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TECHNICAL REPORT

Discrepancies Between Prototype International Data Centre, International Seismological Centre & USGS Seismic Magnitudes

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13. ABSTRACT (Maximum 200 words)

A discrepancy between body-wave magnitudes, from the Prototype International Data Centre (PIDC) and the U.S. Geological Survey (USGS), has persisted since 1995, and amounts to a few tenths of a magnitude unit. Since 1999 we have studied the discrepancy between magnitudes published by different agencies and this final report is comprised of two sections. The first, is a stand-alone paper (published in the 2002 November/December issue of the Seismological Society of America's Seismological Review Letters) comparing the PIDC magnitudes with values assigned by a method that as closely as possible reproduces the Veith-Clawson protocol for reporting seismic body wave magnitudes. That protocol is the most clearly specified, or many different body-wave magnitude scales. The second section here, is a report which documents in detail the actual discrepancies between magnitudes assigned by three key agencies – namely, the USGS, the PIDC, and the International Seismological Centre (ISC).

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CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ——→ BY ——→ TO GET

TO GET ←—— BY ←—— DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_K = (t^o f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 (kg-m^2)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^o C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

**The Gray (GY) is the SI unit of absorbed radiation.

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Section 1

Executive Summary

Almost as soon as the international GSETT-3 experiment began to produce daily bulletins of global seismicity in January 1995, it became apparent that for most seismic events the seismic body-wave magnitudes (mb) assigned by the Reviewed Event Bulletin (REB) of what later became the Prototype International Data Center (PIDC) were somewhat lower than those assigned for the same events by the US Geological Survey's National Earthquake Information Center (USGS/NEIC), as reported in the Preliminary Determination of Epicenters (PDE), a USGS publication. The discrepancy between these two magnitudes, from the REB or the PDE, or (equivalently) from the PIDC or the USGS, has persisted since 1995, and amounts to a few tenths of a magnitude unit. The REB appears only a few days in arrears. The PDE delay has been quite variable but most typically is a few months. Since 1999 we have studied the discrepancy between magnitudes published by different agencies, and this Final Report is comprised of two sections. The first, is a stand-alone paper (published in the 2002 November/December issue of the Seismological Society of America s Seismological Review Letters) comparing the PIDC mb values with mb values assigned by a method that as closely as possible reproduces the Veith-Clawson protocol for reporting seismic body wave magnitudes. That protocol is the most clearly specified, of many different body-wave magnitude scales: it is in spirit a Richter magnitude, made quite specific in practice on the question of what instrument response is assumed (namely, the short-period response of the Worldwide Standardized Seismographic Network). The second section here, is a report which documents in detail the actual discrepancies between mb values assigned by three key agencies namely, the USGS, the PIDC, and the International Seismological Centre (ISC). The ISC publishes its conclusions about two years in arrears.

Section 2

An Assessment of Seismic Body-Wave Magnitudes Published by the Prototype International Data Centre

2.1 Introduction.

A significant initiative in the reporting of global seismicity began in January 1995 with the publication of daily Reviewed Event Bulletins (REBs), a few days in arrears. This work was and still is done in the context of international efforts at verification of the Comprehensive Nuclear-Test-Ban Treaty (CTBT), which when it was finalized in 1996 determined that the seismic monitoring network of the International Monitoring System (IMS) would consist of 50 primary stations contributing data continuously to an International Data Centre (IDC) in Vienna, plus 120 auxiliary stations that recorded continuously but contributed data to the IDC only on request (Richards, 2002).

Until the IDC began daily operations on February 21, 2000, the daily REB was published by the Prototype International Data Centre (PIDC) and a predecessor organization. We shall refer to all the REBs from January 1, 1995 to February 20, 2000 as having been published by the PIDC. This paper focuses on the PIDC teleseismic body-wave magnitudes (m_b). They are important, as a modern effort to measure short- period magnitudes based on what is expected to become a fixed network of global stations, all operating in a standardized way.

Although seismic magnitudes are intended to be a characteristic of the source, it is well known that in practice they are influenced by numerous additional factors such as the particular set of stations reporting individual magnitudes, the instrument responses, and the details of how each station magnitude is assigned. Global bulletins of seismicity, including m_b values, have long been reported, months in arrears, by the Preliminary Determination of Epicenters (PDE) and Earthquake Data Report (EDR) of the U. S. Geological Survey s National Earthquake Information Center (USGS NEIC). They have also been reported, about two years in arrears, by the International Seismological Centre (ISC), based in England. To obtain its published m_b values, the USGS uses voluntarily contributed measurements of ground motion (amplitude *A*, period *T*) from many more stations around the world than those used by the PIDC as well as making measurements of *A* and *T* at NEIC headquarters in Golden, Colorado, from many channels of digital stations available in near real time. The ISC relies entirely upon measurements of ground motion (amplitude *A*, period *T*) from contributing stations including measurements made by the PIDC, the USGS, and numerous additional stations since the ISC does not operate stations and does not analyze seismograms directly. In practice the networks of stations used by the USGS and ISC have changed significantly over recent decades, as various subnetworks have changed both their instrumentation and their reporting practices. Both the USGS and the ISC have always used the Gutenberg—Richter distance corrections to convert measurements of A and T at each station to a station magnitude. Although the PIDC did not have a fixed station set over the years 1995 to 2000 (and the primary and auxiliary networks are still incomplete), its reporting stations were far more constant than those of the USGS and ISC, and it adopted a standardized way of measuring A and T (discussed further, below). The PIDC uses the distance corrections published by Veith and Clawson (1972) to obtain station magnitudes.

Because of the more constant station set, and the standardization of measurements, the PIDC m_b has the potential to achieve a more consistent set of short-period magnitudes, as well as one that is more promptly available after an event than magnitudes published by other organizations. It was therefore of concern that when the PIDC began publishing seismic event bulletins daily in January 1995, it was soon apparent that PIDC body-wave magnitudes (m_b) were systematically lower than PDE m_b values assigned by the USGS. The amount of this discrepancy is approximately 0.4 magnitude units (m. u.), although, as we show in this paper, for large magnitudes the offset is even greater.

Several explanations for the discrepancy have been proposed, beginning with Murphy and Barker (1996) who noted as one contributing cause that some stations which sent A and T values to the USGS, for inclusion in the PDE m_b, had supplied incorrect values of A due to use of a nominal gain rather than using the instrumental gain at the observed T value. Though this problem was part of the discrepancy between PIDC and USGS measurements, it became apparent that it was not a principal contributor because the problem was fixed in 1996 and a significant discrepancy still remained. When ISC m_b values, published about two years in arrears, became available beginning in 1997 for the period in which REB had been published, again it was found that PIDC m_b values were systematically lower by a few tenths of a magnitude unit.

Discrepancies between different magnitudes such as m_b and M_s have long been recognized as a consequence of the way that different types of seismic source (for example, earthquakes and explosions) excite different seismic waves. Such discrepancies are important and useful for purposes of event identification. It is also recognized that with use of different instrument responses there will be differences between different scales measuring the same seismic wave, though it is usually arranged that these scales agree with each other in some average sense. In this regard it is relevant to note that Gutenberg and Richter made their measurements using broadband instruments which registered relatively long-period P-waves (4-10 seconds), whereas during the 1970s and 1980s the USGS began making most of its measurements on short-period instruments in which the P-waves typically had a period close to 1 second, such as those of the Worldwide Standard Seismographic Network (WWSSN). Another shift in the way the measurements were made began in the 1980s, when broadband stations capable of recording digital data began replacing the older analog instruments. In practice, station m_b is now assigned by the PIDC and the USGS from a broadband record after filtering the signal to pass a band of high frequencies. At this point, one might say the devil is in the details, but an overall problem has arisen, with a significant discrepancy between short-period teleseismic magnitudes published by different agencies.

Such a discrepancy has the potential to generate a number of problems because it fundamentally undercuts the concept of any absolute reference level for short-period magnitudes. (All empirical magnitude scales imply that magnitude zero, or some other fixed magnitude, corresponds to a particular amplitude of ground motion at some fixed distance. This amplitude can be taken as a reference level.) If m_b scales are systematically different it follows that quantitative uses of m_b have to make very clear which particular m_b scale is being used, for example to specify monitoring capability in terms of a magnitude threshold, or to work out the details of an application of the m_b-M_s discriminant. (It is difficult enough to explain to decisionmakers the quantitative aspects of verification capability without having to deal with significant variability between magnitude scales.) And if, additionally, a m_b scale changes over time due to some change in reporting stations, or a change in instrument responses and the way in which these affect measurement of A and T values, then there are the dangers of artifacts being misinterpreted as changes in global seismicity (for example, a change in the number of earthquakes per year of m_b 4.0 or greater), or of an actual change in global seismicity going unrecognized because of lack of confidence in the precision of m_b scales.

Subsequent to the preliminary discussion of Murphy and Barker (1996), explanations for the discrepancy between PIDC, USGS and ISC values of m_b have been reported by Willemann (1998), Dewey (1999), and Murphy et al. (2001). Contributing causes include 1) the use by the IMS of arrays (for which the maximum ground motion measured from an averaging beam will tend to be less than the maximum ground motion on a signal channel); 2) the use by the IMS of sensitive stations (reporting most events) that have negative magnitude bias; and 3) the systematic differences between Veith—Clawson (1972) and Gutenberg—Richter (1956) distance corrections.

In this paper we focus on an assessment of m_b values published by the PIDC, so we do not address comparisons with the values published by the USGS and the ISC. Such comparisons, while interesting, are difficult to interpret because of changes in the way in which USGS and ISC magnitudes have been assigned over the last ten years, and also by the uses that the USGS and the ISC have themselves made of measurements of A and T reported by the PIDC (although the USGS stopped using such measurements in August 1996). As a standard against which to compare the PIDC m_b values, we have instead chosen to use the Veith-Clawson m_b, and we have concentrated in this paper on nuclear explosions and some large earthquakes, all of which were easily detected teleseismically. Thus, we avoid the problems of using only a few sensitive arrays (which can dominate the characteristics of seismicity bulletins because most events are small and such events are detected mostly by arrays). We have chosen the Veith—Clawson m_b as a reference because it is a Richter-type m_b (Richter, 1935) that follows a well-defined protocol and is based on a specific instrument response the WWSSN short-period seismometer that was widely used for twenty years and that enabled the use of short-period magnitudes reported with greater precision than those of the previous generation.

To better understand how the PIDC procedure for assigning body-wave magnitudes differs from the classical method by which such short-period magnitudes are assigned, we have simulated Worldwide Standard Seismographic Network short-period signals from broadband records and made the Veith-Clawson measurement (Veith and Clawson, 1972). The displacement response of a typical WWSSN short-period instrument is shown in Figure 1. We do not regard the PIDC

m_b as a Veith-Clawson m_b since, although it utilizes the Veith-Clawson distance corrections, the PIDC frequency band is somewhat higher than the conventional WWSSN short-period band over which the amplitude and period are measured (Figure 1).

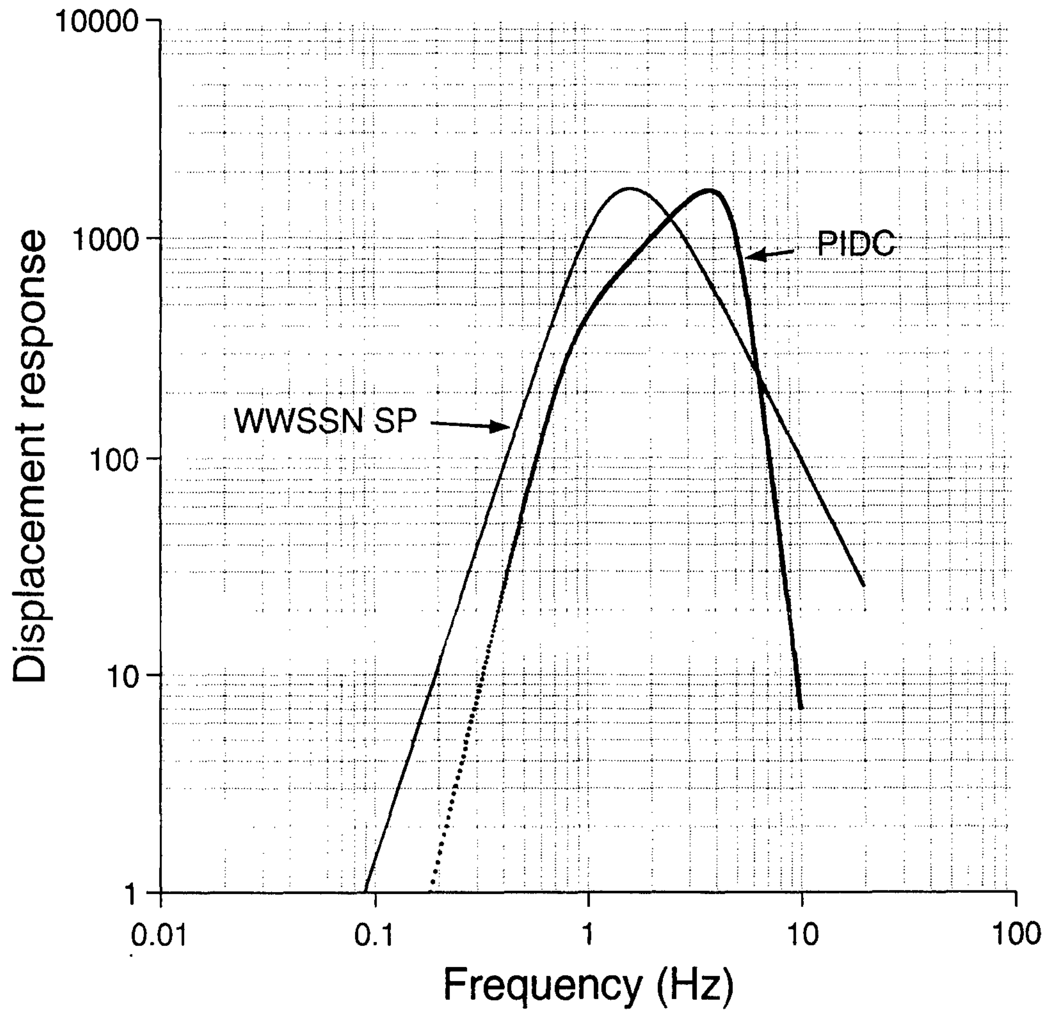


Figure 1. Displacement responses of a typical WWSSN short-period instrument and a typical broadband station after processing the data according to PIDC procedure (0.8 — 4.5Hz bandpass). Note that the PIDC displacement response is asymmetrical and that its peak occurs at a much higher frequency than the WWSSN SP instrument.

The PIDC m_b is determined from vertical-component records from broadband three-component stations or from a coherent beam trace from seismic arrays equipped with mostly short-period sensors. In both cases the signals are bandpass filtered using a third-order Butterworth filter with cutoff frequencies at 0.8 and 4.5 Hz. The displacement response of a typical broadband station after the data are processed according to PIDC procedure is shown in Figure 1. The amplitude and period are then measured from the filtered signal using a time window that starts 0.5 seconds before the P-wave arrival and extends 5.5 seconds after the arrival time. The amplitude is corrected for the response of the bandpass filter and the instrument, at the period corresponding to the maximum amplitude. In contrast, when making a measurement of A and T from a broadband record the USGS NEIC applies a second-order bandpass filter with cutoff frequencies between 1.05 and 2.65 Hz to obtain a station magnitude. The time window from which the NEIC m_b is measured is somewhat longer than the PIDC time window, since the NEIC measures its maximum amplitude and corresponding period in the first ten cycles following the picked P arrival time. The Veith-Clawson distance correction (used by the PIDC) is calibrated to agree with the Gutenberg-Richter distance correction (used by the USGS and ISC) at zero depth, but the two diverge at deeper event depths, with the Gutenberg-Richter correction being higher.

2.2 Data Acquisition and Processing.

This study examined waveform data from 13 underground nuclear tests (UNTs) conducted between 1995-1998: four nuclear tests at Lop Nor (the Chinese test site); six UNTs in the Tuamotu Archipelago (the French test site); one Indian nuclear test; and two Pakistani nuclear tests. For comparison, waveform data from 10 large earthquakes in 1998-1999 are also examined. These earthquake events are representative of the 22 largest (PDE $m_b \geq 6.4$) events in 1998-1999. The location, REB m_b, and PDE m_b for each of these events is given in Table 1. The seismograms used by the PIDC to assign magnitude are from vertical-component records at 89 stations, many (but not all) of which have become part of the International Monitoring System. Seventy of these stations are broadband three-component stations and 19 are array stations. The locations of the 89 stations reporting m_b values to the PIDC are shown in Figure 2. The data were obtained from the Center for Monitoring Research (CMR) via a series of electronic data requests. The dataset was converted from GSE format to AH format to facilitate processing. Instrument responses had to be separately requested from the CMR since the response to a standard PIDC waveform data request does not include the response information. Each instrument response was given in one of two formats — either as poles and zeros or as a frequency-amplitude-phase table.

To simulate the WWSSN short-period (SP) signal, the PIDC velocity response for a particular station is deconvolved and replaced by the WWSSN SP displacement response (Kim and Ekstr m, 1996). The amplitude and period are then measured from the simulated WWSSN waveforms and a body-wave magnitude is assigned based on the Veith-Clawson scale (Veith and Clawson, 1972). To assign the Veith-Clawson m_b the signal strength and period are measured in a 15 sec. time window, beginning from the first P-wave arrival. The amplitude is measured from trough to peak (or peak to trough) and then halved in order to estimate the peak-to-zero ground motion amplitude in nanometers.

Table 1. Body Wave Magnitudes (m_b) Measured for the Events Used in this Study.

Earthquakes:

	YYYYMMDD	LAT	LON	DEPTH(km)	REB m_b±Std	(n_{obs})	m_b(VC)±Std	PDE m_b
1	19980101	23.928	141.927	99.0	5.8±0.3	(22)	6.1±0.4	6.4
2	19980104	-22.205	171.057	38.0	5.5±0.5	(24)	6.2±0.4	6.4
3	19980329	-17.576	-178.988	529.8	5.9±0.4	(12)	6.2±0.3	6.5
4	19980503	22.460	124.919	0.0	5.6±0.4	(20)	6.2±0.4	6.4
5	19981129	-2.032	124.935	0.0	5.7±0.5	(21)	6.5±0.5	6.5
6	19990413	-21.422	-176.307	131.2	6.0±0.4	(17)	6.3±0.3	6.4
7	19990615	18.407	-97.268	0.0	6.0±0.3	(22)	6.4±0.3	6.4
8	19990920	23.781	120.895	0.0	5.4±0.5	(20)	6.1±0.4	6.5
9	19991206	57.499	-154.487	31.9	6.2±0.4	(21)	6.6±0.4	6.8
10	19991211	15.749	119.832	19.5	5.9±0.5	(21)	6.3±0.4	6.5

Nuclear Explosions:

	YYYYMMDD	LAT	LON	REB m_b±Std	(n_{obs})	Reproduced m_b±Std	m_b(VC)±Std	PDE m_b
1	19950515	41.63	88.87	5.7±0.6*	(33)	5.9±0.3	5.9±0.3	6.1
2	19950817	41.60	88.86	5.5±0.6	(49)	5.8±0.3	5.8±0.3	6.0
3	19950905	-21.85	-138.94	4.7±0.3	(20)	4.6±0.3	4.7±0.3	4.8
4	19951001	-22.25	-138.76	5.2±0.3	(15)	5.2±0.3	5.4±0.3	5.4
5	19951027	-21.82	-139.05	5.3±0.3	(35)	5.3±0.3	5.4±0.3	5.4
6	19951121	-21.90	-138.96	4.6±0.3	(16)	4.6±0.3	4.6±0.4	4.8
7	19951227	-21.80	-139.09	5.0±0.3	(22)	5.0±0.3	5.0±0.3	5.1
8	19960127	-22.27	-138.78	5.1±0.3	(37)	5.0±0.3	5.3±0.3	5.3
9	19960608	41.65	88.76	5.7±0.3	(64)	5.7±0.4	5.7±0.3	5.9
10	19960729	41.69	88.35	4.7±0.4	(22)	4.8±0.3	4.7±0.4	4.9
11	19980511	27.07	71.76	5.0±0.4	(51)	5.0±0.4	5.0±0.4	5.2
12	19980528	28.90	64.89	4.9±0.4	(51)	4.9±0.4	4.9±0.4	4.8
13	19980530	28.49	63.78	4.6±0.4	(45)	4.6±0.3	4.7±0.4	4.6

* Amplitude and period data listed in the REB for the Chinese nuclear test on 15 May, 1995 yield an m_b(REB) = 5.9.

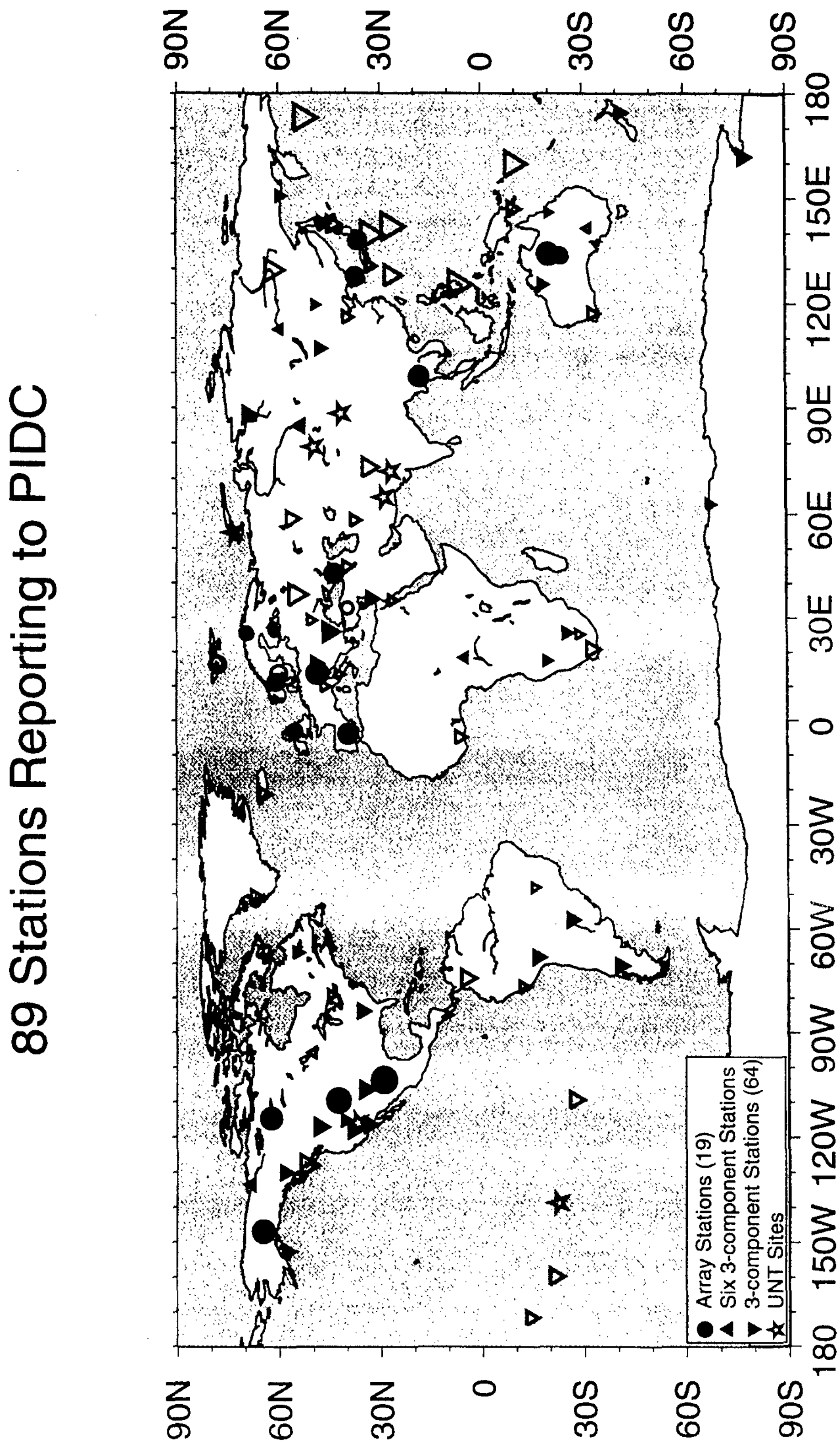


Figure 2. The locations of the 89 stations reporting magnitude values to the Prototype International Data Centre. The symbol size is proportional to the size of the station correction determined by Murphy et al. (2001). Filled symbols are positive station corrections, while open symbols represent negative corrections. Array station locations are plotted as circles, the six most contributing three-component stations are given by triangles, the remaining 64 three-component stations are given by inverted triangles, and underground nuclear explosion test sites are given by stars.

The period is then measured as peak-to-peak at the maximum amplitude. Station body wave magnitudes $m_{b(sta)}$ are calculated using the equation:

$$m_{b(sta)} = \log(A/T) + B(\Delta, h) \qquad (1)$$

where *sta* is the station, A is the maximum half peak-to-trough amplitude in nanometers, T is the period in seconds measured at the maximum amplitude, and B is the Veith-Clawson attenuation correction for distance in degrees (Δ) and depth in kilometers (h) (Veith and Clawson, 1972).

For the 13 underground nuclear tests, the REB magnitude for each of these events was reproduced by following the PIDC protocol for assigning m_b. Thus, the signals were bandpass filtered using the narrow band employed by the PIDC and the amplitude and period were measured using a time window of only 5.5 seconds.

2.3 Results: Underground Nuclear Explosions.

For the 13 underground nuclear tests examined in this study there are a total of 460 individual station observations (body-wave magnitude was assigned for every station reporting an m_b in the REB). We also reproduced the m_b according to PIDC procedures for assigning m_b, except for the array stations, for which we measured amplitude and period from the single reference station instead of calculating the beam trace and measuring the amplitude from the beam trace.

The station body-wave magnitude is an assigned or measured value, not an estimated one. Therefore, to assign the correct m_b to an event it is necessary to both have a well-defined protocol and to follow it correctly. We found that for two UNT events in 1995 (both in Lop Nor, China), the PIDC apparently did not follow its own specified measurement protocol. We have therefore gone back to the original seismograms and reproduced the intended REB m_b, in order to check the published REB m_b as well as to obtain the Veith-Clawson m_b.

The reproduced m_b(REB) for the 13 UNTs is listed in Table 1. Some sample seismograms from the Indian Nuclear Test on 1998 May 11 are plotted in Figure 3. Shown are the raw broadband signal as both velocity and displacement, as well as the corresponding WWSSN short-period signal and the reproduced PIDC velocity signal for station OBN. The actual published m_b(REB) values as well as the corresponding reproduced m_b(REB) values are plotted in Figure 4 for each of the 460 individual station observations. The reproduced m_b(REB) values tend to agree quite well with those published in the REB, with two notable exceptions: a cluster of events where the reproduced values are about 1 magnitude unit (m. u.) greater than the REB values, and another cluster where the reproduced values are approximately 0.6 m. u. lower. These large differences in magnitude all derived from two previously mentioned UNTs in Lop Nor, China on 1995 May 15 and 1995 August 17. They are apparently due to incorrect instrument responses applied by the PIDC for these stations. There is also an error in the network m_b reported by the PIDC for the Chinese nuclear test on 1995 May 15 that is the result of errors (corrected for events in 1996 or later) in the PIDC source code used to average the station m_b values. The network m_b assigned by the PIDC for this event is 5.7, but the actual event m_b — based on PIDC measurements of amplitude and period — should be 5.9 (Table 1).

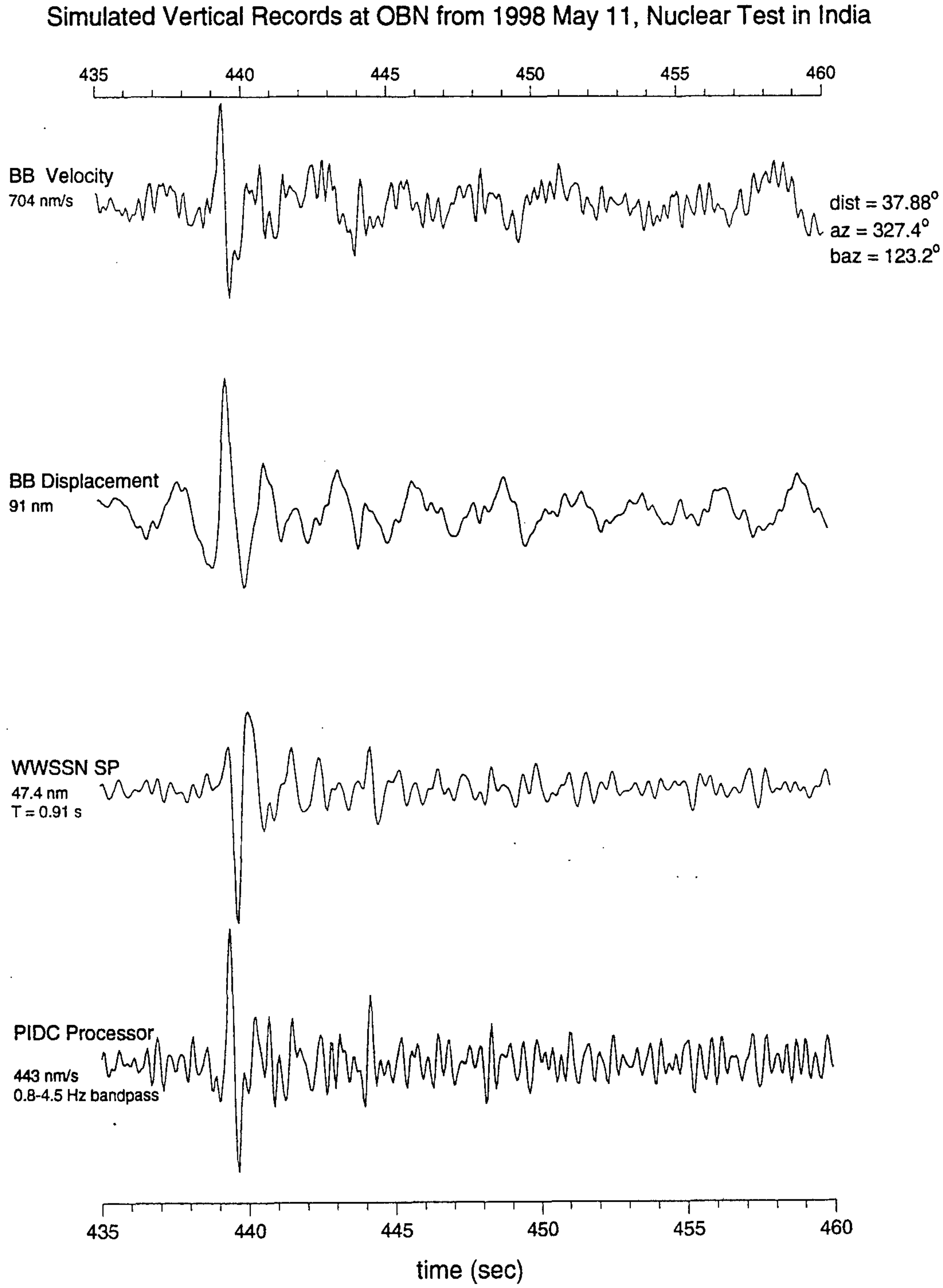


Figure 3. Broadband, vertical record at OBN (Obninsk, Russia) from 1998 May 11 nuclear test in India and records simulated for various short-period instruments. Amplitude values, measured as peak-to-zero or zero-to-trough, are given. For the waveform processed according to the intended PIDC procedure, the corresponding displacement amplitude is 32.0 nm, with a period of 0.45 seconds. Note that the WWSSN short--period record is the clearest.

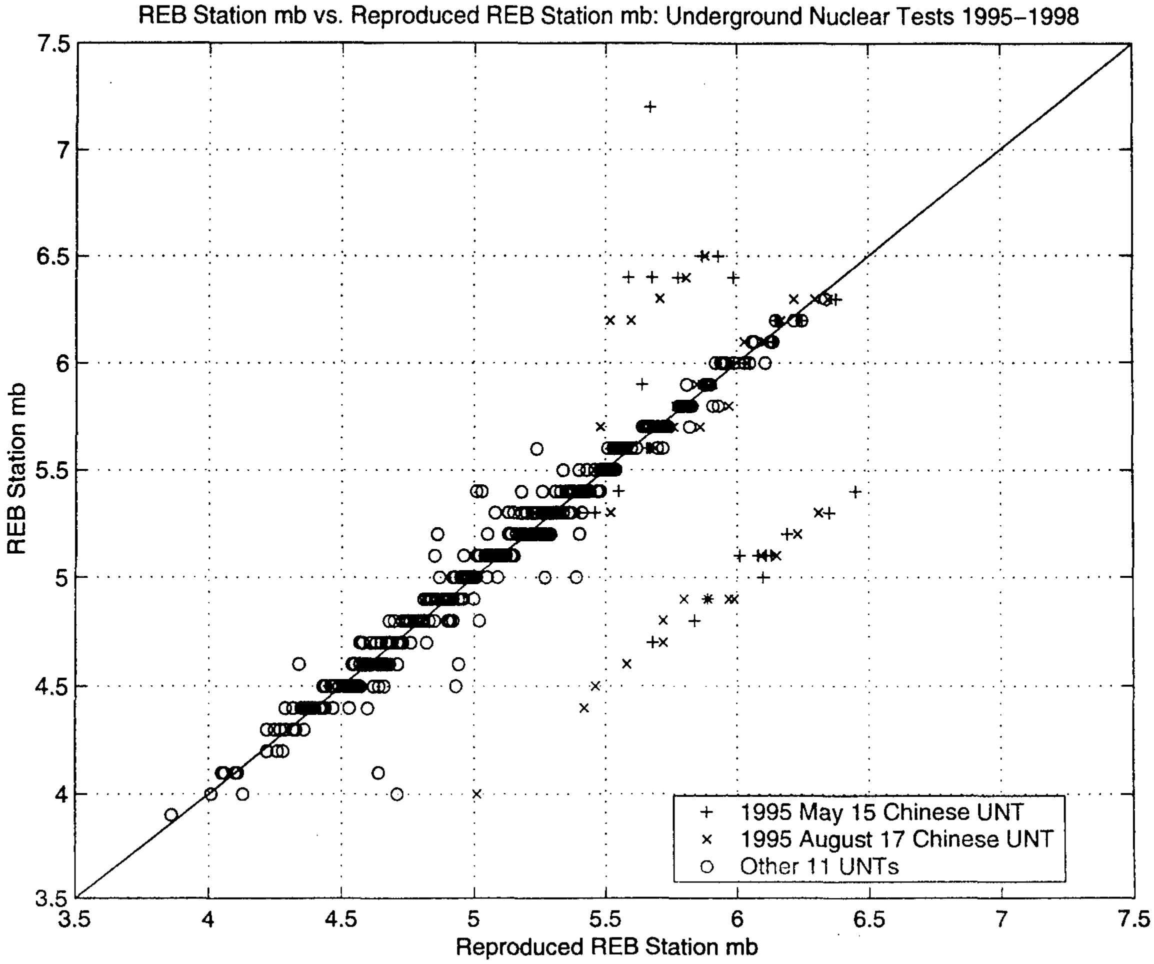


Figure 4. Reviewed Event Bulletin station m_b plotted against the corresponding Reproduced REB station m_b for the 13 underground nuclear tests included in this study. The principal disagreements arise for the two earliest tests (see Table 1), for which the PIDC apparently used some incorrect instrument responses.

In addition to reproducing the REB procedure for assigning m_b for each of the 13 UNTs in the REB, we also determined the Veith-Clawson m_b using simulated WWSSN signals for all of these events. The Veith-Clawson m_b [m_b(VC)] values for the UNTs are given in Table 1. The m_b(VC) values agree quite well with our reproduced m_b(REB) values. With the exception of the two Chinese tests mentioned above, the m_b(VC) and the published m_b(REB) also agree well. The comparison between the reproduced REB m_b values and the Veith-Clawson m_b is shown in Figure 5. The scatter is significantly less than in Figure 4, in part because the reproduced values have corrected the errors in the REB for the aforementioned two Chinese UNTs. The distribution of the difference between the Veith-Clawson body-wave magnitude and the reproduced REB magnitude is shown in Figure 6(a). The mean offset for the UNT data is 0.0, and 75% of the observations are clustered in a very narrow band between —0.1 to +0.1.

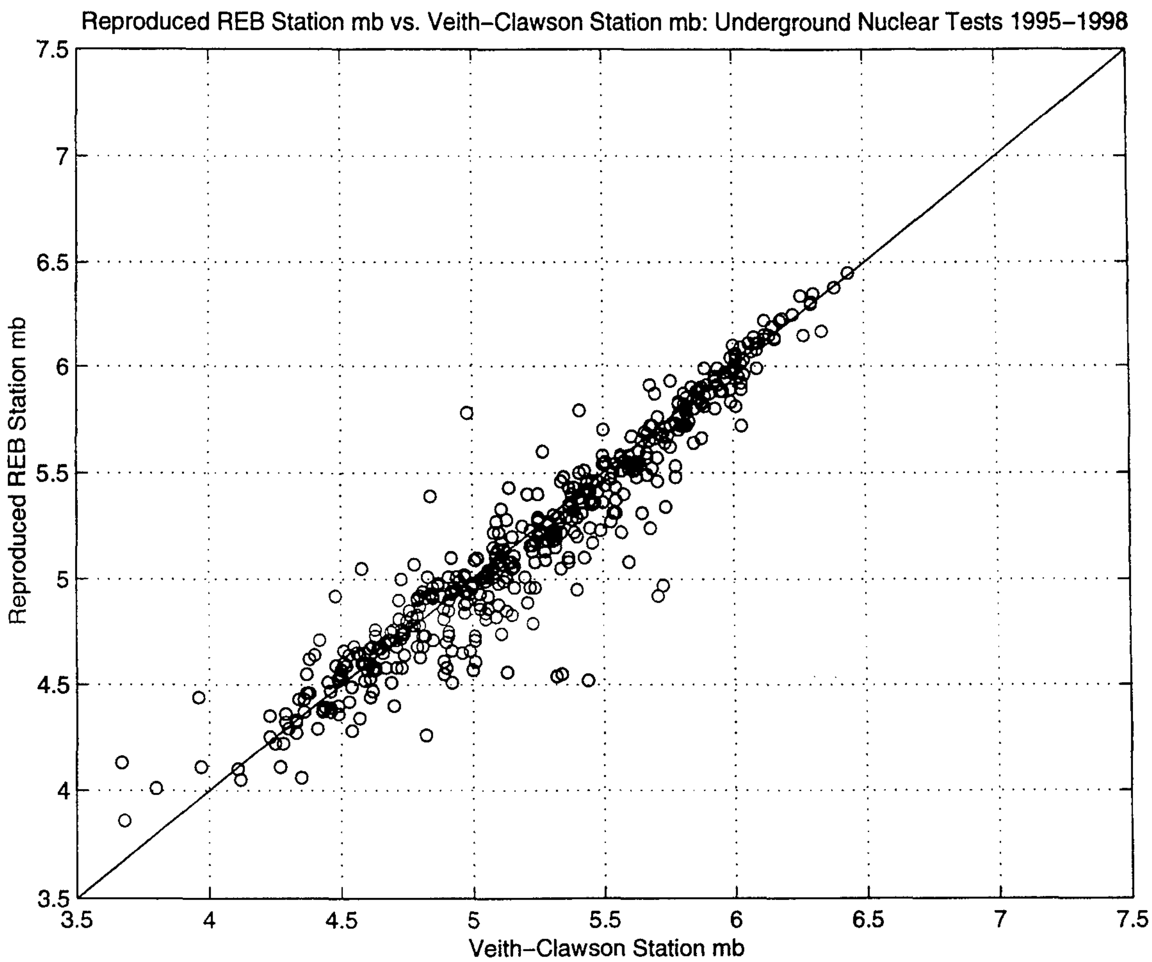


Figure 5. Reproduced REB station m_b plotted against the corresponding Veith-Clawson station m_b for the underground nuclear test data.

2.4 Results: Earthquakes.

In addition to the 13 underground nuclear explosions analyzed in this study, we also examine 10 large earthquakes from 1998-1999 (Table 1). There are a total of 200 individual station observations for the 10 earthquakes, and a Veith-Clawson body-wave station magnitude was assigned for each. A reproduced REB m_b was not measured for the earthquake data because all of the events occur between 1998-1999, and by this point the PIDC was using the correct instrument responses (i. e. the reproduced REB m_b would not differ significantly from the actual published REB m_b). Seismograms for an earthquake in the Philippine Islands on 1999 December 11 recorded at station DLBC are shown in Figure 7. The raw broadband signals (velocity and displacement) recorded by DLBC for this event are shown, along with the simulated WWSSN short-period signal and the reproduced PIDC velocity signal.

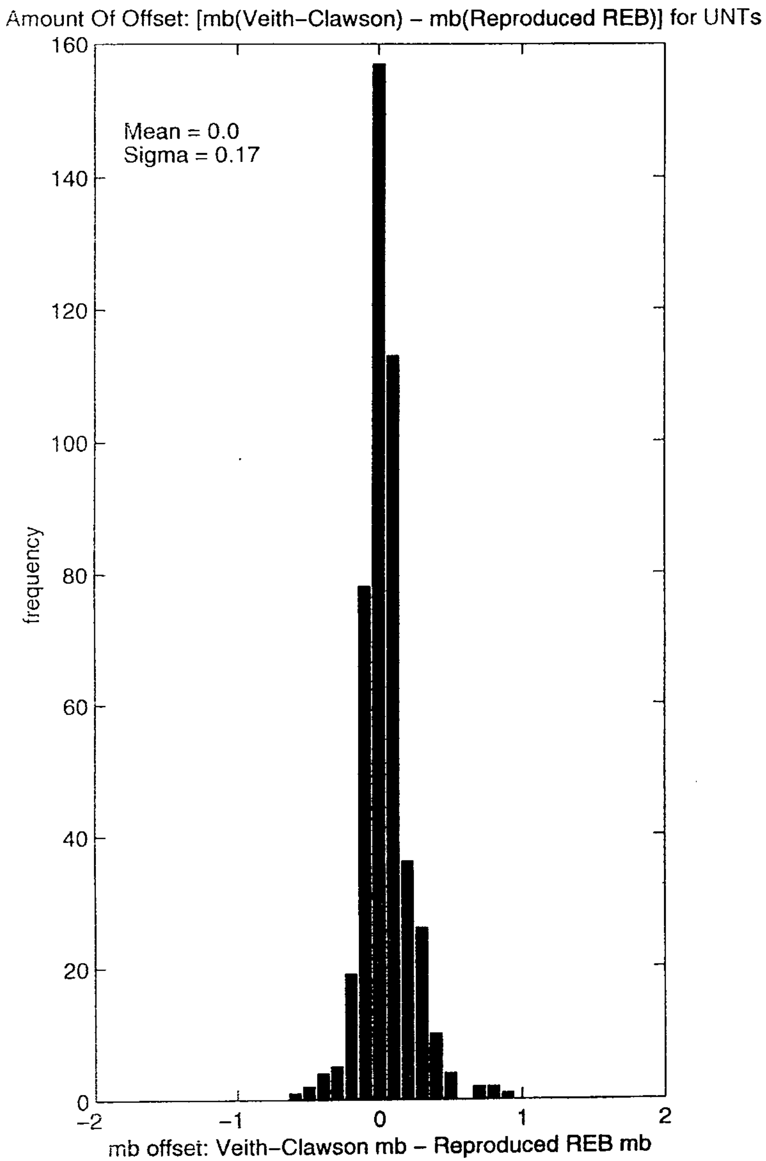
The m_b(VC) for the 10 earthquakes in this study is given in Table 1. The m_b(VC) is greater than the m_b(REB) for all 10 events, with an average discrepancy of 0.5 magnitude units. The m_b(VC) observations are compared with the corresponding m_b(REB) in Figure 8. Only a handful of individual station observations have a Veith-Clawson m_b less than or equal to the REB m_b; the majority have an m_b(VC) greater than the m_b(REB).

The distribution of offsets between the Veith-Clawson body-wave magnitude for the earthquakes and the REB magnitude is shown in Figure 6(b). The distribution has a median offset of 0.4, and a mean offset of 0.5, with 68% of the m_b offset values in the range from 0.1 to 0.7. Note that several of the observations have an offset ≥ 1 m. u. Also, 63% of the observations have an m_b offset of at least 0.4 m. u., indicating that for earthquake populations a discrepancy between the Veith-Clawson body-wave magnitude and the REB magnitude certainly exists.

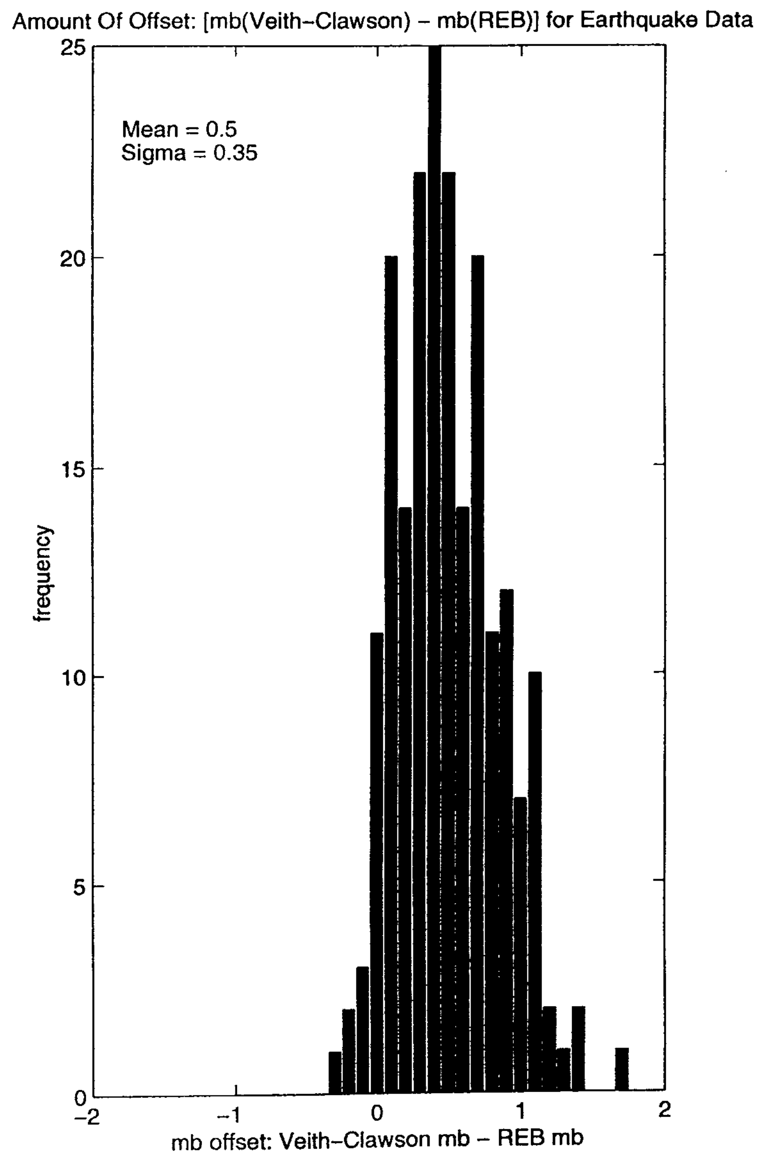
2.5 Discussion.

2.5.1 Magnitude of Earthquakes vs. Magnitude of Nuclear Explosions.

The relationship between the Veith-Clawson m_b and the Reviewed Event Bulletin m_b is different for earthquakes and explosions. The m_b(VC) for the earthquakes examined in this study is greater than the m_b(REB) for all 10 events. Thus, the earthquake population clearly demonstrates the existence of a discrepancy between the m_b(VC) and the m_b(REB), with the REB body-wave magnitude on average being 0.5 magnitude units lower than the Veith-Clawson m_b. The difference between the event m_b(VC) and the m_b(REB) for the 13 underground nuclear tests, on the other hand, is zero on average. This agreement between the m_b(REB) and the m_b(VC) for the UNTs is consistent with the results of Bowers et al. (2002), who found that for six of the UNTs in this study (those in India, Pakistan, and the four in China) their analyst read m_b , which uses a response similar to the WWSSN SP response for frequencies lower than 2 Hz, is quite similar to the REB m_b. The PDE m_b values are also given in Table 1 for both the earthquakes and UNTs. The m_b(PDE) values are somewhat greater than the m_b(VC) values for both the earthquakes (by an average of 0.2 m. u.) and nuclear explosions (by an average of 0.1 m. u.).



(a) Histogram showing the distribution of offsets between the Veith-Clawson station m_b and the reproduced REB station m_b for the underground nuclear test data. Each bin represents a range of offsets with width 0.1 m. u.



(b) Histogram showing the distribution of offsets between the Veith-Clawson station m_b and the REB station m_b for the earthquake data.

Figure 6.

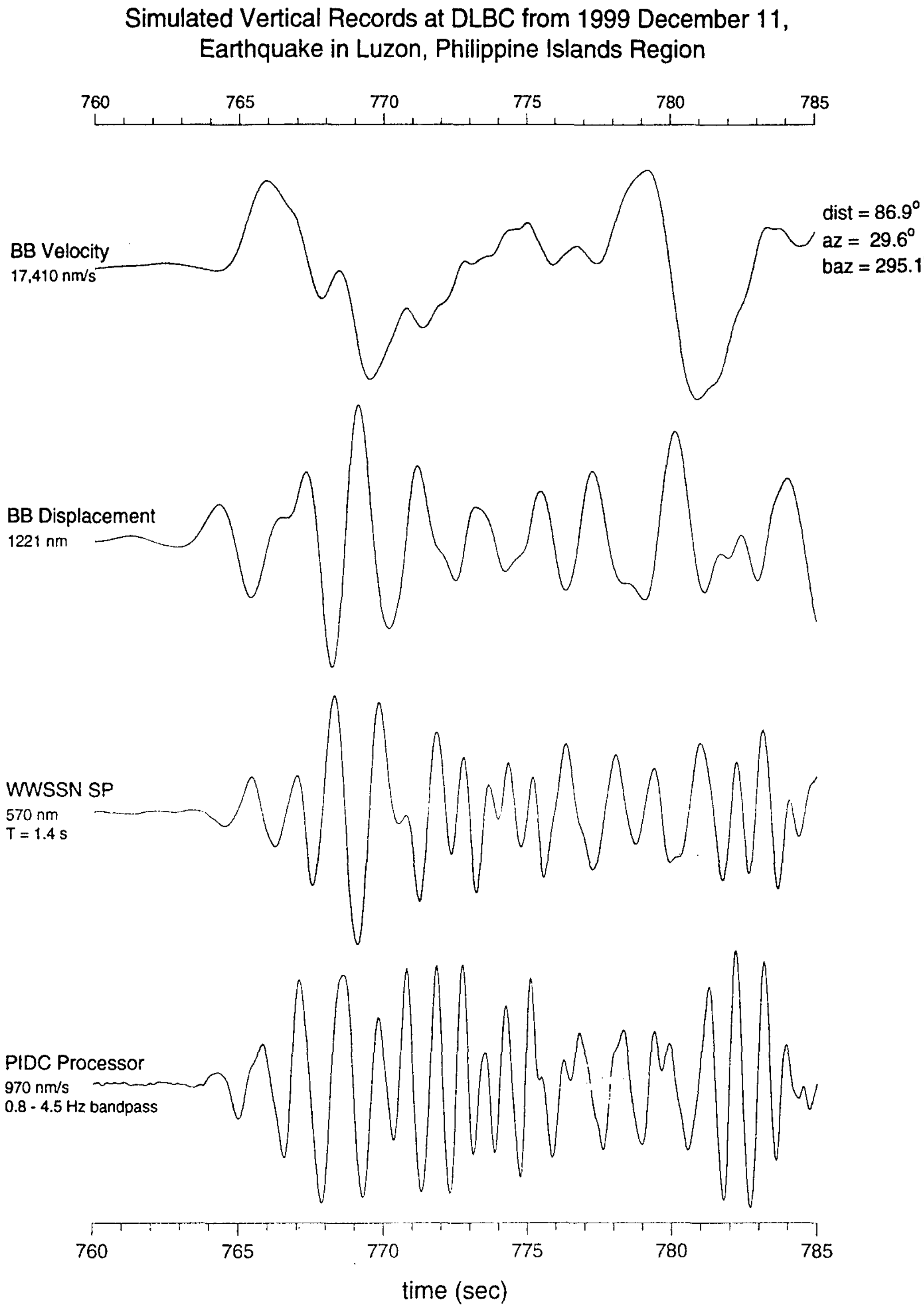


Figure 7. Broadband, vertical record at DLBC (Dease Lake, Canada) from 1999 December 11 earthquake in Luzon, Philippine Islands region. Also shown are the simulated records for a WWSSN short-period instrument and the reproduced PIDC signal. Amplitude values, measured as peak-to-zero or zero-to-trough, are given. For the waveform processed according to the intended PIDC procedure, the corresponding displacement amplitude is 151 nm, with a period of 1.4 seconds.

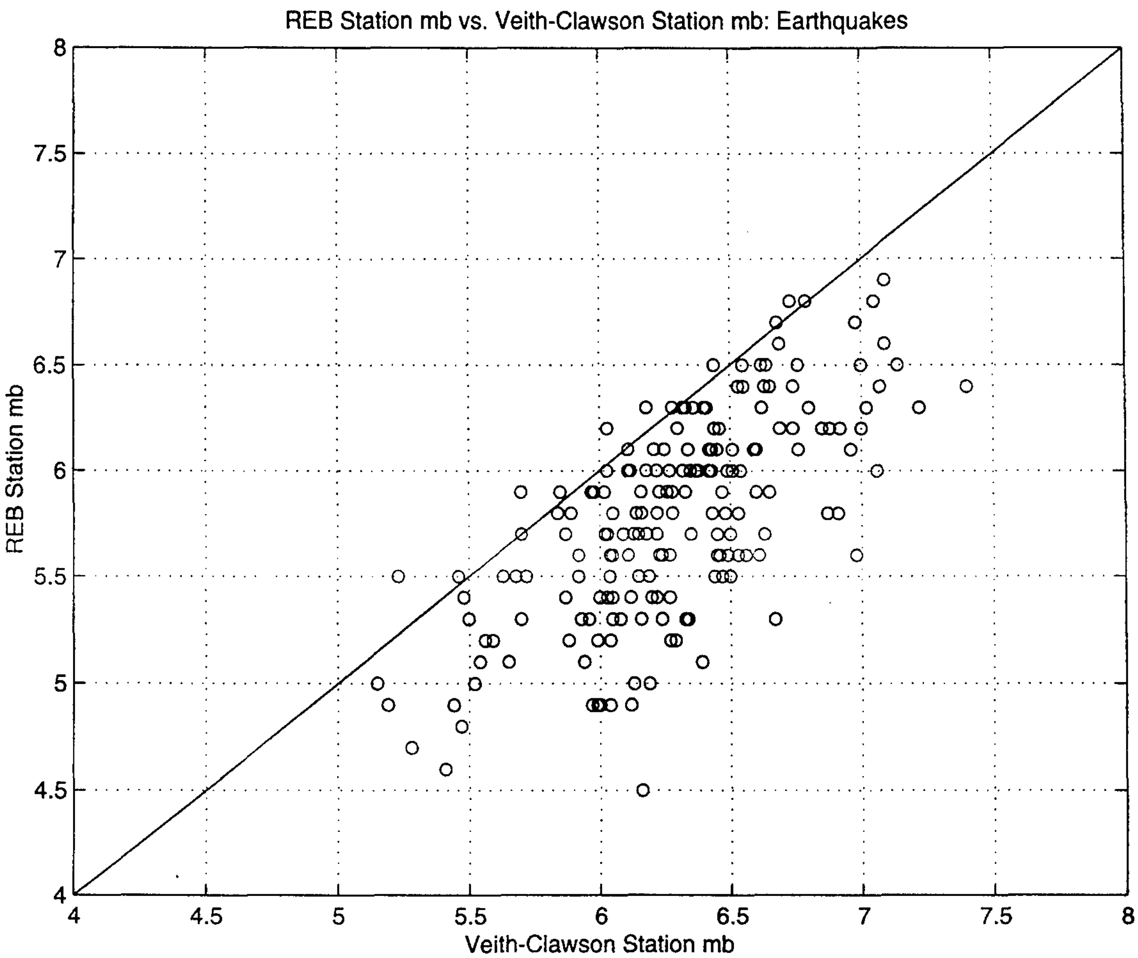


Figure 8. REB station m_b plotted against the corresponding Veith-Clawson station m_b for the earthquake data.

2.5.2 Passband of PIDC Processed Data.

The displacement response of a typical three-component broadband station after processing according to PIDC procedures for purposes of measuring magnitude shows a peak at around 4 Hz, whereas the typical WWSSN short-period displacement response has a peak at around 1.6 Hz (Figure 1). The frequency band of the PIDC (0.8 — 4.5 Hz) is somewhat higher than the conventional short-period passband in which amplitude and period are measured. The passband of the PIDC processed data appears narrower than the passband of a WWSSN short-period response when their peak gains are normalized. Since the procedure followed by the PIDC to determine m_b emphasizes high frequencies, the m_b-M_s discriminant determined by the PIDC may be better than the m_b-M_s discriminant of the USGS (where M_s is assigned the same value by both the USGS and PIDC). However, the frequency band of the PIDC processed data may be too high to capture representative major amplitudes associated with larger earthquakes, because of their lower corner frequencies.

2.5.3 Time Window and Maximum Amplitude.

The Prototype International Data Centre was set up primarily to monitor nuclear explosions and not to study earthquakes, and uses algorithms designed with a shallow, explosive source in mind. The time window utilized by the PIDC for measuring body-wave amplitude from teleseismic P-waves is only 5.5 seconds long (compared to the traditional length of 15 seconds), and is therefore often too short to catch the representative amplitude of an event. For earthquakes occurring in the depth range of approximately 15-40 km, the direct arrival P phases often have much smaller amplitudes than surface reflected depth phases (pP or sP). Thus, for earthquakes occurring at depth ranges between 15-40 km, the maximum amplitude can be missed with the 5.5 second PIDC time window. The length of the time window used (either 5.5 or 15 seconds) was not very important for the underground nuclear test data since these events were near-surface explosions, but the short PIDC time window is a large contributor to the m_b discrepancy observed for the earthquake population. An example of how the short REB time window can result in an underestimate of amplitude is shown in Figure 9. The largest amplitude phase on both records is the pP phase. A body-wave magnitude is assigned based on the simulated WWSSN SP record for two stations (FITZ and VNDA), for both the 5.5 second PIDC time window and the 15 second traditional time window. For station FITZ, the longer 15 second window leads to an increase in m_b of 0.21 m. u. (from 6.27 to 6.48), but for VNDA the effect is much smaller — in this case m_b increases by only 0.04 m. u. (from 6.38 to 6.42). However, for both stations the m_b based on the simulated WWSSN SP signal, but using a time window only 5.5 seconds long (e.g. the length of the PIDC time window), is still greater than the published station REB m_b by about 0.3 m. u. (6.27 vs. 6.0 for FITZ; 6.38 vs. 6.1 for VNDA), indicating that a discrepancy exists even if the shorter 5.5 second window is used instead of the traditional 15 seconds. In other words, the discrepancy in m_b that still persists even when equivalent time windows are used must be due to the difference between the WWSSN filter and that for a station processed according to PIDC procedure.

Simulated WWSSN Short-period Records from a Shallow Earthquake:

1999 December 11, 18:03:36, 15.75N, 119.83E, h=19 km, Luzon, Philippine, REB mb = 5.9

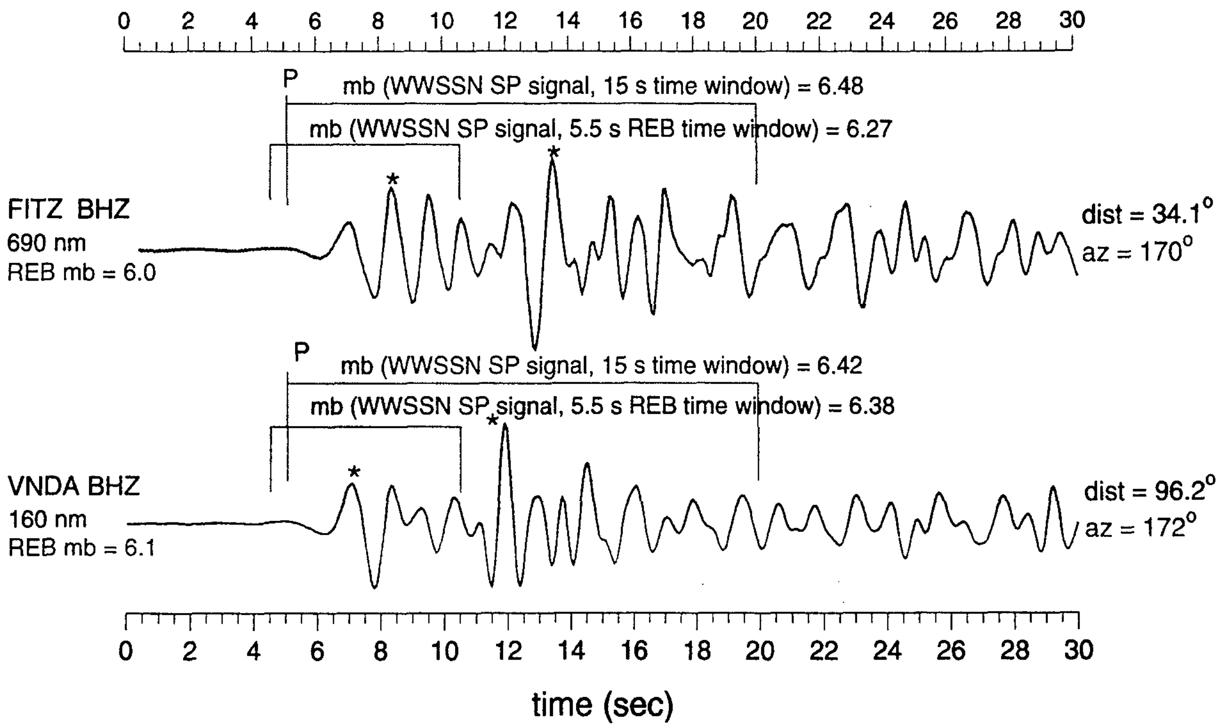


Figure 9. Simulated WWSSN records showing differences in m_b determined from the 5.5 second PIDC time window and the traditional 15 second window. The maximum amplitudes within the different time windows are given by stars. The largest amplitude phase on both records is *pP*.

We found that 64% of the station observations (for the earthquake data) had their maximum amplitude arrive outside of the 5.5 second PIDC time window. Of the 36% of the observations that had their maximum amplitude arriving within the 5.5 second PIDC time window, most belonged to the three events that occurred at very deep depths: 1998 January 01 (h = 99 km), 1998 March 29 (h = 529 km), and 1999 April 13 (h = 131 km). For these three deep events, 90% of the maximum amplitudes arrive within the 5.5 second PIDC time window. We conclude that the PIDC 5.5 second time window is adequate in most cases for deep events, but is a significant problem for shallow earthquakes.

2.5.4 Effect of Depth on Veith-Clawson m_b.

The depths assigned by the USGS in the PDE (Preliminary Determination of Epicenters) are generally greater than those assigned by the PIDC in its REB bulletin, especially for shallow depths. This difference can be attributed to the fact that the PIDC assigns a default depth of 0 km to a significant number of events, whereas for those same events the USGS will assign a more realistic depth or will use its own deeper default depth of 33 km. Since an increase in event depth will result in a lower magnitude [for a given measurement of $\log(A/T)$ at a given distance, where A is the amplitude and T is the period], it follows that the discrepancy between the REB m_b and PDE m_b would be even greater if the REB depths are replaced by those of the PDE in the m_b calculation. This depth effect is shown in Figure 10 for the four earthquakes assigned an REB depth of 0 km. The individual station m_b values are plotted using both the depth given in the REB (circles) and the depth given in the PDE (triangles). Many of the REB m_b values would be lowered by as much as 0.1 to 0.2 magnitude units if the PDE depth were used in place of the REB depth. The event m_b was calculated using both the PDE and REB depth for these four events and is shown in Table 2. This depth effect appears to persist over all teleseismic distances, from 20-103°. Thus, if the same depth were assigned by both agencies, the discrepancy between the REB m_b and PDE m_b would be even larger.

Table 2. Effect on REB m_b of the Different Focal Depths Given by the REB and the PDE for Earthquakes.

EVENT	**REB depth (km)**	**REB mb (depth=REB)**	**PDE depth (km)**	**REB mb (depth=PDE)**
1998 May 03	0.0	5.64	26.0	5.44
1998 November 29	0.0	5.69	45.0	5.46
1999 June 15	0.0	5.99	71.0	5.72
1999 September 20	0.0	5.35	5.0	5.32

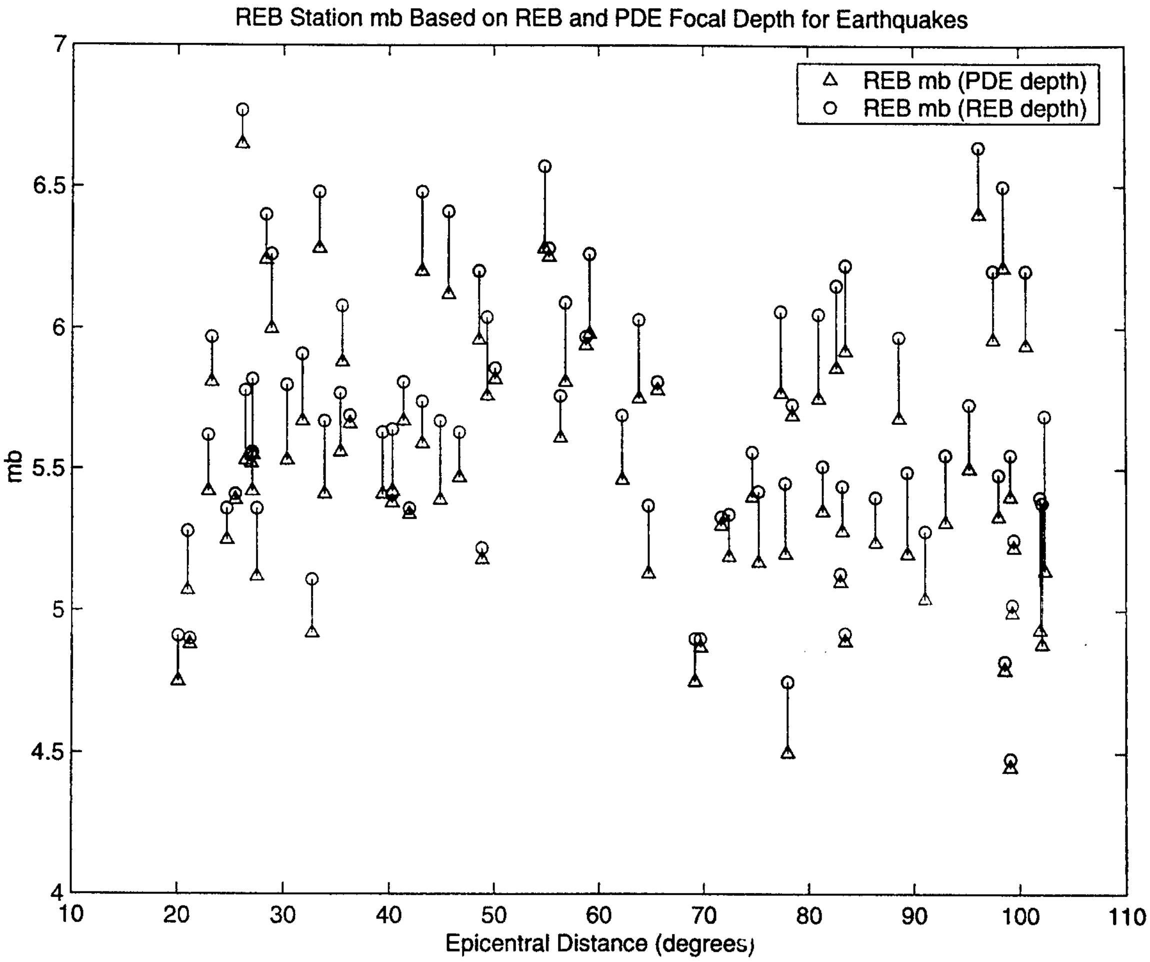


Figure 10. Plot of the REB station m_b values using both the depth given in the REB (circles) and the depth in the PDE (triangles), as a function of epicentral distance — for the four earthquakes in this study assigned a default depth of zero kilometers in the REB.

2.6 Conclusions.

We have obtained Veith-Clawson body-wave magnitudes, m_b(VC), for 10 large earthquakes in 1998-1999 and 13 underground nuclear tests conducted between 1995-1998. Such magnitudes, based on standard WWSSN short-period response, represent a well-defined classical short-period measurement. For the UNTs, the REB magnitude was also reproduced by following the intended PIDC procedure for assigning m_b, noting that some of the m_b measurements from two 1995 events that were given in the REB were computed using incorrect instrument responses. All of the earthquake events have a Veith-Clawson body-wave magnitude that is greater than the m_b published in the PIDC REB, with the average discrepancy between m_b(VC) and m_b(REB) being 0.5 m_b units. For the 13 UNTs, the difference between the m_b(VC) and m_b(intended REB) is zero on average. The Veith-Clawson m_b values for UNTs are very similar to the m_b values given in the REB, and are even closer to the intended REB m_b values, since they are computed using the correct instrument response information. In other words, the different procedures used to compute the Veith-Clawson m_b and PIDC m_b show no net effect on the nuclear explosion data, but a large effect on the earthquake data. We conclude that the PIDC procedure is adequate for shallow, underground nuclear explosions, but not for earthquakes.

The third order highpass filter with a cutoff at 0.8 Hz used by the PIDC appears to be the main cause of magnitude discrepancies, since the $\log(A/T)$ term in the formula (1) above depends on the passband. It may account for a difference of about 0.3 m. u. when compared with m_b measured by the conventional method. Another cause is the 5.5 second time window used to measure the REB m_b. Nearly two-thirds of the waveforms for the earthquake data have maximum amplitudes that arrive after the 5.5 second time window used by the PIDC. These representative amplitudes still fall within the time window of 15 seconds used to measure the Veith-Clawson m_b from simulated WWSSN SP signals. The PIDC procedure for assigning the body-wave magnitude for shallow earthquakes, especially those in the depth range of 15-40 km, is inadequate in that it is systematically different from a well-defined classical measurement made on the same seismograms. We expect that the deleterious effects of the 0.8 — 4.5 Hz filter would be reduced for earthquakes of small size, and possibly have negligible effect for events small enough to have their corner frequency close to this passband.

The depth assigned to an event by the USGS in its PDE catalog is often greater than the depth given by the PIDC REB, especially for shallow events. This is partially due to the fact that the PIDC assigns its default depth of 0 km for a significant number of events, rather than estimating an actual event depth. Since an increase in depth will result in a decrease in the magnitude for given measurements of A and T in the formula (1) above, if the REB depths are replaced by those of the PDE in the m_b calculation, the discrepancy between the two magnitudes will be even greater, in some cases increasing the discrepancy by as much as 0.1-0.2 m_b units.

2.7 Acknowledgements.

We benefited greatly from comments by Ray Buland, Jim Dewey, Lynn Sykes, Jack Murphy, Stuart Sipkin, Ray Willemann, and Karl Veith. Bob Woodward and staff at the Center for Monitoring Research in Arlington, Virginia helped to obtain most of the digital seismograms used in this study. Waveform data from some Global Seismographic Network stations which were also International Monitoring System auxiliary network stations were retrieved from the Incorporated Research Institutions for Seismology (IRIS), Data Management Center in Seattle, Washington. We would like to thank the editor, Dr. Susan Hough, for her prompt response and comments to the manuscript.

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Section 3

Comparison of Teleseismic Body-Wave Magnitudes Published by the Prototype International Data Centre, the U.S. Geological Survey, and the International Seismological Centre

3.1 Introduction.

In order to compare the different mb values assigned by different agencies, it is first necessary to search bulletins published by each agency in order to find the subset of events which all the agencies have reported. Our first approach to this problem was to compare the mb values assigned by the U.S. Geological Survey (USGS) in the Preliminary Determination of Epicenters (PDE), and those assigned by the Prototype International Data Centre (PIDC) in the Reviewed Event Bulletin (REB). This approach, together with studies reported earlier by Granville, Kim, and Richards (2002), found a number of problems with the use of some incorrect instrument responses by the PIDC in the years 1995 and 1996, and with a change in practice (in August 1996) by the USGS in the way that data from PIDC stations were included in the PDE magnitude. Therefore, we undertook a second approach to magnitude evaluations for the years 1997 through 1999, in which PIDC and USGS magnitudes were again compared, with each other and also with the magnitude assigned by the International Seismological Centre (ISC).

Here, we show that PIDC measurements have had a significant effect upon ISC mb values.

3.2 First Comparison: REB and PDE Magnitudes, 1995 — 1999.

To make this preliminary comparison, we carried out the following steps:
(1) The catalog of events published by each agency was reduced to a spreadsheet of the most important parameters, one row per event, including origin time (a floating point number, expressed in days since the continuous international monitoring effort began on January 1, 1995), latitude, longitude, mb, and the number of stations reporting mb. The catalogs for two different agencies were then merged into a single spreadsheet, one for each quarter (thus, twenty spreadsheets for the five years from 1995 to 1999) and sorted on origin times.
(2) A search was conducted for each event, to see if it occurred within a pre-specified time Δt of the event preceding or following and published by the other agency, and also within a pre-specified horizontal distance Δx. The values of Δt and Δx could be easily changed, and after some experimentation to determine appropriate values we did most of our analysis with $\Delta t = 5$ s, and $\Delta x = 60$ km. In this way, typically a few thousand events were discovered in each quarter, for the years 1995 through 1999, that appeared to be the same event reported independently by the two agencies.

(3) For the events in each quarter that had mb values assigned by both the PIDC and the USGS, we sorted each agency s mb values from largest to smallest to enable study of the magnitude distribution in each quarter. As noted below, some interesting changes were found over time, in the USGS magnitude distribution.

Although potentially this three-step search procedure can lead to problems with dense aftershock series, with mismatches in which two different events can incorrectly be taken to be the same event, we found in practice with $\Delta t = 5$ s, and $\Delta x = 60$ km that such problems never arose. However, the same event was sometimes assigned source parameters by the two agencies which were so different (for example, location estimates more than 100 km apart) that it was not possible to identify the fact that the same event had in fact been located by the two different agencies, without increasing Δt and Δx to values that led (for other events) to mismatches. Only through a much more laborious study of one event after another, and comparison of the set of associated signals for each event, could it be determined rigorously which events were in fact in both bulletins (along with the occasional mistake, in which signals had been mis-associated). The International Seismological Center routinely carries out such studies prior to publishing its own bulletin about two years in arrears, and we report on relevant results using ISC analysis, below. It is important to assess such mis-associations for purposes of evaluating the quality and completeness of bulletins, but we found that the mis-associations were sufficiently rare that they do not influence the basic statistics of how different are the mb values (the main subject of the present report).

Using the three-step spreadsheet approach outlined above, we obtained results for each quarter, from 1995 through 1999 (five years, 20 quarters), in order to compare mb values published by the PIDC and the USGS. These basic results are given in Figures 11 through 15. There is one Figure for each calendar year from 1995 to 1999. In each Figure, there are four pairs of sub-figures, one showing the magnitude comparison directly for each quarter, the second showing the cumulative magnitude distribution for that quarter. For example, Figure 11 shows eight sub-figures, one pair for each quarter. The first of each pair, shows the direct comparison of PIDC (REB) and USGS(PDE) magnitudes for the events in that quarter that we could easily identify as having magnitude assigned by each of the two monitoring agencies. The second of each pair, shows the cumulative magnitude distribution, determined by (i) taking all the events in each quarter that were identified as having had their magnitudes assigned by each agency, and sorting the events for each agency into a sequence with descending magnitudes, then (ii) plotting each sequence as magnitude vs. sequence number. For each point plotted, this gives the number of events, of magnitude greater than or equal to the event plotted.

Each of Figures 11 through 15 shows the some similar general features, which may be summarized as follows:
(a) For most events the REB magnitude is lower than the PDE magnitude;
(b) In each quarter there are significant outliers from the main population (see the left-hand sub-figure for each quarter, from Figure 11 to Figure 15).
(c) The cumulative distributions can be used to indicate the range of magnitudes over which significant magnitude differences exist (see the right-hand sub figure for each quarter). They can also be used to assess whether the magnitude discrepancies change with magnitude itself.

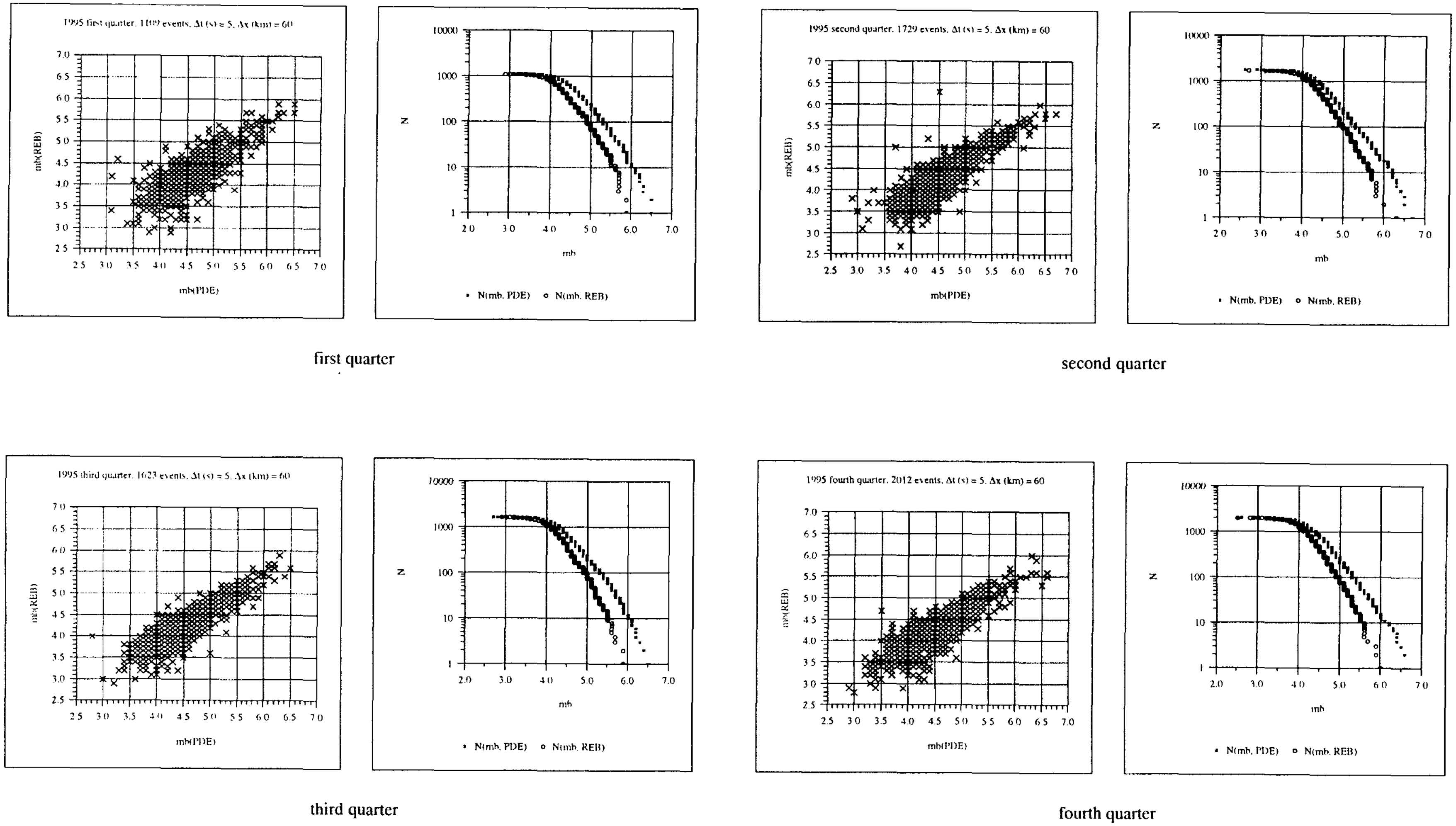


Figure 11. Comparisons of the body-wave magnitude values, mb, published by the USGS in the Preliminary Determination of Epicenters (PDE), and by the PIDC in the Reviewed Event Bulletin (REB). Results are given for each quarter of 1995. Also for each quarter, is shown the distribution of magnitudes assigned by these two agencies. In 1995, REB magnitudes are systematically lower than PDE magnitudes, by an amount that decreases with magnitude value. (This latter conclusion follows, from the non-parallel nature of the two sets of magnitude distributions in each quarter.)

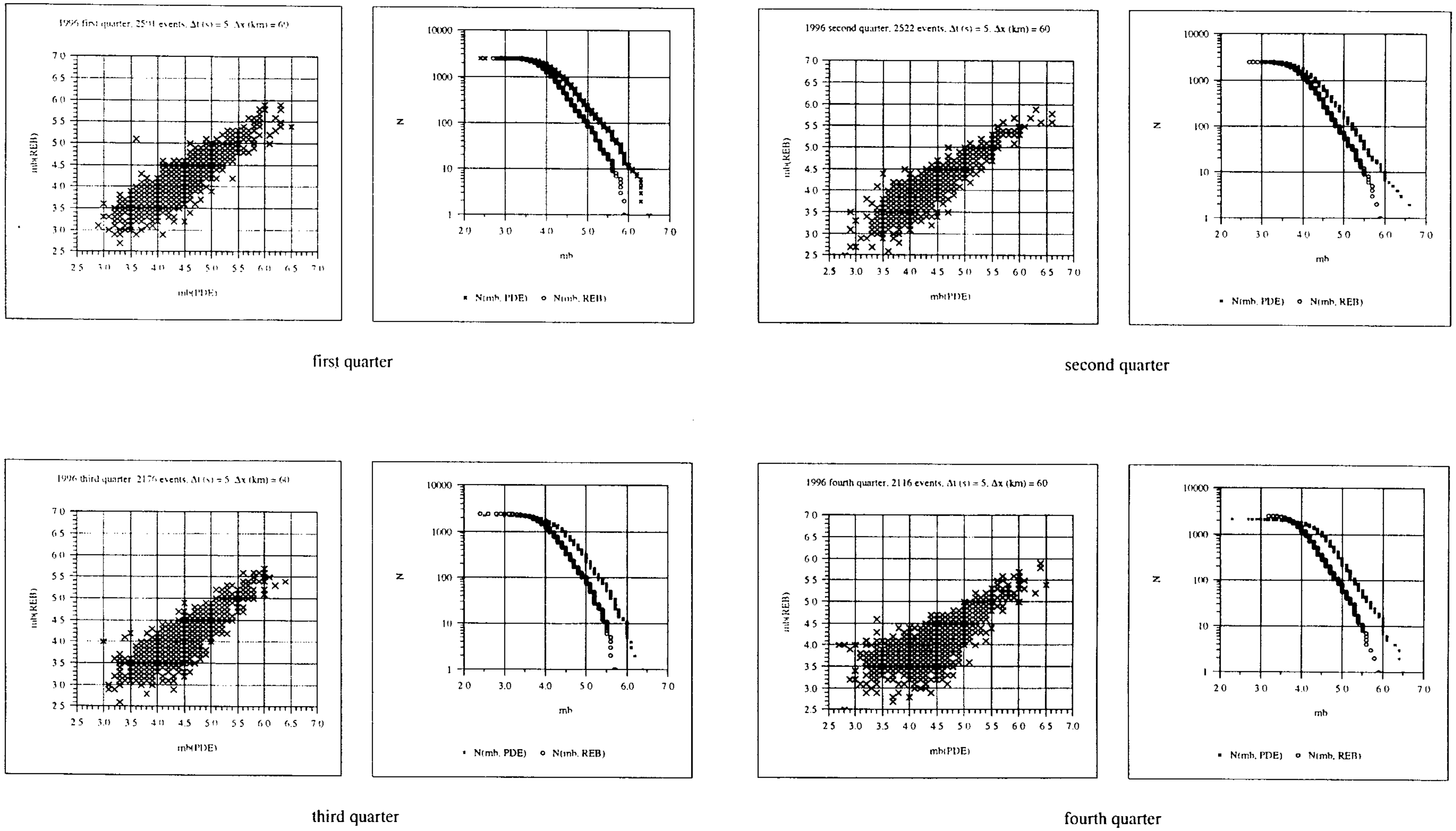


Figure 12. Comparisons of the body-wave magnitude values, mb, published by the USGS in the Preliminary Determination of Epicenters (PDE), and by the PIDC in the Reviewed Event Bulletin (REB). Results are given for each quarter of 1996. Also for each quarter, is shown the distribution of magnitudes assigned by these two agencies. The first two quarters of 1996 have distributions like those of 1995 because the magnitude distributions are clearly non-parallel; the last quarter of 1996 has distributions like those of 1997 because the magnitude distributions are parallel. The third quarter of 1996, is intermediate.

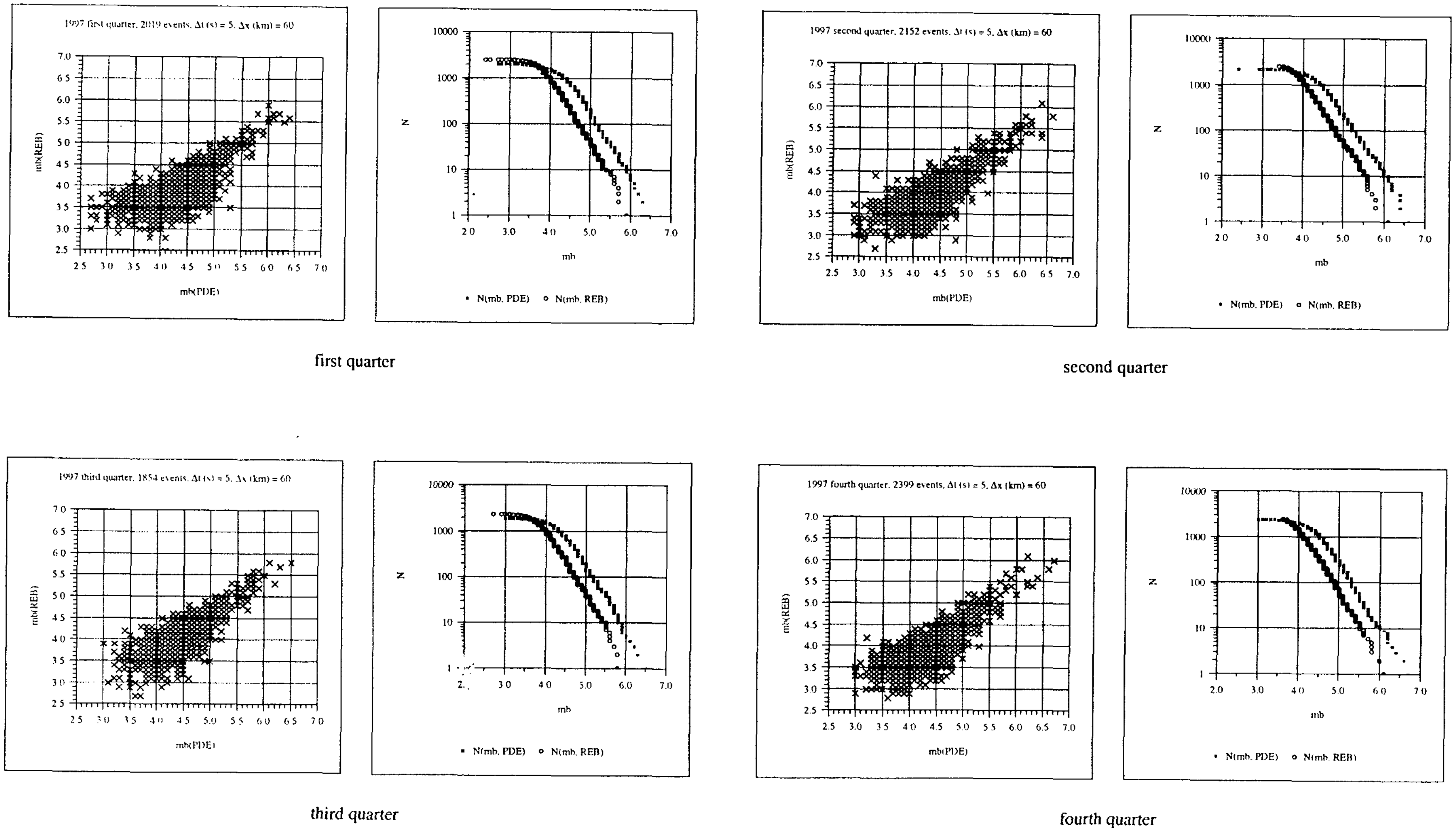


Figure 13. Comparisons of the body-wave magnitude values, mb, published by the USGS in the Preliminary Determination of Epicenters (PDE), and by the PIDC in the Reviewed Event Bulletin (REB). Results are given for each quarter of 1997. Also for each quarter, is shown the distribution of magnitudes assigned by these two agencies. In 1997, REB magnitudes are lower than PDE magnitudes, by an amount that changes little (on average), from PDE mb 4.5 to 6.5. (This latter conclusion follows, from the parallel nature of the two magnitude distributions in each quarter here.)

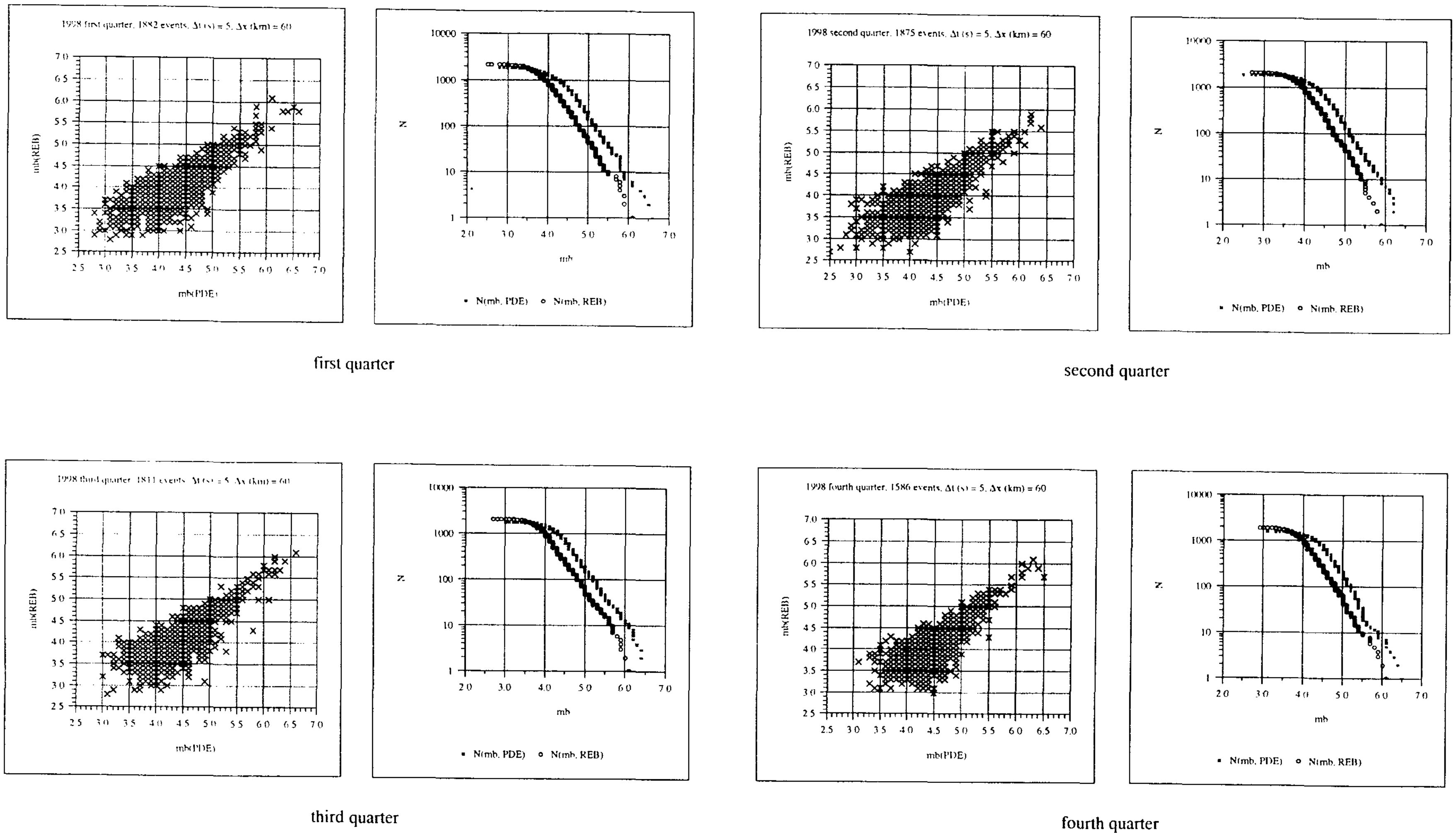


Figure 14. Comparisons of the body-wave magnitude values, mb, published by the USGS in the Preliminary Determination of Epicenters (PDE), and by the PIDC in the Reviewed Event Bulletin (REB). Results are given for each quarter of 1998. Also for each quarter, is shown the distribution of magnitudes assigned by these two agencies. In 1998, REB magnitudes are lower than PDE magnitudes, by an amount that changes little (on average), from PDE mb 4.5 to 6.5. (This latter conclusion follows, from the parallel nature of the two magnitude distributions in each quarter here.)

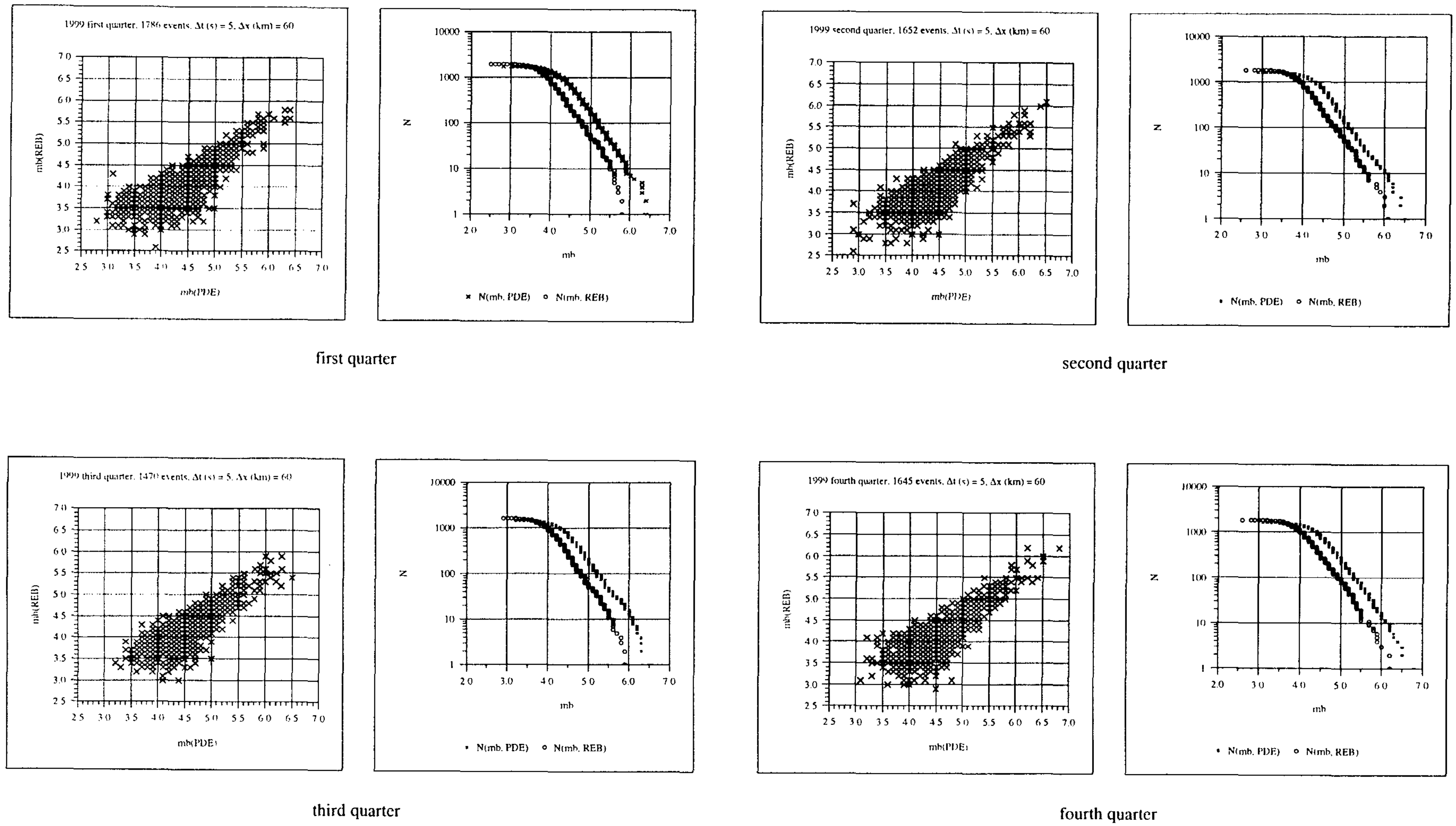


Figure 15. Comparisons of the body-wave magnitude values, mb, published by the USGS in the Preliminary Determination of Epicenters (PDE), and by the PIDC in the Reviewed Event Bulletin (REB). Results are given for each quarter of 1999. *Also for each quarter, is shown the distribution of magnitudes assigned by these two agencies. In 1999, REB magnitudes are lower than PDE magnitudes, by an* amount that changes little (on average), from PDE mb 4.5 to 6.5. (This latter conclusion follows, from the parallel nature of the two magnitude distributions in each quarter here.)

(d) For the first six quarters, from 1995 through the second quarter of 1996 (see Figures 11 and 12), the cumulative magnitude distributions show approximately the same distinctive differences between REB and PDE, namely, that the difference is about 0.4 to 0.5 magnitude units for the larger events in each quarter (usually, around PDE magnitude 6.5), diminishing to a difference of about 0.2 or 0.3 magnitude units for the smaller events (around PDE magnitude 4 or 4.5). Another way to characterize this feature, is to say that the slopes of the two distributions, PDE and REB, are different for each of the first six quarters.
(e) Beginning with the fourth quarter of 1996 as shown in Figure 12, and continuing to the end of 1999 (Figure 15), the cumulative magnitude distributions again show approximately the same distinctive differences between PDE and REB, but for these quarters there is approximately the same slope from PDE magnitude 4.5 to 6.5. Thus, from the last quarter of 1996, the magnitude discrepancy between PDE and REB persists at about the same value (0.4 to 0.5 magnitude units) over a range of about two magnitude units.

It appears that the cause of the systematic change in magnitude distributions noted above, item (d) vs. item (e), is that in the earlier time period the USGS routinely accepted the PIDC s measurements of amplitude and period, in its own procedures for assigning the PDE magnitude. Although the USGS uses Gutenberg-Richter distance corrections, and the PIDC used Veith-Clawson distance corrections, it can be expected that use by the USGS of a significant number of amplitude and period measurements made by the PIDC would tend to make the USGS event magnitudes more like those of the PIDC. Furthermore, this tendency would be stronger for smaller events because the percentage of PIDC measurements, used for each event, typically increased in the USGS database used for assigning the PDE magnitude, in comparison to the percentage of PIDC measurements used by the USGS for the larger events. This increase is due to the fact that for the smaller events, a greater fraction of the work of detecting and supplying amplitude and period measurements is done by the sensitive arrays in use by the PIDC. But in August 1996 (half-way through the third quarter of 1996) the USGS stopped using PIDC measurements of amplitude and period.

This change in practice appears to have had the effect of extending the magnitude discrepancy (0.4 to 0.5 magnitude units), previously noted for the larger events, down to events of much smaller size.

It may also be noted that such changes in practice make it difficult to develop a clear understanding of systematic differences between magnitude scales. It is for this reason that Granville, Kim and Richards (2002), in their assessment of PIDC magnitudes, chose to make a comparison with the classic Veith-Clawson magnitudes, using a simulated Worldwide Standardized Seismographic Network instrument response applied to the same broadband signals previously analysed by the PIDC. In this way, discrepancies could directly be traced to fundamentals of how data windows and data filters were chosen, rather than potentially being confused with changes in practice such as the (rational) 1996 decision by the USGS not to incorporate PIDC measurements into the USGS procedures by which PDE magnitudes are assigned.

As well as a change in the magnitude distribution, occurring in the third quarter of 1996, one can see from Figures 11 through 15 an overall change, occurring in the same quarter, in the shape of the set of points when the REB magnitude is plotted against the PDE magnitude (the left-hand sub-figure for each quarter, Figures 11 through 15). As indicated in Figure 16, prior to August 1996 this shape is approximately symmetric about a 45° line. But after this date, the shape is asymmetrical, in a way that spreads the REB magnitude values, in the range from about 3.25 to 3.75, over a much bigger range of PDE magnitudes, from about 3.0 to 4.5.

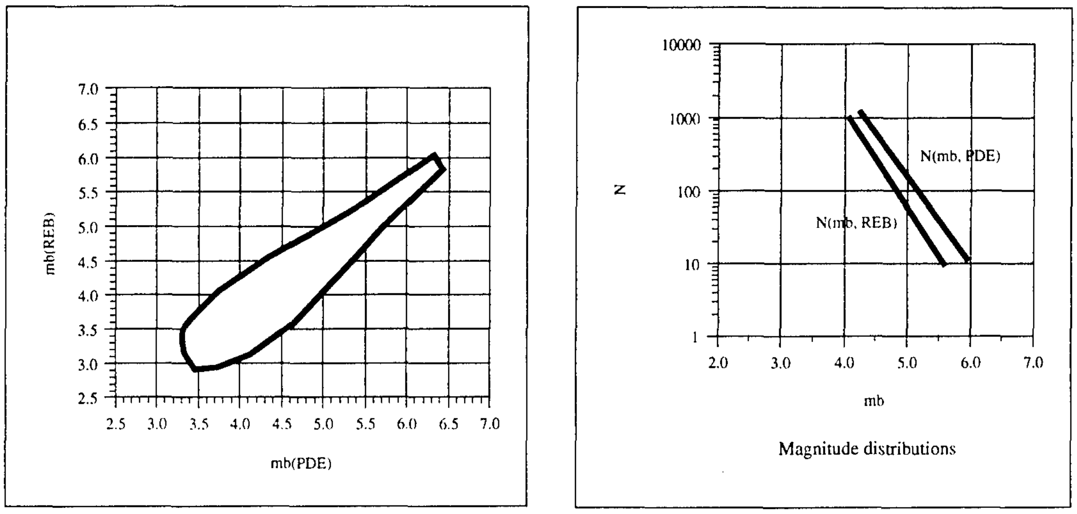
As indicated in the captions to Figures 11 through 16, and in item (a) above, the main conclusion from these comparisons is that there is a significant difference between PIDC and USGS magnitudes. But how does it change from one year to another? One change, not noted previously in (a) through (e) nor in the Figure captions, is in the extent to which outliers are apparent in the direct magnitude comparisons (the left hand sub-figure for each quarter depicted in Figures 11 through 15). These are particularly noticeable in Figure 11, for the first two quarters. Thus, for the first quarter, it was initially a concern that outlying points whose magnitudes reported by the two agencies had values (3.2, 4.6), (3.1, 4.2), (5.4, 3.9) might actually be different events. But closer examination determined that these events appear to be genuine matches (there are no other candidate matches), and that even though their magnitudes are assigned with a difference of more than one full magnitude unit, these really are the same events. In the second quarter of 1995 (see Figure 11), there are points whose magnitudes reported by the two agencies are (4.5, 6.3), (3.7, 5.0), (4.3, 5.2), (3.8, 2.7), and (4.9, 3.5) but again closer inspection shows that these are correct matches. We note that for the 1995 April 10 event whose magnitudes are reported by the two agencies as (4.5, 6.3), the station magnitude reported in the REB from NORESS is 31.3 which is a very considerable amplitude, and is the basis of the network magnitude of 6.3 reported for this event by the PIDC nearly two magnitude units greater than the USGS value of 4.5. Aki and Richards (2002) note that magnitude 4 corresponds to a value of A/T around 0.001 micron/s for a range of teleseismic distances (where A is amplitude of ground motion, and T is the dominant period). Magnitude 31.3 indicates ground motion 2 x 1027 times this value, for a resulting value of A/T equal to 2 x 1018 m/s. Since the Earth s diameter is only of order 107 m, the reported NORESS station magnitude for this event implies ground motion at NORESS which was many orders of magnitude greater than the Earth s diameter. It seems safe to say that the reported NORESS magnitude is a mistake. In the year 1996, first quarter, there is an event with magnitudes (3.6, 5.1). It is a shallow event (unlike most outliers, which are deep). But it is not a mismatch.

Though outliers are apparent in every quarter, it appears there are somewhat fewer outliers in later years, 1997 — 1999.

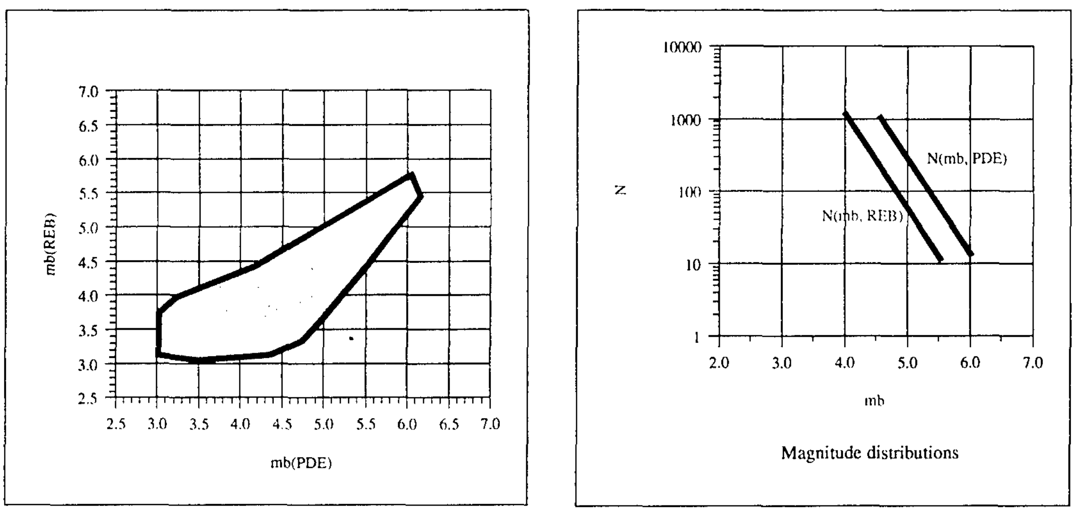
The REB was not produced for the 7 days from May 8 to May 14, 1995.

Granville, Kim and Richards (2002) have given a detailed study of several hundred broadband records, showing for a significant number of stations that the PIDC in 1995 and 1996 did not apply the correct instrument response. Therefore, in order to make comparisons that as far as possible are due to different (but internally correct) procedures for assigning magnitude, we made comparisons between PIDC, USGS, and ISC magnitudes only for the years 1997 — 1999.

In this time period, we have every reason to believe that the problems with incorrect instrument responses, apparent in the early years of publication of the REB, have been resolved.



(a) Typical magnitude comparisons, PIDC and USGS,
for 1995 and the first two quarters of 1996



(b) Typical magnitude comparisons, PIDC and USGS,
for the last quarter of 1996, then through 1999

Figure 16. Summary of main features of Figures 11 through 15. Part (a) shows the shape of the cloud of magnitude points, as being approximately symmetrical about a 45° line; and the magnitude distributions with differents slopes. These are the features of the PIDC and USGS magnitude comparison, prior to August 1996. Part (b) shows an asymmetrical cloud of magnitude points, and magnitude distributions with very similar slopes. These are the features which characterize the comparison after August 1996 when the USGS stopped using PIDC measurements of amplitude and period.

3.3 Second Comparison: REB, PDE, and ISC Magnitudes, 1997 — 1999.

The International Seismological Centre publishes its bulletin of global seismicity about two years in arrears. We worked from the catalogue information in IASPEI Seismic Format (ISF), in which the ISC publishes not only its own analysis for each event, but also the analyses of numerous other agencies including the USGS and PIDC. (The latter is referred to by the ISC as EIDC, standing for Experimental International Data Centre.)

The ISC s analysis has changed in recent years, and it continues to evolve. In 1999, the ISC published information on about 155,000 seismic events (approximately 400 per day). In most cases, these events were too small to be detected at more than one reporting network, and the ISC simply republished information provided by a regional or national data center. But the ISC did re-analyse about 52,000 seismic events in 1999, including all those with magnitudes reported by the PIDC and USGS.

For each of the twelve quarters from 1997 to 1999, we extracted from ISC ISF files the set of seismic events that were assigned mb values by all three agencies that routinely publish bulletins of global seismicity that is, by the PIDC, the USGS, and the ISC. Numbers ranged from a low of 2008 events in the fourth quarter of 1998, to a high of 2883 events in the fourth quarter of 1997. Table 3 shows the number of events in each quarter. Because the ISC s catalogue is comprehensive, the number of events with magnitudes reported by both the PIDC and USGS is the same as the number of events with magnitudes reported by all three agencies.

We note from Table 3 that the ISC reports approximately 500 more events in each quarter, than were discovered in our preliminary analysis (see above). The main reason for the greater number, is that our preliminary analysis searched only for events in both (PIDC, USGS) events lists that were not more than 5 s apart in origin time, not more than 60 km apart in epicenter, and appeared consecutively in the merged event lists. In practice, the locations reported for the same event by all three agencies are often much further apart. Such differences in hypocenter are not the main issue in this study(which mostly concerns seismic magnitudes), but because it is of some interest we show in Figures 17 and 18 the differences in epicenter estimates, in km, for about 2000 events in the last quarter of 1999. These two Figures differ only in their scale, which is –°100°km for Figure 17 and – 500 km for Figure 18 (to show the events not included in Figure 17 and which are therefore mislocated by more than 100 km in latitude or longitude or both). It is of course not possible to decide which location estimate (between those provided by the PIDC, the USGS, and the ISC) is best for each event. But because the ISC uses so many more stations than the PIDC, for many events, it may be expected that the ISC location will usually be the best available. This situation will likely change, if the PIDC or the USGS adopts more sophisticated methods of event location than those currently used (which typically rely upon a standard Earth model, and thus ignore differences in travel time between, for example, shields and tectonic regions).

	Number of events found in each quarter	
quarter	preliminary analysis	found by ISC
1997 q1	2019	2600
1997 q2	2152	2639
1997 q3	1854	2305
1997 q4	2399	2883
1998 q1	1882	2444
1998 q2	1875	2386
1998 q3	1811	2268
1998 q4	1586	2008
1999 q1	1786	2365
1999 q2	1652	2235
1999 q3	1470	2032
1999 q4	1645	2037

Table 3. The number of seismic events, in each quarter from the beginning of 1997 to the end of 1999, for which we found magnitudes reported by both the PIDC and the USGS. In our preliminary analysis, we used the criterion that events had to have origin times separated by not more than 5 s, and epicenters separated by not more than 60 km. The final column of this table shows the significantly greater number of events in each quarter reported by both the PIDC and the USGS (and also by the ISC), as reported by the ISC.

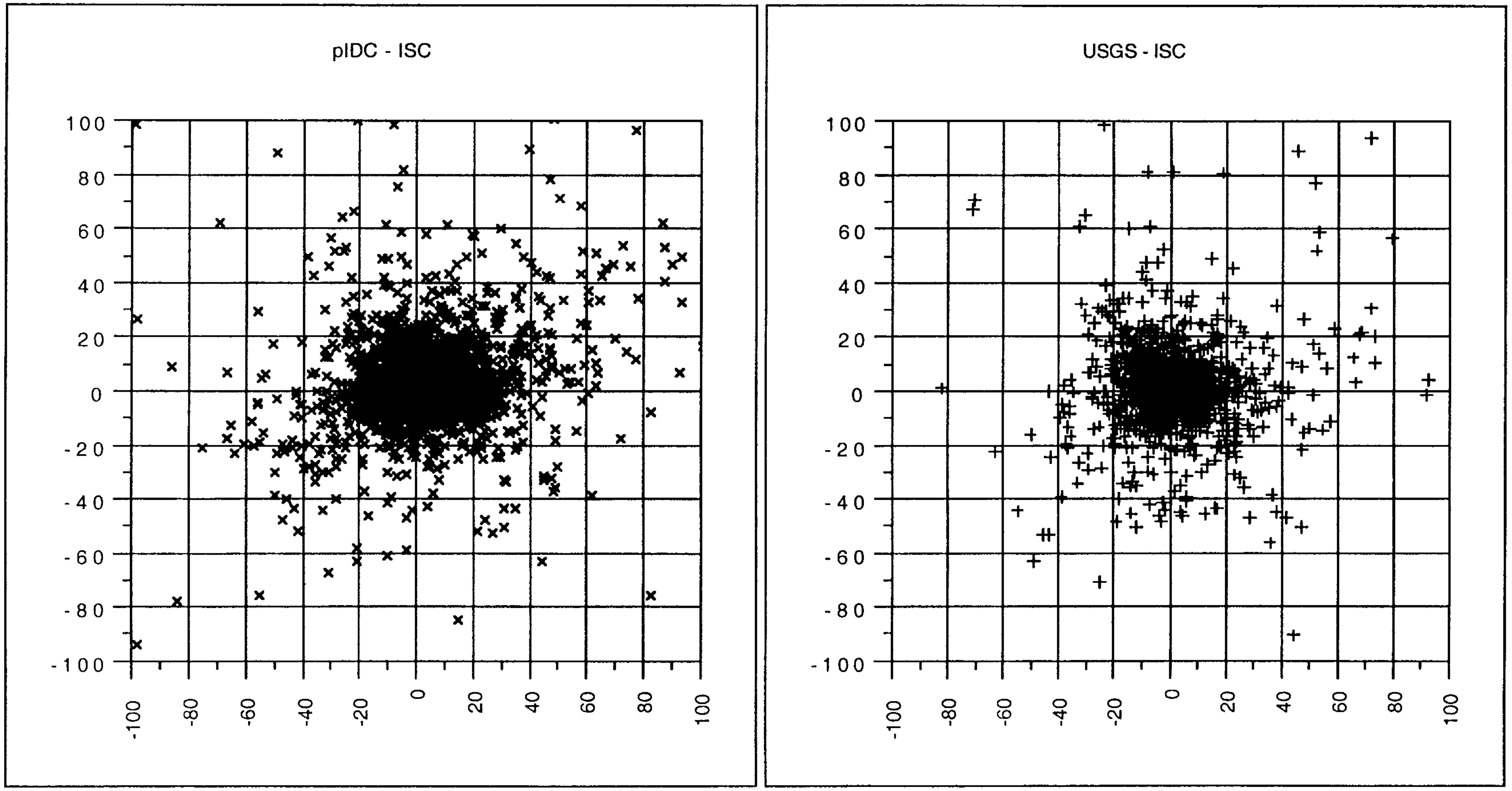


Figure 17. Comparison of epicenters for 2037 seismic events (fourth quarter of 1999), all assigned magnitudes (mb) and located by PIDC, USGS, and ISC. Distances in km. On the left is shown the comparison between the PIDC and the ISC. Note that the scale is limited to ± 100 km, north-south and east-west. There are many events, large enough to have magnitudes assigned independently by the PIDC and USGS, whose epicenter estimates according to the PIDC and ISC differ by more than 60 km. On the right, is the comparison between the USGS and the ISC. There are fewer events in this case (USGS – ISC) with epicenter differences greater than 60 km.

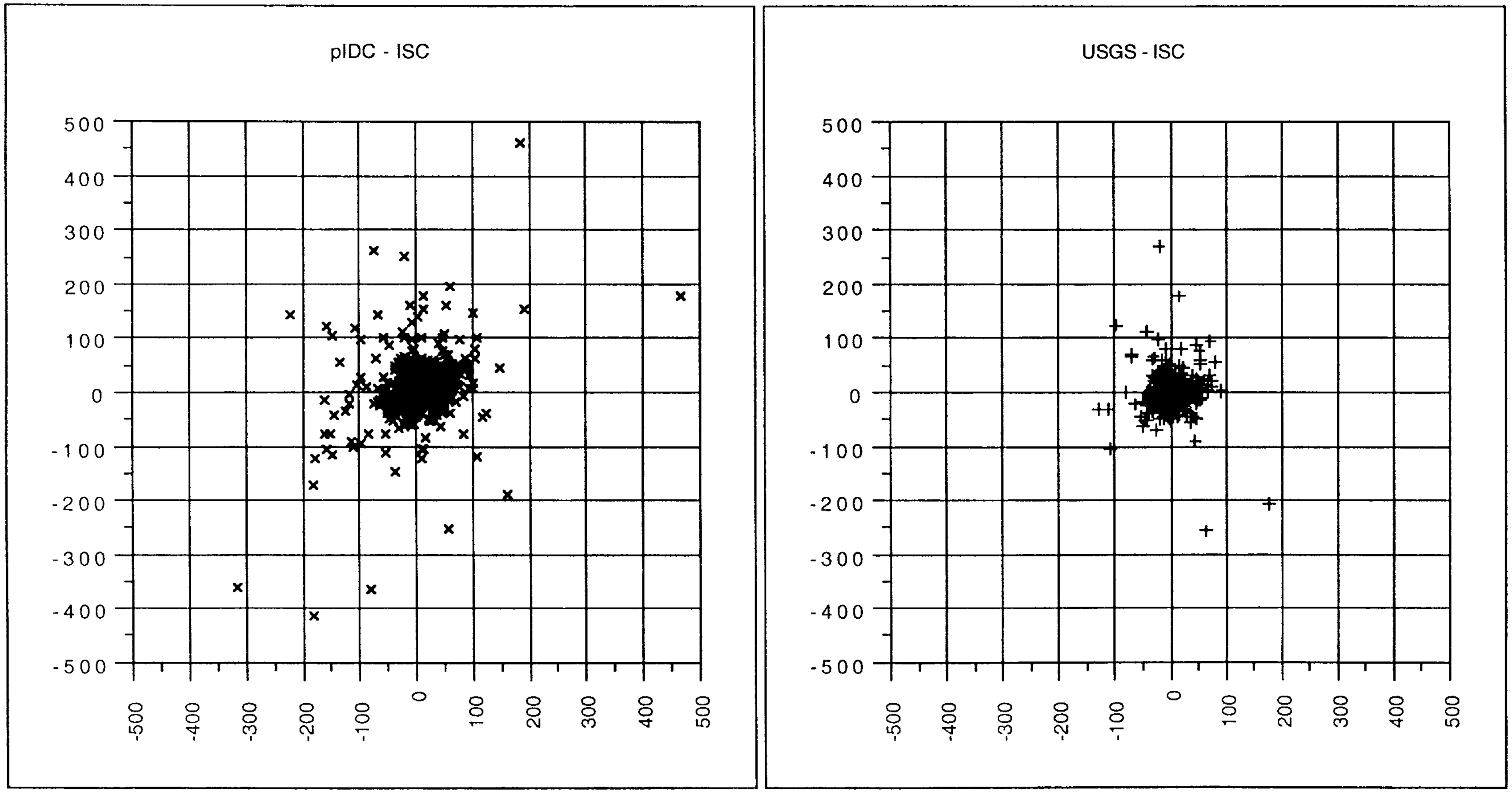
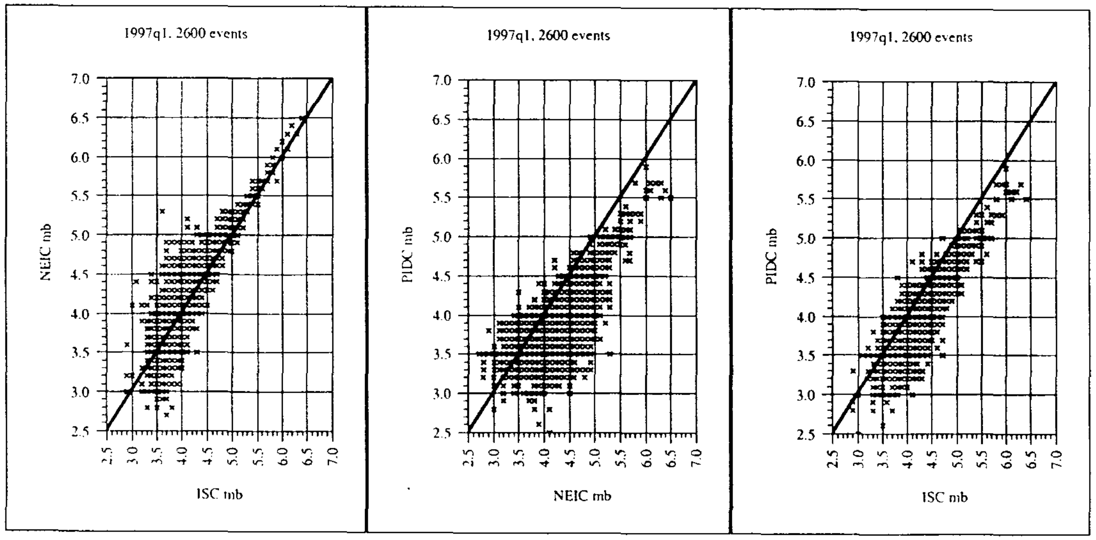


Figure 18. Same as Figure 17, but now with amplitude scales ranging over ± 500 km to enable examination of badly mislocated events. Distances in km. Several tens of events in the fourth quarter of 1999, large enough to have magnitudes assigned independently by the PIDC and USGS, have epicenter estimates located more than 100 km apart, in the PIDC and ISC bulletins. The agreement between USGS and ISC bulletins (see right-hand side) is somewhat better.

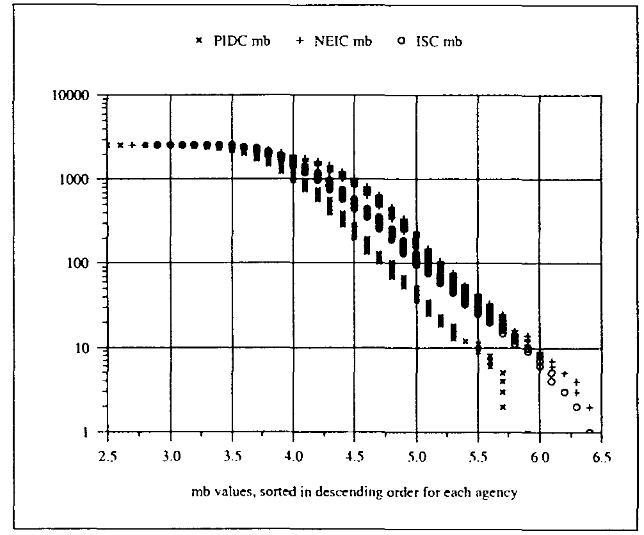
Our main results, in the comparison of PIDC, USGS, and ISC magnitudes, are shown in Figures 19 through 30. There is one Figure for each quarter, in the three-year period from the beginning of 1997 to the end of 1999. Each of these Figures provides several different ways to compare the magnitudes assigned by these agencies.

For example, Figure 19 shows results for the first quarter of 1997 for 2600 events. In the first type of comparison, at the top left of Figure 19, are shown the direct plots of one magnitude against the other, taking the agencies in pairs. Thus, the middle panel of these three, repeats essentially the same information as in the first panel of Figure 13 (but now, from the extensive work of the ISC, as noted in Table 3 it has been possible to find almost 600 more events in this quarter, that have magnitudes assigned by all three agencies). The heavy $x = y$ line in each panel indicates points for which the magnitude values are the same for each of the two agency magnitudes being compared. In this first type of comparison, it is of interest that there is a significant discrepancy between the ISC and NEIC (that is, USGS) magnitudes: the NEIC and ISC magnitude values are quite poorly correlated, at least below magnitude 5.

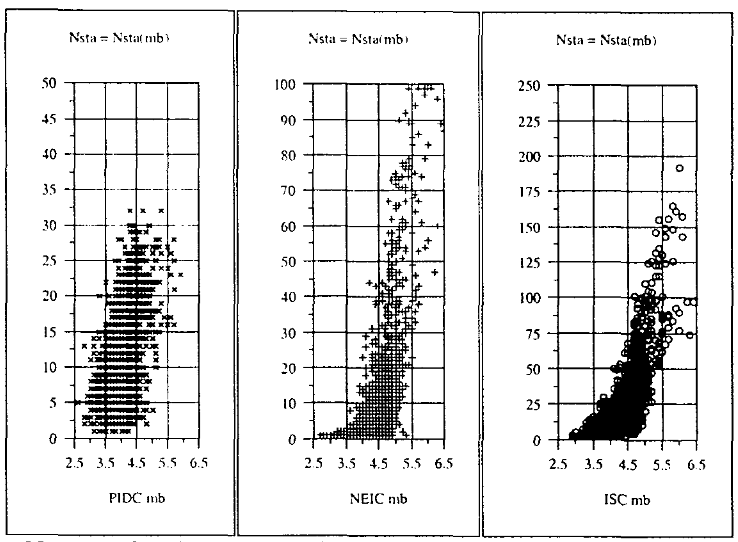
In the second type of comparison, top right of Figure 19, is shown the set of cumulative magnitudes for this quarter as assigned by all three agencies. Over a range of about 1.5 magnitude units there is a constant offset of about 0.4 units between PIDC and NEIC, but the ISC changes from NEIC values at high magnitude, almost to PIDC values at low magnitudes. This is what we found in the previous section, when comparing NEIC (that is, PDE) magnitudes with PIDC magnitudes, prior to August 1996 (that is, for the period when the USGS was using PIDC measurements of amplitude and period). But now we are looking at data from 1997. In making location estimates, the USGS uses arrival times reported by the PIDC for International Monitoring System stations. But for amplitude and period measurements at IMS stations since August 1996, the USGS either makes the measurements in-house, or in some cases accepts them from station operators. The ISC is using PIDC values of amplitude and period, and the question here, is how much the ISC values for the smaller magnitude events are dominated by amplitude and period measurements made by the PIDC. It is a great benefit for the ISC to have information from the PIDC on events at smaller magnitude detected principally by the IMS array stations but does the ISC have additional contributed magnitudes at low magnitude? Note from the direct comparison of PIDC and ISC magnitudes at the top of Figure 19 there there seems to be on average about the same offset (between ISC and PIDC) at lower magnitudes, as the offset at higher magnitudes. But all these magnitudes are given to one decimal place, so each point at lower magnitudes can represent many events, and is not possible to tell from this ISC — PIDC where the centroid of one set of magnitudes lies, corresponding to a constant magnitude on the other scale. It is from the cumulative magnitude distribution, shown at top right, that we see how the ISC magnitude distribution moves between the other two scales, being close to NEIC at large magnitudes so that there is about 0.4 to 0.5 magnitude unit (m. u.) offset from the PIDC mb, for the few largest events, with the ISC — PIDC offset diminishing quite steadily at lower magnitudes.



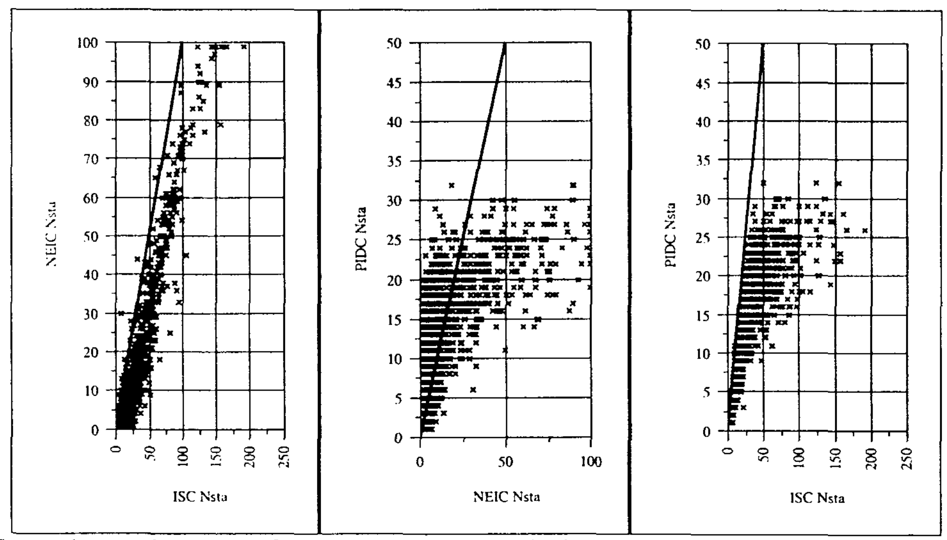
Direct comparisons of magnitude assigned by PIDC, USGS(NEIC), and ISC



Comparison of cumulative magnitude distributions

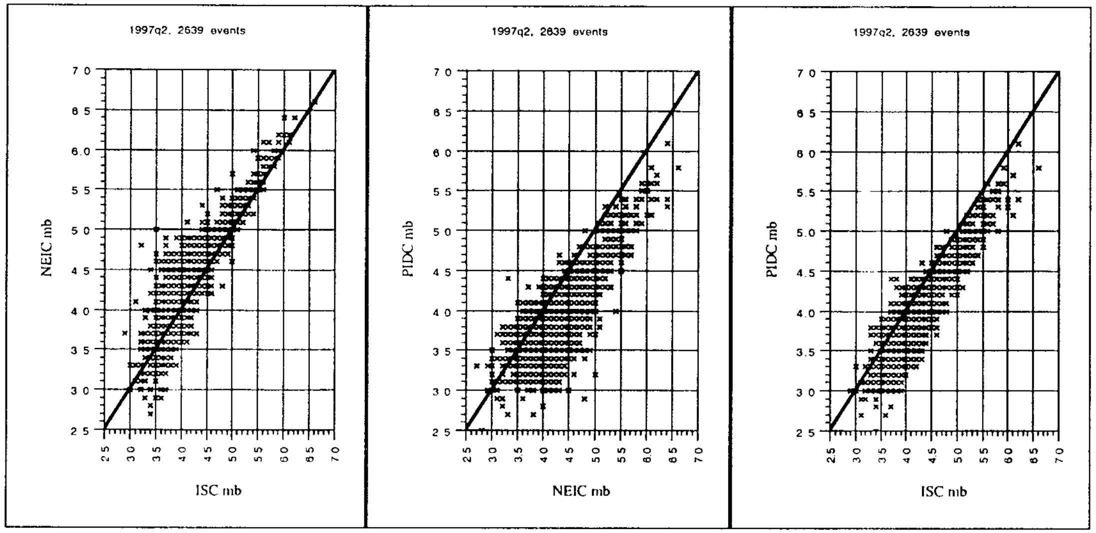


Number of stations vs. magnitude, for different network magnitudes

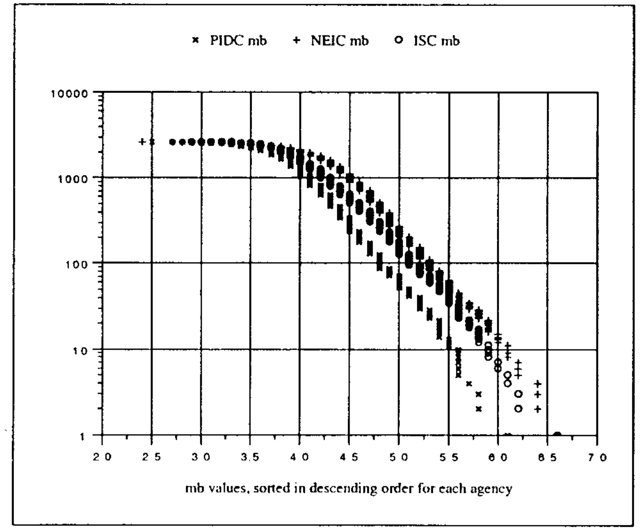


Comparisons, of numbers of stations reporting magnitudes (for each event) to different agencies

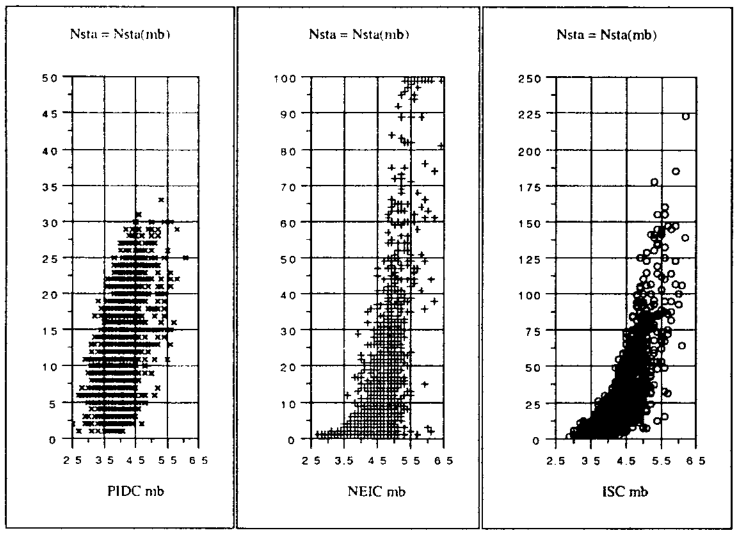
Figure 19. Four different comparisons, of magnitudes assigned by different agencies for 1997, first quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. The typical magnitude 4 event, as monitored by the USGS, has only about five station magnitudes (though considerably more, for a limited number of events). But for the PIDC, as well as the ISC, the typical number is much greater. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.



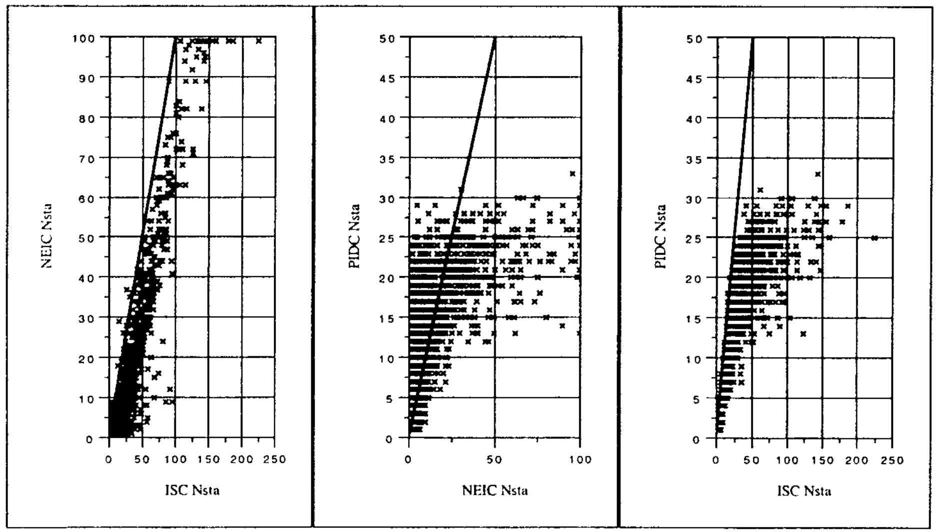
Direct comparisons of magnitude assigned by PIDC, USGS(NEIC), and ISC



Comparison of cumulative magnitude distributions

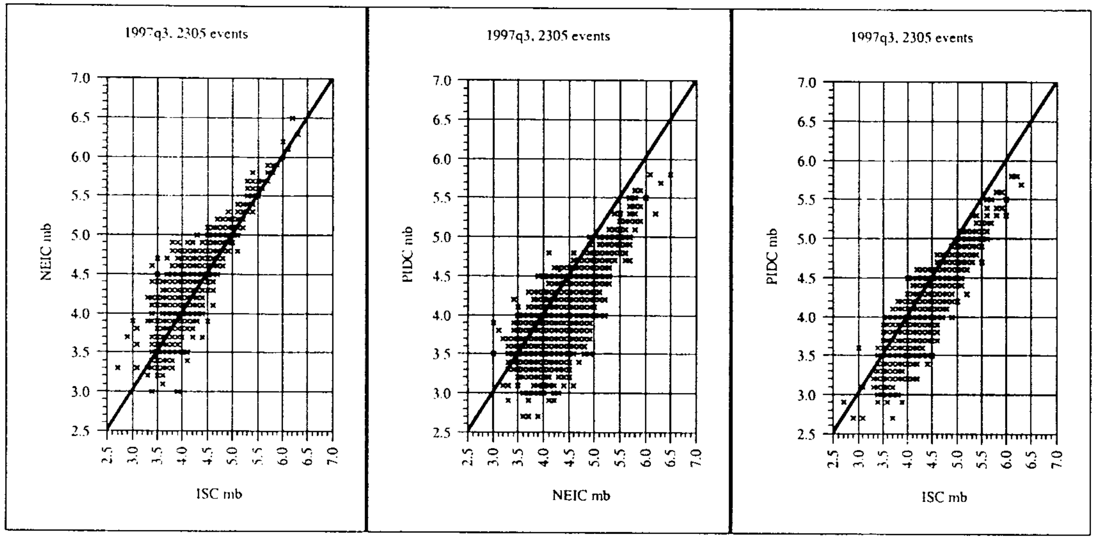


Number of stations vs. magnitude, for different network magnitudes

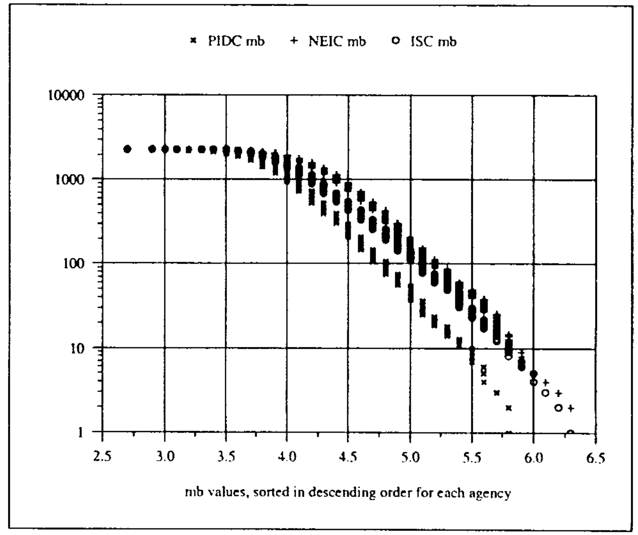


Comparisons, of numbers of stations reporting magnitudes (for each event) to different agencies

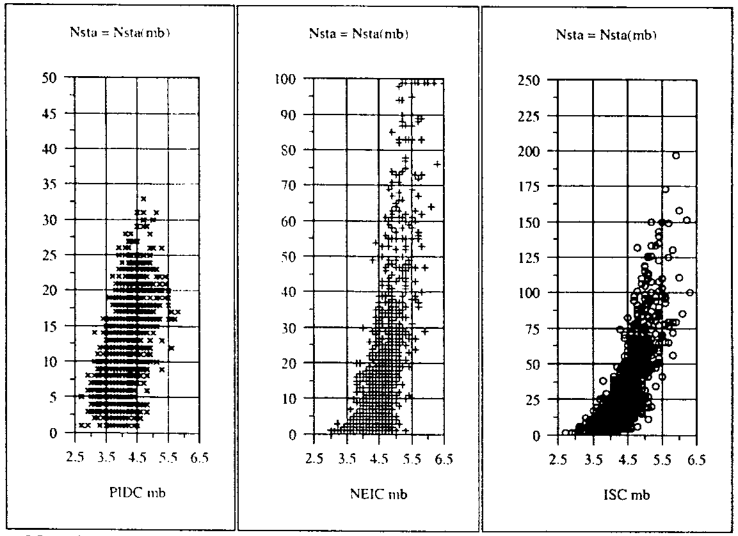
Figure 20. Four different comparisons, of magnitudes assigned by different agencies for 1997, second quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.



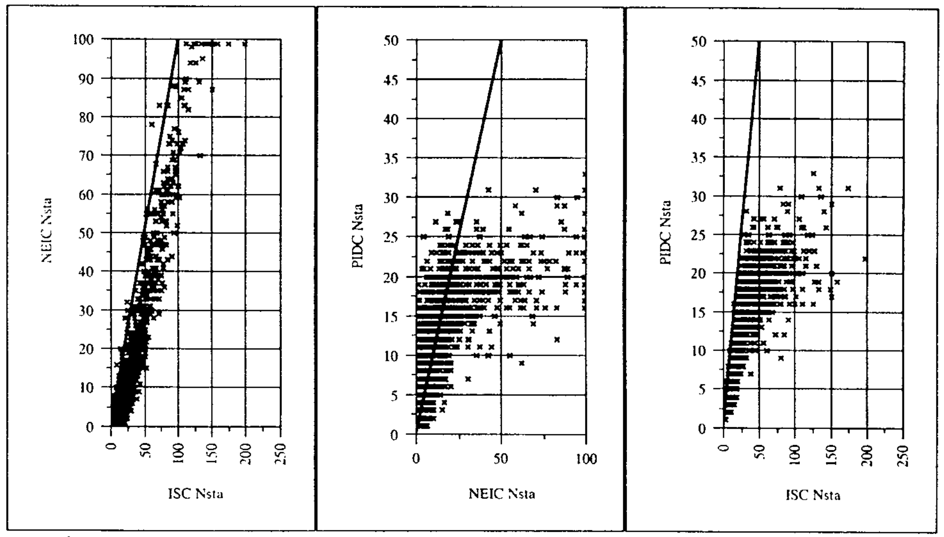
Direct comparisons of magnitude assigned by PIDC, USGS(NEIC), and ISC



Comparison of cumulative magnitude distributions



Number of stations vs. magnitude, for different network magnitudes



Comparisons, of numbers of stations reporting magnitudes (for each event) to different agencies

Figure 21. Four different comparisons, of magnitudes assigned by different agencies for 1997, third quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.

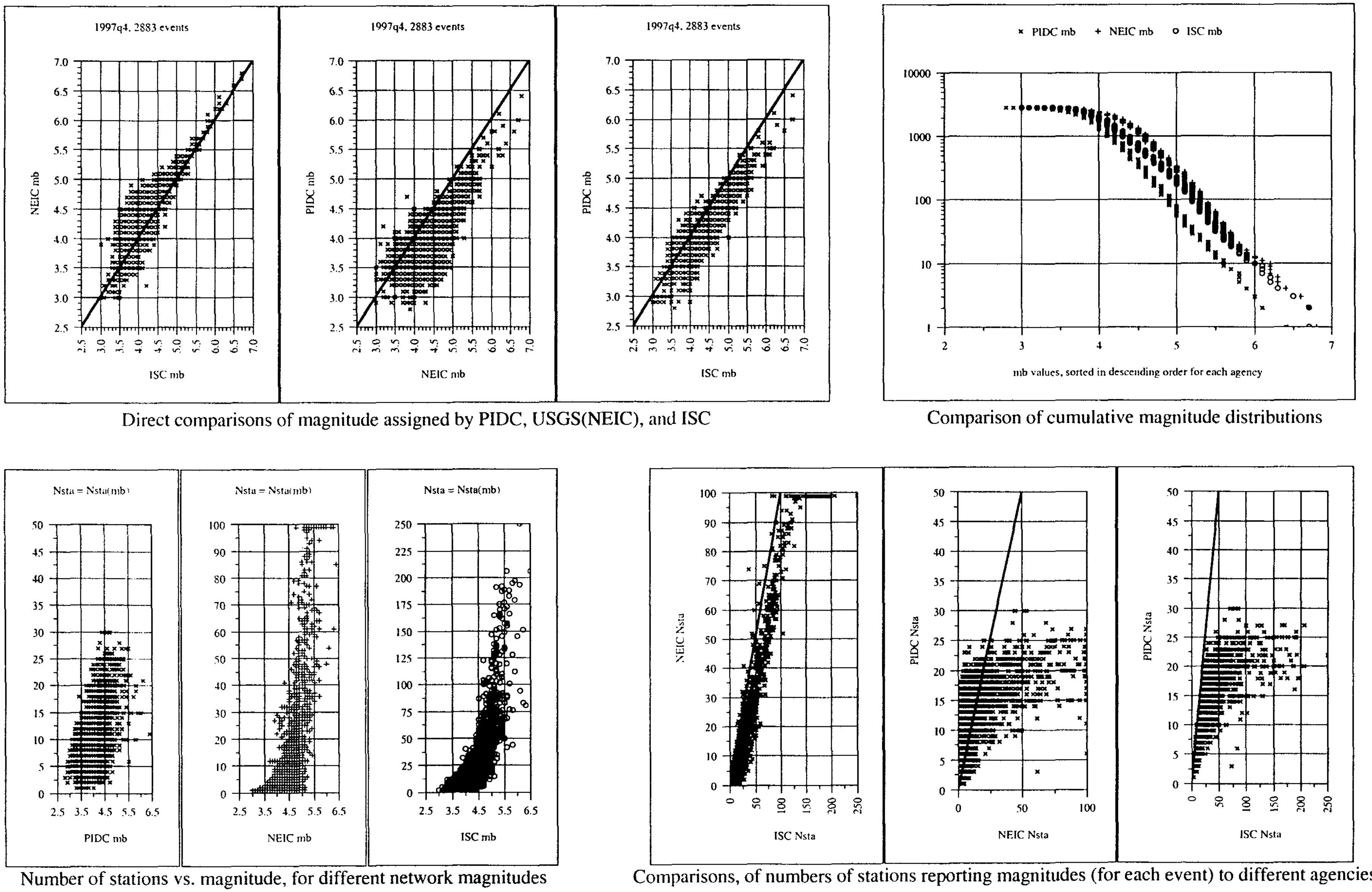
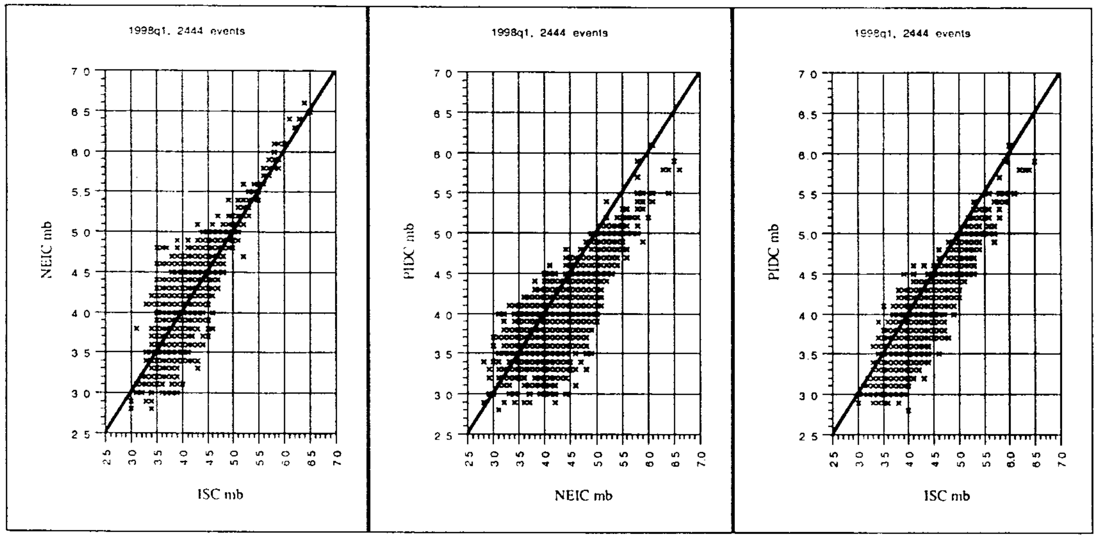
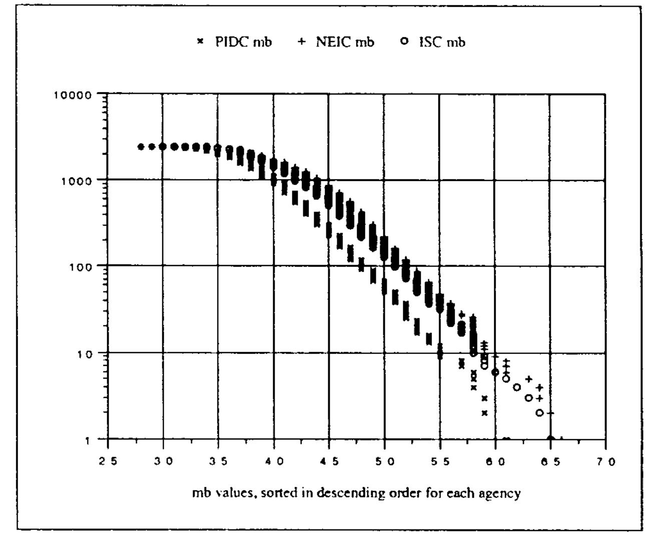


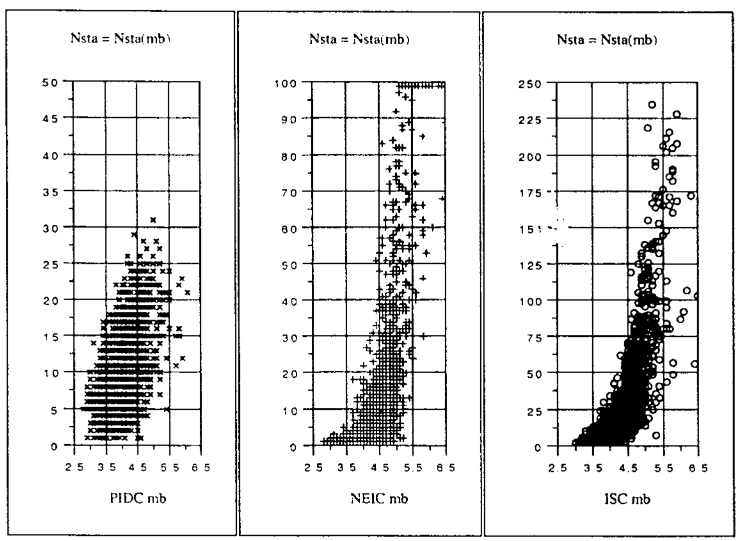
Figure 22. Four different comparisons, of magnitudes assigned by different agencies for 1997, fourth quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.



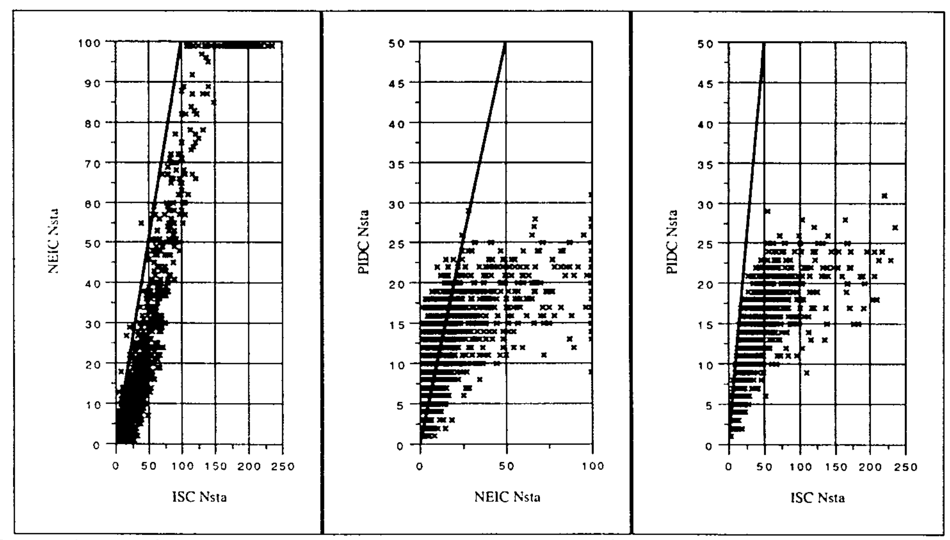
Direct comparisons of magnitude assigned by PIDC, USGS(NEIC), and ISC



Comparison of cumulative magnitude distributions

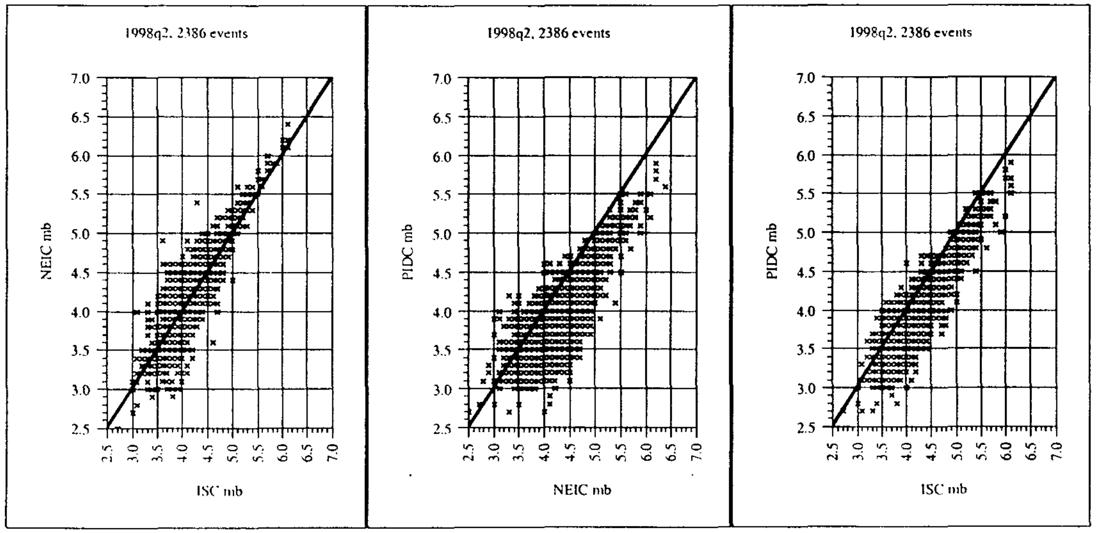


Number of stations vs. magnitude, for different network magnitudes

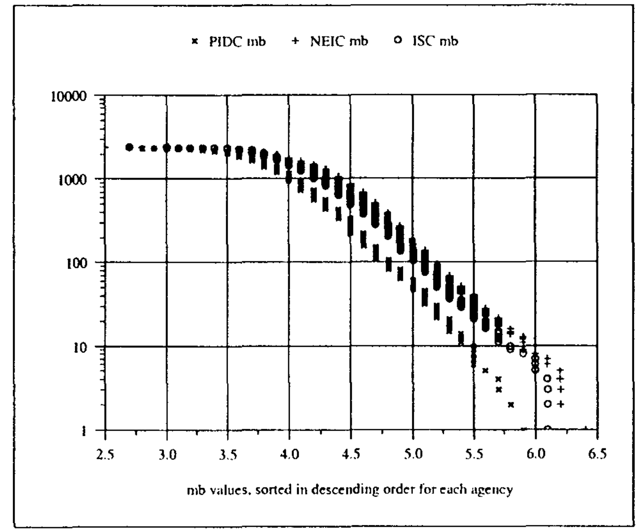


Comparisons, of numbers of stations reporting magnitudes (for each event) to different agencies

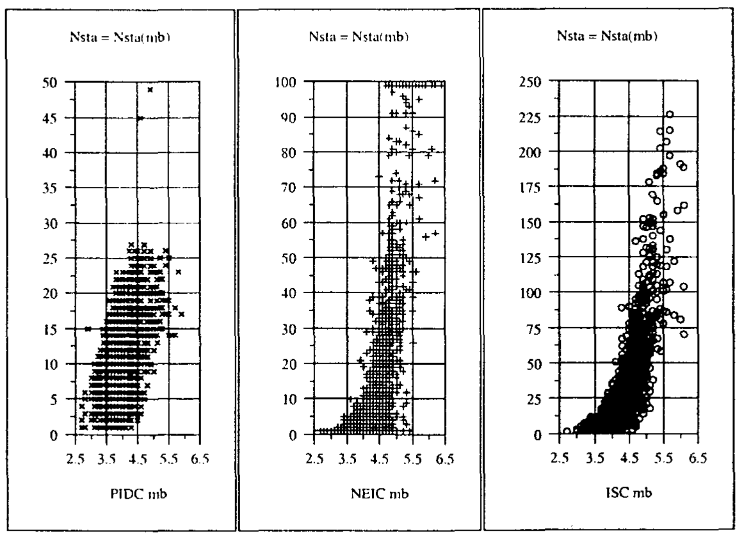
Figure 23. Four different comparisons, of magnitudes assigned by different agencies for 1998, first quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.



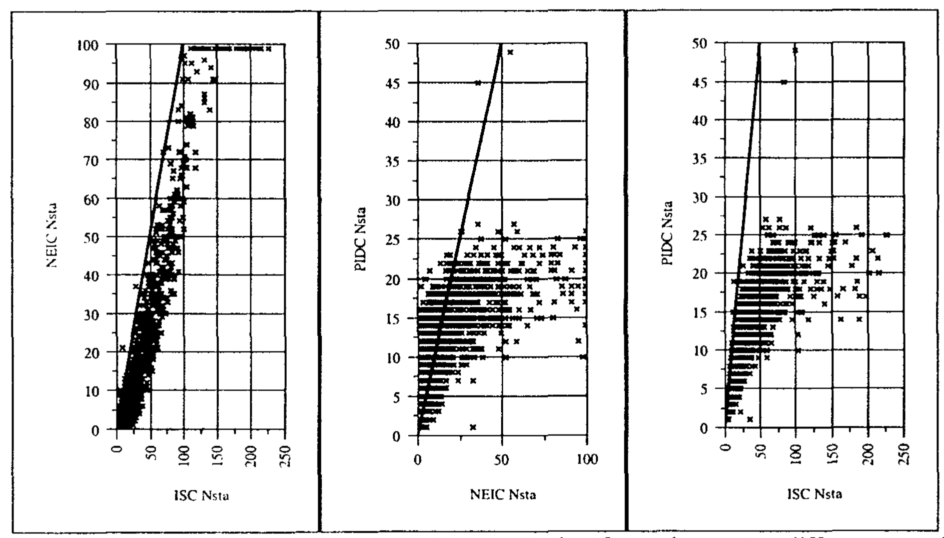
Direct comparisons of magnitude assigned by PIDC, USGS(NEIC), and ISC



Comparison of cumulative magnitude distributions

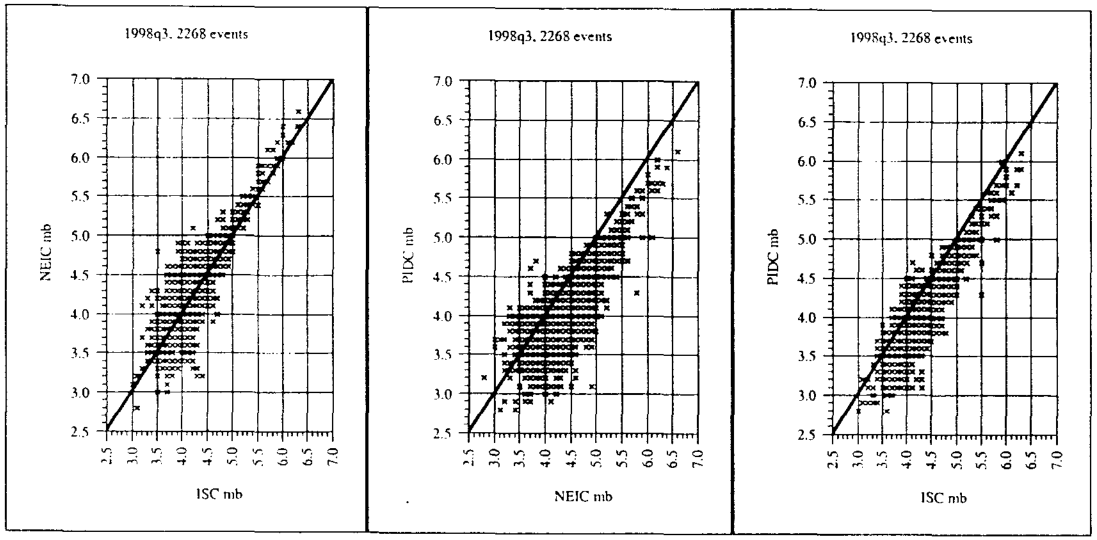


Number of stations vs. magnitude, for different network magnitudes

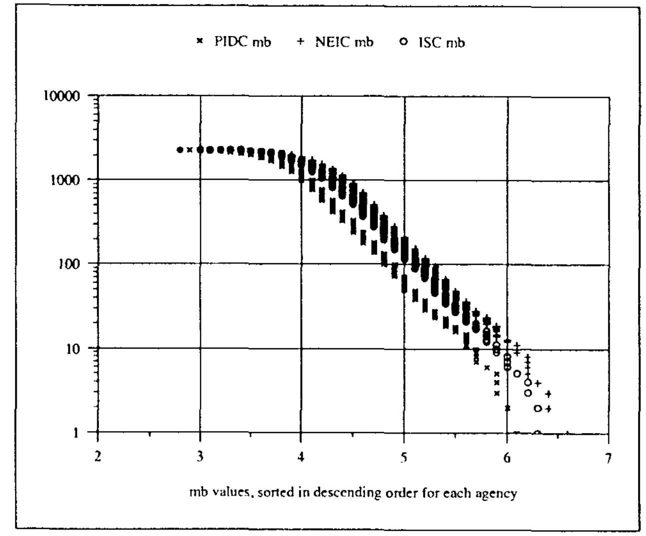


Comparisons, of numbers of stations reporting magnitudes (for each event) to different agencies

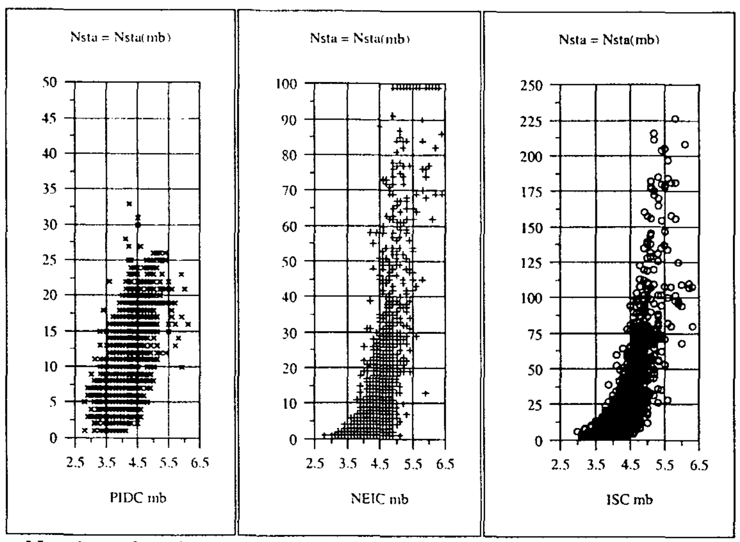
Figure 24. Four different comparisons, of magnitudes assigned by different agencies for 1998, second quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.



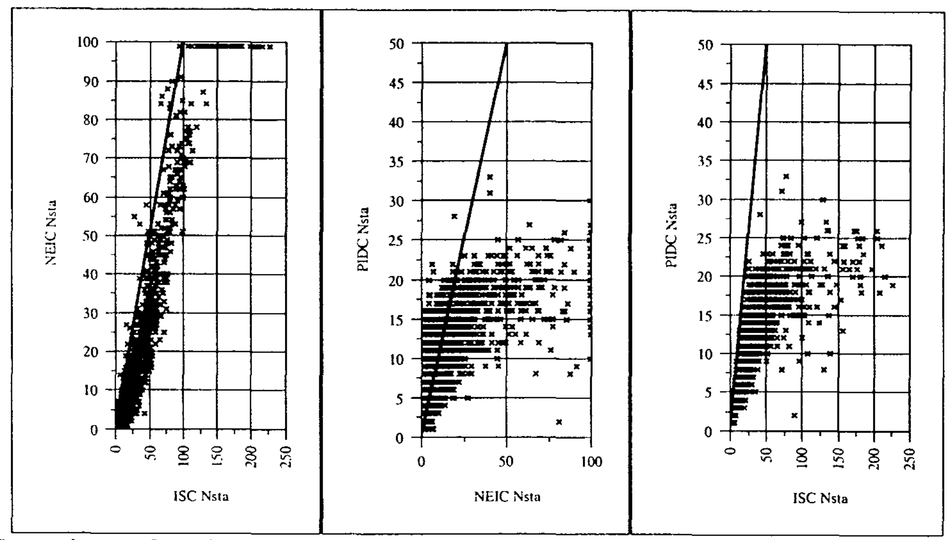
Direct comparisons of magnitude assigned by PIDC, USGS(NEIC), and ISC



Comparison of cumulative magnitude distributions

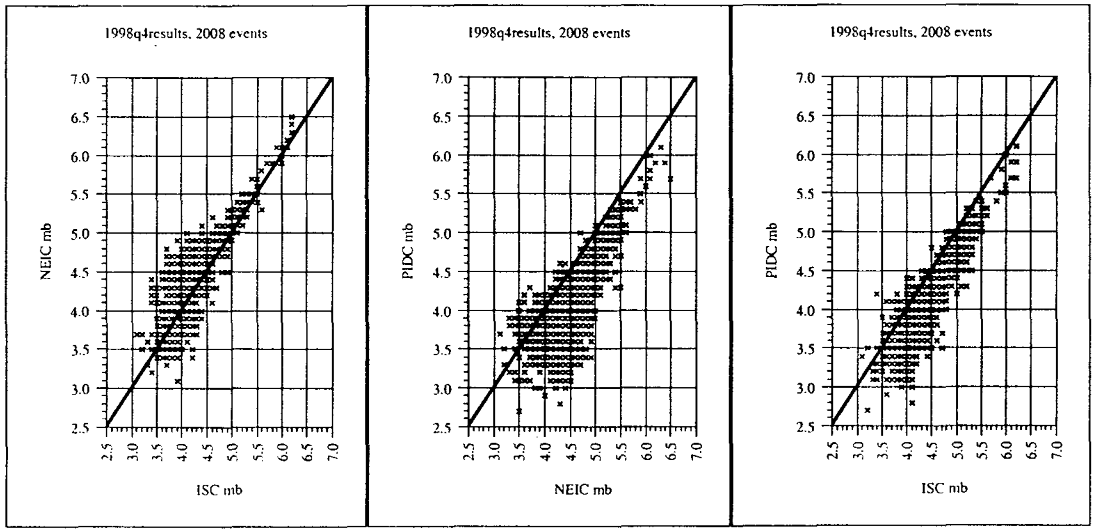


Number of stations vs. magnitude, for different network magnitudes

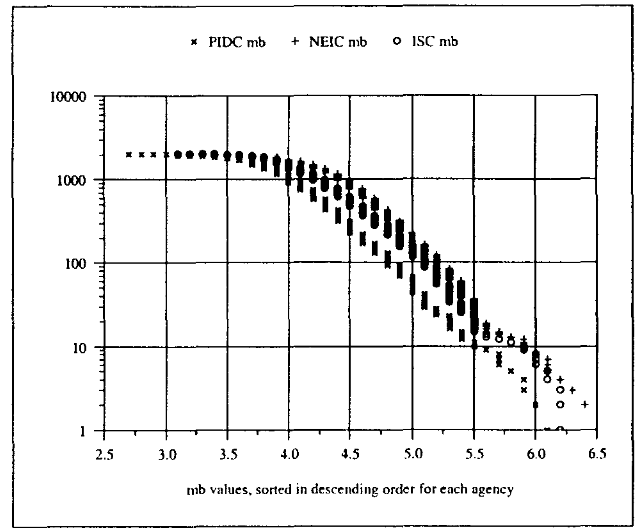


Comparisons, of numbers of stations reporting magnitudes (for each event) to different agencies

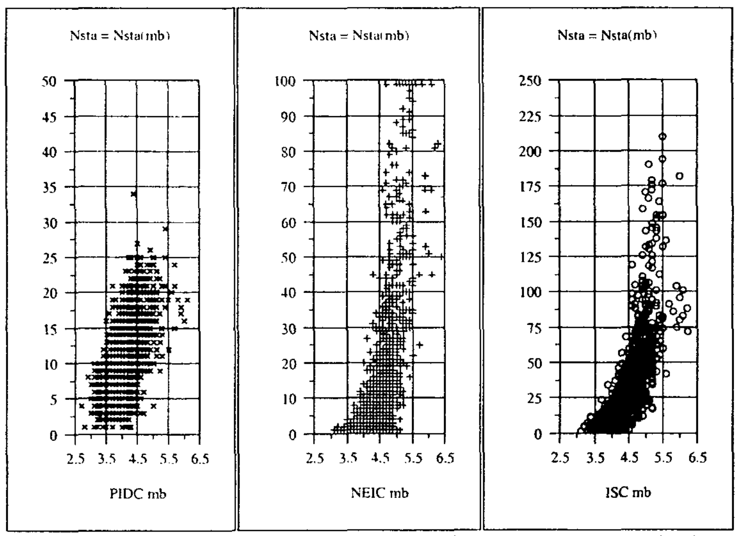
Figure 25. Four different comparisons, of magnitudes assigned by different agencies for 1998, third quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.



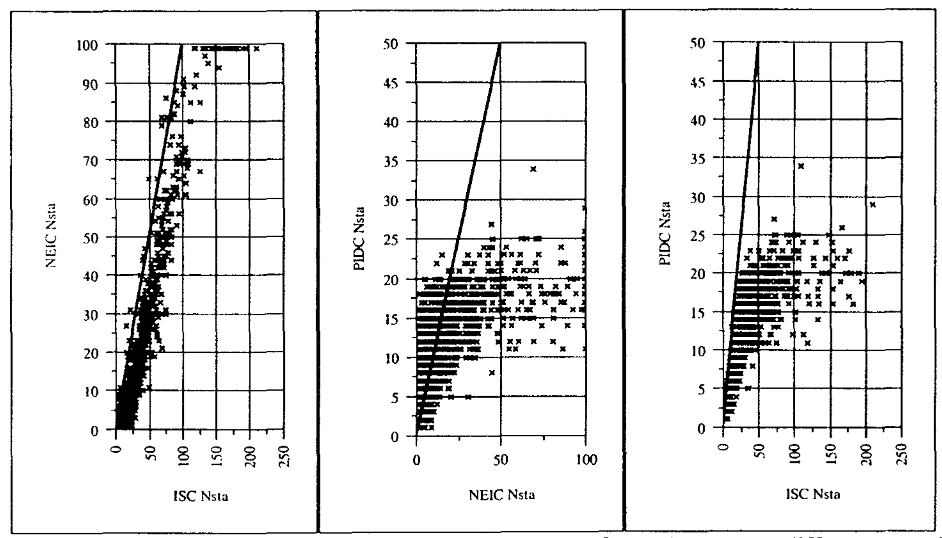
Direct comparisons of magnitude assigned by PIDC, USGS(NEIC), and ISC



Comparison of cumulative magnitude distributions

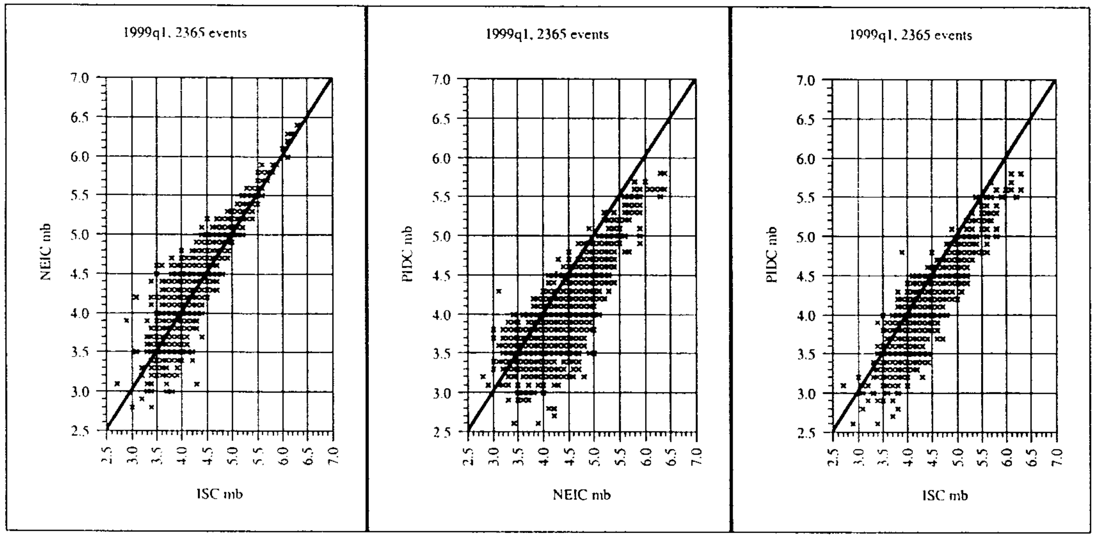


Number of stations vs. magnitude, for different network magnitudes

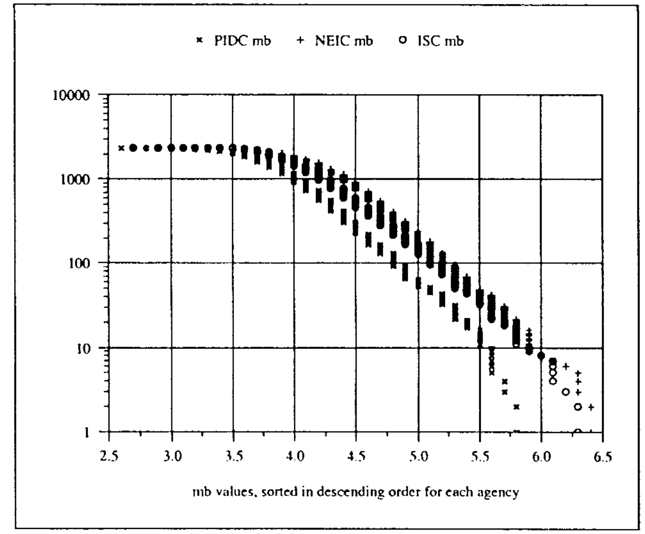


Comparisons, of numbers of stations reporting magnitudes (for each event) to different agencies

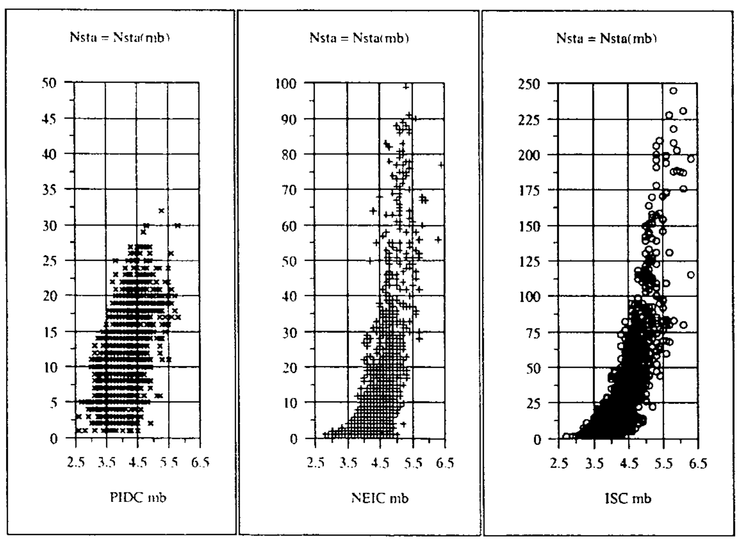
Figure 26. Four different comparisons, of magnitudes assigned by different agencies for 1998, fourth quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.



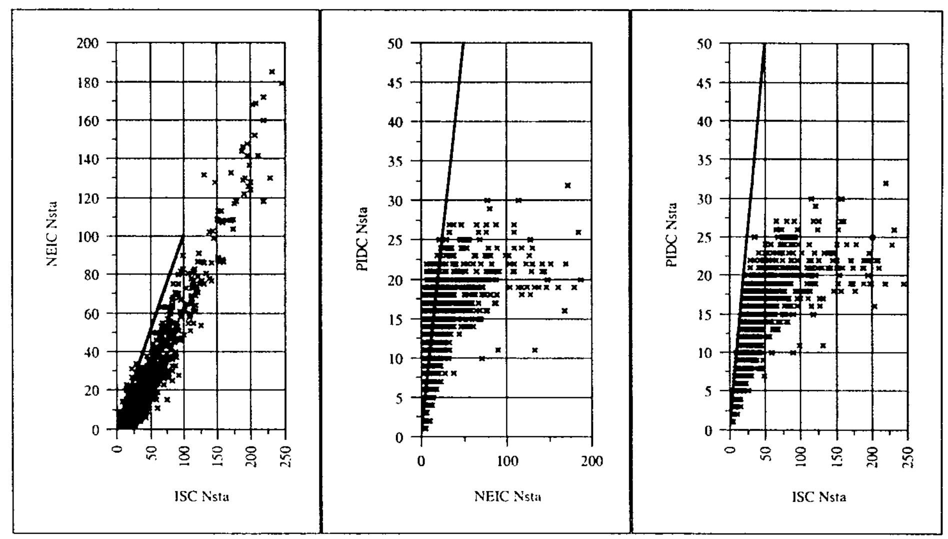
Direct comparisons of magnitude assigned by PIDC, USGS(NEIC), and ISC



Comparison of cumulative magnitude distributions

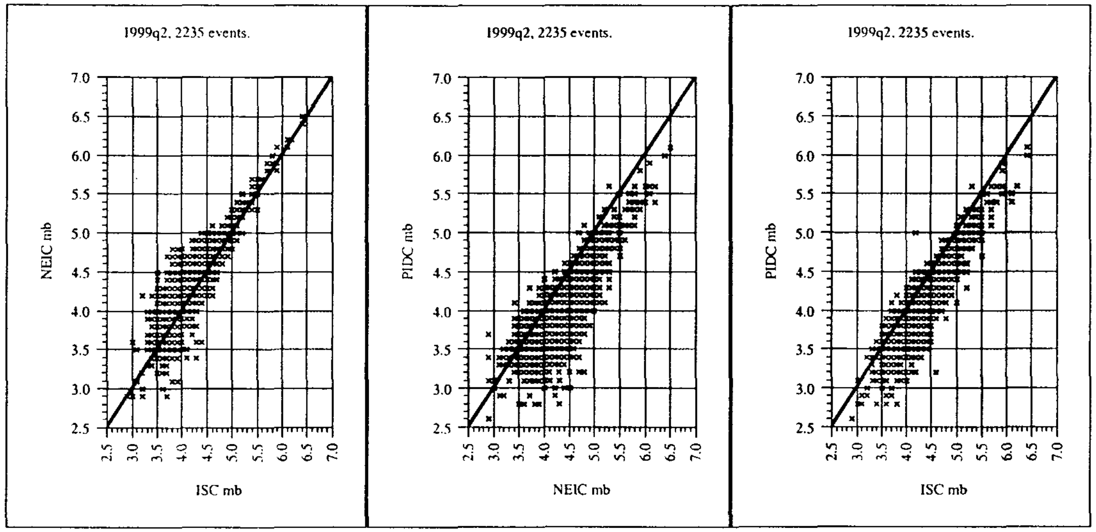


Number of stations vs. magnitude, for different network magnitudes

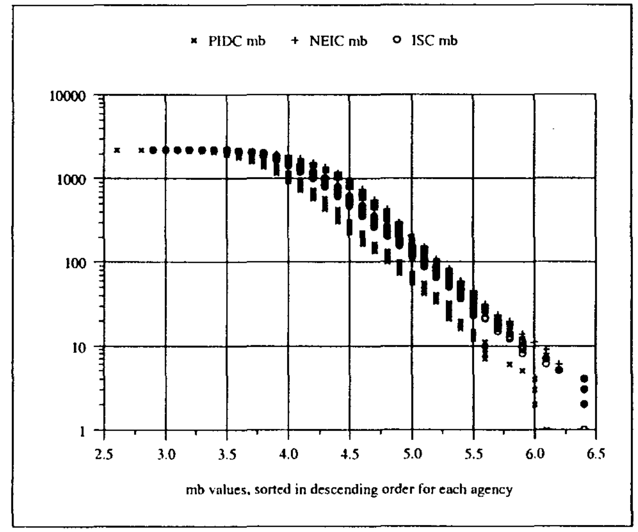


Comparisons, of numbers of stations reporting magnitudes (for each event) to different agencies

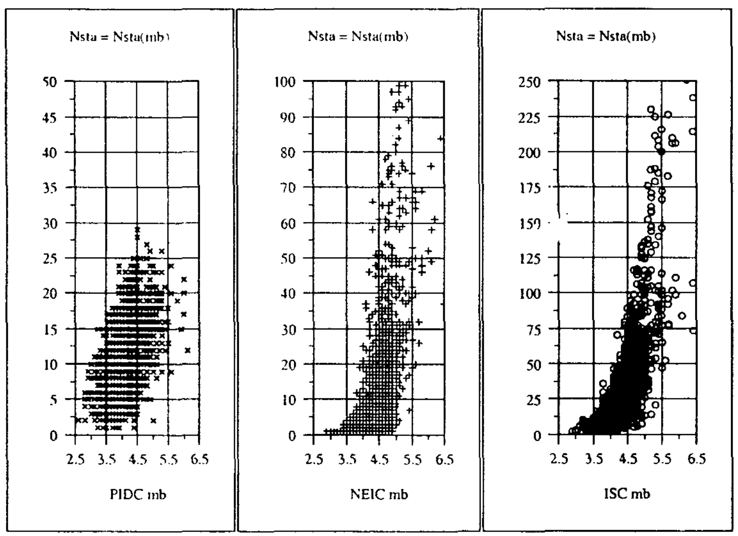
Figure 27. Four different comparisons, of magnitudes assigned by different agencies for 1999, first quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.



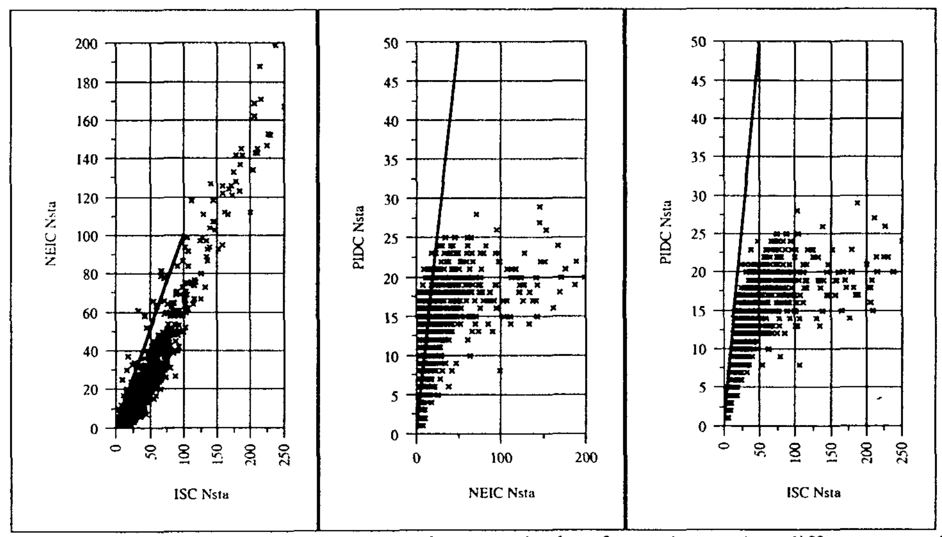
Direct comparisons of magnitude assigned by PIDC, USGS(NEIC), and ISC



Comparison of cumulative magnitude distributions

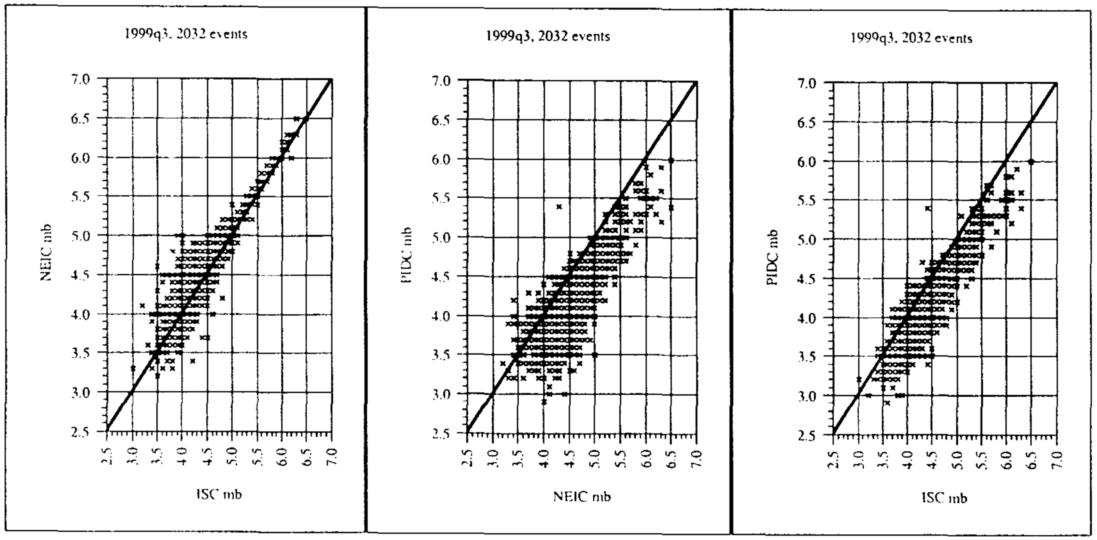


Number of stations vs. magnitude, for different network magnitudes

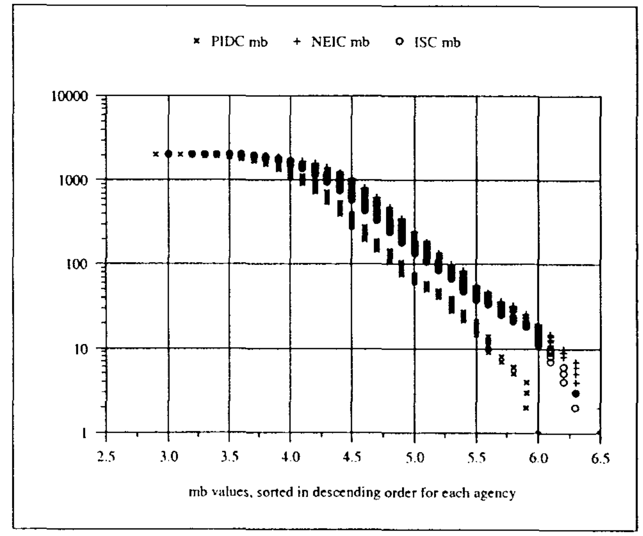


Comparisons, of numbers of stations reporting magnitudes (for each event) to different agencies

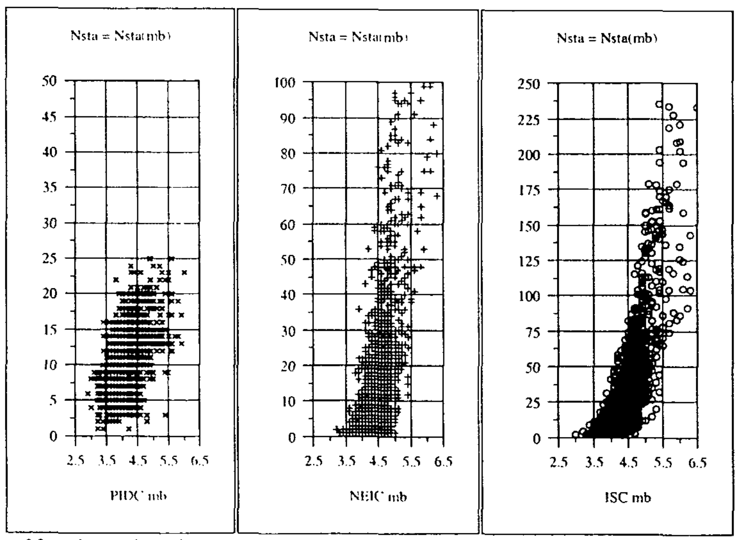
Figure 28. Four different comparisons, of magnitudes assigned by different agencies for 1999, second quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.



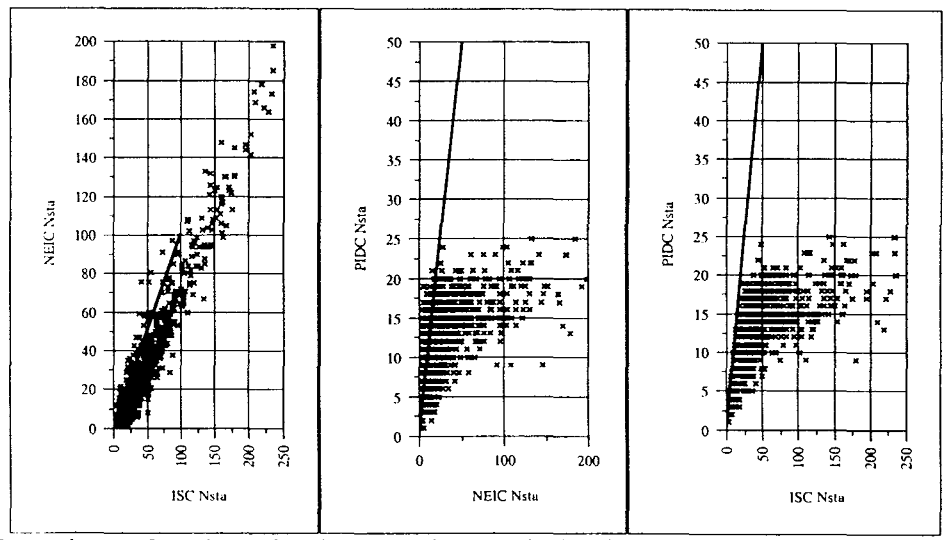
Direct comparisons of magnitude assigned by PIDC, USGS(NEIC), and ISC



Comparison of cumulative magnitude distributions

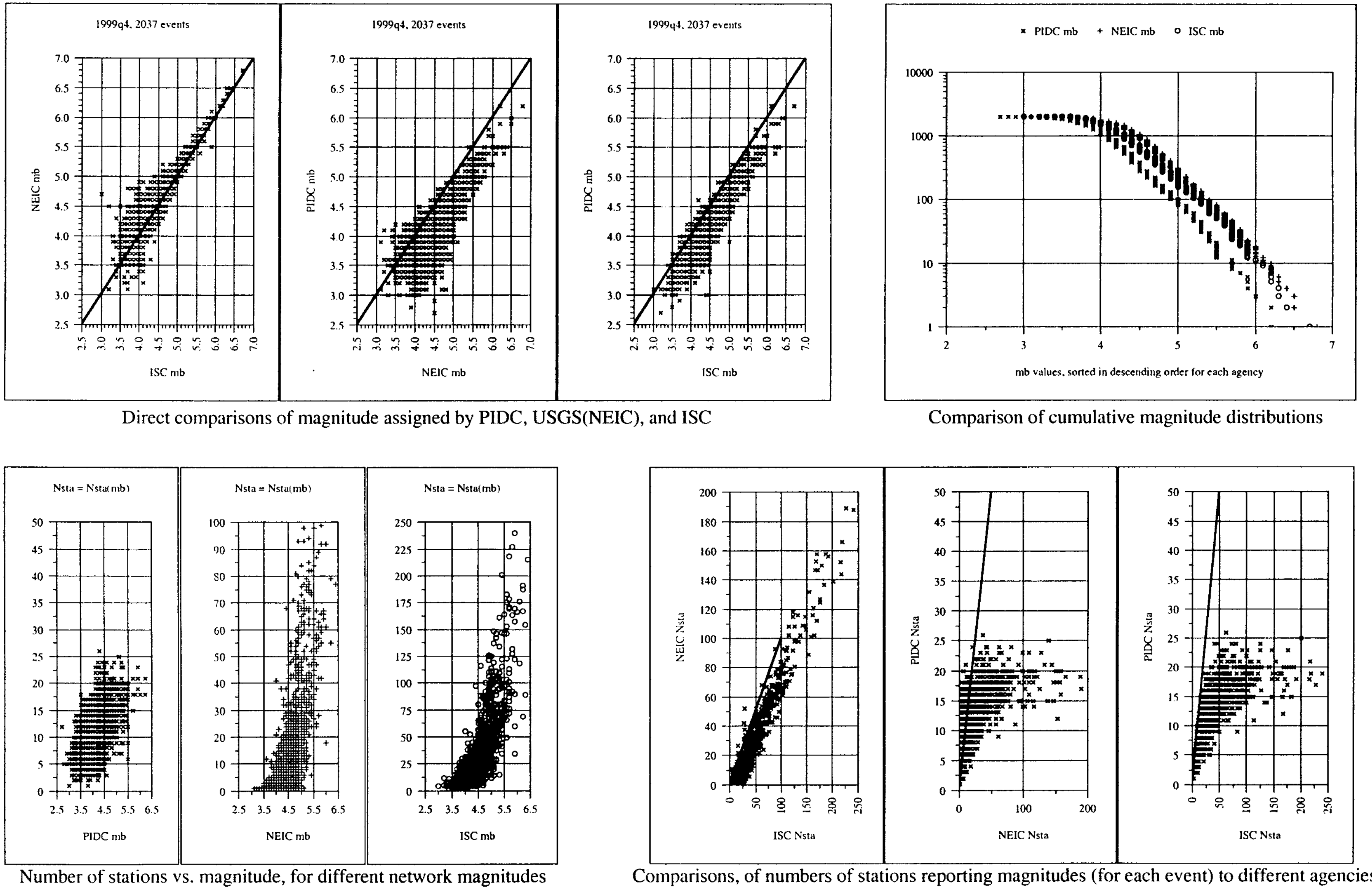


Number of stations vs. magnitude, for different network magnitudes



Comparisons, of numbers of stations reporting magnitudes (for each event) to different agencies

Figure 29. Four different comparisons, of magnitudes assigned by different agencies for 1999, third quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.



Direct comparisons of magnitude assigned by PIDC, USGS(NEIC), and ISC

Comparison of cumulative magnitude distributions

Number of stations vs. magnitude, for different network magnitudes

Comparisons, of numbers of stations reporting magnitudes (for each event) to different agencies

Figure 30. Four different comparisons, of magnitudes assigned by different agencies for 1999, fourth quarter. At top left, is the direct comparison between magnitudes for different pairs of agencies. Top right, shows the three different cumulative magnitude distributions. Bottom left, shows how the number of stations reporting measurements of amplitude and period varies as a function of magnitude, for the different agencies. At bottom right, is shown the direct comparison of stations reporting, for each pair of agencies.

In assessing the degree of dependence of the ISC on the PIDC for reported magnitudes of small events, it should be noted that discussion here is limited only to events for which there are adequate teleseismic detections to permit reporting of measured amplitude and period values by all three agencies. The ISC derives a Gutenberg-Richter mb and the PIDC uses Veith-Clawson distance corrections so the actual station magnitudes will be slightly different for any seismogram used by both the ISC and PIDC. At low magnitude, the ISC reports very large numbers of additional events for which no teleseismic mb is available.

Because of the merging of ISC and PIDC magnitude distributions at low magnitude, as shown at the top right of Figure 19, we conclude that the use, by the ISC, of PIDC measurements of amplitude and period is having a significant effect upon ISC magnitudes.

The third type of comparison (lower left of Figure 19) shows for each of the PIDC, NEIC and ISC mb scales the number of contributing stations as a function of mb. Although as expected the NEIC and ISC have far more stations than the PIDC at magnitudes greater than about 5, it is still difficult to tell how many stations are contributing at lower magnitudes though the Figure caption attempts to make an estimate. However the differences and dependencies between the three agencies become clearer with the final and fourth type of comparison given in Figure 19, which shows comparisons similar to those on the top left of the same Figure, but now using just the number of stations reporting, instead of the magnitude values directly.

It is remarkable in this fourth type of comparison, on the bottom right of Figure 19, how different the three panels are. The line $x = y$ is shown (for which the two numbers would be equal). Almost all the points in the two sub-figures showing NEIC vs. ISC and PIDC vs. ISC lie to the right of this line, indicating that the ISC almost always uses more stations to determine mb than does either the NEIC or the PIDC. This is presumably because the ISC uses almost all the NEIC s and PIDC s magnitude readings, and can only add stations in each case. From the final panel on the bottom right of Figure 19, we see from the significant number of points to the right of the $x = y$ line that indeed the ISC uses significantly more stations for determining mb than does the PIDC, for almost all events. However, it is also clear that the actual value of the ISC event mb at low magnitude is likely to be strongly controlled by the PIDC values, whereas the NEIC magnitudes must be quite independent because there is such a lack of correlation (between NEIC and PIDC) on the number of stations used, for the smaller events (see IDC vs. NEIC panel, in bottom right group of Figure 19).

We have results corresponding to Figure 19 for each of the twelve quarters in 1997 to 1999. These are Figures 19 through 30. The results we have pointed out in Figure 19, are substantially stable for the whole three-year period and are therefore essentially the same for Figures 20 through 30. We repeat the main points as follows:
(i) There is a significant offset between PIDC and ISC magnitudes, as well as that previously noted between PIDC and USGS magnitudes.
(ii) The NEIC and ISC magnitudes are not well correlated below about magnitude 5.
(iii) The cumulative magnitude distribution for each quarter shows an almost constant offset by about 0.4 to 0.5 magnitude units, over a range of about 1.5 magnitude units, for PIDC mb as compared to USGS mb; but the ISC magnitudes show a trend going from USGS values at around magnitude 6, becoming closer to PIDC values at around magnitude 4.

(iii) The ISC uses significantly more stations than does the PIDC or the NEIC, in reporting station magnitudes used to assign ISC mb. The NEIC often uses fewer stations than does the PIDC.

It is thus apparent that the PIDC magnitudes for earthquakes are significantly different from those of other agencies. Between the PIDC and ISC, magnitude discrepancies are themselves a function of magnitude, whereas the PIDC — NEIC magnitude discrepancy is approximately constant over a significant range of magnitudes.

As discussed by Granville, Kim and Richards (2002), there is merit in changing the time window within which the maximum amplitude is measured by the PIDC, in order to reduce differences between PIDC measurements and those of other agencies. An additional complication originating with the non-standard procedures of the PIDC, is that PIDC measurements have now been used by the ISC since 1995. For 1995 and 1996, any errors (for example, in instrument responses) in reporting by the PIDC has been incorporated into the ISC database. And subsequent to 1996 when such errors are minimal, we see in this study that still the PIDC has had a significant effect upon ISC magnitudes, making it very difficult for the ISC magnitudes to be used for example to analyse changes in global seismicity.

3.4 Acknowledgements.

In making comparisons between different bulletins of seismicity, such as we have done throughout the present study, we note that in contrast to those who originally published the bulletins we have had the luxury of choosing which events to study in detail. We have also been free to follow our own procedures without having to meet a daily or monthly deadline to publish a seismicity bulletin ourselves. We acknowledge that different seismicity bulletins, such as those published by the PIDC, the USGS, and ISC, meet a number of different criteria, with some emphasizing completeness, some emphasizing quick publication. We respect the effort that has gone into these bulletins, which are very significantly improved over bulletins available a decade earlier.

Our overall purpose in this research, has been to try and find ways in which the superior data derivable from the International Monitoring System (which for the first time allows global studies of seismic events to be based upon a fixed set of sensitive stations), and the superior analysis potentially that can be developed by the PIDC and IDC (in which a standardized set of procedures are routinely applied by trained analysts), can be applied to the overall benefit of the seismological community and its many customers.

Section 4

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4.1

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