Geophysics R & D needed to support monitoring for compliance with test-ban treaties (LTBT, NPT, TTBT, PNET, and CTBT)

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The four test ban treaties:

LTBT = **Limited Test Ban Treaty** (1963)

also known as the **Partial Test Ban Treaty** or the **Atmospheric Test Ban Treaty**

trilateral (USA, USSR, UK; became multilateral)

prohibits nuclear weapons tests "or any other nuclear explosion" in the atmosphere, in outer space, and under water.

Allowed underground nuclear testing (> 1500 since 1963 – promoted monitoring capability).

TTBT = **Threshold Test Ban Treaty** (1974)

bilateral (USA, USSR)

banned underground nuclear weapons tests of yield greater than 150 kilotons after March 1976

not ratified until 1990 (!) after an extensive series of battles over technical issues (yield estimation)

PNET = **Peaceful Nuclear Explosions Treaty**

bilateral (USA, USSR)

in effect banned underground nuclear explosions done for non-military purposes above 150 kt

(building underground cavities,
putting out oil-well fires
seismic sources for geophysical surveys
making transuranic elements
construction of dams, canals...)

NPT = **Non-Proliferation Treaty** (1970)

the most important nuclear arms control treaty

multilateral
international monitoring provided by the IAEA

bans transfer of nuclear weapons technology between non-nuclear and nuclear weapon states

had a section (Article V) stating that:

> "potential benefits from any peaceful applications of nuclear explosions will be made available to non-nuclear-weapon States Party to the Treaty on a nondiscriminatory basis and ... the charge to such Parties for the explosive devices used will be as low as possible and exclude any charge for research and development"

Treaty on Principles Governing the Activities of States in the Exploration and **Use of Outer Space**, including the Moon and Other Celestial Bodies

[negotiated and in effect, 1967]

includes:

Article IV
States Parties to the Treaty undertake not to place in orbit around the Earth any objects carrying nuclear weapons or any other kinds of weapons of mass destruction, install such weapons on celestial bodies, or station such weapons in outer space in any other manner.

like the LTBT: not associated with formal methods of verification

But these are all now largely superceded by the...

CTBT =

Comprehensive Nuclear-Test-Ban Treaty

negotiated from 1958 to 1996, *though this treaty has still not entered into force (why not?), so in effect we have a nuclear testing moratorium at least by the recognized nuclear weapons states*

Has the most extensively-developed verification procedures of any modern nuclear arms control treaty (six global networks, big budget...)

(on-site verification provisions, similar in some respects to the Chemical Weapons Convention)

Contributions of key technologies to CTBT monitoring of different test environments

Key Technologies / Environment of test	Underground	Underwater	Atmosphere	Near Space
Seismic*	major	major	secondary	none
Radionuclide*	major	major	major	none
Hydroacoustic*	secondary	major	secondary	none
Infrasound*	secondary	secondary	major	none
Electromagnetic	secondary	secondary	major	major
Satellite Imagery	major	major	secondary	secondary

* technologies used by the International Monitoring System (Vienna)

Six different steps in nuclear explosion monitoring:

Detection
(did a particular station detect a useful signal?)

Association
(can we gather all the different signals from the same “event”?)

Location
(where was it?)

Identification
(was it an earthquake, a mining blast, a nuclear weapon test?)

Attribution
(if it was a nuclear test, what country carried it out?)

Yield estimation
(how big was it?)

The CTBT will in practice be monitored by:

- the international CTBT Organization in Vienna, Austria;

- National Technical Means, which for the United States includes the Atomic Energy Detection System (AEDS) operated by the Air Force Technical Applications Center (AFTAC); and

- the loosely organized efforts of numerous institutions, acquiring and processing data originally recorded for purposes other than treaty monitoring

Hundreds of institutions continuously operate thousands of seismometers.
Seismically active regions of North America, Europe, Asia, North and South Africa, and the Middle East are now routinely monitored down to low magnitudes in order to evaluate earthquake hazards.

The main idea.:

use archives of seismic events as an aid to help with monitoring events occurring today.

First, briefly review the main results of a study of Kazakhstan seismicity, using cross-correlation to detect small events:

Multi-Station Validation of Waveform Correlation Techniques as applied to Broad Regional Monitoring
Megan Slinkard, David Schaff, Natalya Mikhailova, Stephen Heck, Christopher Young, Paul G. Richards

(just accepted for publication in the Bulletin of the Seismological Society of America).

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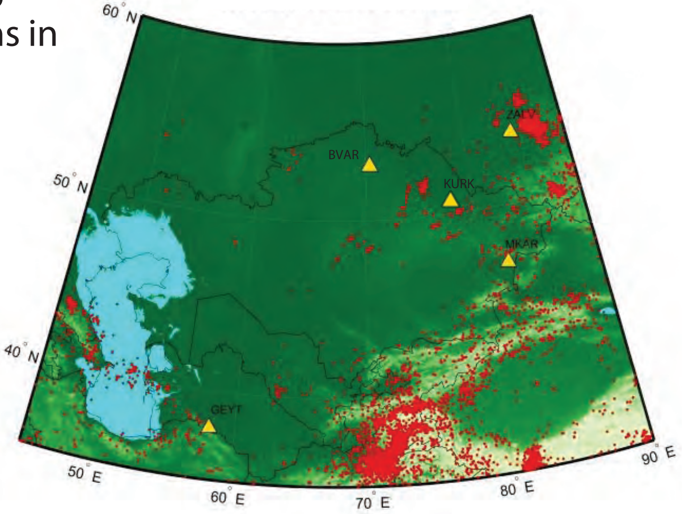
Second, describe preliminary results of cross-correlation as a detector applied to China seismicity, combined with cross-correlation to measure relative arrival times, to enable precise estimates of event location.

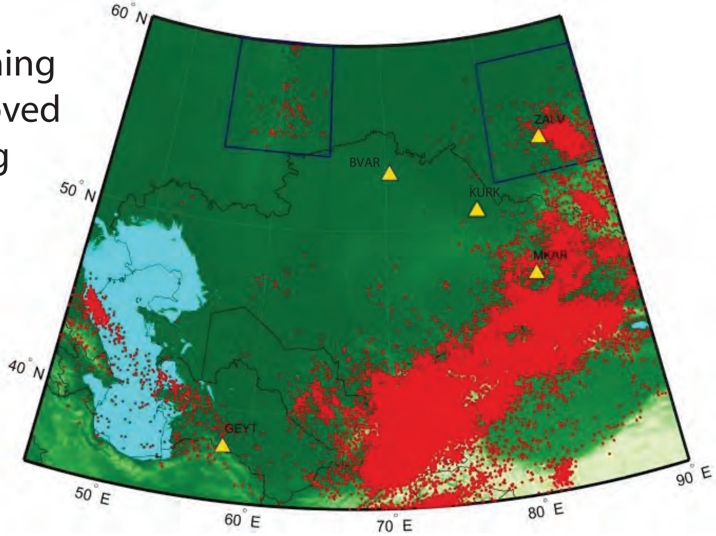
MOTIVATION AND OBJECTIVES

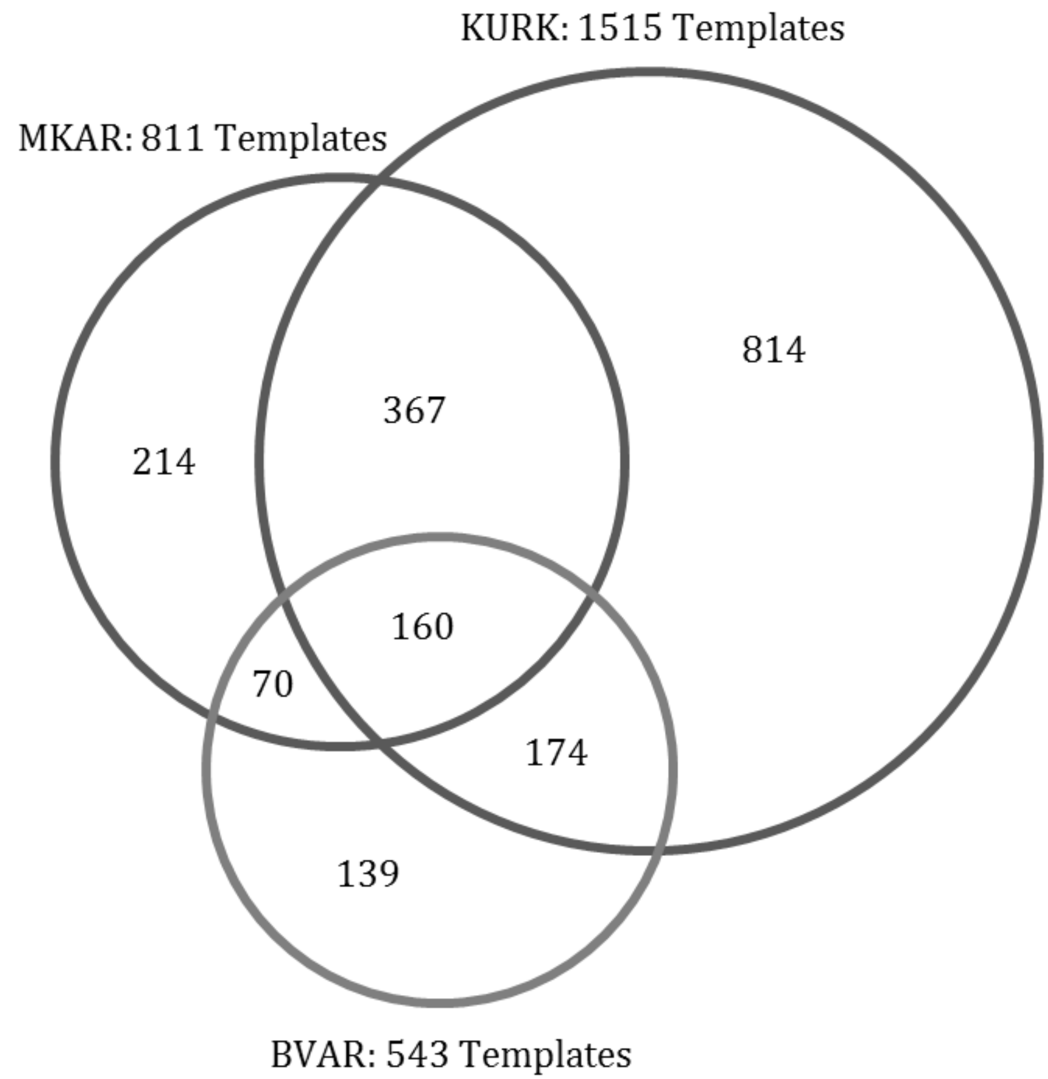
Comparing the CTBTO's LEB catalog to a regional catalog from the Kazakhstan National Data Center (KNDC), which covers central Asia, we note the potential for waveform correlation to enhance the completeness of the LEB catalog.

The LEB catalog had 8015 origins in a 3 year period

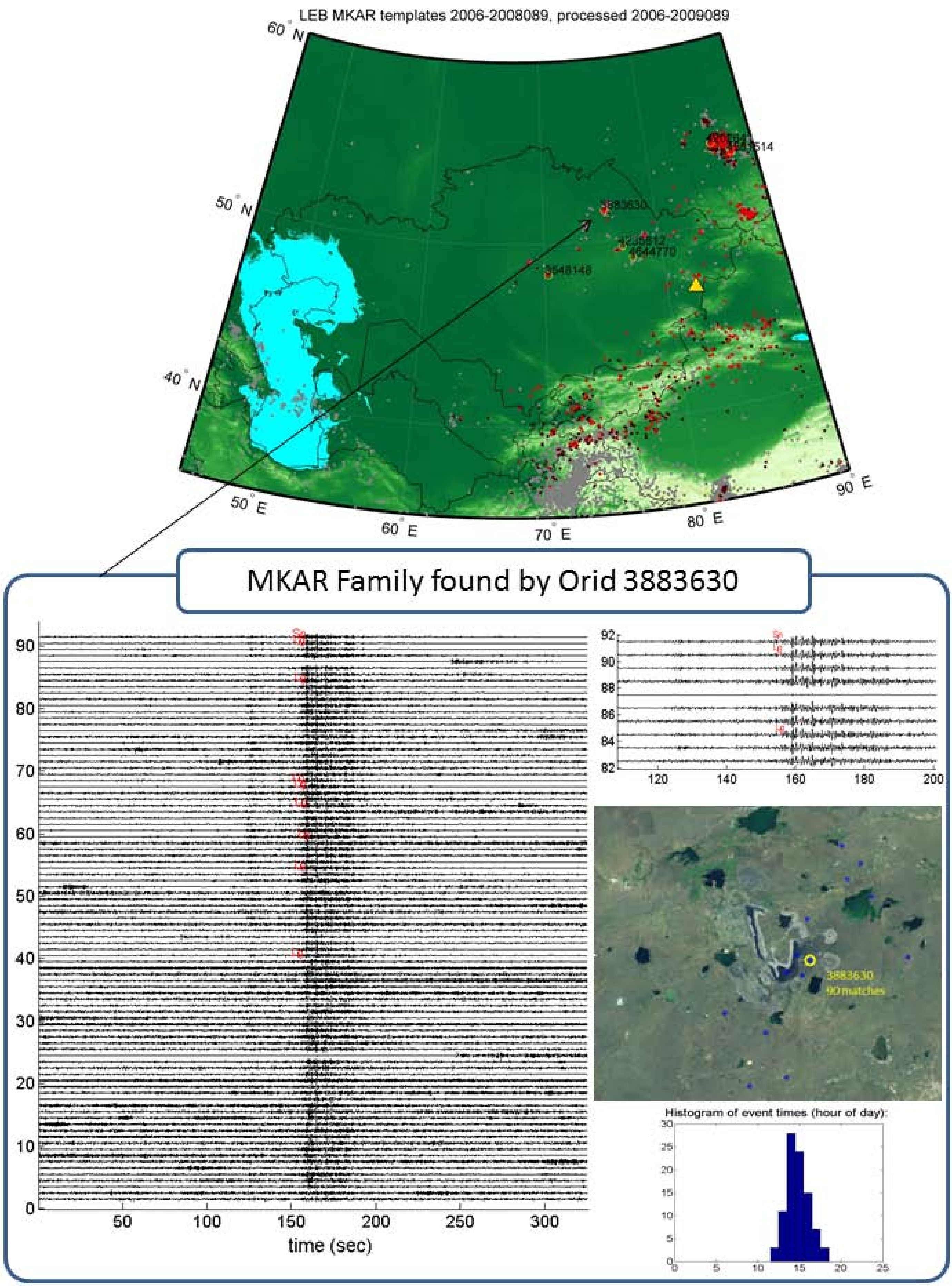


The KNDC regional catalog had over 45000, AFTER mining events were removed (except for mining events in the two boxed regions in Russia)





A total of 1938 events generated the template waveforms used at the three stations. This Venn diagram shows how many events had templates at one, or at two, or at all three stations.



LEB MKAR templates 2006-2008089, processed 2006-2009089
60° N
50° N
40° N
50° E
60° E
70° E
80° E
90° E
3883630
4644770
3548148
MKAR Family found by Orid 3883630
time (sec)
3883630
90 matches
Histogram of event times (hour of day):

Station	**Number of Detections**	**Detections confirmed in the LEB**	**Detections confirmed in the KNDC Catalog**	**Detections confirmed in either catalog**	**Detections confirmed by high correlation (>0.7)**	**Detections confirmed by 2 stations (1481 seen by all 3 stations)**	**Confirmed in some manner**
MKAR (array)	7426 (from 506 of 811 templates)	526	553	927	1309 (183 not in LEB or confirmed by another station)	4740 (64%) (4226 not in LEB)	**5136 (69%)** (4610 not in LEB)
BVAR (array)	3096 (from 193 of 543 templates)	154	67	180	383 (17 not in LEB or confirmed by another station)	2199 (71%) (2054 not in LEB)	**2307 (75%)** (2153 not in LEB)
KURK (3C)	8526 (from 837 of 1515 templates)	693	705	1179	2031 (376 not in LEB or confirmed by another station)	4895 (57%) (4327 not in LEB)	**5648 (66%)** (4955 not in LEB)

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Summary: templates were used to detect more than ten times as many smaller events in continuous data over three years, and most of them were confirmed.

Total number of template waveforms, derived from three years, 2006 to 2008, and applied to the same three year period:

MKAR (811 events, 9 channels)	7299 waveforms
BVAR (543 events, 9 channels)	4887 waveforms
KURK (1515 events, 3 channels)	4545 waveforms.

Data filtered to pass 0.5 – 5 hz; 25 second windows (*Lg* wave).

We searched all 21 channels using a 32 processor network.

We used a detection threshold set separately for each template, for a false alarm rate of about one wrong detection per year.

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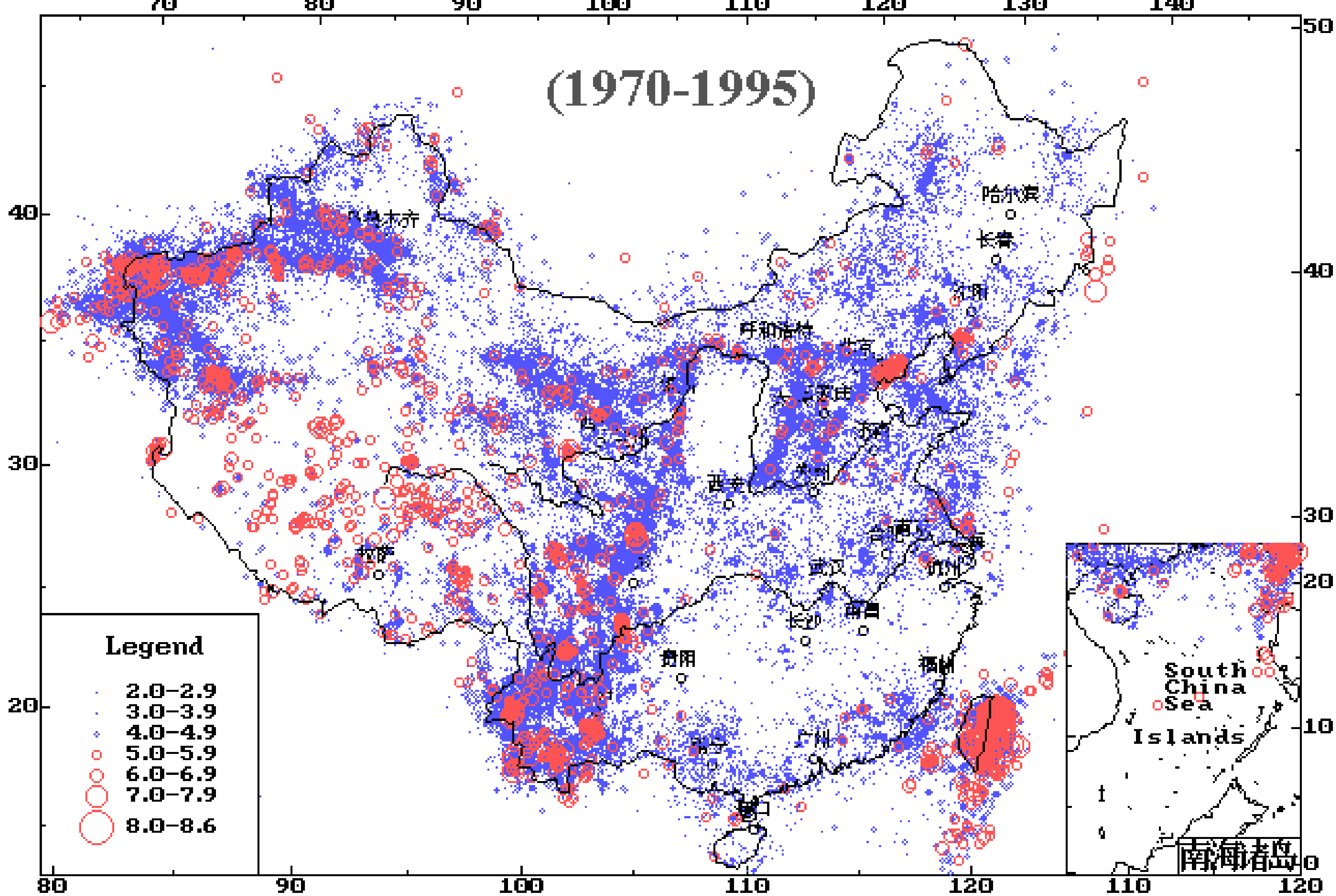
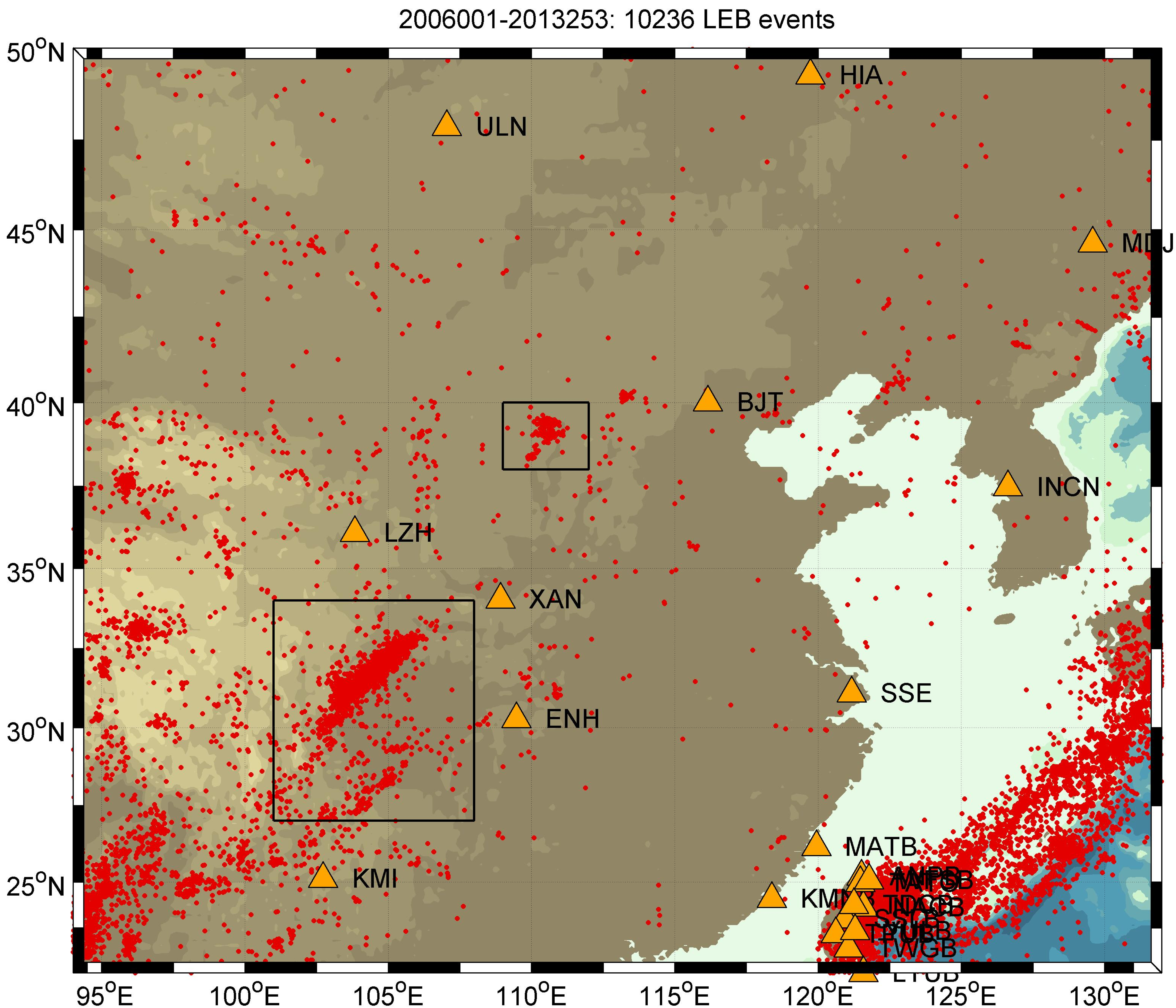
This dataset required only 2.5 days for the computation.

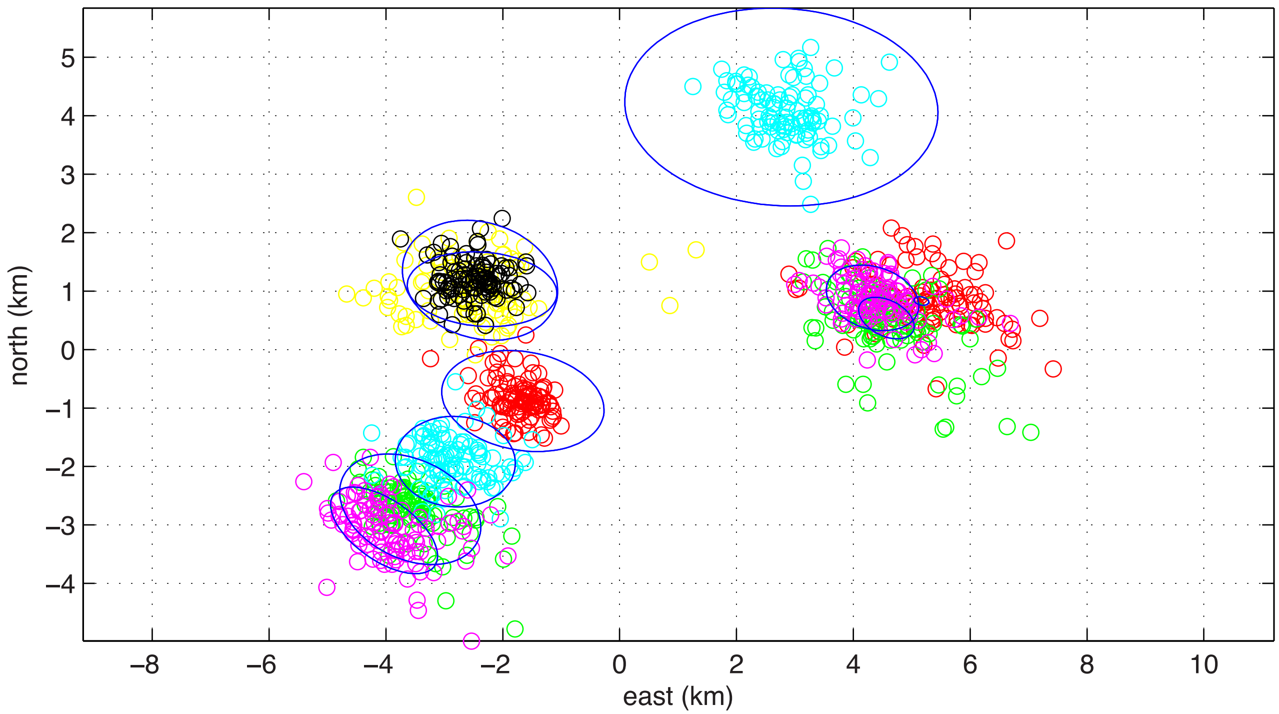
中国地震震中分布图

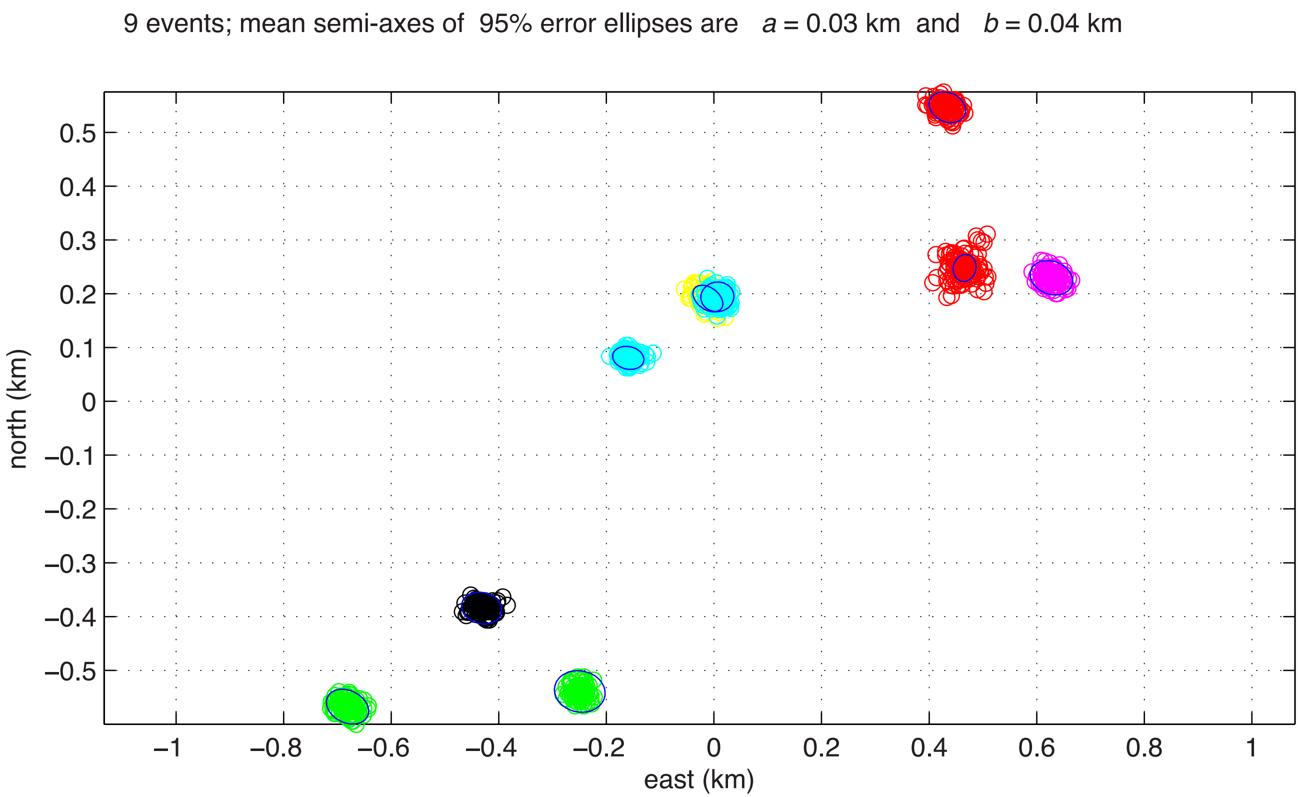
Seismic Epicentral Distribution in China




2006001-2013253: 10236 LEB events
HIA
ULN
MDJ
BJT
INCN
LZH
XAN
SSE
ENH
MATB
KMI
50°N
45°N
40°N
35°N
30°N
25°N
95°E
100°E
105°E
110°E
115°E
120°E
125°E
130°E

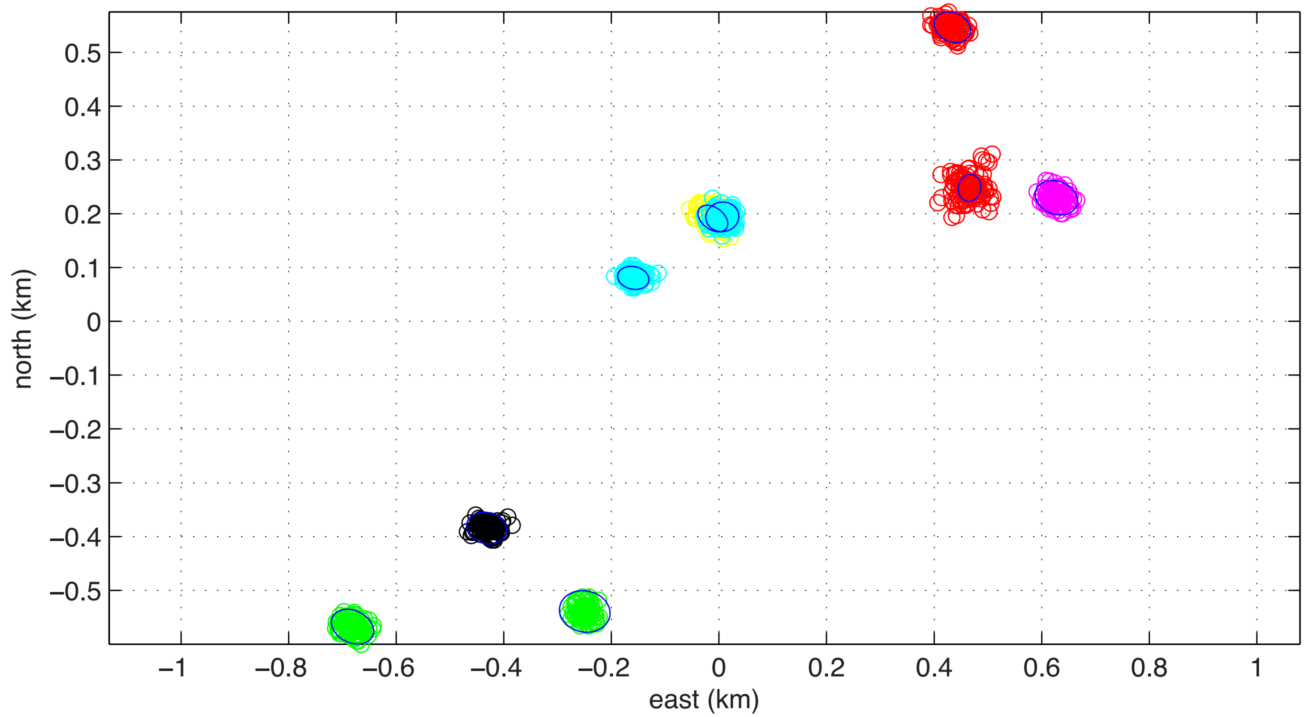
10 events; mean semi-axes of 95% error ellipses are a = 0.72 km and b = 1.15 km

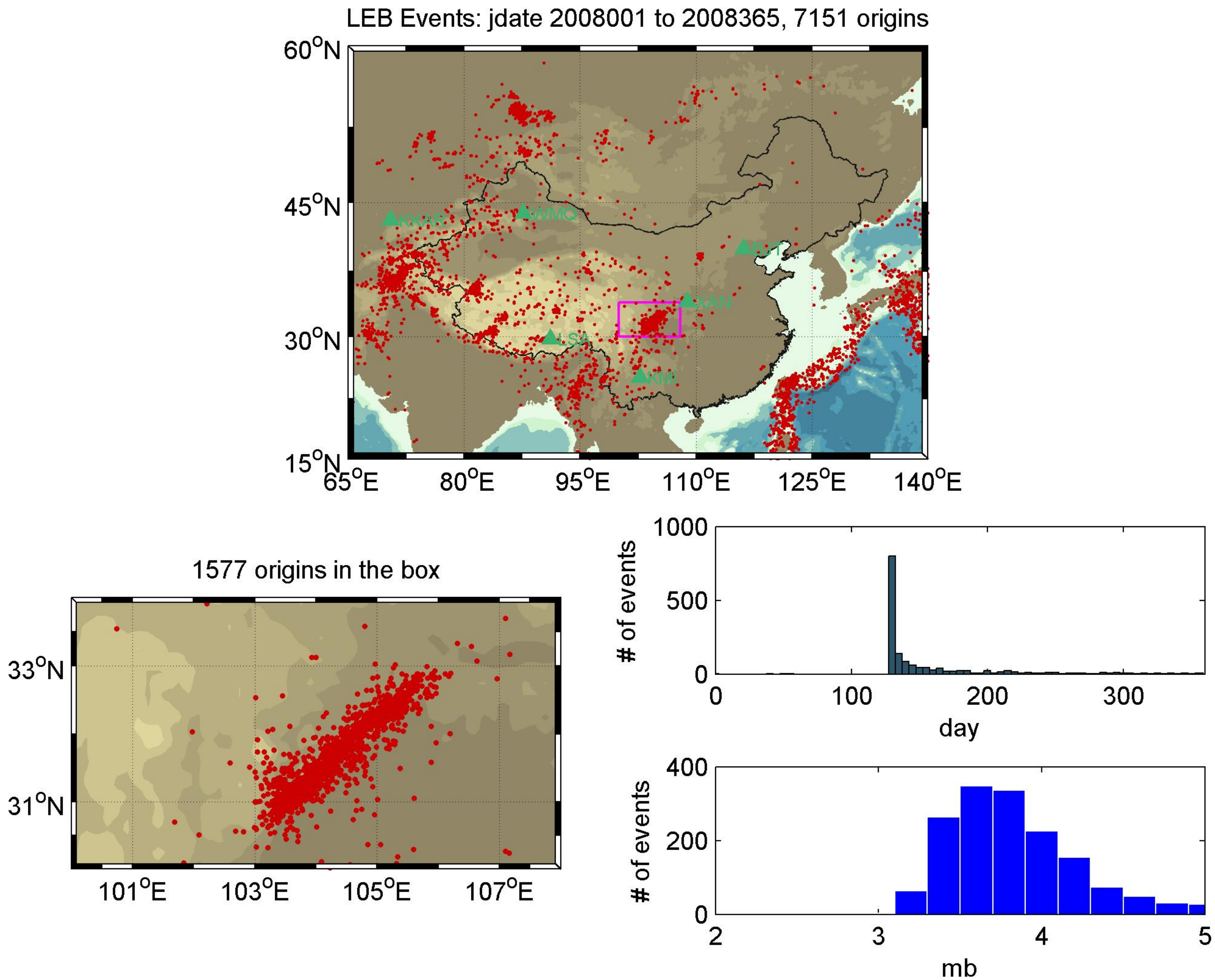



9 events; mean semi-axes of 95% error ellipses are a = 0.03 km and b = 0.04 km
north (km)
east (km)
0.5
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1

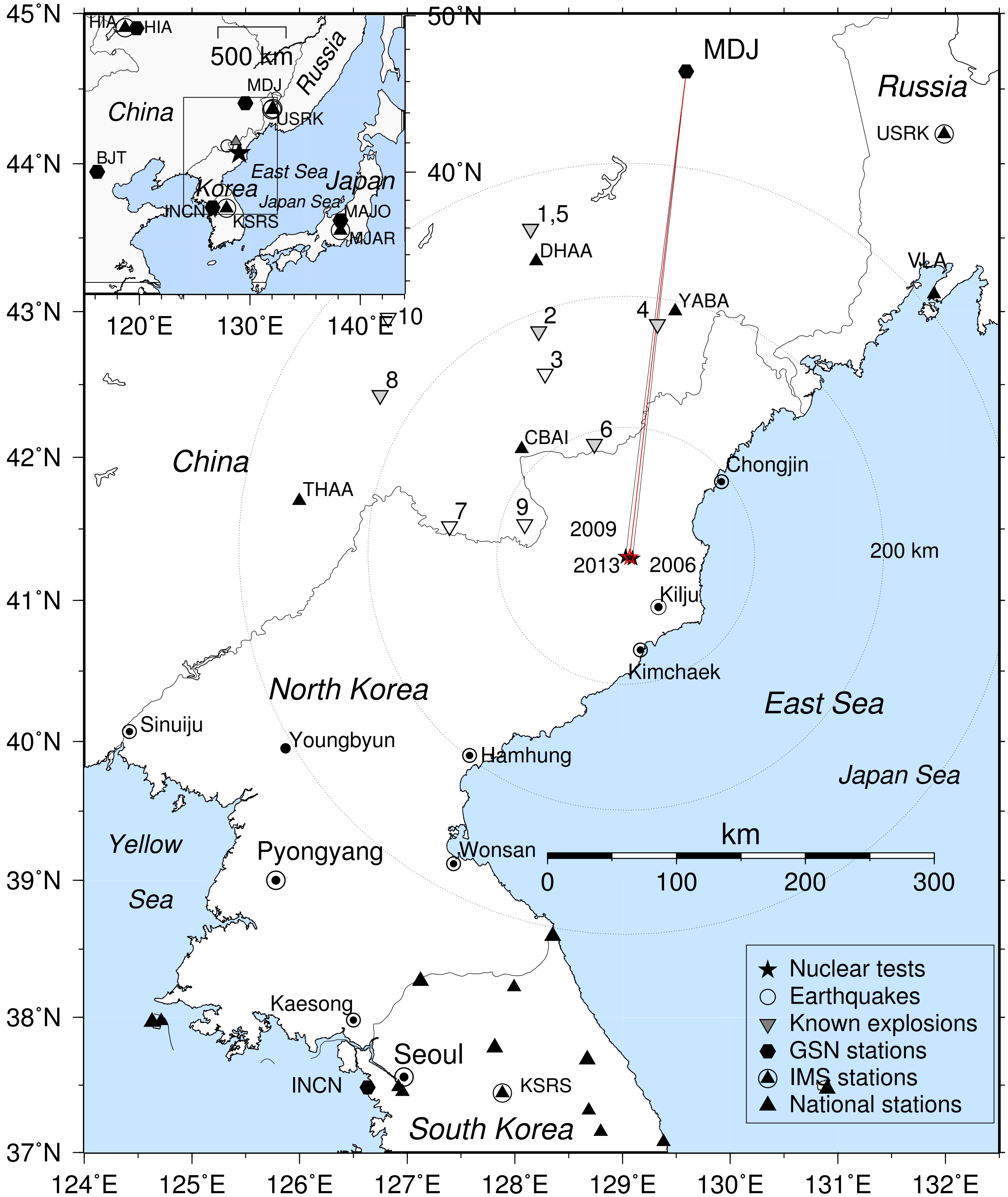
tens of meters!

9 events; mean semi-axes of 95% error ellipses are a = 0.03 km and b = 0.04 km




LEB Events: jdate 2008001 to 2008365, 7151 origins
60°N
45°N
30°N
15°N
65°E
80°E
95°E
110°E
125°E
140°E
KKAR
WMQ
BJT
XAN
LSA
KMI
1577 origins in the box
33°N
31°N
101°E
103°E
105°E
107°E
# of events
1000
500
0
0
100
200
300
day
# of events
400
200
0
2
3
4
5
mb

North Korean Nuclear Test Site & Seismographic Stations in the Region



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Routledge
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Radionuclide Evidence for Low-Yield Nuclear Testing in North Korea in April/May 2010

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Between 13 and 23 May 2010, four atmospheric radionuclide surveillance stations, in South Korea, Japan, and the Russian Federation, detected xenon and xenon daughter radionuclides in concentrations up to 10 and 0.1 mBq/m^3 respectively. All these measurements were made in air masses that had passed over North Korea a few days earlier. This article shows that these radionuclide observations are consistent with a North Korean low-yield nuclear test on 11 May 2010, even though no seismic signals from such a test have been detected. Appendix 1 presents a detailed analysis of the radioxenon data and Appendix 2 describes a hypothetical nuclear test scenario consistent with this analysis, including the possibility that the test used uranium-235 rather than plutonium-239. The analysis suggests that the technical and analytical basis to detect small nuclear tests using radionuclide signatures may be more developed than is generally assumed.

INTRODUCTION

North Korea conducted its first nuclear test explosion on 9 October 2006. The test was carried out underground in a deep tunnel[1] and had an estimated yield of approximately 0.9 kt.[2] Due to the low yield its nuclear character was first questioned, but it was soon confirmed nuclear by regional and distant detections of mBq/m^3 range radioactive xenon isotopes.[3,4] Then, on 25 May 2009, a

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The views expressed in this publication are those of the author and do not necessarily reflect the views of the Swedish Defense Research Agency, the Comprehensive Nuclear-Test-Ban Treaty Organization, the South Korean Government, or any of the institutions involved in the routine reporting of data to the International Data Centre. Data made available from these sources is, however, greatly appreciated. The expert help in applying the WebGrape software to a non-CTBT station that was provided by Dr. Gerhard Wotawa at the Zentralanstalt für Meteorologie und Geodynamik in Vienna, Austria, is also greatly appreciated.

NUKE WATCHING

Readings from monitoring stations suggest that North Korea carried out two nuclear tests at its Mount Mantap site in 2010.

Table 1: Xenon and barium isotopes detected at Geojin, Takasaki, Okinawa and Ussuriysk in May 2010. The hours, upper levels and uncertainties at Geojin are given in italics to indicate that they are estimates based on good experience from similar SAUNA spectra. Uncertainties are given for k = 1 and upper levels are based on a risk level for first kind errors of 5 percent. All concentrations refer to an assumed constant value during the collection time, which is the standard way adopted by the CTBTO[23]

Station	Collection start UTC	Collection stop UTC	^{131m}Xe mBq/m^3	^{133m}Xe mBq/m^3	^{133}Xe mBq/m^3	^{135}Xe mBq/m^3	^{140}Ba μBq/m^3
Geojin	13 May *11:00*	13 May *23:00*	<*0.2*	<*0.2*	2.45 ± *0.2*	10.01 ± *0.6*	
Takasaki	15 May 06:46	15 May 18:46	<0.02	<0.06	<0.10	<0.61	
Takasaki	15 May 18:46	16 May 06:46	0.04 ± 0.03	<0.09	0.16 ± 0.07	<0.57	
Takasaki	16 May 06:46	16 May 18:46	0.05 ± 0.03	<0.08	0.23 ± 0.06	<0.47	
Takasaki	16 May 18:46	17 May 06:46	0.16 ± 0.07	<0.09	1.49 ± 0.11	<0.20	
Takasaki	17 May 06:46	17 May 18:46	<0.04	<0.05	0.52 ± 0.07	<0.06	
Takasaki	17 May 18:46	18 May 06:46	<0.11	0.10 ± 0.06	0.79 ± 0.09	<0.58	
Takasaki	18 May 06:46	18 May 18:46	0.06 ± 0.03	<0.02	<0.10	0.42 ± 0.23	
Takasaki	18 May 18:46	19 May 06:46	<0.07	<0.05	0.18 ± 0.06	<0.52	
Okinawa	15 May 00:23	16 May 00:23					81.9 ± 3.6
Okinawa	16 May 00:23	17 May 00:23					22.7 ± 2.2
Okinawa	17 May 00:23	18 May 00:23					27.5 ± 2.2
Okinawa	18 May 00:23	19 May 00:23					28.1 ± 2.3
Okinawa	19 May 00:23	20 May 00:23					50.8 ± 2.9
Okinawa	20 May 00:23	21 May 00:23					43.8 ± 2.8
Okinawa	21 May 00:23	22 May 00:23					5.2 ± 1.6
Okinawa	22 May 00:23	23 May 00:23					5.0 ± 1.5
Ussuriysk	15 May 01:44	16 May 01:44					4.1 ± 1.4
Ussuriysk	16 May 01:44	17 May 01:40					<15
Ussuriysk	17 May 01:40	18 May 01:40					12.2 ± 2.3
Ussuriysk	18 May 03:44	19 May 01:49					5.3 ± 1.6

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Seismological Constraints on Proposed Low-Yield Nuclear Testing in Particular Regions and Time Periods in the Past, with Comments on "Radionuclide Evidence for Low-Yield Nuclear Testing in North Korea in April/May 2010" by Lars-Erik De Geer

David P. Schaff, Won-Young Kim, and Paul G. Richards

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We have attempted to detect seismic signals from small explosions in North Korea on five specific days in 2010 that feature in scenarios proposed by De Geer. We searched the seismic data recorded by station MDJ in northeastern China, applying three-component cross-correlation methods using signals from known explosions as templates. We assess the capability of this method of detection, and of simpler methods, all of which failed to find seismic signals that would be expected if De Geer's scenarios were valid. We conclude that no well-coupled underground explosion above about a ton occurred near the North Korea test site on these five days and that any explosion would have to be very small (local magnitude less than about 2) to escape detection.

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Projects planned under the CVT, at Lamont (Lamont-Doherty Earth Observatory
COLUMBIA UNIVERSITY | EARTH INSTITUTE) include:

- explain the basis for a classical discriminant ($m_b - M_s$), and why it works so well
- explain why it nearly failed for the 3 nuclear tests by North Korea (2006, 2009, 2013) [but note that other methods worked well]

- improve estimates of the depth of a seismic source (whether earthquake or explosion)

- produce a "*Glasstone and Dolan*" type of review of the technical aspects of nuclear explosion monitoring – for various audiences
  [hundreds of "grey literature" papers]
  ["various audiences" – not just undergrads and grad students ...]