6.9
[illegible] Mar 71	0659:[illegible]	61.310	56.[illegible]	±3.7	±1.9	10.5	0659:56.6	61.280	56.185	±5.2	±3.2	7.7
[illegible]	[illegible]	64.153	54.759	±3.8	±1.9	7.3	1700:02.1	64.124	54.866	±5.4	±3.2	7.5
[illegible] Sep 71	[illegible]	57.563	41.842	±6.9	±3.5	13.6	1100:02.4	57.590	41.862	±10.1	±7.5	[illegible]
[illegible]	1000:[illegible]	61.339	47.492	±4.8	±2.6	7.6	1000:00.7	61.302	47.723	±6.8	±4.6	5.4
[illegible] Oct 71	0500:02.8	51.599	54.336	±3.9	±2.3	11.8	0500:02.3	51.564	54.415	±5.5	±3.7	7.0
[illegible] Dec 71	0659:59.8	47.892	47.945	±4.1	±2.4	11.2	0659:59.2	47.875	48.014	±5.7	±4.0	6.2
[illegible] Dec 71	0621:01.1	49.829	77.947	±4.7	±2.8	13.4	0621:00.3	49.787	78.091	±5.9	±4.8	2.4
[illegible] Aug 72	0300:01.3	49.472	47.955	±4.4	±2.3	11.0	0300:00.6	49.436	48.036	±5.9	±3.9	6.3
[illegible] Aug 72	0347:00.6	50.067	77.578	±4.4	±2.8	13.9	0347:00.0	50.019	77.675	±5.8	±4.8	6.0
[illegible] Aug 72	0600:00.1	73.408	54.157	±3.3	±1.3	11.0	0559:59.5	73.376	54.194	±4.9	±1.9	10.5
[illegible] Sep 72	0700:06.1	67.724	33.338	±3.8	±2.6	7.2	0700:05.3	67.735	33.606	±5.3	±4.1	5.3
21 Sep 72	0900:00.5	52.126	51.783	±4.1	±2.6	11.0	0859:59.9	52.076	51.834	±5.7	±4.2	9.0
[illegible] Oct 72	0900:01.1	46.841	44.681	±4.1	±2.3	10.2	0900:00.5	46.806	44.714	±5.4	±3.5	6.5
[illegible] Nov 72	0127:00.9	49.962	78.648	±4.2	±2.7	14.1	0127:00.2	49.910	78.772	±5.5	±4.3	3.9
24 Nov 72	0900:00.9	51.957	51.597	±6.2	±3.8	12.8	0859:59.9	51.905	51.740	±8.1	±8.9	6.4
24 Nov 72	1000:01.3	51.855	63.930	±4.0	±2.5	13.0	1000:00.8	51.805	63.975	±5.3	±4.1	10.3
19 Apr 73	0433:00.8	50.055	77.494	±4.3	±2.8	13.6	0433:00.2	50.006	77.555	±5.7	±4.6	8.3
[illegible] Aug 73	0200:01.4	42.774	67.182	±4.3	±3.5	13.7	0200:00.8	42.748	67.217	±5.4	±5.7	10.5
28 Aug 73	0300:01.4	50.611	68.198	±4.6	±2.9	13.2	0300:00.8	50.579	68.183	±5.9	±4.9	13.9
19 Sep 73	0300:01.0	45.723	67.590	±4.0	±3.3	13.2	0300:00.3	45.702	67.650	±5.2	±5.0	8.[illegible]
27 Sep 73	0700:01.8	70.774	53.062	±3.3	±1.4	9.6	0700:01.2	70.733	53.287	±5.0	±2.1	6.5
26 Oct 73	0600:00.8	53.583	55.152	±5.2	±3.1	11.0	0600:00.2	53.575	55.218	±7.2	±5.8	6.3
14 Aug 74	1500:02.0	68.977	75.438	±4.2	±1.4	12.2	1500:01.3	68.937	75.580	±5.5	±2.4	6.4
29 Aug 74	1500:01.9	67.139	62.254	±4.7	±1.8	5.5	1500:01.3	67.111	62.504	±5.9	±3.0	16.6

TABLE IV

Travel Time Corrections Resulting From Joint Epicenter Determination

Station	98 STATION NETWORK Travel Time Correction (sec)	Standard Deviation (sec)	No Events	33 STATION NETWORK Travel Time Correction (sec)	Standard Deviation (sec)	No Events
ALE	0.2	0.25	22	-0.1	0.33	22
ALQ	-0.3	0.25	18			
AVE	-0.2	0.26	16			
BER	-0.6	0.25	20			
BLC	0.7	0.23	23	0.4	0.30	23
BMO	0.9	0.20	32	0.5	0.24	32
BNG	1.1	0.27	21	0.6	0.30	21
BNS	-1.0	0.27	16			
BRA	-0.3	0.31	12			
BSF	-0.6	0.25	18			
BUH	-1.1	0.25	18			
BUL	1.0	0.28	26	0.3	0.28	26
CLL	-0.4	0.21	30			
CMP	-2.4	0.29	15			
COL	-0.1	0.24	30	-0.6	0.28	30
COP	-0.6	0.26	17			
CPO	1.2	0.22	23	0.8	0.25	23
DOU	-0.8	0.27	16			
DUG	-0.8	0.24	21			
DUR	-0.9	0.29	13			
EDM	0.3	0.22	26	-0.1	0.26	26
EKA	-0.2	0.23	23	-0.3	0.34	23
ESK	-0.2	0.26	16			
EUR	-0.6	0.21	30	-1.1	0.24	30
FCC	0.5	0.25	18			
FFC	0.9	0.22	25			
FLN	-0.2	0.22	26	-0.3	0.32	26
FSJ	-0.3	0.28	16			
FUR	-1.4	0.24	21	-1.5	0.34	21
GBA	1.6	0.40	21	0.6	0.44	21
GDH	0.2	0.27	16			
GIL	-0.1	0.25	24			
GMA	0.5	0.30	16			
GOL	0.0	0.27	15			
GRF	-1.5	0.22	26			
GRR	-0.1	0.22	25			
HFS	0.6	0.24	25			
HYB	2.1	0.42	18	1.0	0.46	18
IFR	0.0	0.24	20	-0.2	0.30	20

TABLE IV (Continued)

Travel Time Corrections Resulting From Joint Epicenter Determination

	98 STATION NETWORK			33 STATION NETWORK		
Station	Travel Time Correction (sec)	Standard Deviation (sec)	No Events	Travel Time Correction (sec)	Standard Deviation (sec)	No Events
INK	0.7	0.26	21			
ISK	-0.6	0.32	13			
JAS	-0.1	0.24	11			
KAS	-0.9	0.32	15			
KBL	0.6	0.44	18	-0.5	0.51	18
KBS	0.0	0.28	17	-0.2	0.37	17
KDC	1.3	0.26	23	0.8	0.29	23
KEV	0.5	0.24	27	0.4	0.37	27
KHC	-1.1	0.21	31			
KIC	1.0	0.25	20	0.6	0.28	20
KIR	0.8	0.24	26			
KJF	0.9	0.31	13			
KON	-0.2	0.23	25			
KRA	-0.4	0.25	21			
KRR	0.9	0.30	19	0.2	0.30	19
KTG	-1.3	0.28	15			
LAO	-0.4	0.21	29			
LBF	-0.1	0.25	19			
LJU	-1.6	0.25	19			
LMR	-0.5	0.25	19			
LNS	-0.3	0.27	16			
LON	0.2	0.28	15			
LOR	0.0	0.21	28			
MAT	2.5	0.36	21	1.6	0.40	21
MBC	0.1	0.23	28	-0.3	0.30	28
MNY	0.0	0.27	16			
MOX	-0.9	0.20	32	-1.0	0.32	32
NAO	0.8	0.28	15			
NDI	1.3	0.42	24	0.2	0.48	24
NEW	0.3	0.23	25			
NIE	-0.7	0.28	16			
NTI	-0.1	0.24	21			
PMR	1.3	0.25	26			
PNT	0.6	0.24	21			
PRA	-1.3	0.25	19			
PRU	-1.1	0.21	30			
QUE	0.5	0.44	16	-0.6	0.50	16
RES	0.4	0.29	14	0.1	0.35	14
RSL	-0.6	0.25	18			

TABLE IV (Continued)

Travel Time Corrections Resulting From Joint Epicenter Determination

	98 STATION NETWORK			33 STATION NETWORK		
Station	Travel Time Correction (sec)	Standard Deviation (sec)	No Events	Travel Time Correction (sec)	Standard Deviation (sec)	No Events
SCH	0.6	0.25	18	0.4	0.31	18
SDB	0.5	0.29	18	-0.1	0.29	18
SES	0.8	0.22	27			
SHI	0.0	0.38	19	-0.8	0.42	19
SHL	2.3	0.45	15	1.1	0.49	15
SPF	-0.6	0.25	19			
SSC	-0.3	0.22	25			
SSF	0.0	0.21	27			
TCF	-0.6	0.25	18			
TFO	-0.9	0.20	30			
TRO	0.4	0.24	25			
TUC	-0.3	0.27	15	-0.8	0.29	15
TUL	0.5	0.21	25			
UBO	0.0	0.22	24			
UME	0.6	0.25	22			
UPP	0.8	0.23	26			
VIE	-1.7	0.26	18			
VKA	-1.7	0.25	20			
VRI	-0.8	0.33	11	-1.0	0.42	11
YKC	0.9	0.24	23			

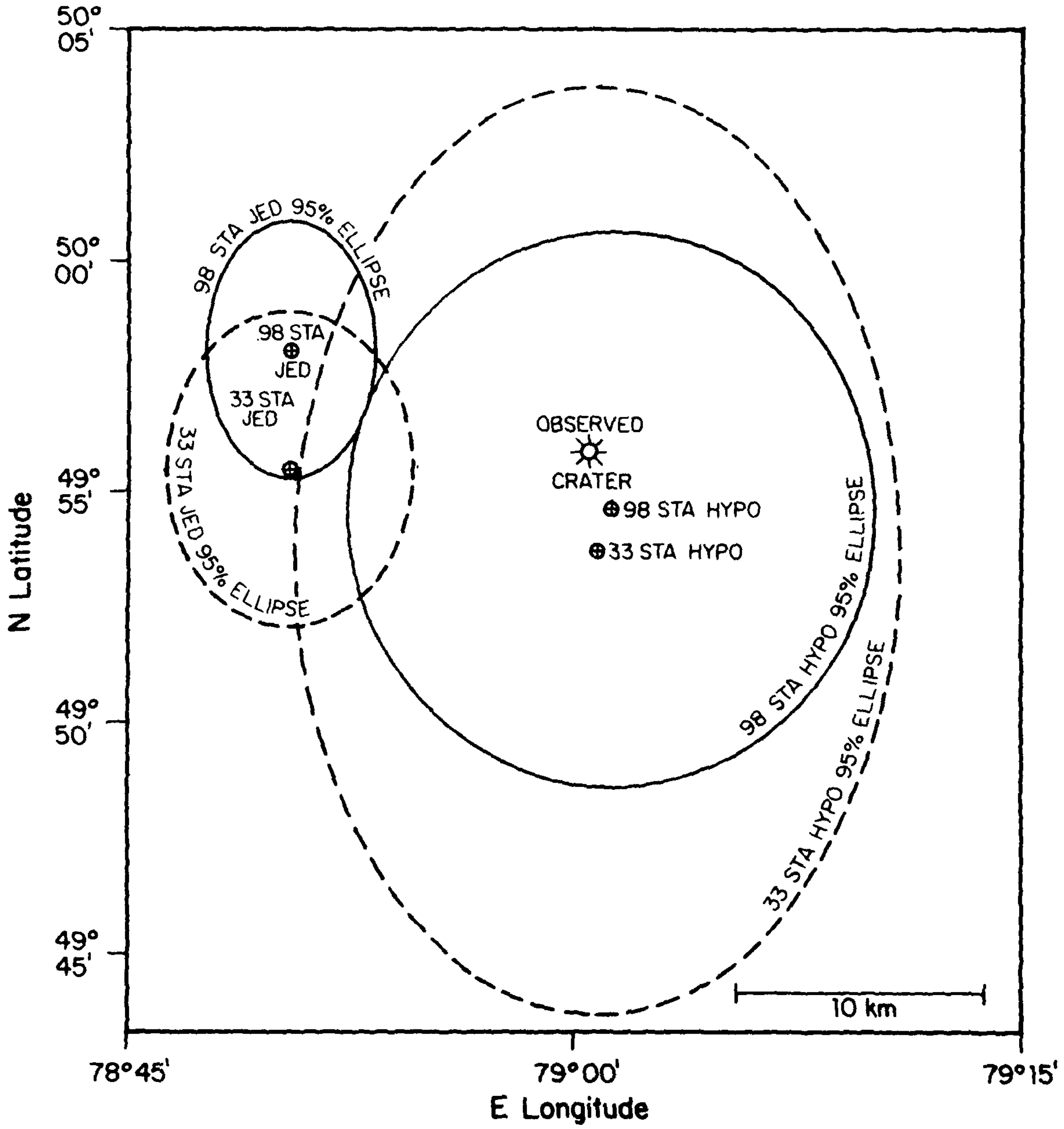

Figure 3. Relative Locations of
15 Jan 65 Event

for this event. In both of these cases, the location error exceeds the 95 percent confidence limits by a factor of two, if we assume that the crater and event are truly associated. This would indicate that the iterative procedures have produced more accurate locations with errors within the stated bounds.

IV. COMPARISON TO PREVIOUS STUDIES

The comparison of travel time corrections derived through various procedures for different travel time curves and geographical regions is of interest for several reasons. It is primarily of importance to estimate the variations which may be encountered between different geographical areas and in analyzing different travel time curves. Through the analysis of these types of variations, it may be possible to estimate the size of an area over which the travel time corrections remain valid.

Comparisons of the residuals determined through the iterative procedure for the 98 station network have been made with summaries by Cleary and Hales (1966), Lilwall and Douglas (1970), Sengupta and Julian (1976), and Masso, Savino, and Bache (1978). As noted in Figures 4 and 5, the Lilwall and Douglas (1970) and Sengupta and Julian (1976) residuals appear to have the largest scatter of those examined. The Lilwall and Douglas (1970) study, using the joint epicenter determination method, also included azimuthal variations in the corrections along with corrections to the travel time relationship. It is, therefore, not completely relevant to consider their corrections the poorest based upon the scatter on the plot.

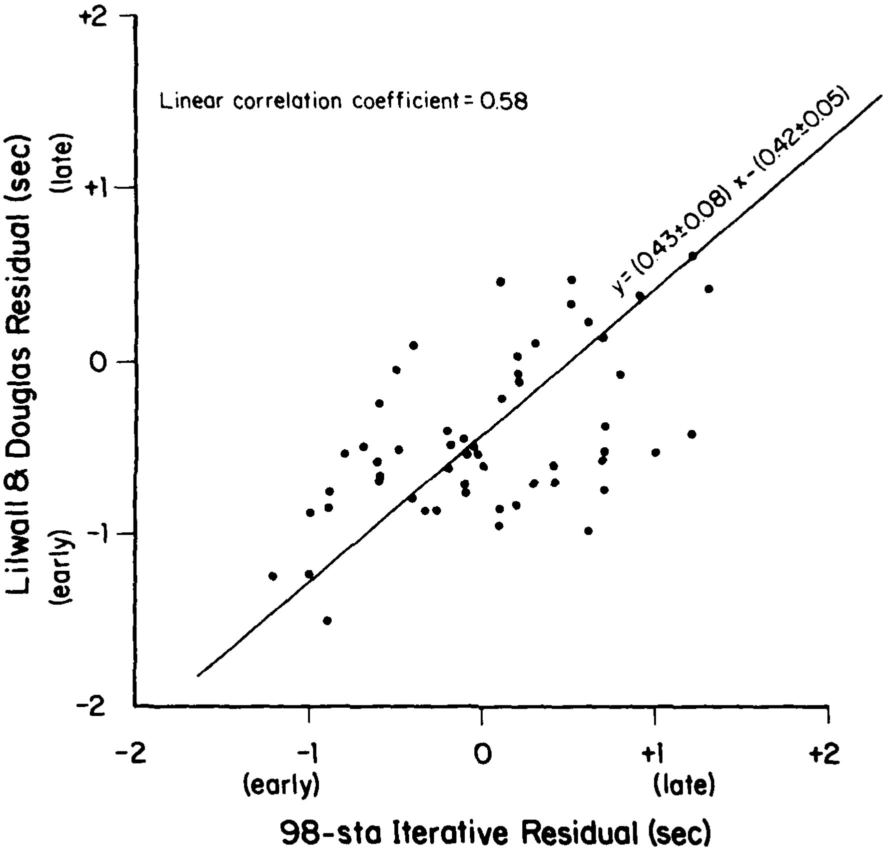

Figure 4. Comparison of Travel Time
Residuals Between Lilwall
and Douglas and This Study

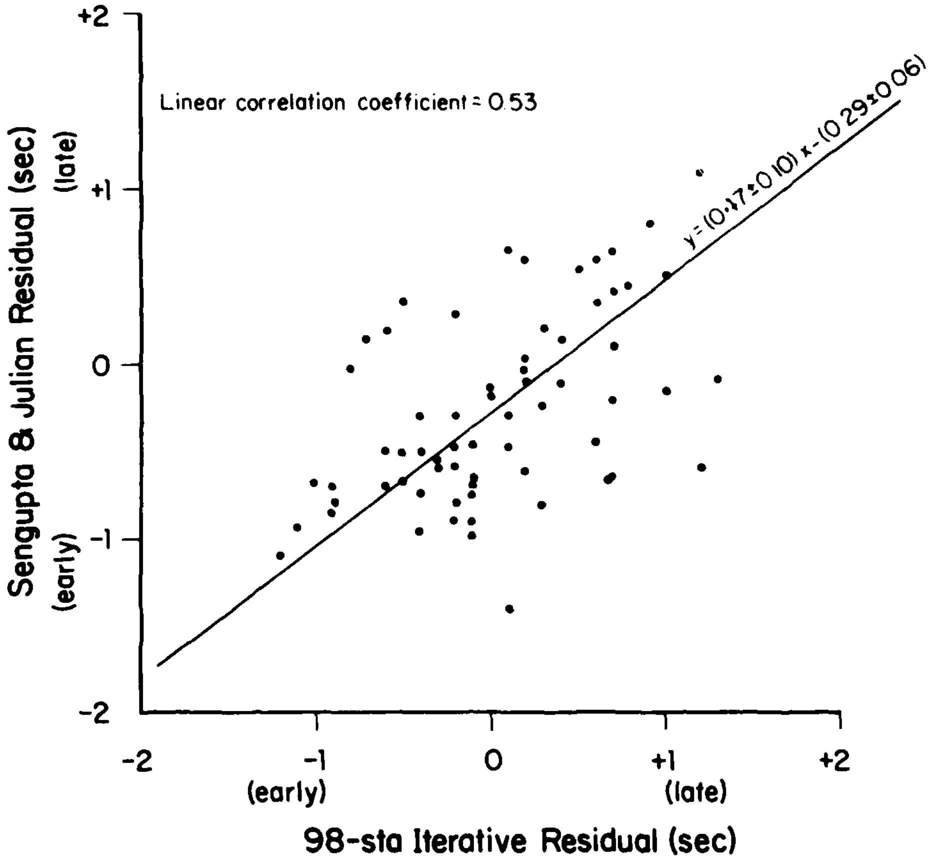

Figure 5. Comparison of Travel Time Residuals Between Sengupta and Julian and This Study

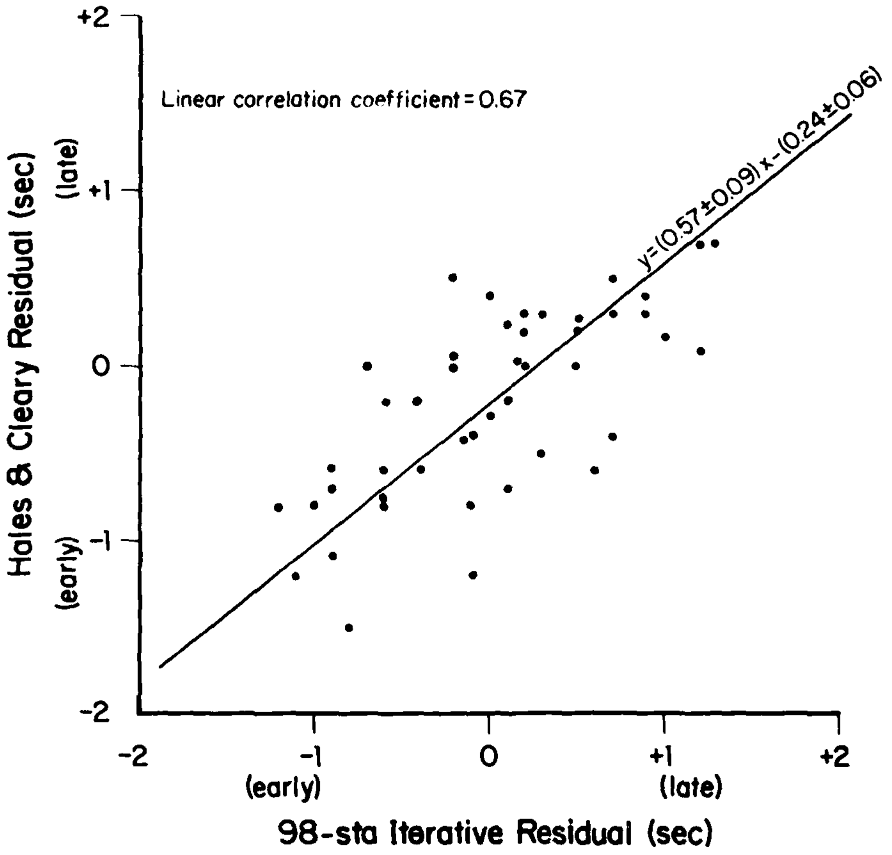

Figure 6. Comparison of Travel Time Residuals Between Hales and Cleary and This Study

The scatter of the residuals observed in this study with those by Cleary and Hales (1966), Figure 6, are more comparable. Sengupta and Julian (1976) rates their residuals, which were based upon a worldwide distribution of deep earthquakes analyzed through an iterative procedure very similar to the one used here, significantly better than other studies since the mean of the standard deviations of their residuals was 0.6 seconds, much smaller than other studies. The mean of the standard deviations of the residuals in this study is 0.5 seconds and by this criteria is, therefore, an improvement over the previous studies, especially when applied to the western Soviet Union source region.

Another recent study by Masso, Savino and Bache (1978) analyzed the International Seismological Centre bulletins from 1964 through 1970 for events with mb $>$ 5.0 as observed at 524 worldwide stations. The scatter, as observed in Figure 7, between their set of residuals for a worldwide event set is slightly smaller in comparison to the results of this study than any other examined. It is, therefore, conceivable that the corrections determined in this study may produce quite accurate epicentral estimates for events outside the geographical spread of events used in the study.

A concept which has been discussed in some detail in recent years relates to the relationship of travel time and magnitude residuals. It is commonly held that early arriving signals correlate with high amplitudes and late arriving signals correlate with more attenuated signals. The classic example of this is North America where signals in the southwestern United States are late and small relative to signals

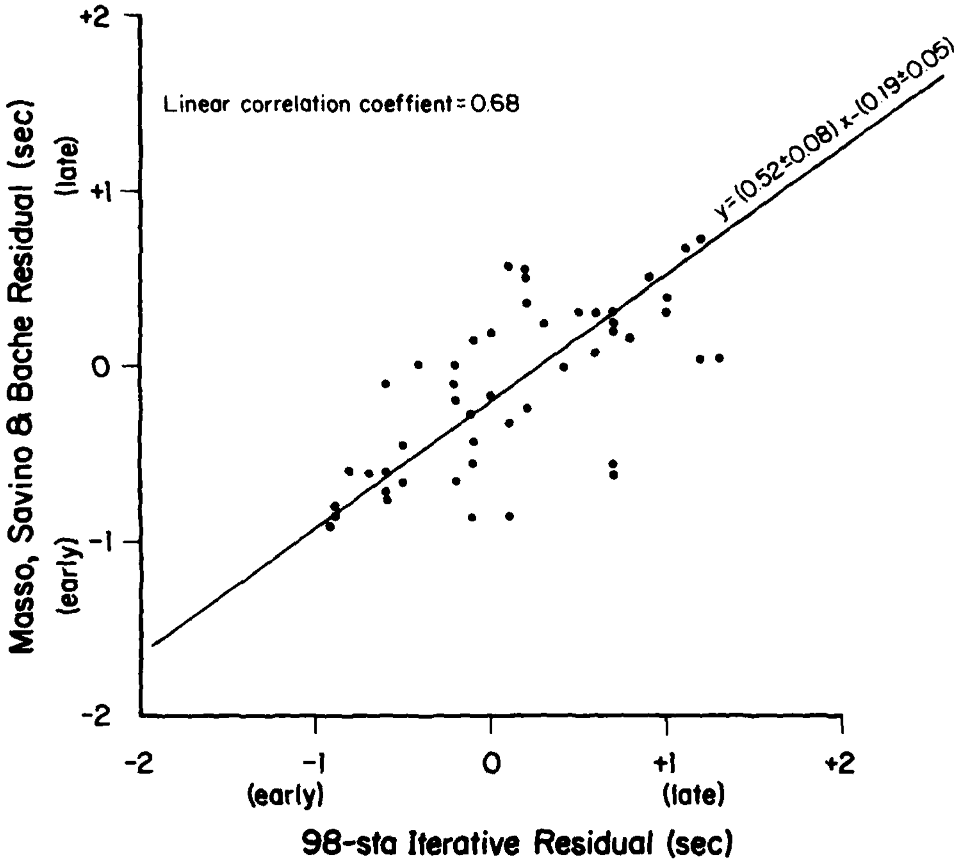

Figure 7. Comparison of Travel Time Residuals Between Masso, Savino & Bache & This Study

recorded in the east. Similar correlations to high heat flow with the higher attenuation and variations in Pn velocities appear very convincing. Analysis of the travel time residuals determined by this study with the magnitude residuals determined by North (1977), corrected to a granite crust, as outlined by Der et al (1978), does not result in a similar conclusion, as seen in Figure 8. It may be that different geographical regions behave differently with respect to these factors. The commonly held relationships are observed in North America where they were first put forth. However, European stations are observed to be all on the high side of the magnitude distribution with travel time residuals fairly evenly balanced between early and late. Africa is distinctively early and low, contrary to the established relationship. This anomalous region in Africa was previously pointed out by Masso, Savino and Bache (1978). This study indicates that correlations, on a worldwide basis, between travel time and magnitude residuals are not as conclusive as magnitude residual versus Pn velocity and may actually represent two different, but related, effects.

V. CONCLUSIONS

A set of travel time correctons have been developed using 33 events in the western Soviet Union. The use of these corrections at the 98 stations examined should make possible improved locations of events in this region. The improved locations of the 33 events in this study are also included.

In developing the travel time corrections, an iterative hypocenter location procedure and the joint epicenter determination procedure were

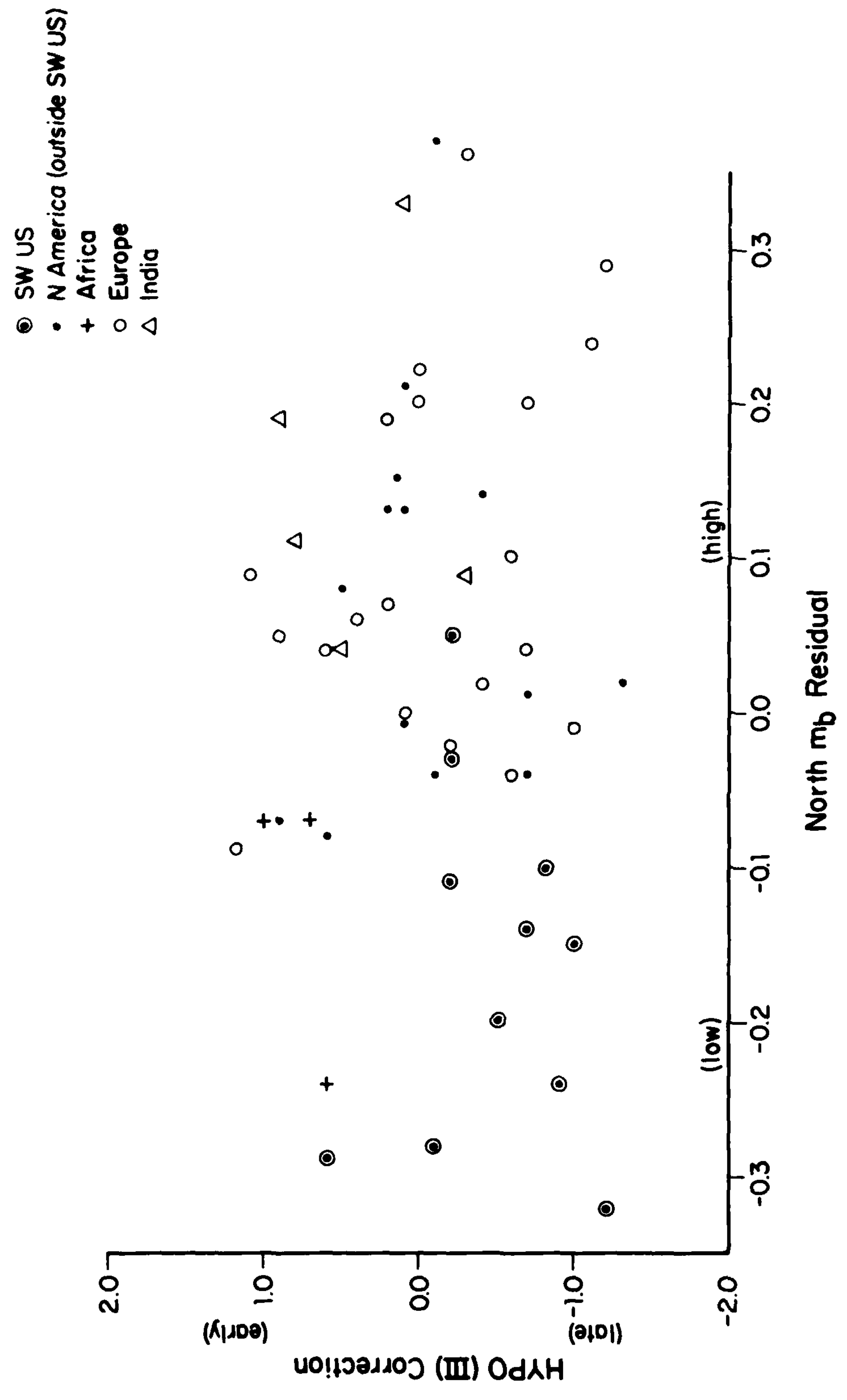

Figure 8. Travel Time Residuals
versus Magnitude Residuals

evaluated. From the analysis of one known event location, it was determined that the iterative technique provided more accurate event locations and travel time corrections. It was also noted that the reduction of the 98 station network to 33 stations to provide a more uniform station pattern did not improve the results of the procedures. It is, therefore, to be concluded that if an adequate azimuthal variation is included in the network, concentrations of stations in certain areas do not significantly bias the results of the iterative procedures.

An analysis of the travel time corrections derived in this study with those of previous studies indicates that these results are as good, or better, than previously reported worldwide travel time corrections and that for the geographical region investigated, they are superior. Comparison of the travel time residuals with previously determined magnitude residuals fails to indicate a strong worldwide correlation of the relationship of early arriving signals with increased amplitudes and late arriving signals with reduced amplitudes as previously observed in North America.

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