LOCATION CALIBRATION OF KAZAKHSTAN BASED ON DTRA (U.S.)-NNC (RoK) JOINT EXPERIMENTS (1997-1999) IN THE FORMER SEMIPALATINSK TEST SITE

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Sponsored by the Defense Threat Reduction Agency
Seismic R&D Support Desk

ABSTRACT

Defense Threat Reduction Agency [DTRA], U.S.A., and the National Nuclear Center [NNC], Republic of Kazakhstan, jointly conducted a series of large chemical explosions during the summer of 1997 through 1999 at the former Semipalatinsk Test Site [STS] in Eastern Kazakhstan. These experiments were carried out primarily as part of the closing of unused tunnels and shafts at the STS under the Co-operative Threat Reduction Program as regulated in the Nunn-Lugar Bill. These explosions provide an excellent opportunity to test the readiness of some national and international seismic monitoring infrastructure. They also offer a valuable suite of GT0 data for calibrating regional seismographs in the Central Asia with a variety of possible immediate application: improved mapping of seismicity for earthquake hazard reduction, fundamental research in seismology, and nuclear treaty verification. Phase arrival picks of these chemical explosions have been measured off digital waveforms recorded at the Kazakhstan Broadband Network (KZNet), Kyrgiz Network (KNet), Talgar Complex Seismological Expedition [TCSE], and Altai-Sayan Experimental & Methodological Seismological Expedition [ASEMSE]. Region-specific, piecewise linear travel-time curves were derived with standard least-squares regressions:

$TT(Pn) = \Delta / 7.94 + 7.56$ (for $300km \le \Delta < 500km$),
$TT(Pn) = \Delta / 8.13 + 8.79$ (for $500km \le \Delta \le 1,000km$),
$TT(Pg) = \Delta / 6.02 + 0.20$ (for $\Delta \le 900km$),
$TT(Sn) = \Delta / 4.69 + 14.98$ (for $\Delta \le 900km$),
$TT(Lg) = \Delta / 3.51 + 0.03$ (for $\Delta \le 1,000km$), and
$TT(Rg) = \Delta / 2.99 + 1.86$ (for $\Delta \le 500km$).

Various relevant, independent geophysical information were then utilized to further constrain the thickness of crustal layers. References used include the 3-dimensional Moho and Conrad depths (Zlavdinov, 1974), the heat flow data (Golitsyn and Liatyf-Zade, 1975), a Deep Seismic Sounding [DSS] profile near Karkaralinsk (Antonenko, 1984), USGS open-file reports (Bonham et al., 1980; Leith, 1987ab, 1989), and miscellaneous NRDC-related publications. The KZ40 model derived in this study gives a fairly satisfactory performance in validation tests:

[1] both the mean and median mis-locations are 3-4 km for the 5 GT0 events tested,
[2] the mean and median errors in depth estimates are within 2 km for the 5 GT0 events tested,
[3] the mean and median of RMS residual, which are measures of misfit, are reduced by 50% as compared to those of IASP91 and J-B models, and
[4] the mean and median mis-locations are reduced by 50% as compared to those of IASP91 and J-B models.

These preliminary results suggest that KZ40, being a very simple one-dimensional crustal velocity model, could be adequate for routine location exercise in the eastern half of Kazakhstan and the southwestern part of Siberia. DTRA is currently collaborating with NNC on the last 100-ton shot planned for STS in the summer of 2000. This Ω-3 experiment is meant to destroy the very last unused tunnel in the Degelen Mountain originally excavated for potential nuclear testing by the former U.S.S.R. The additional seismic data from Ω-3 can be used to refine regional 1-dimensional models (such as KZ40) and pave the road for deriving a more sophisticated 3-dimensional representation of the crust of this region. The bilateral cooperation between the U.S.A. and Kazakshtan in executing these Ω-series experiments offers a prototype for how to conduct these experiments that are needed both for calibration purpose and, in other venues, perhaps for confidence building measures as well.

Key Words: Location, calibration, crustal velocity structure.

PROJECT OBJECTIVE

During the Threshold Test Ban Treaty [TTBT] era, seismic monitoring of nuclear tests relied primarily on teleseismic[1] data. The newly signed Comprehensive Nuclear-Test-ban Treaty [CTBT] shifts the focus of seismic monitoring to events with much smaller magnitudes, which may not be recorded at many teleseismic stations. Accordingly, in-country "regional" seismographs become a key ingredient of the verification regime in the treaty provisions. Seismic wave propagation at regional distances is more complex than at teleseismic distances, due to lateral inhomogeneities in the Earth's crust. As a result, determination of region-specific crustal structure - so-called "*calibration*" - is crucial for the CTBT verification. Improved region-specific crustal structure also finds an immediate utility in seismic hazard reduction. Though detailed 3-D structures are ultimately desirable, 1-D models are more appropriate for most location algorithms currently in use. 1-D models also serve as the starting model in deriving more complex and realistic 3-D models.

The objective of this study is to utilize seismic data collected under the recent tunnel / shaft closure experiments in Semipalatinsk Test Site (STS) for calibration of "*Zone 1*" (≤ 1,000km) regional wave propagation in Eastern Kazakhstan. These high explosive experiments were jointly conducted in the summer of 1997 and 1999 by Defense Threat Reduction Agency (DTRA, U.S.A.) and the National Nuclear Center (NNC) of Kazakhstan, under the Cooperative Threat Reduction Program (CTR). Multimax, Inc., a DTRA contractor, merged regional digital seismograms which were scattered at several institutions, and re-measured the phase picks for further analysis. A phased approach of research has been undertaken at DTRA:

[1] Derive the optimal average (*i.e.*, 1-D) crustal velocity model(s) for improved regional location purpose, based on data collected prior to the summer of 1999.

[2] The 1-D model(s) derived with existing data should be validated with independent data set. The Ω-2 of September 1999 and the Ω-3 (scheduled summer 2000) high explosive tests offer the best opportunity to collect seismic data required for such validation tests.

[3] Pending the performance of 1-D model(s) in seismic location exercise, the Source-Specific Station Corrections can be derived to count for the 3-D effect on travel times of various seismic phases.

This paper describes the results obtained so far under the Phase [1] and preliminary results under the Phase [2].

RESEARCH ACCOMPLISHED

Modern Digital Seismographs in Central Asia

Figure 1 is a map showing the IMS seismic stations near the Semipalatinsk Test Site (STS, shown as a shaded patch)[2] as well as all those seismic events reported in the bulletins of International Seismological Center (ISC) between 1987 and 1993. Within 1,000 km of STS, there are two IMS primary stations/sites (blue pentagons in Figure 1): Zalesovo (ZAL, 53.9°N, 84.8°E) and Makanchi (MAK, 46.8°N, 82.0°E); and three auxiliary stations (blue triangles in Figure 1): Borovoye (BRVK, 53.1°N, 70.3°E), Kurchatov (KURK, 50.7°N, 78.6°E), and Ala-Archa (AAK, 42.6°N, 74.5°E). The Lamont Doherty Earth Observatory (LDEO) of Columbia University has been cooperating with several local institutions in Kazakhstan and the southwestern Siberia of Russia on the installation and operation of modern broadband seismographs.[3]

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[1] So-called "*Zone 3*" in the fifties, which typically refers to distances 2,000km and beyond.

[2] The boundaries of the Semipalatinsk Test Site (STS) were defined and communicated to the U.S. in 1990 upon entry into force of the TTBT. The STS covers an area about 100 km from east to west, and 150 km from north to south (P. G. Richards, personal communications, 1999; See also Khalturin et al., 1999).

[3] LDEO's partners include the Institute of Geophysical Research, National Nuclear Center (NNC), Kazakhstan; Talgar Complex Seismological Expedition (TCSE), Kazakhstan; and Altai-Sayan Experimental & Methodological Seismological Expedition (ASEMSE), Russia. NNC operates Kazakhstan Broadband Network (KZNet), which includes two seismic arrays at Kurchatov and Borovoye. TCSE operates seismographs at Bayanual, Karkaralinsk, and Talgar. ASEMSE operates Yeltsovka (See Appendix A). IRIS supports the Kirghiz Network (KNet), which includes the auxiliary station Ala-Archa

Seismicity Around STS and DTRA-NNC Calibration Events

The seismicity of Eastern Kazakhstan (43°-55°N, 68°-88°E) is much weaker than that of the Tienshan Mountain Range to its south or the Altai Mountain Range to its east (Figure 1). Earthquakes in or around STS have been very rare. The red, gray, and green disks shown in Figure 1 represent shallow (<10km), medium-depth (10-33km), and deep (>33km) seismic events, respectively, based on catalogs published by the International Seismological Center (ISC, in England) between 1987 and 1993. The shallow events in STS shown in Figure 1 are nuclear tests conducted by the U.S.S.R. prior to the signing of CTBT. Deep earthquakes do exist in the Tienshan Mountain, which is about 1,000 km away from the STS. *To calibrate the seismic wave propagation within the stable Kazakh shield, man-made, controlled seismic events would be the best source and any of such opportunities should be embraced and fully exploited.* Six major HE tests have been conducted at the STS during the summer between 1997 and 1999 (Table 1). The biggest shots were of 100 tons, detonated in the tunnels 214 and 160 of Degelen Mountain. The remaining four shots are of 25 tons each. Several teleseismic seismographs have recorded most of these chemical explosions.

Table 1. DTRA-NNC Calibration Events '97-'98

Date	O.T.	N°	E°	Elev	DoB	Charge	Remark
970803	08:07:20.04	49.9412	78.7860	335	50	25	1311*
970831	07:08:38.75	49.8837	78.8148	332	300	25	1381*
970928	07:30:15.13	49.8794	78.8493	329	550	25	1349*
980822	05:00:18.90	49.7667	77.9908	716	0	100	214**
980917	07:19:40.55	49.9810	78.7559	320	30	25	1071
990925	07:00:06.00	49.7819	78.9663	___	___	100	160***

* : Depth-of-Burial Experiments in Balapan. ** : Ω-1 Experiment in Degelen. *** : Ω-2 Experiment in Degelen.

Travel-Time Regression and Additional Geophysical Constraints

Since the source parameters of these HE tests are exactly known - *i.e.*, they are the so-called "GT0" events, the arrival times as well as the distances to seismographs can be accurately measured. Standard least-squares regressions provide the best linear fit of travel times as a function of great circle distance. If non-GT0 events were used, the uncertainty in travel time and/or the distance should be taken into account. This can be accomplished with the Monte-Carlo procedure in which each data point is perturbed according to the pre-defined probability distribution (Jih, 1993). Figures 2 shows results of regressing travel times of Pn and Pg on distance, using the first five events listed in Table 1. The results can be summarized as follows:

$$TT(Pn) = \Delta / 7.94 + 7.56, \quad 300km \le \Delta < 500km.$$
$$TT(Pn) = \Delta / 8.13 + 8.79, \quad 500km \le \Delta \le 1{,}000km.$$
$$TT(Pg) = \Delta / 6.02 + 0.20, \quad \Delta \le 900km.$$
$$TT(Sn) = \Delta / 4.69 + 14.98, \quad \Delta \le 900km.$$
$$TT(Lg) = \Delta / 3.51 + 0.03, \quad \Delta \le 1{,}000km.$$
$$TT(Rg) = \Delta / 2.99 + 1.86, \quad \Delta \le 500km.$$

There are often more than one crustal models whose predicted travel-time curves would match the observed ones. This is exactly the same situation in interpreting the receiver function with crustal models. It is therefore necessary to utilize some independent information, such as the lab measurement of rock composition and velocity *etc.*, to further constrain the crustal model. Previous geophysical studies provide very useful constraints on this region: 3-D Moho and Conrad depths (Zlavdinov, 1974), the heat flow data (Golitsyn and Liatyf-Zade, 1975), DSS profile near Karkaralinsk (Antonenko, 1984), USGS open-file reports (Bonham *et al.*, 1980; Leith, 1987ab,

(AAK). More detailed description of these facilities can be found in Kim et al. (1996).

1989), and other publications (*e.g.*, miscellaneous NRDC-related studies). Combining the velocity regression results (Figure 2) and these geophysical studies, three crustal models, KZ40, KZ45, and KZ50, with crustal thickness of 40, 45, and 50km, respectively, are proposed (Figures 3). The upper mantle velocities of these three models are slightly different, with thicker crust associates with faster P- and S-velocities.

Re-location Results and Metrics of Location Performance

Figure 4 shows the LocSAT locations of the event 970803 using eight different crustal models including JB, IASPEI-91, Southwestern Siberia model (Emanov *et al.*, 1999), a gradient model based on a Deep Seismic Sounding [DSS] profile near the STS (Antonenko, 1984), a discretized version of the DSS model (Leith, 1989), as well as the three models developed in this study: KZ40, KZ45, and KZ50. For each model, the 95% coverage ellipse and RMS residual are printed, along with the absolute error in the origin time, epicenter (measured by mislocation in km), and depth. Six models give excellent depth estimates for this event: JB, IASPEI91, Leith (1989), KZ40, KZ45, and KZ50. Models associated with larger error in depth tend to give larger error in the origin time as well. The majority of models lead to a mislocation of only a few kilometers.

The location performance of each crustal model can be evaluated with five metrics, each being averaged over five events: [1] the size of 95% coverage ellipse, [2] the RMS residual, [3] the rectified error in the origin time, [4] the mislocation, and [5] the rectified error in depth estimate. These 8 by 5 metrics are tabulated in Table 2 (top). The performance can also be measured with the median of the metrics (Table 2, bottom).

The International Seismological Centre [ISC] and the CTBT International Data Center [IDC] in Vienna use the J-B and IASPEI-91 models, respectively, as the baseline model in their routine location operations. The National Earthquake Information Center [NEIC] of US Gelogical Survey has been using the J-B tables for several decades. All the events tested so far move closer to the Ground Truth [GT] locations when KZ-series of region-specific models are used. In fact, both the mean and median mislocation are reduced by more than 50%. Another metric that shows a dramatic improvement is the RMS residual, which is a measure of misfit (in seconds). Smaller RMS residual means better fit. Table 2 indicates that RMS residual also gets a 50% reduction.

Leith (1989) proposes to discretize the gradient crust of Antonenko's (1984) DSS model to get around the same software restriction Thurber (1990) had faced. It is interesting to note that Leith's (1989) model gives a perfect depth estimate for each of the six events. KZ40, KZ45, and KZ50 models perform very well across all five metrics. Models associated with larger error in the depth estimate lead to larger error in origin time as well (*e.g.*, the southwestern Siberia model of Emanov *et al.*, 1999; and the DSS model of Antonenko, 1984).

Table 2. Metrics of Location Performance

Model	μ[C-Elps]	μ[RMS]	μ[Δ(OT)]	μ[Δ(XY)]	μ[Δ(H)]
J-B	143	1.30	1.57	8.82	0.20
IASPEI-91	148	1.36	0.15	8.12	0.20
SW Siberia	170	0.86	1.17	3.44	12.34
Antonenko (1984)	194	0.76	1.98	5.16	17.14
Leith (1989)	177	1.60	0.48	7.38	0.00
KZ40 (this study)	168	0.58	0.31	2.80	0.86
KZ45 (this study)	170	0.56	0.39	3.38	2.56
KZ50 (this study)	171	0.52	0.43	3.74	3.28

μ[X]: mean of metric "X" over five events.

C-Elps: area enclosed by 95% coverage ellipses (km^2). RMS: RMS travel-time residuals (second).

Δ(OT): rectified error in origin time (second). Δ(XY): mislocation in epicenter (km). Δ(H): rectified error in depth (km).

Table 2. Metrics of Location Performance (Continued)

Model	m[C-Elps]	m[RMS]	m[Δ(OT)]	m[Δ(XY)]	m[Δ(H)]
J-B	155	1.30	1.65	9.40	0.10
IASPEI-91	161	1.40	0.13	8.90	0.10
SW Siberia	174	0.80	1.06	4.20	12.50
Antonenko (1984)	221	0.70	1.95	5.10	16.50
Leith (1989)	185	1.70	0.55	7.70	0.00
KZ40 (this study)	173	0.60	0.35	2.90	0.30
KZ45 (this study)	174	0.50	0.36	3.10	0.60
KZ50 (this study)	174	0.50	0.16	3.60	1.60

m[X]: median of metric "X" over five events.

C-Elps: area enclosed by 95% coverage ellipses (km^2). RMS: RMS travel-time residuals (second).

Δ(OT): rectified error in origin time (second). Δ(XY): mislocation in epicenter (km). Δ(H): rectified error in depth (km).

Re-location with IMS Stations Only

The models KZ40, KZ45, and KZ50 are derived with phase readings from events exclusively from the region of study. One would naturally expect regionalized model(s) like these to perform better than do global average models such as IASPEI-91 and J-B, which are not "calibrated" for this specific region. This is indeed the case (see Figure 4). Ideally other events that have not been used in constructing the velocity models should be relocated as an independent check. Alternatively, a sub-optimal check is to re-locate the six events with some phases (stations) excluded. Figure 5 shows the re-location results for the event 990925 with IMS stations only. This is a semi-independent test of the models that can be effortlessly performed at this point - an *ad hoc* measure temporarily used until new data are available for testing. This exercise by itself is also an important test from the CTBT verification point of view. *The IMS stations in this region - Borovoye, Kurchatov, Zalesovo, and Makanchi - appear to be able to locate the 100-ton shot with very reasonable accuracy and precision, provided that region-specific models (such as the KZ-series) are used.*

CONCLUSIONS AND RECOMMENDATIONS

The DOB and Ω-series events provide excellent examples of calibration shots which are needed worldwide for CTBT monitoring. These events provide a prototype for how to conduct these experiments and, could act as an international example of what needs to be done for the CTBT, both for calibration and, in other venues, perhaps for confidence-building measures. Regional and local seismic observations of these shots at different depths-of-burial (DOB) in tunnels, when combined with previous calibration work such as the Nevada Test Site Nonproliferation Experiment and the 1960s Lake Superior experiments, can provide fundamental information on detection thresholds and location calibration in different geological areas. Such a program covering all areas of the world is necessary for the CTBT monitoring regime. During these experiments in STS, one successful - and important - example of instrument deployment and data collection has been set by LDEO of Columbia University under contracts to DTRA and LLNL.

From calibration point of view, the DOB and Ω series experiments offer an excellent opportunity to calibrate the region's propagation properties for many regional and local seismic phases. In addition to phases that are routinely used in regional location exercise, such as Pn, Pg, Sn, and Lg, this study also utilizes the phase PmP. The calibration procedure described in this paper is straightforward and simple to implement. It is a procedure very similar to interpreting the wide-angle refraction profile. The resulting 1-D models appear to be suitable for the shield region of Eastern Kazakshtan. There are indications that these KZ-series crustal velocity models could be applicable to the Southwestern Siberia as well. Emanov *et al.* (1999) use an one-layer simple crustal model to locate events in the Kuzbass-Abakan mining region. Their model gives travel time curves very close to what the KZ-series models would give.

The IMS stations in this region - Borovoye, Kurchatov, Zalesovo, and Makanchi - appear to be able to locate the 100-ton shot with very reasonable accuracy and precision, provided that region-specific models (such as the KZ-series) are used. However, the models developed in this study need to be tested with some really independent data set, *i.e.*, with events that have not been used in deriving the models. A precious opportunity for such tests would be DTRA-NNC's Ω-2 and Ω-3 HE experiments. The Ω-2 experiment of 25 September 1999 also provided an opportunity for on-site inspection team from both DTRA and the CTBTO (in Vienna) to conduct a mock inspection exercise (DTRA, 1999).

This study presents a simple calibration procedure, J_5, which utilizes several GT0 events to derive averaged 1-D crustal model(s). The resulting 1-D crustal model appears to be suitable for regional (≤1,000 km) location purpose in this area which encircles two CTBT primary IMS sites (ZAL, MAK) and three existing auxiliary stations (BRVK, KURK, and AAK). Several metrics shown in the attached Table clearly illustrate how regionalized 1D models (such as KZ45) can improve the location:
[1] the mean and median of RMS residual, which are measures of misfit, are reduced by 50% as compared to those of IASPEI-91 and JB models,
[2] the mean and median mislocation are reduced by 50% as compared to those of IASPEI-91 and JB models,
[3] the mean and median mislocation are 3-4 km for the 5 GT0 events tested,
[4] the mean and median errors in depth estimates are within 2 km for the 5 GT0 events tested.
An alternative approach of utilizing these precious GT0 events is to establish the Source-Specific Station Correction [SSSC] surface for each seismic phase of interest. A follow-up study of comparing the performance of SSSC against 1-D average models in locating events away from STS is planned. A surprising feature of Leith's (1989) discretized model is that it gives the perfect depth estimate for all six events. Why this model performs in this peculiar manner needs to be carefully explored.

ACKNOWLEDGEMENTS

This project is a joint effort of the *Sensor and Geotechnical Applications Branch (CPFG)* of Defense Threat Reduction Agency (DTRA) and Multimax, Inc. Multimax is supported under DTRA contract *DSWA01-98-C-0156* issued by the *Arms Control Technology Division (DTRA/OST)*. The analyses of Multimax-furnished phase arrival readings were conducted at the *Seismic R&D Support Desk* of DTRA/CPFG. Additional support for seismo-acoustic data acquisition came from the Bureau of Verification and Compliance (DOS/AC/VC) and DoD Washington Headquarters Services (WHS).

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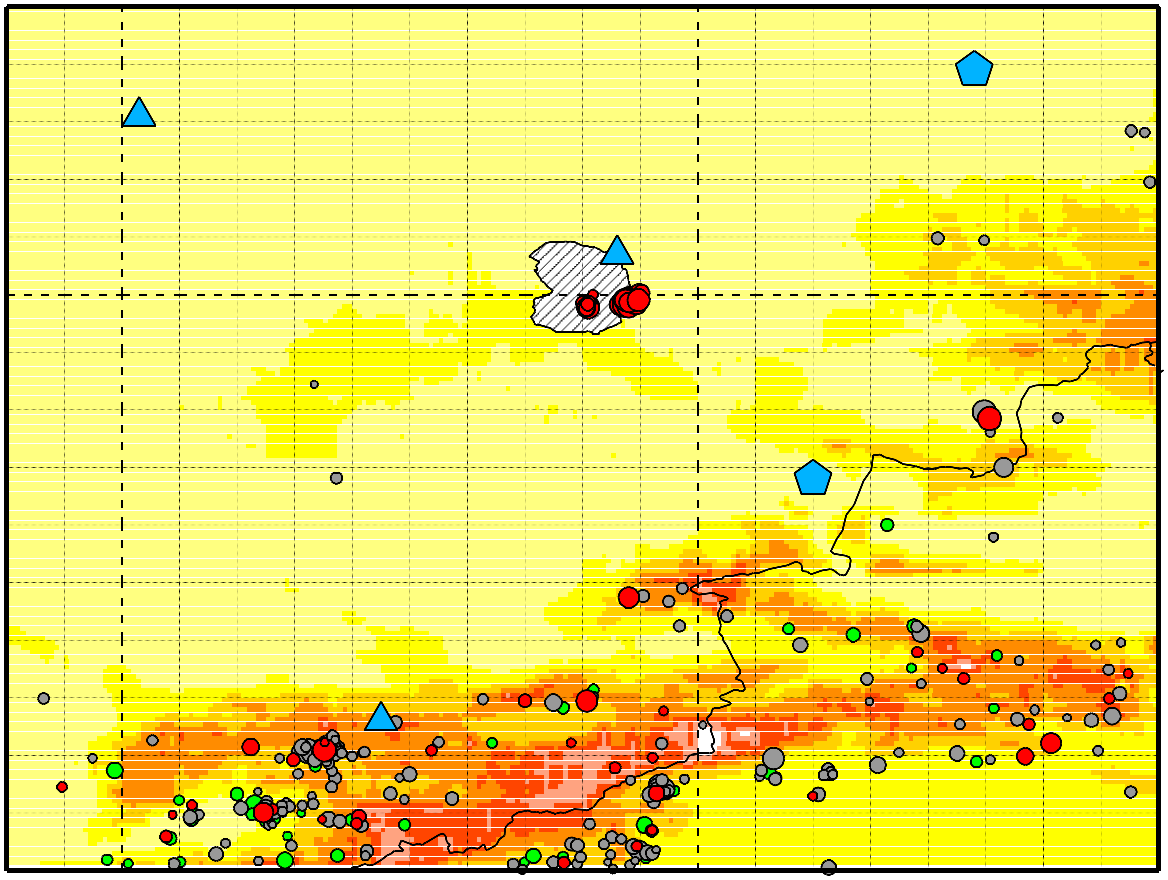
ISC SEISMICITY & IMS STATIONS AROUND STS & MAKANCHI



Large & moderate (Ms >= 4.0) events in Central Asia, 1987-1993

304 events with hypocenters/magnitudes published by ISC:

Red: 67 shallow (<= 10km) events, including UNEs in Semipalatinsk

Gray: 184 events of medium depth (10 < H <= 33; Green: 53 deep events (H > 33)

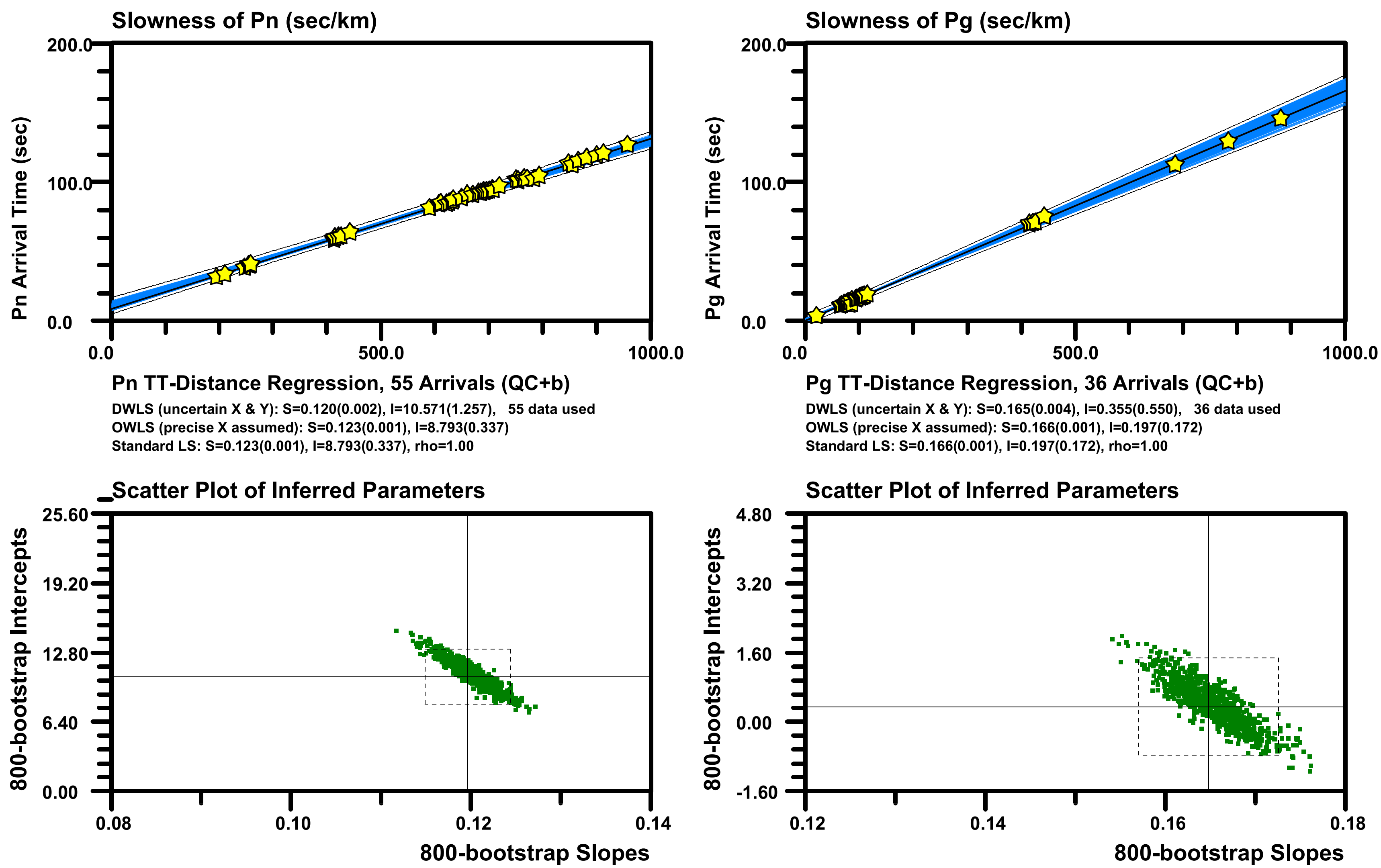
Blue pentagons: IMS primary stations MAK & ZAL

Blue triangles: IMS auxiliary stations AAK, BRVK, KURK

STS (official boundary digitized by Paul G. Richards)

Figure 1

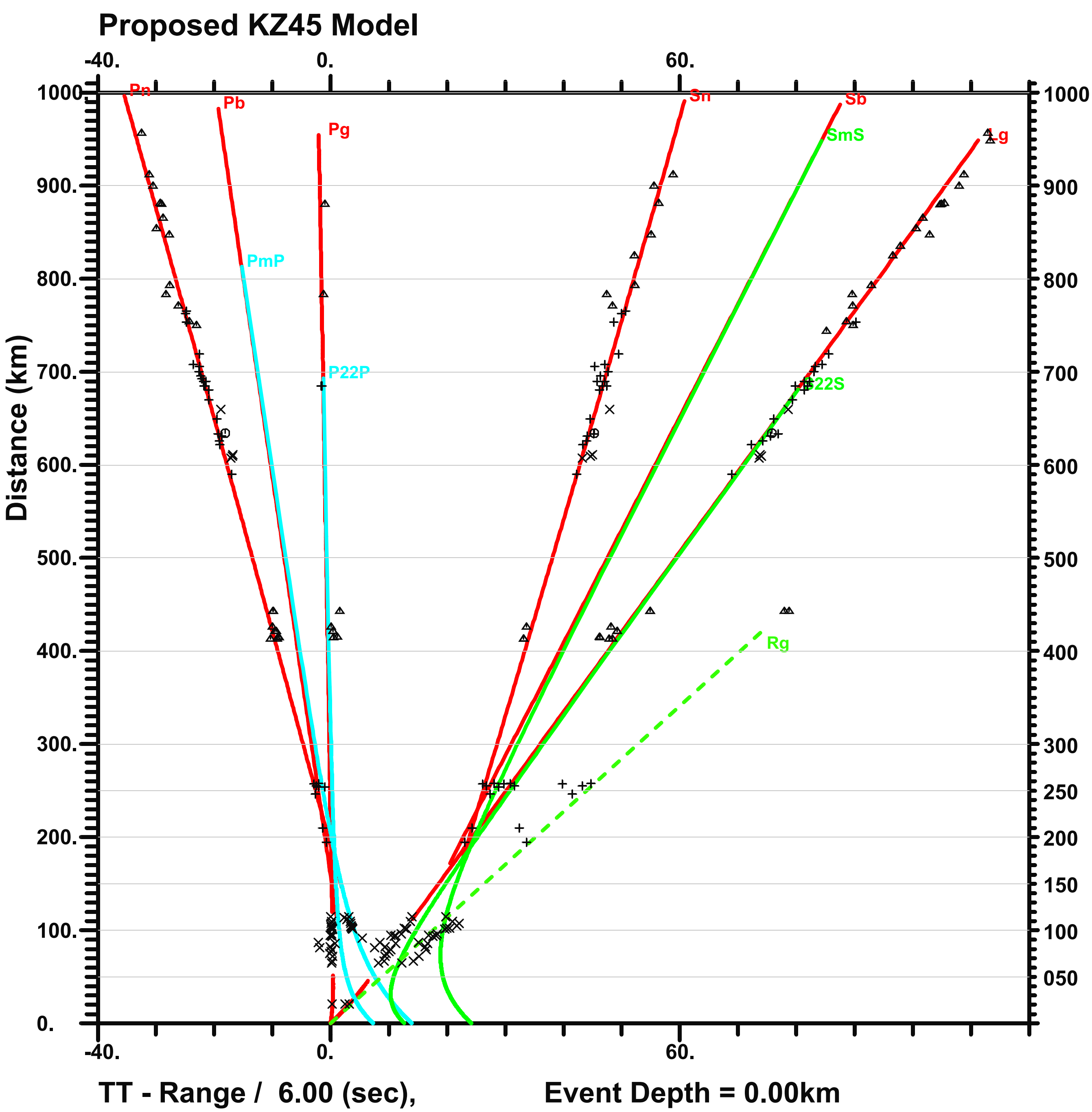
V(Pn) & V(Pg) IN KAZAKHSTAN



95% confidence interval of slope: 0.120+/-0.005
95% confidence interval of intercept: 10.571+/-2.523
[97.5% quantile of t(53 D.o.F.), 2.007, used]

95% confidence interval of slope: 0.165+/-0.008
95% confidence interval of intercept: 0.355+/-1.119
[97.5% quantile of t(34 D.o.F.), 2.034, used]

Figure 2

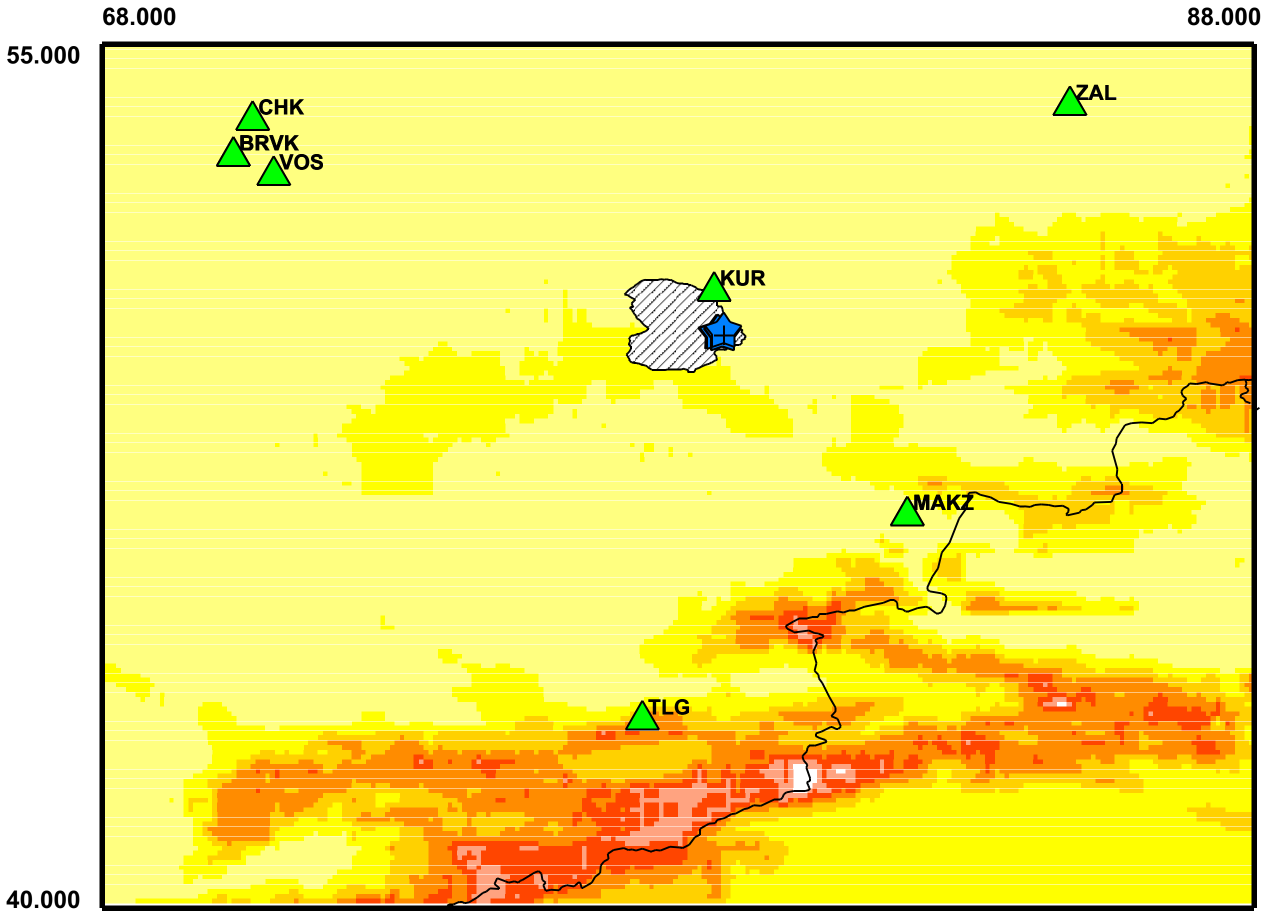


Eastern stations
Southern stations
Western stations
Northern stations

Adaquate for 68E-88E, 40N-55N; 1,000 km within STS
0km: 5.40, 3.05; 5-22km: 6.09, 3.53; 22-45km: 6.95, 4.00;
45km: 8.05, 4.60; 205km: 8.35, 4.80

Figure 3

LocSAT Locations of 970803



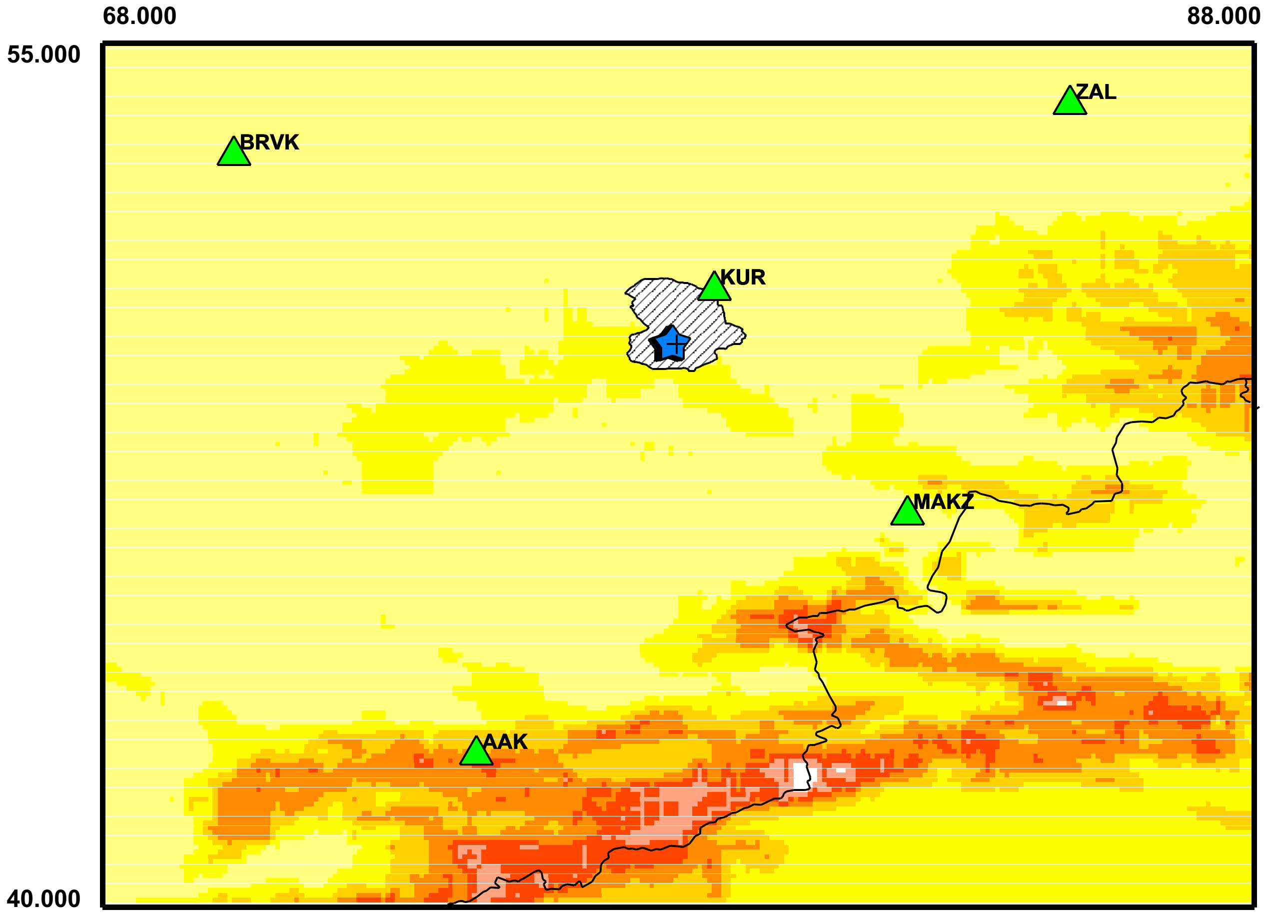
Event 970803, 28 picks, GT info: 0807 20.04 49.9412N 78.7860E 0.05km

J-B model location = 8:7:18.350, 49.976 78.667 0.000
95% C-ellipse=187km^^2, RMS res=1.2s, Error [OT=-1.74s, XY=9.4km, H=-0.1km]
IASPEI91 model location = 8:7:20.044, 49.979 78.694 0.000
95% C-ellipse=192km^^2, RMS res=1.3s, Error [OT=-.04s, XY=7.8km, H=-0.1km]
SW Siberia model (ASEMSE) location = 8:7:21.075, 49.978 78.769 8.401
95% C-ellipse=217km^^2, RMS res=0.7s, Error [OT=1.06s, XY=4.3km, H=8.4km]
DSS (Antonenko, 1984) location = 8:7:21.774, 49.986 78.770 11.959
95% C-ellipse=278km^^2, RMS res=0.6s, Error [OT=1.76s, XY=5.1km, H=11.9km]
Discretized DSS (Leith, 1989) location = 8:7:20.605, 50.013 78.786 0.050
95% C-ellipse=223km^^2, RMS res=1.4s, Error [OT=.56s, XY=8.0km, H=0.0km]
KZ50 (this study) location = 8:7:20.201, 49.964 78.772 0.000
95% C-ellipse=208km^^2, RMS res=0.5s, Error [OT=.16s, XY=2.7km, H=-0.1km]
KZ45 (this study) location = 8:7:20.387, 49.963 78.766 0.000
95% C-ellipse=203km^^2, RMS res=0.5s, Error [OT=.36s, XY=2.8km, H=-0.1km]
KZ40 (this study) location = 8:7:20.427, 49.959 78.759 0.000
95% C-ellipse=201km^^2, RMS res=0.5s, Error [OT=.36s, XY=2.8km, H=-0.1km]

STS (Richards et al., 1999)

Figure 4

LocSAT Locations of 990925.ims



Event 990925.ims, 17 picks, GT info: 0500 6.00 49.7819N 77.9663E 0.00k

J-B model location = 5:0:3.615, 49.753 77.798 0.000

95% C-ellipse=289km^^2, RMS res=1.3s, Error [OT=-2.40s, XY=12.5km, H=0.0km]

IASPEI91 model location = 5:0:5.371, 49.759 77.824 0.000

95% C-ellipse=298km^^2, RMS res=1.5s, Error [OT=-.60s, XY=10.6km, H=0.0km]

SW Siberia model (ASEMSE) location = 5:0:7.445, 49.775 77.879 15.530

95% C-ellipse=323km^^2, RMS res=0.7s, Error [OT=1.40s, XY=6.3km, H=15.5km]

DSS (Antonenko, 1984) location = 5:0:9.974, 49.777 77.896 38.189

95% C-ellipse=387km^^2, RMS res=1.1s, Error [OT=4.00s, XY=5.1km, H=38.2km]

Discretized DSS (Leith, 1989) location = 5:0:6.101, 49.779 77.852 0.000

95% C-ellipse=342km^^2, RMS res=1.8s, Error [OT=.10s, XY=8.2km, H=0.0km]

KZ50 (this study) location = 5:0:6.622, 49.765 77.876 6.686

95% C-ellipse=336km^^2, RMS res=0.4s, Error [OT=.60s, XY=6.8km, H=6.7km]

KZ45 (this study) location = 5:0:6.484, 49.766 77.871 2.811

95% C-ellipse=323km^^2, RMS res=0.4s, Error [OT=.50s, XY=7.1km, H=2.8km]

KZ40 (this study) location = 5:0:6.007, 49.764 77.863 0.000

95% C-ellipse=311km^^2, RMS res=0.5s, Error [OT=0s, XY=7.7km, H=0.0km]

STS (Richards et al., 1999)

Figure 5